FFA design update

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Outline

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

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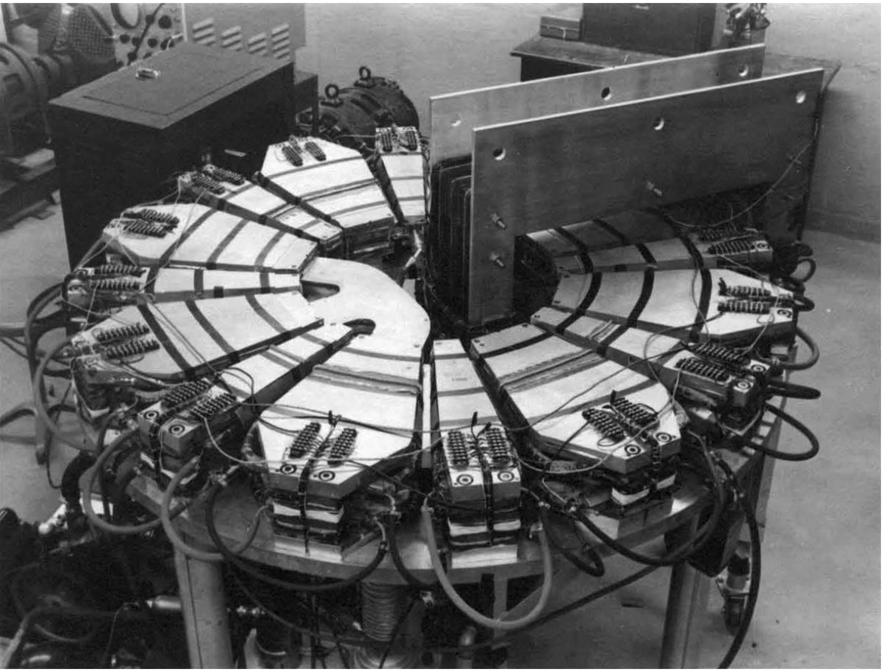
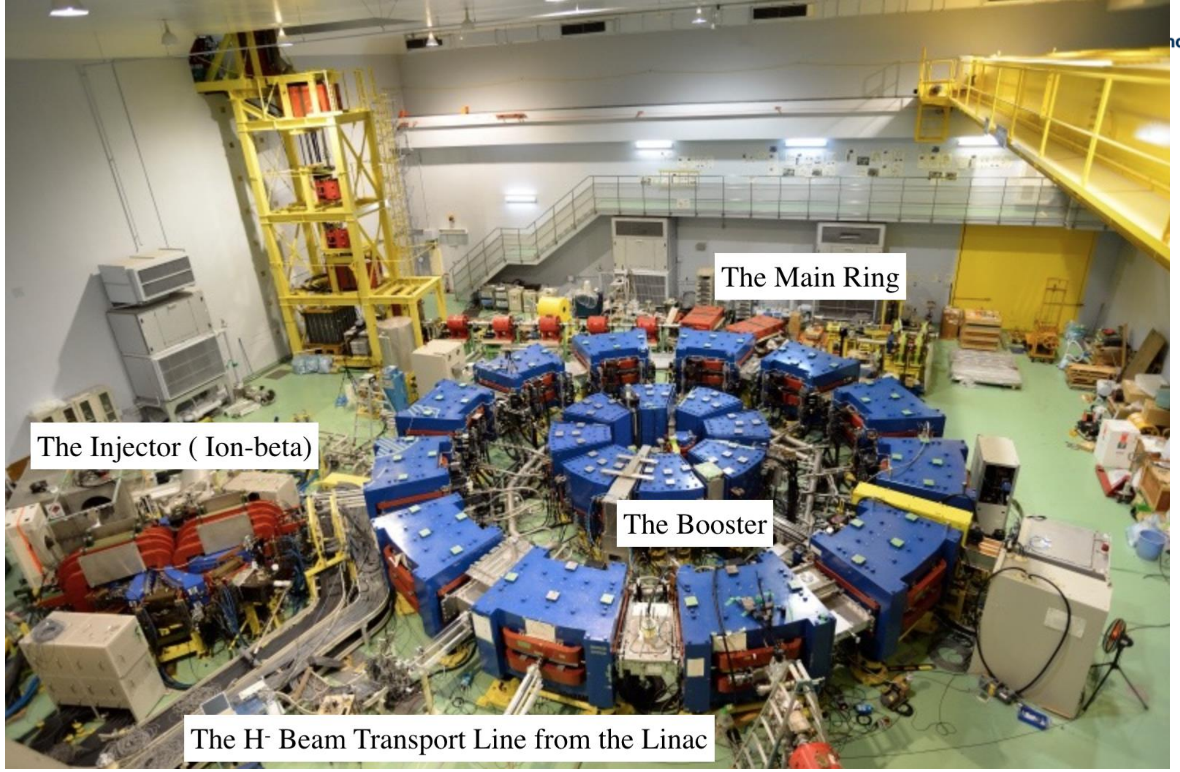
FFA –Fixed Field Alternating gradient accelerators

- Invented independently by A. Kolomensky, T. Okhava and K. Symon in 50ties
- They enjoyed rapid developments at the time and almost vanished afterwards
- They came back in 2000 with the first proton FFA developed at KEK by Y. Mori's group

