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Design of FFA magnet for LhARA

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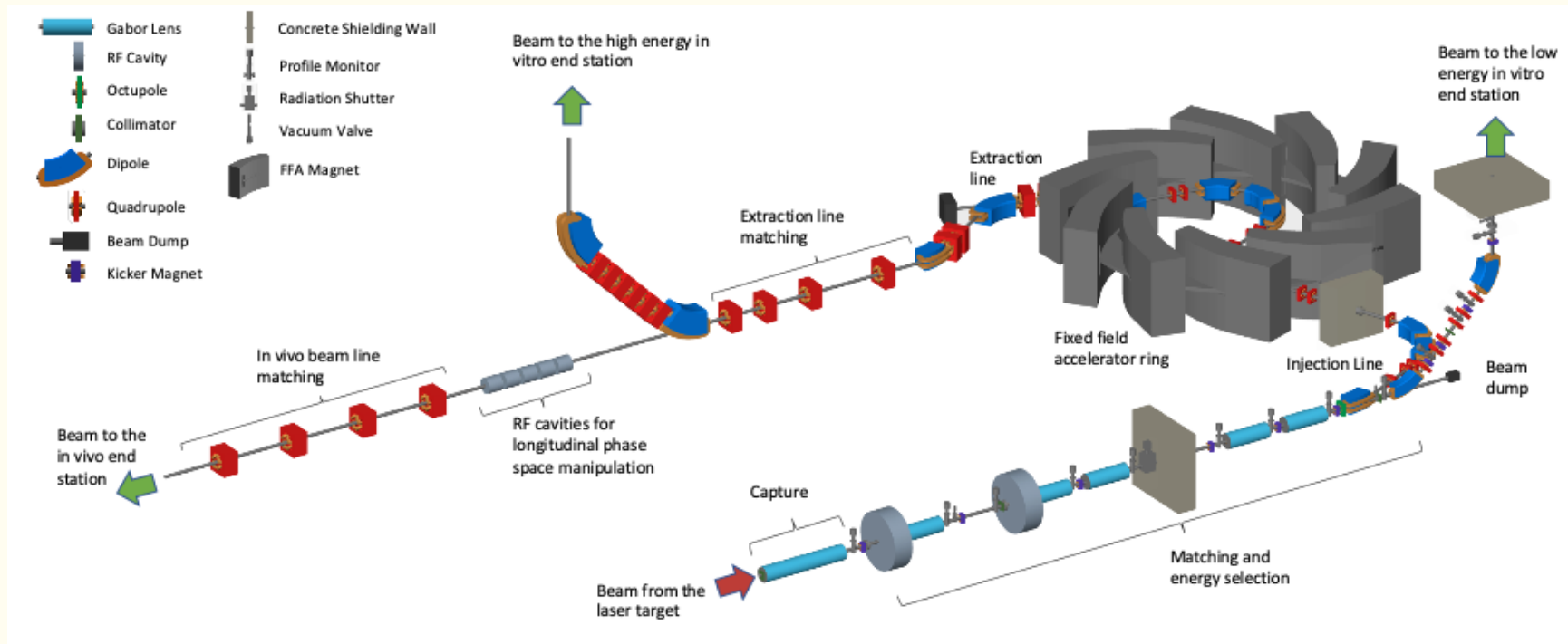
Content

1. What is LhARA
2. Target field
3. Magnet and coil geometry
4. Optimising of current
5. Adjusting fringe field
6. Final tune result

1. What is LhARA

LhARA

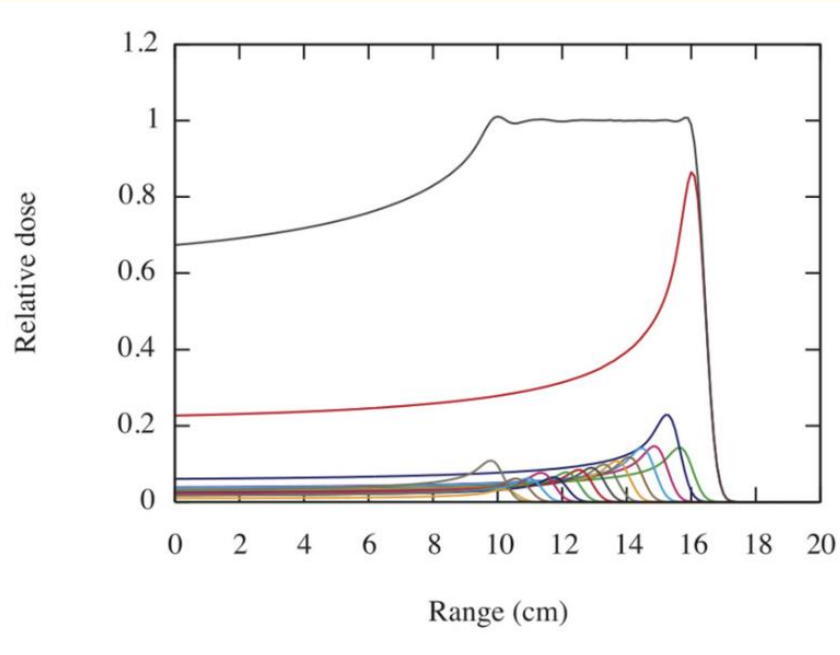
Laser-hybrid Accelerator for Radiobiological Applications, dedicated to radiobiology research



Laser target: Up to 15 MeV proton beam at 10Hz

FFA: Variable extraction energy 15-127 MeV

Variable extraction energy



Combine beams of different energy to create a spread out Bragg peak

Injection energy and total B field varied for different extraction energy

Verify behavior at 2 different extraction energies 127 MeV and 57 MeV.

