LhARA-FFA Design

J. Pasternak, IC/RAL-STFC, 26/02/2025

Introduction

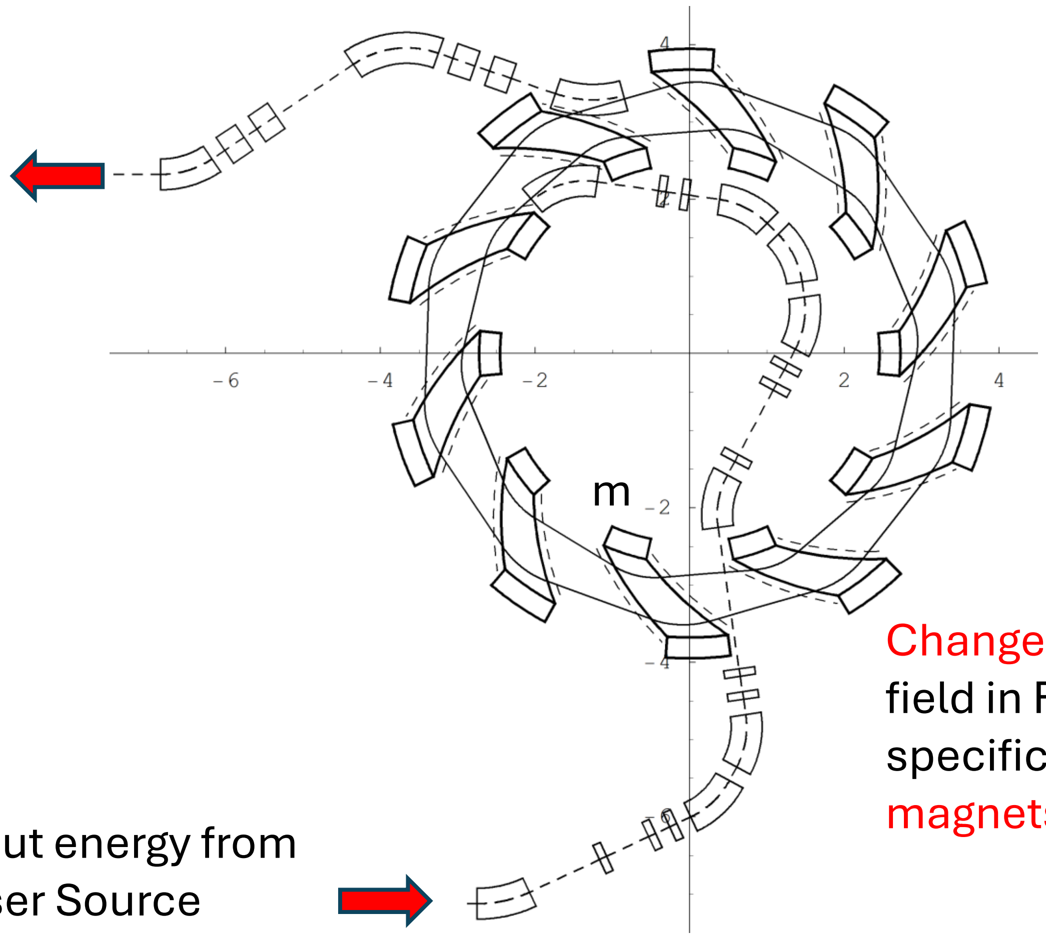
- Why FFA?
  - Synchrotron can do the job, but we learn nothing new
    - FFA is upgradable to 100Hz or more
- What LhARA FFA is good for?
  - The most economic solution for variable energy FFA in the range of energies required for radiobiology (upgradable to proton therapy)
- What LhARA FFA provides
  - Novel concept for magnet
  - Variable energy, multi-ion capable, high rep rate machine
    - Next step in developing FFA for hadron therapy