FFA and their properties



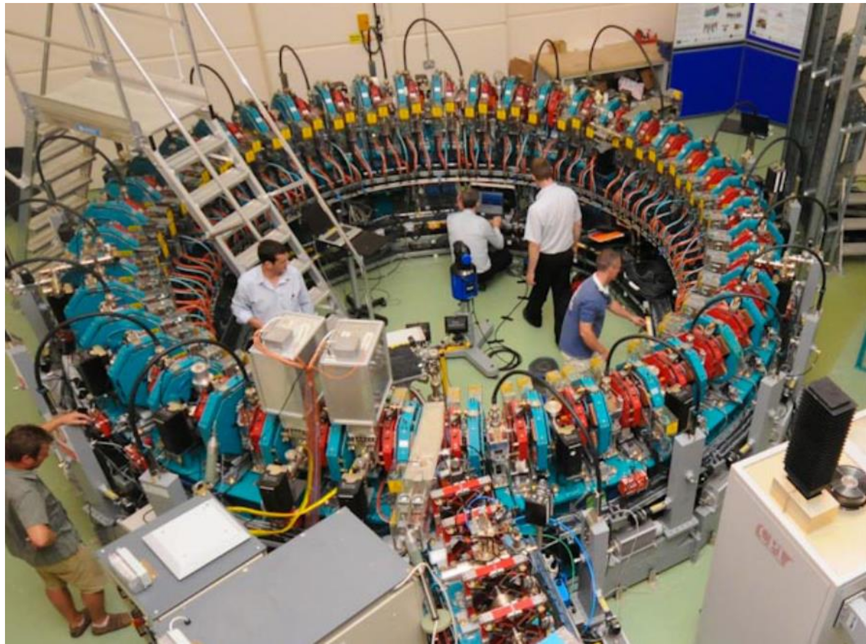
Mark I, first FFA



FFA complex at KURNS

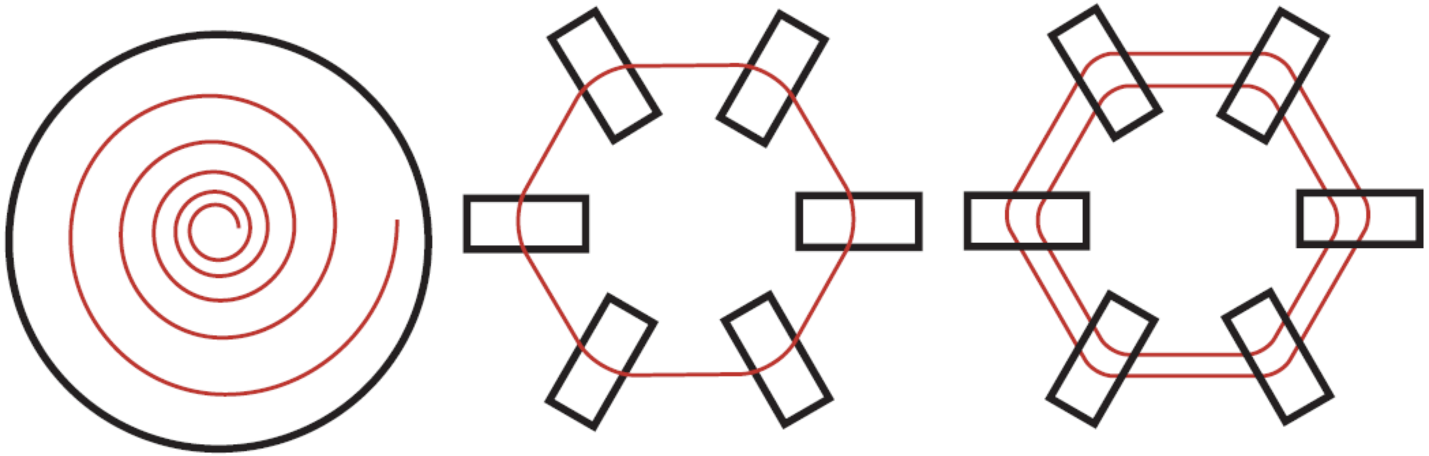
Advantages of FFAs for muon accelerators:

- Lack of ramping
- Large intrinsic momentum acceptance
- Typically large transverse acceptance



EMMA in DL

FFA vs other circular machines

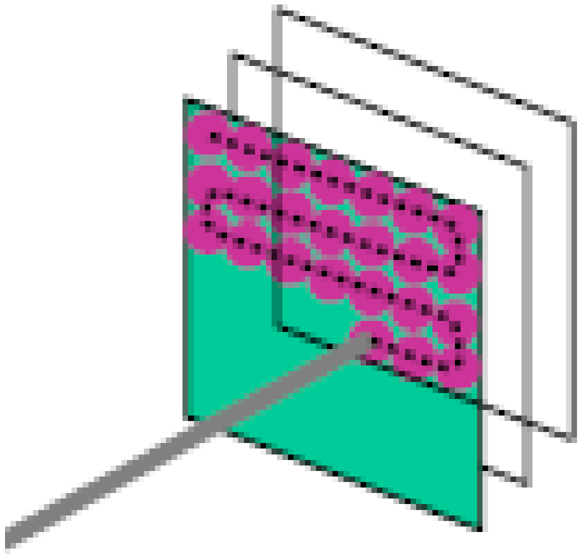


Machine	Cyclotron	Synchrotron	FFA
Magnetic field	constant	changing	constant
RF frequency	constant	changing	changing (not always)
Orbit	changing	constant	changing
Tune	changing	constant	constant (not always)

