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

General information:

Applicant

Dr. Miriam Brosi, Lund University, MAX IV Laboratory, Lund, Sweden, 34, female, defense: 31.01.2020

Assignment KIT-division

Division V

Host Institute and contact person at KIT

Institute for Beam Physics and Technology (IBPT), Prof. Dr. Anke-Susanne Müller

Field of study and Helmholtz-program

Helmholtz program: Matter, Matter and Technology, Accelerator Research and Development (ARD)

Description of international experience such as position program, purpose, duration

In addition to participating in several international conferences and workshops, my working environment has often been international with colleagues from various countries. From 10/2021 to 12/2021, I worked as guest scientist at the Laboratory PhLAM at the Université de Lille in France on a detailed comparison of two Vlasov-Fokker-Planck simulation codes for the propagation of beam distributions under the influence of collective effects with the French national synchrotron SOLEIL and KARA at KIT as example cases. Since 01/2022, I am now working as postdoctoral researcher at the MAX IV laboratory of the Lund University in Sweden. In the accelerator development group, I focus on theoretical and experimental studies of collective effects in the ultra-low emittance ring of the 4th generation synchrotron light source at MAX IV.

Description of leadership experience

During my PhD, I supervised and co-supervised one bachelor and three master students, working on measurement data analysis, simulations of influences of arbitrary impedances on beam dynamics, machine learning based data analysis and fast, single-shot measurement methods, respectively. Furthermore, during three semesters, I served as tutor ("Übungsleiter") for bi-weekly exercises for lectures on accelerator physics. For four years, I was involved in organizing and supervising the accompanying simulation and hands-on course on the accelerator. As postdoc, I lead the project for the replacement of the main storage ring magnet power-supplies, supported by the chief electrical engineer. I coordinated the efforts, acted as contact to suppliers and wrote the specification for the procurement, including calculations on stability tolerances. In addition, I scientifically advise a PhD student on their investigation of additional impedances added into the accelerator and the resulting influence on collective effects, who will defend his thesis in May this year. Besides my main research as postdoc at MAX IV, I lead the effort to establish a new time-correlated single-photon counting setup as standard diagnostic for the accelerator operation. This currently includes the supervision of a bachelor student with the task to extent the setup for bunch shape measurements.

Information about the Project:

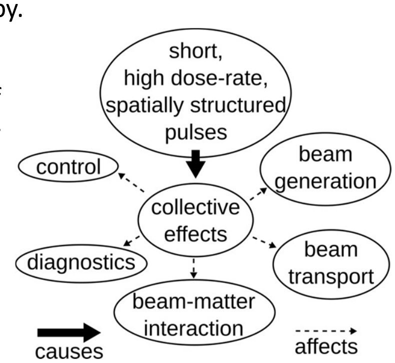
Abstract / Intent/ Goal

Particle accelerators play a vital role in a multitude of scientific fields such as the field of radiotherapy (RT). Novel radiotherapy methods, such as FLASH RT (very high doses in short pulses) and Microbeam RT (spatially fractionated pulses), are based on temporally and spatially structured accelerator-based particle beams with high requirements for the beam properties. These requirements cause strong effects caused by the coexistence of many particles in the densely populated pulses, summarized under the term collective effects, for which the knowledge of influence on RT beams is currently incomplete. As these can affect the dose distribution on target, an important aspect for radiotherapy, the investigation of collective effects for such

beams is of the essence. The proposed project aims at improving the required understanding to increase the predictability and enhance control of accelerator-based electron beams for FLASH RT and Microbeam RT. It will furthermore study applicable detection methods and assess possibilities as well as limitations of temporal and spatial pulse shaping and modulation of accelerator-based RT beams with the ultimate goal to generate custom beam shapes and dose distributions on target.

The proposed research project agrees very well with the core objectives of the Helmholtz program Matter and Technology (MT) with the topic Accelerator Research and Development (ARD) covering the dynamics, detection and control of short-pulsed accelerator beams with custom properties. These topics fall precisely in the research activities at the Institute for Beam Physics and Technology (IBPT), home to the KIT electron accelerators. The strong ties to the MT topic Detector Technologies and Systems (DTS) with the in-house partner at KIT, the Institute for Data Processing and Electronics (IPE), will be a valuable asset for the project. Furthermore, the project aligns perfectly with the new KIT-center Health Technologies, strengthening the important component of accelerator research with respect to radiotherapy.

Formal and Scientific Requirements (short)



The goal of the project 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 based on temporally and spatially structured accelerator-generated beams. The incorporation of collective effects in the envisioned start-to-end simulation and exploring solutions for the inverse problem will provide the required improvement in predictability and at the same time, combined with beam shaping, a significantly increased control on the final distribution on target. The work plan consists of three work packages, with WP A and WP B running in parallel and WP C building on the outcome of the first two.

WP A - Complex beam dynamics and collective effects: WP A will focus on the complex dynamics in accelerator-generated particle beams with the challenging properties required for FLASH and Microbeam RT. To this end, the influence of collective effects will be investigated in the accelerator as well as the beam transport through matter to the irradiation target. The investigations will include simulations and experiments with the linear accelerator FLUTE as testbed. In beam-matter interaction, collective effects have not yet been considered due to the typically significantly more relaxed beam properties in conventional RT. Based on my experience with different simulation methods of collective effects such as Monte Carlo, particle tracking, phase-space density propagation and the application of covariance matrices, multiple options will be evaluated for the incorporation into beam-matter interaction calculations. Based on this, we will develop a beam propagation simulation taking into account the interaction between beam particles. The objective of WP A is to achieve increased predictability of the RT beam properties on target by developing a start-to-end simulation including collective effects.