Energy Variability using Laser Accelerated Ions

Variable extraction energy from FFA within 1 s (20-127.4 MeV) at fixed geometry

+

pulse by pulse variation with kicker could be implemented

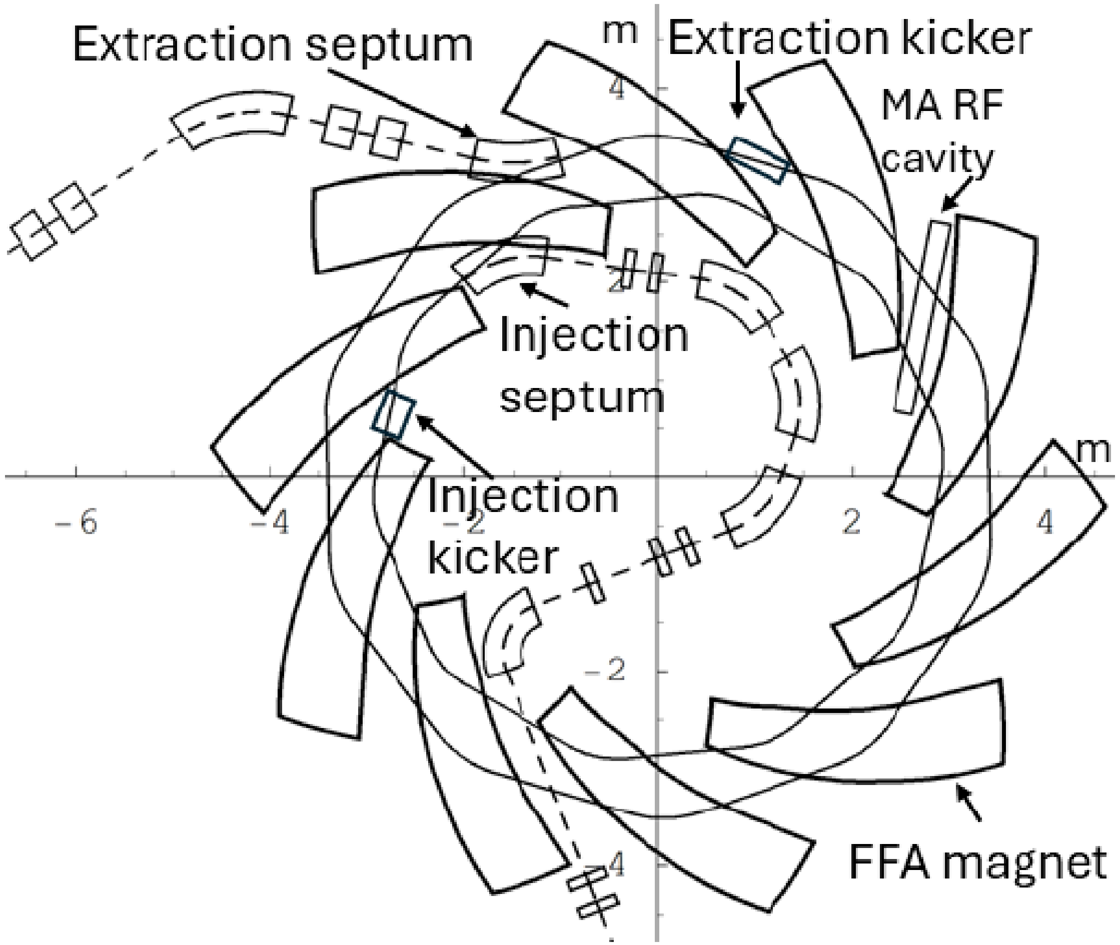


Change of the value of magnetic field in FFA and transfer lines for a specific energy operation (laminated magnets)

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

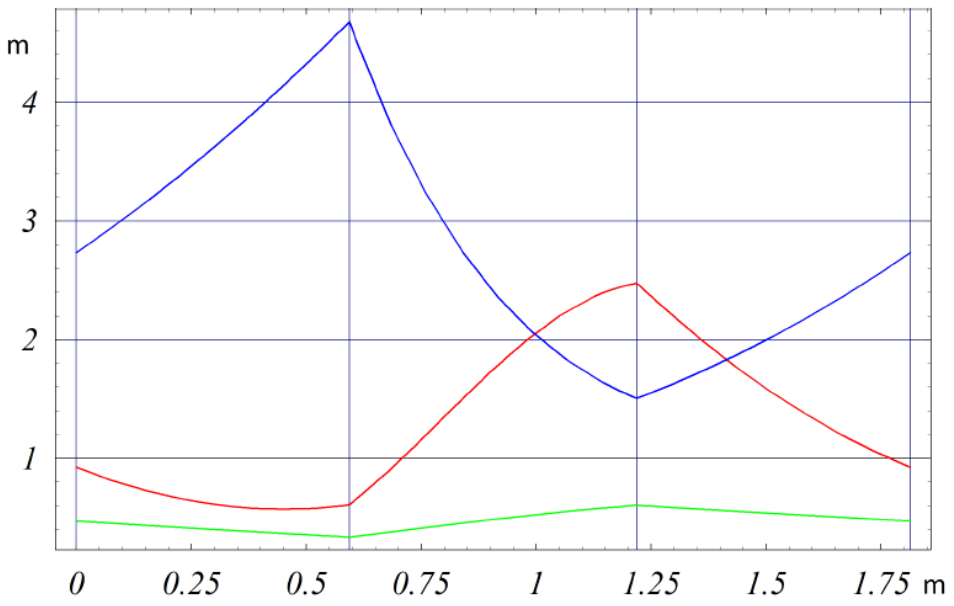
Design Principles

- LhARA-FFA design follows from the RACCAM design
- Single spiral scaling FFA
  - Single magnet per cell, compact (no negative bends), zero-chromatic, strong focusing
- Choice of cell number -> a compromise between the orbit excursion and the drift length
- Magnet packing factor -> a compromise between the size of the machine and the orbit excursion
- Max field (~1.4T) fixed to allow for room temperature magnets with controllable saturation
- Magnet design based on distributed trim coils -> allows for tunability
  - Essential for a variable energy operation
  - Synergy with FETS-FFA