2. Target field

Integrated scaling law

Scaling law: $B(r, \theta) = B(r_0, \theta) \left(\frac{r}{r_0}\right)^k$

Instead we make the integrated field scaling

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

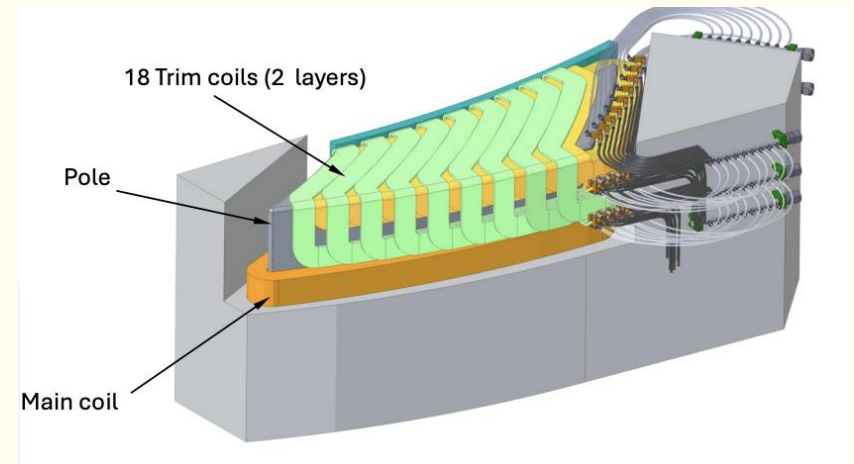
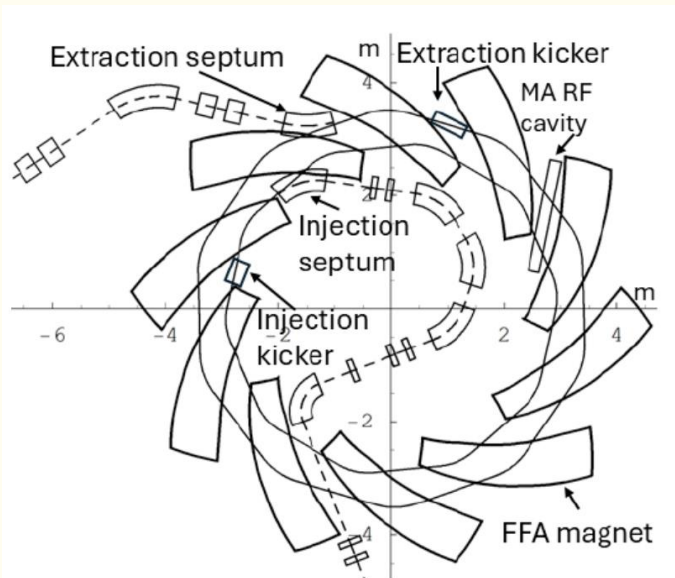
This is the same as making the average B field scaling if it's a singlet.
Slightly different for doublet (FETS-FFA magnet talk tomorrow)

To first order the horizontal tune roughly constant
Vertical tune variation will need to be investigated later on

3. Geometry of magnet and coils

Geometry of the magnet

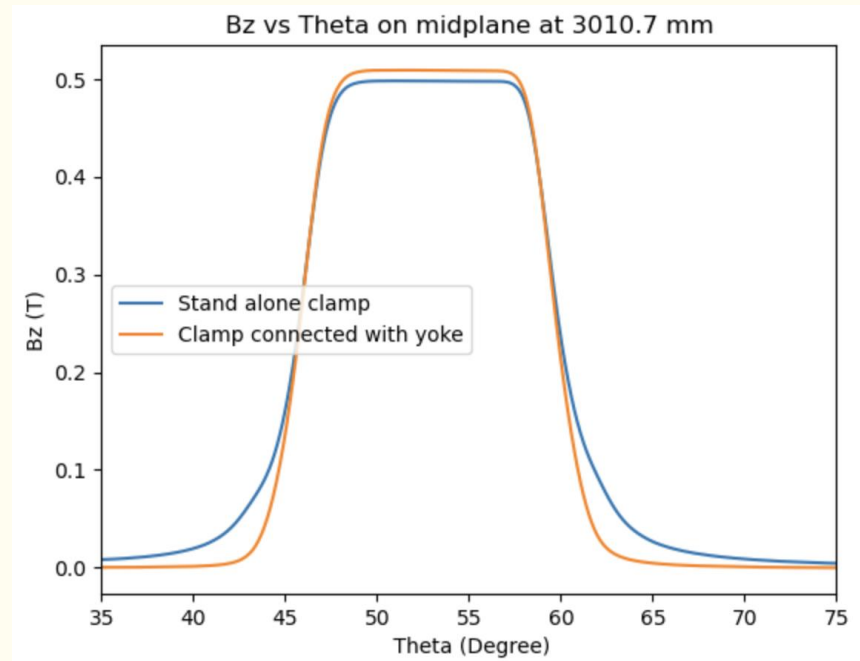
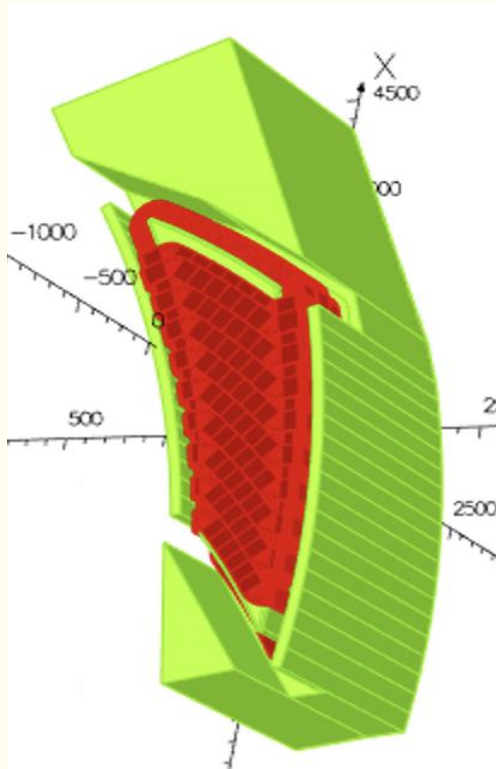
- Spiral angle 53.9 degrees
- 10 fold symmetry
- Full gap of iron 96 mm
- Field gradient generated by radially dependent trim coils, each with a different current setting