WP B - Temporal and spatial pulse shape dependence of detection mechanisms and diagnostic tools: The extreme properties of the temporally and spatially structured beams not only affect the beam dynamics but also increase the complexity of applicable detection mechanisms and diagnostic tools. A big challenge for dosimetry is the very high dose rate of the short pulses in electron FLASH RT, which lead to an increasing non-linearity in the detector response. It is proposed to exploit the flexible pulse-properties combined with the ultra-short electron bunches at FLUTE to test a variety of dosimetry detectors and benchmark the available, theoretical dosimetry correction factors for ion-recombination towards even shorter pulse-length. Furthermore, possibilities for measuring the 2-dimensional dose distribution will be evaluated. To test the spatial resolution, the electron beam at FLUTE could be modulated e.g., by using collimators or masks. In this context tests of new detector types developed at KIT, such as radiation hard CMOS-pixel detectors, could be incorporated as well as tests at facilities with proton or ion beams (e.g., HIT in Heidelberg or GSI in Darmstadt). In addition to RT diagnostics, different shot-by-shot capable accelerator-based diagnostics will be evaluated regarding the required resolution and stability for medical applications. The objective of WP B is to gain improved insight into the influence of temporal or spatial pulse modulation on detection and diagnostics to provide recommendations for applicable methods depending on the beam parameters.

WP C – Targeted beam modulation and beam shaping: After finding the forward solution, meaning the evolution of shape during transport via the start-to-end simulation in WP A, WP C aims at solving the inverse problem. This includes determining and shaping the initial distribution to obtain a desired shape on target. To this end, WP C will explore possibilities and define the physical limitations of accelerator-based pulse shaping and modulation by comparing different methods, e.g., a spatial light modulator on the electron-gun laser, and conducting measurements with the diagnostics selected in WP B. Furthermore, WP C will examine possible methods and algorithms to solve the mentioned inverse problem, with the optimal method likely depending on the algorithm chosen for the start-to-end simulation. Several possible methods can be imagined, from systematic maps of final to initial distributions resulting in a type of catalog, over analytical or numerical inversions of the transport matrix in form of covariance matrices, up to employing machine learning algorithms. After this connection between final and initial distribution is established, it will be combined with the tested beam shaping methods, enabling the generation of an initial particle distribution which, for example, preemptively compensates for the deformation during propagation to the target as well as the possible generation of (within certain limits) user-definable final particle distributions on target. The capability of this method will be experimentally tested and the limits in the achievable distributions on target will be explored.
The outcome of WP C will provide a deep insight into the possibilities of predicting as well as generating and controlling custom, temporally and spatially modulated particle distributions in linear accelerators alongside the main goal of contributing towards the advancement of advanced radiotherapy methods.

Envisioned cooperations: The closest cooperation with be with the Institute for Beam Physics and Technology (IBPT) where the group will be situated. This will give easy and extended access to the accelerator test-facilities FLUTE, KARA, as well as the planned storage ring cSTART and a laser-wakefield accelerator under construction. The Accelerator Technology Platform (ATP) at KIT will provide an extensive infrastructure for accelerator research as well as a close connection to the detector development at the Institute for Data Processing and Electronics (IPE). Cooperations with Prof. Dr. Oliver Jäkel from the Heidelberg Ion Beam Therapy Center (HIT) and German Cancer Research Center (DKFZ), as well as with Prof. Dr.-Ing. Christian Graeff and Dr. Lennart Volz from the GSI Helmholtz center for Heavy Ion Research are planned. Initial discussions with Prof. De Carne (ITEP) have been initiated in the area of energy efficient and sustainable accelerators for medical applications, and spin-off projects from this Helmholtz IG will be planned in the future.

Communication structures: The participation in relevant conferences such as the International Particle Accelerator conference (IPAC) or the Flash Radiotherapy and Particle Therapy conference (FRPT) and smaller workshops will enable the communication and discussion of results as well as help to establish new connections and provide access to the latest developments. For master students trips to the DPG spring meetings are planned, as first opportunity to present their research to a wider community. Research results will furthermore be published in, preferably, open access journals and presented at Helmholtz meetings.

Financial plan

The work plan foresees two postdoctoral researchers (year 2&3 and year 4&5) and two doctoral students (year 1-3 and year 3-5) in addition to the group leader. It is envisioned to give master students the possibility to contribute to different sub-work packages. Additionally, some funds are requested to employ student assistants for a total of 3 years distributed as required. The other costs consist of smaller detectors and consumables for experiments as well as travel costs for the participation in conferences and workshops. No larger investment is needed, considering the existing accelerators and infrastructure at KIT.

	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Group leader position*	100200	103206	106302	109491	112775	531975
2 Postdocs (100%, à 2 years)*	-	88683	91343	94083	96906	371016
2 PhDs (75%, à 3 years)*	59850	61645	126989	65399	67361	381246
Student assistants (3 years)	4368	4368	4368	8736	4368	26208
Material costs	29200	9000	7500	6500	3000	55200
Travel costs	4000	9500	12000	8000	12000	45500
Total	197618	276402	348503	292210	296411	1411146

*The personnel costs follow the DFG Personnel Rates. An annual rise of 3% has been included.