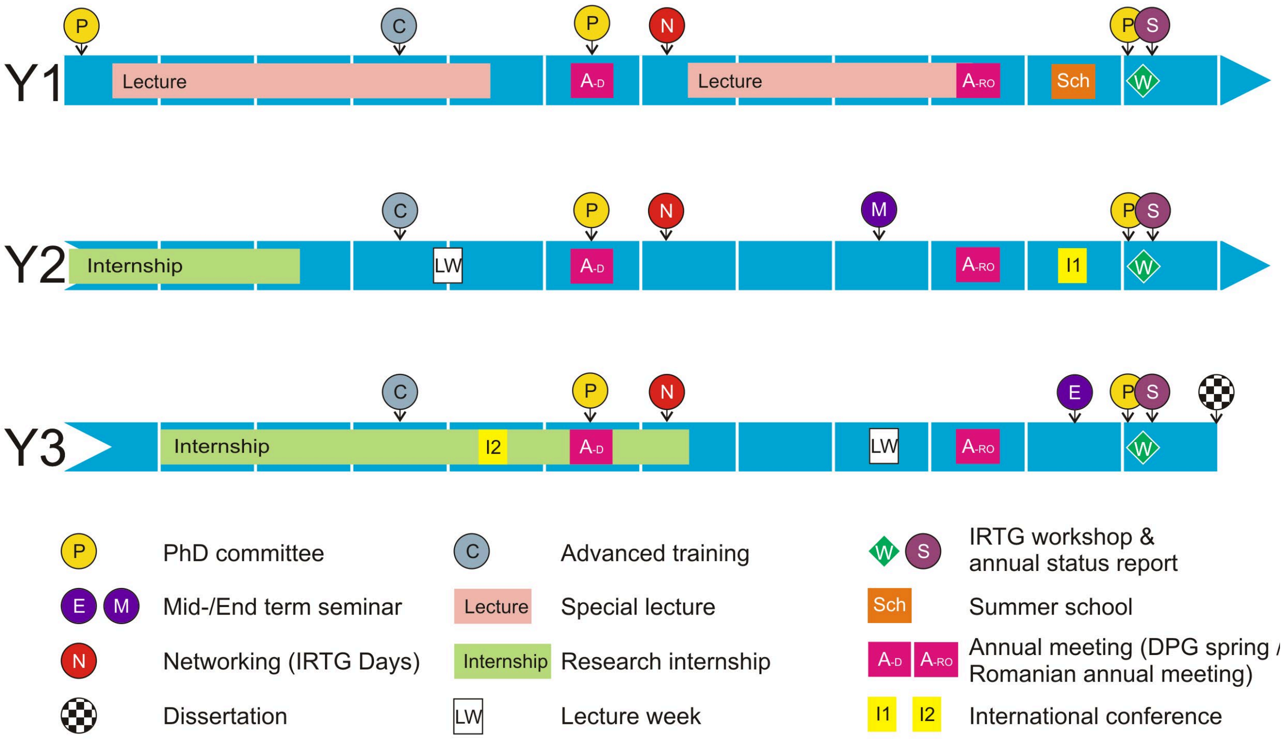
IGK 2891 Nuclear Photonics

Establishment Proposal

Funding Period: 01.10.2023 to 30.09.2028
Coordinating University: Technische Universität Darmstadt
Designated Spokesperson (D): Prof. Dr. Dr. h.c. mult. Norbert Pietralla
Designated Spokesperson (RO): Dr. habil. Eng. Calin Alexandru Ur



Title Page:

Top*: Photographies from ELI-NP*

Bottom*: Schematic timeline of the qualification and supervison concept for a research trainee within this International Research-Training Group "Nuclear Photonics". The program provides optimum support for successfully completing the doctoral research in 36 months. A trainee can start in October. The excellent research projects (see Sect.3) within the fields of Nuclear Photonics, either at TU Darmstadt or at University POLITEHNICA Bucharest represent the backbone of the training concept (indicated in blue). Various measures of the qualification program (see Sect. 4) provide career advancement and represent important aspects of the supervision concept, at the same time (see Sect. 5). A preliminary version of this concept had successfully been applied within a previous research-training group (GRK 2128 "AccelencE") and is further developed, here, for an international setting. Two extended mutual research internships at the foreign partner institutions with well-defined co-supervision support the international research experience of the junior scientists. Clear responsibilities of both, the research trainees and the research trainers, are stipulated in written supervision agreements and provide a transparent research environment for successful doctoral studies of the participating junior scientists.*

IGK 2891 Nuclear Photonics

Applicant university/universities

Lead applicant university with financial responsibility in Germany	Lead research institution with financial responsibility in Romania
Technische Universität Darmstadt Karolinenplatz 5 D-64289 Darmstadt	University POLITEHNICA of Bucharest Splaiul Independenței 313 RO-060042 Bucharest

Designated spokespersons

Spokesperson (D):	Prof. Dr. Dr. h.c. mult. Norbert Pietralla
Spokesperson (RO):	Dr. habil. Eng. Calin Alexandru Ur

Proposed funding period: 01.10.2023 to 30.09.2028

Submission deadline: 01.10.2022

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1 General Information

1.1 Applicant Universities

	Name of university
Applicant university with financial responsibility in Germany	Technische Universität Darmstadt (TUDa)
Lead university with financial responsibility in Romania	University POLITEHNICA of Bucharest (UPB)

1.2 Designated Spokesperson

Last name, first name, academic title	Research area
D: Pietralla, Norbert, Professor Dr. Dr. h.c. mult.	Nuclear and Accelerator Physics
RO: Ur, Calin Alexandru, Dr. habil. Eng.	Nuclear Physics, Accelerator Engineering

1.3 Participating Researchers

At the Technische Universität Darmstadt (TUDa)

Last name, first name, academic title	Research area
Arnold, Michaela, Dr.	Accelerator Physics
Aumann, Thomas, Prof. Dr.	Nuclear Physics
Bagnoud, Vincent, Prof. Dr.	Laser Physics
Boine-Frankenheim, Oliver, Prof. Dr.	Accelerator Science, Plasma Physics
Enders, Joachim, Prof. Dr.	Nuclear Physics, Accelerator Physics
Galatyuk Tetyana, Prof. Dr.	Nuclear Physics
Isaak, Johann, Dr.	Nuclear Physics
Kuschel, Stephan, Dr.*	Laser Physics
Martínez-Pinedo, Gabriel, Prof. Dr.	Theoretical Nuclear Physics
Roth, Markus, Prof. Dr.	Plasma Physics
Walther, Thomas, Prof. Dr.	Laser Physics and Quantum Optics
Werner, Volker, Dr.	Nuclear Physics

*in appointment procedure for tenure-track assistant professorship at TU Darmstadt

At the University POLITEHNICA of Bucharest (UPB)

Last name, first name, academic title	Research area
Balabanski, Dimiter, Prof. Dr. Eng.	Nuclear Physics
Doria, Domenico, Dr.	Laser Plasma Physics
Matei, Catalin, Dr.	Nuclear Physics, Accelerator Physics
Tanaka, Kazuo A., Prof. Dr.	Laser Plasma Physics
Ticos, Catalin, Dr. habil.	Plasma Physics
Tsoneva, Nadia, Dr.	Theoretical Nuclear Physics
Ursescu, Daniel, Dr. habil.	Laser Plasma Physics

The group of scholars comprises 21 scientists based either at Darmstadt or at Bucharest, Romania, and who serve as Research Trainers (RTs). The RTs from TUDa include 9 professors with permanent appointment and 4 established researchers who all have a track record in the field of Nuclear Photonics but who have not yet received a permanent professorship. Out of the latter, Dr. Kuschel is currently in the appointment procedure for a tenure-track qualification professorship at TUDa, Dr. Isaak holds a competitive ATHENE Young-Investigator Group Leader position and is preparing his habilitation. Drs. Arnold and Werner are permanent staff scientists at TUDa. All of them are granted the right to independently guide junior researchers, ad personam, in their doctoral research work at the Physics Department of TUDa. Their inclusion as RTs in this IRTG supports their careers for additional academic experience. With the appointment of Dr. Kuschel, together with the recent appointment of Prof. Bagnoud in 2021, TUDa has made another bold step for a strong faculty in the field of Nuclear Photonics in preparation for this IRTG.

The Bucharest-group of RTs comprises 8 experienced scientists, all of them holding a professor title or being habilitated or in the habilitation process at the UPB, or in the case of Dr. Ursescu, at the Univ. of Bucharest. All of them are granted the right to independently guide junior researchers in their doctoral research work. Since the establishment of the *European Extreme-Light Infrastructure – Nuclear Physics* (ELI-NP) at the Romanian *National Institute for Physics and Nuclear Engineering* (IFIN – Horia Hulubei), internationally leading scientists have been attracted around ELI-NP and the UPB has created a strong academic program for Nuclear Photonics. This includes very experienced professors (Balabanski, Tanaka, Ur) along with more recently habilitated scientists at an earlier stage of their careers, too. All of them can draw from extended international experience and visibility. Profs. Balabanski and Ur and Dr. Matei are experimental nuclear scientists. Prof. Tanaka and Drs. Doria, Ticos, and Ursescu are high-power laser scientists, and Dr. Tsoneva is a theoretical nuclear physicist. Their fields of internationally highly visible competences match and complement the expertises provided by the group of RTs from TUDa. Prof. Tanaka had served as the Research Director of ELI-NP since 2016, wherefore he had interupted his academic activities since then. His term had ended and he is fully devoted to his research training activities within this IRTG.

The group of RTs, given above, has developed in four positions concerning junior group leaders from the group envisioned in the pre-proposal: Dr. Rödel had chosen to leave the field and Dr. Cortes had moved to Japan for private reasons. Research-training projects at TUDa with corresponding scientific content will instead be supervised by Drs. Kuschel and Isaak. The group of RTs at Bucharest has also changed in two positions: Dr. Isaak preferred the offer of a longer-term position at TUDa over the permanent position at ELI-NP, keeping his contributions to Nuclear Photonics research training within the consortium, and Dr. Matei currently finishing his habilitation at UPB has replaced Prof. Badescu who declared to abstain from contributing to the IRTG for personal reasons.

1.4 Funding Period and Start Date

1st October 2023 to 30th September 2028 (5 years)

1.5 Number of Doctoral Researchers

This IRTG addresses research training of doctoral researchers in the fields of Nuclear Photonics. Positions for doctoral researchers in medicine or for postdoctoral researchers are not requested.

Funded from IRTG

	Financing duration per person (in months)	**Persons whose funding starts in the first funding period**	**Persons whose funding starts in the second funding period**
Doctoral researchers	36	28	15

Funded from other sources

	Persons during the first funding period
Doctoral researchers	10

Participating from partner institution

	Persons during the first funding period
Doctoral researchers	40

Cohort structure at TUDa

	Σ	**First funding period**										**Second funding period**							
		Year 1		**Year 2**		**Year 3**		**Year 4**		**Year 5**		**Year 6**		**Year 7**		**Year 8**		**Year 9**	
Cohort 1 *"Grp A"*	11 +2	🟦	🟦	🟦	🟦	🟦	🟦												
Cohort 1 *"Grp B"*	2 +2			🟦	🟦	🟦	🟦	🟦	🟦										
Cohort 1 *"Grp C"*	2 +1					🟦	🟦	🟦	🟦	🟦	🟦								
Cohort 2 *"Grp A"*	11 +2							🟥	🟥	🟥	🟥	🟥	🟥						
Cohort 2 *"Grp B"*	2 +2									🟥	🟥	🟥	🟥	🟥	🟥				
Cohort 2 *"Grp C"*	2 +1											🟥	🟥	🟥	🟥	🟥	🟥		
Cohort 3 *"Grp A"*	11 +2													🟩	🟩	🟩	🟩	🟩	🟩
Cohort 3 *"Grp B"*	2 +2															🟩	🟩	🟩	🟩

Table 1: Three cohorts of 20 research trainees, each, will be formed. Training positions are requested for 36 months (colored periods). Each cohort considers 15 positions requested from the DFG and 5 matching positions from other sources, such as core funds from the State of Hesse (given as "+2" or "+1" in the second column). Each cohort will include a limited number of training positions (sub-groups B and C, including 2 requested positions, each, and 2 or 1 matching positions from other sources) for providing research training opportunities also for interested junior researchers who graduate out-of-phase with the start of the majority of the positions (sub-group A). This results in a benefitial mix of experience levels in the group of research trainees, after the initial phase of the first two years. Then, 20 positions for doctoral researchers will be available at TU Darmstadt, in total, at any given point of time. A similar situation applies to UPB. The State of Hesse made an extraordinary investment by funding the LOEWE research project "Nukleare Photonik" in preparation of this IRTG from 2019 until Sept. 2023. This program had helped to pre-attract students and junior researchers in Nuclear Photonics locally and internationally. They will be encouraged to apply for research training positions within this IRTG in year 1, too (see Sect. 5.1). Positions for members of Group B of Cohort 3 will be continued for at least 12 months more from other sources that will become available from the matching of Group A.

Combined expertise in the fields of high-intensity laser science and nuclear physics is rare, but very much needed. The demand on well-trained researchers in the field of Nuclear Photonics is high. Prominent examples for the need of well-trained scientists in Nuclear Photonics are international research infrastructures, such as the Extreme-Light Infrastructure (ELI) in Europe, national high-power laser laboratories, or commercial initiatives, such as the Darmstadt start-up company *Focused Energy* (www.focused-energy.world), that alone are looking for dozens of scientists trained in Nuclear Photonics per year. The State of Hesse had responded early to these demands. In 2019 it established at TUDa the research project "Nukleare Photonik" in preparation for this IRTG and supports it from 1.1.2019 – 30.9.2023 with 4.8 Mio.€ total funds within its science-development program LOEWE. All eight junior researcher positions in the LOEWE project are filled. The demand on the job market and the request of junior scientists for research training in the emerging and appealing fields of Nuclear Photonics require that we apply for 15 positions for doctoral researchers per cohort. Additional 5 junior researchers per cohort will be funded from other sources as committed already in the endorsed pre-proposal. The same structure is foreseen for the Romanian partner institution and the Romanian funding agency has prepared itself for this request (see Sect. 8). All junior researchers will equally profit from the program and the support of the IRTG for their research training.

We foresee a graduation time of 3 years, such that three cohorts of research trainees can benefit from this program. This range is ambitious, but it is based on the experience from about two decades of research training in photonuclear reactions and plasma physics at TUDa, taking into account that the intense research training within the IRTG will extraordinarily support the trainees in reaching their research goals fast. The LOEWE research project on Nuclear Photonics at TUDa had initially been granted by the State of Hesse for 48 months from January 2019 to December 2022. In order to jumpstart this IRTG the state funds had cost-neutrally been extended by the ministry until 30.9.2023 such that the researchers trainees can enter efficiently running research programs. This situation is expected to be very attractive for the best junior researchers in these fields, internationally, for securing a sufficient pool of competitive applicants for the initial recruiting for this IRTG over the summer 2023. We furthermore expect that the demand for research training in Nuclear Photonics will continue to be large in the following years, too. We thus want to provide training opportunities in the following years, as well. Correspondingly, we foresee smaller late-starting sub-groups of the three cohorts, and consequently partly overlapping cohorts. This has the benefit that incoming junior researchers mix with more experienced doctoral researchers for ensuring continuity of junior researcher's participation and efficient transfer of knowledge at both partner institutions and amongst the groups based at TUDa or at UPB. The training timeline, shown in Fig. 34 on p. 40 or on the title page, expects regular beginning of the research training in October and graduation after 36 months. Research Trainees on matching positions may enter the program at any time as soon as a training slot becomes available.

2 Profile of the Research Training Group

The proposed International Research Training Group (IRTG) addresses the training of junior scientists in the newly emerged, interdisciplinary field of ***Nuclear Photonics*** which bridges from photonuclear reactions and the generation of energetic particle beams by present-day high-intensity lasers to their applications in research and commercial technology. The training program exploits unique capabilities at TU Darmstadt (TUDa) with its facilities for **MeV-ranged photon beams** at the superconducting electron accelerator S-DALINAC along with its research program at the **PHELIX high-intensity laser system** at the Darmstadt GSI Helmholtz Centre, and at the University POLITEHNICA of Bucharest (UPB) with its research program at the European ***Extreme-Light Infrastructure – Nuclear Physics*** (ELI-NP) facility in Magurele featuring two synchronized 10-PW lasers and the VEGA system for the production of quasi-monochromatic γ–ray beams from Laser-Compton Backscattering (LCB), which is under construction. The research projects tackle contemporary challenges for the development of laser-generated particle beams, utilize photonuclear reactions for fundamental nuclear research, and develop detector technology and experimental methods beyond the state of the art.

TUDa is renown for an excellent world-leading research track record in electron-accelerator science and photonuclear reactions, ranging from the leading exploitation of LCB beams for photonuclear research (**Aumann, Enders, Isaak, Pietralla, Werner**) or the laser-based generation of most intense particle beams (**Bagnoud, Boine-Frankenheim, Kuschel, Roth**) to the establishment of the first performant superconducting multi-turn Energy-Recovery LINAC in the world (**Arnold, Boine-Frankenheim, Enders, Pietralla**), thereby pushing the technology for an ultimate, fourth-generation LCB γ–beam facility for nuclear science and applications in nuclear astrophysics (**Martinez-Pinedo**). Excellent expertise on the latter is emphasized by the award of one of the 2022 Leibniz Prizes and by an ERC Advanced Grant. This strength is complemented by leading expertise in quantum optics (**Walther**) and particle-detector technology (**Galatyuk**). TUDa is furthermore fostering the emergent field of Nuclear Photonics by having appointed **two new faculty** in this field in the last two years alone, in preparation for this IRTG. Nuclear Photonics research in this breadth, excellence, and international visibility is absent at any other university in Germany.

In 2012, the European Commission and the Romanian Government approved the design, development and construction of the ELI-NP facility from European Regional Development Funds and from funds of the Romanian Government to establish world-leading instrumentation for fundamental research and applications in the field of Nuclear Photonics. ELI-NP houses the **two most powerful laser systems** in the world, operational with a **peak power of 10 PW, each** and is constructing the **Variable-Energy Gamma beam system** (VEGA) designed for providing brilliant quasi-monoenergetic gamma-ray beams with unprecedented narrow bandwidth and intensities. A versatile research program has been suggested at ELI-NP and an adequate scientific staff had been attracted to Romania with academic affiliation to the UPB. This world-wide unique large-scale research infrastructure provides exciting and unprecedented research opportunities in Nuclear Photonics reflected in the program of this IRTG.

This IRTG on Nuclear Photonics brings together the leading scientists in this field at TUDa and at Bucharest with matching expertise. It is motivated by the urgent need for well-trained scientists in this growing field in Europe, and world wide, and for collaboration and mutual exchange of outstanding expertise of the RTs for efficient scientific usage of the newly established European infrastructure at Bucharest. This IRTG will offer its research trainees from both institutions privileged access to the full suite of leading scientific infrastructure on Nuclear Photonics in Europe. It will, thereby, provide unprecedented research training for scientific work force in Nuclear Photonics of the next decades.

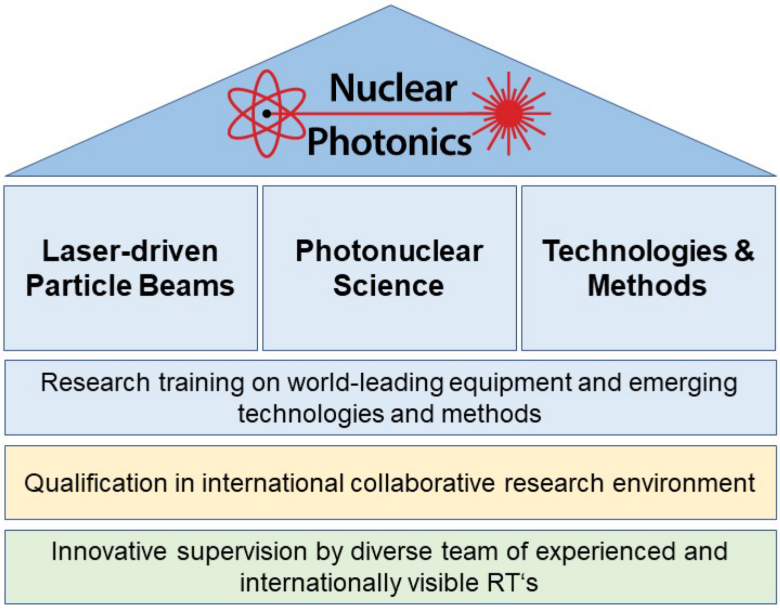


Figure 1: *Schematic overview on the concept of this IRTG. Nuclear Photonics is an emerging interdisciplinary research field. It comprises advances on high-power laser-driven generation of beams of MeV-ranged photons, of light and heavy ions, and of brilliant neutron bursts. Research on photonuclear science will provide precious data for nuclear structure physics, nuclear astrophysics, natural nucleosynthesis, and nuclear fission research, along with their scientific interpretation. Advances in laser-target interactions, specific aspects of particle accelerator science, radiation-hard particle detectors, and developments in metrology will expand the technological and methodological reach of Nuclear Photonics. Research trainees will benefit from world-leading instrumentation in this field which they can exploit for their research project in an international collaborative and intellectually challenging environment with the guidance by a diverse team of experienced research trainers.*

The research training plan of the proposed IRTG embraces the entire scientific production chain of Nuclear Photonics from the fundamental methods for the laser-induced generation of photon- and particle beams and their detection and quantitative characterization to their usage in fundamental research in nuclear science and nuclear astrophysics or for potential technological applications. All research projects (see Sect. 3) expand beyond the current state of the art in three related areas of research:

A. Development of novel laser-generated radiation sources
B. Scientific exploitation of MeV-ranged photon beams
C. Advancement of methodology and instrumentation for Nuclear Photonics

They define the project areas of the proposed research program. Each project is led by two RTs, one from TU Darmstadt, responsible for guiding the research trainee to their graduation, and one from UPB. This establishes or extends close collaborations at both training sites from the start. The basis of the IRTG is set by the suite of excellent and challenging research projects (see Sect. 3) and the experience of its RTs (see above and Sect. 1.3) ensuring an exciting research environment for all trainees. The research projects are heavily intertwined with each other fostering a collaborative and supportive atmosphere among the trainees. The junior researchers will primarily be based at their home institution, but will benefit from participation in the research projects of their co-RTs at the respective other institution, e.g., during their extended internships at the partner institution. Each trainee from both partner institutions will have access to the experimental and computing facilities in both countries and will benefit from the common overarching qualification and supervision concept as summarized in Figure 2. Annual workshops, advanced training offers, lecture weeks provided by external experts, opportunities for networking with peers from other international research institutions, and attendances of national science meetings, international summer schools and scientific conferences will complete the qualification program.

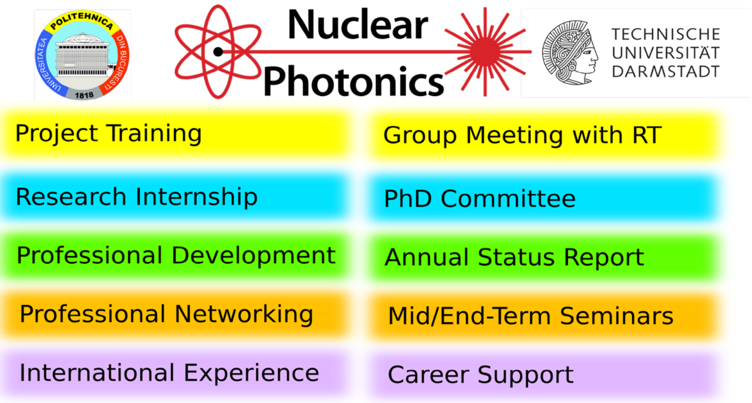


Figure 2: *Qualification program and supervision concept of the IRTG. They consist of well-selected measures geared towards supporting scientific excellence, as well as early scientific independence and international visibility (See Sects. 4 and 5 for details).*

The supervision of the research trainees is based on a dedicated well proven concept with further developments for this international setting (see Sect. 5). Besides regular meetings with their RTs, bi-annual meetings of the PhD committees, involving also an external mentor, will aid to ensure that appropriate progress is made. The annual in-person workshops and a hybrid seminar series serve as a stage for progress reports and lecturing experience. The IRTG is embedded in an open-minded, inclusive, and scientifically challenging environment at both universities. Beyond the research training and scientific qualification, the IRTG will raise interest of its participants in the history, society, and political processes in the country of the partner institutions by lectures to these topics during the annual workshops.

This present proposal includes advances in reaction to the requests and recommendations of the DFG Review Board 307-311. Section 3 provides the requested, more detailed overview on the 40 initial training projects. It is by far the longest section of the entire proposal which itself is limited to 65 pages, in total. The justification of their number is provided in Sect. 1.5 and further elaborated on in Sect. 3. The detailed demarcation of the research program within this IRTG to the programs addressed in the Collaborative Research Center SFB 1245 and the expiring Research Training Group GRK 2128 is provided in Sects. 6.2 and 6.3. Opportunities for advanced training in the environment of TUDa, in particular, by the graduate organizations INGENIUM and HGS-HIRe, are included in the IRTG's program.

3 Research Program

Motivation and Foundation of the Research Program: *"Just as the 20th century depended on the electron to witness advances in electronics and electricity, the 21st century relies on the photon to propel many scientific breakthroughs in different fields."* This statement is a quote from record 413590 published 26 February 2020 on the Community Research and Development Information Service (CORDIS) of the European Union and emphasizes the paramount importance of quantum optics, laser science, photonic reactions with matter, and the corresponding technology for sustained European competitiveness in scientific and commercial activities. A significantly growing labor market for well-trained scientists is anticipated. While most of the commercial applications address low or moderate intensity laser technology, or photons with energies up to the UV or X-ray regime, there is a panoply of scientific challenges and conceivable commercial applications that would benefit from high-intensity lasers or from photons with energies exceeding the X-ray regime. The emerging field of **Nuclear Photonics** addresses the laser-induced generation of particle beams and the scientific exploitation of photonuclear reactions [1]. The establishment of ELI-NP through the support of the European Commission aims at boosting the impact of Nuclear Photonics on fields of fundamental scientific research as well as on commercial applications. Reaching this goal requires an educated work force, trained on the challenges related with the exploitation of ultra-high intensity lasers, induced radiation and photonuclear reactions, capable of applying and developing corresponding instrumentation and methodolgy. This IRTG addresses these important aspects by offering a **world-class research training on Nuclear Photonics** by leading scientists in the fields at the fore-front of the corresponding science and technology.

This IRTG focuses on the qualification of excellent international junior scientists from natural or engineering sciences who choose a career in Nuclear Photonics for their doctoral studies in an international environment. Both partner institutions offer privileged access to extraordinary infrastructure, unparalleled in the world and complementing each other for the field of nuclear photonics, including the superconducting S-DALINAC electron accelerator with its continuous-energy bremsstrahlung facilities, the PHELIX laser system at GSI, and the ultra-high intensity lasers or the VEGA construction at ELI-NP. The applicant institutions have gathered a strong group of experts with a long-standing record of accomplishments in the fields and of respective academic guidance. Less-senior goup leaders have been included in the group of RTs. They, too, have demonstrated their potential by recent significant contributions to the fields of Nuclear Photonics. Their inclusion in the group of RTs in a collaborative environment will foster their research training experience (see below).

3.1 Objectives and Work Program

The proposed IRTG will focus on the new research field of *Nuclear Photonics*, which develops and utilizes laser-generated particle beams or MeV-ranged photon beams and combines novel radiation sources with methods and technologies from nuclear physics for applications in nuclear research or commercial technology. The IRTG is motivated by the urgent need for well-trained scientists in this rapidly growing research area in Europe and world wide, and by the outstanding instrumentation under construction or already at the disposal to the applicants [2–5].

In 2012, the European Commission and the Romanian Government approved the design, development and construction of the *European Extreme-Light Infrastructure – Nuclear Physics* (ELI-NP) from European Regional Development Funds and from funds of the Romanian Government to establish world-leading instrumentation for fundamental research and applications in the field of Nuclear Photonics. ELI-NP houses the two most powerful laser systems in the world, operational with a peak power of 10 PW, each [4,5], and the Variable-Energy Gamma beam system (VEGA) providing brilliant quasi-monoenergetic gamma-ray beams with unprecedented narrow bandwidth and intensities [6] to be completed in 2025. A versatile research program has been suggested at ELI-NP [4,6–8]. This world-wide unique large-scale research infrastructure provides exciting research opportunities in Nuclear Photonics that we address in the scientific program of the proposed IRTG. While the two world's most intense 10-PW lasers had been established on time at ELI-NP, the construction of the VEGA system is delayed due to the financial failure of the vendor. Scientific and technological collaboration between ELI-NP and the experts at TU Darmstadt on the completion of the VEGA construction is urgently needed for realizing its establishment, commissioning, and future scientific exploitation. The research training plan embraces this entire scientific and technological production chain of Nuclear Photonics from the fundamental methods for the generation of ultra-intense photon- and particle beams to their detection and quantitative characterization as well as their usage in fundamental research or for potential technological applications. The training projects will expand beyond the current state of the art in three related areas of research:

A. Development of novel laser-generated radiation sources
B. Scientific exploitation of MeV-ranged photon beams
C. Advancement of methodology and instrumentation for Nuclear Photonics

Main focus of this IRTG is to progress on various aspects related to the technology, methods, and exploitation of Nuclear Photonics. The core research ideas address the generation of particle beams from high-intensity lasers, including the production of MeV-ranged photon beams, light charged ions, or neutrons, and the control and synchronization of laser pulses, as well as their scientific application.

Photonuclear reactions are applied to world-leading fundamental research on a variety of nuclear phenomena, including dipole excitations of particle-bound nuclear quantum states, their level densities and strength functions, the decay pattern of particle-unbound structures and resonances, and nuclear fission modes. The technology that has become available requires the development of advanced instrumentation and methods including new tools capable of coping with and exploiting the high intensities and providing the required precision.

The proposed research projects are well suited for training young researchers in the interdisciplinary fields of Nuclear Photonics, precisely exploiting the synergies between the research facilities in Darmstadt, namely S-DALINAC at TU Darmstadt or PHELIX at GSI, and ELI-NP in Magurele, Romania. The list of project areas, numbers of requested PhD positions, and those positions provided by other funds matching the project are given in the table below:

Table 3.1: Project Areas of the IRTG and number of requested and matching positions.

	Project Area Name	request	match
A	Novel laser-generated radiation sources	10	3
B	Scientific exploitation of MeV-ranged photon beams	11	3
C	Advanced instrumentation for nuclear photonics	9	4

Project Area A: Novel laser-based radiation sources
(RTs: Arnold, Bagnoud, Boine-Frankenheim, Doria, Kuschel, Roth, Tanaka, Ursescu, Walther)

Project Area Overview: Research Area A will address the development of photon and particle beams with unprecedented characteristics such as intensity, emittance, brilliance, and time structure [4,5,9,10]. Proton, neutron and gamma-ray beams will be produced by the relativistic interaction of high intensity lasers with solid and gaseous targets [4,6,7,10–21]. With the dual 10-PW laser-system at ELI-NP, a world-wide unique laser infrastructure is in operation which will allow to enter new frontiers in the ultra-relativistic interaction regime [5].

