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Authors

Arnold, Michaela

Brauch, Adrian

Dutine, Manuel

et al.

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Design study for an energy-efficient MeV-ranged photon-beam facility

Michaela Arnold^{1,a}, Adrian Brauch¹, Manuel Dutine¹, Joachim Enders¹, Ruben Grewe¹, Maximilian Herbert¹, Lars Jürgensen¹, Maximilian Meier¹, Norbert Pietralla^{1,b}, Kiriaki Prifti¹, Tim Ramaker¹, Felix Schliessmann¹, Dominic Schneider¹, Volker Werner¹, Mohammad W. Ahmed^{2,12}, Karsten Albe³, Lambert Alff³, Dimitar L. Balabanski⁴, Christopher P. J. Barty^{5,6}, Steve Benson⁷, Jonny Birkhan¹, Oliver Boine-Frankenheim^{8,9}, Herbert De Gersem⁸, Lisa B. Dingeldein¹, Calvin R. Howell^{10,12}, Johann Isaak¹, Robert V. F. Janssens^{11,12}, Stephan Kuschel¹, Catalin Matei⁴, Fatemeh Sadat Moujani Ghomi¹, Vincent Pruy¹, Markus Roth¹, Calin A. Ur⁴, Thomas Walther¹³, Peter H. Williams¹⁴, Ying K. Wu^{10,12}, and Andreas Zilges¹⁵

¹ Institute for Nuclear Physics, Technische Universität Darmstadt, Department of Physics, 64289 Darmstadt, Germany

² Department of Mathematics and Physics, North Carolina Central University, Durham, NC 27707, USA

³ Institute for Materials Science, Technische Universität Darmstadt, Department of Materials Science and Geoscience, 64287 Darmstadt, Germany

⁴ Extreme Light Infrastructure Nuclear Physics (ELI-NP), Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), 077125 Magurele, Romania

⁵ Department of Physics and Astronomy, University of California - Irvine, Irvine, CA 92697, USA

⁶ Lumitron Technologies, Irvine, CA 92617, USA

⁷ Benson Laser Consulting, LLC, Yorktown, VA 23690, USA

⁸ Institute for Accelerator Science and Electromagnetic Fields, Technische Universität Darmstadt, Department of Electrical Engineering and Information Technology, 64289 Darmstadt, Germany

⁹ GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

¹⁰ Department of Physics, Duke University, Durham, NC 27708, USA

¹¹ Department of Physics and Astronomy, The University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA

¹² Triangle Universities Nuclear Laboratory (TUNL), Durham, NC 27708, USA

¹³ Institute for Applied Physics, Technische Universität Darmstadt, Department of Physics, 64289 Darmstadt, Germany

¹⁴ STFC Daresbury Laboratory and Cockcroft Institute, Warrington WA4 4AD, UK

¹⁵ Institute for Nuclear Physics, Universität zu Köln, 50923 Cologne, Germany

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Abstract The efficient use of energy resources for scientific research is a challenging and timely topic, in particular for scientific fields that require particle accelerator facilities, such as particle or nuclear physics. Accelerator facilities capable of providing high electron beam currents with minimum emittance to ultra-relativistic energies are needed for the production of intense, MeV-ranged, quasi-monochromatic photon beams for photonuclear research and nuclear photonics applications. This contribution presents a design for such an electron accelerator which is capable of recycling most of the kinetic energy of the ultra-relativistic electrons by beam deceleration after a quasi destruction-free usage, thereby lowering significantly the electrical power consumption footprint of operating the accelerator without compromising beam delivery performance. We provide for the first time a technically quantitative design for a thrice-recirculating, superconducting energy-recovery LINAC (ERL) with individual beam transport focusing primarily on its use as a driver for a source of MeV-ranged photons from a laser-Compton backscattering (LCB) scheme. As a specific example, we choose an ERL design for maximum electron energy of 520 MeV at an electron current of up to 26 mA in continuous wave mode at 1.3 GHz. This allows for 0.79 mA average current in a pulsed mode at 39.4 MHz, providing unprecedented spectral densities on the order of $10^5 \gamma/(\text{eV s})$ on target for photon energies around 5 MeV with the aforementioned repetition rate. Our *Design* concept of an *Individually recirculating Compact ERL* (DICE) is discussed. Options for its scientific use are sketched.

^a e-mail: marnold@ikp.tu-darmstadt.de (corresponding author)

^b e-mail: pietralla@ikp.tu-darmstadt.de (corresponding author)

1 Introduction

Precise information on the properties of atomic nuclei, their structure, and reactions can impact many areas of science and applications. Examples are provided by the quest for understanding nuclear forces, by nuclear astrophysics, or detector technology for particle physics and many others. First of all, the nuclear many-body system is a fascinating research object by itself [1–3]. It represents the prime example for a strongly coupled, multi-component quantum system. It, thus, shows a variety of structures that originate in the competition between collective motion and single-particle features and its two-component character [4, 5]. In addition, the responses of nuclei to external disturbances need to be known precisely when it comes to the design of particle detectors [6]. The accurate interpretation of signals from sophisticated detectors for neutrinos, for instance, requires a detailed knowledge on weak interaction processes in nuclei of their detection material. Nuclear reaction rates can be decisive input for nuclear astrophysics research [7, 8], as well.

One approach to obtain precise information on nuclear quantum states is given by the study of their response to electromagnetic radiation. Photonuclear reactions, see Refs. [9, 10] and references therein, provide an enormous potential for precision studies of atomic nuclei and for a variety of applications. As photons have no rest mass, their impact on nuclei induces the smallest possible angular momentum transfer. Photons interact electromagnetically with the nucleus *at the photon point*, i.e., the photonuclear reaction process can be fully separated without any ambiguity from the—potentially unknown—nuclear structure properties that, in turn, can then be measured to highest accuracy. Most nuclear structures that feature a significant photoabsorption cross-section reside in a range from 0.5 MeV to about 20 MeV excitation energy in the giant resonance region. Linearly polarized photon beams offer the analysis of azimuthal angular distributions and carry precious information on parity quantum numbers. Narrow bandwidth of the photon beam facilitates the identification of decay channels, while high spectral density of the photon beam supports the counting statistics and, hence, the precision of the data.

Usage of energetic photons on nuclear energy scales has been limited, only, by the available photon sources, such as specific γ -radiation from the electromagnetic decay of nuclear excited states, bremsstrahlung from the interaction of electron beams with matter, or more recently the photons created by scattering of laser beams from ultra-relativistic particle beams, denoted as *laser-Compton backscattering* (LCB). The latter provides a quasi-monochromatic, energy-tunable, fully polarized γ -ray beam. In the LCB scheme, the strongest boost in photon energy is achieved in a 180° backscattering setup. It corresponds to final γ -ray energies of

$$E_\gamma = 4\bar{\gamma}^2 E_{\text{Laser}}. \quad (1)$$

Here, $\bar{\gamma} = E_e/m_e c^2 \gg 1$ is the relativistic factor of the colliding electrons with energy E_e , mass m_e and the speed of light c . $E_{\text{Laser}} = hc/\lambda$ is inversely proportional to the wavelength λ of the interaction laser in the laboratory frame, the Planck constant h is used. Corresponding facilities have been set up [11–13] and operated for years in various energy regimes. Indeed, the energy range of about 0.1–100 MeV is ideal for photonuclear research [9, 10, 14–16], provided that the beam's intensity is high enough. Opportunities for scientific research with monochromatic γ -ray beams resulting from LCB sources have been discussed recently during the *International Workshop on Next Generation γ -ray Source, 2016, USA* and published in Ref. [16] and in the technical design reports for the European Extreme Light Infrastructure-Nuclear Physics (ELI-NP) [17].

The brightest LCB beams require maximum luminosity for the collision between the laser and the ultra-relativistic particle beam along with the lowest possible energy spread of the latter. Such a scheme calls for a laser–electron collider with the intense ultra-relativistic beam being delivered by a linear accelerator (LINAC) for minimum emittance.

An energy-efficient operation of a high-energy, high-current LINAC requires a significant amount of energy recycling for economic and environmental reasons. This can be achieved by a superconducting multi-turn energy-recovery LINAC (ERL). By this accelerator layout, the externally provided radio-frequency (RF) power can be kept at a minimum while enabling high-beam currents at the same time. Recently, some of us have demonstrated efficient energy recycling in a superconducting multi-turn ERL for the first time [18]. Therefore, an LCB beam from a superconducting multi-turn ERL has been proposed as a 4th-generation γ -ray light source [10, 19, 20]. Such a system has not been realized so far. It is the purpose of the present article to provide a design study for a 4th-generation γ -ray light source. More degrees of freedom and, thus, an operational advantage are offered by separate return arcs. So a dual design of the LINAC is presented that allows for such an individual beam transport [21] before and after the laser–electron collision (see Fig. 39 in Ref. [16]). This approach improves the wall-plug efficiency of the γ -ray source while providing high intensities at enhanced operational stability; it will be referred to as *Design concept of an Individual-Recirculating Compact ERL (DICE)* for the remaining part of this manuscript. It is the purpose of this contribution to first present the associated design concept. Here, we provide the first quantitative design of a 4th-generation γ -ray light source based on the LCB process on an external laser with an *individual recirculation design* for the electrons whose energy is to be recovered.

The specifications of the considered facility are motivated by the envisioned experimental program as discussed elsewhere [16, 17] and expanded in Sect. 3. The ERL machine as driver on the one hand and a γ -ray beam on the other hand may well be suited for a number of additional applications that such a facility may serve. Some of these applications will be addressed in Sect. 3, as well. It is partly based on our previous scientific exploitation of photonuclear reactions with intense quasi-monochromatic MeV-ranged photon beams over the last 25 years [9, 10]. The main specifications for the MeV-ranged photon beams, that were chosen for the present design study, are:

- Quasi-monochromatic photon beam with a bandwidth of 2 % or less: This bandwidth is required for the intended research on nuclear level densities and gamma-ray strength functions in nuclear resonance fluorescence (NRF) (see Sect. 3.1.2). A recent experimental example which was only made possible by a special high-resolution mode of the HI γ S facility is given by our observation of systematical deviations from the Porter–Thomas distribution in ^{150}Nd [22]. Resolving the transition energies of γ -rays from nuclear states with excitation energies below the particle threshold, say $\approx 5\text{--}8$ MeV in heavy nuclei, to their ground states and their first excited state, which in deformed nuclei may typically lie as low as 100 keV, requires an energy resolution of 1–2 %.
- Energy of the photon beam between 1 MeV and 20 MeV: This γ -beam energy is required for the intended research on the nuclear isovector giant dipole resonance (IVGDR) (see Sect. 3.1.2 and Fig. 12). A recent experimental example from the HI γ S facility is given by our observation of Smekal–Raman Scattering off the isovector giant dipole resonance of ^{154}Sm [23]. Exciting the IVGDR, which in heavy nuclei occurs at energies between 10 and 20 MeV, requires a corresponding beam energy. For the sake of giving a concrete case, we have studied a design for a machine which provides a γ -beam energy of ≈ 15 MeV in LCB reactions on an ultraviolet laser beam. Higher beam energies are equally possible with small adjustments.
- Photon beam linear polarization of at least 99 %: Linear polarization of the γ -beam provides access to non-trivial azimuthal angular distributions of ejectiles. It is, for instance, indispensable for polarimetry at energies above ≈ 4 MeV, see, e.g., Ref. [14], or for studies of giant nuclear resonances and their internal decays to excited states, see e.g., Ref. [23].
- Photon flux of at least 10^5 $\gamma/(\text{eV s})$ on target: Nuclear self-absorption measurements, see, e.g., Sect. 3.1.1 or Ref. [24], provide model-independent precision data on nuclear excitations. The data-taking for Fig. 13 lasted for 3 weeks at a photon flux density of about 10^3 $\gamma/(\text{eV s})$. This was possible because the level width of the 0_1^+ state of ^6Li is 8 eV, which is exceptionally large. Nuclear excitations that are accessible by the NRF method typically exhibit level widths on the order of 0.1 eV. Precise data on this majority of nuclear states, similar to those shown in Fig. 13, require about two orders of magnitude higher spectral densities for being feasible in realistic beam times.
- In observance of Goal 12 of the United Nation’s “Sustainable Development Goals”, the power consumption of the facility should not be excessive. RF power consumption on the order of a few MW may be considered acceptable. For being specific, we require an overall power consumption of the facility on the order of 10 MW. This requirement can be achieved, only, in ERL mode if a large current is needed. A quantitative comparison of the estimated power consumption of the facility operating in conventional mode or ERL mode is provided in Sect. 1.2.

These justifications for the definition of the specifications of the design reflect our scientific preferences of the authors. They have motivated us to this work. More details are given in Sect. 3. A technical design report of a facility sketched below might be accompanied by a significantly extended description of the science cases. A comprehensive account of that is beyond the scope of this article and is not intended. Instead we have chosen to seriously study the viability of a performant multi-turn superconducting ERL as a driver for an LCB source which covers the specifications motivated above. For being concrete, we chose an electron beam energy with a relativistic gamma factor of 10^3 and a beam current of 0.79 mA (in LCB mode) to fulfill the specifications. For simplicity, we considered a commercially available system for the interaction laser, e.g., an infrared laser with a wavelength of 1030 nm. The facility’s LCB performance could be increased by optimizing the interaction laser. We refrained from this task in this article because we chose to focus on the electron accelerator’s design. The proposed layout of the machine parameters will allow for fulfillment of the specifications above and are given in subsequent sections along with an overview on the estimated power consumption of the facility and its power-saving potential when operating in ERL mode.

1.1 Overall layout of DICE

DICE is layed out as a superconducting, multi-turn, individually recirculating ERL with a racetrack-like design using multiple recirculation beamlines. The recirculating lattice will be built as a separate beam transport system (see Sect. 1.3) to allow for a maximum number of degrees of freedom during beam tuning. Its compact design together with the recycling of the electron beam’s energy using the same superconducting radio-frequency (SRF)

Table 1 Intended numerical values for the parameters of DICE

Parameter	Unit	Value
Electron injection energy (maximum)	MeV	10
Electron end energy (maximum)	MeV	520
Electron bunch charge (maximum)	pC	20
Electron average current (maximum, facility)	mA	26
Electron average current (maximum, in LCB mode)	mA	0.79
RF frequency	MHz	1300
Repetition rate (facility)	MHz	≤ 1300
Repetition rate (in LCB mode)	MHz	39.4
Electron normalized emittance	mm mrad	2
Electron RMS momentum spread at interaction point	%	< 0.7
Electron RMS bunch length at interaction point	mm	< 3

cavities in multiple passes allows building DICE on a comparatively small footprint and makes its operation cost-efficient and energy-efficient.

An extensive amount of beam parameters and design choices is possible; some of these will also address the cost optimization of the facility, e.g., number of recirculation beamlines versus the length of each SRF section. In this paper, only one possible design for DICE is given and discussed in detail. The presented design of DICE allows for electron beam energies of up to 520 MeV with an excellent beam quality and high average currents of up to 26 mA. We aim at a normalized emittance of 2 mm mrad, based on measurements at cERL [25] and according to our experiences. Intended numerical values for the parameters are listed in Table 1. The design of DICE offers a very flexible accelerator facility for delivering high-intensity photon and high-current electron beams to experiments. In addition to the LCB configuration, which is the main focus in this article, other options for beam delivery configurations are discussed in Sect. 3.3.

