FFA post-accelerator for LhARA

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30/09/2022, FFA'22

Outline

- Introduction
- LhARA baseline
- Ideas for the slow extraction
- Conclusions

Imperial College London

Science & Technology Facilities Council ISIS

LhARA

LhARA Laser-hybrid Accelerator for Radiobiological Applications

- 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.
- We are now funded project within ITRF initiative and we starting on Monday 3rd October to deliver CDR in 2 years time

Imperial College London

Science & Technology Facilities Council ISIS

Who are we?

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

Partners

University
Clinical
Laboratory
Industry
Accelerator

Corerain 鲲云科技

LEO Cancer Care

MAXELER Technologies
Maximum Performance Computing

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

The Rosalind Franklin Institute

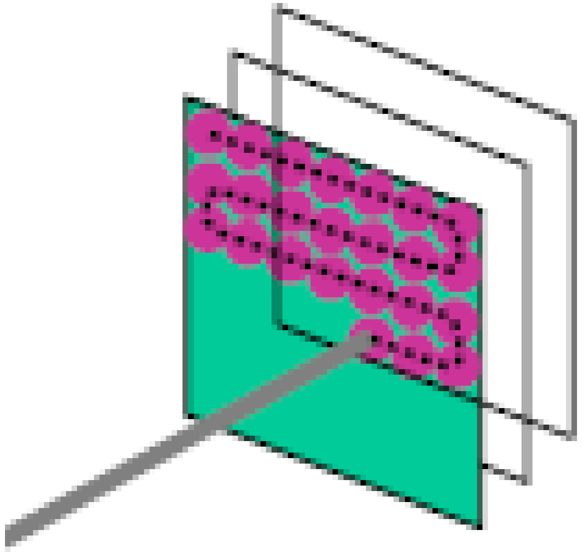
NPL National Physical Laboratory

The LhARA consortium

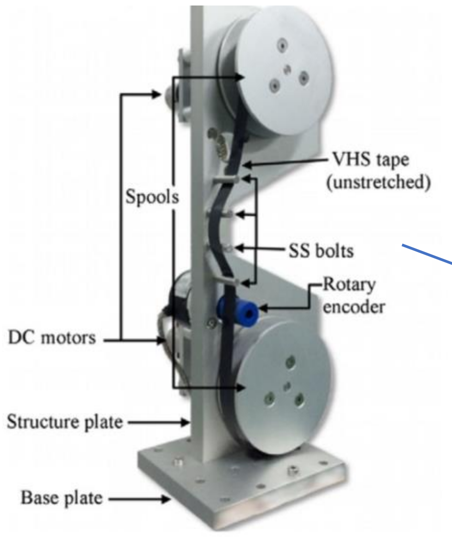
Motivations for a Medical/Radiobiological FFA (Fixed Field Accelerator)

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



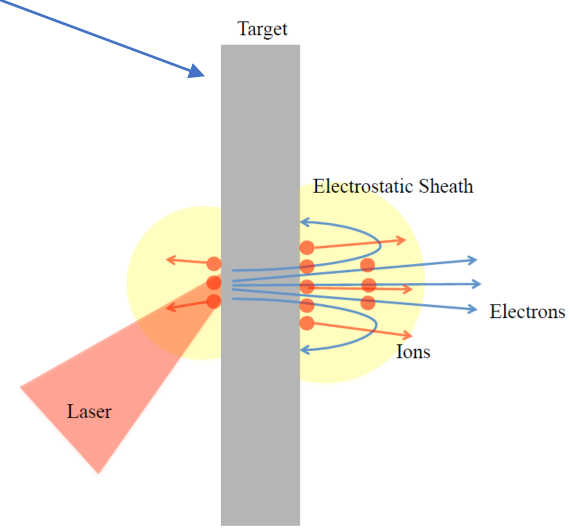
Current status of laser accelerators



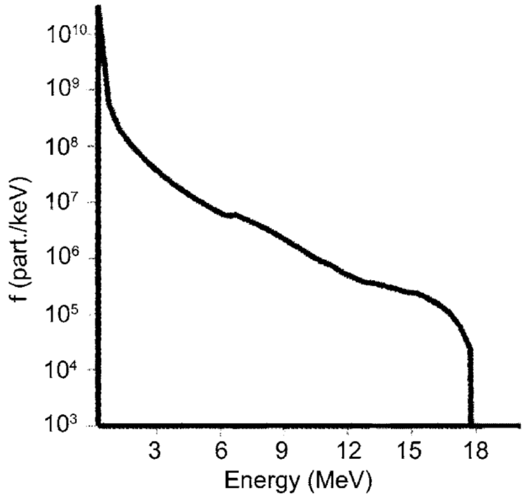
Noaman-ul-Haq et al. PRAB (2017)

