LhARA Facility Design and Integration WP1.6

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On behalf of WP6

ITRF & LhARA Project 6 Month Design Review Meeting

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Imperial College London

JAI John Adams Institute for Accelerator Science

Science & Technology Facilities Council ISIS

BDSIM

LhARA Laser-hybrid Accelerator for Radiobiological Applications

Outline

- CAD model
- Baseline studies
- New baseline candidate studies
- Stage 2 overview
- Ongoing studies and next steps
- Summary

CAD Model Workflow

- Automatic generation of spreadsheet containing component surveys
- Generated from BDSIM model
- Matches component naming scheme

LhARAGeometrySurvey-v0.1

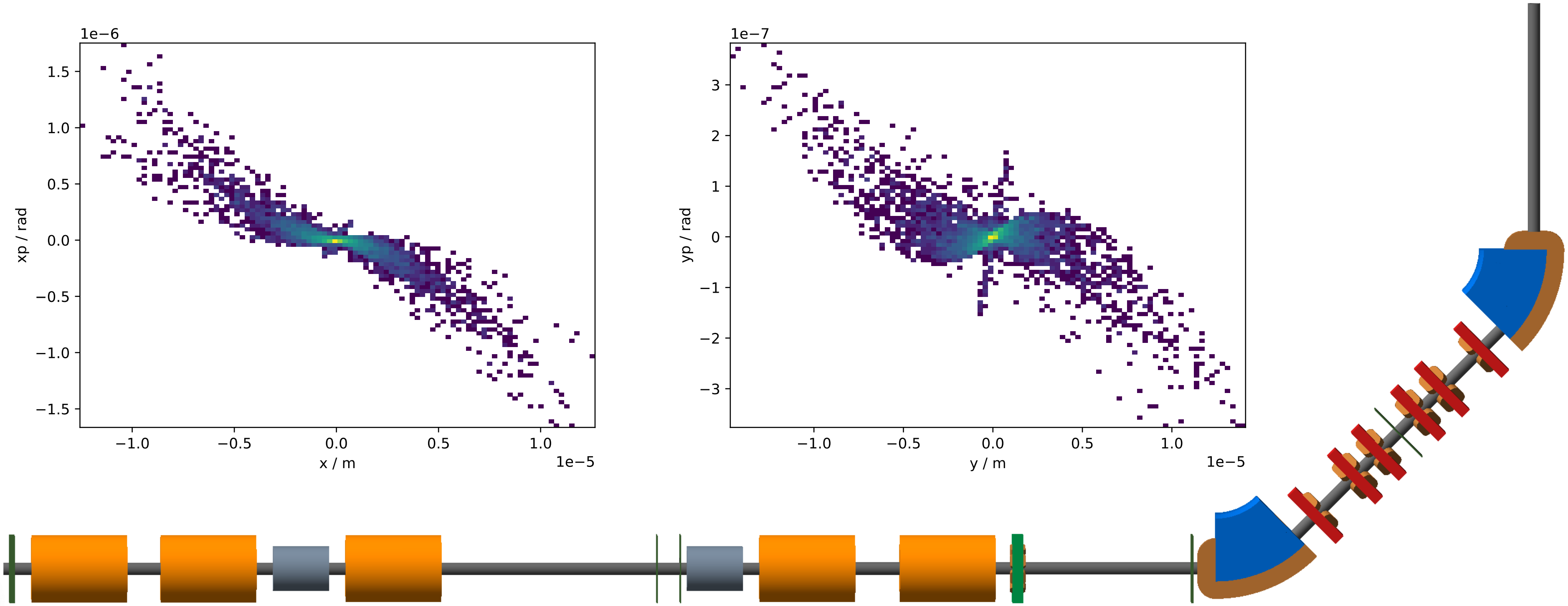
	A	B	C	D	E	F	G	H	I	J	K	L
1		0										
2	0	STAGE1INVITRO Component List										
3	1	Document Name: lhara-v1.0 component coordinates										
4	2	8/12/2022										
5	3	Notes: Units = mm.										
6		Section	X	Y	Z	Component Position	Component Name	Component Type	Aperture Type	Hor. Half Aperture	Ver. Half Aperture	Comments
7	0	TR	0	0	-100.000	Start	LHA_TR_VAC_DRI_00	drift	circular	50.000	50.000	
8	1	TR	0	0	-75.000	Middle	LHA_TR_VAC_DRI_00	drift	circular	50.000	50.000	
9	2	TR	0	0	-50.000	End	LHA_TR_VAC_DRI_00	drift	circular	50.000	50.000	
10	3	TR	0	0	-50.000	Start	LHA_TR_DIA_COL_01	ecol	circular	2.870	2.870	
11	4	TR	0	0	-25.000	Middle	LHA_TR_DIA_COL_01	ecol	circular	3.305	3.305	
12	5	TR	0	0	0	End	LHA_TR_DIA_COL_01	ecol	circular	2.000	2.000	
13	6	TR	0	0	0	Start	LHA_TR_VAC_DRI_01	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
14	7	TR	0	0	75.000	Middle	LHA_TR_VAC_DRI_01	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
15	8	TR	0	0	150.000	End	LHA_TR_VAC_DRI_01	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
16	9	TR	0	0	150.000	Start	LHA_TR_MAG_SOL_01	solenoid	circular	50.000	50.000	
17	10	TR	0	0	578.500	Middle	LHA_TR_MAG_SOL_01	solenoid	circular	50.000	50.000	
18	11	TR	0	0	1007.000	End	LHA_TR_MAG_SOL_01	solenoid	circular	50.000	50.000	
19	12	TR	0	0	1007.000	Start	LHA_TR_VAC_DRI_02	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
20	13	TR	0	0	1082.000	Middle	LHA_TR_VAC_DRI_02	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
21	14	TR	0	0	1157.000	End	LHA_TR_VAC_DRI_02	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
22	15	TR	0	0	1157.000	Start	LHA_TR_VAC_DRI_03	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
23	16	TR	0	0	1232.000	Middle	LHA_TR_VAC_DRI_03	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
24	17	TR	0	0	1307.000	End	LHA_TR_VAC_DRI_03	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
25	18	TR	0	0	1307.000	Start	LHA_TR_MAG_SOL_02	solenoid	circular	50.000	50.000	
26	19	TR	0	0	1735.500	Middle	LHA_TR_MAG_SOL_02	solenoid	circular	50.000	50.000	
27	20	TR	0	0	2164.000	End	LHA_TR_MAG_SOL_02	solenoid	circular	50.000	50.000	
28	21	TR	0	0	2164.000	Start	LHA_TR_VAC_DRI_04	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
29	22	TR	0	0	2239.000	Middle	LHA_TR_VAC_DRI_04	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
30	23	TR	0	0	2314.000	End	LHA_TR_VAC_DRI_04	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
31	24	LEL	0	0	2314.000	Start	LHA_LEL_HRF_CAV_01	cavity_pillbox	circular	50.000	50.000	
32	25	LEL	0	0	2564.000	Middle	LHA_LEL_HRF_CAV_01	cavity_pillbox	circular	50.000	50.000	
33	26	LEL	0	0	2814.000	End	LHA_LEL_HRF_CAV_01	cavity_pillbox	circular	50.000	50.000	
34	27	LEL	0	0	2814.000	Start	LHA_LEL_VAC_DRI_01	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length
35	28	LEL	0	0	2889.000	Middle	LHA_LEL_VAC_DRI_01	drift	circular	50.000	50.000	Reserved for Gabor Lens physical length

STAGE1INVITRO | STAGE1ABORT | STAGE1INJECTION | STAGE2ABORT | STAGE2RING | STAGE2INVITRO | STAGE2INVIVO

- Model origin position:
  - Centre of the exit plane of the target housing flange

