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.

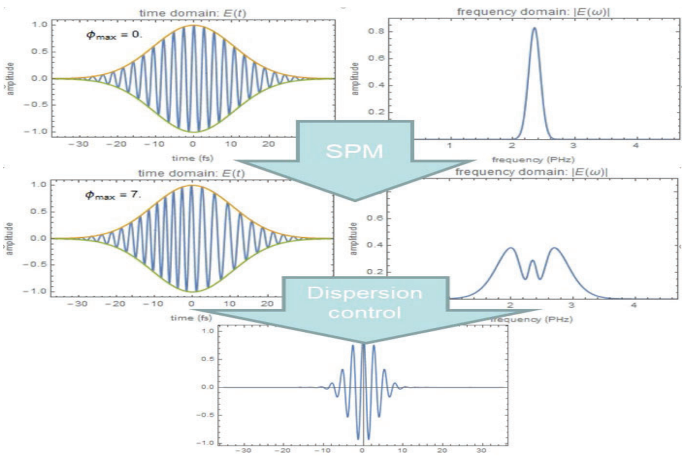


Figure 3: *Top: representation of a 10 cycle pulse in time and frequency domain; Middle: the same pulse, after passing through non-linear Kerr effect spectral broadening; Bottom: the temporal shape of the pulse after compensating the dispersion, corresponding to a two cycle pulse.*

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.

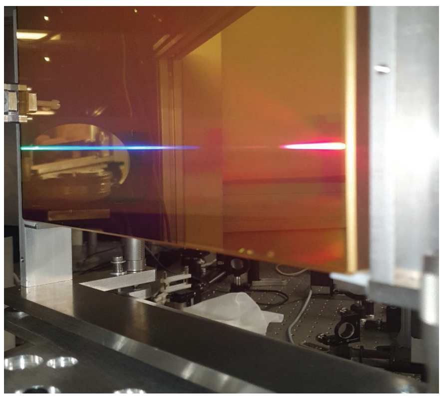


Figure 4: *Grating-based stretchers used in CPA lasers are responsible for deleterious temporal contrast degradations.*

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.

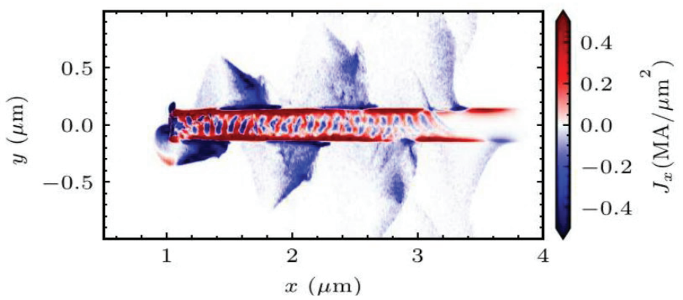


Figure 5: *One of the nano wires is shown for PW laser pulse irradiation. The laser pulse bushes up in vacuum from left to right along the surface, while wake field is driven inside the nanowire in a solid density [137].*

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.

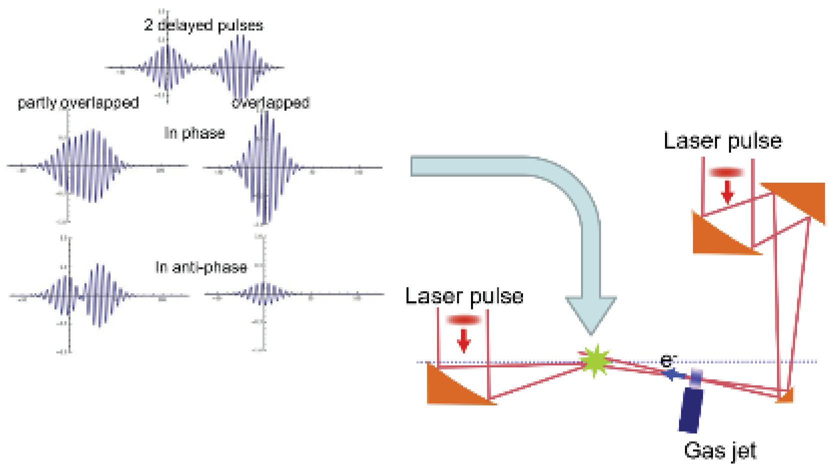


Figure 6: *Implementation of all laser-based Compton γ-ray source using laser accelerated electrons; it requires advanced spatial and temporal overlap of the laser pulses, achievable through active stabilization of the delay.*

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.

