Simulation of the Accelerator Facility

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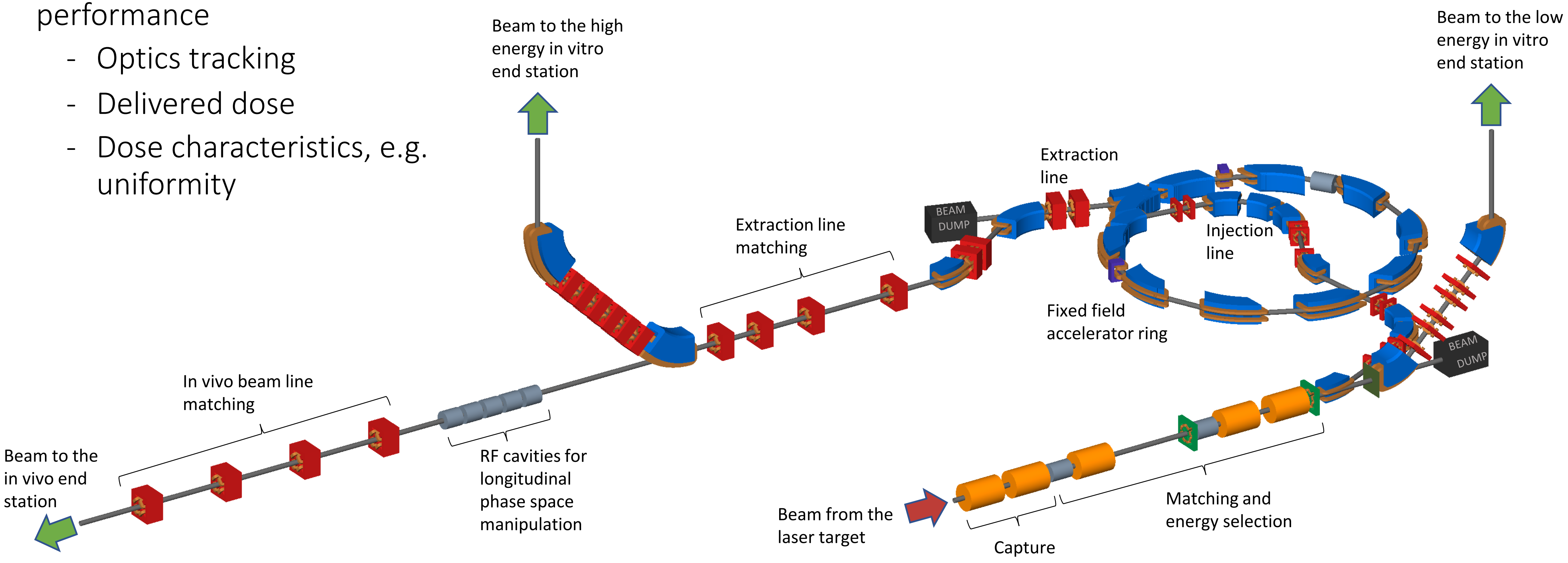
LhARA Beamline

- Start-to-end simulations to evaluate machine performance
  - Optics tracking
  - Delivered dose
  - Dose characteristics, e.g. uniformity



Simulation Codes

- MADX and BeamOptics used for calculating lattice optical functions
  - Idealistic machine description

- Two pronged approach:

BDSIM: Beam Delivery Simulation

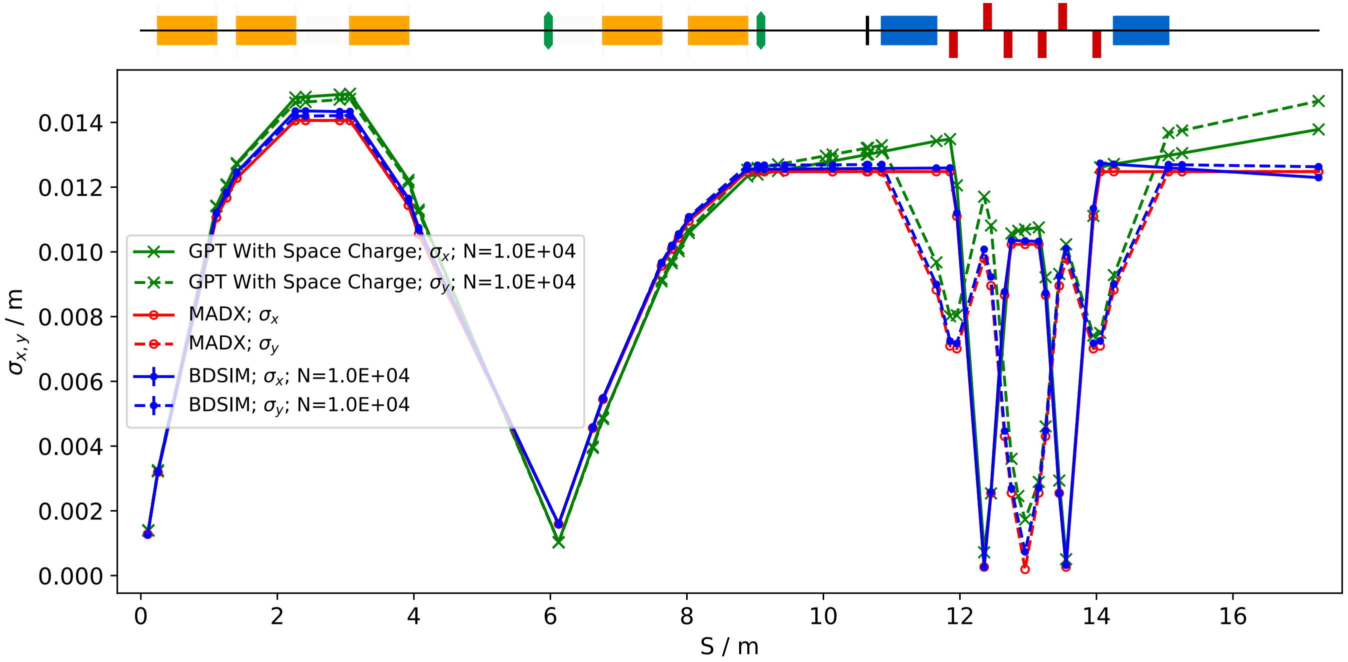
- Beam tracking through programmatically constructed 3D beam line model
- Geant4 based – simulates particle-matter interactions
- Primary purpose is to model energy deposition, beam losses, & dosimetry
- Highly flexibility – apertures, fields, beam, etc.
- Visualisation