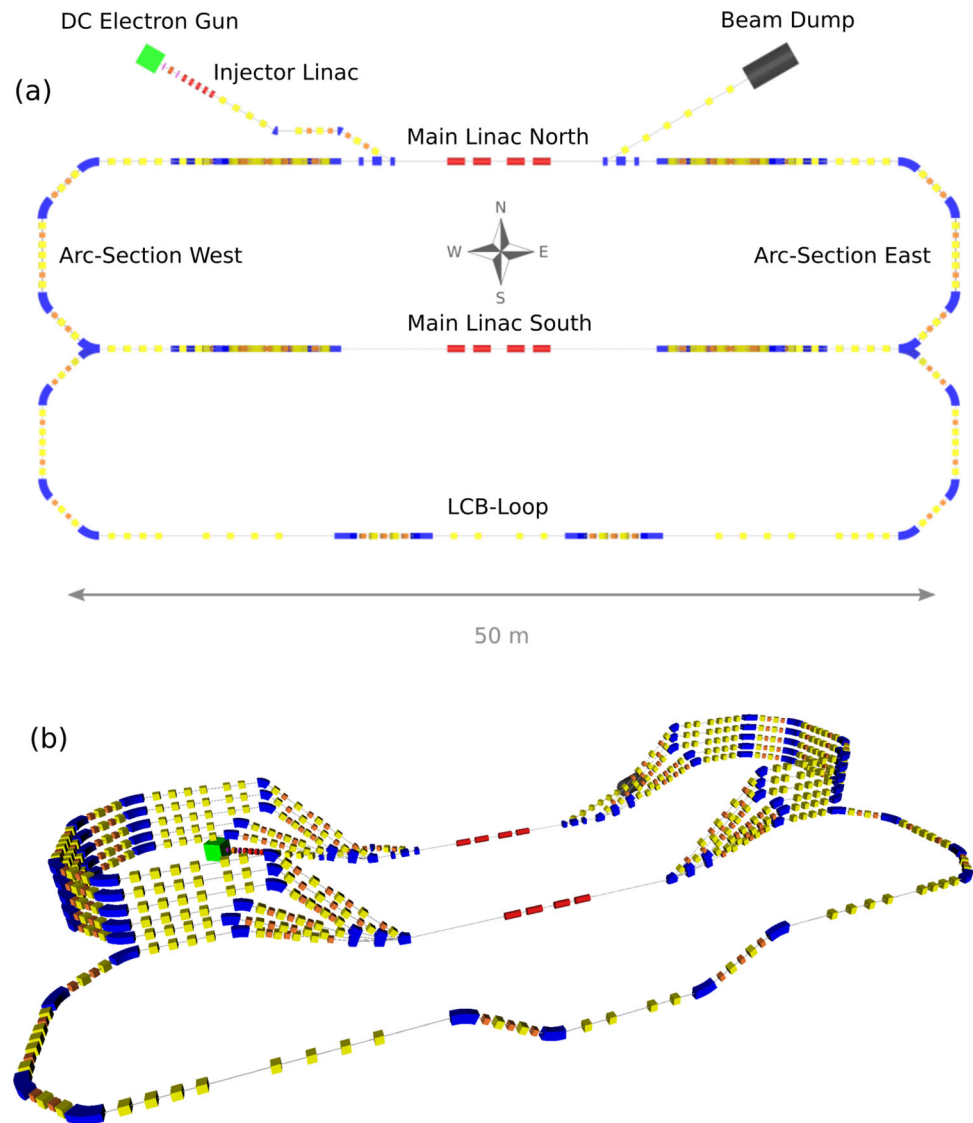
The proposed concept design is shown in Fig. 1. The beam is generated in a DC electron source (see Sect. 2.1). The injector section is accelerating the beam to a total energy of up to 10 MeV using an SRF booster. It contains five two-cell cavities, see Sect. 2.2. A magnetic chicane supports the achromatic merge into the recirculation beamlines. Each main accelerator section of this double-sided design can add up to 85 MeV energy gain, leading to up to 170 MeV energy gain per recirculation beamline (see Sects. 2.3 and 2.4). The beam is accelerated three full turns allowing for different operation schemes (see Sect. 2.5). Then the highest beam energy is extracted to the interaction loop (see Sect. 2.6). This loop contains the interaction point where the intended LCB reactions will take place and where the high-energy electron beam may be fed into further beamlines for conventional external beam usage of an electron accelerator without energy recycling; this option will not be further discussed in this article. The interaction loop is providing the phase shift needed for the ERL mode. Downstream of the interaction point, the beam is decelerated three-times down to injection energy and finally extracted to the beam dump. The presented concept intends that the first deceleration of the electrons will take place in the same LINAC section which had previously provided the beam's last acceleration. This feature ensures that the energies of the decelerated beam differ from the energies of the yet-to-be-accelerated beam in the corresponding recirculation arc. The electron beams with different energies will be guided in separate beamlines with their individual beam-guiding elements until, at injection energy, the beam is transferred to the beam dump. There, it could be used for parasitic experiments with bremsstrahlung or for photofission production of radioactive isotopes, instead of being simply dumped (not shown in Fig. 1, more details are provided in Sect. 3.2).

For a better orientation, the following nomenclature is used (see Fig. 1): The wind rose is defining the section of the machine. The energy of the beam in the subsequent arc (west or east) is added to distinguish between the different vertically stacked arcs. E.g., “E435” is corresponding to the east arc with the energy of 435 MeV. The two linear main accelerator sections are named “north” and “south”. A number is added to represent the number of pass through this section. E.g., “S3” means the third passage through the south main accelerator.

1.2 Energy-recovery LINAC

The ERL scheme represents a layout for the energy-efficient operation of a linear accelerator. In this operation mode, the electron bunches are guided back into the main accelerator downstream of an interaction point. During the preceding interaction, the bunches must not be disturbed significantly to guarantee a proper transport back to the superconducting cavities. The length of the path back to the main accelerator is set in a way that the electron bunches re-enter the main accelerator with a phase shift of approx. 180° in comparison to the accelerating

Fig. 1 Concept design of DICE. The shown configuration supports LCB experiments while operating in ERL mode. **a** Top view of DICE with an overview of the different sections. **b** The perspective view displays the vertically stacking of the different recirculation beamlines



field. The exact phase difference is given by longitudinal beam-dynamics simulations. During the deceleration, the electrons' kinetic energy is fed back to the RF field in the cavities and is used for the acceleration of subsequent electron bunches. Thus, there is nearly no externally provided RF power needed to maintain the RF field in the cavities during acceleration. Only the RF power needs for the injector accelerator as well as the compensation of losses in the main accelerator system have to be provided externally.

The ERL technology enables the beam current to be increased with having nearly no additional external RF power needs. Our design study of an accelerator best suited for nuclear photonics applications utilizes the ERL technology and builds on our recent experiences with it [18, 26]. Further challenging projects, such as the LHeC considered for establishment at CERN [27], also require an ERL for the energy-efficient generation of the needed electron beam.

The ERL concept was first formulated in 1965 by Maury Tigner [28]. The first normal-conducting ERL was operated at Chalk River Nuclear Laboratories in 1975 [29]. In 1986, the first SRF ERL was operated at Stanford [30]. Both have been single-turn ERLs. The first multi-turn ERL, although normal-conducting and, hence, incapable of efficient energy-recycling, was set into operation in Novosibirsk in 2008 (two-turn) and 2013 (four-turn) [31–33], called NovoFEL. The first and so far only ERL that operated with a beam power of above 1MW was the JLAB FEL [34]. Up to this point, there was no multi-turn SRF ERL operation. However, superconductivity is mandatory for efficient energy-recycling and hence for energy-efficient operation of future projects with high-power beams.

In 2019, the first multi-turn SRF ERL operation was demonstrated: CBETA at Cornell University operated in a four-turn configuration [35]. As the beam current on which CBETA was operated at that time was too low, no

Table 2 Power-consumption estimate of the DICE facility operating in conventional mode or ERL mode. It is based on a conservative extrapolation from the operation of the S-DALINAC [36] and available data of similar components. Uncertainties are estimated for the dominating consumers, only. The savings have been calculated on the unrounded values

Item	Unit	Values for 0.79 mA		Values for 26 mA	
		non-ERL	ERL (99 %)	non-ERL	ERL (99 %)
Solid-state amplifier RF system	MW	3.2(3)	0.09	105(10)	2.9(3)
Electromagnets (DC)	MW	13(3)	13(3)	13(3)	13(3)
Cryoplant, 4 K operation	MW	0.3	0.3	0.3	0.3
Infrastructure	MW	0.5	0.5	0.5	0.5
Vacuum pumps	MW	0.2	0.2	0.2	0.2
Gun and laser systems	MW	0.03	0.03	0.03	0.03
Total power consumption	MW	18(3)	14(3)	120(10)	17(3)
Saving due to ERL operation	%		18		86

energy-recycling could be demonstrated. In 2021, some of us demonstrated the first performant multi-turn SRF ERL operation with beam currents of up to 7 μ A and energy-recycling efficiencies of up to 87 % at the S-DALINAC [18], the superconducting electron linear accelerator at TU Darmstadt [36]. Further details on the development of ERLs can be found in Ref. [37]. A review article is highlighting the positive aspects of this technology as well as the current and future R&D projects [38].

To emphasize the economical potential of an ERL, Table 2 provides estimates for the power consumption of the full facility discussed in this article. Our estimate is based on our experience with the operation of the S-DALINAC [36] and available data for components as those intended for DICE. Two scenarios are compared: a moderate-beam power scenario with a beam current of 0.79 mA and a beam power of 0.4 MW, and a high-beam power scenario with a beam current of 26 mA and a beam power of 13.5 MW. At moderate-beam power, the beamline magnets are dominating the power consumption although the RF system consumes already about 19 % of the total power if the beam's kinetic energy is not recovered. For the high-power scenario, the RF system dominates the power consumption. ERL operation can now reduce the facility's power footprint by more than 80 %. An ERL efficiency of 99 % is taken into account for this estimate. In addition, we have considered Nb₃Sn-coated copper cavities for a future machine. Thus, the operational temperature of the SRF system of DICE was intended to be 4 K instead of about 2 K, which is standard for the operation of niobium cavities. This increase of the operational temperature of the cryoplant will lead to a grid power reduction factor of three as compared to current-day technology, see, for example Ref. [39]. However, even if a four-times larger power consumption of the cryoplant would have been taken into account, it would have not significantly changed the result. Future colliders, e.g., the one envisioned for the LHeC at CERN [40, 41], intend beam powers of the order of 1 GW. Beam powers of that size in a LINAC must utilize ERL technology for obvious economical reasons.

1.3 Separate beam transport

ERLs are desirable due to their potential for high-quality beams at moderate power consumption. Their efficiency can be further increased by employing a multi-turn concept. In this way, a LINAC can be passed multiple times to achieve higher electron energies. For a multi-turn ERL layout, there are two beam transport options: accelerated and decelerated beams of the same energy can be either transported commonly or separately [16, 42].

At all three existing multi-turn ERLs (NovoFEL, CBETA and S-DALINAC), common beam transport is used and significant particle losses were experienced [18, 33, 35]; the latter is a consequence of coupled beam tuning and the challenge of adjusting and tuning of the magnetic system. This problem can be overcome by using separate beam transport. Here, accelerated and decelerated beams can be individually tuned, which allows for an individual setting of (1) the transverse confinement, (2) the longitudinal dispersion, and (3) the slope of the RF crest (raising or falling) per beamline that connects a LINAC exit with a LINAC entrance. To benefit from this tuning options, DICE is designed to utilize separate beam transport. As a consequence, the main acceleration requires the LINAC to be split into two sections, with the option to bypass one of the LINAC sections after maximum acceleration [42], which results in a racetrack layout as shown in Fig. 1.

2 Facility design

2.1 Electron source

Some of the most performance-defining parameters of an accelerator, such as beam current and emittance, are set by the particle source. It is, therefore, of great importance to carefully choose the design of the source when designing a particle accelerator.

The proposed parameters of DICE (see Table 1) require an electron source capable of providing a pulsed low-emittance, high-current beam. DC photo-electron guns are capable of fulfilling these requirements and have already been established as reliable sources for ERL applications [43–45]. An advantage of their design is the capability of operating any type of photocathode, providing the choice of using either robust cathodes, e.g., CsK₂Sb (multi-alkali), for unpolarized beams or strained-lattice GaAs cathodes for polarized beams.

The up to now most successful DC photo-gun design was developed at JLAB [46] and has been implemented at Cornell University and BNL, reaching record-high-beam currents of up to 60mA for CsK₂Sb and up to 52mA for GaAs photocathodes [44, 47, 48]. While this design requires an external SF₆ tank to suppress corona discharges, it has been adapted to implement a compact inverted-insulator geometry (IIG) in order to discard the bulky SF₆ tank [49].

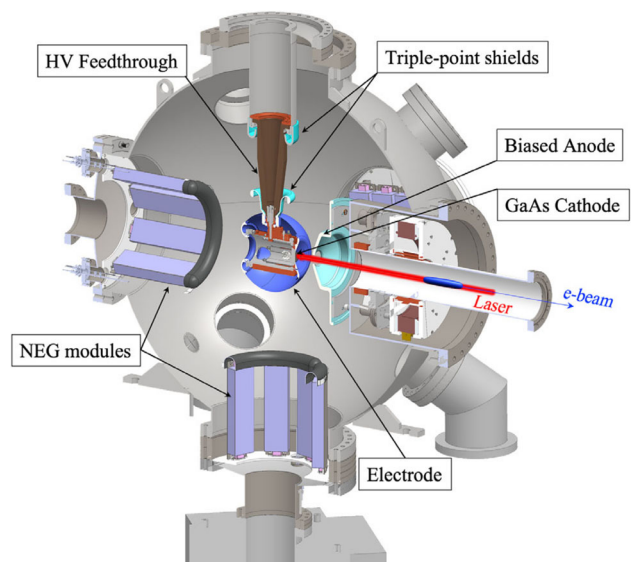
Polarized electrons are not required for the operation of a laser-Compton backscattering source at DICE. Thus, we propose an IIG DC photo-gun design based on the JLAB IIG design to be operated with multi-alkali photocathodes (e.g., CsK₂Sb), in order to reach emittances < 1mmrad for the desired beam current and repetition rate. Recently, further optimization has been conducted at JLAB to improve the performance of the IIG design [50]. Successful gun commissioning and operation has also been conducted at BNL to meet the requirements of the electron-ion-collider (EIC) project [51]. Hence, the proposed design is already mature and will be able to meet our requirements. A cross-sectional view of the BNL IIG design is shown in Fig. 2.

Multi-alkali photocathodes, in particular CsK₂Sb, are usually operated at laser wavelengths in the range of 500 to 550 nm. For DICE, we propose a laser system capable of providing enough power to sustain prolonged photocathode operation in this wavelength region with a repetition rate of 1.3GHz. Such a system has been conceived and successfully tested for the proposed ERL injector prototype at Cornell University [44], providing 800fs pulses with average power of 65W at a repetition rate of 1.3GHz and a wavelength of 520nm [52]. Since this laser system generates 520nm light by frequency-doubling of a 1040nm laser beam, it provides the opportunity of simultaneous use for both the photo-electron source and the LCB source (see Sect. 2.6) of DICE. Using a beamsplitter, both applications can be supplied by the same laser system, hence enabling direct synchronization between gun, accelerator, and LCB source.

Future applications of polarized beams at DICE can be implemented by adding an additional laser system with a wavelength of 780nm for use with GaAs photocathodes. Part of us have recently investigated different procedures for increasing GaAs photocathode durability for high-current applications [53].

For photocathode preparation, we propose a setup placed in a separate laboratory with photocathode transfer to the gun by means of a transport chamber. This will allow the preparation of photocathodes independent of beam time at the accelerator, hence greatly reducing the maintenance time required for inserting a new photocathode

Fig. 2 Cross-sectional view of the IIG photo-gun design of the EIC project at BNL. The spherical vacuum chamber has a diameter of approx. 80 cm. Figure taken from Ref. [51] under license CC BY 4.0



into the gun. Alternatively, a local activation setup could be operated in parallel with gun operations if the process can be controlled remotely and at least partially automatized. The latter has been demonstrated recently for NEA GaAs cathodes [54].

2.2 Injector section

The injector section of DICE will be designed to provide a high-intensity beam while preserving the normalized emittance created by the DC photo-electron gun. It will feature solenoids and a normal-conducting buncher downstream of the gun, followed by a superconducting booster LINAC containing five two-cell cavities. The DICE injector shall provide a kinetic energy of 9.5 MeV and the option to generate a correlation between energy and longitudinal position along the bunch, called chirp. The value for the kinetic energy from the injector is chosen to reduce space-charge effects and phase slippage in the next accelerating cavities as well as for serving NRF experiments [10] alternatively to finally dumping the decelerated and ejected beam in a beam dump. In this way, NRF experiments can be operated with the decelerated ERL beam parasitically while serving the LCB experiment at maximum energy at the same time (see also Sect. 3.3.3). The weaker space-charge effects resulting from the acceleration process allow for a larger distance between the exit of the booster LINAC and the entrance of the first main LINAC, especially for a larger distance between the dipole magnets of the injection achromat that is necessary to merge the injector beamline with the high-energy beamlines. Hence, several quadrupole magnets and several sextupole magnets are intended to ensure first- and second-order achromaticity as well as an arbitrary first- and second-order longitudinal dispersion. This requires at least three dipole magnets, three quadrupole magnets, and three sextupole magnets in a special arrangement [55]. This longitudinal dispersion in combination with a possible chirp allows for sufficiently complex manipulation of the longitudinal phase space. As further discussed in Sect. 2.4, higher-order dispersion shall be explicitly taken into account in the design of DICE. The layout of the DICE injector section is shown in Fig. 3.

The longitudinal simulations of the recirculating lattice (see Sect. 2.5) define the beam parameters that the injector section must provide at its endpoint (see Table 3). The Cornell University ERL injector prototype (CEIP) has proven to be suitable [47], and is thus adapted for DICE. A simulation and optimization of the CEIP for 20 pC bunch charge and the respective initial parameters at the starting point of the simulation reported in Ref. [57] was performed with the goal to meet the required parameters for the further transport within the recirculation beamlines. The gun voltage was set to 398 kV for these simulations. The simulation was performed using ASTRA [58] and the layout of the lattice as well as the field maps were generously provided by Adam Bartnik (Cornell University) [59]. The lattice was tuned manually, and similar behaviors for the normalized mean emittance ϵ_n and

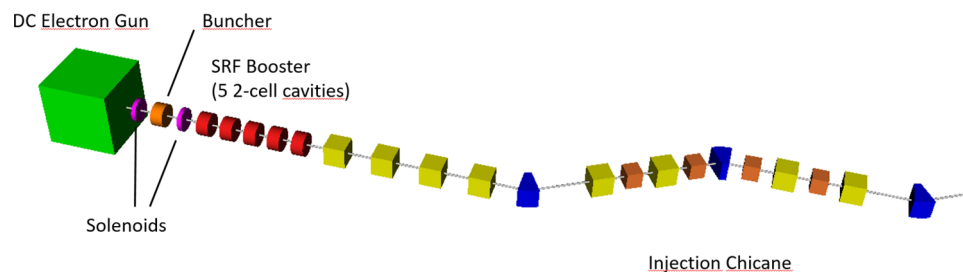


Fig. 3 Perspective view of the injector of DICE. The beam is extracted from the DC electron gun (green), prepared by solenoids (magenta) and a buncher cavity (orange, cylinder) for the acceleration in the booster's cavities (red). Downstream of this first acceleration, quadrupole magnets (yellow), dipole magnets (blue), and sextupole magnets (orange, cuboid) ensure a proper transport into the main accelerator

Table 3 Comparison between the simulated beam parameters after the booster LINAC and the required specifications for DICE. The specifications at the end of the injector beamline are based on Ref. [56], see also Sect. 2.5. All parameters given by σ refer to the standard deviation

Beam parameter	Unit	After booster	Required for DICE
Bunch charge	pC	20	20
Norm. horizontal emittance	mm mrad	0.24	0.8
Norm. vertical emittance	mm mrad	0.24	0.5
Norm. mean emittance ϵ_n	mm mrad	0.24	0.65
Bunch length σ_t	ps	5.27	6.7
Injection energy	MeV	10.26	9.5
Energy spread $\sigma_{\delta, \text{energy}}$	%	0.13	0.15

relative kinetic energy spread $\sigma_{\delta, \text{energy}}$ were achieved at the end of the injector section as in Ref. [47]. Table 3 shows a detailed comparison between the required beam parameters and the achieved beam parameters. The CEIP adaption surpasses the required specifications and can therefore be used for DICE.