Recommended Baseline Updates

- Addition of a second energy selection collimation
  - Necessary for Stage 2 operation
  - 0.2m downstream of stage 1 collimator (GL3 focal length)
  - Settings to be optimised
- 1st Octupole removed:
  - No discernible impact on bunch distribution
  - Phase space difference at the stage 1 end station (on – off):



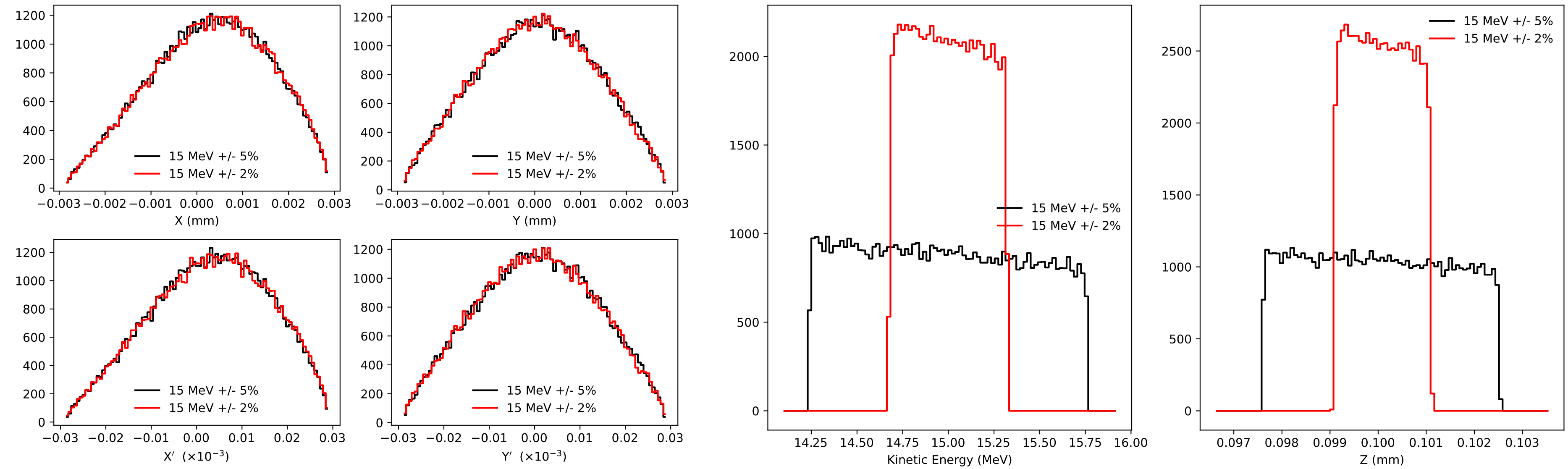
Beam Parameters

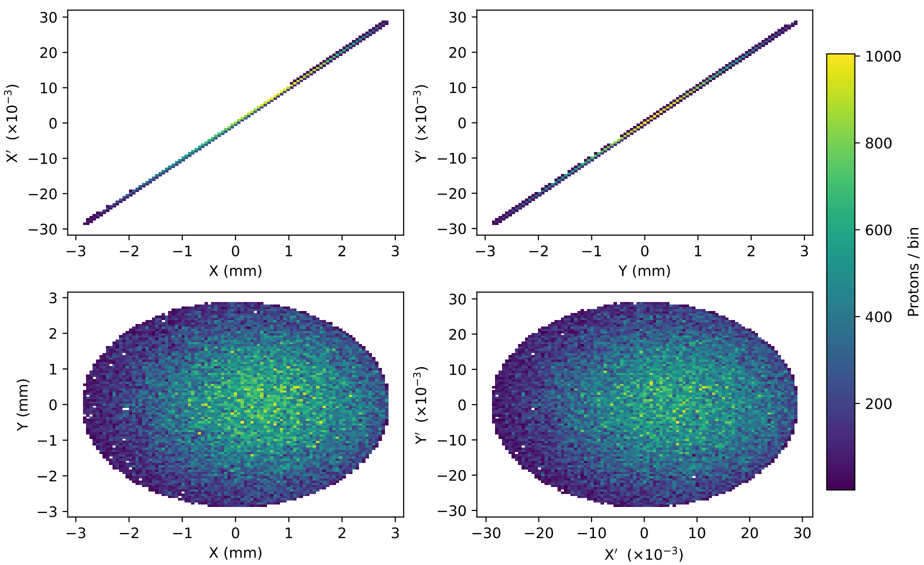
	Smilei Sampled Beam	SCAPA Beam	Pre-CDR Beam
Mean RMS emittance [m]	1.43×10^{-8}	7.98×10^{-8}	3.26×10^{-7}
Mean beta [m]	141.34	21.62	4.89
Mean alpha	-1418.43	-222.23	-50.22

- Large discrepancy between SMILEI sampled beam and assumed pre-CDR emittance
  - Not fully understood. 2D simulations known to suffer from several issues.
  - SMILEI beam not considered reliable

- 3D SCAPA simulation shows improved agreement
  - Down-sample to 15 MeV ± 2%
    - 15 MeV ± 5% for collimation studies