Tape target

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

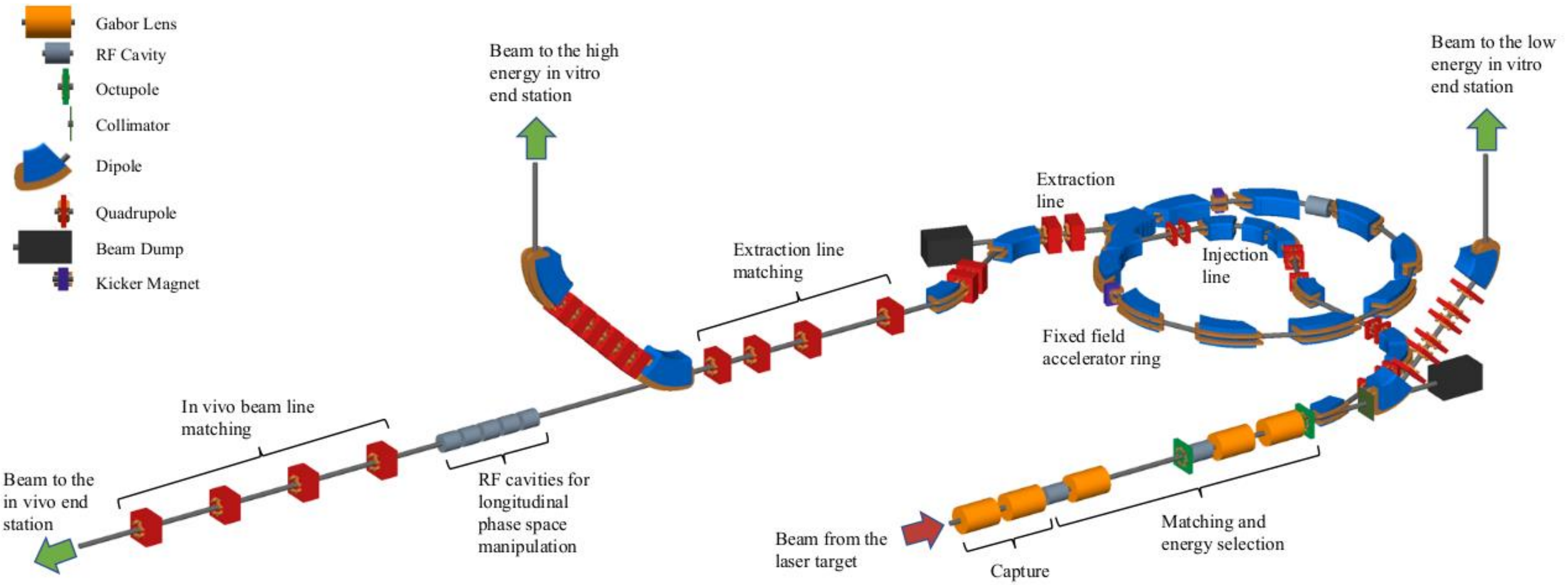


15MeV energies for LhARA injection achievable as part of thermal particle distribution