2.3 Main LINAC sections

The maximum total energy set for the present design study is 520 MeV. Each main LINAC shall be passed three times for acceleration: while an increased number of main LINAC passes is more cost-effective, technical limits constrain the maximum number of passes with regard to beam break-up (BBU). Consequently, a main LINAC must provide an energy gain of 85 MeV per pass. This can be achieved by using four nine-cell 1.3 GHz TESLA-type cavities [60] per main LINAC, hence the energy gain per cavity pass is 21.25 MeV, corresponding to a gradient of approx. 20.5 MV/m. Depending on the further design of DICE and the state of the art in the field, an adaptation of the gradient may be in order. The energy gain per LINAC pass will be kept constant, resulting in a modified number of cavities per LINAC section. The design total energies of the electrons outside of the two main LINAC sections are 10, 95, 180, 265, 350, 435, and 520 MeV, respectively. For merging the injection beamline and splitting the fully decelerated beam toward the beam dump, achromatic magnetic chicanes are installed in the straight section of the northern main LINAC.

2.4 Recirculation beamlines

After each pass of a main LINAC section (either for acceleration or for deceleration), the beam leaves the corresponding LINAC section with a different centroid energy. Due to the necessity of beam bendings for recirculation and the use of static magnetic fields, the beams overlapping in the main LINAC sections are inevitably split toward different trajectories. Here, the goal is to split the beams in such a way that small beam envelopes and transverse dispersion terms result.

Since separate beam transport is used, the number of beamlines is higher compared to common transport for the same number of main LINAC passes: When using separate beam transport, recirculating beamlines for intermediate energies not existing in common beam transport are necessary on each side of the main LINACs. Hence, more beamlines need to be split and merged. Consequently, quadrupole and sextupole magnets that are necessary for focusing and dispersion manipulation can only be installed close to the splitter magnet to a limited extent depending on the beampipe diameter, the device widths, and the degree of spreading by the splitter magnets. Thus, larger absolute values of the transverse dispersion result compared to common beam transport with the same number of main LINAC passes. We have considered identical quadrupole magnets as well as sextupole magnets in this concept study for simplicity. For the final design of DICE, energy-dependent quadrupole magnets as well as sextupole magnets might be used. They can be optimized for size and therefore placed closer to the splitter magnets if desired. This would allow for even smaller maximum absolute values of the transverse dispersion. The current design of a splitter/merger section for DICE is shown in Fig. 4.

The longitudinal dispersion cannot be tuned in the vertical splitter or merger sections, respectively, when no intermediate dipole magnets are installed with quadrupole and sextupole magnets in front of them and behind it [55]. However, a certain longitudinal dispersion inevitably results in the splitter and the merger sections as well as in the injector chicane and the dump chicane (which are achromatic but not isochronic). Tuning of the longitudinal dispersion that acts along a recirculation beamline which connects the exit of one main LINAC with the entrance of the other main LINAC is realized in the corresponding horizontal-180°-bending section (see Fig. 5, tracked with the software *legant* [61]): The first- (R_{i6}) and second-order (T_{j66}) longitudinal dispersions acting from s_1 to s_2 are given by Ref. [62]¹

$$R_{56, s_1 \rightarrow s_2} = \int_{s_1}^{s_2} \left(\frac{R_{16, s_1 \rightarrow s}}{\rho_{0,H}(s)} + \frac{R_{36, s_1 \rightarrow s}}{\rho_{0,V}(s)} \right) ds \quad (2)$$

and

$$T_{566, s_1 \rightarrow s_2} = \int_{s_1}^{s_2} \left(\frac{R_{26, s_1 \rightarrow s}^2}{2} + \frac{T_{166, s_1 \rightarrow s}}{\rho_{0,H}(s)} + \frac{R_{46, s_1 \rightarrow s}^2}{2} + \frac{T_{366, s_1 \rightarrow s}}{\rho_{0,V}(s)} \right) ds, \quad (3)$$

if there is no coupling of the horizontal and the vertical phase space. This is realized, in particular, if a single achromat only causes exclusively horizontal or exclusively vertical bending of the design trajectory. Here, $\rho_{0,H} \in$

¹Equations (2) and (3) have the opposite sign compared to the equations given in Ref. [62] since a different definition of the longitudinal coordinate is used in that work.

Fig. 4 Side view of a splitter/merger section designed for DICE. Dipole magnets are depicted in blue, quadrupole magnets in yellow, and sextupole magnets in orange

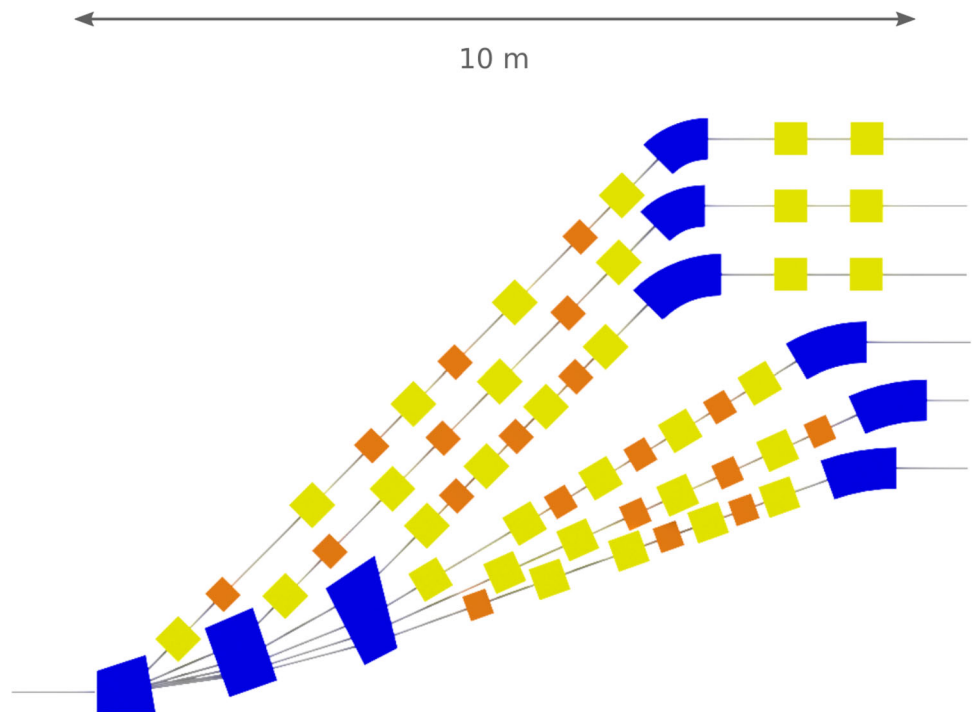
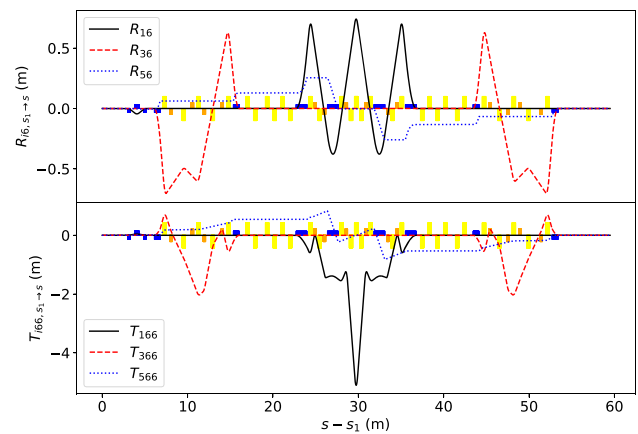


Fig. 5 Dispersion values along the first draft of the recirculation beamline “east 95 MeV” (E95), starting at the exit of the last cavity of the northern main LINAC (s_1) and ending at the entrance of the first cavity of the southern main LINAC (s_2), that is, $s_1 \rightarrow s_2 = \text{E95}$. Here, the isochronous case $R_{56, \text{E95}} = T_{566, \text{E95}} = 0$ is shown



$\overline{\mathbb{R}} := \mathbb{R} \cup \{+\infty, -\infty\}$ indicates the horizontal design bending radius and $\rho_{0,v} \in \overline{\mathbb{R}}$ indicates the vertical design bending radius with $1/\rho_0 = 0$ if $|\rho_0| = \infty$.

Tuning of arrival times at the main LINACs and thus choosing of the RF slope (raising or falling) is conducted by path-length adjustments per recirculation beamline. Here, the path-length adjustment system is either implemented along the horizontal 180° -bending section (dispersion preserving) or only over the last 90° -bending section. The latter requires retuning of the quadrupole and sextupole magnets located between the two 45° -dipole magnets in case of a path-length adjustment.

Depending on the ratio of the RF frequency and the bunch repetition rate, it may be useful to achieve a certain bunch filling pattern in order to suppress BBU [63]. If it is decided to implement a certain bunch filling pattern, this can be achieved by adjusting the dispersion-free sections downstream of the splitter magnets and the dispersion-free sections upstream of the merger magnets equally, i.e., lengthening or shortening them by a corresponding multiple of the RF wavelength. However, the chosen section lengths and thus the chosen bunch filling pattern will then be constant—in contrast to the path-length adjustments for tuning of arrival times as mentioned above.

Table 4 Parameters of the simulations. All four cavities of a main LINAC have been set identically; hence, there is only one degree of freedom per main LINAC, which is the off-crest phase ϕ

Degree of freedom	Unit	Mode A	Mode B	Mode C
ϕ_{N1}	°	1.4	7.4	7.4
ϕ_{S1}	°	1.0	19.9	19.9
$R_{56,\text{injection}}$	m	0	0	0
$R_{56,E95}$	m	0	0.13	0.13
$R_{56,W95}$	m	0	− 0.13	− 0.13
$R_{56,E180}$	m	0	− 0.06	− 0.06
$R_{56,W180}$	m	0	0.06	0.06
$R_{56,E265}$	m	0	0.06	0.06
$R_{56,W265}$	m	0	− 0.06	− 0.06
$R_{56,E350}$	m	0	− 0.21	− 0.21
$R_{56,W350}$	m	0	0.21	0.21
$R_{56,E435}$	m	0	0.27	0.27
$R_{56,W435}$	m	0	− 0.27	− 0.27
$R_{56,E520}$	m	0	0	0.31
$R_{56,W520}$	m	0	0	− 0.31
$T_{566,\text{injection}}$	m	0	0	0
$T_{566,E95}$	m	0	0.41	0.41
$T_{566,W95}$	m	0	− 0.40	− 0.40
$T_{566,E180}$	m	0	− 0.01	− 0.01
$T_{566,W180}$	m	0	0.01	0.01
$T_{566,E265}$	m	0	− 1.00	− 1.00
$T_{566,W265}$	m	0	1.00	1.00
$T_{566,E350}$	m	0	− 0.17	− 0.17
$T_{566,W350}$	m	0	0.17	0.17
$T_{566,E435}$	m	0	3.64	3.64
$T_{566,W435}$	m	0	− 3.64	− 3.64
$T_{566,E520}$	m	0	0	0.01
$T_{566,W520}$	m	0	0	− 0.01

2.5 Operation modes

Three operation modes are contemplated for DICE to be prepared for the requirements of possible future experiments:

- Mode A: isochronous and quasi on-crest.
- Mode B: non-isochronous and off-crest, optimized for minimum momentum spread at the LCB interaction point.
- Mode C: non-isochronous and off-crest, optimized for minimum bunch length at the LCB interaction point.

The main parameters of the machine settings are provided in Table 4 for all three operation modes considered. For these simulations, we neglected collective effects and instabilities, such as space-charge, coherent synchrotron radiation, and BBU. These effects will be taken into account for the simulation of the final design.

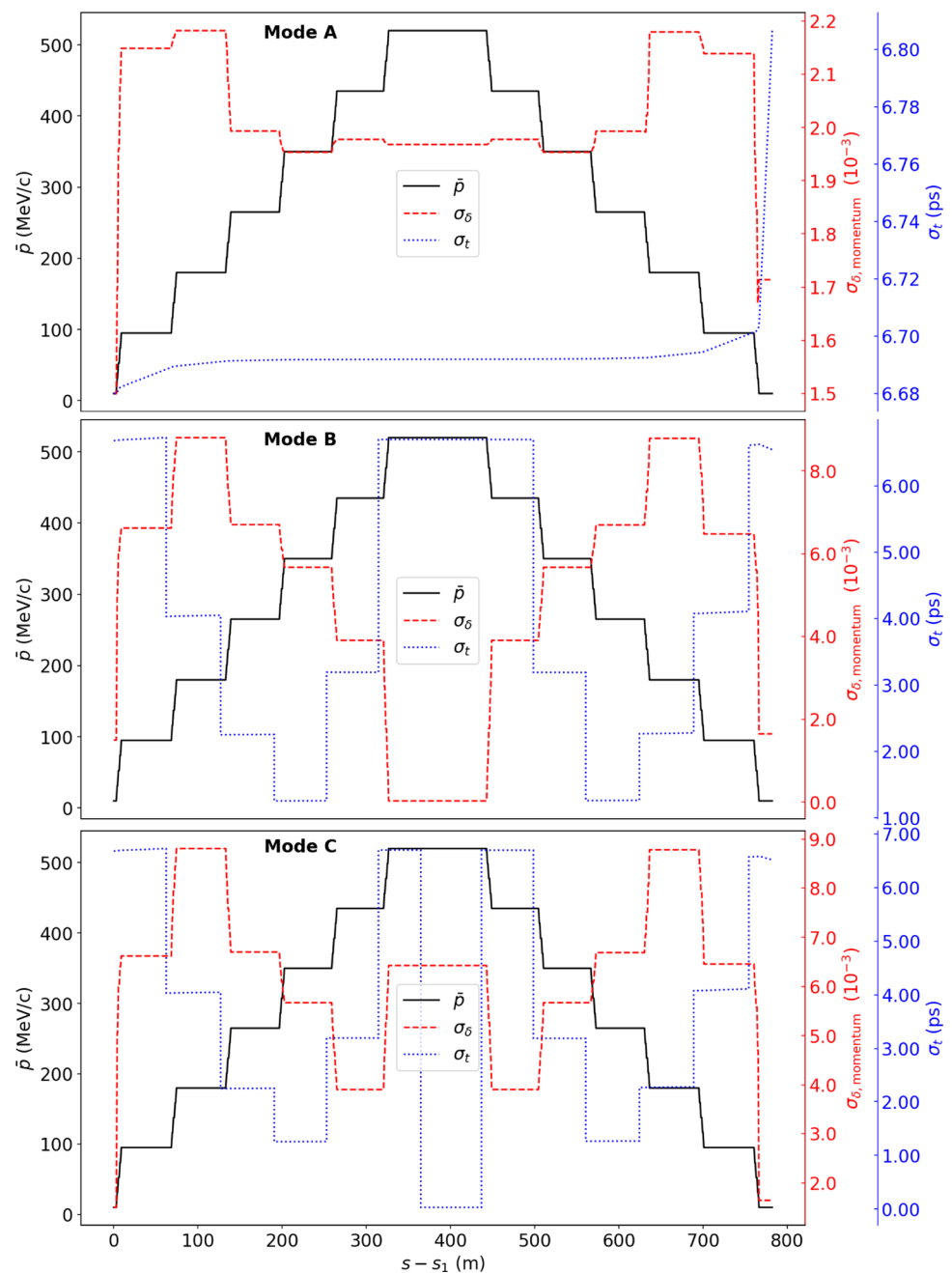
In mode A, the electrons are accelerated and decelerated almost on-crest² of the RF field while the longitudinal dispersion vanishes from a LINAC exit to a LINAC entrance. In this mode, the relative momentum spread and bunch length are almost preserved. In mode B and mode C, the electrons are accelerated and decelerated off-crest of the RF slope while the longitudinal dispersion is non-zero. In mode B, the longitudinal phase space is sheared

²Operating slightly off-crest allows for compensation of flight-time effects and phase slippage.

in such a way that its shape after maximum acceleration and maximum deceleration is almost identical to the one after the booster LINAC; hence, the relative spread at maximum energy is decreased by a factor $10/520$. In mode C, the longitudinal phase space is sheared identical to mode B until the last acceleration where the remaining accelerating RF slope is used to maintain the chirp while the final longitudinal compression results from the longitudinal dispersion acting from the exit of the main LINAC to the interaction point. The deceleration phases and longitudinal dispersion values downstream of the interaction point are chosen such that the steps in the longitudinal phase space are reversed.

