LhARA: Stage 1 and FFA Injection Line

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LhARA FFA Review Meeting

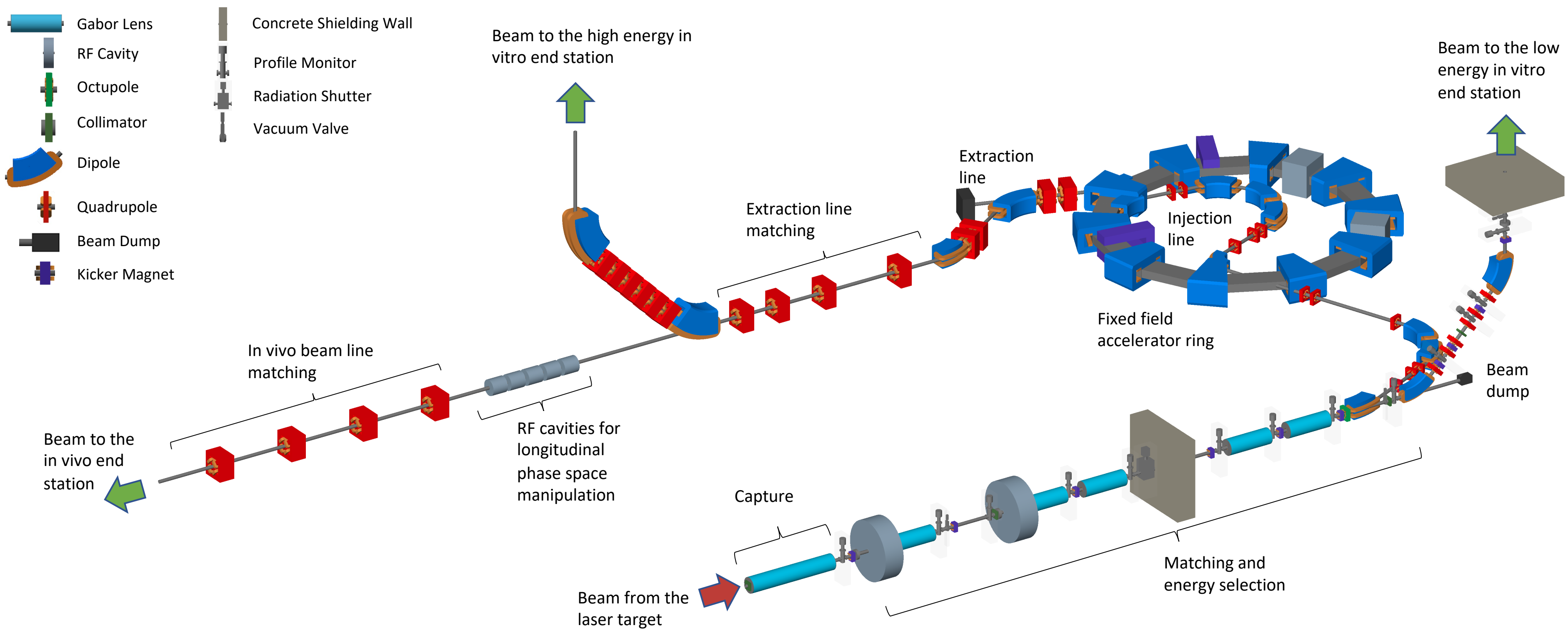
26th February 2025

ROYAL HOLLOWAY UNIVERSITY OF LONDON

LhARA Laser-hybrid Accelerator for Radiobiological Applications

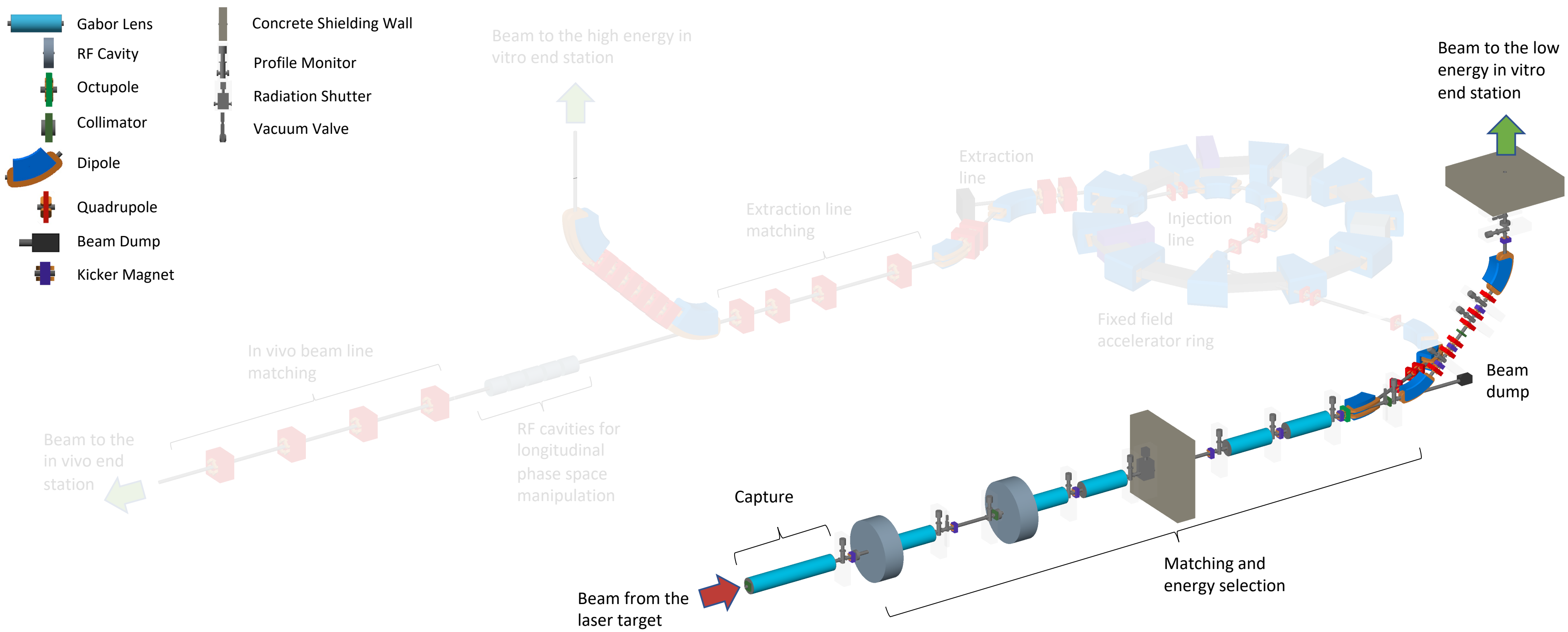
JAI John Adams Institute for Accelerator Science

LhARA: Layout



- Stage 1: Laser target acceleration, 15 MeV protons, 1 in-vitro end station
- Stage 2: FFA acceleration, up to 127 MeV protons, 1 in-vitro end station, 1 in-vivo end station.