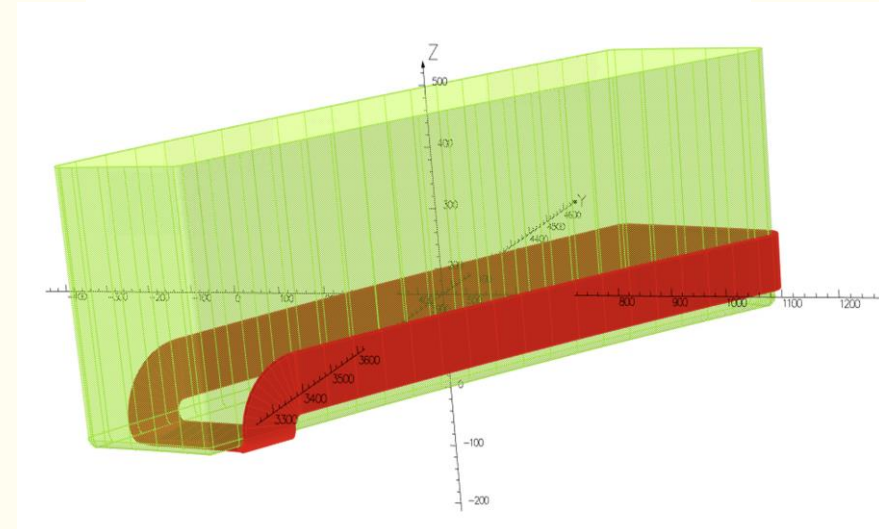
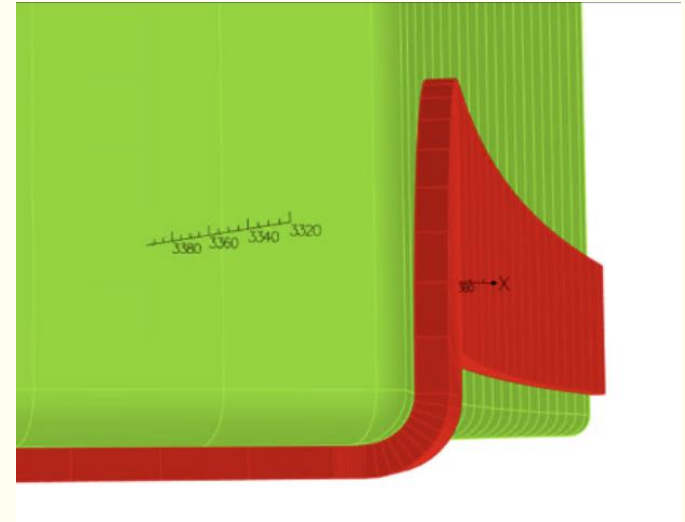
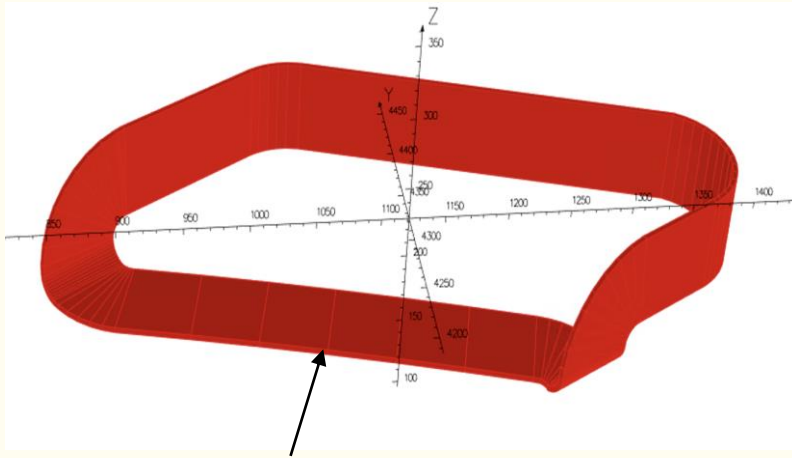
Geometry of the clamps

