Simulation of LhARA

27/03/2020

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LhARA Simulations

- MADX and BeamOptics used for calculating lattice optical functions
  - Idealistic machine description
  - End-to-end simulations to evaluate machine performance

- Two pronged approach:

GPT: General Particle Tracer

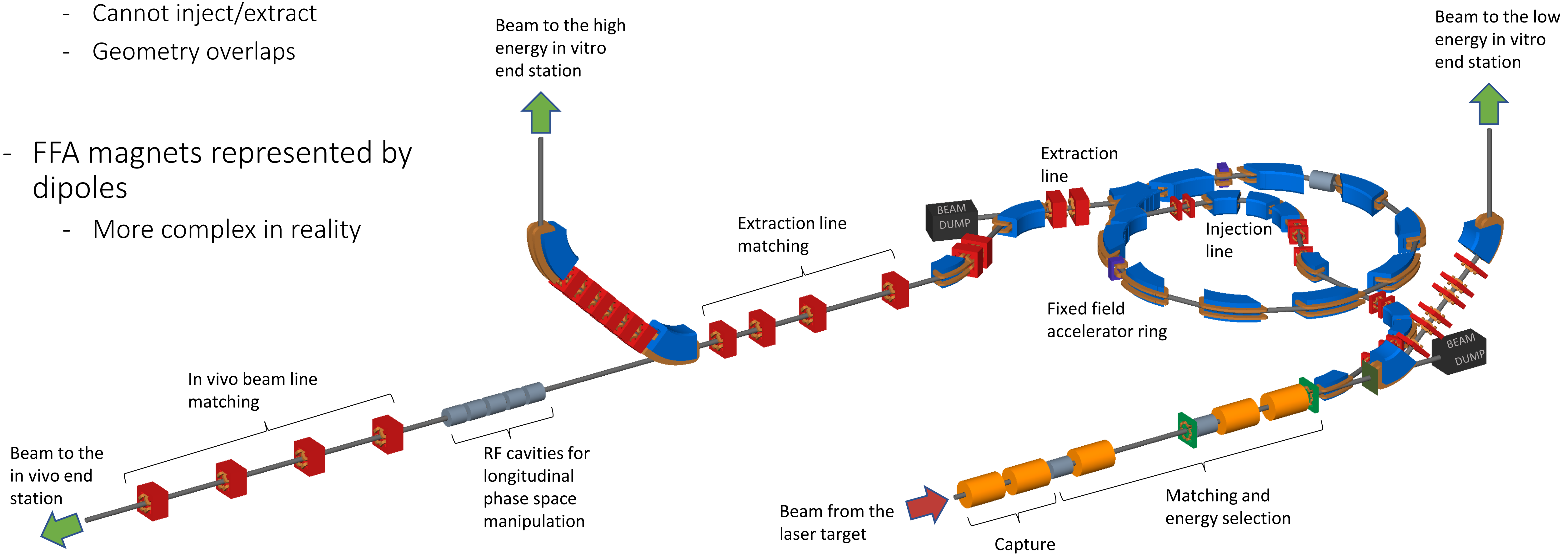
- Space charge effects

BDSIM: Beam Delivery Simulation

- Particle-matter interactions
- Materials and apertures
- Beam losses
- Energy deposition & dosimetry
- Visualisation

LhARA Visualised in BDSIM

- Simulate individual machine sections
  - Cannot inject/extract
  - Geometry overlaps
- FFA magnets represented by dipoles
  - More complex in reality



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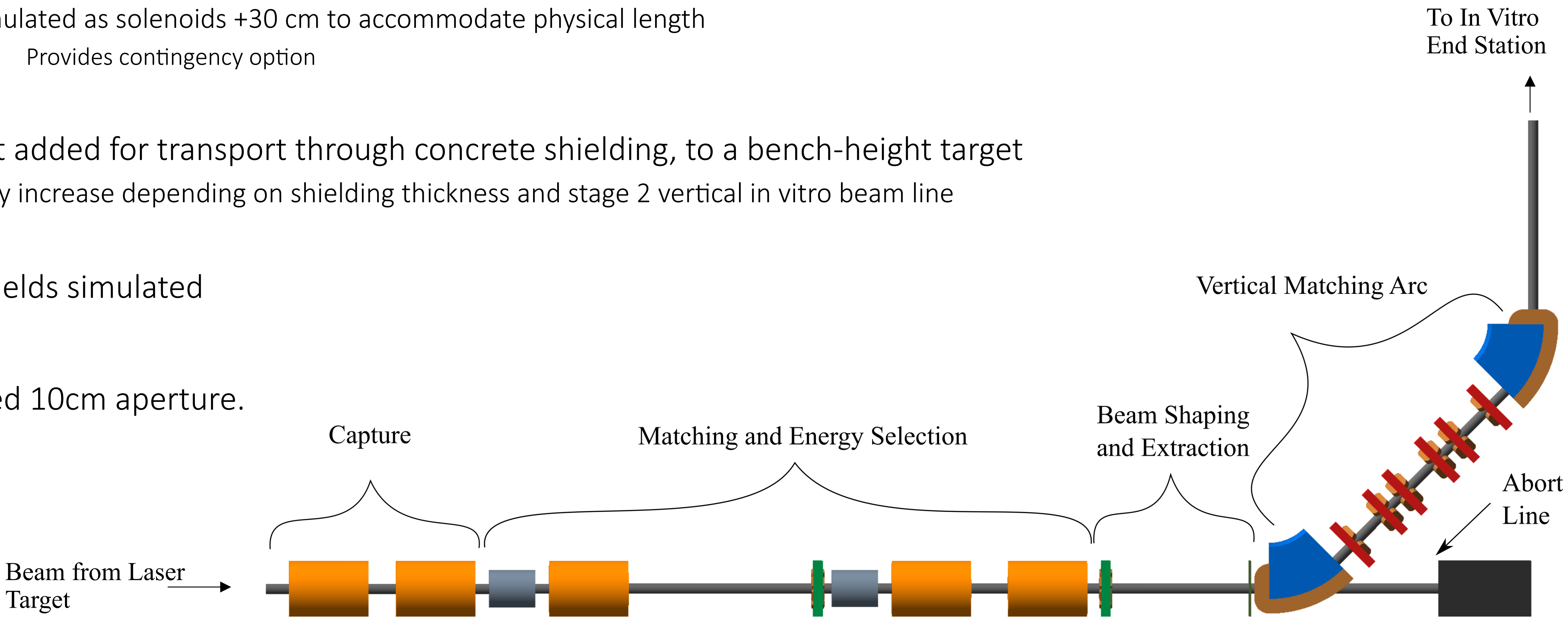
LhARA Stage 1 Model

- Gabor lenses for focusing in both planes
  - Simulated as solenoids +30 cm to accommodate physical length
    - Provides contingency option

- 2m drift added for transport through concrete shielding, to a bench-height target
  - May increase depending on shielding thickness and stage 2 vertical in vitro beam line

- No RF fields simulated

- Assumed 10cm aperture.