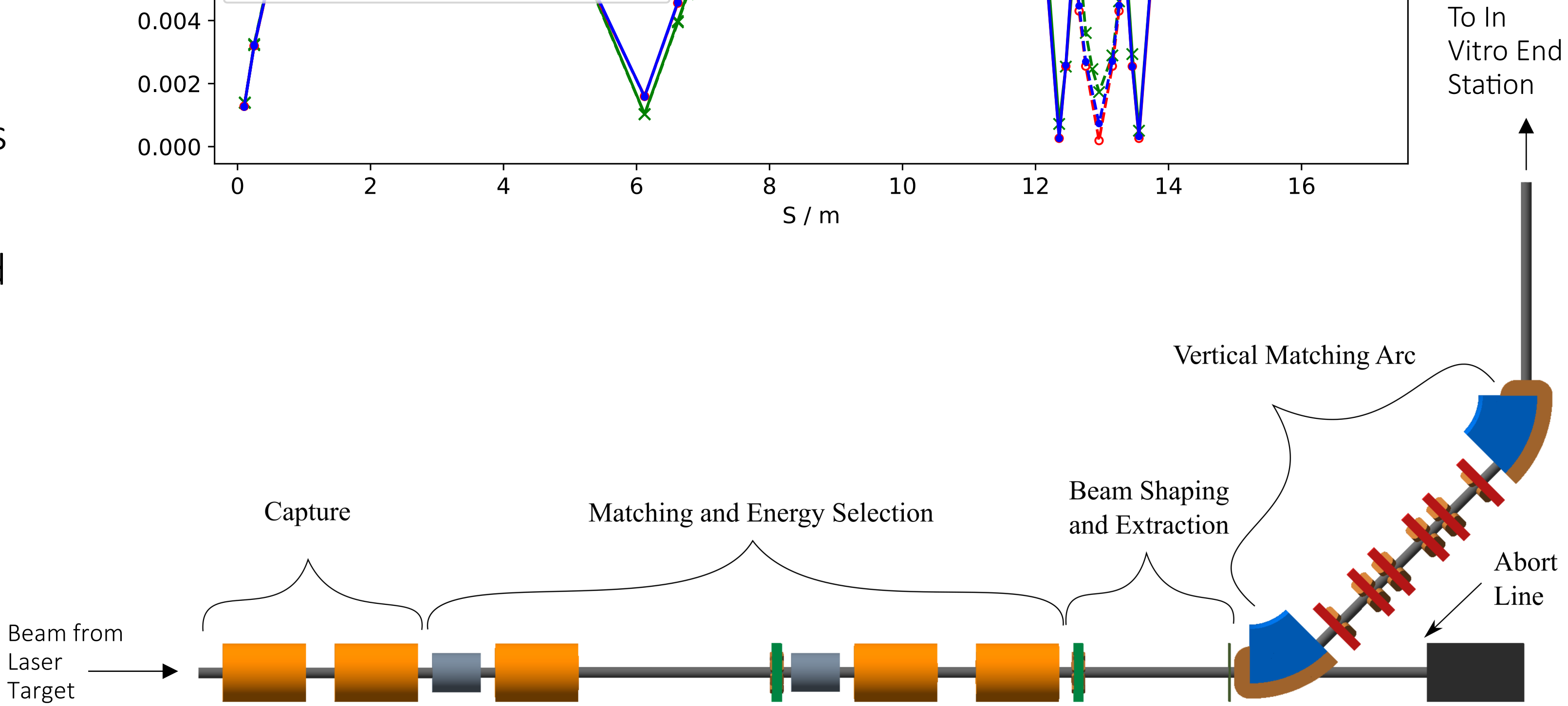
GPT: General Particle Tracer

- Space charge effects
- Customisable fields
- Limited simulation of losses
- User defined beam – possible to exchange particle coordinates with BDSIM via external file.

Optical Performance & Validation

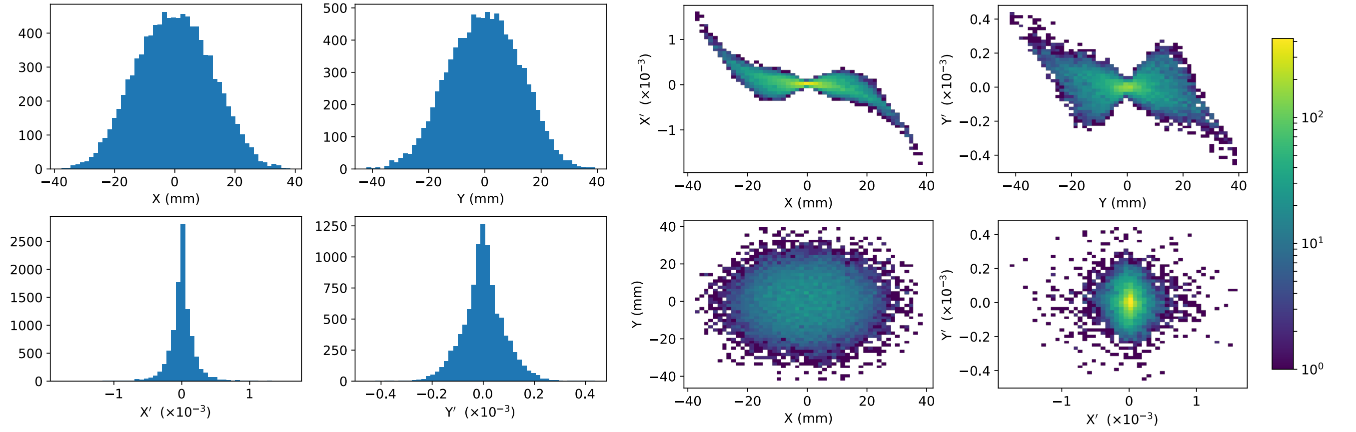
- Original model :
  - Gabor lenses simulated as solenoids
  - Collimation and beam shaping not simulated
  - 2m drift added for transport through to a bench-height target
  - No RF fields simulated
- Excellent agreement between MADX and BDSIM
- Reasonable agreement seen between BDSIM and GPT with space charge
- Emittance growth prior to the first Gabor lens
  - Divergent beam at the end station
- Capture section Gabor lenses can be tweaked
- Focus in both transverse planes after third Gabor Lens still a concern

