Stage 1 and Stage 2 vision

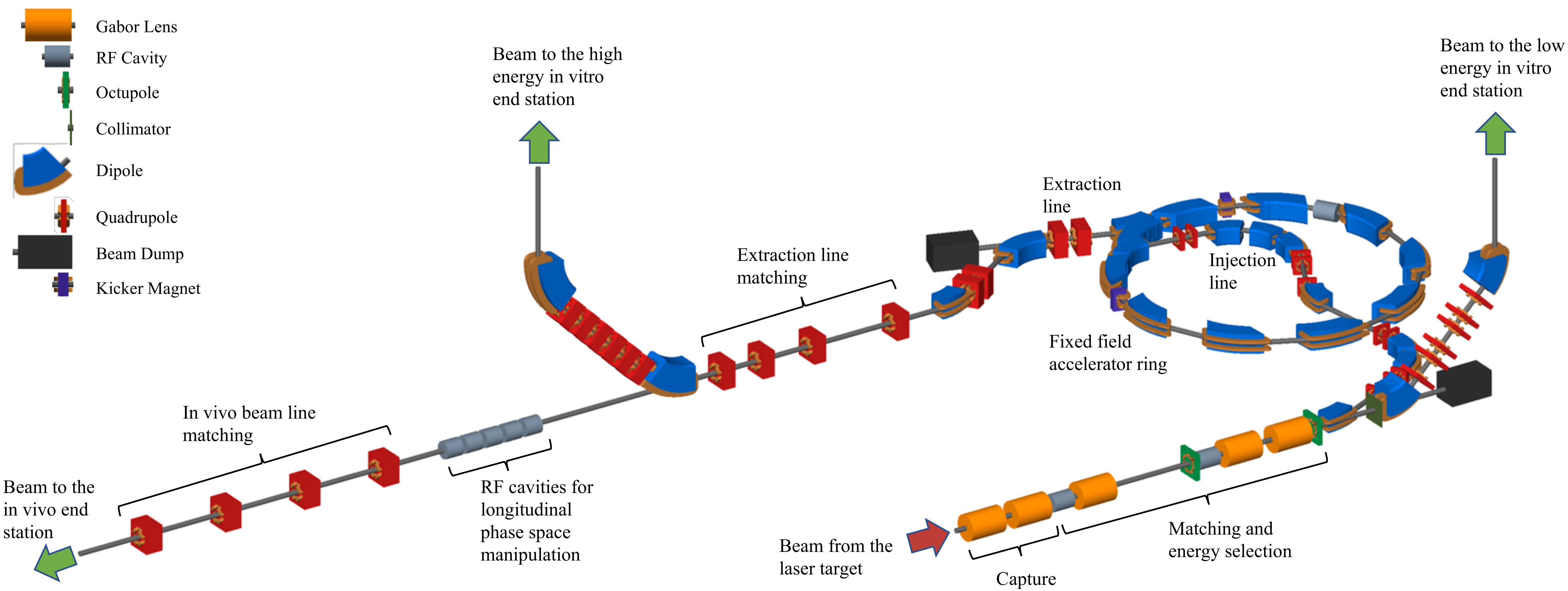
J. Pasternak

27/10/2022, LhARA Review

Outline

- Introduction
- LhARA baseline, Stage I
- LhARA baseline, Stage II
- Conclusions

LhARA Layout

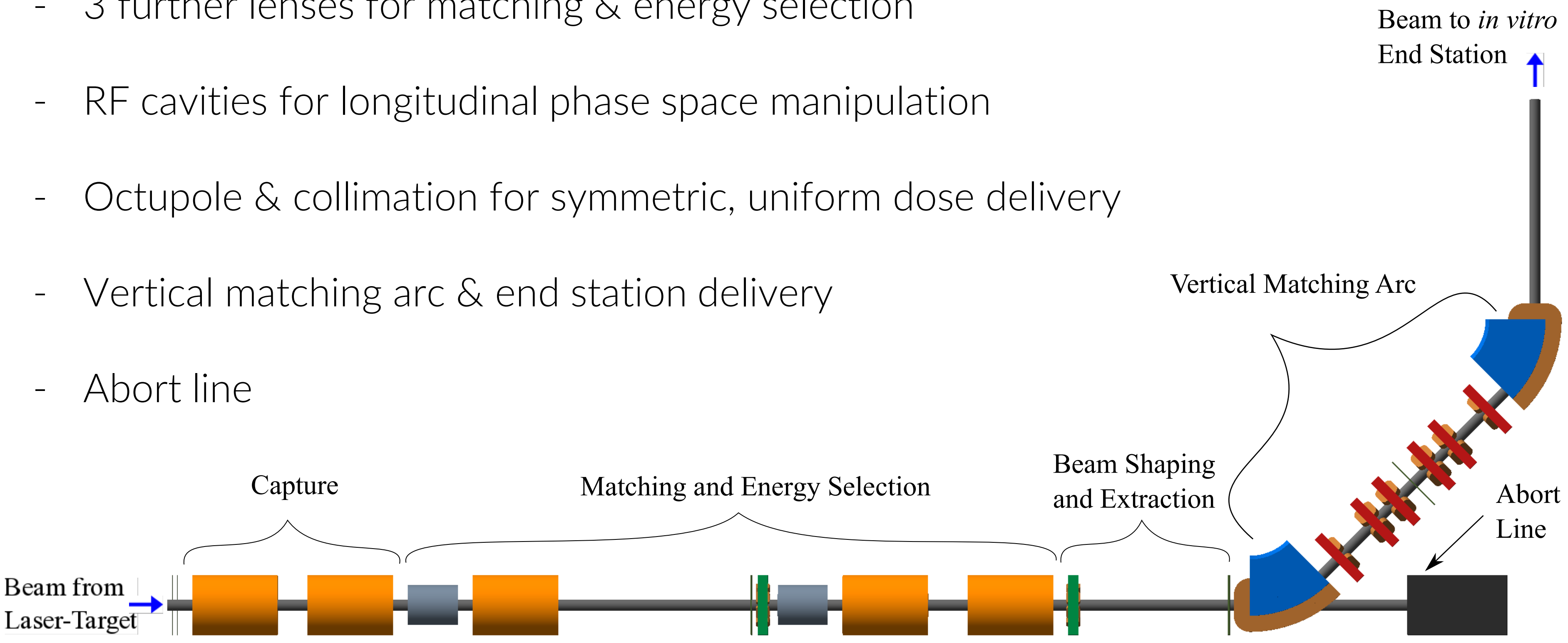


Full pre-CDR Technical Note:
https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Communication/Notes/CCAP-TN-01.pdf

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 for point to parallel optics
- 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

