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LhARA

Laser-hybrid Accelerator for Radiobiological Applications

LhARA the facility for radiobiological research with an FFA in its heart

J. Pasternak, on behalf of LhARA Collaboration

01/12/2020, FFA’20 Workshop

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

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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.

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Who are we?

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Imperial College London
Department of Physics
Faculty of Medicine

ICR The Institute of Cancer Research

Medical Research Council
UKRI
Oxford Institute for Radiation Oncology

University of Oxford

JAI John Adams Institute for Accelerator Science

CCAP Centre for the Clinical Application of Particles

Imperial College Academic Health Science Centre

Cancer Research UK | Imperial Centre

NHS Imperial College Healthcare NHS Trust

Manchester 1824 The University of Manchester

University of Birmingham

Queen's University Belfast

Royal Holloway University of London

University of Strathclyde Glasgow Department of Physics

University of Liverpool

University of Birmingham | Positron Imaging Centre

University of Birmingham | Cyclotron Facility

The Cockcroft Institute of Accelerator Science and Technology

University of Surrey Ion Beam Centre

University
Clinical
Partners
Accelerator
Laboratory
Industry

NHS University Hospitals Birmingham NHS Foundation Trust

NHS The Clatterbridge Cancer Centre NHS Foundation Trust

institut Curie

UKRI Science and Technology Facilities Council
ASTeC
Particle Physics Department
ISIS Neutron and Muon Source

CLF central laser facility

Corerain 鲲云科技

The Rosalind Franklin Institute

NPL National Physical Laboratory

LEO Cancer Care

Maxeler Technologies Maximum Performance Computing

The LhARA consortium

Review and publications

- LhARA team performed an intensive design work culminated by the international review last March
  - A very positive feedback was received
  - Pre-CDR was completed
- Recent work was summarised in the article published in Frontiers in Physics

July 12, 2020 Final—revision 2 CCAP-TN-01

Laser-hybrid Accelerator for Radiobiological Applications (LhARA)

Conceptual Design Report

The LhARA collaboration

G. Aymar [1], T. Becker [2], S. Boogert [3], M. Borghesi [4], R. Bingham [5,1], C. Brenner [1], P.N. Burrows [6], T. Dascalu [7], O.C. Ettlinger [8], S. Gibson [3], T. Greenshaw [9], S. Gruber [10], D. Gujral [11], C. Hardiman [11], J. Hughes [9], W.G. Jones [7,20], K. Kirkby [12], A. Kurup [7], J-B. Lagrange [1], K. Long [7,1], W. Luk [7], J. Matheson [1], P. McKenna [5,14], R. Mclauchlan [11], Z. Najmudin [8], H.T. Lau [7], J.L. Parsons [9,21], J. Pasternak [7,1], J. Pozimski [7,1], K. Prise [4], M. Puchalska [13], P. Ratoff [14], G. Schettino [15,19], W. Shields [3], S. Smith [16], J. Thomason [1], S. Towe [17], P. Weightman [9], C. Whyte [5,14], R. Xiao [18]

frontiers in Physics

ORIGINAL RESEARCH
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Check for updates

LhARA: The Laser-hybrid Accelerator for Radiobiological Applications

Galen Aymar [1], Tobias Becker [2], Stewart Boogert [3], Marco Borghesi [4], Robert Bingham [1,5], Ceri Brenner [1], Philip N. Burrows [6], Oliver C. Ettlinger [7], Titus Dascalu [8], Stephen Gibson [3], Timothy Greenshaw [9], Sylvia Gruber [10], Dorothy Gujral [11], Claire Hardiman [11], Jonathan Hughes [9], W. G. Jones [8,12], Karen Kirkby [13], Ajit Kurup [8], Jean-Baptiste Lagrange [1], Kenneth Long [1,8], Wayne Luk [8], John Matheson [1], Paul McKenna [5,14], Ruth McLauchlan [11], Zulfikar Najmudin [7], Hin T. Lau [8], Jason L. Parsons [15,16], Jaroslaw Pasternak [1,8], Juergen Pozimski [1,8], Kevin Prise [17], Monika Puchalska [18], Peter Ratoff [14,19], Giuseppe Schettino [20,21], William Shields [3], Susan Smith [22], John Thomason [1], Stephen Towe [23], Peter Weightman [8], Colin Whyte [5] and Rachel Xiao [24]*

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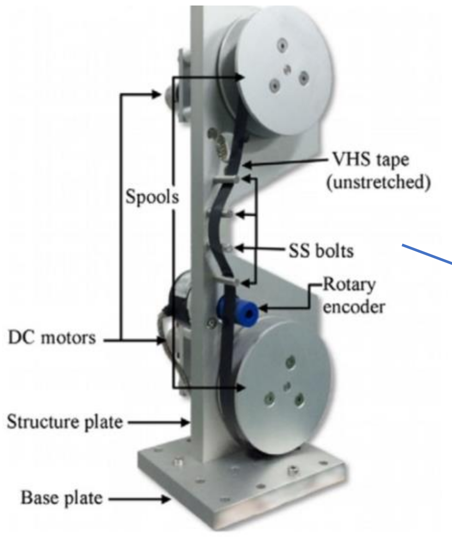
Frontiers in Physics | www.frontiersin.org September 2020 | Volume 8 | Article 567738

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

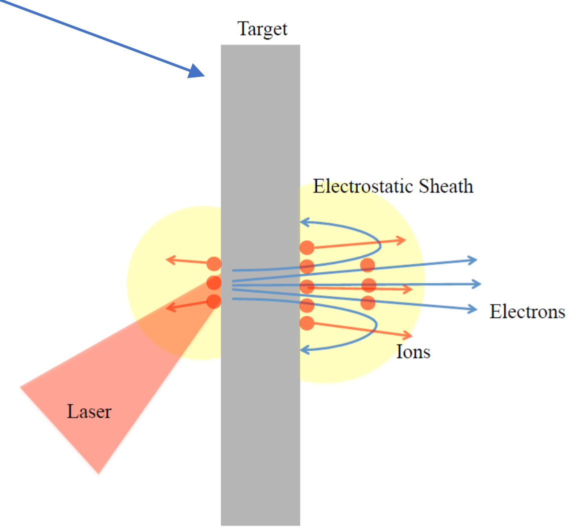
Current status of laser accelerators



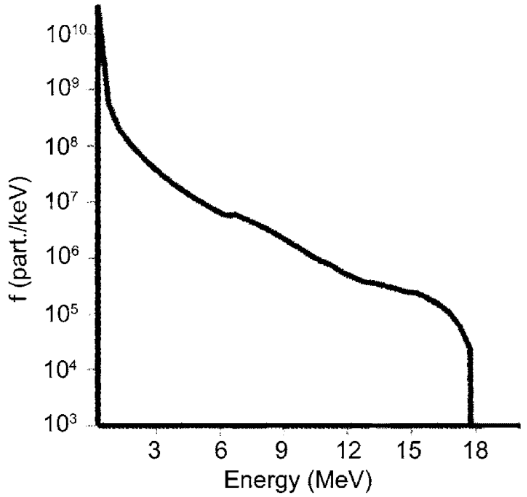
Noaman-ul-Haq et al. PRAB (2017)