Research in area A comprises laser-induced gamma-ray beam production. On one hand, this will be addressed by the laser interaction with micro-structured solid-density targets [22] in near-critical plasma channels [23,24]. The proposed experiments with the 10 PW lasers at ELI-NP might be the basis for studying strong-field quantum electrodynamics [25,26] and phenomena in astrophysical plasmas [27]. On the other hand, the program includes the first demonstration of a fourth-generation photon source at the S-DALINAC electron accelerator at TU Darmstadt [3,28] and its quantitative characterization for beam diagnostics or spectroscopy. An advanced design of an optical cavity for photon-beam production is at the center of experimental techniques for LCB at high repetition rate [29,30] and is crucial for the completion of ELI-NP's VEGA system.

Ion acceleration in a wide parameter space will be studied at the PHELIX laser at GSI and at the laser facilities at ELI-NP. The onset of relativistically induced transparency (RIT) of solid-density plasmas [9,14] and radiation pressure [11–13,31–33] represent intriguing effects in the ultra-relativistic regime that can be exploited to improve proton and ion acceleration from thin foil targets. Several experimental techniques, that are established at smaller laser systems, must be adapted for scaling up experiments to the 10-PW level [20]. These developments include the control of the laser pulse contrast [2], plasma mirrors for contrast cleaning [34], diagnostics for laser-accelerated particles [RT1,RT2,21], high repetition rate targetry [35–37], proton beam transport [38–41], and radiological studies [42,43]. Pump-probe experiments with two high-power laser beams will become possible with the experimental infrastructure at ELI-NP [4,5,26,44–51].

As an application, laser-driven proton beams will be converted into short-pulsed neutron beams [52–55], that are ideally suited for time-resolved neutron radiography and spectroscopy. Laser-based neutron sources have high application potential, e.g., in the nondestructive analysis of materials [54,56], e.g., for sensitive components or high-level nuclear waste. High-energy proton and neutron sources will be developed at ELI-NP with characteristics that hitherto require nuclear reactors or spallation sources at kilometer long accelerators.

Project Area B: Scientific exploitation of MeV-ranged photon beams
(RTs: Aumann, Balabanski, Enders, Isaak, Martinez-Pinedo, Matei, Pietralla, Tsoneva, Werner)

Project Area Overview: Photonuclear reactions will be applied for contemporary nuclear science from nuclear structure to astrophysics, topics to which some of the RTs have previously made transformative contributions. The research projects range from photonuclear disintgrations of light nuclei and tests of nuclear structure theory [RT3,57,58], to the properties of nuclear resonances [59,60] and fission processes [61,62] of heaviest nuclei. These topics are relevant for our understanding of cosmic objects such as binary neutron-star mergers and for the assessment of nuclear reaction rates that are relevant for the s-, p- and r-processes of nucleosynthesis [RT4,63–66] or even for primordial Big Bang Nucleosynthesis [67].

Research Area B addresses studies of photonuclear reactions with quasi-monoenergetic photon beams, provided currently at the HIγS facility at the Triangle Universities Nuclear Laboratory (TUNL), Durham, NC, and with advanced parameters by the VEGA system of ELI-NP in the near future, and with continuous-energy bremsstrahlung at the S-DALINAC [3]. The structure of nuclear dipole modes ranging from light isotopes in the A~10 mass regime [RT3,68] towards heavy deformed nuclei in the rare-earth and actinides region will be investigated experimentally by scanning the nuclear photoresponse at the continuous-energy bremsstrahlung beams at TU Darmstadt. These experiments will be complemented by detailed studies of regions of particular interest with high energy resolution and sensitivity at the quasi-monochromatic photon beams. For these studies, different simulation tools have been developed which take into account the characteristics of the photon beams and the available detector arrays [69–73].

The experimental data will be compared to microscopic nuclear structure theory based on an extended quasiparticle-random-phase approximation with multiphonon coupling [57,58], which was used to predict new modes of nuclear excitation [65,74–77]. Exploiting the linear polarization of the provided quasi-monochromatic gamma-ray beams [RT5], magnetic dipole excitations of heavy deformed nuclei [78–81] will be investigated for clarifying the distribution of orbital and spin-M1 strength [82,83] as a function of nuclear deformation. Electric dipole strength will be studied with total photoabsorption measurements at the photon tagger NEPTUN at TU Darmstadt below and above the particle-separation threshold [RT6,84–86] contributing information on the nuclear dipole polarizability which itself contains precious information on the density dependence of the nuclear symmetry energy [65,87–90]. The latter is an important prerequisite for the understanding of objects with extreme neutron excess as, for instance, occurring in the crust of neutron stars. Especially, the evolution of the GDR as a function of nuclear deformation has become of particular interest due to recent data from inelastic proton and real-photon scattering experiments [91]. Furthermore, photonuclear disintegration processes will be studied above the particle-separation threshold [86].

The modeling of the observed elemental abundances depends, among other quantities, on nuclear photon strength functions. Intense quasi-monoenergetic linearly-polarized photon beams enable the disentanglement of different contributions of nuclear photon strength functions with new techniques [92–95] including the method of nuclear self absorption [96–98]. The experimental data will be interpreted with respect to nuclear structure phenomena and their relevance for r-process nucleosynthesis in binary neutron-star mergers [RT4,99]. Studies of key photonuclear reactions will shed light on the p-process nucleosynthesis [66].

While extensively used on a large-scale for the generation of electricity, the nuclear fission process still cannot be described accurately on a macroscopic level [100]. Hence, the fine-structure of photo-induced fission processes of transuranium actinides will be studied in dedicated photofission experiments [61,62,101–103] with the quasi-monoenergetic photon beams at ELI-NP and HIγS exploiting correlations between fragment observables [61,101] using a position-sensitive ionization chamber [104]. The experimental nuclear fission data will be interpreted in microscopic descriptions [105,106] Sub-barrier fission studies will provide deeper understanding of the fission barriers [107].

Project Area C: Advanced instrumentation for nuclear photonics

(Arnold, Enders, Galatyuk, Isaak, Matei, Tanaka, Ticos, Ur, Ursescu)

Project Area Overview: This research area is devoted to the development of methods and instrumentation for work areas A and B, capable of producing, coping with, and exploiting the extreme peak intensities of novel particle and laser beams. It will comprise the development of dedicated instrumentation for the special needs of research in the fields of Nuclear Photonics including scientific contributions to the completion of the VEGA system.

Laser-induced particle acceleration may be further enhanced by optimizing the laser-target interaction. The training projects will address the most promissing research topics either by optimizing the laser pulse delivered onto the target or by utilizing solid targets with particular features. Subsequent characterization, capture, and transport of laser-generated charged-particle beams require the development of particular transport ion-optics and of radiation-hard particle detectors with high spatial segmentation and best possible time resolution [4,26,46,47] (so-called 4-D detectors). 4-D particle detectors with a time resolution of better than 50 ps and improved radiation hardness based on diamond detectors [108,109] or on the Low-Gain Avalanche-Diode (LGAD) technology, will be developed and applied [110] for instance for the characterization of laser-generated radiation from work area A.

In order to study dipole strengths around the particle threshold and gamma/neutron-decay branches, the simultaneous detection of γ-rays and neutrons is necessary. Existing detector arrays need to be newly arranged and combined to make use of the specific angular distributions of gamma-rays and neutrons emitted from the nucleus after excitation by a fully-polarized beam. Also, further developments of the detector signal readouts are necessary [111–113].

Tools and methods for improving the performance and control of ELI-NP’s VEGA system are addressed including developments on VEGA electron-beam diagnostic elements applying methods from artificial intelligence for improved beam tuning and stabilization, developments of novel gamma-beam diagnostics and monitoring capabilities [RT7,114–117], and studies on optimizing the lattice of VEGA’s storage ring for increased intensity of gamma-beam production.

While VEGA will be a third-generation gamma-ray source based on the process of Laser-Compton backscattering (LCB) [18] on an ultra-relativistic ($\gamma > 10^3$) electron beam in a storage ring, its intensity and brilliance are subject to the inevitable emittance limitations inherent to a storage-ring design. For overcoming this limitation towards brilliances even beyond what will be available soon at the VEGA system of ELI-NP, we will develop the design of brilliant MeV-ranged photon sources using different a further advanced approach. We will investigate the design of a fourth-generation gamma-ray source based on the process of LCB on an electron beam from a linear accelerator (linac) with superior emittance as compared to a storage ring [RT8]. The lattice of an ultimate fourth-generation photon sources based on LCB on the beam of a high-power energy-recovery linac will be established. As the emittance of an electron linac is ultimately limited by its electron gun, research on laser-cathode photo-guns [118] aim at lowest possible emittance.

MeV-ranged photon beams from fourth-generation photon sources will make new methodological approaches possible. Photonuclear cross sections are usually determined relative to well-known calibration standards [94,119–123]. To date, the precision of those standards is limited for instance due to imprecise knowledge of the effective temperature of the investigated chemical compound [RT3,96,98,124]. Therefore, a new method based on temperature-dependent self-absorption experiments will be further advanced to enable measurements of natural nuclear level widths providing improved data for commonly used calibration standards with unprecedented precision.

3.1.1 Scientific Coherence and Justification of the Envisaged Research Projects

While geared primarily towards excellent research training on some of the most challenging research topics of Nuclear Photonics, the projects have been carefully selected for making coherent progress for maximum impact of Nuclear Photonics on even larger scientific or societal challenges. Let us make here two examples, only, for clarity:

(i) Many research projects, either at the partner institutions (e.g., SFB 1245, ELEMENTS) or internationally (e.g., the international IReNA network and its partners) strive for understanding the formation of chemical elements in the Universe. This IRTG develops tools for potential application of Nuclear Photonics in these endeavors. For example, aspects on the primordial Big-Bang nucleosynthesis are addressed in project B-1. The rapid neutron-capture process, responsible for the natural synthesize of the heaviest chemical elements in astronomical events, terminates in the r-process fission cycle. Fission processes and the structure of fissile nuclei are addressed in projects B-10 – B-13. The structure and abundance of seed nuclei or the aspects of (neutron-)capture reactions are addressed in projects B-2 – B-9. Corresponding experiments will benefit from advances on photon-beam generation, diagnostics, and detection from projects C-6 – C-10. Future photonuclear reactions will benefit from the development of ever more intense artificial MeV-ranged photon beams from projects A-4 – A-7, C-11, and C-12. Multistep neutron capture reactions on short-lived excited nuclear states may be observable in the laboratory, only, by using super-intense high-power laser-generated neutron bursts. Their development is directly addressed in projects A-12 and A-13, while they can benefit from advances of laser-generated charged particle beams and their diagnosis as addressed in projects A-8 – A-11, C-4 and C-5, or by the initial interaction of high-power lasers with target material as addressed in projects A-1 – A-3, and C-1 – C-3. This IRTG comprises expertise ranging from the enabling technology to the scientific interpretation.

(ii) In a similar manner, commercial or societal applications of Nuclear Photonics developments are conceivable. Examples could apply laser-generated MeV-ranged photon beams or neutron bursts and could range from non-invasive isotope-selective nuclear inventory of used fuel rods of nuclear power plants with spatial resolution, or inspection of cargo, to non-destructive analysis of geological or historical objects or the search for damages in public constructions and energy generation from laser-induced nuclear fusion reactions. In a similar way, as discussed above, do the individual projects and the specific expertises of the RTs collaboratively support the larger research and development goal.

This list can be extended, e.g., to prospects for future particle-accelerator technology or for laser-generated pump-and-probe experiments on ultra-short time scales. We stress that all research projects are interdependent and all of them are required to secure an optimum research training environment for the trainees. For the sake of clarity, details are given below on each of the potential research project proposals for the first cohort of this IRTG, as requested by the Evaluators of the Pre-proposal.

3.1.2 List of Envisaged Research Projects

Table 3.2: Project offers to the research trainees of the first cohort sorted by project areas. Matching projects in italics and subscript "m".

	Title	RT
A-1$_m$	*Enhanced intensities of 10-PW ultra-short laser pulses by optical Kerr non-linearities and diffraction*	*Ursescu, Bagnoud*
A-2$_m$	*Coherent control of pulses at PHELIX and ELI-NP*	*Bagnoud, Ursescu*
A-3	Increased coupling efficiency with 1-10 PW laser pulses to-nano structured targets	Tanaka, Roth
A-4	Spatio-temporal correlation control of laser pulses for γ-production	Ursescu, Bagnoud
A-5	Efficiency of high-power γ-beam generation by laser-interaction with structured targets	Doria, Kuschel
A-6	Characterization of Laser-Compton γ-sources from electron linear accelerators	Arnold, Ur
A-7	High-finesse optical cavity for a Laser Compton-based γ-ray source	Walther, Ur
A-8	Laser-driven ion acceleration towards 10 PW at optimized temporal profile of the laser pulse	Bagnoud, Ursescu
A-9	Optimization of LS and RIT mechanisms for the acceleration of high-Z ions using a multi-PW laser	Doria, Kuschel
A-10	Quasi-monoenergetic ion acceleration from multi-component targets	Kuschel, Ursescu
A-11	Capture and transport of high-energy laser accelerated ions	Boine-Frankenheim, Ticos
A-12$_m$	*Scaling ion beam production for neutron sources to the spallation relevant regime*	*Roth, Ticos*
A-13	Design of a neutron-source for high-energy neutrons at ELI-NP	Roth, Ticos
B-1	Study of photodesintegration reactions with silicon-strip detectors for Big-Bang Nucleosynthesis	Matei, Isaak
B-2	Nuclear level densities and photon strength functions in ^{56}Fe	Isaak, Balabanski

B-3	Towards simultaneous neutron- and γ-decay measurements around the particle threshold	Werner, Balabanski
B-4	Studies of p-process photo-particle reactions	Matei, Werner
B-5$_m$	*Electric dipole response of nuclei with $Z \leq 50$*	*Balabanski, Aumann*
B-6$_m$	*Magnetic-dipole spin-flip strength in medium-mass collective nuclei*	*Werner, Tsoneva*
B-7	Effects of the nuclear mean-field on the dipole response functions of atomic nuclei	Tsoneva, Martinez-Pinedo
B-8	Evolution of the GDR spectral function in even-even Nd isotopes from photo-absorption	Aumann, Balabanski
B-9$_m$	*Energy-dependence of the GDR's gamma-decay branching ratio in deformed rare-earth isotopes*	*Pietralla, Ur*
B-10	Influence of the N=126 neutron shell closure on the properties of pygmy and giant dipole resonances in heavy nuclei	Tsoneva, Martinez-Pinedo
B-11	Sub-barrier photofission studies with polarized brilliant γ beams	Balabanski, Enders
B-12	Correlation experiments in fission reactions induced by quasi-monochromatic polarized photon beams	Enders, Balabanski
B-13	Microscopic description of collective inertias for fission	Martinez-Pinedo, Tsoneva
B-14	Search for low-energy dipole modes of transuranium actinides	Pietralla, Ur
C-1	Spatio-temporal metrology for tailored ultra-intense laser pulses driving relativistic particle acceleration	Ursescu, Bagnoud
C-2$_m$	*Increased laser intensity with re-entrant cone in 10 PW regime*	*Tanaka, Boine-Frankenheim*
C-3	Target morphology and its implications on laser-plasma accelerators	Ticos, Roth
C-4	Steering of laser-plasma accelerated particles for applications	Ticos, Arnold
C-5	4D Particle detection employing low-gain avalanche-diode technology	Galatyuk, Doria
C-6$_m$	*Control of VEGA's Electron Beam and Optimization of its Emittance by AI Methods*	*Matei, Arnold*
C-7	Set-up and Luminosity Characterization of VEGA's 1.Phase LCB-Beam	Balabanski, Arnold
C-8	Advanced gamma beam diagnostics detectors for polarization and intensity monitoring	Ur, Pietralla
C-9$_m$	*Exploiting segmented HPGe-detectors and digital signal processing for γ-ray spectroscopy*	*Ur, Isaak*
C-10	Advanced lattice of a storage ring as a photon source	Ur, Boine-Frankenheim
C-11	Electron-gun optimization for laser Compton backscattering and nuclear-photonics applications	Enders, Ticos
C-12$_m$	*Lattice of an individually-recirculating energy-recovery linac as a 4th generation photon source*	*Arnold, Ur*
C-13	Temperature-controlled self-absorption technique towards precision excitation strength measurements in heavy nuclei	Isaak, Ur

A-1$_m$: Enhanced intensities of 10-PW ultra-short laser pulses by optical Kerr non-linearities and diffraction (Ursescu, Bagnoud)

One path to reach beyond extreme laser pulse intensities at the state-of-the-art PW-class laser facilities is shortening the pulse duration. In order to achieve this, increase of the pulse spectral bandwidth is required. This can be reached only through non-linear optical processes, such as optical Kerr effect, with the additional demand for preserving the energy and focus quality to best possible extent [125–130]. The removal of distortions (post-compression) is possible by dispersive elements, *e.g.*, chirped mirrors. The potential intensity increase is up to five times [125] or more in glass PW-class laser systems, upscaling extreme laser-driven phenomena.

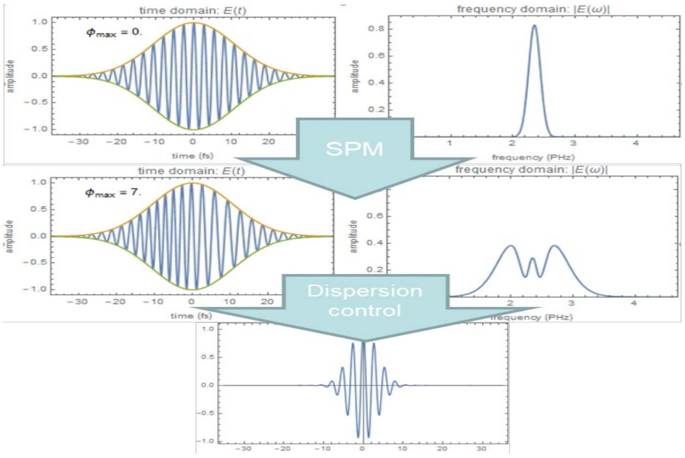


Figure 3: *Top: representation of a 10 cycle pulse in time and frequency domain; Middle: the same pulse, after passing through non-linear Kerr effect spectral broadening; Bottom: the temporal shape of the pulse after compensating the dispersion, corresponding to a two cycle pulse.*

The key question to be addressed by the doctoral researcher: What is the best compromise between large bandwidth (from spectral broadening) and recompression capabilities (of the post-compression method)? The doctoral researcher will (a) study the spectral evolution induced by non-linear optical effects, including simulations of the propagation of the spectrally-enhanced pulses, (b) perform validation studies on the achievable intensity and peak power using energy, spatial and temporal characterization devices, possibly including a laser pulse tomography device such as INSIGHT, and (c) complementary observe the enhanced intensity effects in interaction with materials.

The PhD work has the potential to identify the path towards intensities above 10^{24} W/cm^2 at the most powerful laser worldwide, HPLS@ELI-NP, preserving the European leadership in the field and to upgrade the capabilities of the PHELIX laser beyond the PW peak power level.

The current project A-1 is connected to the project A-2 with respect to the laser metrology involved and it represents a key enabling technology, enhancing the capability of providing unique results for particle beam production (gamma, ions, neutrons) as requested in projects A-5, A-9, A-12, and A-13.

A-2$_m$: Coherent control of pulses at PHELIX and ELI-NP (Bagnoud, Ursescu)

ELI-NP will most likely pioneer experiments at laser peak powers of 10 PW, which sets the conditions for exploring laser-plasma interactions at intensities that have been not reached before [131]. For interactions with solid targets, the temporal contrast of the laser plays a defining role in the type of interactions conditions that can be reached. This is due to the fact that the temporal profile of short laser pulses exhibits various features that are hard to control, while the ionization of the target happens at intensities up to 10 orders of magnitude below the maximum achievable intensity, sometimes nanoseconds before the laser pulse reaches its peak intensity. As a result, an uncontrolled and unwanted pre-plasma expansion takes place, which in many cases can ruin the experimental conditions. For a given laser system, the higher the laser intensity the earlier the ignition of the pre-plasma occurs. Therefore, it is essential to work on the temporal contrast of a 10-PW laser system beyond the state-of-the art.

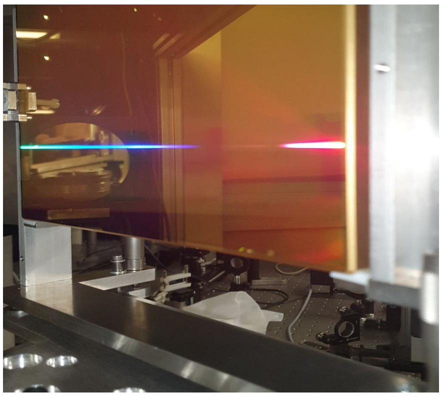


Figure 4: *Grating-based stretchers used in CPA lasers are responsible for deleterious temporal contrast degradations.*

The doctoral researcher in this project will apply new concepts that we recently developed [132] to the PHELIX laser for demonstration purpose and extend them to the ELI-NP laser in order to produce temporally-clean laser pulses with a high level of control over the required dynamic range. Validation experiments are foreseen at both PHELIX and ELI-NP to quantify the improvements in terms of target pre-expansion. For this, we will rely on the expertise developed at TU Darmstadt and ELI-NP in plasma diagnostics and simulations to support this work [133]. This also paves the way for the experimental investigation of temporal pulse shaping techniques in a way that supports the advanced acceleration schemes envisioned within the IRTG [134].

A-3: Increased coupling efficiency with 1-10 PW laser pulses to-nano structured targets (Tanaka, Roth)

In high intensity laser and matter interaction physics, nano-structured targets have been proven to have strong interactions with intense laser beams [135,136]. The previous experimental studies have used up to 100 TW to 1 PW laser pulses and have shown significant increase of fast electrons/ions and x-rays from the interactions because of the increased coupling efficiency. By introducing a nano-structured target (like a nano brush) that has thousands of nanowires (100-200 nm dia. x 1-10 mm length) on a substrate, a focused pulse of intense laser light penetrating between the nano-structures could interact very strongly with them [137].

In this project, the doctoral researcher:

a) will learn how to simulate such intensity increase using a PIC code.
b) will apply the simulation result to design the laser experiment
c) will conduct the laser irradiation experiment onto the nano-structured targets.

The proposed project is ideally suited for training doctoral researchers in theoretical and experimental nuclear photonics in learning the behaviors of the intense electromagnetic waves at one of the most advanced laser facilities under the supervision of the expert scientists.

The doctoral researcher will gain expertise in the handling of PIC simulation code, the interpretation of the numerical results, the design and performing of the laser experiment with the nano-structured target. The designing of the experiment will include to prepare the diagnostics to measure the focused laser intensity. Once the design preparation is completed, he or she will conduct the experiment. The doctoral researcher will acquire well balanced expertise in both, theory/simulation and experimental techniques.

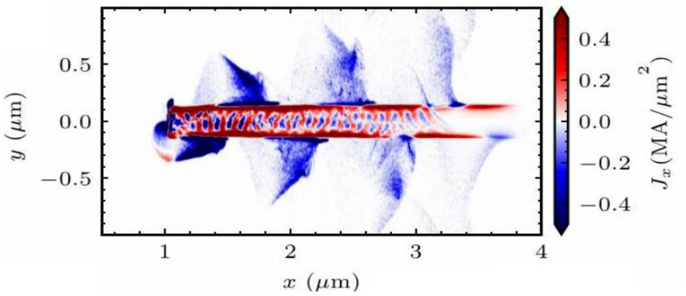


Figure 5: *One of the nano wires is shown for PW laser pulse irradiation. The laser pulse bushes up in vacuum from left to right along the surface, while wake field is driven inside the nanowire in a solid density [137].*

The optimization of the experiment using PIC simulation includes the scanning range of laser focused intensity, types of the nano-structured targets, and the selection of the diagnostics. The laser coupling efficiency to the nano-structured targets will be monitored by gamma-ray detectors, digital data acquisition systems, and fast electron/ion energy spectrometers. The combination of the PIC simulation, the experimental design and the execution of the experiment will be suited in a) the usage of a recently established experimental technique and b) guaranteeing a well-balanced research capability for the envisioned doctoral thesis with subsequent publication of the results in high-impact peer-reviewed journals.

A-4: Spatio-temporal correlation control of lases pulses for γ-production (Ursescu, Bagnoud)

One path to reach beyond extreme laser pulse intensities is (coherently) adding ultrashort pulses. In order to achieve this, spatial and temporal superposition of the pulses is required. This can be implemented through the pulse delay control at sub-micrometer / femtosecond scale and through phase control of the pulses. Even if the superposition is not perfect, active control of synchronization can provide the needed temporal resolution enhancement in pump-probe experiments such as Compton scattering gamma sources, where ultraprecise space-time overlap of the pulses is critical for the quality of the gamma source and hence can serve as a sensitive diagnosis of the spatio-temporal correlation. The doctoral researcher will investigate what is the smallest temporal drift and jitter achievable [138–

140] with active control in PW-class laser systems by (a) development and usage of a high temporal resolution shot-to-shot jitter measurement device using an ultrafast optical shutter [141], (b) implementation of a feedback loop for temporal drift compensation, (c) extraction of the relative phase noise using spectral interference device, and (d) study of methods for the stabilization of the optical path difference between two pulses using interferometric methods. Validation of the jitter reduction to few femtoseconds range will be performed in laser-electron collisions for γ-ray generation.

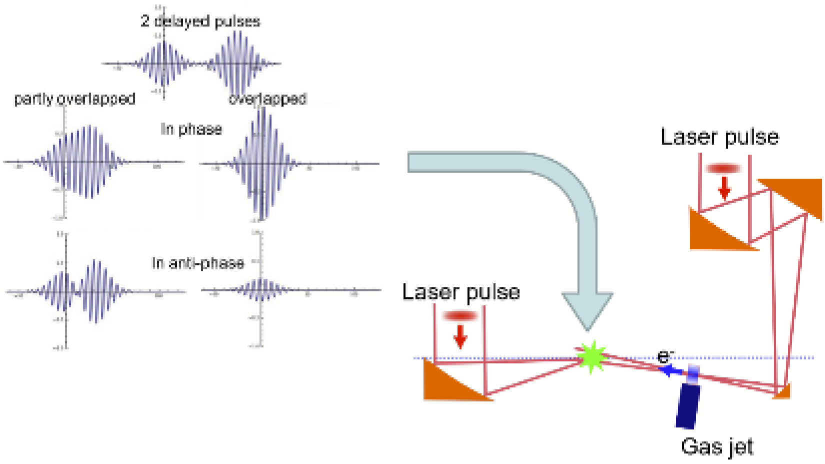


Figure 6: *Implementation of all laser-based Compton γ-ray source using laser accelerated electrons; it requires advanced spatial and temporal overlap of the laser pulses, achievable through active stabilization of the delay.*

A-5: Efficiency of high-power γ-beam generation by laser-interaction with structured targets (Doria, Kuschel)

The generation of high-power gamma burst is among the primary topics of research in high-power laser facilities [26]. A laser-based gamma-ray source may be applicable in material sciences, gamma-ray probing for material interrogation, in nuclear physics, to excite isotopes for further use, as well as for laboratory astrophysics research, testing theories on astrophysical gamma-ray burst generation and behavior of quantum electrodynamics (QED) plasma in pulsar magnetospheres. Currently, a lot of effort is directed toward the theory and PIC simulations of bright gamma beam generation from laser-plasma interaction [142–145]. The simulations indicate an efficiency of laser-to-gamma energy conversion up to 20% for a 10 PW laser. Although, many theoretical papers have been produced there are not many experiments at around 1 PW laser power and none above such power [146]. In this project, the doctoral researcher will (a) study the generation of very bright gamma-ray beams of several 10s MeV of photon energy employing a multi-petawatt laser beam and (b) test PIC simulations and expected scaling laws of laser-to-gamma energy conversion.

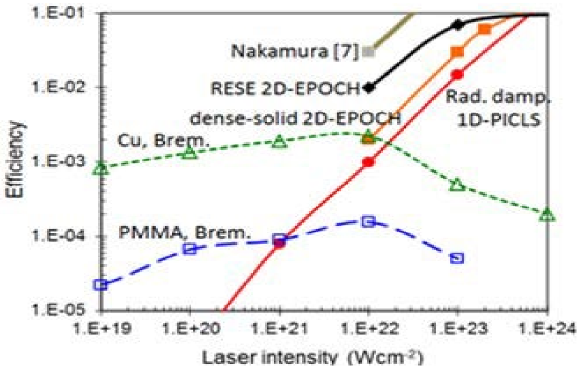


Figure 7: *Efficiency of laser-to-γ ray conversion as a function of laser intensity [26].*

The project is suited for training young researchers in experimental laser-plasma physics and bright gamma-ray source development and characterisation. Such sources will be beneficial for the future research in both fundamental and applied physics at leading facilities, such as ELI-NP. The doctoral researcher will gain expertise in laser technology, and plasma physics and will be handling different types of detectors for plasma and gamma beam characterization.

The project is a challenging pioneering work that uses established experimental techniques and diagnostics along with unprecedented laser power. It guarantees a well-balanced research topic for a doctoral thesis with subsequent publication of the results in high-impact peer-reviewed journals.

A-6: Characterization of Laser-Compton γ-sources from electron linear accelerators (Arnold, Ur)

A brilliant, quasi-monochromatic beam of MeV-ranged photons for applications in Nuclear Photonics may be produced by Laser-Compton Backscattering (LCB): the collision of a laser beam with an ultra-relativistic electron beam [147]. The VEGA-system at ELI-NP [148] is a 3rd generation LCB source using the electron beam of a storage ring for the scattering process. Even higher brilliance can be expected from 4th generation LCB sources using intense electron beams from a linear accelerator without degradation of beam emittance from synchrotron radiation. A corresponding LCB source will be established at the S-DALINAC [28] at TU Darmstadt. The set-up, shown in Figure 8, is provided to this IRTG.

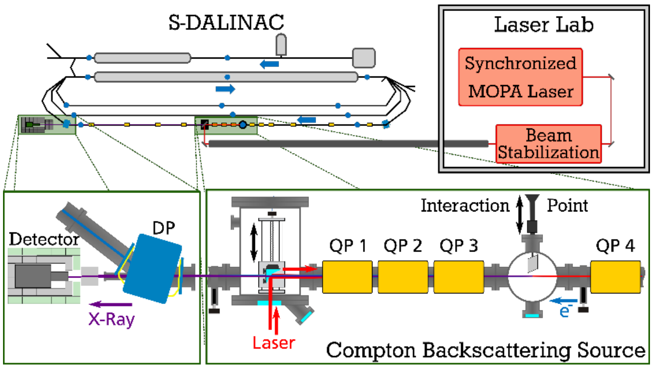


***Figure 8**: Layout of the set-up for laser Compton backscattering at the S-DALINAC. (DP: dipole magnet, QP: quadrupole magnet).*

The main scientific goal of this project will be fundamental research towards a brilliant LCB source. The doctoral researcher will (a) study the characteristics of the photon beam as a function of the parameters of the electron beam and operational conditions – both experimentally and by simulations, (b) provide the experience gained from the set-up and experiments done at the S-DALINAC to the completion and further improvement of VEGA, and (c) extract the results to develop and design the ultimate 4th generation source to be driven by a superconducting energy-recovery linac (ERL) [RT8].

The project is based on available infrastructure at the S-DALINAC. It will serve as a baseline for an advanced design of this set-up at VEGA which will be established in project C-7, that then will be used for the demonstration and first characterization of the VEGA beam monitors in project C-8.

In turn, this project will profit from an extended set of parameters that can be studied after the installation of an optical laser cavity provided by project A-7. The results of both projects as well as of projects C-11 and C-12 will provide the basis to develop a future powerful 4th generation source at a superconducting ERL. Further connections exist to other projects working on beam diagnostics or beam guiding elements as C-5 and C-6.