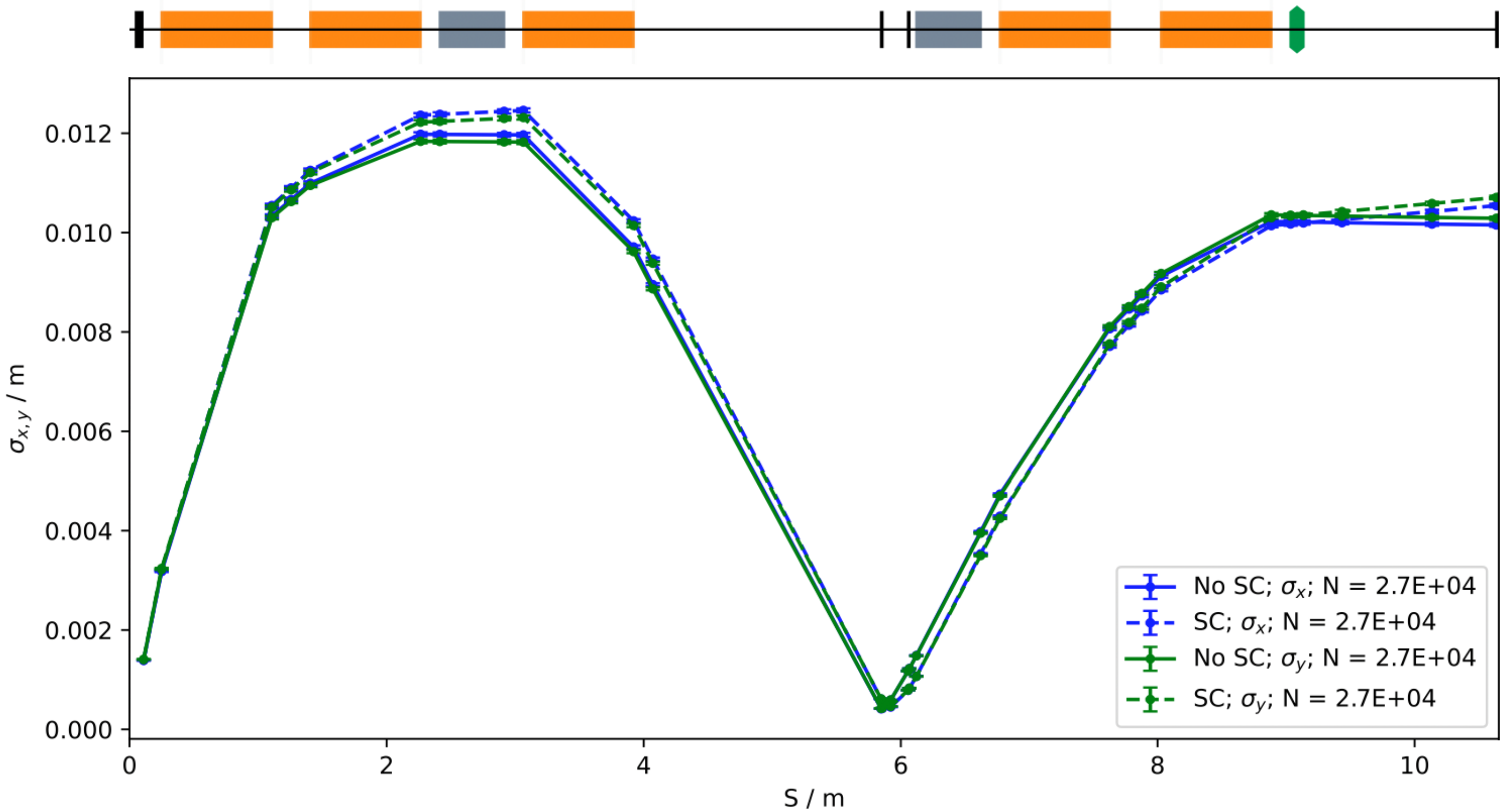
SCAPA Beam Phase Space





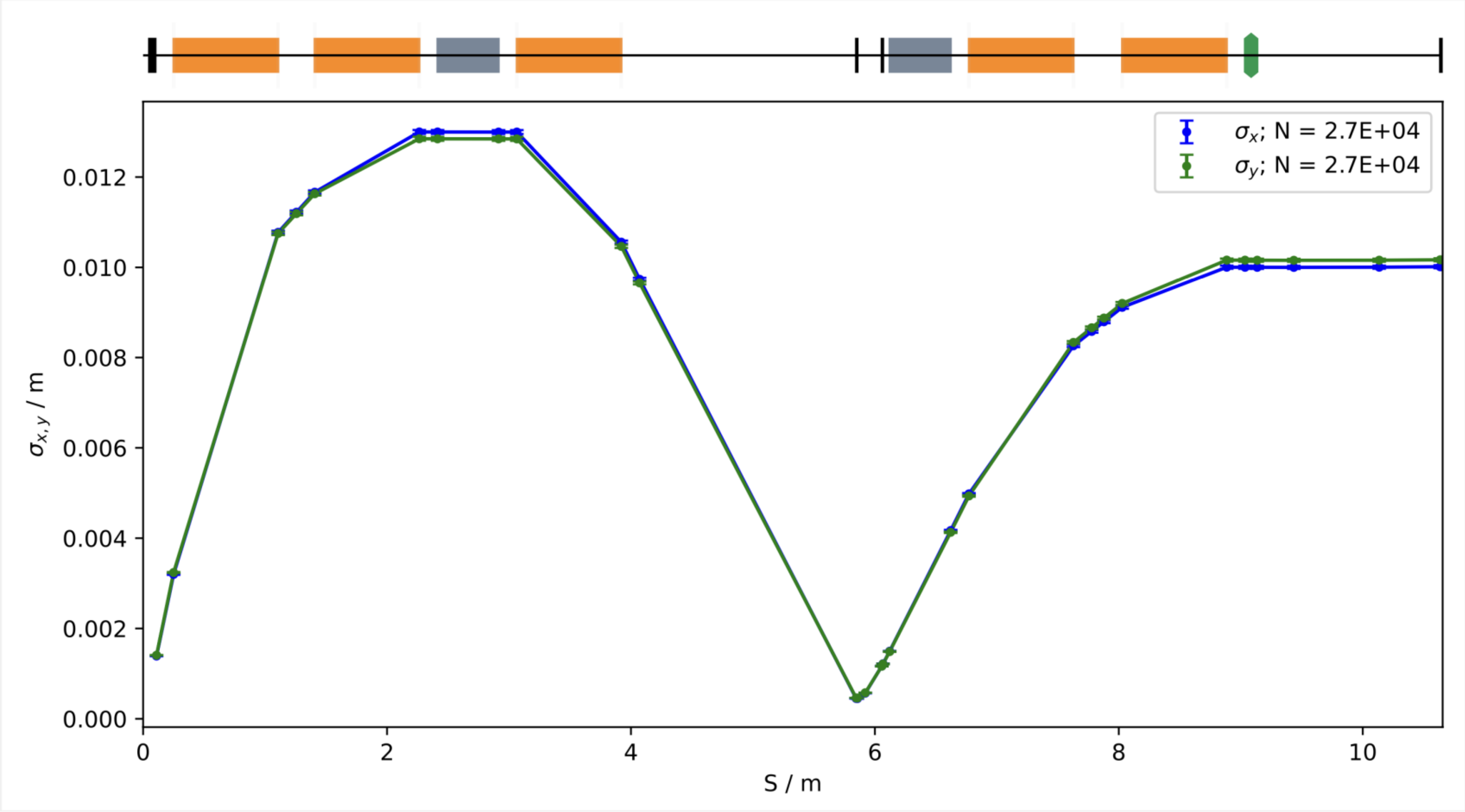
- Vacuum nozzle transmission ~ 77%
- Minimal spectral impact
    - Greater emphasis on downstream collimators performance
- Horizontal offset does not impact tracking performance
- Strong influence of nozzle exit aperture

Stage 1: Space Charge Mitigation



- Requirements:
  - Parallel beam between GL2 & GL3 (flexibility to accommodate RF, shielding wall, …)
  - GL3 focal plane at the stage 1 energy collimator location
  - Parallel beam after GL5

Gabor Lens Strength Optimisation



- Solutions found
- 1.4 T solenoid field limit
- Optimise collimation, octupoles, etc.…

- GPT utility program: GDFSOLVE
  - Solver accounting for space-charge effects

Gabor Lens Strength Optimisation

	Nominal			Optimised		
	Solenoid	Gabor Lens		Solenoid	Gabor Lens	
	Field (T)	e^- Density ($\times 10^{15}$)	Voltage (kV)	Field (T)	e^- Density ($\times 10^{15}$)	Voltage (kV)
GL1	1.438715	5.479	33.018	1.391631	5.126	30.892
GL2	0.527115	0.735	4.432	0.591842	0.927	5.587
GL3	0.813923	1.753	10.567	0.816040	1.763	10.622
GL4	0.728404	1.404	8.463	0.839703	1.866	11.247
GL5	0.633802	1.063	6.407	0.572477	0.867	5.227

- Nominal stage 1 Gabor lens settings optimised
- Additional solutions for smaller spot sizes