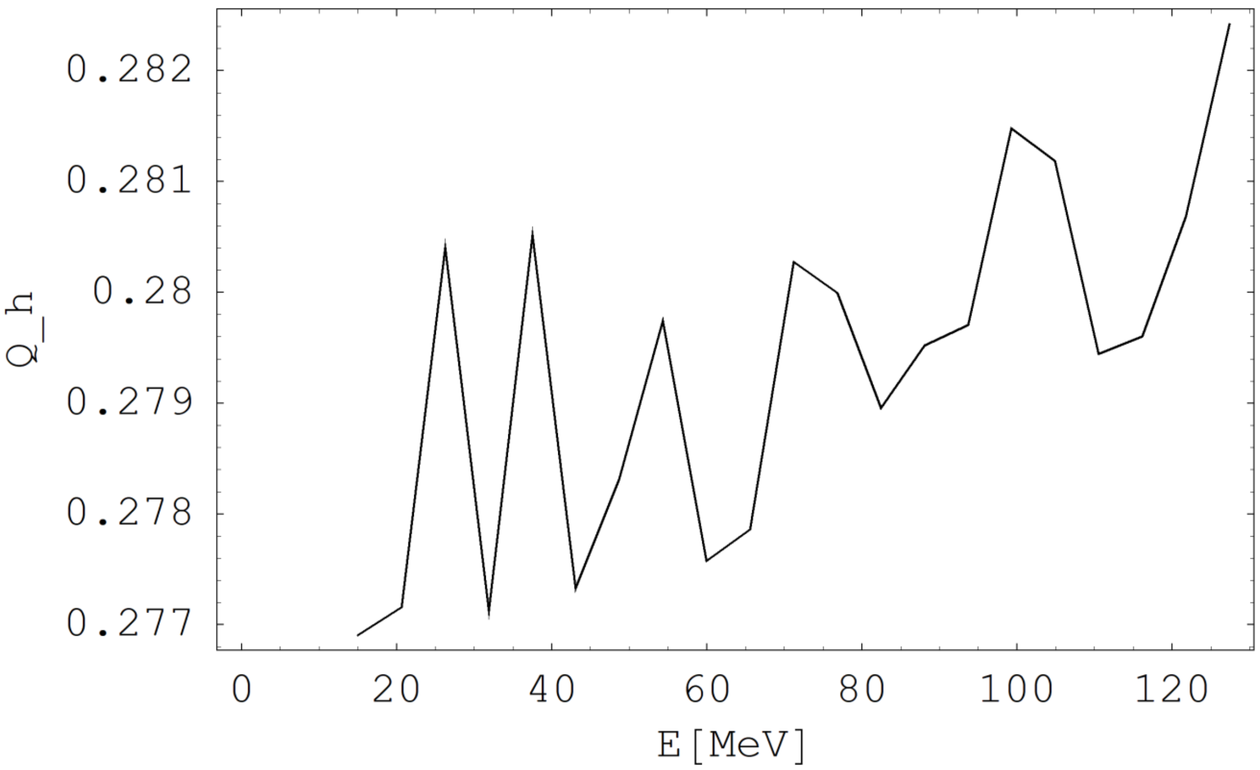
LhARA- FFA Design

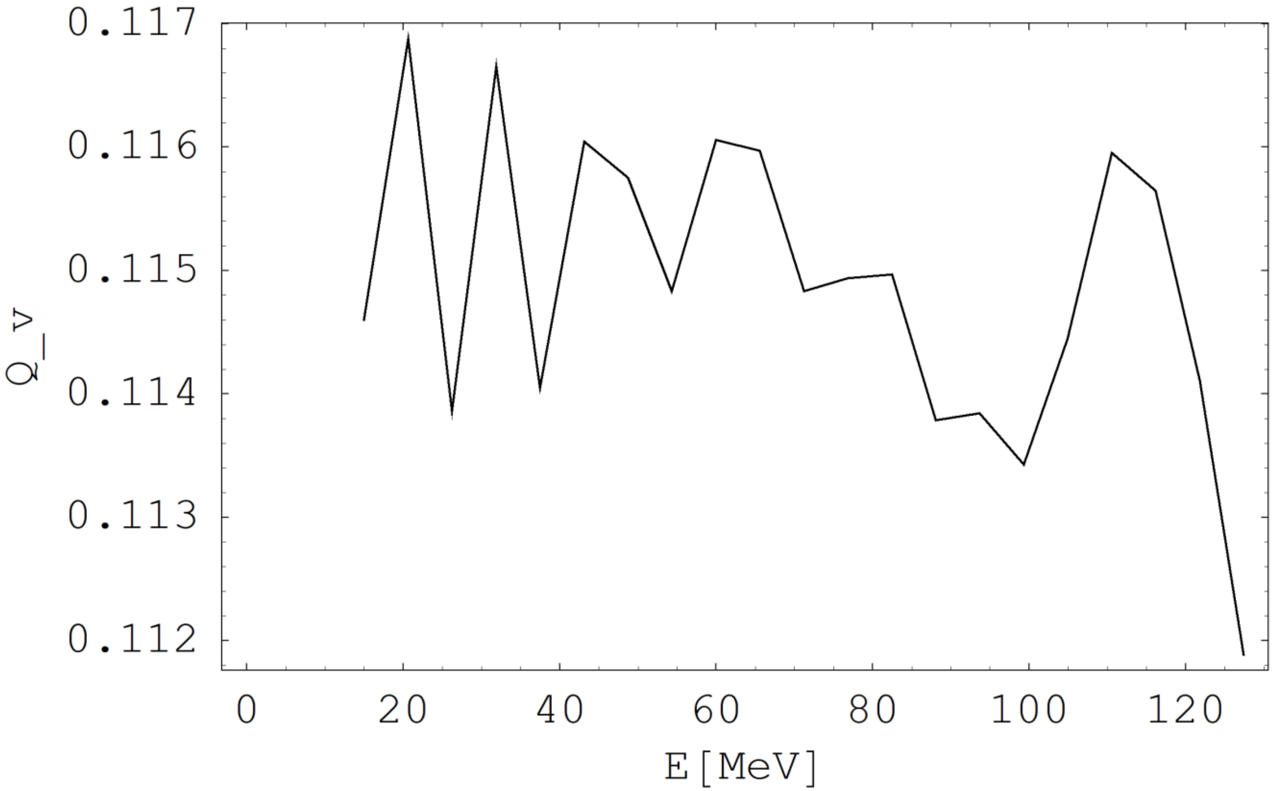
Parameter	units	value
Number of cells		10
k		5.23
Spiral angle	degrees	53.9
R_{inj}	m	2.914
R_{ext}	m	3.477
R_{max}	m	4.61064
B_{ext}	T	1.405
Orbit excursion	m	0.56
Straight section length at injection	m	1.2
Straight section length at extraction	m	1.43
Magnet packing factor		0.34
