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Helmholtz Young Group Investigator proposal

Beam Dynamics and Collective Effects in the Generation and Propagation of Structured Beams for Advanced Accelerator-based Radiotherapy

Introduction

Particle accelerators nowadays play a vital role in a multitude of scientific fields. They have become highly complex over time and with them the field of accelerator physics. New developments are continuously pushing the understanding and the technological limits towards increasingly extreme beam properties. In electron accelerators, this includes ultra-short pulses at high intensities in linear accelerators or free electron lasers as well as transversely narrow pulses for ultra-low emittance synchrotron light sources. The extensive research conducted today aims for a deep understanding of the involved beam dynamics occurring in these extreme beam conditions and the required diagnostics. The extreme conditions lead to strong effects caused by the coexistence of many particles in the densely populated pulses. This is summarized under the term collective effects. They describe self-interaction of particles within the beam as well as the interaction with the environment, both of which are dependent on the detailed particle distribution. The study of collective effects is an active research topic and has been the main focus of my research in the last years.

At the same time, the current development of two advanced approaches in accelerator-based radiotherapy (RT) pushes in the same direction of high intensity beams with temporal or spatial structuring. FLASH RT is based on the delivery of very high doses in short pulses and Microbeam RT focuses on spatially fractionated beams. In both methods, a significant widening of the therapeutic window is observed. The resulting normal tissue sparing effect is expected to improve treatment outcomes and reduce overall toxicity for the patients resulting in a better quality of life after treatment. The beam properties used for FLASH and Microbeam RT go beyond the prediction and beam diagnostic capabilities in conventional RT. One difficulty is the increasing non-linearity in the response of usual dosimetry methods at high dose-rates. The increased requirements on dosimetry as well as on the overall diagnostics and simulation of the beam dynamics in the accelerators used for beam generation open up new challenges and possibilities. At the same time, the extreme beam properties in the novel radiotherapy methods require to push the understanding of the involved complex beam dynamics and collective effects in this active and exiting research field.

The proposed project therefore aims at improving the understanding, predictability and control of the accelerator-based electron beams involved in FLASH and Microbeam RT. The entry point will be to extend the research on collective effects in accelerators to cover the beam properties required for FLASH and Microbeam RT, profiting from my expertise in this field. Subsequently, this project will expand the study beyond the particle accelerator into the beam-matter interaction up to the target tissue. The influence of collective effects during the transport from the accelerator through matter onto the target, which up until now was sparsely studied, will be explored in detail. Based on these studies, the effective relation of input particle distribution to the dose distribution on target will be explored. This enables, the attempt to solve the inverse problem, i.e. determining the required input distribution for a desired dose distribution on target. First tests of targeted beam shaping will be a part of this project. With this kind of control, the outcome of the project will be a significant contribution to FLASH and Microbeam RT as well as to the general advancement of accelerator physics.

Contents

1 Research Goals and Expected Outcomes?

2.2 Objectives

The extreme pulse properties in FLASH and Microbeam RT lead to several open questions to be answered. The high dose-rates achieved have a strong effect on the underlying mechanisms: from the improved biological interaction with healthy tissue being the main advantage and driving point, to the increased non-linearity in dosimetric measurements, high requirements in beam based diagnostics, and the presence of complex dynamics and self-interaction leading to collective effects in the accelerator-generated particle beams. Collective effects in radiotherapy beams have yet to be investigated. Thinking further, collective effects acting on the beam can lead to significant deformations of the charge distribution and therefore of the produced dose distribution, resulting in the need for mitigation or compensation and ideally shaping of the generated RT pulse. Which, under certain conditions, might be extendable to generate modulated beams for Microbeam RT directly in the accelerator.

The main goal of the proposed project is to provide a fast and comprehensive assessment of radiotherapy beam properties and the resulting deposited dose on target as well as improved control thereof. Due to the high flexibility of electron research accelerators and the possibilities of beam shaping at beam generation, this project primarily focuses on electron based beams, with the possibility for transfer later on to heavier particles, contributing to the active research conducted on FLASH and Microbeams RT.

The following four objectives are selected:
I. Increased predictability of RT beam properties on target by development of start-to-end simulation including collective effects
II. Improved insight into the influence of temporal or spatial pulse modulation on detection and diagnostics to provide recommendations for applicable methods depending on beam parameters
III. Exploring the possibilities and defining the physical limitations of accelerator-based pulse shaping and modulation
IV. Investigating methods and algorithms solving the inverse problem, i.e. calculating the required initial beam distribution from a desired beam shape on target (based on I. - III.)

These objectives will be achieved by investigating the influence of collective effects on the beam generation, beam transport, beam-matter interaction and diagnostics in novel electron radiotherapy methods with temporally and spatially structured beams. Therefore, different interactions of beam particles with one another, described as collective effects, will be considered and incorporated into theoretical calculations and simulations of the transport of the particle beam from start-to-end, not only within the accelerator but also extended to the transport through matter (e.g., air or water) (objective I.). Furthermore, systematic studies on the dependence of different detection mechanisms and diagnostic tools on temporal and spatial pulse shapes combined with varying intensity will give insight into which diagnostic tools are suitable to aid in reliably delivering the desired conditions (objective II.). The investigation on the possibility to modulate the beam in the accelerator will pursue and compare different methods which will provide different temporal and spacial modulations. It will also entail studies on which modulations can be achieved on the final target when taking the transport through matter into consideration (objective III.). Employing the improved and extended simulation (from the first objective) to predict the resulting distribution on the target, might allow to consider the effects of the beam transport already during the generation of the beam. And if successful, this could enable the generation of a temporal and spatial particle distribution which preemptively compensates for the deformation expected during the propagation of the particle distribution from generation to the target. As a result, it would become possible to generate (within certain parameter limits) user-definable final particle distributions on the target (objective IV.).

2 Relation to Helmholtz Mission and Programme?

3 Relation to Research Programme of IBPT and KIT?

2.6 Justification for the choice of host institution(s)

The Karlsruhe Institute of Technology (KIT) provides an exceptionally well-suited research environment with an unique combination of multidisciplinary research infrastructures and strategic collaborations between institutes in complementary research fields as well as with external institutions. KIT provides the opportunity to combine academic and fundamental research with application-based and goal-oriented research. For me, the possibility to profit from the motivation and ingenuity of students and early-carrier researchers and at the same time from the access to large-scale research facilities, is an attractive combination. The interdisciplinary KIT Center “Health Technologies” is an interesting addition to the KIT research landscape opening new possibilities and has been one of the inspirations for investigating accelerator physics in the context of radiotherapy within the proposed project.

Another piece of the puzzle is the research bridge “Medical Technology for Health (MTH)” as part of the longstanding strategic partnership with the Heidelberg University HEIKA (Heidelberg Karlsruhe Strategic Partnership). The resulting, close connection to the Heidelberg Ion-Beam Therapy Center (HIT) at the University Hospital Heidelberg and the German Cancer Research Center (DKFZ) offers the project the collaboration with experts in radiotherapy and medical physics, such as Prof. Dr. Oliver Jäkel and Prof. Dr. Dr. Jürgen Debus, and furthermore provides the possibility for experimental studies with protons or ions at the experimental area of the accelerator complex at HIT. Furthermore, a joint master program in biomedical engineering in cooperation with the University Heidelberg is planned to start in the winter semester 24/25 strengthening this important research area by attracting young talents. The initiators behind this program would welcome my contribution towards lectures and supervisions of potential students. Additionally, members of the physics faculty such as dean of studies Prof. Dr. Quast and former vice-dean Prof. Dr. Husemann have declared their support for my involvement in a newly planned module of lectures on physical foundations of technologies.