A-7: High-finesse optical cavity for a Laser Compton-based γ-ray source (Walther, Ur)

In recent years inverse Compton scattering (ICS) based setups have become feasible in order to efficiently generate narrow linewidth, high brightness MeV-ranged photon beams perfectly suited for tackling current problems in photonuclear reactions, material science, chemistry and biology [6]. ICS generates the MeV-ranged photons by scattering high intensity laser photons off an ultra-relativistic, bunched electron beam counterpropagating with the laser photons. Several factors impact the efficiency of this process: laser intensity, bandwidth and its repetition rate as well as timing and the spatial overlap of laser beam and electron beam. Very favorable conditions can be achieved using high finesse cavities. In close collaboration with projects A-6, C-7, C-10, and C-12, the goal of this project is to design a complete ICS setup including all mechanical, and optical components as well as the vacuum chamber layouts needed for the mirror mounts etc. for ICS reactions on electron beams, either from a traditional linac, from an energy recovery linac, or from a storage ring. In addition, we will perform simulations of the overall gamma-ray yield, bandwidth etc. In the past, we gained vast experience in designing and setting up various different resonators [149–151] including cavities with an elliptical focus [152] offering a possible advantage with regard to the optimum overlap between the laser radiation and the electron beam within the interaction region. Our in-house software tools specifically written for the design of resonators employing evolutionary algorithms to optimize the design will be invaluable [153]. For the complex locking requirements, we have gained valuable experience using a flexible FPGA board employing PyPRL [154]. Two laser systems, a fiber amplifier based system generating flexible Fourier bandwidth limited pulses (pulse duration 50 – 250 ps, repetition rate up to several MHz) [29] and a

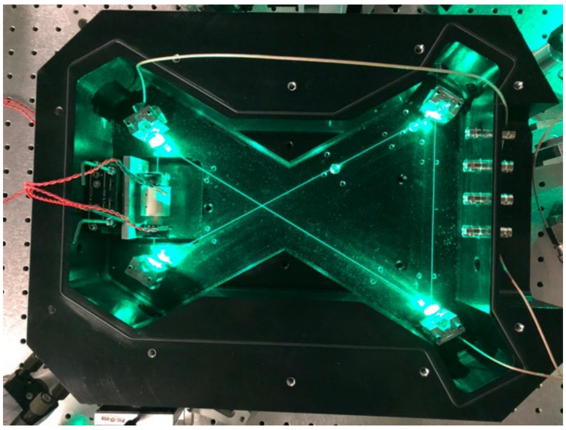


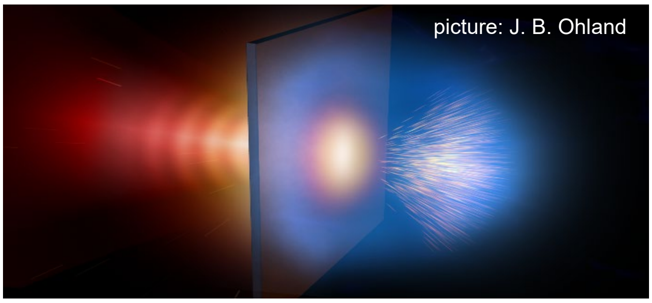
***Figure 9**: Enhancement cavity for the generation of green light and elliptical focus which might act as a model system for the much larger cavity required for the resonant enhancement of laser intensity for the ICS setup. Clearly, a monolithic design such as the one depicted cannot be used for the ICS setup.*

commercial mode-locked ps-laser with high peak powers are available for first proof-of-principle experiments of the design.

Thus, in this project, the doctoral researcher will (a) design the optical setup for a high-finesse cavity for an Inverse Compton Scattering based photon source and (b) design the mechanical setup necessary to incorporate the high finesse cavity with the inhouse energy recovering linac.

A-8: Laser-driven ion acceleration towards 10 PW at optimized temporal profile of the laser pulse (Bagnoud, Ursescu)

Laser-driven ion acceleration has been studied with high-intensity lasers around the world for the last 20 years [155]. The exact underlying process driving the acceleration depends greatly on the experimental conditions [156]. This explains why the extrapolation of the acceleration performance to new intensity regimes has not been succesfully predicted by simulations and modelling, so far. Under this assumption, the dawn of the 10-PW laser era inaugurated by ELI-NP opens new horizons for laser-driven ion acceleration that urgently need to be studied experimentally. Several interaction mechanisms yield strong spatial acceleration fields for given geometries of target and laser interaction. This will be studied within the framework of the IRTG (e.g. project A10). Here, we will focus on relatively thick targets in the micrometer range. Such targets are very robust against non-ideal laser parameters and offer a good base for numerical benchmarking.



picture: J. B. Ohland

***Figure 10**: Artistic view of a laser plasma interaction with a thin foil. The 10-PW laser facilities at ELI-NP will allow to enter the ultra-relativistic regime producing photon and particle beams with unprecedented characteristics.*

The scaling of the acceleration process from the sub-petawatt regime up to 10-PW will be studied as the ELI-NP facility brings its capability online. In addition, complementary experiments will be conducted at PHELIX in Darmstadt where the PHELIX has been used recently to obtain some of the best experimental results in the field [157]. At PHELIX, the experimental conditions (pulse duration) are significantly different from ELI-NP. Data from both facilities help to complete the picture.

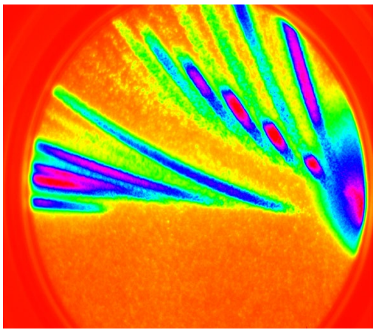
A-9 Quasi-monoenergetic ion acceleration from multi-component targets: (Kuschel, Ursescu)

Target-normal-sheeth acceleration (TNSA) is typically the dominant laser-driven ion-acceleration mechanism from thin foils or liquid targets. This process yields an exponential ion energy spectrum up to a cut-off energy [158] and thus the entire ion spectrum is typically dominated by an exponential shape. Most applications however, require a defined ion beam energy. The situation, changes dramatically when multi-component targets are used: Different charge states of different elements can separate in space and energy and will therefore be accelerated in confined energy bands as simulations have shown. Preliminary experiments have also shown this effect already on a 1 Joule – class laser system, parasitically to other experiments (Figure 11). A systematic study to explore how this effect can be exploited for any kind of application is missing to date.

This project aims to gain spectral control over the accelerated ions making them usable for various applications generally requiring specific energies or energy bands, such as medical treatment, imaging, or neutron generation. It will involve experiments but also requires modeling from paricle-in-cell (PIC) simulations.

This study paves the way towards quasi-monenergetic ion acceleration and has the potential to increase the number of accelerated ions in the high-energy part of the distribution. Other acceleration mechanisms, such as radiation-pressure-acceleration [159] or relativistic transparency regimes will be explored as well using the high energy and high intensity facilities available at ELI-NP.

***Figure 11:** Raw Thomson Parabola image displaying multiple ion species and charge states. Some of the ion species are strongly separated into distinct energy intervals. This image was taken during another experimental campaign by Kuschel.*



A-10: Optimizing Radiation Pressure Acceleration of high-Z ions at a multi-PW laser (Doria, Kuschel)

High-power laser-matter interaction can involve several processes and features that can greatly affect the acceleration of ions, as for instance, heating up and deterioration of the target during the interaction, the laser field polarization orientation, target, and plasma characteristics, laser intensity and temporal contrast, QED processes, etc. [12,160–163]. Understanding the dynamics of laser-plasma interaction with a multi-petawatt laser is of fundamental importance for generating ion beams with the optimum properties needed for many studies, either in fundamental or applied research.

In this project, the doctoral researcher will (a) study the acceleration mechanism known as Radiation Pressure Acceleration (RPA) with particular attention to the Light Sailing (LS) and Relativistic Induced Transparency (RIT) mechanisms and (b) study in particular the acceleration of high-Z ions and its control and optimization to achieve quasi-monochromatic energy ion bunches using a multi-petawatt (up to 10 PW) laser beam.

The project is a challenging pioneering work that uses established experimental techniques and diagnostics along with unprecedented laser power, guaranteeing a well-balanced research topic for the envisioned doctoral thesis with subsequent publication of the results in high-impact peer-reviewed journals.

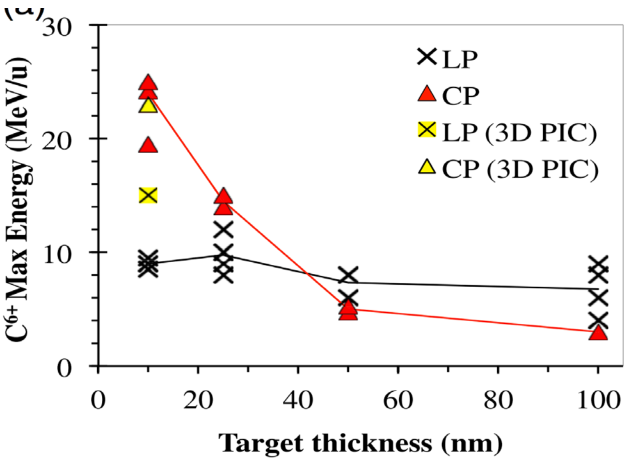


Figure 12: *Dependence of the carbon ion energy from the laser polarization and target thickness in the LS acceleration regime [12].*

A-11: Capture and transport of high-energy laser accelerated ions (Boine-Frankenheim, Ticos)

Laser acceleration of light ion beams has been very successful. Energies of more than 70 MeV have been reached for protons at several laser systems. However, the capture and transport of the “unconventional” beam distribution generated by the different acceleration mechanisms is possible, only, for a selected energy range. This limits the applications of laser-accelerated ions when compared to “conventional” compact accelerators with high performance standards [164]. Experiments demonstrated important differences between laser generated protons (or light ions) and beams from conventional accelerators: (a) a large energy and angular spread (see Figure 13); (b) significant shot-to-shot fluctuations in energy profiles; (c) extremely short pulse duration. These features require laser specific approaches in beam selection and handling (see e.g. [38,165]). With ELI-NP’s 10 PW HPLS a tenfold increase in laser energy for ultrashort pulses becomes experimentally available. Advanced capture and transport beamline concepts must be developed for the expected higher ion energies and increased ion beam current densities. The goal is to maximize the transmission for selected energy ranges.

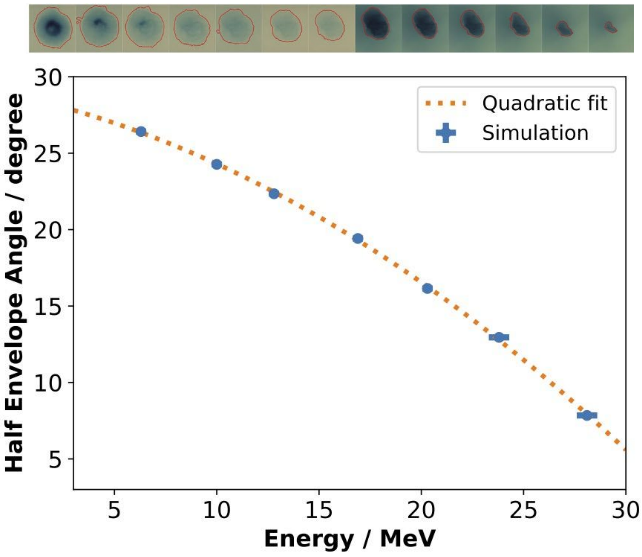


Figure 13: *The initial beam divergence reconstructed from measurements (top ribbon).*

The doctoral researcher will (a) model and optimize the beam transport of laser-accelerated ion beams, starting from the initial plasma distribution behind the target (Figure 13) to the injection or matching point for the application of such beams and (b) explore and develop advanced focusing elements, like plasma lenses or superconducting solenoids, for an efficient capture of laser accelerated ion beams with repetition rates matched to the laser systems. Important for the design and settings of a capture/transport section are estimates of the shot-to-shot fluctuations of this ballistic distribution obtained from PIC simulations. The simulation and data models will also be used to propose directions to optimize the beam distribution. Besides the energy distribution of the laser accelerated beams, the initial divergence is crucial for the capture efficiency [39]. In addition to pulsed solenoids and permanent quadrupole magnets (PQM), the use of a plasma lens will be investigated. Plasma lenses were already used at GSI [166]. Recently they have been successfully applied to laser-accelerated electrons [167] and protons (at BELLA). A plasma lens for the capture of laser-accelerated ions has the advantage over PQMs of symmetric and variable focusing, in addition to higher gradients. Detailed studies of plasma lenses compared to conventional arrays of PQMs and superconding solenoid magnets are planned, including magnetic field simulations to use the obtained fields or multipoles in beam dynamics programs, such as MADX or COSY, which allow automatic adjustments of the optics.

A-12$_m$: Scaling ion beam production for neutron sources to the spallation relevant regime (Roth,Ticos)

This project is closely linked to the projects A-1, A-3, A-4, A-8 and A-10 and focuses on the optimization of the combination of targets and laser parameters (intensity, chirp, pulse shape) to maximize the particle energy for a laser-driven proton beam. The goal of this project is to stablish a high-energy proton source exceeding 100 MeV to impact a high-Z converter for laser-neutron production.

The project will support the researcher working on A-13 and they will form a team to understand the underlying mechanisms. The research trainee will explore the transition from TNSA [168] to RIT [169] to LS acceleration and will benchmark simulated results with experiments at ELI-NP. The goal is to identify the sweet spot with respect to particle numbers, ion bunch pulse duration and the particle energy for optimum neutron production. The doctoral researcher will work on the implementation and further development of the required diagnostics, the target design and handling in close connection to the laser team. Simulation tools are available at TU Darmstadt and a close collaboration with project A-11 is foreseen, too.

For the target development and characterization the doctoral researcher will be supported by the TU-Darmstadt target laboratory. Targets will be produced and characterized at TUDa and the target supply technology will be adapted to the need of the high-intensity experiments at ELI.

A-13: Design of a neutron-source for high-energy neutrons at ELI-NP (Roth, Ticos)

The production of directed bursts of neutrons by ultra-intense lasers is a new and exciting technology [53] that can help addressing important societal challenges. While in the recent years the neutron number and repetition rate has improved [52], the maximum neutron energy is so far limited by the incoming, laser accelerated particle beam. ELI-NP offers a new approach as the 10 PW option allows for ion acceleration above current limits. Once ion beams in excess of 200 MeV can be accelerated [47] the neutron production mechanism could be altered from nuclear excitation and deuteron breakup, the dominant neutron production mechanism so far, to the more efficient spallation regime.

In spallation, not only the neutron number can be even higher than the number of the incoming ion beam particle numbers, but also the maximum neutron energy can reach energies, comparable to the incoming ion kinetic energy. In this project the doctoral researcher will (a) develop a scheme to generate high-energy laser-driven neutrons and optimize their properties. He/She will learn modern particle tracking codes and use them to design the experiment, the neutron converter, and the experimental setup and (b) conduct experiments at ELI-NP and benchmark the simulated results. The research trainee will test the use of high-energy neutrons for applications in nuclear technology.

The proposed project is closely linked to the project A-2. The 10 PW laser pulses will be used and combined with novel targets to reach ion energies exceeding a few 100 MeV. Novel diagnostics have to be developed and implemented as well as the physical understanding of the acceleration mechanism will be matured. The research group will be combining the expertise from the group of Roth at TUDa with the group of Ticos at ELI-NP. The unique capabilities of the TUDa Target and Detector Laboratory will be used to train scientists, develop diagnostics and targets and to prepare the experiments at the PHELIX and ELI-NP facility.

B-1: Study of photodesintegration reactions with silicon-strip detectors for Big-Bang Nucleosynthesis (Matei, Isaak)

Big Bang nucleosynthesis (BBN) is responsible for the production of several light elements in the Universe: deuterium, helium, and lithium isotopes, and traces of beryllium and boron. The good agreement between the theoretical prediction of the abundance of these elements with observations confirms hot big bang cosmology and makes BBN the earliest reliable probe of the Universe. However, the production of lithium isotopes is a longstanding problem known as the “primordial lithium problem” [170].

The ELI-NP team has already carried out a study of the ^{7}Li(γ,t)^{4}He reaction [67] at HIγS at energies above 4.5 MeV and is approved for additional beam time in Spring of 2023 to measure the reaction closer to astrophysical region of interest around E_γ~3.5 MeV. The ^{7}Li(γ,t)^{4}He experiment at HIγS marked the first time a large-area silicon detector array was placed in a γ-ray beam and generated reliable data and results. However, the data analysis at lower energies was challenged by the beam-induced electron background. One method to deal with this background is to implement Pulse Shape Discrimination (PSD) for electron discrimination and ion identification through a digital-electronics data acquisition.

Apart from ^{7}Li, also ^{6}Li is an element which was formed during BBN via the ^{2}H(α,γ)^{6}Li reaction. There is also disagreement between observations and calculations of ^{6}Li formation during BBN, also known as the “second lithium puzzle” [171]. A recent measurement from the LUNA collaboration [172] calculated a rate even lower than previously reported which increases the discrepancy.

The ELISSA [173] array at ELI-NP is a silicon-strip detector array which can support several detector configurations: position-sensitive one-sided or double-sided silicon strip detectors. The array is foreseen to be upgraded to fully digital-electronics DAQ. Developing and benchmarking Pulse Shape Analysis methods for light-ion particle identification is an ideal project for a doctoral researcher through the combination of relevant physics with instrumentation and method implementation.

The doctoral researcher will (a) develop PSD methods for particle discrimination with the ELISSA array, (b) measure the ^{6}Li(γ,d)^{4}He reaction and other BBN-relevant reactions using one of the new configurations of the ELISSA array, and (c) calculate and update the ^{2}H(α,γ)^{6}Li reaction rate for BBN.

B-2: Nuclear level densities and photon strength functions in ^{56}Fe (Isaak, Balabanski)

One of the most important approaches to model nuclear reactions is the Hauser-Feshbach formalism [174] treating compound nuclear reactions in a statistical fashion. It is applied in energy regions where the properties of individual nuclear resonances are not well known or cannot be studied separately. One essential quantity is the nuclear level density (NLD) which reflects the number of nuclear levels for a given energy interval. Another crucial quantity related to the electromagnetic decay of the nucleus is the photon strength function (PSF). The PSF defines the average probability of absorption and emission of electromagnetic radiation by the nucleus.

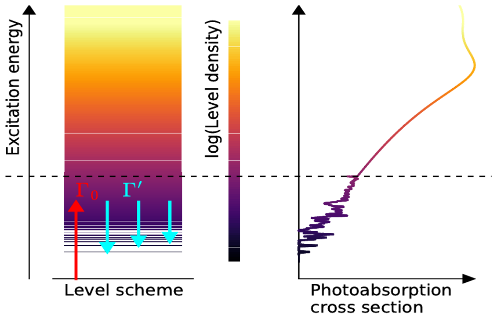


Figure 14: *Left: Exponentially increasing NLD with excitation energy. Right: Photoabsorption cross section which is directly linked to the PSF.*

In this project, the doctoral researcher will (a) develop and pioneer an integral approach that uses the nuclear self-absorption technique [RT3,96,98,124] to measure NLDs for spin-1 states of ^{56}Fe and (b) apply a model-independent method for the extraction of PSFs [93,94] from the excitation and de-excitation channel of ^{56}Fe. The self-absorption measurements will initially take place at the HIγS facility and later-on at the VEGA system at ELI-NP exploiting the high-intensity and narrow bandwidth LCB beams and the available state-of-the-art gamma-ray detection systems. The experiments will provide an independent measurement of the NLD decoupled from the measurement of the PSF for spin-1 states in the quasi-continuum below particle separation thresholds for ^{56}Fe. The obtained data sets will help to further constrain stellar reaction rates in the s-process path of the nucleosynthesis and they will allow a direct comparison to existing results from complementary experiments [175,176].

B-3: Towards simultaneous neutron- and gamma-decay measurements around the particle threshold (Werner, Balabanski)

A prominent potential manifestation of neutron skins, the pygmy dipole resonance (PDR), emerges from their oscillation against the proton-neutron saturated core. From data on the PDR one can obtain more reliable parameters for the nuclear equation of state which is ultimately needed also for the description of exotic objects such as neutron stars.

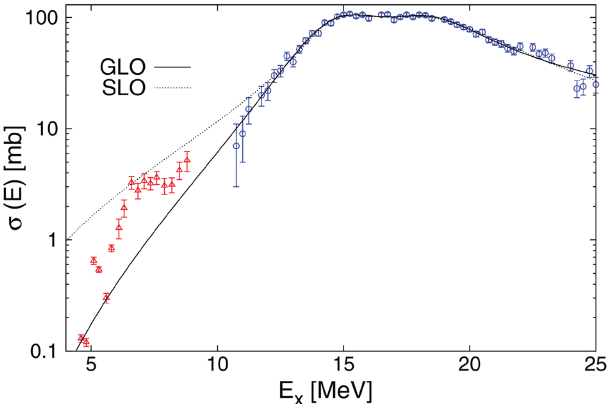


***Figure 15:** (from [119]) (γ,γ') data from HIGS [119] (red) along with (γ,n) data from Saclay [194] (blue), both for ^{76}Se. (γ,n) data may need to be rescaled according to Ref. [177]. Depending on renormalization and choice of model for the GDR the amount of PDR excess near 7 MeV is highly uncertain.*

Starting in the A~50 mass region [120], up to the heaviest stable elements, the PDR is manifested in an electric dipole (E1) excitation mode on the low-energy tail of the GDR. As opposed to neutron-rich rare isotopes, stable nuclei are accessible to high-statistics experiments which allows to investigate in detail the amount and nature of the resulting E1 excitation strength. The PDR is often located in the vicinity of the particle threshold, hence, emission of neutrons (or in some cases protons) from PDR states becomes possible, which escape observation in standard NRF experiments, hence, available (γ,γ') and (γ,n) data are from different experiments and may require renormalization [177]. We intend to overcome this issue by employing both, neutron (eventually also proton) and gamma detectors, simultaneously in the same experiment. At ELI-NP, both types of detectors are readily available [RT7,178], and will be combined for a first experiment on a nucleus where inconsistencies in literature gamma- and neutron data are present, such as ^{76}Se, see Fig. 17. First experiences with the combination of gamma and neutron detectors will be obtained at the bremsstrahlung sites at the S-DALINAC facility.

B-4: Studies of p-process photo-particle reactions (Matei, Werner)

In natural nucleosynthesis processes, heavy neutron-deficient nuclei cannot be produced by neutron capture reactions, but through photon- or proton-induced reactions (*p*-process). A complete network calculation of the *p*-process nucleosynthesis includes hundreds of isotopes, as shown in Figure 16. The calculations are tested experimentally at rate-limiting paths of the network.

The data about the (γ,p) and (γ,α) reactions in the corresponding Gamow window is scarce and is often based on the observation of the time-reversal (p,γ) and (α,γ) cross sections. A breakthrough development of the quality of the reaction database requires measurements of the cross sections of key *p*-process nuclei.

In experiments with LCB beams, cross-section measurements for *p*-process (γ,p) and (γ,α) have not been reported. There are two accepted experiments at HIγS, TUNL, Duke University, that aim at measurements of the ^{112}Sn(γ,p), ^{112}Sn(γ,α) and ^{102}Pd(γ,α) reaction cross sections. The ELI-NP team is leading these studies and has already successfully performed a photo-disintegration experiment, studying the ^{7}Li(γ,α)^{3}H reaction [67] at he HIγS facility, where the experimental technique was mastered.

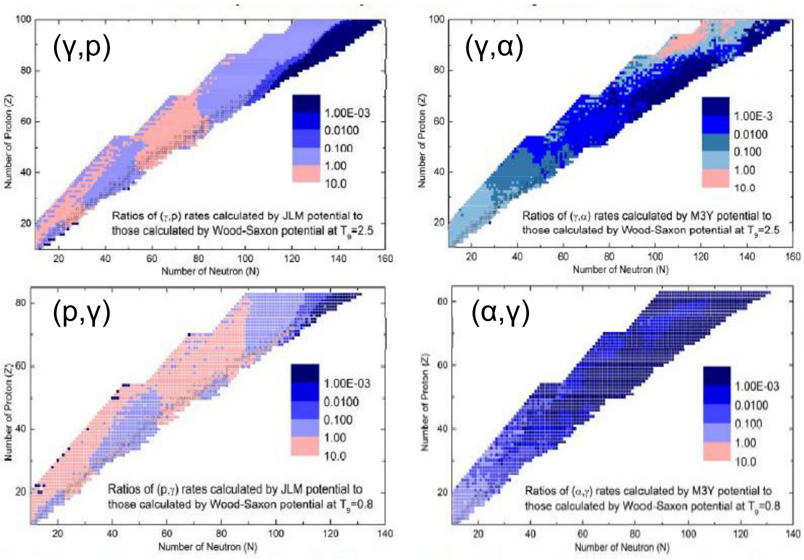


***Figure 16:** Optical model reaction network calculation of the p-process nucleosynthesis [66].*

The answer to the following key question will be sought within this project, namely: What are the cross sections for key *p*-process gamma-charged-particle reactions? These data will provide constraints of the nuclear models for the description of nuclear astrophysics *p*-process.

The doctoral researcher will study the cross sections of key *p*-process (γ,p) and (γ,α) reactions, *e.g.*, ^{96}Ru(γ,p), ^{96}Ru(γ,α) and ^{98}Ru(γ,α) at energies between 8 and 20 MeV, which covers the Gamow window for these reactions. It is worth noting that the abundances of the ^{96,98}Ru isotopes are low. The project will benefit form the fact that ^{96,98}Ru material is available at TU Darmstadt. In the experiments, the proton and α-particle energies, intensities and angular distributions will be measured.

The obtained experimental results for the transitional Ru isotopes will be compared to the existing experimental data on the time-reversal reactions, i.e. ^{92}Mo(α,γ) [179,180] and ^{94}Mo(α,γ) [180]. In addition, (γ,xn) reaction cross sections can be obtained in the experiment, by sending the beam to the available neutron arrays, which allows in addition to measure the neutron energies and angular distributions.

B-5$_m$: Electric dipole response of nuclei with Z ≤ 50 (Balabanski, Aumann)

Quantities of key interest in nuclear structure physics are photon strength functions (PSF) of different multipolarity. They describe the average probability of absorption and emission of electromagnetic radiation of given multipolarity by the nucleus. The low-lying dipole states, which are excited in NRF experiments, characterize various collective and single-particle nuclear excitation modes, such as, the scissors mode, the spin-flip mode, and the pygmy dipole resonance. The project will provide first direct measurements of the *E*1 strength, and in particular of the PDR, in the *Z* ≤ 50 transitional nuclei.

Below the *Z* = 50 closed shell Sn nuclei, weak deformations start to build in, *e.g.*, the observed band structures in ^{106}Pd were reported to correspond to a quadrupole deformation of β_2 = 0.175 [181], as demonstrated in Figure 17, where calculations within the tilted-axis cranking model [182] are presented. The low-lying *E*1 states in the transitional Pd nuclei are expected to be weak and strongly fragmented.

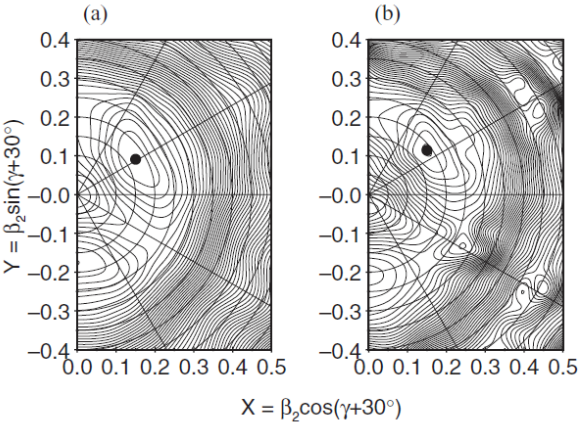


***Figure 17:** Potential energy surfaces of the lowest-lying band structures in ^{106}Pd calculated within the tilted-axis cranking model [181].*

In this project, the doctoral researcher will expand the existing knowledge for the *E*1 strength below the *Z* = 50 shell and study in detail the *E*1 strength in the ^{104,106,108}Pd (*Z* = 46) nuclei. The answers of two key questions will be sought within this project, namely:

a) What is the E1 strength in transitional nuclei below the *Z* = 50 shell?

What is the dependence of the *E*1 strength in the transition from vibrational to rotational nuclei?

The obtained experimental results for the transitional Pd isotopes will be compared with the existing experimental data for the Cd (*Z* = 48) [183–186] and Sn (*Z* = 50) [RT9,187] nuclei. The experiments will make it possible to extract also the low-lying *M*1 strength in the ^{104,106,108}Pd (*Z* = 46) nuclei. The project is guaranteeing a well-balanced research topic for the envisioned doctoral thesis with subsequent publication of the results in high-impact peer-reviewed journals.

B-6$_m$: Magnetic-dipole spin-flip strength in medium-mass collective nuclei (Werner, Tsoneva)

The nuclear isovector-spin M1 (IVSM1) response is one of the fundamental nuclear excitations, and is an analog of Gamow-Teller (GT) strength. It is of particular interest for neutrino-nucleus scattering, since IVSM1 states can be excited in the process of neutral-current neutrino scattering [188–190]. Hence, the IVSM1 response is relevant in view of neutrino detection, as well as considering the open problem of quenching of the M1 strength. Data on the IVSM1 response is scarce – since the energy region of the IVSM1 response often coincides with the onset of E1 strength, i.e., the PDR and the low-energy tail of the GDR, it is difficult to extract in gamma spectroscopy. Another approach is the use of proton scattering, with the drawback that the extraction of M1 strength is model dependent. This problem shall be overcome by using and further developing the method of “integral spectroscopy”. Fully-polarized

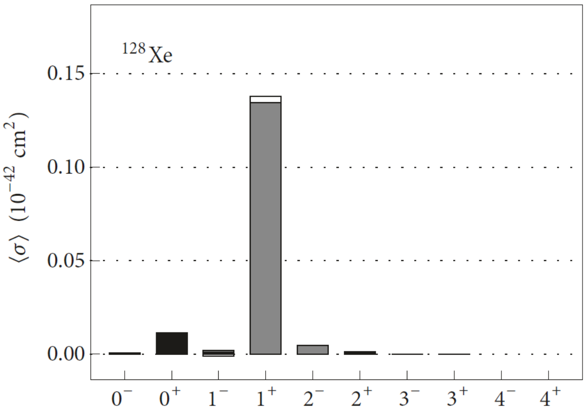


***Figure 18:** (from [262]) Contributions of multipole channels J≤4 to the total averaged cross section for solar neutrinos off ^{128}Xe (black: vector, grey: axial-vector, open: interference) from QRPA calculations.*

MeV-ranged photon beams from LCB sources will be used to excite the E1 and M1 dipole response of a given nucleus over the energy interval of the beam, and decay-gamma radiation is detected with $LaBr_3$ detectors. When individual states cannot be resolved in the energy region of interest, this method allows to measure the overall excitation cross section, and filter out the amount of M1 strength making use of polarimetry [93,95].