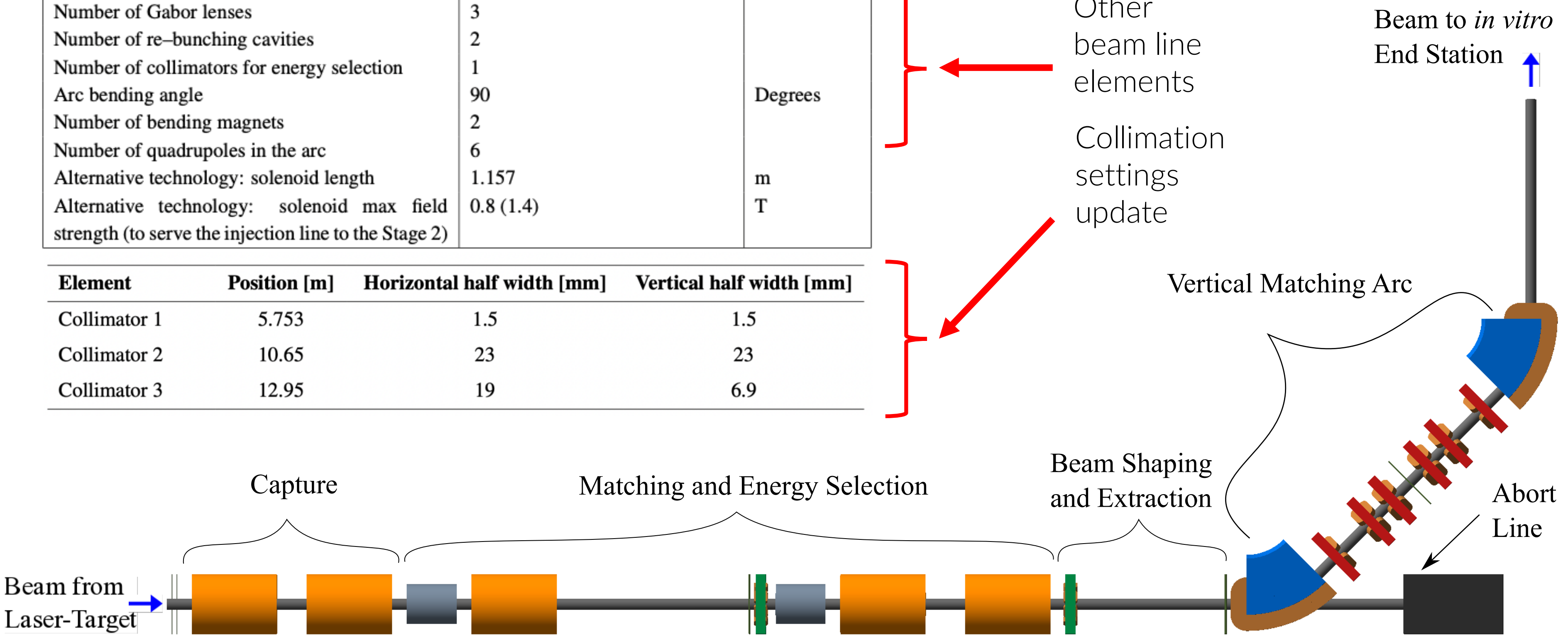
Alternative: solenoids

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

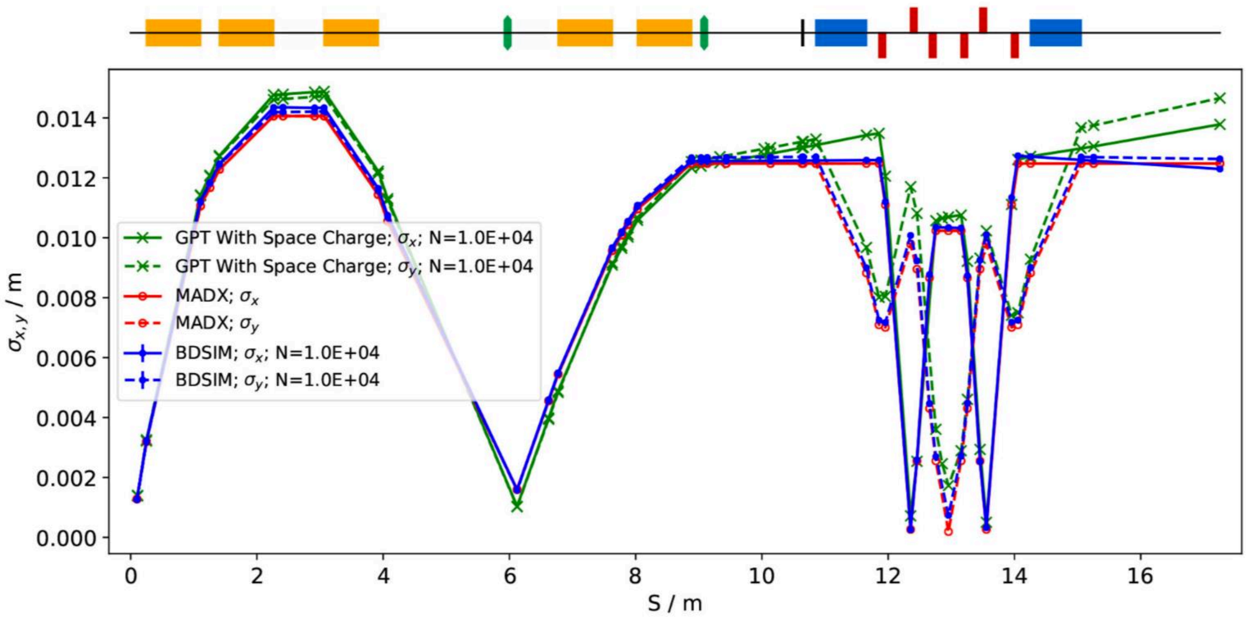


Particle Tracking

- 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
- 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 Delivery Simulation

General Particle Tracer (GPT)

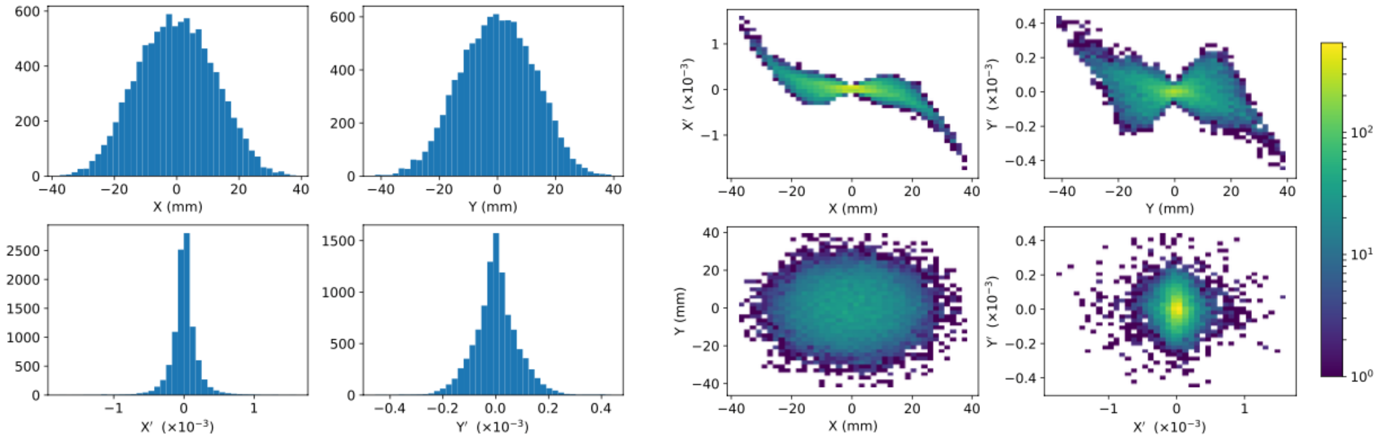


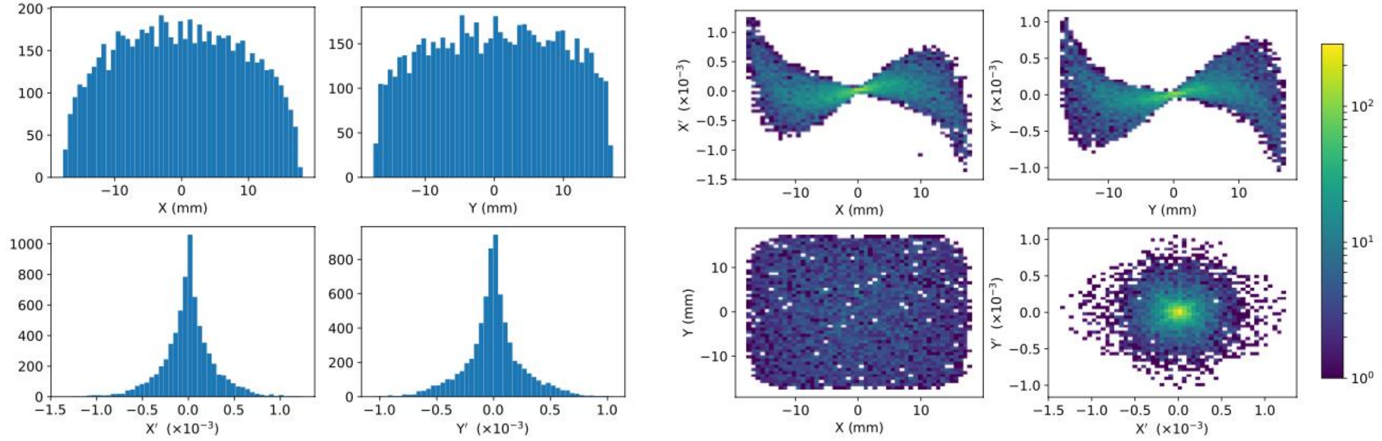
Beam Phase Space

- Phase space aberration arises in Gabor lenses / solenoids

- Octupoles & collimation improves beam uniformity

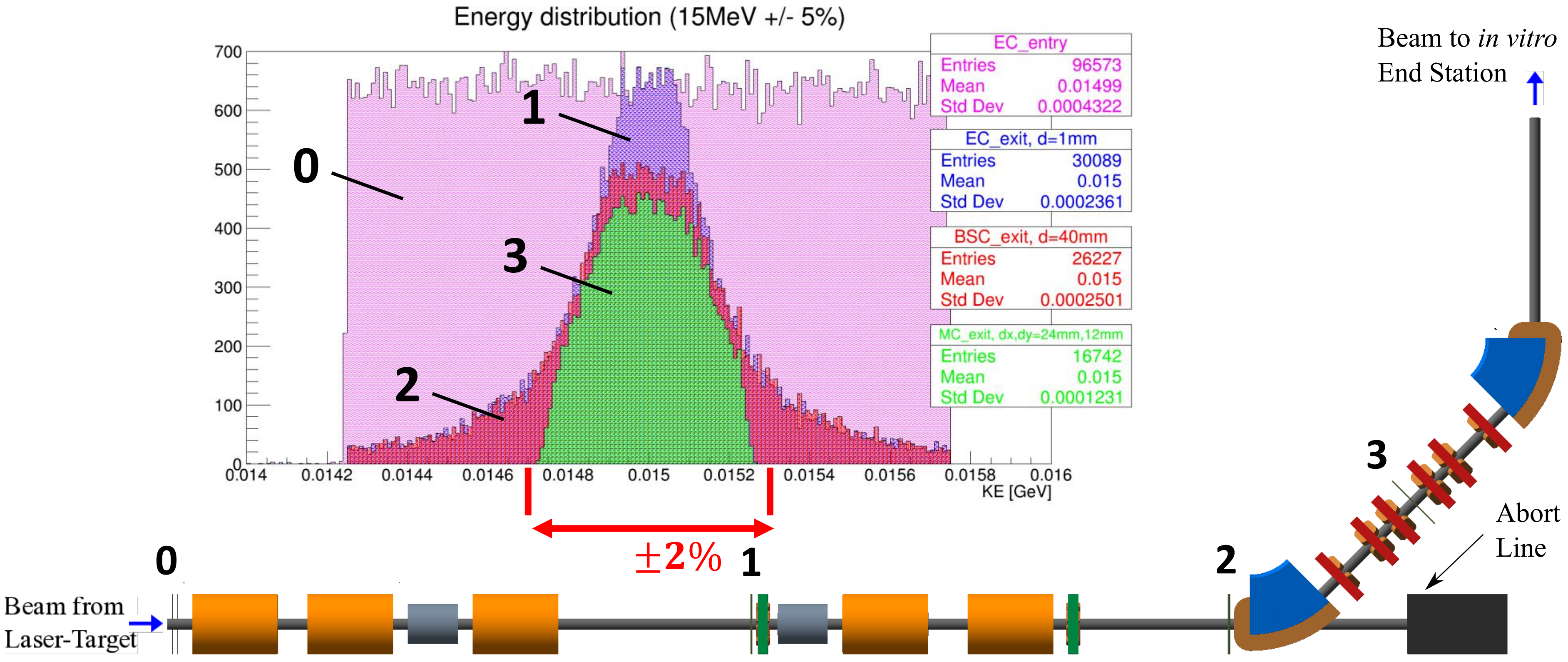
- Reduction in transmission.