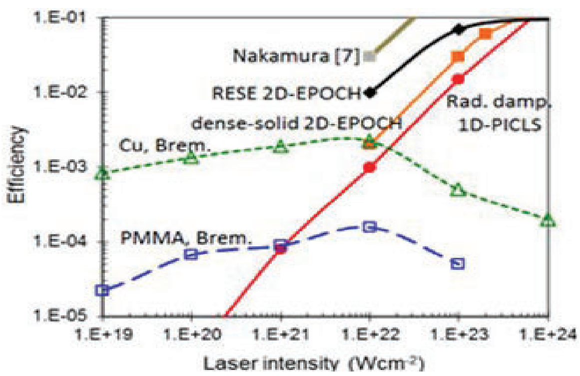


Figure 7: *Efficiency of laser-to-γ ray conversion as a function of laser intensity [26].*

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.

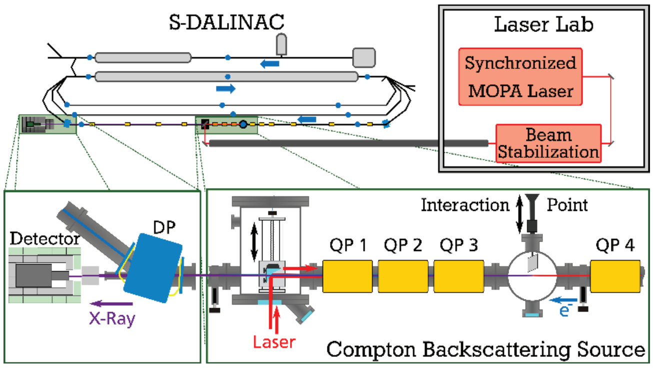


***Figure 8**: Layout of the set-up for laser Compton backscattering at the S-DALINAC. (DP: dipole magnet, QP: quadrupole magnet).*

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

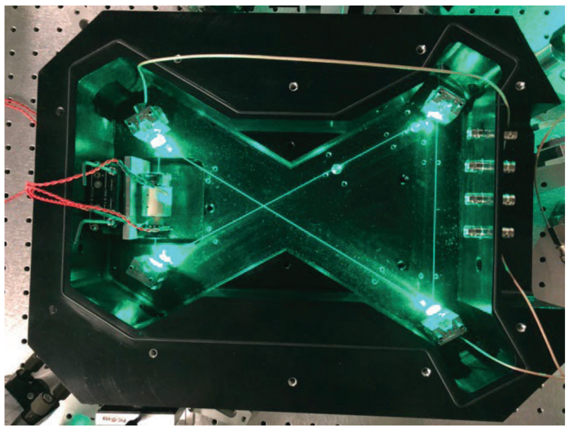


***Figure 9**: Enhancement cavity for the generation of green light and elliptical focus which might act as a model system for the much larger cavity required for the resonant enhancement of laser intensity for the ICS setup. Clearly, a monolithic design such as the one depicted cannot be used for the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

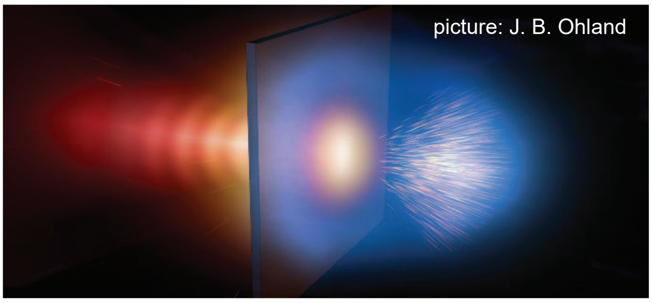


Figure 10*: Artistic view of a laser plasma interaction with a thin foil. The 10-PW laser facilities at ELI-NP will allow to enter the ultra-relativistic regime producing photon and particle beams with unprecedented characteristics.*

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.

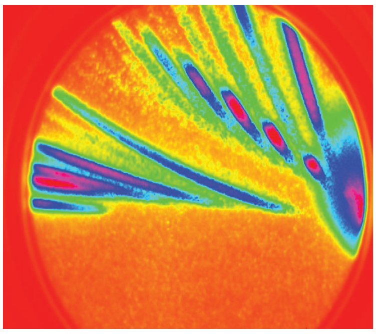
A-9 Quasi-monoenergetic ion acceleration from multi-component targets: (Kuschel, Ursescu)

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.