Beam radius	9.0 mm	8.0 mm
GL4	1.027919	0.940095
GL5	0.953825	0.489305

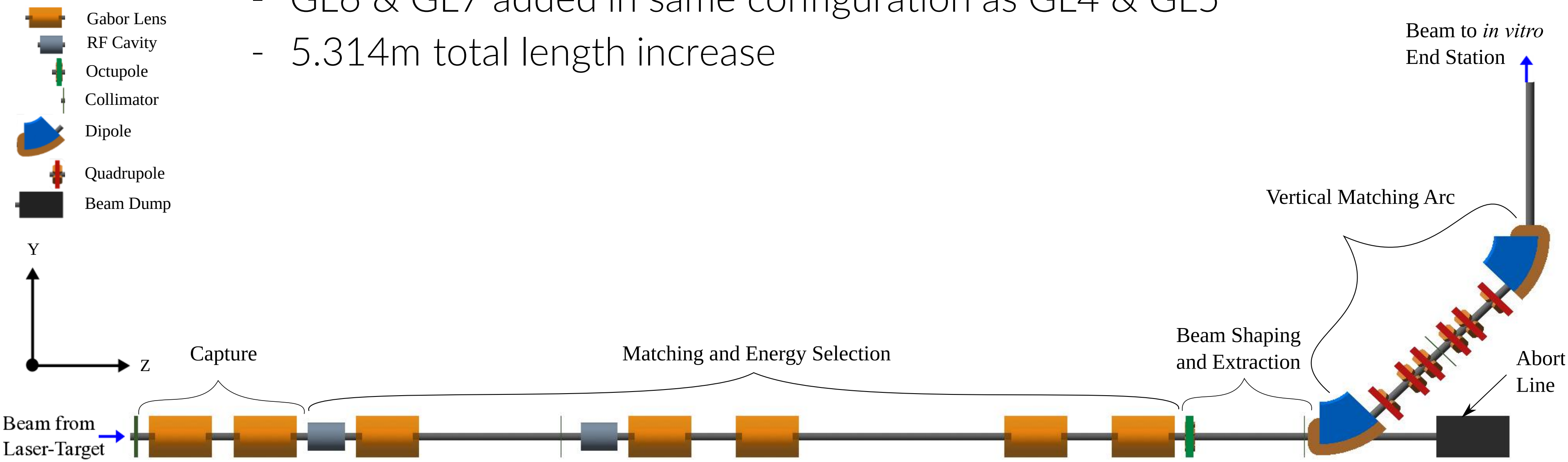
- Difficulties in achieving beam parameters for FFA injection requirements (β = 50m).
    - Challenging without space-charge considerations

7 Gabor Lens Configuration

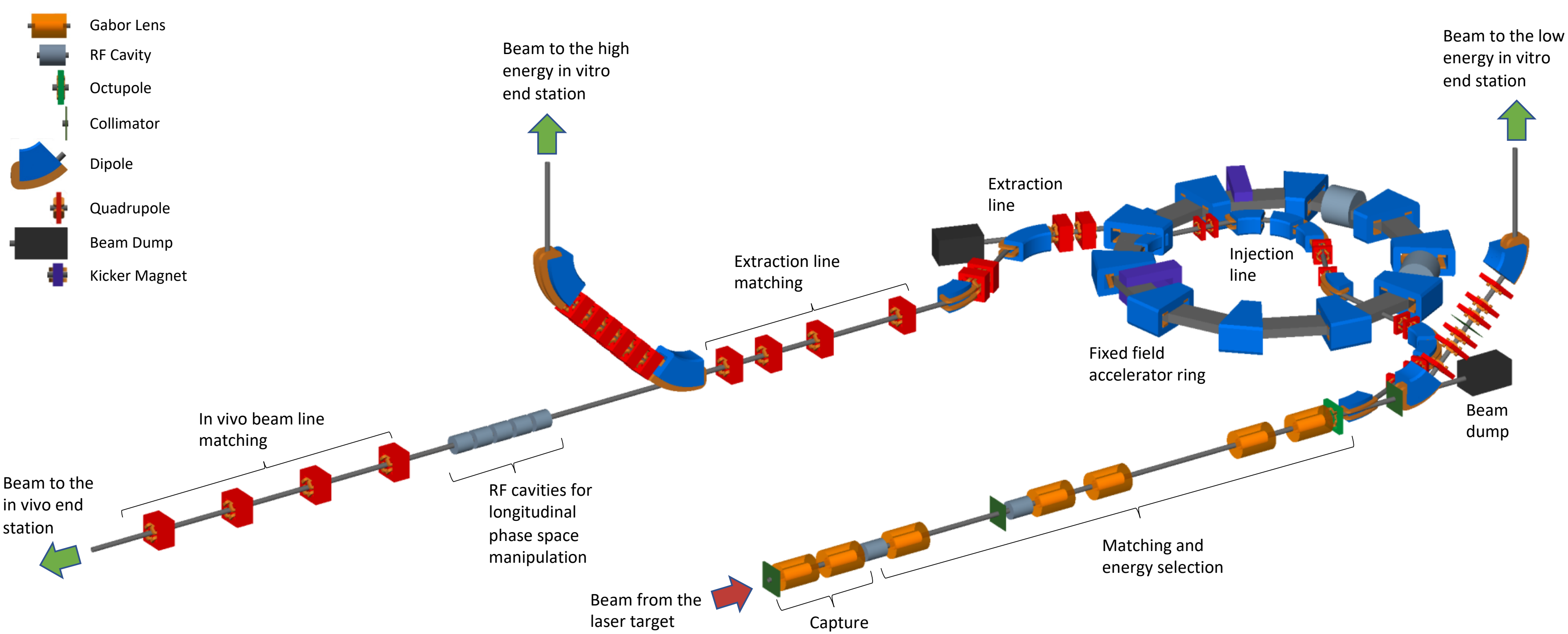
- Investigation of 7 Gabor lens / solenoids configuration

- Single energy collimator

- Geometry modifications:
  - Extra 0.2m between GL4 & GL5
  - 2.5m long drift after GL5
  - GL6 & GL7 added in same configuration as GL4 & GL5
  - 5.314m total length increase