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

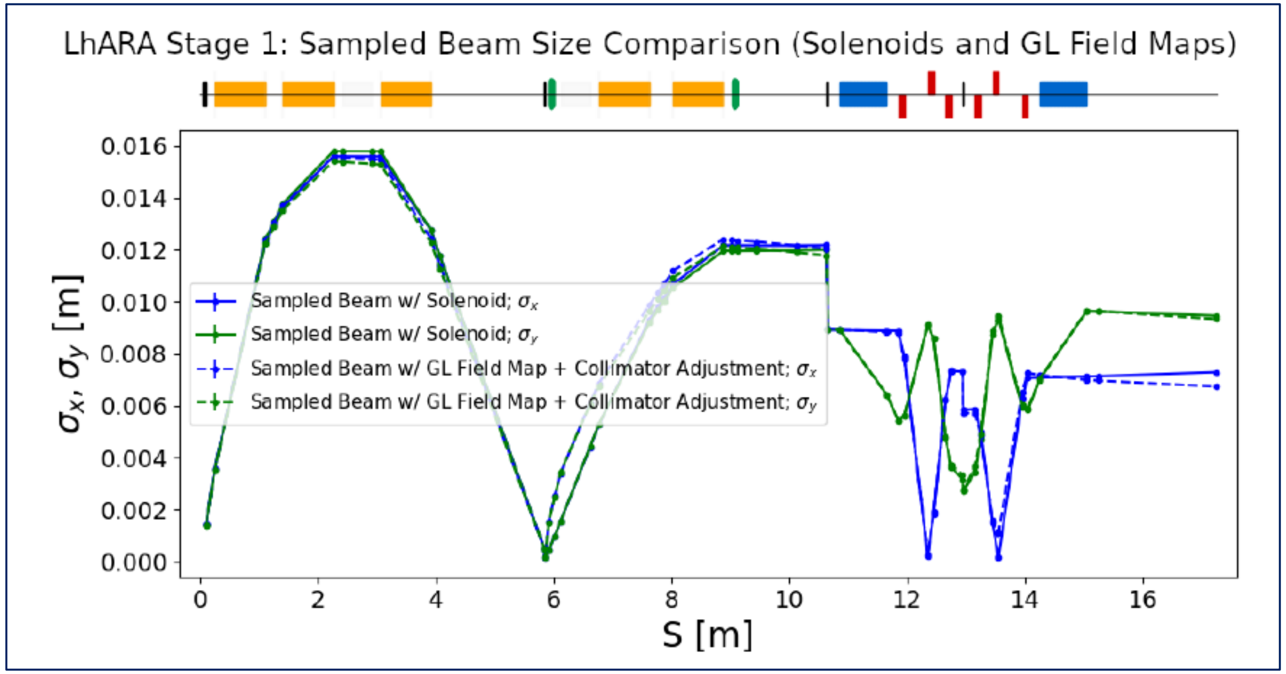


Design Updates

- 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

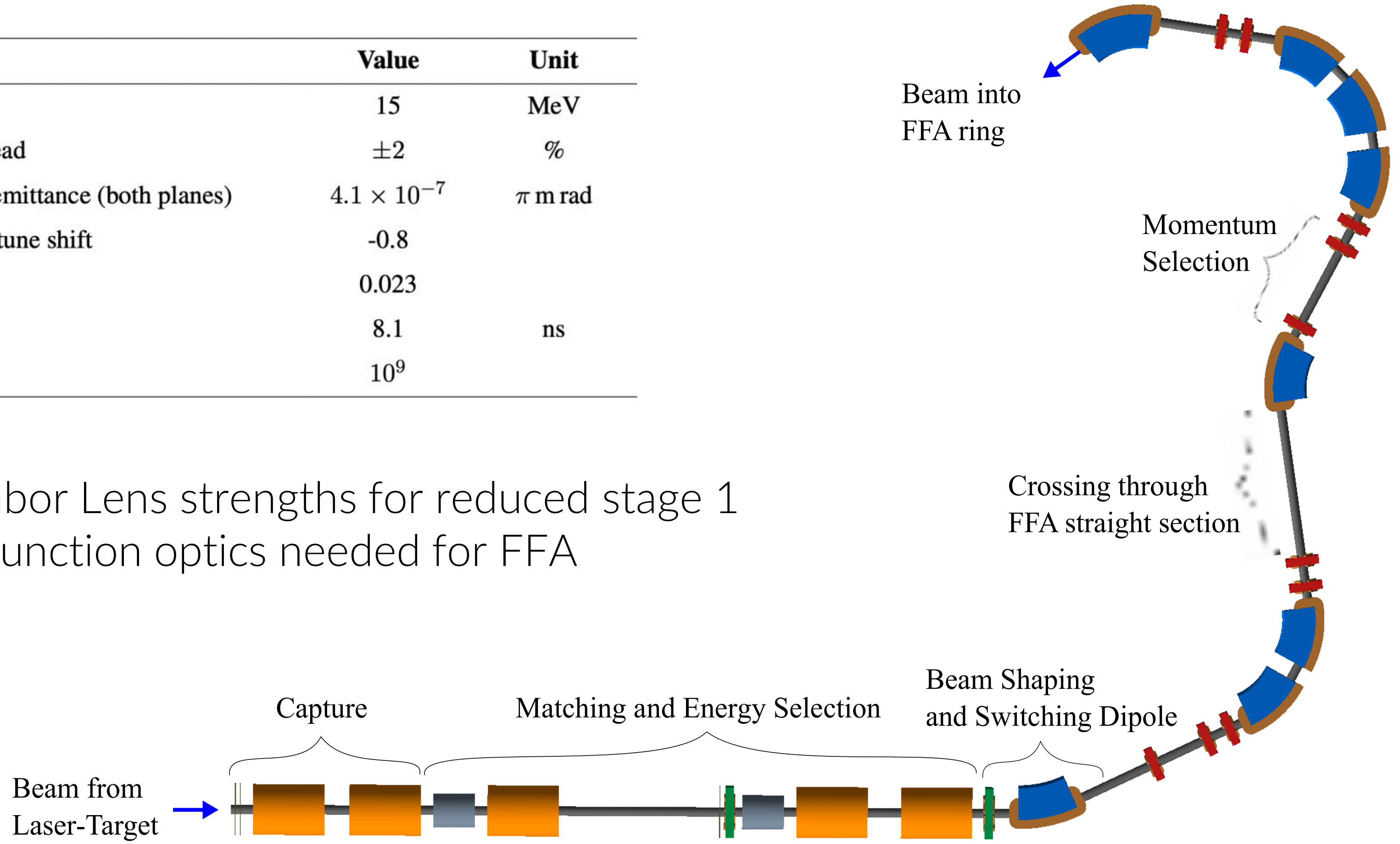


Stage 2:Injection Line

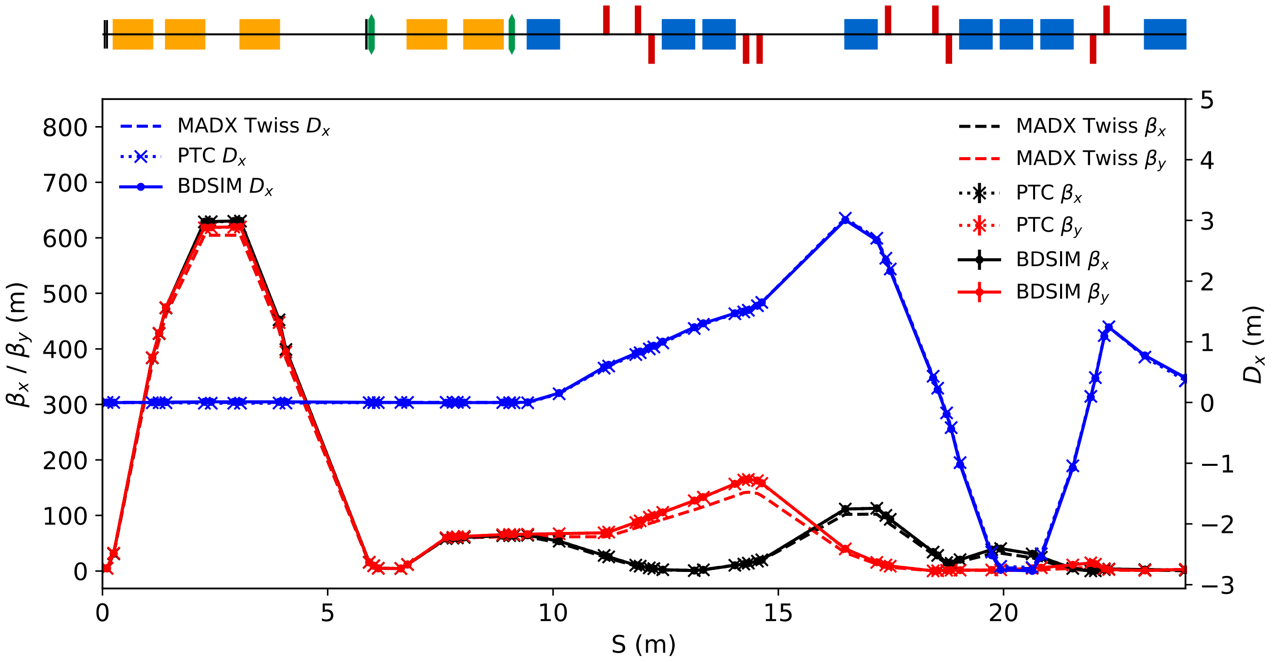
Parameter	Value or range	Unit
Injection line		
Number of bending magnets in the injection line	7	
Number of quadrupoles in the injection line	10	