Magnet opening angle	degrees	12.24
Magnet gap - distance between flat poles (full)	cm	9.5
Max $B\rho_{inj}$	Tm	0.562
Max $B\rho_{ext}$	Tm	1.685
Ring tunes		(2.79, 1.22)
γ_T		2.516
RF frequency	MHz	1.46-6.48
h		1,2 or 4
RF voltage	kV	4 (for 2 cavities)



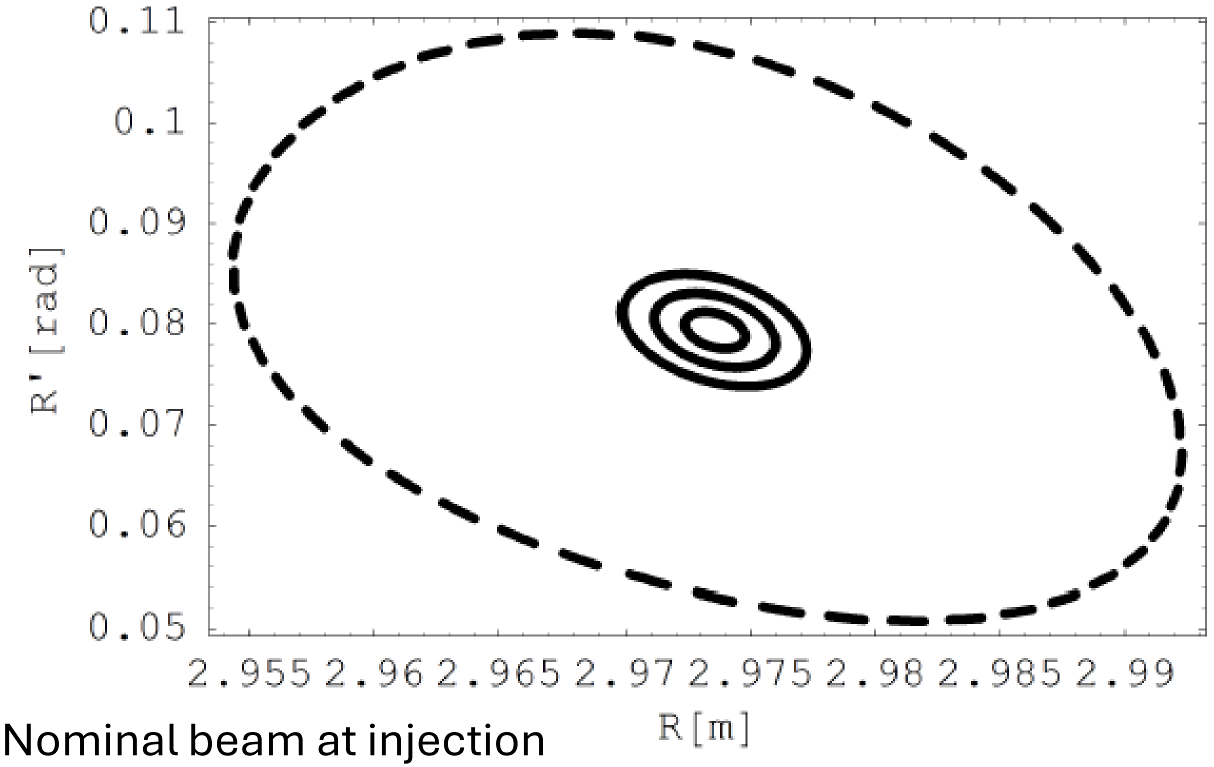
Betatron functions (red-H and blue-V) and dispersion (green) in one lattice cell (using the hard-edge model)

