LhARA: Baseline Design & Simulations

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LhARA Collaboration Meeting

14th October 2022

Outline

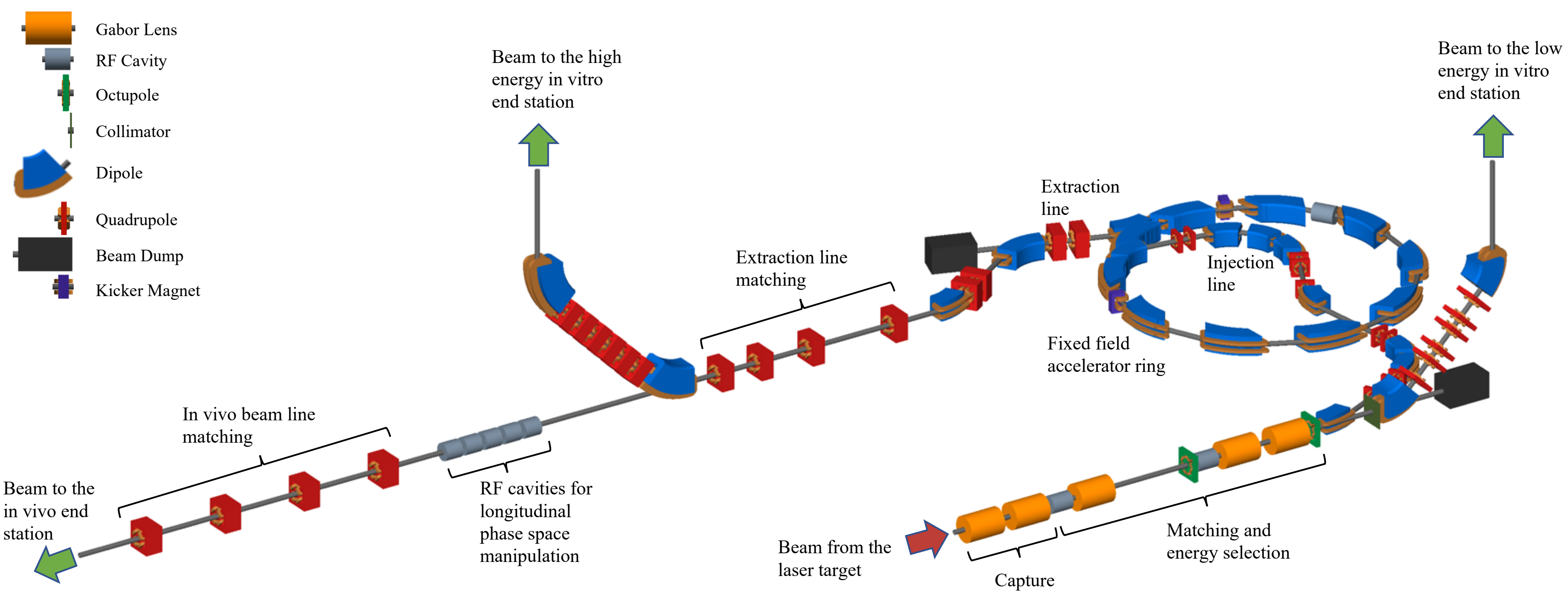
1. Stage 1 overview

2. Stage 1 performance evaluation with Monte Carlo simulations

3. Stage 2 injection line

4. Stage 2 FFA, extraction line, *in-vitro*, & *in-vivo* beam lines.

The LhARA Accelerator

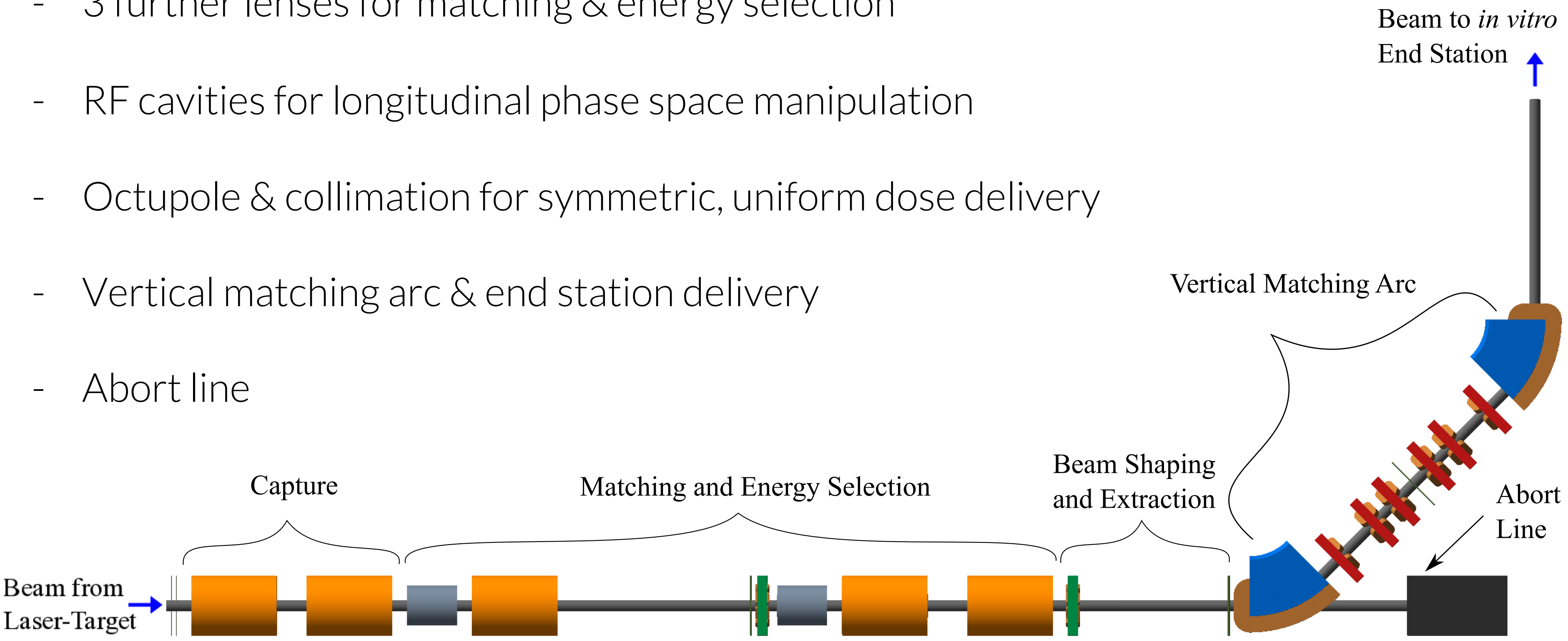


Full pre-CDR Technical Note:
https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Communication/Notes/CCAP-TN-01.pdf

Baseline Design Technical Note:
https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Communication/Notes/CCAP-TN-11-LhARA-Design-Baseline.pdf

Stage 1 Overview

- Beam up to 15 MeV protons & ions
- Vacuum nozzle before capture section for momentum cleaning
- 2 Gabor lenses in the capture section
- 3 further lenses for matching & energy selection
- RF cavities for longitudinal phase space manipulation
- Octupole & collimation for symmetric, uniform dose delivery
- Vertical matching arc & end station delivery
- Abort line