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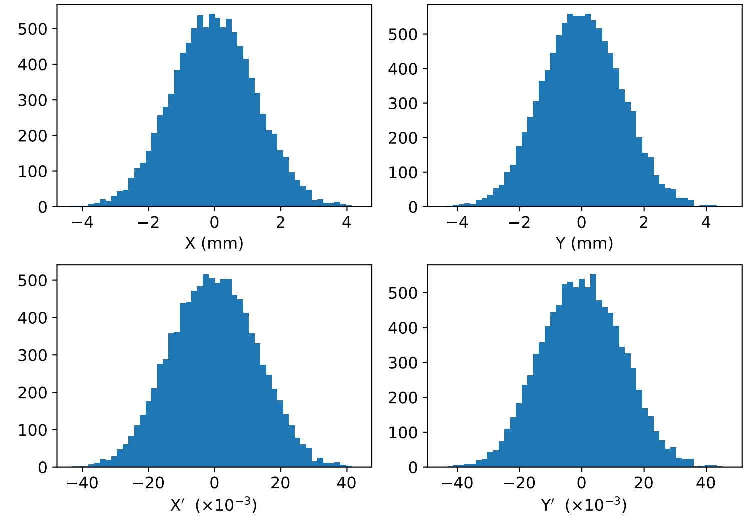
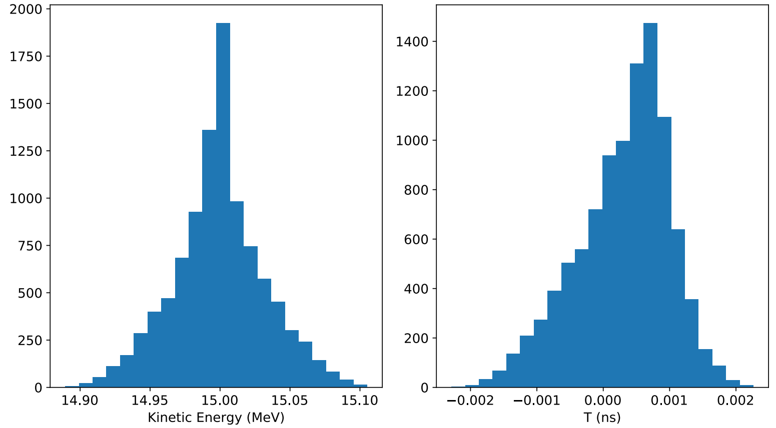
Idealised Beam

- Assumed ideal beam for lattice optimization
  - Beam width (1.7 µm), pulse duration (25 fs), divergence (50 mrad)
  - Maximum of 10^9 protons per shot (100 pC)
    - Contaminants (e-, ions) will reduce bunch charge
    - Unknown composition - assume maximum as worst case scenario

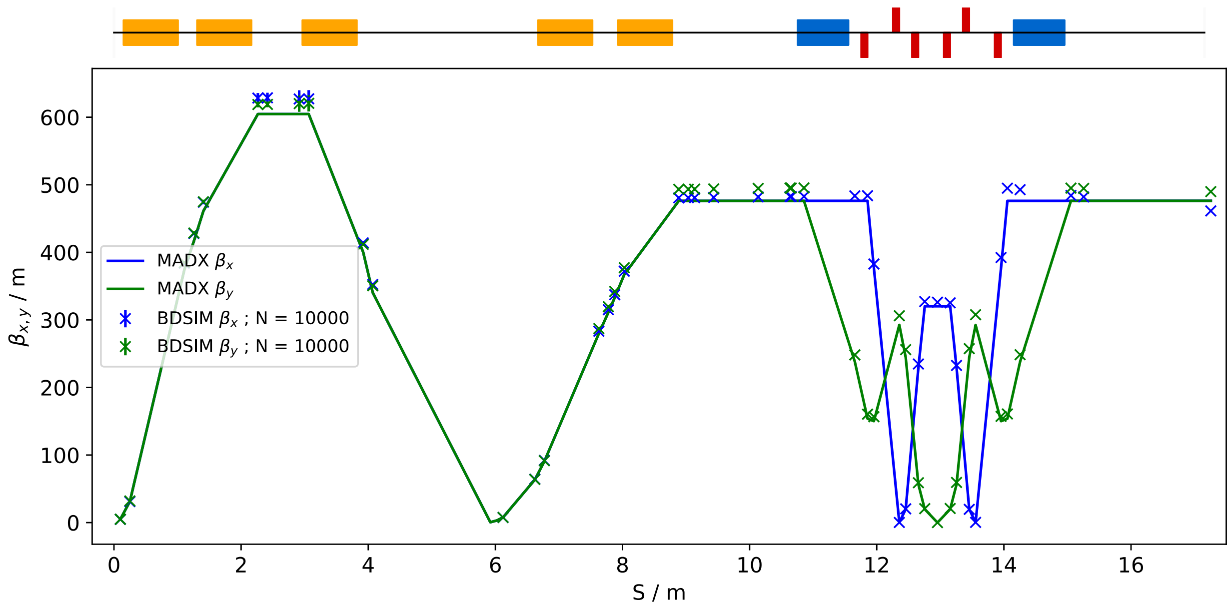
- Charge density causes an immediate emittance growth
  - Estimate beams wider than 0.1 mm experience diminishing space charge effects

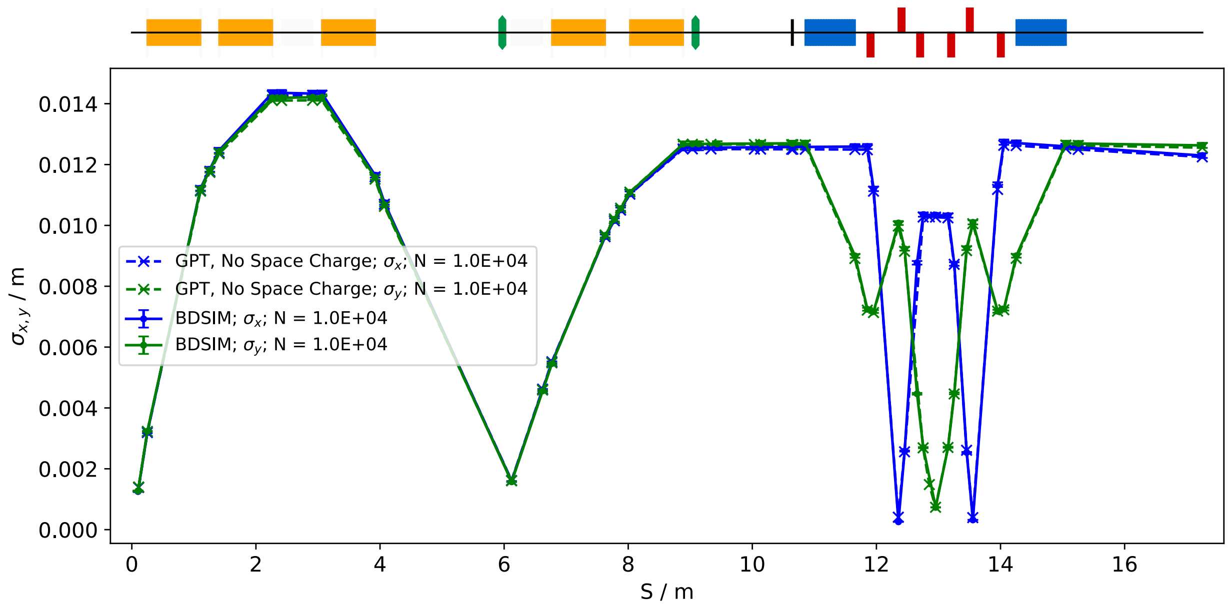
- Simulate between 5-10 cm with space charge
  - Within the confines of the laser target housing
  - 10000 particles in all simulations





