Imperial College London

Science & Technology Facilities Council ISIS

Status of LhARA design for Stage I and II

J. Pasternak, FFA'19, CCAP plenary meeting, 11/12/2019

Outline

- Introduction and motivations
- General layout
- Gabor lens
- Optics
- End Station
- Stage 2
- FFA types under consideration
- Baseline design
- Magnet options
- Conclusions and future plans

Introduction

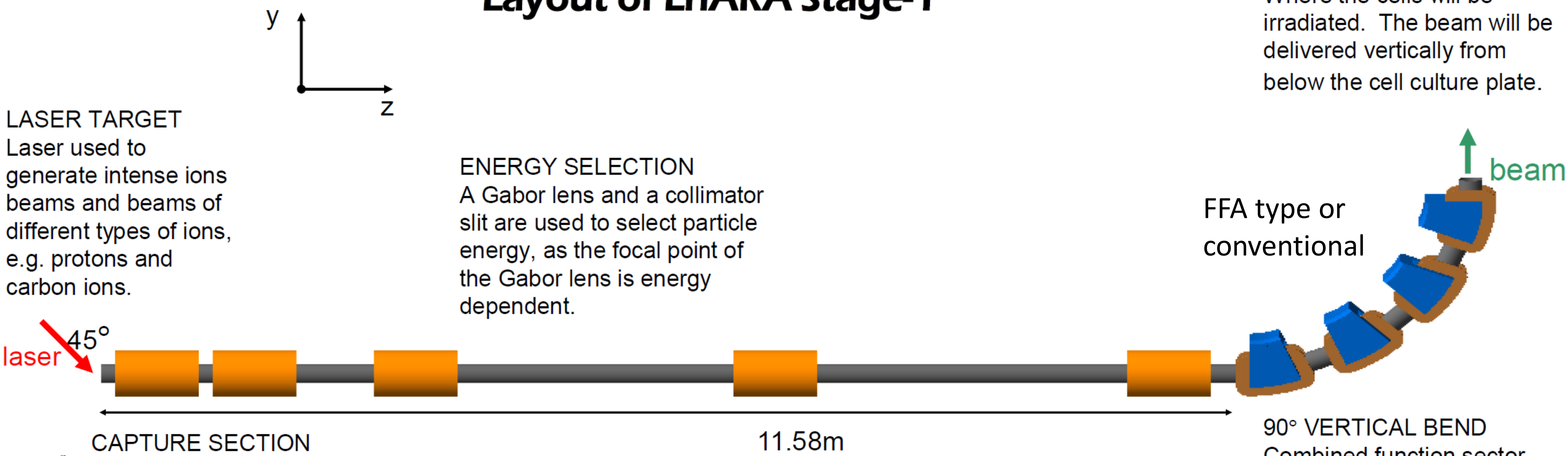
- Laser hybrid Accelerator for Radiobiological Applications (LhARA) was proposed within the Centre for the Clinical Application of Particles (CCAP) at Imperial College London as a facility dedicated to the systematic study of radiobiology with protons in-vitro at ~15MeV at Stage 1 and with multiple ions in-vitro and in-vivo at Stage 2.
- It will allow for a study with proton beams in a novel regime of dose delivery (FLASH) at Stage 1
- It will open the study to use multiple ions (including Carbon) at Stage 2.
- It aims to demonstrate a novel technologies for next generation hadrontherapy.

Layout of LhARA Stage-1

END STATION
Where the cells will be irradiated. The beam will be delivered vertically from below the cell culture plate.

LASER TARGET
Laser used to generate intense ions beams and beams of different types of ions, e.g. protons and carbon ions.

ENERGY SELECTION
A Gabor lens and a collimator slit are used to select particle energy, as the focal point of the Gabor lens is energy dependent.



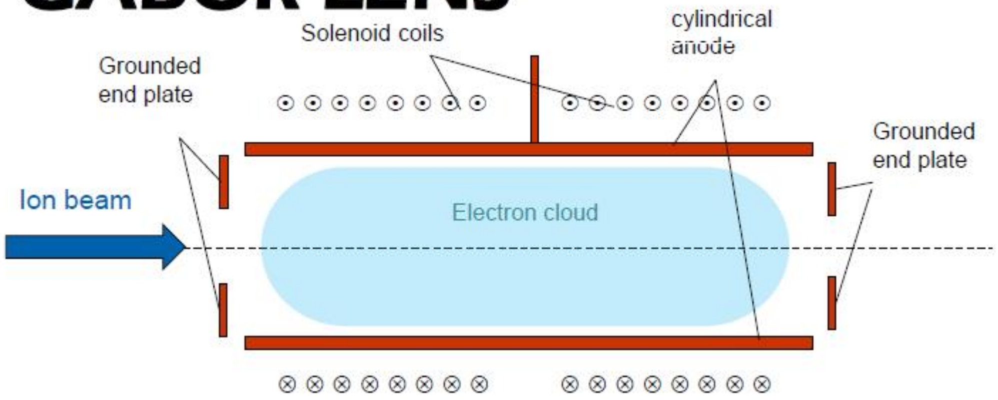
CAPTURE SECTION
Gabor lenses used for compact focussing to capture the large divergence and energy spread of the laser driven ion beam.

Solenoids are a possible backup

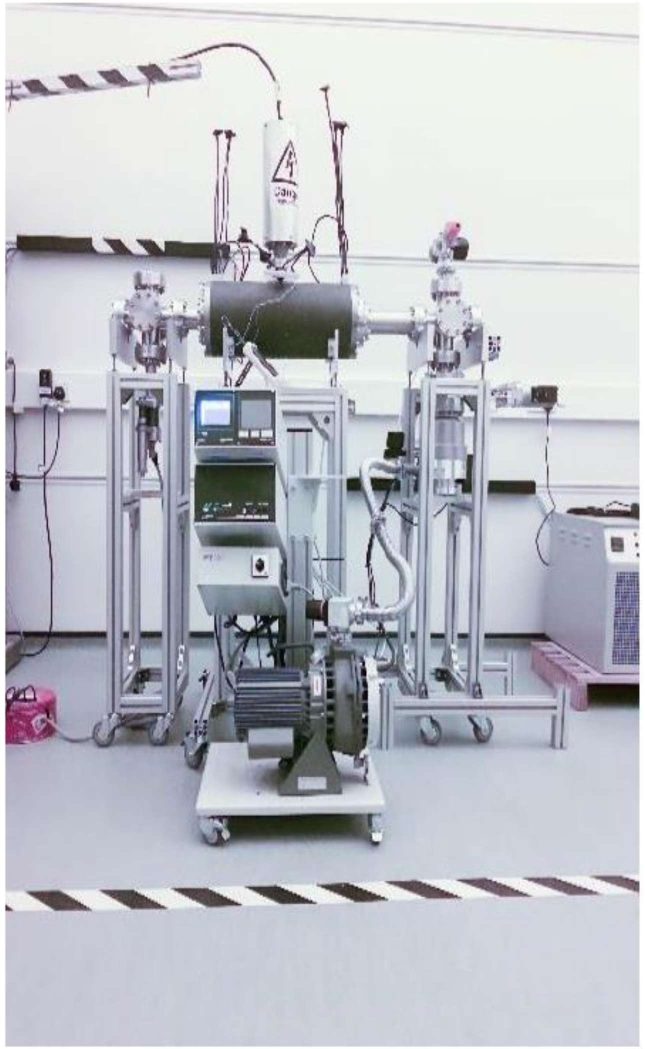
MATCHING
Two Gabor lenses are used to adjust the beam size and divergence in the end station.