Tracking examples were conducted using the software *elegant* [61]. Figure 6 shows the simulated behavior of the longitudinal beam parameters for the three operation modes considered. The corresponding evolution of the longitudinal phase space is provided in Figs. 7, 8, and 9. The initial bunches are assumed to be uncorrelated Gaussian distributions. A vanishing linear correlation can be realized by tuning the chirp via the booster LINAC and the longitudinal dispersion in the injector achromat. For the tracking examples, a certain bunch length was chosen to demonstrate the importance of second-order dispersion terms and to identify bottlenecks. Hence, the values $\sigma_t = 6.7$ ps and $\sigma_{\delta, \text{momentum}} = 1.5 \cdot 10^{-3}$ measured for the cERL injector for a bunch charge of 7.7 pC [56]

Fig. 6 For modes A to C, the simulated longitudinal quantities centroid momentum $\bar{p}$, relative momentum spread $\sigma_{\delta, \text{momentum}}$ and bunch length σ_t are shown as a function of the position s relative to the exit of the injector achromat s_1 . Since the longitudinal dispersion is implemented via elements of zero length at the end of a section, jump discontinuities appear for σ_t . However, since space-charge effects and influences due to synchrotron radiation are not included here, σ_t is correctly evaluated in each main LINAC section. Thus, the results for $\bar{p}$ and $\sigma_{\delta, \text{momentum}}$ are valid for the entire tracking since they are only changing inside a main LINAC. All parameters given by σ refer to the standard deviation



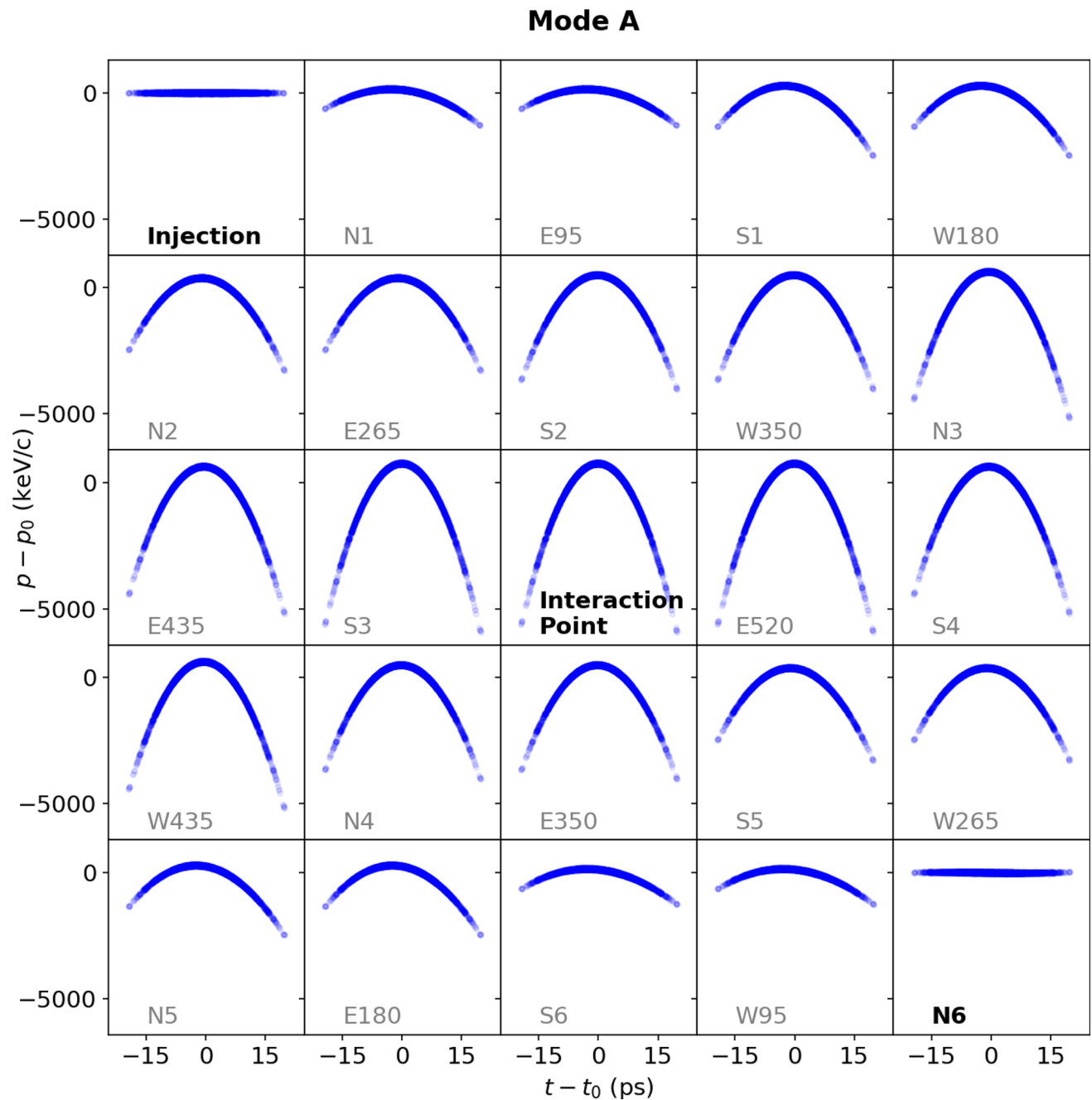


Fig. 7 Simulated longitudinal phase space downstream of the injector achromat for mode A. Each panel shows the phase space present after passing the named section (northern main LINAC (N), southern main LINAC (S), eastern recirculation beamline (E), western recirculation beamline (W)). The one- σ parameters at the interaction point are: bunch length of 6.69ps, momentum spread of $1.97 \cdot 10^{-3}$. Collective effects and instabilities, such as space charge, coherent synchrotron radiation, and BBU, have been neglected

have been used here as initial standard deviations rather than considering the short bunches available at CEIP [47]. This means, the simulation of the longitudinal phase space evolution is quite conservative.

The corresponding values of the degrees of freedom, listed in Table 4, highlight the necessity of second-order longitudinal dispersion terms. The results for mode B and mode C show that a pronounced increased relative momentum spread relative to the start section is required in some interim sections. These values are critical with respect to the maximum values of —R16— and —R36— in the corresponding recirculation beamlines. Therefore, the lattice has to be revised as soon as the tracking of the longitudinal phase space has been extended including collective effects and instabilities.

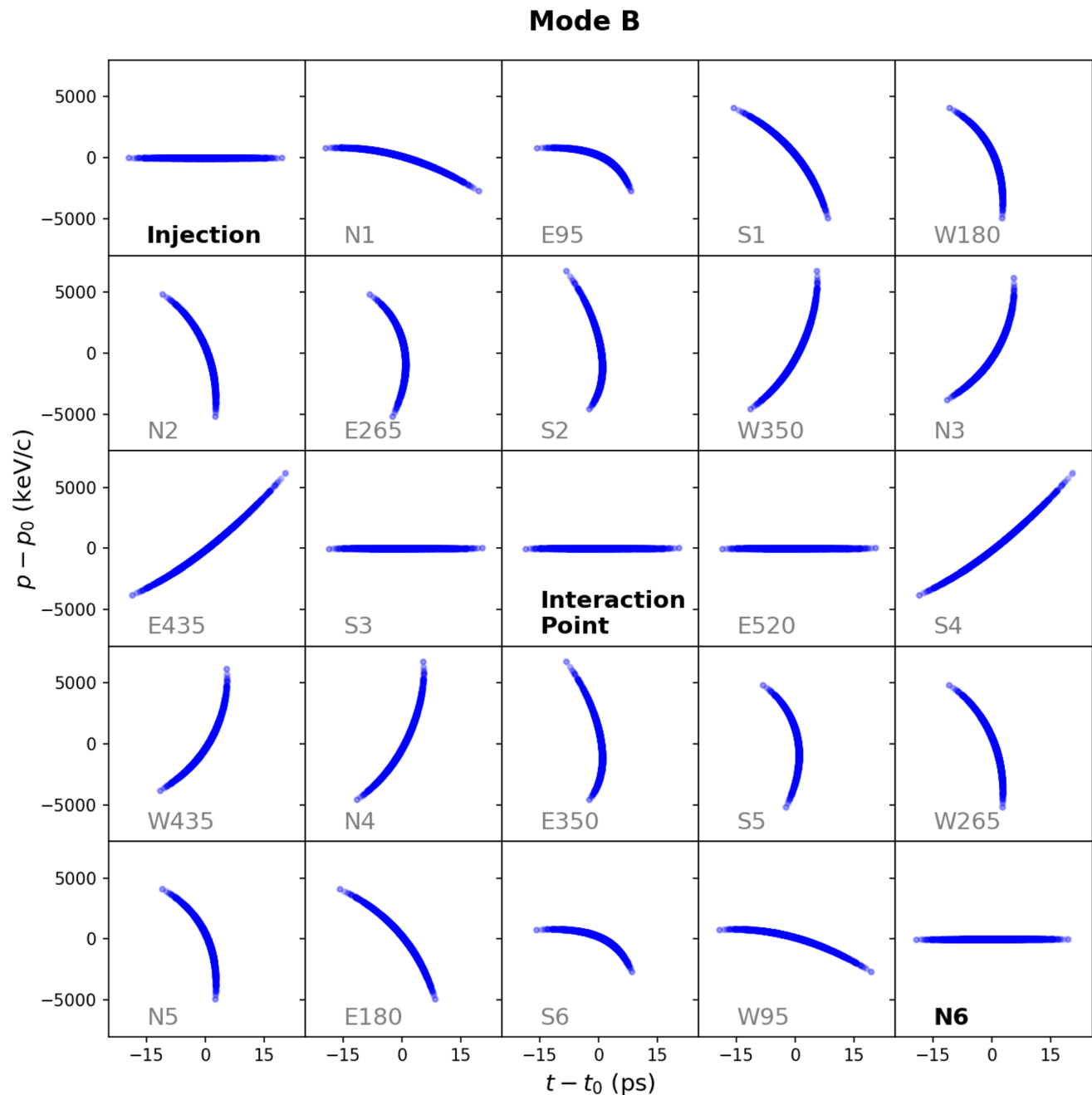


Fig. 8 Simulated longitudinal phase space downstream of the injector achromat for mode B. Each panel shows the phase space present after passing the named section (northern main LINAC (N), southern main LINAC (S), eastern recirculation beamline (E), western recirculation beamline (W)). The one- σ parameters at the interaction point are: bunch length of 6.70ps , momentum spread of $2.93 \cdot 10^{-5}$. Collective effects and instabilities, such as space-charge, coherent synchrotron radiation, and BBU, have been neglected

2.6 Interaction point: laser-Compton backscattering

Quasi-monochromatic, MeV-ranged, energy-tunable, polarized photon beams from a laser-Compton backscattering source are highly appreciated for many research applications in nuclear physics. In the LCB process, a photon collides with an ultra-relativistic electron through which it will be backscattered and boosted in energy in the laboratory frame of reference (see Eq. (1)). The challenge for an LCB source is the maximization of the intensity of the high-energy photon beam despite the fact that the cross-section for Compton scattering, and hence the electron-photon interaction probability, is very small. A large electron-photon scattering luminosity requires a

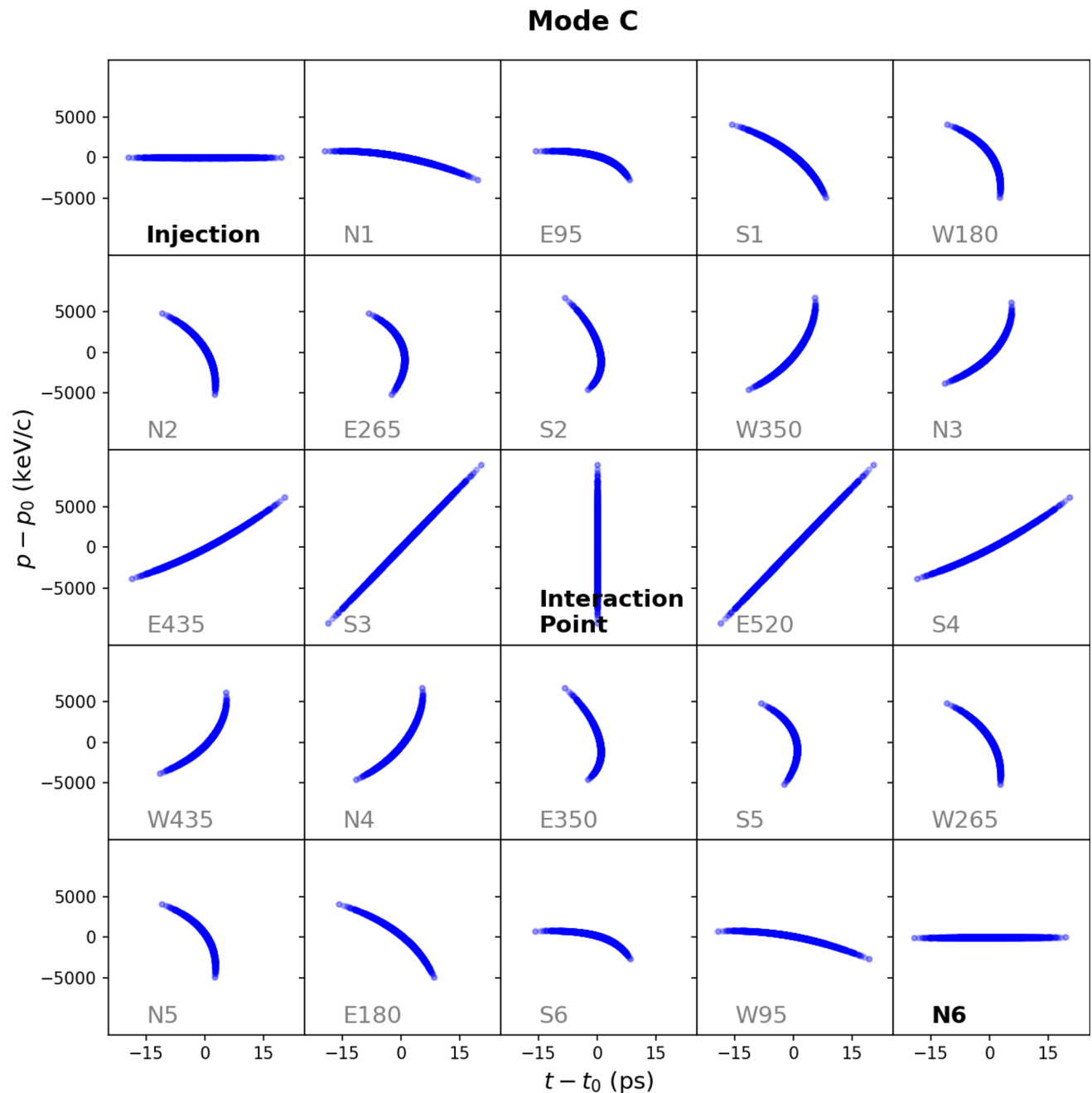


Fig. 9 Simulated longitudinal phase space downstream of the injector achromat for mode C. Each panel shows the phase space present after passing the named section (northern main LINAC (N), southern main LINAC (S), eastern recirculation beamline (E), western recirculation beamline (W)). The one- σ parameters at the interaction point are: bunch length of 0.03ps , momentum spread of $6.43 \cdot 10^{-3}$. Collective effects and instabilities, such as space charge, coherent synchrotron radiation, and BBU, have been neglected

well-focused high-intensity photon beam from a high-power laser system to best overlap with an equally-well focused, intense electron beam in space and time. An LCB source, thus, fully benefits from the excellent beam properties of the designed accelerator, in particular, from its low emittance and high-energy resolution. Using an ERL such as DICE for an LCB source may, therefore, be considered ideal.

We assume a state-of-the-art, commercially available laser system for the interaction laser. The optical system of an LCB source may consist of a chirped pulse amplification (CPA) laser system and an optical cavity at the interaction point to reuse the remaining photons to further increase the intensity of the photon beam. The advantages of a CPA laser system are the short pulse length ($<1\text{ps}$) combined with a flexible repetition rate that

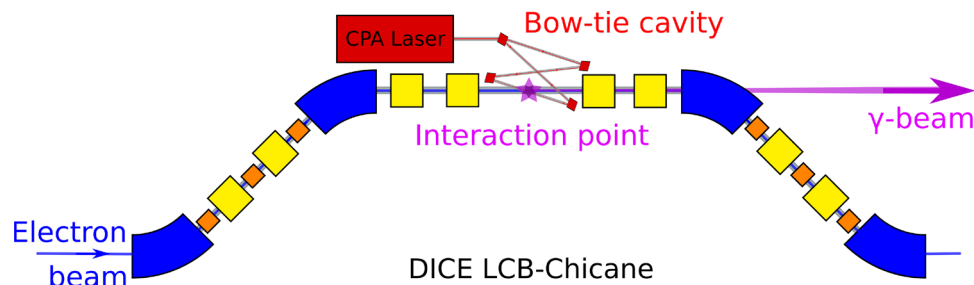


Fig. 10 The picture shows the LCB design for DICE. A bow-tie cavity will be placed in the experimental chicane to enhance the laser power of the CPA laser system even further. The cavity will be tilted slightly (exaggerated depicted in the image) to bring the mirrors outside of the electron beam in order to, thus, prevent the usage of mirrors with holes

can be synchronized with the accelerator, due to the seed laser. At the same time, a sufficiently large output power of up to several 100W is technically feasible. In order to ensure uninterrupted operation, it is advisable to use laser systems that are proven to be robust and stable. A typical amplifier material with very good thermal properties and a high pump efficiency is Yb:YAG. The material can be directly diode-pumped allowing for a more compact design and higher uptime. In addition, repetition rates up to several 100MHz can be achieved. The relatively long wavelength of 1030nm from Yb:YAG systems and thus the reduced scattered photon energy of the LCB source can be compensated for by commercially available high harmonic generation (HHG) modules, second or third harmonic, which doubles or triples the resulting photon energy, respectively. Most of the modules are sold together with the laser systems, to achieve a wavelength of 515nm and 343nm, respectively. This wavelength range enables, as mentioned in Sect. 2.1, the dual use of the laser system for the electron source simultaneously with the LCB source. A reliable and proven laser system is very important for operation. Most of the commercial available systems are being used successfully in continuous operation at a wide variety of facilities.