The doctoral researcher will adopt this technique, which we had developed at the HIγS facility, to the specific capabilities of the VEGA system at ELI-NP, providing state-of-the-art detection systems and potentially offering higher brilliance of the beam. We will investigate isotopes in the rare-earth region, starting with Sm isotopes which span a broad structural range between spherical and deformed nuclei. We will start with the magic ^{144}Sm and the deformed ^{154}Sm, before testing the rare radioactive ^{146}Sm, which will only be possible at ELI-NP. To study the influence of a proton sub-shell at Z=58 on the IVSM1 response, we also intend to obtain data on ^{140,142}Ce. The new data will be confronted with microscopic theory such as QRPA or QPM [191], building on previous work in this mass region [192]. Simultaneously, we will obtain data on the E1 strength of the PDR, which is located in the same energy region.

B-7: Effects of the nuclear mean-field on the dipole response functions of atomic nuclei

(Tsoneva, Martinez-Pinedo)

This project focuses on new aspects of the microscopic structure of nuclear excitations, in particular pygmy and giant resonances [57,58,63–65,74,77,193]. In theory, the low-energy dipole spectral distributions associated with the pygmy dipole resonance (PDR) are compatible with neutron skin vibrations against the isospin-symmetric nuclear "core", which is clearly evident from studies of the transition densities. An observable that is sensitive to induced skin effects in nuclear excitations, especially at low energies, is the dipole polarizability, which is important for the skin and symmetry energy confinement of neutrons, the equation of nuclear matter, and for astrophysical applications [65]. The nuclear reaction cross-sections associated with the s- and r-process of nucleosynthesis of the heaviest nuclei in space objects are strongly dependent on the low-energy part of the dipole strength function of the dipole photoabsorption and the PDR [63,64]. The theoretical method to be used in this project is one of the most sophisticated microscopic models to describe PDR and GDR, based on energy-density function theory (EDF) and augmented by the multiphonon-coupled quasiparticle-phonon model (QPM) able to take into account the fragmentation of low-energy single-particle strength [57,58,63–65,74,77,193]. Recent studies on PDR within the EDF+QPM are shown in Figure 19 [193].

In this project an elaborate nuclear ground state obtained from spectral energy-density function theory (SEDF) and considering mean-field (MF) correlations in terms of quasiparticle states given by dynamic BCS theory will be applied [58]. The nuclear excited states will be calculated within three-phonon QPM [57,74]. The doctoral work will include studies on effective MF and residual interactions. The goals to be achieved are: theoretical improvements in the description of the fine and coarse structure of the dipole spectral distributions, namely:

a) the MF picture, seen in the ground state occupation probabilities
b) the fragmentation of the single-particle strength
c) the energy shifts and fragmentation of spectral functions in general
d) and the comparison with the experiment.

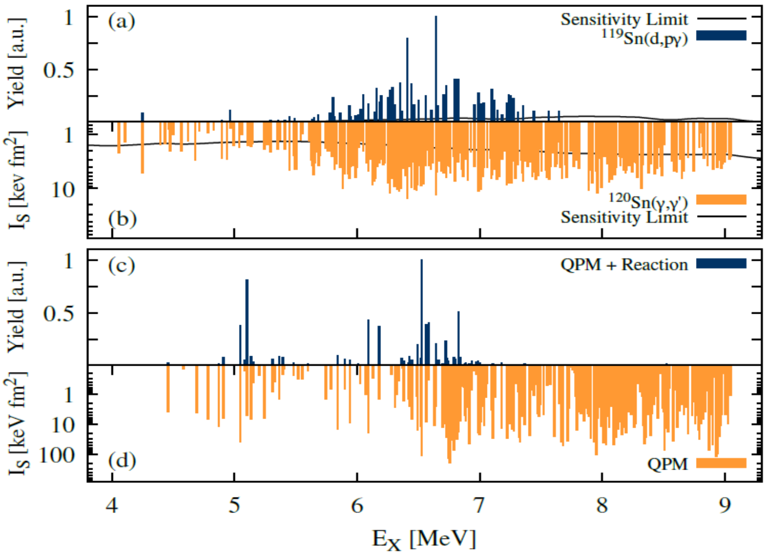


Figure 19: *(a) Relative γ-ray yields from ^{119}Sn(d,pγ), (b) energy-integrated cross sections IS for ^{120}Sn(γ,γ') [193]. All transitions shown in (a) were also observed in the NRF experiment. Sensitivity limits are based on a maximum error on the peak area of 30%. (c) Relative ^{119}Sn(d,pγ) yields from the QPM+reaction formalism and (d) predicted energy-integrated cross sections, both taking into account γ-decay branching predicted by the QPM [193]. Theoretical (d,p) cross sections were calculated at scattering angles identical to the experiment. Experimental and theoretical yields were normalized to the strongest transition.*

B-8: Evolution of the GDR spectral function in even-even Nd isotopes from photoabsorption (Aumann, Balabanski)

The Isovector Giant Dipole resonance (IVGDR) is often viewed as an oscillation of the proton and neutron distributions against each other. This picture is supported by the observation that in deformed nuclei the IVGDR is split into two components (K-splitting) corresponding to movements of the density distributions along the two major axes of deformation, giving rise to two frequencies of oscillation. In fact, the double-humped structure observed for ^{150}Nd is a famous text-book example [194,195] as seen by the green data points in Figure 20.

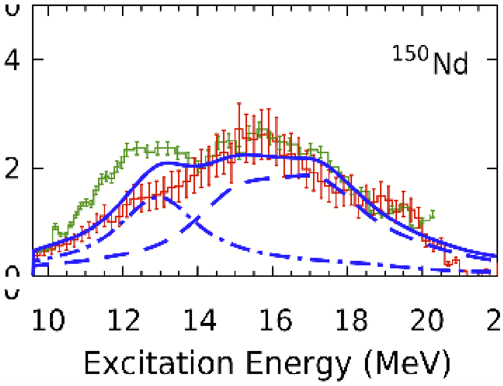


Figure 20: *Part of Figure 4 of [191]. Shown is the photoabsorption cross section deduced from the (gamma, xn) data (green) and the new measurement [191] shown in red.*

Recently however the photo absorption cross section has been remeasured applying a new method, namely relativistic Coulomb excitation with a beam of high-energy protons. The surprising result is that the double humped structure is not observed [91] as seen by the red data points.

So far no direct photoabsorption data have been measured for these nuclei. The older data relied on photon-neutron reactions (γ, xn) to infer the photoabsorption cross section.

The most direct way to determine the absorption cross section is the direct measurement of the absorption of the photons (γ-rays) when traversing a target, i.e. the outgoing and incoming intensity of a beam of photons passing through a thick target (optimal transmission is only about 10 %) is recorded and from the attenuation of the photon beam the cross section is deduced. The advantage is that the complete absorption is measured directly and completely independent off any particular exit channel.

The doctoral researcher will therefore measure the direct photoabsorption cross section for the isotopes ^{144,146,148,150}Nd with the existing photon-tagger NEPTUN [196] and fast target changer PROTEUS at the S-DALINAC. The photon-tagger was substantially upgraded in the last years and the full energy-range of interest from about 5 to 35 MeV can be covered with a single setting of the NEPTUN magnet and thus just one setting for the energy of the electron beam provided by the S-DALINAC.

The attenuation of the photon beam is dominated by atomic processes, mainly pair-production at high energies. Thus the atomic contribution needs to be calculated and carefully subtracted from the total cross section to obtain the nuclear absorption of interest here. It should be noted, that the variation of the atomic cross section exhibits a very smooth energy dependence, so that the shape of the nuclear photoabsorption can be analyzed even if there are remaining uncertainties concerning the overall scale of the atomic absorption.

B-9$_m$: Energy-dependence of the GDR's gamma-decay branching ratio in deformed rare-earth isotopes (Pietralla, Ur)

The photonuclear reaction cross section is dominated by the Isovector Giant Dipole Resonance (IVGDR) located at excitation energies of about 78 $A^{-1/3}$ MeV, typically around 15 MeV for heavy nuclei [195,197] see B-7, above. It is associated in the simple geometrical liquid-drop model with translational out-of-phase motion of the neutron fluid versus the electrically charged proton fluid about their common center of mass, thereby giving rise to the emission of electric dipole (E1) radiation or, correspondingly, to the peak in the photoabsorption cross section. The IVGDR is the prime example for a collective nuclear mode. In nuclei with axially-symmetric quadrupole-deformed ground states, the photoabsorption cross section shows two maxima interpreted as translational isovector motion along the long axis of the nuclear ellipsoid with intrinsic angular momentum projection K=0 or along the short axes with K=1. This energy splitting of the IVGDR is considered as the most direct evidence for the amount of nuclear ground-state deformation in the literature. Their gamma-decay into the members of the K=0 ground-state rotational band are believed to follow the Alaga rules for E1 transitions with $\Delta K=0$ or 1, respectively. Despite of its fundamental character, the details of the emission of E1 radiation by the IVGDR are largely unknown. The IVGDR is unbound and, hence, predominantly decays by fast neutron emission, leaving measurements of its gamma-decay as a function of the excitation energy an experimental challenge. In particular, IVGDR's gamma-decay branching ratios in deformed had been unknown until now. We have recently pioneered a method for measuring the gamma-decay branching ratio of the IVGDR as a function of excitation energy by exploiting the quasi-monochromacy and the polarization of the energetic photon beams from laser-Compton backscattering sources. The first successful experiment was performed on the deformed nucleus ^{154}Sm. The data presented in Figure 21 show that the gamma-decay of the IVGDR of the well-deformed nucleus ^{154}Sm does not agree with the predictions of the Alaga rule. Instead, they seem to exhibit transitional character as proposed in Ref. [198] while a full quantitative understanding is still lacking.

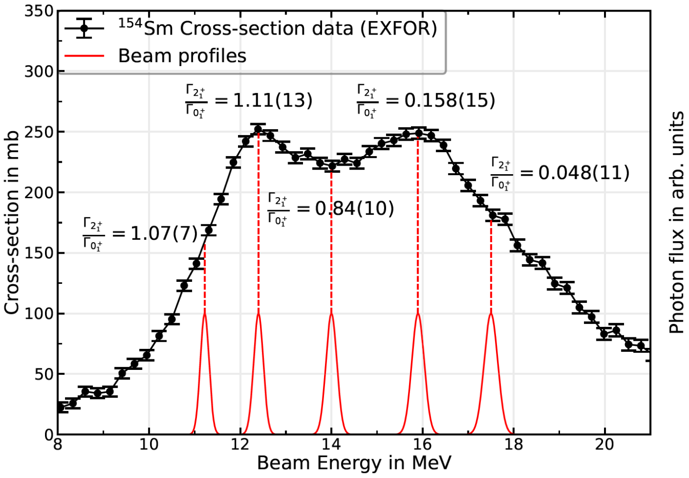


Figure 21: *Data on the gamma-decay of the GDR of the deformed nucleus ^{154}Sm taken recently by our group at the HIγS facility.*

We intend to study the gamma-decay branching ratio of the IVGDR in the isotopes ^{150,152}Sm, and in ^{170}Er, which has the largest valence space of all stable rare-earth nuclides. Comparison to the data on ^{154}Sm and to the data on the spectral function of the photoabsorption cross section from Project B-8 are expected to clarify the structural mechanism responsible for the gamma-decay of the IVGDR.

B-10: Influence of the N=126 neutron shell closure on the properties of pygmy and giant dipole resonances in heavy nuclei (Tsoneva, Martinez-Pinedo)

The proposed project aims to train young researchers in theoretical nuclear physics and applied studies of photonuclear reactions and astrophysics in leading institutions in this research field [RT10,199]. The main goal of the study is to focus on new aspects of the spectroscopic properties of nuclear excitations, in particular the role of the closure of the nuclear N=126 shell on nuclear dynamics and the collectivity of pygmy and giant dipole resonances in heavy nuclei [57,74,77]. In this aspect, from systematic studies of nuclei from the N=126 region, connections can be made in a broader scientific context, namely between nuclear structure, neutron shell closure, nuclear collectivity, neutron skin, pygmy dipole resonance (PDR), giant dipole resonance (GDR), dipole polarizability, symmetry energy, the equation of state of nuclear matter and astrophysics [57].

In particular, the PDR can have important contributions to the nucleosynthesis of the heaviest nuclei in cosmic objects such as neutron stars and binary star mergers, as well as to the s- and r-processes of nucleosynthesis shown in Figure 22 and in Refs. [57,63–65]. Effects of nuclear shell closure at the magic number N=126 play an important role in determining the nuclear abundance of the s- and r-process [200]. The doctoral work will be carried out using advanced nuclear structure and nuclear reaction methods incorporating energy-density functional theory and extended by a multi-phonon coupling quasiparticle-random-phase approximation approach [57,63–65,74,77] in order to gain a deeper understanding of the microscopic structure of nuclear excitations and the mechanism of nuclear

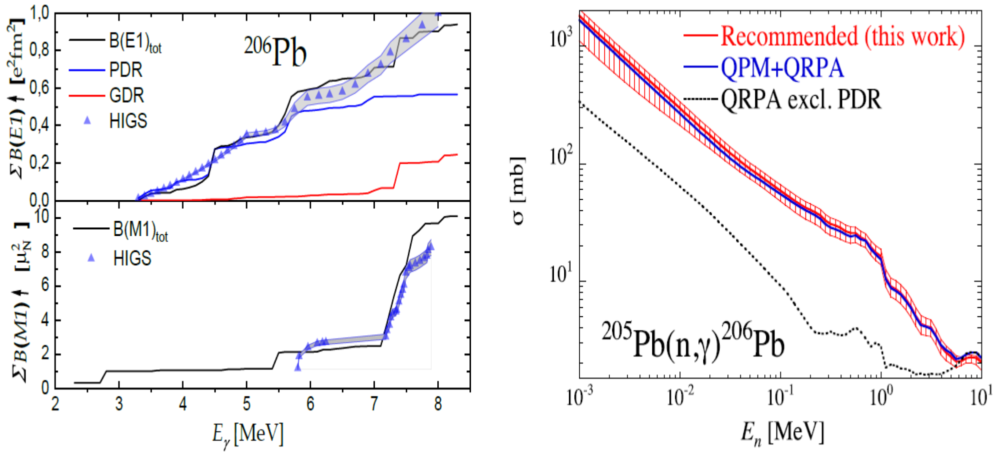


Figure 22: *Left: Cumulative B(E1) (top) and B(M1) (bottom) strength in ^{206}Pb obtained from integrating the corresponding distribution of E1 and M1 strength up to an energy $E_\gamma \leq S_{1n}$= 8.1 MeV. Right: Radiative capture cross section ^{205}Pb(n,γ)^{206}Pb using as input the experimental (HIGS) E1 and M1 dipole strength (red curve) or the three-phonon QPM and QRPA predictions (blue curve). The dotted line is obtained with the QRPA strength excluding the PDR contribution [65].*

collectivity. The obtained nuclear structure results can be further integrated into calculations of relevant astrophysical reactions in nuclear reaction models. The PhD project is divided into sophisticated pioneering work (a) Theoretical predictions of new modes of nuclear excitation and their influence on the s- and r-process of nucleosynthesis in heavy nuclei at N=126 neutron shell closure for the purpose of novel experiments at ELI-NP and (b) provision of theoretically and experimentally interesting research work for the desired doctorate.

B-11: Sub-barrier photofission studies with polarized brilliant γ beams (Balabanksi, Enders)

Since the early days of photofission research an enhancement of the photofission cross section was observed at sub-barrier energies, which was referred to as an ‘isomeric shelf’, and was related to the existence of resonance structure (transmission resonances) due to the coupling of excited states from the different wells of the multi-humped potential barrier [201–204]. The process is schematically described in Figure 23. Transmission resonances are understood as due to coupling from the first minimum of the potential energy surface (PES) to states in the second or third minimum.

So far, transmission resonances in light actinides have been studied primarily in light-particle-induced nuclear reactions, see e.g., Ref. [RT10,205]. The interpretation of these results is complicated due to the statistical population of the states in the second (and third) minimum, while photofission experiments provide the required selectivity. Previous experiments with LCB beams at HIγS were not conclusive, since one of them reported enhancement of the sub-barrier photofission cross section [206], but a follow up experiment related it to background effects [207]. The cross section was not studied to lowest energies of interest and the results suffered from insufficient resolution. A more systematic approach with detectors providing higher resolution is needed for answering this important question. This key problem will be addressed at the MeV-ranged photon beams of ELI-NP.

In this project, the doctoral researcher will study the photofission cross sections in ^{238}U and ^{232}Th at energy range of 4 – 6 MeV, which covers the expected region of transmission resonances in these nuclei. In the experiments, the yields, kinetic energy, mass, charge and angular distributions of the fission fragments will be measured.

The answers of two key questions will be sought within this project, namely:

a) Is there enhancement of the sub-barrier photofission cross section?
b) Are there transmission resonances in ^{232}Th and ^{238}U?

This PhD work will study the sub-barrier cross section in ^{232}Th and ^{238}U and provide answer to some long-lasting questions related to:

a) the fine structure of the isomeric shelf,
b) the excited states in the 2nd (and 3rd) well,
c) the topology of the fission barrier.

In addition, the ELITHGEM array can be coupled to the ELIGANT-GN neutron array and provide a fission trigger for measurements of the neutron spectra, multiplicities and angular distributions.

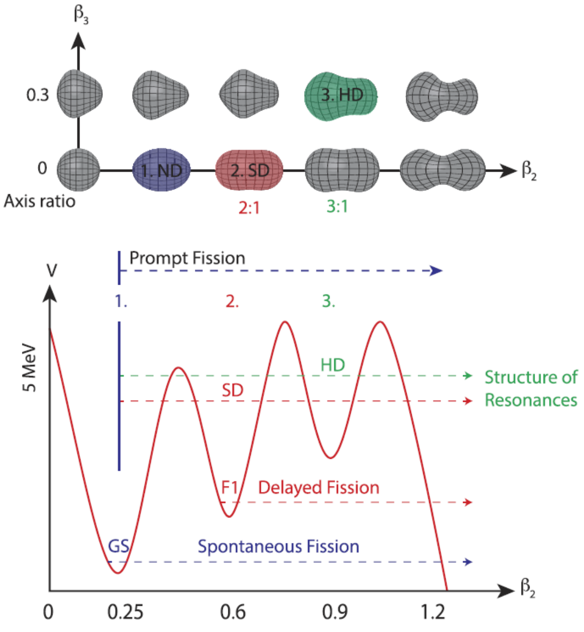


Figure 23: *Schematic description of the fission process and the appearance of transmission resonances. In the upper part of the figure the deformation and the shape of the nucleus is shown, and in the lower part, a two-dimensional plot of the potential barrier.*

B-12: Correlation experiments in fission reactions induced by quasi-monochromatic polarized photon beams (Enders, Balabanksi)

In spite of its age and industrial use, nuclear fission still cannot be described accurately on a microscopic level (e.g., Refs. [208]). Both robust experimental data as well as theoretical modeling are, however, necessary for a precise understanding of, e.g., astrophysical applications [209], in particular pertaining to the astrophysical r-process, or technical ones, like the quest for improved reactor modeling [210], nuclear-waste transmutation, or proliferation control. Photonuclear reactions [211], proceed through the electromagnetic excitation of the fissioning nucleus from its ground state by dipole and quadrupole excitations. The combination of double Frisch-grid ionization chambers (FGIC, available at TU Darmstadt [104] and ELI-NP [212]) for the detection of fission fragments (FF) and powerful neutron detector arrays (such as ELIGANT-GN [178]) allows us to measure FF yield, total kinetic energy (TKE), azimuthal and polar angular distributions [61], and yield and angular distribution of the prompt fission neutrons (PFN) simultaneously and correlate the distributions. A CAD sketch of the foreseen setup with the Darmstadt FGIC [104] and ELIGANT-GN [178] is shown below.

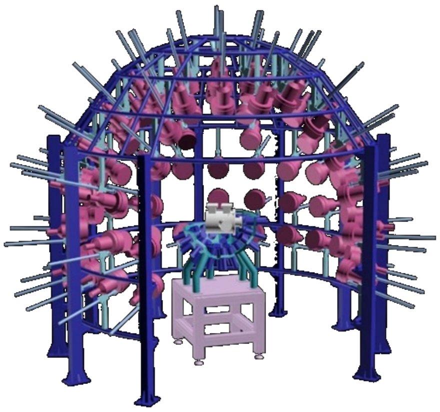


Figure 24: *CAD drawing of TU Darmstadt's segmented FGIC with ELIGANT-GN.*

This project studies photon-induced fission above the barrier to understand the roles of low-lying collective excitations in the fission process. The doctoral researcher working on this project will (a) for the first time measure the FF yields, TKE, and angular distributions from the $^{240,242}\mathrm{Pu}(\vec{\gamma},f)$ reactions to extract information on the intermediate states and fission modes [213] in these nuclei from studying correlations between these observables and (b) will identify for the first time PFN spectra at an in-beam photofission experiment at energies slightly above the fission barrier. The proposed program will continue and enlarge the joint successful efforts of the Darmstadt and Bucharest groups [214].

B-13: Microscopic description of collective inertias for fission (Martinez-Pinedo, Tsoneva)

Fission plays a fundamental role to understand the stability of superheavy nuclei and the nucleosynthesis of heavy nuclei by the *r*-process [RT4]. Microscopic systematic calculations of fission barriers and associated reaction rates for *r*-process nuclei have recently become available [105]. This input is fundamental to understand the production of translead nuclei by *r*-process and its impact on electromagnetic transients associated to neutron star mergers [106]. A key challenge in these calculations is the description of collective inertias along the fission path. Ref. [105] reports systematic calculations of collective inertias using two different schemes, the adiabatic time-dependent HFB theory and the Gaussian-overlap approximation to the generator coordinate method and found important differences in the collective inertias that lead to substantial effects in the predicted spontaneous fission lifetimes. These results were obtained within the perturbative cranking approximation, where time-odd fields are neglected. Such time-odd terms are responsible for the spin-response of the nucleus and hence magnetic-dipole modes as those studied in project B-13 constitute an ideal benchmark of the underlying functional and many-body approach.

Recently, a new method for the calculation of collective inertias based on the local quasiparticle random-phase (QRPA) approximation has been developed [215]. The advantage of this method is that it allows for a consistent treatment of dynamical effects neglected in the cranking approximation. Further-

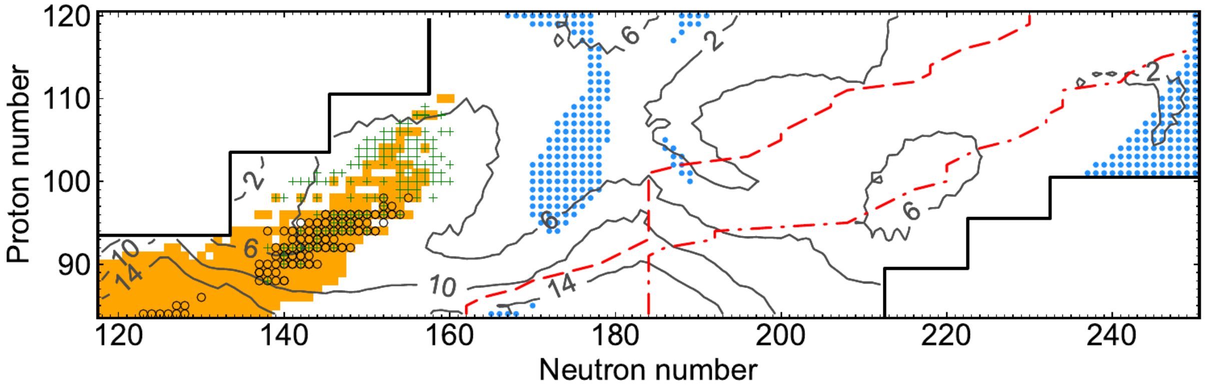


Figure 25: *Landscape of superheavy nuclei showing in orange squares those nuclei with known masses. Nuclei with experimentally measured fission barriers and spontaneous fission lifetimes are marked with open circles and crosses, respectively. Dashed and dot-dashed lines illustrate the location of the r-process path and represent the heaviest isotope of each element with S_n≳2 and S_n≳0 MeV, respectively. Contour lines show the highest predicted fission barrier, in MeV. Neutron separation energies and fission barriers are based on the BCPM functional [105].*

more, the same QRPA approach used for the calculation of inertial masses can be used for the calculation of the electromagnetic response of the nucleus. The doctoral researcher will implement the QRPA scheme for the calculation of collective inertias in the fission calculations. The approach will be benchmarked against electromagnetic response data measured in B-8, B-9, and B-14. In addition, the fission experiments on B-11 and B-12 will benchmark our predictions for fission barriers. This project shares common theoretical techniques with B-10. This work will also be part of a long lasting and fruitful collaboration with Samuel Giuliani and Luis Robledo from the Autonomous University of Madrid.

B-14: Search for low-energy dipole modes of transuranium actinides (Pietralla, Ur)

Dipole excitations of actinide nuclei are important for scientific, technological, and safety reasons. Exotic neutron-rich actinides, for example, form the end-point of the rapid-neutron capture process (*r*-process) of the nucleosynthesis processes in binary neutron-star merger events, such as GW081708 [216]. The *r*-process is held responsible for the production of the heavy elements in the Universe [RT4]. When the probability for neutron-induced fission reactions is higher then primary dipole decays in (n,γ) reactions, then the just synthesized actinides undergo fission and the corresponding fission fragments represent two new seeds for further *r*-process reactions. While the exotic actinides involved in the *r*-process cannot be accessed experimentally with current methods, the quantitative understanding of the natural nucleosynthesis relies on the extrapolation of nuclear models (see B-13) to these exotic isotopes and on their sufficient experimental validation for experimentally accessible nuclides. Moreover, technologically, transuranium actinides form the majority of the long-lived radioactive waste from nuclear power generation. The engineering of methods for their transmutation and disposal relies on our understanding of their properties. Penetrating gamma-rays inducing photonuclear reactions in specific actinides, that themselves are dominated by dipole excitations, allow for the isotope-selective inspection of bulk material or devices and thereby for obtaining a non-invasive measurement of the radioactive inventory of a given container. This has obvious technological and safety potential. Unfortunately, data on photonuclear reactions on transuranium actinides are very sparse. Limited information exists on ^{237}Np and on ^{239,240}Pu, only [RT10], up to now.

We have started a program for characterizing the dipole excitation modes of transuranuim actinides by the method of Nuclear Resonance Fluorescence. Samples with an activity of up to 1 GBq can be studied at the Darmstadt High-Intensity Photon Set-up (DHIPS) at the S-DALINAC for calibrating the strength scale against a photon-flux calibration standard. Parity-quantum numbers, decay branching ratios, and weak excitations can be studied very sensitively using monochromatic gamma-ray beams. At DHIPS in Darmstadt, we have recently studied the NRF spectrum of ^{242}Pu ($T_{1/2}$ = 4 10^5 a), so far the heaviest isotope ever studied with NRF. The target material was produced by the Oak Ridge National Laboratory. The data presented in Figure 26 show the NRF spectrum of ^{242}Pu with lines from the samples activity subtracted. The characterization of the NRF lines from ^{242}Pu represent one of the major objectives of the European IMPULSE project at ELI [217].

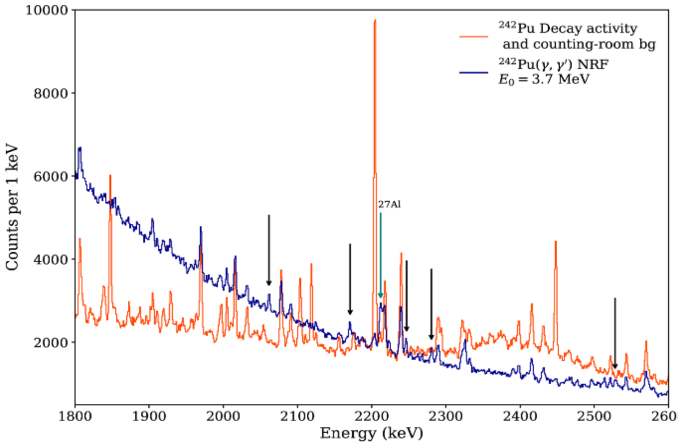


Figure 26: *First NRF measurement on a ^{242}Pu sample (blue), taken recently at the S-DALINAC at Darmstadt, and compared to an activity measurement of the sample (red). Black arrows indicate NRF lines.*

We intend to study NRF from the isotopes ^{244}Pu ($T_{1/2}$ = 8 10^7 a), and ^{248,250}Cm ($T_{1/2}$ = 3 10^5 a, 1 10^4 a) for the first time. The data from DHIPS and from monochromatic gamma-beams, either from the HIγS facility or from VEGA will provide first information on dipole modes of these transuranium actinides and will support the theoretical modeling of their structure as well as potential technological applications.

C-1: Spatio-temporal metrology for tailored ultra-intense laser pulses driving relativistic particle acceleration (Ursescu, Bagnoud)

The spatial or temporal characterization of ultrashort pulses assumes decoupling of the laser pulse parameters. This might not be the case in real life facilities, and this affects the peak intensity of the pulse, in particular when using complex pulses such as vortex beams [218–220]. Hence methods to characterize and control the spatio-temporal couplings (STC) are needed [221–223]. In this way, one can better understand the actual peak intensity of the pulse and the interaction of the laser pulses with the matter. The technique shall be complemented with propagation codes that describe the STC evolution.

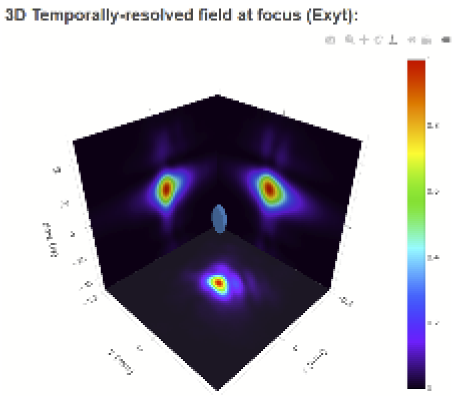


Figure 27: *Reconstructed spatio-temporal structure of an ultrashort laser pulse.*

The doctoral researcher shall study the achievable resolution and dynamic range in STC measurements and develop methods to introduce STC in a controlled manner, using the following methods:

a) Development of high resolution STC measurement device
b) Implementing a feedback loop for STC introduction/compensation
c) Use a propagation code to predict the evolution of the STC [220]
d) Assess the effect of the STC in relativistic particle acceleration experiments, as in [224]

The validation of the implementation of the laser pulse STC metrology and control shall be performed through the use of the developed methods in experiments such as the ones related to relativistic particle acceleration, important for the Nuclear Photonics domain. The research trainee will develop besides the theoretical and simulation skills also the complementary hands-on experience in the implementation of laser driven experiments for particle beam production.

C-2$_m$: Increased laser intensity with re-entrant cone in 10 PW regime (Tanaka, Boine-Frankenheim)

In the current status of high peak power values in the world laser systems, 10 PW laser system operated at ELI-NP will achieve the highest focused intensity of 10^{23} W/cm^2 in 20 femtosecond pulse regime [225]. Using this laser system, many highly relativistic, nuclear physics such as the nonlinear QED, the laser-gamma ray conversion, electron/ion acceleration, and nuclear battery will be tested at ELI-NP to open a door way to new science horizon. In this project, we propose new approach to obtain even higher focused laser intensity without refurbishing the laser system [199]. By introducing a small (50 micron: cone length x 5 micron: cone tip) re-entrant cone, we have shown a possibility to increase the focused laser intensity by more than ten times. This means that the focused laser intensity of 10^{23} W/cm^2 could be further increased to over 10^{24} W/cm^2 [226].

