WP6 Progress

William Shields
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LhARA Collaboration Meeting #7

8th April 2025

WP6 Progress

C. Whyte, yesterday:

MILESTONES

Task Name	Start	Finish	Resource Names
WPA	Tue 01/10/24	Mon 30/06/25	
Task 7	Tue 01/10/24	Fri 30/05/25	J. Parsons
7.1 Develop beamline and bespoke facilities at SCAPA for radiobiology experimentation	Tue 01/10/24	Fri 30/05/25	
7.2 Preliminary radiobiology results at SCAPA	Tue 01/10/24	Fri 30/05/25	
Task 9	Tue 01/10/24	Fri 30/05/25	R. Gray
9.1 Demonstration of beam delivery to end station at SCAPA	Tue 01/10/24	Fri 30/05/25	
Task 4	Mon 30/06/25	Mon 30/06/25	J. Bamber
4.1 Report on Ion Acoustic Results		Mon 30/06/25	
Task 5	Mon 30/06/25	Mon 30/06/25	R. Amos, T. Price
5.1 Deliver PoPLaR end-station	Mon 30/06/25	Mon 30/06/25	
WPB	Tue 01/10/24	Mon 30/06/25	
Task 2	Mon 30/06/25	Mon 30/06/25	
2.1 Assessment of beam performance during PoPLaR experiment on SCAPA	Mon 30/06/25	Mon 30/06/25	
Task 3	Mon 30/06/25	Mon 30/06/25	
3.1 Progress report on increased voltage penning trap simulations and operation	Mon 30/06/25	Mon 30/06/25	
Task 6	Mon 30/06/25	Mon 30/06/25	
6.1 Review of FFA R&D work	Mon 30/06/25	Mon 30/06/25	
WPC	Tue 01/10/24	Mon 30/06/25	
Task 1	Mon 07/04/25	Tue 08/04/25	C. Pugh, C. Whyte
1.1 Initial PoPLaR and LhARA update: Collaboration Meeting	Mon 07/04/25	Tue 08/04/25	
Task 8	Wed 30/04/25	Mon 30/06/25	P. Price
8.1 Peer group meeting		Wed 30/04/25	
8.2 Benefits map for LhARA		Mon 30/06/25	

- FFA Review Meeting February 26th 2025.
  - Report draft nearly complete, to be sent to reviewers asap.

WP6 Progress

- Stage 1 status update & Stage 2 injection line (me)
- Stage 1 beam delivery (Matt)
- FFA status update (Jaroslaw)
- FFA magnet progress (Ta-Jen)
- Engineering & Integration (Clive)

LhARA: Stage 1 and FFA Injection Line

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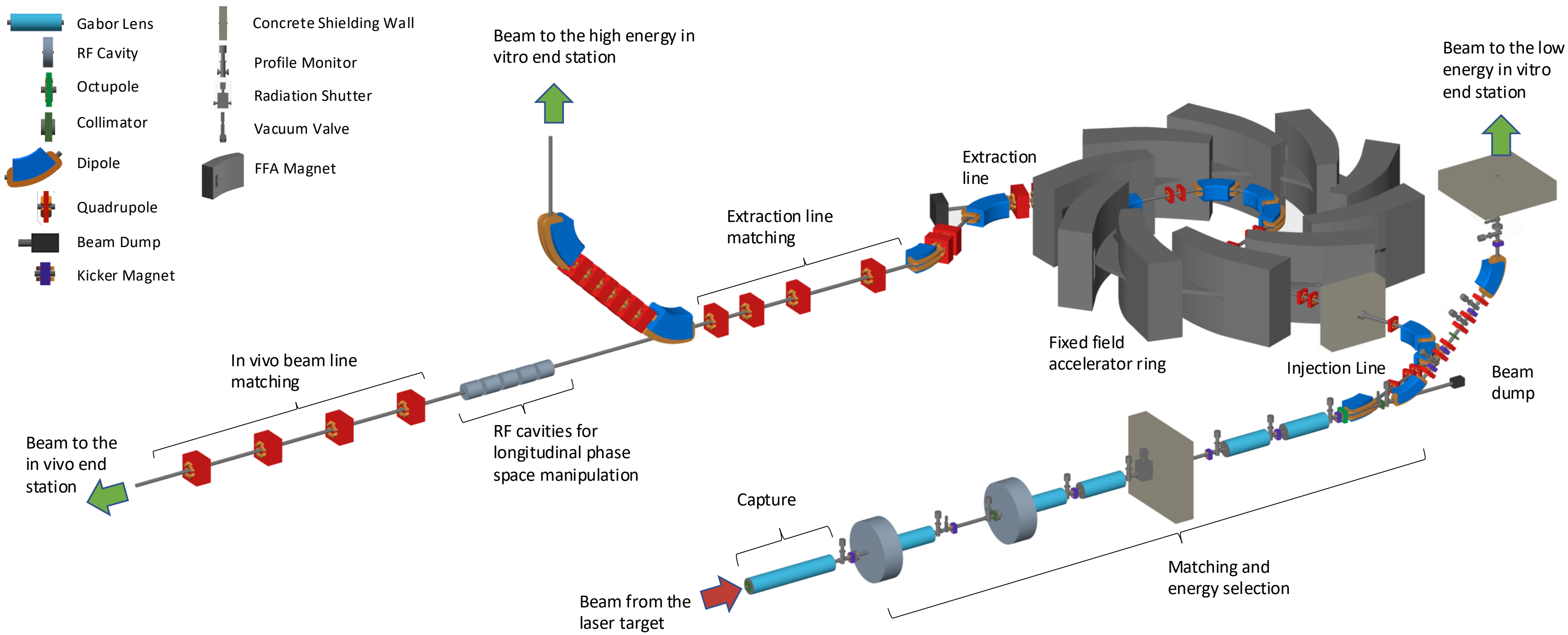
LhARA: Layout



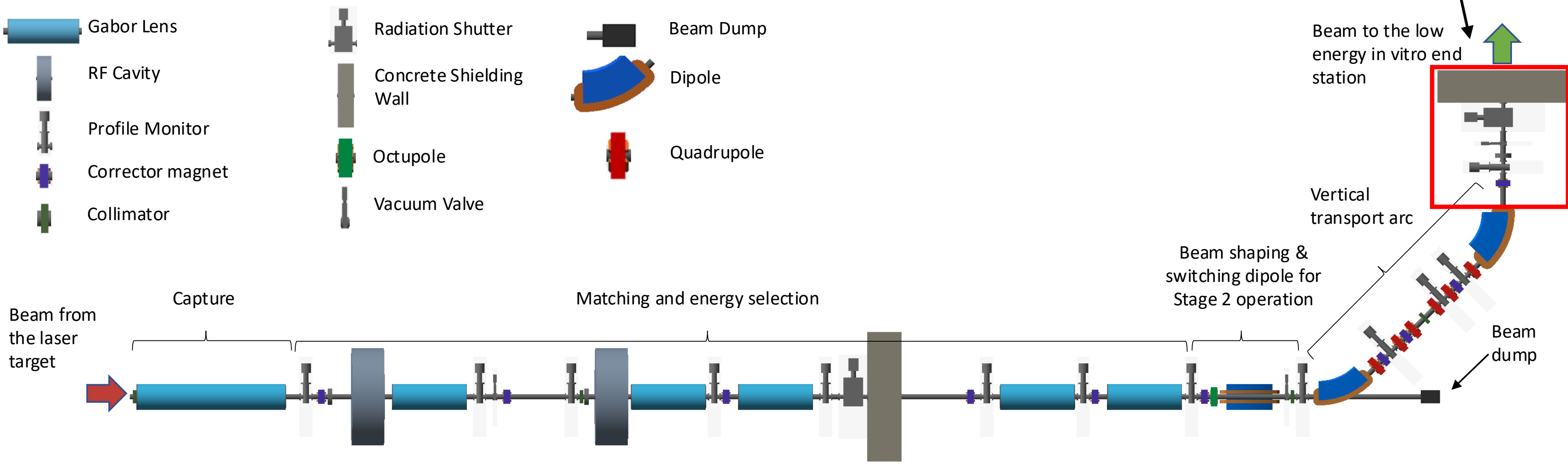
- Updated FFA & injection line designs.

