Design of the LhARA accelerator facility

J. Pasternak, CCAP Plenary Meeting, 24/06/2020

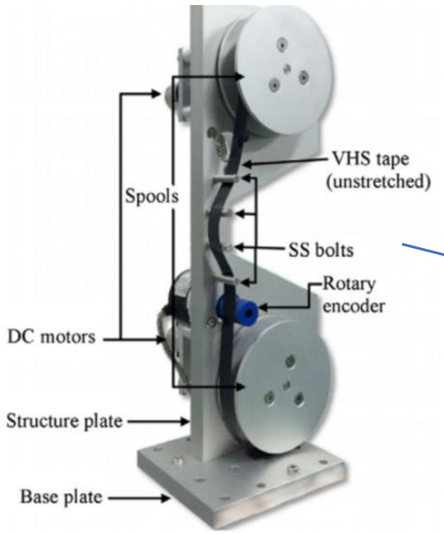
Outline

- Introduction and motivation
- Laser source
- Gabor lens
- Stage 1 baseline
- Stage 1 alternative
- FFA post-accelerator
- Stage 2 injection
- Optics for Stage 2 end stations
- R&D needs
- Conclusions

Introduction

- Laser hybrid Accelerator for Radiobiological Applications (LhARA) was proposed within the Centre for the Clinical Application of Particles (CCAP) at Imperial College London as a facility dedicated to the systematic study of radiobiology.
- It will allow study with proton beams with a flexible dose delivery (including a novel FLASH regime) at Stage 1
- It will open the study to use multiple ions (including Carbon) at Stage2 for both in-vitro and in-vivo end stations.
- It aims to demonstrate a novel technologies for next generation hadrontherapy.

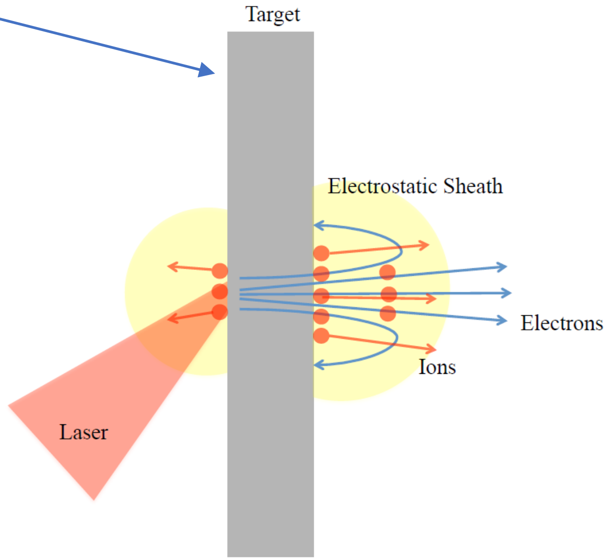
Current status of laser accelerators



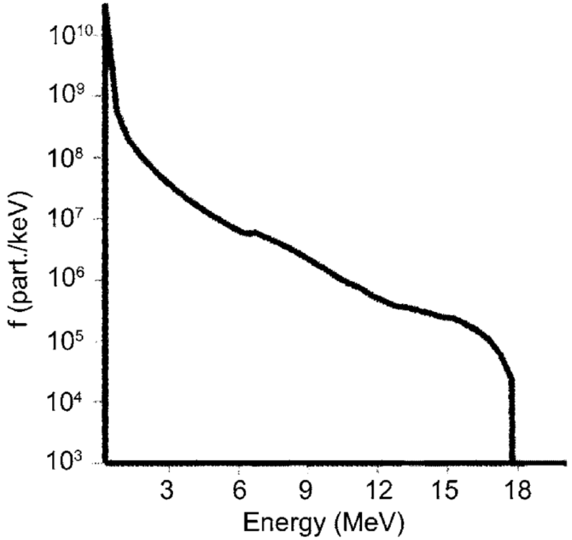
Noaman-ul-Haq et al. PRAB (2017)

Tape target

Many acceleration methodologies, but most studied and best characterised is sheath acceleration



15MeV energies for LhARA injection achievable as part of thermal particle distribution

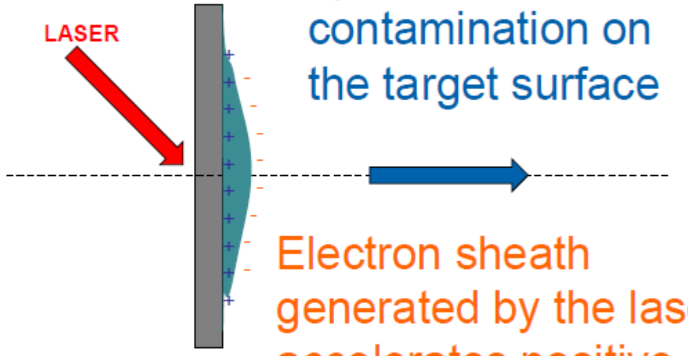


From O. Ettlinger

Initial Beam from the Laser Source

- Small emittance (~4.1x10^{-7} π.m.rad)
- Huge energy spread
- Very small beam size
- Very large divergence
- Neutral at the beginning then space charge dominated
- Mixture of states

LASER SOURCE

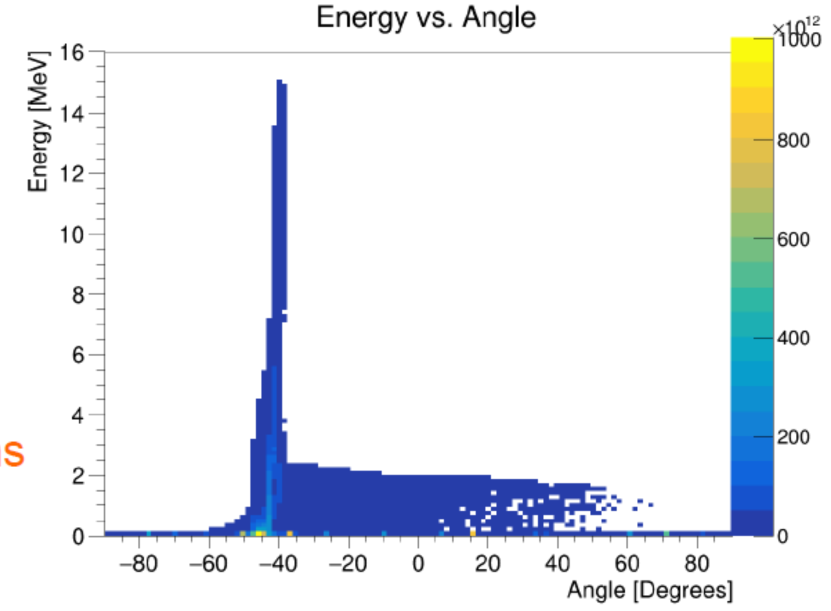


Positive ions from hydrocarbon contamination on the target surface

Electron sheath generated by the laser accelerates positive ions from the target

- Produces intense beams and multiple species, e.g. proton and carbon ions.