Stage 1 Design Parameters

Proton and ion capture		
Beam divergence to be captured	50	mrad
Gabor lens effective length	0.857	m
Gabor lens length (end-flange to end-flange)	1.157	m
Gabor lens cathode radius	0.0365	m
Gabor lens maximum voltage	65	kV
Number of Gabor lenses	2	
Alternative technology: solenoid length	1.157	m
Alternative technology: solenoid max field strength	1.3	T

Gabor Lenses

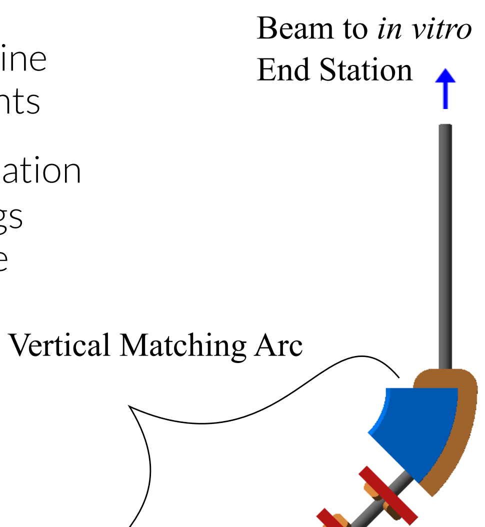
Alternative: solenoids

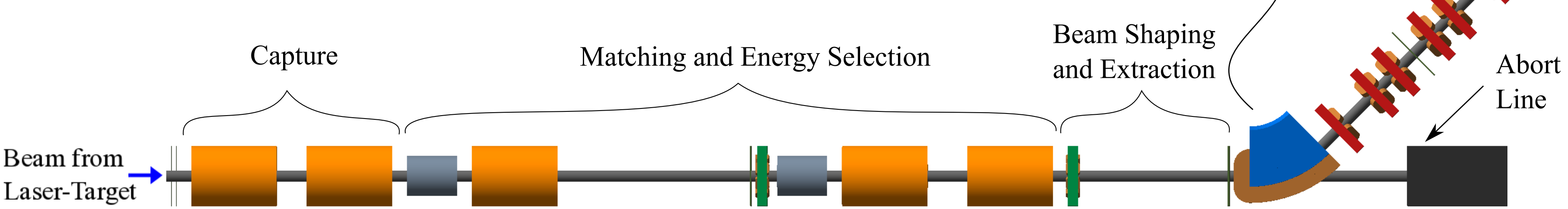
Stage 1 beam transport: matching & energy selection, beam delivery to low energy end station		
Number of Gabor lenses	3	
Number of re–bunching cavities	2	
Number of collimators for energy selection	1	
Arc bending angle	90	Degrees
Number of bending magnets	2	
Number of quadrupoles in the arc	6	
Alternative technology: solenoid length	1.157	m
Alternative technology: solenoid max field strength (to serve the injection line to the Stage 2)	0.8 (1.4)	T

Other beam line elements

Collimation settings update

Element	Position [m]	Horizontal half width [mm]	Vertical half width [mm]
Collimator 1	5.753	1.5	1.5
Collimator 2	10.65	23	23
Collimator 3	12.95	19	6.9





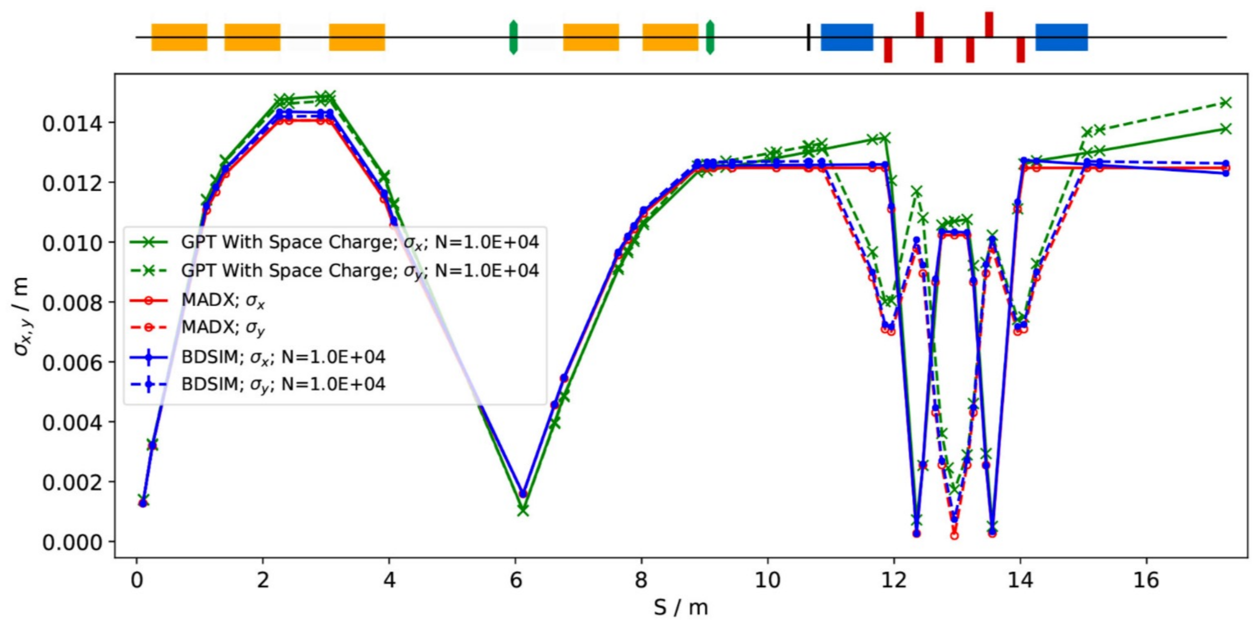
Particle Tracking

- MADX: Initial design
- Hybrid Monte Carlo strategy:
  - BDSIM: Accelerator tracking + particle-matter interactions (Geant4)
  - GPT: Particle tracking + space charge forces
- Gabor lenses modelled as equivalent strength solenoids

Beam Delivery Simulation

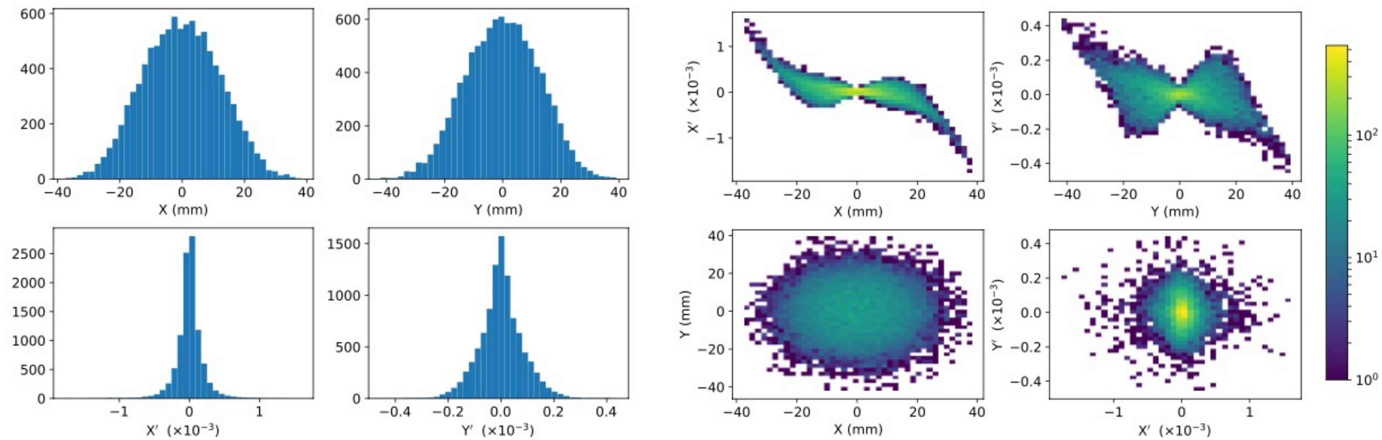
General Particle Tracer (GPT)