The Accelerator Technology Platform (ATP) at KIT combines KIT-internal expertise and infrastructures relevant for accelerator research, development and application. This includes among others experts and infrastructure on advanced detector technologies studying, for example, ultra-fast and radiation hard detection systems, which offers the possibility for collaborations on newly-developed detector systems. With the proposed project relying on the possibility to conduct systematic measurements on accelerators and beams, KIT with the Institute for Beam Physics and Technology (IBPT) is an ideal environment in that it provides easy and extended access for in-house researchers to its electron accelerators. Both accelerators serve as accelerator test facilities leading to a high flexibility in beam conditions and the possibility to tailor operation modes to experimental requirements. To this end, the accelerators are equipped with extensive, state of the art diagnostics. The 2.5 GeV storage ring and synchrotron light source KARA (Karlsruhe Research Accelerator) provides short x-ray pulses. Additional operation modes have been implemented, for example, a short-pulse operation for the investigation of the dynamics in short bunches as well as the development and tests of novel, fast diagnostic methods. The second accelerator is the linear electron accelerator FLUTE (Ferninfrarot Linac- und Test-Experiment). It is designed to provide ultra-short electron pulses with an energy of around 6 MeV after the low-energy section and with energies of up to 50 MeV and bunch lengths down to femtoseconds after the full accelerator. The electron pulses in FLUTE are generated with a femtosecond chirped laser-driven photo-injector. Of great importance for the proposed project, is the recent implementation of a spatial light-modulator which allows spatial and temporal shaping of the laser pulse and therefore control of the initial electron distribution. A 50 MeV laser-plasma accelerator is being built as part of the ATHENA project. This will open the opportunity to test the developed simulation and diagnostic methods on a different type of accelerator and investigate the possibilities and limitations of LPA beams for radiotherapy in cooperation with the newly established group from Prof. Dr. Matthias Fuchs. Last but not least, KIT offers a strong background in mathematical and computational science with the Scientific Computing Center (SCC) and the KIT Center ”MathSEE” (Mathematics in Sciences, Engineering, and Economics). The KiT-RT (Kinetic Transport Solver for Radiation Therapy) [18] simulation code has been recently developed by the research group Computational Science and Mathematical Methods (CSMM).

Even with KIT being my alma mater, I am convinced that KIT offers an unparalleled opportunity, based on the multidisciplinary research environment, the close collaboration with the university Heidelberg and the Heidelberg ion-therapy center and new additions such as the KIT-Center “Health Technologies” and is therefore the best-possible choice as host institution for the proposed project. The direct and timely access to flexible accelerator test-facilities generating ultra-short pulses of high energy electron and photon beams within the same institution is a strong advantage. In combination with the detector experts in engineering science, it is a perfect fit for the experimental part of the project. The new additions and developments at KIT as well as the wide variety of research fields promises multidisciplinary input and solution-finding in an inspiring, dynamic and nurturing environment for me to successfully establish myself as junior research group leader. Embedded in one of Germany’s leading healthcare and technology regions, the proposed project will be especially well positioned to provide an important contribution towards the advancement of novel accelerator-based radiotherapy methods.

4 Current Status of Research?/State of the art and preliminary work?

4.1 State of the art: radiotherapy

Radiotherapy (RT) has always been a very valuable tool in cancer treatment [1]. In Europe, radiotherapy is recommended as part of the treatment plan for more than 50% of cancer patients [2]. Reducing side effects while maintaining or even enhancing treatment efficacy in the future will improve the quality of life of the patients. Radiotherapy uses ionizing radiation to damage the DNA within the tumor cells, which prevents the cells from reproducing and eventually leads to their death. The external beam radiotherapy (EBRT) is based on accelerator-generated high-energy beams delivering a targeted dose of ionizing radiation to the affected area. As some areas of healthy tissue are unavoidable irradiated the dose rate is carefully chosen to keep a balance between tumor control and normal tissue tolerance. The range between radiation doses that effectively destroy cancer cells while only causing minimal damage to healthy tissue and organs is called the therapeutic window [3]. A widening of this window is one of the main goals of present day radiotherapy research.

FLASH RT is a novel approach which focuses short pulses with very high dose rates to enhance tumor cell lethality while minimizing damage to surrounding healthy tissue. In conventional external beam RT typically around 30 fractions with 1.8 - 2 Gy per fraction are delivered with a dose rate ranging from 0.2 to 20 Gy/min. For FLASH RT, dose rates of more than 40 Gy/s (=2400 Gy/min) were observed to be effective in combination with pulse trains shorter than 500 ms and a total dose of 10 Gy or more [3]. The resulting significant widening of the therapeutic window (see Figure 1) allows a higher dose per fraction than in conventional radiotherapy without causing severe side effects, such as acute normal tissue reactions or long-term complications. Several suspected mechanisms behind the beneficial FLASH effect [4] are being investigated. And while the exact mechanisms are not yet fully determined, the effect has been experimentally demonstrated for irradiation with photons, electrons and ions. The presented project will primarily focus on electron beams.

The high dose rates result in difficulties with standard dosimetry techniques showing deviations from the required linear detection efficiency [5]. So is, for example, the Fricke dosimetry nearly independent of does rate up to approximately 2 Gy per pulse, which is exceeded under FLASH conditions. Therefore, the primary standard for dosimetry in conventional electron RT is not applicable to FLASH RT. To this end, the effects leading to the observed deviations between expected and detected dose are under investigation and new dosimetry calibration procedures and detectors are being tested [6]. Recent work has, for example, included further investigations of ion-recombination in ionization chambers including improved ways of calculating the recombination correction factors [7]. In addition, systematic tests of possible, alternative detection mechanisms such as solid-state calorimeters and small-volume and active dosimeters were conducted [5], [8]. Active detectors and real-time diagnostics become increasingly relevant as well for beam monitoring as each of the few high dose pulses carries a non-negligible amount of the total dose described for treatment, increasing the required per shot accuracy as fluctuations in dose per pulse no longer average out. Besides the obvious need to establish accurate dosimetry methods, the prediction of the expected dose on target can be improved by including collective effects into the simulations. This will be described further in the state of the art: accelerators and collective effects section. For most standard medical accelerators the FLASH conditions are challenging if not impossible to achieve, requiring substantial improvement or the development of dedicated FLASH accelerators [9]. In the meantime, dedicated accelerator facilities with compatible beam conditions are employed as test-beds.

Another possibility to achieve reduced normal tissue damage are spatially structured beams used in **Microbeam Radiotherapy (MRT)** [10]. The spatial intensity modulation at the micrometer scale has shown the potential to widen the therapeutic window. The underlying biological mechanisms are suspected to have significant overlap with the mechanisms behind the FLASH effect due to the similarly high dose and dose rates in the micron-sized individual beamlets in the array of parallel microbeams [10]. Earlier studies with electron GRID radiotherapy [11] and recent studies with protons showed promising results in the sparing of healthy tissue [12]. Nevertheless, most studies on MRT have been conducted with X-rays. The unidirectional microbeams with spot sizes of 25 - 100 $\mu\mathrm{m}$ and a spot spacing of 50 - 200 $\mu\mathrm{m}$ are produced by inserting a multi-slit collimator into an x-ray beam with very small divergence produced at a 3rd generation light source [13]. This dependence on large infrastructure synchrotron sources is one of the main challenges in MRT today. With most research focusing on the modulation of the beam outside the accelerator close to the target area, accelerator-based electron beam modulation remains an open research question.