Clamps placed at constant angle away from the pole

Connected magnetically with the pole improves efficiency



Geometry of a trim coil



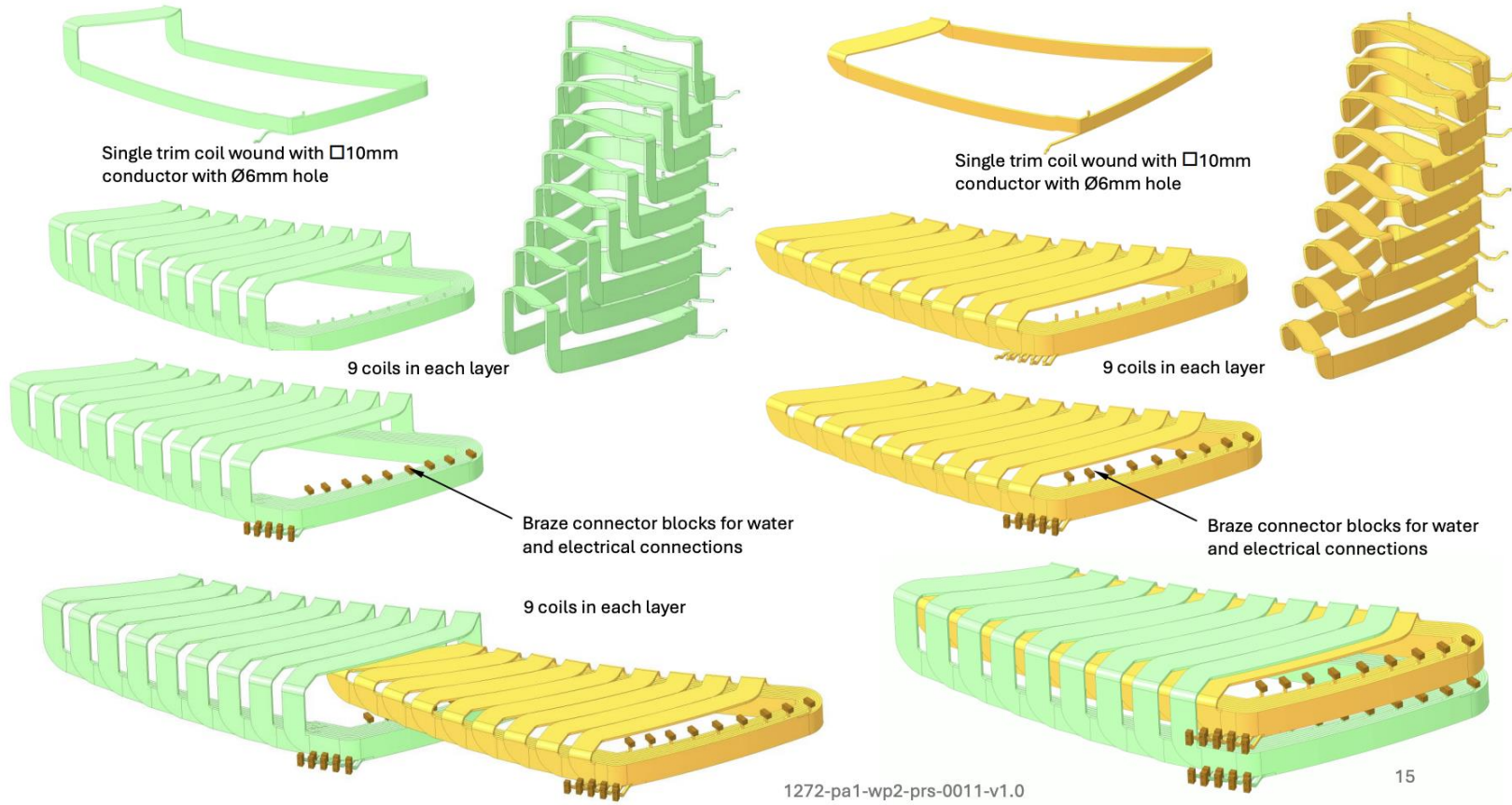
The match the scaling law, the constant radius area should be as large as possible

The return part shaped accordingly to the pole to minimize space taken up

Modelled in Opera 3D via Metaopera¹

Geometry of trim coils stacked together

Trim Coils



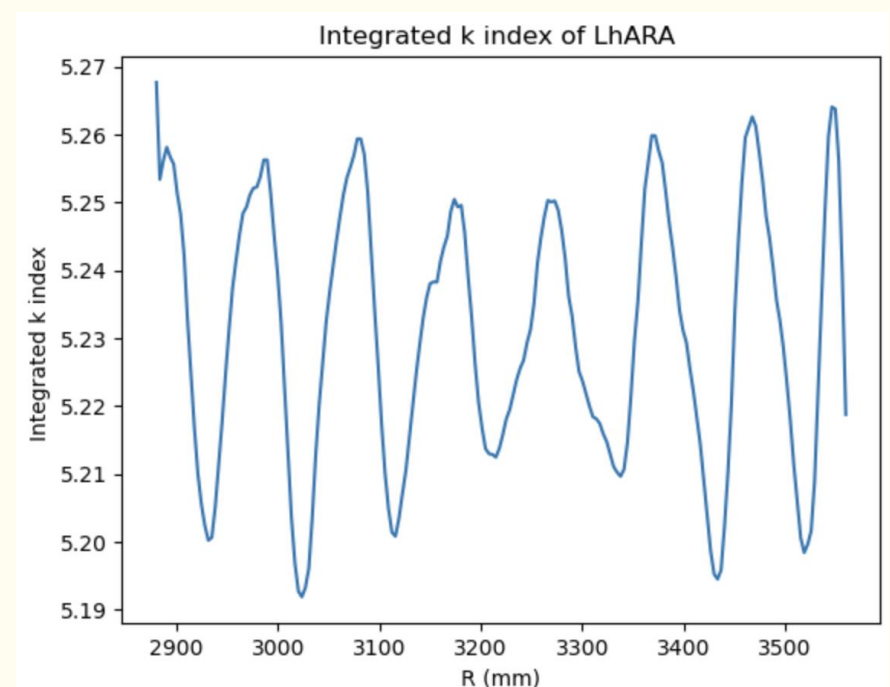
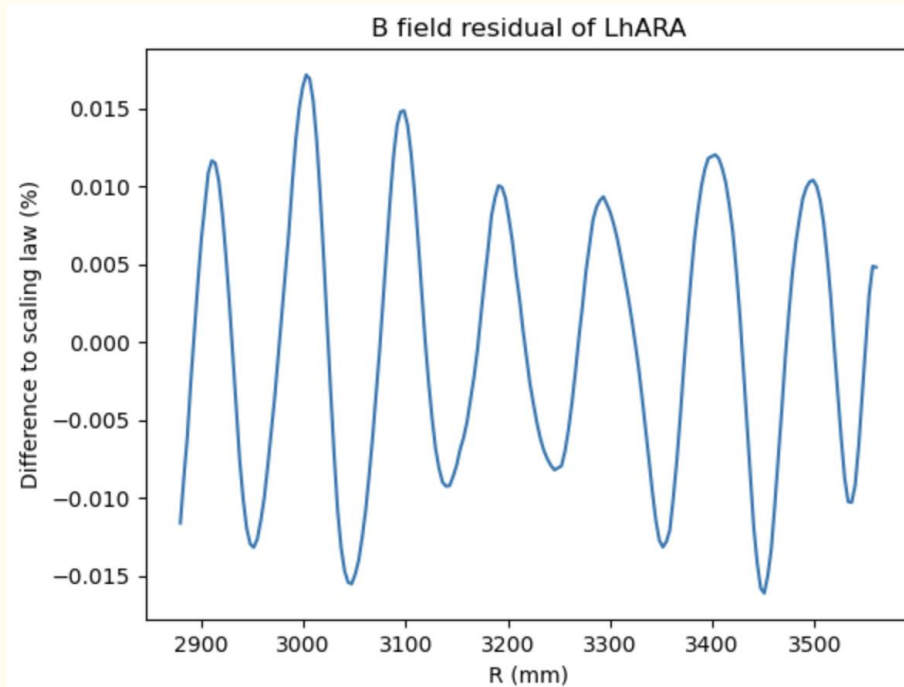
Cross the pole face at different radius, returns stack longitudinally
Two vertical layers slot into each other