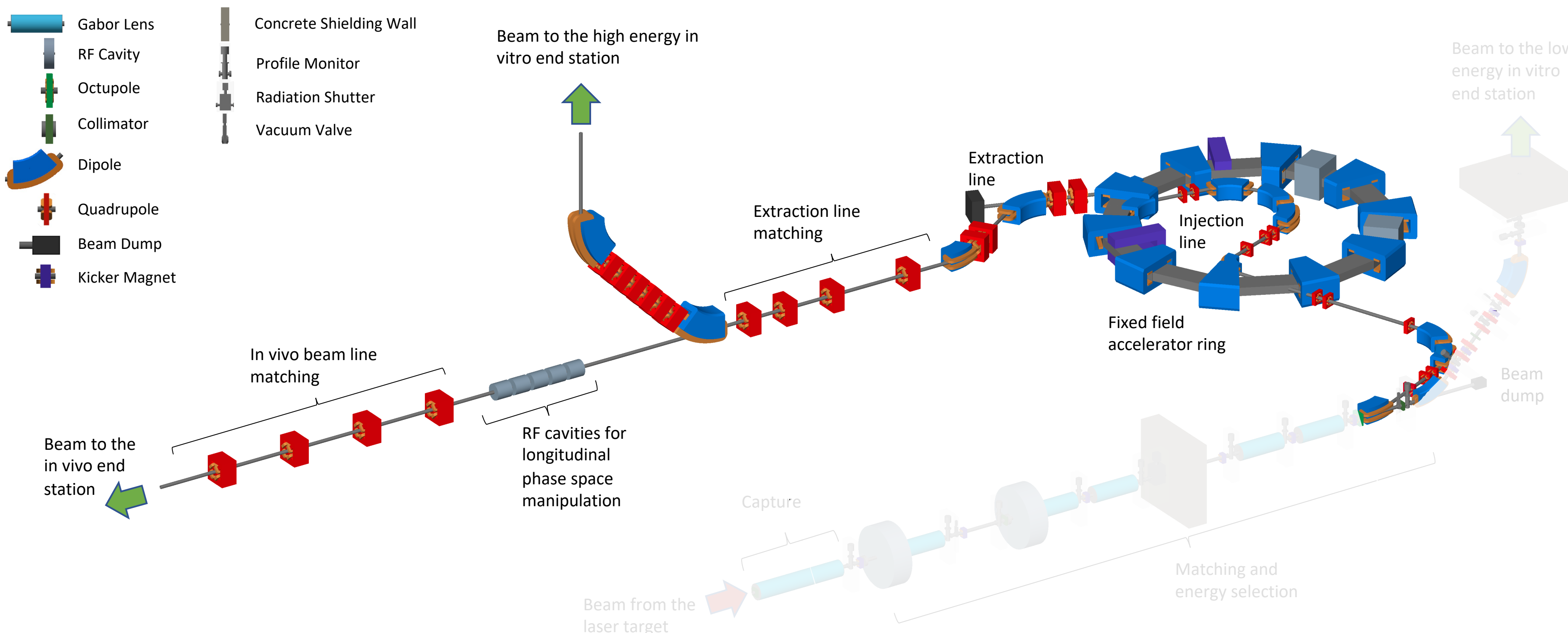
LhARA: Layout



- Stage 1: 15 MeV protons, 1 in-vitro end station
  - End station spot size flexibiliy

- Stage 2: Up to 127 MeV protons, 1 in-vitro end station, 1 in-vivo end station.

LhARA: Layout

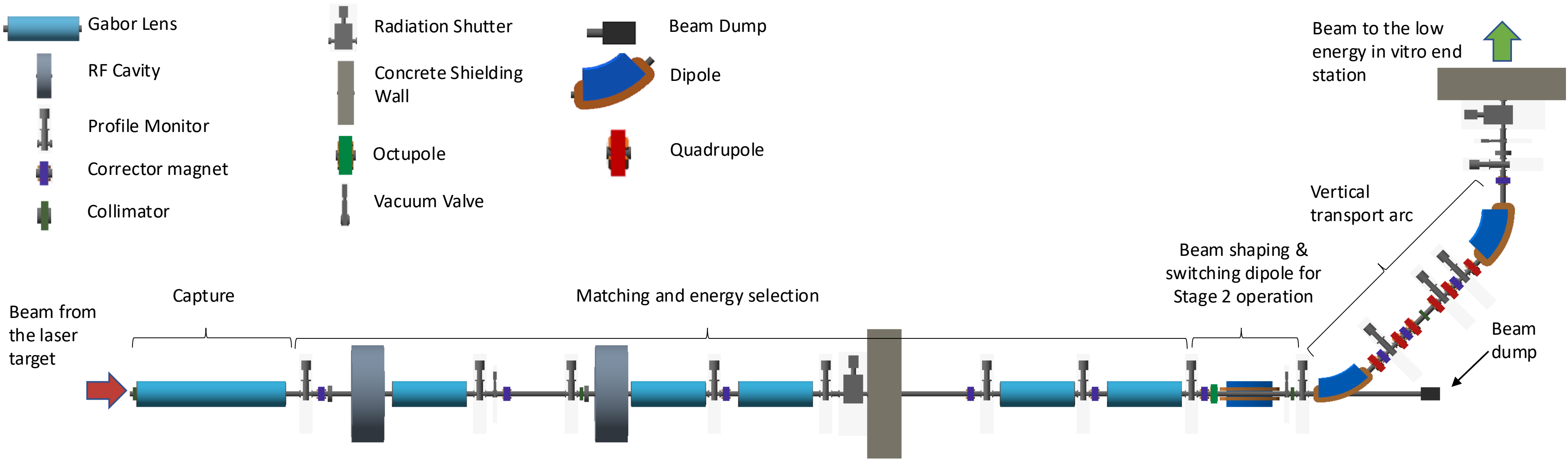


- Stage 1: 15 MeV protons, 1 in-vitro end station

- Stage 2: Up to 127 MeV protons, 1 in-vitro end station, 1 in-vivo end station.

Stage 1: Layout

- Locations and key dimensions defined :
  - Gabor lens
  - Arc magnets
  - RF cavities
  - Collimators
  - Corrector magnets
  - Vacuum valves
  - Wall current monitors
  - Profile monitors
  - Shielding walls
  - Radiation shutters
  - Octupole
  - Beam dump
  - Stage 2 switching magnet



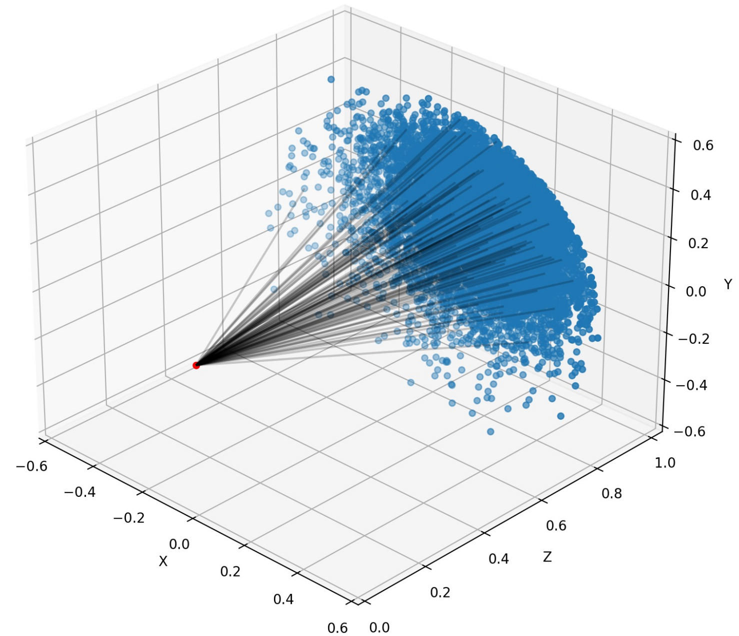
Parameterised Source Distribution

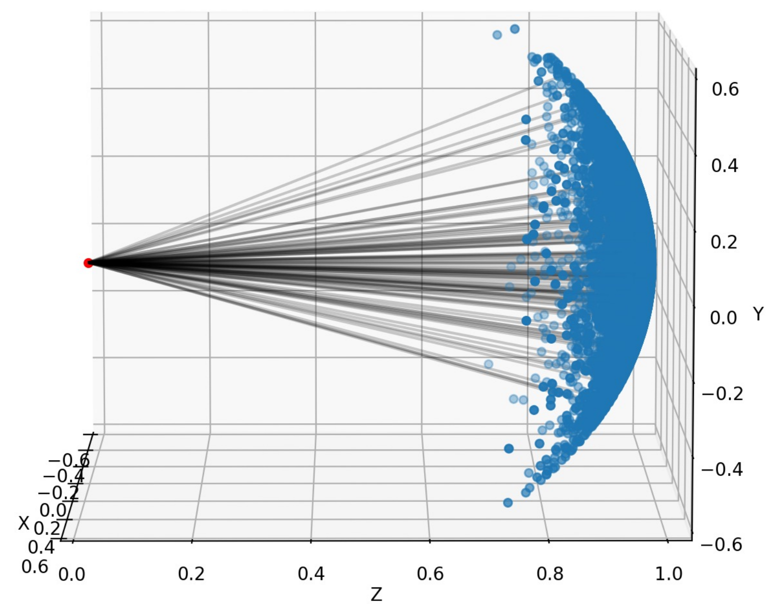
- LhARALinearOptics
  - K. Long, M. Maxouti, N. Dover
  - Optics, losses, particle source

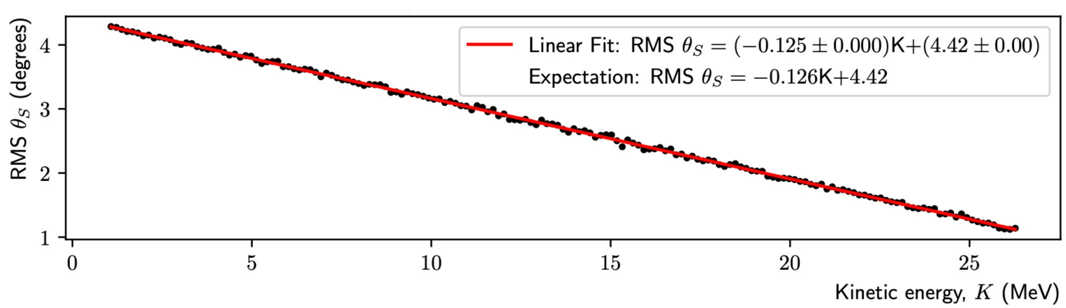
- Angular distribution generated as a cone centred on the normal to the foil surface.
  - The opening angle of the cone taken from:

$$\sigma_{\theta_S}(E) = 20° - 15° \frac{E}{E_{max}}$$

  - Low KE angle taken to be 20°, linearly decreases such that angle at E_{max} is 5° (based on [1]).
  - The distribution of the polar angle, θ_s, approximated as Gaussian
  - 11° at 15 MeV (25 MeV E_{max})