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

- <u>No major changes</u>

- Stage 1 beam delivery
  - Matt Pereira & Rehanak Razak



Stage 1 Emittance

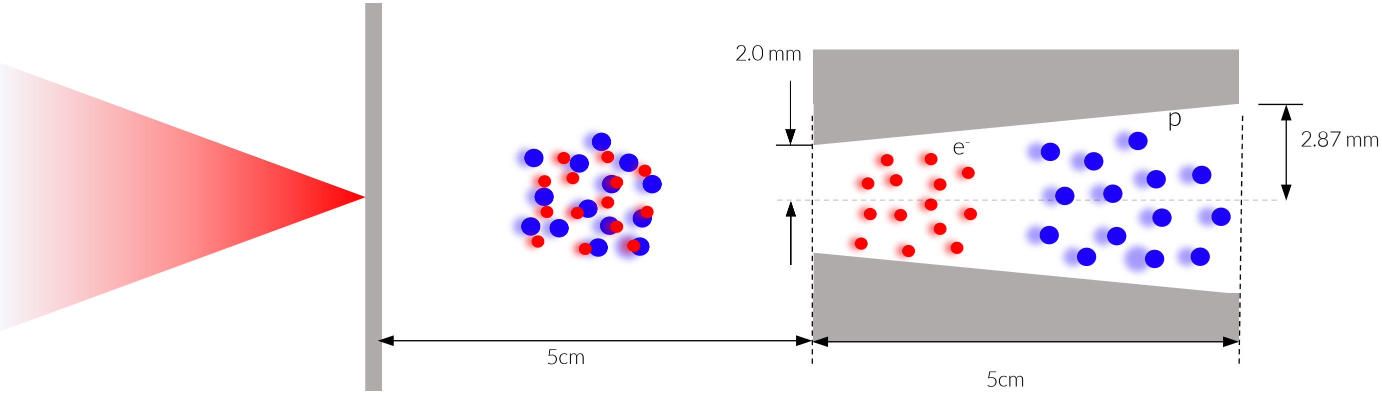
- Methodology:
  - Generate 15 MeV ± 2% beam (LhARALinearOptics)
  - Track 5cm assuming a charge neutral beam.
  - 2mm radial filter
  - Track 5cm with space charge
  - 2.87mm radial filter

Beam Property	Parameterised Beam, $\theta_s = 11°$	
	Horizontal	Vertical
TWISS α	**-355**	**-357**
TWISS β (m)	**35.35**	**35.51**
Emittance (m rad)	**5.91e-8**	**5.87e-8**
Beam Size (m)	**1.43e-3**	**1.43e-3**

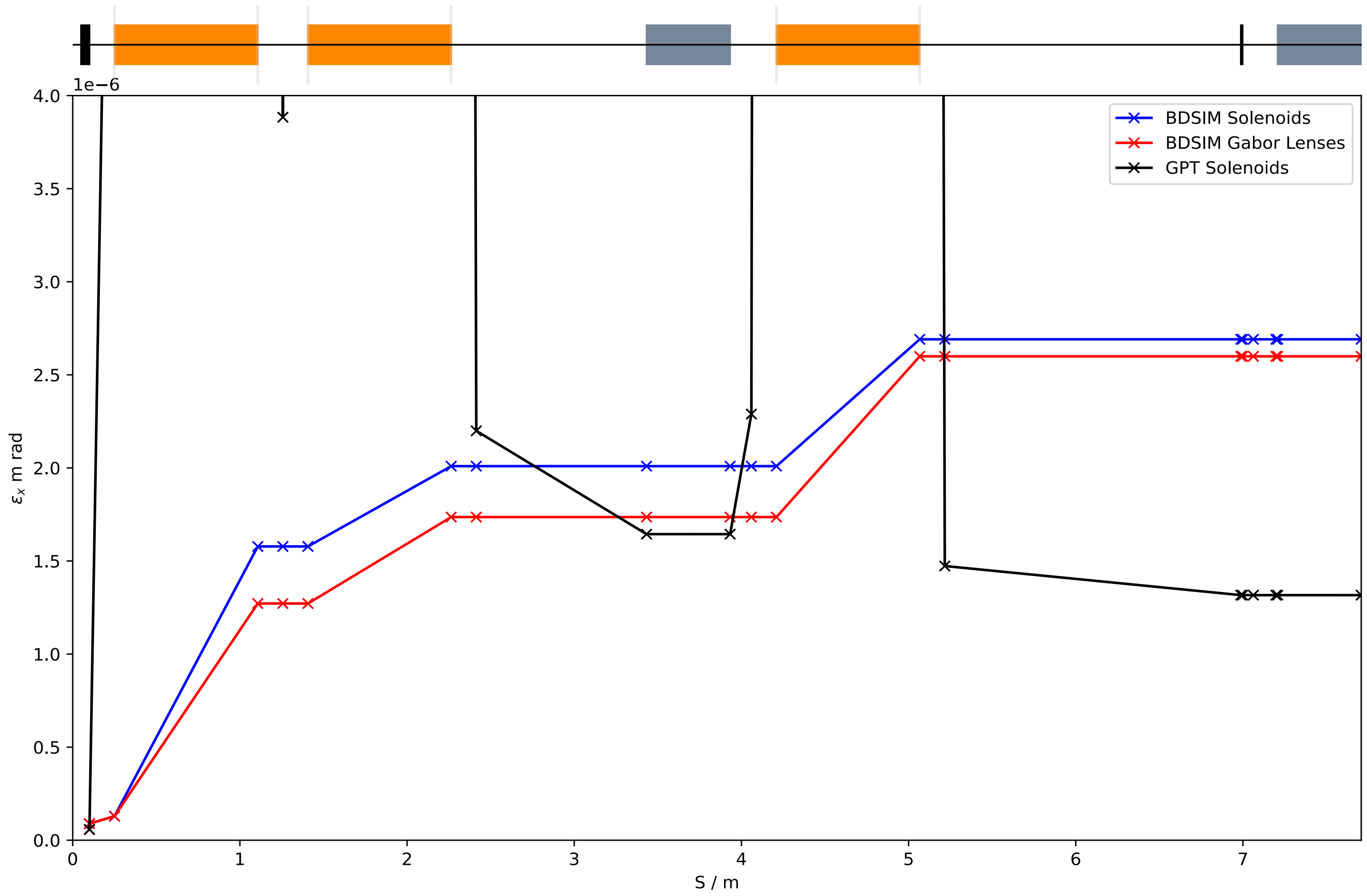
- Nozzle for maintaining vacuum between target housing & Gabor lens

At the injection line start: $\varepsilon_{x,y}$ ~**4.3e-6**

Why is the emittance so much larger downstream?