An LCB setup for beam diagnostics is currently under construction at the S-DALINAC [64]. For this project, we rely on Amplitude's Tangor 100 system [65].

For a first parameter study of the DICE LCB source, Amplitude's Tangor 300 series [66] was considered. An infrared (IR) and green option are available. For the ultraviolet (UV) option, we used the IR system as basis and adapted the parameters based on our experience by the typical parameter changes when using a third harmonic. We use these systems for our simulations. Laser systems with significantly higher intensities might be considered instead—at a corresponding cost increase.

For this first design, an optical bow-tie cavity is considered for the LCB source at DICE as shown in Fig. 10. It is designed to store the laser photons and therefore multiply the number of photon-electron bunch collisions at the interaction point. The advantage of such a four mirror design is that the frequency locked to the laser and the focus at the interaction point are independent from each other. For DICE, the calculations were performed by assuming a power gain of 5000. Power gains of up to 10000 are intended in a Fabry-Pérot cavity design presented in Ref. [67]. The bow-tie cavity of DICE will be tilted by a small angle against the electron beam axis. A tilted design has already been developed and successfully studied at cERL [68]. It demonstrates the technical feasibility of the proposed design. Nevertheless, we will evaluate the different laser resonator geometries during the conceptual design process of the LCB setup for DICE. A Fabry-Pérot cavity resonator geometry would be another approach and is presented in Ref. [69]. The collision configuration will be optimized depending on the chosen resonator design.

Table 5 shows the input parameters for an analytical calculation of the LCB source parameters for DICE. The values (see Table 6) have been obtained using a Python-Code [64], based on Ref. [70]. The laser beam was approximated by a round beam at the interaction region for this first calculation. Its shape will be simulated depending on the final choice of the laser resonator geometry during the conceptual design. The intracavity powers for the three different laser systems have been chosen to be challenging in terms of the mirror and the stability of the full system. During the conceptual design, it will be evaluated which intracavity powers could be used depending on the state of the art to achieve a stable and reliable system. The electron beam parameters and scattering geometry have been fixed to one example. In this case, the bow-tie cavity was not tilted against the electron beam axis. Thus, the head-on configuration was calculated. The scattering angle will be defined by the final resonator design and will be used for the calculation of the parameters of the LCB source during the conceptual design. Further options on the design are mentioned in Sect. 3.3.3. Table 6 summarizes the resulting output parameters for the LCB source. Two distinct cases are presented: (1) a minimal bandwidth mode with a small collimation of $33\mu\text{rad}$ and a larger electron focus of $70\mu\text{m}$, and (2) a maximum spectral density mode with a larger collimation of $333\mu\text{rad}$ and a smaller electron focus of $40\mu\text{m}$.

For comparison, the performance of current photon sources has been presented in Tab. 2 in Ref. [10].

Table 5 Input parameters for an analytical calculation of the LCB source at DICE. Three different laser options are shown. Two different collimators as well as two electron beam spot sizes have been considered

Input parameter	Unit	DICE infrared	DICE green	DICE ultraviolet
Laser				
Wavelength	nm	1030	515	343
Output power	W	300	150	100
Spectral bandwidth	nm	< 3	< 3	< 1
RMS pulse length	ps	< 1	< 1	< 1
Pulse energy (39.4 MHz)	μJ	7.61	3.81	2.54
Repetition rate	MHz	39.4	39.4	39.4
M^2		< 1.35	< 1.35	< 1.35
Optical cavity				
Focal spot size	μm	50	50	50
Power gain		5000	5000	5000
Pulse energy in cavity (39.4 MHz)	mJ	38.05	19.05	12.70
Effective optical power at interaction point	kW	1500	750	500
Electron beam				
Energy	MeV	520	520	520
Energy spread (mode B)		$2.93 \cdot 10^{-5}$	$2.93 \cdot 10^{-5}$	$2.93 \cdot 10^{-5}$
Normalized emittance	mm mrad	2	2	2
RMS spot size (min. bandwidth)	μm	70	70	70
RMS spot size (max. sp. density)	μm	40	40	40
Bunch charge	pC	20	20	20
Operating frequency LCB mode	MHz	39.4	39.4	39.4
Beam current LCB mode	mA	0.79	0.79	0.79
RMS bunch length (mode B)	ps	6.7	6.7	6.7
Setup geometry				
Laser e-beam scattering angle	mrاد	0	0	0
γ -collimation half angle 1	μrad	33	33	33
γ -collimation half angle 2	μrad	333	333	333

Table 6 Output RMS parameters of an analytical calculation of the LCB source at DICE for three different laser systems in head-on collision configuration. Two different collimators for the γ -ray beam together with different electron beam spot sizes are compared. The distance from the interaction point to the collimator was assumed to be 30 m

Parameter of the LCB source	Unit	DICE infrared	DICE green	DICE ultraviolet
Minimal energy (100 MeV electrons)	keV	184	367	550
Maximum energy (520 MeV electrons)	MeV	4.9	9.8	14.5
Min. bandwidth: 33μrad collimator (1 mm radius) 520 MeV, 70μm electron beam				
Bandwidth	%	0.3	0.6	0.3
Total flux (4π solid angle)	γ/s	$1.4 \cdot 10^{12}$	$3.4 \cdot 10^{11}$	$1.5 \cdot 10^{11}$
Flux in bandwidth	γ/s	$2.4 \cdot 10^9$	$5.8 \cdot 10^8$	$2.6 \cdot 10^8$
Spectral density	$\gamma/(\text{eV s})$	$5.5 \cdot 10^4$	$4.0 \cdot 10^3$	$2.1 \cdot 10^3$
Max. spectral density: 333μrad collimator (1 cm radius) 520 MeV, 40μm electron beam				
Bandwidth	%	3.4	3.5	3.4
Total flux (4π solid angle)	γ/s	$2.5 \cdot 10^{12}$	$6.2 \cdot 10^{11}$	$2.7 \cdot 10^{11}$
Flux in bandwidth	γ/s	$3.5 \cdot 10^{11}$	$8.7 \cdot 10^{10}$	$3.8 \cdot 10^{10}$
Spectral density	$\gamma/(\text{eV s})$	$8.2 \cdot 10^5$	$1.0 \cdot 10^5$	$3.1 \cdot 10^4$

3 Opportunities for an experimental research program

The machine sketched above for a specific choice of parameters can be utilized for a variety of experimental programs and applications. Its outstanding feature is the intense, quasi-monochromatic, energy-tunable, polarized γ -ray beam which will outperform any currently existing facility by two to three orders of magnitude with respect to its beam's spectral density on target for energies above about 3 MeV. This feature can guarantee a fertile basis for prolific research activities for decades.

While this quasi-monochromatic γ -ray beam is generated in the machine's ERL modus, the beam is dumped at injection energy. A suitable design of the beam dump will enable the machine's simultaneous usage as a bremsstrahlung source with very high current and, hence, large flux for further and complementary research on photonuclear reactions or for a variety of bremsstrahlung applications, including the production of positrons or of radioisotopes for scientific or commercial usage, in parallel to the ERL operation.

Besides the collision of the electron beam with the external laser beam for LCB beam production, also other collider options, such as an electron-ion collider in an adjacent ion-storage ring, or generation of a coherent free-electron laser (FEL) beam are conceivable in ERL mode, if desired.

As an alternative to its ERL operation, the facility can be operated, albeit at lower beam currents, in conventional mode, where the beam is used at an external target or deteriorated so much that it cannot be held within the acceptance of the recirculations of the machine. All options for usage of a high-power continuous-wave electron accelerator remain available comprising inclusive (e, e') , and exclusive $(e, e'\gamma)$, $(e, e'f)$, $(e, e'n)$, $(e, e'x)$, where x denotes a charged particle, nuclear reactions on solid targets and materials for scientific or commercial applications. Last but not least, the machine itself is a valuable object of study for many aspects of accelerator science for powerful multi-turn ERLs.

In short, the sketched facility, with the selected parameters as concrete examples, can offer
in ERL operation:

- Quasi-monochromatic γ -ray beam; $0.2 \text{ MeV} < E_\gamma < 15 \text{ MeV}$
- High-flux bremsstrahlung; $E_0 < 10 \text{ MeV}$
- FEL; $\lambda_{\text{FEL}} \approx 25 \text{ nm}$, depending on the choice of the undulator
- Electron-ion collider; requires an ion machine

in non-recirculating operation (at reduced beam current of up to $100 \mu\text{A}$):

- Electron irradiation of solids for scientific or commercial usage including fixed-target experiments for electron-induced nuclear reactions

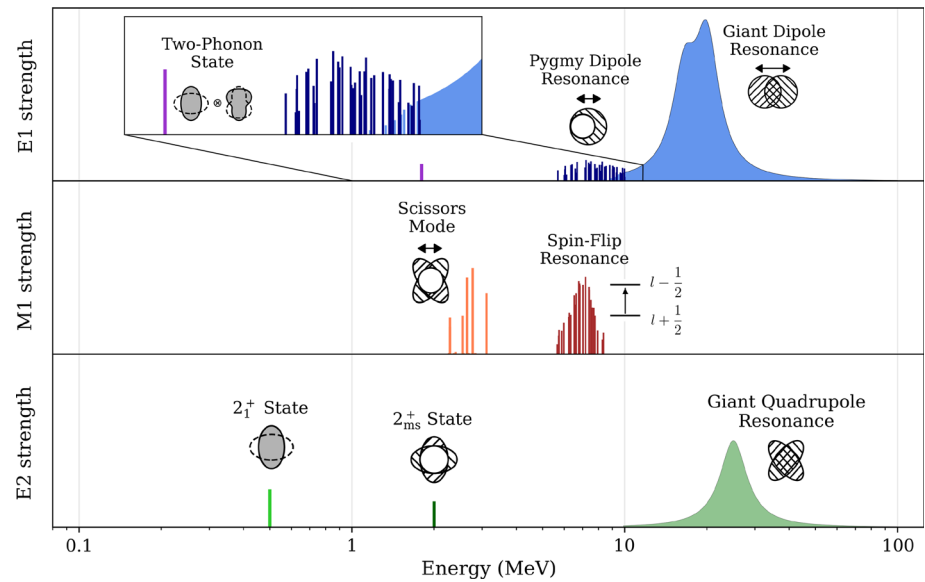
Below, we will sketch a few examples for potential research activities at DICE. An extensive list of excellent scientific research programs with monochromatic γ -ray beams from LCB sources has been discussed during the *International Workshop on Next Generation γ -ray Source, 2016, USA* and published in Ref. [16] and in the technical design reports for ELI-NP [17]. A few additional recent examples are given in Sect. 3.1. Opportunities with intense bremsstrahlung at the ERL's beam dump, that are available parasitically to the ERL operation, are sketched in Sect. 3.2. Further experimental capabilities or options for alternative usage of the machine will be mentioned shortly in Sect. 3.3. Such optional extensions may require alternative parameter settings for the operation of the accelerator or additions to the infrastructure of the sketched facility.

3.1 Photonuclear reactions

The use of γ -ray beams in nuclear physics has multiple aspects, ranging from nuclear structure studies and measurements of nuclear properties for astrophysics to fundamental aspects of quantum physics or medical and commercial applications [10, 16, 17]. The frontiers for photonuclear reactions which will be tackled and extended by DICE can be summarized as follows:

- **The precision frontier:** Not only the high intensities, but also the narrow bandwidth of next-generation γ -beam facilities will allow for unprecedented precision in the measurement of nuclear observables, especially when paired with developments of suitable experimental techniques (see below), and will give much enhanced sensitivity to the measurement of energy-dependent effects, in particular in (quasi-)continua of excited states.
- **The availability frontier:** Today's comparatively low γ -beam intensities typically require the use of photonuclear reaction targets on the gram scale. With orders of magnitude higher intensity, this requirement will shift to the milligram scale, hence opening experimental access to many rare isotopes, in particular radioactive ones like trans-actinides, for photonuclear science.

Fig. 11 Nuclear structure phenomena accessible with real photons. Low-lying structures include $E1$, $M1$, and $E2$ individual collective excitations, whereas at medium excitation energies, still below particle-separation thresholds, one typically encounters increasing degrees of fragmentation and statistical behavior culminating in unbound resonances above threshold, e.g., the giant dipole or quadrupole resonances, with significant spreading. Figure taken from Ref. [9] under license CC BY 4.0



- **The intensity frontier:** The highly intense beams will surpass any other existing machine in the range above 3 MeV. New experimental techniques that currently would require an unrealistic amount of several months of beamtime, can be executed in days and, hence, become feasible. New experimental methods, e.g., based on nuclear absorption techniques at the quantum-state level and Doppler modifications, will open up new experimental horizons. Furthermore, substantially increased intensity will enable researchers to overcome obstacles like γ -absorption from shielding for many applications.

Figure 11 gives a coarse overview of the nuclear phenomena accessible to photonuclear science, ranging from special individual states at low energies to broader resonances, distributed over many states or in a quasi-continuum at high energies.

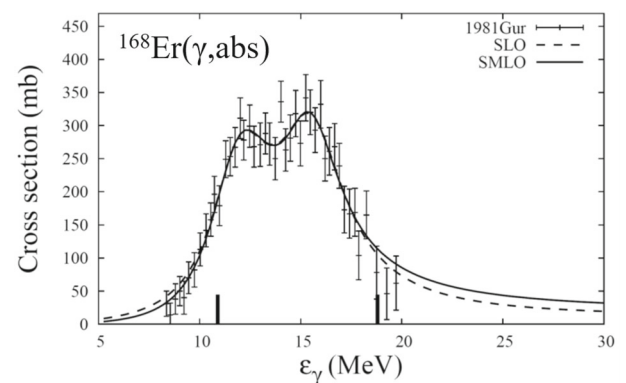
3.1.1 Photoabsorption for nuclear physics and material science

The LCB γ -ray beams from DICE, complementary to those produced in bremsstrahlung (see Sect. 3.2), will lead to new photonuclear studies using the method of photoabsorption, surpassing what is possible at existing facilities in terms of reach in isotopes, reach in intensity, and, hence, reach in physics problems to be addressed. This method rests upon the absorption of the γ -ray beam in the material of interest.

Photoabsorption above particle-separation threshold

Photoabsorption data on nuclear giant resonances exist for decades, see, e.g., Ref. [71]. Most of them have been obtained in the 1960s to 1980s and merely reveal the existence and gross properties of the resonances. One typical example for the nuclear giant dipole resonance (GDR) is shown in Fig. 12 for the deformed rare-earth nuclide ^{168}Er . In many cases, the so-called photoabsorption data have been obtained by the measurement of induced liberated neutrons and are inaccurate with respect to other decay branches, such as (γ, p) etc. or the neutron

Fig. 12 Photoabsorption data on the GDR of ^{168}Er . The shown level of precision of the photonuclear absorption data is typical for heavy nuclei. It is insufficient for progress on insight in a possible fine structure of the GDR. Reprinted and adapted minimally from Ref. [71], ©(2018), with permission from Elsevier



multiplicity. The current status of data is insufficient for a more detailed understanding of giant resonances for keeping pace with the development of corresponding microscopic theory preventing appropriate scientific progress. The improved photon flux available at a facility such as DICE will enable photoabsorption measurements on giant resonances with significantly improved precision and accuracy within days of beamtime that previously would have taken weeks for lower quality data.

Photoabsorption below particle-separation threshold

Below threshold, nuclear excited states are hadronically bound and can, only, decay internally. Their electromagnetic decay rates result in level widths on the order of eV or below. Corresponding photoabsorption lines cannot be resolved by ordinary γ -ray spectrometers. Nevertheless, they can be studied by performing NRF on a secondary target of the same isotope. This process is called self-absorption [9, 10]. In fact, self-absorption offers a means to directly measure excitation cross-sections of nuclear resonances, without the measurement of the complete spectrum of de-excitation γ -rays and without the need to compare to, potentially uncertain, calibration standards. Measurements with photon beams of significantly higher intensity will allow for the establishment of new ways for much more precise photon flux calibrations and consequently much more precise results from photonuclear experiments than known today. An early example for high-precision self-absorption experiments is provided in Fig. 13 for the case of the excited 0_1^+ state of ${}^6\text{Li}$ with isospin $T = 1$.

Examples for the use of photoabsorption for nuclear structure and astrophysics research, as well as material science, can be given from first experiments of this type which exploited γ -ray beams from bremsstrahlung: specific excited states can be measured to high precision using this technique, making use of relative measurements which eliminate uncertainties in beam fluxes. Namely, the overall beam flux and its (atomic) attenuation by absorber targets can be measured by any isotope with sufficiently large cross-sections introduced as a witness into the same beam as the isotope of interest. Resonant absorption by the isotope of interest in the absorber is then measured against the signal from the witness target in the detection setup. This technique named relative self-absorption (RSA) yields high-precision values for excitation strengths, e.g., $M1$ strength, which then serves as benchmark for modern ab-initio theory. Hereby, it is important to narrow down experimental uncertainties to at least the uncertainty level of given theories. This has been exemplified in recent experiments on ${}^6\text{Li}$ (see Fig. 13) [24].