[1] F. Nurnberg, M. Schollmeier, et al., Review of Scientific Instruments 80 no. 3, (03, 2009) 033301

Parameterised Source Distribution

- KE spectrum from [2], unable to predict cut-off KE:

$$\frac{dN}{dE} = \frac{n_{e0} c_s t_{laser} S_{sheath}}{\sqrt{2ET_e}} \exp\left(-\sqrt{\frac{2E}{T_e}}\right)$$

- Model in [3] has cut off given by:

$$E_{max} = X^2 E_{i,\infty}$$

$$\frac{t_{laser}}{t_0} = X\left(1 + \frac{1}{2}\frac{1}{1-X^2}\right) + \frac{1}{4}\ln\left(\frac{1+X}{1-X}\right)$$

- Probability of particle generated in E -> E+dE:

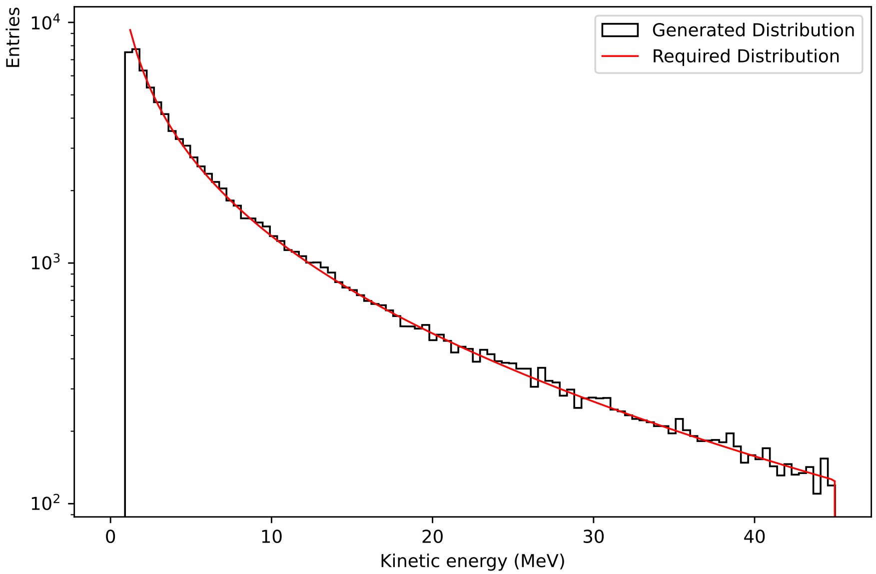
$$\delta\mathcal{P} = g\left(E\right)\delta E \qquad g(E) = \frac{1}{\mathcal{N}}\frac{dN}{dE}$$

$$G(E) = \int_{E_{\min}}^{E_{\max}} g(E)dE$$

$$G(E) = \frac{2}{\mathcal{N}}\frac{n_{e0} c_s t_{laser} S_{sheath}}{\sqrt{2T_e}}\sqrt{\frac{T_e}{2}}\left[\exp\left(-\sqrt{\frac{2E_{\min}}{T_e}}\right) - \exp\left(-\sqrt{\frac{2E}{T_e}}\right)\right]$$

$$E = \left[\sqrt{E_{\min}} - \sqrt{\frac{T_e}{2}}\ln\left(1 - \frac{G(E)}{G(E_{\max})}\right)\right]^2$$

Parameter	Definition	Value	Unit
E_{laser}	Laser energy	10	J
I	Laser intensity	9×10^{20}	W/cm^2
λ	Laser wavelength	0.8	μm
t_{laser}	Laser pulse duration	$< 5 \times 10^{-14}$	s
r_0	Laser spot radius	4.0	μm
d	Target thickness	$400 - 600 \times 10^{-9}$	m
θ	Half angle divergence	0.436	rad
P_{laser}	Laser power	1.0×10^{14}	W
E_{min}	Minimum energy	1.0	MeV

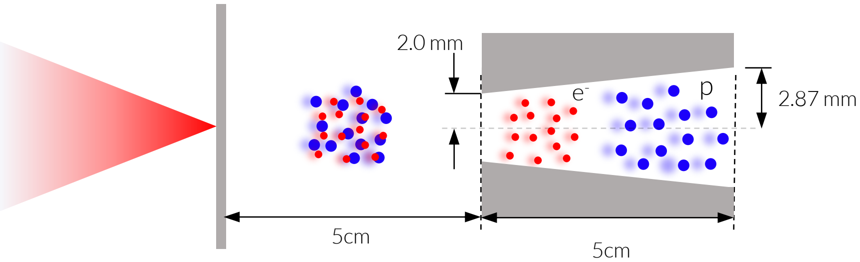


[2] J. Fuchs, P. Antici, et al.," Nature Physics 2 (01, 2006)
[3] J. Schreiber, F. Bell, et al., Physical review letters 97 (08, 2006) 045005

Stage 1 Nozzle

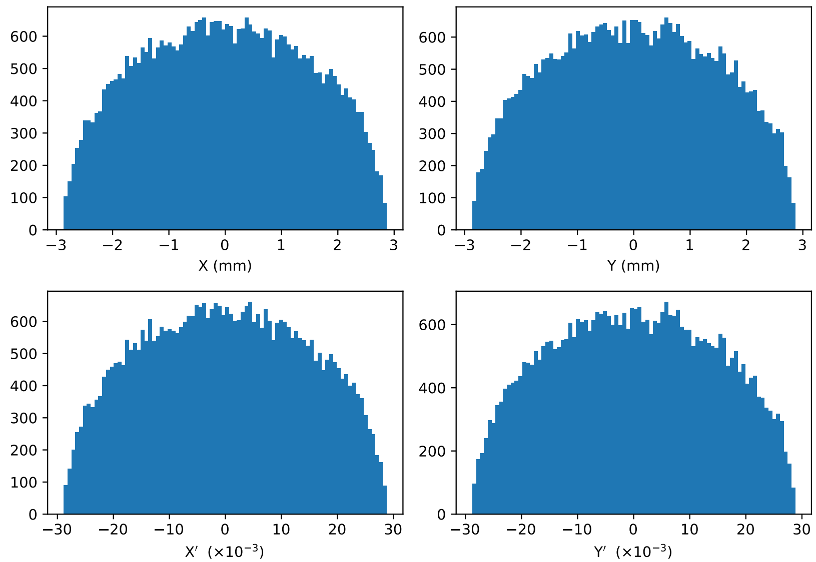
- Methodology:
  - Generate 15 MeV ± 2% beam (LhARALinearOptics)
  - Track 5cm assuming a charge neutral beam.
  - 2mm radial filter
  - Track 5cm with space charge
  - 2.87mm radial filter

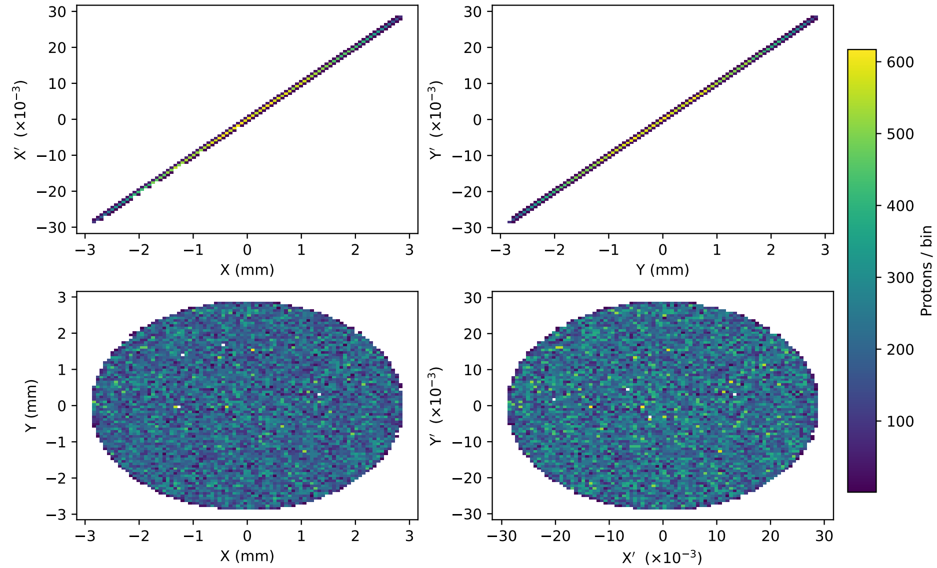
Transmission (%)	Nozzle Entrance	Nozzle Exit
OSIRIS SCAPA Simulation,	88.7	68.0
Parameterised Beam, $\theta_s = 11°$	**7.9**	**4.1**
Parameterised Beam, $\theta_s = 2.75°$	87.5	55.9