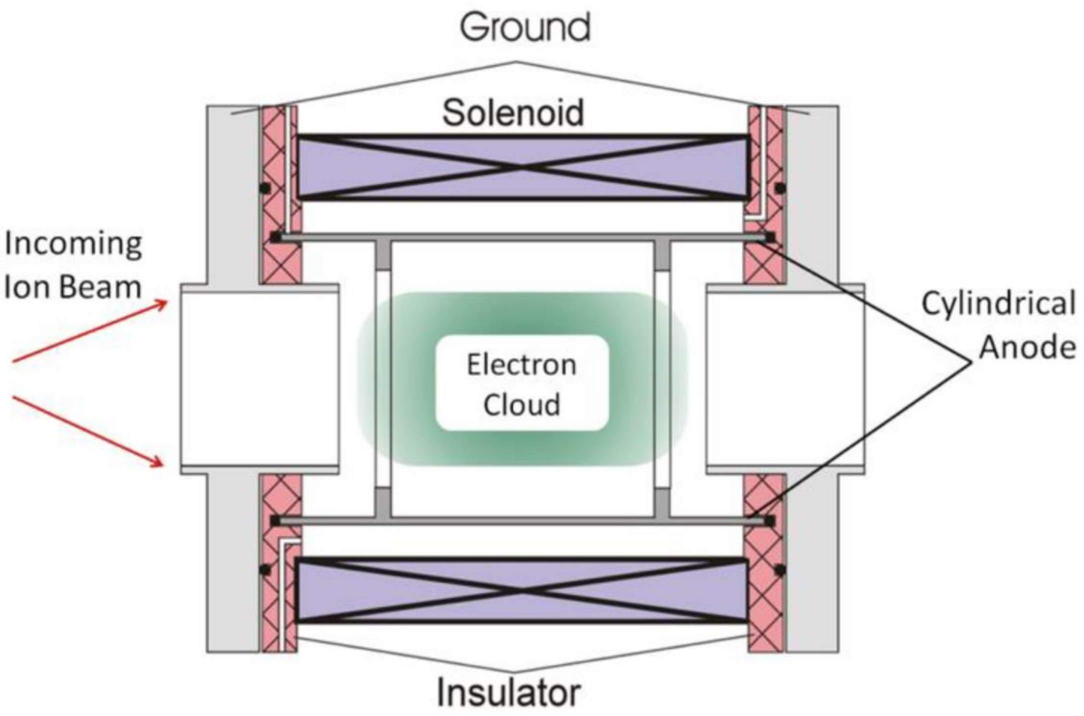
Energy vs angle with respect to laser beam direction

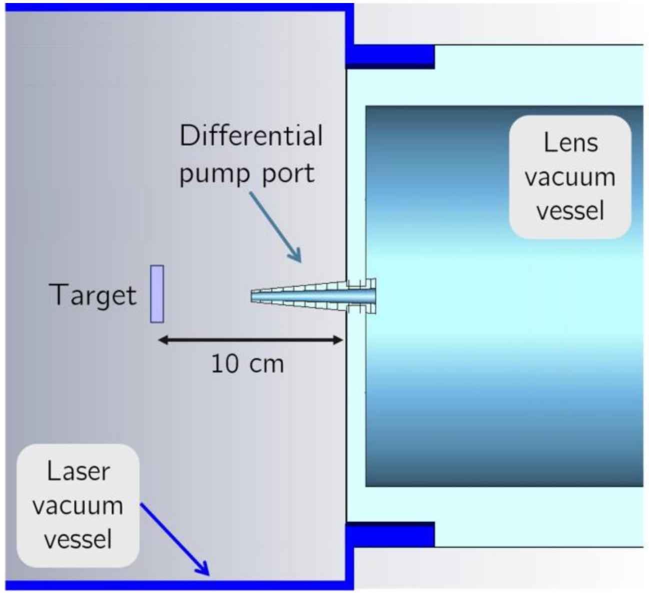


Laser driven ion beam simulation using EPOCH.

Gabor Lenses for strong focusing

- Focus in both planes simultaneously, strength is energy dependent
  - Cost effective solution compared to SC solenoids
- Chosen as a baseline solution for the capture system and focusing in Stage 1
- Design based on Penning-Malmberg trap
- Require high vacuum to operate
- Subject to intensive 3D PIC simulation effort to inform a stable solution (to mitigate diocotron instability)
- Can be replaced by solenoids, if needed.