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

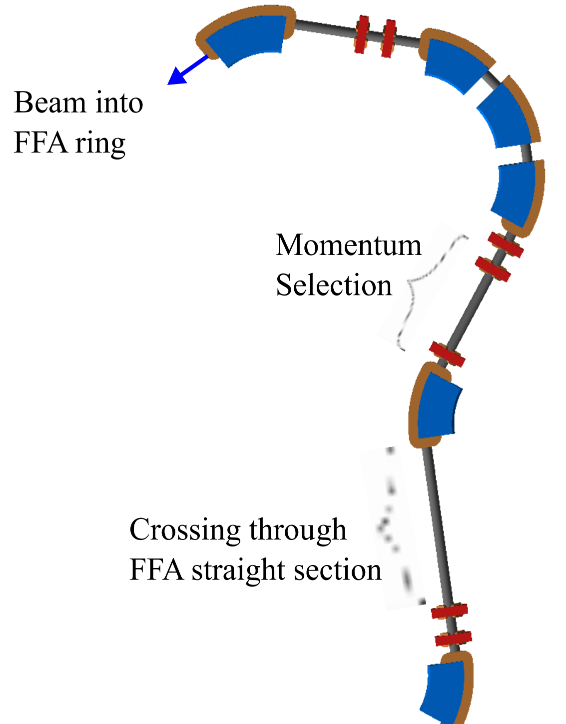


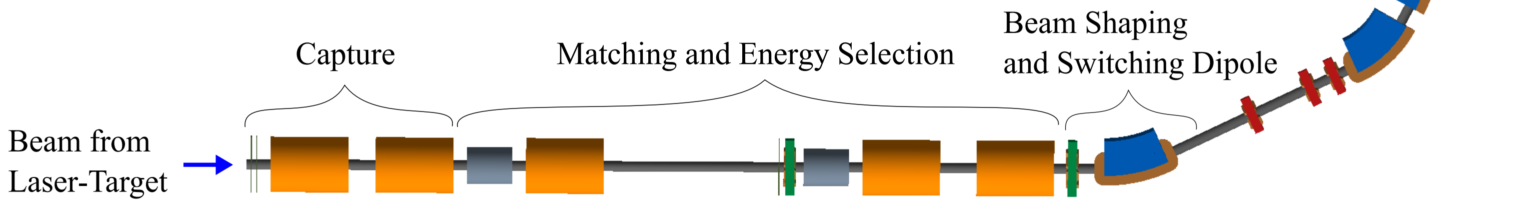
Stage 2:Injection Line



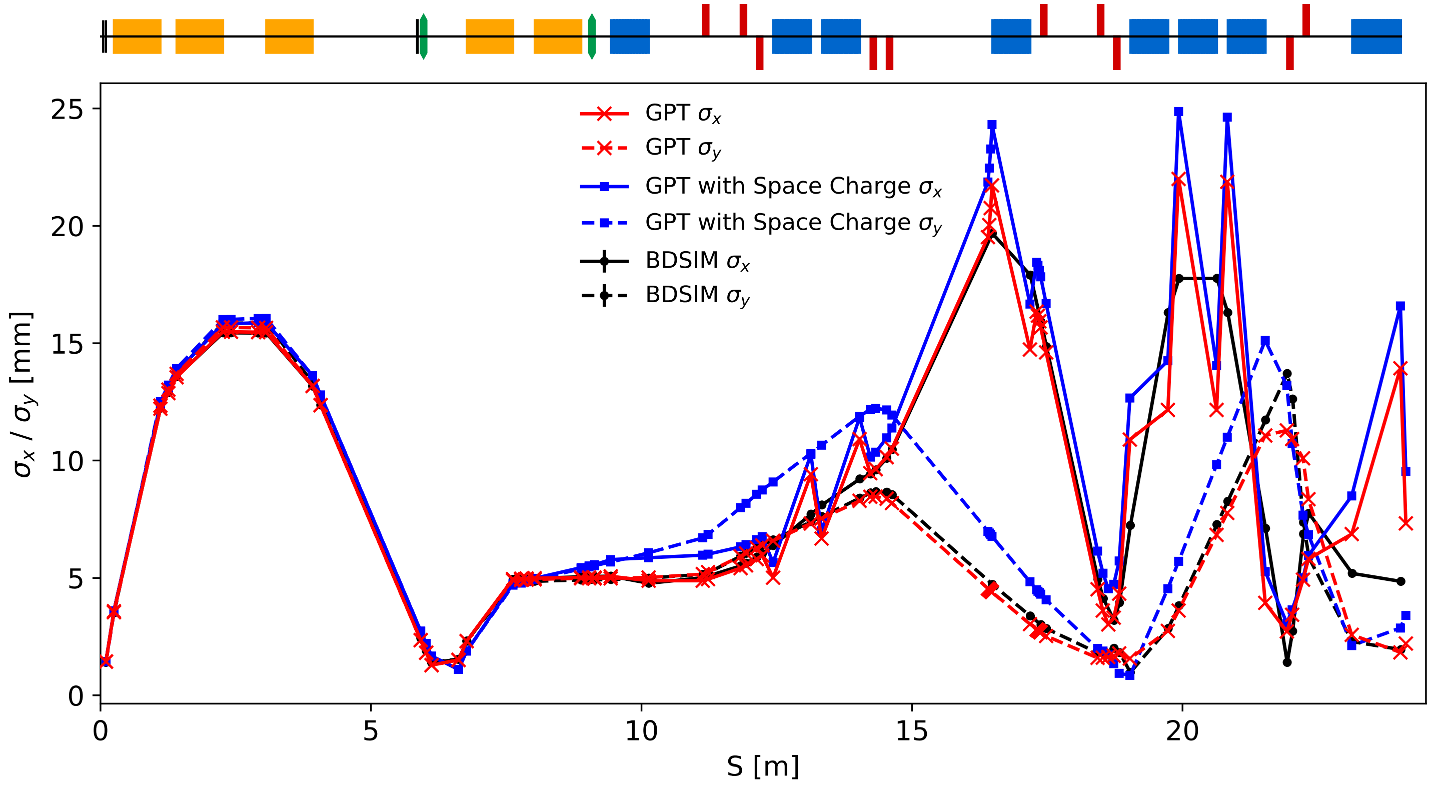
- Excellent agreement between BDSIM and PTC with idealised beam (10k primaries).

- 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 post-accelerator

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	

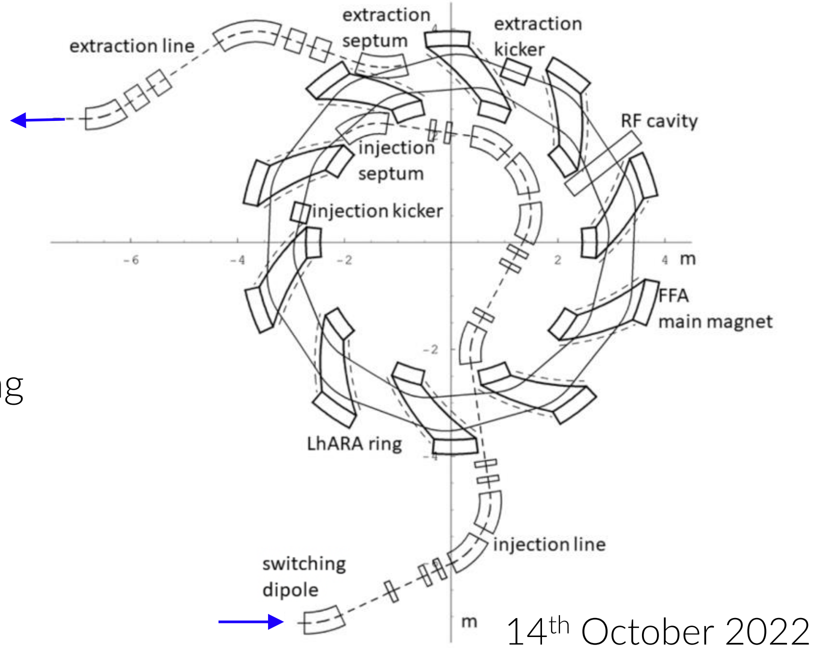
- FixField simulations show good performance
  - Non-linearities, fringe fields
  - No space charge