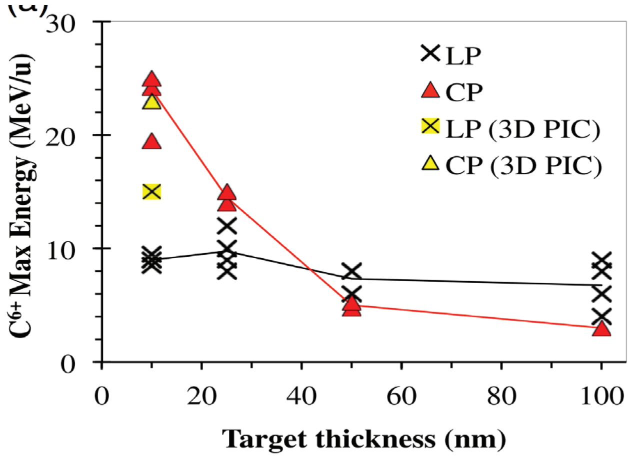


Figure 12: *Dependence of the carbon ion energy from the laser polarization and target thickness in the LS acceleration regime [12].*

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.

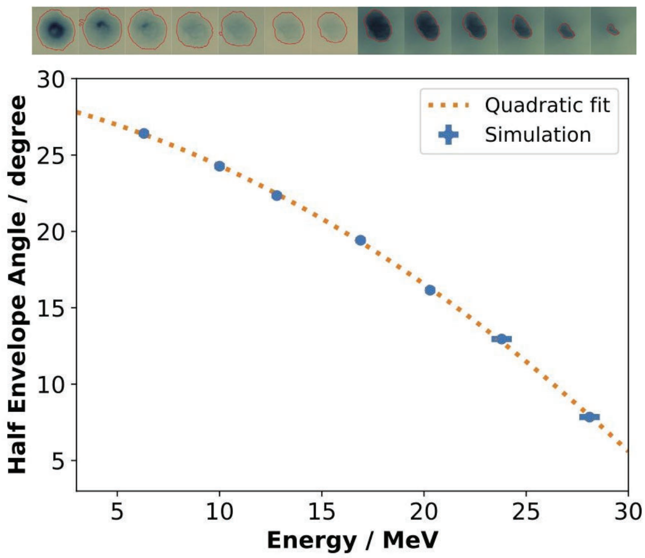


Figure 13: *The initial beam divergence reconstructed from measurements (top ribbon).*

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 $^{7}Li(\gamma,t)^{4}He$ 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 $^{7}Li(\gamma,t)^{4}He$ 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 $^{2}H(\alpha,\gamma)^{6}Li$ 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 $^{6}Li(\gamma,d)^{4}He$ reaction and other BBN-relevant reactions using one of the new configurations of the ELISSA array, and (c) calculate and update the $^{2}H(\alpha,\gamma)^{6}Li$ 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.

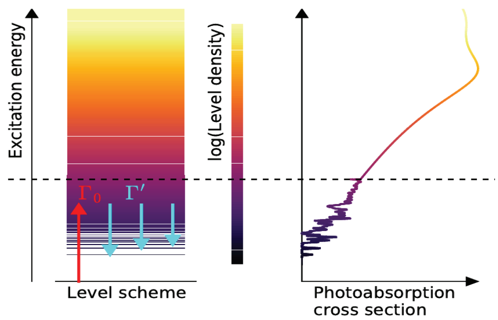


Figure 14: *Left: Exponentially increasing NLD with excitation energy. Right: Photoabsorption cross section which is directly linked to the PSF.*

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.

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.

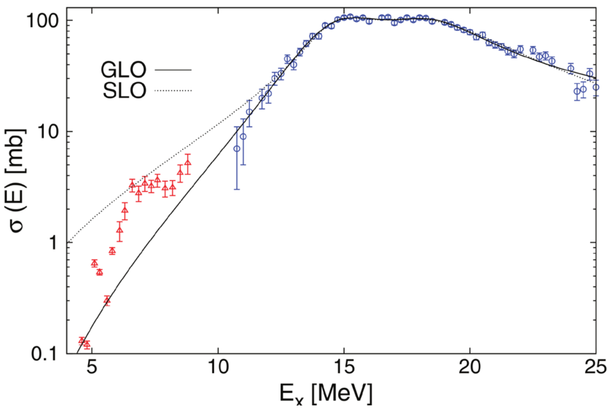


Figure 15: *(from [119]) (γ,γ') data from HIGS [119] (red) along with (γ,n) data from Saclay [194] (blue), both for ^{76}Se. (γ,n) data may need to be rescaled according to Ref. [177]. Depending on renormalization and choice of model for the GDR the amount of PDR excess near 7 MeV is highly uncertain.*

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.