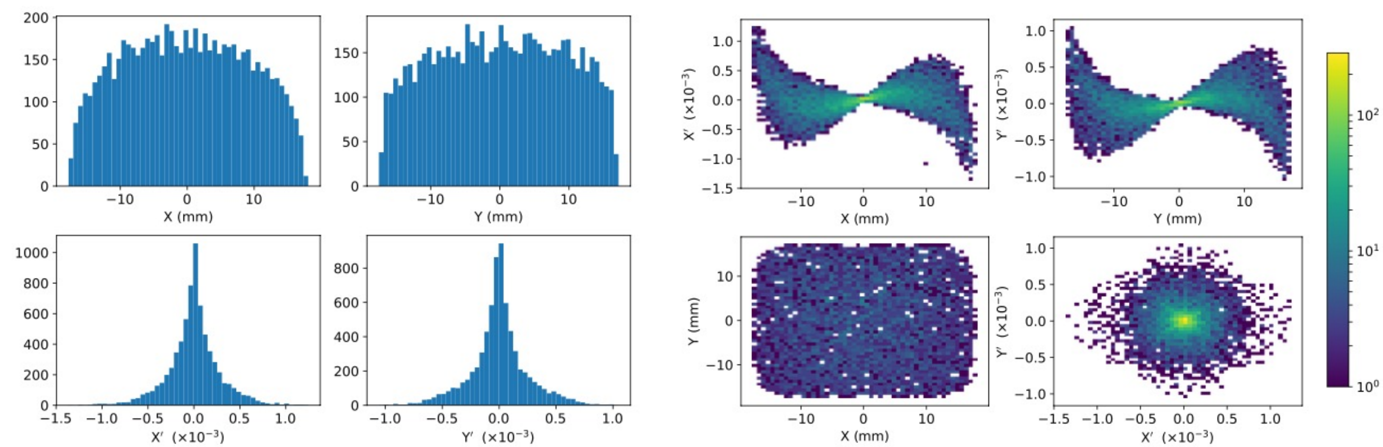
- Low energy contaminants between S=0-5cm
  - S=5-10 cm modelled with space charge
- Excellent tracking agreement between tracking codes
- Small space-charge induced emittance growth



Beam Phase Space

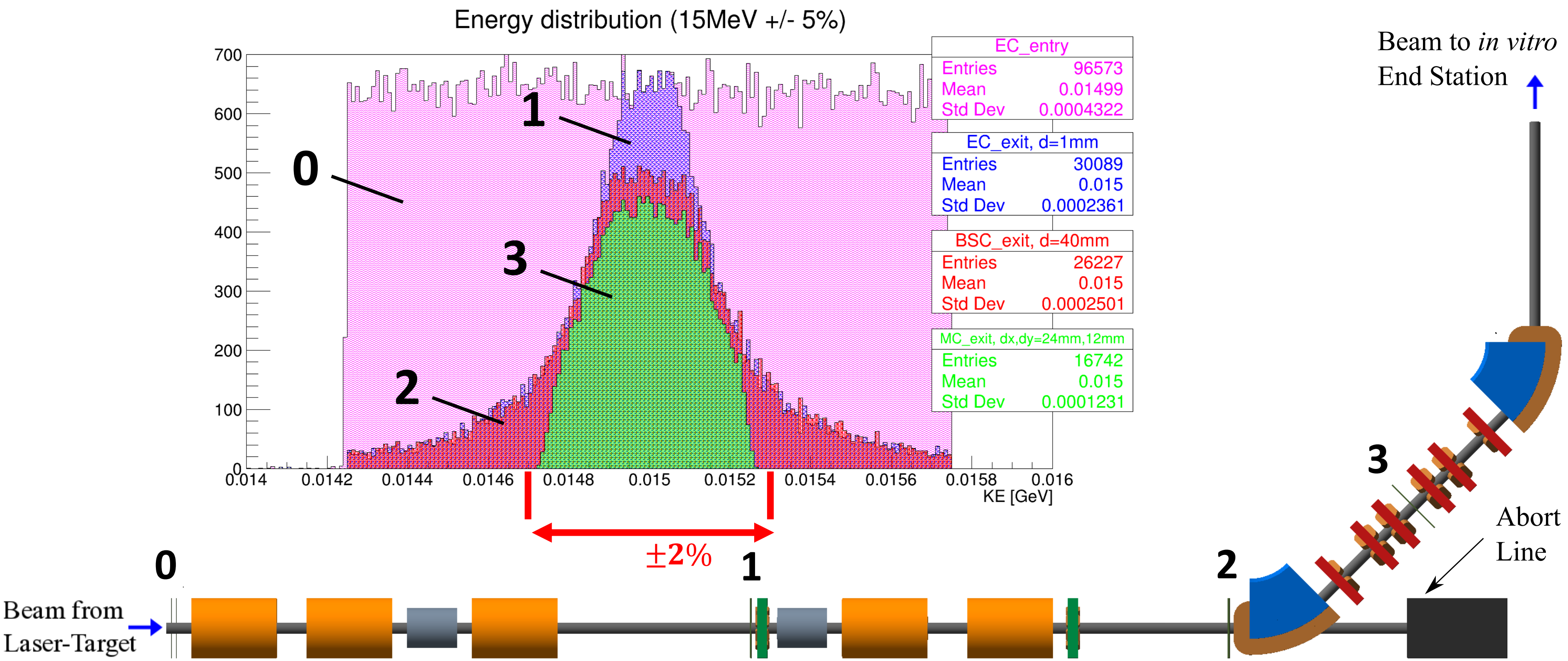
- Phase space aberration arises in Gabor lenses / solenoids
- Octupoles & collimation improves beam uniformity
- Reduction in transmission.