A different way for normalizing the data with respect to photon flux and atomic attenuation, as compared to the previously presented data, was introduced by Barty and colleagues [72] (see Sect. 3.1.6). It can be used for applying the RSA technique to LCB beams as provided by DICE. This transfer will, due to the much higher beam fluxes at resonance, further increase the achievable level of precision.

A potential source of uncertainty in such RSA experiments, if not appropriately dealt with, was identified to originate from potentially unknown zero-point motion of atoms in the target and related uncertainty of molecular theory [24]. Namely, the sensitivity of RSA experiments reaches the level where thermal motion of atoms in the target lattice play a sizeable role. On the one hand, this could lead to systematic uncertainty of the nuclear measurement, if not appropriately dealt with. On the other hand, it opens up a new route to research opportunities in nuclear solid-state physics, due to the directional information provided by the direction of the γ -ray beam penetrating the bulk material. To deal with this aspect, the temperature dependence of the nuclear absorption can

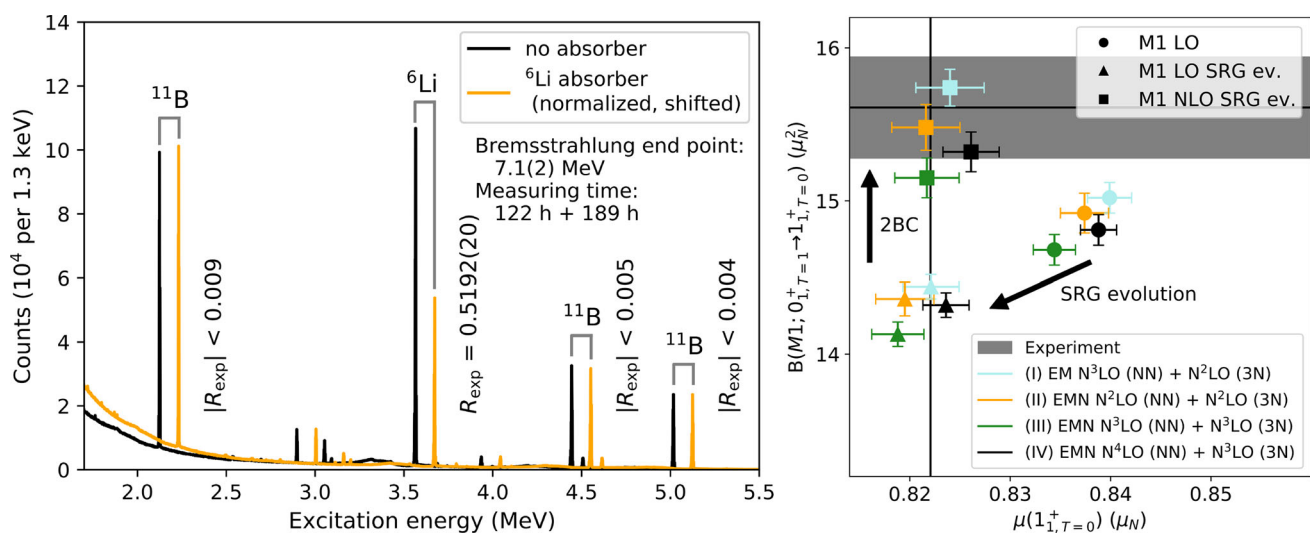


Fig. 13 Relative self-absorption measurement of ${}^6\text{Li}$ to a ${}^{11}\text{B}$ witness target, used to normalize beam flux and overall attenuation. The resulting high-precision data challenge modern theory. Reprinted with permission from Ref. [24] ©(2021), by the American Physical Society

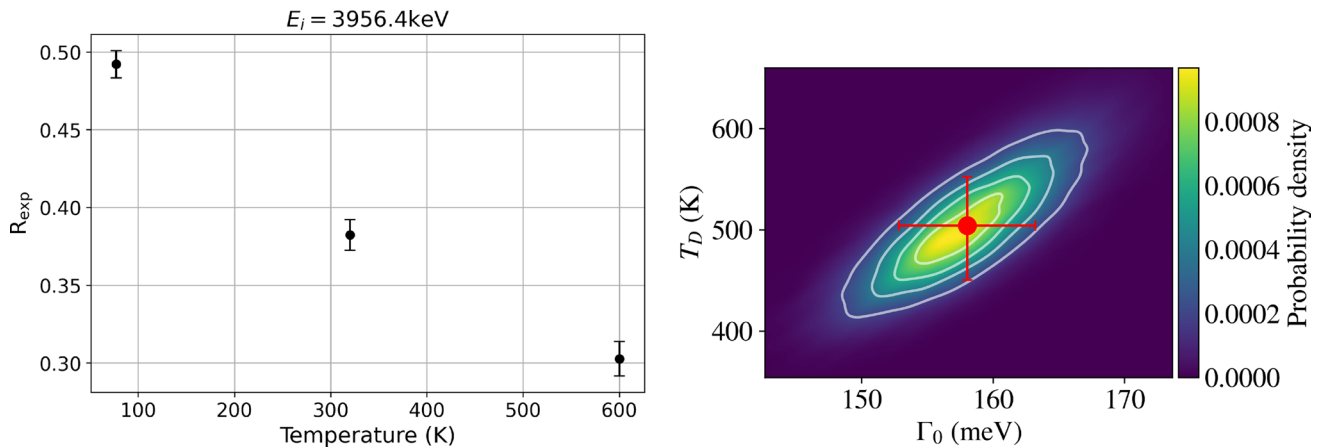


Fig. 14 Data derived from TRSA measurements show a clear temperature dependence which is based in the temperature-dependent thermal motion. Measurements at different temperatures then result in best values of the ground-state width of a state and of the atomic zero-point motion in the solid or, e.g., for the Debye temperature in the Debye approximation as shown on the right. Figure adopted from Ref. [73]

be considered. First experiments controlling the temperatures of absorber and scatterer in RSA experiments, hence temperature-dependent, relative self-absorption (TRSA) have been performed using bremsstrahlung beams at the S-DALINAC: A clear dependence of the measured self-absorption of excited states on the ambient temperature has been observed in ^{27}Al [73] as shown in Fig. 14. In this way, Debye temperatures (when employing the Debye approximation) and ground-state excitation widths can be measured simultaneously. Deviations from the Debye approximation are found to have interesting potential for testing thermal velocity distributions from molecular theory.

3.1.2 Nuclear resonance fluorescence

NRF refers to exclusive photon scattering reactions on nuclear resonances that are excited by an incident photon while the photon from the de-excitation is detected. Physics questions that can be addressed by NRF have recently been reviewed in great detail [9, 10]. Recent progress in the field builds on the work performed at DYNAMITRON at University of Stuttgart, the S-DALINAC at TU Darmstadt, γELBE at HZDR, or at HI γ S at TUNL, Durham, NC and others. However, the intensity frontier of DICE supersedes the available ones and will allow investigating very rare, even radioactive materials with half-lives down to a few hundred years, which will only be available in quantities of tens of micrograms (as opposed to typical target masses on the order of grams nowadays). Therefore, phenomena like the nuclear $M1$ scissors mode, quadrupole-octupole coupled structures or single-particle excitations in odd-mass nuclei, typically present at low energies below 4 MeV, can be investigated in new isotopes, and can potentially provide finger prints for sensitive isotopes like some heavy actinides.

Toward higher energies, one typically finds resonances from an $M1$ spin flip, for which data are very sparse, but which is particularly interesting for nuclear structure and astrophysics due to its relation to Gamow–Teller decays, and to detector technology for particle physics due to its likelihood to be excited in neutrino-scattering processes. DICE will enable researchers to pick out these spin-flip- $M1$ states from the sea of dominating $E1$ excitations, which are due to the low-energy tail of the GDR or the so-called pygmy dipole resonance (PDR) residing on top of its tail.

These electric-dipole phenomena may geometrically correspond to oscillations of the full proton and neutron bodies, and of neutron skins against the proton–neutron saturated core, respectively. They provide access to the nuclear dipole polarizability which has been found to be related to the density dependence of the nuclear symmetry energy and, hence, to an important aspect of the equation of state of nuclear matter required for our understanding of the properties and dynamics of neutron stars. DICE will enable precision studies of not only the energy location and excitation strength of these structures, but the decay behavior of these resonances. The latter tests direct the formulation and the very concept of photon strength functions. These are in widespread use for simulating reaction networks for the processes responsible for the genesis of the heavy chemical elements in the universe. Notably, the photon strength functions accessible in NRF measurements are intimately related to the respective level densities of $J = 1$ states that can be measured very cleanly without resorting to assumptions on a composition of nuclear spin quantum numbers. Through the use of LCB beams and simultaneous investigation of upward and downward strength functions, in combination with photoabsorption experiments, it will be possible to determine level densities over the full energy range of the measurements.

NRF measurements can also be applied to unbound resonances; namely, the GDR is excited from the ground state by a sizeable electric-dipole matrix element. Since the GDR resides at excitation energies beyond the proton and neutron thresholds, its decay via particle emission dominates. Still, the large $E1$ matrix element to the ground state causes internal decay of the GDR by γ -emission back to the ground state, or to higher-lying excited states, with a probability in the percent range. This phenomenon has recently been measured at HI γ S for the first time to good precision over the entire energy range of the GDR [23]. It offers new observables for the study of the very nature of giant resonances, and for nuclear deformation which is imprinted in the distribution and decay behavior of giant resonances. The possibility to excite narrow-energy slices of the resonances, to study their (energy-dependent) γ -decay behavior, as well as their impact on our understanding of the nuclear many-body system has recently been demonstrated [23] as shown in Fig. 15. Much more detailed studies will become possible using LCB beams from DICE. Making use of the new techniques for LCB beams, the everlasting problems which arise from inconsistencies between literature data sets on dipole-excitation cross-sections [74], can also be addressed as well. These inconsistencies of literature data are a severe hindrance in the interpretation of nuclear data in terms of GDR or PDR, the existence of fine structure, and normalization of existing data on a common ground, which can be revisited and resolved by the use of next-generation LCB beams.

In contrast to the prompt coupling of the photoexcited collective resonance to the electromagnetic radiation field through internal decay, their decays by particle emission is dominant although it proceeds through the much longer lived stage of a compound nucleus configuration. Its decay into short-lived states of the daughter nucleus by simultaneous particle emission is of high interest, since it allows accessing the interplay between statistical and structural properties of the nucleus. As such, different energy regions, e.g., of the GDR can be scanned for determining the population of states in the respective decay daughter and its variation with respect to excitation energy and angular momentum. This distribution of the particle-decay cross-section over specific daughter states is, to date, unknown. Our recent data on the GDR of ^{154}Sm taken at HI γ S demonstrate that a corresponding route of research is feasible: We started a first analysis of the spin and energy distribution of these daughter states. This is possible through the measurement of the decay- γ -rays from excited states of the daughter nucleus using high-resolution HPGe detectors, subsequent to the population of these states in the decay of the initially photoexcited GDR by particle emission.

Fig. 15 The GDR of ^{154}Sm , excited and measured in its γ -decay channel at HI γ S. Its decay branching ratio (top), absolute photo-excitation cross-section (middle, compared to data from the EXFOR data base and Carlos et al. [75]) and absolute elastic-scattering (ES) cross-section to the ground state (bottom) are simultaneously measured. The blue bands are a fit of the geometrical model to the photoabsorption data (middle) and to the measured NRF branching ratio (top) and well describe the elastic photon scattering cross-section (bottom) by using dispersion relations. Figure taken from Ref. [23] under license CC BY 4.0

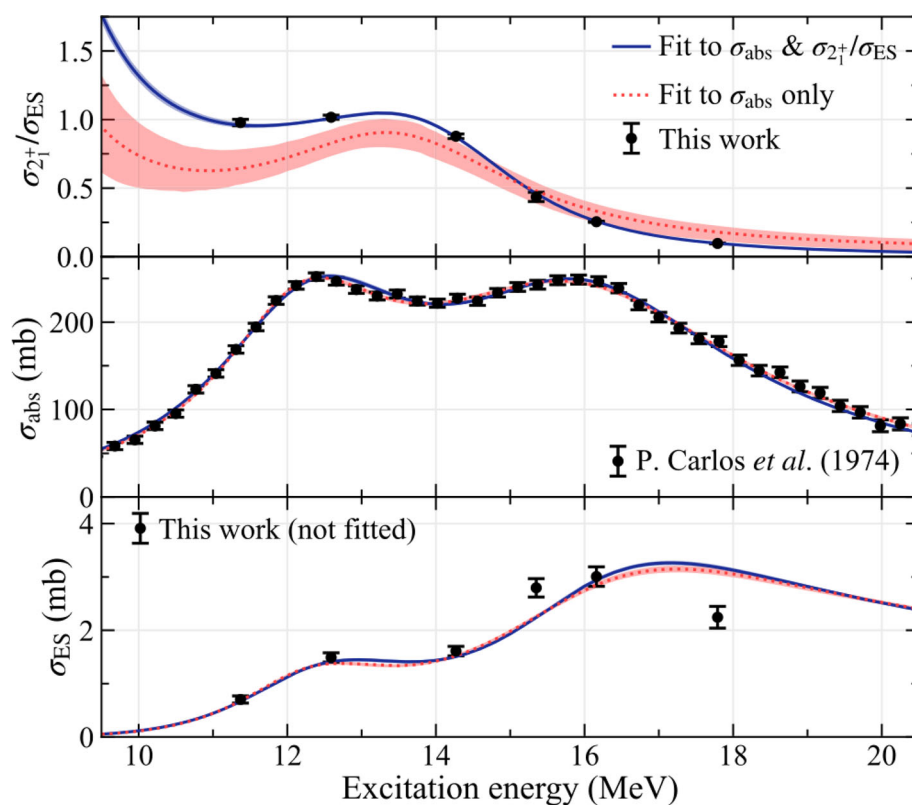
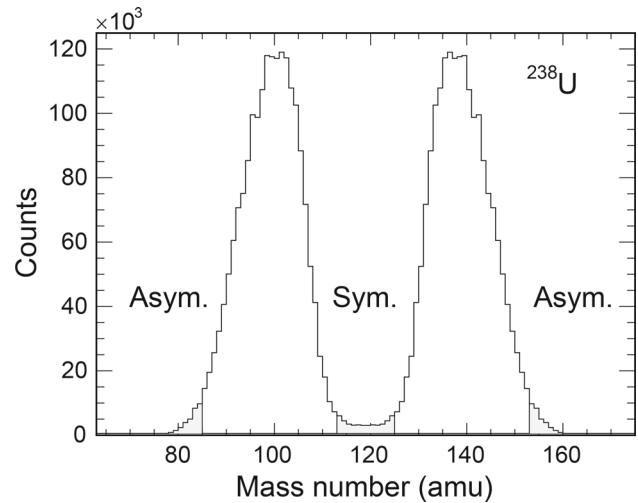


Fig. 16 Pre-neutron mass distribution extracted from an experiment at the HI γ S facility using 11.2MeV γ -rays impinging on a ^{238}U spectroscopic target ($\rho x \approx 100 \mu\text{g}/\text{cm}^3$). Further analysis required cuts on the symmetric and far-asymmetric regions shown in grey. Taken from Ref. [83] under license CC BY-NC-ND 4.0



3.1.3 Photofission

Photonuclear reaction studies with DICE will be able to include photon-induced fission experiments [76, 77]. The narrowband spectrum of polarized γ -rays at DICE will enable researchers to study fission fragments and their properties as a function of excitation energy and angular momentum of the fissioning nucleus. Properties of the fissioning system, its excited intermediate states, and information on the fission barrier can be inferred from fission-fragment yields, their angular distributions, or from measuring prompt fission neutrons and γ -rays in coincidence, too [78].

The energy range intended for the LCB γ -ray beam at DICE is ideally suited to investigate the barrier region of photofission where low-lying collective deformed excitations are believed to influence fission observables strongly. Measurements in this energy region complement existing bremsstrahlung data (see, e.g., Ref. [79]).

As most transuranium nuclides are available in very small quantities only, a high overall flux as well as the high brilliance of the γ -ray beam will be mandatory. At several $10^9 \gamma/\text{s}$, it will be possible to study photofission beyond the U/Pu region systematically. The anticipated high flux will allow access to sub-barrier resonances (see, e.g., Ref. [76] and Refs. therein) or even to the so-called isomeric shelf [80] where cross-sections are very small. With increased sensitivity, it will also be possible to investigate correlations of different fission-fragment properties [81], including prompt neutrons or γ -rays [82]. In addition to providing a variety of new data for refining empirical and microscopic approaches to nuclear fission, such measurements address nuclear-data needs for applications.

An example is illustrated in Fig. 16, which shows the pre-neutron fragment-mass yield distribution of the $^{238}\text{U}(\gamma, f)$ distribution at 11.2MeV γ -ray energy measured at the HI γ S facility [83]. To better understand the origin of symmetric and very asymmetric fission events, angular correlations have been analyzed after gating on the grey-shaded areas, according to previous data by Wilke et al. [84]. Even at 11.2MeV where the cross-section is large due to the proximity of the first maximum of the GDR, more than 60 h of data-taking time was necessary for this experiment using a thin spectroscopic target. Hence, a significant intensity increase is mandatory to extend such investigations towards lower energies with both lower cross-sections ($\sim$ factor 1/10) and smaller fractions of events fissioning symmetrically ($\sim$ factor 1/5), in particular which in addition to the angular distributions also prompt gammas or neutrons are to be analyzed (efficiency $< 10\%$).