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

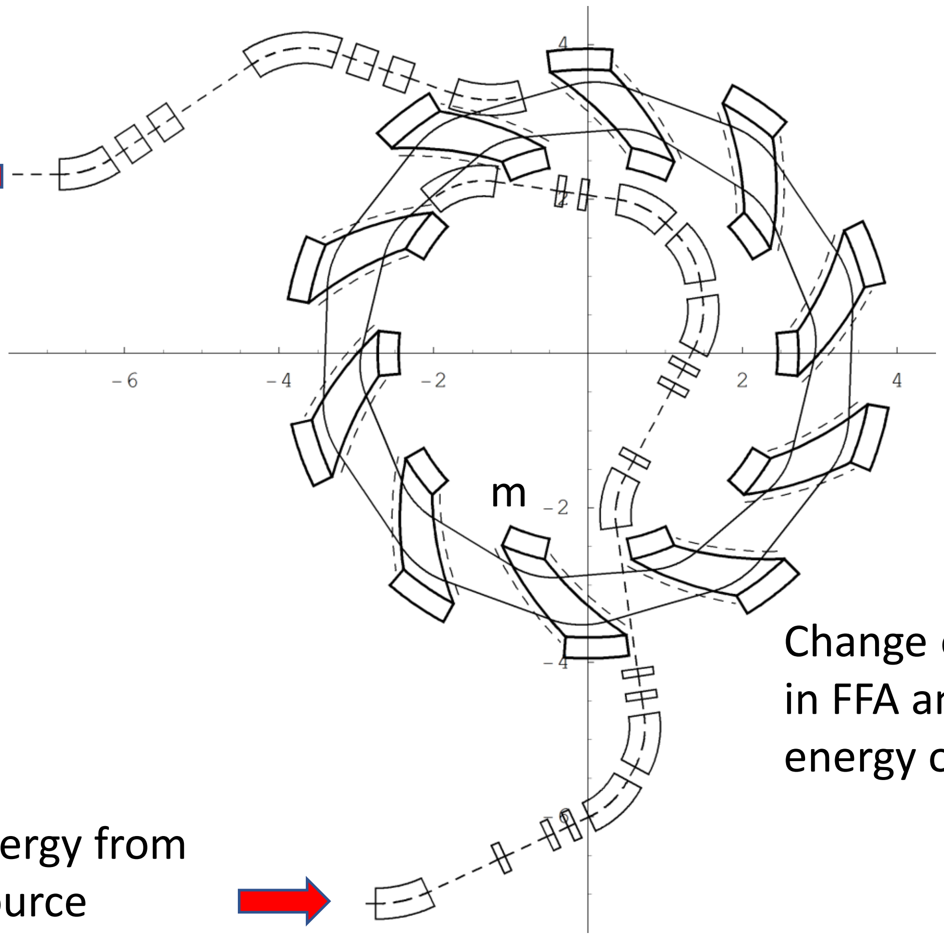


Energy Variability using Laser Accelerated Ions

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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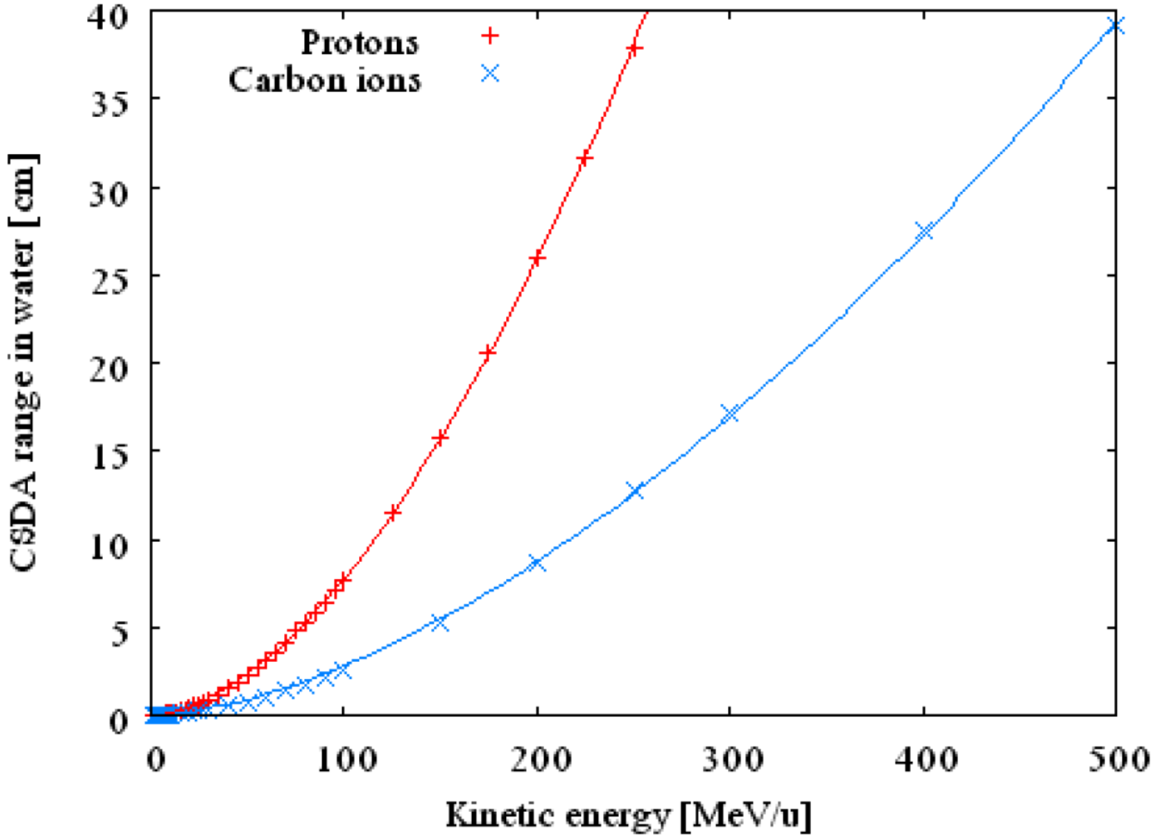
LhARA