LhARA Schematic



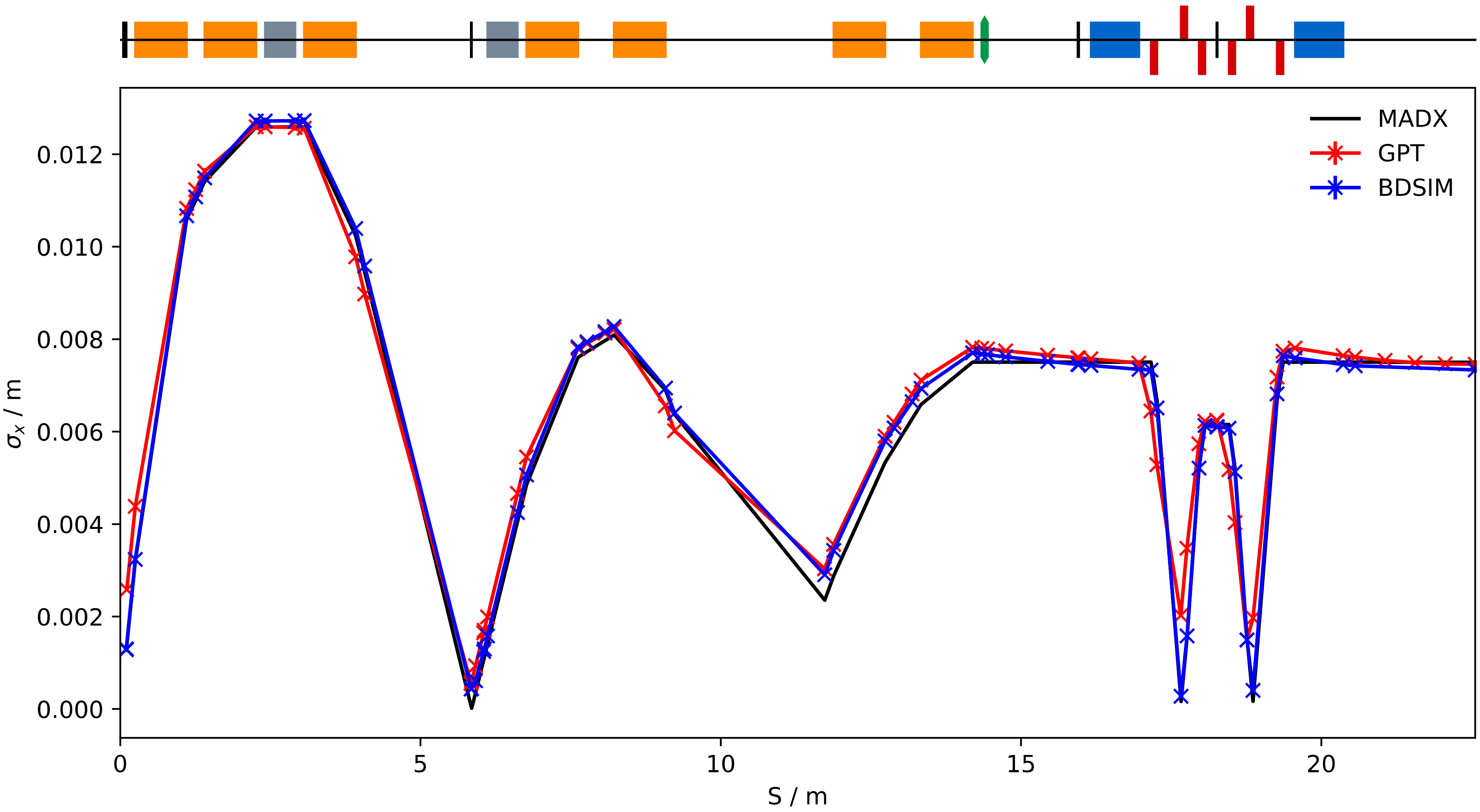
7 Gabor Lens Configuration

- Common settings of GL1-GL3 for all optical solutions
- 6 solutions for spot size flexibility
- 2.0 mm beam meets stage 2 injection line requirements

	Solenoid	Gabor Lens	
	Field (T)	e^- Density ($\times 10^{15}$)	Voltage (kV)
GL1	1.4000	5.188	31.265
GL2	0.5724	0.867	5.226
GL3	0.8139	1.753	10.566

Beta Value (m)	Beam size at the end station (mm)	GL4	GL5	GL6	GL7
704.89	7.5	1.0051	0.9014	0.6994	0.6551
489.51	6.25	1.0051	0.8647	0.7377	0.7106
313.28	5.0	1.0051	0.8247	0.7947	0.7984
176.22	3.75	1.0051	0.7715	0.8040	0.9829
78.32	2.5	0.9060	0.8018	0.2661	1.2793
50.0	2.0	1.1875	0.5833	1.4000	0.3982

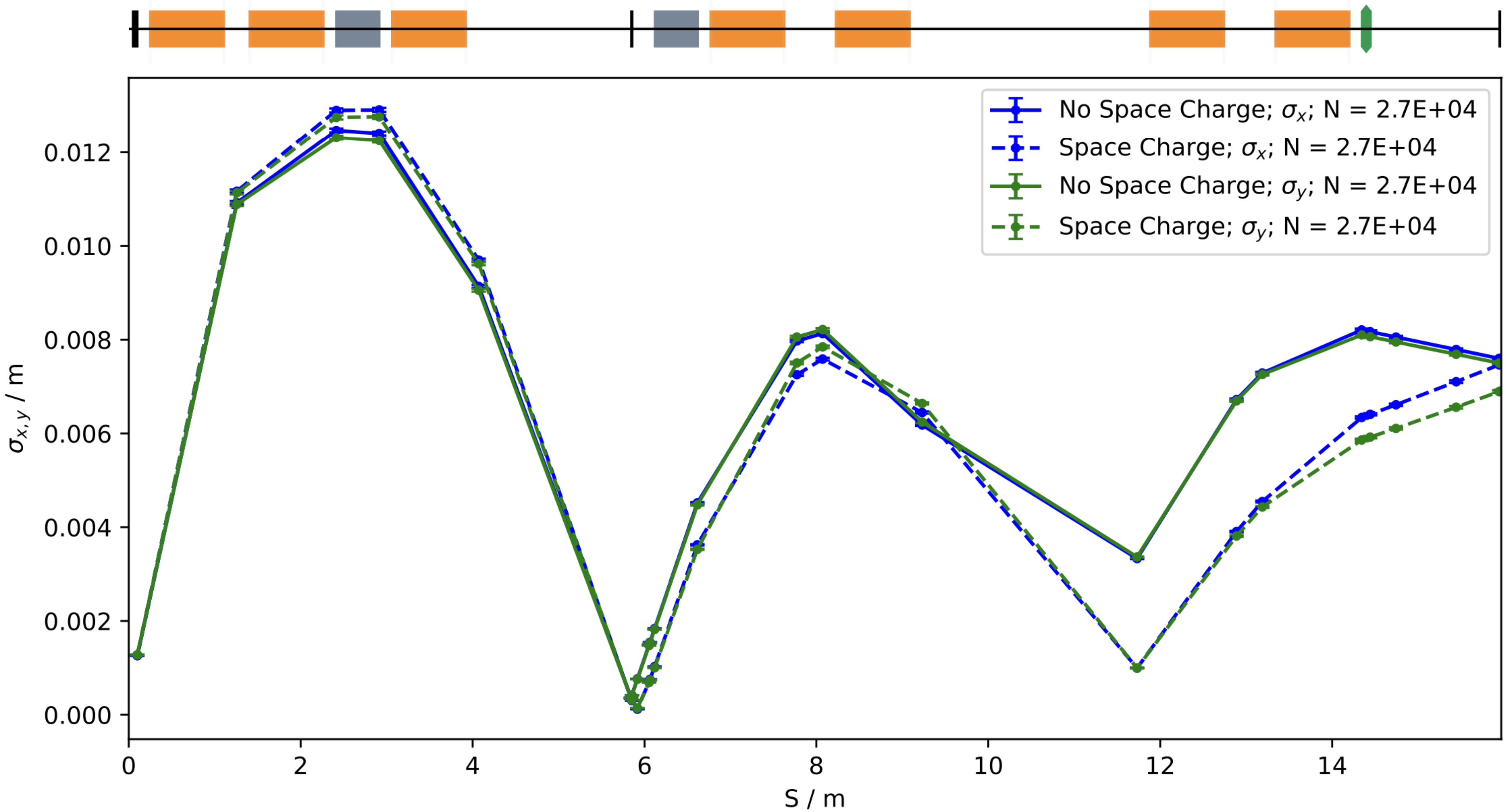
Model Validation (7.5mm Beam)