Optical Validation



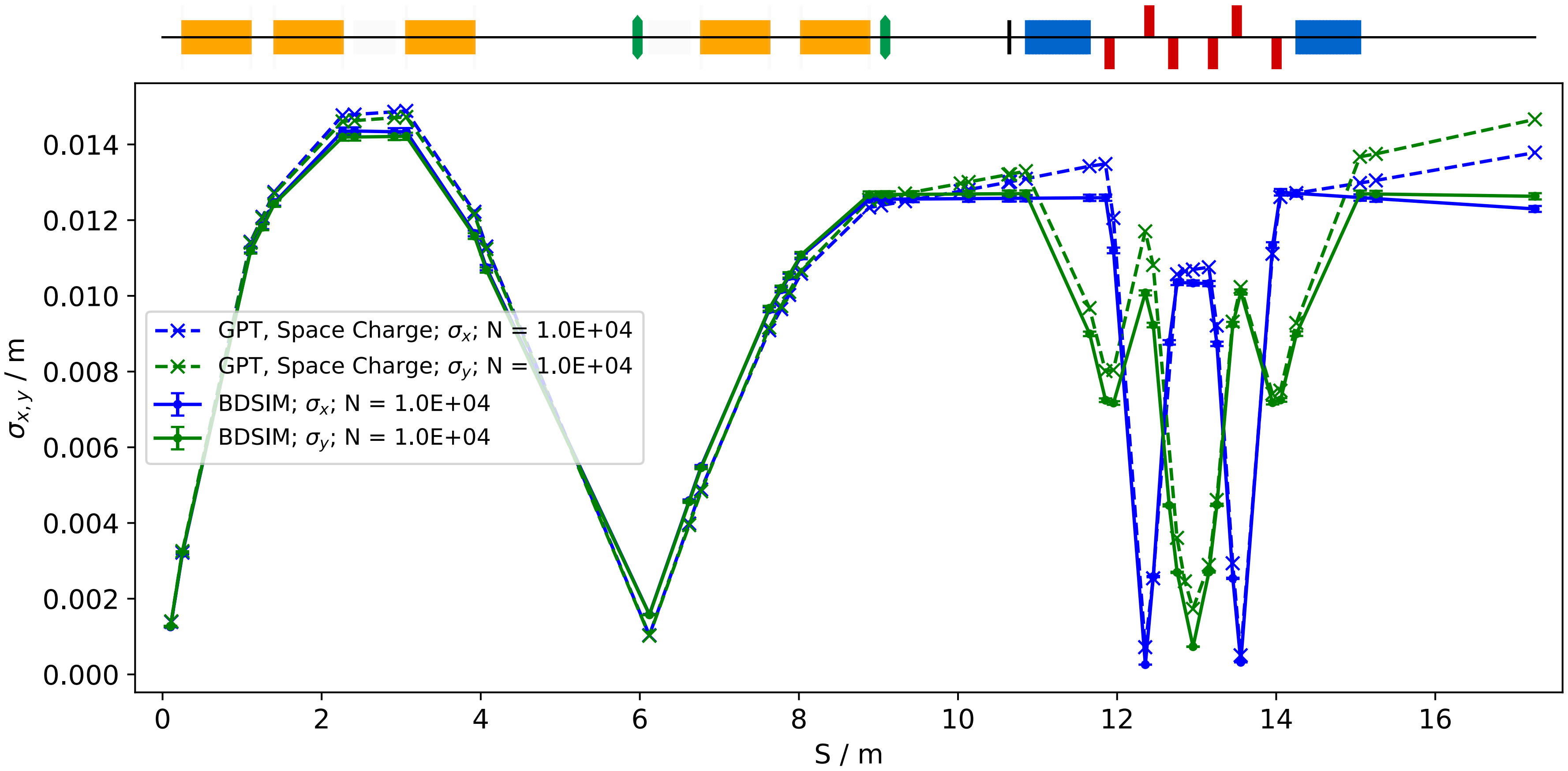


- Excellent agreement between MADX and BDSIM

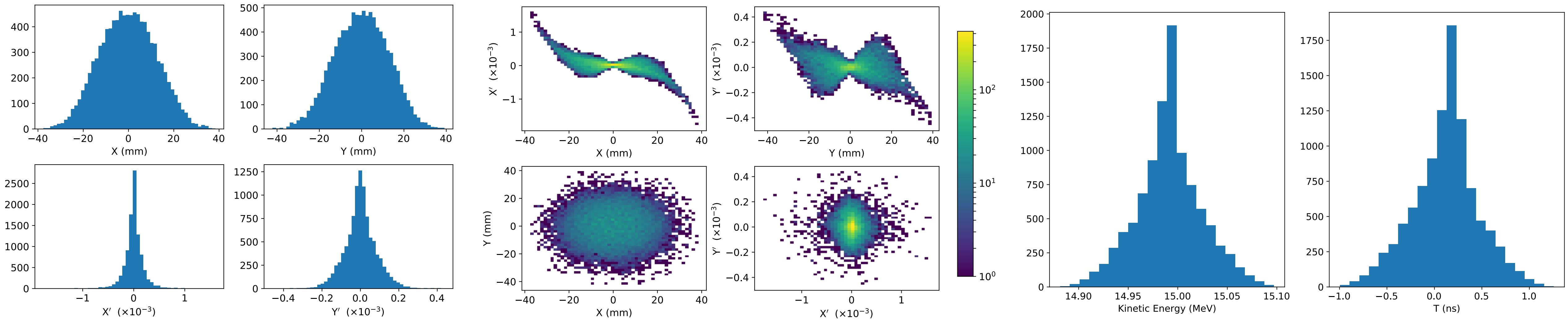
- Excellent agreement between and GPT without space charge.