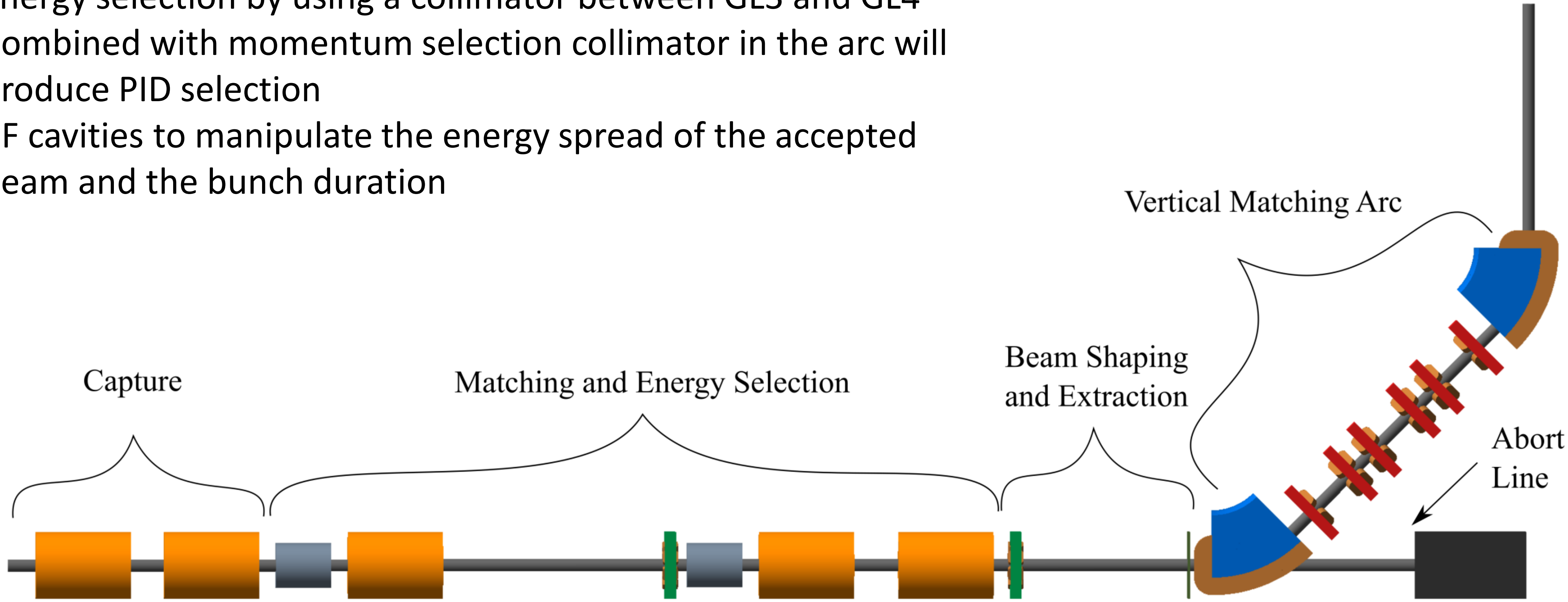


From C.G. Whyte

Target-capture interface

LhARA Stage 1, baseline lattice

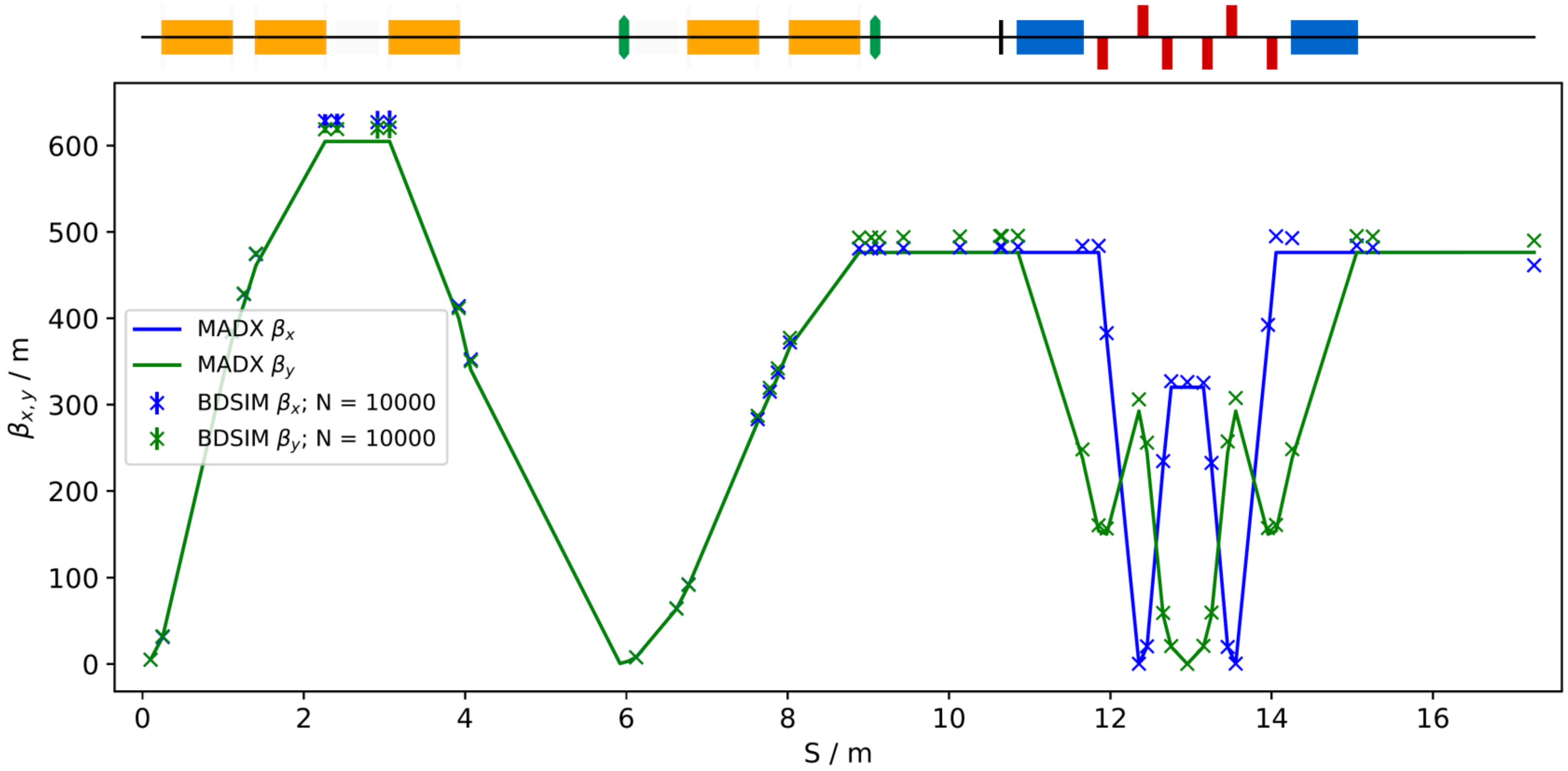
- Energy selection by using a collimator between GL3 and GL4
- Combined with momentum selection collimator in the arc will produce PID selection
- RF cavities to manipulate the energy spread of the accepted beam and the bunch duration



LhARA Stage 1, optics

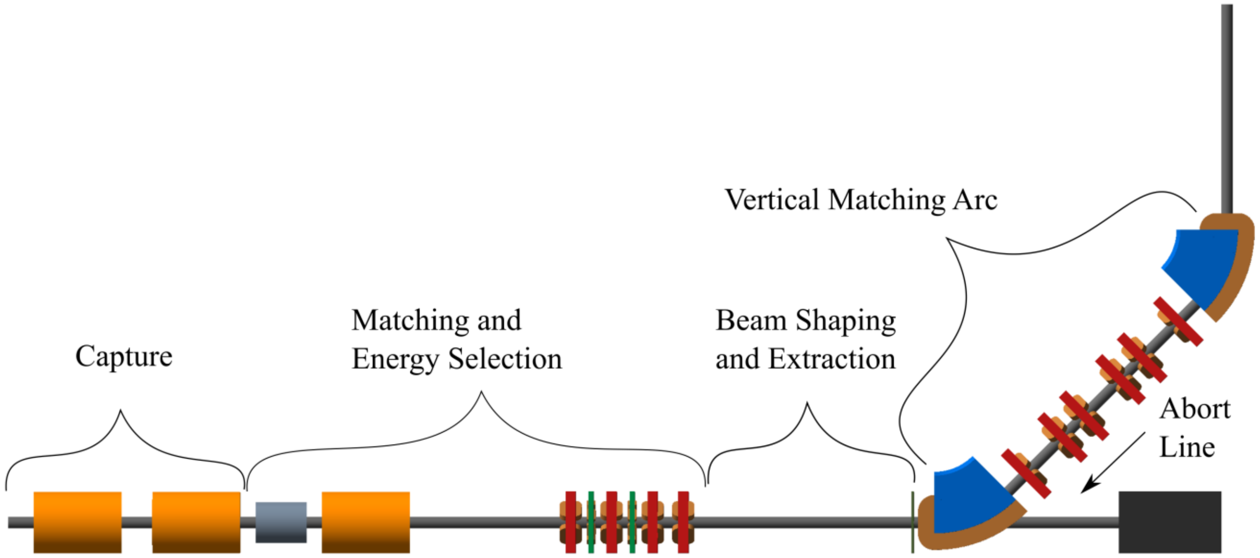
- Initial beam assumed neutral first (5cm) and then space charge must be taken into account
- Strong focusing in both planes by Gabor Lenses (or solenoids) essential in the capture section
- Matching to very small spot size unavoidable and used for the energy selection
- Matching with two lenses to the optically transparent, achromatic arc
- Redistribution of phase space using octupoles to create an uniform beam

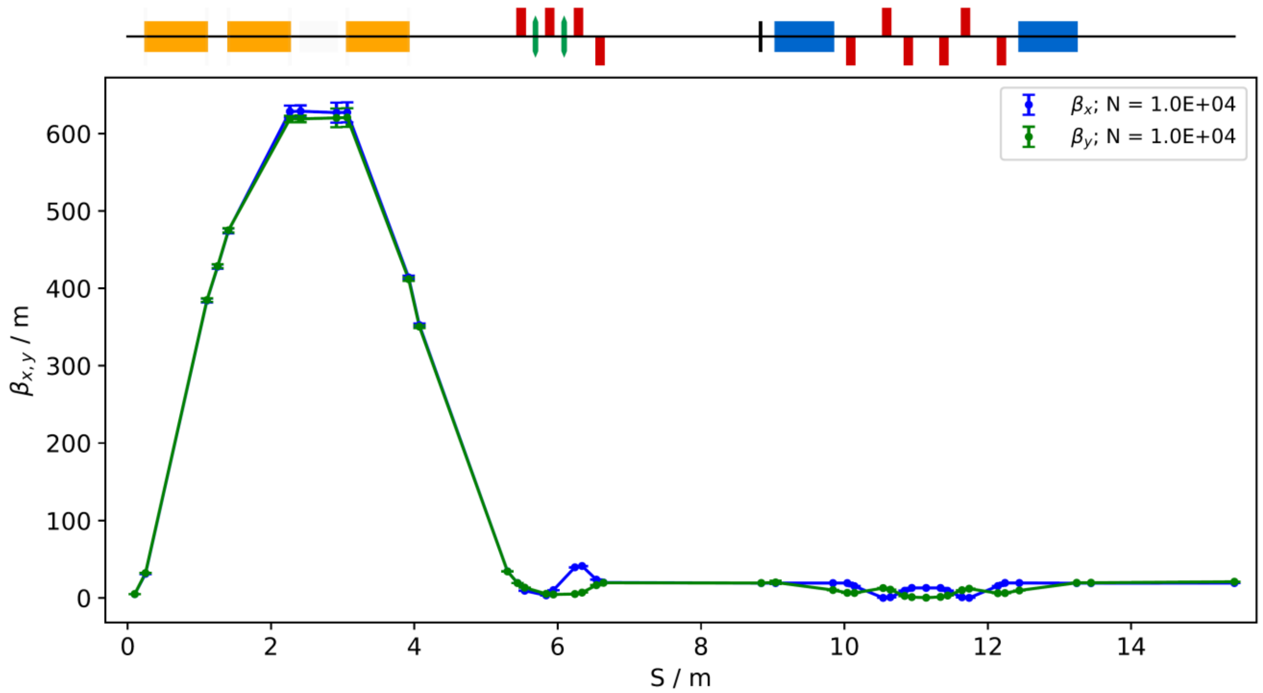
Achromatic vertical arc



For performance, please see the next talk by W. Shields

Lhara Stage 1, alternative design



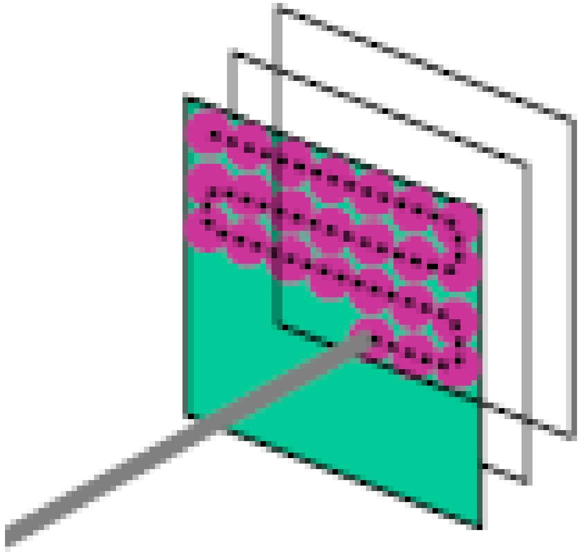


- Alternative design uses quadrupoles to avoid focusing to the spot in both planes simultaneously (a space charge mitigation)
- Octupoles would be in the right optical locations
- Optics optimisation with the space charge to be done and the performance to be demonstrated