4. Optimisation of currents

Field error, 127 MeV extraction energy

127 MeV extraction energy: BL_0 : 1.44 Tm , r_0 :3.477m, k : 5.23

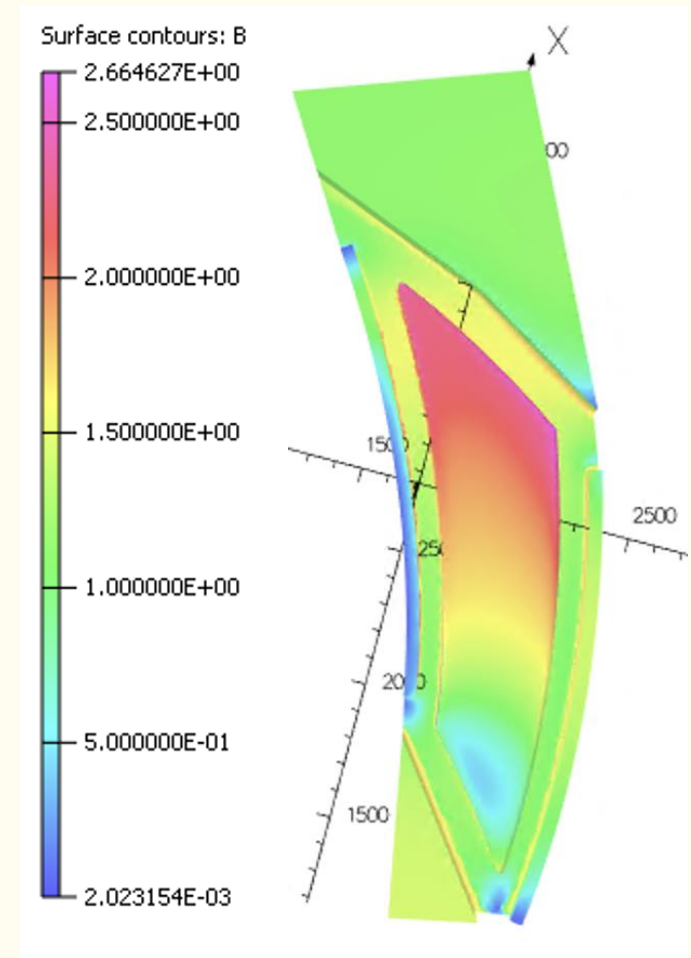
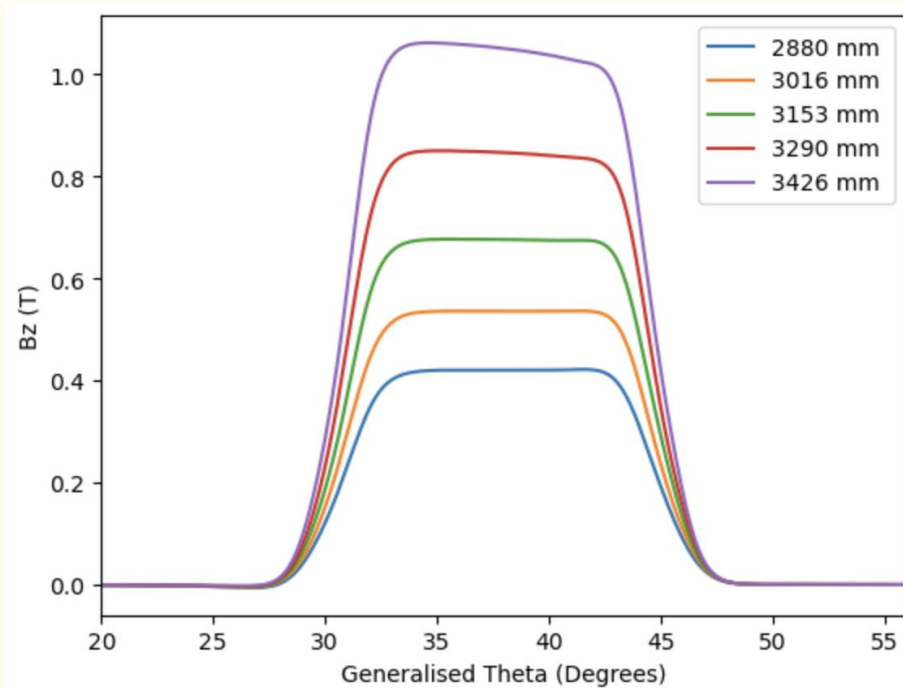
$$BL = BL_0 \left(\frac{r}{r_0}\right)^{k+1}$$



Oscillation in residuals due to the discretization of trim coils

Saturation level

Part of the pole reaching 2.66T
Flat top of field distorted at higher radii due to saturation and will have an impact on the tune