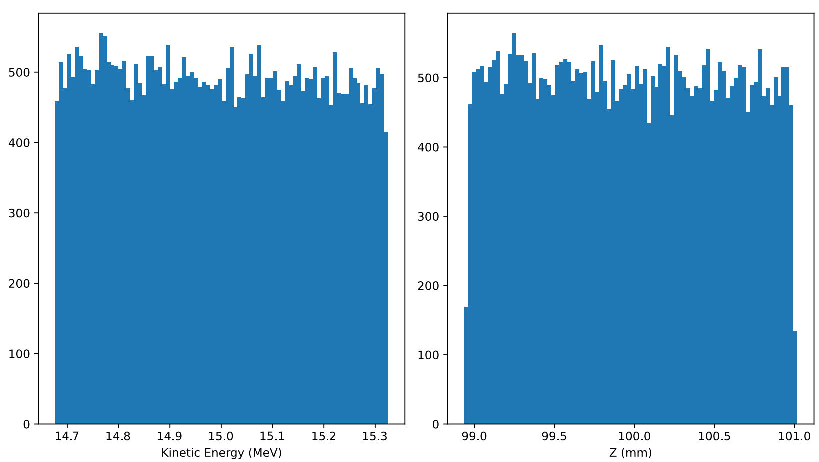


Beam Property	OSIRIS SCAPA Simulation		Parameterised Beam, $\theta_s = 11°$		Parameterised Beam, $\theta_s = 2.75°$	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
TWISS α	-199	-209	**-355**	**-357**	-341	-342
TWISS β (m)	19.65	20.60	**35.35**	**35.51**	33.89	33.93
Emittance (m rad)	8.53e-08	8.11e-08	**5.91e-8**	**5.87e-8**	5.77e-8	5.75e-8
Beam Size (m)	1.28e-03	1.28e-03	**1.43e-3**	**1.43e-3**	1.39e-3	1.40e-3

Stage 1 Beam at the Nozzle Exit



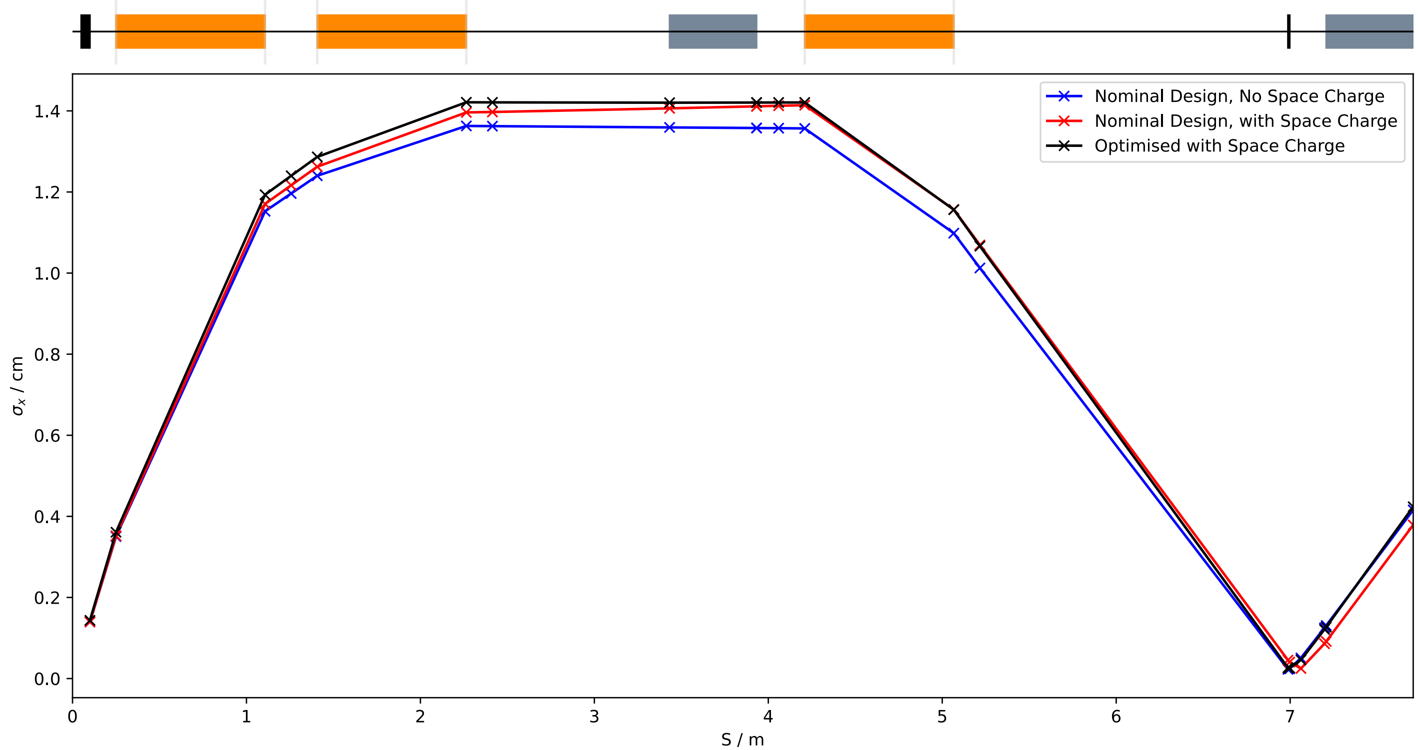




- Final 15 MeV ± 2% beam for particle tracking simulations

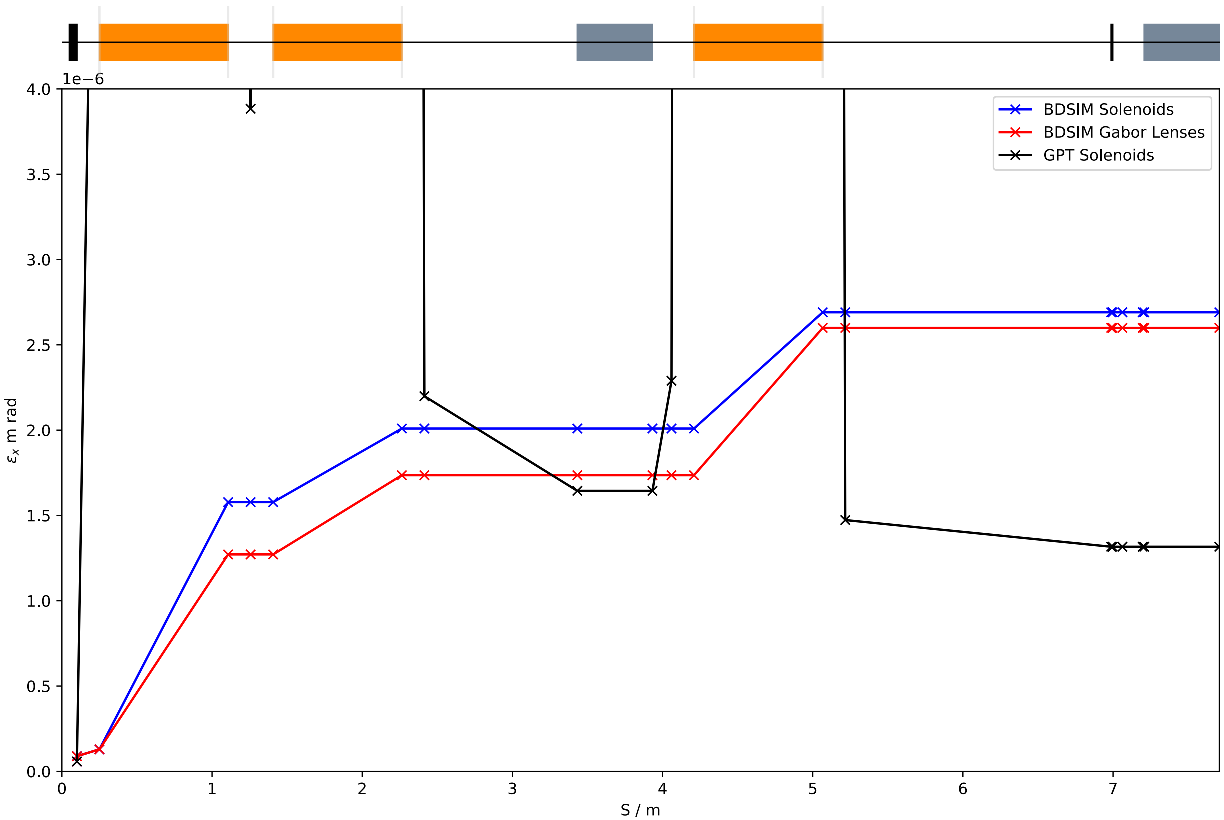
- Small differences observed with change in bunch charge (% level).