Energy Spread Control

- 3 collimators:
  - 1: Energy collimation
  - 2: Beam shaping
  - 3: Momentum cleaning
- Work by T.S. Dascalu
- Momentum cleaning required for removing energy distribution tails
- 2% energy spread achievable with only a modest transmission decrease



Design Updates

- Modified Gabor lens strengths & alternative solenoid strengths

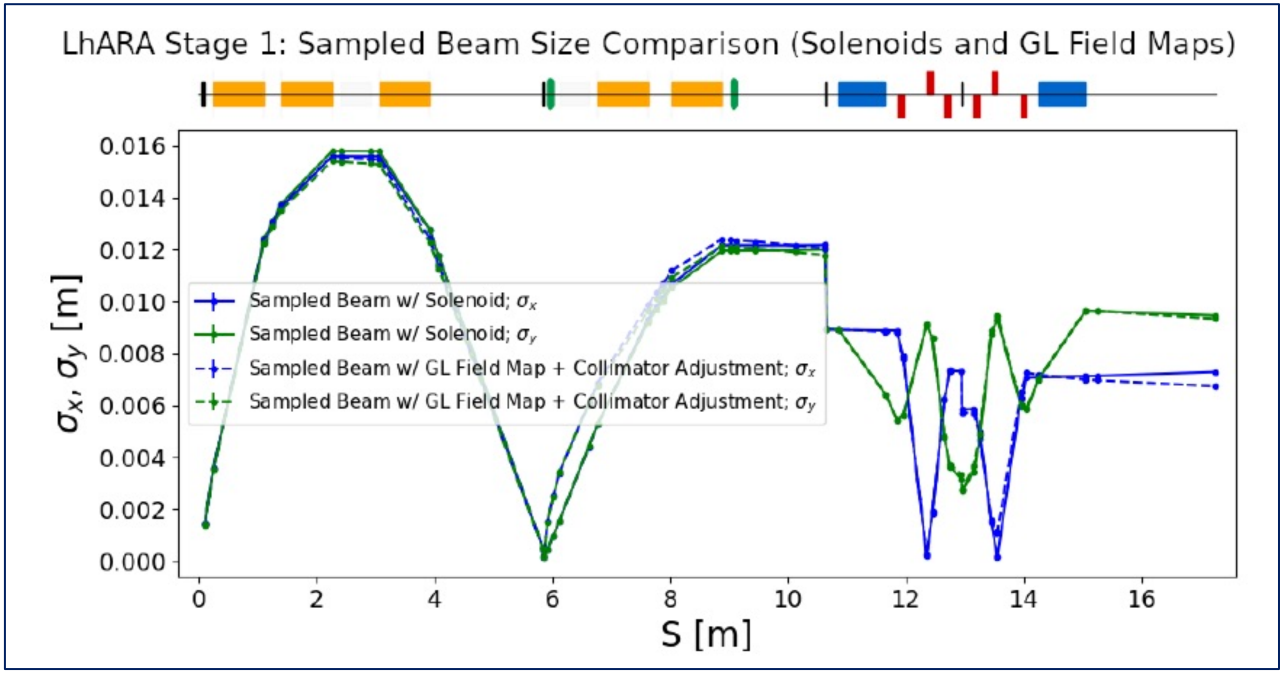
- Optimise beam transmission in conjunction with updated collimator settings.

- Comparable simulation performance with field maps replacing solenoids

- Wien filter for energy selection if solenoids are selected.

Element	Modified Parameter	Original Value	Re-optimised Value
Gabor Lens 1	Magnetic field	$B = 1.2868$ [T]	$B = 1.4387$ [T]
Gabor Lens 2	Magnetic field	$B = 0.6671$ [T]	$B = 0.5271$ [T]
Gabor Lens 3	Magnetic field	$B = 0.8139$ [T]	(unchanged)
Gabor Lens 4	Magnetic field	$B = 0.6852$ [T]	$B = 0.7284$ [T]
Gabor Lens 5	Magnetic field	$B = 0.6542$ [T]	$B = 0.6338$ [T]