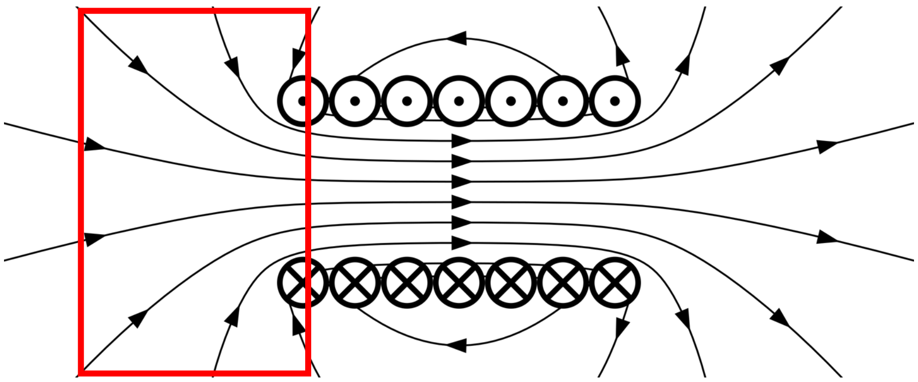
Emittance Growth from Solenoids



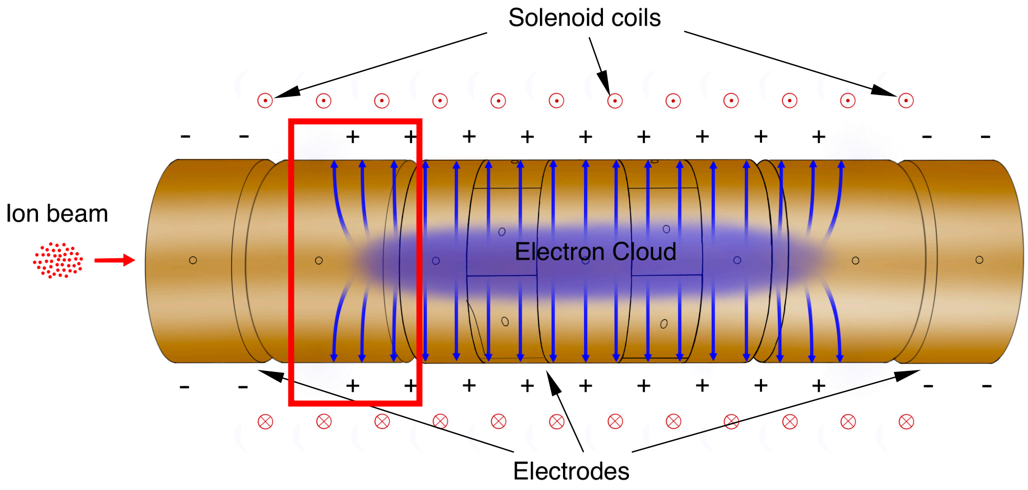
- Emittance growth from capture fields, space charge not modelled.
  - GPT emittance jumps due to recording beam in fringe fields.
  - Gabor lens limited to radial E-field (plasma), no confinement fields.

Fringe Modelling

- Solenoid fringe fields known to have a significant impact on transverse beam dynamics
  - Linear & nonlinear effects.
  - BDSIM modelling:
    - Hard-edged solenoid body
    - Thin integrated fringe kicks
  - Field maps in Matt's talk.

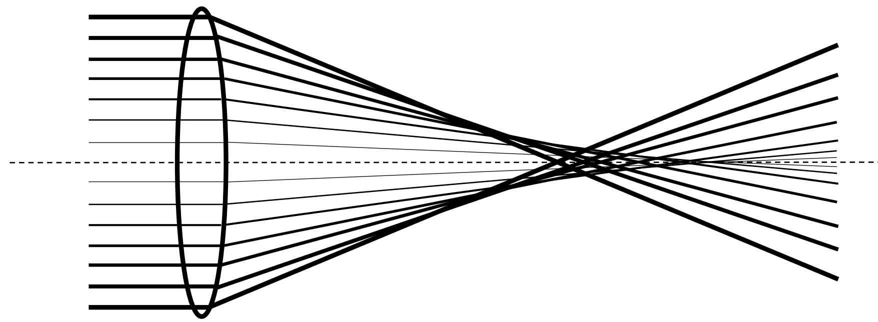


- Gabor lens only modelled as hard edged, radial field.
  - Is the longitudinal distribution of the e- cloud understood? Realistically not hard-edged?
  - Is there significant impact on the ion beam dynamics from these Gabor lens "fringes"?
  - Simulations required.

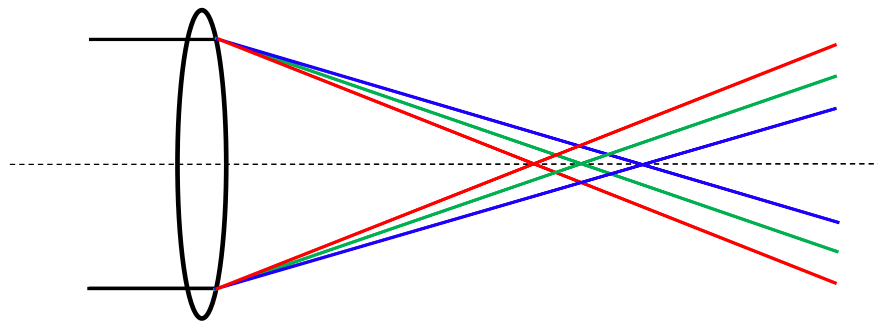


Solenoid Aberrations

- Spherical aberrations:
  - Result from the radial variation of the longitudinal solenoid field
  - Stronger focusing force at larger radii
  - <u>Hard to mitigate</u>



- Chromatic aberrations:
  - Result from the energy spread of the particle beam
  - Stronger focusing of lower energies, weaker focusing of higher energies.



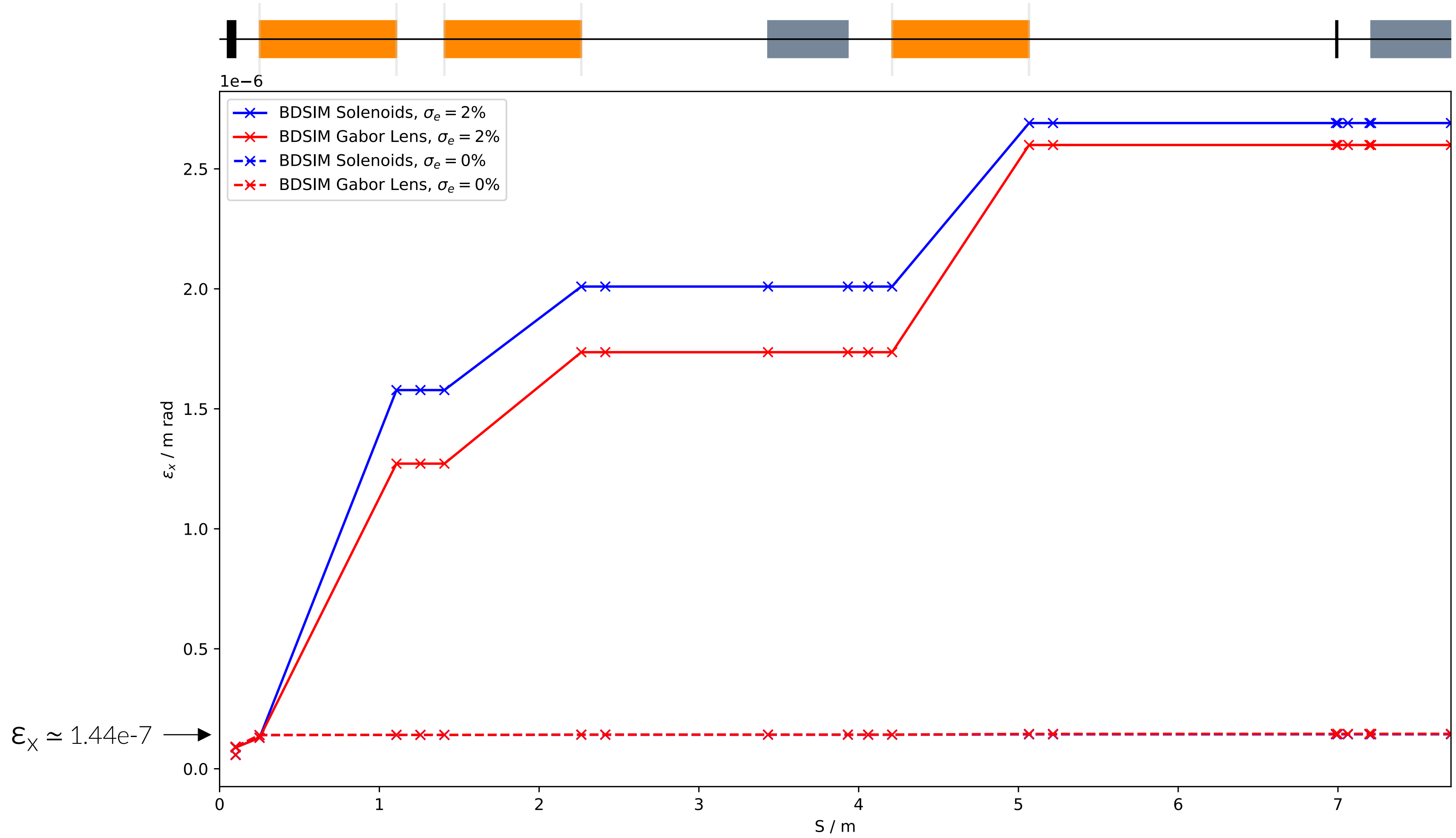
- Quadrature contributions to beam size:

$$R_f^2 = \left(\frac{\varepsilon}{R_0} f\right)^2 + \left(2R_0 \frac{\Delta E}{E}\right)^2 + (C_s R_0^3)^2$$

Sinha, G. et al., Sci Rep 14, 9778 (2024).