- Simulate FFA design in OPAL for space charge modelling

- 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

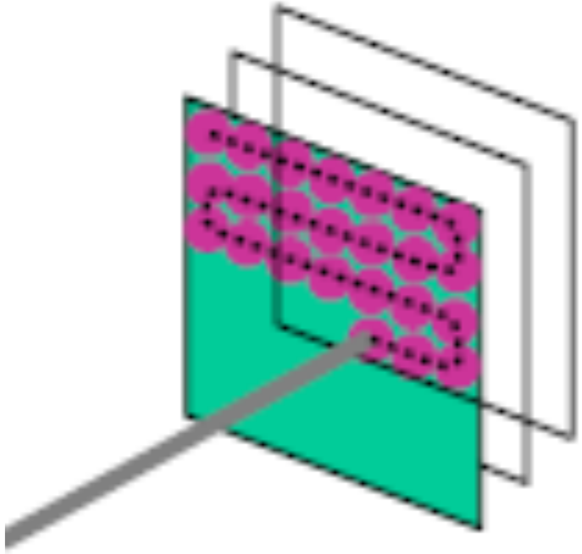


14th October 2022

Motivations for a Medical/Radiobiological FFA (Fixed Field Accelerator)

Advantages of FFA for medical/radiobiological applications:

- High/variable dose delivery (high rep rate – 10-100 Hz)
- Variable energy operation without enegy degraders
- Compact size and low cost ->less RF power, cheaper and simpler magnet power supplies than an equivalent RCS
- Simple and efficient extraction, similar to RCS
- Stable and easy operation, more stable than RCS
- Multiple extraction ports (optionlal)
- Bunch to Pixel active scanning possible, but slower extraction may be also possible
- Multiple ion capability

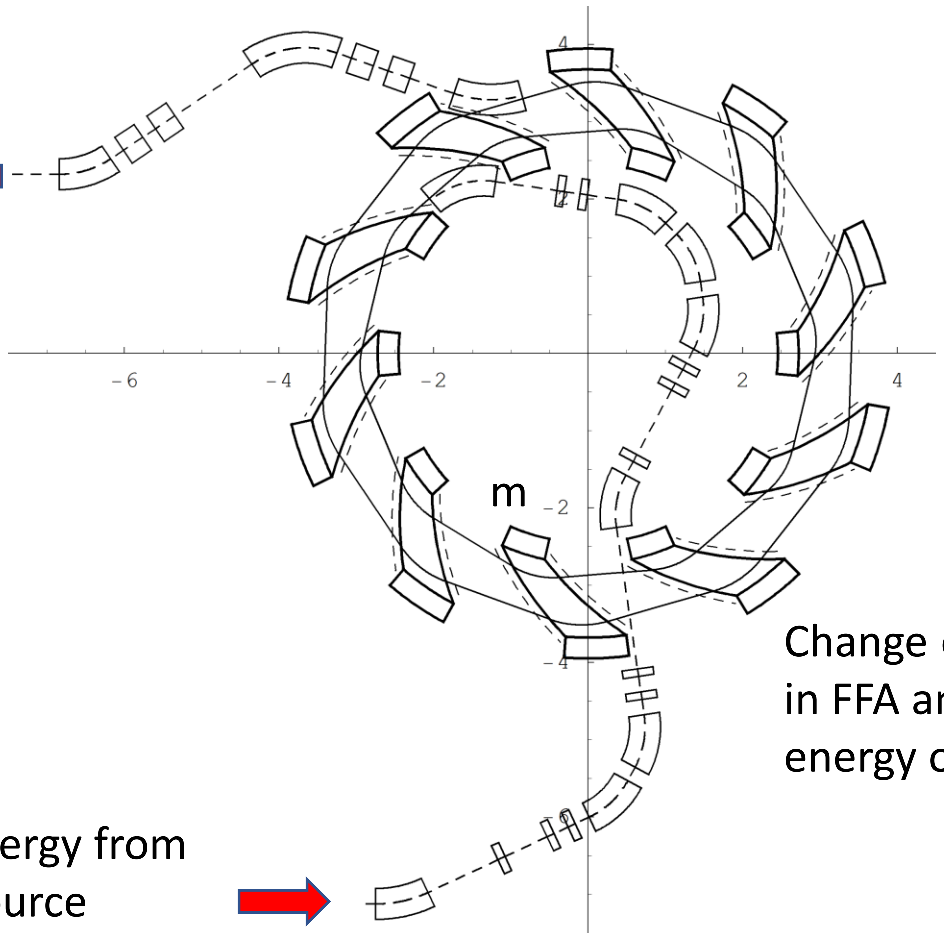


Energy Variability using Laser Accelerated Ions

Variable extraction energy from FFA within 1 s (20-125 MeV) at fixed geometry

+

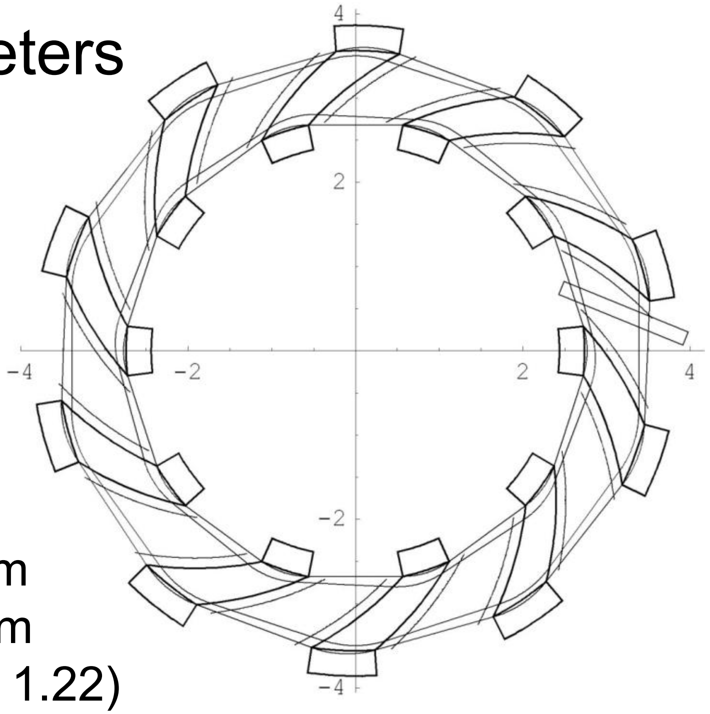
pulse by pulse variation with kicker could be implemented

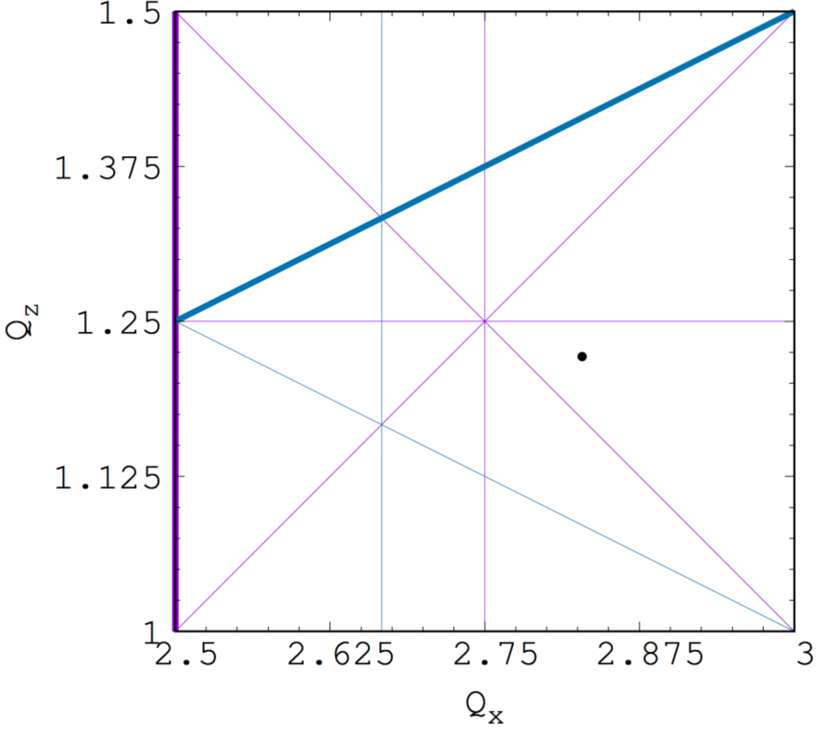


Change of the value of magnetic field in FFA and transfer lines for a specific energy operation (laminated magnets)

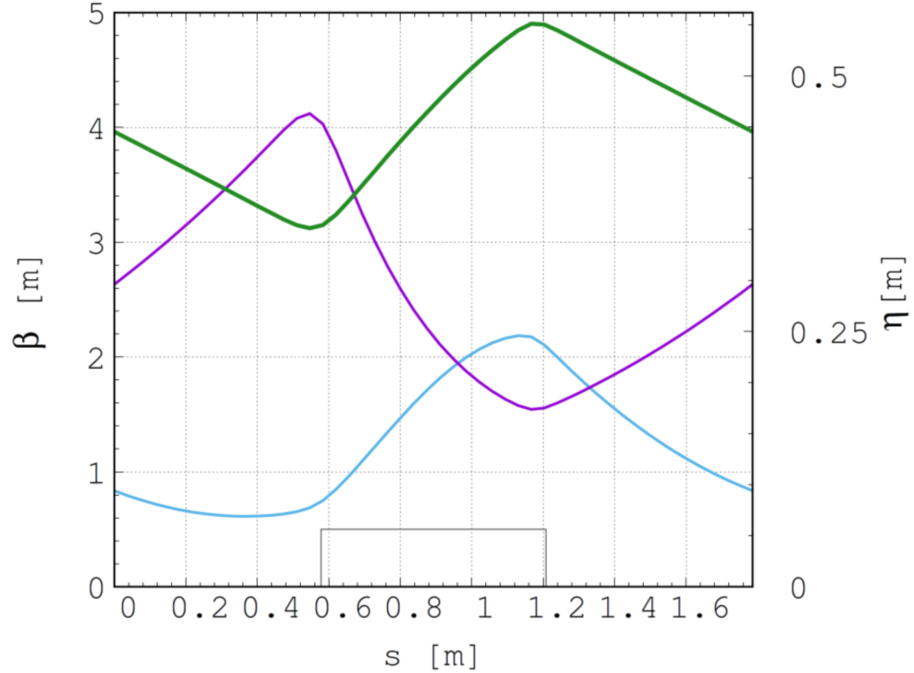
Variable input energy from the Laser Source (multiple ions are possible)