In this project, the doctoral researcher

a) will learn how to simulate such intensity increase using PIC code.
b) will apply the simulation result to design and to conduct the increase of focused laser intensity

The proposed project is ideally suited for training young researchers in both theory and experiments in nuclear photonics. He or she will learn the behaviors of the intense electromagnetic waves in the re-entrant cone at one of the most advanced laser facilities under the super vision of the expert scientists. It will be an outstanding outcome once the highest intensity in the focused spot is achieved.

The doctoral researcher will gain expertise in the handling of PIC simulation code, the interpretation of the numerical results, then design and optimization of the focused laser experiment. The designing of the experiment will include to prepare the diagnostics to measure the focused laser intensity.

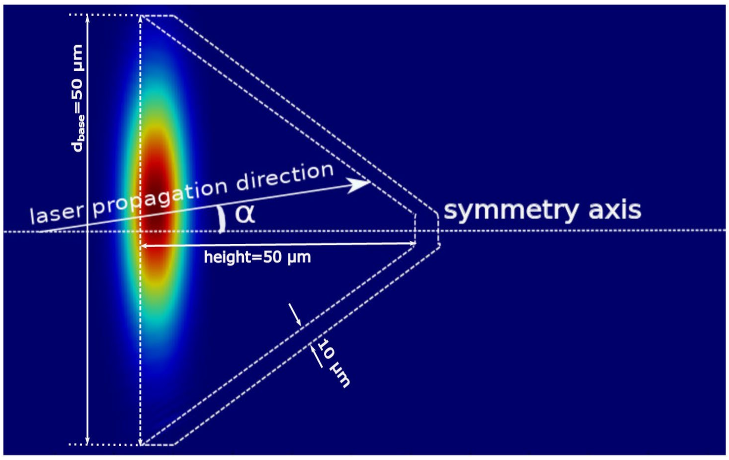


Figure 28: *The cross section of the re-entrant cone is shown as dotted conical shape. The laser pulse comes in from the left. The laser pulse is squeezed to the increased intensity towards the narrower cone tip. This picture shows a setup of this scheme in PIC simulation.*

The optimization of the experiment using PIC simulation includes the laser focused intensity scanning range, types of the re-entrant cones, the selection of the diagnostics. One of the major diagnostics will be different types of gamma-ray detectors, digital data acquisition systems, and electron/ion energy spectrometers. Handling the combination of the PIC simulation, the experimental design and the execution of the experiment he or she will obtain excellent capability in the usage of both PIC simulation and recently established experimental technique. This project will guarantee a well-balanced research topic for the envisioned doctoral thesis with subsequent publication of the results in high-impact peer-reviewed journals.

C-3: Target morphology and its implications on laser-plasma accelerators (Ticos, Roth)

The target normal sheath acceleration (TNSA) is a robust mechanism for proton and ion acceleration from solid targets when irradiated by a high-power laser. Extensive studies have been carried out to enhance this acceleration process either by optimizing the laser pulse delivered onto the target or by utilizing targets with particular features. Targets with different morphologies such as the geometrical shape (thin foil, cone, spherical, foam-like, etc.), with different structures (multi-layer, nano- or microstructured with periodic striations, rods, pillars, holes, etc.) and made of different materials (metals, plastics, etc.) have been proposed and utilized [15,227–230].

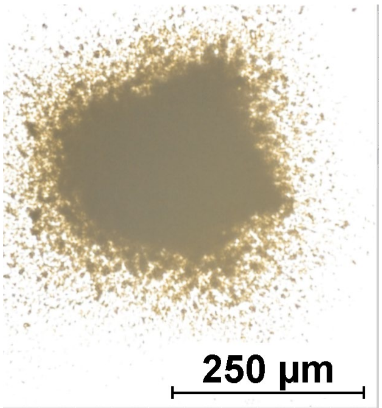


Figure 29: *Carbon foam deposited on a Si surface (courtesy of A. Măgureanu and V. Crăciun).*

Here we propose to focus on microstructured targets (e.g. thin bilayers laminates, or a foam deposited on a thin layer, and microspheres levitated in the focal spot of the laser), as shown in Figure 29. The proposed project attempts to capture how the morphology of the solid target and its composition is transposed into higher proton energy, taking into consideration also the laser parameters. In this project, the doctoral researchers will (a) propose, design and realize new targets (e.g., nanostructured and levitated clusters of spherical microparticles), (b) characterize particles fluxes and energy of accelerated particles after laser irradiation, and (c) propose target optimization for more efficient proton/ion acceleration

C-4: Steering of laser-plasma accelerated particles for applications (Ticos, Arnold)

Along with the rapid development of high-power lasers it was discovered that the ultra-intense beams of nuclear particles (such as protons and ions) produced by them can have important applications in the medical field [231]. Other uses of protons are in tomography, radiography and imaging [232,233]. One common requirement is the control of the beams in terms of flux, divergence and energy [234]. In the case of radiotherapy for curing cancer with heavy ions and protons (hadron therapy) produced by lase plasma accelerators (LPAs) there is an apparent extra benefit which consists in the short duration of the particle bunches, of the order of ps. This feature gives access to the “Flash” irradiation regime at very high dose rates, in the 10^5-10^9 Gy/s range, many orders of magnitude higher than the typical dose of 0.3 Gy/s (or ~2 Gy/min) delivered by classical accelerators [21,235]. “Flash” radiotherapy is less studied and thus not yet applied as a treatment method but the preliminary laboratory and clinical results were so encouraging that they triggered a huge interest in the scientific community [236].

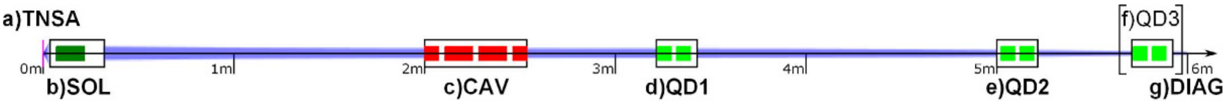


Figure 30: *Sketch of the LIGHT beamline at GSI consisting of a solenoid (SOL), a radio-frequency cavity (CAV), 2 quadrupoles (QD1 and QD2), and a diagnostics bench (from ref. [237]).*

Beamlines for steering ions and protons produced by LPAs have been proposed in the past and their operation was demonstrated at particle energy ranges of tens of MeVs, as shown in Figure 30, [237]. Yet, the main challenges remain, and these are the further reduction in size of the steering structures and the enhancement of their capabilities in terms of particle energy selection.

In this project, the doctoral researcher will (a) propose and design a novel steering/focusing system using accelerator concepts (Twiss parameters, etc.) with the goal of reducing its size while obtaining an optimum conditioned particle beam with energy up to 100 MeV and (b) simulate the operation and the dose for relevant laser-plasma parameters using existing software solutions (e.g., SIMION, Particle Beam Optics, TraceWin, MatRad, etc).

C-5: 4D Particle detection employing low-gain avalanche-diode technology (Galatyuk, Doria)

In order to perform a precise characterization of laser-generated charged-particle beams in work area A, it is necessary to use modern and fast particle detectors that can simultaneously measure positions with precision better than $50\,\mu m$ (sigma) and time with precision below $50\,ps$ (sigma) or better. Low-Gain-Avalanche-Diodes (LGADs) is the most promising technology which meets these requirements as recently demonstrated [110,238,239]. The LGAD sensor R&D is progressing fast, including the radiation hardness aspects [240] and LGADs with higher fill factors [241,242].

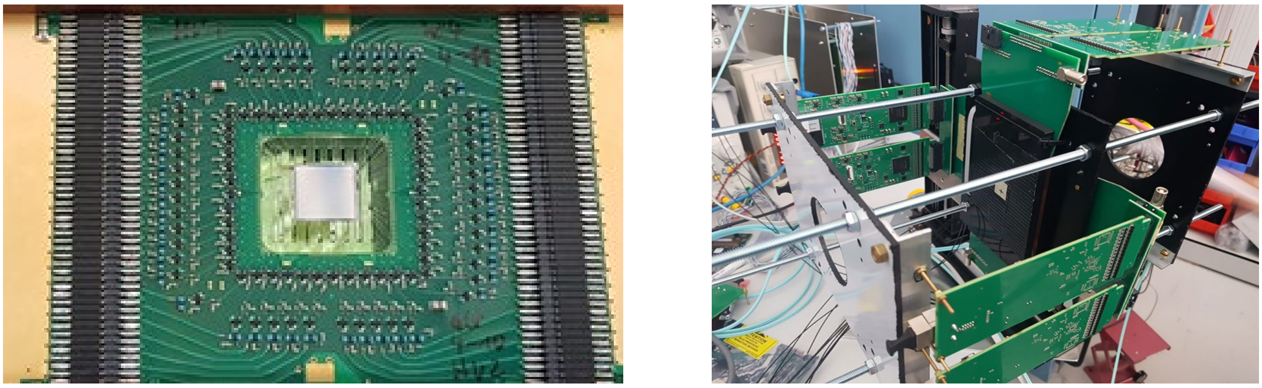


Figure 31: *(Left) Photo of the LGAD sensor mounted on a dedicated PCB equipped with 96 readout channels consisting of 2 stages of fast analog amplifiers. The LGAD prototype sensor has a form factor of 1cm x 1cm and has a single-sided segmented readout in the form of 86 strips with a* $100\,\mu m$ *pitch. The sensor strips are connected to the amplifiers by* $20\,\mu m$ *thick Al bond wires. (Right) The prototype setup consisting of two LGAD sensors with orthogonal strip orientation connected to a DiRich5s1 board performing signal discrimination and TDC measurement.*

Within this project, we propose an LGAD-based detection system based on custom discrete frontend electronics (FEE) and a new generation of LGAD sensors. This system consists of LGAD strip sensors with a sensor pitch of $100\,\mu m$ connected to 86 readout channels of our custom FEE. In order to minimize the effect of the sensor on the beam characteristics, the sensor will also be thinned to a thickness of less than $100\,\mu m$.

The main tasks of the doctoral researcher foreseen in this project:

a) electrical characterization of state-of-the-art LGAD sensors like strip capacitance, inter-strip capacitance, IU characteristics.
b) participation in the design of next-generation LGAD sensors based on Deep Trench Isolation (DTI) technology with the goal to improve the fill factor above 96%.
c) design, construction and tests of a prototype system optimized for characterization of laser-generated charged-particle beams.
d) preparation and development of software for readout and calibration of sensors, analysis of experimental data and presentation of results.

The foreseen activities will give the opportunity to get acquainted with the design and construction process of sensors under the supervision of world-class specialists in the LGAD technology. In addition, the research trainee will learn about the operation of the entire readout chain of timing detectors and will gain expertise in data analysis obtained from test experiments. The experimental results and innovation of the detection system will be excellent material for participation in international conferences and publications in high-impact peer-reviewed journals.

C-6$_m$: Control of VEGA's Electron Beam and Optimization of its Emittance by AI Methods (Matei, Arnold)

VEGA will operate a 700 MeV electron beam from a warm normal-conducting linac [148]. Its control system will be operated using EPICS [243] - a very versatile, open-source software framework used and developed by many accelerators around the world, including the S-DALINAC at TU Darmstadt. Controlling an accelerator means also to interact with diagostics of the machine, e.g. targets, wire-scanners, beam position monitors. They are automatized to simplify regular measurements that are needed for the characterization of the electron beam. The project will first focus on the automated determination of the beam emittance [244] of the VEGA linac. In a next step, a surrogate model of the VEGA system will be generated and verified with measurements [245]. This will allow for an optimization of the emittance based on the surrogate model and measured data using machine-learning techniques. The obtained results will be verified by measurements in a last part of the project. During the internship, the junior researcher will profit from the long-term experience of the EPICS-based control system at S-DALINAC, e.g. [246], as well as the ongoing research activities on the field of surrogate models and machine-learning optimized control of an accelerator. The beam quality of the LCB beam, that is set-up in project C-7, will greatly benefit from the results.

C-7: Set-up and Luminosity Characterization of VEGA’s 1.-Phase LCB-Beam (Balabanski, Arnold)

The VEGA system of ELI-NP will produce MeV-ranged photon beams from LCB reactions of a synchronized external laser with the 700-MeV electron beam from its normal-conducting electron linear accelerator [148]. In its initial phase, starting 2024, LCB beams will be generated at reduced repetition rate as compared to the full system from head-on collisions of the laser with the electron beam. The vacuum chamber for the laser-Compton collisions, the coupling mirrors of the external laser beam into the electron beam line of the accelerator, along with their stabilization system, and the electron beam’s position fine-tuning steerer magnets in front of the collision point will be set-up. Wire-scanners will be used for measurements of the electron beam positions. Piezo-actuators-driven off-axis-paraboloide-mirrors will be used for the anti-collinear injection of the laser beam into the electron beam line. A corresponding system is currently under construction, already, at the S-DALINAC at TU Darmstadt [247]. The internships of the junior researcher at TU Darmstadt will be most beneficial for a rapid knowledge transfer from the system at TU Darmstadt to ELI-NP and will strongly support the timely completion of VEGA. Operation and performance of the LCB beam will later-on be characterized experimentally by using feedback from the beam monitor established in project C-8.

C-8: Advanced gamma beam diagnostics detectors for polarization and intensity monitoring (Ur, Pietralla)

The ELI–NP project aims at opening new opportunities in basic and applied nuclear physics research with intense MeV-ranged beams [248]. The Variable Energy Gamma (VEGA) System of ELI–NP had been designed to produce intense gamma-ray beams with spectral densities of about 10^4 photons/s/eV, a narrow relative bandwidth (<0.5%), high degree of linear polarization (>95%) and tunable energy over a wide range from about 1 MeV to 19.5 MeV. The small geometrical dimension of the beam will allow the use of small targets of extremely expensive or highly radioactive materials. While the establishment of the VEGA set-up had been delayed, it is collaboratively progressing with expected completion in 2025. In parallel, the experimental instruments need to be established, too. To optimize the operation for photonuclear reactions experiments it is critical to have the proper means to accurately control the spatial, spectral and temporal characteristics of the gamma beam [117].

The project proposes to develop equipment and techniques meant for the optimization and monitoring of the gamma beams at ELI–NP. Two main categories of equipment are considered: i) diagnostics equipment for the optimization of the gamma beam delivery and ii) monitoring devices of the beam features during the operation of the gamma beam system. The first category of devices can block the beam as its purpose is mainly for adjusting the beam quality at the exit of the gamma beam system. The second category of devices have to run continuously during experiments and they should generate none or minimum interference with the beam. Irrespective of their category of use, the following diagnostics devices are being developed (i) beam flux monitor to measure and monitor the beam intensity, (ii) beam position imager to spot the beam position for alignment and diagnostics purposes, (iii) Compton spectrometer, to measure the beam energy, intensity and polarization for monitoring purposes, (iv) sampling calorimeter for a fast combined measurement of the beam average energy and intensity, to be used during machine commissioning and development.

In this project, the doctoral researcher will (a) develop detector systems, including the data acquisition system and the interface with the gamma beam system operators, for the measurement of gamma beam characteristics, such as energy, intensity, polarization, over a wide range of gamma-ray energies and (b) develop GEANT4 simulations to determine the response of different detectors that have to be optimized for the use as gamma beam diagnostics, such as Ge detectors, $LaBr_3(Ce)$ scintillator detectors, Si detectors, liquid scintillator neutron detectors [117]. Users will benefit from accurate information about the beam characteristics during the experiments at VEGA which is critical for extracting precise information about reaction cross sections or nuclear level widths [249].

C-9$_m$: Exploiting segmented HPGe-detectors and digital signal processing for γ-ray spectroscopy (Ur, Isaak)

Investigation of nuclear structure following photonuclear reactions is performed via high resolution gamma-ray spectroscopy with large volume HPGe detectors or $LaBr_3(Ce)$ fast scintillator detectors. Gamma-ray spectroscopy provides the means for the recovery of several physical quantities characterizing the excited nuclear states, such as: excitation energies, level widths, gamma–decay branching ratios, spin quantum numbers, and parities. When combined with Nuclear Resonance Fluorescence (NRF) these quantities are determined in a completely model independent way [RT10]. The advanced characteristics of the gamma beams available at ELI–NP in the future and the use of high efficiency detection systems will offer a fore-front infrastructure for investigation of photonuclear reactions.

The main detection system for NRF studies at ELI-NP is a multi–detector array (*ELIADE* – **ELI**–NP **A**rray of **DE**tectors [RT7]) based on the use of segmented CLOVER-type composite high–purity Ge detectors and large volume $LaBr_3(Ce)$ scintillator detectors able to detect with high resolution and high efficiency gamma rays with energies up to several MeV in the presence of the high radiation background produced by the gamma beams. This will lead to a significant enhancement of the measurements' sensitivity leading to the possibility of investigating weak, exotic phenomena otherwise hindered. The signals from the Ge detectors will be continuously digitized. As discussed in Ref. [250] the segmented CLOVER detectors possess some gamma–ray interactions position-identification capabilities by using pulse-shape analysis. By combining pulse-shape analysis with the high probability to absorb the background radiation in the frontal segments one can develop algorithms to further reduce the pile–up of NRF events with background events while maintaining the Pb absorber in front of the detectors at small thickness. The signals from the detectors will be readout with high-sampling-rate digital electronics.

The project proposes to develop gamma-ray spectroscopy techniques based on digital data acquisition optimized towards the reduction of the background generated by the annihilation of positrons produced by intense high-energy gamma beams in the target and by the Compton scattering of the gamma rays in the detector material by using the segmentation of the detectors. Pulse-shape analysis algorithms will be developed with the capability to give a localization of the gamma rays interactions in the crystal and analysis tools able to eliminate the unwanted background events from the data will be made. Moreover, by reading out individually the signals from the anti-Compton crystals one can improve the efficiency of removing the Compton events from the spectra while preserving a larger number of good events in the photopeaks. This will greatly improve the sensitivity of the experiments [251].

In this project, the doctoral researcher will (a) develop realistic simulations of the signals from the segmented Ge crystals with the goal to localize the interactions of the gamma rays in the crystals, (b) develop GEANT4 simulations of the photonuclear reactions and the interaction of the resulting gamma rays with the detector to understand the nature of the background that will affect the measured gamma-ray spectra, and (c) develop the data acquisition system to include the digital readout of the signals from the anti-Compton crystals and use them to perform a 'smart' reduction of the background in the gamma-ray spectra. The results of the project will be used to improve the sensitivity limit of the experiments performed at ELI-NP in the future. This will ensure the performance of a high-level experimental work in experimental techniques with immediate application to the needs of the ELI-NP facility.

C-10: Lattice of a storage ring as a photon source (Ur, Boine-Frankenheim)

The VEGA system of ELI-NP is designed as a gamma-ray source based on the Inverse Compton Scattering (ICS) principle, where a beam of relativistic electrons collides with a high-power laser beam to upshift the laser photons to MeV energies [252].

An initial phase of the VEGA system will use a LINAC-based source which has the advantage of generating high peak brightness gamma-ray beams due to the low emittance of the electron beam. However, the low repetition rate of the electron source results in low luminosity unless the number of electrons per bunch and the laser pulse energy are increased significantly. One viable solution to increase the luminosity is to use the LINAC as an injector into a high-repetition storage ring. A storage ring could provide a high average flux, angular spectral density, and brightness required for the VEGA system.

This project aims at optimizing the design for an efficient storage ring with a small divergence for the electron beam, a large momentum aperture to contain most of the electrons scattered by the laser, provide sufficient beam lifetime to store the beam, and thereby support the establishment of the VEGA system towards meeting its design parameters. The project will use the experience at TU Darmstadt/GSI in designing and developing the SIS-100 synchrotron at FAIR [253] and operating an electron accelerator. The doctoral researcher will (a) simulate the lattice of the present storage ring design and verify that it achieves VEGA's completion criteria, (b) study possible optimizations for the design/upgrade of the storage ring for the VEGA system, (c) include a laser interaction in a start-to-end simulation to achieve required gamma-ray beam parameters over the entire energy range, and (d) validate various operation modes for arbitrary energy changes. Operation and performance of the VEGA system will later-on be characterized experimentally by using the beam monitor established in project C-8.

C-11: Electron-gun optimization for laser Compton backscattering and nuclear-photonics applications (Enders, Ticos)

Brilliant, quasi-monochromatic, polarized photon sources as from laser Compton backscattering (LCB) depend on the properties of the electron beam (e.g., Ref. [254] and Refs. therein). The luminosity of the process depends on the spatial and temporal overlap of the photon pulse with the laser bunch. At storage-ring LCB facilities such as the ELI-NP VEGA system, the revolution frequency in the ring defines the electron bunch's time structure [255]. Due to the storage-ring concept, the effective beam current at such facilities is high, but synchrotron radiation limits the quality of the beam properties that is carried on to the X-ray or γ-ray beam properties [254]. In order to increase the brilliance of the high-energy photon beams of LCB sources ("4th generation"), low emittance electron beams with very high intensity are necessary. In contrast to the continuous-wave operation of machines like the S-DALINAC, increasing luminosity can be achieved if both electron beam and photon beam (defined by the driving laser or an optical cavity, see A-7) operate at about the same time structure, but the high average electron beam current is maintained.

This project is aimed at developing a high-intensity, high-bunch-charge laser-driven pulsed electron gun for the S-DALINAC as a blueprint for developments towards a future ERL-based "4th generation" LCB photon source. The design will start from a DC photogun employing GaAs or K_2SbCs cathodes at up to -300 kV with a laser system pulsed at a subharmonic frequency of the S-DALINAC. The doctoral researcher working on this project will (a) conclude from LCB X- and γ-ray source designs back on the properties of the incident electron beam, (b) simulate an electron-source fulfilling the requirements obtained in a., (c) develop optimization strategies for the quantum efficiency and operational lifetime of, in particular, K_2SbCs cathode in reflection geometry, and (d) modify existing electron sources at TU Darmstadt to validate aspects of items b. and c. experimentally.

The proposed project combines different aspects of research and development for the optimization of an LCB photon source, starting from simulations of the photon beam to the design of the electron gun and improving operational conditions. The work is based upon preliminary research at the S-DALINAC where an LCB setup for beam diagnostics is being developed [28], and the experience with the development of GaAs-based photo-electron sources [256], including driver lasers [257] and electrostatic optimization [258], and investigations on quantum efficiencies and lifetimes of GaAs-based photo-cathodes [259,260].

C-12: Lattice of an individually-recirculating energy-recovery linac for a 4th generation photon source (Arnold, Ur)

The brilliance of photons produced by laser Compton Backscattering (LCB) is depending on the quality of both incident beams: the electron and the laser beam [147]. The best quality of an electron beam can be achieved in a linear accelerator. The emittance of the gun can be transported downstream to the interaction without significant degradation of the beam quality as the full beamline is passed only once. The beam current is limited in comparison to a storage ring that uses multiple-injections of the pre-accelerated beam in the same ring. A linear accelerator must accelerate a high beam current during a single acceleration process, resulting in a high beam loading and thus a need of high radio-frequency (RF) power. An energy-recovery linac (ERL) [RT8] can be used to overcome this limitation. In an ERL, the beam is recirculated several times and guided to an interaction with small impact on the electron beam quality, e.g. a LCB source. Downstream the interaction, the beam is guided back to the accelerating structures and enters them on the decelerating phase. The kinetic energy of the beam is transferred back to the electromagnetic field in the cavity while traversing the linac section. The RF power is recovered and the beam can be dumped at injection energy. A superconducting ERL ensures a high repetition-rate. Up to today, only two accelerators world-wide have been operated as a superconducting, multi-turn ERL: CBETA (USA) [261] and S-DALINAC at TU Darmstadt, where only the latter was able to demonstrate a significant recycling of the beam power, see Figure 32.

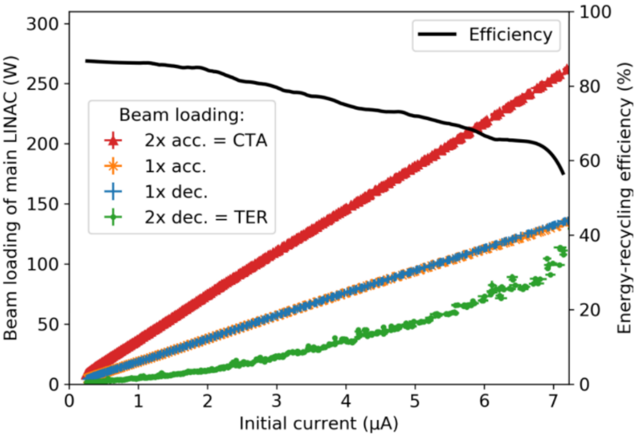


Figure 32: *Total beam loading of main accelerator and recycling efficiency for different initial beam currents.*

This project is aimed to work towards a superconducting ERL with a lattice for robust recirculation and a high recovering efficiency. This project will focus on a so called individually-recirculating ERL, being a candidate for a perfect machine to provide a 4th generation LCB source. In this project, the doctoral researcher will (a) study the common transport of S-DALINAC ERL as a function of lattice settings, (b) simulate the lattice of an individually-recirculating, multi-turn ERL, (c) include an LCB interaction in a start-to-end simulation to achieve the maximum RF recovery while minimizing the momentum spread at the LCB interaction, and (d) develop and design a future 4th generation source operating at a superconducting ERL. The proposed project combines simulations with experimental techniques to work on a very promising ERL lattice for a future LCB source. The work will use the LCB source at the S-DALINAC for verifying the simulations for an ERL-based LCB source. The project is closely related to projects A-4 – A-7 and C-7 – C-11.

C-13: Temperature-controlled self-absorption technique towards precision excitation strength measurements in heavy nuclei (Isaak, Ur)

A well known technique to obtain lifetimes and level widths in a wide range of energies is the use of Nuclear Resonance Fluorescence (NRF) and Self-Absorption (SA) [RT10]. In recent years a new technique called Relative Self-Absorption (RSA) has been developed at TU Darmstadt [RT3,RT10] in the framework of the SFB 1245 (see Sect 6.2). It had been demonstrated on light nuclei that the RSA technique provides reduced systematic uncertainty for values of the level widths compared to traditional NRF and SA, opening a promising route to precision measurements. As example, the M1 decay width of the first excited 0^+ state of ^{6}Li has been measured [RT3] and was used to understand the importance of 2- and 3-body interactions in the framework of chiral Effective Field Theory and of the role of 2-body currents (2BC) in decay transitions (see Fig. 33). Remaining systematical uncertainties are related to the uncertain knowledge of the effective temperature of the nuclei in the solid targets which depends on the, in detail complicated, binding potential of the nuclei of interest in the solids. By varying the thermodynamic temperature of the scattering target or of the absorber, the effective temperature can be determined, directly. A temperature-controlled target system has been procured at TU Darmstadt from DFG funds within the SFB 1245. It can cool down the target to liquid nitrogen temperature or heat it up to a high temperature exceeding 600 K. Temperature-controlled self absorption (TRSA) will be developed in the SFB 1245 for application to light nuclei.

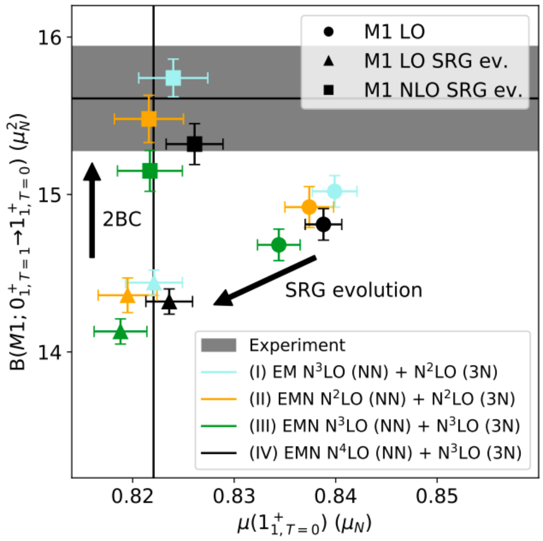


Figure 33: *Results for B(M1; 0_{+1},T =1 → 1_{+1},T =0) of ^{6}Li and theoretical calculations based on ab inito theory . The effect of the SRG and 2BC are shown. Taken from*

This project will concentrate on research training on the TRSA method and on developing its extension to heavy nuclei where the Doppler motion at a certain temperature is smaller than in light nuclei. The doctoral researcher will conduct a detailed methodological study of the TRSA technique on ^{27}Al and ^{208}Pb, that are ideal cases for a proof-of-principle extension of the TRSA technique for its application to heavy nuclei in the bremsstrahlung beam at the S-DALINAC at TU Darmstadt and to its application in quasi-monoenergetic LCB beams at VEGA at ELI-NP in the future. The latter bears new challenges with respect to proper normalizations that need to be overcome. He or she will investigate (a) the precision and sensitivity that can be reached with TRSA as a function of the nuclear mass, and (b) how the normalizations of the sub-measurements, with and without absorber, at a given target temperature can be done. The latter requires a close collaboration with projects C-8 and C-9 for the monitoring of the beam profile and the luminosity determination from gamma-radiation from the target.

3.2 Handling of Research Data

For the purpose of research data management, a dedicated data management plan (DMP) will be created for each project in the beginning and updated continuously during the project. The following section describes in more detail the concepts and measures taken to ensure a reliable and sustainable management of the obtained research data in this IRTG.

Characteristics and scope of the data: The projects within the IRTG (discussed in Section 3.1) will generate a variety of new data from measurements, theoretical calculations, methodogical developments, and technical designs of new equipment for future applications in the field of Nuclear Photonics. The data anticipated to be collected will include

- measurements of laser pulse characteristics of the high-power lasers available at PHELIX and the HPLS of ELI-NP
- digital images of the laser pulses wavefront are stored for purposes of diagnostics and characterization of laser pulses for experiments
- nuclear spectra obtained in photonuclear reaction studies exploiting the high-intensity photon sources at S-DALINAC and at VEGA
- digitally sampled signals from the segmented Ge detectors to be used for pulse shape analysis
- data from the monitoring devices of the gamma beams concerning energy, intensity, polarization
- software and analysis tools to extract nuclear structure information from experimental and theoretical projects
- documentation of the development of novel detection systems and targets

The generated data and software are crucial to fulfil the goals of the individual projects and, hence, the overall scope of this IRTG to advance the state-of-the-art of different research areas ranging from laser and plasma physics to nuclear structure studies on new excitation modes and properties to improve our understanding on the synthesis of the elements in the Universe over novel methodological and technological developments towards commercial and civil applications. The data will be recorded and stored as text files, list-mode data, images and technical drawings.

The expected data volume is very different from project to project. While experiments using the high-power lasers typically generate several TB of data per experiment, measurements of photonuclear reactions usually produce data of a TB of data per experiment when no pulse shapes are saved and about 100 TB per experiment when the pulse shapes are saved. The data from the high-power laser system of ELI-NP is stored and archived locally on dedicated storage infrastructure. The data is stored in hdf5 files that are then compressed in zip archives. The data can further be processed, be filtered and be delivered to the users in different data and file formats. The expected total data volume within the IRTG required to be stored long-term is in the regime of about 200 TB per year.

Documentation and data quality: The documentation of the data handling for each project will start with the creation of a Data Management Plan (DMP). Several tools for a systematic planning and treatment of the expected research data are available. The TU Darmstadt provides the TUdmo service that is based on the DFG-funded Research Data Management Organizer (RDMO). It allows to create a DMP based on a pre-defined questionnaire and manage it collaboratively during the course of the project.

The DMP will be discussed and re-evaluated during the bi-annual PhD committee meetings and adapted to the current progress and developments of the PhD project if necessary.