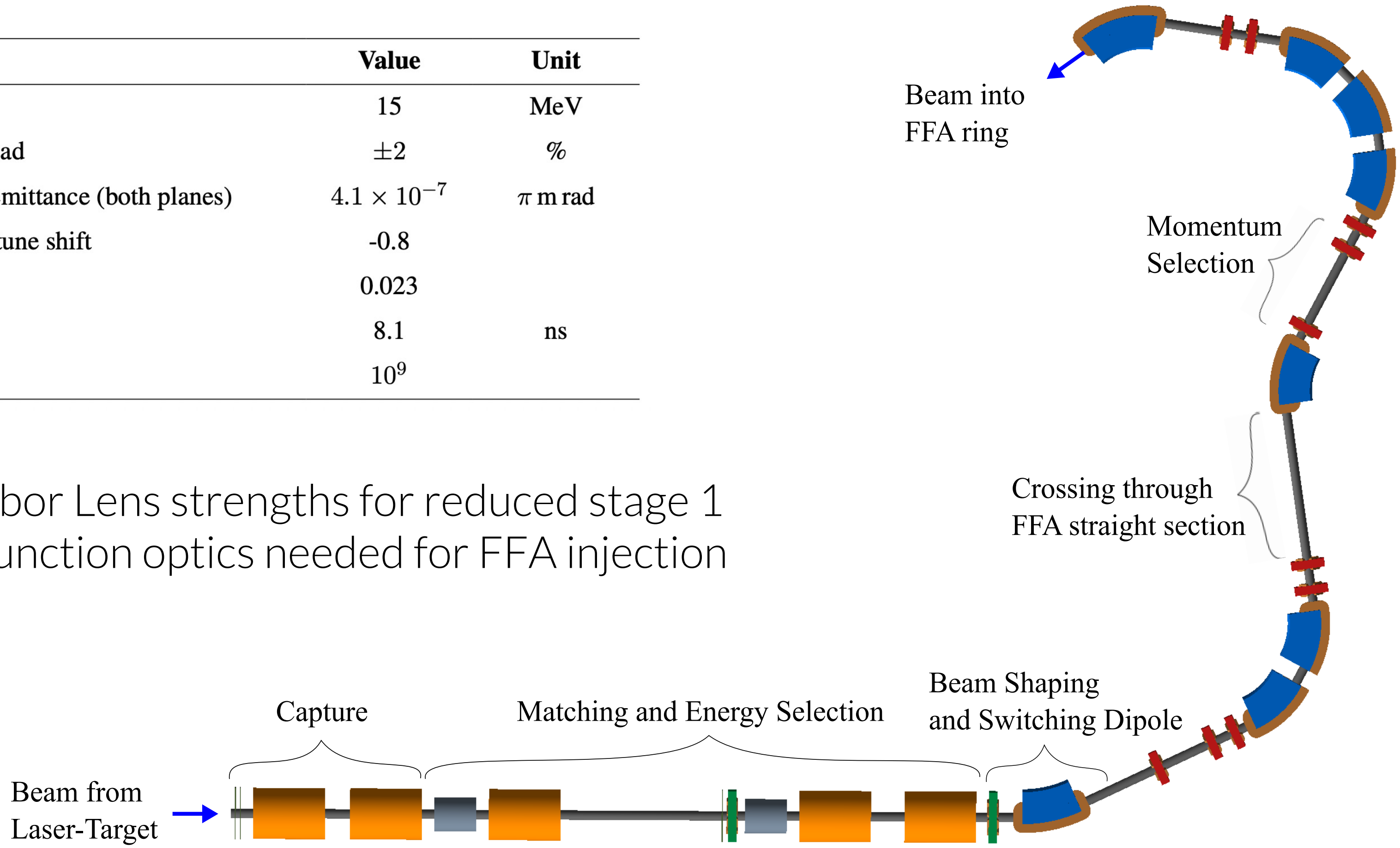
Equivalent solenoid field strength



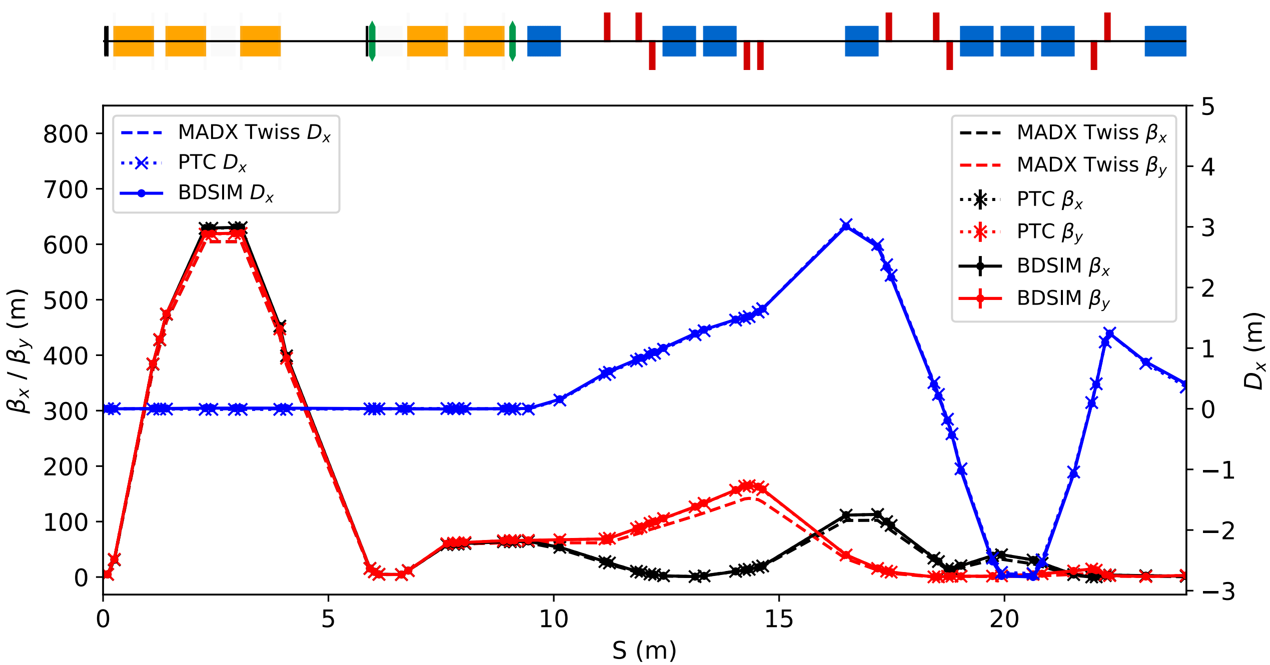
Parameter	Value or range	Unit
Injection line		
Number of bending magnets in the injection line	7	
Number of quadrupoles in the injection line	10	

Parameter	Value	Unit
Beam energy	15	MeV
Total relative energy spread	± 2	%
Nominal physical RMS emittance (both planes)	4.1×10^{-7}	π m rad
Incoherent space charge tune shift	-0.8	
Bunching factor	0.023	
Total bunch length	8.1	ns
Bunch intensity	10^9	

- Modified Gabor Lens strengths for reduced stage 1 Twiss Beta function optics needed for FFA injection