From O. Ettlinger

Layout of the full LhARA facility

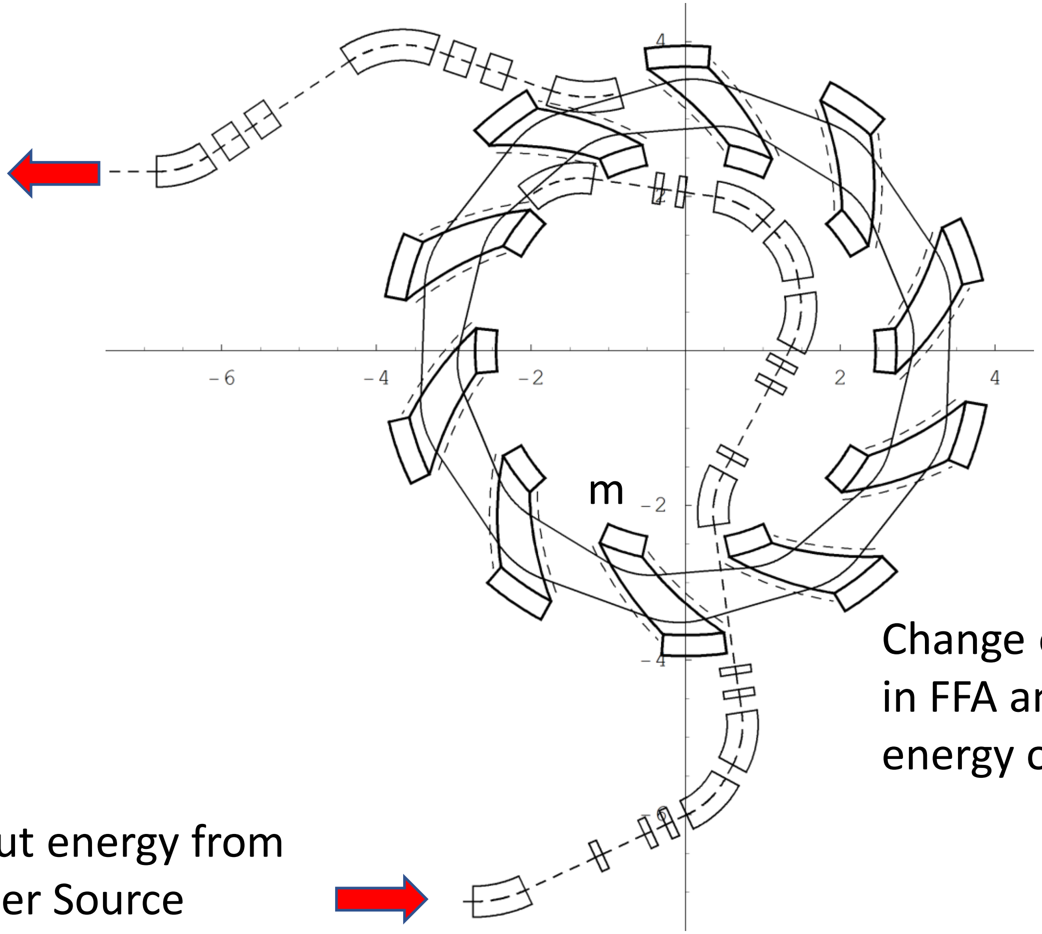


Energy Variability using Laser Accelerated Ions

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

+

pulse by pulse variation with kicker could be implemented

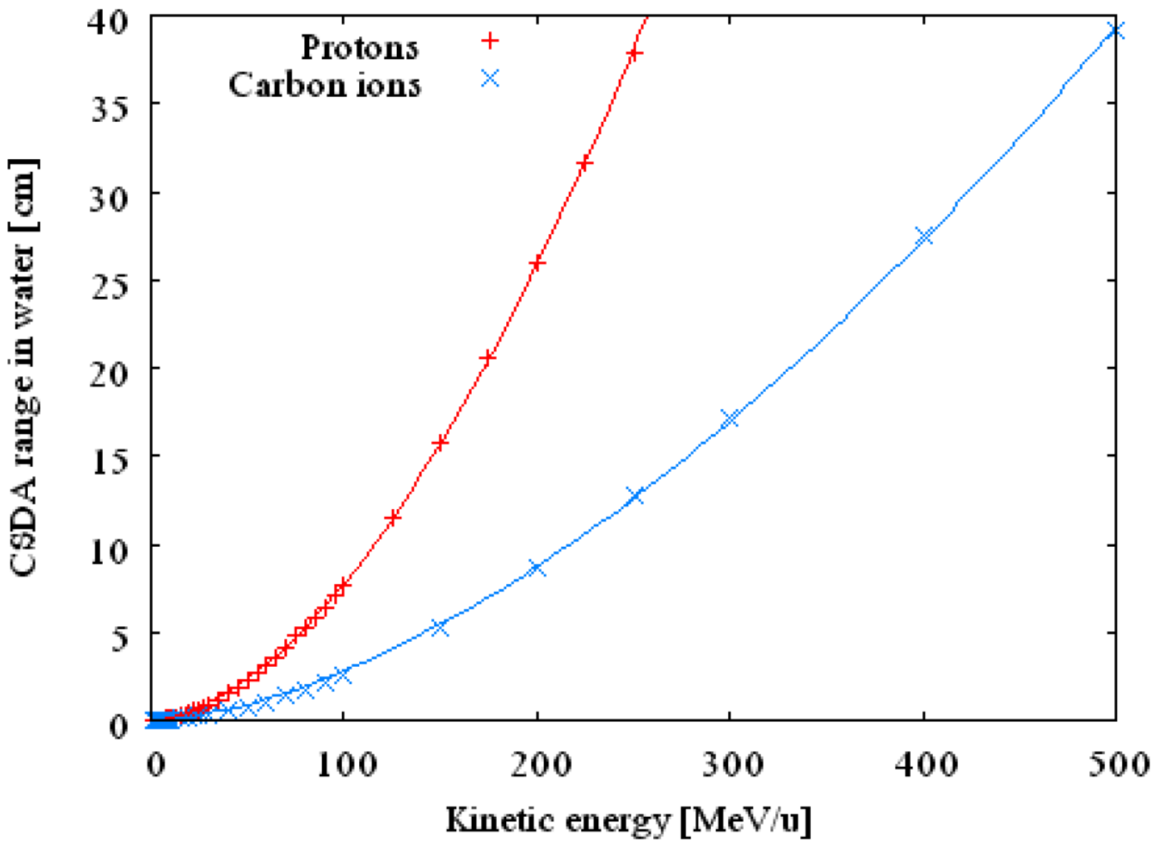


Change of the value of magnetic field in FFA and transfer lines for a specific energy operation (laminated magnets)

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

Energy for LhARA Stage 2

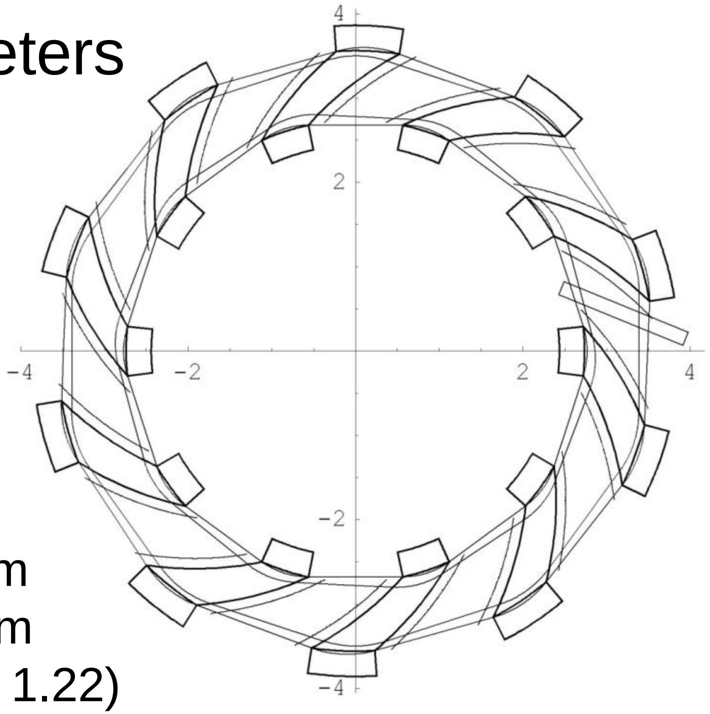
- FFA accelerator can typically accelerate by a factor of 3 in momentum (or more). This allows to easily achieve 127.4 MeV (starting from 15 MeV).
  - Acceleration by a factor of 4 could be possible
- This would correspond to 33.4 MeV/u for C6+.

