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

Guest scientist at Laboratory of Physics of Lasers, Atoms and Molecules (PhLAM) at the Université de Lille, France, 2 month between 10/2021-12/2022: I worked 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.

Postdoctoral researcher at MAX IV laboratory, Lund University, Sweden, > 2 years, since 01/2022: 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 was the tutor ("Übungsleiter") for bi-weekly exercises for students attending the lectures on accelerator physics. Over 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 of the optimized power-supplies, 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 also function as a bunch shape measurement method.

Information about the Project:

Abstract / Intent/ Goal

*<Please describe planned measures, future viability/sustainability of the topic, viability of the cooperation>*ADD FIRST SENTENCE: THIS PROJECT WILL….goal, by doing ….new method….

This is of critical importance to Helmholtz....Matter and technology....
What will be realized....with the goal to ..change world
KIT best possible conditions as.....IBPT and Health-tech Center.....and close proximity and cooperation with Heidelberg for Cancer...close ties to IPE/Detectors/DTS program for pulsed 2d detectors (example ....) profitieren von der flexibilität von testfacility... FLUTE und den geplanten Plasma beschleunigern...als quelle für ultra-kurze electron pulse

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 ...

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. And compensation by beam shaping?control?

The work plan consists of three work packages, with WP A and WP B running mostly in parallel and WP C building on the out come 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 on the beam 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 on how collective effects can be incorporated into beam-matter interactions will be evaluated. Based on this, the best implementation method will be selected for a beam propagation simulation through the accelerator and matter interactions, not only considering single particles 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 temporal and spatially structured beams not only affect the beam propagation but also increase the complexity of applicable detection mechanisms and diagnostic tools. A big challenge in the dosimetric diagnostic are the 2-dimensional distribution in Microbeam RT as well as the very high dose rates in the short pulses in electron FLASH RT, with the later leading to an increasing non-linearity in the detector response.

test bed/benchmark calibration factors… and extend tests to even shorter pulses….

Supporting with accelerator based diagnostic for example….

Systematic studies of the dependence on temporal and spatial pulse shapes combined with varying intensity will give insight into which diagnostic tools can reliably provide a fast and comprehensive assessment of the shot to shot beam conditions.

My experience with fast diagnostics helps…

The objective of WP A is an 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.

WP C - Beam modulation and beam shaping: *Explore …possibilities to shape beam spatially and temporally (e.g. spatial light modulator)*

observe evolution of shape during transport, based on simulation tool from WP A and diagnostics from WP B

solve inverse problem, Investigation of methods and algorithms to calculate the required initial beam distribution from a desired beam shape on target

test generating custom distributions on target (by compensating or considering effects during transport…

*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*

Exploring the possibilities and defining the physical limitations of accelerator-based pulse shaping and modulation

*Investigating methods and algorithms solving the inverse problem, i.e. calculating the required initial beam distribution from a desired beam shape on target (based in **I.** - **III.**)*

cooperation

communication structures

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, 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 relevant conferences and workshops which will enable the communication and discussion of results as well as help with establishing new connections and give access to the latest developments. 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 Postdoctoral researchers (100%, à 2 years)*	-	88683	91343	94083	96906	371016
2 Doctoral students (75%, à 3 years)*	59850	61645	126989	65399	67361	381246
Student assistants (in total 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.