During data collection, metadata specific for the corresponding research community will be documented by means of electronic logbooks such as ELOG and institutional Wiki pages already in frequent use at TU Darmstadt, the PBU, and at ELI-NP. In particular, we aim to implement recommendations developed within PUNCH4NFDI where our RT Dr. Isaak is actively involved. The ELI-NP high-power laser system operation teams use different online logbook tools to record the daily operations and laser shot data. At this moment these tools are based on Google online tools like Google Forms and Google Spreadsheet. The data are periodically archived locally on the ELI-NP servers. This data is used to produce reports on the operation activities and beam delivery. Self-developed software and its usage in the analysis of experimental and theoretical data will be documented with version-control tools such as GitHub and GitLab. This ensures an improved comprehensibility, reproduceability and reusability of the generated research software by third parties.

In particular in the international environment of the IRTG and due to the geographical distance between the individual researchers, the usage of digital tools is crucial. As each doctoral researcher will have a local RT at her/his institution and an external RT at the partner institution, it will be mandatory to document and share the progress in their research projects with electronic logbooks that are available online for their collaborators and RTs. This will ensure direct communication and check of the data handling and analysis by the doctoral researchers and, consequently, a close-meshed data quality assurance by their RTs.

Storage and technical archiving during the projects: The storage infrastructure at the Institute for Nuclear Physics at TU Darmstadt is continuously extended to match the needs of its users. Very recently, the State of Hesse has approved a funding of 45 kEUR to extend the capabilities of the existing storage servers. With a current capacity of more than 0.5 PB, raw and processed research data obtained within the IRTG will be archived long-term at the Institute for Nuclear Physics. In addition, the TU Darmstadt provides access to its institutional data repository TUdatalib for all RTs affiliated to TU Darmstadt allowing to store 2 TB of data p.a. for long-term archiving (more than 10 years).

The storage infrastructure at ELI-NP is under development and it was recently extended to match the needs of users. Recently, a 0.5 PB storage system has been installed at ELI-NP, and in the upcoming future additional extension of this storage space is envisaged. The storage space available at the moment will comfortably cover the need of data storage for a few years for raw and processed data, including their back-up.

Legal obligations and conditions: The research data management of the involved institutions, TU Darmstadt, PBU and ELI-NP is based on the "*Guidelines for Safeguarding Good Research Practice*" of the DFG. ELI-NP is a User Facility where researchers from around the world can propose experiments. ELI-ERIC and the ELI-Facilities aim to preserve and manage Data according to the 'FAIR' principles. ELI-NP has established the rules for data management in collaboration with ELI ERIC and they are listed in the document called "*Terms and Conditions of Access*"[1]. These form the legal obligations and conditions for the research data management within the IRTG. The research data are primarily used by the doctoral researchers and their RTs. The RTs are responsible for managing the usage and distribution of the acquired data.

Enabling of subsequent reuse and long-term accessibility: The unpublished research data will be made available to all participants of the IRTG and upon request to third parties. Once the data are in the process of being published as part of an article in a peer-reviewed journal, they will be curated at TUdatalib, described with appropriate metadata, so that a Digital Object Identifier (DOI) can be assigned to the dataset and published under a suitable open license. This dataset is then explicitly citable in the upcoming publication via the DOI and clearly findable and reusable by third parties. The same guidelines are applied to the publication of research software developed during the projects. ELI-NP will provide access to the data storage for all RTs of the IRTG allowing to store the data for long-term (more than 10 years). In addition, ELI-NP has a tape archiving system as permanent storage for the raw data.

Responsibilities and resources: The RTs and the Research Data Manager (RDMr) at the Institute for Nuclear Physics, Dr. Johann Isaak, and the head of the ELI-NP IT Department, Dr. Mihai Ciubancan are responsible for the compliance with the RDM guidelines of the partner institutions and with the

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[1] https://up.eli-laser.eu/downloads/Science-Call-TCA.pdf

"*Guidelines for Safeguarding Good Research Practice*". The RDMr will raise awareness for the importance of sustainable RDM within the IRTG by providing training and advice to its members (doctoral researchers and RTs). For that purpose, a dedicated training course will be developed that covers the aspects of RDM relevant for the research of Nuclear Photonics such as efficient usage of electronic logbooks and the establishment and development of data management plans. Customized training will be provided to the doctoral researchers such as digital documentation tools such as digital logbooks, Wikis and versioning via GitLab.

3.3 Relevance of Sex, Gender and/or Diversity

This IRTG addresses research training on laser-induced generation of particle beams, photonuclear reactions, and corresponding methods and technology. These fields of research suffer from underrepresentation of female and possibly also of non-white scientists across all countries in Europe. Gender and ethnic background of culture of the researchers are relevant for training female and non-white junior scientists in Nuclear Photonics who can serve in the future as role models for successful female and non-white scientists in the corresponding fields in order to help reaching equal participation of these underrepresented groups.

3.4 Supplementary Information on the Research Context

Fundamental research on laser-induced generation of particle beams, photonuclear reactions, and corresponding methods and technology could eventually result in insights or technological developments that could have a remote potential for being used or misused in the context of nuclear weapon technology. For most of the research projects a potential abuse of the results is not even remotely conceivable. For some, such as the search for dipole excitations of transuranium actinides, a possible defensive potential could be conceivable, depending on the resulting data. If the studied nuclei would exhibit extraordinarily strong dipole excitations, then these nuclear quantum excitations could be used for an assay of unknown actinide material or search for it in bulk matter or cargo containers using γ–ray beams. Corresponding screening devices could make unauthorized shipment of actinide material more difficult and would be beneficial.

All research projects have been assessed by the Spokespersons of this IRTG according to the procedures recommended by the Ethics Commission of TU Darmstadt. The Ethics Commission examines research proposals to determine whether they are acceptable on ethical grounds and checks whether research proposals are compliant with the university's Zivilklausel (Civil Clause). The assessment provided no objections against the execution of the research plans.

4 Qualification Program

This IRTG focuses on the qualification of excellent international junior scientists from natural or engineering sciences who choose a career in Nuclear Photonics for their doctoral studies in an international environment. Both partner institutions provide and have privileged access to extraordinary infrastructure, unparalleled in the world and complementing each other for the field of nuclear photonics, including the superconducting S-DALINAC accelerator with its continuous-energy bremsstrahlung facilities, the PHELIX laser system at GSI and the ultra-high intensity lasers or the VEGA system at ELI-NP. The applicant institutions have gathered a strong group of experts with a long-standing record of accomplishments in the fields and of respective academic guidance. Less-senior goup leaders have been included in the group of Research Trainers (RTs). They, too, have demonstrated their potential by recent significant scientific contributions to the fields of Nuclear Photonics. Their inclusion in the group of RTs in a collaborative environment will foster their research-training experience.

The structured qualification of junior scientists on novel and challenging scientific topics, in an international, collaborative, and interdisciplinary environment, is the core of this IRTG. It is achieved by a specifically-designed framework that enables doctoral researchers to produce independent research findings with international visibility (see Sect. 3.1) within an appropriate time period of three years. At the same time, the framework will qualify the junior researchers for the international academic and non-academic job market. Its components are outlined below. Some aspects of the qualification program have been previously developed and tested successfully within the eight years of experience in the cross-institutional research training program, GRK 2128 "AccelencE", in accelerator science which was established by the DFG and successfully evaluated under the leadership of the Designated Spokesman of this IRTG (see also Sect. 6.3).

4.1 Qualification Program

The qualification concept aims at the following qualification goals to be acquired by the members of the IRTG after their successful completion of the program:

a) excellent scientific competences on a particular aspect of Nuclear Photonics' science and technology,

b) overview and broad scientific understanding of key technologies and competences involved in Nuclear Photonics,

c) overview and broad understanding of the scientific activities of the international Nuclear Photonics community and related fields, in general,

d) fundamental skills for scientific participation and leadership.

The qualification program envisaged for the IRTG rests on four pillars: Individual project training, professional development, networking, and career support. It is designed to provide clear goals and benchmarks for the efficient and successful completion of the doctoral studies. Graduation times of three years are aimed at. If unforeseen obstacles, not caused by the junior researchers nor RTs, may arise (e.g., delayed delivery times for equipment, delayed approval times for beam time requests, reduction of training opportunities due to unexpected developments of the pandemic etc.) the PIs are committed to provide personnel funding until due completion of the thesis. Nevertheless, a graduation time of three years is accounted for (see Sect. 1.5).

The qualification program is tailored to best prepare excellent junior researchers for the international academic and non-academic job market related to the fields of Nuclear Photonics. Figure 34 shows a schematic timeline of the qualification program for the research trainee from entering the IRTG to successful graduation in a three year qualification program. Its measures are intertwined and some of them are important components of the supervision concept, too (see Sect. 5). The qualification program is discussed in detail below. It enhances and expands doctoral researchers' individual competences and conveys expertise that goes beyond the researchers' subject areas and thus provides a broader qualification. Its clear structure helps the junior researchers to successfully complete their doctoral studies on time.

Sketch of the main pillars of the qualification concept: The individual project training ensures high quality of the research. Particular emphasis is made on a constant evaluation of the progress of the research projects as described in Sect. 5. In order to prepare the research trainees for their challenging research projects, they are offered attendance of basic and advanced lectures and advanced training on cross-sectional competences,

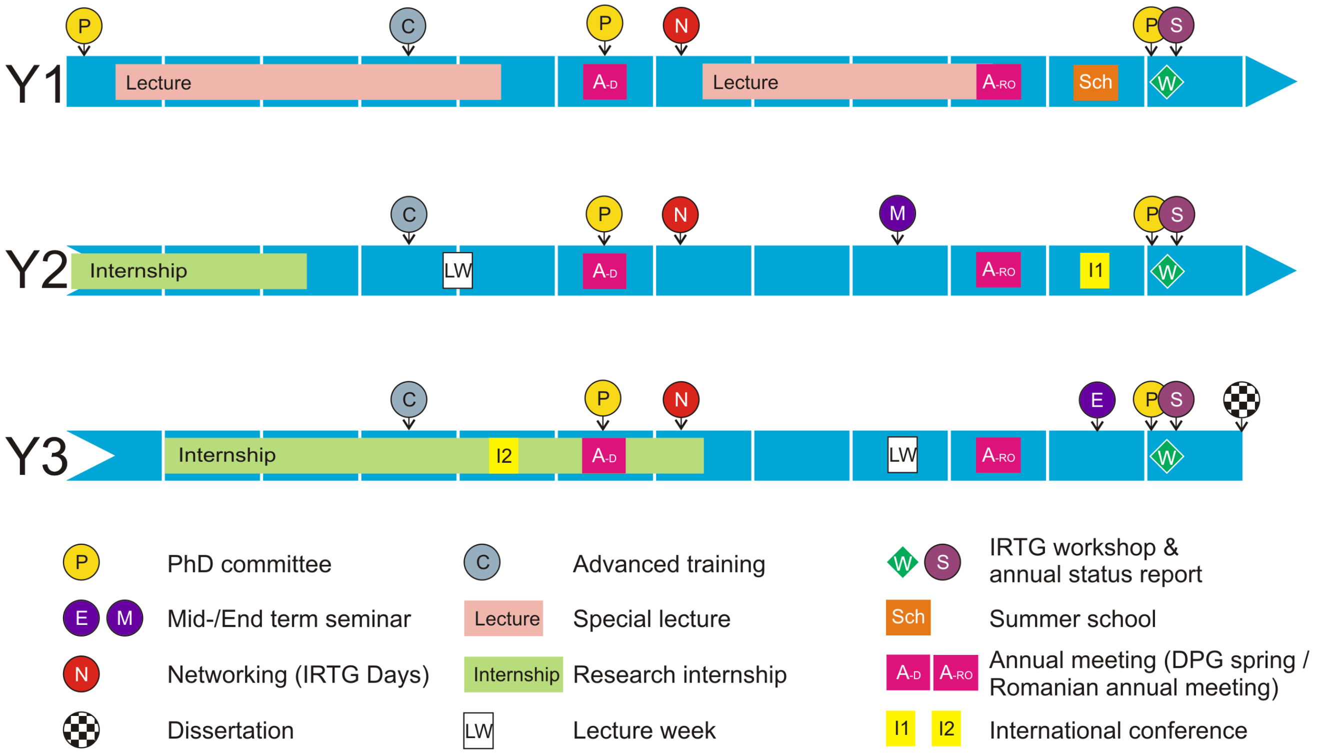

Figure 34*: Schematic timeline of the qualification and supervison concept for a research trainee within this International Research-Training Group “Nuclear Photonics”. The program provides optimum support for successfully completing the doctoral research in 36 months. A trainee can start in October. The excellent research projects (indicated in blue; see Sect.3) within the fields of Nuclear Photonics, either at TU Darmstadt or at University POLITEHNICA Bucharest, and two extended research internships at the partner institution (green) represent the backbone of the research training concept. Various measures of the qualification program (see Sect. 4) provide career advancement and represent important aspects of the supervision concept, at the same time (see Sect. 5).*

The table on the following page lists all IRTG specific events.

Table 4.1: IRTG specific events. The term „Supervisors" is given for the Research Trainers (RTs) chosen by the doctoral researcher for the guidance on his/her research project.

Type of Measure	Duration	Chapter	Frequency	Contents	Target Group	Location	Prospective Instructor	Participation compulsory
PhD committees	1 h	5.2	Every 6 months	Status of project, next steps, conferences, publications, advice	Doctoral researchers	Online meeting	Supervisors, further members	Yes (recorded in writing)
Advanced training	3 – 5 days	5.2	Two per year available	Soft-skill courses, networking, lecture weeks on special topics	Doctoral researchers	Home institute	Course instructors, Supervisors	strongly recommended
IRTG workshop	3 – 5 days	4.1.2	annually	Presentation of own achievements, networking, broadening of knowledge	All members	Alternating	Supervisors	yes
Annual status report (written)	2 – 4 pages	4.1.2	annually	Written contribution (research + RDM plan)	Doctoral researchers	Home institute	Supervisors, further members	yes
Mid-term seminar	1 h	4.1.2	Once per trainee	Presentation results of 1st internship, preparation for 2nd internship	Doctoral researchers	Hybrid	Supervisors	yes
End-term seminar	1 h	4.1.2	Once per trainee	Presentation to prepare for disputation	Doctoral researchers	Hybrid	Supervisors	yes
Special lecture	1 term, each	4.1.2	see Table, Sect. 4.1.2	see Table in Sect. 4.1.2	MSc students, Doctoral researchers	Home institute	RTs, Professors of university	on recommendation
Summer school	1 – 2 weeks	4.3.1.	Once	Intensify knowledge on special topics	Doctoral researchers	Extern	Lecturers of school	strongly recommended
IRTG days	1 – 2 days	4.3.2	annually	Meeting with other peer group, networking, presenting own work	Doctoral researchers	Home institute	PhD students	yes
Research internship	2 and 6 months	4.4	Twice	Internship at the partner institution	Doctoral researchers	Partner institute	RTs or senior researchers of partner institute	yes
Annual national meeting	5 days	4.1.2	annually	Presenting own achievements, networking, broadening knowledge	All members	Germany	Conference organisation	strongly recommended
Lecture week	3 – 5 days	4.1.2	twice per year	Block lecture on specialized topic related to IRTG	Doctoral researchers	Home institute / online	Lecturers	strongly recommended
International conference	5 days	4.3.1	Once or twice	Presenting own work, networking, new ideas by learning from others	Doctoral researchers	Extern	Conference organisation	strongly recommended

4.1.1 Project Training

The individual research project (see Sect. 3) of each junior researcher is the backbone of the qualification program. Each project is embedded in one of the research areas of this IRTG and will be supervised by at least one RT from TU Darmstadt and one from the UPB. These supervisors guarantee successful progress in the research. This is ensured by the dedicated supervision concept as described in detail in Sect. 5.

4.1.2 Professional Development

Basic and advanced lectures: Lectures about topics of particular interest to the junior researchers of the proposed IRTG will be offered that are not part of the mandatory master programs. This includes new lectures at TUDa on "*Intense Laser Beams*" (Bagnoud), "*Photonuclear Reactions in Nuclear Structure Physics*" (Isaak), or "*Laser Plasma Based Particle Acceleration and Secondary Radiation Sources*" (Kuschel). Each lecture will emphasize the aspects relevant to Nuclear Photonics and will be regularly offered. To promote the participation of research trainees from both partner institutions, the lectures will be transmitted via video-conferencing to the partner institutions. A list of the lectures that may be recommended to the incoming research trainees is given in Table 4.2.

Table 4.2: List of lecture courses and seminars that provide key competences in Nuclear Photonics.

Lecture Name	Venue	Lecturer	Offered
Basic Lectures			
Accelerator Physics	TUDa	Boine-Frankenheim	every summer term
Measurement Methods in Optics	TUDa	Bagnoud	every summer term
Measurement and Dosimetry of Ionizing Radiations	UPB	Ur	every term
Optics and Lasers for Applications	UPB	Ursescu	every winter term
Advanced Lectures			
Plasma Physics	TUDa	Boine-Frankenheim	every winter term
Physics of Particle Detectors / Introduction to Heavy-Ion Physics	TUDa	Galatyuk	every term
Nuclear Astrophysics	TUDa	Martinez-Pinedo	every winter term
Energy from Nuclear Fusion	TUDa	Roth	every summer term
Basic and Applied Research at the ELI-NP Infrastructure	UPB	Balabanski	every summer term
New Advanced Lectures			
Intense Laser Beams	TUDa	Bagnoud	every summer term
Photonuclear Reactions in Nuclear Structure Physics	TUDa	Isaak	every winter term
Laser Plasma Based Particle Acceleration and Secondary Radiation Sources	TUDa	Kuschel	every summer term
Advanced Topics in Nuclear Structure and Astrophysics - Theory	UPB	Tsoneva	every winter term
Laser-driven Ion Acceleration and Gamma Flash Generation	UPB	Doria	every winter term
Nuclear Astrophysics with Gamma Beams	UPB	Matei	every summer term
Advanced Laser-Plasma Interaction	UPB	Tanaka	every winter term

Seminars

Research Seminar on Nuclear Photonics	Online	Doctoral researchers, Introduction by RTs	every term
Physics and Technology of Accelerators (Seminar)	TUDa	Boine-Frankenheim, Enders, Pietralla	every term

Summer schools: As part of the first year, junior researchers will be encouraged to attend a summer school on a topic related to their projects. The supervising RTs will provide a list of appropriate schools which would offer special competences for the successful execution of the individual research project. Attendance of an ELI Summer School event is strongly recommended for all junior researchers. The attendance of summer schools is an important part of the measures on international experience and networking, too (see Sect. 4.3).

Lecture weeks: To get a deeper knowledge of the field, annual one-week long lecture weeks will be established. For this, external experts will be invited to hold a compact topical lecture course of 3 – 4 lectures in a hybrid format (in person and online). Junior researchers will contribute to the lecture weeks by short presentations on their projects, which then can be discussed in depth with the lecturer. Lecture weeks are foreseen to happen once each year, alternating between TU Darmstadt and UPB. The participation in the second and third year is strongly recommended. Junior researchers from the host institutions will be encouraged to attend in presence. Interaction between the junior researchers and the external lecturers further supports their international networking into the scientific community.

Courses on Key Competences: All junior researchers within the IRTG can profit from the programs of TU Darmstadt's graduate organizations *Ingenium* and HGS-HIRe (see Appendix 10.9.2.4). Both provide networking and training measures to enhance the qualification of early career researchers on professional key-competences to promote their academic and non-academic careers. All junior researchers of this IRTG are invited to take part in the three-stage soft-skill course program of HGS-HIRe. These courses provide basic skills in working as a team, leading a team, making presentations, and provide preparation for the phase after finishing the dissertation. For more details see Sect. 5.2.

Research Data Management: Members of the IRTG will be supported in the management of their research data by a Research-Data Management Officer supported by resources of TU Darmstadt (see Sect. 3.2) from the beginning of their participation in this IRTG. An introduction to professional RDM is included in the Welcome Package documentation of the research trainees. Lectures on the "FAIR-principles" (ensuring Findable, Accessible, Interoperable, and Reusable data from this IRTG) of research-data management and the continued development of the individual RDM plans represent a fix building block for each Annual Workshop (see below).

Good Scientific Practice: Guidance to good scientific practice will be given during the semi-annual PhD committee meetings. Further information on good scientific practice will be offered in the Welcome Package handed out to every beginning research trainees of the IRTG, in presentations offered by *Ingenium*, and during the IRTG Annual Workshops. The latter will provide a selection of the material offered by the German Ombudsman for Research Integrity, in particular, the modules on "*Introduction to Good Scientific Practice*", "*Scientific Misconduct*", "*Data Handling*", "*Publishing*", "*Supervision*", and "*Conflicts of Interest*" followed by an open discussions of the junior researchers and the RTs.

IRTG Annual Workshop / Status Reports: Members of the IRTG will retreat once a year for a 5-days workshop to review and discuss the scientific progress. Each junior researcher will give an oral presentation showing the status of his/her project. Their research data management plan (RDM) will be included and discussed. External lectures and an excursion will complement the workshop program. The annual workshops include, each, two "open discussions" of up to five sub-groups of its members, trainees and RTs, to commonly chosen research topics for the identification of new research goals. They also include a regular "open discussion" on the status of the qualification program and the supervision concept and their further development. One of the PhD committee meetings of each junior researcher will be conducted at the workshop. Lectures on ***research data management*** and on the ***rules of good scientific practice*** will be a fix item in the workshop agenda every year, as well as discussions on the development of the IRTG's scientific program, on potential measures for enhanced ***inclusion of marginalized groups in science*** and an evening session on **information on the host countries** supporting this IRTG (see Sect. 4.3).

Each junior researcher will provide a conference-style three-to-four pages long contribution on their own presentation to be handed in within four weeks after the workshop. The reports will include the updated RDM plans as an appendix. Preparation of these Status Reports will support the junior researchers in presenting the progress of their research project and, thereby, develop their publication skills. These contributions will be compiled as an annual "IRTG Progress Report" and provided to the members of the IRTAB (see Sect. 5.5) as a basis for their progress evaluation of the program.

IRTG seminar: During the overlap of the Romanian academic year with the lecturing times in Germany, i.e., mid-October to mid-February, and mid-April to the end of May, a weekly IRTG seminar will be held via video communication software. Research trainees from TUDa or from UPB or external guests will make scientific presentations on contemporary research topics in Nuclear Photonics followed by a scientific discussion. Each seminar will start by an introduction into the scheduled talks provided by one of the RTs.

Mid- and End-term seminars: About one to one-and-a-half years after the start of their training, each junior scientist will present her/his results of the first internship during a **mid-term seminar**. The seminar presentation will be complemented by the preparation for the second internship. This seminar will, on one hand, help training the junior scientists to present scientific work related to their project and, on the other hand, will encourage them to obtain a deeper knowledge of a topic related to their individual project that will be studied during the internship. Within about 3 months before their doctoral defense, the advanced junior researchers will give their **end-term seminar** on the scientific advance achieved by the doctoral project. The seminar will facilitate the junior researcher's preparation for the doctoral defense. The mandatory mid- and end-term seminars will be scheduled during in the program of the IRTG seminar (see above).

Transition to next Generation of Doctoral Researchers: On establishment of the IRTG, 40 young researchers are expected to start their research and qualification within the program in Germany and in Romania within the first two years. They will have been selected from the pool of international applicants (see Sect. 5.1) including those that have been pre-attracted at TU Darmstadt and at UPB through preceding programs, e.g., the preparatory LOEWE research focus "Nuclear Photonics" funded by the State of Hesse until Sept. 2023, or the Ira Rischowski program. The concept of overlapping cohorts ensures that some of the trainees will be on a more experienced level than the new incomers. They will be encouraged to help the incoming doctoral researchers for creating a collaborative team spirit. This supports the diversity of scientific and professional skills within the group of junior members of the IRTG and it ensures an efficient intra-group transfer of knowledge and experience on details in the responsibilities of the junior researchers, such as handling of ancillary technical infrastructures, data analysis tools etc. A welcoming and cooperative research atmosphere in the IRTG will encourage the junior researchers to collaborate and support each other based on the measures of the qualification program. When a trainee has reached the doctoral degree, the corresponding research training position will become available for new participants. For ensuring a sufficient pool of qualified applicants to the international calls, interested master students can be admitted as potential next generation young researchers. They will be allowed to participate in essential parts of the training program, such as collaborating on the research projects of the trainees, attending the IRTG seminars or colloquia, summer schools, IRTG days, as well as participating in the annual IRTG workshops. These measures will ensure a smooth transition to the next generation. Additional female candidates will be attracted at the master level through the Ira Rischowski program (see Sect. 5.3) until equal participation of women will be reached.

4.2 Visiting Researchers

International experts on the field of Nuclear Photonics will be regularly invited as lecturers of the lecture week, as external guest scientists participating in the Annual Workshops, or as seminar speakers. These scientists are invited to stay for some time to collaborate on common research activities or to promote the research on the projects of the IRTG. They are available for the junior researchers for questions and advice. Doing so, the junior researchers of the IRTG can build up networks to international labs giving them opportunities for their careers after graduation.

One example for the guest scientists may be given by Prof. Dr. Gerard Mourou (Ecole Polytechnique). He spoke in a colloquium at TUDa to the topic of "*From chirped pulse amplification to ELI and beyond: Science of high energy, single-cycled lasers*" in summer 2018, shortly before he was awarded the Nobel Prize for Physics 2018. Further examples for visiting researchers are the other members of the IRTAB (see Sect. 5.5), scientists from the Czech or Hungarian pillars of ELI, members of the research groups working at the HIγS facilty at TUNL, Durham, NC, U.S.A. (see Appendix 10.9.2.4), LBNL, Berkeley, LLNL, Livermore, or at the Helmholtz Centres Dresden-Rossendorf or DESY, Hamburg, or at the Helmholtz Institutes at Jena or Mainz, to name a few.

4.3 Additional Qualification Measures

4.3.1 International Experience and Visibility

Attendance of international conferences: Junior scientists will be encouraged to make oral contributions to at least one, preferentially two international conferences before graduation. In order to provide high visibility to the research achievements of the research trainees it is foreseen that international conferences will be attended in the second half of the project work.

Information on the host countries: The participants of this German-Romanian IRTG will be provided with information on various topics of interest about these two host countries. The topics will be defined by the research trainees. They may comprise historical, contemporary political, or sociological topics, or information on research infrastructures, research funding opportunities, or the situation on the job market. The program of every Annual Workshop will contain one evening session on one or two of these topics. That will be provided either by invited guest lecturers with particular qualification on these topics or by the RTs as an introduction to an open discussion among the participants of the Annual Workshop.

4.3.2 Professional Networking

IRTG-Days: This will be a 2-day meeting between the junior scientists of this IRTG with a group of junior researchers from another institution selected by the research trainees of the IRTG. It will be held at Bucharest or at Darmstadt alternating every year. The junior researchers themselves will select scientific topics of their interest and explore them with their guests through presentations and discussions. Social events in the evening will strengthen the communication and networking between the peer groups. The corresponding format has been developed in the MGK of the SFB 634 at TUDa and successfully continued in the GRK 2128 "AccelencE" and the MGK of the SFB 1245. It had always been highly appreciated by the junior researchers.

Networking with all RTs: The junior researchers have the possibility to network not only with their supervisors. They will be able to discuss the scientific progress of their work or possibilities for their personal careers with all RTs of the IRTG at the annual workshop or as needed also at other occasions.

Academic and scientific events: The academic and scientific events described in this section serve as part of their professional development and can bolster the personal interaction of the junior researchers. The lecture weeks and the summer school will contribute to the networking of the junior scientist with their peers, and help them build and maintain close contact among them. The IRTG Annual Workshop, the annual meetings of the Physical Societies and participation in international conferences will additionally give them the opportunity to meet renowned lecturers and provide them enough time for personal interactions with external scientists, e.g., during the IRTG Annual Workshop.

4.4 Research Visits to the Partner Institution

Research internships at the partner institution are the second core component of the research training through close collaboration with the partner institution. Every research project has a co-supervisor assigned at the partner institution. Junior researchers from TU Darmstadt with their experience, e.g., on experiments using bremsstrahlung beams, laser-generated neutron beams, or accelerator science, will work during their research project for about 8 months, in total, at ELI-NP. In that time, they benefit from the local expertise, from performing experiments at ELI-NP along with taking advantage of the dedicated stay in this next-generation light-source facility. They will also contribute to the user program at

ELI-NP, thereby establishing a network of outside users of the facility and learn the latest techniques for broadening their expertise on the field of Nuclear Photonics. Furthermore, their experiences will contribute to expanding the scientific programs at TUDa and UPB.

Junior scientists of the UPB visiting TU Darmstadt for these extended internships will mutually benefit from the possibility to complement their research with the research opportunities provided by the infrastructure and expertise available at TUDa. E.g., they can deepen their experience on electron accelerator technology and instrumentation, utilize the bremsstrahlung beam at the S-DALINAC for a broad scan of photonuclear cross sections in an extended energy range, identifying regions of interest to be later studied in more detail at ELI-NP. Or, they can use the NEPTUN tagger for experiments at energies beyond the reach of ELI-NP. In addition, they can make use of the academic environment at TU Darmstadt, e.g., for extending their knowledge of nuclear structure theory.

Two stages of these internships are foreseen. A shorter visit of about two-and-a-half months during the first year, which will be focused on making the junior scientists familiar with the techniques and scientific opportunities at the partner institution, and a second internship lasting at least 5 months during the second year where they will apply the acquired knowledge to perform advanced research related to their projects or prepare parts of their thesis with guidance by their external RT. This exchange will help to build a strong community around Nuclear Photonics and both partner institutions profit from research work within this international collaborative environment.

Based on the planned internships the young researchers are invited to write a short “lab & travel diary” to document their stay at the partner institution and host country. Besides a part reporting on their scientific focus and research activities, they are encouraged to describe their personal and subjective impression on their daily life in the host country. The format of the “lab & travel diary” is free to choose and can range from a written report to social media stories (e.g., Twitter feed or Instagram story) to disseminate their internship to a broader community and gain first expertise in science communication.

5 Supervision and Career Advancement, Gender Equality, Organisation and Quality Management

5.1 Announcement and Selection Procedure

The IRTG attracts applicants from Germany, Romania, and from abroad. International advertisements of position openings are distributed (e.g. as an electronic, printable flyer) by mailing lists, web postings, and direct contacts to colleagues in the field starting in June 2023. A common mailing list for TUDa and UPB for announcements will be established. The Ira Rischowski-program (see Sect. 5.3) will serve as a prominent attractor for female junior researchers and will be further advertised internationally by TU Darmstadt. The applicants are asked to hand in their usual application documents, such as curriculum vitae, certificates, two reference letters and one page describing their research interest. An admissions committee will be formed to rank the incoming applications by excellence, matching to the positions, and motivation, and will present the result for discussion to the board of RTs. The decision will be presented to the IRTAB for further advice on the selection of candidates. Promising applicants are invited for interviews either in person at the participating universities or via video conferences. The final admission is jointly done by the board of RTs on a proposal of a potential supervisor.

5.2 Supervision and Career Advancement

The supervision concept aims at ensuring a well-structured, efficient, and transparent promotion process for all junior researchers within the IRTG. The overall scheme is depicted in Fig.34 in Sect. 4.1. It combines the project-oriented, classical supervision in a research project for doctoral research with the active participation in a larger-scale, international and collaborative project. It aims at respecting the balance between promoting early scientific independence and detailed guidance to obtain scientific excellence. A **formal supervision agreement** between the two supervisors and the junior researcher will be established, and the junior researcher will receive a welcome package outlining the definition of the IRTG, the steps in the qualification scheme, and the **Code of Conduct** among the participants.