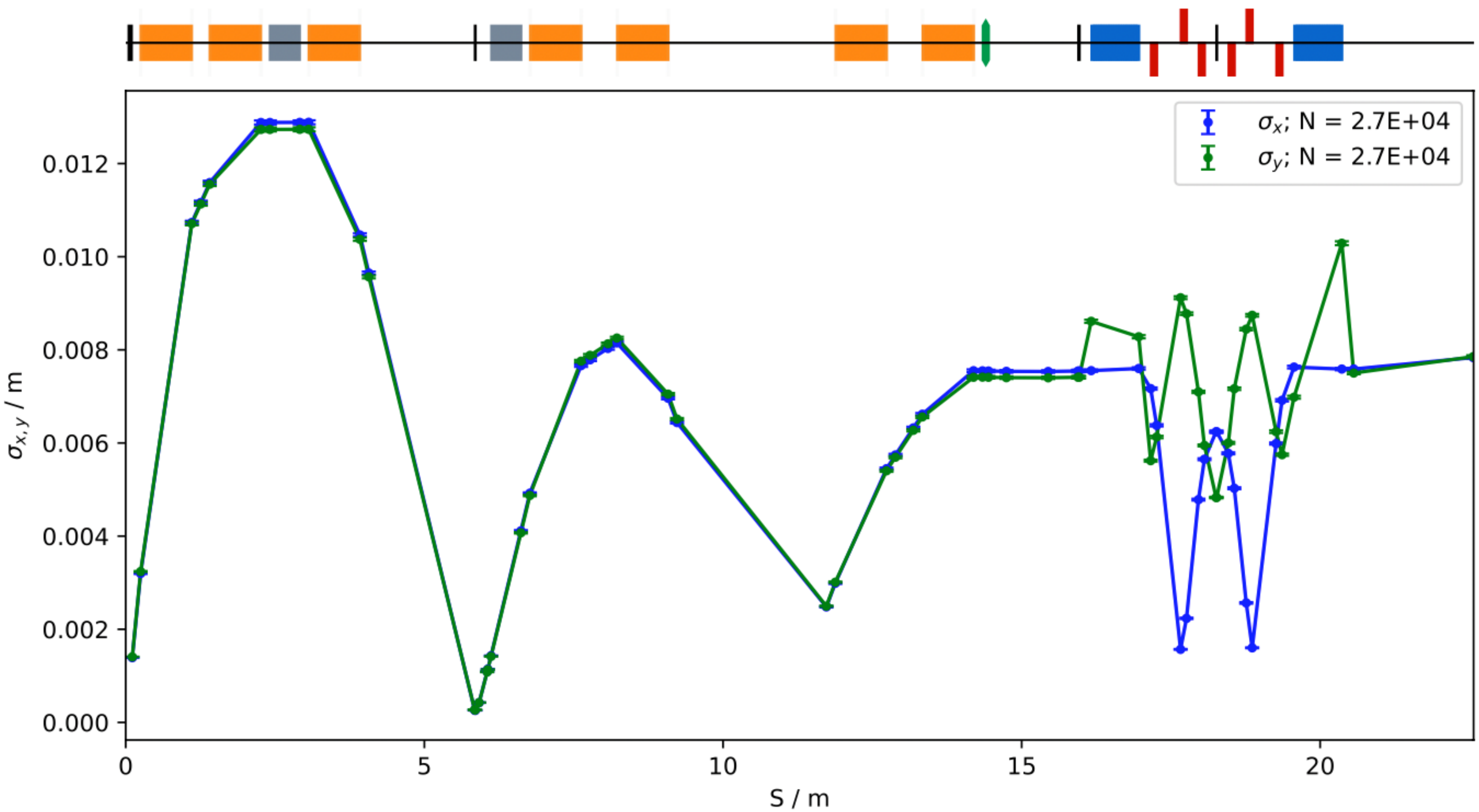
- Non-Gaussian beam
- Beam partially within GPT magnetic fields

Space Charge Modelling

- Space charge impacting performance
  - Same requirements as 5 lens configuration

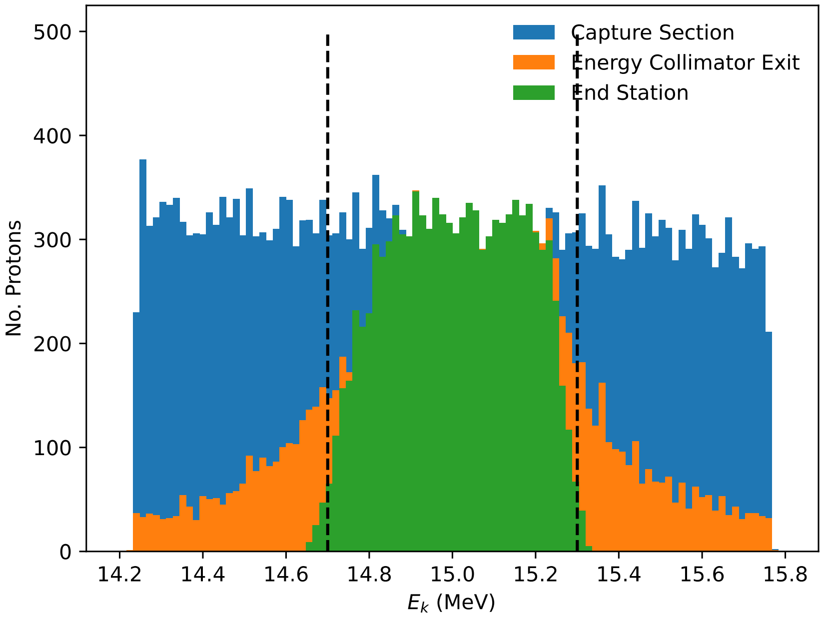


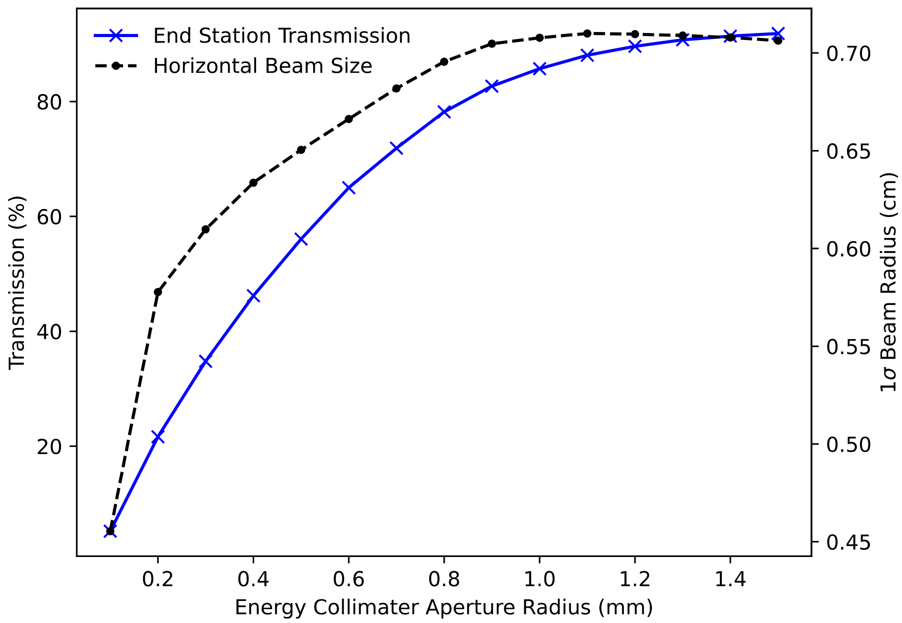
Matching Optimisation



- Optimised solutions for 7.5, 6.25, & 5.0 mm spot size with space charge
- Smaller beams remains focus of ongoing work.