Stage 1: Capture and Energy Selection

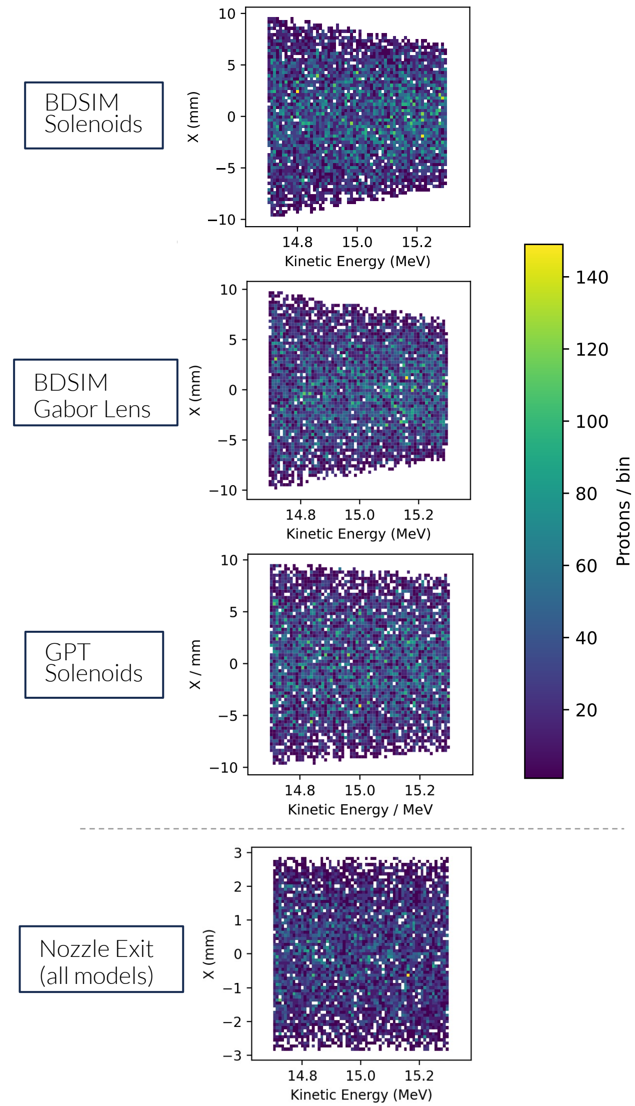


Solenoid (%)	SCAPA OSIRIS Simulation		Theta S = 11		Theta S = 2.75	
	KS (m^{-1})	B (T)	KS (m^{-1})	B (T)	KS (m^{-1})	B (T)
GL1	2.4917	1.4	2.4917	1.4	2.4917	1.4
GL2	1.0187	0.5724	1.0168	0.5713	1.0175	0.5717
GL3	1.4485	0.8138	1.4486	0.8139	1.4486	0.8139

Stage 1 Emittance



- X-energy correlations at S=7.7m:



- Emittance growth from capture fields, space charge not modelled.
  - GPT emittance jumps due to recording beam in fringe fields.
  - Gabor lens limited to radial E-field (plasma), no confinement fields.
- Spherical and chromatic aberrations.

Stage 1 Emittance

- Emittance control in rf cavities and solenoids, PRSTAB **12**, 024210 (2009).
  - DOI: [10.1103/PhysRevSTAB.12.024201](https://doi.org/10.1103/PhysRevSTAB.12.024201)

- LINAC4
  - Comparable beam sizes to LhARA; 6.4 mm radius (rms).
  - Space charge negligible, kinetic energy (95 KeV), energy spread 0.25%.

- <u>"The higher the beam divergence at the entrance of a solenoid, the higher the emittance increase".</u>

- Highest LhARA solenoid field: 1.4T.

- Ongoing investigation.

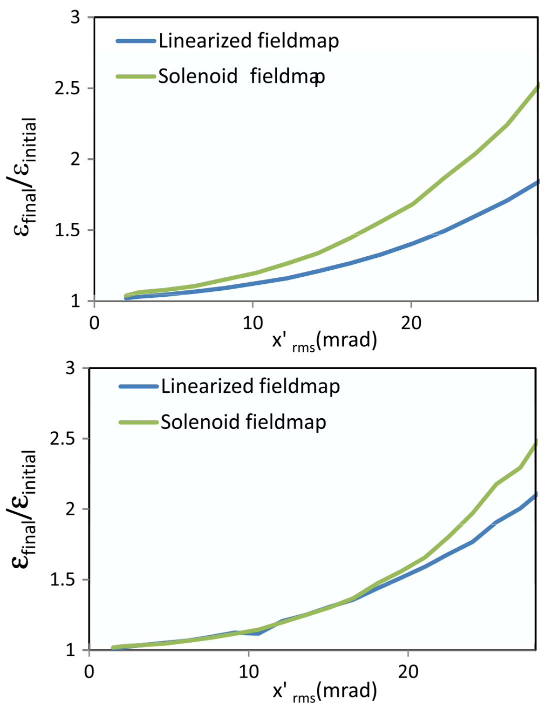


FIG. 8. (Color) Increase of emittance in solenoidal channels, $B = 0.6$ T. Top: initial emittance 8.0π mm mrad. Bottom: initial emittance 4.5π mm mrad.

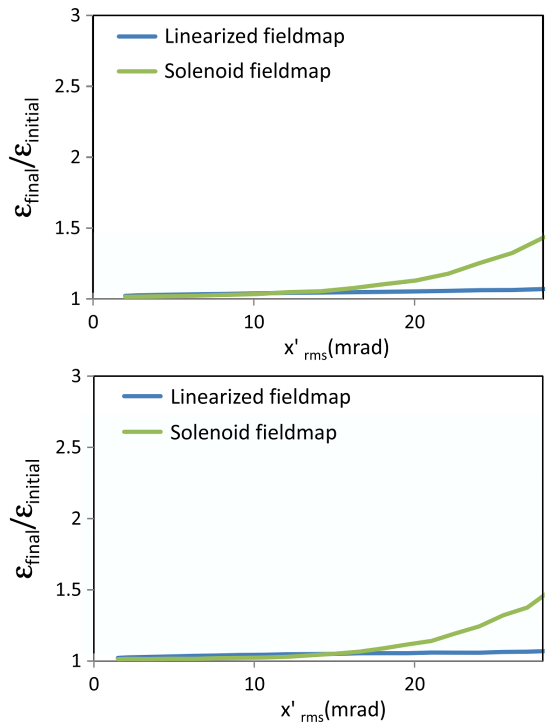


FIG. 9. (Color) Increase of emittance in solenoidal channels, $B = 0.36$ T. Top: initial emittance 8.0π mm mrad. Bottom: initial emittance 4.5π mm mrad.