90° VERTICAL BEND
Combined function sector magnets and collimators are used to select momentum and deliver the beam vertically to the end stations.

GABOR LENS



- The Gabor lens uses an electron plasma to generate a strong electro-static focusing field.
- Assembled lens prototype is being tested at Imperial.

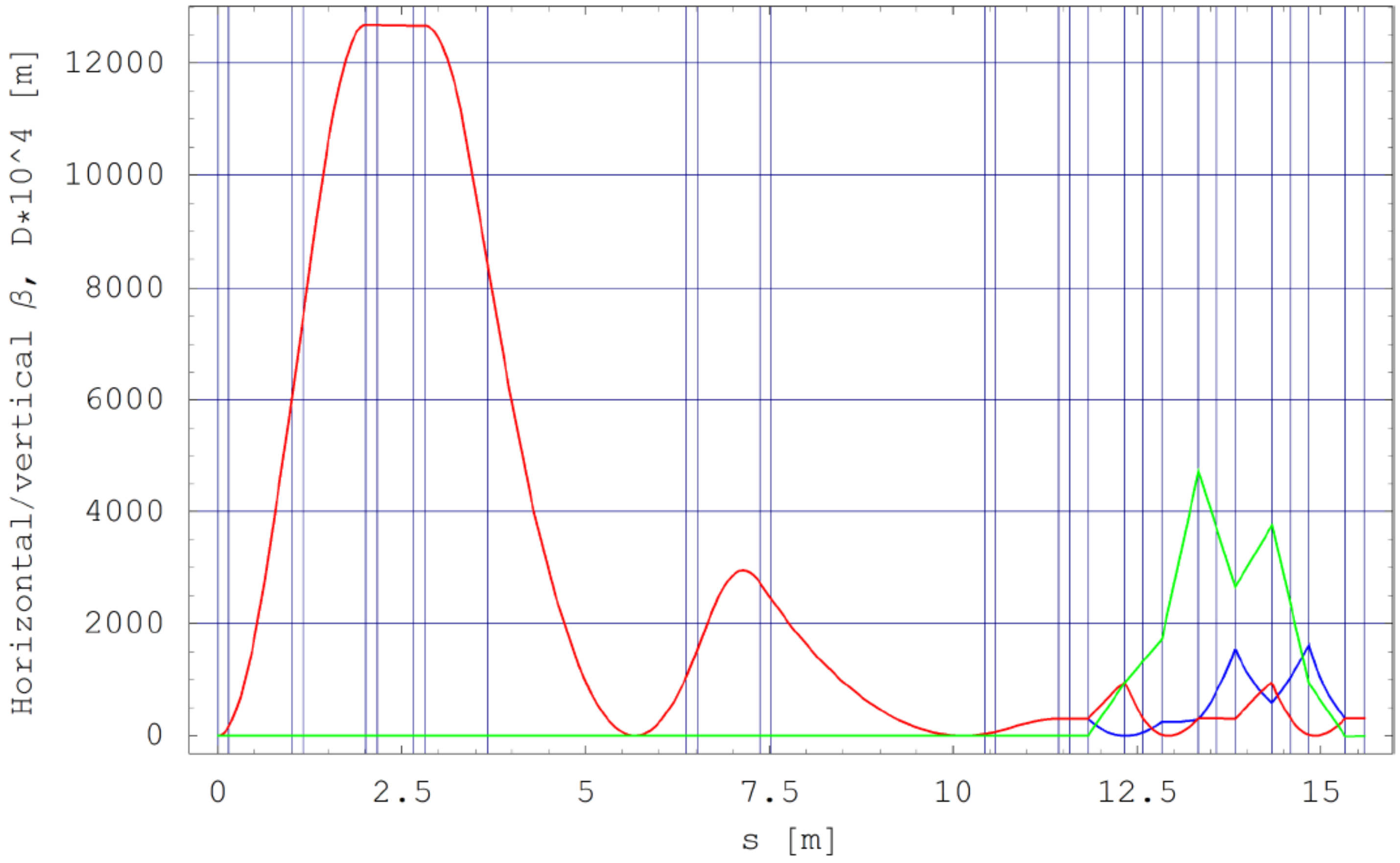


Parameters of Gabor lenses

Table 1: Parameters of Gabor lenses assumed in LhARA

Parameter	Value	Units
Total length	1.157	m
Effective focusing length	0.857	m
Max. Cathode voltage	65	kV
Cathode radius	0.0365	m