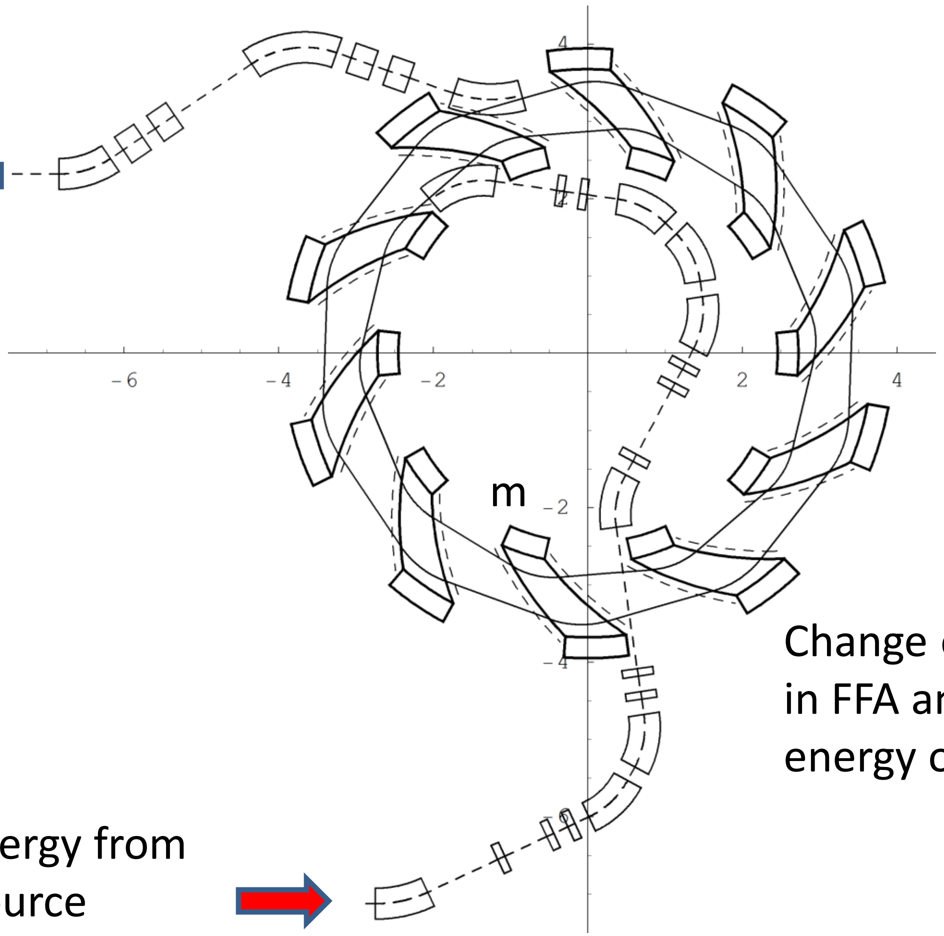
Motivations for a Medical/Radiobiological FFA (Fixed Field Accelerator)

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
- Simple and efficient extraction
- Stable and easy operation
- Multiple extraction ports
- Bunch to Pixel active scanning possible.
- Multiple ion capability



Energy Variability using Laser Accelerated Ions



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

+

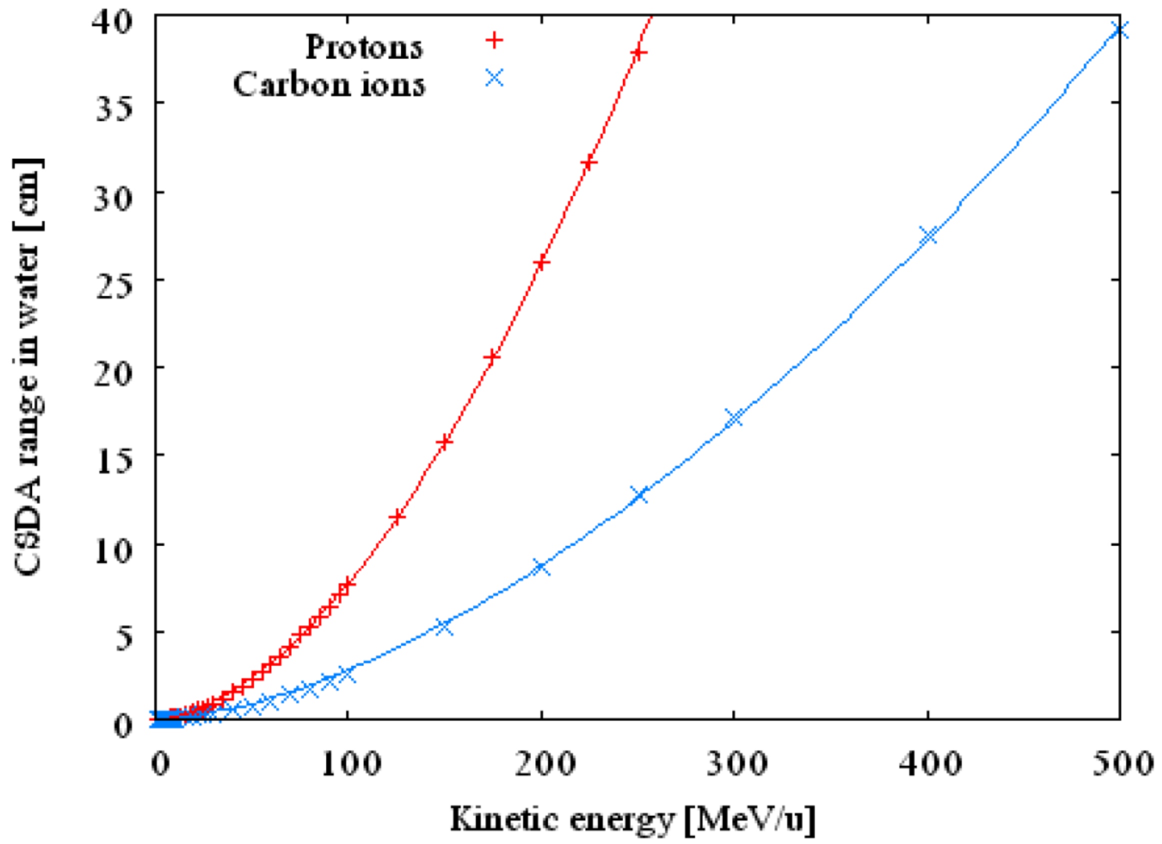
pulse by pulse
variation with kicker
could be implemented