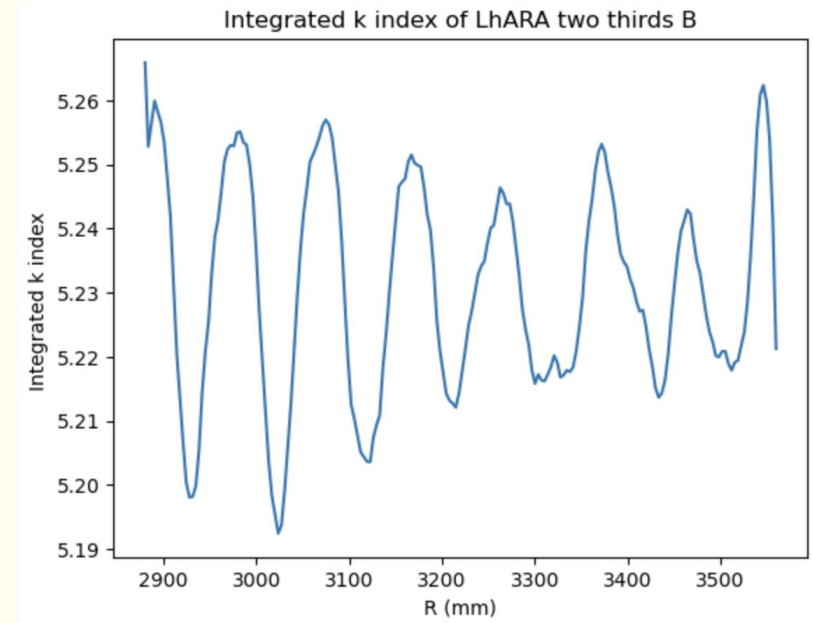
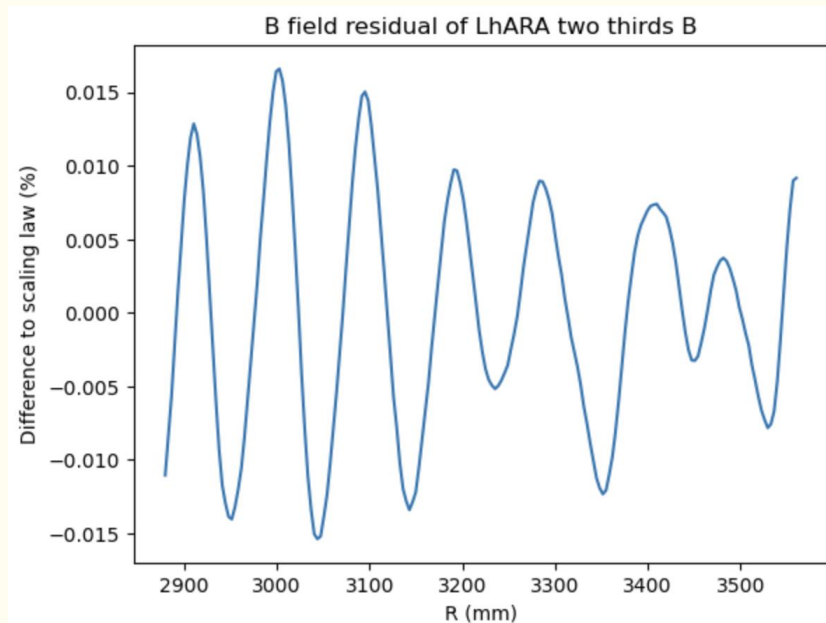
(Plotted in a coordinate that undoes the spiral angle)

Field error, 57 MeV extraction energy

Setting BL_0 to $\frac{2}{3}$ of the original value

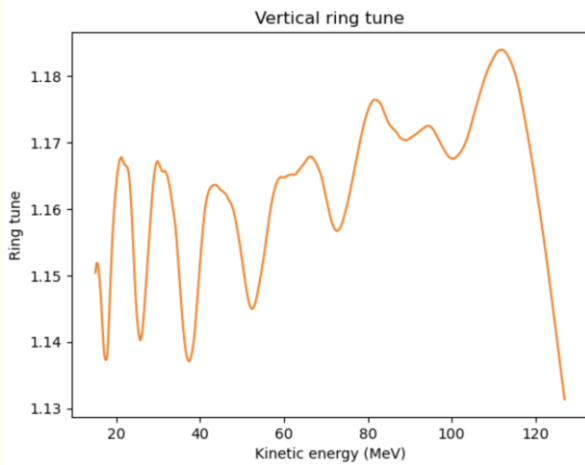
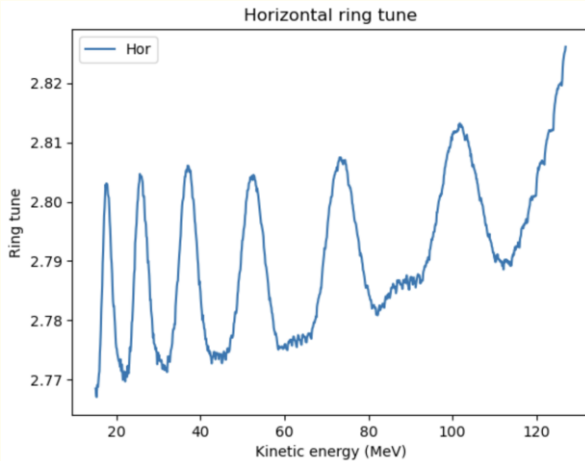
57 MeV extraction energy : BL_0 : 0.96 Tm , r_0 : 3.477m, k : 5.23

$$BL = BL_0 \left(\frac{r}{r_0}\right)^{k+1}$$

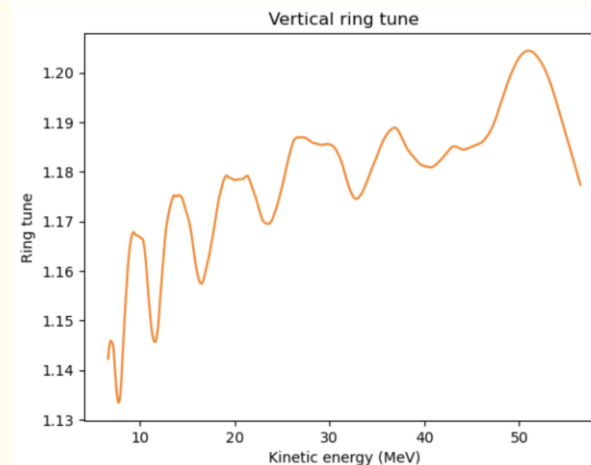
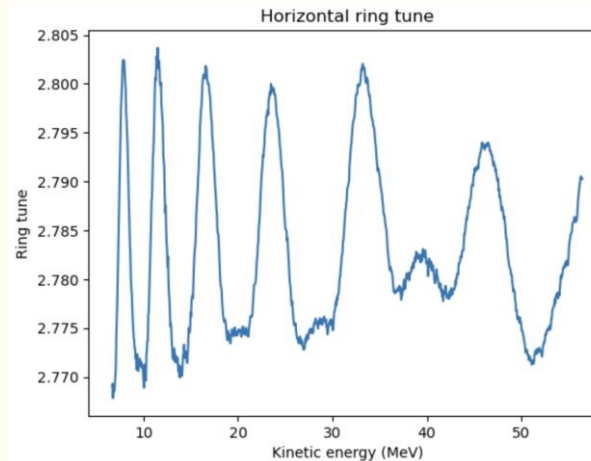