Optics in LhARA Stage 1

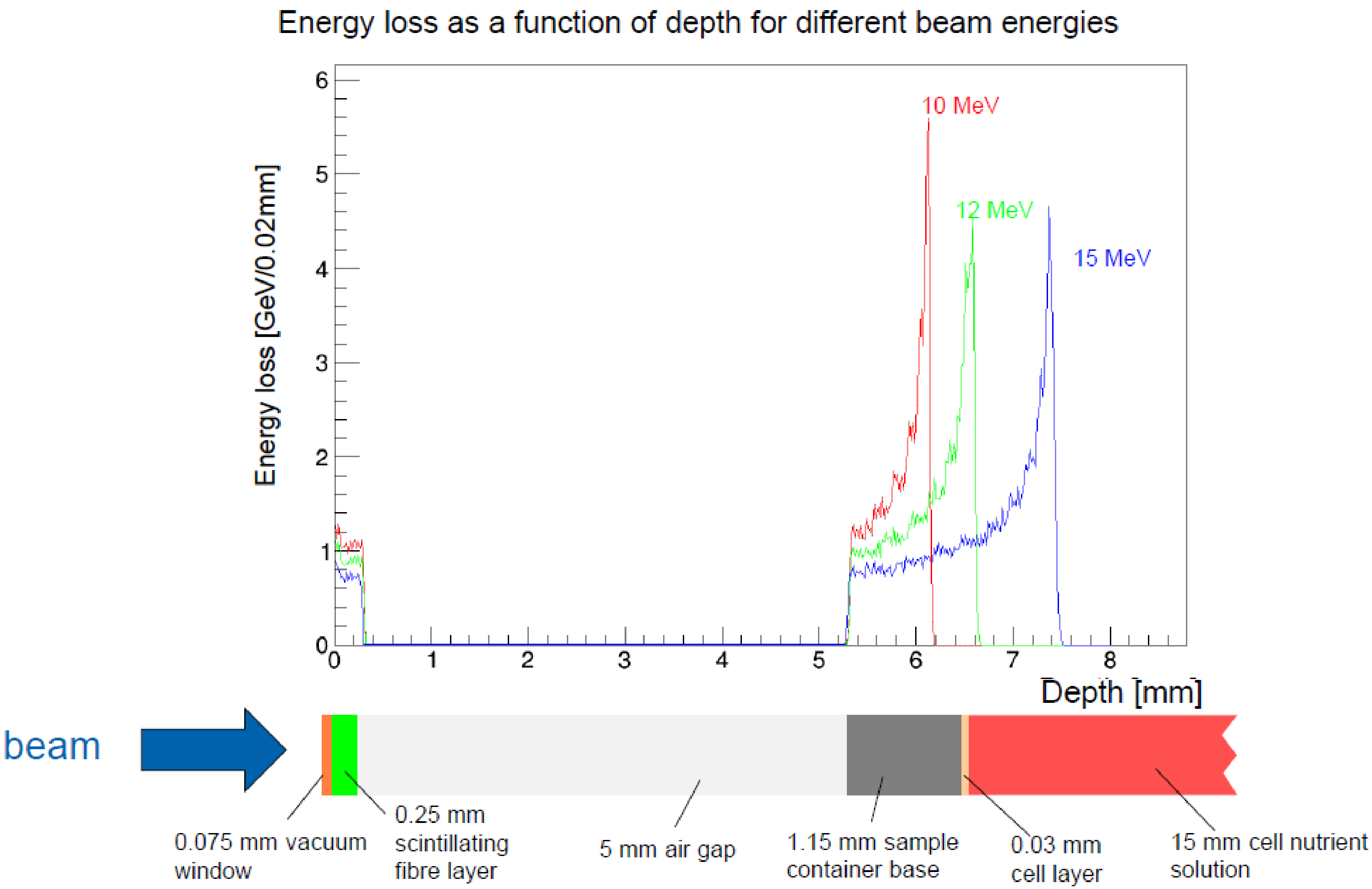


Vertical (red) and horizontal (blue) betatron functions, and dispersion (green, scaled by 10^4 in order to be visible on the plot) in LhARA Stage 1.

LhARA Stage 1 parameters

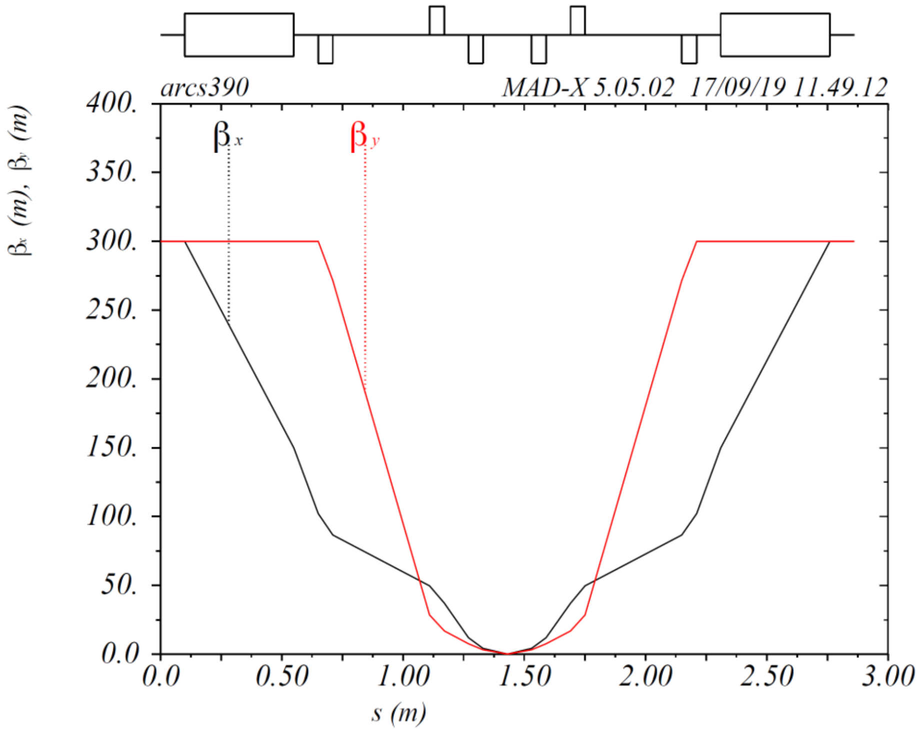
Parameter	Value	Units
Total length	15.58	m
Length w/o arc	11.58	m
Rep. rate	10	Hz
Initial pulse duration (FWHM)	35	fs
Beam spot size at the target (FWHM)	4	um
Physical emittance (rms)	0.021	π.mm.mrad
Proton energy range	12-15	MeV
Final energy spread	±2%	-
Mean dose rate	2	Gy/min
Final spot size (total diameter)	1-15	mm
Final bunch intensity	10^6-10^8	-

End Station

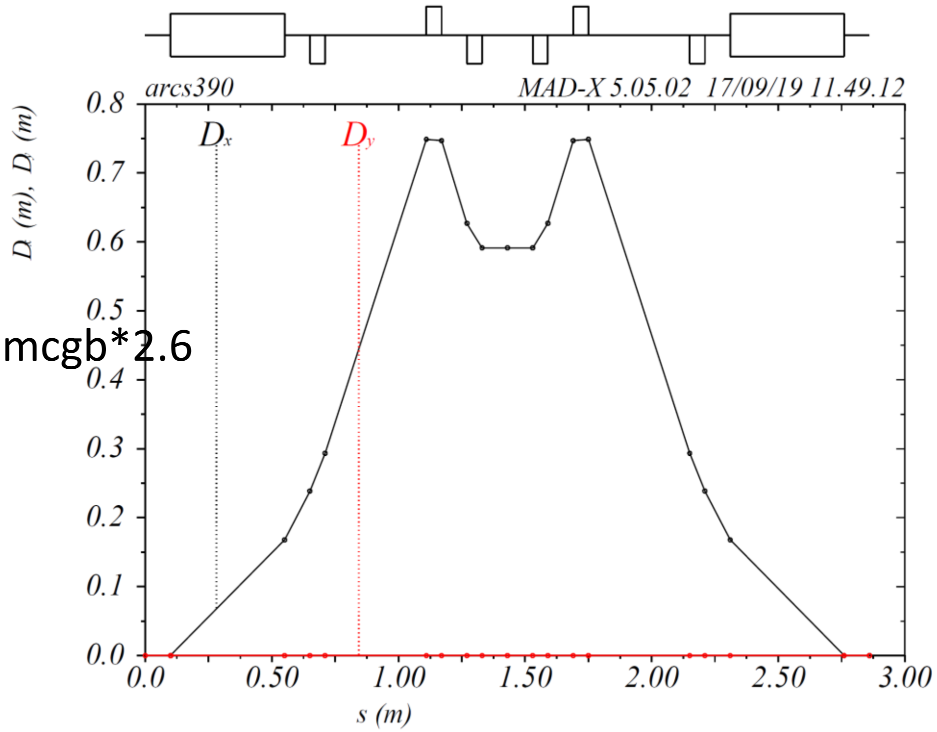


Energy loss as a function of depth for different beam energies
Energy loss [GeV/0.02mm]
Depth [mm]
10 MeV
12 MeV
15 MeV
0
1
2
3
4
5
6
7
8
beam
0.075 mm vacuum window
0.25 mm scintillating fibre layer
5 mm air gap
1.15 mm sample container base
0.03 mm cell layer
15 mm cell nutrient solution