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

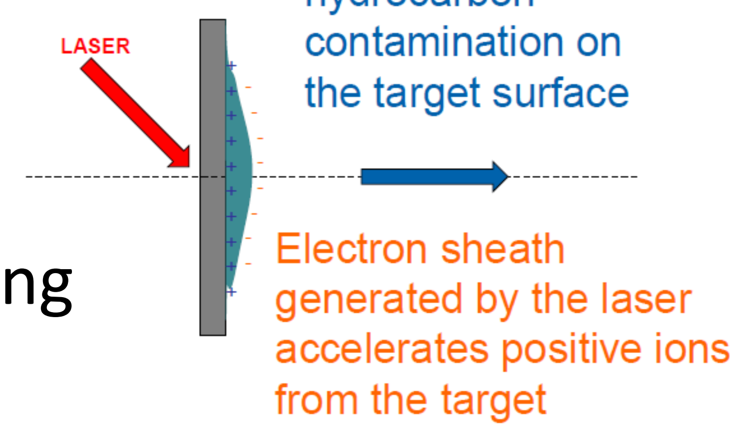


From O. Ettlinger

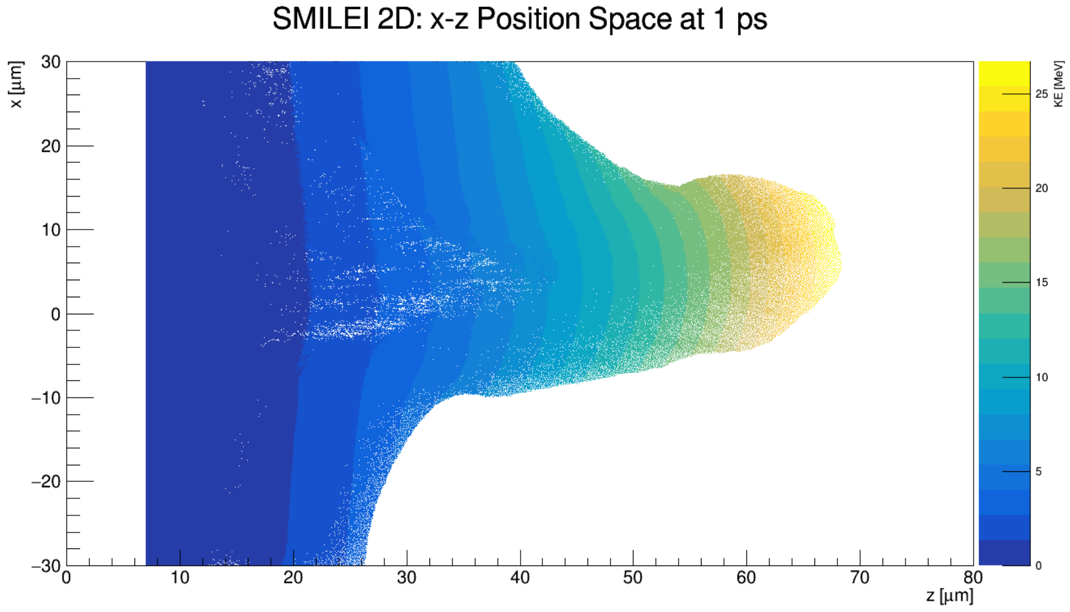
Initial Beam from the Laser Source

- Small emittance ($\sim 4.1 \times 10^{-7}\,\pi$.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



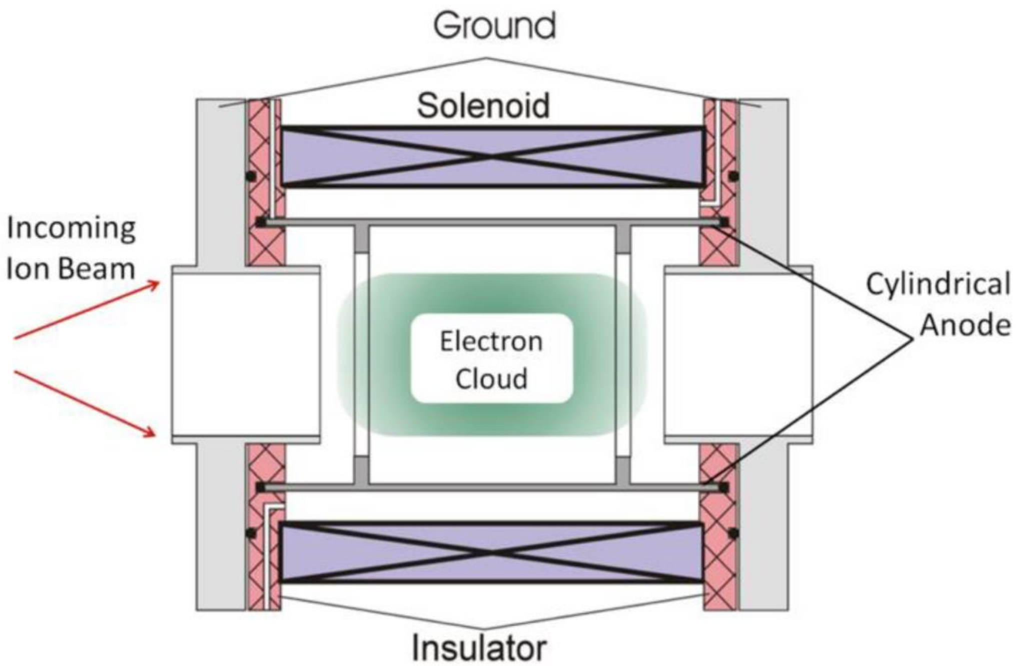
- Produces intense beams and multiple species, e.g. proton and carbon ions.

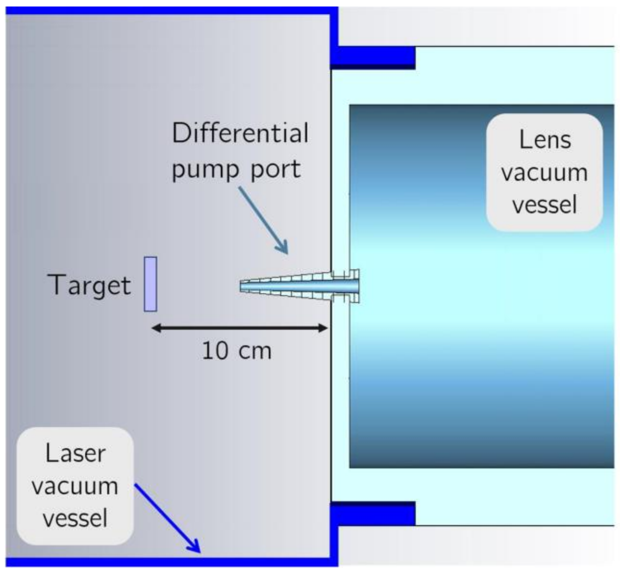


Results obtained using SMILEI PIC code:
J. Derouillat et al., Comput. Phys. Commun. 222, 351-373 (2018),

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.