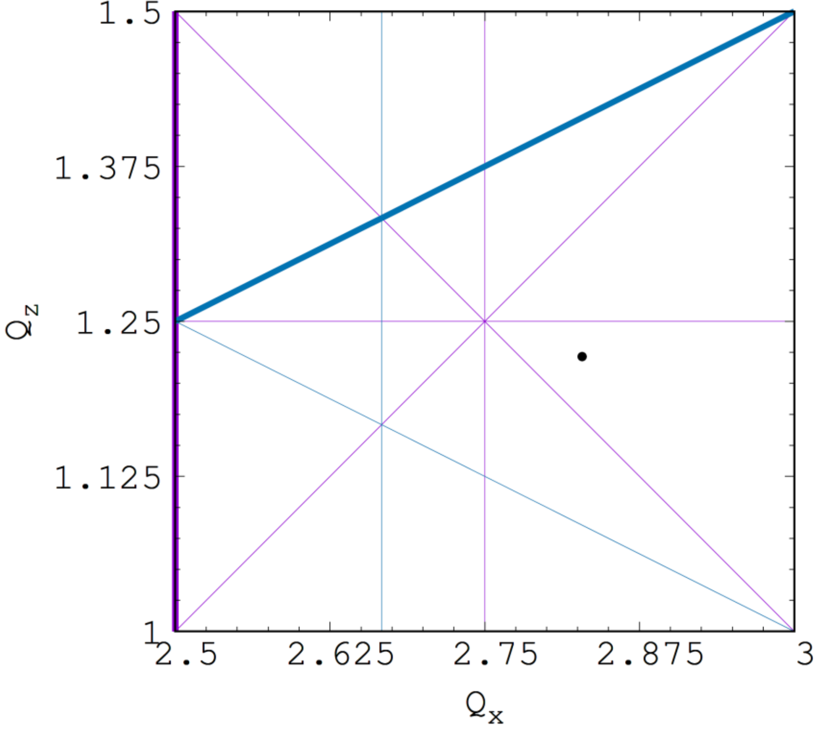


FFA lattice types for considerations

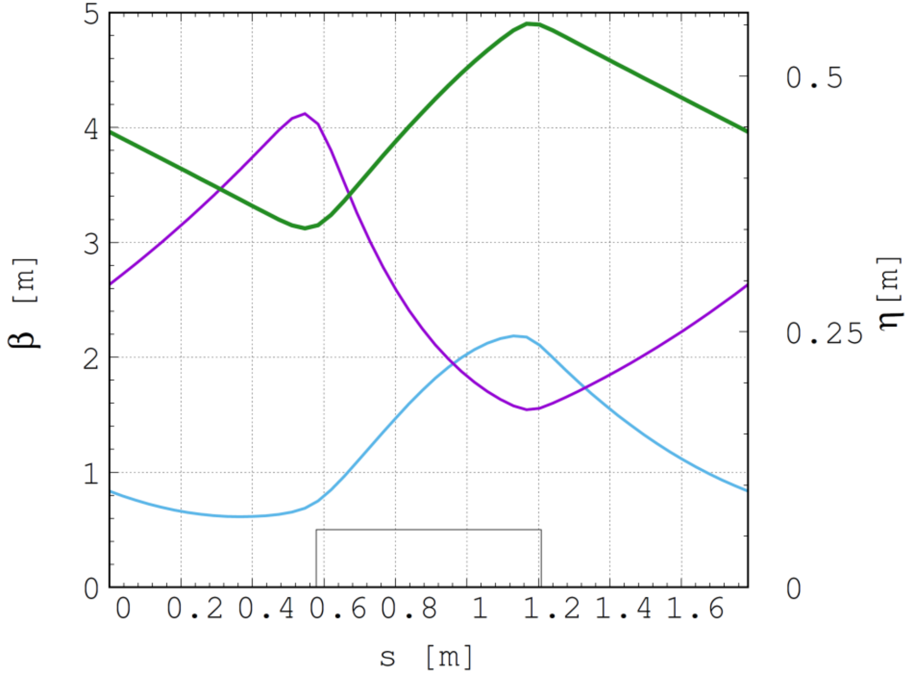
- Single scaling spiral FFA
  - Chosen for the baseline
  - Single magnet per lattice cell
  - Spiral magnet needed
- VFFA –Vertical FFA
  - In considerations for ISIS upgrade at RAL
  - Requires VFFA magnets (2 or 3 per cell) – work in progress
- Tilted sector type
  - Simple magnet geometry
  - Two magnets per cell
  - Requires a dedicated chromaticity correction (work in progress)

LhARA baseline Ring Parameters





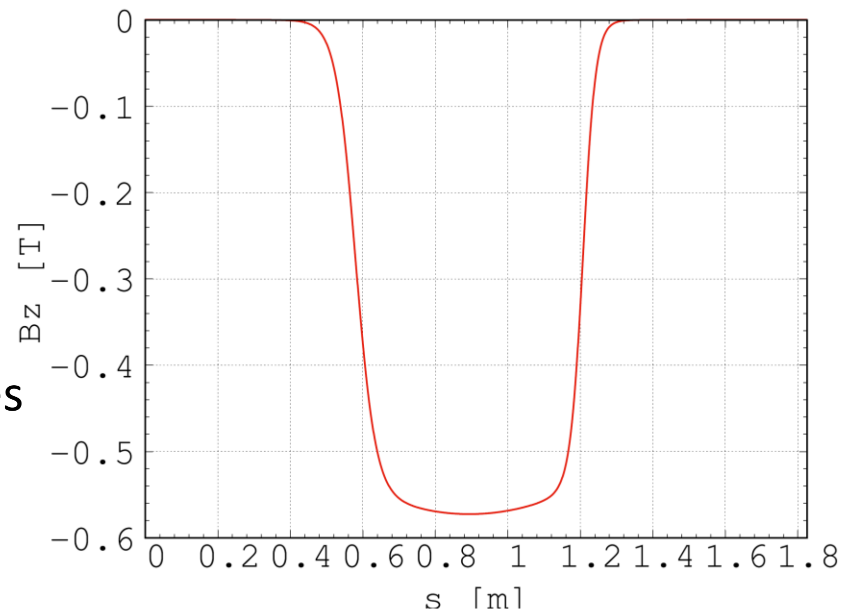
- N 10
- k 5.33
- Spiral angle 48.7°
- R_{max} 3.48 m
- R_{min} 2.92 m
- (Qx, Qy) (2.83, 1.22)
- B_{max} 1.4 T
- p_f 0.34
- Max Proton injection energy 15 MeV
- Max Proton extraction energy 127.4 MeV
- h 1
- RF frequency
  for proton acceleration (15-127.4MeV) 2.89 – 6.48 MHz
- Bunch intensity few×10^8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