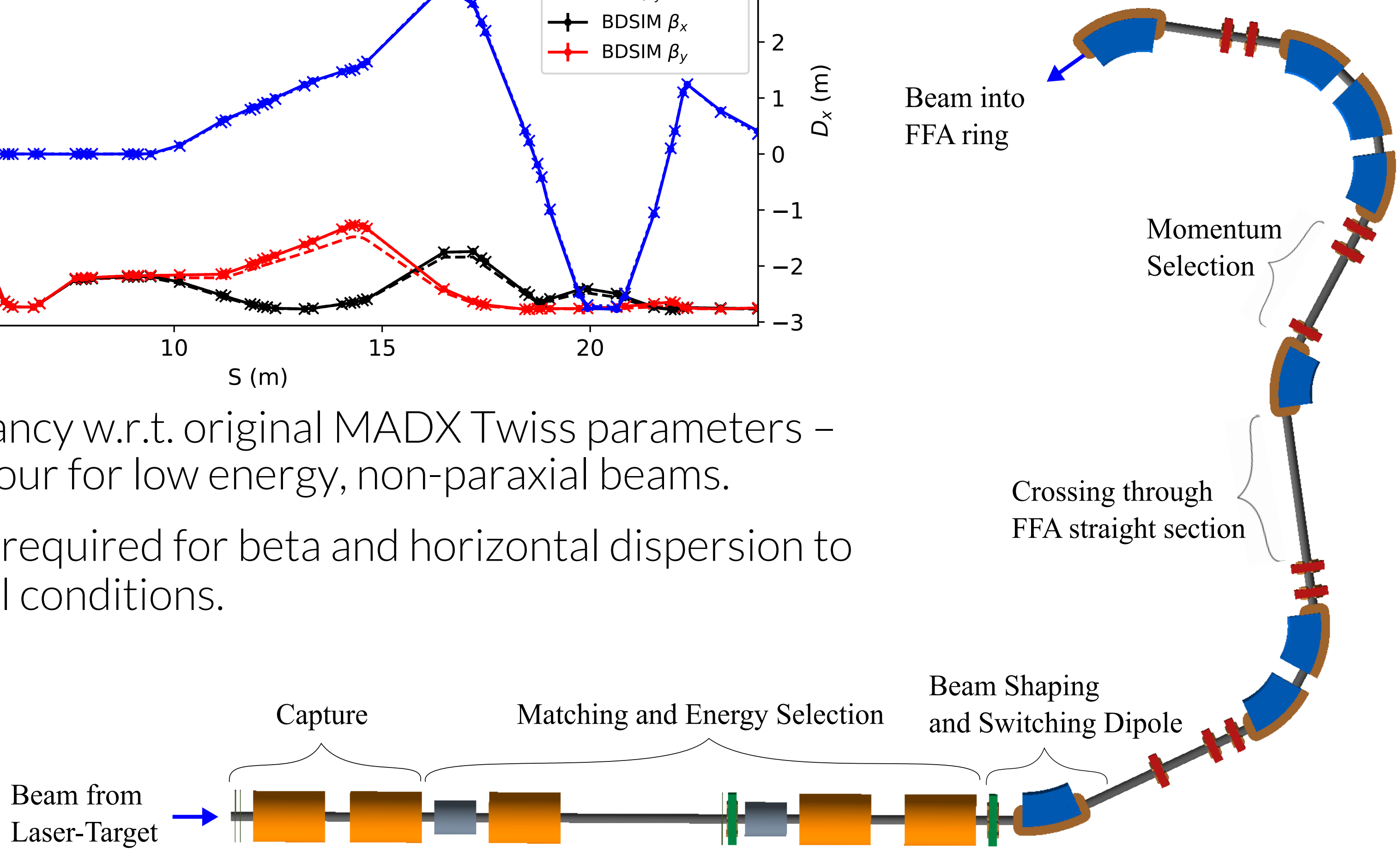


Stage 2:Injection Line

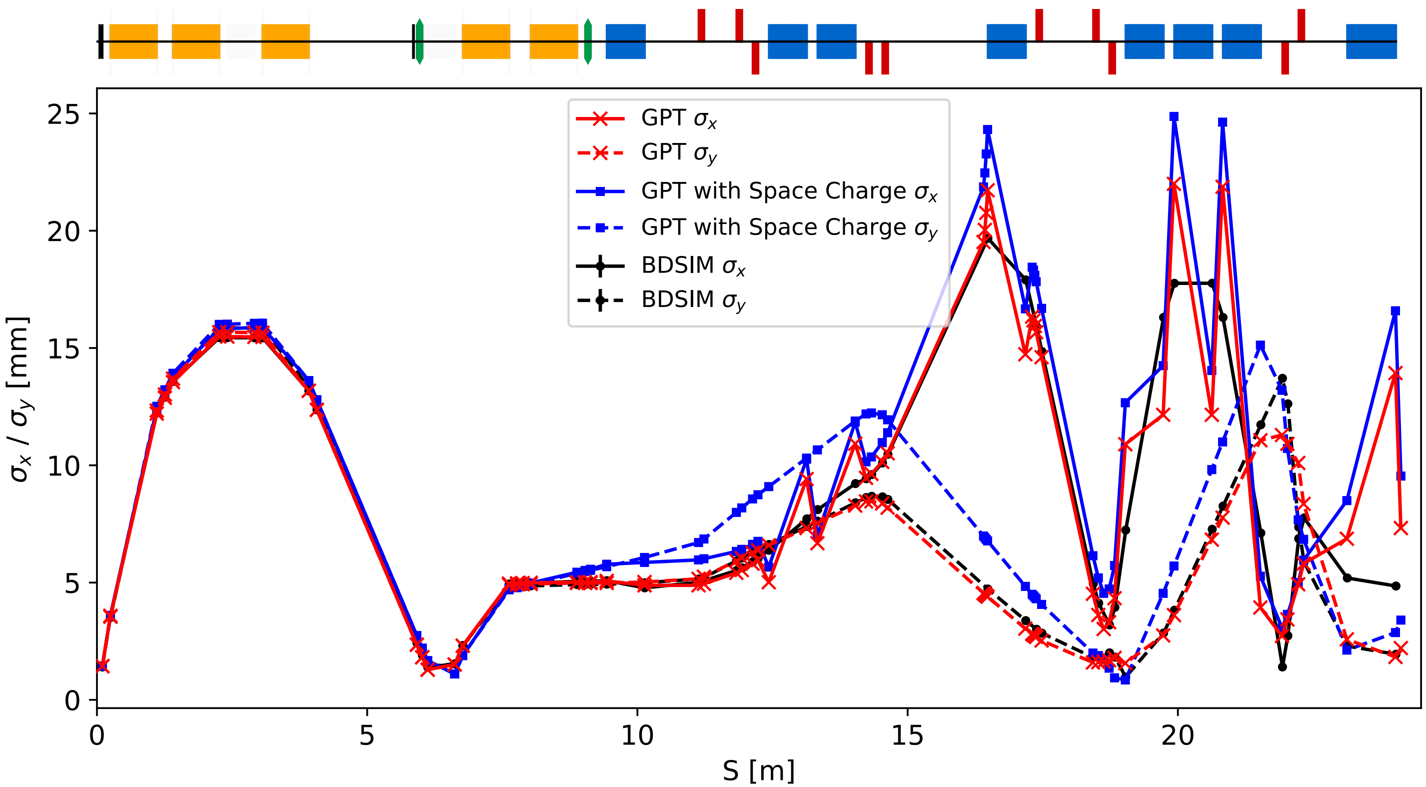


- Excellent agreement between BDSIM and PTC with idealised beam (10k primaries).

- Slight discrepancy w.r.t. original MADX Twiss parameters – known behaviour for low energy, non-paraxial beams.
- Minor tweaks required for beta and horizontal dispersion to match FFA cell conditions.



Injection Line Performance



- Beam simulated in GPT with & without space charge.
- Good agreement between BDSIM and GPT without space charge.

- Emittance growth observed when modelling space charge forces.
  - Final dimensions do not match FFA cell requirements - optimisation is required.

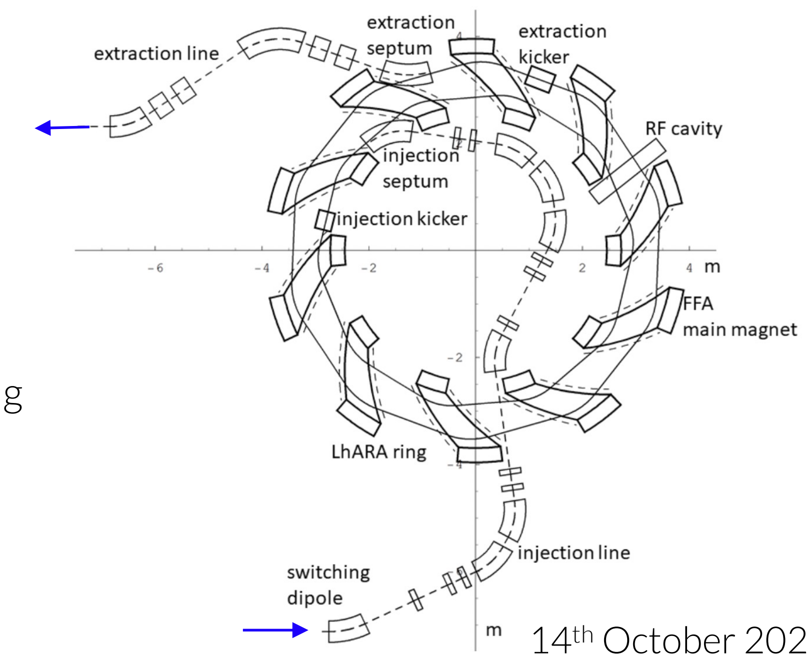
- Horizontal beam size jumps due to GPT output capturing the bunch partially within sector-bend fields

FFA Ring

Parameter	Value or range	Unit
FFA		
FFA: Machine type	single spiral scaling FFA	
FFA: Extraction energy	15–127	MeV
FFA: Number of cells	10	
FFA: Orbit R_{min}	2.92	m
FFA: Orbit R_{max}	3.48	m
FFA: Orbit excursion	0.56	m
FFA: Number of RF cavities	2	
FFA: RF frequency	1.46–6.48	MHz
FFA: Max B field	1.4	T
FFA: Ring tune (x,y)	(2.83,1.22)	
FFA: Number of kickers	2	
FFA: Number of septa	2	

- Factor 3 gain in momentum, up to 127 MeV in energy for protons, 33.4 MeV/u for C^{6+} ions.
- Trade-off between orbit excursion and straight section lengths to accommodate injection & extraction systems
- 2 cavities for operational stability

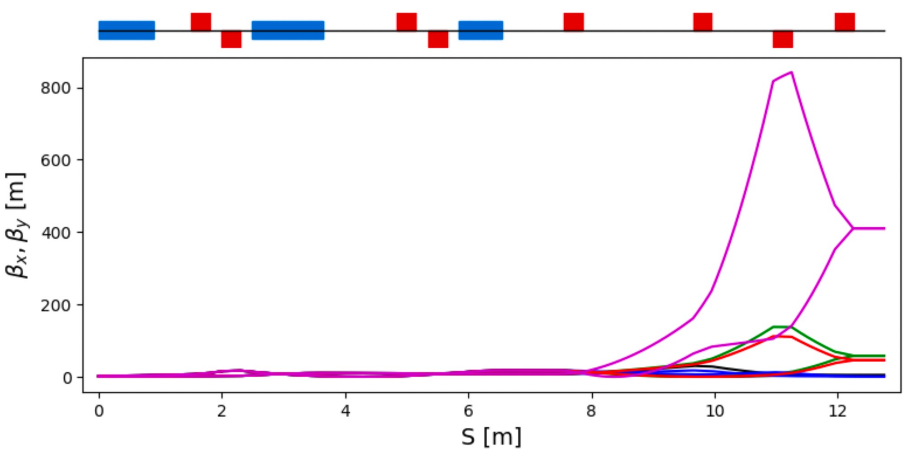
- FixField simulations show good performance
  - Non-linearities, fringe fields
  - No space charge
- Simulate FFA design in OPAL for space charge modelling