In summary, it can be concluded, that the high temporal or spatial structuring for both novel radiotherapy methods, FLASH RT and Microbeam RT, leads to an increased complexity in the diagnostics of the beam properties and the dose as well as in the generation. In addition to the capability to generate and diagnose beams for FLASH RT, also the beam dynamics under the extreme beam properties need to be investigated in great detail to understand and simulate the resulting effect on the beam properties on target.

4.2 State of the art: accelerators and collective effects

As discussed above, the requirements of new advanced radiotherapy methods on particle accelerators are high and current research on FLASH RT is consequently mainly performed on dedicated accelerator research facilities with a focus on electron accelerators. The additional advantage is the possibility to benefit from the flexibility in operation parameters, such as variable pulse length or intensity, and the

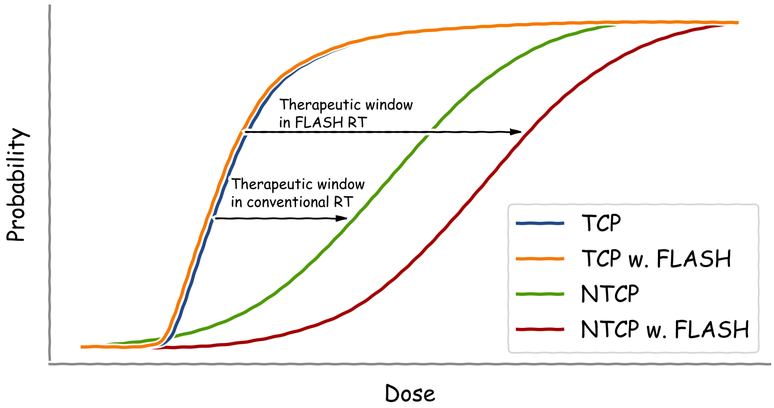

Figure 1: Sketch of the therapeutic window increasing as normal tissue complication probability (NTCP) is shifted to higher dose for FLASH RT and tumor control probability (TCP) remains.

higher degree in versatile instrumentation and diagnostics. This allows systematic studies and parameter mappings to assist the search for the best suitable parameter set for a widening of the therapeutic window. Furthermore, at current RT accelerators, the diagnostic measures focus mainly on the dose detected after the accelerator. The wide range of fast and accurate diagnostics available and employed in research accelerators opens up access to fast and extensive information on the beam properties, such as charge, energy, position, pulse shape, and more [6]. The proposed project will exploit this further than currently done to increase the extend of monitoring and control over the produced pulses and to provide recommendations on the most suited, complementary diagnostics methods for RT.

In general, research accelerators cover a wide variety of different use-cases and machine types, with circular and linear accelerators (linac) being the most common types. Over all, the beam properties can range from continuous beams to bunched beams consisting of particle packages (bunches), from MeV to several GeV or for colliders even TeV beam energies, from artificially elongated bunches with very narrow transverse sizes and divergence (ultra-low emittance [14]) to wider but ultra-short bunches down to femtosecond pulse durations [15]. For electron accelerators, the electrons are either generated via thermionic emission or with a laser pulse on a photo-cathode. The latter case provides control over the pulse length as well as the transverse distribution of the generated initial electron bunch by modulating the incident laser pulse [16]. This offers further possibilities for studies of spatially structured pulses and the possibility for accelerator-based beam modulation of radiotherapy beams will be investigated within this project.

In a continuous effort, research accelerators are characterized to a higher and higher degree with regards to a wide variety of effects including complex contributions to the beam dynamics such as collective effects. In general, the dynamics of accelerated particles is influenced by fields of different origin. External magnetic fields are applied for guiding and focusing the particle beams as well as external electromagnetic fields which are used for the basic acceleration itself but also for fast deflection in the context of diagnostics or for shaping the longitudinal charge distribution by so-called higher harmonic cavities resulting in complex shapes of the electromagnetic potentials. These dynamic boundary conditions lead to complex, non-linear dynamics of the accelerated particles. On top of this, self-generated electromagnetic fields act back on the particles and on the surrounding material. These self-interactions and interactions with the environment depend on the number and distribution of the particles within a bunch and are therefore often referred to as collective effects [17].

Each charged particle is surrounded by its electromagnetic field. The field interacts with all nearby materials such as a vacuum chamber, matter it passes through and also neighboring particles within the same bunch. These interactions can result in a force acting back on the charged particle leading to a change in movement direction or energy. The effective resistance that the charged particle experiences due to these interactions are described with frequency dependent impedances. Furthermore, in the same way one particle affects all neighboring particles, each particle is affected by the superposition of the fields of all other particles within the bunch. The resulting fields are referred to as wake fields and depend directly on the distribution of the charged particles in a bunch as well as on beam energy and the material properties of the surrounding structures. Both quantities are connected, as the impedance Z multiplied by the Fourier-transform of the charge distribution $\tilde{\rho}$ equals the Fourier-transform of the wake field V [17]: $V\left(t\right) = \int_{-\infty}^{\infty} \tilde{\rho}\left(f\right) Z\left(f\right) e^{i2\pi f t} \mathrm{d}f$ This equation also directly shows, that depending on the shape and length of the particle distribution, the overlap in frequency with the impedance changes and therefore affects the resulting strength of the self-generated electromagnetic field.

Collective effects cause various issues in accelerator beam dynamics, such as emittance growth, energy loss, beam instabilities, overall degradation of performance and deformation of the temporal and spatial shape of the particle bunch. The mitigation and control of these effects is an ongoing topic in accelerator physics and advanced models and algorithms are developed to predict the influence of collective effects on the particle beams throughout the entire system. Collective effects have not been considered in the past in conventional accelerator-based RT due to the rather long pulses and therefore low momentary intensity and dose-rates. Furthermore, they are typically not included in calculations of the beam transport through matter often based on Monte Carlo or particle tracking. Common simulation tools include FLUKA, EGSnrc, BDSIM or the KiT-RT (Kinetic Transport for radiation therapy) framework designed for easy extendibility [18]. The inclusion of collective effects into the beam-matter interaction calculations is going to be an important topic within this project. Examples of collective effects with potential relevance for RT beams include space charge wake fields [19], coherent synchrotron radiation (CSR) [20] and resistive-wall wake fields [21] and are present in both circular and linear accelerators. The presence of these effects leads to instabilities like intra-beam scattering, the transverse mode-coupling instability

[22], micro-wave instability [21] and the micro-bunching instability [23], all of which I have studied in electron storage rings in the past, as described in the following.

4.3 Open questions and challenges? not here???

Some of the aforementioned most pressing questions and challenges for accelerator-based FLASH RT and Microbeam RT are listed below:

- With the FLASH effect not yet fully understood, the optimal dose and dose-rate parameters are still to be determined.
- The high dose-rates result in a non-linear dependence in the dosimetry standards.
- Time resolved diagnostics to determine the shot to shot accuracy are required due to small number of high dose pulses.
- The expected influence of collective effects on the beam dynamics during generation as well as during the beam transport through matter in not commonly considered.
- The production of structured beams for Microbeam RT poses a challenge.