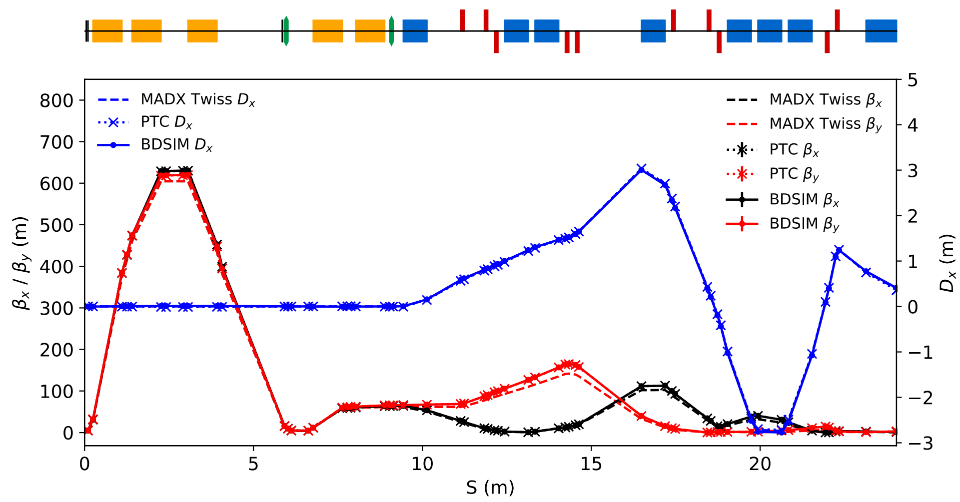
Preliminary Collimator Investigation

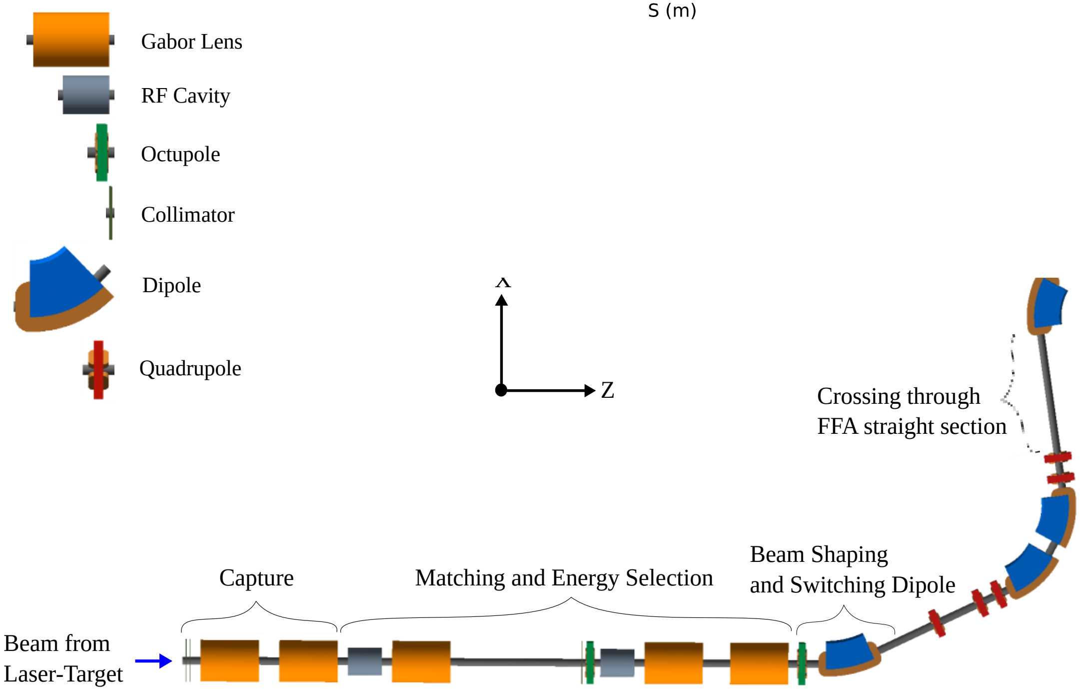




- Beam spectrum reduced to ± 2% spread at the end station
- Modest losses – transmission > ~ 80%
- Further optimisation required.

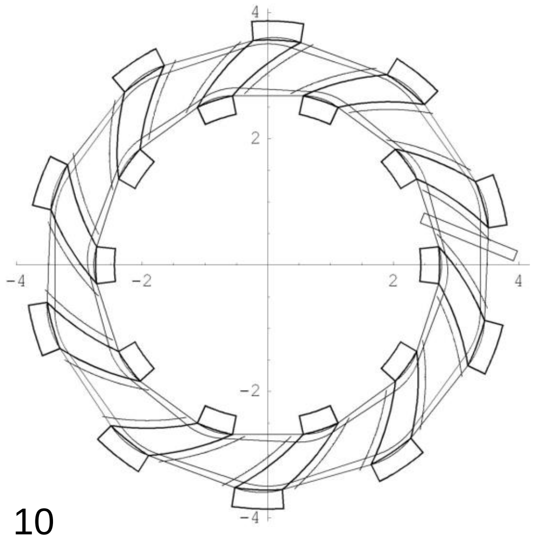
Stage 2: Injection line

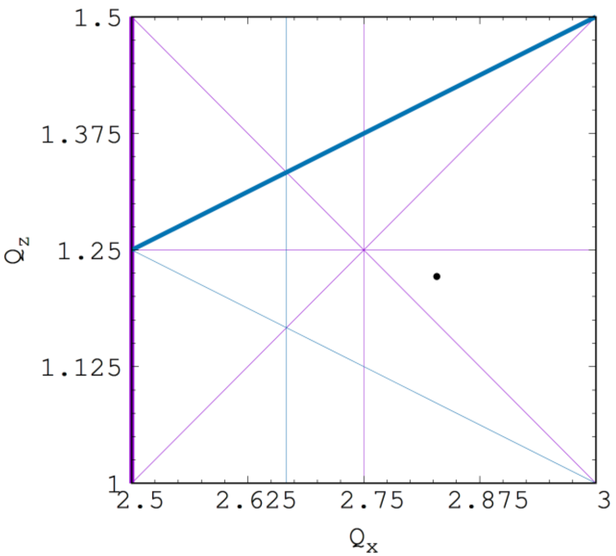


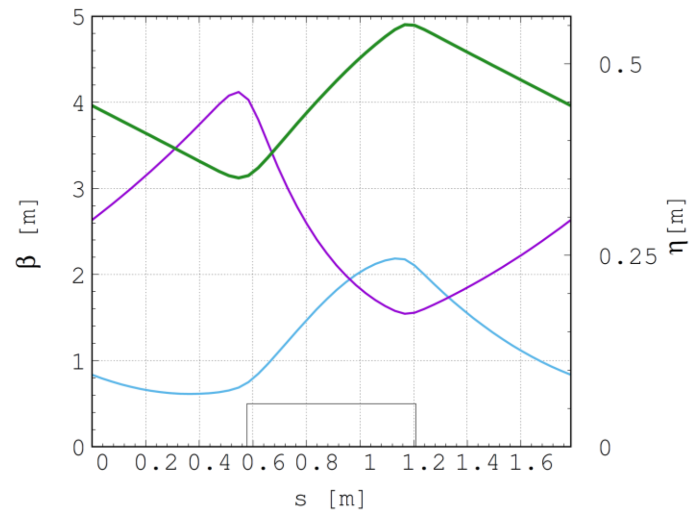


- Excellent agreement between BDSIM and PTC with idealised beam (10k primaries) for the baseline.
- Space charge optimisations required.
- Update needed to incorporate the shielding wall between the Stage 1 room and the FFA room.

LhARA baseline FFA ring parameters



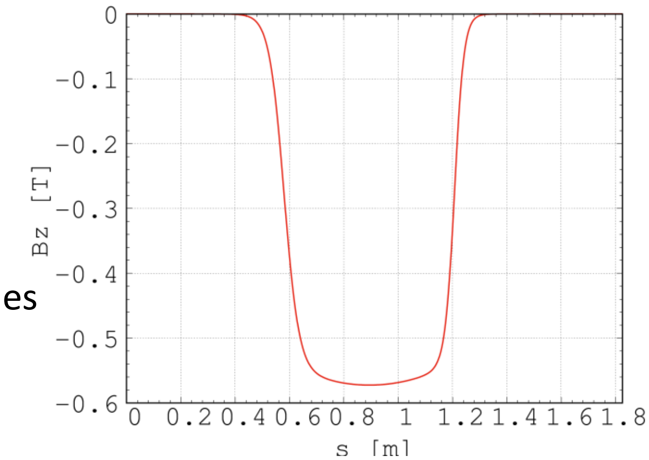




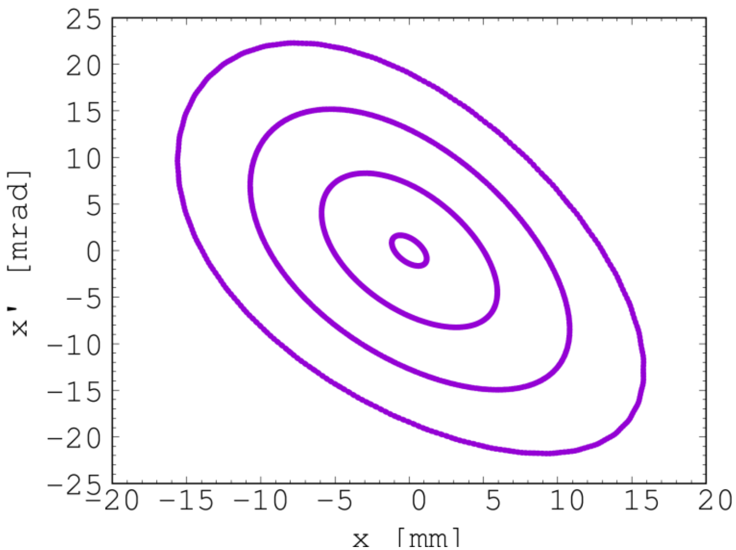
- N 10
- k 5.33
- Spiral angle 48.7°
- R_{max} 3.48 m
- R_{min} 2.92 m
- (Qx, Qy) (2.83, 1.22)
- B_{max} 1.4 T
- p_f 0.34
- Max Proton injection energy 15 MeV
- Max Proton extraction energy 127.4 MeV
- h 1
- RF frequency
  for proton acceleration (15-127.4MeV) 2.89 – 6.48 MHz
- Bunch intensity up to ~10^9 protons
- Range of other extraction energies possible
- Other ions also possible