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

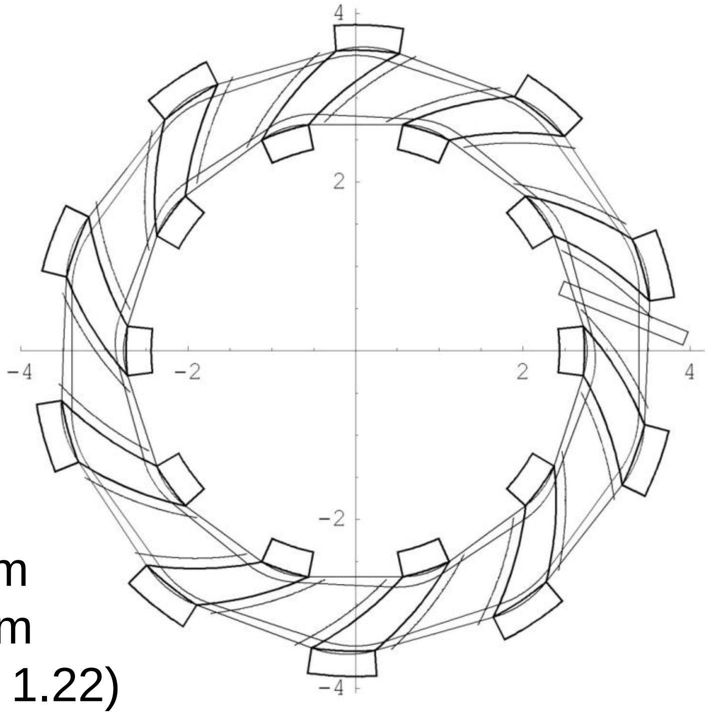
Variable input energy from
the Laser Source
(multiple ions are possible)

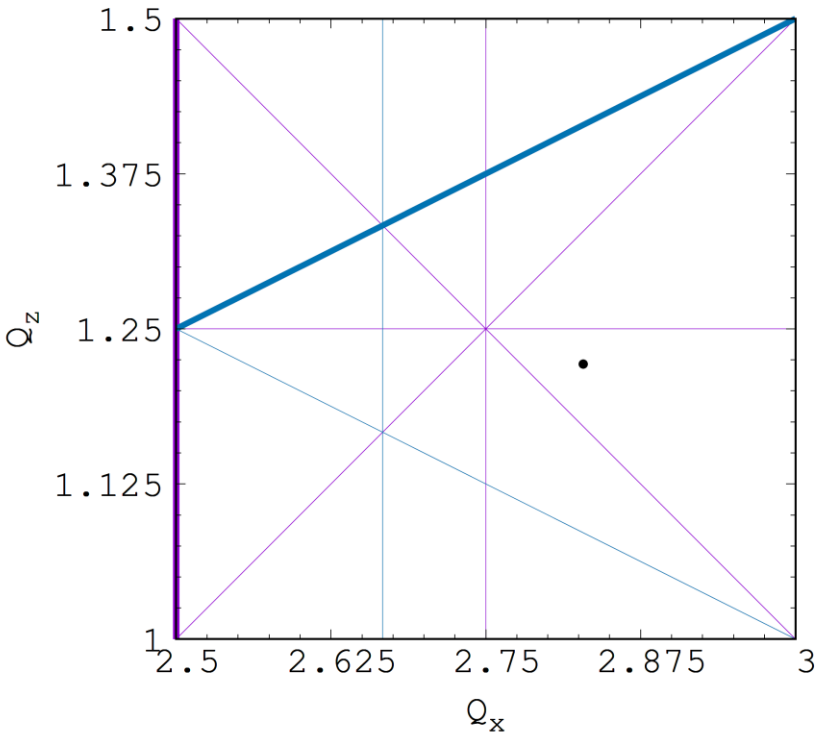
Energy for LhARA Stage 2

- FFA accelerator can typically accelerate by a factor of 3 in momentum (or more). This allows to easily achieve 127.4 MeV (starting from 15 MeV).
  - Acceleration by a factor of 4 would be possible. This corresponds to 217 MeV protons.
- This would correspond to 33.4 (58.7) MeV/u for C6+.



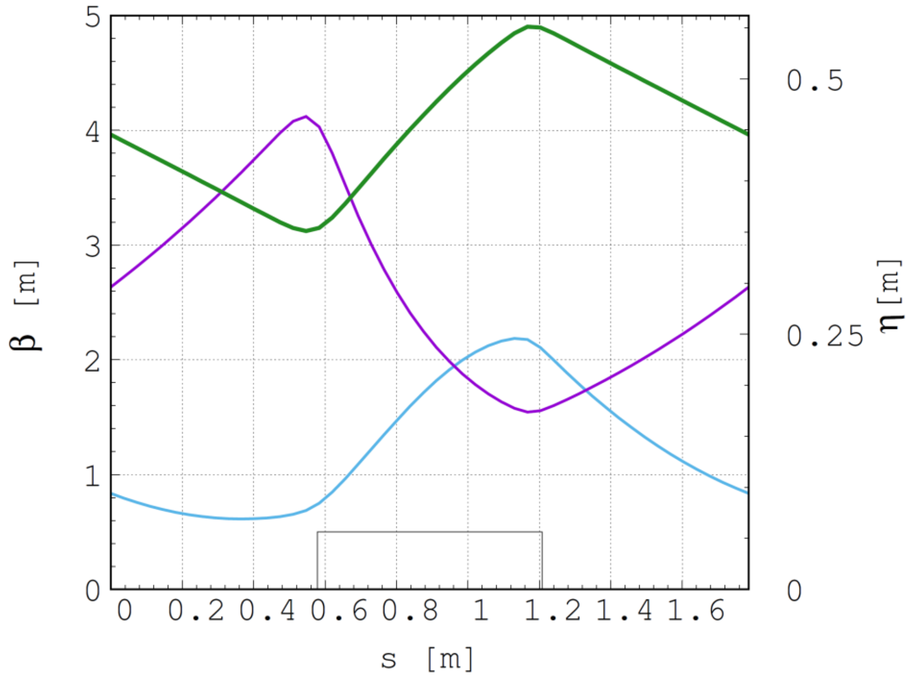
LhARA Ring Parameters



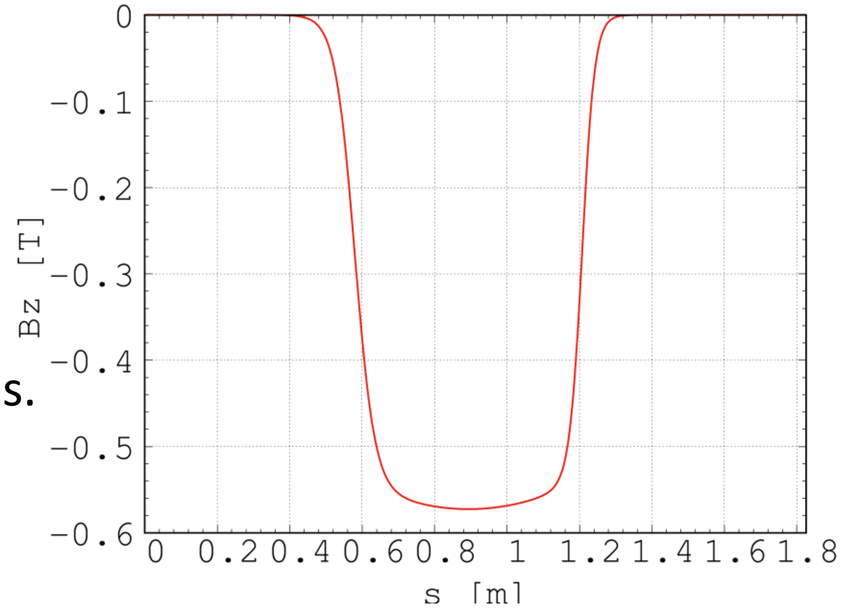


N	10
k	5.33
Spiral angle	48.7°
R_{max}	3.48 m
R_{min}	2.92 m
(Qx, Qy)	(2.83, 1.22)
B_{max}	1.4 T
p_f	0.34
Max Proton injection energy	15 MeV
Max Proton extraction energy	127.4 MeV
h	1
RF frequency for proton acceleration (15-127.4MeV)	2.89 – 6.48 MHz
Bunch intensity	few×10^8 protons

