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 always been international with colleagues with various international backgrounds. From 10/2021-12/2021, I worked as guest scientist at the Laboratory of Physics of Lasers, Atoms and Molecules (PhLAM) at the Université de Lille in France for 2 month on a detailed comparison of two Vlasov-Fokker-Planck solver simulation codes for the propagation of particle distributions under the influence of collective effects with the french national synchrotron SOLEIL and KARA at KIT as example cases. Since more than 2 years, 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 on the influence of arbitrary impedances on beam dynamics, data analysis based on machine learning and fast, single shot measurement methods, respectively. Furthermore, during three summer semesters, I served as the tutor ("Übungsleiter") for bi-weekly exercises for the lectures on accelerator physics. In four years, I was involved in organizing and supervising the accompanying simulation course and practical hands-on course on the accelerator. As postdoctoral researcher, 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 main contact to potential suppliers and wrote the specification for the procurement, including calculations on the stability tolerances and their effects on operation. Furthermore, I scientifically advised a PhD student on their investigation of additional impedances added to the accelerator and the resulting influence on the studied collective effects, who will defend his thesis in May this year. Besides my main research as postdoc at MAX IV, I have lead the efforts to establish a new time-correlated single-photon counting setup as standard fill pattern diagnostic for the accelerator operation. This includes currently the supervision of a bachelor student with the task to extend the setup to a bunch shape measurement method.

Information about the Project:

Abstract / Intent/ Goal

Particle accelerators play a vital role in a multitude of scientific fields such as the field of accelerator-based radiotherapy (RT). Both, accelerator physics and accelerator-based RT, have become highly complex where new developments push the understanding and the technological limits towards increasingly extreme beam properties. In electron accelerators, this includes ultra-short, high intensity pulses in linear accelerators and transversely narrow pulses in ultra-low emittance synchrotron light sources. These conditions lead to strong effects caused by the coexistence of many particles in the densely populated pulses, summarized under the term collective effects. In RT, the current development of two advanced approaches pushes in the same direction: FLASH RT is based on the delivery of very high doses in short pulses and Microbeam RT focuses on spatially fractionated beams.

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 new, extreme beam properties go beyond the prediction and beam diagnostic capabilities in conventional RT. A push in the understanding of the involved complex beam dynamics and collective effects is therefore required.

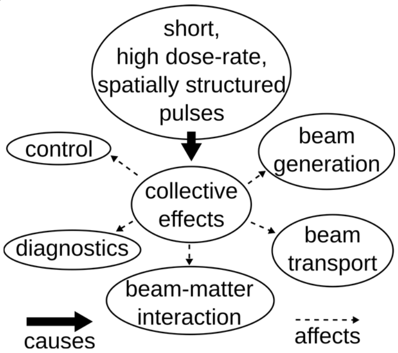
With the proposed project, I therefore aim at improving the understanding, predictability and control of the accelerator-based electron beams involved in FLASH and Microbeam RT and assess applicable detection methods. The entry point will be to extend the research on collective effects in accelerators 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, investigating the influence of collective effects during the transport through air and matter, which up until now was sparsely studied. 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 conducted within 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. more on why helpful acc ...

Novel radiotherapy methods 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 and Microbeam RT. It will furthermore study applicable detection methods and assess possibilities as well as *limitations of 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. It fits very well into the research activities within the context of. The strong ties to the partner topic Detector Technologies and Systems (DTS) with the strong 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 very well 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 on the beam transport through matter onto the irradiation target. The investigations will include simulations as well experiments with the linear accelerator FLUTE at KIT 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 simulations, particle tracking, phase-space density propagation via the Vlasov-Fokker-Planck equation and the application of covariance matrices, multiple options will be evaluated on how collective effects can be incorporated into beam-matter interaction calculations. Based on this, we will develop a beam propagation simulation through the accelerator and matter interactions, considering not only single particle effects but also taking into account the interaction between the 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 in the dosimetric diagnostic are the very high dose rates of the short pulses in electron FLASH RT, which lead to an increasing non-linearity in the dosimetric detector response. It is proposed to exploit the flexibile pulse-properties combined with the ultra-short electron bunches at FLUTE to test a variety of dosimetry detector types 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, for example, by using collimators or a mask at the accelerator exit. In this context also tests of new detector types under development at KIT, for example 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 the GSI in Darmstadt). Additional to RT *beam diagnostics, different accelerator-based diagnostic methods with shot-by-shot capabilities 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 the require initial distribution based on the desired shape on target as well as attempting to shape the initial beam distribution accordingly. 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 inverse problem to calculate based on a desired final distributions the required initial particle distribution, with the optimal method likely depending on the algorithm chosen for the start-to-end simulation. 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 a transport matrix described in form of covariance matrices, up to employing machine learning algorithms. After this connection between the final and the initial distribution is established, it will be combined with the tested beam shaping methods, enabling the generation of a initial particle distribution which, for example, preemptively compensates for the deformation during propagation from generation to target as well as the possible generation of (within certain parameter 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 in general provide a deep insight into the possibilities of predicting as well as generating and controling custom, temporally and spatially modulated particle distributions in linear accelerators alongside the main goal of contributing towards the advancement of advanced radiotherapy methods such as FLASH RT and Microbeam RT.

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 with Prof. Dr Oliver Jäkel (in ch.) from the Therapiezentrum (HIT) and Deutsches Krebsforschungszentrum (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.*

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 with establishing new connections and provide access to the latest developments. For potential master students trips to the DPG spring meetings are planned, as opportunity to present their research for the first time to a wider community. Research results will furthermore be published in preferably open access journals and presented at Helmholtz internal 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 in different sub-work packages. Additionally,

	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

some funds are requested to employ student assistants for a total of 3 years distributed over the project duration as required and interested students are available. 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.

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