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.

Energy for LhARA Stage 2

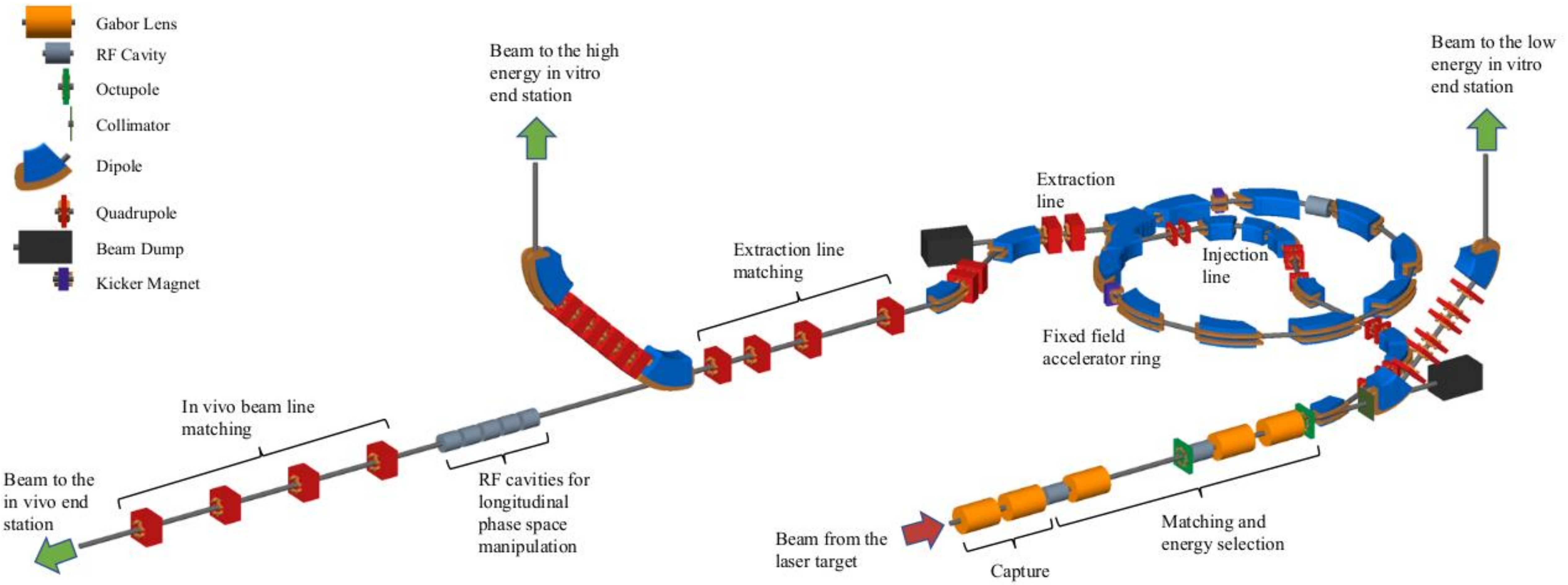
- FFA accelerator can typically accelerate by a factor of 3 in momentum (or more). This allows to easily achieve 127.4 MeV (starting from 15 MeV).
  - Acceleration by a factor of 4 could be possible
- This would correspond to 33.4 MeV/u for C6+.