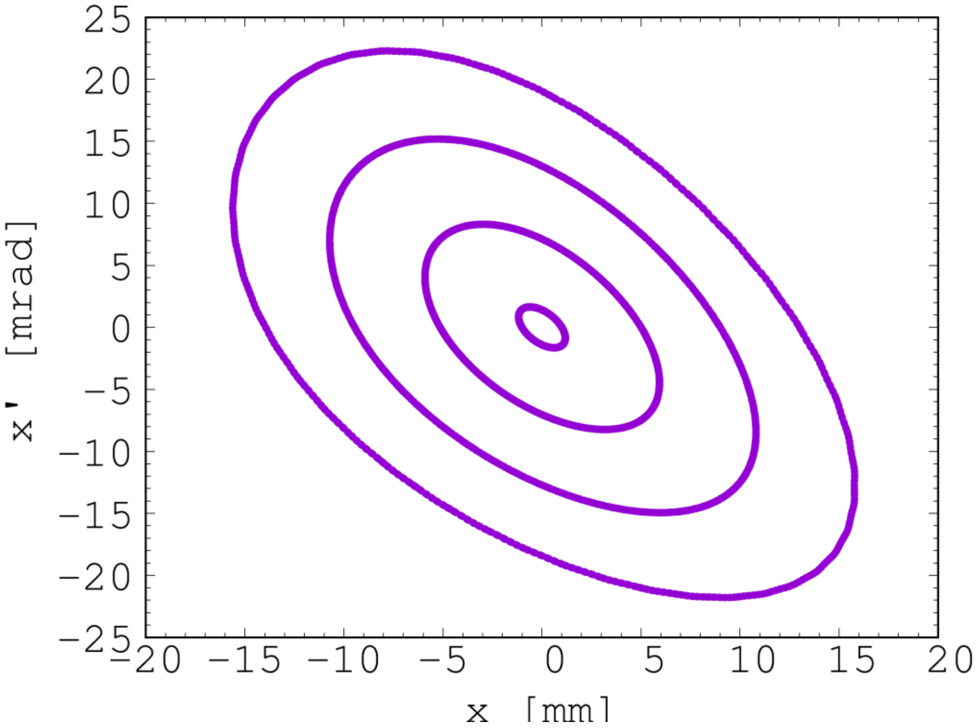
- Range of other extraction energies possible
- Other ions also possible

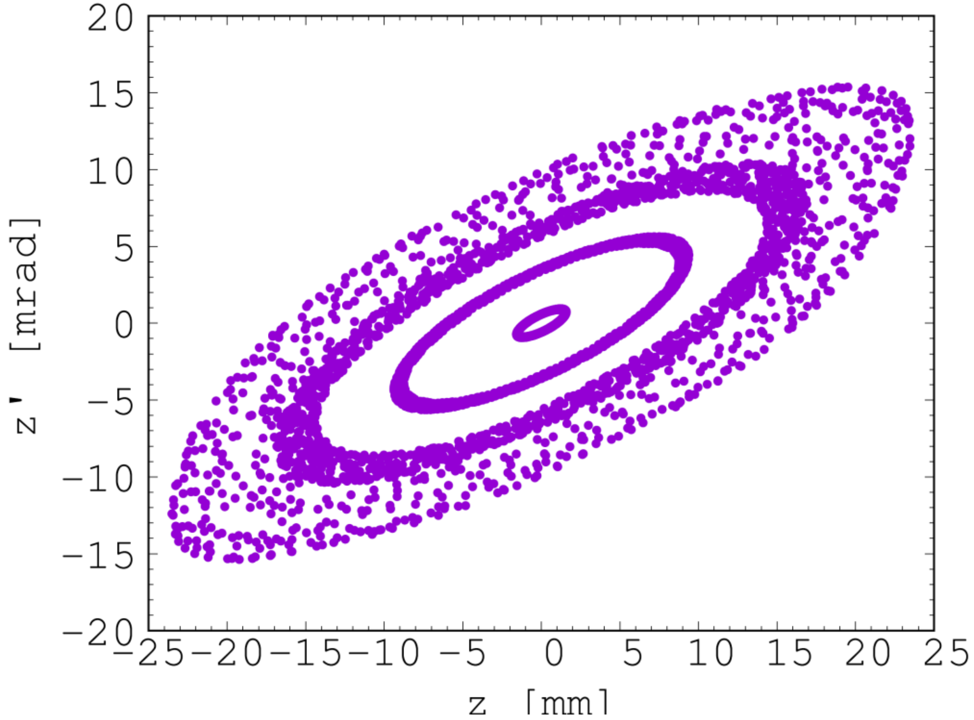


LhARA Ring Tracking



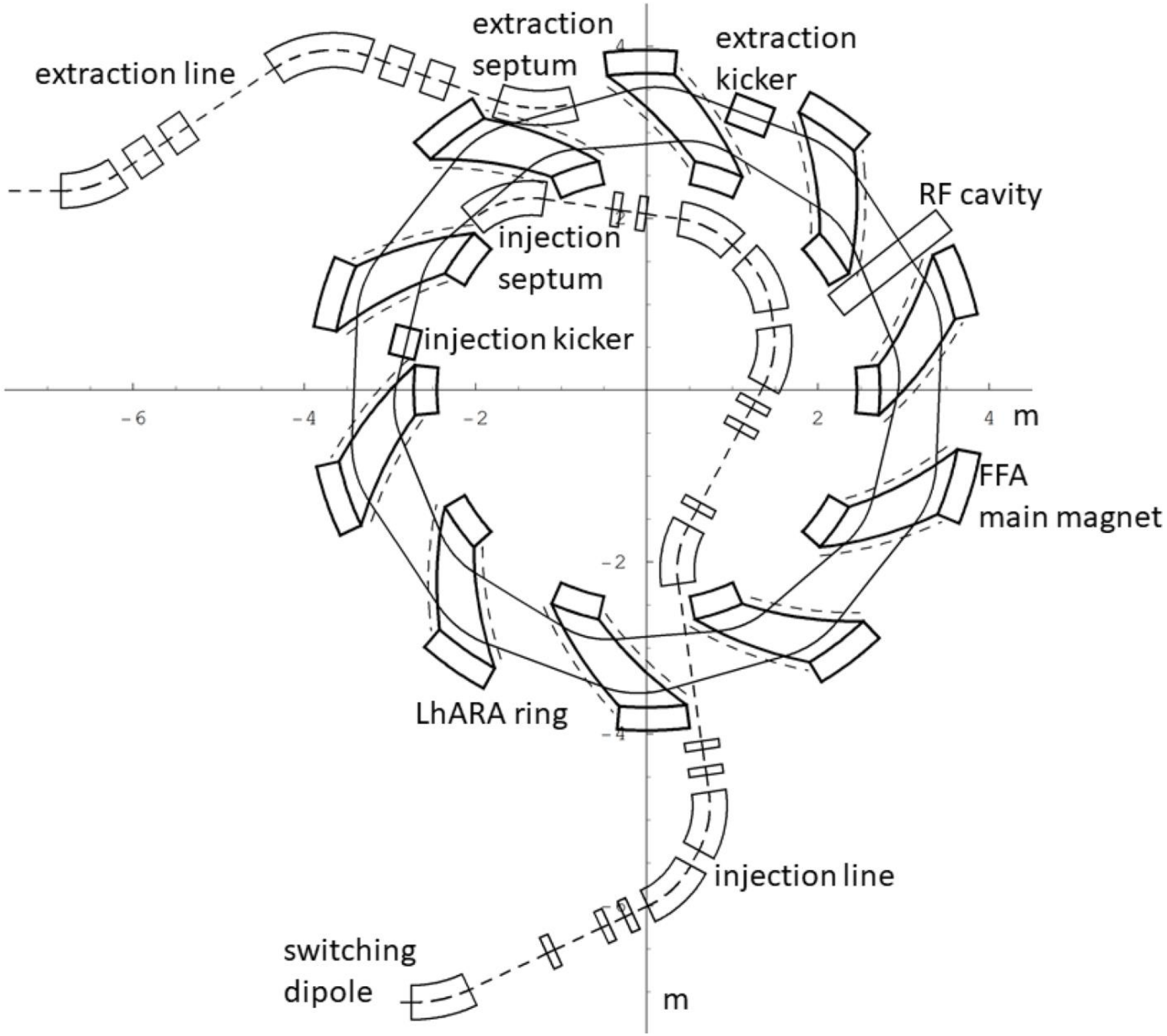
- Performed using proven stepwise tracking code
- It takes into account fringe fields and non-linear field components
- Results show dynamical acceptances are much larger than physical ones.
- No space charge effects included yet.



