Design of FFA magnet for the laser-hybrid accelerator for radiobiological applications (LhARA)

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LhARA-FFA and its goals

LhARA, which stands for "Laser-hybrid Accelerator for Radiobiological Applications," is a flexible facility dedicated to research in radiobiology. Using a Fixed Field Alternating (FFA) gradient accelerator, a proton beam with extraction energies ranging from 15 MeV to 127 MeV can be produced. A more detailed description of the facility can be found in [1]. To avoid beam loss, the magnets must satisfy the following requirements:

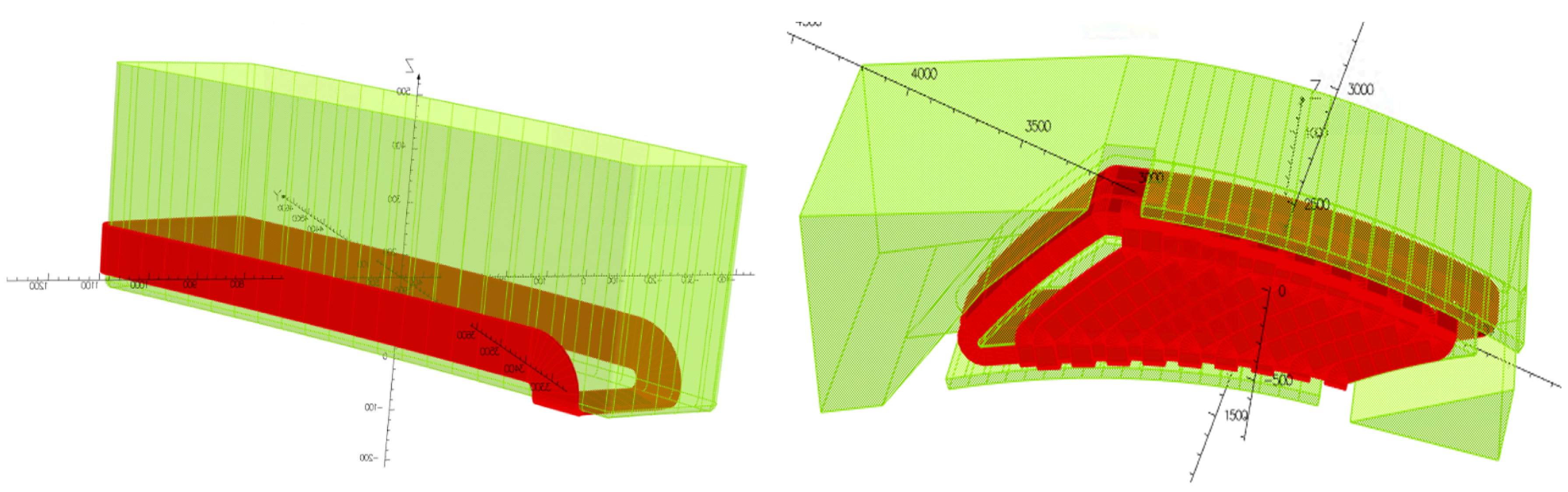
- Zero chromaticity during acceleration (constant tune)
- Constant working tune point for different energy ranges
- Sufficient physical and dynamical apertures

The FFA ring is composed of ten identical cells; each featuring a single combined-function spiral magnet. Clamps are added on the transverse sides of the pole to contain the fringe field, the parameters of the magnet are shown in Table 1.

Table 1: Parameters of the magnet

spiral angle (deg)	53.9
k value	5.23
Minimum orbit excursion (mm)	2880
Maximum orbit excursion (mm)	3530
Target horizontal ring tune	2.79
Target vertical ring tune	1.17

The magnetic field profile is achieved through a combination of distributed conductors: a main coil, and 18 trim coils. A dipole field is generated by the main coil wound around the pole. The trim coils cross the flat surface of the magnet pole and return towards the outer radius of the pole. Each carrying a different set of current, a field gradient can be achieved.



Procedure

One of the ways to achieve zero chromaticity is to arrange the integrated magnetic field $BL(r)$ with the scaling law:

$$BL(r) = BL_0 \left(\frac{r}{r_0}\right)^{k+1}, BL(r) = \int B(r,\theta) r d\theta \quad (1)$$

where r and θ are cylindrical coordinates, r_0 is the reference radius chosen and BL_0 the integrated magnetic field at that radius.