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

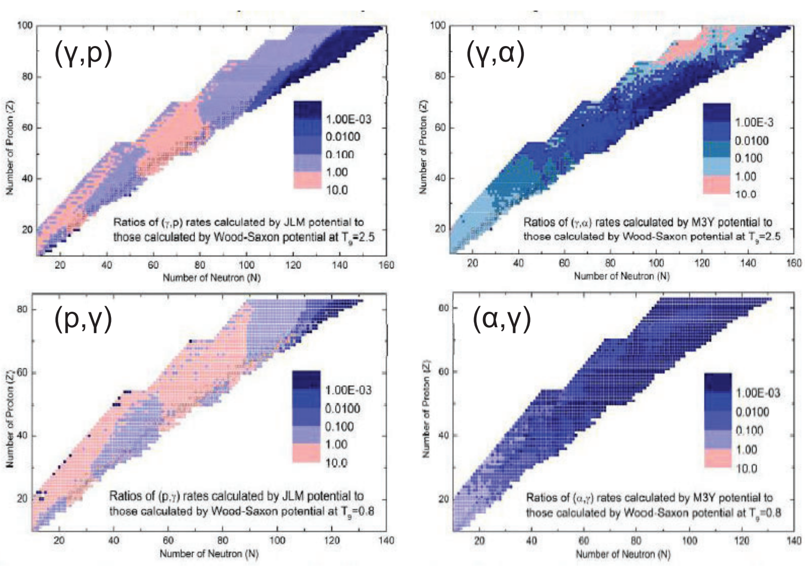


Figure 16: *Optical model reaction network calculation of the p-process nucleosynthesis [66].*

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.

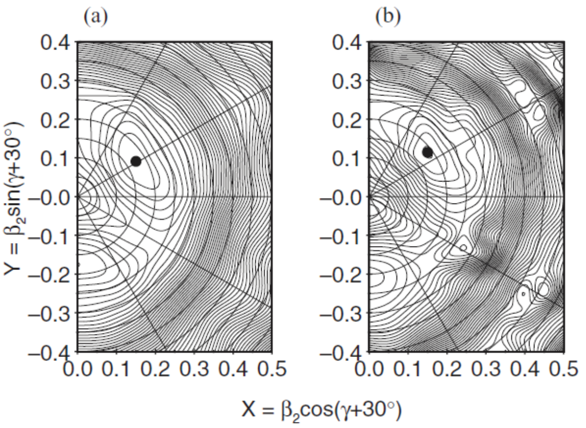


Figure 17: *Potential energy surfaces of the lowest-lying band structures in ^{106}Pd calculated within the tilted-axis cranking model [181].*

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

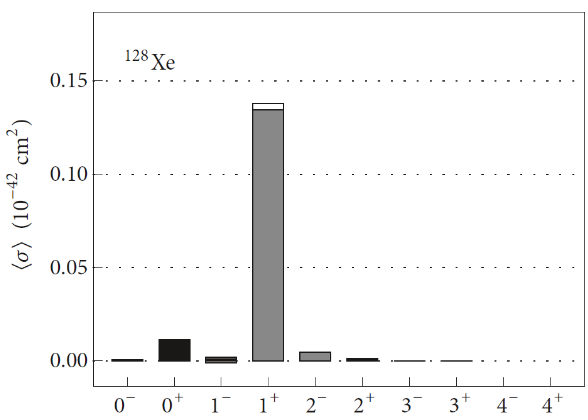


Figure 18: *(from [262]) Contributions of multipole channels J≤4 to the total averaged cross section for solar neutrinos off ^{128}Xe (black: vector, grey: axial-vector, open: interference) from QRPA calculations.*

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.