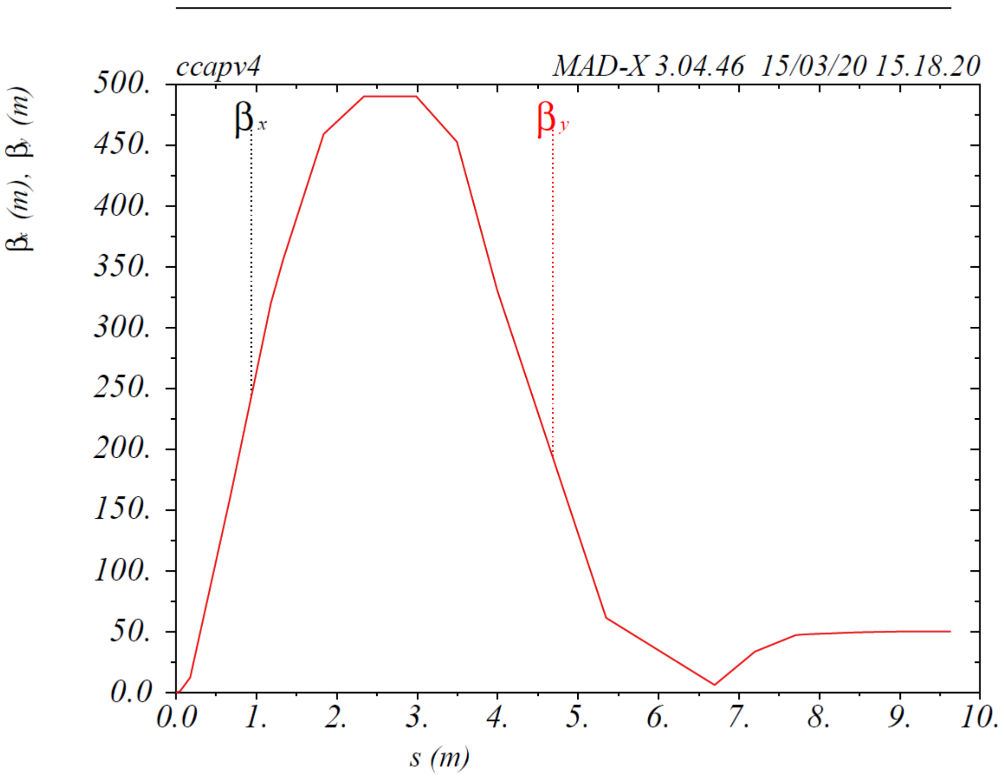


FFA Ring with subsystems

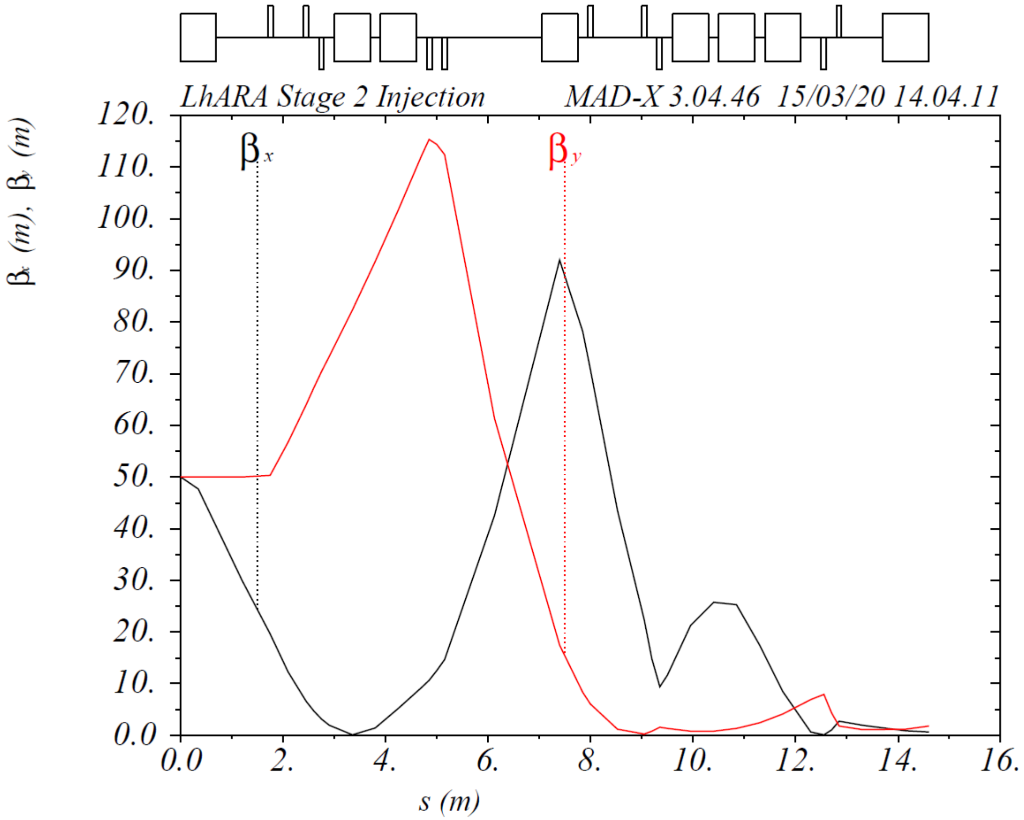
Parameter	unit	value
Injection septum:		
nominal magnetic field	T	0.53
magnetic length	m	0.9
deflection angle	degrees	48.7
thickness	cm	1
full gap	cm	3
pulsing rate	Hz	10
Extraction septum:		
nominal magnetic field	T	1.12
magnetic length	m	0.9
deflection angle	degrees	34.38
thickness	cm	1
full gap	cm	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



Injection optics

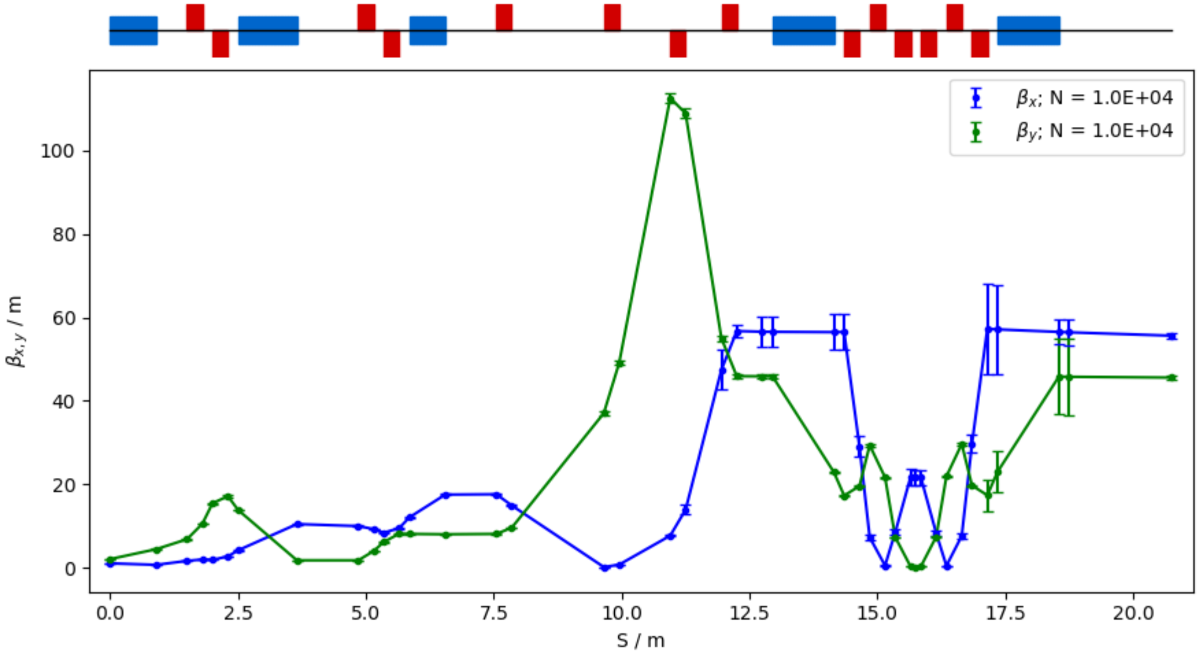


- Stage 1 can be tuned to match the injection line
- Focus point changes location and requires a dedicated collimation system
- Focusing can be realised with normal conducting solenoids