R_f: radius at focal plane
ε: emittance
R_0: initial beam radius
f: focal length
$\frac{\Delta P}{P}$: energy spread
C_s: spherical aberration coefficient

Zero Energy Spread



- Very clear chromatic contribution to the transverse emittance.
- Cannot mitigate without impacting dose rate.

Emittance Growth In Literature

- 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, broadly similar beam parameters to LhARA
    - 6.4 mm radius (rms).
    - Space charge negligible, 95 KeV, energy spread 0.25%.

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

- LhARA:
    - $X'_{rms} \simeq Y'_{rms}$ = 14.39 mrad
    - Highest solenoid field: 1.4T

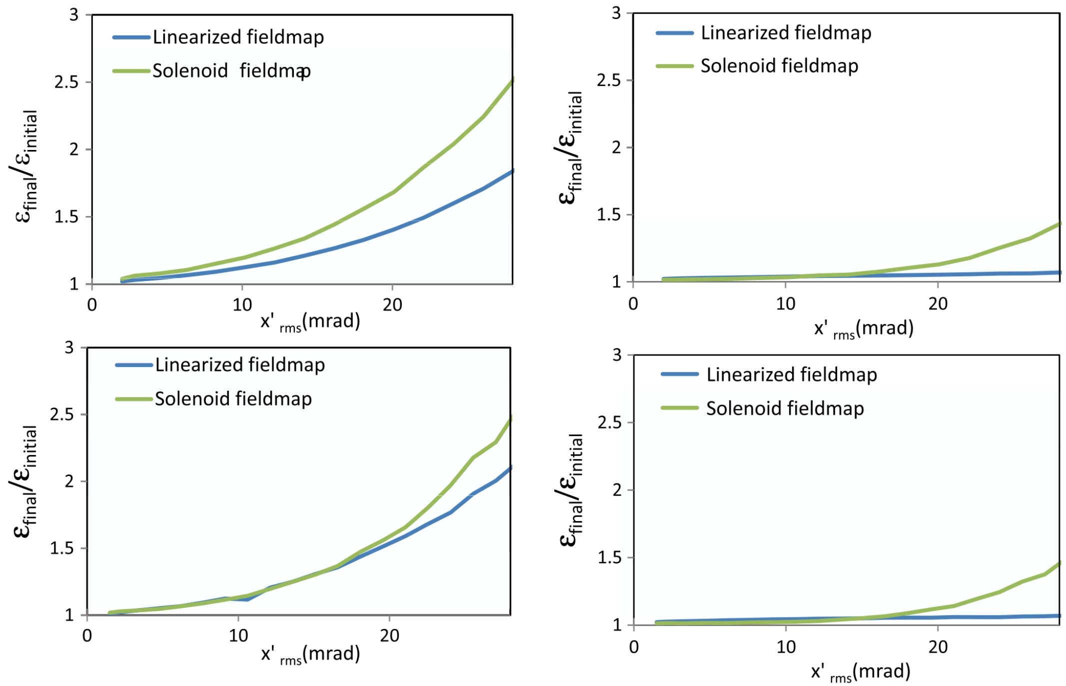
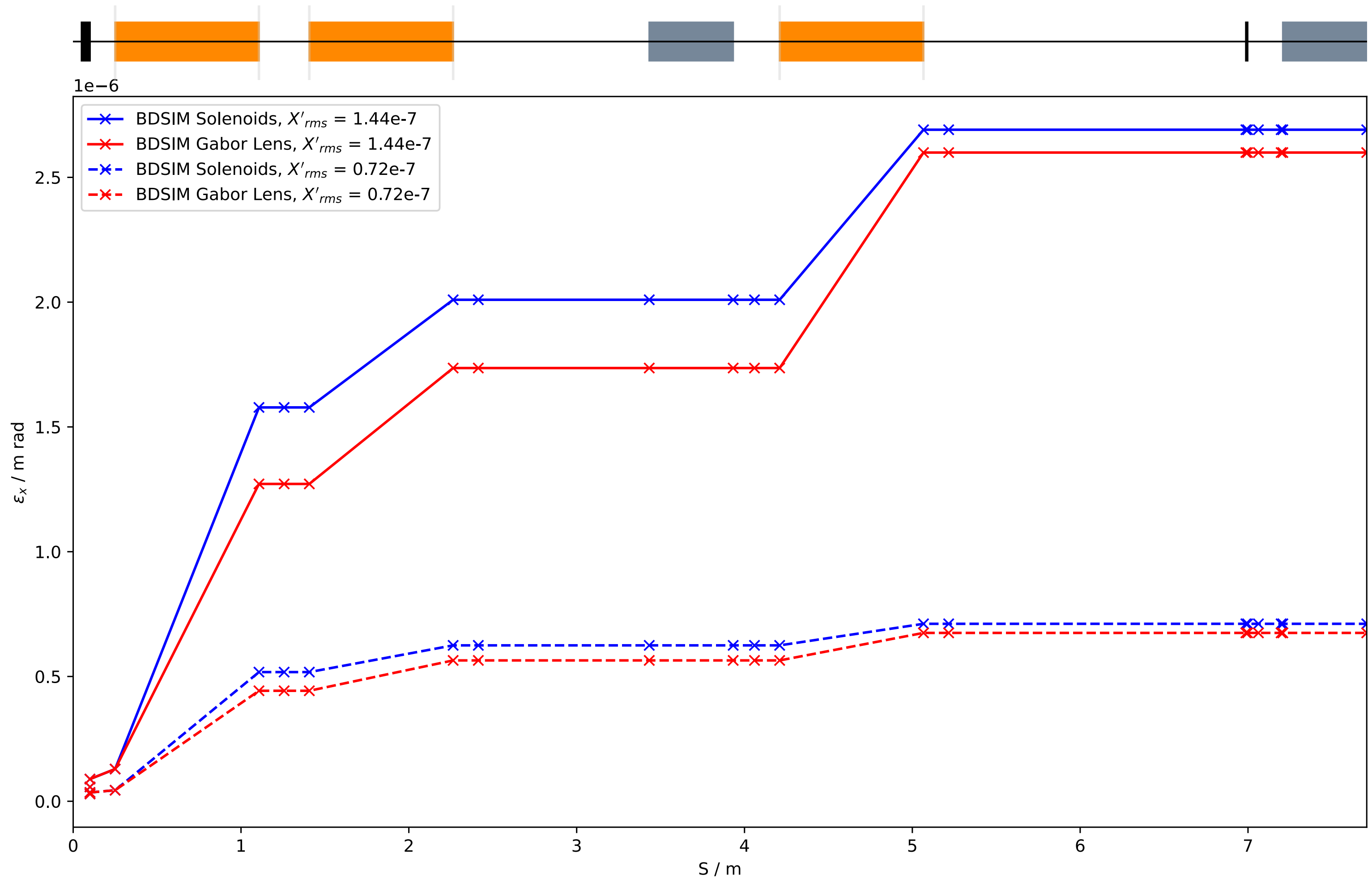


FIG. 8. (Color) Increase of emittance in solenoidal channels, $B = 0.6$ T. Top: initial emittance 8.0π mm mrad. Bottom: initial emittance 4.5π mm mrad.

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.

- Could decreasing LhARA's initial emittance reduce downstream emittance growth?