Ring tune

127 MeV extraction energy



57 MeV extraction energy



Some variation of horizontal
tune at 127 MeV

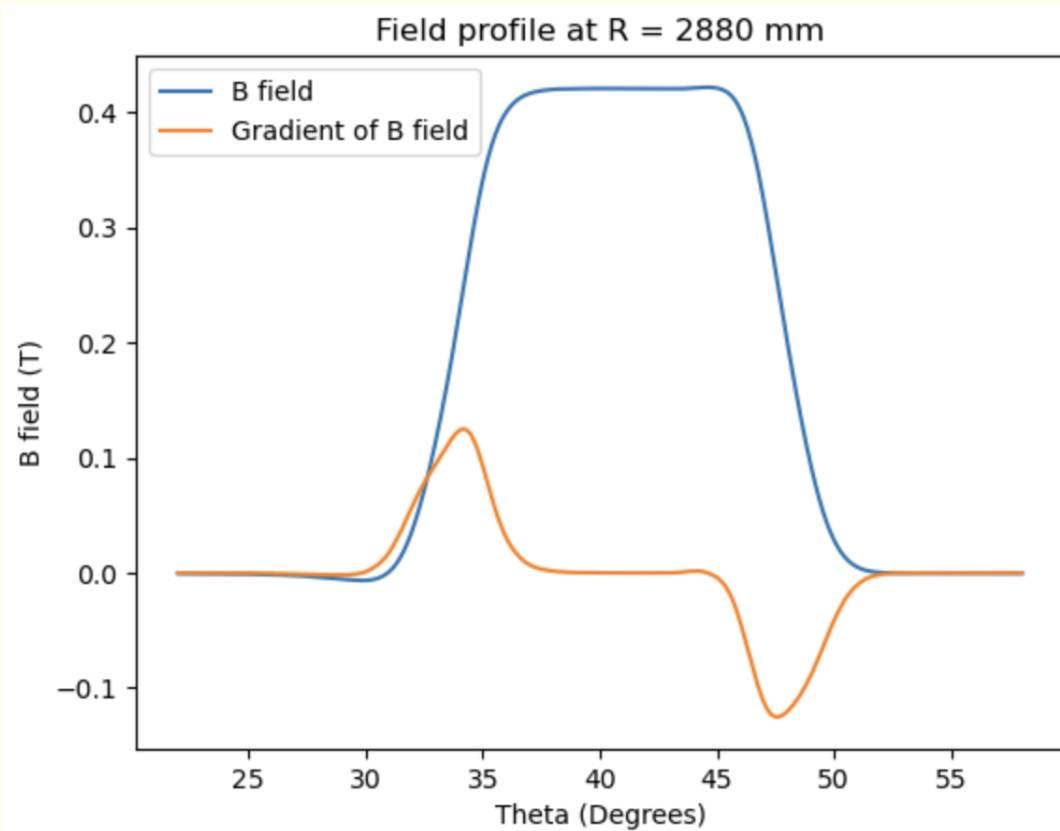
Vertical tune variation to be
minimized by shaping the field
clamps

5. Adjusting fringe field

Spiral angles

Spiral angle of the magnet may not be the same as the spiral angle of the B field.

Calculate the integrated average gradient of the field to define magnetic field boundary



$$\theta_{COM} = \frac{\int G \theta d\theta}{\int G d\theta}, G = \frac{\partial B_z}{\partial \theta}$$

$$\text{Spiral angle } \xi = \arctan \left(r * \frac{d\theta}{dr} \right)$$

For entry and exit sides of magnet separately ξ_{en}, ξ_{ex}

Tanh model of fringe field

This describes the fringe field length of the magnet at the entrance and exit separately.
The larger $C1$ is the shorter the fringe field

$$B = \frac{B_0}{(1+\exp(F_{en}))(1+\exp(F_{ex}))}$$

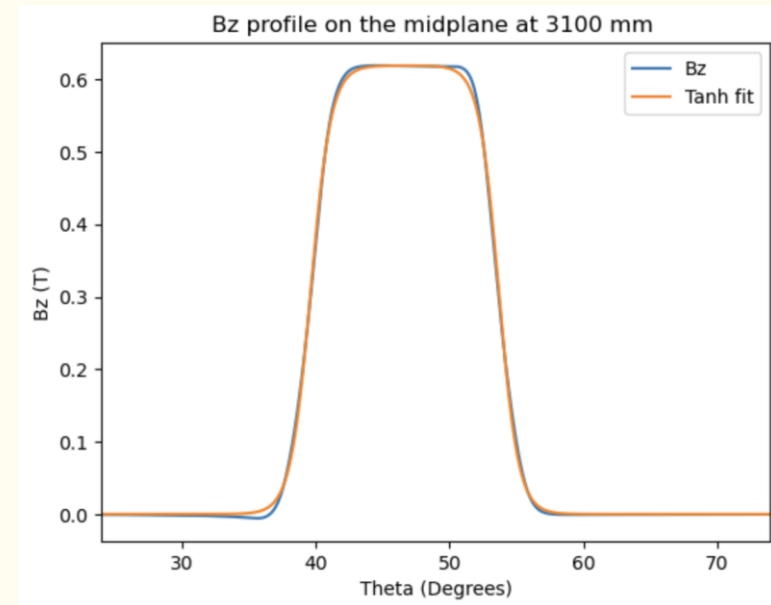
$$F_{en}(\theta) = C1_{en} \frac{r_0}{\lambda_0} (\theta_{EFBen} - (\theta - \tan\xi_{en} \ln \frac{r_0}{\lambda_0})), F_{ex}(\theta) = C1_{ex} \frac{r_0}{\lambda_0} ((\theta - \tan\xi_{ex} \ln \frac{r_0}{\lambda_0}) - \theta_{EFBex})$$