Optical Performance

- Reasonable agreement seen between BDSIM and GPT with space charge
- Further 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

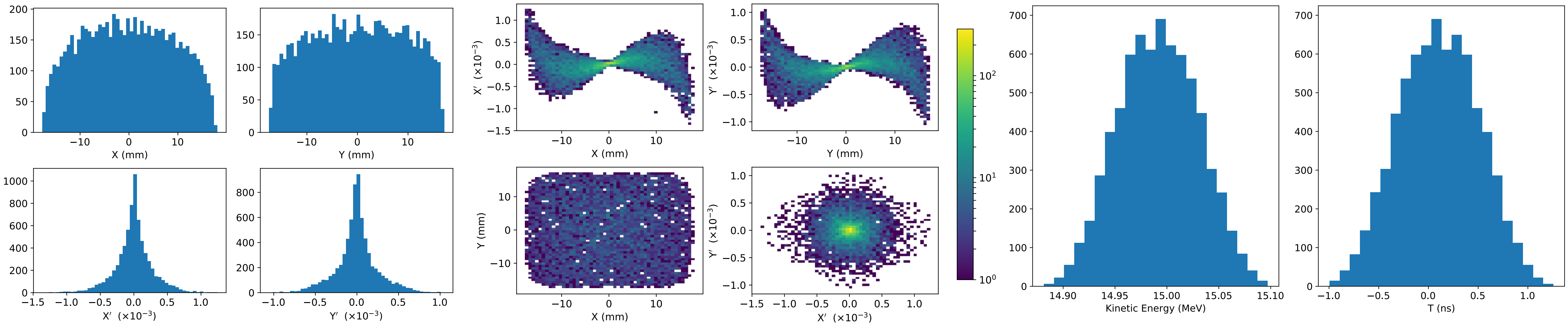


End Station Idealised Phase Space



- Gaussian beam delivered to the end station
- Aberrations arising in the Gabor lenses cause ‘butterfly’ shape seen in the transverse phase space
- Near 100% transmission.

Phase Space Post Beam Shaping



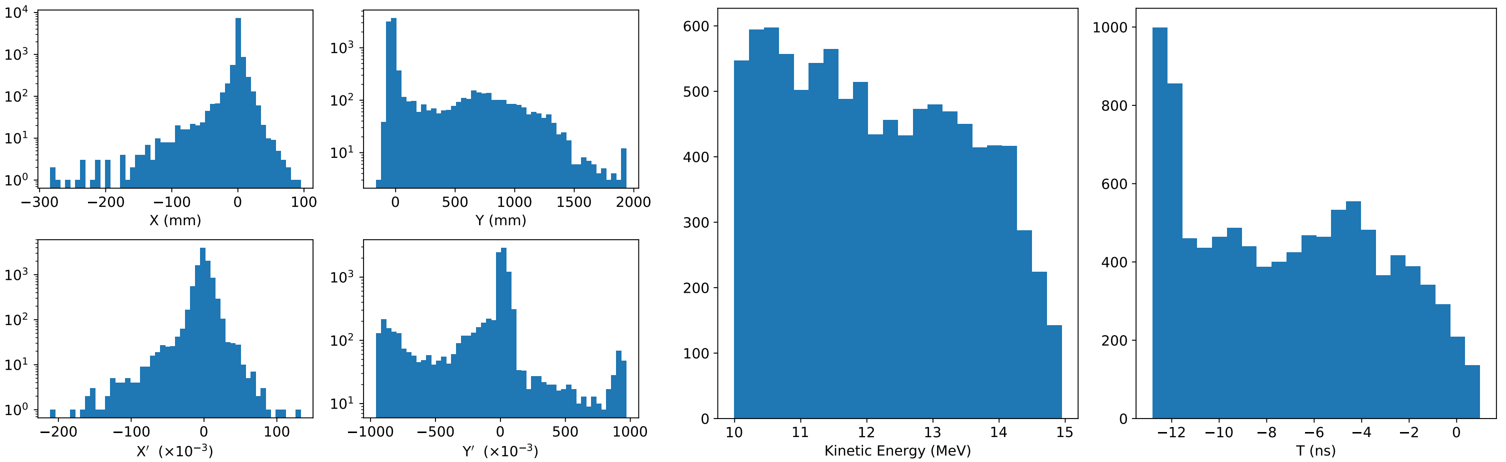
- Spatial uniformity observed
  - Arbitrary octupole strengths, collimator aperture of 4 cm diameter
  - Square distribution typical of such schemes
- Approx. 70% beam line transmission
  - Almost all losses in the collimator, minimal secondaries reach end station.
- Further simulation effort required
  - Optimise octupole and collimator locations, strengths, and apertures.

Laser-Target Simulation Derived Beam

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

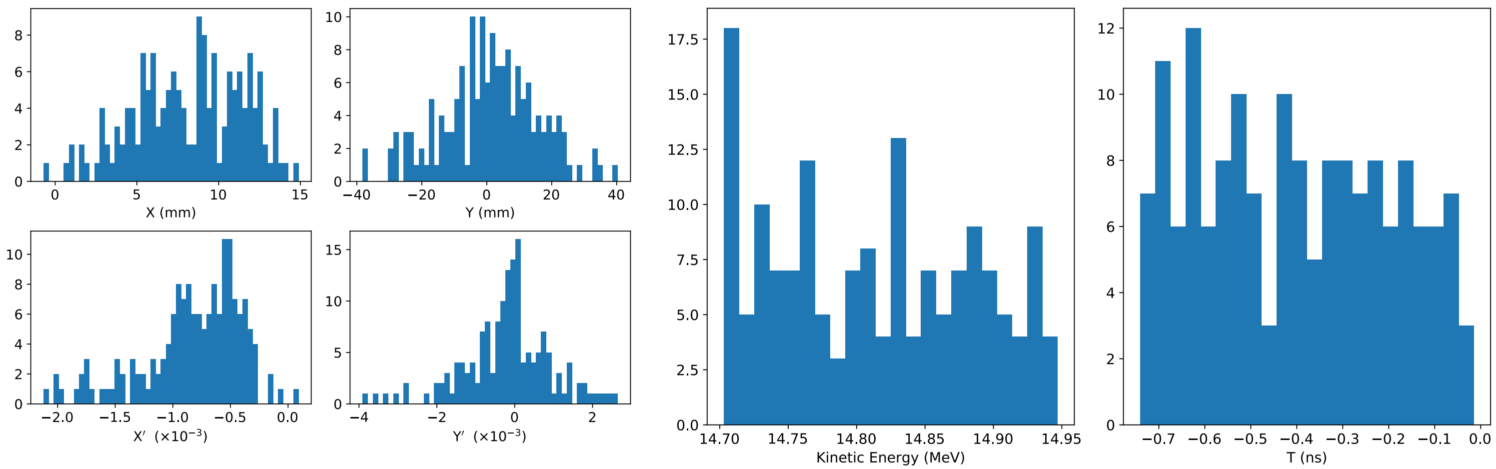
- Large distributions at the end station
  - Magnets set for 15 MeV, significant losses of off-energy particles