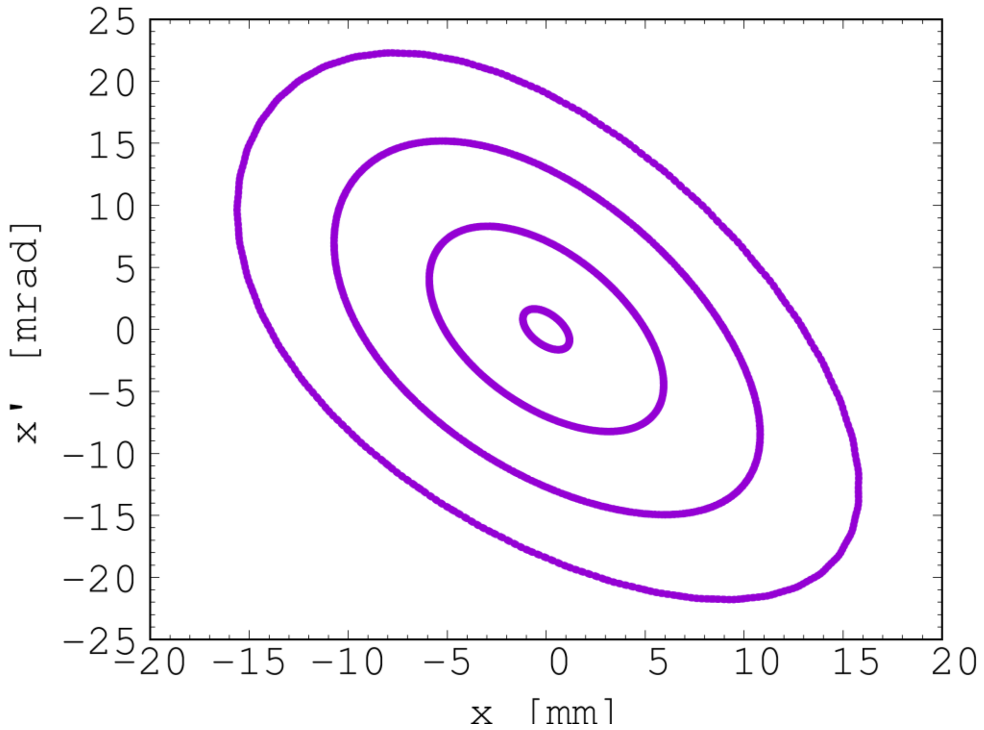


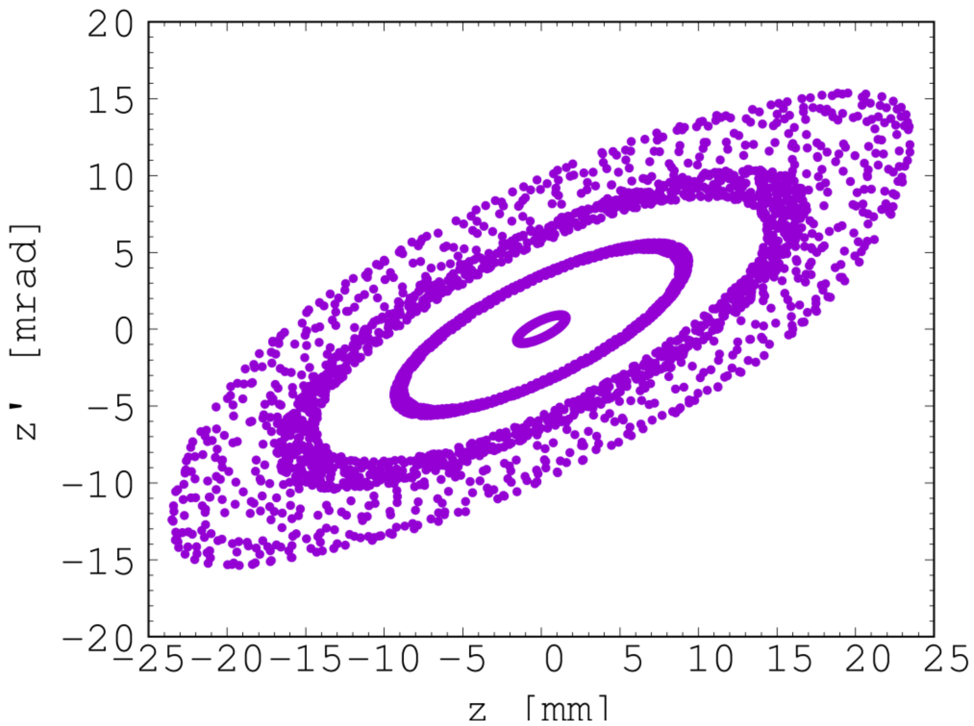
J. Pasternak, IC London

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

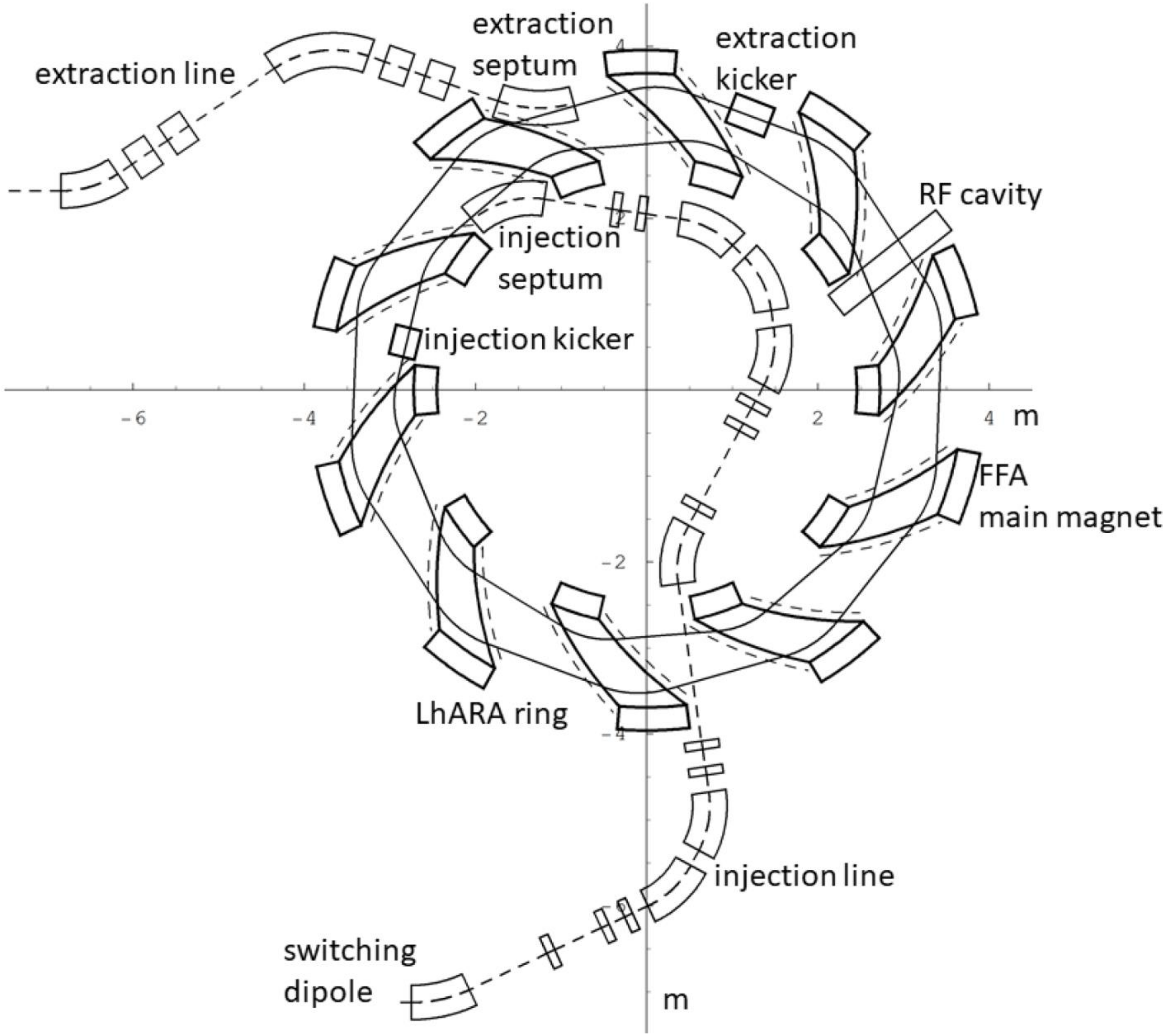






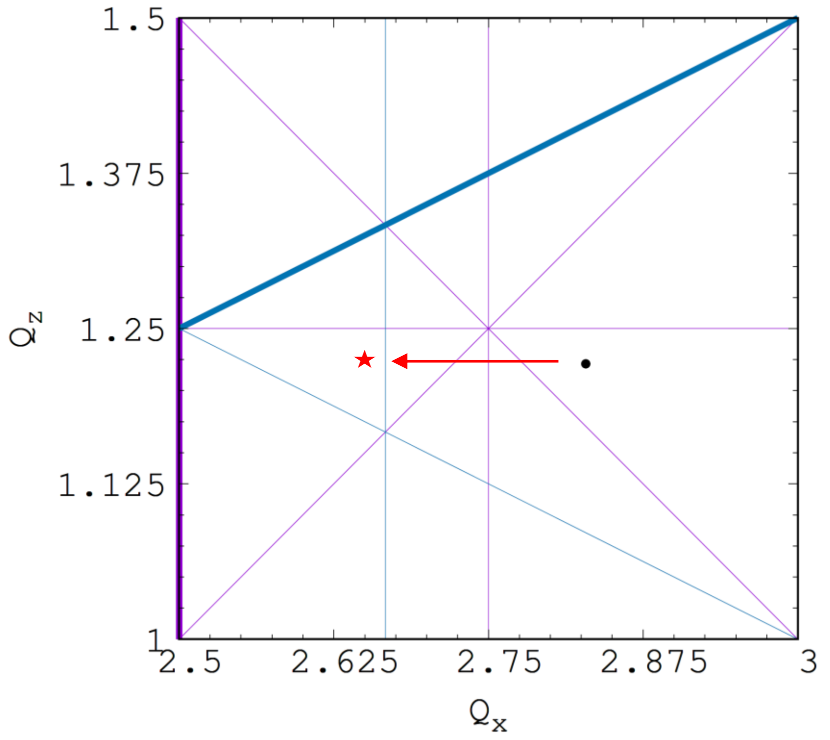
FFA Ring with subsystems

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



Preliminary ideas for the Slow Extraction from LhARA FFA

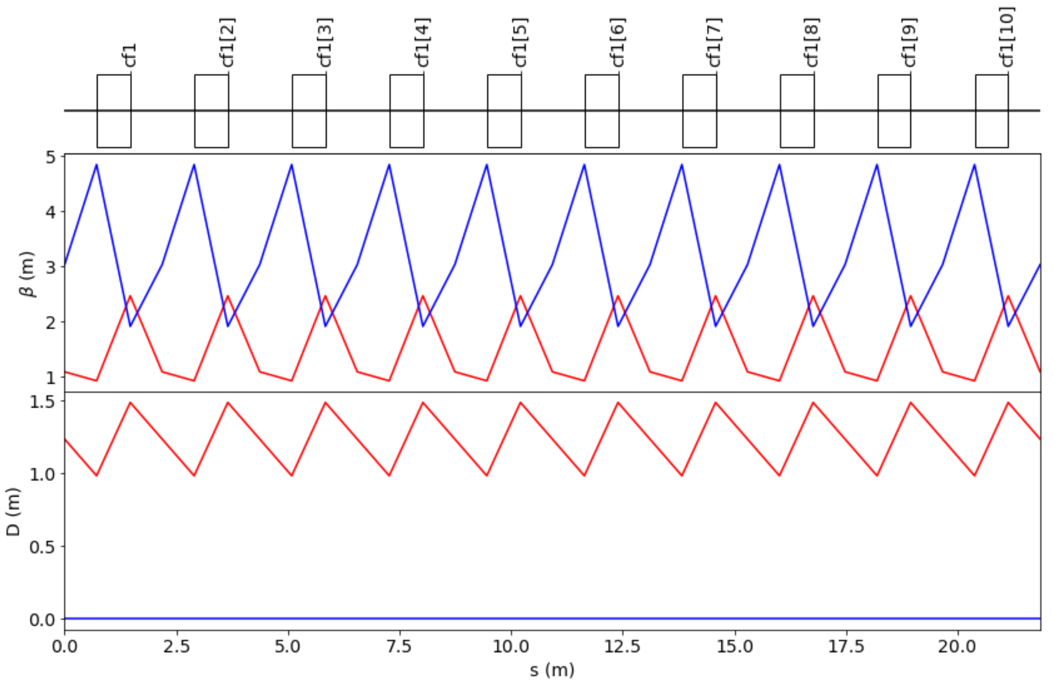
- N 10
- k 4.642
- Spiral angle 46.7°
- R_{max} 3.48 m
- R_{min} 2.86 m (6cm more than in baseline)
- (Qx, Qy) (2.66, 1.22)