Stage 1 Optics for Stage 2 Injection

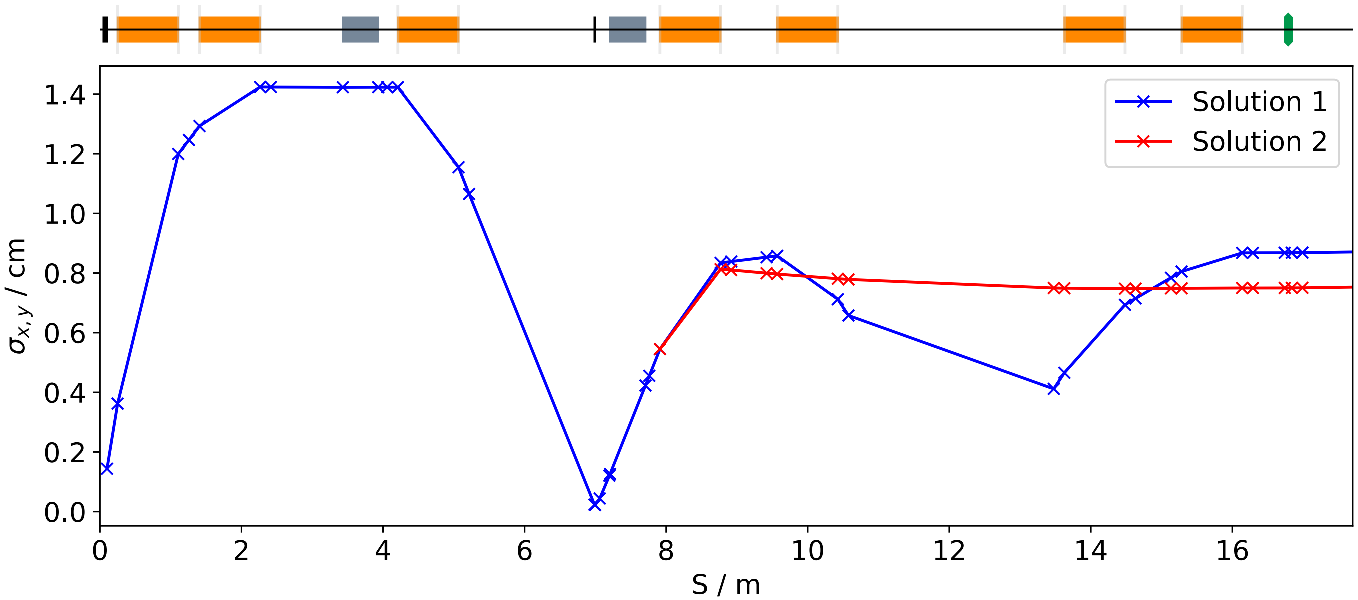
- Challenges meeting baseline injection line beam parameters
  - At switching dipole: $\varepsilon_{x,y}$ ~**4.3e-6**, $\beta_{x,y}$ ~25m, $\sigma_{x,y}$ ~ 1.00 cm.
- Solutions prioritise $\alpha_{x,y} = 0$.

Solution 1:

```
Alpha x: -0.09
Alpha y: -0.11
 Beta x: 17.92
 Beta y: 18.01
 Emit x: 4.30e-06
 Emit y: 4.29e-06
```

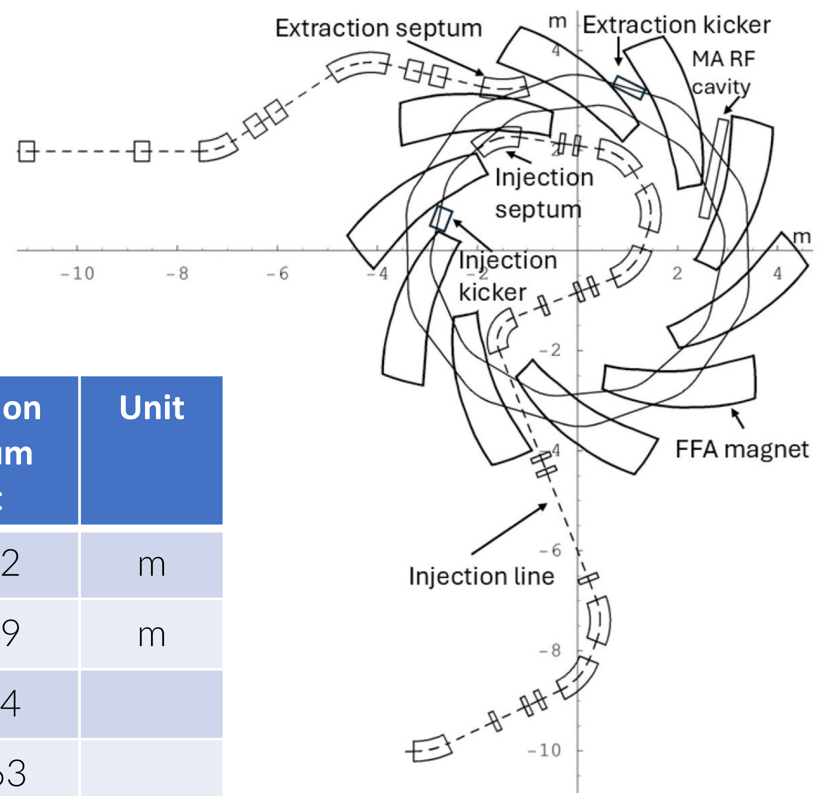
Solution 2:

```
Alpha x: -0.112
Alpha y: -0.169
 Beta x: 17.49
 Beta y: 17.37
 Emit x: 3.22e-06
 Emit y: 3.235e-06
```

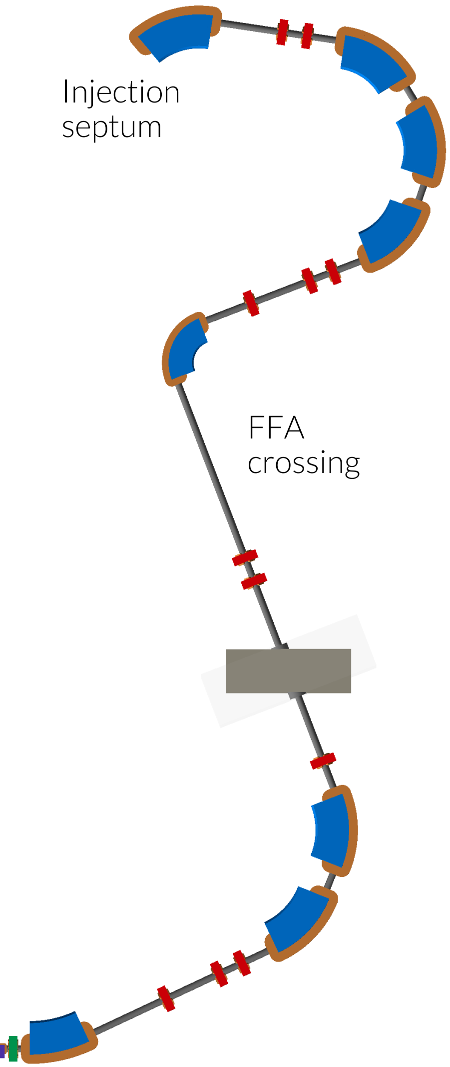


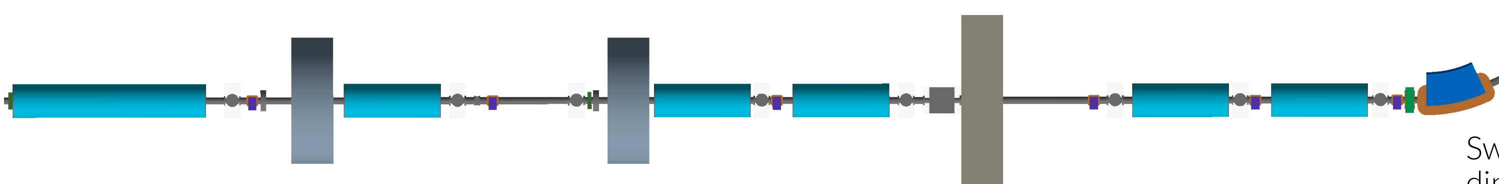
Solution	Solenoid 4 B Field (T)	Solenoid 5 B Field (T)	Solenoid 6 B Field (T)	Solenoid 7 B Field (T)
1	1.0719	0.8482	0.7448	0.4998
2	1.0976	0	0	0.1176