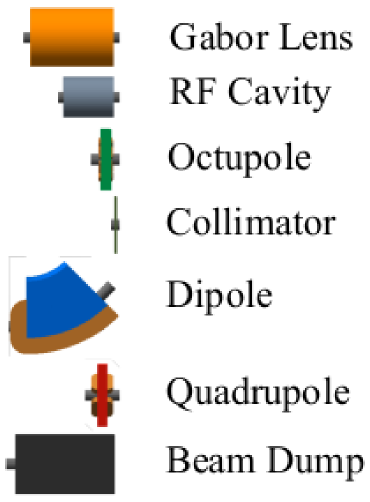


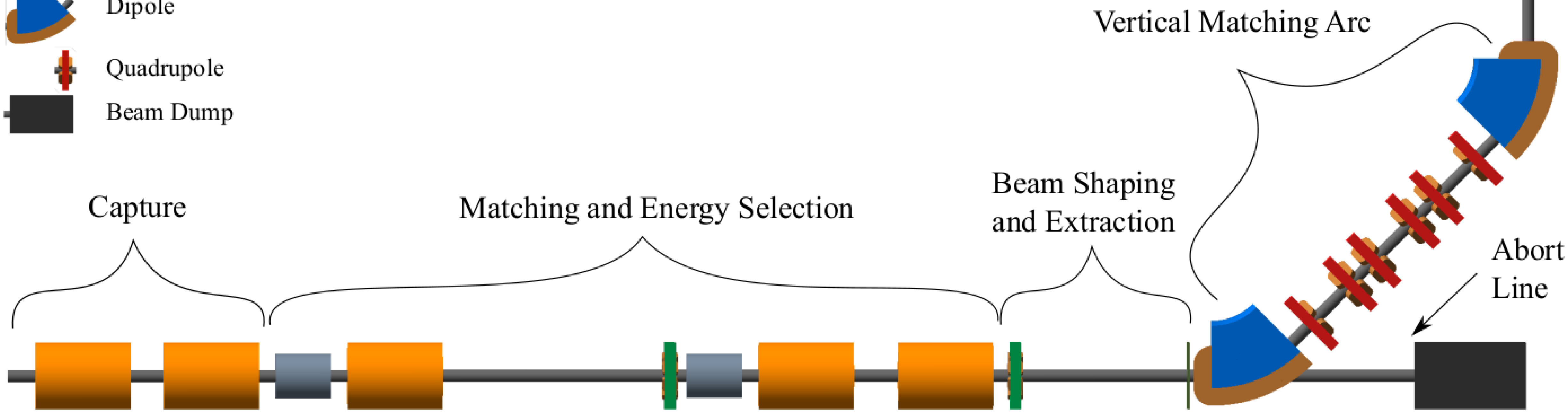
Target-capture interface

From C.G. Whyte

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

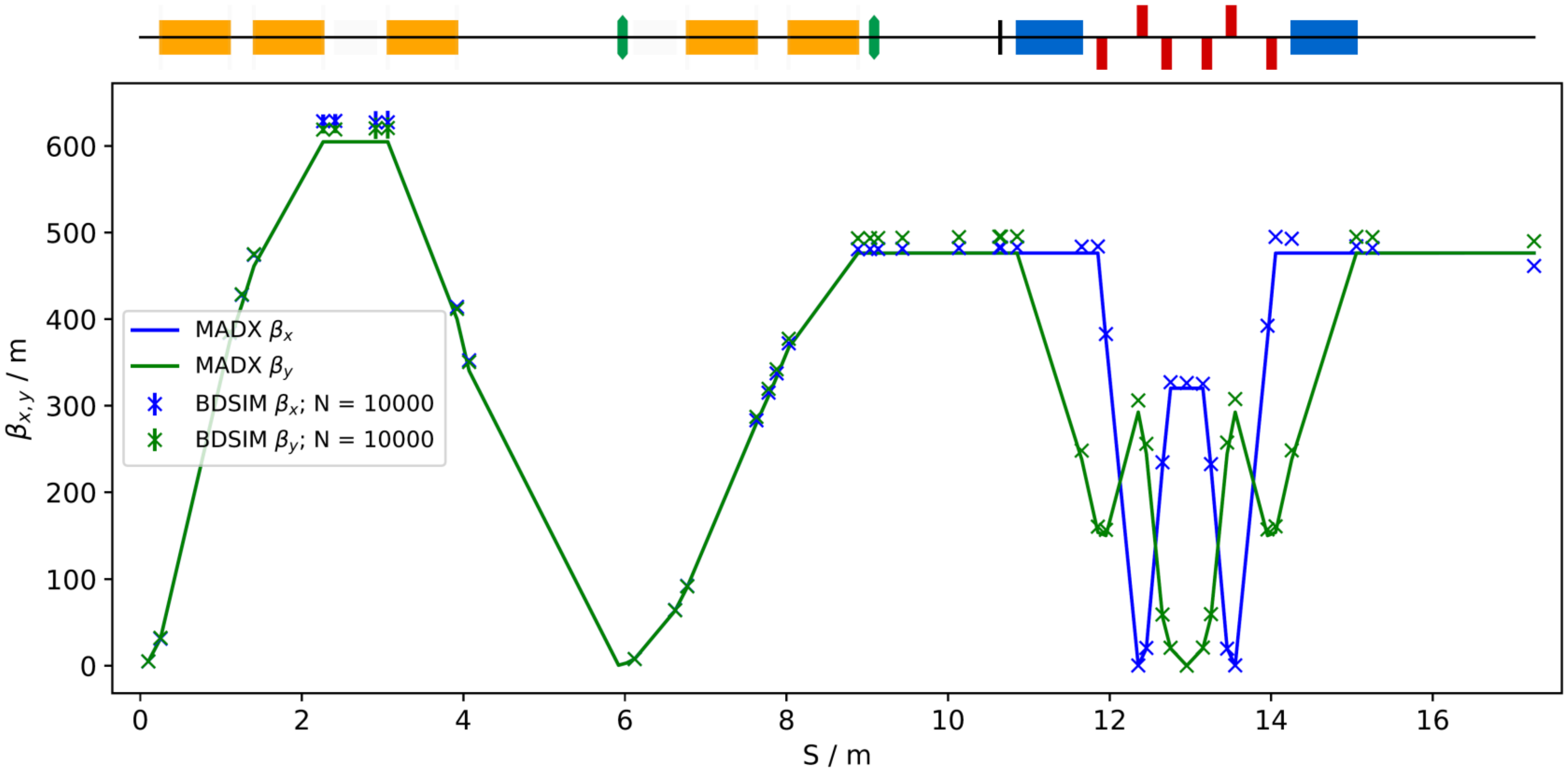




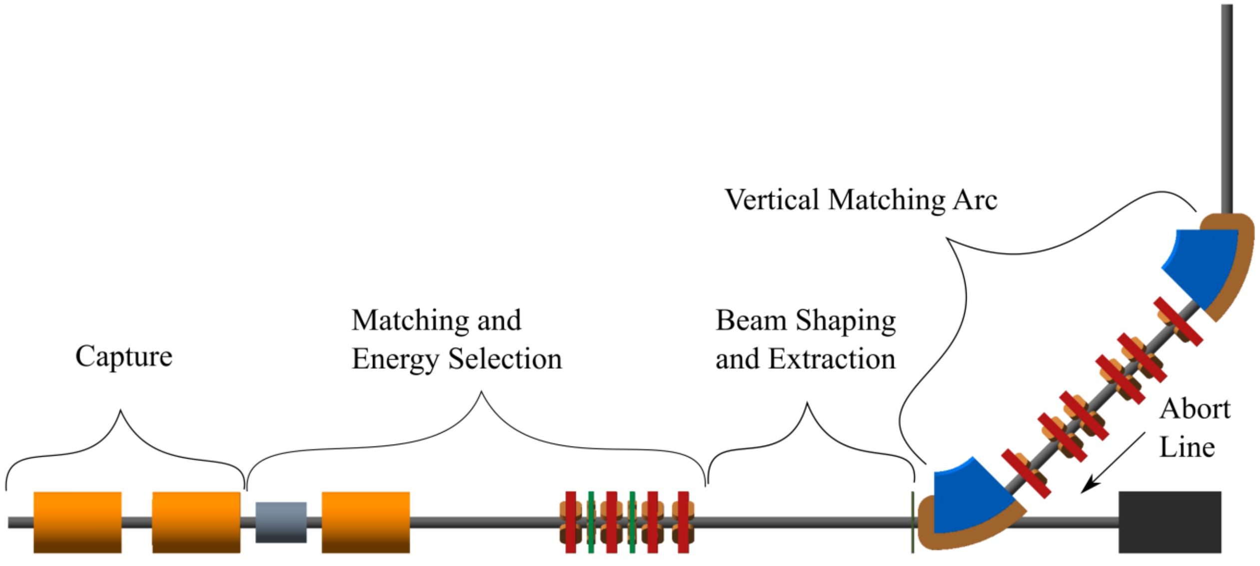
LhARA Stage 1, optics

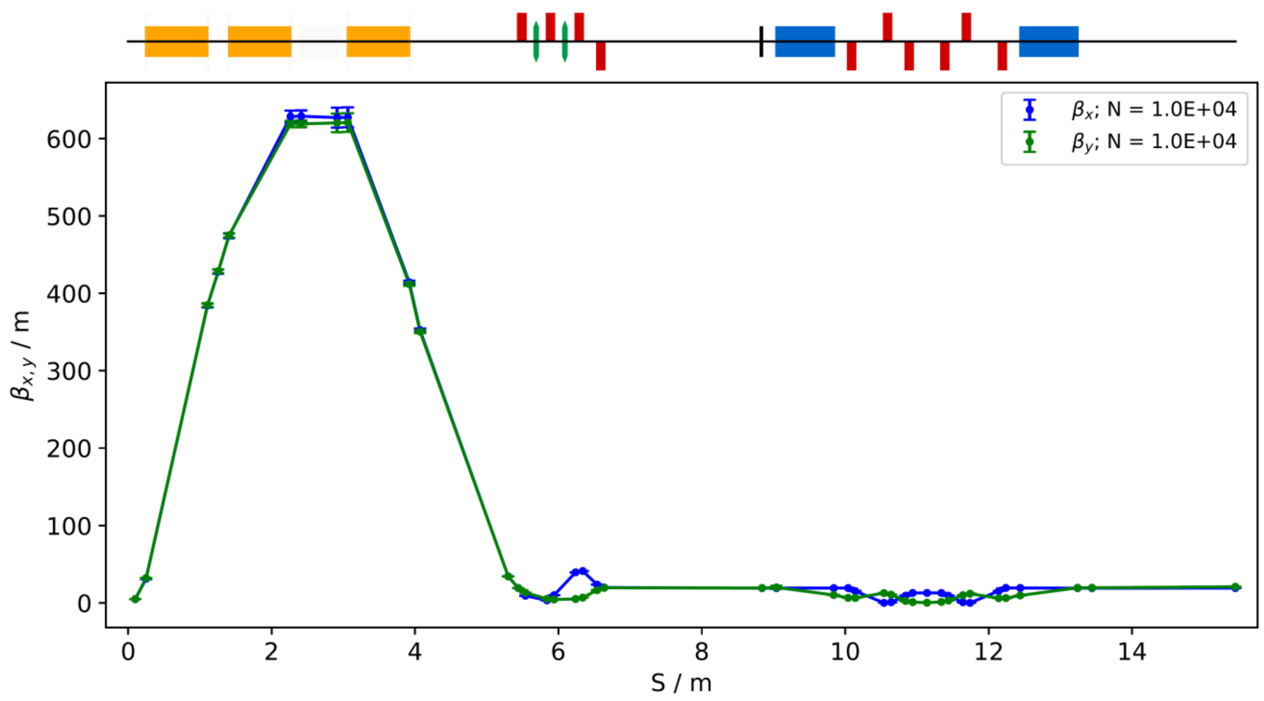
- Initial beam assumed neutral first (5cm) and then space charge must be taken into account
- Strong focusing in both planes by Gabor Lenses (or solenoids) essential in the capture section
- Matching to very small spot size unavoidable and used for the energy selection
- Matching with two lenses to the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