10-15 MeV



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

15 MeV ± 2%



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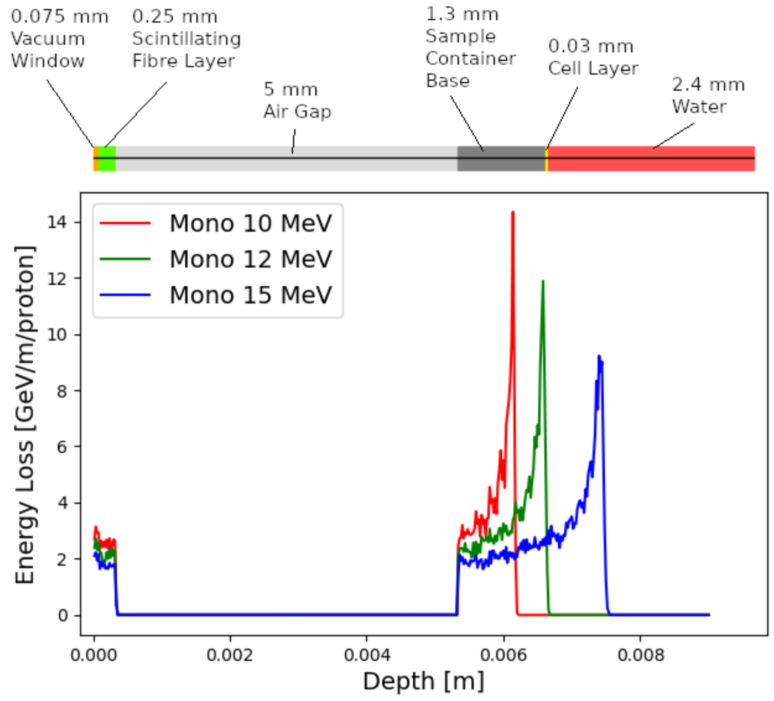
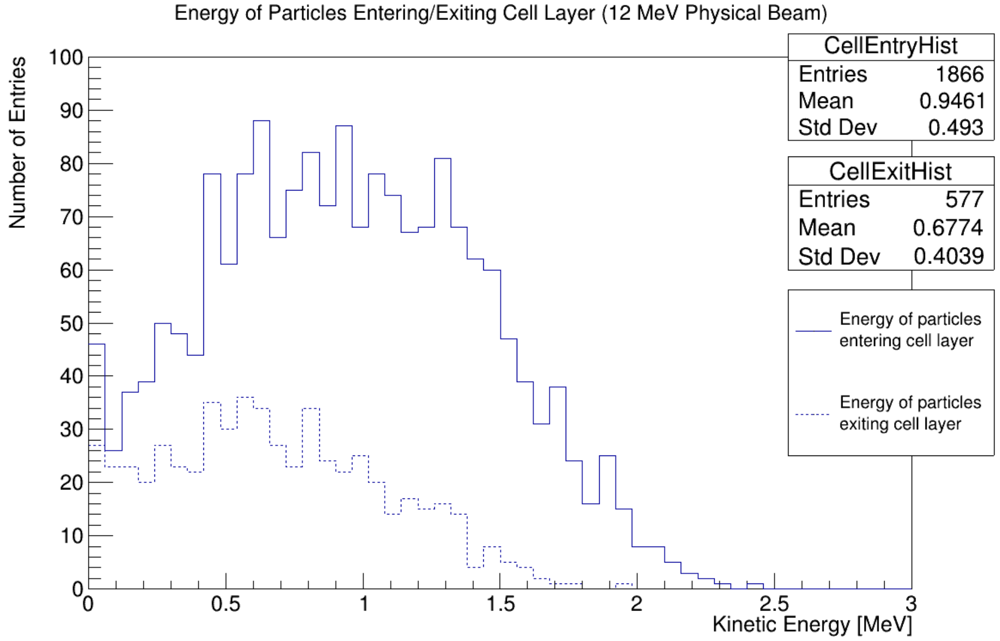
End Station Simulations



- 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



- Cell transmission with EPOCH derived beam (12 MeV ± 2%)
  - Total energy deposited in the cell layer of 9.63×10^{-6} Gy,
  - Maximum dose per pulse (10^9 protons) of about 5.16 Gy.