Group Meeting with RT: The first level of supervision will consist of weekly meetings with the supervising RT and the other doctoral researchers working on the same sub-topic. Junior researchers at both institutions can join via video conferencing. These meetings will give the junior researchers the opportunity to discuss the status of their research project, and to seek for advice on possible problems as well as guidance for the next tasks. These meetings will also allow them to acquire an overview over the work of the entire sub-group and the projects of other junior scientists. Individual meetings with the supervising RT will also be allocated, if the junior researcher or RT require it.

PhD committee: Each junior researcher will be designated a PhD committee when entering the IRTG. The PhD committees consist of the junior scientist, two RTs of the IRTG including the primary supervisor and the co-supervisor of both partners. It can also include an experienced researcher acting as a mentor. The committee will be selected by the doctoral researchers after consultation with the supervisors. PhD-committee meetings will take place twice a year. The junior researcher will present the scientific achievements over the past 6 months and will outline the research plans for the future 6 months. The committee will revise the progress and establish objective agreements for the subsequent half year. Recommendations on advanced training, attendance of conferences, or other issues will be provided. Minutes of the meeting will be taken, filed, and distributed to the members of the committee, only. These minutes will serve as a gauge for the follow-up meeting.

Annual Status Report: All junior scientists will present an oral status report at the IRTG Annual Workshop to all the members of the community. Presentation skills acquired through advanced training will be applied. The peers will give feedback on the presented scientific progress and will be encouraged to discuss the interrelations and inter-dependencies of the projects. Junior researchers will provide a three-to-four-pages long workshop contribution to be compiled as an annual “IRTG Progress Report” which will be useful for later reference. The annual Progress Report will be submitted to the IRTG’s IRTAB for external research-training quality control.

Mid/End Term Seminars: The mid- and end-term seminars (see Sect. 4.1) will be integral part of the supervision process. The qualification- and supervision-concept will aim at maintaining a close contact of each junior researcher with his/her RTs at both locations. It is based on the encouraging experiences from previous research training groups, and joint training experiences, where the feasibility and efficiency of the program had been demonstrated.

5.2.1 Career Advancement

Advanced training: The junior researchers from both institutions are encouraged to enrole in the local graduate programs, e.g., taking advantage of *Ingenium*, the umbrella organization for promoting early career researchers, free for all participants of this IRTG. It provides courses on professional skills, networking and training measures for all members of the IRTG. In addition, all junior researchers of this IRTG are offered membership of the graduate school “*HGS-HIRe for FAIR*” which provides networking events, lectures, and power weeks related to the science and technology on nuclear physics and professional competences. Thereby, all junior researchers can receive further advanced training and establish networks with their peers working in related fields, particularly from the international FAIR facility and supporting universities world-wide. The offer for advanced training include modules on science communication to the public in cooperation with the Science Communication Center of TUDa. The training program based on advanced studies at UPB includes five compulsory disciplines, of which two are specialized disciplines, established by the doctoral supervisor and approved by Doctoral School Council, and three are disciplines that ensure transversal competences: Ethics, Research Methodology and Scientific Authorship, Project Management.

Experience in academic supervision of students: The junior researchers, themselves, will be offered to co-supervise bachelor and master students working on related research projects or labcourse training at their local institutions. This experience will develop their teaching and group-leading skills.

Experience in scientific guidance: Established researchers at both institutions, not holding a permanent professorship, yet, will supervise research trainees (see also Sect. 1.3). To provide ideal conditions for the training of junior scientists, the proposed IRTG also takes care of the promotion of junior group leaders, who did not yet reach the level of tenured professorship, to a more advanced level of their academic careers. This includes freshly appointed faculty on a tenure-track assistant professorship (Kuschel) and established scientists during or shortly after their habilitation procedure at UPB (Doria, Matei, Tsoneva) as RTs to actively contribute to the IRTG research-training program, and to foster their career paths by additional experience in research-training supervision and scientific guidance. Dr. Kuschel will also provide an important contribution to the advanced lecturing program (see Sect. 4.1). In 2027, the tenure committee of TUDa will evaluate Dr. Kuschel's scientific and academic track records and will provide a recommendation to the President of TUDa on whether or not the criteria for tenure have been met. On positive recommendation, Dr. Kuschel will be provided with a permanent professorship at TU Darmstadt. In addition, Drs. Arnold, Isaak and Werner are included as RTs. All of them have previously demonstrated their excellence among their peer group either by scientific prizes (e.g., DPG Accelerator prize 2021 for Arnold, or ATHENE Young-Investigator group leader award at TUDa for Isaak, which recently received its extension on positive evaluation), by international evaluation in competitive situations (Associate Professorship at Yale University for Werner and Visiting Professorship at Osaka University for Isaak), by evaluated leadership in coordinated research structures, such as SFB 1245 (Werner), GRK 2128 (Arnold, Werner), the LOEWE research project "Nuclear Photonics" (Arnold, Werner), and the Hessian cluster project ELEMENTS (Arnold), or by the outstandingly high impact of their scientific oeuvre (>10 high-impact papers with impact factors >7 for Werner). Their independent lead of individual research projects will support their academic development and scientific visibility for their future careers. Dr. Isaak will provide an important contribution to the advanced lecturing program, too (see Sect. 4.1). TU Darmstadt and IFIN-HH have agreed upon a Memorandum of Understanding that a permanent position at IFIN-HH will be provided to Dr. Isaak after his position at TU Darmstadt would have been ended.

Creation of an alumni network: As a contribution to the future careers of the research trainees, an international network of Nuclear Photonics alumni will be maintained. It may contribute to informing future junior researchers on career opportunities either in science, academia, or in the commercial job market. Former researchers of TU Darmstadt and UPB, who have recently completed their doctoral research in areas akin to Nuclear Photonics, will be invited for being included in this initiative. It is planned that Nuclear Photonics alumni will also be invited to the IRTG days in the second funding phase of the IRTG for sharing their experiences on their time after having left the IRTG program.

5.3 Equality in Research

The promotion of a diverse scientific environment is a fundamental aspect of this IRTG. Diverse teams (in terms of gender, ethnicity, cultural social background etc.) can lead to new perspectives and enhanced creativity and innovation. Moreover, diversity creates a welcoming environment which can attract a wider talent pool. TUDa and UPB have implemented a variety of institutionalized measures to enhance diversity, including dedicated equality offices at department- and university-levels.

In recent years, progress has been made in diversifying the scientific community, in particular regarding gender. According to the eurostat publication from 10.02.2020, "In 2018, of almost 15 million scientists and engineers in the EU, 59% were men and 41% women". In Romania the corresponding percentage amounts to 41%, too, while for Germany it is much lower at 33%. For experimental physics and electrical engineering, however, the number of women is still comparatively low, with less than 20% of female junior researchers in Germany and lower numbers as the scientific career advances. A sustained effort is still necessary to keep increasing the number of female researchers. To favor a diverse team of RTs as role models, the proposed IRTG encourages the promotion and visibility of Dr. Arnold, Prof. Galatyuk, and Dr. Tsoneva as role models, as well as to sensitize all RTs and members to the joint effort in creating a welcoming and diverse research environment. Further strategies to promote diversity within this IRTG are:

- Commitment to fill at least 35 % of the IRTG-positions with female scientists.
- The Ira Rischowski-program to particularly attract female researchers at an early stage of career (see below)
- Wide-spread publicity of open positions in community mailing lists and sites with international visibility, such as the CERN Courier and the Nuclear Physics News, to attract junior researcher from different backgrounds.
- Striving for diversity on the invited lecturers at the Lecture Weeks, Special Lectures, IRTG-Days, and IRTG Annual Workshop.
- The regular inclusion on discussions regarding equality in the IRTG Annual Workshop.

- Specialized mentoring for under-represented groups within the IRTG, making use of offerings of the university equality offices.
- Support activities to strengthen the understanding between people of different cultures and the importance of internationalization.
- Definition of a Code-of-Conduct for respectful interaction amongst all IRTG members with different cultural backgrounds.
- Creation and active support of a family-friendly environment, e.g. creation of possibilities for home office or through centralized services.

The equal opportunities offices of the TU Darmstadt and UPB supervise and coordinate the various gender equality initiatives in cooperation with the family-support and dual-career services. The equal opportunity efforts of TU Darmstadt and UPB focus on the career advancement for women up to leading positions, the compatibility of family and scientific career as well as family-friendly workplaces in research. Both universities operate dedicated equal-opportunities offices and participate in relevant national audits, policy initiatives and nationwide professional networks in the field of gender-diversity politics. TU Darmstadt is fully committed to the DFG Research-Oriented Equity and Diversity Standards. Similarly, UPB participates in task forces and working groups on gender and diversity based on its membership in a number of European and international associations (e.g., CESAER's Taskforce human resources, EELISA European University Task force on gender equality in research). Large efforts were made to reconcile research and parental responsibilities. The IRTG uses existing measures of both universities and complements them by IRTG specific measures. The equal-opportunities offices of both participating universities support the IRTG on these measures.

UPB has established a Diversity Team and governance mechanisms to support and contribute to further Equal Opportunities, Inclusion, and Diversity, to raise awareness, safeguard, promote desirable actions, and combat malpractice. Gender Equality Officers in the Diversity Team are fully responsible for the implementation, monitoring and evaluation of diversity-related activites. Additionally, UPB has developed and implements a Gender Equality Plan. Regarding academic positions, UPB is close to achieving gender parity: 43% of the positions are occupied by women (see Table 5.1).

Table 5.1. Distribution of UPB's academic staff by gender in all fields of science (as of August, 2022).

	Professor	Associate Professor	Lecturer	Teaching Assistant	Total women	Total men
Total women	93	137	247	88	563	
Total men	205	191	238	103		737

Ira Rischowski-Program for Nuclear Photonics: The fields of nuclear physics, laser, plasma, and accelerator physics and electrical engineering suffer in Germany from a reduced attractivity for female junior scientists as compared to other fields. E.g., the GRK 2128 in accelerator science had succeeded in attracting a number of female doctoral researchers corresponding to about 15% of all trainees. This level of female participation in doctoral programs is unsatisfactory. The small number of qualified female applicants on position offers provided the main obstacle for reaching gender equality in that field. In order to provide a better situation for Nuclear Photonics, the international recruitment process for female researchers in Nuclear Photonics must start earlier.

For better being able to recruit excellent foreign women for doctoral researchers' positions, it is desirable to educate high-potentials in the fields of the IRTG already at the master level at TUDa, and provide them with means to make early contact with this scientifically challenging and specialized field. However, moving to Darmstadt for a two-years long master study may be financially inhibitive for many excellent female students from abroad. To remedy this situation, TUDa and its Institute for Nuclear Physics have established in 2020 an annual awarding of two-years stipends for exceptionally-talented female master students from abroad for conducting their master studies in the fields of Nuclear Photonics at TUDa. Highly-talented female master students had already been attracted from Albania, India, and Russia. This "Ira Rischowski-Program" provides female master students from abroad with a stipend of 600,- € per month for up to 24 months for the completion of their master theses in the fields of Nuclear Photonics at Darmstadt. The Ira Rischowski-Award winners are selected by a panel dominated by female physicists. The "Ira Rischowski-graduates” represent excellently educated candidates for positions within the IRTG. This innovative measure should improve the number of highly qualified female applicants for position openings in the IRTG, by having them made familiar with the research on Nuclear Photonics at Darmstadt already during their master studies for being able to advantageously competing for one of the research-training positions within this IRTG. This career advancement program for high-potential female students is key for reaching the 35% goal of female doctoral researchers in the IRTG.

Equal Opportunities: The education and further advancement of a new generation of highly qualified female scientists is one objective of the TU Darmstadt and UPB. The STEM fields, including the fields in physics and accelerator science relevant for Nuclear Photonics, historically suffer from a particularly low percentage of female junior scientists. At their physics departments, the percentage of female physicists at different career stages is comparable to the national average. The fraction of female among the doctoral candidates in physics reaches 20% (as of 2021) at TU Darmstadt and 39,4% (as of 2022) at UPB; for the post doctoral researchers the corresponding fractions are 18% (TU Da) and 0 % (UPB). The fraction of female professors is 17% at the department of physics at TU Darmstadt and 40% at UPB (for all fields as of 2022).

The IRTG starts from a low level with a total of 14% of female RTs (2 out of 13 at TU Darmstadt and 1 out of 8 at UPB) in line with the averages quoted above. The numbers involved are small and reveal a large uncertainty considering any statistical interpretation. However, it is obvious that measures for supporting equal participation of women are needed to enhance gender diversity on all levels. In order to boldy boost the number of excellently trained female researchers in the field, we aim for a higher participation of female junior researchers in the IRTG at the challenging level of 35% of all research trainees. Bold steps in the direction for reaching this goal have been made by pre-attracting female junior researchers in the LOEWE research project “Nuclear Photonics” at TUDa and by the Ira Rischowski program. Support of the latter is of paramount importance for reaching the equality goals. First stipendees have been recruited in 2021 and 2022 and are additionally supported by own core funds. It aims at attracting excellent female master students from abroad in order to train them for a subsequent participation in the doctoral programs at TU Darmstadt.

A. Research Training Group Members		
	% Goal	
	M	**F**
Doctoral Researchers	< 65	> 35
Postdoctoral Researchers	--	--

B. Participating Researchers				
	Number Status Quo		**% Status Quo**	
	According to establishment proposal			
	M	**F**	**M**	**F**
Postdoctoral Researchers*	2	1	67	33
Junior Professors, Independent Junior Research Group Leaders	3	1	75	25
Professors C3/W2	7	1	87	13
Professors C4/W3	6	0	100	0
Total	18	3	86	14

* Research staff with a doctoral degree but without their own working group

In order to facilitate an increase of the number of women on every qualification level different measures have been and will be implemented. The female RTs at TU Darmstadt continue to actively participate in the Saturday Morning Physics at TU Darmstadt (lecture series for school pupils), Girl's Day (open houses for school pupils), "Schülerinnen Schnuppertage" (a one-week internship for school pupils), the website "Kann ich MINT" (targeting directly female school pupils), Big Sister (buddy-program for first year female students from abroad or with history of migration), Femtec.Network (cooperation of technical universities and international companies, preparation of female students for professional practice), Mentoring Hessen (4 different programs for mentoring, training, networking aiming at different levels: ProCareer.MINT, ProCareerDoc, ProAcademia, ProProfessur). In the last 5 years, UPB has implemented dedicated projects aiming to reduce academic dropout. The projects addressed vulnerable freshmen (low achievers being at risk to leave the study program before getting the certification). The students benefited from coaching and mentoring sessions, remedial learning activities, study visits to companies and meetings with mentors from industry. To support STEM education, UPB has established an office to promote STEM education in secondary schools. A dedicated team offers counselling to pupils, subject-matter preparation, study visits and interactions with researchers.

Compatibility of Family and Scientific Career: TU Darmstadt and UPB put considerable emphasis on ensuring that family-life is made compatible with studying at university or pursuing an academic career. In June 2021 TU Darmstadt has been re-audited for the sixth time. In this process the "berufundfamilie Service GmbH" evaluates the conditions for studying and working with focus on a good compatibility of both with family. In 2014 TU Darmstadt joined the best-practice club "Familie in der Hochschule" and signed the corresponding charta. Doing so, the university has committed to a family-oriented management culture. TU Darmstadt developed a family-friendly environment for research, teaching and study, which is under further development continuously in order to adapt to the needs of scientists. The efforts include two childcare centers at TU Darmstadt, which may aid by ad-hoc childcare in case of travel of a parent. In addition, newly hired professors and their partners get support on their change to TU Darmstadt by the service point "Dual Career und Wohnen".

In 2020, the European Commission recognised with the 'HR Excellence in Research Award' UPB's progress in aligning its human resources policies to the 40 principles of the Charter & Code, based on a customized action plan/HR strategy. Therefore, UPB is committed to supporting a fair balance between the private and professional lives of all staff. In line with this, UPB promotes staff stability and the permanence of employment. Moreover, UPB's employees benefit from childcare services offered by UPB Kindergarten and Primary School. Based on the actions proposed in the Gender Equality Plan, UPB has initiated a support and exchange network for women staff (She Engineer - SHINE) to promote career models, exchange practices and experiences and support women in general. All female employees of UPB receive a financial incentive on the 8th of March. Young researchers, regardless the gender, can benefit from a social residence on UPB campus. The IRTG members are aware of the opportunities offered by the Universities.

All members of the IRTG are committed to the goal of providing an equal-opportunity environment. The following specific to IRTG equality measures are foreseen:

- Continued active recruitment of female researchers from all over the world already for their master studies through the "Ira-Rischowski Program" for supporting highly capable female master students from abroad for conducting their master studies in the fields of nuclear physics, nuclear photonics, or accelerator science at TU. Graduates from this program will represent excellent candidates for positions within this IRTG.
- Offer career support for female researchers (individual coachings, academic transferable-skill trainings, networking, and mentoring).
- Offer individual career and work-life-balance support for all members of the IRTG (working from home, support the existing daycare facilities, etc.)
- Inviting renowned female scientists for lectures and seminars.
- UPB will develop a MOOC on diversity to address BSc, MSc, and Ph.D. students.
- To support the integration of the research dimension in research and teaching, UPB will update the existing toolkit and create an online resource center to provide employees with relevant information.
- The Diversity Team of UPB is to launch a thematic newsletter in October 2022. It will inform the academic community about courses, best practice examples, and related activities.

5.4 Organisation

The organization of the IRTG is defined in its bylaws, which we intend to base on those of projects like the previously successfully evaluated research training group GRK 2128, and which will be agreed upon by the board of RTs upon inauguration of the IRTG. It is managed by the Spokespersons supported by a central secretary at TU Darmstadt (50% position), the board of RTs including the Representatives of the research trainees, and three topical committees for teaching, research, and networking. Structural decisions are made by the General Assembly or by the board of RTs, the latter of which meets three to four times a year. The General Assembly meets at least once a year, e.g., during the annual workshops of the IRTG. Competences and responsibilities of each body are defined in the bylaws of the IRTG.

5.5 Additional Quality Management Aspects

Monitoring the Success of the Research Trainees

The progress of each single PhD project is monitored and steered through the semi-annual PhD committee meetings as outlined in Section 4.1. The status of the PhD projects is furthermore documented by the mandatory Annual Status Reports. The junior scientists are also encouraged to present their scientific achievements at international conferences and to publish their results in peer-reviewed journals. The supervising RTs are responsible for this encouragement and for guidance in writing scientific publications.

International Research Training Advisory Board (IRTAB)

The quality management of the IRTG is supported by its **International Research Training Advisory Board** (IRTAB). It will be founded on establishment of this IRTG and is proposed to continue its work over its entire period of tenure. It comprises a diverse team of four internationally renowned scientists in the area of Nuclear Photonics at different levels of their careers and with diverse experiences with research training, including the 2018 Nobel Laureate, Prof. Mourou, who all have agreed to support this IRTG with their expertise:

- **Prof. Dr. Calvin Howell** (TUNL, Duke Univ., NC, U.S.A.),
- **Prof. Dr. Gerard Mourou** (Palaiseau, Paris, France),
- **Dr. Lieselotte Obst-Hübl** (LBNL, Berkeley, CA, U.S.A.), and
- **Prof. Dr. Andreas Zilges** (Universität zu Köln).

The IRTAB monitors and evaluates the progress and success of the IRTG. In particular, it will receive the annual status reports of the IRTG and be asked for advice on (i) the recruitment process, (ii) the qualification program, (iii) the scientific development, and (iv) the overall IRTG management.

6 Environment of the Research Training Group

6.1 Environment

Technische Universität Darmstadt

TU Darmstadt enrolls more than 25,000 students with about 300 professors in 13 departments. Its topical profile is given by about 50% engineering sciences, 35% natural sciences, and 15% humanities. It is the university's structural strategy to focus on and strengthen its research competences in fields that involve fore-front technology in combination with highly visible fundamental research for the benefit of the society and economical development. 'Nuclear Science' is one vivid component of this strategy. The university's research profile is defined by three interdisciplinary Research Fields, one of them being "Matter and Materials" which includes the university's **Profile Theme 'Nuclear Science'**.

The university's support for the field of Nuclear Science was boosted by its strategic decision for supporting the international **Facility for Antiproton and Ion Research** (FAIR) at Darmstadt, in particular, in the fields of nuclear structure physics, accelerator technology, and nuclear photonics. Its commitment to these fields has created an outstanding interdisciplinary environment for fore-front research resting on four pillars: (i) a broad and unique group of academicians and scholars for nuclear science at TU Darmstadt, (ii) the in-house **electron accelerator S-DALINAC**, (iii) the involvement in the lead of the internationally visible research on nuclear and photonuclear science at GSI Helmholtzzentrum für Schwerionenforschung GmbH at Darmstadt and at its international FAIR facility, and (iv) its institutionalized support for interdisciplinary research and training activities. This IRTG is meant to open the internationally competitive in-house research on Nuclear Photonics at TU Darmstadt and at the GSI facility to the international ELI-community for maximizing research capabilities and scientific impact.

The commitment of TU Darmstadt and its supporting State of Hesse to the research field of nuclear photonics is highlighted by the establishment of the research focus program ‘Nuclear Photonics’ supported within the Hessian excellence program LOEWE by 4.3 Mio.€ in the time period 1.1.2019 – 30.9.2023 in preparation of this IRTG, and within the cluster project ELEMENTS in the time period 1.4.2021 – 31.3.2025 by 7.9 Mio.€, in total. The LOEWE research focus program has enabled TU Darmstadt to attract highly-visible experienced researchers in Nuclear Photonics for establishing thriving young-investigator groups, e.g., the group of Dr. Isaak, in collaboration with the pre-existing faculty and in cooperation with ELI-NP. The demand by junior scientists for research training positions in the field of Nuclear Photonics is very high. The cluster project ELEMENTS had foreseen the **establishment of a tenure-track professorship “Laboratory astrophysics with heavy-ion and laser beams”** meant to broaden the range of applications of Nuclear Photonics to the astrophysical research. This aspect is emphasized in our proposal for the establishment of the IRTG. TUDa has made the corresponding offer to Dr. Kuschel and the appointment procedure is currently progressing. Establishment of this IRTG will provide the newly appointed faculty with an ideal environment for career development.

The major research infrastructure at TU Darmstadt is its superconducting linear electron accelerator S-DALINAC in the Institute for Nuclear Physics. It has been in operation for experiments in nuclear physics, radiation physics and nuclear astrophysics since 1991. It has been worldwide the first superconducting continuous-wave electron accelerator in its energy range. Due to its coverage of low-momentum transfers with high resolution, it is well suited for nuclear structure research: The S-DALINAC is equipped with two sites for the production of **bremsstrahlung for applications in nuclear photonics** and two magnetic spectrometers for the detection of scattered electrons with high-energy resolution. The two sites for the production of bremsstrahlung deliver photons either with energies up to 10 MeV and high photon fluxes of about 1,000 photons per (eV s cm^2), or with energies up to 30 MeV and single-photon’s energy tagging capability with a high resolution of 30 keV. This **NEPTUN photon tagger** has recently been upgraded by 607 k€ provided by the DFG. It is capable of accepting an electron beam energy of 70 MeV and tagged photons can be produced in the energy range from 5 to 35 MeV with maximum spectral densities of 1 photon/(eV s) collimated into a cone with opening angle of about 3 mrad. The S-DALINAC is the major in-house research infrastructure for Nuclear Photonics at TUDa.

In 2018 the TU Darmstadt has fully commissioned a third recirculation beam line of the S-DALINAC. This investment was done in the scope of a DFG-supported major-research instrument totaling 363 k€ with a 50% cost share of the university. The new recirculation beam line was used to first operate the S-DALINAC as an energy-recovery linear accelerator (ERL) enabling research for an **advanced photon source of 4th generation** for nuclear-photonics applications by laser-Compton backscattering (LCB). The corresponding laser system is funded within the major-research instrument program of the DFG with a 50% cost share of the university and is currently being procured. In 2021 the S-DALINAC was used to demonstrate a **performant, superconducting, multiturn ERL** for the first time in the world.

The faculty at TU Darmstadt is also leading the scientific program at the **Petawatt High-Energy Laser for Heavy Ion EXperiments** (PHELIX) at the GSI Helmholtz Centre for Heavy-Ion Research at Darmstadt (see below). The target laboratory of TU Darmstadt has established unique capabilities and expertise for the fabrication of delicate micro-structured targets for Nuclear Photonics applications. On establishment of this IRTG, the then urgently needed **position of a technician in the target laboratory** will be filled. Research on photonuclear reactions at Darmstadt are currently supported by the Hessian LOEWE research focus program ‘Nuclear Photonics’ for developing the field at TU Darmstadt for a leading participation in the scientific program at the European ELI. The proposed IRTG will be of paramount importance for supporting the research and training in the field of Nuclear Photonics at TU Darmstadt because the seed-funds project of the Hessian Ministry HMWK which has helped to further develop the field of Nuclear Photonics must expire in September 2023.

University POLITEHNICA of Bucharest

UPB is the oldest and largest university of technology in Romania with its foremost mission being engineering training at all levels (B.Sc, M.Sc, Ph.D.). UPB is a transmitter and a creator of science and technology consisting of 15 Faculties, 2 Departments, 43 R&D Centers, 1312 academic and 506 non-academic staff, 22.771 undergraduate and 4.643 postgraduate students. UPB has the mission to increase knowledge and innovation, two key concepts of knowledge-based economy and society.

The Doctoral School of "Engineering and Applications of Lasers and Accelerators" (EALA), one of the 14 doctoral schools in UPB, was established in 2015 based on the partnership agreement between University POLITEHNICA of Bucharest (UPB), the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), the National Research-Development Institute for Laser, Plasma and Radiation Physics (INCDFLPR) and the National Research-Development Institute for Materials Physics (INCDFM), concluded in 2013 to achieve excellence in training and research, and optimize its use in common share of human, material and financial resources. Most of the EALA PhD students are studying in relation with ELI-NP and IFIN-HH.

Since the 1980s years, a 4-years long undergraduate educational program of “Physics Engineering” has been started at UPB, providing each year a scheduled training with a dominant physics component within curricula (optics, lasers, plasma, solid state, nuclear-applied, computational physics) for about 30 engineers. This program has been coordinated by the UPB Department of Physics (DF-UPB) and is hosted by the Faculty of Applied Sciences (FSA). Also, a 4-semesters Master program dedicated to the ELI-NP topics has been running since 2010 in DF-UPB. Most of the lecturers at EALA are scientists from ELI-NP and IFIN-HH (e.g., Drs. D. Ursescu, C. Ur, N. Marginean, Gh. Pascovici). A second master program, focused on the engineering topics of the ELI-NP facility, is running in the faculty of Mechanical Engineering of UPB.

According to the partnership agreement between the research institutes IFIN-HH, INCDFLPR, INCDFM and UPB, doctoral researchers from EALA have access to all scientific research papers and all facilities between partner institutions, some of them being registered on the ERRIS platform, including the Extreme Light Infrastructure - Nuclear Physics (ELI-NP) at IFIN-HH.

Non-university environment

GSI Helmholtzzentrum für Schwerionenforschung GmbH (GSI) *at Darmstadt*: TU Darmstadt enjoys a vivid environment for the field of nuclear science and nuclear photonics. It was among the founding partners of GSI, which supports a comprehensive activity in the science of ion accelerators and high-intensity lasers. The international Facility for Antiprotons and Ion Research (FAIR) comes into existence adjacent to the campus of GSI. FAIR will be one of the major international research infrastructures in Europe. FAIR represents currently the largest construction of particle accelerators worldwide with an international investment of approximately 3 billion EUR, and the State of Romania being an ordinary Share Holder. Some of the RTs are involved in various aspects in the establishment of FAIR, too. While the proposed IRTG will focus on laser-generated particle beams and their applications, it will benefit from FAIR’s expertise on sizeable ion accelerator complexes for highest intensities, in particular for the completion of the VEGA system at ELI-NP.

PHELIX is a versatile laser facility at GSI delivering intense laser beams with energies up to 1 kilojoule or likewise powers up to 500 TW. PHELIX is a flashlamp-pumped Nd:glass system employing two frontends (fs- and ns-frontend), a pre-amplifier and a main amplifier. PHELIX serves three experimental areas: At the Z6 experimental area the worldwide unique combination of intense laser radiation with heavy ion beams generated at GSI’s accelerator facility (UNILAC) enables experiments in the field of plasma physics, nuclear physics and atomic physics. In addition, stand-alone experiments with intense laser beams can be carried out for studies such as X-ray laser generation, proton acceleration or neutron-beam production. For moderate beam intensities up to 10 TW the laser laboratory with an additional pulse compressor and target chamber are available. For the generation of laser intensities of >1020 W/cm² the chirped pulse amplification scheme (CPA) is used where a sub-picosecond laser pulse is stretched in time, amplified and recompressed afterwards. High energy beams are generated by the nanosecond frontend, which delivers arbitrary pulse shapes and pulse durations between 1 and 10 ns.

On April 1st, 2021, the state of Hesse established the cluster project ELEMENTS at Darmstadt, Frankfurt (leading partner) and Gießen together with GSI. ELEMENTS aims at developing the structures at the participating institutions for a successful application for a Cluster of Excellence in the next round of the Federal German Excellence Strategy. ELEMENTS aims at the comprehensive investigation of the physics governing the cosmic events of binary neutron-star mergers, from the production of gravitational wave signals depending on the properties of the nuclear equation of state to the synthesis of heavy chemical elements in the rapid-neutron capture process terminating in the r-process fission cycle and the corresponding observable electromagnetic transients known as kilonova signals. ELEMENTS had foreseen the hiring of additional academic staff in the field of nuclear photonics. The appointment of Dr. Kuschel for the tenure-track professorship with denomination “Laboratory astrophysics with heavy-ion and laser beams” at TU Darmstadt is currently on-going. It is foreseen that Dr. Kuschel will become a member of this IRTG.

Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) *at Magurele, near Bucharest:* IFIN-HH is the largest Romanian institute for research. It enrolls 800 employees, out of which about 200 people work at ELI-NP. IFIN-HH's mission is to generate, collect and disseminate knowledge in nuclear physics research and engineering and to actively participate in the transfer of specific expertise and technologies to society. The strategic objectives pursued by IFIN-HH are aimig at: obtaining results of high relevance at international level in fundamental, experimental and theoretical research, in nuclear physics and related fields; achieving competitive results with direct relevance to the economic and social environment, in applied nuclear physics research and engineering; providing a competent source of knowledge in the field of nuclear physics in support of the governance system, education system, and public information.

The main research directions took into account the scientific priorities identified in the fundamental research strategy in Romania (http://www.nipne.ro/about/mission/) and aim at complying with the strategic scientific plan for physics research in Romania within the ESFRO program (http://www.ifa-mg.ro/esfro/). Most of the topics can be found in the NuPECC's Long Range Plan: “Perspectives in Nuclear Physics” (http://www.nupecc.org/pub/lrp17/lrp2017.pdf) and in the European strategy for Particle Physics (https://europeanstrategy.cern). The high-priority research directions implemented at IFIN-HH are: nuclear physics and astrophysics, elementary particle physics, theoretical physics, physics of life and the environment, tools, methods, applications of nuclear physics and nuclear engineering, computational physics, and information technology.

As part of the collaboration at CERN and FAIR, IFIN-HH developed support laboratories for the related research activities. A relevant achievement is the detector laboratory, where some of the equipment was built which is part of the ALICE experiment at the LHC accelerator at CERN and of the CBM experiment at FAIR. For the collaboration with CERN, a GRID system was built in IFIN-HH, consisting of several Tier-2 nodes, thus making the center with the highest computing and storage power in Romania. The most relevant part of IFIN-HH’s research strategy is the implementation of the European ELI-NP facility.