LhARA baseline Ring Parameters





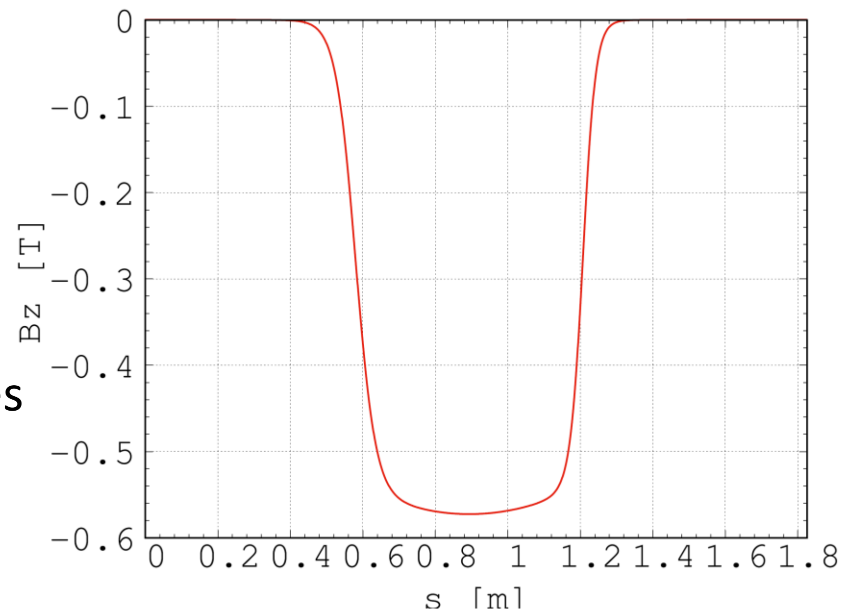
- N 10
- k 5.33
- Spiral angle 48.7°
- R_{max} 3.48 m
- R_{min} 2.92 m
- (Qx, Qy) (2.83, 1.22)
- B_{max} 1.4 T
- p_f 0.34
- Max Proton injection energy 15 MeV
- Max Proton extraction energy 127.4 MeV
- h 1
- RF frequency
  for proton acceleration (15-127.4MeV) 2.89 – 6.48 MHz
- Bunch intensity few×10^8 protons
- Range of other extraction energies possible
- Other ions also possible