3.1.4 Photodissociation

With an estimated beam flux on target of several 10^8 – $10^9 \gamma/\text{s}$ with 0.6 % energy resolution, further astrophysically relevant photon-induced reactions such as (γ, n) , (γ, p) , (γ, α) (or other particle-emission channels) will become better accessible. For example, DICE will enable $^{16}\text{O}(\gamma, \alpha)$ cross-section measurements at much lower center-of-mass energies than what is achievable at present facilities like HI γ S with current active-target technology, herewith reaching the Gamow window. This reaction is one of the most important for the stellar nuclear fuel cycle, and cross-section data at low energies have been notoriously difficult to obtain. Such data are urgently needed in order to enable a reliable extrapolation into the energy region of highest importance for astrophysics.

Furthermore, DICE will have the narrow-energy bandwidth required for hadronic parity violation measurements in photodisintegration of the deuteron near its threshold [17, 85], and which is within about a factor of 4 of the required on-target γ -ray beam intensity. Hence, measurements of unprecedented precision with significant impact on the physics of nuclear few-body systems will be within reach with this next-generation γ -beam facility.

3.1.5 Photoactivation

The LCB γ -ray beams from DICE can be used to selectively excite states feeding (or depopulating) nuclear isomers. If a target can be obtained in the excited state of the given isotope, which is rarely possible in small quantities, then the impinging brilliant photon beam can be used to search for excited states on top of this isomer. Such states would carry fingerprints of its nuclear structure, but also offer ways to depopulate the otherwise relatively stable isomeric states in a given photon bath. This, for example, is of high relevance for aspects like the isomeric $^{180\text{m}}\text{Ta}$ occurring in nature and its use as a stellar clock [86].

Conversely, nuclear levels photoexcited from the ground state can feed into long-lived isomers of a given isotope—directly or following particle-emission [87]. Therefore, the respective photo-excitation and following decay path can be used as a production mechanism for medical isotopes, e.g., the isomeric $^{195\text{m}}\text{Pt}$, ^{225}Ac or others [88].

For both mechanisms, the small bandwidth of the LCB beam will enable researchers to choose specific pathways of the (de)populating γ -cascades—a novel capability which has not been available before. Further opportunities for photo-activation studies are described in more detail in Ref. [17].

3.1.6 Potential applications

The techniques of photoabsorption measurements, as described in the previous sections, are well suited for applications ranging from nuclear proliferation to medical application. Whereas the former is already quite well developed with definite ideas and designs developed in the field, the latter of course requires far more development since the technique would be directed at human tissue. However, both are already on pathways to commercial application (see, e.g., Ref. [89]). The novel concept of DICE, with expected γ -ray intensities from LCB about 2–3 orders of magnitude higher than existing forefront facilities, will enable the efficient use of photoabsorption techniques for technical applications.

Scan for specific isotopes

The scan of containers with nuclear material, as they particularly and abundantly result in the deconstruction of nuclear power plants and long-term storage of nuclear waste, is a subject of high relevance and high societal impact. Typical approaches to perform imaging of containers include γ -rays or neutrons, and even more exotic particles like muons (which have been used to attempt tomography of the Fukushima Daiichi reactors [90]). The latter approach, regarding the limited size of typical nuclear waste containers and the difficulties in producing and detecting muons, is not in favor for the use of muons. Likewise, neutrons can penetrate materials deeply, and are often used for imagery. However, their usage for imagery is limited in cases when the containers of the inventory, which is to be expected, have been particularly designed for shielding against neutron penetration, as is typically the case for containers for storing highly active waste. γ -rays are subject to attenuation, in particular within heavy shielding materials, but offer better access to the inventory of containers designed for neutron shielding. The use of LCB beams in combination with NRF techniques has been demonstrated using NRF for nondestructive assays [91]. Hence, γ -rays allow to search for specific isotopes through known resonances, in particular with the application of resonant photoabsorption techniques [92]. The problem of attenuation can hereby be overcome by providing a sufficiently high amount of initial γ -rays, hence ensuring sufficient transmission through the object of interest.

A project at TU Darmstadt has simulated the γ -ray transmission through shielded nuclear waste containers: This project showed the applicability of intense γ -ray beams for scanning containers such as the Konrad containers intended for long-term storage of low- and medium-radioactive waste in the intended German final repository for such nuclear waste, Schacht Konrad. Figure 17 shows simulations incorporating a realistic Konrad vessel, filled with typical abundances of material and typical shielding, impinged by a high-intensity γ -ray beam as it could be achieved at DICE. The unprecedented high intensities provided at DICE will allow for a significant γ -ray transmission, even through a Konrad container filled with 1.5 m of concrete and 15 cm of uranium metal, at a photon energy of 5 MeV. This, in turn, enables the use of absorption methods as outlined in Sect. 3.1.1 and below.

In this approach, the LCB beam would be tuned to specific nuclear resonances of any isotope that the container shall be tested for. A detection station behind the container would then contain a witness target (composed of that specific isotope) and a normalization target for a relative measurement and normalization of the beam intensity. A picture of the setup is shown in Fig. 18, comparing the relative amounts of a witness signal with and without placing an absorber, for the case of ^7Li , which recently also served to demonstrate the power of the technique [93]. The normalization target should have a similar (ideally same) atomic number as the isotope of interest, and non-resonant scattering off that target would be measured in a simple scintillator shell surrounding the target. The witness target, placed in a second setup just behind the normalization target, would be placed into the same type of detection setup. The difference in rates, measured through the ratio of both setups, then serves as an indicator of the level of resonance absorption at the specific photon energy in the isotopic material of interest, which occurred within the container, and which is proportional to the amount of that isotope in the path of the beam. This method allows not only imagery of a container, but more importantly a direct quantification of

Fig. 17 Numerical simulation of the radiation field produced by a Konrad storage container holding a uranium-loaded slab of concrete and being irradiated by a monochromatic beam of 5 MeV photons. The color code gives the fraction of the initially impinging beam per cm^2 detected on the beam axis. Despite its attenuation due to shielding and stored material, the penetrating beam is strong enough to allow applying RSA techniques for isotope identification and quantification

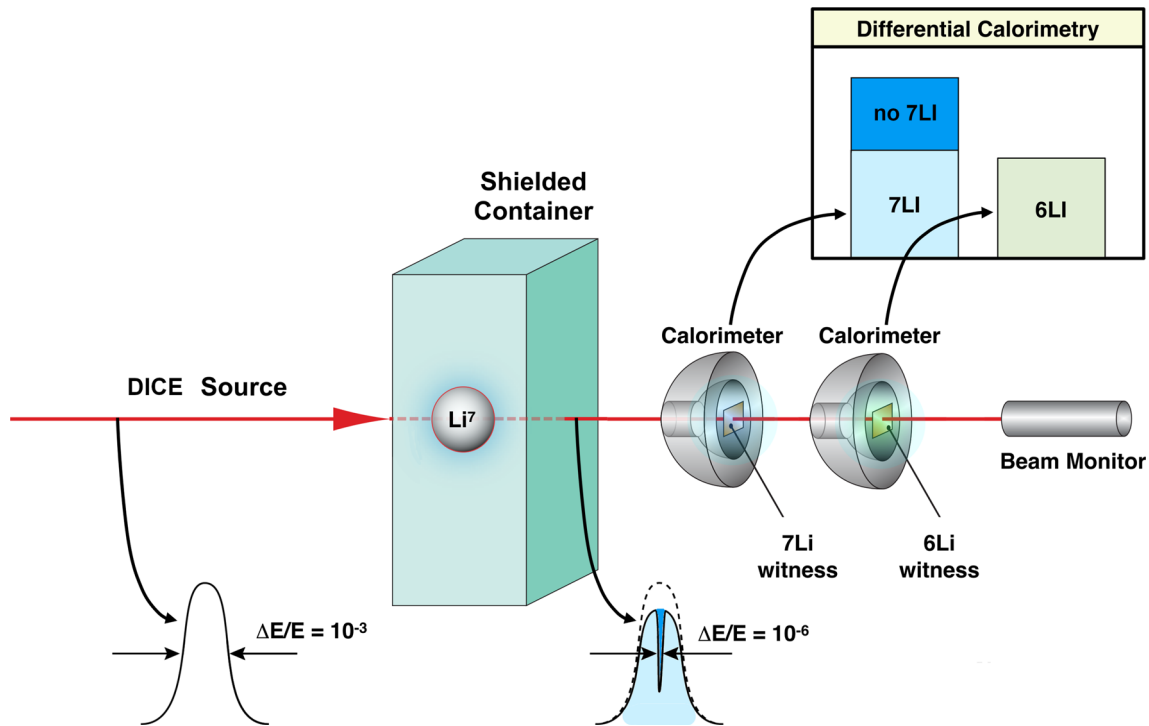
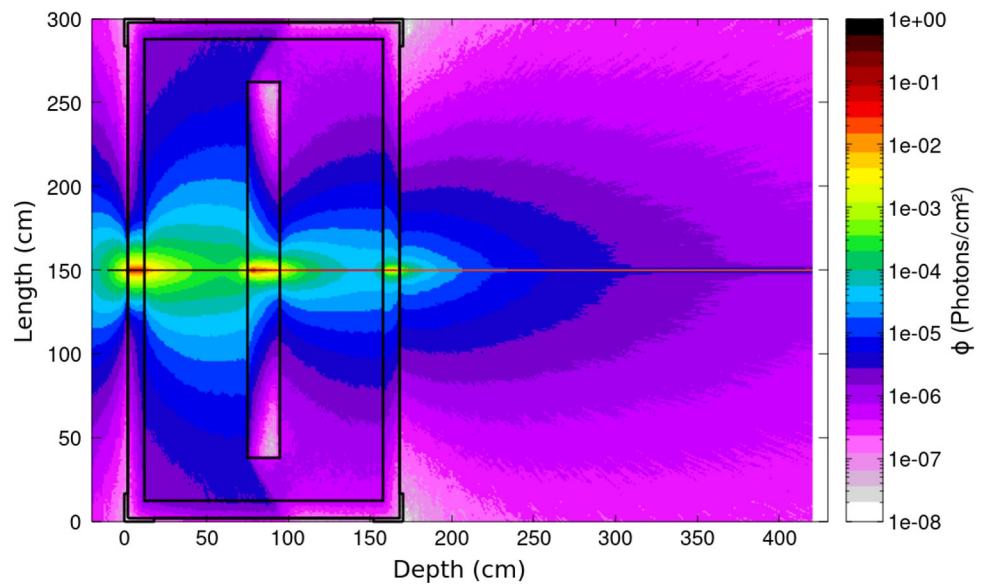


Fig. 18 Schematic of an RSA setup to determine, for example, the quantity of ^7Li in a container from the variation of the resonant γ -scattering signal downstream for situations with or without resonantly absorbing ^7Li material in the interrogated container. Its isotope ^6Li is used as a non-resonant normalization target. If ^7Li is present in the interrogated container, then the ratio of the resonant signal to the normalization signal is depleted relative to a situation with no ^7Li present in the container (indicated by the dark-blue area). Figure modified from Ref. [72]

any isotope present in such a container, which, in turn, is to be compared to the initial documented storage and predicted temporal evolutions following the decays of stored materials.

Medical imaging and treatment studies

The envisaged beams could be interesting for another line of application, namely the complementary use of intense electron and LCB γ -ray beams could be explored, e.g., for tumor treatment [89, 94]. For example, using the same electron beam, X-rays, and high-energy γ -rays could be provided. For X-ray production, the beam would

impinge a solid radiator target, and the resulting bremsstrahlung would be collimated. In this way, classic X-ray imaging could be performed, e.g., for tuning the beam position to the desired spot. Then switching on the laser interaction, the resulting γ -ray beam would irradiate the tissue. This concept could be further explored for future use as a medical application.

Towards the low-energy end of the γ -ray beams provided by DICE, further medical and technical applications comprise, e.g., the possibility of dual-energy X-ray imaging, see, e.g., Refs. [95–97] and Refs. therein.

3.2 Bremsstrahlung at the beam dump

Beams from bremsstrahlung have proven to be an invaluable tool in NRF for obtaining a broad view of the nuclear dipole response and for precise measurements of photonuclear cross-sections relative to calibration standards, since they provide a broad-range (“white”) continuous-energy γ -ray spectrum that can be interpolated between calibration points with little systematical uncertainties. The DICE facility is suited to encompass the full suite of photonuclear studies. Beyond the already mentioned LCB approaches, which are focused on exciting specific states or narrow-energy ranges, DICE can also offer a broadband γ -ray beam of bremsstrahlung at its final beam dump to obtain a broad picture of the nuclear photo-response over a broad energy range.

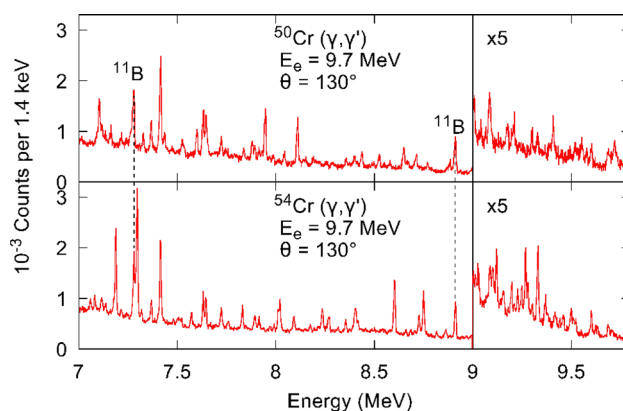
Photonuclear measurements with bremsstrahlung aid particularly in identifying the overall location of dipole-excited states, and offer a means to calibrate over that broad range by the measurement of unknown excited-state cross-sections of an isotope of interest relative to those of a calibration standard. An example is given in Fig. 19, showing a spectrum obtained with a HPGe detector during irradiation of a target isotope with a bremsstrahlung beam at the S-DALINAC. Over a broad energy range, even up to energies near 10 MeV, sharp peaks appear above the smooth background, stemming from resonantly excited states of the isotope of interest and of the reference isotope, ^{11}B , contained in the target. This allows the determination of scattering cross-sections for each of these γ -ray transitions over the full energy range by simply comparing the peak areas with the areal number density of nuclides present in the target.

With DICE, this scientific goal can be efficiently realized in a parasitic way, namely by using the decelerated electron beam at the beam dump during ERL operation. Instead of dumping the decelerated beam, which still carries energies around 10 MeV, it can be used to impinge on a dedicated radiator target, where it induces bremsstrahlung. The white bremsstrahlung spectrum can then be collimated and used to irradiate NRF targets of interest, surrounded by γ -ray detectors, just like in existing bremsstrahlung setups as available at the S-DALINAC [99, 100] or γ ELBE [101]. Nevertheless, due to the high current available at DICE, the latter provides significantly higher achievable intensities than available at the S-DALINAC or γ ELBE. Moreover, the pulse structure of the bremsstrahlung of 39.4 MHz provides new opportunities to search for nuclear isomers in the ns range populated by photonuclear reactions.

The maximum energy of such experiments would be dictated by the used ERL beam, hence by the energy of the decelerated electron beam. Should more dedicated settings be necessary for well-identified science cases, one could consider to either not fully decelerate the beam and use a partially decelerated beam extracted at an earlier point, or even use parts of DICE in a dedicated single-pass mode in order to deliver a beam of fully tuneable energy to the bremsstrahlung site. In many cases, though, bremsstrahlung beams up to an energy of about 9–10 MeV can be used to obtain information on the broad photo-response of nuclei, hence a parasitic use of the dumped beam would be a rewarding and easily-obtainable extension for DICE. The use would not be restricted to science cases, but bremsstrahlung beams can also be used for first broadband scans in applications.

Overall, both the γ -ray beams from DICE, bremsstrahlung and LCB, will complement each other in new photonuclear studies, surpassing what can be done at existing facilities in terms of reach in isotopes, reach in intensity,

Fig. 19 Spectra of decays of states of Cr isotopes, excited via bremsstrahlung γ -rays at the S-DALINAC, recorded with a HPGe detector. γ -ray transitions are observed over a broad range of energies, yielding cross-sections for each observed transitions. Reprinted with permission from Ref. [98] ©(2019), by the American Physical Society



and hence reach in physics problems to be addressed. Along with newly developed experimental methods, e.g., TRSA or photo-activation/-fission, it will provide an instrument to search for new physics in the photo-response of nuclei, to elucidate long-lasting problems such as the fine structure of the GDR/PDR, and offer means to test and perform in applications like scans for sensitive materials.

3.3 Further potential

In this paper, a concrete conceptual design of DICE was presented with the scope to serve an LCB experiment. Moreover, DICE will be capable of a variety of machine settings and experiments. Some further options are sketched in the following:

- There will be two main categories of machine operation:
 - Energy-recovery LINAC mode: DICE will be operated in ERL mode to achieve highest intensities for dedicated experimental setups. Utilizing the energy-recovery technology requires that the electron beam is only slightly affected in an experiment so that the beam can be guided back to the main LINACs for deceleration. Possible experiments are LCB (see Sect. 2.6) or the collision with an ion-beam (see Sect. 3.3.1).
 - Conventional mode: DICE will be operated in conventional accelerating mode with fixed-target experiments. The beam will be dumped at high energies downstream of the interaction, see Sect. 3.3.2.
- The maximum beam energy can be increased by adding additional SRF modules to both main LINACs and by applying a scaling of the magnetic strengths of magnets installed in the recirculation beamlines. The layout of the lattice can be changed and extended to allow for further experimental capabilities, see Sect. 3.3.3.