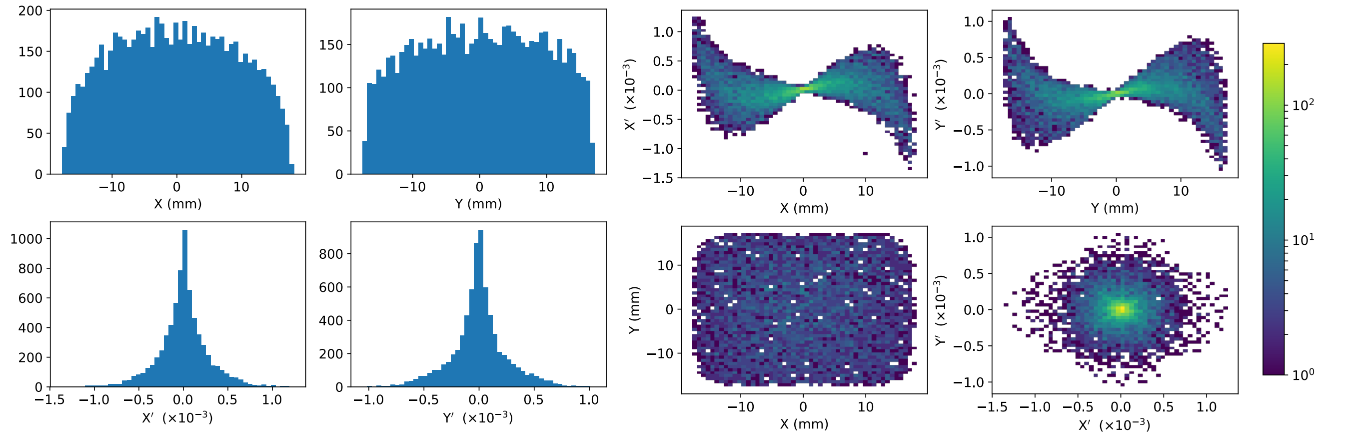




Idealised Phase Space at the End Station

- Assumed ideal beam for lattice optimization
  - 10^9 protons per shot (100 pC)- charge density causes an immediate emittance growth
- Contaminants (e-, ions) of unknown quantities will reduce bunch charge
  - Simulate first 5 cm without space charge
- Simulate between 5-10 cm with space charge
  - Within the confines of the laser target housing
- Gaussian beam delivered to the end station
  - Near 100% transmission
- Aberrations arising in the Gabor lenses cause ‘butterfly’ shape seen in the transverse phase space
- Octupoles and collimators improve spatial uniformity
  - Approx. 70% transmission, heavy collimator losses, minimal secondaries reach end station.



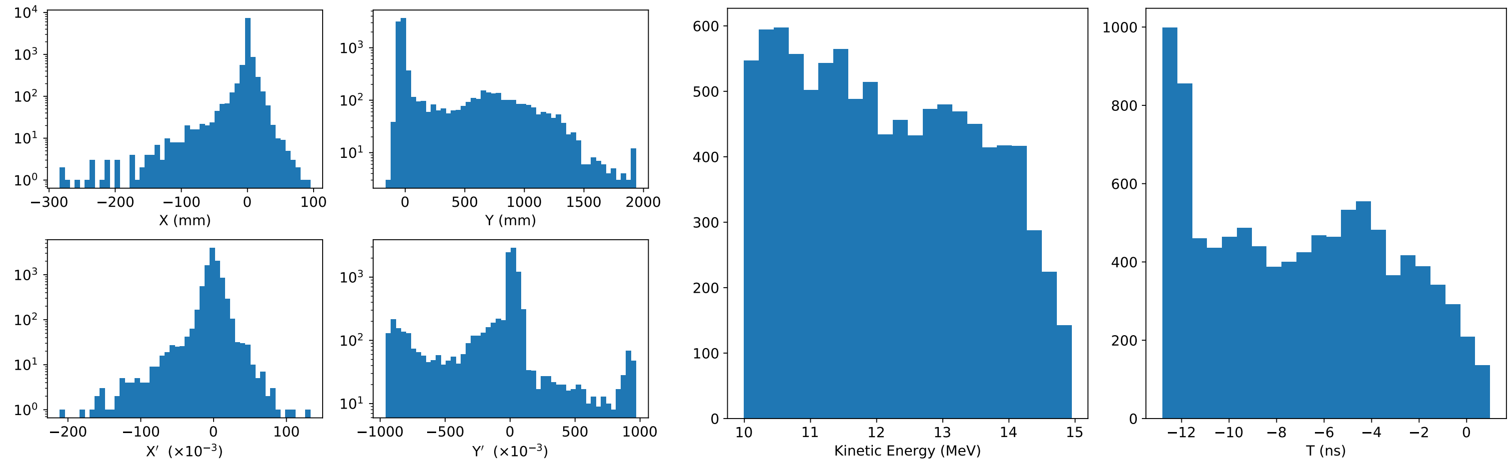


Laser-Target Simulation Derived Beam

- Beam generated with EPOCH
  - Energy cuts of 10-15 MeV.
  - Low population at design energy

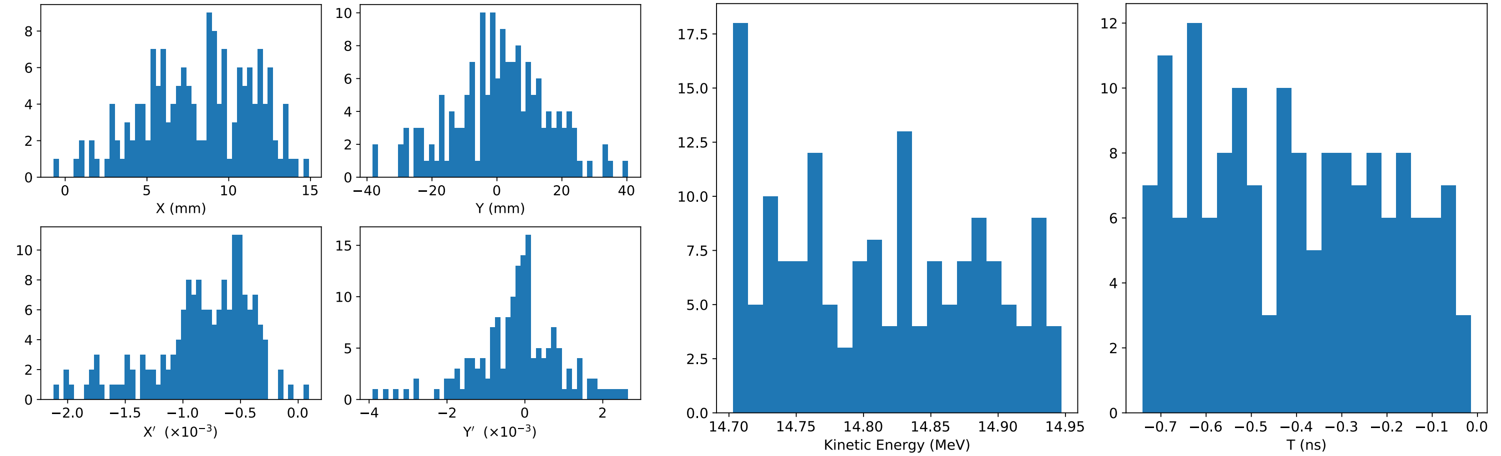
- Large distributions at the end station
  - Magnets set for 15 MeV, significant losses of off-energy particles