Separated function arc for Stage I

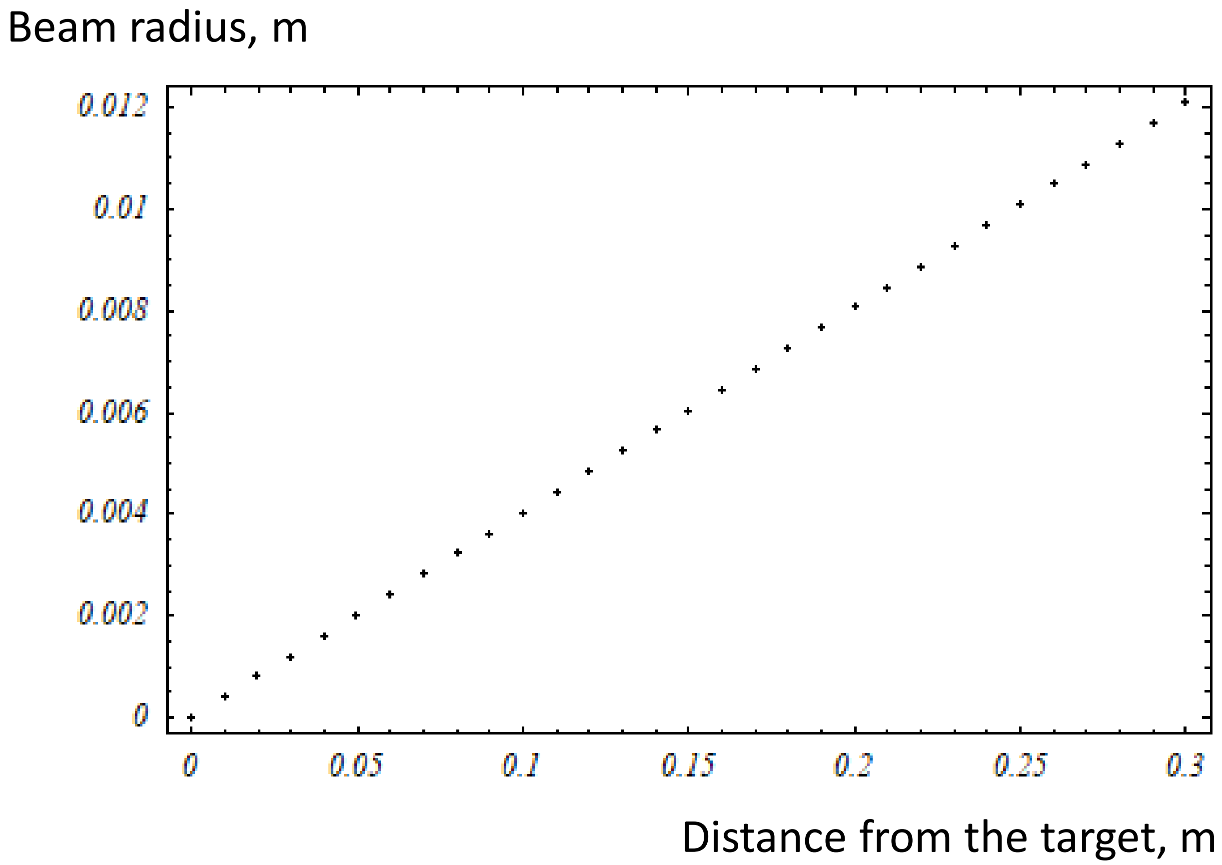


emcgb*2.6



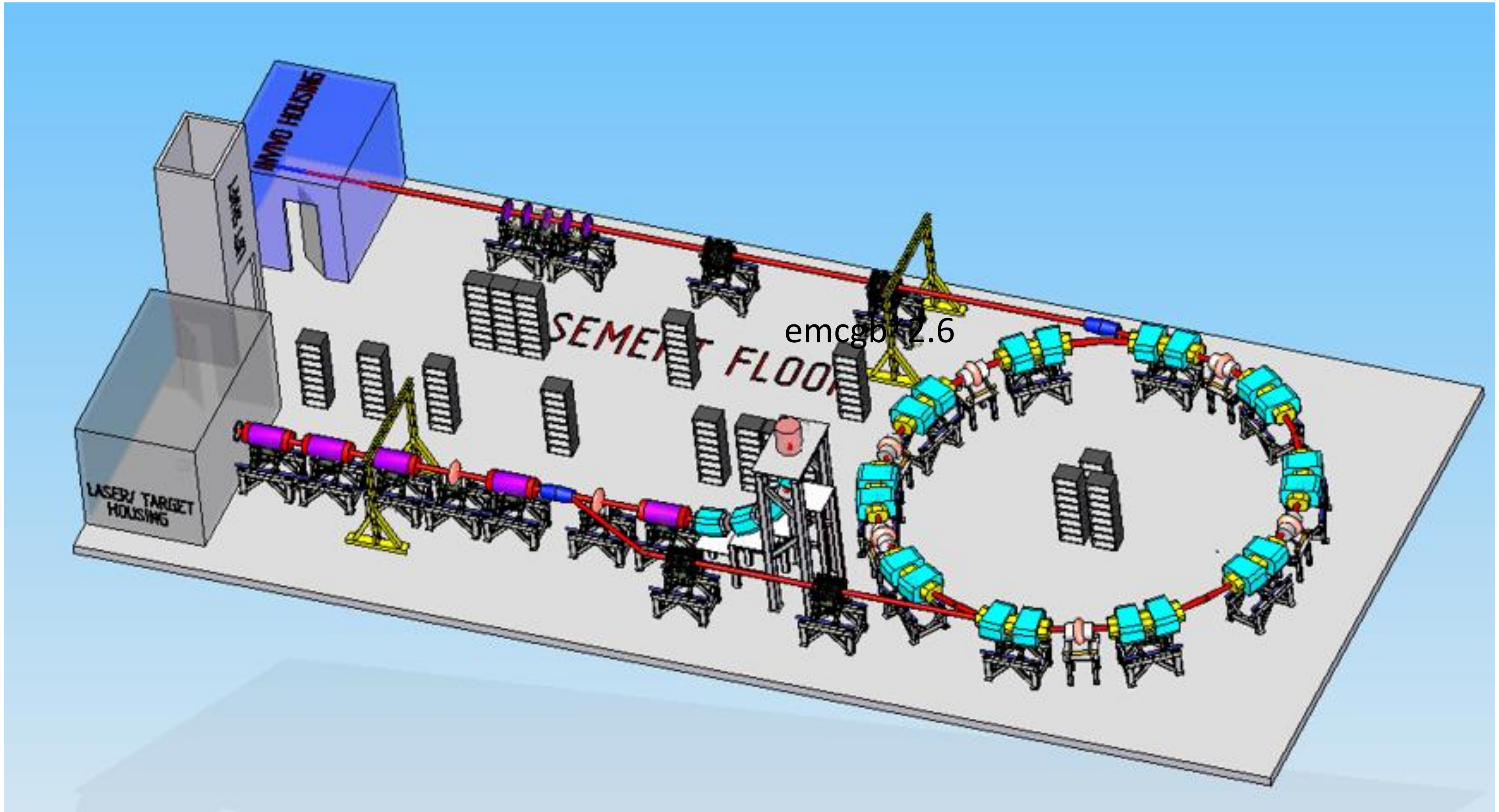
6 quadrupoles and two bending magnets

Optical requirement for the vacuum slit size between the target and the first Gabor Lens



- Target and Gabor Lens operation have a different specification for vacuum
- It is proposed to separate them by the narrow slit to facilitate pumping
- The minimum size of the slit dictated by the beam size has been calculated (2σ size, allowing for emittance growth by a factor of ~2.6)