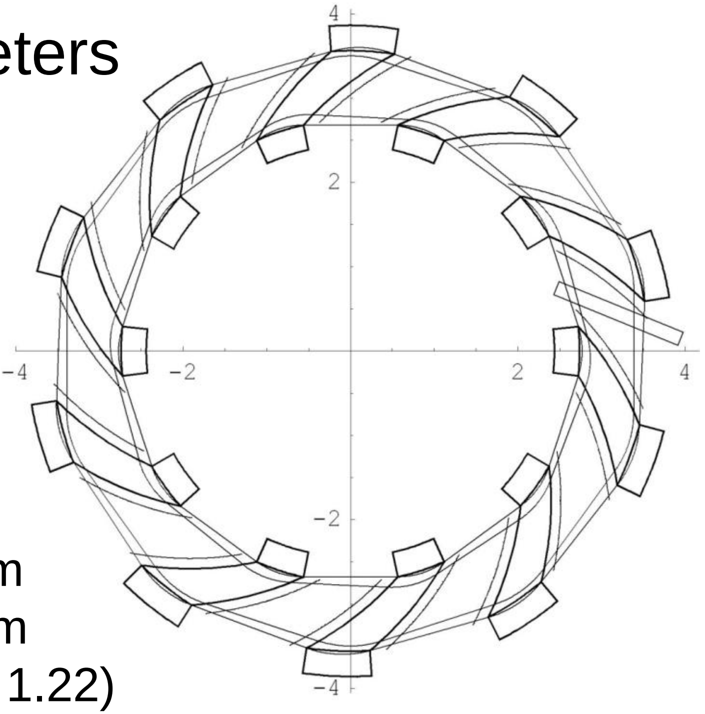
FFA lattice types for considerations

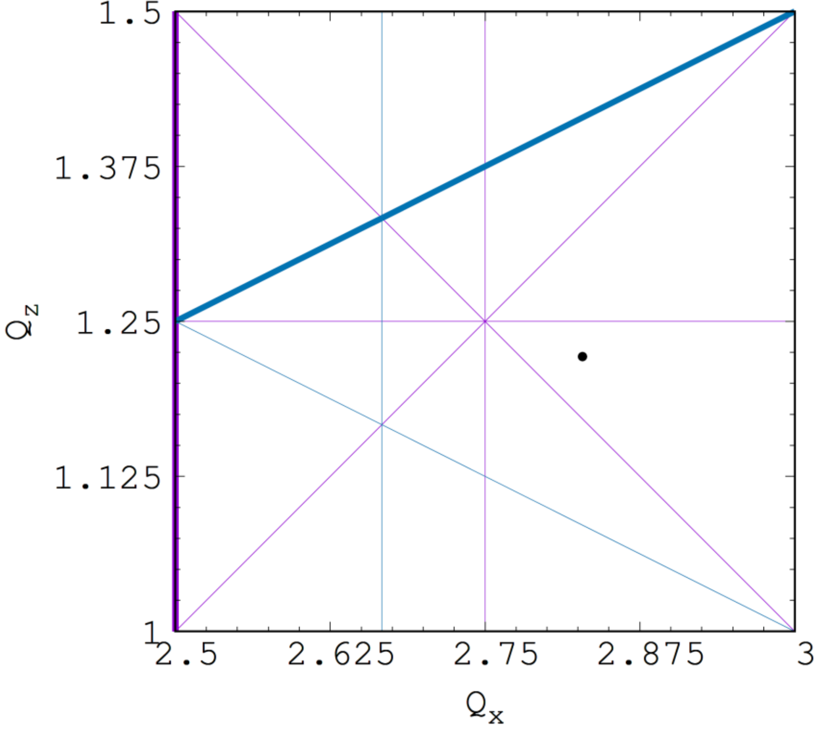
- Single scaling spiral FFA
  - Chosen for the baseline
  - Single magnet per lattice cell
  - Spiral magnet needed
- VFFA –Vertical FFA
  - In considerations for ISIS upgrade at RAL
  - Requires VFFA magnets (2 or 3 per cell) – work in progress
- Tilted sector type
  - Simple magnet geometry
  - Two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