In general, a sound understanding of the effects involved in the dynamics of temporally and spatially structured RT beams is required for the generation, the propagation as well as the detection of the resulting high dose-rate pulses. Identifying the contributing collective effects and shedding more light onto their deforming influence is therefore crucial to accurately predict the particle, and therefore, dose distribution on target.

4.4 Previous relevant work of Dr. Brosi?/Preliminary work on beam dynamics, collective effects and diagnostics

In the last years, I have performed systematic studies of the longitudinal as well as transverse collective effects and instabilities influencing the bunch shape in all dimensions. The main goal was to investigate phenomena occurring under extreme operation modes to understand and circumvent resulting performance limitations while contributing to the general advancement of the field. The studied conditions included high charge in single bunches, dedicated short bunch-length operation modes at the storage ring KARA [24] and small transverse bunch-sizes in the ultra-low emittance synchrotron light source MAX IV [21], [22], all conditions prone to instabilities leading to dynamic sub-structures in the charge density of the bunches. For the investigations, I conducted experimental studies and systematic simulations.

To evaluate the expected collective effects in the context of this proposal, simulations will be a valuable tool for which I have gained extensive experience in my previous research. For example, my studies of the micro-bunching instability, which occurs at bunch lengths in the order of several picoseconds or less, showed for example, an additional region of instability for certain parameters at lower bunch charge as predicted by the text-book equations [24]. To perform the theoretical calculations, I used the Vlasov-Fokker-Planck solver Inovesa [25], which simulates the longitudinal dynamics under the influence of the coherent synchrotron radiation impedance. To this end, the particle density distribution in the longitudinal phase space is calculated via the Vlasov-Fokker-Planck equation for each time step. I was involved in the scientific conceptualization of the code as well as testing the software and extensive benchmarking against measurements to assess the correctness of the results. Later, I extended the simulation to also include the influence of the geometric and resistive-wall impedance for studies of the micro-wave instability at MAX IV [21]. With these simulations I could very well reproduce the deformations in the longitudinal bunch shape observed experimentally (see Figure 2). This again proved the potential of Inovesa to simulate the temporal development of the particle density distribution under the influence of collective effects caused by different types of impedances. Another simulation method capable of calculating the development of a particle bunch under the influence of collective effects is particle tracking, where the individual particle paths are calculated opposed to the particle density in Inovesa. Using the particle tracking tool mbtrack2 [26], I could recently show in simulations as well as in measurements that for certain settings in the accelerator's magnetic lattice, a single-particle dynamics effect can be used to reduce the impact of the collective effect underlying the transverse mode-coupling instability [22]. This instability is caused by transverse wake fields and can lead to drastic beam blow ups resulting in complete loss of particles. The capability to prevent resulting particle losses reveals possible ways of combating this instability in future low-emittance electron storage rings.

Both simulation methods, particle tracking as well as phase-space density propagation employing the Vlasov-Fokker-Planck equation, are possible options to be explored for the planned calculations of the collective effect influence during the beam transport through matter. Furthermore, another viable starting point is based on the past work at CERN, to calculate beam-matter interaction using covariance matrices [27], which are a common tool used to transport beam properties along the accelerator.

For the proposed project, another important aspect in the investigation of collective effects are systematic measurements with a sufficiently high temporal resolution to resolve the resulting dynamics, be it separating the consecutive revolutions of a bunch in a ring based accelerator or resolving the shot to shot differences between consecutive bunches in a linear accelerator. I was part of the team that developed a new ultra-fast readout system, to study the influence of the micro-bunching instability on the emitted CSR and the deformation of the longitudinal bunch shape [28]. The system enabled time-resolved measurements of the CSR intensity emitted by each bunch at every revolution in the synchrotron [29], as well as the synchronization with an electro-optical bunch-profile monitor. The resulting synchronized measurements, together with my simulations using Inovesa, provided further insight, with a high temporal resolution, into the formation of sub-structures in the longitudinal bunch shape causing the observed fluctuations in the emitted CSR [30]. Based on my work, a feedback system has been designed at KIT with the goal to mitigate and control the micro-bunching instability [31].

My experience with the development of the fast readout system [28] as well as the utilization of multiple fast beam diagnostic systems and detectors, such as fast beam current transformers for time resolved charge measurements, beam position monitors, fluorescence screens, fast photo diodes, THz sensitive Schottky diode detectors [17] and more complex systems such as electro-optical bunch profile monitors [32], and synchrotron radiation monitors will be a great basis for the proposed experiments.

The extensive research conducted in the field of accelerator physics today aims for a deep understanding of the involved beam dynamics and collective effects especially in beams under extreme conditions, like short bunch lengths or high intensities and the diagnostics thereof. At the same time, with RT moving to beams with high temporal or spatial structuring for novel methods including FLASH RT or MRT, this research becomes more and more relevant, laying out the program for the proposed project.

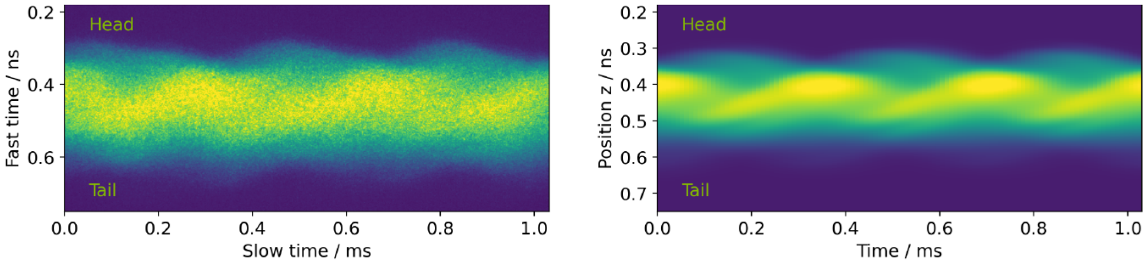

Figure 2: Measurement (left) and simulation (right) of the longitudinal bunch profile on the vertical axis and the temporal evolution on the horizontal axis.

5 Work Packages?

To achieve the objectives, the work program is structured in the following work packages A-C:

WP A Complex beam dynamics and collective effects	**A1** Dynamics and collective effects in accelerator-based generation of temporally or spatially structured beams	**A1.1** Cases study on collective effects in proposed dedicated RT accelerators
		A1.2 Measurements and simulations of RT beams generated in FLUTE
	A2 Beam-matter interaction for high intensity, temporally and spatially structured pulses	**A2.1** Study existing models and simulations
		A2.2 Simulation with existing models for FLUTE parameters (compare to WP B2.1)
		A2.3 Extending model and simulation by incorporating collective effects
	A3 Implementation of start-to-end simulation including beam dynamics and beam-matter interaction	
WP B Systematic investigation on temporal and spatial pulse shape dependence of detection mechanisms and diagnostic tools	**B1** For accelerator beam diagnostics	**B1.1** Experimental tests (cf. to WP A1.1)
		B1.2 Assess shot to shot resolution and provide recommendations for applicable methods depending on beam parameters
	B2 For dose and dose-rate diagnostics (dosimetry)	**B2.1** Exp. test dependence of different dosimetry methods on pulse-property
		B2.2 Benchmark theoretical correction factors in dosimetry with respect to high dose rates
		B2.3 Set-up 2D dose distribution measurement
	B3 Assess feasibility of 2D beam diagnostics outside of vacuum e.g., fluorescence screens	
WP C Beam modulation and beam shaping	**C1** Exploration of methods for temporal and spatial shaping of pulses	**C1.1** Simulation based on accelerator optics
		C1.2 Experiment e.g., spatial light modulator
	C2 Evolution of shaped pulses during transport	**C2.1** Simulations based on results from WP A
		C2.2 Experimental measurements at FLUTE
	C3 Investigation of methods and algorithms to calculate the required initial beam distribution from a desired beam shape on target (based on WP A3)	
	C4 Tests of generating custom dose distributions on target (simulation and experiment)	**C4.1** Test of compensating the effect of beam transport
		C4.2 Tests of generating custom (user-definable) final distributions