Towards Stage 2

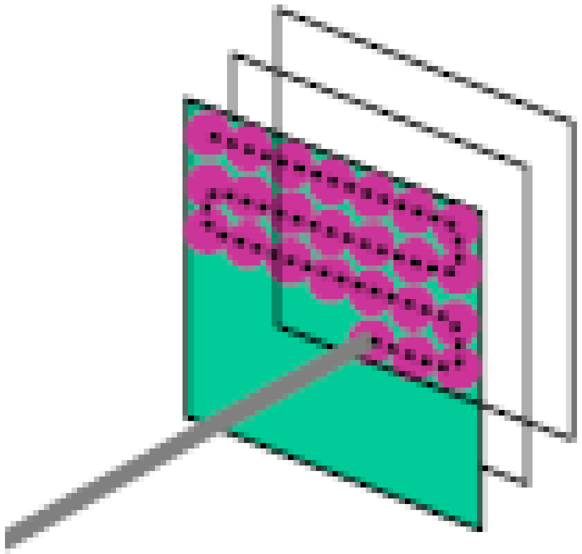


Thanks to L. Clark from RAL

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

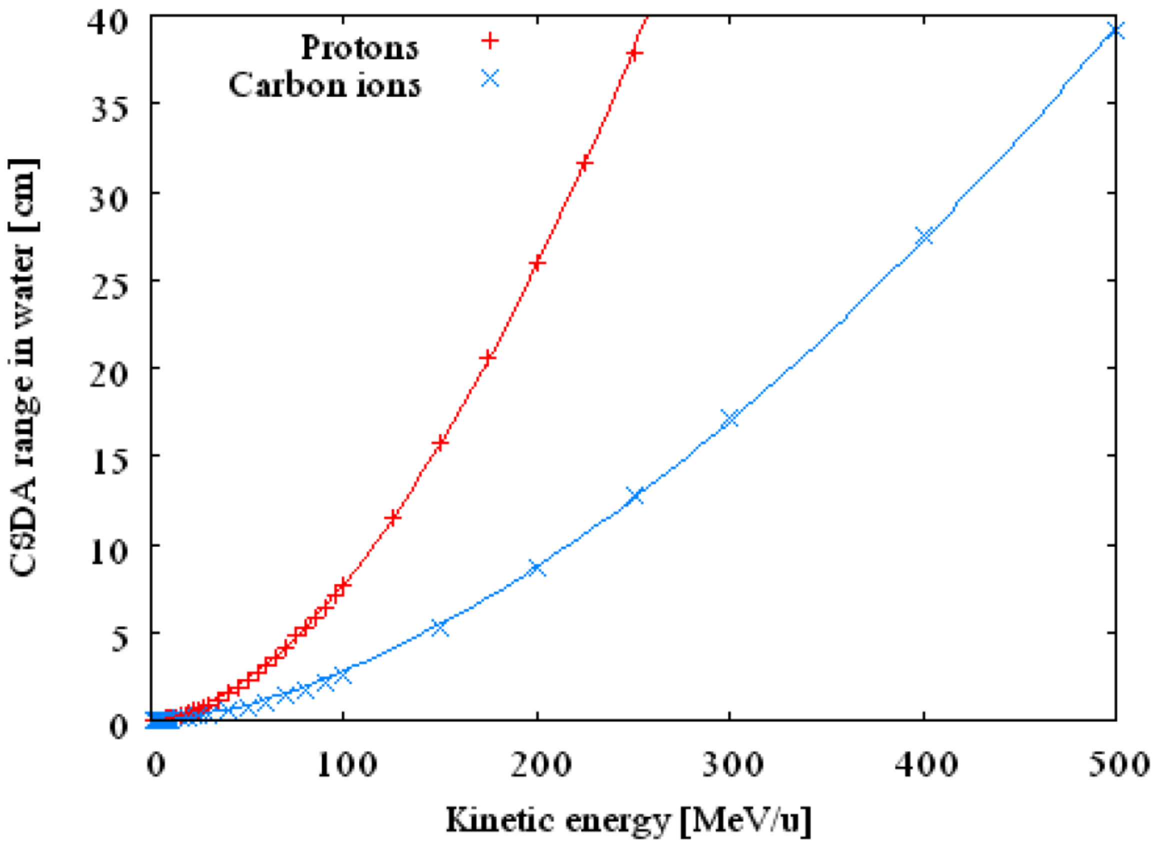
Advantages of FFA for medical/radiobiological applications:

- 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 treatment.
- Multiple ion capability

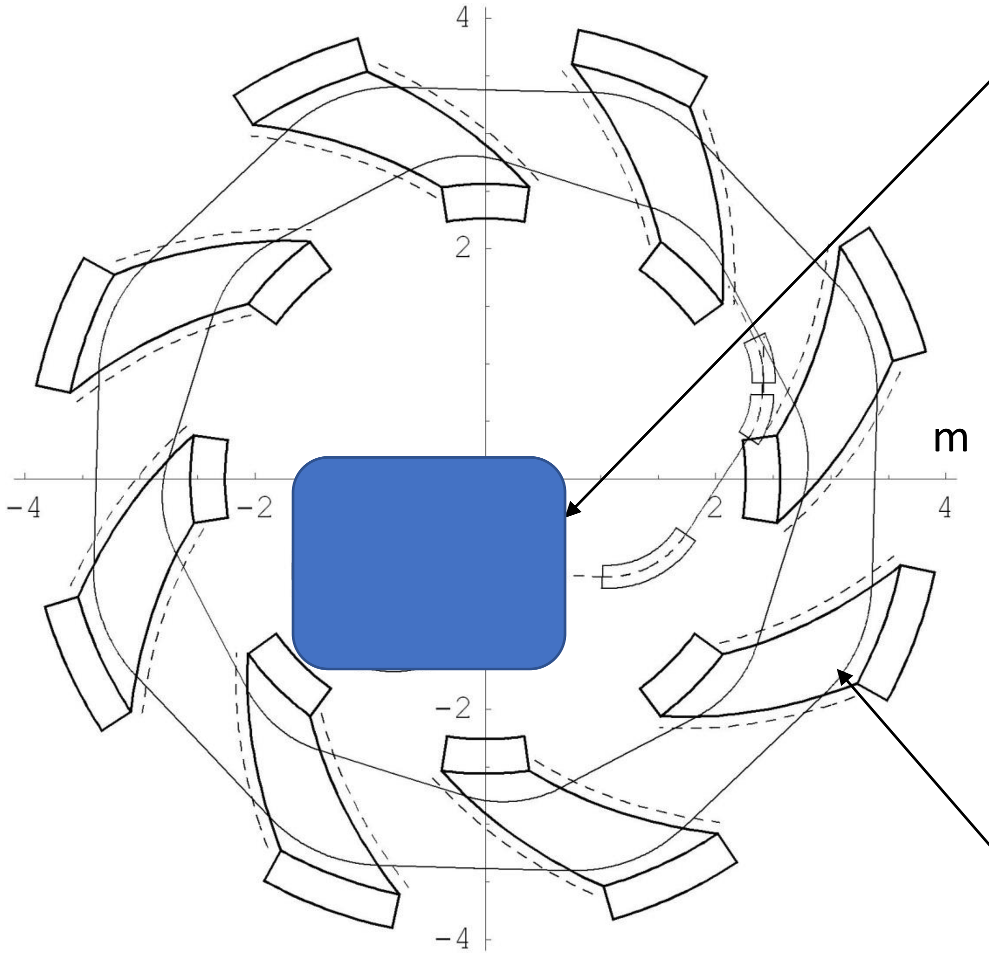


Energy for LhARA Step 2

- FFA accelerator can typicaly 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+.
- … and this is still not a lot with respect to penetration depth in water…