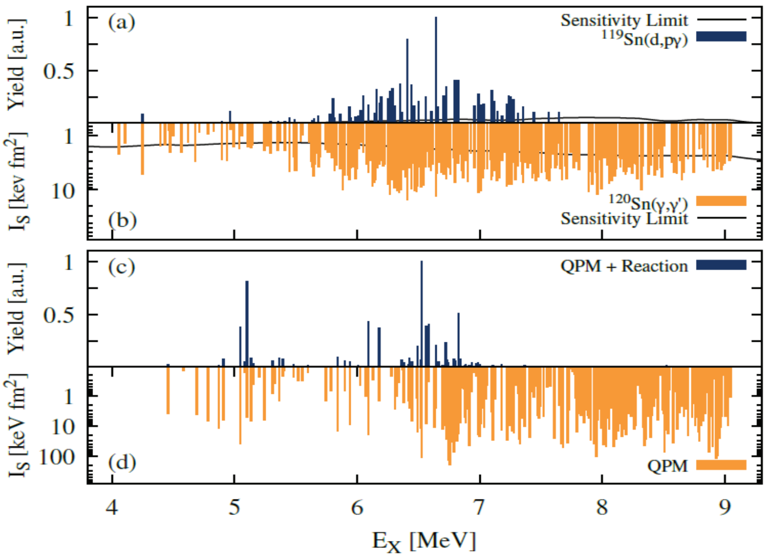


Figure 19: *(a) Relative γ-ray yields from ^{119}Sn(d,pγ), (b) energy-integrated cross sections IS for ^{120}Sn(γ,γ') [193]. All transitions shown in (a) were also observed in the NRF experiment. Sensitivity limits are based on a maximum error on the peak area of 30%. (c) Relative ^{119}Sn(d,pγ) yields 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.

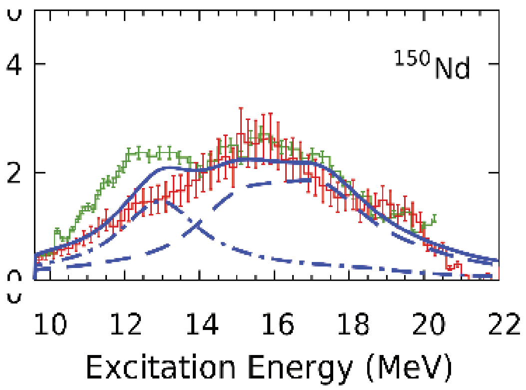


Figure 20: *Part of Figure 4 of [191]. Shown is the photoabsorption cross section deduced from the (gamma, xn) data (green) and the new measurement [191] shown in red.*

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 ΔK=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.

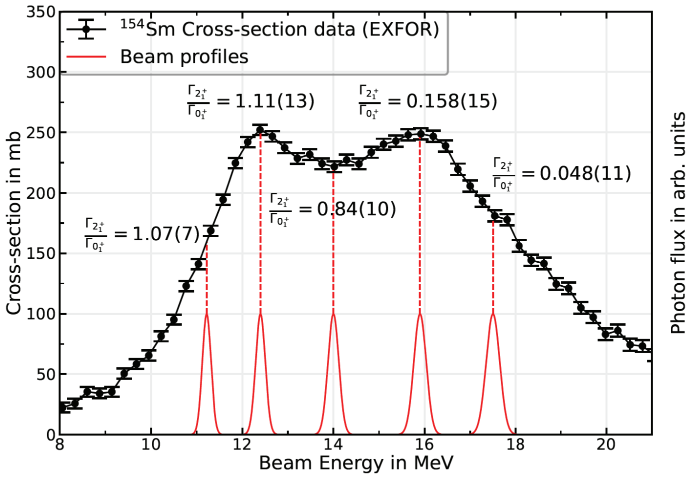


Figure 21: *Data on the gamma-decay of the GDR of the deformed nucleus ^{154}Sm taken recently by our group at the HIγS facility.*

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

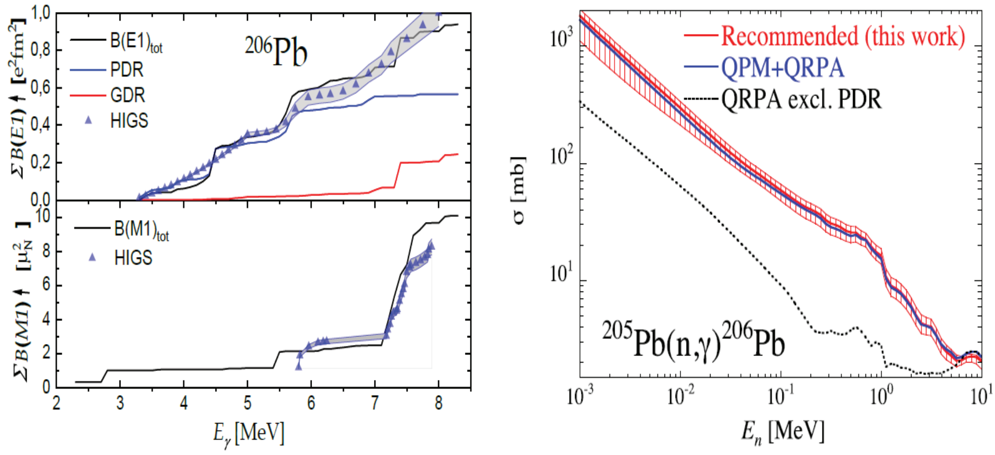


Figure 22: *Left: Cumulative B(E1) (top) and B(M1) (bottom) strength in ^{206}Pb obtained from integrating the corresponding distribution of E1 and M1 strength up to an energy $E_\gamma \leq S_{1n}$= 8.1 MeV. Right: Radiative capture cross section ^{205}Pb(n,γ)^{206}Pb using as input the experimental (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.