Achromatic vertical arc



Lhara Stage 1, alternative design



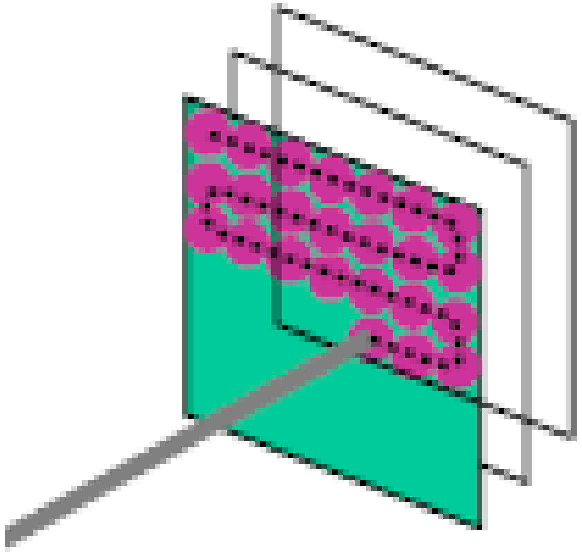


- Alternative design uses quadrupoles to avoid focusing to the spot in both planes simultaneously (a space charge mitigation)
- Octupoles would be in the right optical locations
- Optics optimisation with the space charge to be done and the performance to be demonstrated

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

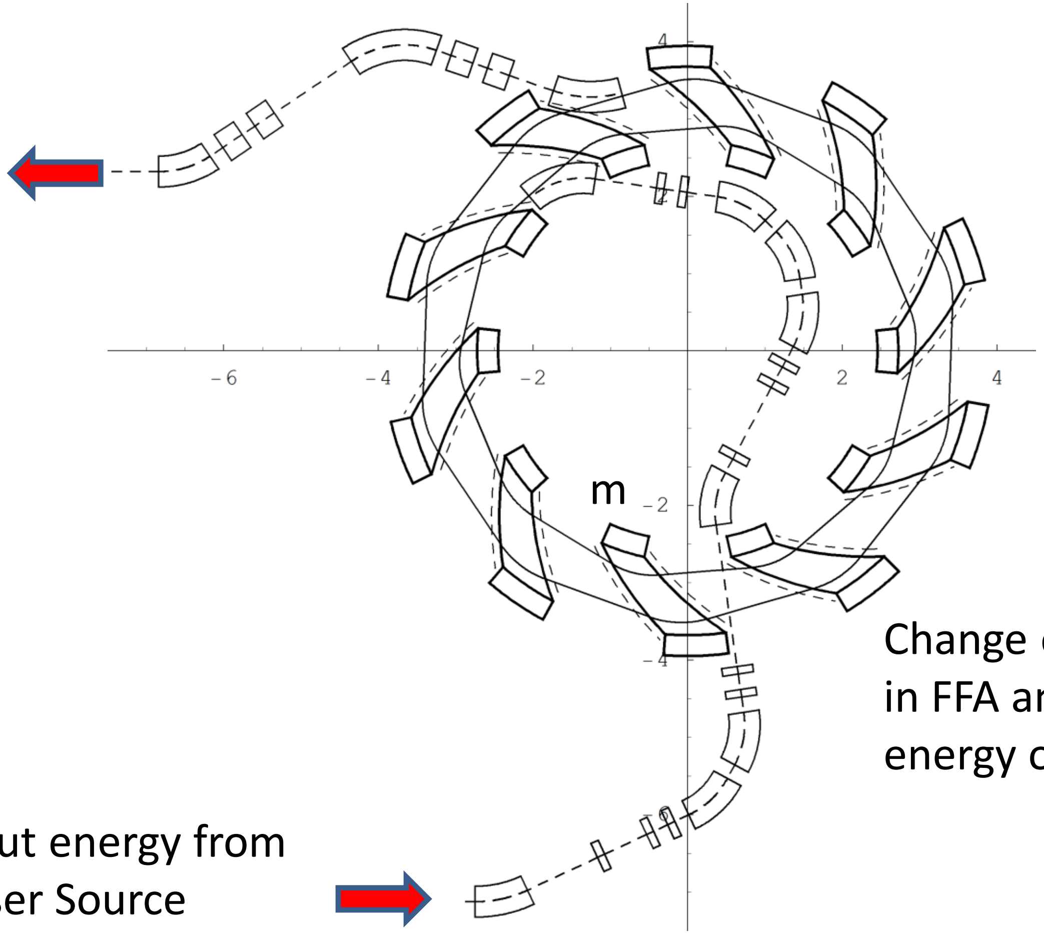


Energy Variability using Laser Accelerated Ions

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)