3.3.1 Electron-ion collider

Electron-scattering experiments on nuclei have proven to provide invaluable information on nuclear structure and quantities such as nuclear charge radii or transition densities for nuclear excitation, in the past, using electron beams impinging on stationary (stable) targets. The electron as an elementary particle with little rest mass and spin is an ideal tool to investigate the interior of the atomic nucleus, since it can deeply penetrate the nuclear matter. Hence, sensitivity to internal nuclear currents arises.

The concept of DICE will not only allow extracting electron beams in the classical way to deliver them to a target station (see Sect. 3.3.2), but, with the envisioned beam intensities, may also allow using internal or even non-stationary targets. Such targets could, for example, be hadronic beams like nuclei stored (in bunches) in a storage ring, which then collide with the high-intensity electron beam. Colliding-beam kinematics allows reaching particular regions of momentum transfer, which are accessible through scattering at small angles where the elementary Mott cross-section is high. This additional gain will, subsequently, make it possible to reach sufficient luminosities on the order of $10^{29}/(\text{cm}^2 \text{ s})$ to perform electron-scattering experiments even on unstable nuclei, for which the preparation of stationary targets would be impossible. This concept has been discussed in the ELISE project [102–104] at FAIR in Germany, and a first realization has been reached at SCRIT at RIKEN-RIBF in Japan [105, 106].

Physics goals can be the investigation of changes in nuclear shell evolution in nuclei far from stability (see, e.g., Refs. [107, 108]), density distributions within nuclei, in the extremes even the formation of “bubble nuclei” [109–112], benchmarking nucleon-stripping reactions with the non-hadronic electron probe and investigate quenching of correlations with proton-to-neutron separation energy asymmetry [113], or the study of neutron-skin formation and the equation of state through excitation and observation of respective nuclear resonances.

A determination of the neutron form factor and neutron radii is, besides its relevance for the understanding of nuclear structure and tests of nuclear theories, particularly important to constrain the neutron equation of state (EOS) close to saturation density. It has been shown in many theoretical papers, that the neutron-skin thickness is a very sensitive observable to determine the slope of the neutron EOS or symmetry energy: For example, Typel and Brown [114] calculated the neutron-skin thickness for ^{208}Pb for different Skyrme–Hartree–Fock and relativistic mean-field theories as a function of the derivative of the neutron EOS, or neutron pressure. A very pronounced correlation is observed, suggesting that an accurate measurement of the neutron-skin thickness will provide a precise constraint on the neutron pressure (close to saturation density). For neutron-rich exotic nuclei, the effect is more pronounced due to the development of larger neutron skins. For the doubly-magic ^{132}Sn nucleus, for instance, the predicted skin thickness for the same calculation is around 30 % larger [114], implying also that the slope of the increasing skin thickness as a function of $N - Z$ provides additional constraints on the slope of the neutron EOS. Further science cases for electron-ion collisions are provided in Ref. [102]. Fixed-target experiments on thin samples are briefly discussed in the next section.

3.3.2 Fixed-target experiments in classical electron acceleration

The DICE electron beam could also be used in a classical way, impinging on a stationary target, on the expense of energy recovery. The conventional mode, with the high electron beam intensities provided, would be ideally suited for electron-scattering experiments on stationary, stable targets as mentioned above. The physics scope would be similar as outlined for the (e, A) -collider option above, but extends the investigations to phenomena with much smaller cross-sections due to the much larger number of target nuclei, hence larger luminosity than what would be available in an (e, A) -collider. Examples for nuclear phenomena to become accessible are given by higher-multipolarity nuclear modes, and by a broad variety of exclusive electron-induced reactions with coincident detection of secondary particles, such as $(e, e'\gamma)$, $(e, e'f)$, $(e, e'n)$, or $(e, e'x)$. This, in turn, gives access to entirely new research programs that could not have been addressed so far, because of lack of experimental opportunities. Such options have started to demonstrate their scientific potentials already at much lower luminosity.

For example, the combination of γ -spectroscopy with electron-scattering experiments, $(e, e'\gamma)$, has recently been established at the S-DALINAC [115] and first demonstrated to be applicable to heavy open-shell nuclei. In such experiments, the spectroscopy of the outgoing electrons allows setting a condition on the excitation energy of the nucleus, whereas the simultaneous measurement of emitted γ -rays then singles out decays from certain excitation-energy regions. Such studies are ideal for quantifying γ -ray strength functions that are required for large-scale nuclear simulations. The method can be applied to certain structural phenomena, like specific excited states that get selected, or to scans of (giant) resonances and determination of their γ -decay behavior, or even their particle decay and population of excited states in daughter nuclei, even beyond the dominant dipole resonances like the GDR or Spin- $M1$.

Another opportunity for DICE could be the placement of relatively thin targets or gas jets in its beam in ERL mode. Such experiments with an internal target, in particular gas jet targets, are intended at MESA at Johannes Gutenberg-Universität Mainz [116]. DICE, albeit not primarily designed for it, could extend the range of available momentum transfers on the gas jet targets compared to MESA due to its significantly higher energy.

Electron-induced fission reactions may be studied at DICE on radioactive targets of transuranium elements. Improved microscopic theory for actinides and the role of fission reactions in terminating the rapid neutron-capture process (r -process) of cosmic nucleosynthesis [8, 117] have recently lead to a revival of scientific interest in the details of nuclear fission reactions. The cosmic synthesis of heavy elements through the r -process has been proven through the recent observation of a kilonova event by the new approach of multi-messenger astronomy [118, 119]. Evidence for the synthesis of actinides in such events is still missing. Searches in this direction enjoy high priority. Most of them rely on detailed measurements of or predictions for the properties of the fission reactions, such as their γ -ray yield and their fragment mass distribution. At DICE, heavy radioactive isotopes of interest with half-lives down to a few hundred years could be studied in electrofission reactions. Their excitation energies can be determined using standard electron spectrometers. At sufficient excitation energy close to the maximum of the barrier, fission processes would set in, and the resulting mass distributions and kinematics could be studied with high statistics, e.g., as a function of excitation energy and momentum transfer. This offers a unique approach to nuclear fission, complementing the method of photofission (see Sect. 3.1.3), neutron-induced, or ion-beam-induced fission studies. Concepts for dedicated experimental setups for electrofission studies have recently been developed at TU Darmstadt [120].

Making use of extracted beams, secondary radiation from γ -induced reactions could be provided to users investigating surfaces and condensed-matter physics, in particular neutrons (comparable to the nELBE setup at HZDR [121]) or positrons (cf. Ref. [122]). We note that from GaAs, cathodes polarized electrons could be provided whose polarization can be transferred to positrons [123], thereby opening a wide variety of applications, e.g., in surface and material sciences (see, e.g., Ref. [124] for an overview). With high electron currents, also neutron-rich isotopes could be produced, either by photofission or electrofission mechanisms, in sufficient quantities for their harvest and further scientific usage, e.g., in dedicated ion traps or eventually, depending on required luminosity and production cross-section, for (e, A) -collisions as mentioned in the previous section.

Therefore, with dedicated electron spectrometers optimized for requirements for high-energy resolution and high acceptance, and a suite of dedicated ancillary detectors or additional infrastructure, precision studies on stable isotopes or radioactive species could be performed with DICE, complementing data obtained on the photo-response of nuclei that provide information on nuclei “at the photon point”. This would enrich and complement a physics program focused on photonuclear reactions—the primary goal of DICE.

3.3.3 Options for alternative parameters and layout

The parameters and the layout of DICE presented in this manuscript are one initial choice that was selected for a concrete discussion of the potential of DICE and the feasibility of its realization. Other options for the parameters may be considered or preferred depending on the goal of the facility. Depending on user interest, funding schemes, space limitations, or institutional framework hosting such a facility, the operational parameters and the layout of

the DICE energy-efficient electron accelerator can be adapted. In this subsection, we sketch potential modifications to the basic lattice of DICE for expanded technological and scientific capabilities. Some of them have already been addressed briefly above.

Upgrade of the LCB source: In general, there are many knobs to optimize the different parameters of the source, e.g., electron beam repetition rate, emittance, bunch charge, etc. This will be studied in more detail during the conceptual design. For the current state, there exist two main options based on the presented design (see Tables 5 and 6):

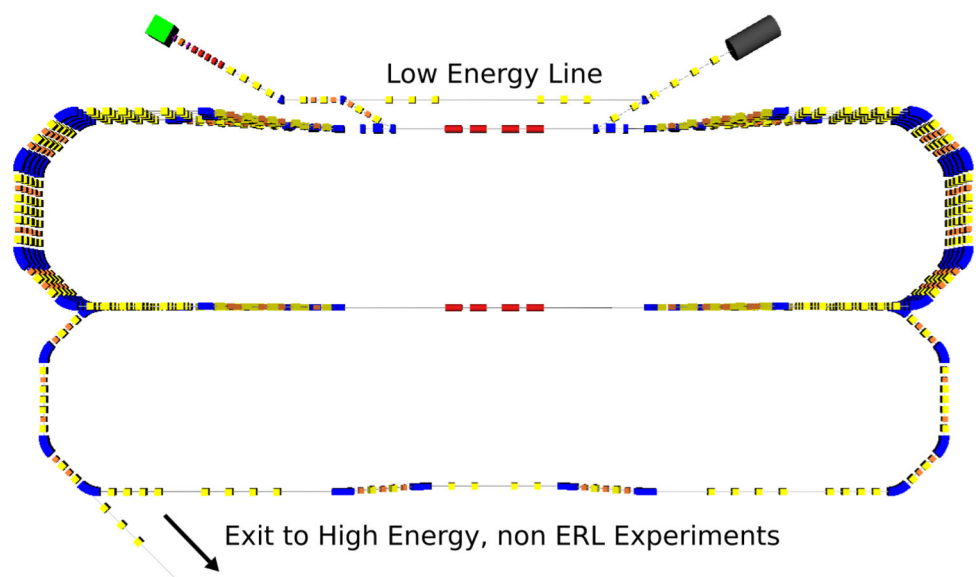
- **Increase in γ -ray energy:** The electron beam energy could be raised to 800MeV (from 520MeV) by adding additional SRF modules to the main LINACs and by applying a scaling of the magnetic strengths of magnets installed in the recirculation beamlines. With the same three laser systems, the resulting γ -ray beam will have maximum energies of 11.6MeV (IR), 22.9MeV (green) and 33.9MeV (UV). These γ -ray energies will provide better and complete access to nuclear isovector GDRs across the entire nuclear chart, and will allow obtaining a data point even at higher energies than relevant for the GDR for cross section calibration.
- **Increase in the γ -ray flux:** The bunch charge of the electron beam may be increased to 80pC (from 20pC) by modifications of the gun. A comparable bunch charge of 77pC has been achieved in Ref. [44]. In this way, the achievable values for the γ -ray flux will increase by a factor of four. This optimization allows reducing target masses for photonuclear reactions by a factor of four for achieving the same luminosity, or potentially increasing the precision of the measurements by higher count rates.

High-energy, non-ERL experiments: The beam could be extracted to other experimental areas instead of being recycled after the interaction point in ERL mode. A layout is presented in Fig. 20. This obvious and simple modification to the basic lattice presented in Fig. 1a allows the usage of DICE as a state-of-the-art high-current conventional electron accelerator. Fixed-target experiments as discussed in Sect. 3.3.2 can be operated here.

Energy-tunable, stand-alone NRF experiments up to 10 MeV: In the presented design of DICE, NRF experiments are possible as parasitic experiment during ERL operation, utilizing the facility very efficiently. A drawback of this scheme is the fixed energy for NRF, always being the energy the injector accelerator has to be tuned to for the ERL setting. One additional option could be to have a shortcut directly downstream of the injector accelerator to the injector beam dump line, where an NRF setup could be installed. This shortcut (low-energy line) is also shown in Fig. 20. It would enable a versatile tunable beam for NRF experiments without having to use the full facility. In such an operation, there would be the option that the rest of the facility is shut down for maintenance.

Expansion of experimental capabilities to an (e, A) -collider: DICE will be operated in ERL mode as presented in this paper. After decelerating the beam down to injection energy, it will be transported further instead of being dumped. The slowed-down ERL beam will be cleaned for further transport and accelerated to up to 25MeV in a booster module. At this energy, it is stopped in a dedicated target to produce radioactive ion beams via photofission. A setup like at ARIEL at TRIUMF in Vancouver, BC, Canada [125, 126] can be used.

Fig. 20 Schematic layout of DICE with a high-energy exit. Fixed-target experiments can be operated here. Also a low-energy line was added as shortcut for directly using the injector beam for NRF experiments



The produced radioactive ions are then accelerated and transported to a storage ring to be stored. The electron beam of DICE running in ERL mode is at the same time used for a collision with these ions.

Integration of a FEL for lithography applications: Another ideal application for use with an energy-efficient ERL layout are FELs. Depending on the electron energy and design of the undulator that initiates the FEL process, FEL radiation sources range from μm to sub-nm wavelengths [127]. Extreme ultraviolet (EUV) radiation that falls into this very broad range of wavelengths is presently discussed for lithography applications. “Next generation” lithography targets wavelengths around 5–10 nm [128]. This wavelength window may be in reach for a dedicated setup at the DICE facility, provided (a) sufficient space is available, (b) the beam energy is increased to about 800 MeV (see above in paragraph “Upgrade of the LCB source: Increase in γ -ray energy”), (c) the system is operated with a subharmonic injection with increased bunch charge, potentially requiring an (S)RF gun as electron source. One example of such a setup and its applications is discussed in Ref. [128].

4 Summary

Scientists need to take an efficient usage of energy resources for their scientific research seriously. The emerging research field of nuclear photonics draws from the availability of intense, MeV-ranged, quasi-monochromatic, fully polarized photon beams. These photon beams for photonuclear research and applications can be produced by the scattering of laser light from a beam of electrons at ultra-relativistic energies. High spectral densities of the MeV-ranged photon beams from LCB benefit from minimum emittance of the electron beam, such as it can be provided by a linear accelerator. Since the Thomson cross-section for an interaction between a photon and an electron is comparatively small, the interaction rate is limited. This, on one hand, requires highest possible electron beam currents for achieving a high intensity of the MeV-ranged photon beam and lets, on the other hand, a significant part of the electron beam pass the interaction region with the laser unreacted. Their ultra-relativistic energies would be wasted if not recovered and recycled.

This contribution presents a concept for an electron linear accelerator optimized for the production of intense, MeV-ranged, quasi-monochromatic, energy-tunable, fully polarized photon beams for reduced energy consumption. It makes use of the concept of energy recovery by decelerating the beam after its interaction in the experiment. The deceleration in the electromagnetic fields of the accelerator’s SRF modules contribute thereby to driving the RF-fields and allowing for a reduced need of externally provided RF power for the accelerator’s operation. This requires superconducting RF modules such that the recycled energy is not wasted on ohmic losses while the power consumption footprint is kept at a modest level without compromising on the photon beam’s intensity and spectral density.

We provide a quantitative conceptual design for a thrice-recirculating, SRF ERL with individual beam transport, focusing primarily on its use as a driver for a source of intense, MeV-ranged, quasi-monochromatic, energy-tunable and fully polarized photon beams. We chose a certain set of accelerator parameters as a specific example. We considered a maximum electron energy of 520 MeV to be accelerated (and afterward decelerated) by electromagnetic fields oscillating in superconducting cavities at a radio-frequency of 1.3 GHz. We further considered electron bunch charges of up to 20 pC for example, resulting in a maximum electron beam current of up to 26 mA when every RF bucket is filled by a bunch. Our conceptual design is restricted to the longitudinal beam dynamics and dispersion simulations as these are the key challenges in the design of such a machine. Detailed analyses of the transverse beam dynamics are outside of the scope of this presentation. We consider the bunch charge of 20 pC to be sufficiently small for not posing too severe technical challenges. For photon beam production, we considered an operation mode in which only every 33rd RF bucket is filled, resulting in electrons periodically arriving at the laser-interaction point at a repetition rate of 39.4 MHz corresponding to an average current of 0.79 mA. That frequency can be well matched to the frequency of an intense interaction laser and is well suited to be beneficially operated in coincidence with typical radiation detectors in experimental setups. Utilizing an optical cavity for photon-beam production with a power gain of 5000, we expect unprecedented spectral densities on the order of $10^5 \gamma/(\text{eV s})$ on target for photon energies around 5 MeV with the aforementioned repetition rate. This Design concept of an *Individually-recirculating Compact ERL*, short DICE, is discussed.

Options for its scientific exploitation are sketched. The anticipated intense photon beam would provide a variety of unprecedented research opportunities for photonuclear reactions and their applications. Traditional methods will become applicable to samples with much smaller sizes than before, expanding the reach of photonuclear reactions. New experimental methods will become available or may be developed. Nuclear observables will become accessible by photonuclear reactions or can be obtained with unprecedented precision for new scientific insights. Examples for these advances have been provided. They document the science potential of a facility such as DICE. While the design task and primary application focuses on photonuclear reactions with an LCB γ -ray beam driven by a multi-turn ERL, the application potential and experimental versatility of such a facility is much broader, and related to “classic” electron scattering, radioactive-beam physics, medical applications, solid-state investigations,

material science, nuclear engineering studies, and many more. Many of these aspects could be addressed by DICE within an energy-efficient approach that is needed for science exploration in the second half of the 21st century.

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Data availability Data are contained within the article.

Declarations

Conflict of interest The authors declare no conflict of interest.

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