10-15 MeV



- Kinetic energy cut of 15 MeV $\pm$ 2% shows poor statistics
  - Approx. 2% transmission
  - Indicative of Gaussian distribution.

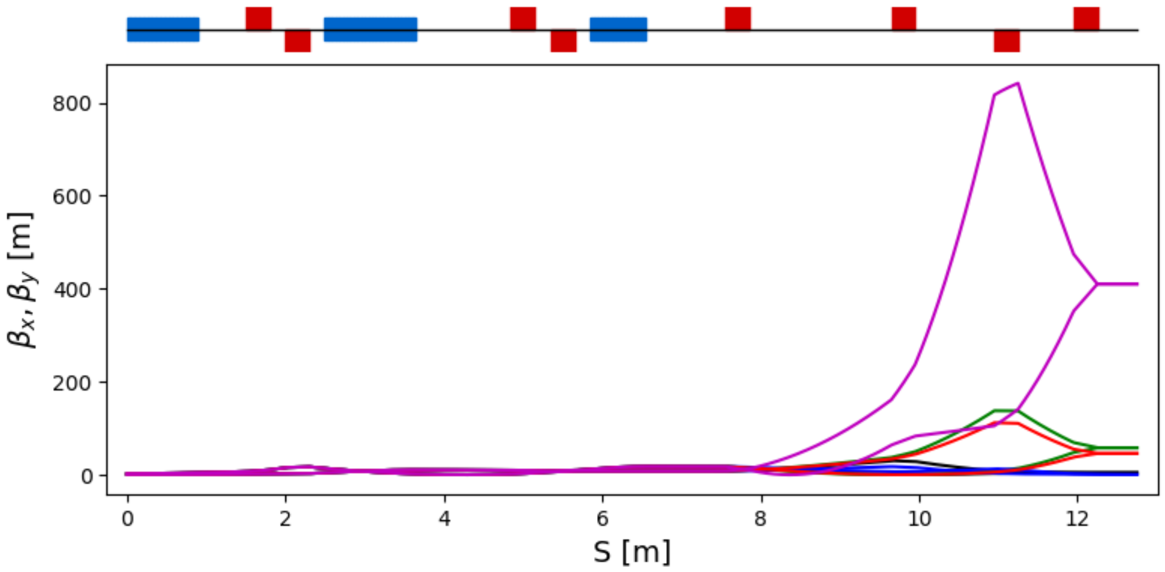
15 MeV ± 2%

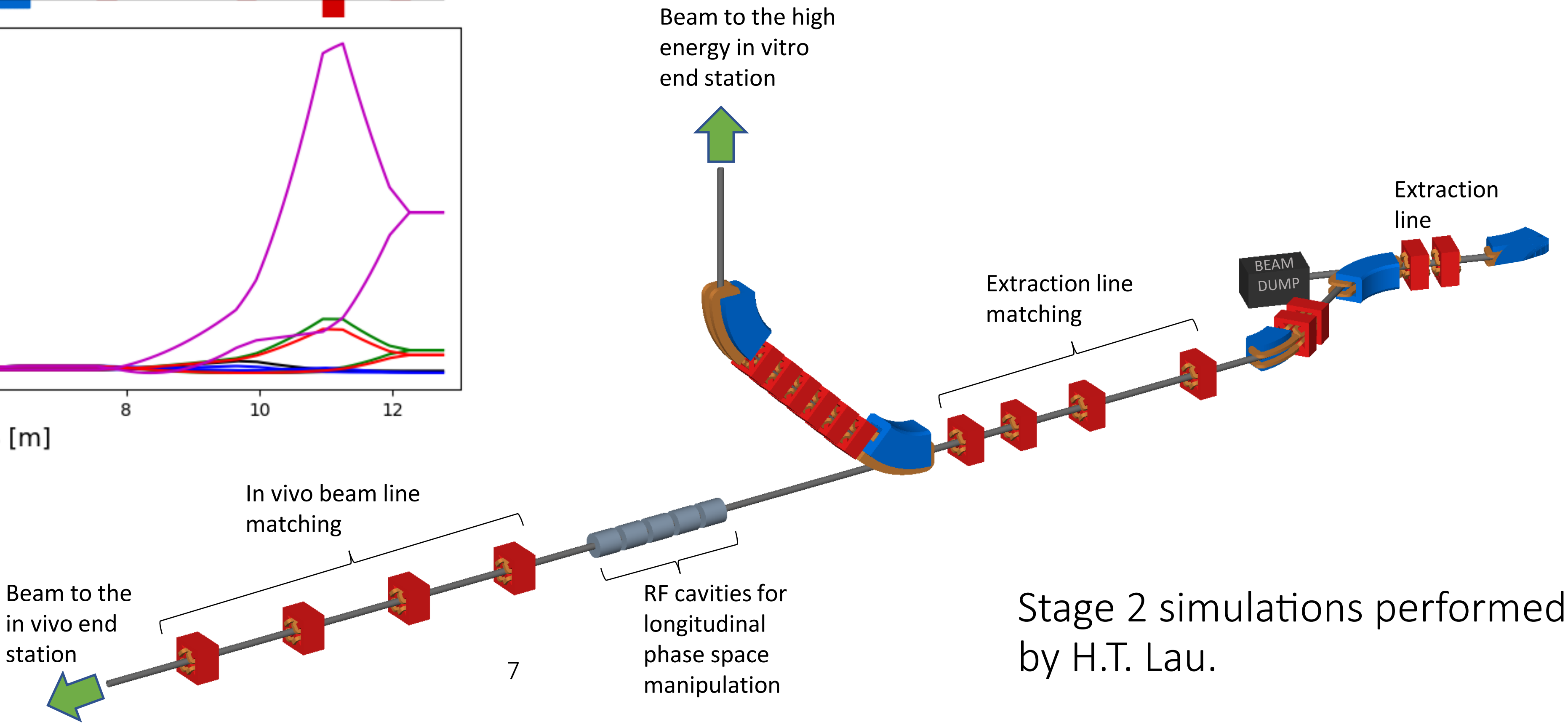


Stage 2 Simulations

- Potential factor 10 variation in emittance
  - Extraction energy at 40 or 127.4 MeV
  - Space charge is still a concern