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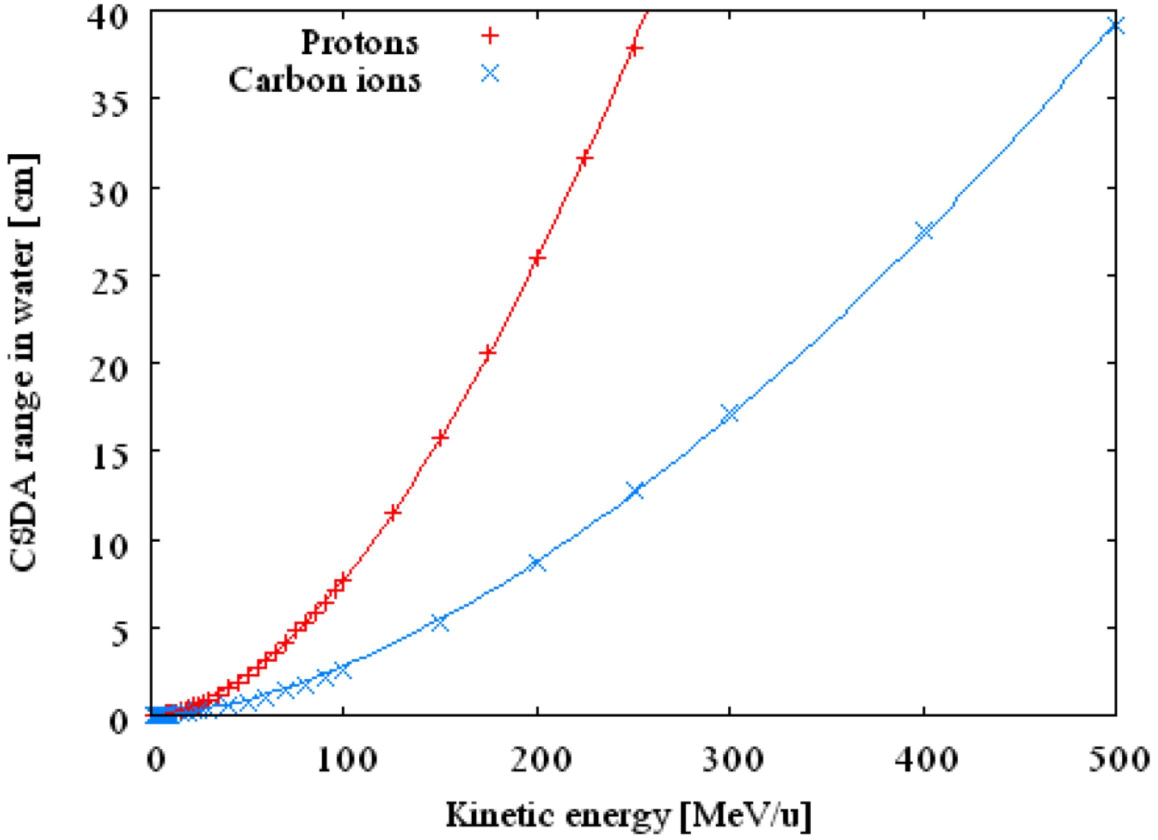
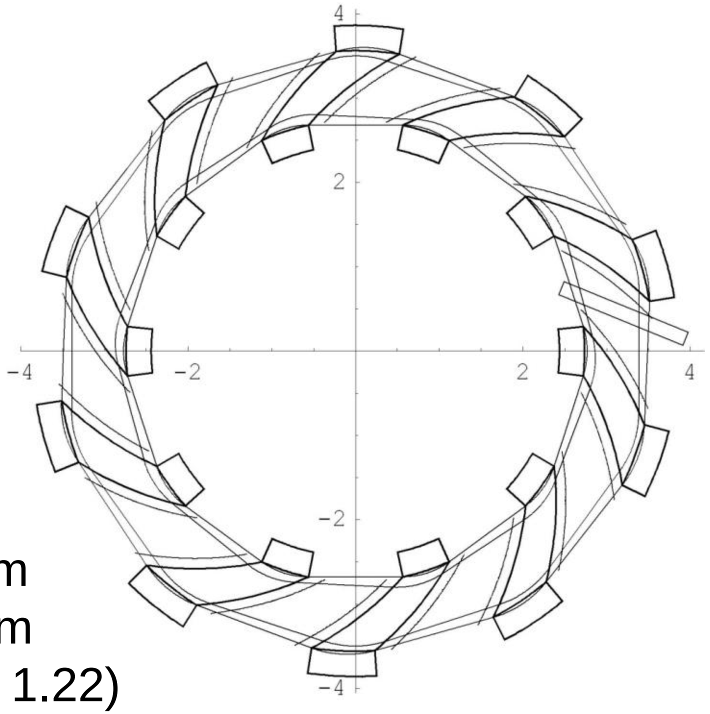
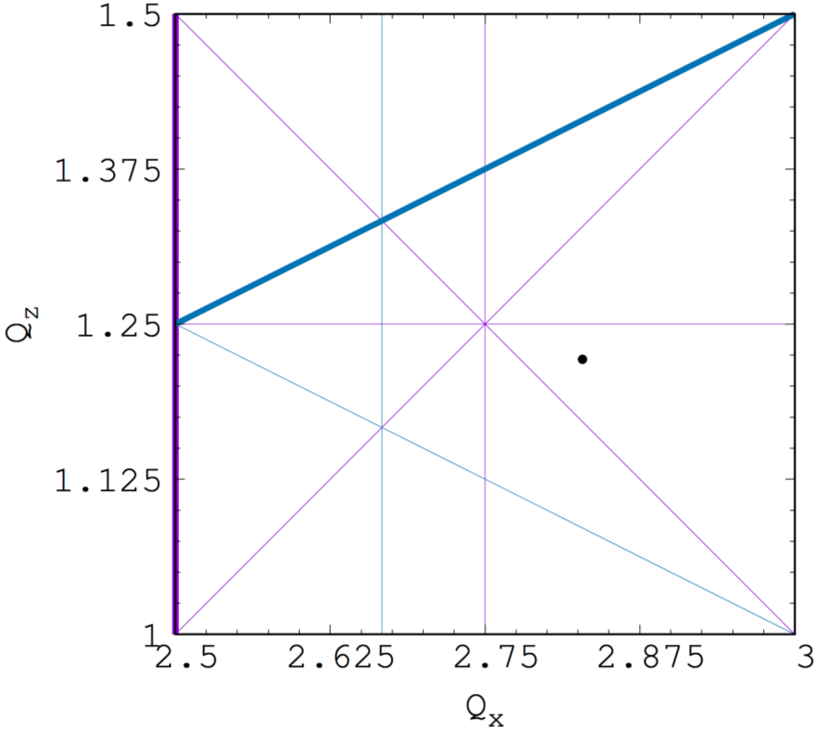
Energy for LhARA Stage 2

- 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 could be possible
- This would correspond to 33.4 MeV/u for C6+.