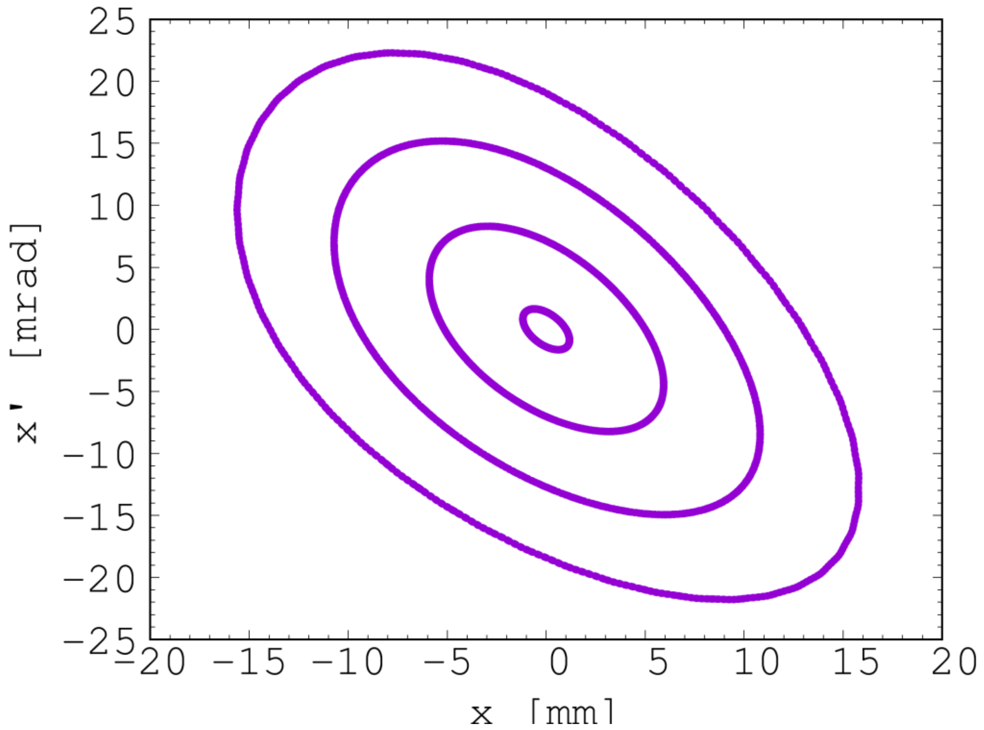


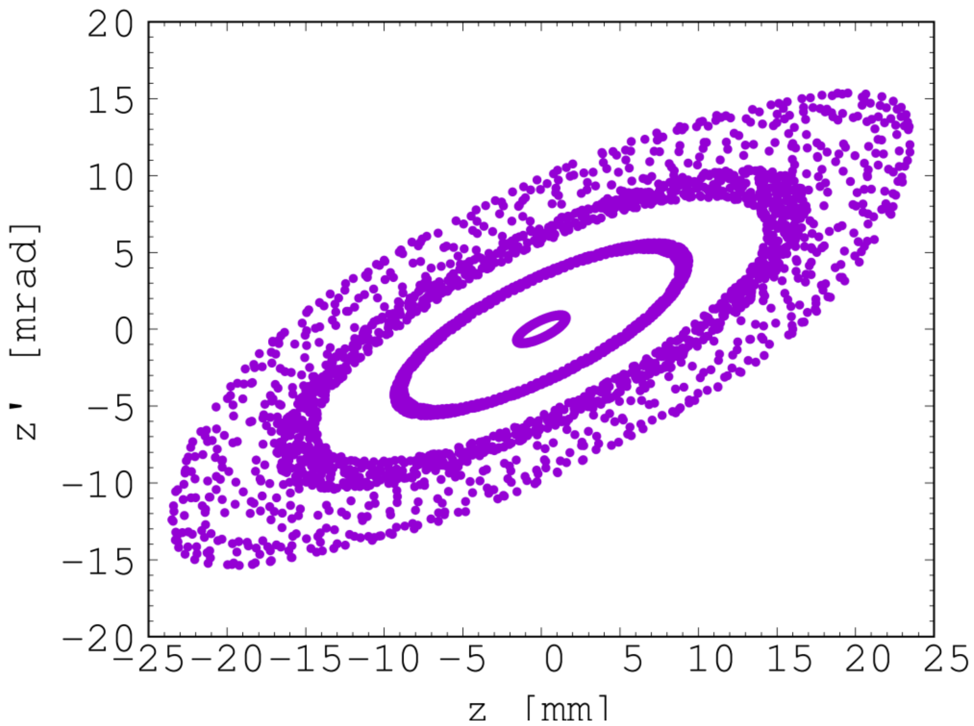
J. Pasternak, IC London

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



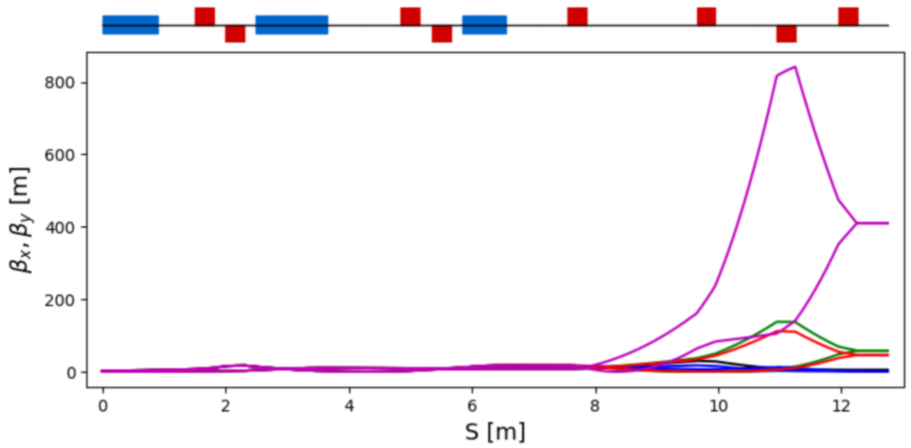


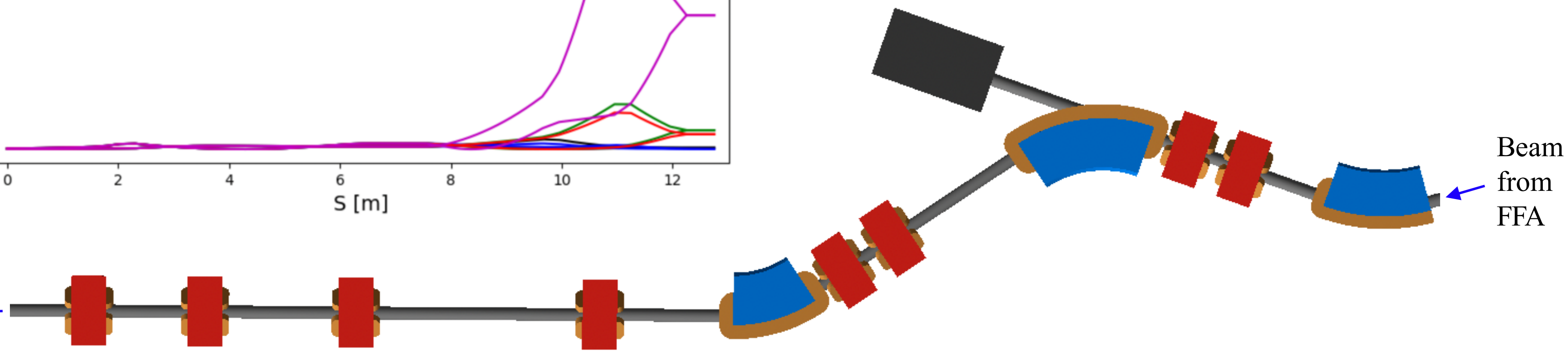


Stage 2 Extraction Line

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	

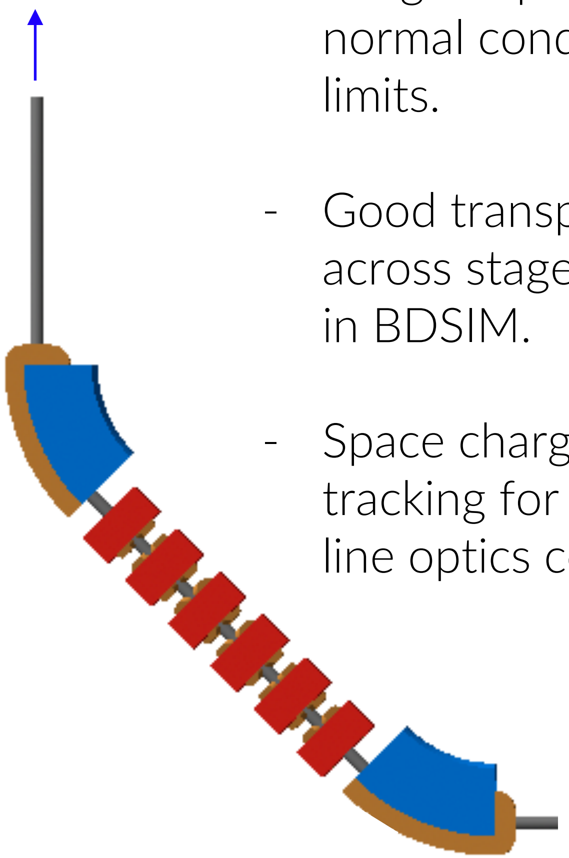
- Flexibility to accommodate uncertainties in extracted FFA emittance
  - Up to a factor 10 larger
  - Space charge
- Optics flexibility to also offer wide range of beam conditions to serve end stations.
  - 1– 30 mm spot size
- Closed dispersion after the final dipole

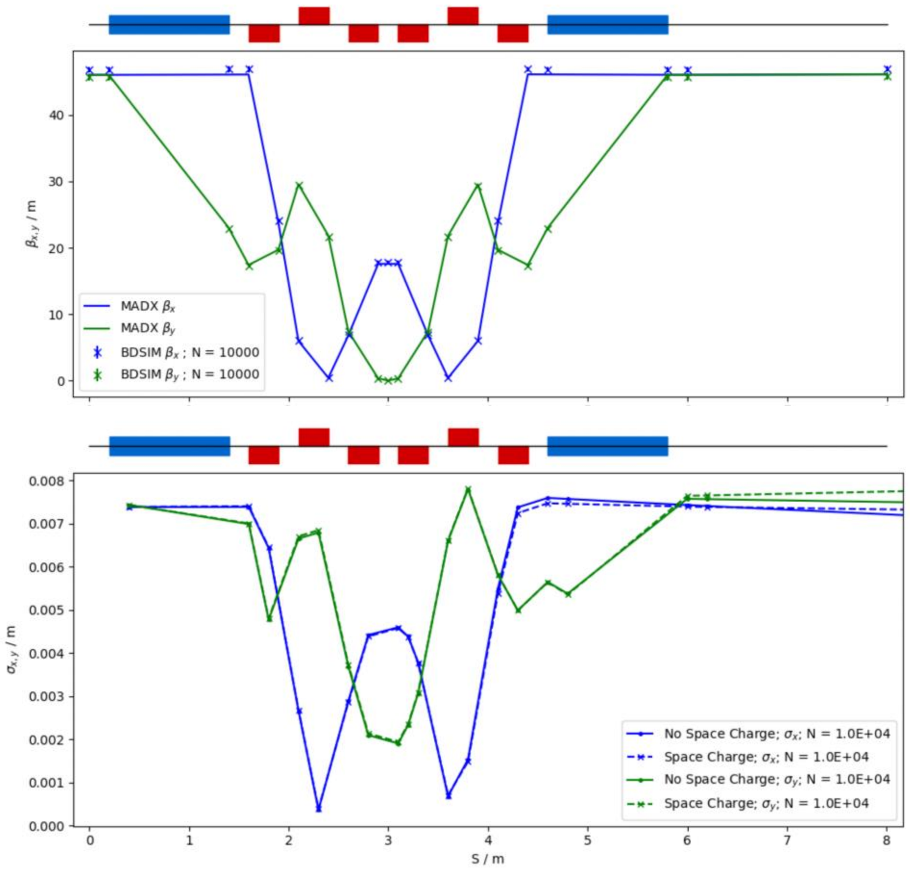




Stage 2 *in-vitro* Line

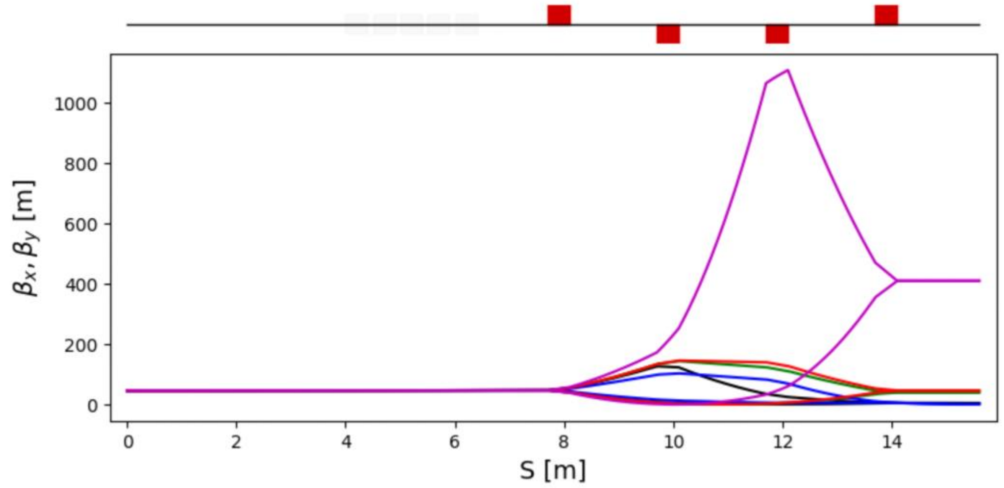
- Scaled version of the stage 1 low energy *in-vitro* beam line.
- Longer dipoles to remain in normal conducting magnet limits.
- Good transport performance across stage 2 energy range in BDSIM.
- Space charge impacts tracking for all extraction line optics configurations.