ELI-NP represents the most advanced research facility in the world in the field of Nuclear Photonics. It was built as the nuclear physics pillar of the Pan-European Distributed Extreme Light Infrastructure

Figure 34: *Extreme Light Infrastructure – Nuclear Physics at Magurele, Romania. Left: Part of the Experiment Building housing the two 10 PW lasers and the VEGA system; Right: the laser hall of the 10 PW lasers.*

(ELI). It represents the largest investment ever made in scientific research in Romania, co-financed by the European Commission and the Romanian Government from Structural Funds via the European Regional Development Fund (ERDF).

ELI-NP implements unique, world class, research equipment: a high-power laser system with two 10 PW laser arms aiming to provide the highest possible laser intensities worldwide and a high intensity quasi-monochromatic gamma-beam system. The high-power lasers are operational since 2020 and the experimental setups are gradually commissioned and put in operation. The High-Power Laser System (HPLS) of ELI-NP with both 10-PW lasers and including their basic scientific infrastructure will be fully operational by 2023. ELI-NP will also comprise the Variable-Energy GAmma-beam system (VEGA) which will provide an intense beam of quasi-monochromatic energy-tunable MeV-ranged photons. Due to the financial failure of the vendor in 2022, the VEGA system will be completed by IFIN-HH itself. Scientific and technological support, advice, and collaboration by the groups at TU Darmstadt will be essential for this task. The institutionalized cooperation of the experts from both partners within this IRTG Nuclear Photonics is of paramount importance for the field of Nuclear Photonics, for the success of the European ELI project, for IFIN-HH, and for the State of Romania. ELI-NP will be operated as user facility where access to beam time will be granted free of charge, merely based on scientific merit evaluated by an international selection committee. First research proposals had been invited in 2022.

IFIN-HH implemented a personnel strategy aiming at attracting young people. The selection of young people is made in collaboration with partner universities, starting with the 3rd year of study, via internships in IFIN-HH laboratories. This activity continues with the completion of the diploma or dissertation. For doctoral studies the students are integrated in the groups of the institute and autonomously carry out research work under the supervision of experienced scientists.

The proposed IRTG will be of paramount importance for supporting the research and training at the University POLITEHNICA of Bucharest in the field of nuclear photonics.

Cooperation between TU Darmstadt and UPB/IFIN-HH

The partner universities have established a track record of institutionalized academic cooperation already since the year 1974. Since the years of the 1990s this cooperation was strengthened in the fields of economical engineering and electrical engineering, later-on broadened to the fields of laser physics, particle accelerator and nuclear science. Since 31.10.2014 TU Darmstadt and University POLITEHNICA of Bucharest are partners of a vivid ERASMUS+ exchange program including the fields of electrical engineering, energy science, and material science.

Since 2009, scientists from TU Darmstadt have been involved in shaping the scientific vision for the European ELI project. In October 2013, IFIN-HH and TU Darmstadt's Research Cluster "*Matter and Radiation Science*" have initially agreed upon a Memorandum of Scientific Collaboration on the implementation phase of ELI-NP. In October 2014, the memorandum between IFIN-HH and the TU Darmstadt has been expanded to include the entire university. This collaboration addressed the development of the ELI-NP experimental areas; the definition of the experimental program; the development of necessary instrumentation; the training of highly-skilled human resources in the field; and the promotion of ELI-NP as an international facility. More than a dozen scientific articles in the field of nuclear photonics with common co-authors from TU Darmstadt and from IFIN-HH have been published over the years.

6.2 Distinction between the Research Training Group and a Collaborative Research Centre

TU Darmstadt possesses one of the largest faculty groups in nuclear physics in Germany and considers "Nuclear Science" as one of its university-profile defining research themes[2]. In fact, the Institute for Nuclear Physics with 18 active faculty, is the largest institute of the entire university. Consequently, it carries one of the strongest research programs in nuclear science in the country, including two Collaborative Research Centers (CRCs), **SFB 1245** and **TRR 211**, both, running in their second funding periods, are currently preparing for their last funding periods for their final harvest of science results. Both CRCs focus on research themes that are very much distinct from the field of Nuclear Photonics. They either have no or only marginal scientific overlap with this IRTG. In addition, the Department for Informatics hosts a cross-disciplinary CRC, **SFB 1119**, which includes the application of lasers for quantum

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[2] https://www.tu-darmstadt.de/forschen/forschungsfelder/matter_materials_mm/index.en.jsp

encryption. It has no scientific overlap with this IRTG. Details on the distinctions between this IRTG and the CRCs at TU Darmstadt are given below.

TRR 211 "Strong-Interaction Matter under Extreme Conditions" seeks to provide theoretical effort to reproduce and study matter at the extremes of temperature and density through heavy-ion collisions by applying the theory of the strong interaction, QCD, to these environments. It comprises groups from the universities at Bielefeld, Darmstadt, and Frankfurt. **Prof. Galatyuk** is a principal investigator in the TRR 211, too. There, she leads the project B04 which studies electroweak signals from hot and dense matter at high baryon densities. There is no scientific overlap with the present IRTG where Prof. Galatyuk offers guidance on a research topic which exploits her leading expertise on radiation-hard ultrafast responding charged-particle detectors for the characterization of laser-induced particle beams or accelerator diagnostics in Nuclear Photonics applications.

SFB 1245 "Nuclei: From Fundamental Interactions to Structure and Stars" is developing a systematic understanding of atomic nuclei across the nuclear chart based on effective field theories (EFTs) of the strong interaction. These theoretical descriptions are tested with key experiments at international facilities and at the Darmstadt electron accelerator S-DALINAC. **Profs. Aumann, Martinez-Pinedo, Pietralla** and **Dr. Werner** are principal investigators in the SFB 1245, too. There, they lead the projects A01 (Pietralla), A05, A06 (Aumann), B01, B06 (Martinez-Pinedo), and B02 (Werner), that either test nuclear structure theory predictions with experiments on light nuclei (A01), on halo nuclei (A05) or even on nuclei beyond the neutron drip-line (A06), constrain theory applications by electromagnetic observables (B02), or study the theory of neutrino-nuclear interaction (B01) for nucleosynthesis in core-collapse supernovae (B06). Prof. Pietralla had been the Deputy Spokesperson of SFB 1245 in the period January 2016 – October 2022. There is no or, at most, remote scientific overlap with the present IRTG. Three projects of the SFB 1245 (A01, B02, and B04) partially utilize photonuclear reactions using bremsstrahlung beams at the S-DALINAC (A01 and B04) while project B02 studies N=50 isotones using LCB beams at the High-Intensity γ–ray Source at the Duke Free-Electron Laser Laboratory at Duke University, Durham, NC, U.S.A. A few research projects, foreseen for this IRTG, exploit outstanding methodological progress, e.g., the establishment of the Relative Self-Absorption technique, and investments in research instruments, e.g., the upgrade of the focal-plane detector of the NEPTUN photon-tagger at the S-DALINAC. The SFB 1245 does not use any laser-induced charged particle beams and does not focus on research training in Nuclear Photonics.

SFB 1119 "Crossing" provides cryptography-based security solutions enabling trust in new and next generation computing environments. It had been established in 2014 and has entered its final funding period. **Prof. Walther** is a principal investigator in the SFB 1119, too. There, he leads the project P04 which studies an extension of a four-party-network by spatially separating the parties to prototype a functional city-wide quantum-key distribution network. There is no nuclear component in the research in SFB 1119 and no scientific overlap with the present IRTG where Prof. Walther offers guidance on a research topic for establishing an optical cavity for laser-electron beam collisions for the production of narrow bandwidth MeV-ranged photon beams for Nuclear Photonics applications.

The leading scientific activities of some RTs of this IRTG in well-established CRCs in their final funding periods secures a broad range of diverse competences in scientific fore-front topics of the research trainers for the benefit of a broad research training in Nuclear Photonics.

6.3 Distinction between the proposed and previous Research Training Groups

As TU Darmstadt is one of the few German universities that operate an in-house particle accelerator with a very successful research program, it provides high-level research training in accelerator science. In 2016, the DFG started its funding of the Research Training Group **GRK 2128** "AccelencE" in accelerator science which will finish in September 2025 and has already recruited its final cohort of research trainees. The GRK 2128 comprises groups from the universities at Darmstadt and Mainz. It has offered a structured promotion program for research on energy-recovery linear accelerators (ERLs), a new generation of particle accelerators complying with aspects for energy sustainability. In 2021, the S-DALINAC has been successfully operated as the first superconducting multiturn ERL in the world for which significant energy-recycling could have been measured. In fact, the technology of ERLs can impact on the field of Nuclear Photonics, in particular, with respect to the technologically exciting opportunity for a future establishment of a fourth-generation light source. This IRTG on Nuclear Photonics can, thus, benefit from pre-established electron-accelerator infrastructure which is unique in the world for a development towards applications in the field of Nuclear Photonics. While the previous GRK 2128 focused on the ERL aspect of electron accelerator technology, the present IRTG will focus on the production and application of high-intensity laser-induced particle beams and photonuclear reactions and methods.

The designated Spokesperson of this IRTG, **Prof. Pietralla**, had been the founding Spokesperson of the GRK 2128. He stepped down from this post in 2020, when **Prof. Enders** has taken over this duty. **Profs**. **Boine-Frankenheim, Enders, Galatyuk, Pietralla**, and **Drs. Arnold** and **Werner** are principal investigators in the GRK 2128, too. In contrast to the previous GRK 2128 dealing with electron accelerators, Prof. Boine-Frankenheim and Galatyuk offer research training on topics related to laser-induced ion beams in this IRTG while Profs. Enders and Pietralla and Dr. Werner offer research training on photonuclear reactions that are entirely distinct from the projects they supervised in the GRK 2128 on accelerator science or magnetic spectrometers. The other project of Prof. Enders and the two projects supervised by Dr. Arnold in this IRTG will develop technology towards a future, fourth-generation light source for Nuclear Photonics that partially build on main accomplishments made by them and others within the previous GRK 2128 but clearly progress beyond them.

7 Modules and Funding

7.1 Module Research Training Group

7.1.1 Funding for Staff

7.1.1.1 Doctoral Researchers

According to the approved pre-proposal, we apply for sustained funding of 15 doctoral researchers' positions at TU Darmstadt with 75% of a full-time position over the entire five years of the first funding period of this IRTG, with a delayed filling of 2 requested positions after 1 year and of 2 other requested positions after 2 years, as justified in Sect. 1.5. For the entire time, these 15 positions will be complemented by 5 positions for doctoral researchers pledged from other sources at TU Darmstadt and by 20 doctoral researchers' positions at UPB (see Sect. 8). After three years of research training, doctoral researchers from the first cohort of 20 doctoral researchers at TU Darmstadt (Group A) will complete their PhD and leave the IRTG. The vacant positions will subsequently be filled according to the recruitment concept (see Sect. 5.1)., and so on. All doctoral researchers of TU Darmstadt will work collaboratively in this IRTG on its complex research program described in Sect. 3. The requested salary level of 75% is adequate for doctoral researchers in fields of high-technology in physics and typically granted by the DFG, e.g., within the GRK 2128.

7.1.1.2 Doctoral Researchers in Medicine: no request

7.1.1.3 Postdoctoral Researchers: no request

7.1.1.4 Qualifying Fellowships: no request

7.1.1.5 Student Assistants: no request

7.1.2 Funding for Direct Project Costs

7.1.2.1 Equipment up to €10,000, Software and Consumables: no request

25.000,- € p.a. will be provided as an additional core support of the TUDa. It can be used freely. We reserve these funds for unforeseen procurement of necessary small equipment and consumables.

7.1.2.2 Travel

Funds for national and international travel are fundamental for the qualification program and the career advancement measures within this IRTG, see Sect. 4 and 5. It provides the participating junior scientists with the opportunity to visit relevant international summer schools and conferences.

The two internships of about 3 and 6 months duration at the UPB, see Sect. 4.4, are essential parts of the IRTG and require significant funding. A fixed rate of 277,50 € for the return flight per internship is calculated (based on contemporary offers of air carriers). The guest house of ELI-NP will serve as accommodation (30€ / night). The per diem for Bukarest for the year 2021 amounts to 26 € / day [see (ARVVwV) of 2.10.2020]. In an average 3 years period, 20 doctoral researchers will make two internships at Bucharest of 8 months = 240 days, in total. We, hence, budget 20/3a *(240 *(30€ + 26€) + 2x277,50€) = 93.300 € p.a. starting in 2024. These internships will be complemented by video meetings for an intense collaboration on the individual research projects.

Each participant is encouraged to attend one international summer school (like the “Talent School” program, the “National Nuclear Physics Summer School”, “La Rabida”, “Nuclear Physics in Astrophysics”, USPAS, CERN accelerator school, “International Summer School on Plasma Physics” and “Summer School on Plasmas in Super-Intense Laser Fields” in Erice etc.) at the beginning of his/her project work. Later the junior scientists are requested to attend at least one, preferably two international conferences before graduation (e.g., “Nuclear Photonics”, INPC, EuNPC, ARIS, Bormio-conferences, CGS, COMEX, Zakopane, INTDS, IPAC, LINAC, IBIC, ERL-workshop, Laser Plasma Accelerator Workshop (LPAW), Hirschegg Meeting etc.) to present their progress to an international community and to disseminate the scientific results obtained within this IRTG. Including conference fee, housing, per diem, and transportation, we estimate a cost of 2.000 € per international conference or summer-school participation. For the Darmstadt group, we, hence, budget 20/3a * 3 * 2.000 € = 40.000 € p.a. National travel money is needed for visiting the DPG spring meetings (20 * 500 € p.a.; not in 2023).

Visits will be very important for the research activities of the doctoral researchers, mostly during the internships. Corresponding travel funds are requested. We consider two research related international travel needs of 860 €, each, per doctoral researcher over 3 years. For the TUDa group we expect 20/3a * 2 * 860 € = 11.500 € p.a.

For all required air travel, we request funds for compensating the generated CO_2 emmission. On average, return air travel between Frankfurt and Otopeni airports generates 0.6 t of CO_2 equivalent. We prefer to compensate the estimated CO_2 emission of the TUDa group by supporting GreenTech’s Emission Reduction by PET Recycling, Romania for a cost of 42,50 € / t provided by the Gold Standard [https://marketplace.goldstandard.org/products/plastic-recycling-romania-europe]. For compensating all air travel, we estimate for every trip a CO_2 footprint equivalent to the distance between Frankfurt and Bucharest. We, hence, budget 20/3a * 7 * 0.6 t * 42,50 €/t = 1.190 € p.a. for CO_2 compensation.

Travel to the annual Nuclear Photonics workshops is requested in module 7.6.

Therefore, we request the travel funds for the five year funding period as follows. For all expenses other than the internships and DPG-meeting participations a corresponding fraction is asked for the years 2023 (3 months) and 2028 (9 months):

Internships (2024 – 2028)	93.300,- EUR p.a.
National and international travel expenses (summer schools, conferences)	50.000,- EUR p.a.
Expenses for research travel	11.500,- EUR p.a.
CO_2 compensation for air travel	1.200,- EUR p.a.

7.1.2.3 Visiting Researchers

External researchers visiting the IRTG and its members represent an important pillar of the networking and qualification goals (see Sect. 4.2). International experts in the fields of Nuclear Photonics are invited for lecture weeks and seminars and will be asked to stay for some time, usually 1-2 weeks. This request includes travel support for the IRTAB Members, including the 2018 Nobel Laureate, Prof. Mourou. For the group at TUDa we budget funds for 10 visitors p.a. at 1.600 € per visit.

We request for the full years 2024 to 2027 funds for visiting researchers in the amount of 16.000 € p.a. and a corresponding fraction is asked for the years 2023 (3 months) and 2028 (9 months):

Funds for visiting researchers (for 12 months period)	16.000,- EUR p.a.

7.1.2.4 Experimental Animals:

no request

7.1.2.5 Other:

no request

7.1.2.6 Publications

Publications in high-impact journals are very important to gain visibility and represent a prestigious currency in science. These journals often ask for an article processing charge (APC) to allow for an open-access (OA) version of the paper. Open-access will support and facilitate the world-wide dissemination of the IRTG's scientific results. An estimation of the required publication funds is based on experience from the past years. Within the IRTG we expect to publish per year about 10 letters in the high-impact journals *Physical Review Letters* (APC = $3675), about 20 regular articles in *Physical Review C/D* (APC = $2625), and about one *Nature Communications* (APC = 4890 EUR) every two years, which results in about 92000 EUR per year in terms of publication costs. For the purpose of OA publications, funds of the TUDa as well as the University and State Library will be deployed as available (vouchers, DEAL contracts, OA funds, etc.). In addition, IRTG scientists will strive to retain rights for secondary publication via the TUprints Repository in their license agreements with the publishers (Green Open Access as stipulated by TU Darmstadt's Open Access Policy https://www.ulb.tu-darmstadt.de/media/ulb/pdf/OA-Policy_TUDarmstadt.en.pdf). For publications for which none of these funding options is available, publication costs of 4000 EUR p.a. are requested. Consequently, IRTG's research papers will be disseminated either via Gold or Green Open Access publications.

Publication fees (2024 – 2028) .... 4.000,- EUR p.a.

7.2 Module Replacements: no request

7.3 Module Coordination

The IRTG is based on the cooperation of RTs from TU Darmstadt and the University POLITEHNICA of Bucharest. To support the spokespersons and the RTs, a modest administrative support (50% FTE at Darmstadt, see "DFG Personnel Rates for 2022, DFG form 60.12 from 01/22") is required. The tasks include:

- Central budget accounting (including research travel, controlling, and reporting to the DFG
- Support of the continuous recruitment process
- Central support for organization of seminars, visitors, lectures, workshops and RT meetings
- Documenting and monitoring of PhD Committee Meetings
- Support for measures in Public Relations
- Coordination of Gender Equality Measures of the IRTG in cooperation with the Gender Equality office

In summary we request in the module coordination:

50% E9 Secretary .... 26.400,- EUR p.a.

7.4 Module Temporary Substitutes for Clinicians: no request

7.5 Module Mercator Fellows: no request

7.6 Module Project-Specific Workshops

As a central element of the IRTG program, an **annual workshop** is foreseen. As detailed in Sects. 4 and 5 the IRTG will retreat once a year for one week to discuss the scientific progress achieved by the junior researchers. The IRTG workshops will include invited external lecturers, and an excursion.

The first workshop will take place in 2024. Therefore, we request funding for participation of the TUDa group in 5 workshops in total (40 participants from Darmstadt @ 5 nights @ 130 € + 500 € travel per participant + travel expenses for 5 invited speakers @ 1.000 €)

We request for each IRTG Annual Workshop (5 in total, 2024 – 2028)................. 51.000,- EUR p.a.

Within the **IRTG Lecture Weeks** (see Sect. 4.1.2) various external experts will be invited once a year for a period of one week, each, alternating in Germany or in Romania. In order to avoid excessive travel, the participants from the other country participate remotely. Lecture weeks have been proven to be a very important qualification concept, e.g., in the GRK 2128 or in the MGK of the SFB 1245. The first lecture week will be organized at Darmstadt in November 2023.

We request for each event in Darmstadt (3 in total; 1 event, each, in 2023, 2025, and 2027):

Invited Speakers, travel, coffee breaks, meals etc. .... 5.500,- EUR p.event

As outlined in Sect. 4.1.2, the IRTG annually organizes its **IRTG-Days** alternating in Germany or in Romania, starting in 2024 in Darmstadt. The junior scientists invite a peer group from another institution in the country for a two-day meeting. In order to avoid excessive travel, the participants from the other country participate remotely. The hybrid format supports the hybrid presentation skills of the trainees and of the guests, and it serves the networking goal.

We request for each IRTG-Days at Darmstadt (3 in total; 1 event, each, in 2024, 2026, and 2028):

Travel expenses for 15 junior researchers (Train, Hotel)	3.300,- EUR p.event
Coffee breaks (4), meals (3) for 50 people	3.500,- EUR p.event

7.7 Module Public Relations

Public relation activities aim at providing information at different levels. We plan to address different groups with the following measures. Student assistants are needed for supporting visits of the interested public (see below) or to support the outreach activities in general.

Live experience of local research infrastructure for the public: The accelerator S-DALINAC, the PHELIX system at GSI, and the ELI-NP facility are accessible by the public. Visits are offered on a regular schedule with the support of student assistants. The S-DALINAC is regularly visited by more than 400 high-school students in the framework of guided tours, e.g., during the lecture series "*Saturday Morning Physics*" at TUDa (see Figure 36). GSI and ELI-NP offer similar public guided tours. These facilities are essential parts of the research and qualification program. The junior researchers can show their research and their working place directly to the interested public. The events are announced on appropriate platforms. Student assistants prepare these public visits and support the guided tours.

Figure 35: *Photography of the audience of the Saturday Morning Physics program at TU Darmstadt. For thirteen years the program reaches about 400 pupils in secondary high school per year and it regularly includes a lecture on accelerator science and a tour to the S-DALINAC which is led by PIs of this IRTG.*

Science communications workshop for the junior researchers: For the development of the next generation of brilliant scientists it is very important that they learn how to communicate their science to a diverse public (from experts to children). They will also have the chance to train their skills for presenting their research achievements, for example, in new courses offered by the recently-established Science Communication Center at TUDa.

Support of graduate school JUAS to attract possible applicants for the IRTG: Further outreach is foreseen by continued support of the graduate accelerator school JUAS (Joint Universities Accelerator School), which is held every January to March in Archamps, France, close to CERN. International students and junior researchers attend. By sponsoring this school, the IRTG gains visibility to the international participants that provide the right audience for the recruitment process of the IRTG. Students from TUDa have participated regularly in JUAS courses since its establishment in 1994. Two RTs of the present IRTG (Dr. Isaak, Dr. Arnold) have profited from their attendance of JUAS. Since 2020, an annual seminar held by Dr. Arnold has been included in the JUAS courses.

Material to support public relations activities: A German-language video on the relevance of the field of Nuclear Photonics at TUDa had recently been created for informing interested junior researchers on this career opportunity[3]. A virtual tour of the S-DALINAC was created, too. It includes explanations of the different components of the accelerator and is regularly presented to the interested public[4]. The research of the IRTG will be presented in a video. It will introduce the field, its main research topics, the facilities involved and inform on the program of this IRTG. This video will be used to gain a higher visibility of the program and to inform possible candidates about the research training opportunities. External graphics designers will be consulted to support the science communication with the preparation of graphical material for publications or presentations. A flyer with information about the IRTG will complete the efforts in the Module Public Relation.

The funds requested within this module are intended to increase the visibility of the participating institutes and their research in public even further. We request funding for:

Two Student Assistants (à 41 h per month, 6 months p.a.)	8.600,- EUR p.a.
External graphics designer (material for publications, presentation material)	1.000,- EUR p.a.
Production of IRTG video (2024)	9.700,- EUR
Flyers (2024, 2026)	2 x 900,- EUR
Supporting the accelerator school JUAS (2024 – 2028)	2.000,- EUR p.a.

7.8 Module Start-Up Funding: no request

7.9 Module Standard Allowance for Gender Equality Measures

The IRTG requests funds of 15.000,- € per year for supporting the existing institutional measures organized by the equal-opportunities office at TUDa as well as for own capacities for childcare and for additional career support for IRTG members. For details see Sect. 5.3.

The innovative Ira Rischowski Program should improve the number of highly qualified female applicants for position openings in the IRTG, by having them made familiar with the research on Nuclear Photonics at Darmstadt already during their master studies. TU Darmstadt is determined to provide three additional Ira Rischowski-Awards per 2-year period (for support of up to 24 months, i.e., for a total cost of up to 14.400,- €, or 7.200,- € p.a. per student). A cost share of 50% for the costs of the Ira Rischowski-Program is requested from the DFG, i.e. 50% x 3 x 7.200,- € p.a. = 10.800,- € p.a.

The following funds for enhancing gender equality in Nuclear Photonics are requested:

Participation share to the Equal Opportunities Office TUDa	2.500,- EUR p.a.
Support of the Ira Rischowski-Program	10.800,- EUR p.a.
Workshops/courses for career development of women	900,- EUR p.a.
Ad-hoc childcare	800,- EUR p.a.

Table 7.1: Request overview – positions for research trainees.

Staff	Hours as percentage of full time	Number	Duration (from – to)
Module Research Training Group:			
Doctoral Researcher or Comparable	75%	11	01.10.2023 – 30.09.2026
Doctoral Researcher or Comparable	75%	2	01.10.2024 – 30.09.2027
Doctoral Researcher or Comparable	75%	2	01.10.2025 – 30.09.2028
Doctoral Researcher or Comparable	75%	11	01.10.2026 – 30.09.2028
Doctoral Researcher or Comparable	75%	2	01.10.2027 – 30.09.2028
Postdoctoral Researcher or Comparable	n./a.	0	n./a.
Module Temporary Substitutes for Clincians	n./a.	0	n./a.

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[3] https://www.ikp.tu-darmstadt.de/forschung_kernphysik/verbundprojekte/details/nukleare_photonik/index.de.jsp
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Table7.2: no requests

Staff	**2023** from Oct.	**2024**	**2025**	**2026**	**2027**	**2028** through Sept**.**	**Total (€)**
Module Research Training Group: Support Staff (Student Assistants)	0	0	0	0	0	0	0
Module Replacements	0	0	0	0	0	0	0

Table 7.3: no requests

Fellowships	**Basic amount EUR / month**	**Number**	**Duration (from – to)**
Module Research Training Group:			
Qualifying Fellowships	n./a.	0	n./a.
Doctoral Fellowships in Medicine	n./a.	0	n./a.

Table 7.4: Request overview – program funds

Other Project Funds	**2023** from Oct.	**2024**	**2025**	**2026**	**2027**	**2028** through Sept.	**Total (€)**
Module Research Training Group:							
Travel	13.200	156.000	156.000	156.000	156.000	142.800	780.000
Visiting Researchers	4.000	16.000	16.000	16.000	16.000	12.000	80.000
Other	0	0	0	0	0	0	0
Publications	0	4.000	4.000	4.000	4.000	4.000	20.000
Module Coordination:							
Coordination	6.600	26.400	26.400	26.400	26.400	19.800	132.000
Other Modules							
Module Project Specific Workshops	5.500	57.800	56.500	57.800	56.500	57.800	291.900
Module Public Relations	2.150	22.200	11.600	12.500	11.600	9.450	69.500
Module Standard Allowance for Gender Equality Measures	3.325	15.000	15.000	15.000	15.000	11.675	75.000
Total	**34.800**	**297.400**	**285.500**	**287.700**	**285.500**	**257.500**	**1.448.400**

In support of the funds requested in this proposal, the TU Darmstadt will provide a core support of 25.000 € per year to the IRTG. These funds are foreseen to enable the procurement of needed equipment and consumables for the execution of the research projects by the junior researchers.

8 Complementary Funding by the Partner Institution

The Institute of Atomic Physics (IFA, www.ifa-mg.ro) is a Romanian public institution subordinated to the State Authority for Research (at present, the Ministry of Research, Innovation and Digitalization), with the primary role of funding research activities in the atomic and sub-atomic domain and related areas, particularly the participation of Romania in research programs of European and international scientific organizations in the field.

DFG and IFA agreed on/established a Memorandum of Understanding (MoU) with the purpose to support joint research and training activities conducted by scientific partners in Germany and Romania: in particular, the Implementation Guidelines for Joint Support of International Research Training Groups (IRTGs) by DFG and IFA have been also agreed/established.

The main instrument to implement the National Strategy for Research, Development, and Innovation (RD&I) in Romania is the National Plan for RD&I with a typical duration of 5 years for calls. (No new calls can be launched within the current National Plan; the next one is expected to be launched in a couple of months). The component of the National Plan dedicated to supporting research activities at the Extreme Light Infrastructure – Nuclear Physics (ELI-NP, Romania), is the ELI-RO Programme conducted by IFA.

The main steps in funding by IFA a German-Romanian IRTG proposal around ELI-NP, within the ELI-RO Programme, are the following:

- The joint proposal has to be submitted to IFA as specified in the Information Package for the dedicated Call and the IRTG type of project. (A Call might be launched for more types of projects, the rules for the IRTG case being in accordance with the MoU and the Implementation Guidelines established by DFG and IFA.)
- If the proposal fulfills the eligibility criteria (specified in the Information Package), it is assessed by the International Scientific Advisory Board (ISAB) of the ELI-RO Programme according to the evaluation criteria (also specified in the Information Package and fully agreed by DFG and IFA).
- If the joint proposal is scored above 70 (of 100) points, it is eligible for funding and ISAB recommends the budget to be allocated to the project by the Romanian side (in the limit of the available funds for the Call).
- If the joint proposal is positively evaluated also by DFG, it is included in the list of selected projects for funding that IFA submits to the State Authority for Research for approval and budget allocation.
- Once approved the results of the Call by the State Authority for Research, IFA enters into a contract with the coordinating institution of the project.
- The joint proposal will be supported by IFA for a maximum of 9 years, divided into two funding periods, the first one being 3+1+1 years, the second one being 3+1 years. Continuation of funding after the first funding phase may only be granted on the basis of a successful renewal proposal.

The detailed funding request for the Romanian partner institution to the Romanian IFA is not part of the current funding request IGK 2891 to the DFG by the Technische Universität Darmstadt. Nevertheless, it may be of interest to the Evaluators of the proposal on the German side to look at the details of the funding request of the University POLITEHNICA Bucharest in Romania. The details are given in the appendix B.8 separately attached to this proposal.

9 Declarations

9.1 Connections to Collaborative Research Centres

A partial topical connection between this ITGR exists with the Collaborative Research Centre SFB 1245. The deliniation between both programs has been detailed in Sect. 6.2. A statement by the SFB 1245 on the intended coordination between the two collaborative projects is provided in appendix B.9.1. Topical connections do not exist to SFB 1119 and TRR 211, hence, no statements are needed.

9.2 Collaboration with other Partners

The experimental program of this IRTG will make use of the in-house electron accelerator S-DALINAC at TUDa, the PHELIX laser at GSI, the ELI-NP facility at IFIN-HH, Romania, and the High-Intensity γ–ray Source (HIγS) at the Duke Free Electron Laser Laboratory at Duke University, Durham, North Carolina, U.S.A. Letters of intent and support from the directorates of GSI/FAIR, IFIN-HH, TUNL, and the HGS-HIRe have been attached in the appendices B.9.2.1 – B.9.2.4.

9.3 Cooperation with Industrial, Commercial or Service Enterprises

N./A.

9.4 Doctoral Admission of Qualifying Fellows

N./A.

9.5 Proposal Submission to other Funding Organisations

This proposal has not been submitted to any other funding agency. A related proposal for funding the Romanian group within this IRTG has been submitted to the IFA in Romania.

9.6 Letter of Intent from the Partner

TUDa enjoys a close cooperation with UPB for several decades. A declaration of the rectorate of the UPB on UPB’s commitment to this IRTG is attached in appendix B.9.6.

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Appendices to the Report

App.A:	Biographical Sketches of Participating Researchers
App.B.8	Budget Request of UPB to IFA
App.B.9.1	Declaration of the SFB 1245
App.B.9.2.1	Letter of Intent – GSI
App.B.9.2.2	Letter of Intent – IFIN-HH
App.B.9.2.3	Letter of Intent – TUNL
App.B.9.2.4	Letter of Intent – HGS-HIRe
App.B.9.6	Letter of Intent – UPB