Energy Variability using Laser Accelerated Ions



Variable input energy from Laser source (multiple ions are possible)

Variable extraction energy from FFA within 1 s (75-180 MeV)

+

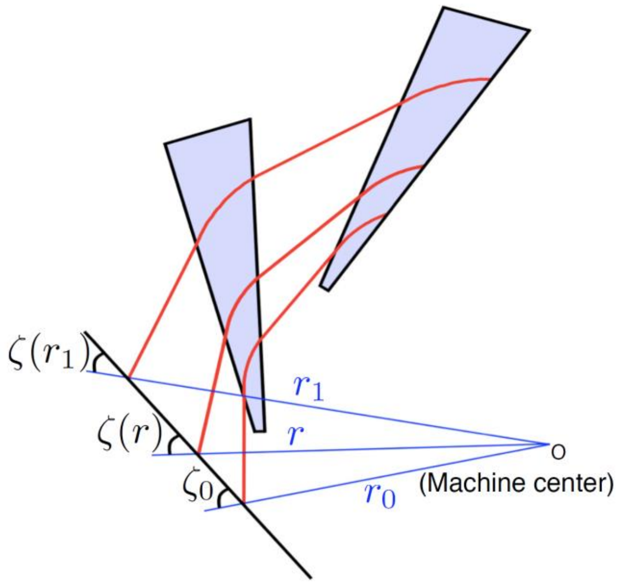
pulse by pulse variation with kicker system

Variable magnetic field in FFA (laminated magnets)

FFA types

- Scaling single spiral type
  - RACCAM project
  - Cost effective
- Scaling double spiral type
  - Two magnets per cell, higher flexibility
  - Considered for ISIS upgrade at RAL
- Vertical Scaling
  - Under study at RAL for ISIS upgrade
- Tilted Sector Type
  - Single Tilted Sector ruled out
  - Double Tilted Sector (two magnets per cell) - concept under development

Proposed by JB Lagrange



What is scaling spiral FFA?

B_y on the median plane:

Reference field at r_0

Field index

$$B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k \cdot \mathcal{F}(\theta - \tan\zeta \ln \frac{r}{r_0}).$$

Flutter function

Spiral angle

$$\mathcal{F}(r,\theta) = \mathcal{F}_{\text{En.}}(r,\theta) \times \mathcal{F}_{\text{Ex.}}(r,\theta)$$

$$\mathcal{F}_{EFB}(d) = \frac{1}{1+\exp[p(d)]}, \quad p(d) = C_0 + C_1 d/g + \ ... \ + C_5 (d/g)^5$$

$g \sim R/R_0$ and is related to gap size and magnet clamp

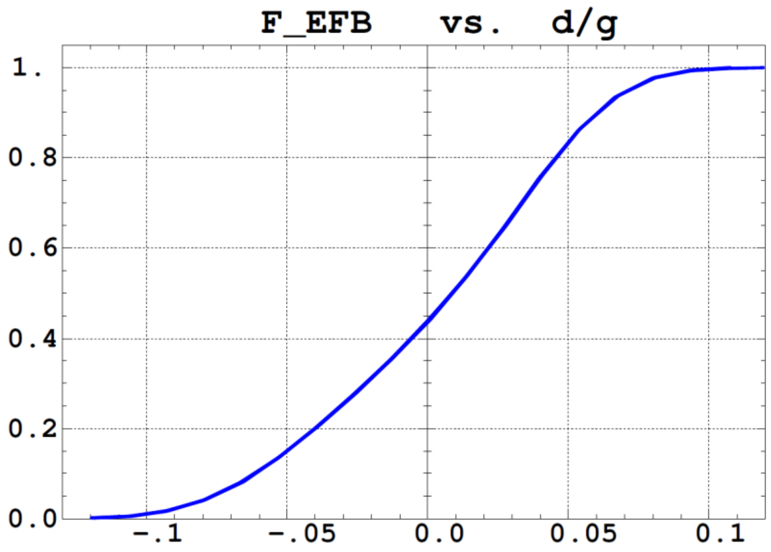
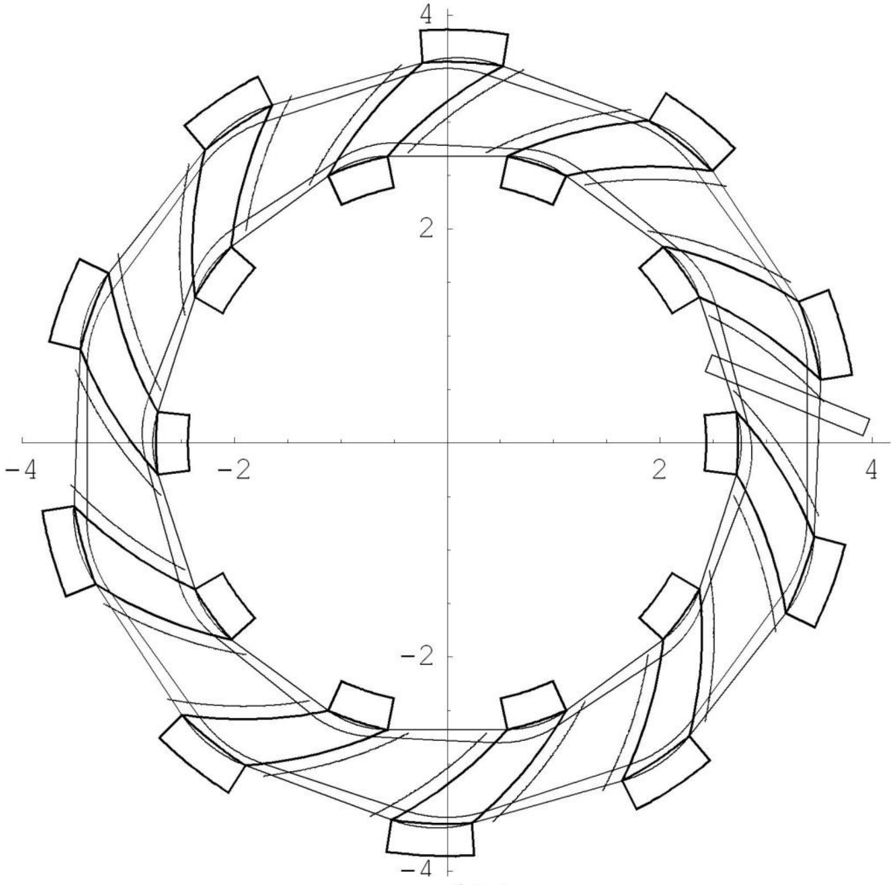
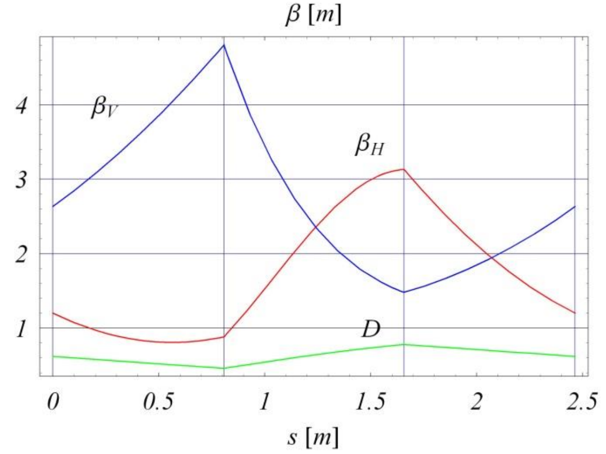


Figure 3: Typical fringe field shape, $\mathcal{F}_{EFB}(d/g)$ (Eq. 3).