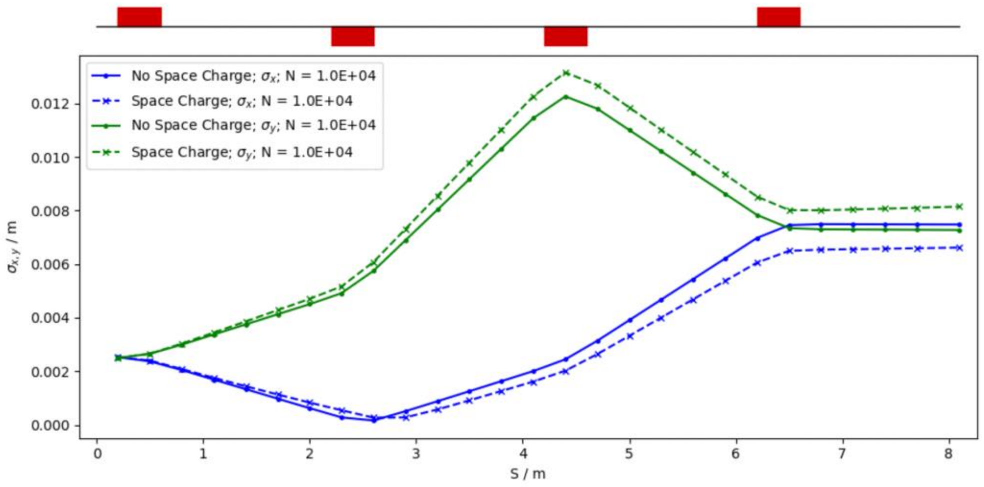




Stage 2 *in-vivo* Line

- 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



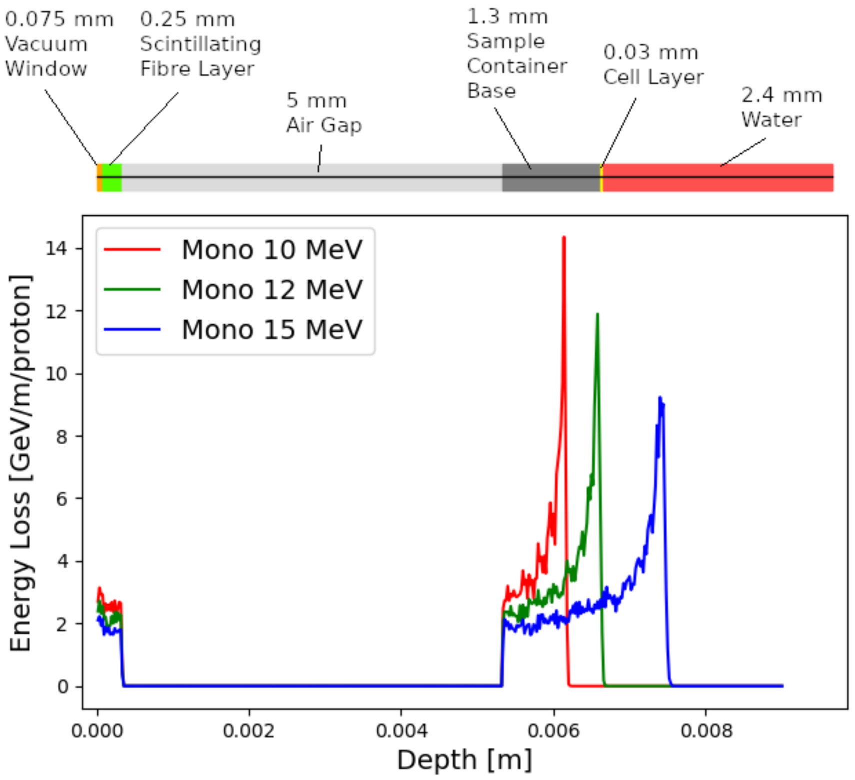


To *in-vitro* end station

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

Industrial/Science Collaborations for FFA design

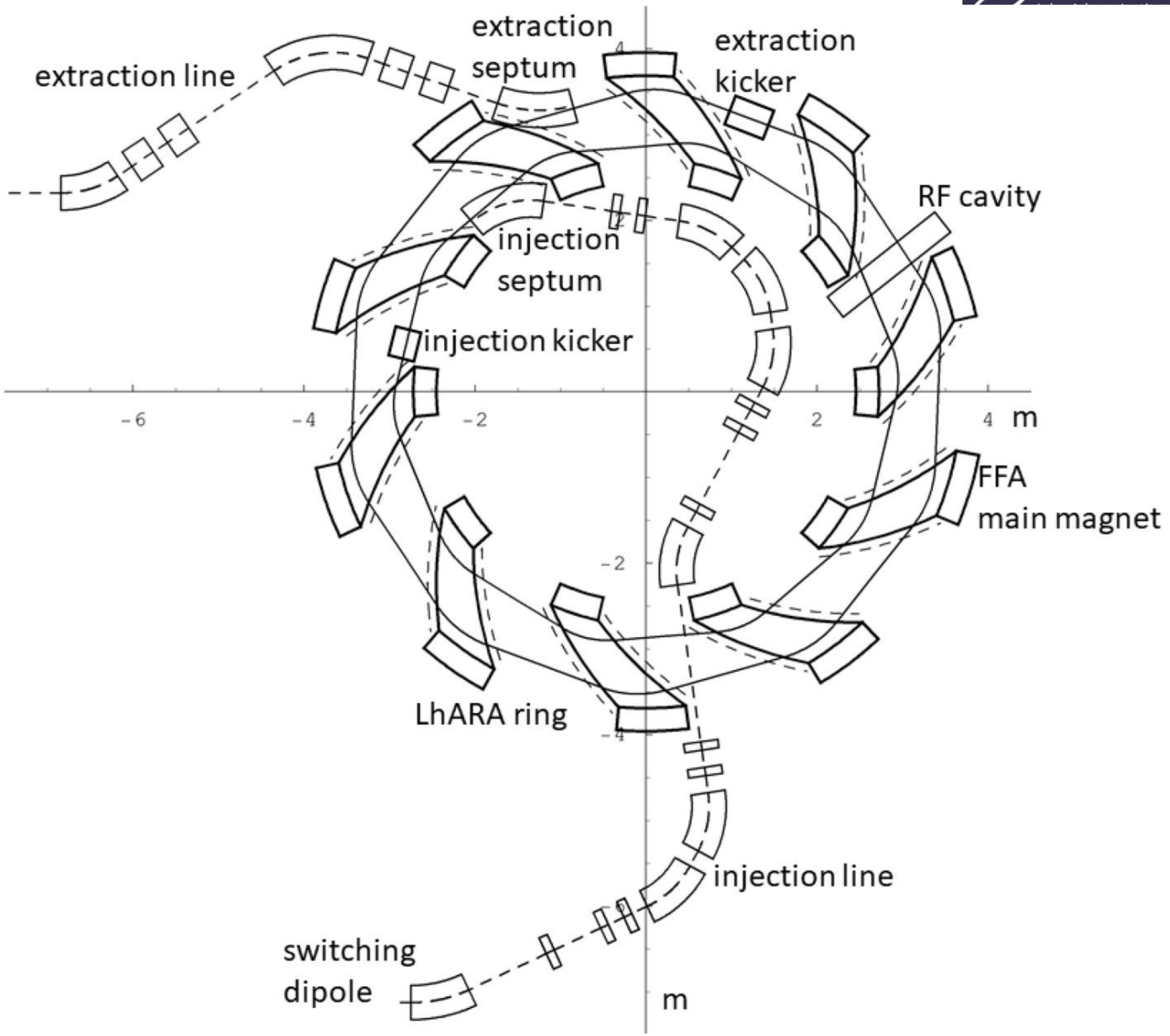
- FFA Magnet – SigmaPhi
  - Constructed RACCAM magnet
  - Expected to construct FETS FFA magnet prototype
- MA RF cavity
  - Existing solutions at KURNS, J-PARC, Kyushu University, CERN
  - Established collaboration with RAL-ISIS
  - Several manufacturers for MA cores
- Sustainability
  - Please see Neil's talk

Conclusions

- LhARA Stage 1 can use Gabor lenses or solenoids
  - Good baseline design has been created
- LhARA at Stage 2 can use FFA-type ring as a post-accelerator enabling variable energy beams of various types of ions
  - Injection line line design has been created, but needs to be updated
  - RF system based on MA cavities are being explored
- The cost effective, spiral scaling FFA chosen for the baseline shows a good performance in tracking studies
- Feasible ring injection, extraction and beam transport to the end stations at Stage 2 have been designed
- Essential R&D items:
  - finalisation of the lattice design (type, working point, etc.)
  - the main FFA magnet, and
  - the RF system for the ring

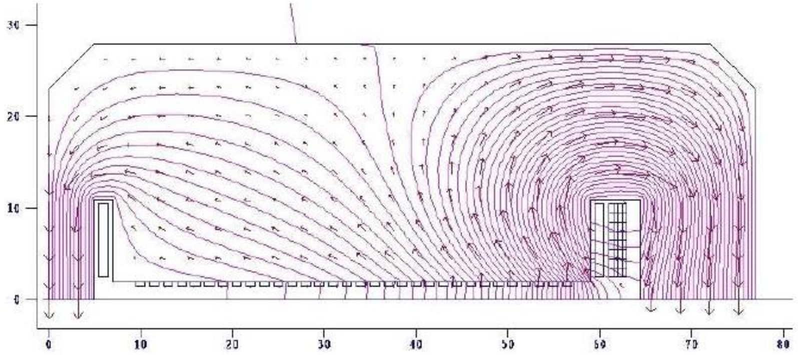
FFA Ring with subsystems

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



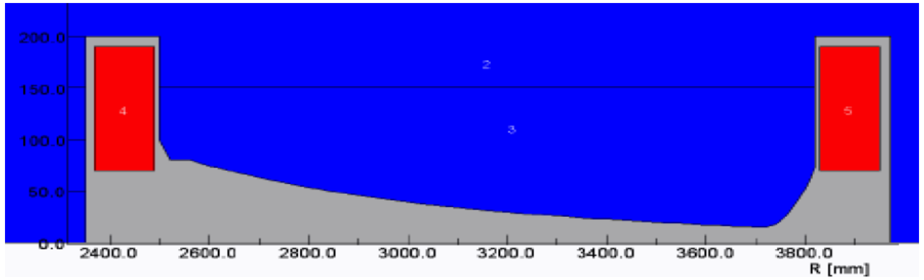
Essential R&D

Magnet types to be considered



Magnet with distributed conductors:
- Parallel gap – vertical tune more stable,
- Flexible field and k adjustment,

•Chosen for IonBeta machine at Kyoto University (KURNS)



„Gap shaping" magnet:
•Developed by SIGMAPHI for RACCAM project
•Initialy thought as more difficult
•Behaves very well
•Chosen for the RACCAM prototype construction

- For LhARA magnet with parallel gap with distributed windings (but a single current) would be of choice with gap controlled by clamp. Concepts like an active clamp could be of interest too.

- Another important aspect of the R&D is the technology transfer for Magnetic Alloy (MA) loaded RF cavities for the ring. Those type of cavities are in routine, operation for example at J-PARC, Kyoto University (KURNS) and at CERN