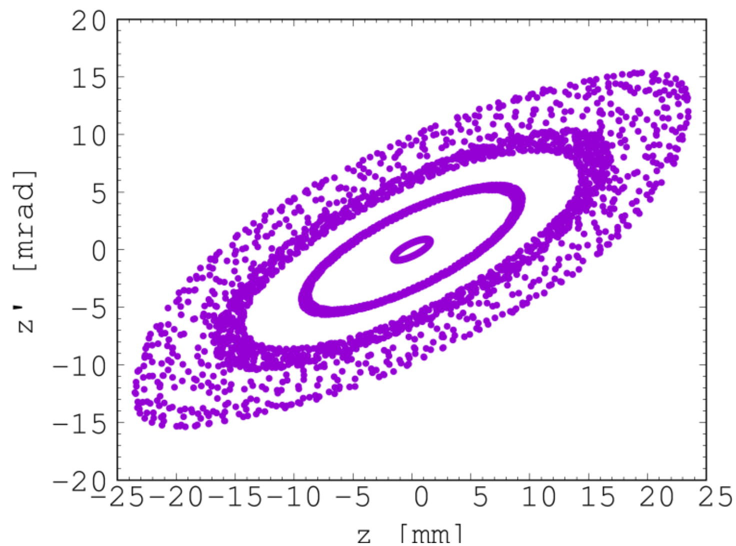
LhARA FFA ring tracking

LhARA Ring Tracking



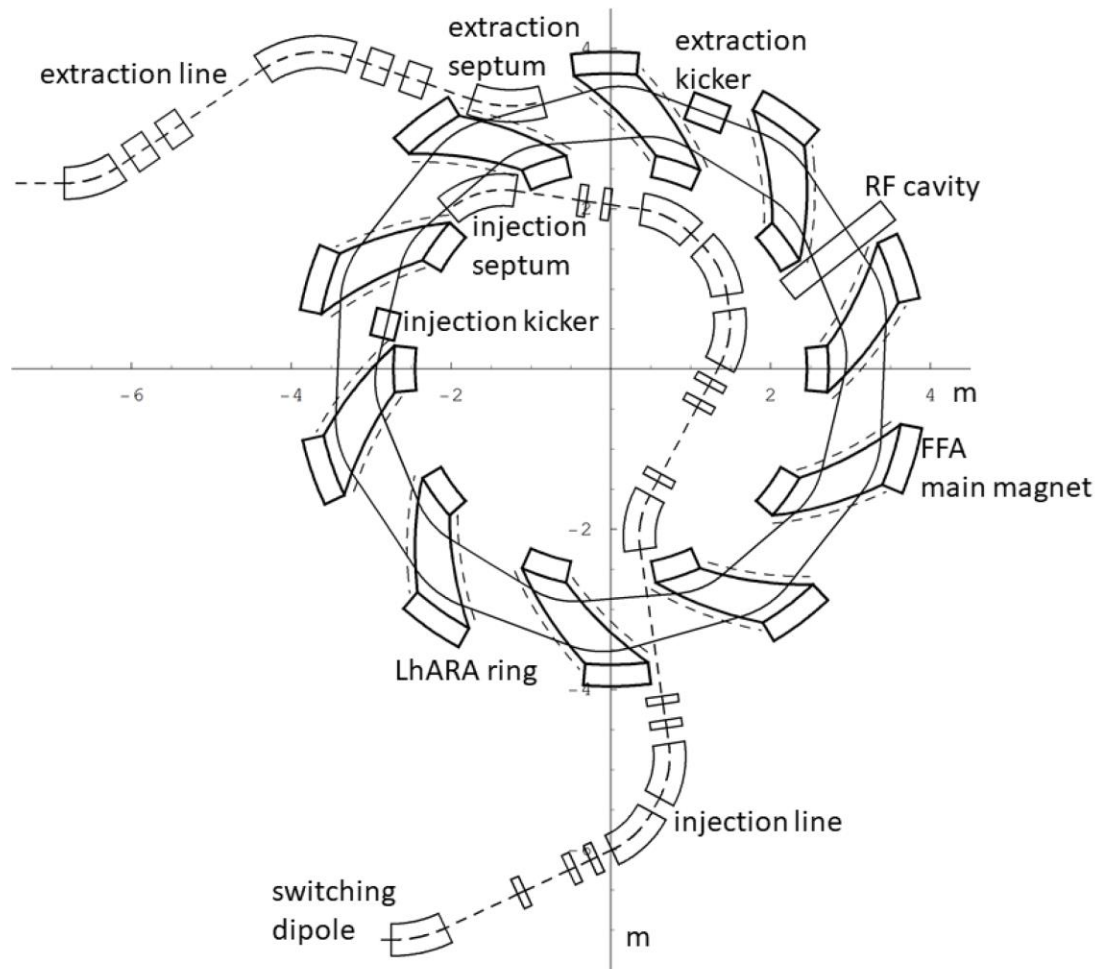
- Performed using proven stepwise tracking code
- It takes into account fringe fields and non-linear field components
- Results show dynamical acceptances are much larger than physical ones
- No space charge effects included yet
- Tracking performed using FixField code





FFA Ring subsystems

Parameter	unit	value
Injection septum:		
nominal magnetic field	T	0.53
magnetic length	m	0.9
deflection angle	degrees	48.7
thickness	cm	1
full gap	cm	3
pulsing rate	Hz	10
Extraction septum:		
nominal magnetic field	T	1.12
magnetic length	m	0.9
deflection angle	degrees	34.38
thickness	cm	1
full gap	cm	2
pulsing rate	Hz	10
Injection kicker:		
magnetic length	m	0.42
magnetic field at the flat top	T	0.05
deflection angle	mrad	37.4
fall time	ns	320
flat top duration	ns	25
full gap	cm	3
Extraction kicker:		
magnetic length	m	0.65
magnetic field at the flat top	T	0.05
deflection angle	mrad	19.3
rise time	ns	110
flat top duration	ns	40
full gap	cm	2



Ongoing & Next Steps

- Vlasov solver for co-propagating beams
- Continued optimisation for spot size flexibility
- Collimator & octupole settings
- RF cavity performance
- Wien filter for particle selection
- Alternative lattices (quadrupoles)
- FFA tunability
- Injection line redesign
- Stage 2 beam transport optimisation
- RF & FFA magnet conceptual designs

Summary

- Last 6 months saw a very significant progress in Stage 1 studies
  - Development of the components naming scheme and BDSIM/CAD interface
  - In understanding the input beam properties
    - Still more studies needed, especially to include effects from the electron distribution
  - Space charge optimisation with GPT
    - Verification with a different code in progress
  - Development of the flexible optics with a new baseline candidate
- Stage 2 has a solid baseline, but further updates are required
  - Foundations for the FFA magnet and RF cavity conceptual designs has been established