Original RACCAM Machine Parameters

- N 10
- k 5.
- Spiral angle 53.7°
- R_{max} 3.46 m
- R_{min} 2.8 m
- (Qx, Qy) (2.77, 1.64)
- B_{max} 1.7 T
- p_f 0.34
- Injection energy 6-15 MeV
- Extraction energy 75-180 MeV
- h 1
- RF frequency 1.9 – 7.5 MHz
- Bunch intensity 3×10^{9} protons

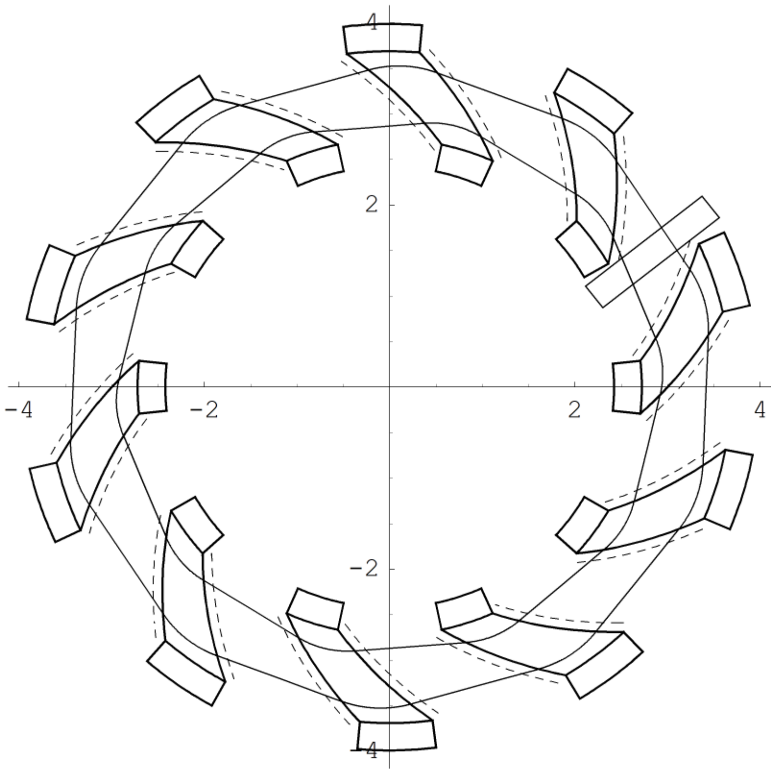


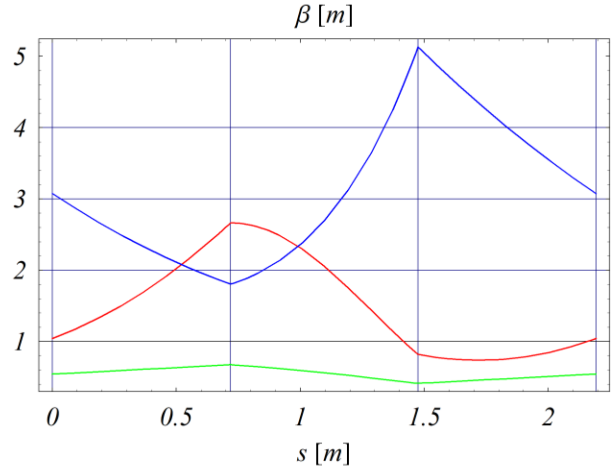


RACCAM
Research project

LhARA Ring Parameters

- N 10
- k 5.19
- Spiral angle 47.64°
- R_{max} 3.49 m
- R_{min} 2.92 m
- (Qx, Qy) (2.82, 1.23)
- 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 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

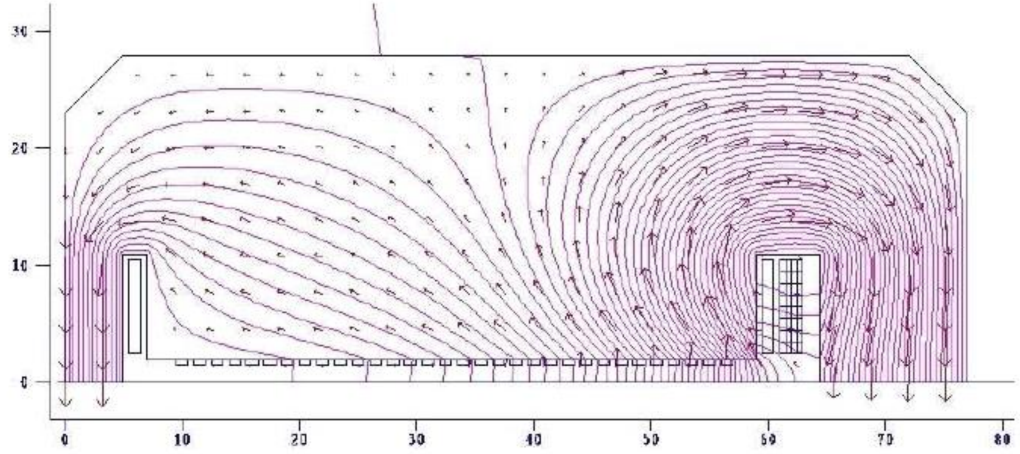




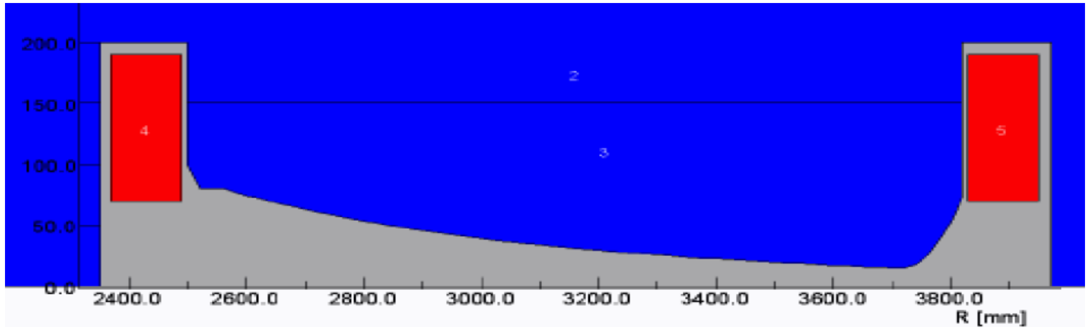
Some RF scenarios for various modes

- Main proton mode: h=1, V~0.5 kV, 15-127.4MeV, 2.89 – 6.48 MHz
- Min energy proton mode: h=2, 1.68-15 MeV, 1.95-4.83 MHz
- Main carbon mode: h=1, 3.77-33.4MeV/u, 1.46 – 3.55 MHz
- Min energy carbon mode: h=4, 0.42-3.77 MeV, 1.95-4.83 MHz