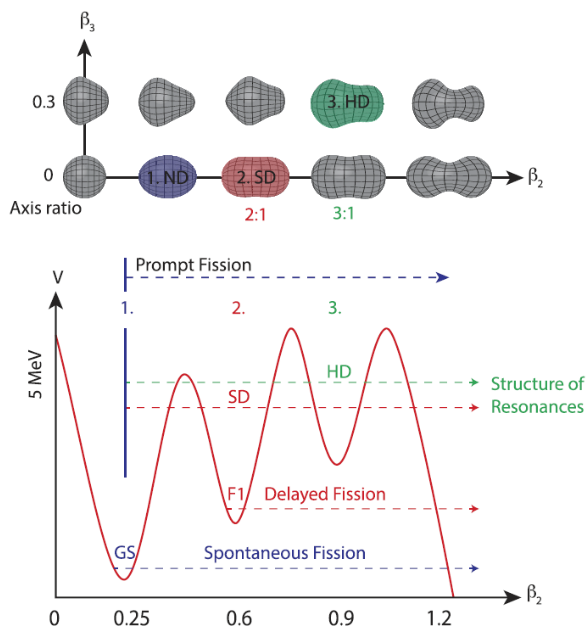


Figure 23: *Schematic description of the fission process and the appearance of transmission resonances. In the upper part of the figure the deformation and the shape of the nucleus is shown, and in the lower part, a two-dimensional plot of the potential barrier.*

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.

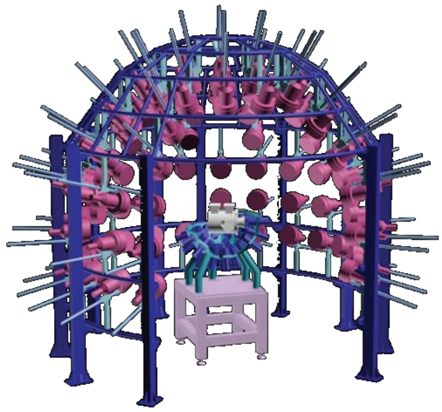


Figure 24: *CAD drawing of TU Darmstadt's segmented FGIC with ELIGANT-GN.*

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-

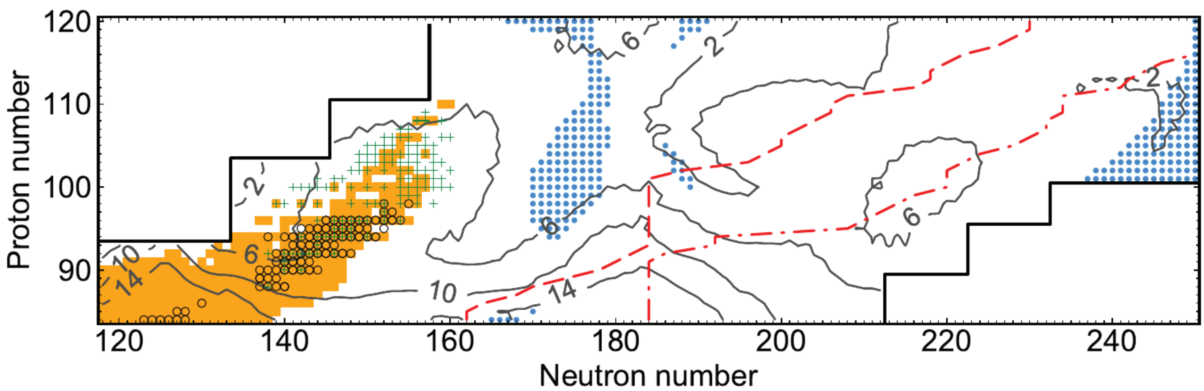


Figure 25: *Landscape of superheavy nuclei showing in orange squares those nuclei with known masses. Nuclei with experimentally measured fission barriers and spontaneous fission lifetimes are marked with open circles and crosses, respectively. Dashed and dot-dashed lines illustrate the location of the 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].