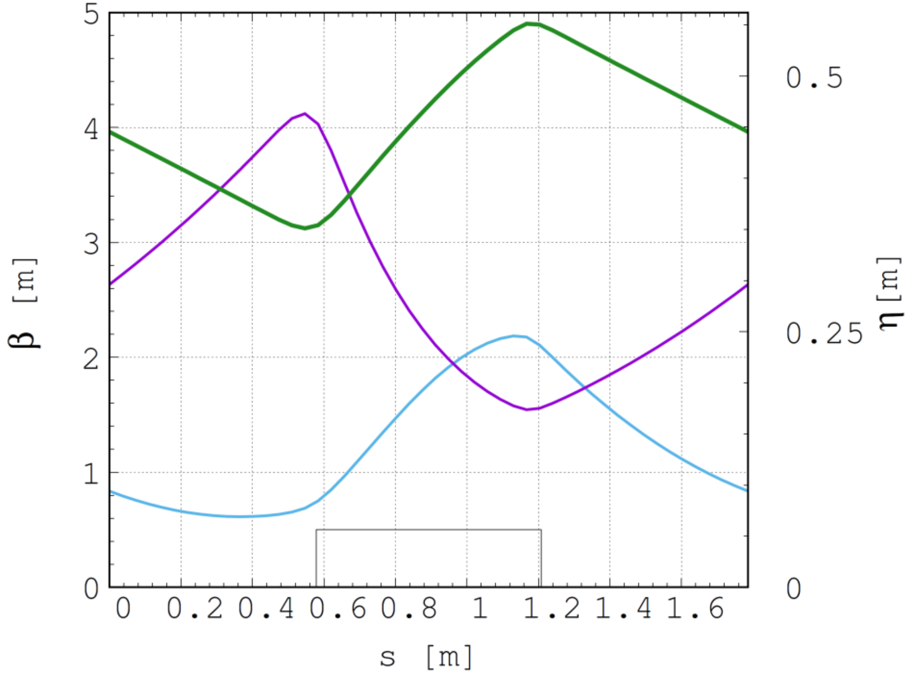


LhARA Ring Parameters



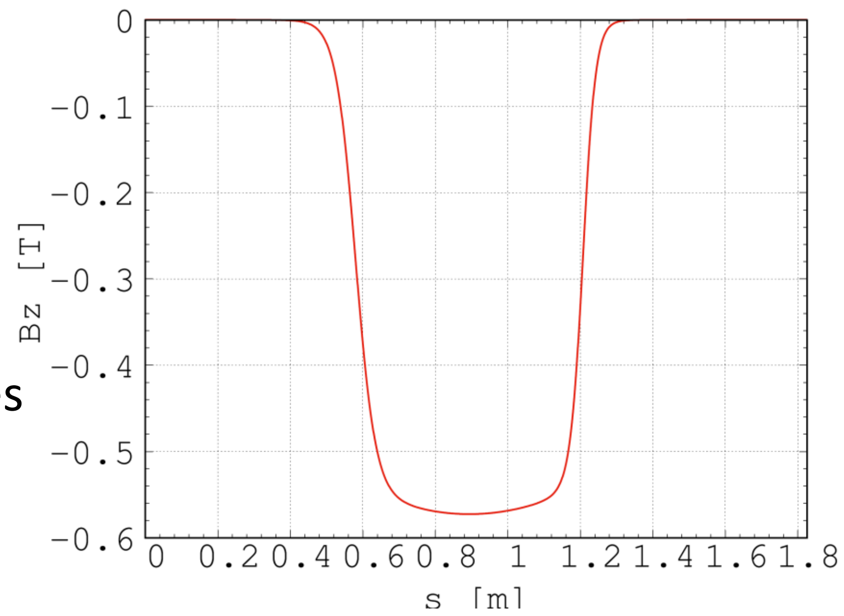


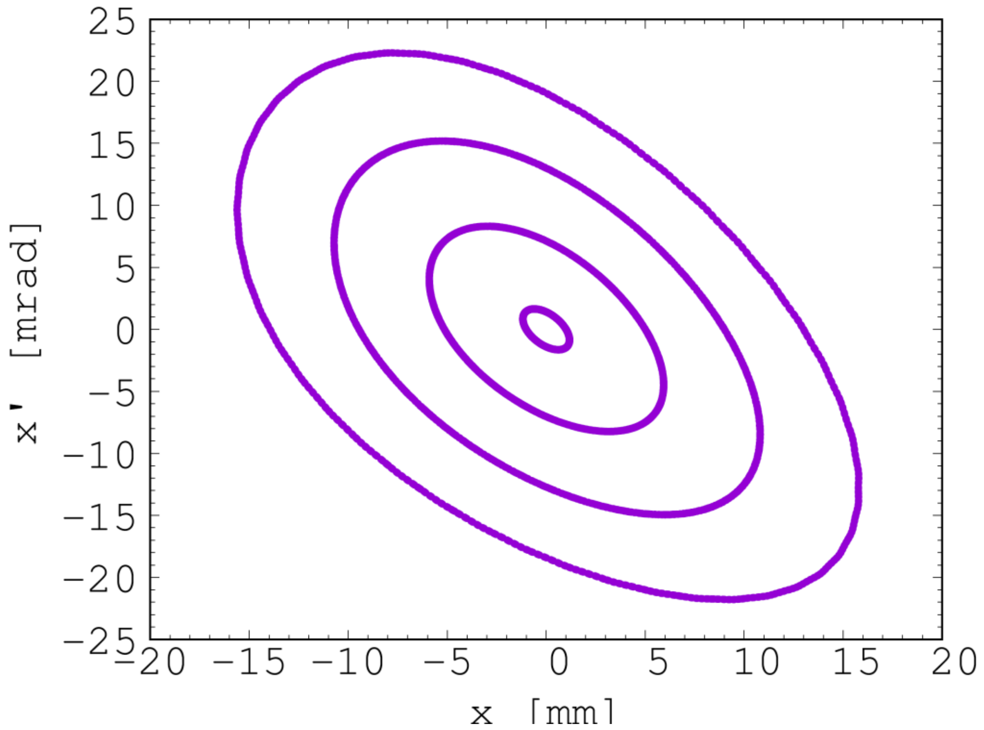
- N 10
- k 5.33
- Spiral angle 48.7°
- R_{max} 3.48 m
- R_{min} 2.92 m
- (Qx, Qy) (2.83, 1.22)
- B_{max} 1.4 T
- p_f 0.34
- Max Proton injection energy 15 MeV
- Max Proton extraction energy 127.4 MeV
- h 1
- RF frequency
  for proton acceleration (15-127.4MeV) 2.89 – 6.48 MHz
- Bunch intensity few×10^8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

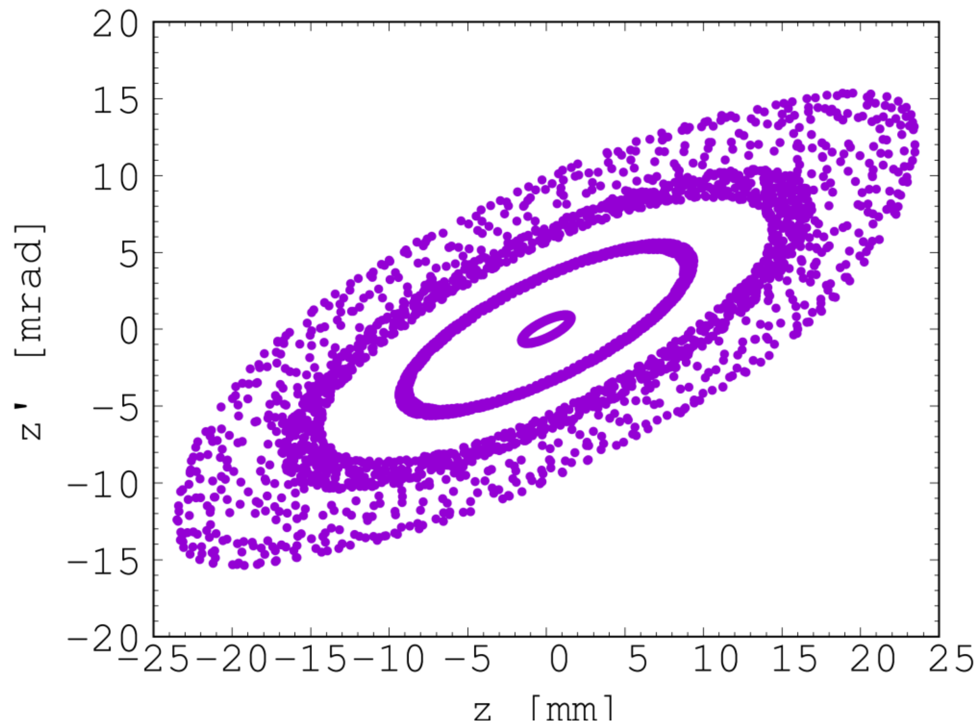


LhARA Ring Tracking

- 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
- Tracking performed using FixField code







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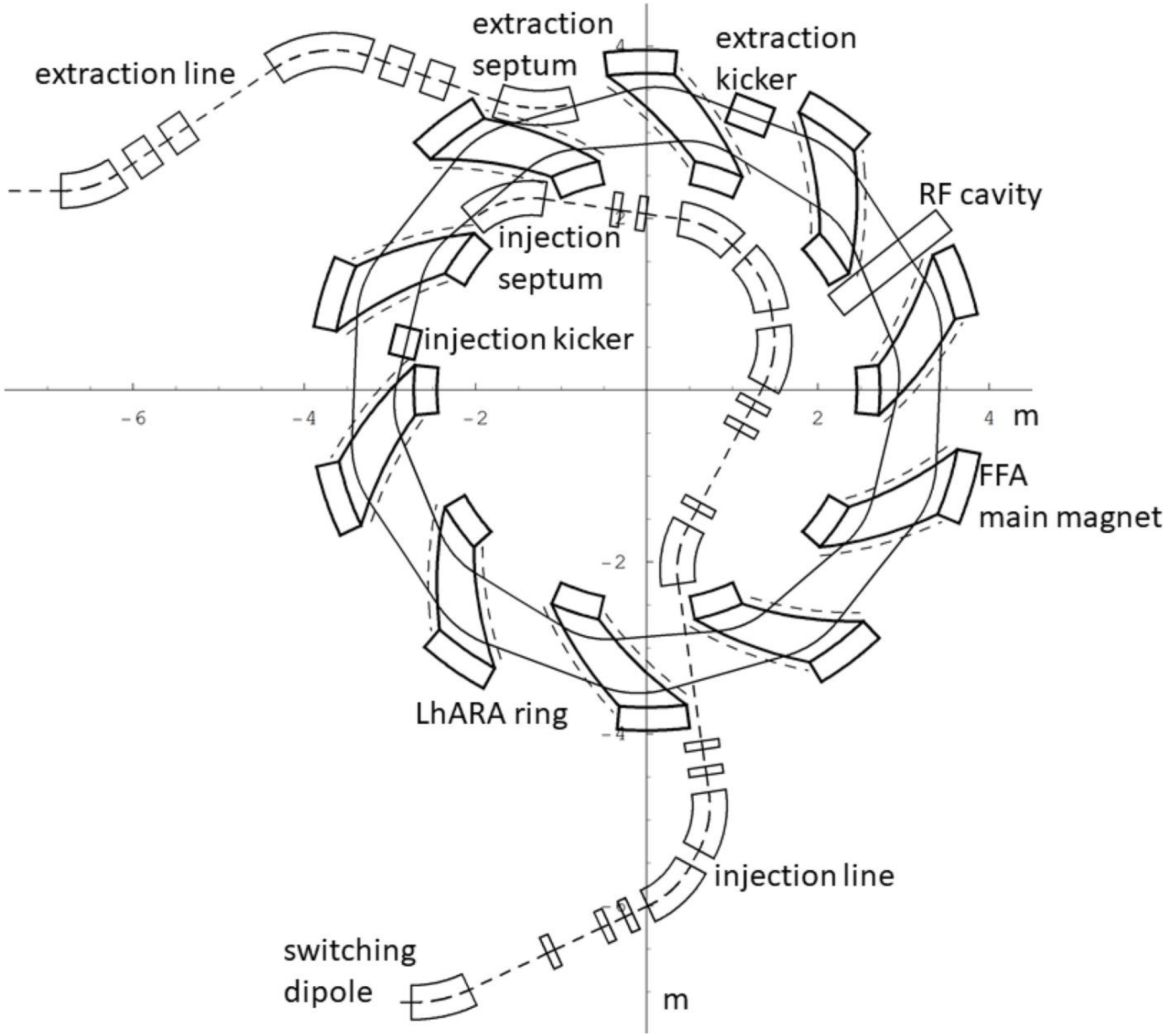
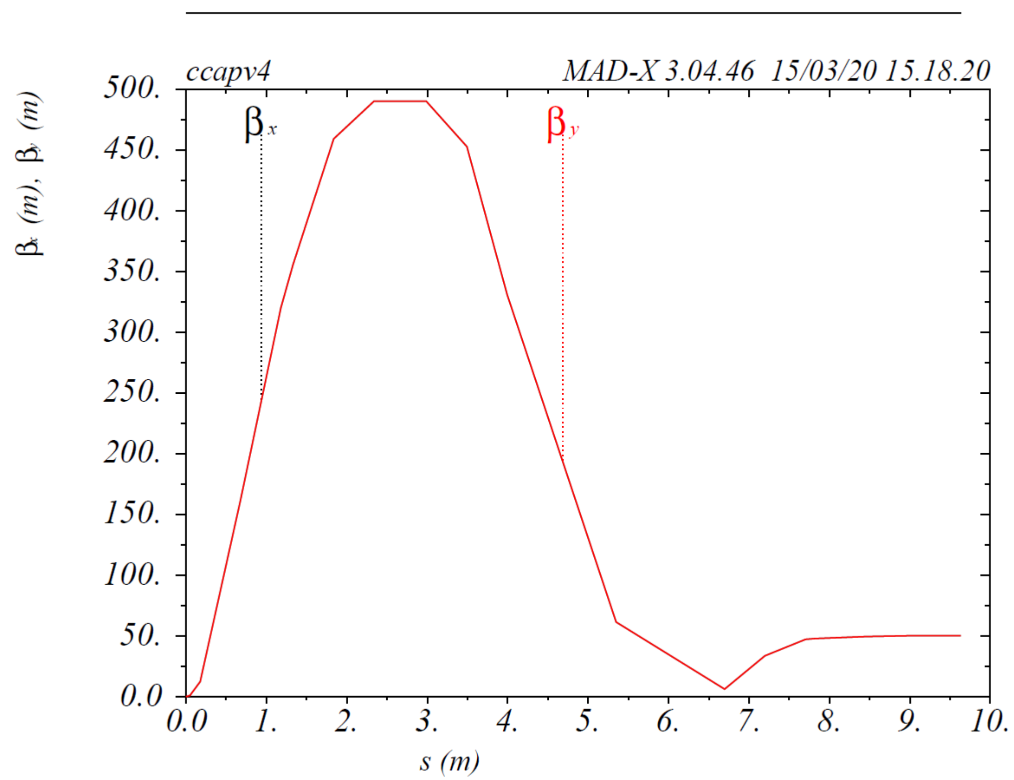
FFA Ring with subsystems