The field value k defined as:

$$k(r) = \frac{r}{BL(r)} \frac{\partial BL(r)}{\partial r} - 1 \quad (2)$$

The spiral angles are calculated using the angle of the centre of moment, $\theta(r)_{COM}$:

$$\theta(r)_{COM_{En,Ex}} = \frac{\int \frac{\partial B(r,\theta)}{\partial \theta} \theta d\theta}{\int \frac{\partial B(r,\theta)}{\partial \theta} d\theta} \Big|_{\frac{\partial B(r,\theta)}{\partial \theta}<0, \frac{\partial B(r,\theta)}{\partial \theta}>0} \quad (3)$$

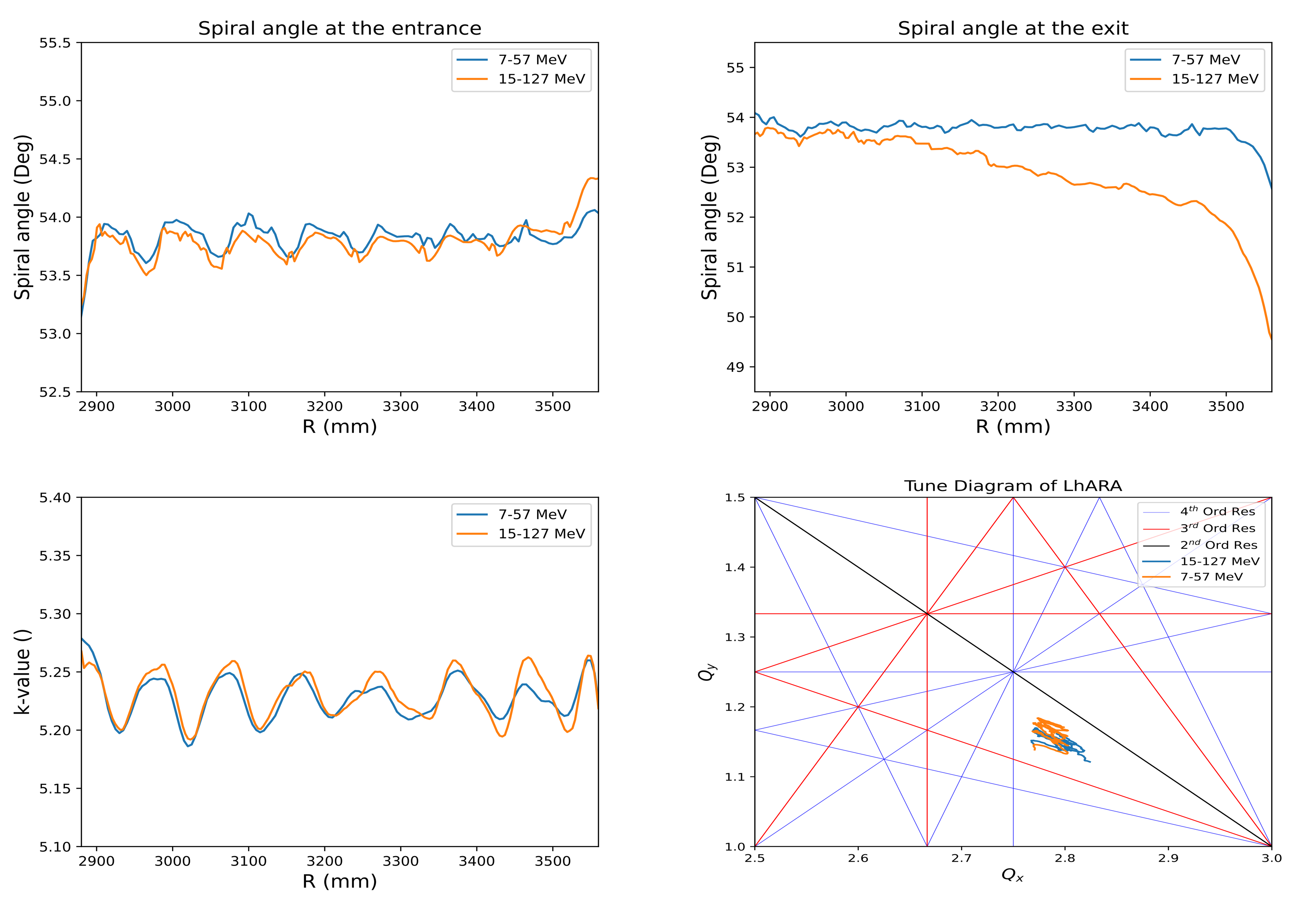
The sign of edge focusing at the boundaries of the magnet are opposite; θ_{COM} for the entrance (En) and exit (Ex) side of the magnet are calculated separately.

The spiral angles can then be calculated using

$$\zeta(r)_{En,Ex} = arctan\left(r \frac{\partial \theta(r)_{COM_{En,Ex}}}{\partial r}\right) \quad (4)$$

Optimised field quality

Two energy ranges were studied: a maximum-energy case with 15 MeV injection accelerated to 127 MeV, and a low-energy case with 7 MeV injection accelerated to 57 MeV. 3D field maps were obtained and tracked in Fixfield [2]. The final values of the field index k, spiral angle ζ and the ring tunes are shown below.



Conclusion

The ring tune of LhARA FFA has been shown to avoid resonances up to fourth order for two separate energy ranges. Further work will be done on reducing the fringe field extent variation to further reduce the tune spread, allowing a greater margin of error. The performance of the ring will also be confirmed for the full extraction energy range (15-127 MeV). Finally, a study at different energy ranges is needed to check that the dynamic aperture is sufficient for machine operation.

References

[1] W. Shileds et al, Proc. IPAC'25, Taipei, Taiwan, 2025, this conference (TUPB103).
[2] J-B. Lagrange, IPAC'21, Campinas, Brazil, (TUPAB209).