- Optics configurations to deliver beam between 1 and 30 mm.

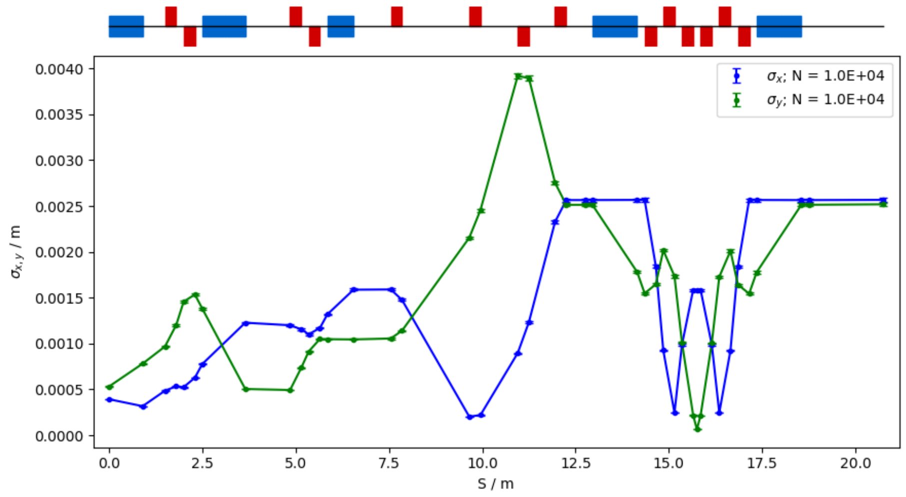




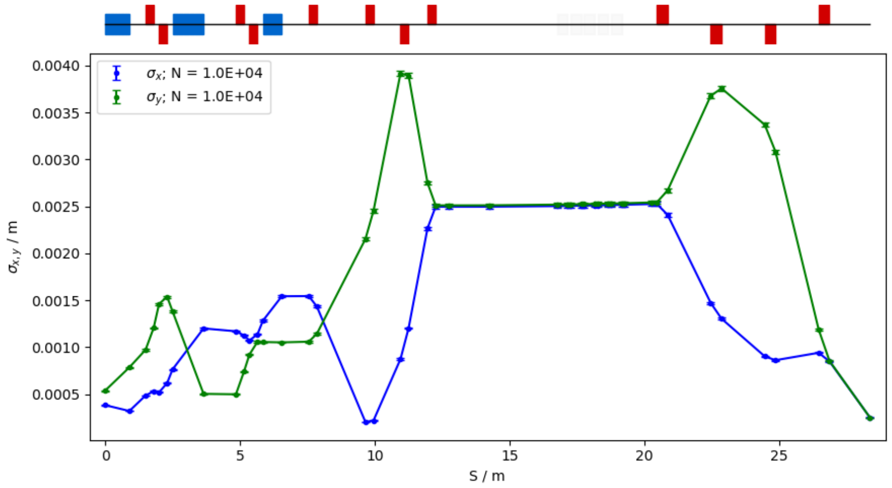
Stage 2 simulations performed by H.T. Lau.

Stage 2 In Vitro & In Vivo Beam Lines

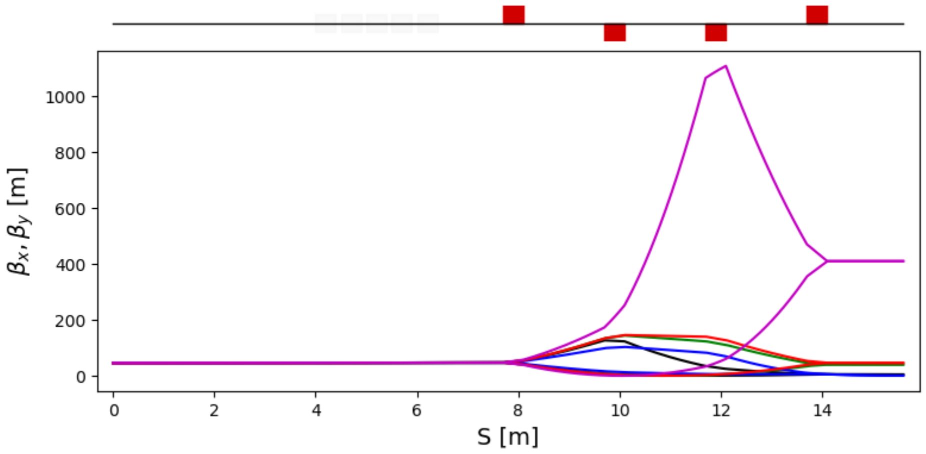
- Successful tracked through to in vitro end station
  - Full width beam size within 1-3cm target
  - Optical performance appears minimally affected by space charge for largest beam sizes
  - Smaller spot size configuration is affected but can be compensated in extraction line.