Layout of the full LhARA facility

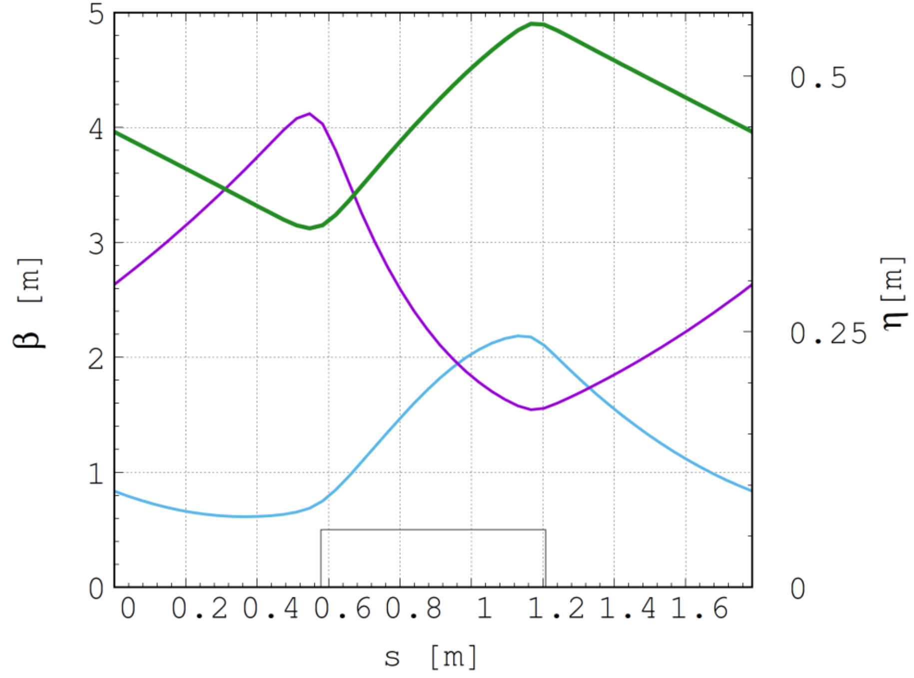


LhARA baseline Ring Parameters



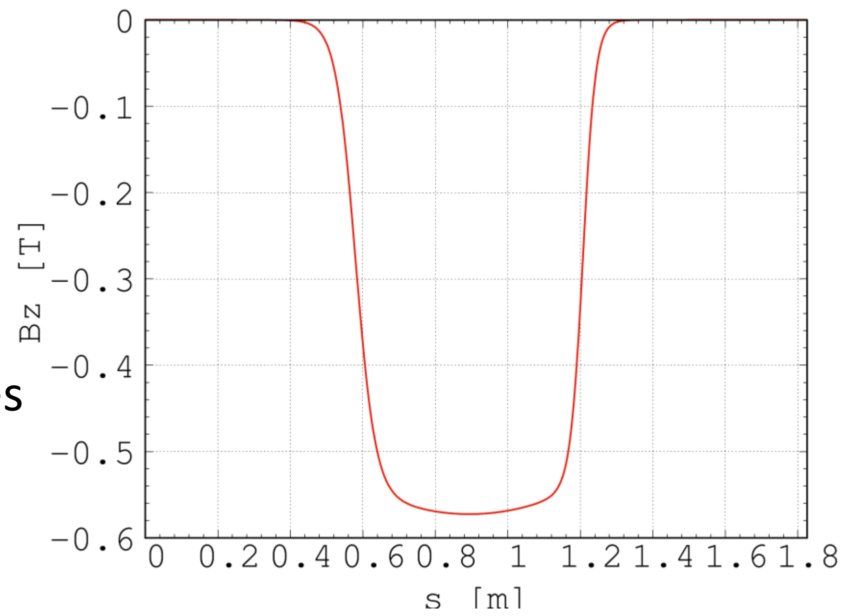


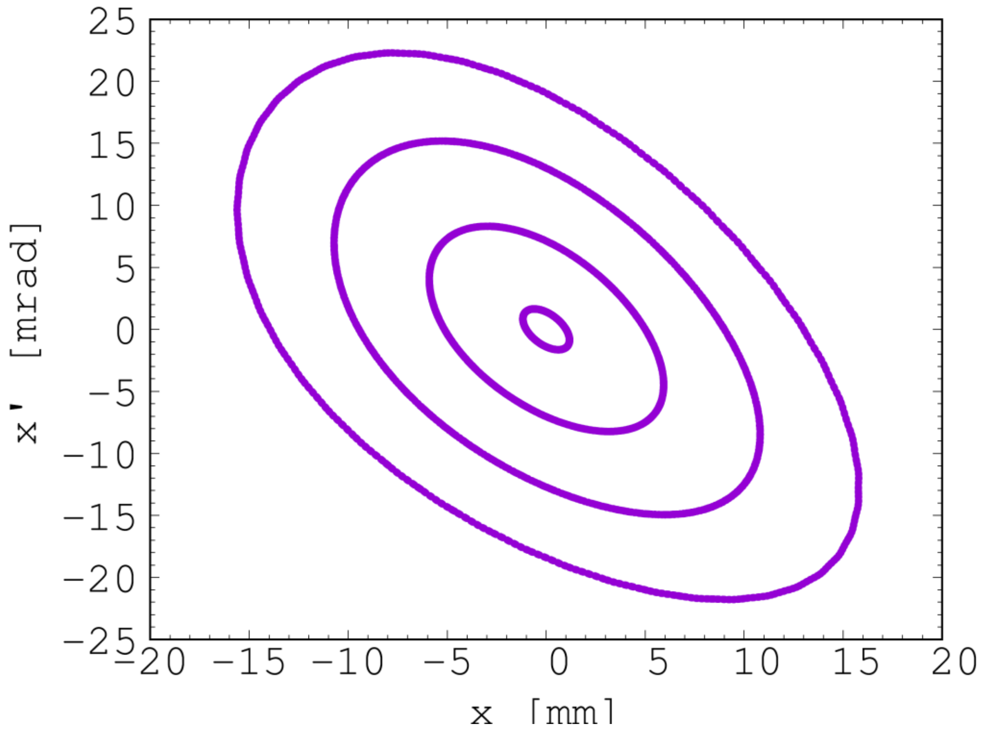
- N 10
- k 5.33
- Spiral angle 48.7°
- R_{max} 3.48 m
- R_{min} 2.92 m
- (Qx, Qy) (2.83, 1.22)
- B_{max} 1.4 T
- p_f 0.34
- Max Proton injection energy 15 MeV
- Max Proton extraction energy 127.4 MeV
- h 1
- RF frequency
  for proton acceleration (15-127.4MeV) 2.89 – 6.48 MHz
- Bunch intensity few×10^8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