Magnet Types Considered for RACCAM



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



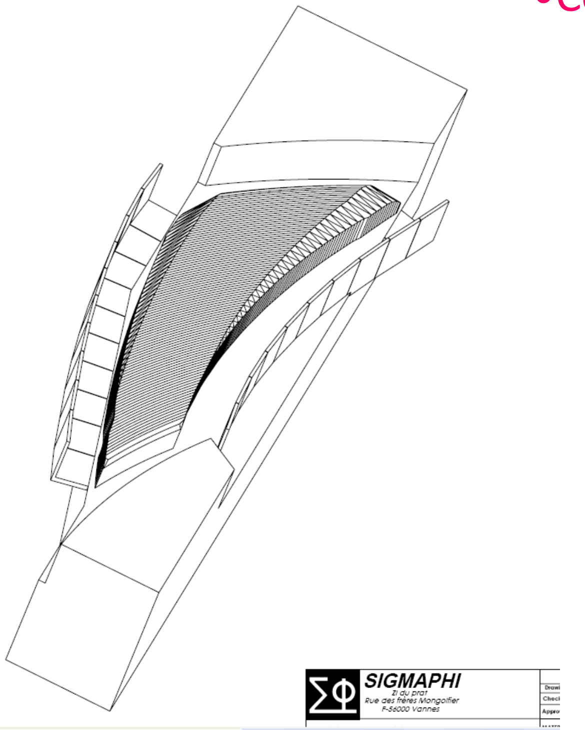
„Gap shaping" magnet:
- Developed by SIGMAPHI
- Initialy thought as more difficult
- Behaves very well!
- Chosen for prototype construction!

For LhARA magnet with parallel gap with distributed windings (but single current) would be of choice with gap controlled by clamp. Concepts like an active clamp could be of interest too.

RACCAM Spiral FFA Magnet

- Prototype magnet parameters have been successfully designed and constructed in collaboration with SIGMAPHI!
- Magnet uses combination of variable chamfer and field clamp to stabilize the tune.
- Special shape chosen in order to optimize the mass (16 t).
- Power consumption 18 kW
- Magnet is of the laminated type for energy variability.
- Costructed in 2008.

RACCAM Research project

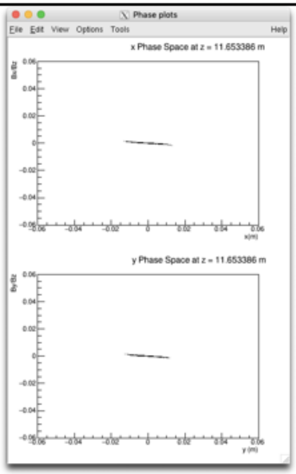
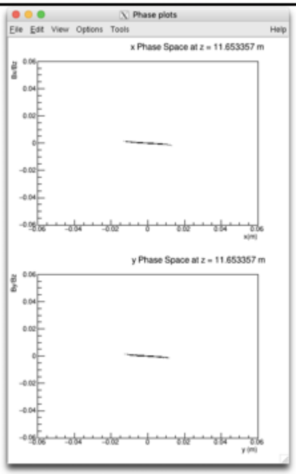
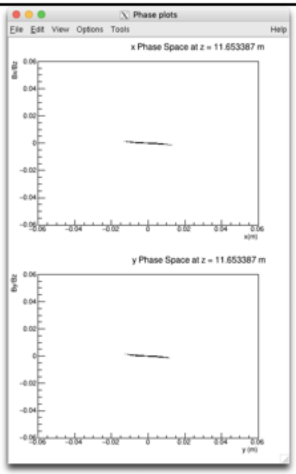
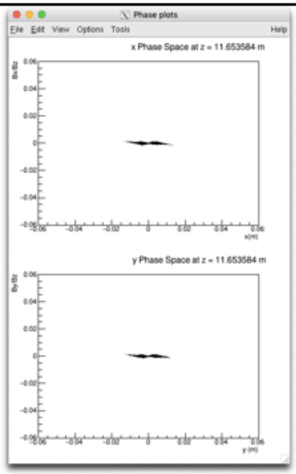
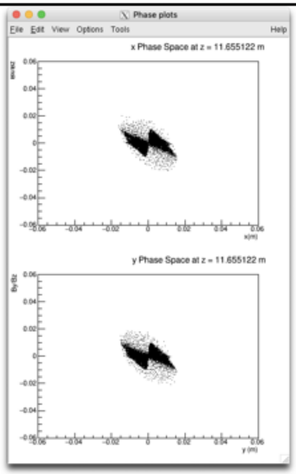
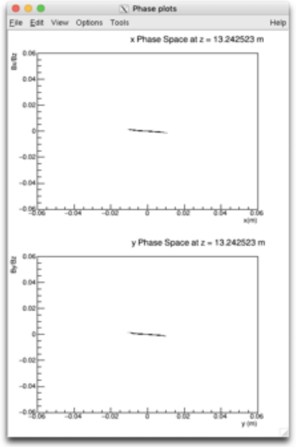
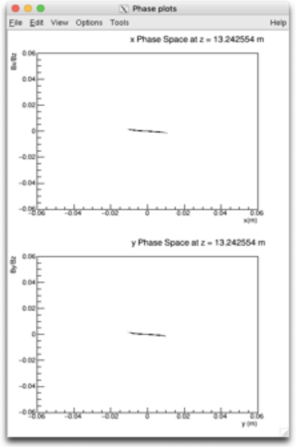
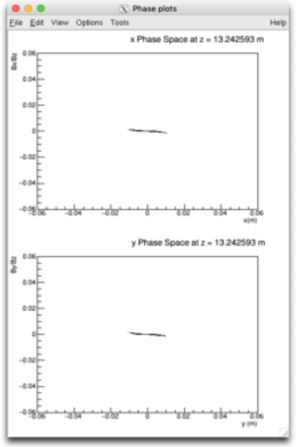
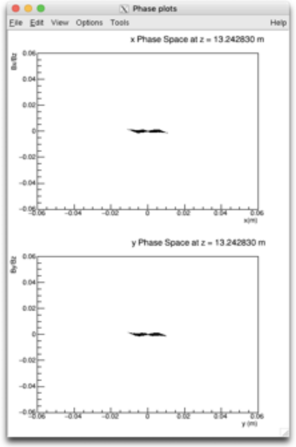
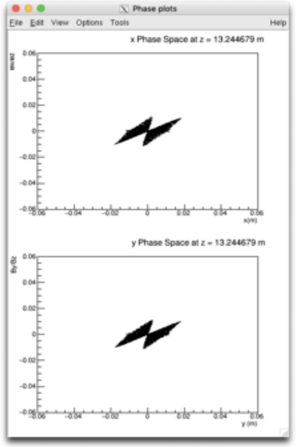


Conclusions and future plans

- Significant progress has been achieved on the design of LhARA Stage 1
- The conceptual design of the arc is now the next milestone, work in synergy with ISIS upgrade at RAL
  - Tilted sector FFA concept to be exploited
  - Full backup with separated function magnets is feasible
- LhARA at Stage 2 can use FFA-type ring accelerator enabling variable energy beam of various types of ions
- It will allow for in-vivo studies with protons and other types of ions + further in-vitro studies with ion beams
- Various types of FFA can be considered for the LhARA ring
- Single spiral-type seems the most cost effective at the moment
- Baseline design based on adjusted RACCAM parameters is a solid choice for further studies
- We are working towards CDR now

Spare

Space charge effects in Stage 1 – Phase space plots (GPT)

22					
25					
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