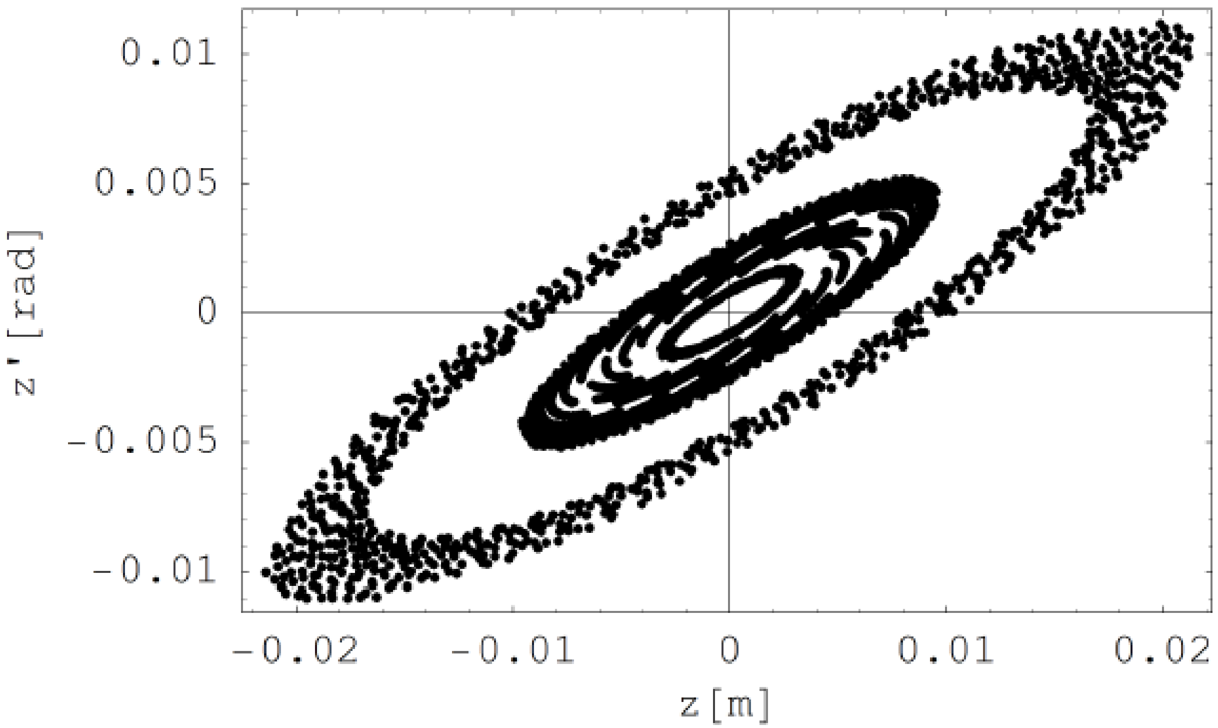
LhARA- FFA Tunes evolution





DA Study





Nominal beam at injection

Parameter	unit	value
Beam energy	MeV	15
Total relative energy spread		$\pm 2\%$
Nominal physical RMS emittance (both planes)	π m rad	2.8×10^{-6}
Incoherent space charge tune shift		-0.14
Bunching factor		0.023
Total bunch length	ns	8.1
Beam intensity		10^9