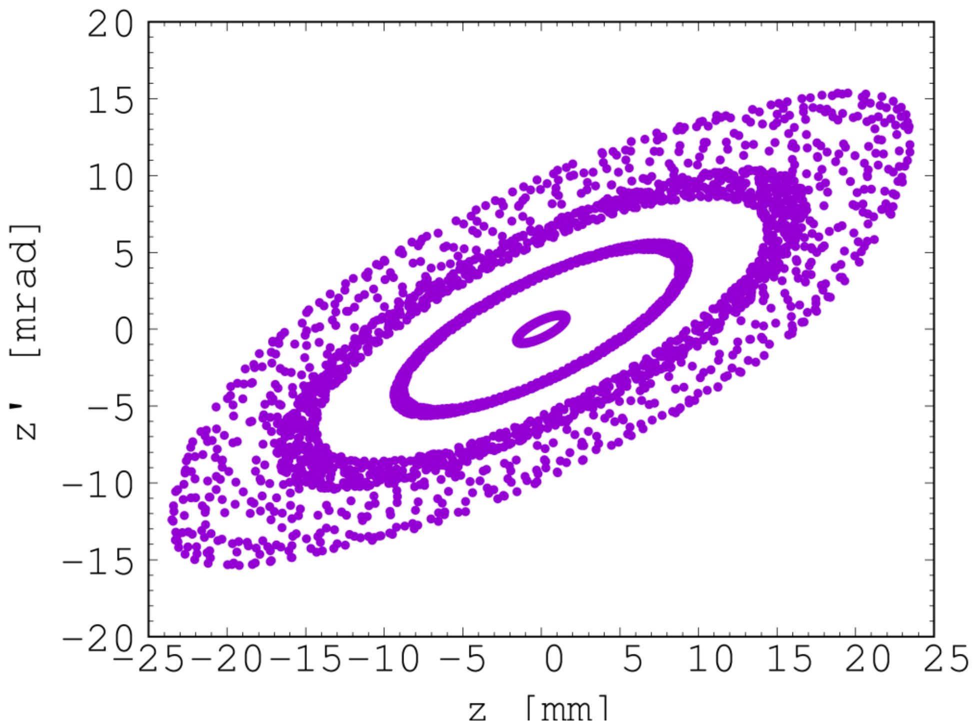


LhARA Ring Tracking

- 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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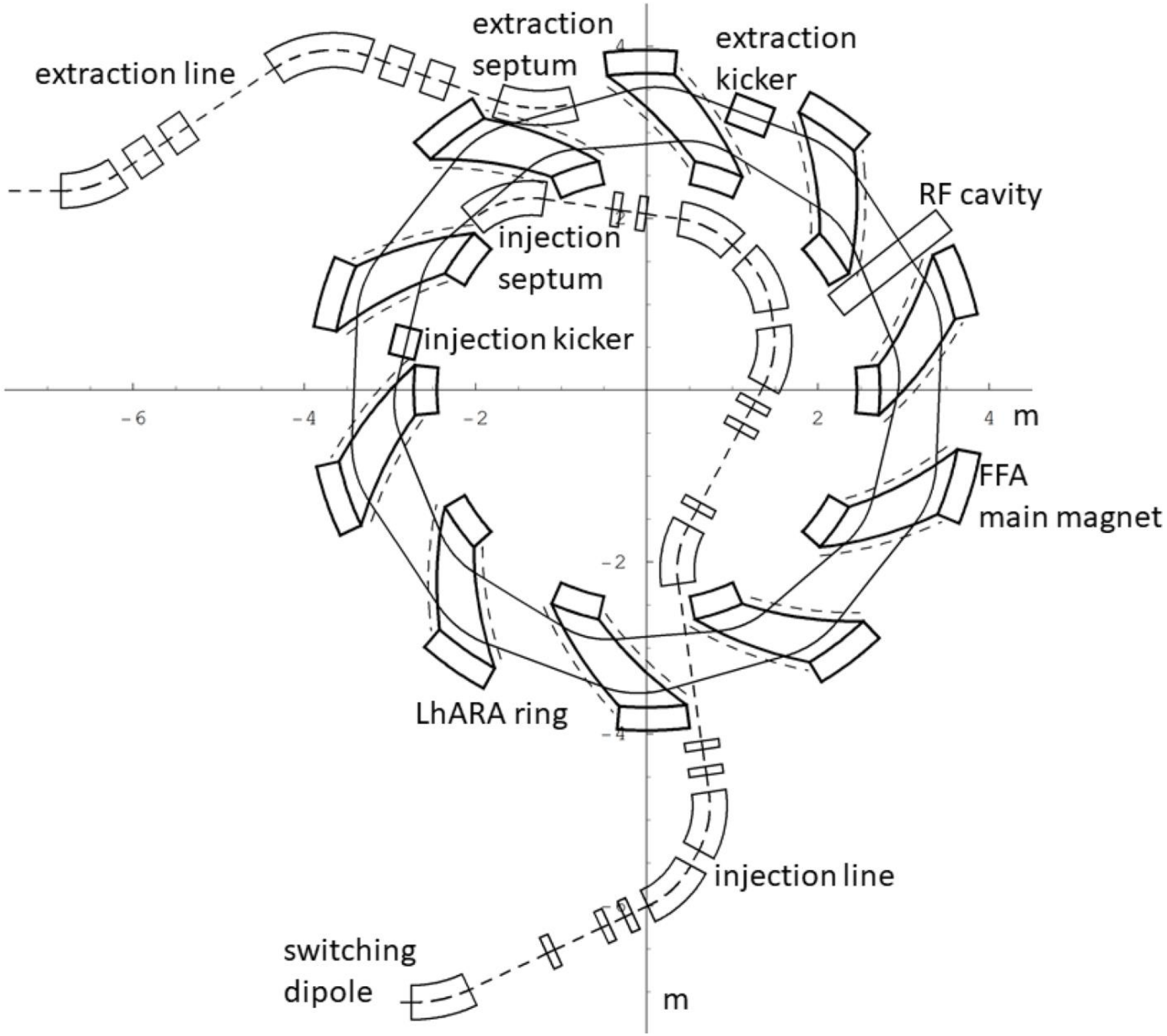
FFA Ring with subsystems