Nominal Injection Line Model

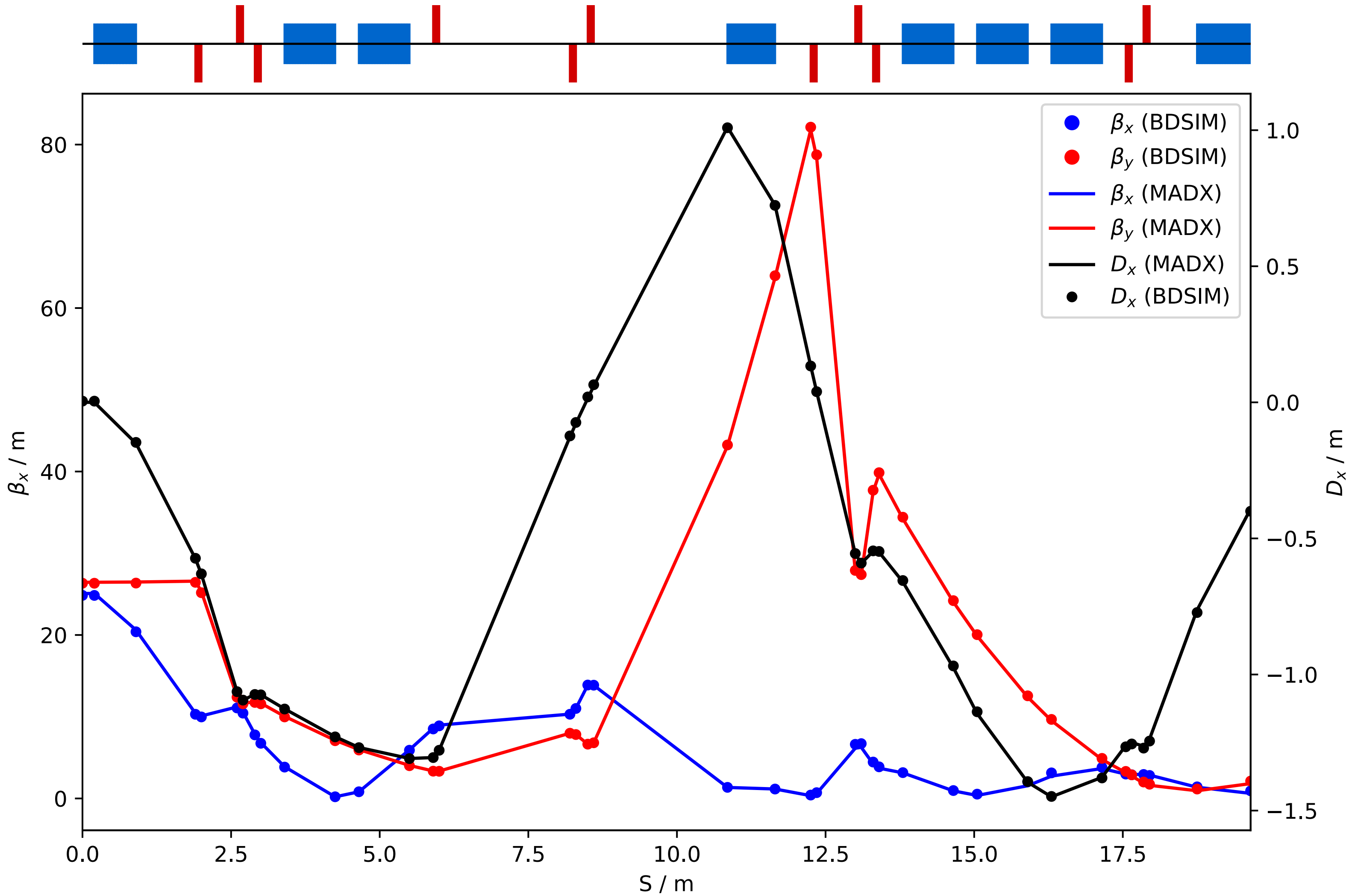


Beam Parameter	Switching Dipole Entrance	Injection Septum Exit	Unit
β_x	25.08	0.622	m
β_y	26.45	1.819	m
α_x	0	0.074	
α_y	0	-0.963	
D_x	0	0.392	m

