# beam dynamics and collective effects in structured beams for advanced accelerator based radiation therapy

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# Motivation

The present advances in accelerator based RT, like FLASH RT or Microbeam RT, lead to operation parameters of the used accelerators that can not anymore be described by simple linear optics and beam dynamics. Instead, due to the development towards higher intensity combined with shorter pulse lengths and transverse modulations, the consideration of non-linear and complex optics as well as beam dynamics influenced by collective effects becomes necessary for accelerator RT sources.

Further closing the gap between accelerator science and medical physics from the accelerator side is an important step and will help in paving the way towards accurate predictability, diagnostic and metrology of advanced RT with particle accelerators.

# Status quo

- RT is an important tool in cancer therapy, continuous development towards improved tolerability and increase of the therapeutic window
- two promising candidates recently: FLASH RT and spatially fractionated RT (MRT)
- not yet in clinical settings
- both dependent on particle accelerators and most medical linacs not sufficient

FLASH RT

- requirements on stability and metrology of the used beams not yet fulfilled
  - primary standard of standard particle RT not directly applicable
  - discrepancy observed between measured dose and simulated
  - non-linearity in detectors at ultra-high dose rates (e.g. high ion recombination rate) $\rightarrow$ improved by UHDpulse project, still open questions
  - simulation of dose does in most cases do not consider interaction between beam particles
  - most diagnostic focuses on beam outside accelerator, potential of fast and accurate accelerator diagnostic not fully exploited (e.g. shot by shot charge, position, size, ... measurements)
- optimal parameters such as pulse duration, intensity and energy not yet medically clear
  - input to possible parameter areas, that can be provided reliably by accelerators needed
  - new accelerator types (e.g. laser-based ones for higher energies) bring also different beam dynamic effects to be considered, such as high energy spread, shot-to-shot variation, ...

# Status quo

Spatially structured RT

- Microbeam RT mainly studied with x-rays but similar potential for particle beams as demonstrated with GRID therapy
  - modulation done mostly close to target
- spatially modulated beams (non-Gaussian dose distribution) relevant to accommodate either irregular/uneven patient surfaces (e.g. electron conformal therapy ECT) or achieve homogeneous dose distributions
  - mostly handled by scanning, masks/collimators or bolus ECT

General

- no interaction between beam particles considered in most simulations (e.g. FLUKA, EGSnrc, BDSIM with Geant4)
- OPAL does include 3D space charge, seems to mainly be used for proton therapy

$\Rightarrow$ Little to no mentioning of consideration of collective effects, which (from accelerator physics point of view) is expected to play an increasing role with decreasing pulse length and increasing pulse intensity, as well as with spatial structuring of the beam.

# Goals

I would like to investigate how and which collective effects known in the accelerator beam dynamics affect the beam transport, beam-matter interaction and diagnostics in novel electron radiotherapy methods with temporally and spatially structured beams.

- improve predictability of RT beam properties and deposited dose on target
  - improve understanding of dynamic in generation of short or spatially structured RT beams
  - investigate accelerator diagnostics that will be beneficial in new medical accelerators
  - improve simulation of beam transport through matter by including collective effects
  - contribute to development of improved dosimetry detectors by testing at variety of beam conditions
- characterise possibility to generate different temporal and spatial distributions on target already during beam generation
- provide start-to-end simulations of RT beams, from inside the accelerator through the air into the target by combining beam dynamics, beam-matter interaction and collective effects simulations
  - first step: direct prediction of the resulting temporal&spatial distribution on target
  - second step: consider deformation in beam transport already during the beam generation
  - aiming towards the generation of a spatial distribution which preemptively compensates for the expected changes, possibly allowing arbitrary user-definable final distributions

# Methods

- Experimental:
  first test bed: FLUTE
  - ultra-short pulses (variable length, and charge)
  - spatial light-modulator (modulate spatial distribution)
  - multitude of diagnostic (including virtual diagnostic via surrogate modeling)
  - possibly joined measurements to test detector prototypes? (e.g. for dosimetry of ultra short pulses, or maybe pixel detectors to resolve 2D distribution
- Theoretical:
  - for accelerator dynamics start with existing simulation tools (ASTRA, AT, Ocelot, ...)
  - for beam-matter interaction start with existing simulation tools (FLUKA, EGSnrc, BDSIM, OPAL, ...)
  - several option to include collective effects in beam transport through matter
    - Monte Carlo simulations
    - particle tracking
    - phase-space density propagation
    - covariance matrices (based on statistical particle ensembles)
- regular cross-checks between experimental results and improved simulations