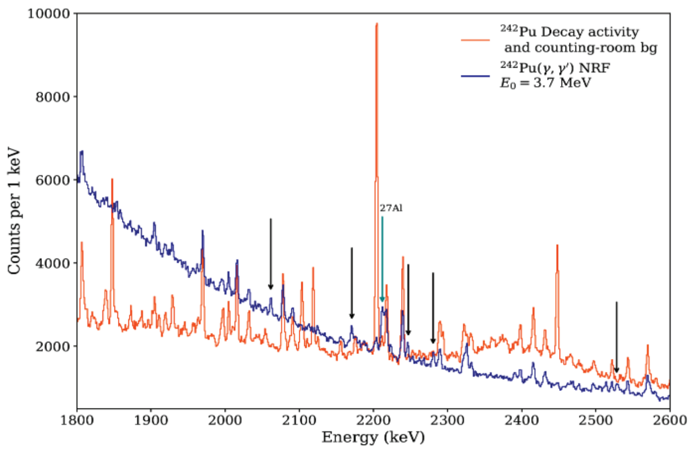


Figure 26: *First NRF measurement on a ^{242}Pu sample (blue), taken recently at the S-DALINAC at Darmstadt, and compared to an activity measurement of the sample (red). Black arrows indicate NRF lines.*

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.

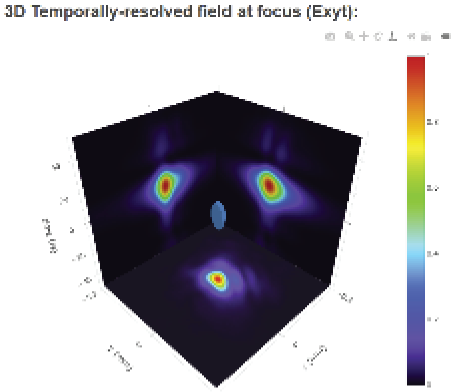


Figure 27: Reconstructed spatio-temporal structure of an ultrashort laser pulse.

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.

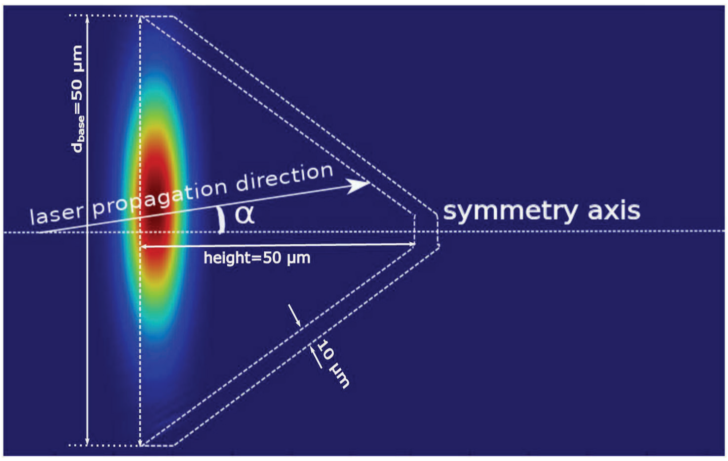


Figure 28: The cross section of the re-entrant cone is shown as dotted conical shape. The laser pulse comes in from the left. The laser pulse is squeezed to the increased intensity towards the narrower cone tip. This picture shows a setup of this scheme in PIC simulation.

The 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.

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].

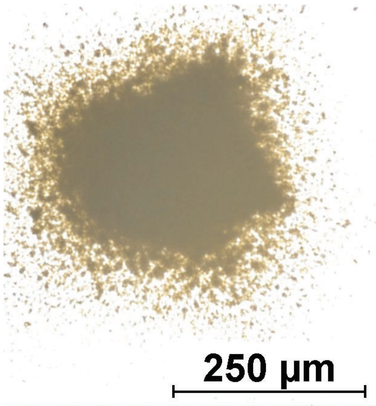


Figure 29: *Carbon foam deposited on a Si surface (courtesy of A. Măgureanu and V. Crăciun).*

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

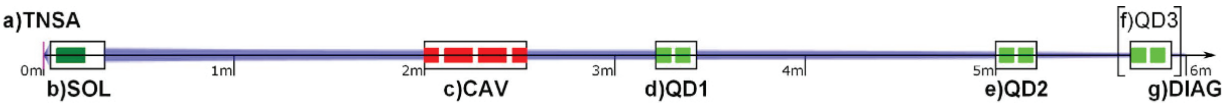


Figure 30: *Sketch of the LIGHT beamline at GSI consisting of a solenoid (SOL), a radio-frequency cavity (CAV), 2 quadrupoles (QD1 and QD2), and a diagnostics bench (from ref. [237]).*

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].