WP A: As new, advanced radiotherapy modalities rely on high intensity, short or spatially structured particle beams, the influence of interactions between the beam particles will be increased compared to conventional radiotherapy. Work package A will study the influence of these collective effects on the beam in the accelerator as well as on the beam transport through matter onto the irradiation target. Sub-work package A1 will focus on the resulting beam dynamics during the beam generation in the accelerator by, firstly, conducting a case study of the influence of collective effects during the beam generation for FLASH and Microbeam RT in proposed, dedicated accelerators (WP A1.1). Established accelerator simulation tools, such as ASTRA, AT or Ocelot will be studied as each includes a different set of collective effects. WP A1.2 will use the linear accelerator FLUTE at KIT as a testbed and compare measurements and simulations of different beam parameters resembling the desired RT beam properties. The second sub-work package (WP A2) will focus on the influence of the extreme beam properties (high intensity, temporally and spatially structured) on the beam-matter interaction on the way from the accelerator to the target tissue inside the patient. In WP A2.1 the existing models and simulation tools used in beam transport trough matter will be reviewed and in WP A2.2 simulations with a variety of possible beam properties generated by FLUTE will be conducted with codes commonly employed in radiotherapy settings, like BDSIM (Geant4), EGSnrc, FLUKA and the new KiT-RT framework. WP A2.3 will investigate, in the context of beam-matter interaction, how different possible interactions between the beam particles themselves affect the passage through matter. To this end, collective effects known from accelerator physics, such as space charge, intra-beam scattering, transition or coherent synchrotron radiation effects and ion- or electron cloud effects (depending on the beam particle type) are evaluated and their relevance depending on beam properties estimated. As next step, in WP A3, the effects will be incorporated into the calculations for the beam transport through matter and combined with simulations of the dynamics in the accelerator to create a start-to-end simulation tool. Multiple options on how the different simulations and calculations are to be combined will be evaluated, in order to find the best implementation method for beam propagation simulation through the accelerator and matter interactions not only for single particles but also taking into account collective effects. Possible methods include Monte Carlo simulations, particle tracking, phase-space density propagation by solving the Vlasov-Fokker-Planck equation and the application of covariance matrices. The successful completion of WP A will deliver objective I.

WP B: The extreme beam properties not only affect the beam propagation but also increase the complexity of applicable detection mechanisms and diagnostic tools. WP B1 will focus on accelerator-based beam diagnostic, such as fast beam current transformers, beam position monitors, fluorescence screens and more complex systems such as electro-optical bunch profile monitors [32], synchrotron or transition radiation monitors among others, with regards to their suitability for and ability to detect high intensity, temporally and spatially structured particle bunches with a high accuracy. Experimental tests are planed in WP B1.1 and will be compared with simulations from WP A1b. This will give input for the assessment in WP B1.2 on the potential of different diagnostic methods as support for RT beam diagnostics with shot to shot capabilities and the required adequate resolution and stability for medical applications. Work package B2 will focus on the effect the high dose rate generated by short beam pulses has on the dosimetry detectors. In WP B2.1, the ultra-short electron pulses from FLUTE and the ultra-short photon pulses generated at the KIT synchrotron light source with the electron storage ring KARA can be used for experimental tests of different dosimetry methods and their dependence on beam properties such as pulse length, intensity, transverse size and energy. As starting point an advanced Markus chamber and the newly-developed flash-diamond detector [8] will be tested towards the dependence on pulse length. Based on these measurements, also the recent developments of improved theoretical dosimetry correction factors for ion-recombination [7] can be validated with the ultra-short pulses (WP B2.2). And work package B2.3 will investigate possibilities for measuring a 2-dimensional dose distribution. For tests of the spatial resolution, the electron beam at FLUTE could be modulated, for example, by using collimators or potentially a mask at the accelerator exit. Furthermore, to measure the 2-dimensional particle distribution, typical accelerator diagnostics such as fluorescence screens for profile monitors will be assess for application outside the accelerator vacuum in WP B3 as preparation for WP C. In this context also detector test of new detector types under development at KIT, for example radiation hard CMOS-pixel detectors [33], could be incorporated as well as tests at facilities with proton or ion beams (e.g., HIT in Heidelberg or the GSI in Darmstadt). Completing WP B successfully will achieve objective II.

WP C: This work package aims to understand the physical and theoretical limits of accelerator-based beam modulation and shaping for the application in radiotherapy. The first step (WP C1) will be to explore different methods for temporal and spatial manipulation of the beam shape. This will be based, firstly, on simulations exploring a variety of options for different possible accelerator types operating as RT sources (WP C1.1). One general option would be, for example, to employ the accelerator focusing magnets to modify the bunch shape, by over-focusing the beam at the accelerator exit. Secondly, in WP C1.2, the possibility on modulations of the source distribution, will be experimentally tested by modulating the gun laser spot on the electron-gun with the spatial light modulator set-up a FLUTE [16]. The second step (WP C2) includes then the investigation of the evolution of the modulated bunch shape during the transport through the accelerator and through matter on to the target. The investigation of the bunch shape evolution will consist of simulations (WP C2.1) based on the results in work package A, which can then be compared with experimental measurements in WP C2.2, using the diagnostics tested in WP B. Upon finishing WP C1+C2, we can attain objective III. WP C3 and C4, will then investigate how and to what extend it is possible to generate a custom particle distribution and thereby a custom dose distribution on target tissue. To this end, WP C3, will examine possible methods and algorithms for calculating, based on a desired final distributions, the required, corresponding initial particle distribution in the accelerator. As this work will build on the work from work package A3, especially on the designed start-to-end simulation, the optimal methods will likely depend on the algorithm chosen in WP A3. Several possible methods can be imagined, ranging from systematically mapping final distributions for a wide variety of initial distributions resulting in a type of catalog, over the analytical or numerical inversion of the transport matrix described in form of covariance matrices, up to employing machine learning algorithms trained on arbitrary bunch shapes propagated through the start-to-end simulation. When this connection between the final and the initial distribution is established, it can be combined with the beam modulation methods established in WP C1. WP C4.1 will, as a first step, employ this to compensate the effect the beam transport has on the pulse shape by considering these deformations already during the beam generation. And in WP C4.2 the capability of this method will be tested and the limits in the achievable distributions on target will be explored. With this, the last objective (IV.) will be achieved.