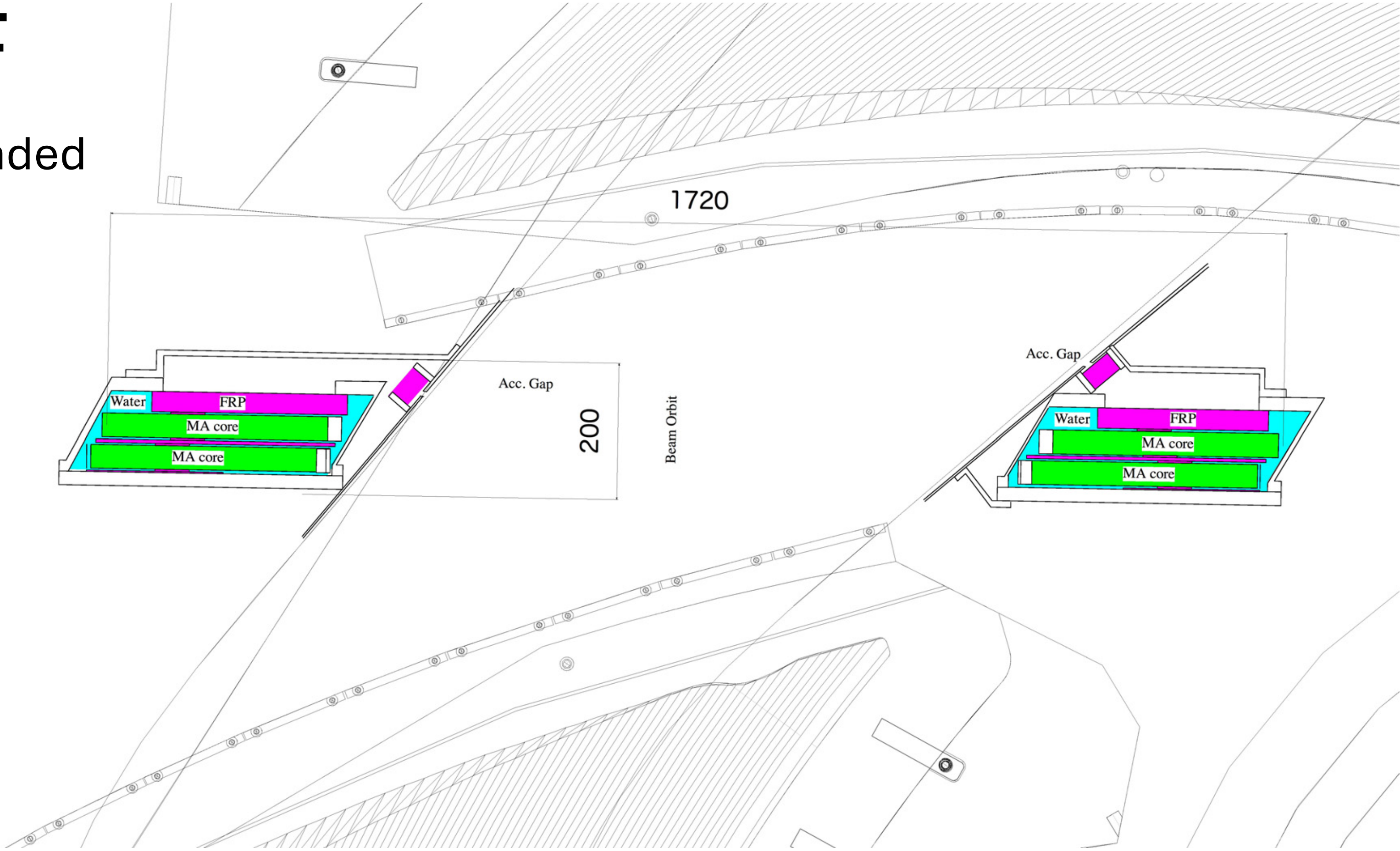
Dynamical acceptance study using 3D field map by tracking 100 turns at 25 MeV. 1σ, 2σ, 3σ, and DA limits are shown in both transverse planes, (left) horizontal and (right) vertical, respectively. Note that 1σ emittance corresponds to 2.8 Pi mm mrad.

RF

- Two potential solutions, MA and ferrite loaded
- One reference created for RACCAM (MA)

Parameters for RACCAM

	Cavity
Number of gaps	1
Peak rf voltage	3 kV
Size of cavity	2.0 m x 1.2 m x 0.2 m
Size of core	1.7 m x 1.0 m x 0.03 m
Aperture of core	1.0 m x 0.3 m
Q	0.6
Power density in core	< 0.5 W/cc
	Amplifier
Output power	25.0 kW
Operation class	Class AB
Plate voltage	6 kV
Anode Current	10 A
Tetrode	RS1084CJ