- B_{max} 1.4 T
- p_f 0.34
- Max Proton injection energy 15 MeV
- Max Proton extraction energy 127.4 MeV
- h 1



- The horizontal tune moved just below the 3rd order resonance
- Tune can be moved towards the resonance at the end of acceleration with k-coils
  - Orbit could be adjusted be bumpers or by the control of beam momentum using RF
- It is not clear, if natural sextupolar component will be enough to control the slow extraction fully
  - RF KO can be used
  - Additional sextupolar winding around the extraction orbit could be added
  - Electrostatic septum will be needed downstream the magnetic one

Requirements for conventional Slow Extraction:

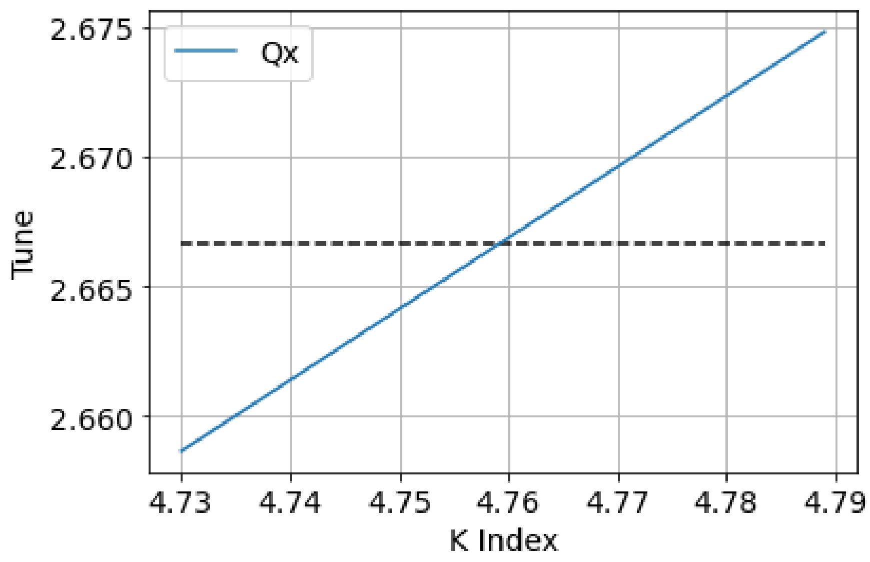
- Tune near **third-order resonance** (2.666 or 3.333)
  - Can be provided by matching k-index
- Substantial sextupole strength
  - k2L = 0.92 per cell
  - Cancels out to total virtual S = 0.0006
  - Dedicated resonant sextupole required
- Controlled excitation of particles into resonance, e.g.
  - Transverse x' kick to particles via RF-KO exciter
  - Fast-reacting quadrupole to sweep tune
  - Ramping of k-index with time