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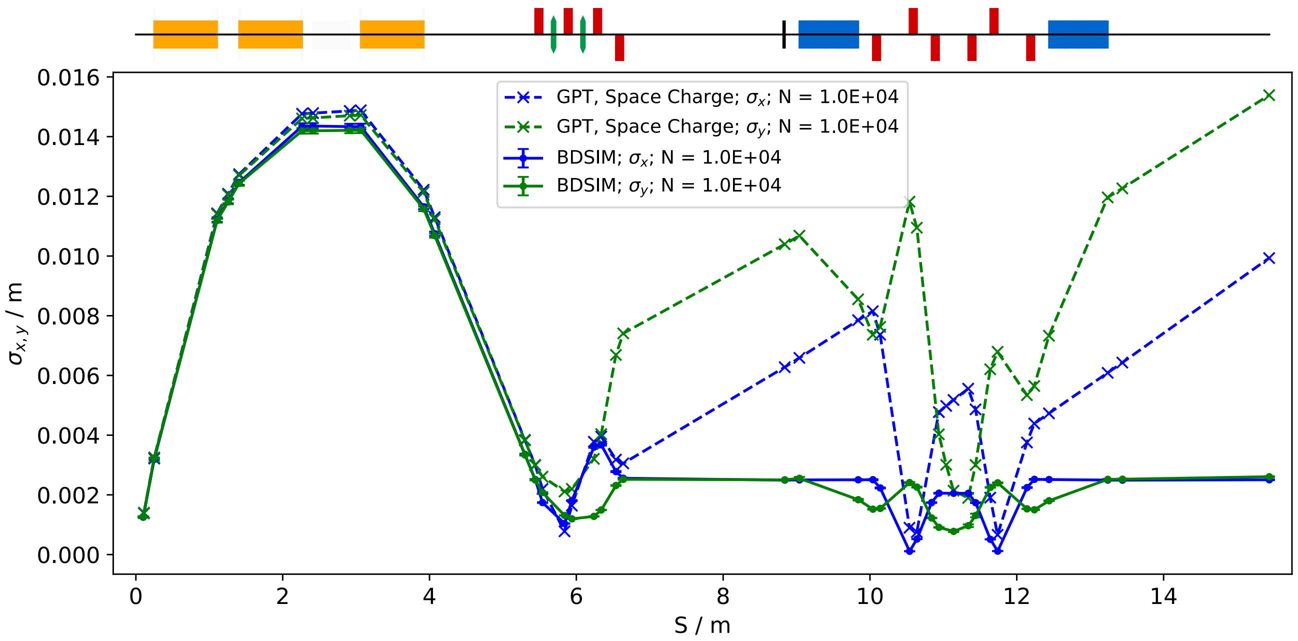
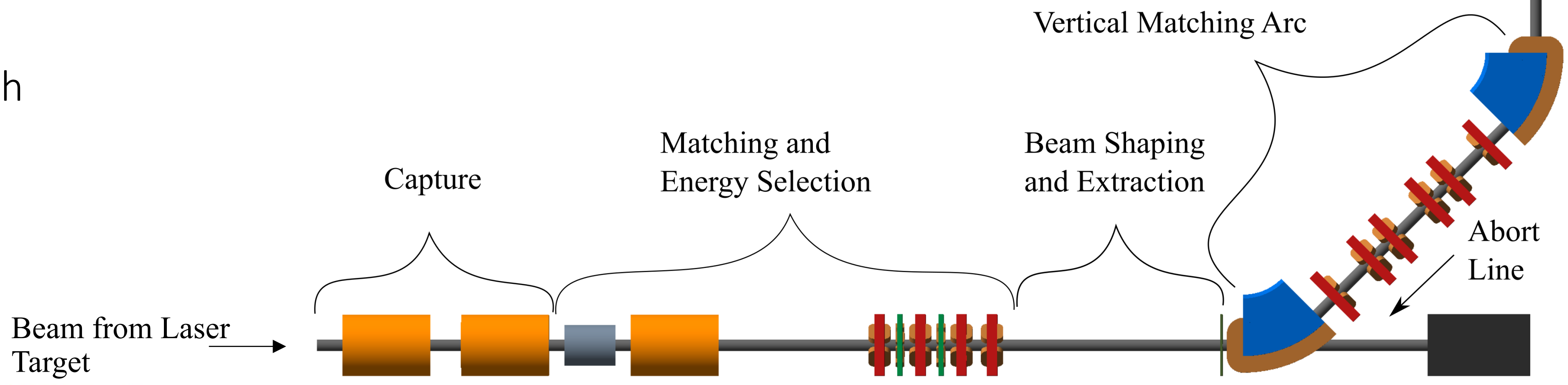
Stage 1 Alternate Design

- Replace Gabor lenses with four quadrupoles
  - Single plane focus
  - Octupoles shifted to optimum locations

- Significant performance from Initial emittance growth
  - 15 MeV ideal beam
  - Larger beam parameters at entrance of first quadrupole