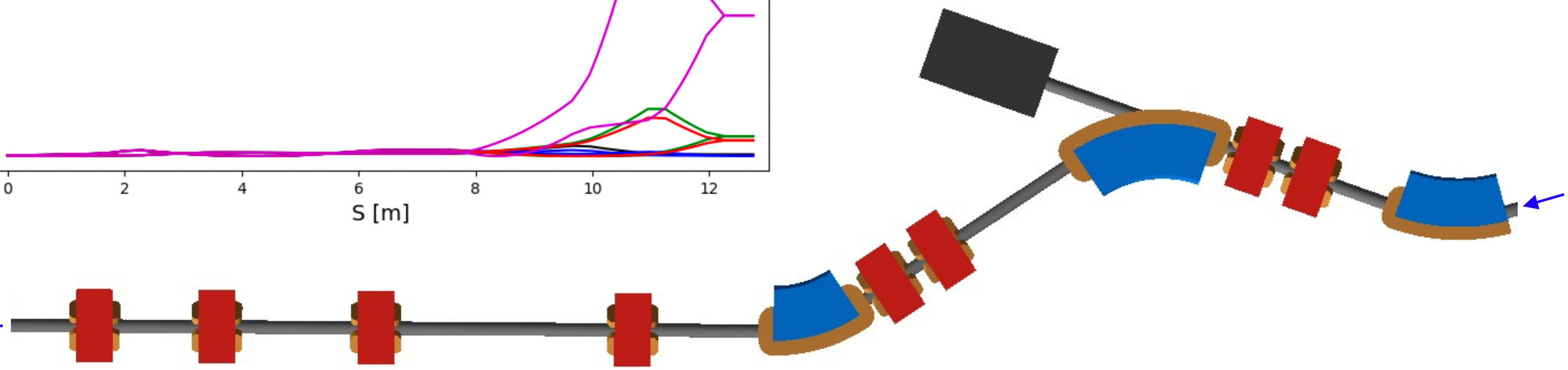


Stage 2 Extraction Line

Parameter	Value or range	Unit
Extraction line		
Number of bending magnets in the extraction line	2	
Number of quadrupoles in the extraction line	8	
Vertical arc bending angle	90	Degrees
Number of bending magnets in the vertical arc	2	
Number of quadrupoles in the vertical arc	6	
Number of cavities for longitudinal phase space manipulation	5	
Number of quadrupoles in the in vivo beam line	4	

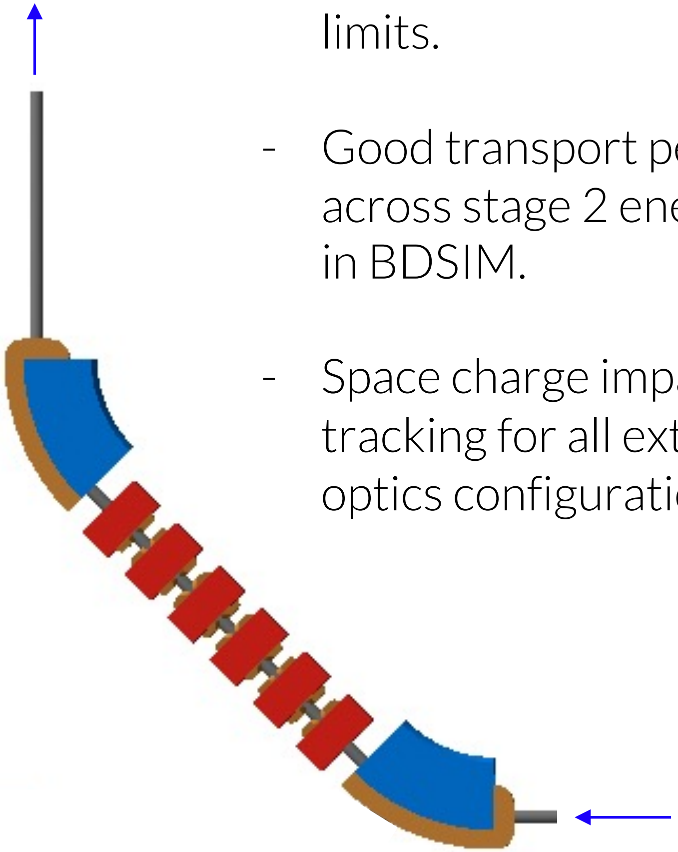
- Flexibility to accommodate uncertainties in extracted FFA emittance
  - Up to a factor 10 larger
  - Space charge
- Optics flexibility to also offer wide range of beam conditions to serve end stations.
  - 1– 30 mm spot size
- Closed dispersion after the final dipole