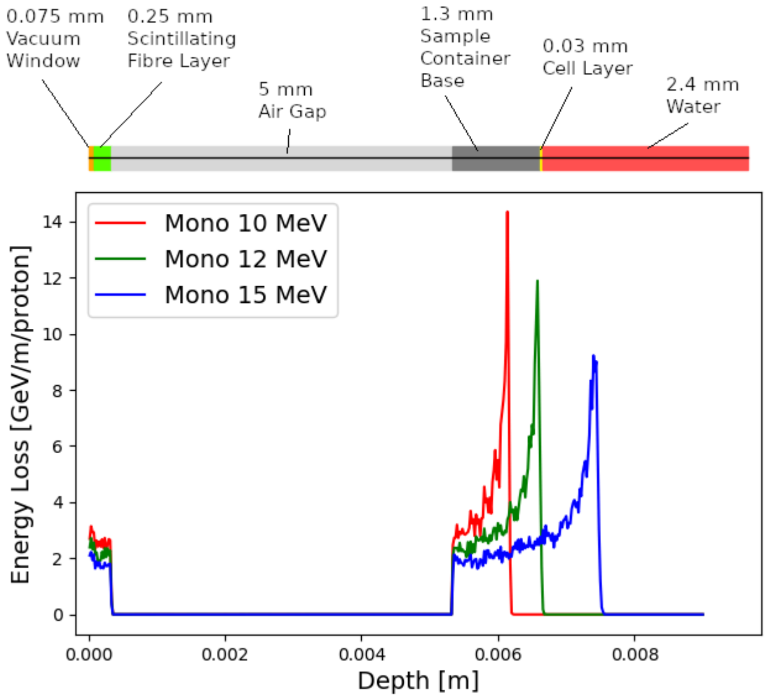


- Flexible in vivo beam delivery- optics configurations can deliver beam between 1 and 30 mm
  - Beams < 1 mm are possible but would be non-parallel



- All configurations at 40 MeV and 127 MeV are affected by space charge
  - Further fine tuning required.





End Station Simulations

- Energy deposition in end station target materials with BDSIM (H.T. Lau)
  - Investigate the Bragg peak location relative to the expected position of the cell layer
- Three monoenergetic idealised beams
  - 12 MeV beam yielded the Bragg peak closest to the cell layer
- Dose calculated from energy deposited in water phantom
  - Instantaneous dose calculated with bunch lengths of:
    - 7.0 ns for 12 and 15 MeV protons (in vitro)
    - 41.5 ns for 127 MeV protons (in vitro)
    - 75.2 ns for 33.4 MeV/u Carbon (in vitro)
  - Average dose rate based on 10 Hz laser source repetition rate

	12 MeV Protons	15 MeV Protons	127 MeV Protons	33.4 MeV/u Carbon
Dose per pulse	7.1 Gy	12.8 Gy	15.6 Gy	73.0 Gy
Instantaneous dose rate	1.0×10^9 Gy/s	1.8×10^9 Gy/s	3.8×10^8 Gy/s	9.7×10^8 Gy/s
Average dose rate	71 Gy/s	128 Gy/s	156 Gy/s	730 Gy/s

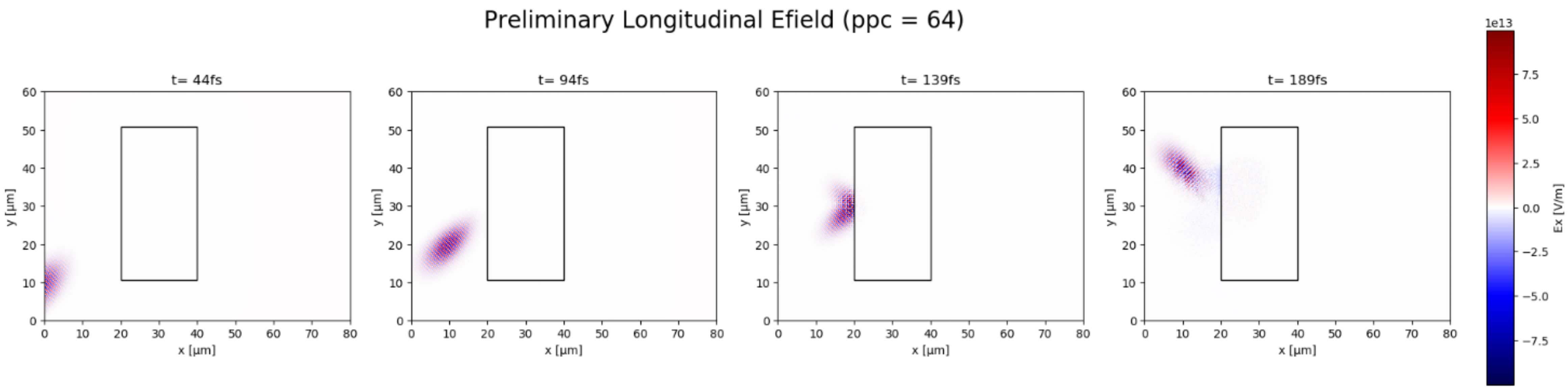
Improving the LhARA Beam Line model

- Increased accuracy of beam characteristics produced at the laser target
  - Reduce reliance on assumed beam properties.

- Replace solenoids with Gabor Lens field map
  - Scales with energy
  - More complicated fields possible

- Machine optimization:
  - Modify Gabor lens strengths to counter space charge effects
  - Update collimation and octupole settings & positions to improved dose uniformity
  - Include collimators to simulation energy selection system
  - Add RF fields to model longitudinal phase space manipulation