6 Work Plan?

6.1 Time plan

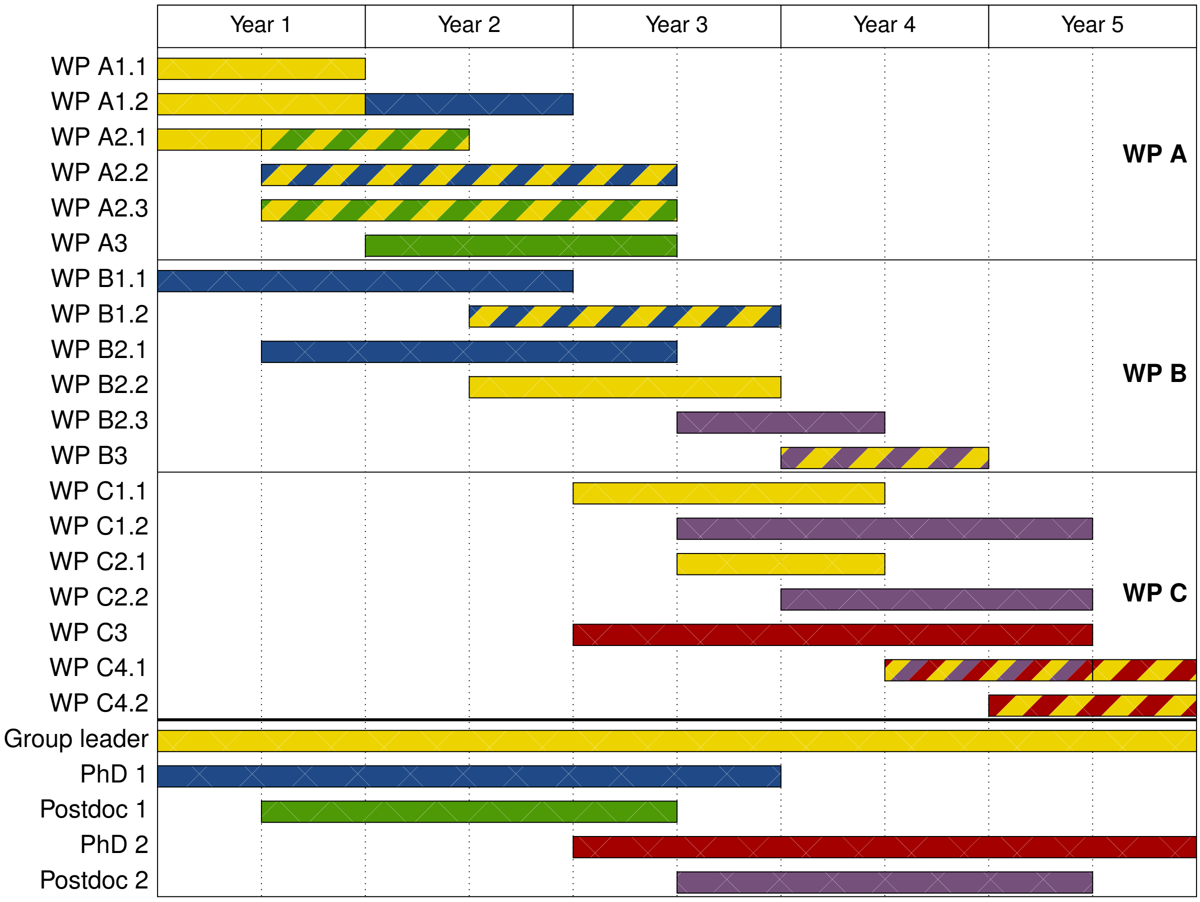

Figure 3: Time plan showing the individual work packages colorcoded by responsible team member as well as the time frame of each team members within the project in the lower part.

6.2 Group structure

The work program is designed for me as group leader and a total of 2 postdoctoral researchers and 2 doctoral students. There will be one postdoctoral researcher and one doctoral student in the first haft of the project and the same number in the second half, with half a year overlap between the doctoral students in the middle (see Figure 3 lower part).

To generally coordinate the work efforts and discuss outcomes and upcoming steps a weekly team meeting will be established. In addition, regular bi-weekly work package specific meetings will take place focusing on the respective challenges and problems to solve. For doctoral students, additionally, a weekly one-on-one meeting with me about their individual progress is intended which will give them the possibility to ask question in a more confidential and relaxed setting. In total, each team member should have no more than 3 regular meetings per week not including spontaneous discussions as well as more relaxed coffee break conversations.

The work of this project will be distributed, as described in the following, onto the planned group members with the time schedule shown in the graph below (Figure 3):

Doctoral student (PhD 1) (starting between month 1 and 6, 3 years duration):
Research topic: Experimental study of the influence of advanced radiotherapy beam properties such as short bunch length, charge, energy and transverse size on accelerator beam dynamics, diagnostics and detected dose. The research will mainly focus on experimental measurements of the effects of extreme beam properties at the linear accelerator FLUTE accompanied by supporting simulations and will contribute to work packages A1.2, A2.2, B1 and B2.1.

Doctoral student (PhD 2) (starting month 25, 3 years duration):
Research topic: Investigation of theoretical methods and algorithms to solve the inverse problem of custom accelerator-based beam modulation for advance radiotherapy. The main focus will be the theoretic work on a solution for WP C3 by finding an exploitable connection between the final particle distribution and the corresponding initial one. Therefore, the research will build on the start-to-end simulation from WP A3. It will likewise contribute to the simulation based tests while also closely collaborating on experimental tests in WP C4.1+4.2.

Postdoctoral researcher (Postdoc 1) (starting month 7, 2 years duration):
Research topic: Establishing start-to-end simulation for beam transport of accelerator-generated novel RT beams. This will entail exploring methods to propagate structured beams through the accelerator as well as through matter, including not only single particle to matter interactions but also considering collective effects during the beam transport through matter. The research will include the work on WP A2.1+2.3 and will be the main contributor for WP A3.

Postdoctoral researcher (Postdoc 2) (starting month 31, 2 years duration):
Research topic: Experimental exploration of temporal and spatial shaping of accelerator beams and 2D particle and dose diagnostics. This position will cover the experimental work on possibilities for accelerator-based beam modulation (WP C1.2). The work will furthermore devise 2D diagnostics for the particle and dose distribution (WP B2.3 + B3) enabling the experimental observation of the deformation of the beam modulations during transport (WP C2.2). The postdoctoral researcher will work with the doctoral student (PhD 2) on testing the algorithms for targeted beam shapes (WP C4.1).

Group leader (5 years):
Besides my planned involvement in lectures, I, as group leader, will coordinate and be involved in all work packages as discussion partner and supervisor. Furthermore, I will take on the following work packages partially or fully: A1.1, A2.1 (partially), A2.3 (partially), B1.2 (partially), B1.3 (partially), B2.2, C1.1, C1.2 (partially), C2.1, C4.1 (partially), C4.2 (partially).

In shared work packages, the work will be distributed by subtopic and a close communication will be maintained with the corresponding team member.

It is envisioned to give master students the possibility to contribute in different work packages. Possibilities would be, for example, in WP A3 (supervised by the first postdoctoral researcher) by testing different implementation possibilities for collective effects in beam-matter interactions, or setting up a new diagnostics system in the scope of WP B3 or also WP C2.2 supervised by the second postdoctoral researcher. It would offer a great opportunity for the postdoctoral researchers to gather experience in supervising students. And furthermore, student assistants will support the project for example during experiments and measurement campaigns, with documentation, data organization or implementing specific data analysis scripts.