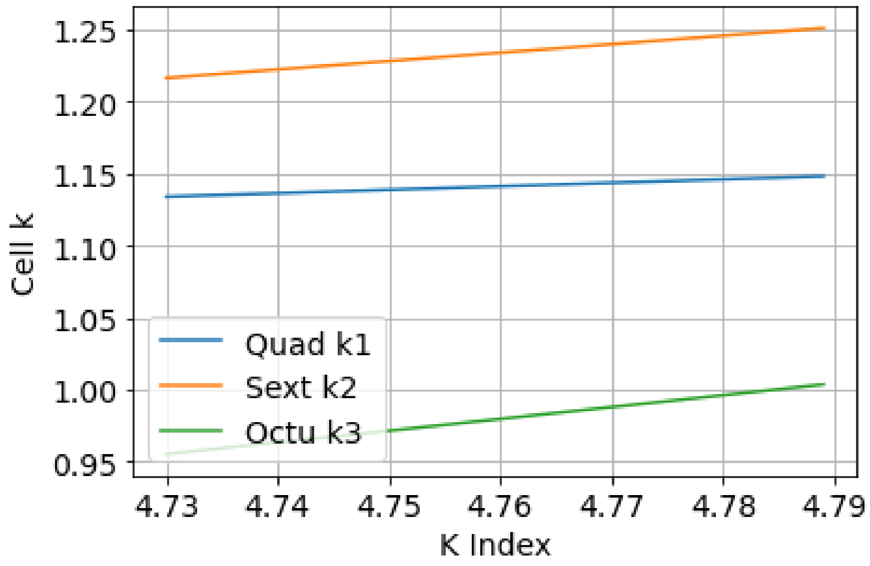


Optics of LhARA FFA at Extraction Orbit

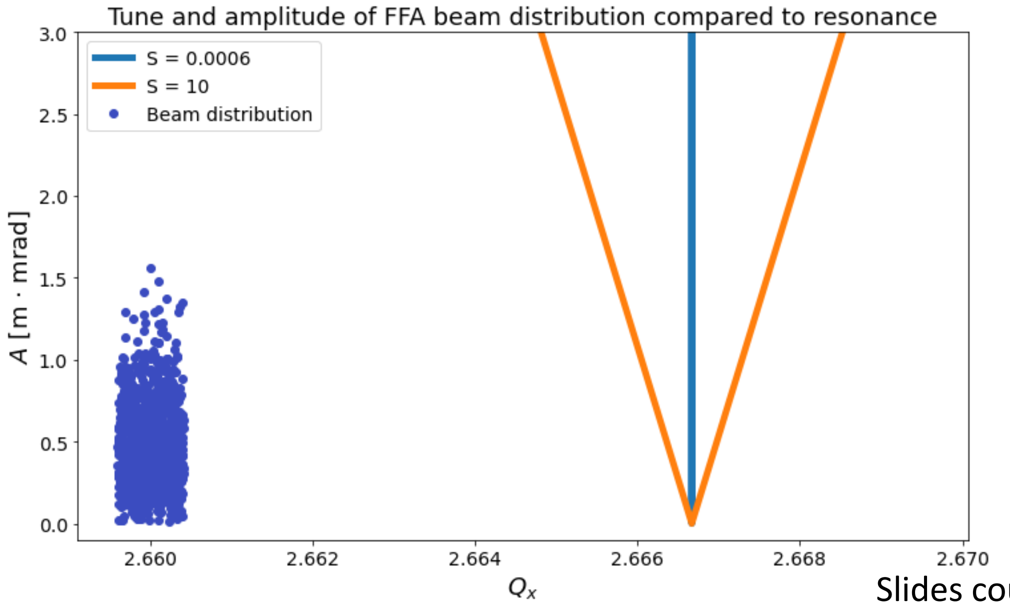
Slides courtesy of R. Taylor

Ramping k-index into resonance





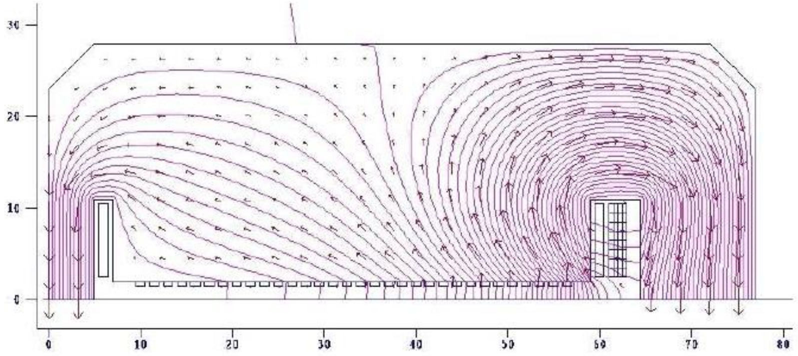
- Increasing k-index by 0.06 to pass horizontal tune through the resonance (black dashed line)
- Consequently affects multipolar fields in FFA cell
  - Increases quadrupole, sextupole and octupole strength
- Unstable region of Steinbach-space changing as a function of time during the extraction
  - Effect should be small



Slides courtesy of R. Taylor

Essential R&D

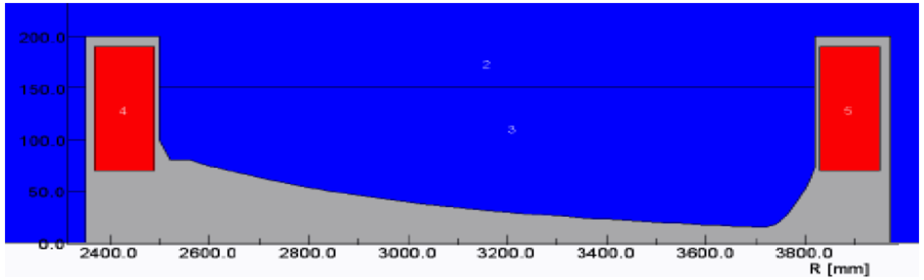
Magnet types to be considered



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

Conclusions

- 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 chosen for the baseline shows a good performance in tracking studies
- Other types of the FFA lattices are being considered
- Feasible ring injection, extraction and beam transport to the end stations at Stage 2 have been designed
- Preliminary ideas for the slow extraction from LhARA FFA have been drafted
  - Dedicated sextuple may be needed
- Essential R&D items:
  - finalisation of the lattice design (type, working point, etc.)
  - the main FFA magnet, and
  - the RF system for the ring