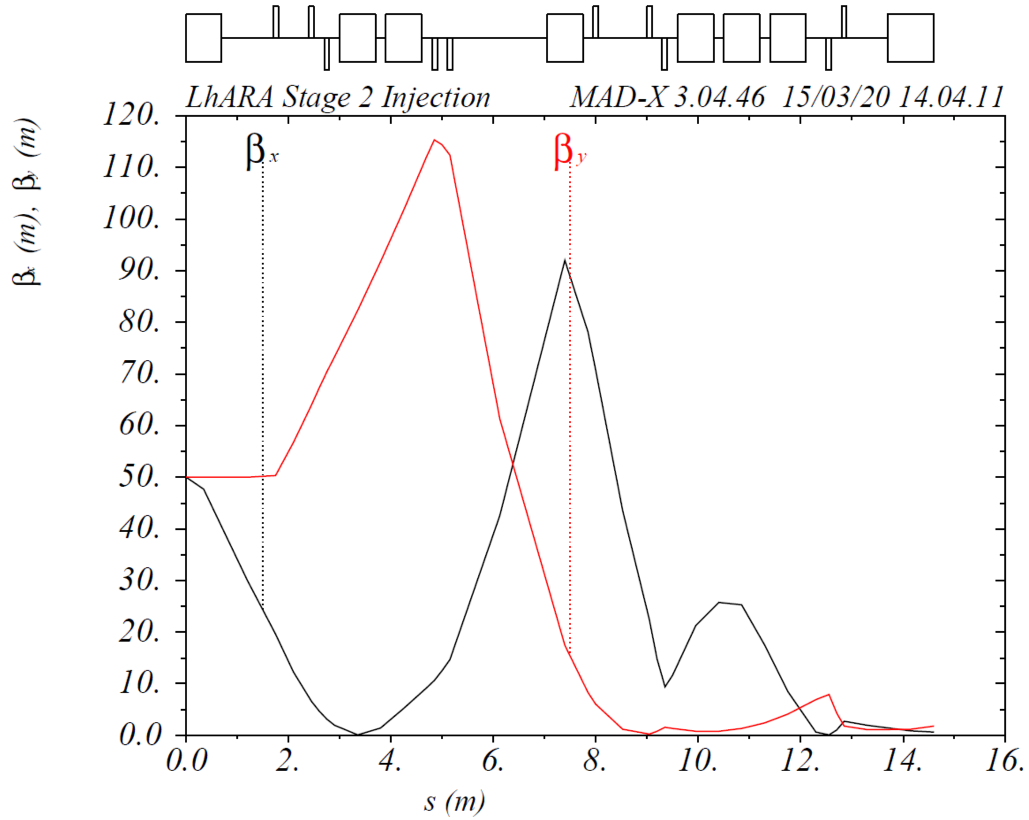
Parameter	unit	value
Injection septum:		
nominal magnetic field	T	0.53
magnetic length	m	0.9
deflection angle	degrees	48.7
thickness	cm	1
full gap	cm	3
pulsing rate	Hz	10
Extraction septum:		
nominal magnetic field	T	1.12
magnetic length	m	0.9
deflection angle	degrees	34.38
thickness	cm	1
full gap	cm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

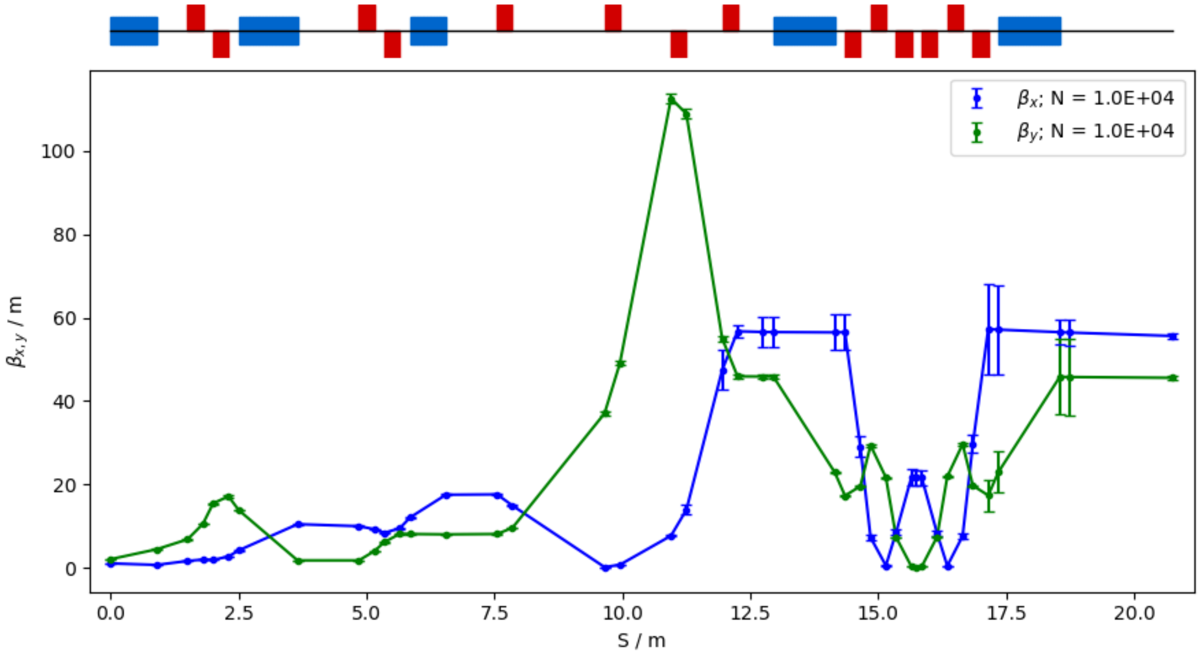


- Stage 1 can be tuned to match the injection line
- Focus point changes location and requires a dedicated collimation system
- Focusing can be realised with normal conducting solenoids