- Improved performance with capture section Gabor lens tweaks

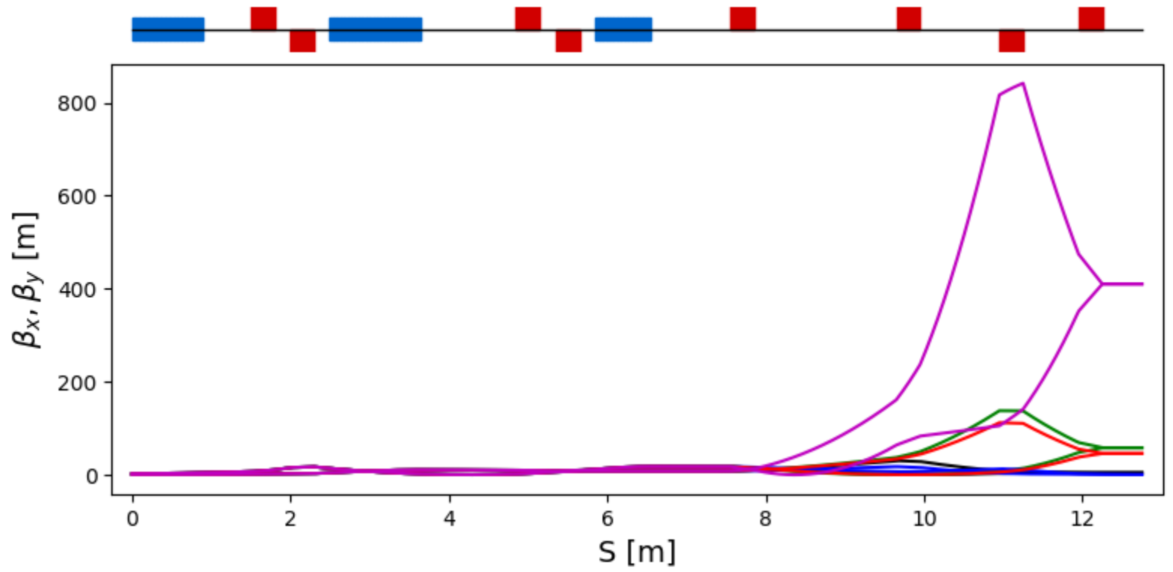


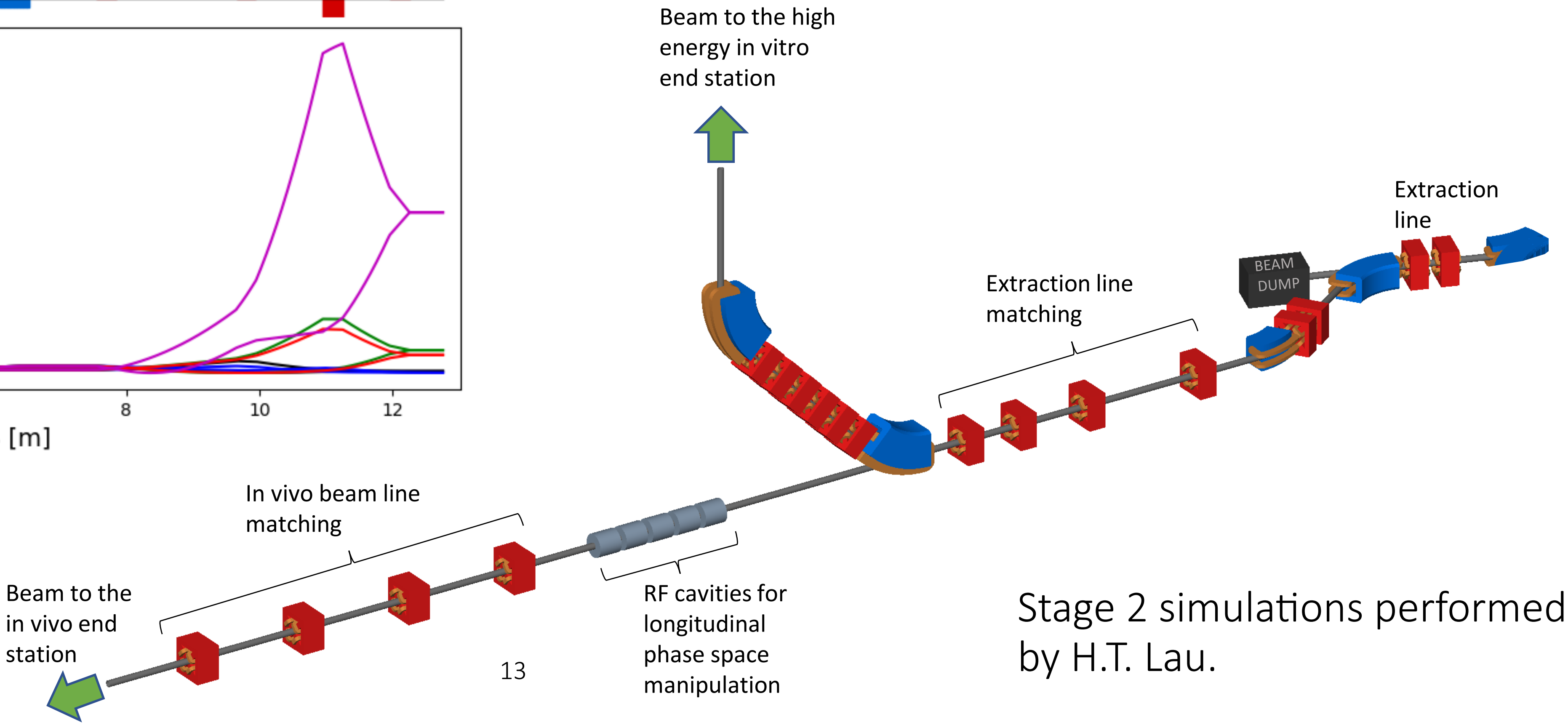


Stage 2 Simulations

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

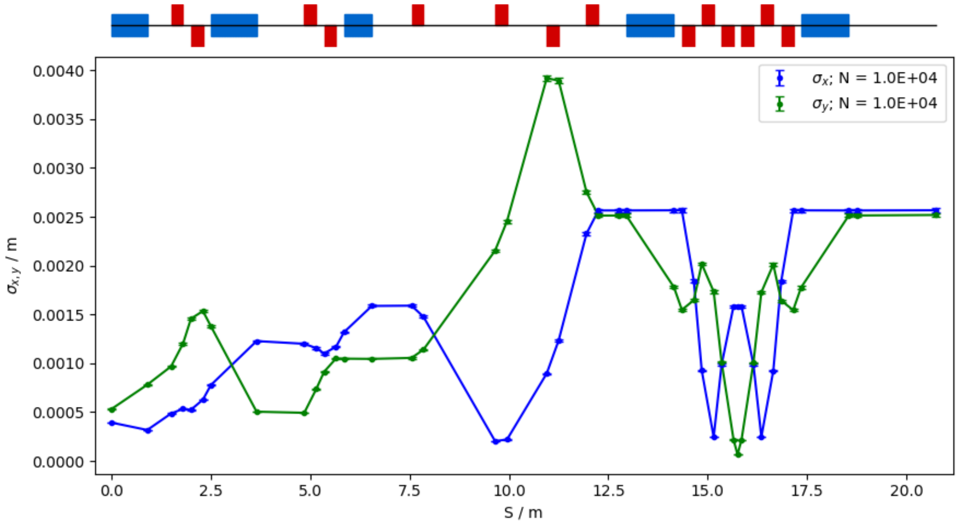
- Optics configurations to deliver beam sizes over three orders of magnitude ($\beta_{x,y}$ = 0.46m to 410m).





Stage 2 simulations performed by H.T. Lau.

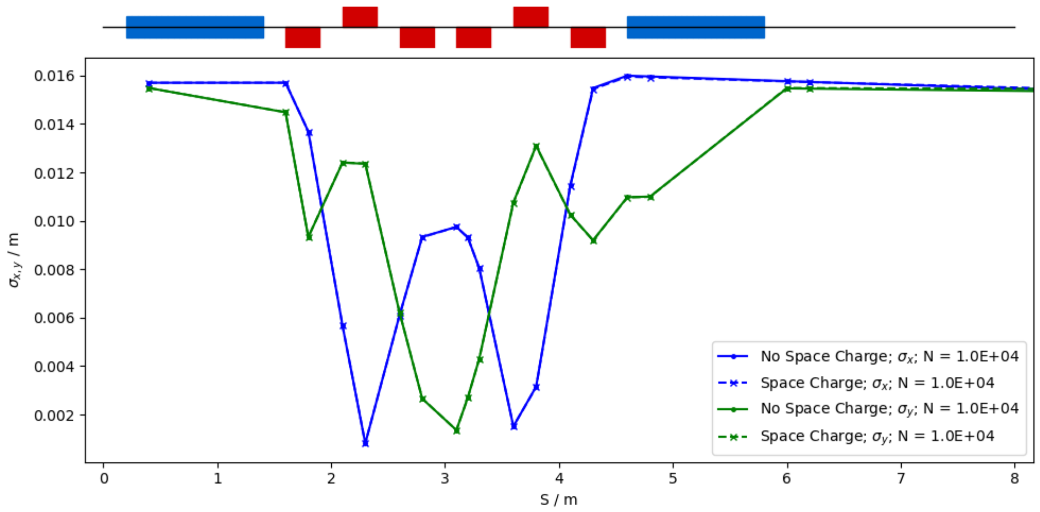
Stage 2 In Vitro Beam Line

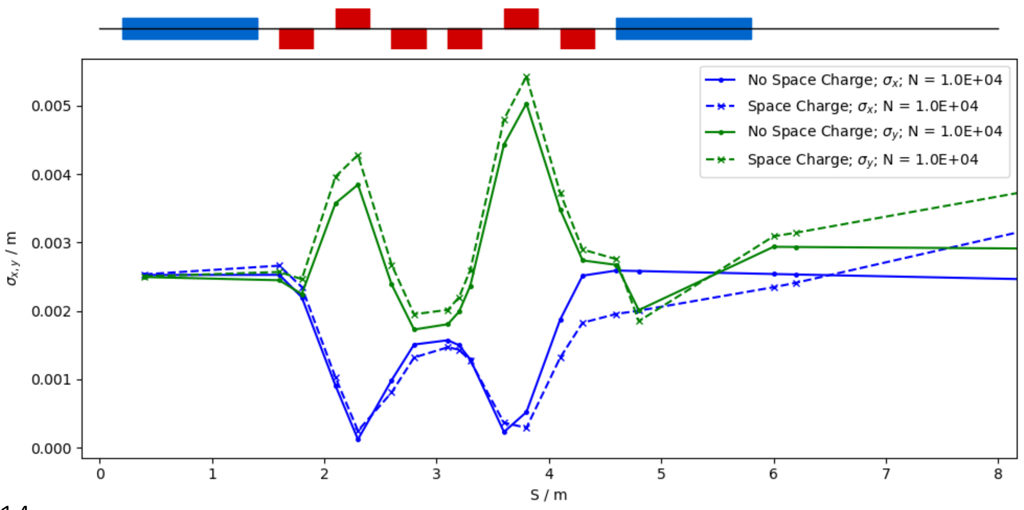


- Successful tracking through full extraction line and vertical in vitro line
  - Full width beam size within 1-3cm target.