Reduced Initial Divergence

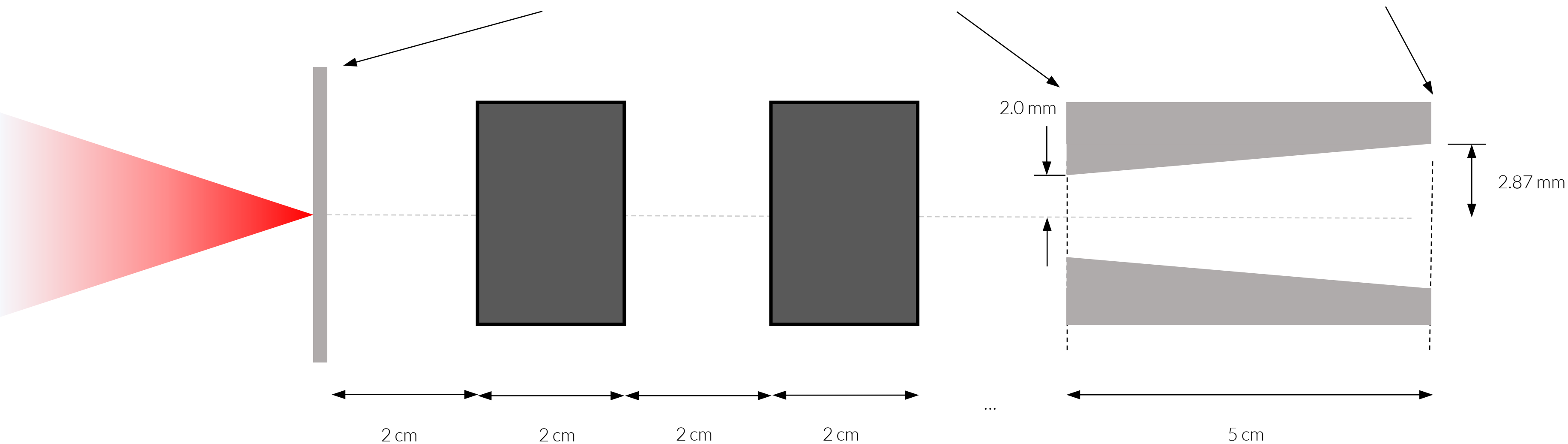


- Test - factor 2 reduction in X'_{rms} -> factor ~4 reduction in emittance.

PMQs for Capture

- Current beam parameters:

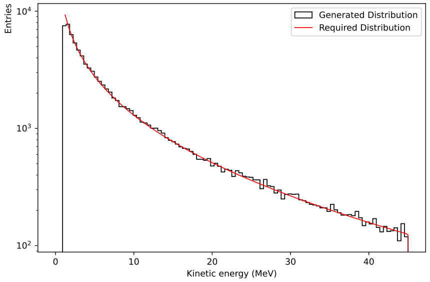
Location	Start		Nozzle Entrance		Nozzle Exit	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
TWISS α	-0.009	-0.01	**-468**	**-467**	-355	-357
TWISS β (m)	4.9e-5	4.9e-5	46.59	46.48	35.35	35.51
Emittance (m rad)	3.3e-7	3.3e-7	8.70e-8	8.69e-8	5.91e-8	5.87e-8
Beam Size (m)	4.0e-6	4.0e-6	1.99e-3	1.99e-3	1.43e-3	1.43e-3

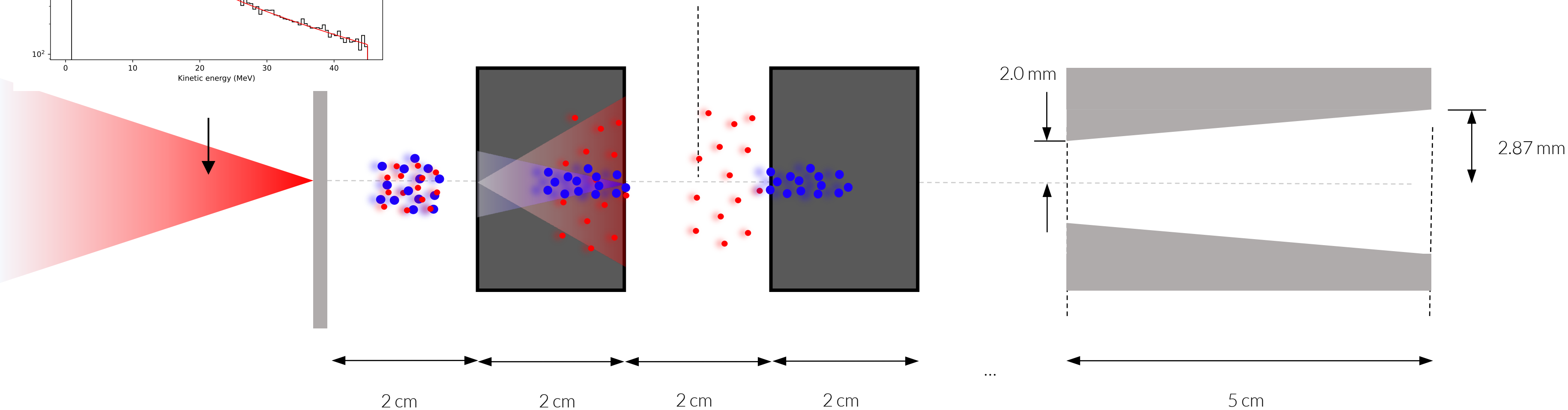


- Aim: <u>reduce α</u> at the nozzle entrance but not at the expense of significant losses
    - Move the nozzle downstream

PMQs for Capture

- Complex beam dynamics:
    - Broad proton & ion spectrum
    - Co-propagating with electrons
    - Earlier PMQ transverse charge separation
    - Longitudinal drift separation





- Considerations: space charge, number of quads, losses, PM demagnetisation
- More modelling!

Stage 1 Optics for Stage 2 Injection

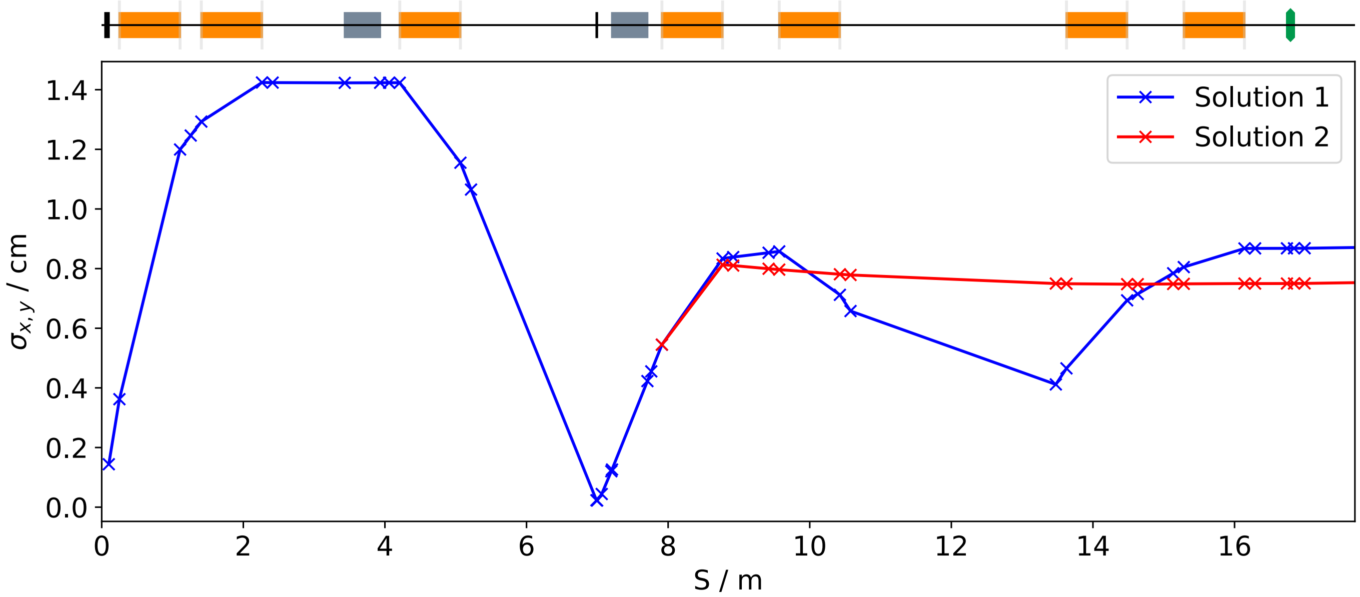
- Challenges meeting baseline injection line beam parameters
  - At switching dipole: $\varepsilon_{x,y}$ ~**4.3e-6**,
    - Target: $\alpha_{x,y} = 0$, $\beta_{x,y}$ ~25m. Challenging to achieve.
  - Solutions prioritise $\alpha_{x,y}$