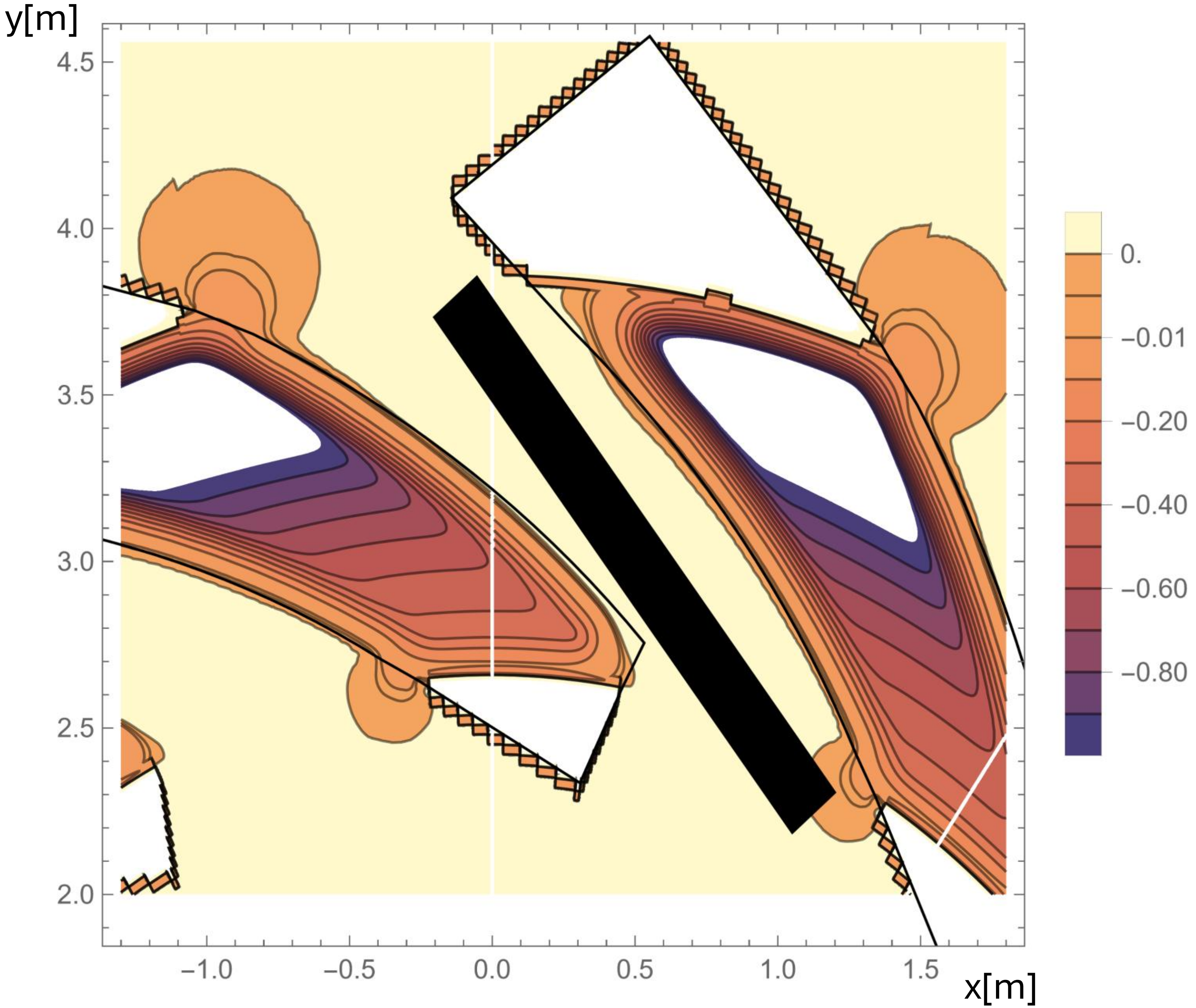


C. Ohmori et al.,PAC'09, TU5PFP026

Parameters for LhARA

Parameter	Value
Proton RF frequency	2.89–6.48 MHz
Voltage per cavity	4 kV
Bunch intensity	10^9 protons/bunch
Harmonic number	1
Horizontal aperture	65–85 cm
Vertical aperture	7 cm (approx.)