Laser Target Simulations with Smilei

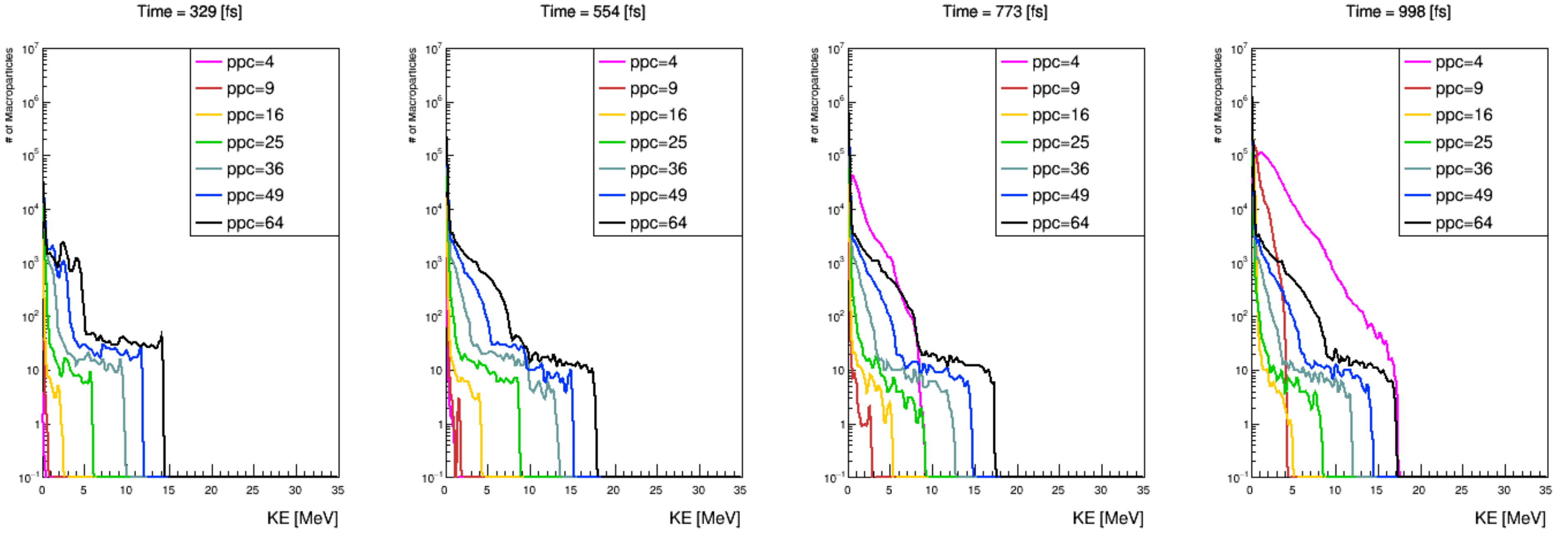


Longitudinal electric field to visualize a laser pulse on a foil target. Rectangle in black represents the foil.

- Smilei is a particle-in-cell (PIC) code for plasma simulations.
- Solves Maxwell's equations (for EM fields) and Vlasov equations (for particle species).
- Figure visualizes a laser pulse on a 20 μm thick foil represented by the black rectangle.

Work performed by H.T. Lau.

Smilei Simulations: Convergence Testing



Spectrum of proton macroparticles from back of foil for various PPC settings at different timesteps.

- Proton macroparticle kinetic energy spectrum at back of the foil (i.e. x≥40 μm) at various timesteps. Particle per cell (PPC) varied in order to find convergent solution.
- Low PPC values suffer from numerical heating effects (observed for pink (PPC=4) curve).
- Convergence not yet reached as there is still a significant discrepancy between different PPC settings.

Work performed by H.T. Lau.

Gabor Lens Field Map

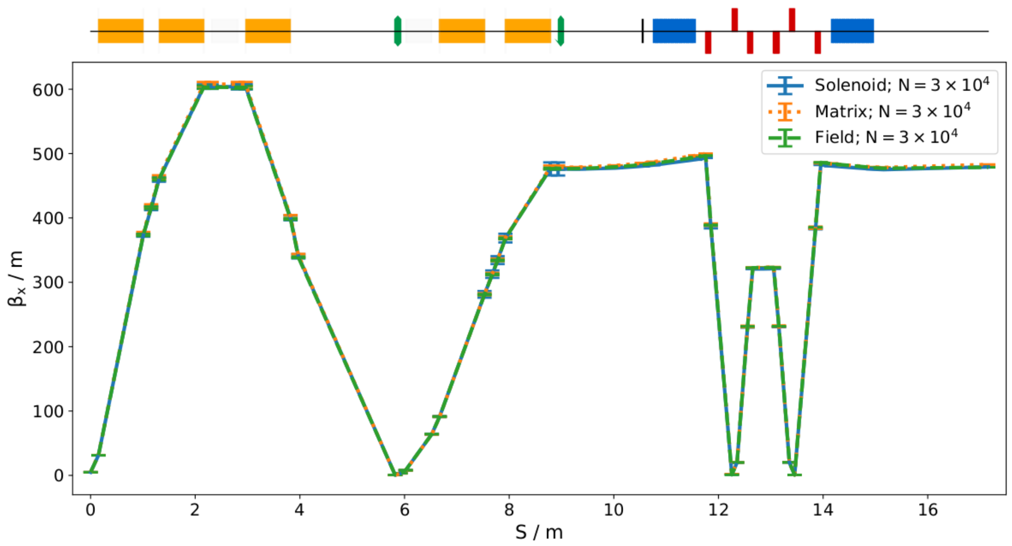
- Replace solenoids with Gabor lenses implemented as:
  a) 6D transfer matrices obtained from linearized Hamiltonian
  b) <u>Electrostatic field maps</u> (energy dependent focal length- allows collimation studies)

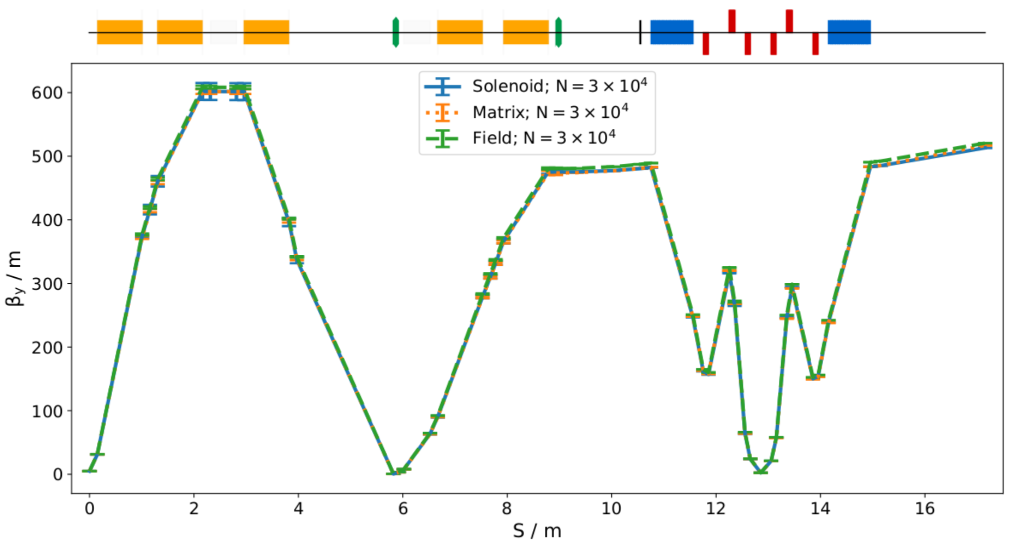
- Keep the same focusing strengths
- Optimal operation of the lens – (1)
- Homogeneous space-charge field – (2)
- Full agreement in optics calculated with BDSIM:

$$n_{e,max}{}^{1} = \frac{\epsilon_0}{2m_e} B_{GL}^2 \quad (1)$$

$$E_r = -\frac{e n_e}{2\epsilon_0} r \quad (2)$$

[1] M. Reiser, "Comparison of Gabor lens, gas focusing, and electrostatic quadrupole focusing for low-energy ion beams," (1989)
DOI: 10.1109/PAC.1989.72912