6.3 Scientific equipment

• Far-infrared linac and test experiment (FLUTE) ○ Linear electron accelerator ○ Extensive accelerator diagnostic for beam characterization, including beam charge, position, profile and energy measurements ○ Water-equivalent RW3 slab phantom from PTW for dosimetry measurements ○ Electrometer UNIDOS Tango from PTW for dosimetry measurements

• Karlsruhe Research Accelerator (KARA) ○ Electron storage ring based synchrotron light-source ○ Extensive accelerator diagnostic for beam characterization, including beam and bunch charge, position, profile, and synchrotron light monitors

• HoreKa (Hochleistungsrechner Karlsruhe) ○ High performance computing center ○ Access based on project proposals ○ Free of charge

• bwUniCluster ○ High performance computing center ○ Access granted on university level ○ Free of charge

6.4 Handling of research data/Research data plan

This project will produce research data that covers a wide variety of data types, sizes and formats. Measurement data will originate from the multitude of accelerator beam diagnostic systems such as charge measurement, beam position information, transversal bunch profiles monitors or gun laser parameters, as well as from dose measurements in the water phantom. The total amount of measurement data generated over the course of the 6 year project duration is estimated to be in the several TBytes range. This is mostly due to the multitude of diagnostics running during accelerator experiments combined with systematic parameter scans including imaging data from 2D profile measurements. Simulations will be conducted with multiple existing simulation tools like EGSnrc, FLUKA, ASTRA or Ocelot. Furthermore, results from theoretical calculations such as self implemented simulation tools are expected and will contribute to the resulting research data as well as the developed software tools themselves. Due to the use of particle tracking simulations and the possibility to run simulations on an HPC cluster, the estimated amount of simulation data is also in the range of several TBytes.

The file formats will depend on the diagnostic systems or simulation tools and can range from TXT, PNG, JSON or CSV to proprietary file formats or custom binary files. If the original format is not easily accessible and/or additional metadata should be saved with the original data, it will be converted to files of the hdf5 file-format (Hierarchical Data Format version 5). In the past, I have used this format extensively and it has proven to be very useful to store complex data. It is accessible with a wide variety of programming languages and provides the possibility for internal structuring of the stored data in groups with attributes. This allows the collection of related data, such as the output from different diagnostic tools, as well as the addition of metadata. In this way, all the information from different sources required to evaluate measurement results are bundled together, including metadata such as operational parameters of the accelerator. The same principle can be applied to data resulting from calculations and simulations. Furthermore, to keep the context of the simulation and improve the re-usability, all the simulation input parameters and settings can be stored as metadata in the attributes of the hdf5-files. Also, in cases where the stored data is not in SI units conversion factors can be included in the metadata. When software is built from scratch, the hdf5 file-format will be used directly. A consistent filename convention will be implemented including the date (human readable, ISO8601), a short name for the detector or simulation tool, and further information. Additional information relevant for later analysis or re-use of the data will be, as mentioned earlier, saved as metadata, either live during the measurement, for example, by reading accelerator parameters provided online from the accelerator control-system (EPICS) (including Unix timestamps) or, alternatively, added later in post-processing. All relevant accelerator settings, parameters or properties are by design saved continuously in a Casandra database. A corresponding post-processing workflow can be based on an existing Python framework developed by me which was successfully used to process more than 50 TByte of measurement data during my PhD studies.

To document experiments, the digital logbook ELOG will be used, which is used in multiple accelerator facilities as a documentation standard. Data files can be attached to the corresponding entries either directly or as link to files on a file server of the institute. For more extensive documentation, an instance of a wiki is available at the institute. Sub-spaces for individual teams can be created with corresponding access rights. There, information or discussions regarding multiple measurements or simulations can be stored. Within the framework of scientific research, regular comparisons between simulated and measured data will be performed to ensure consistency and increase data quality. Furthermore regular reference measurements at well known conditions are performed to characterize the detection chains. Regular meetings and discussions on the acquired data will be held to minimize human bias (four eyes principle). For the development of software a GitLab instance will be used. This provides a version controlled and simple possibility to save, transfer and jointly work on source codes. With the usage of GIT (distributed version control system), there is also the possibility to implement basic quality control mechanisms, e.g. git hook frameworks like pre-commit, which check the integrity of the source code before committing. For all python scripts the PEP8 coding-style convention will be respected.

For immediate storage during the runtime of the project, the data will be saved on the institute's own servers with backups which allow to manage the access rights via user-groups. A specific group directory would be created with a systematic folder structure to allow the storage of the generated measurement and simulation data sorted by type and date. In addition, to ensure minimal data loss, every personal PC of group members will be equipped with an external backup hard drive and each member will be instructed to perform regular backups.

For long-term storage and archival of data the multi-petabyte storage systems of the host institution (e.g. LSDF) including the archival on tape will be used. A minimum storage period of 10 years is default for these services, which are provided at no cost. In addition, RADAR4KIT, a research data repository, can be used to bundle data and metadata, store and archive this data with the possibility to provide public access later on. For publications, high-level derivative data can be added as supplementary material on the journal web-page. For simulation data, from publicly available simulation code, the minimal set of parameters to recreate the data will be added. The corresponding full data sets can be published in KITopen via RADAR4KIT, receive a DOI and are open access. Software developed in the framework of this project is planned to be open-source and published on services such as GitHub.

Group members will be provided with the possibility to learn the usage of technologies regarding data management used for the project. Due to the continuous availability throughout the project and previous experiences with large data and software management, the applicant will take on the task of coordinating the handling of research data for the project supported by the IT team of the host institute. Since the usage of established storage solutions is foreseen, the long-term storage and archival responsibility after the project ends lies with KIT. Research data management within the project and used services will conform to the guidelines published by KIT ("Guidelines for Responsible and Sustainable Research Data Management at KIT (RDM Policy)") as well as the DFG code of conduct, and the EU open science policy.

6.5 Financial plan

Brosi, Miriam Katharina: To lead the proposed project in the Emmy Noether programme, the funding for the position as junior research group leader is requested for the expected project duration of 6 years consisting of two funding periods (36 + 36 months). The position will be filled by applicant, Miriam Katharina Brosi. Personnel Cost Category EUR / year (as of 2024) EUR / Sum (6 years)* Head of independent junior research group 100200 648135 *An annual rise of 3

5.2.1 Funding for Staff

For the proposed work program the funding for two doctoral students, two postdoctoral researchers, and several student workers is requested.

The first doctoral student will be employed for three years on a 75% position and is planned to start shortly after the project start, latest after half a year (1-6 month after project start). The PhD thesis will be on the topic of: Experimental study of the influence of advanced radiotherapy beam properties such as short bunch length, charge, energy and transverse size on accelerator beam dynamics, diagnostics and detected dose. The candidate should have some experience in experimental work, including setting up and handling sensitive diagnostic hardware. This topic offers a round work package suited to result in a PhD thesis. It offers opportunities for the student to shape and combine different tasks according to their own vision to deliver the independent research results required for a dissertation, while still receiving the required guidance.