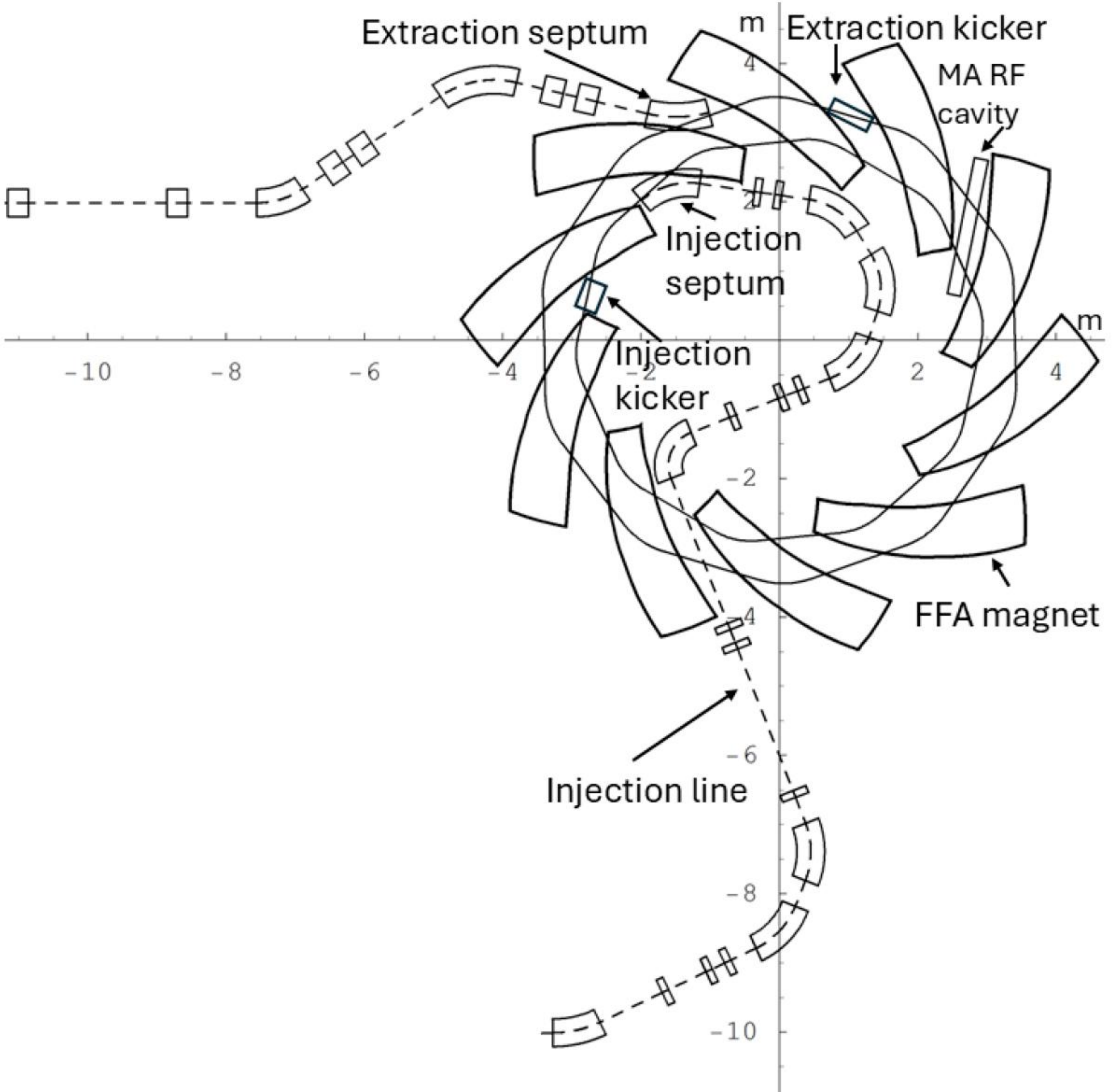
RACCAM RF cavity in LhARA



Field on median plane in T

Injection/extraction

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	3.1
pulsing rate	Hz	10
Extraction septum:		
nominal magnetic field	T	0.93
magnetic length	m	0.9
deflection angle	degrees	28.5
thickness	cm	1
full gap	cm	2.2
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	3.1
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	2.2



Diagnostics

- Beam loss: plastic scintillators or photomultiplier tubes
- Beam position: beam scrapers, intercepting wires, electromagnetic pickups
- Current: Faraday cups, electromagnetic pickups
- Tune: electromagnetic pickups
  - With RF knock-out for the horizontal plane
  - With exciter in the vertical plane
- All above methods have been demonstrated for synchrotrons/FFAs, but no dedicated study for LhARA has been performed so far

Conclusions

- LhARA at Stage 2 requires a variable energy FFA
- The cost effective, single spiral scaling FFA chosen for the baseline shows a good performance in tracking studies and promissing feasibility
- Preliminary design for the magnet has been created (see Ta-Jen's talk)
  - Key is the zero-chromaticity for different energies which is now demonstrated

Future LhARA-FFA programme (1)

- Transverse optics and beam dynamics
  - Alternative working points (for example for the slow extraction)
  - Error study
  - More DA evaluations
- Longitudinal dynamics
  - RF programme
  - Bunch length manipulation
  - Acceleration with tilted cavity
- Space charge
  - Condition at injection
  - Bunch evolution after injection

Future LhARA-FFA programme (2)

- Main FFA magnet
  - Further optimization
  - Straight trim coils option
- RF
  - Evaluation of potential options
  - MA cavity parameters (RACCAM design – a starting point)
  - MA cavity e-m simulations
- Injection/extraction
  - C-shape kicker parameters
  - Kicker e-m simulations
  - Septa?

Future LhARA-FFA programme (2)

- Diagnostics
  - Collaboration with RAL
- Mechanical engineering
  - Transitions between various elements under tight space constrains
    - Further work is needed