Work performed by T.S. Dascalu

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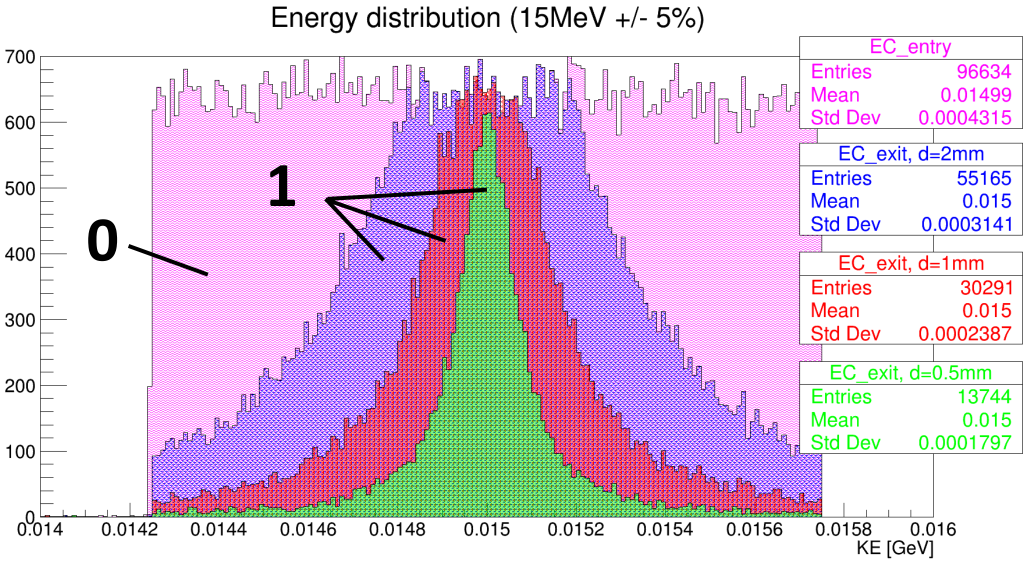
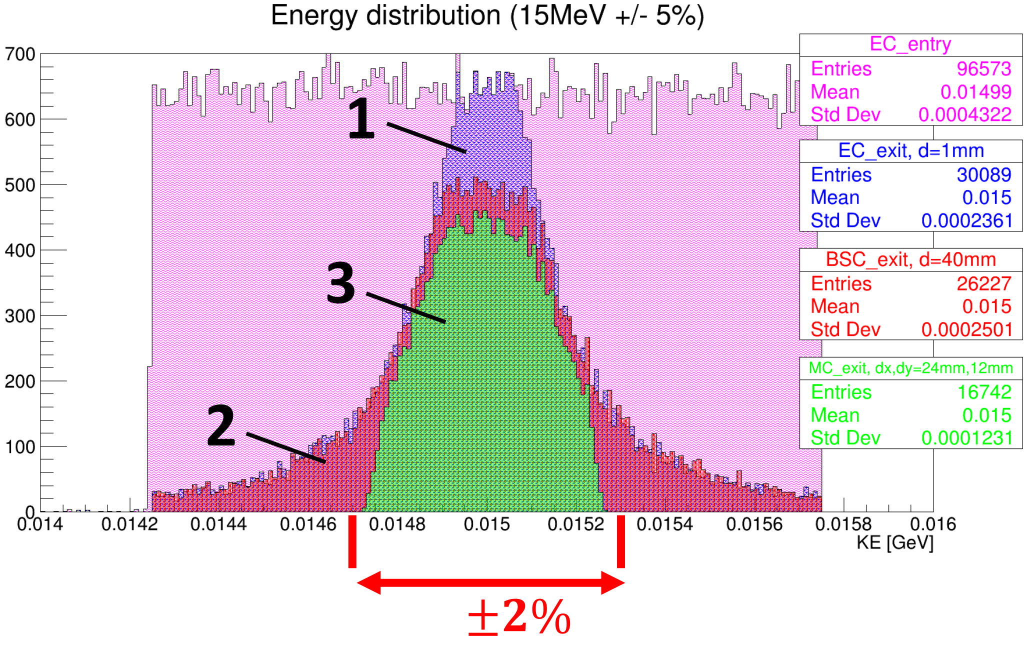
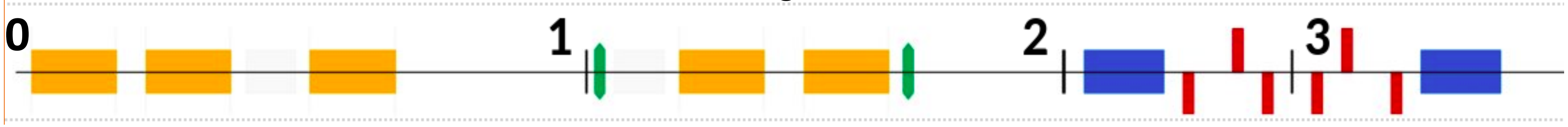
Energy Collimation Studies

- Simulation of $N = 1{\times}10^5$ protons in BDSIM
- Flat initial energy profile $15\ MeV \pm 15\%$ (labelled “0”)
- 3 collimators
  1) Energy collimation (at beam focus)
  2) Beam shaping
  3) Momentum cleaning
- Energy spread may be controlled only with first collimator by changing the aperture size (top fig.)
- Momentum cleaning is required to remove the tails of energy distribution (bottom fig.)





LhARA Stage 1 beamline



Work performed by T.S. Dascalu

Summary

- 1-3cm uniform dose is deliverable to the stage 1 in vitro end station
  - Space charge has an impact optical performance
  - Physically representative beam delivered to the end station
    - Large energy variation results in losses

- Flexibility in the Stage 2 in vitro and in vivo beam lines

- Instantaneous doses of 1.8×10^9 Gy/s (15 MeV) and 3.8×10^8 Gy/s (127 MeV) achieved

- Model improvements identified and are underway
  - Gabor lens field maps to replace solenoids
  - Improved beam accuracy
  - Optimization

Thank You!