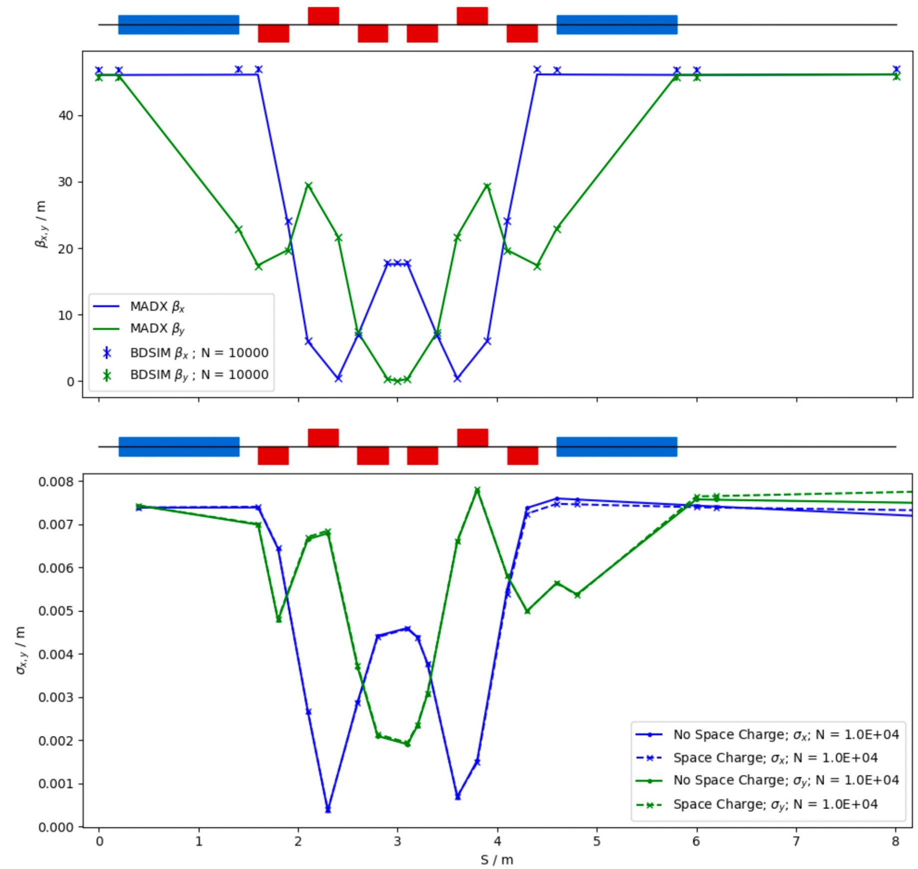




Stage 2 *in-vitro* Line

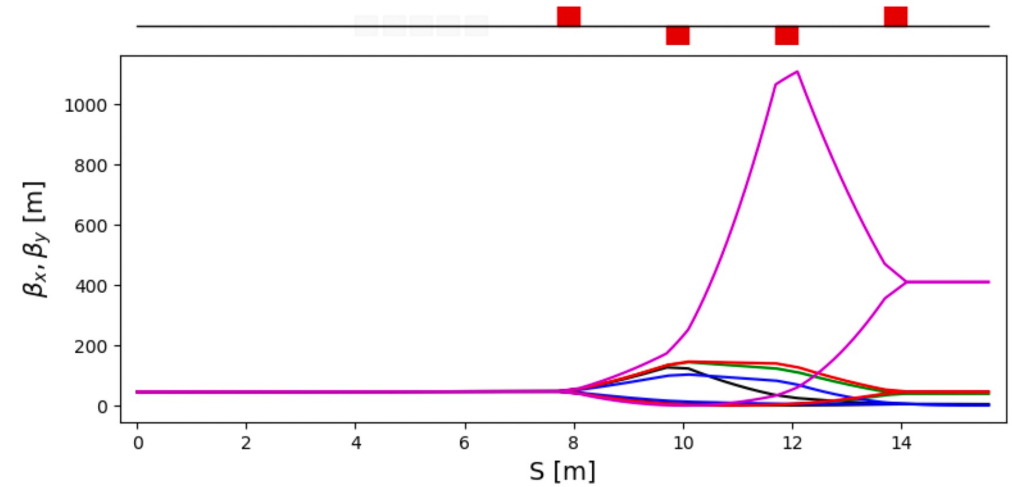
- Scaled version of the stage 1 low energy *in-vitro* beam line.
- Longer dipoles to remain in normal conducting magnet limits.
- Good transport performance across stage 2 energy range in BDSIM.
- Space charge impacts tracking for all extraction line optics configurations.

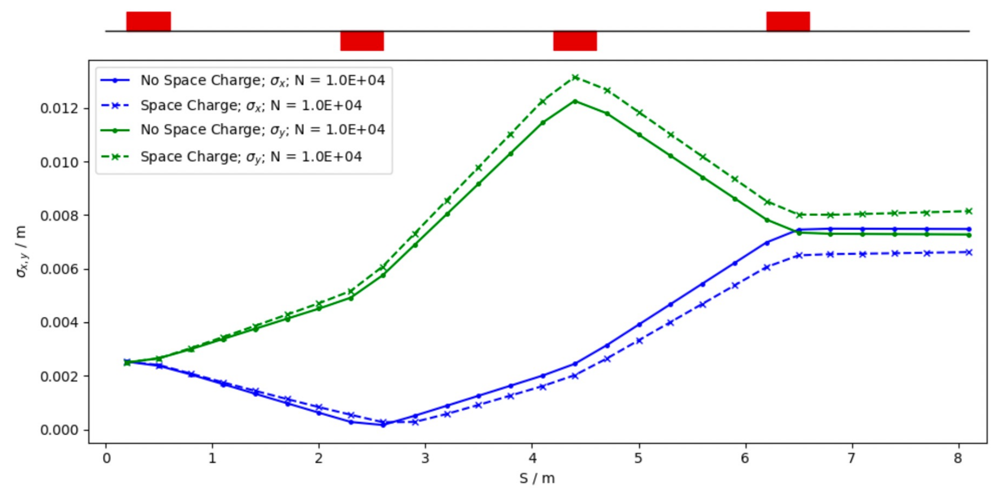




Stage 2 *in-vivo* Line

- Beam delivered from un-energised *in-vitro* dipole
- Drift to clear *in-vitro* arc & accommodate RF systems & diagnostics
- Optics flexibility to deliver beams sizes of 1-30 mm
- Significant impact of space charge forces for nominal emittance beam



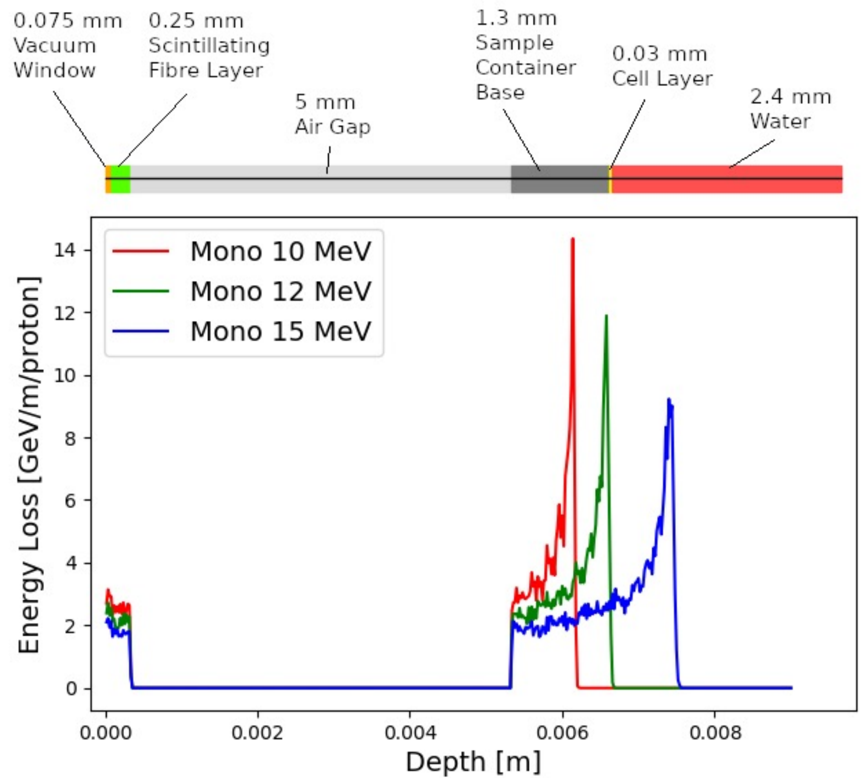


To *in-vitro* end station

Beam from extraction line

Deliverable Dose Estimation

- BDSIM energy deposition in end station target materials (H.T. Lau, IC).
- Monoenergetic idealised beams
  - Radiobiological effects from different Bragg curve regions
- Equivalent water phantom volume simulated at Bragg peak depths
  - 10 Hz repetition rate



	protons			carbon
Kinetic energy	**12 MeV**	**15 MeV**	**127 MeV**	**33.4 MeV/u**
Bunch length	7 ns	7 ns	41.5 ns	75.2 ns
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

Summary

- Successful stage 1 design capable of dose delivery into the FLASH regime.
- Working stage 2 design for FFA, & *in-vitro* and *in-vivo* beam lines
- Number of validated Monte Carlo models
  - Well supported workflow
  - Ideal for new stage of design studies

Thank you

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