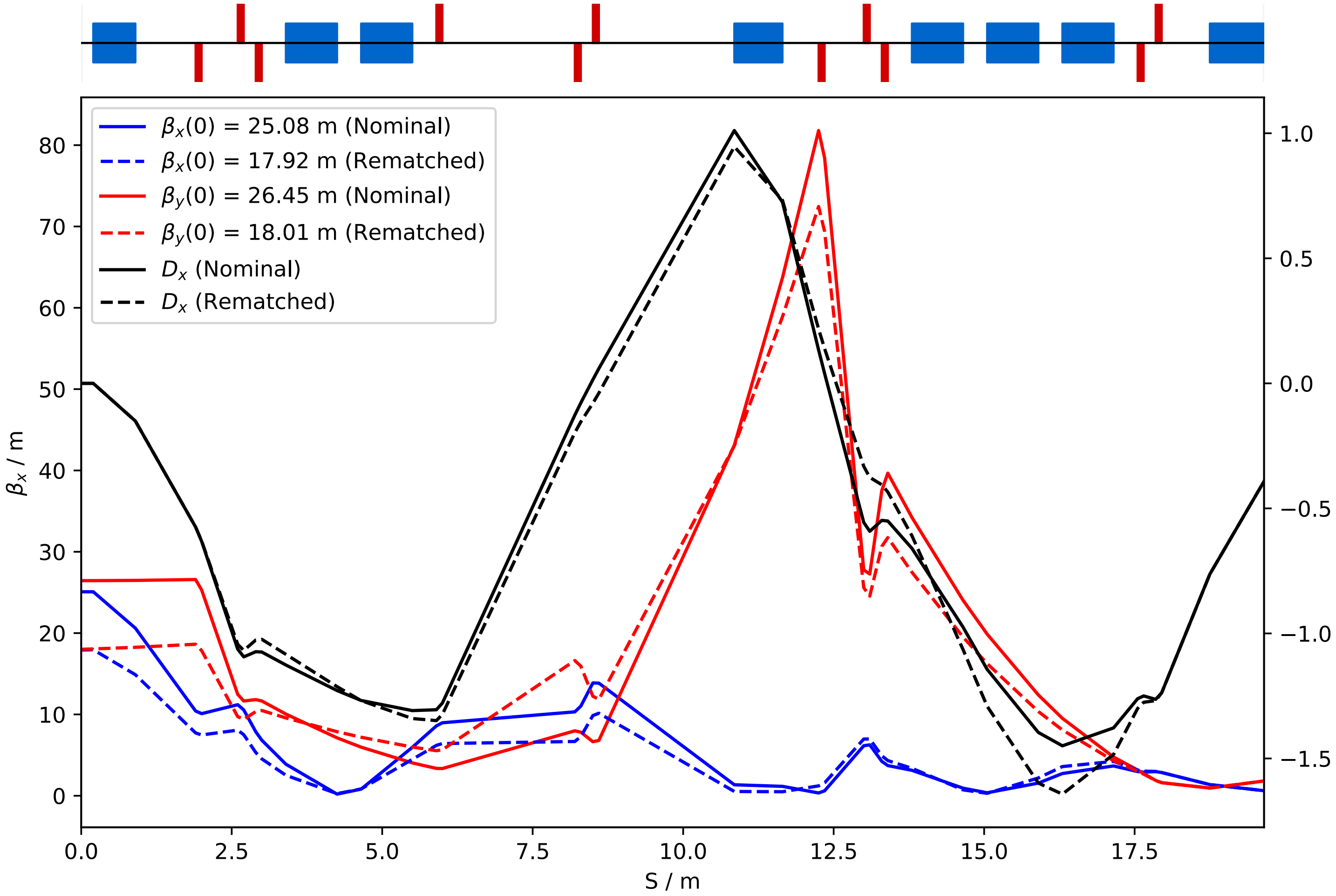




Nominal Injection Line Optics

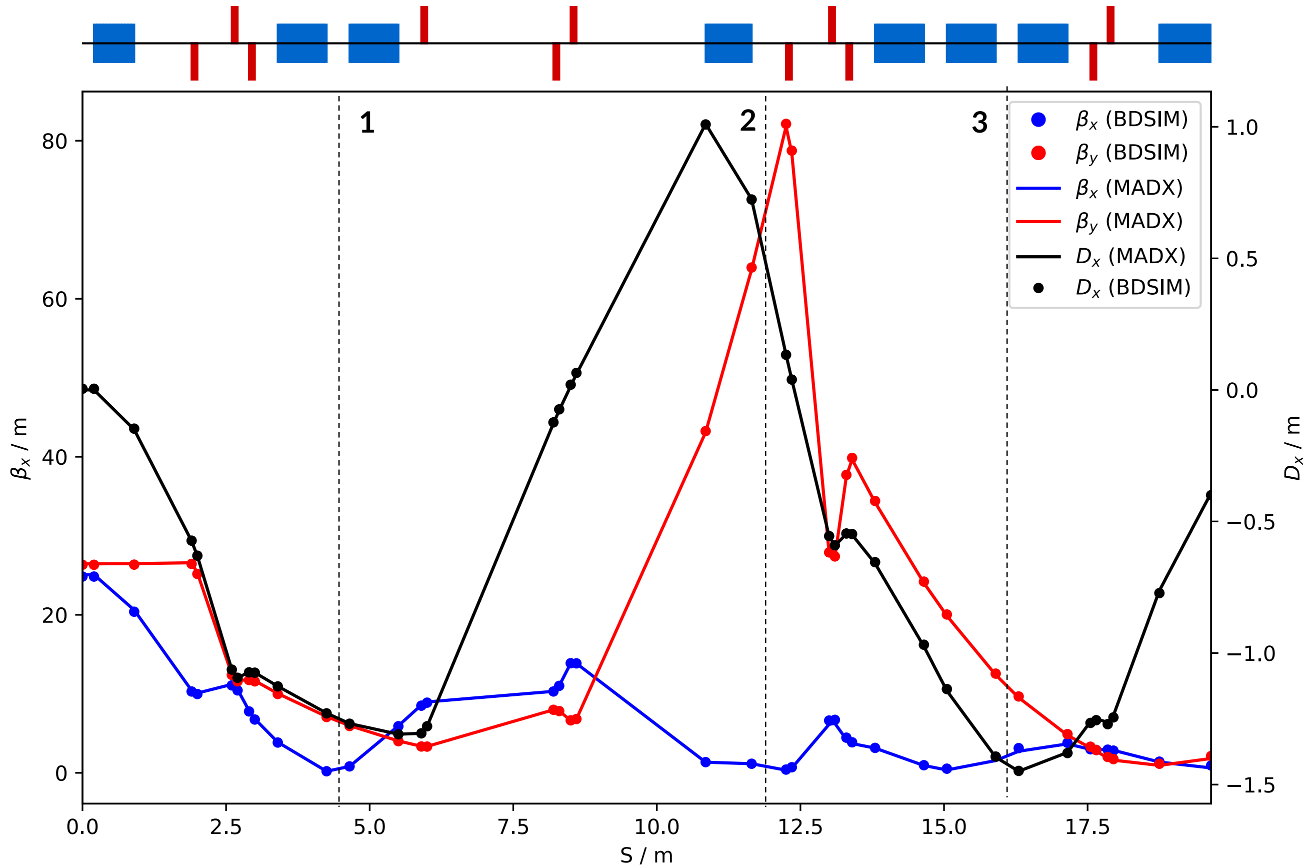


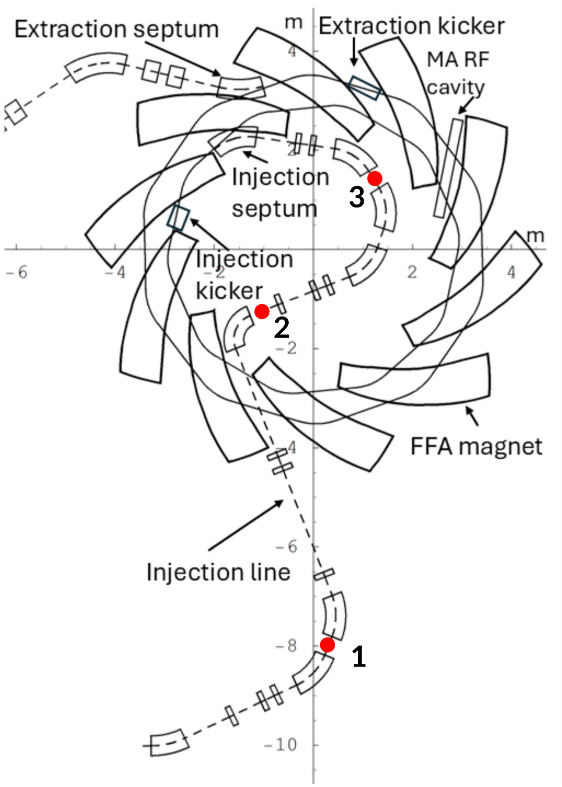
Optimised Injection Line Optics



- Injection line is flexible, handles alternative initial conditions.

Injection Line Collimation

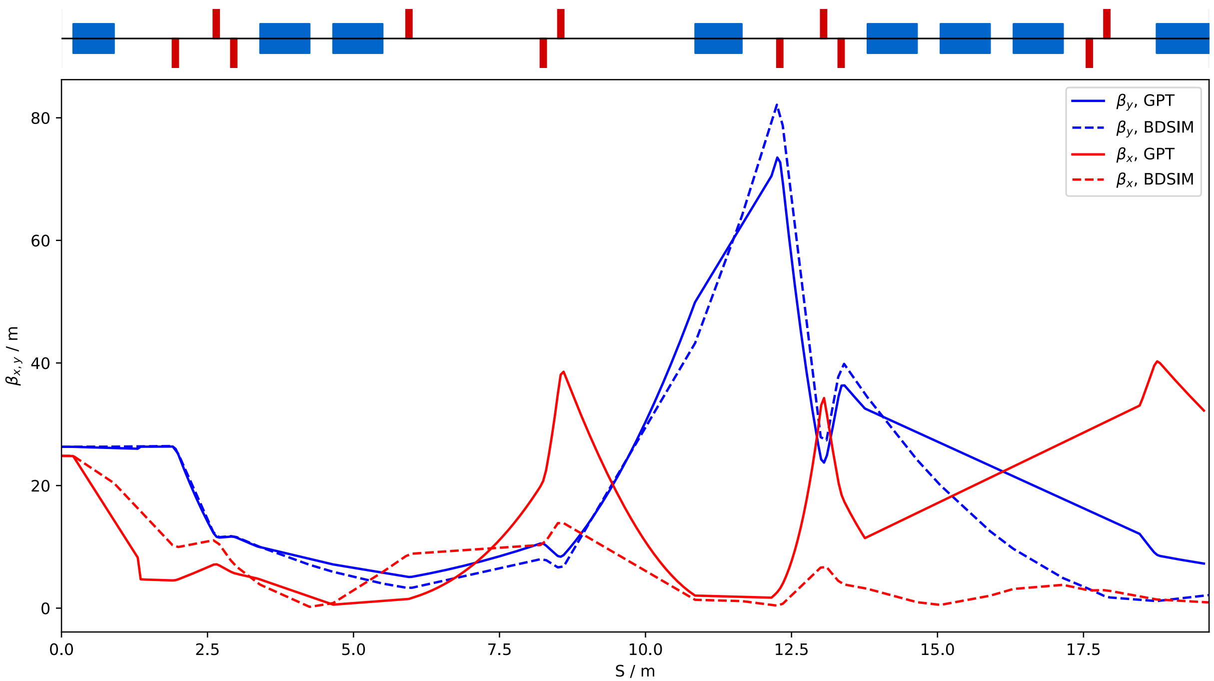


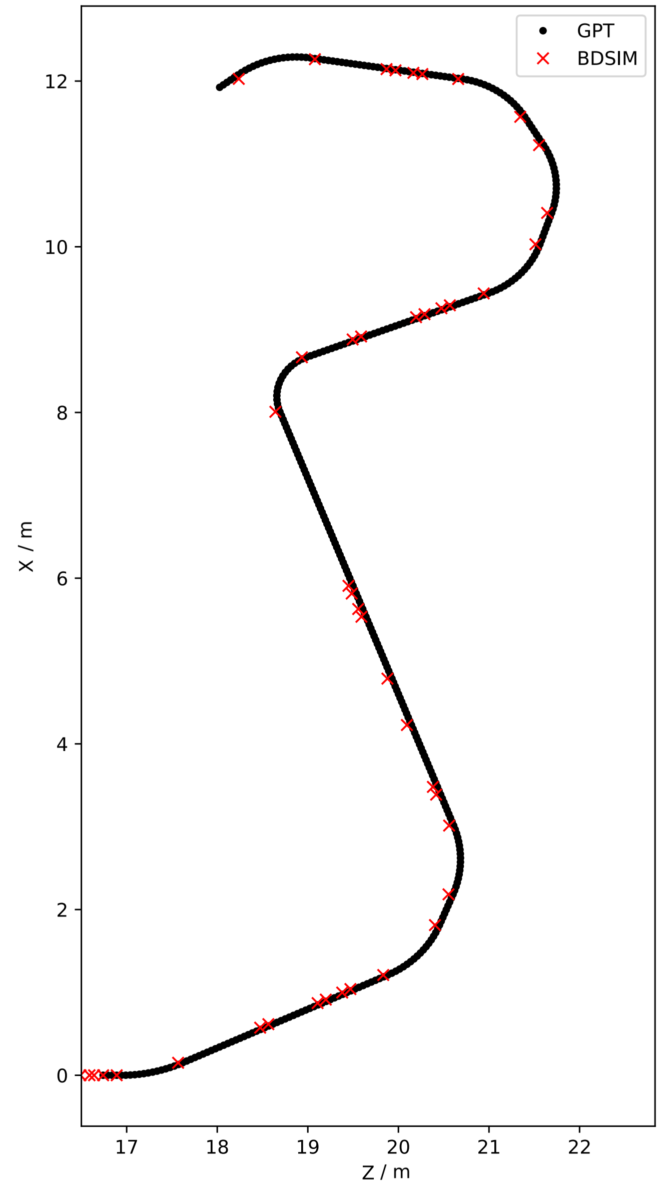


1) 0.4m between dipoles 2 & 3 (in stage 1 room)
2) 0.6m between dipole 4 & downstream quadrupole.
3) 0.4m between dipoles 6 & 7.

Modelling in GPT (Space Charge)

- Survey (reference particle) in good agreement.
- Challenges modelling the full beam:
  - Septum magnet exit conditions not met.
  - Missing data around dipoles 5-7.
  - <u>Space charge solver non-convergence errors.</u>
  - <u>No calculation of dispersion</u> (needed for optimisation).
  - Alternative code being sought.





Summary

- Emittance growth seen in Stage 1 beam transport.

- Injection line shown to be flexible.

- Impact of space charge is ongoing.

Thank you

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