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
```

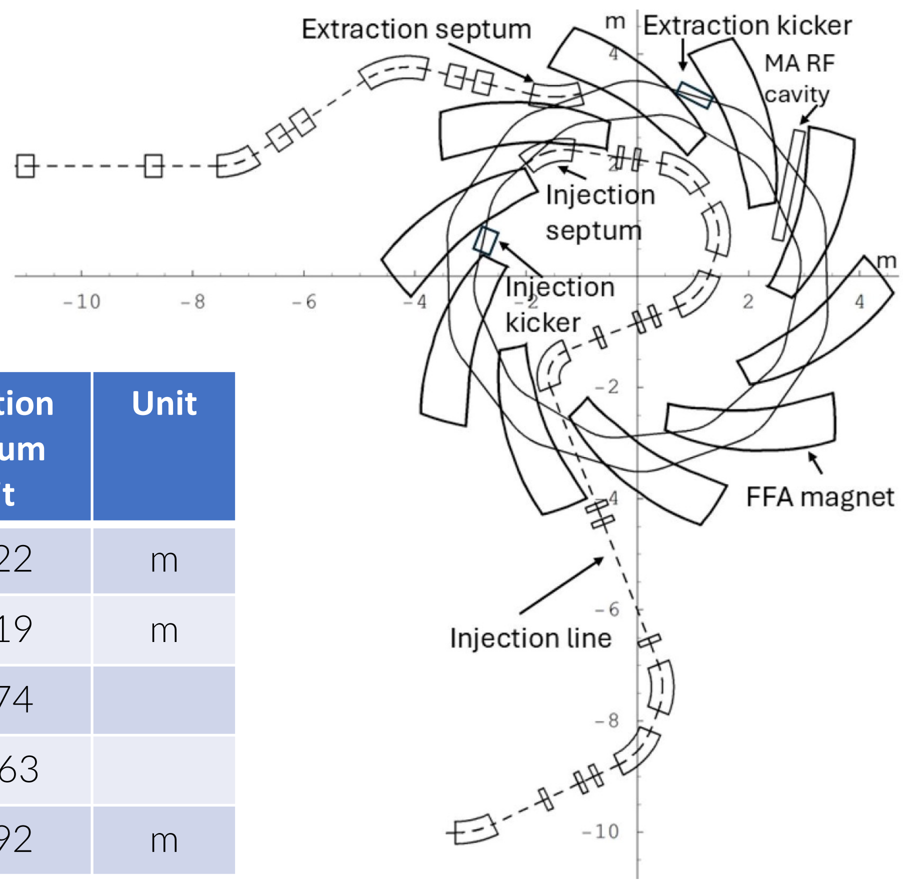
Solution 2:

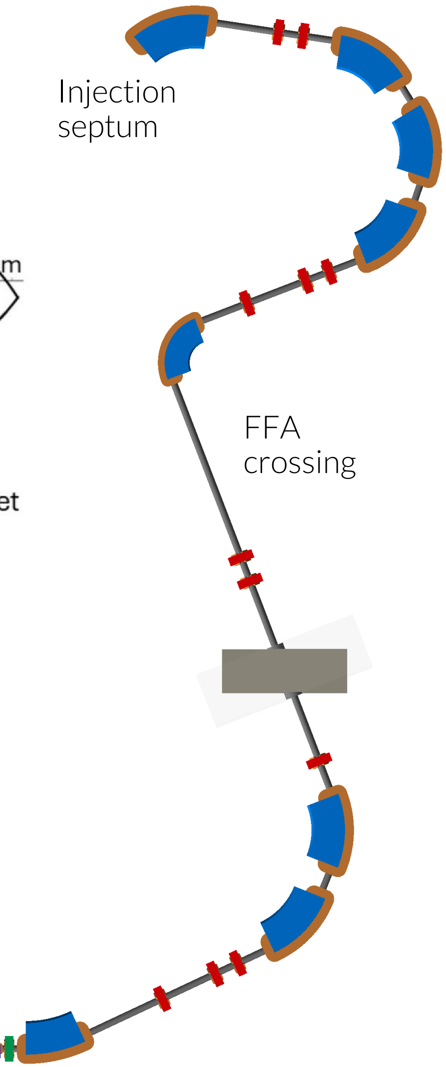
```
Alpha x: -0.112
Alpha y: -0.169
 Beta x: 17.49
 Beta y: 17.37
 Emit x: 3.22e-06
 Emit y: 3.235e-06
```



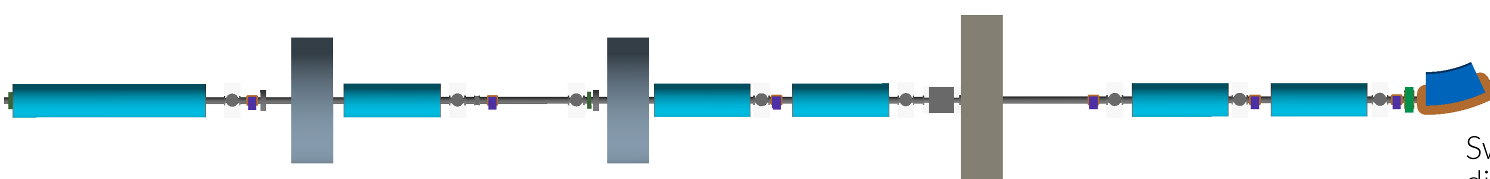
Solution	Solenoid 4 B Field (T)	Solenoid 5 B Field (T)	Solenoid 6 B Field (T)	Solenoid 7 B Field (T)
1	1.0719	0.8482	0.7448	0.4998
2	1.0976	0	0	0.1176

Nominal Injection Line Model