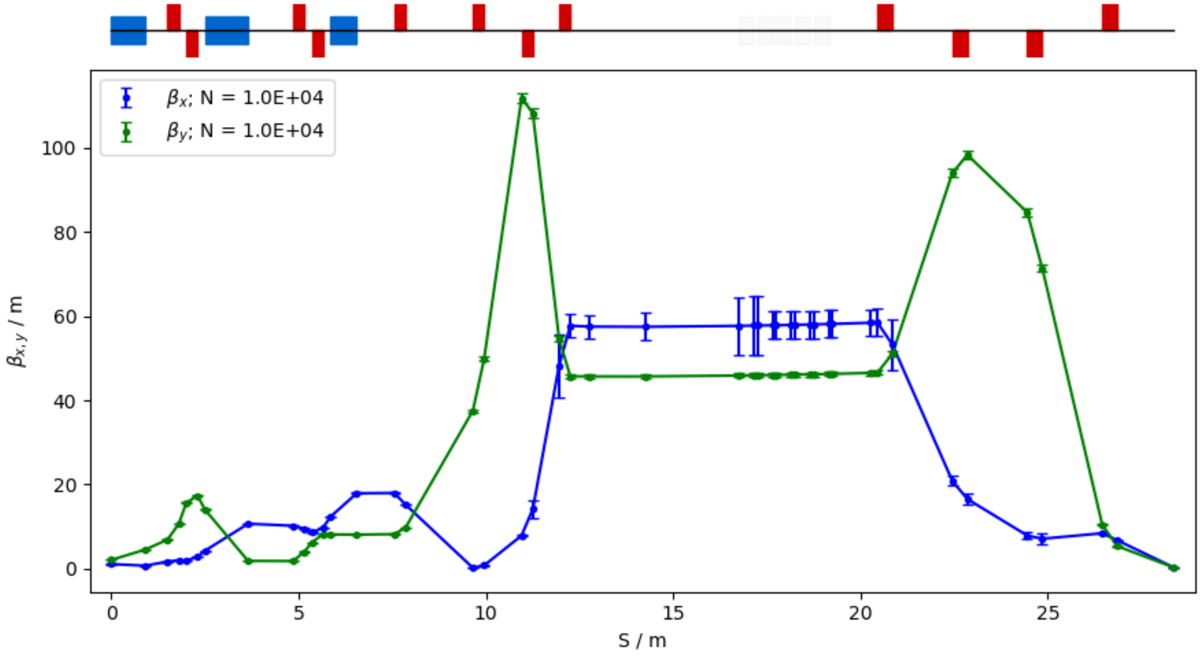


Optics from the switching dipole to the injection septum has been designed

Extraction optics



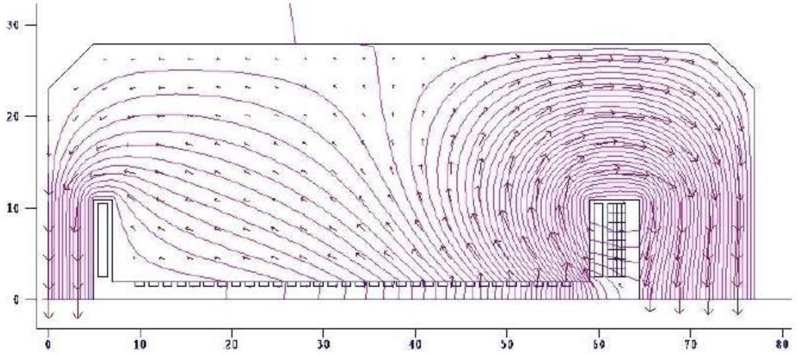
Optics for Stage 2 in-vitro end station, the arc optics scaled from the Stage 1



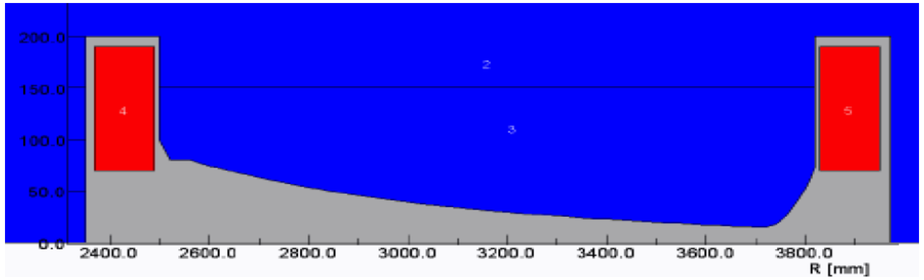
Optics for Stage 2 in-vivo end station, a dedicated final focus has been designed

Essential R&D

Magnet types to be considered



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

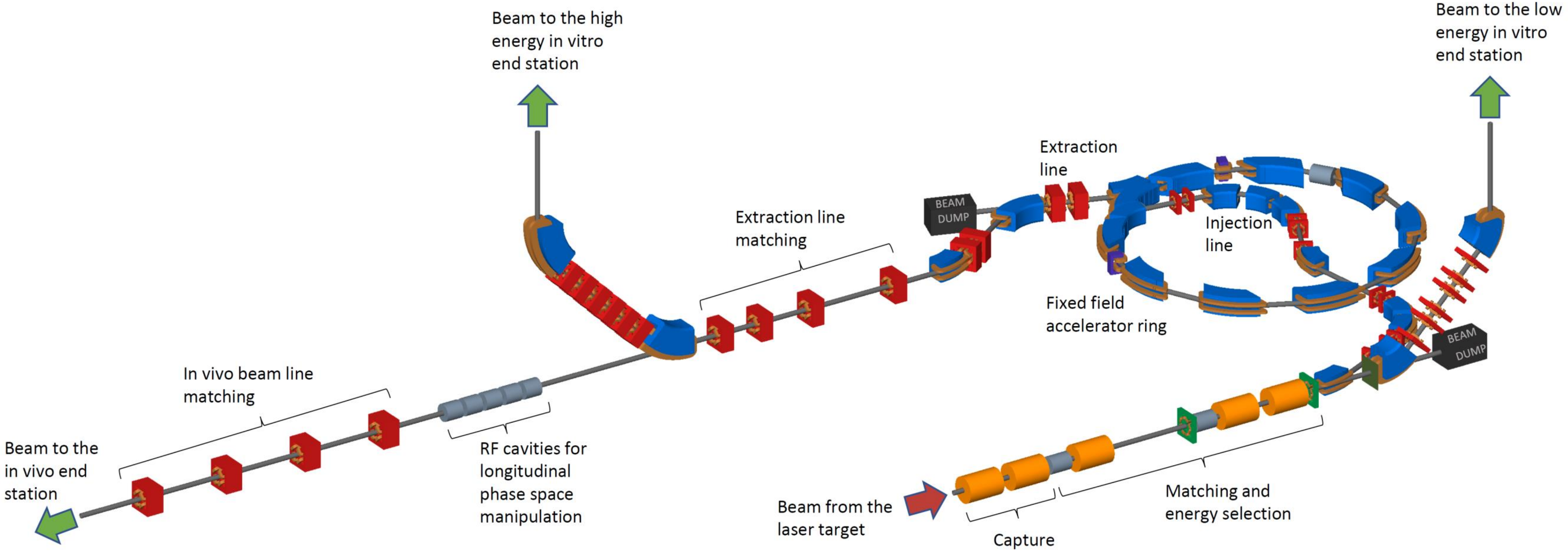


„Gap shaping" magnet:
- Developed by SIGMAPHI for RACCAM project
- Initialy thought as more difficult
- Behaves very well
- Chosen for the RACCAM prototype construction

- 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

Layout of the full LhARA facility



Conclusions

- Conceptual design of LhARA is in a very good shape:
  - Stage 1 design is compact and flexible, and performs very well even including the space charge effects (see W. Shields' talk).
  - LhARA at Stage 2 can use FFA-type ring as a post-accelerator enabling variable energy beams of various types of ions. The cost effective, spiral scaling FFA 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:
  - Gabor lens
  - the main FFA magnet, and
  - the RF system for the ring