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



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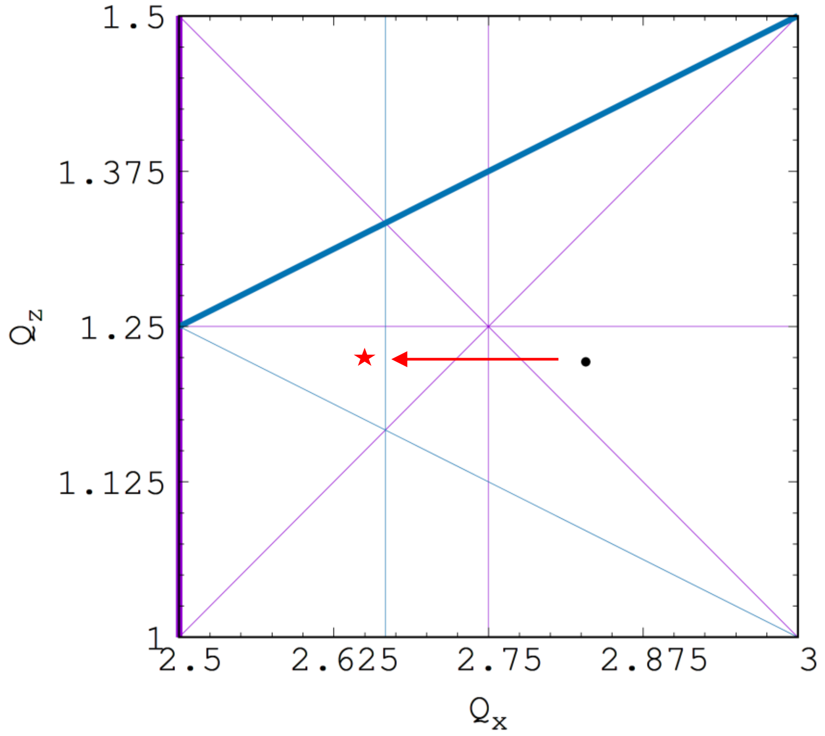
Preliminary ideas for the Slow Extraction from LhARA FFA

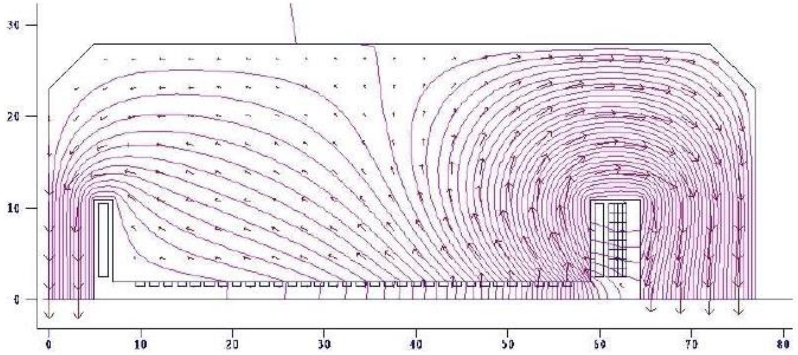
N	10
k	4.642
Spiral angle	46.7°
R_{max}	3.48 m
R_{min}	2.86 m (6cm more than in baseline)
(Qx, Qy)	(2.66, 1.22)
B_{max}	1.4 T
p_f	0.34
Max Proton injection energy	15 MeV
Max Proton extraction energy	127.4 MeV
h	1

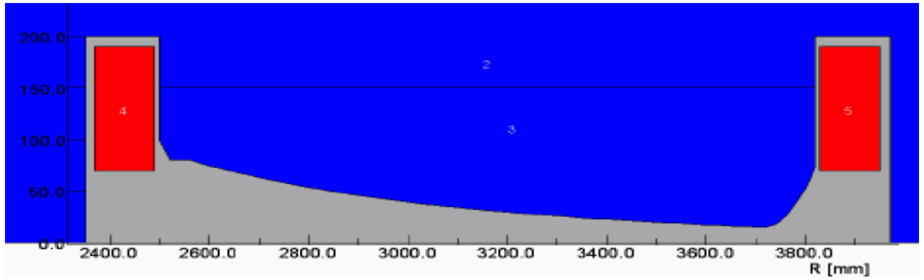


- The horizontal tune moved just below the 3rd order resonance
- Tune can be moved towards the resonance at the end of acceleration with k-coils
  - Orbit could be adjusted be bumpers or by the control of beam momentum using RF
- It is not clear, if natural sextupolar component will be enough to control 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

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
- Essential R&D items:
  - finalisation of the lattice design (type, working point, etc.)
  - the main FFA magnet, and
  - the RF system for the ring

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Conclusions

- Thanks to their unique properties, like high acceptance and lack of ramping, FFA accelerators may be ideally suited as muon machines.
- nuSTORM is a serious candidate to serve both neutrino physics and R&D for a Muon Collider
- PRISM may become the next generation flagship programme for lepton flavour violation
- VFFA can be an ideal machine for muon acceleration in a Muon Collider and also serve for ISIS-II. Its technology may be addressed in a prototype ring FETS-FFA.
- FFAs can be applied in radiobiology (LhARA) or in a future hadrontherapy.