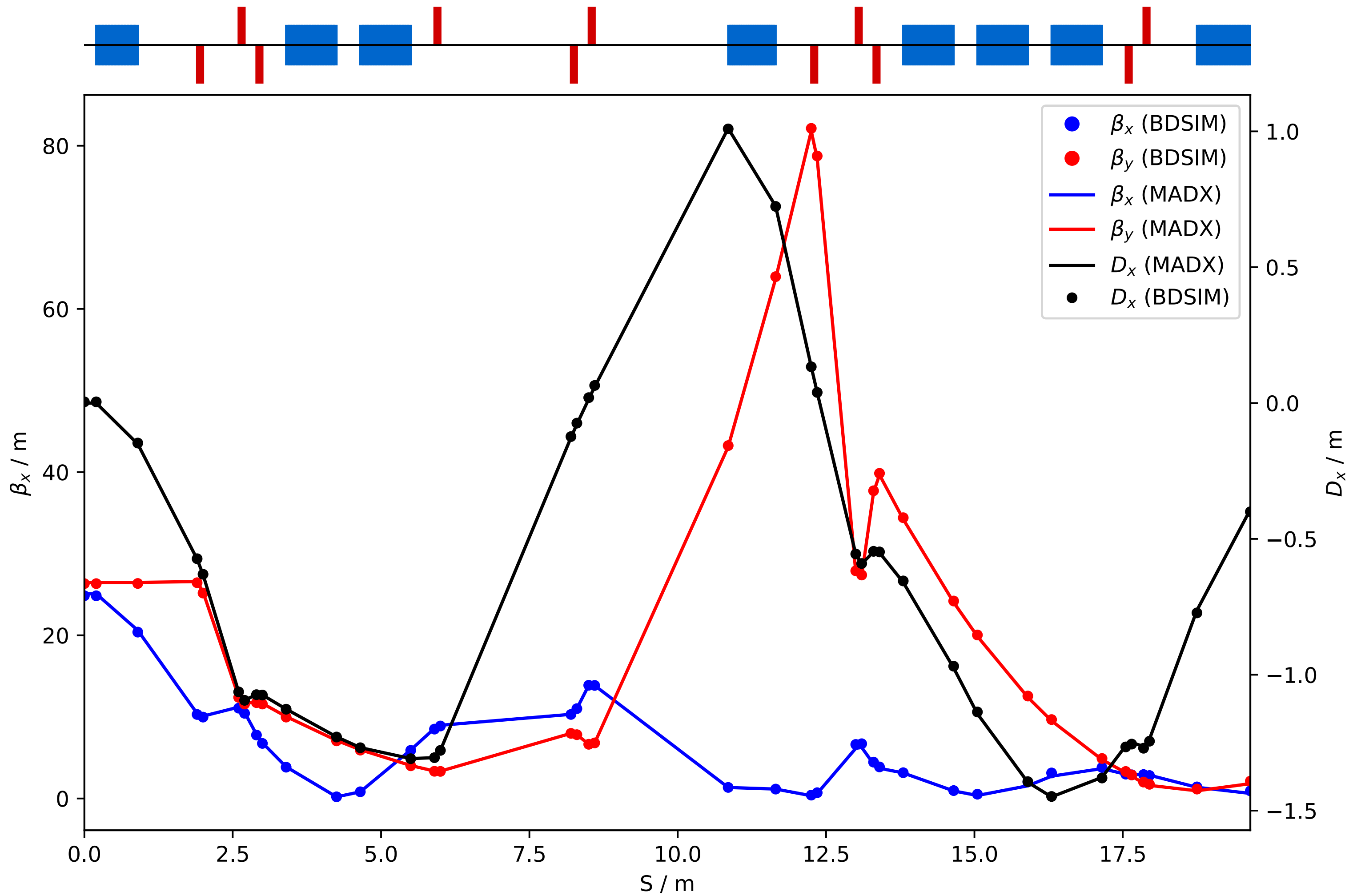




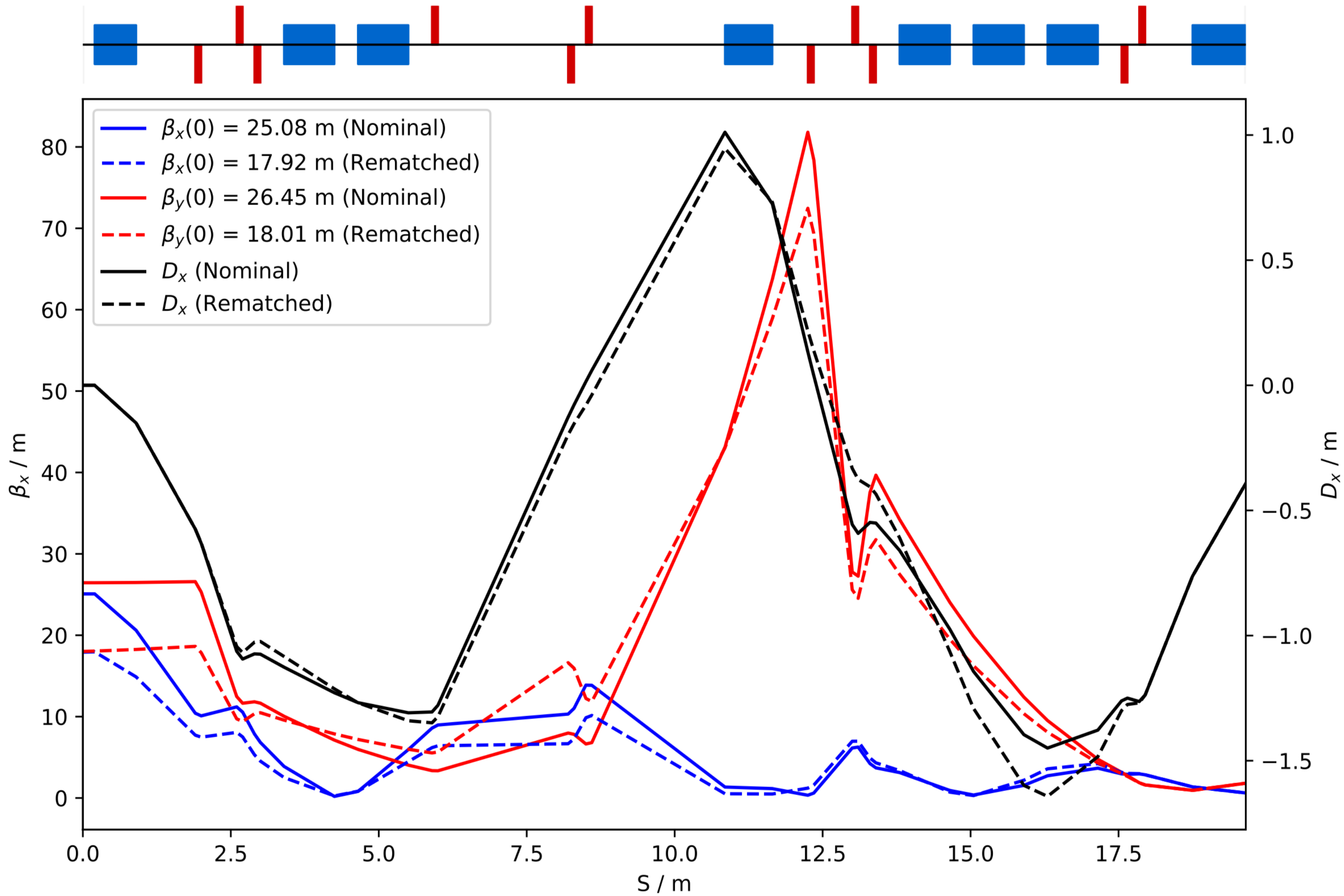
Beam Parameter	Switching Dipole Entrance	Injection Septum Exit	Unit
β_x	25.08	0.622	m
β_y	26.45	1.819	m
α_x	0	0.074	
α_y	0	-0.963	
D_x	0	0.392	m



Nominal Injection Line Optics

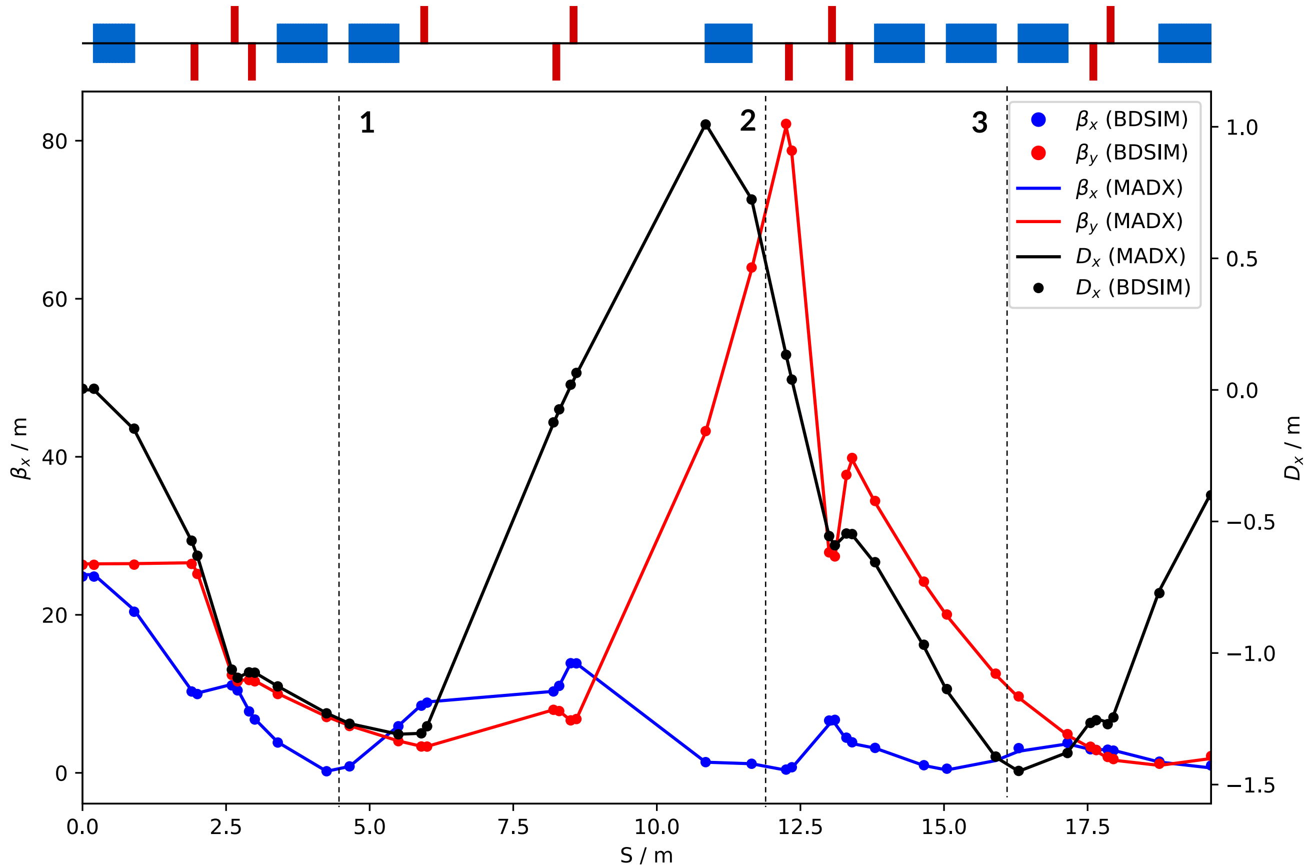


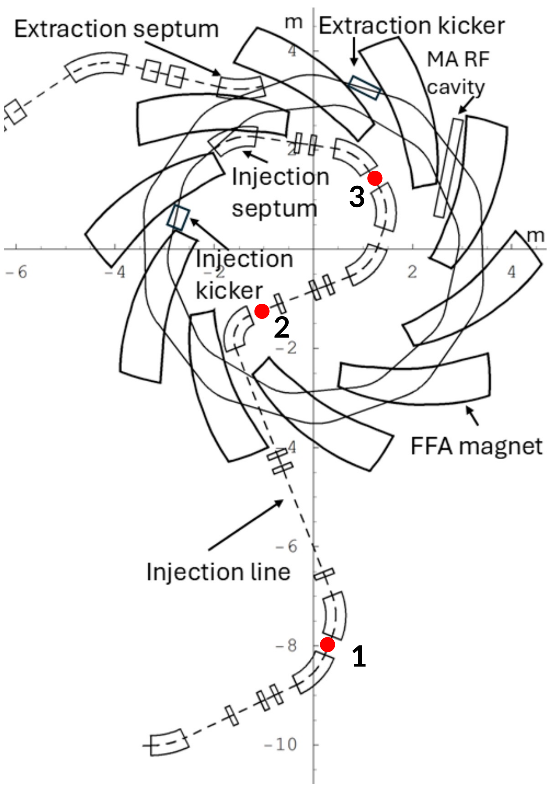
Optimised Injection Line Optics



- Injection line is flexible, handles alternative initial conditions.

Injection Line Collimation

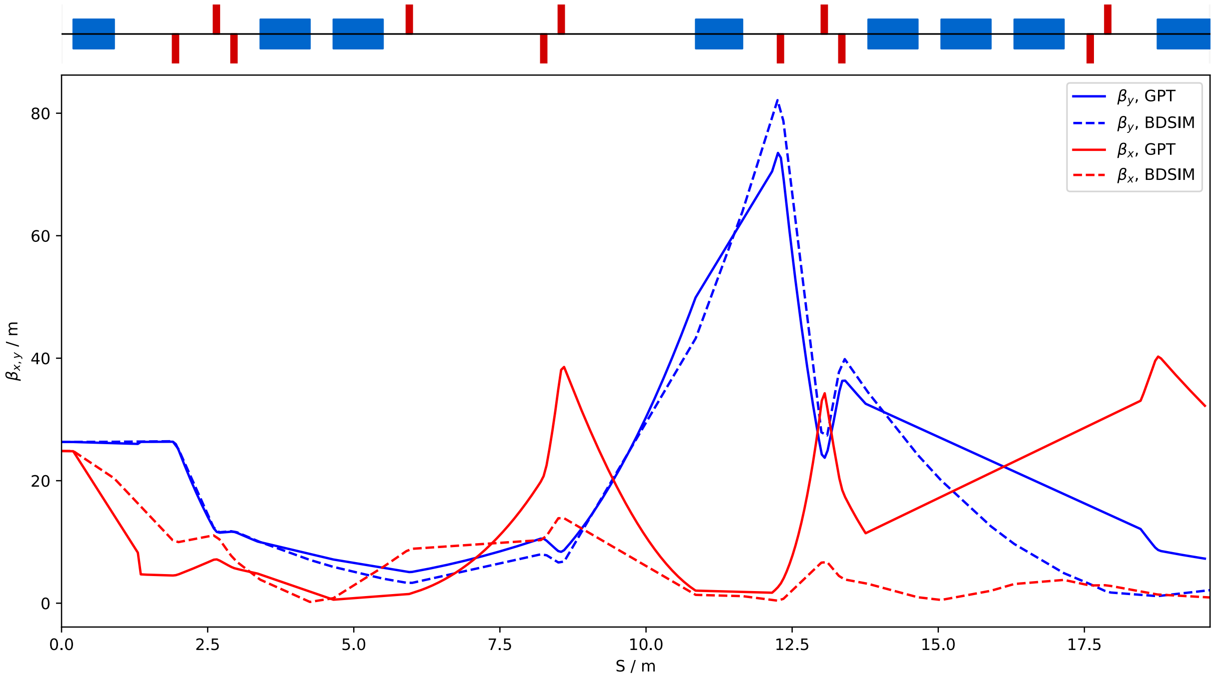