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].

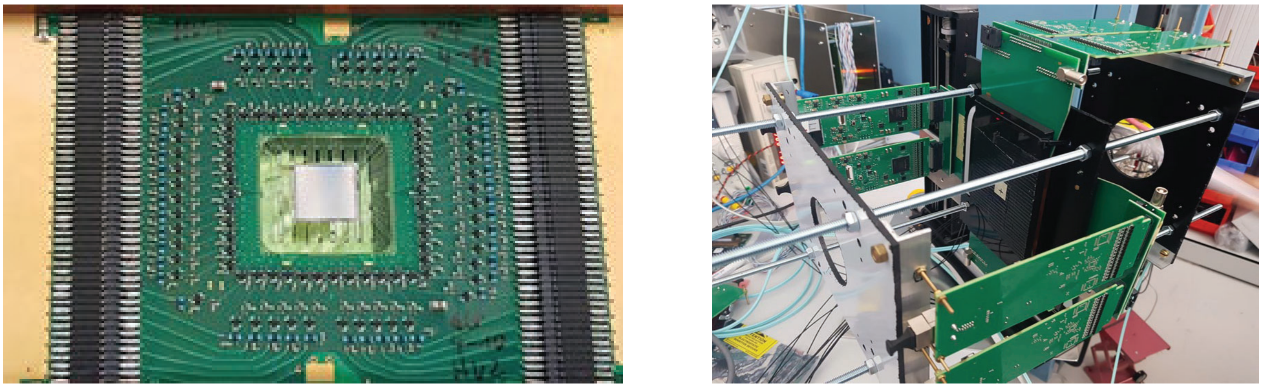


Figure 31: *(Left) Photo of the LGAD sensor mounted on a dedicated PCB equipped with 96 readout channels consisting of 2 stages of fast analog amplifiers. The LGAD prototype sensor has a form factor of 1cm x 1cm and has a single-sided segmented readout in the form of 86 strips with a $100\,\mu m$ pitch. 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.

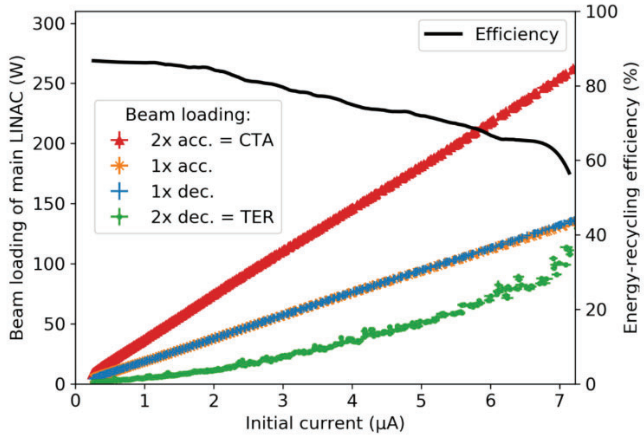


Figure 32: *Total beam loading of main accelerator and recycling efficiency for different initial beam currents.*

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.

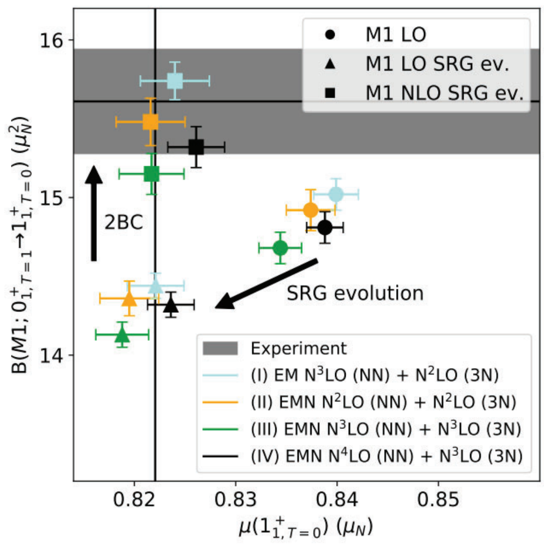


Figure 33: *Results for $B(M1; 0^+_{1,T=1} \rightarrow 1^+_{1,T=0})$ of ^{6}Li and theoretical calculations based on ab inito theory . The effect of the SRG and 2BC are shown. Taken from*

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.