The second doctoral student will be employed for three years on a 75% position. This position should start in the second half of project year 3 (30 month after project start). The work will focus on: Investigation of theoretical methods and algorithms to solve the inverse problem of custom accelerator-based beam modulation for advance radiotherapy. A candidate is envisioned with a background or strong motivation in mathematical methods and computational physics. For this project the doctoral student would have the possibility and time to evaluate different possible methods towards their feasibility fo the project goal while collecting experience and learn about all of them. This will result for the project in a good overview of the available methods while also providing the student with a broad knowledge for their following career steps.

For both doctoral students, to allow for some unplanned, but not uncommon, delays, due to e.g., unexpected down times of accelerators or other technical challenges, during the work on the PhD thesis, an additional, optional half year per doctoral position is requested, so that the contract could be extended to prevent financial stress for the students during the final stage of their thesis.

The first postdoctoral researcher will be employed for two years on a 100% position and is planned to start at the beginning of the second project year (12 month after project start). The planned work will include the incorporation of collective effects into beam-matter interaction and the implementation of a start-to-end simulation combining beam transport simulations in the accelerator with simulations of the transport through matter. A candidate with a strong background in many-particle systems, radiation transport through matter, or theoretical accelerator physics with experience in simulation programming is envisioned. The higher level of prior experience and knowledge required for this task, is more suited for a postdoctoral researcher position (compared to a doctoral student), which would furthermore allow the researcher to work as a more independent team member.

The second postdoctoral researcher will be employed with 100% for two years and is planned to start at the beginning of the fourth project year (36 month after project start). Due to the experimental nature of the assigned work packages, an experimental physicist with an extensive background in fast, time-resolved diagnostics and detectors as well as short pulse physics would be suitable. Alternatively, an electrical engineer working in detector development for 2-dimensional pulse detection with some basic experience in accelerator physics would be a good fit. In order to ensure a continuous progress in this stage of the project, the tasks should be carried out by a postdoctoral researcher who, due to previous experience can more efficiently solve upcoming challenges. Additionally, the project will benefit from the contribution of prior knowledge in fields such as detector engineering and from the capability of the postdoctoral researcher to supervise a master student. At the same time, would the increased independence of the postdoctoral researcher allow them to define their own research profile and gain experience in supervision.

Additionally, some funds are requested to employ student assistants for a total of 3 years distributed over the project duration as required and interested students availability. The working time will be adjusted in such a way that the monthly salary corresponds to a “Minijob” (in 2024: €538/month maximum net salary) according to the customary rates for student assistants at KIT (in 2024: without completed master degree, €13.25/h netto). This results in a maximum of 40 working hours per month. The tasks will include support for setup, execution and documentation of experiments.

Personnel Cost Category Start year EUR / year (as of 2024) EUR / Sum (6 years)* Postdoctoral researcher (1002 86100 180026 Postdoctoral researcher (1004 86100 193897 Doctoral researcher (75(3 years) 1 59850 184990 Doctoral researcher (75(3 years) 3 59850 196256 Extension possibility for Doctoral researchers (75(in total 1 year) 4 & 6 59850 65400 Student assistants (in total 3 years) distributed 8736 28394 Sum

848963 *An annual rise of 3

Besides the accelerators, diagnostic tools and equipment already available at the host institute, the funding for the following items are requested. Two different dosimeter types will be bought for systematic and comparative measurements under different beam conditions and pulse lengths. The Advanced Markus Chamber is a plane-parallel ionization chamber with a small sensitive volume, suited for high dose per pulse conditions. The second selected detector is the flashDiamond, a synthetic single crystal diamond detector, recently developed for ultra-high dose rates. The detectors are from PTW Freiburg GmbH and were specifically selected to be compatible with the electrometer and slab phantom from the same company available at the institute. For measuring the 2-dimensional dose distribution, radiographic films will be used, for example GAFCHROMIC EBT3 or Kodak EDR2. Since the films are consumables, multiple boxes (à €1000) will be required. A total cost of €10000 is estimated over the project duration. A humidity logger in the experimental hall will be used during beam propagation measurements in air. An estimate of €1000 is requested to this end. For complementary electronics accessories, such as signal cables, adapters and connectors for detector readout and power supplies a fixed amount of €7000 is estimated. An additional €5000 is requested for supplementary readout electronics such as amplifiers or attenuators for detector signals as well as trigger signals from the accelerator systems. Mounting materials to e.g., build mounts for detector systems or other constructions required for experiments are estimated with a total of €5000 during the project duration. Optical components are planned with €10000 to cover lenses, mirrors, mounts, and further laser laboratory supplies for the experiments with the spatial light modulator. A dedicated PC is forseen as control and read-out station for the experiments. This will allow a fast handling and post-processing of results including the augmentation with additional meta-information. Portable hard drives will be used to quickly transfer working copies of the results for further analysis.

Equipment Cost / € flashDiamond dosimetry detector (PTW) 9500 Advanced Markus Chamber dosimetry detector (PTW) 2700 Radiographic films 10000 Humidity+temperature logger 1000 Electronics accessories 7000 Supplementary readout electronics 5000 Mounting materials 5000 Optical components and lab supplies 10000 Experimental control PC + portable hard drives 5000 Sum 55200

The participation in relevant conferences and workshops will enable the communication and discussion of results as well as help with establishing new connections and give access to the latest developments. For the travel to international conferences an average cost of €2500 is allocated, which also contains conference fees (e.g., typically around €700 for the international particle accelerator conference (IPAC)) and assumes a total trip duration of 6-7 days. For national travels an amount of €1500 is estimated to cover travels of up to 6 days. For me, in the role of group leader, an average of one international and one national trip per year is envisioned. For each doctoral researcher one international trip and two national trips are allocated within their contract duration, this could include a summer-school within Europe, e.g., Cern Accelerator School. For each postdoctoral researcher two international trips are planned. For all potential master students together, a total of three national trips to the DPG spring meetings are planned, to give them the possibility to present their research for the first time to a wider community out-side the university setting. This amounts to following funds: Number of travels International National Sum / Euro Doctoral researcher 1 1 2 5500 Doctoral researcher 2 1 2 5500 Postdoctoral researcher 1 2

5000 Postdoctoral researcher 2 2

5000 Group leader 6 6 24000 Master students (in total)

3 4500 Sum 12 13 49500

7 Cooperation and communication plan?

- Prof. Dr Oliver Jäkel (in ch.), Heidelberg University and Heidelberger Ionenstrahl Therapiezentrum (HIT) and Division Head of “Medical Physics in Radiation Oncology” Deutsches Krebsforschungszentrum (DKFZ).

- Prof. Dr. med. Dr. rer. nat. Jürgen Debus, i.a. Scientific-medical Director (Heidelberger Ionenstrahl-Therapiezentrum (HIT)) and Medical Director (Klinik für Radioonkologie und Strahlentherapie).

- Prof. Dr. Anke-Susanne Müller, Institute Director, Institute for Beam Physics and Technology, Karlsruhe Institute of Technology.

- Dr. Erik Bründermann, Head of Department: Accelerator Research and Development + Operations II, Institute for Beam Physics and Technology, Karlsruhe Institute of Technology, Honorable Guest Professor of Shizuoka University, Japan.

- Prof. Dr.-Ing. Christian Graeff, Deputy Research Director of the Department of Biophysics, GSI Helmholtz center for Heavy Ion Research, Darmstadt.

- Dr. Lennart Volz, Medical physicist, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, expert on ion-based radiotherapy, particle imaging and treatment planning.