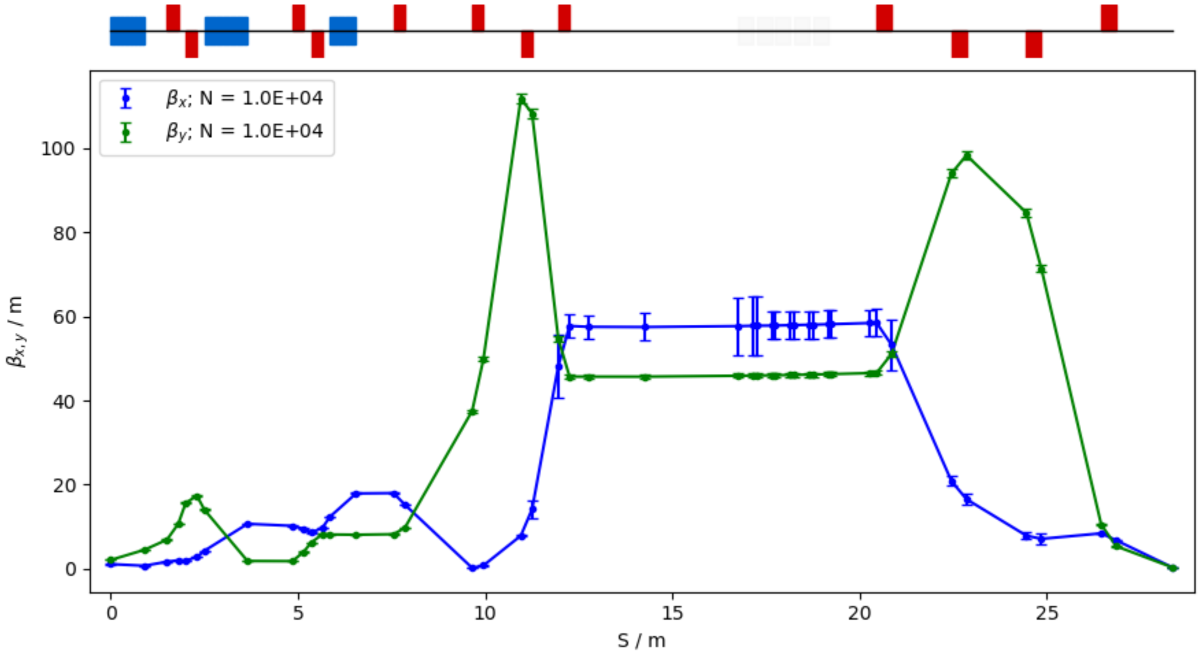


Optics from the switching dipole to the injection septum has been designed

Extraction optics



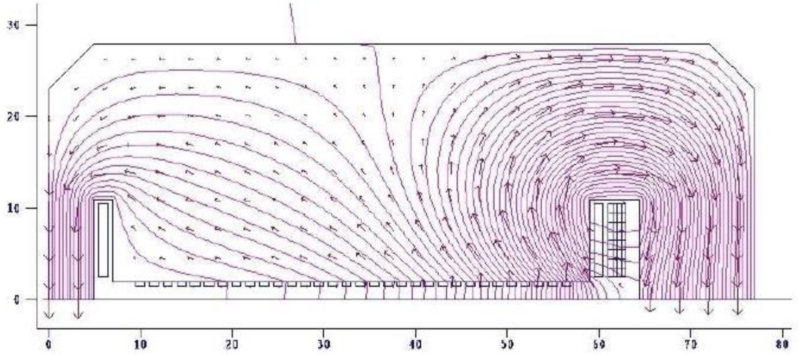
Optics for Stage 2 in-vitro end station, the arc optics scaled from the Stage 1

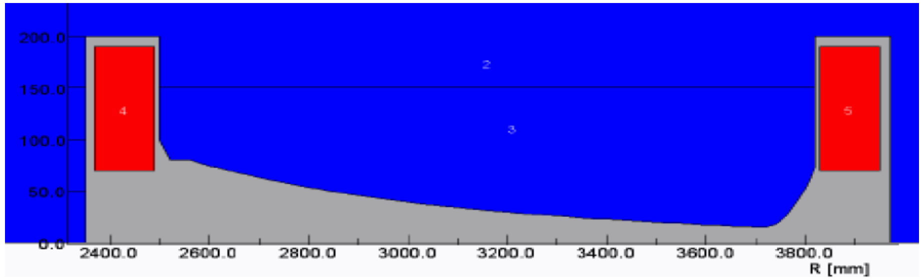


Optics for Stage 2 in-vivo end station, a dedicated final focus has been designed

Essential R&D

Magnet types to be considered



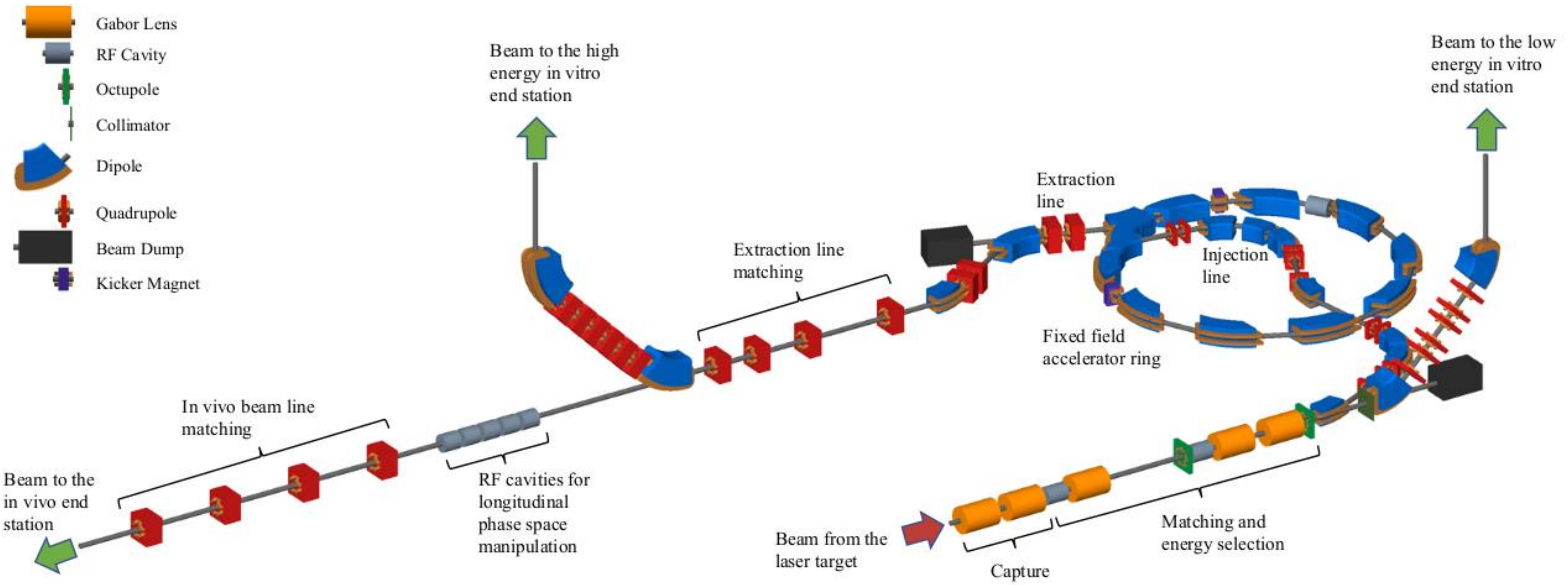


Magnet with distributed conductors:
- Parallel gap – vertical tune more stable,
- Flexible field and k adjustment,

„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
  - 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