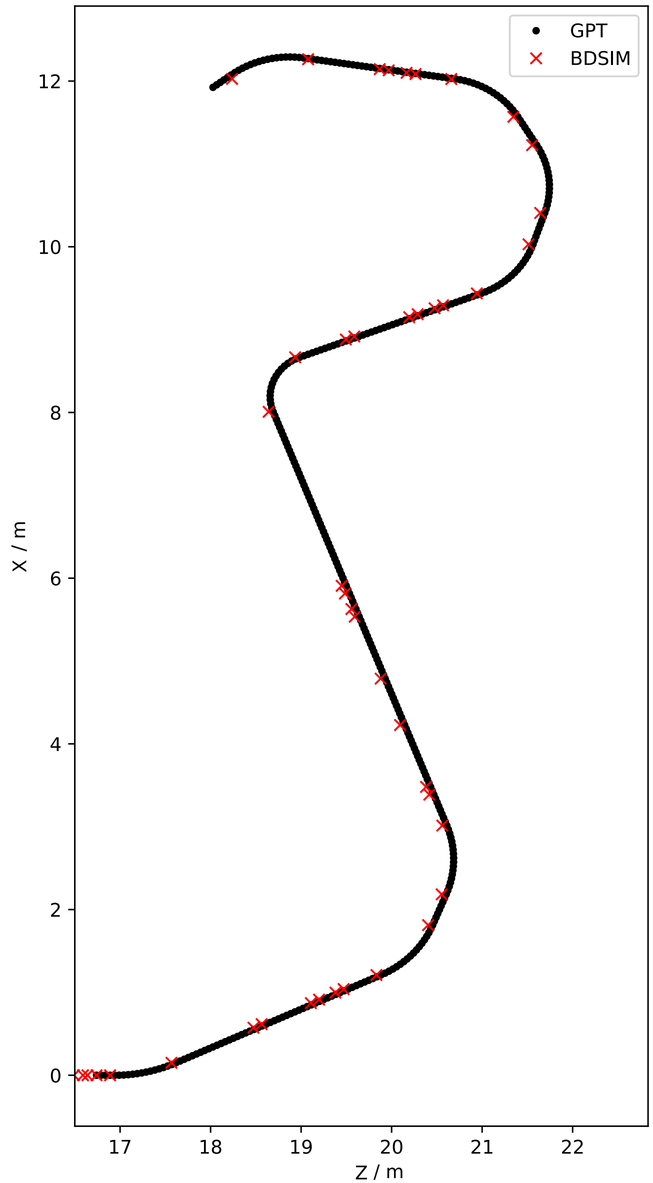


1) 0.4m between dipoles 2 & 3 (in stage 1 room)
2) 0.6m between dipole 4 & downstream quadrupole.
3) 0.4m between dipoles 6 & 7.

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

- Solenoid aberrations contribute to stage 1 emittance growth.

- PMQ study planned to reduce initial emittance.

- Flexible injection line model, space charge modelling remains a challenge.

Thank you

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