- Simulations ($\beta_{x,y}$ = 40m) shows optical performance appears minimally affected by space charge

- Lower beta (4.5m) configuration affected due to smaller beam size
  - Can be compensated in extraction line.





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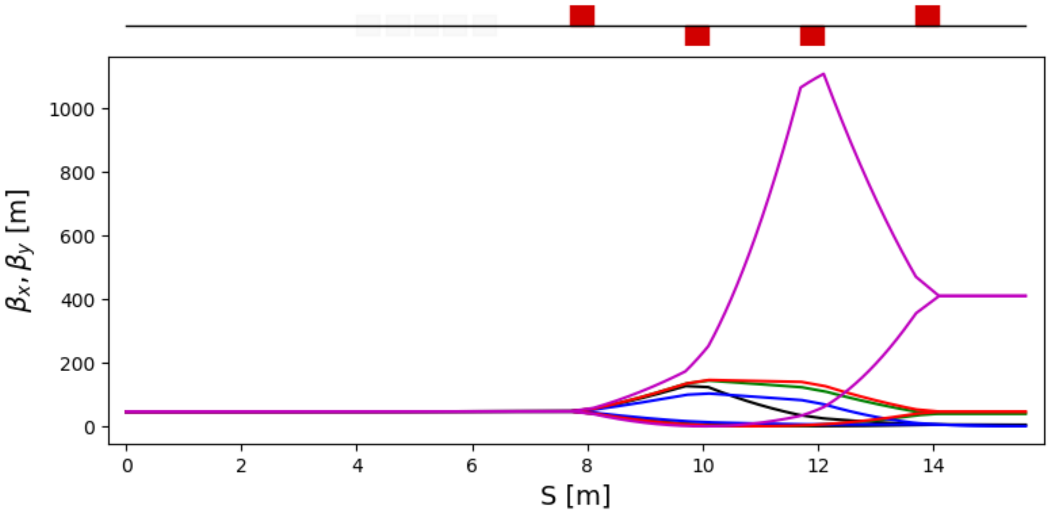
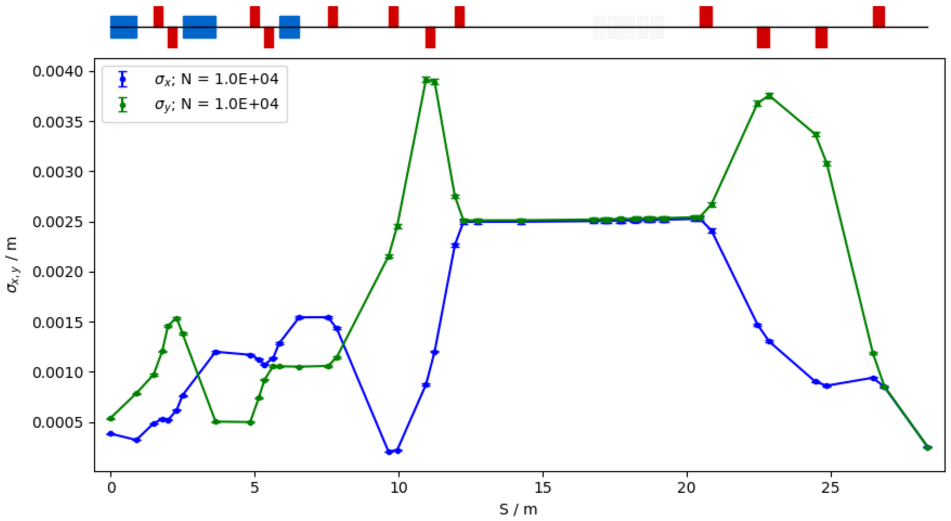
Stage 2 In Vivo Beam Line

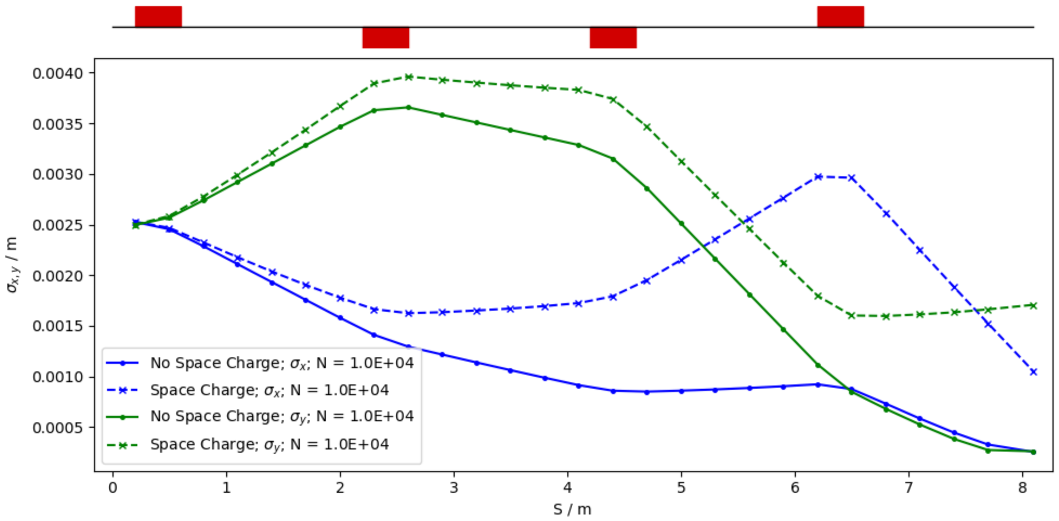


- Optics configurations to deliver beam sizes over three orders of magnitude ($\beta_{x,y}$ = 0.46m to 410m).
  - Assumed initial $\beta_{x,y}$ = 46m.

- Beam smaller than 1mm is possible, but it is non-parallel
  - Repercussions for scanning magnets

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





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Summary

- 1-3cm uniform dose is deliverable to the stage 1 in vitro end station
    - Space charge has an impact optical performance
    - Further optimization is required

- Physically representative beam delivered to the end station
    - Large energy variation results in losses
    - Further simulations will improve statistics

- Flexibility in the Stage 2 in vitro and in vivo beam lines
    - Further optimization required
    - Improve beam quality for in vivo spot scanning

- Well placed to improve models and accuracy
    - Gabor lens field maps to replace solenoids
    - RF fields