Independent Parameters

- λ_0 : Gap height of the pole
- B_0 : Max B field
- $\xi_{en,ex}$: Spiral angles from the previous equations

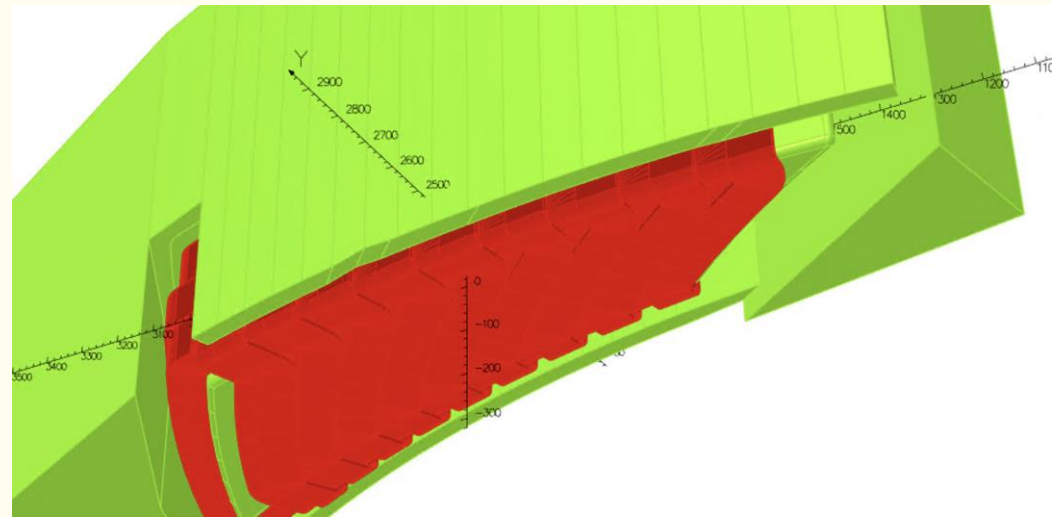
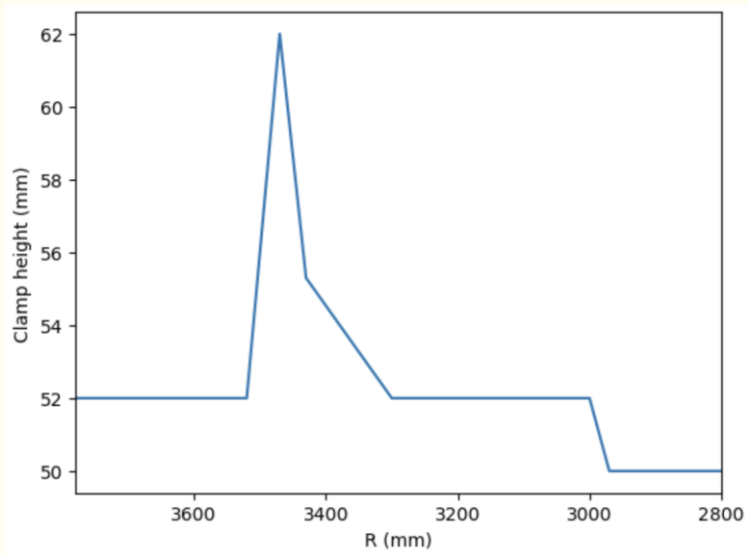
Parameters to fit

- $C1_{en,ex}$: Describes the fringe field length
- $\theta_{EFBen,ex}$: Describes the effective field boundaries



Clamp height optimisation

Vary the clamp height to achieve better tune spread. Iterations were done with tune spread as the target.

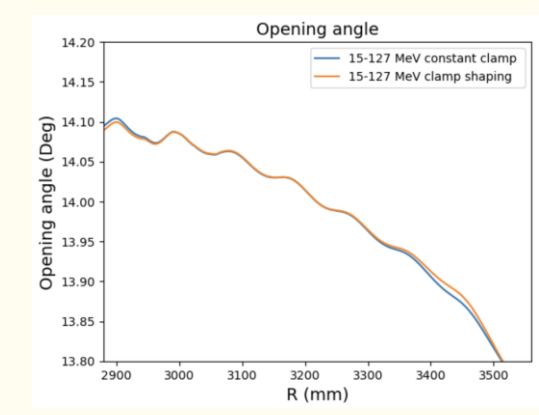
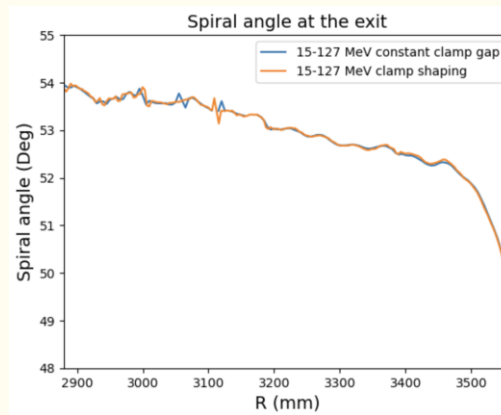
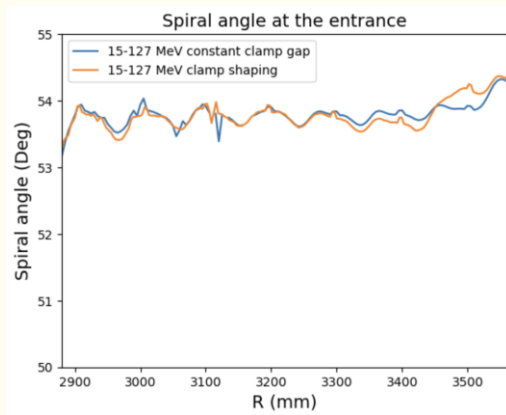
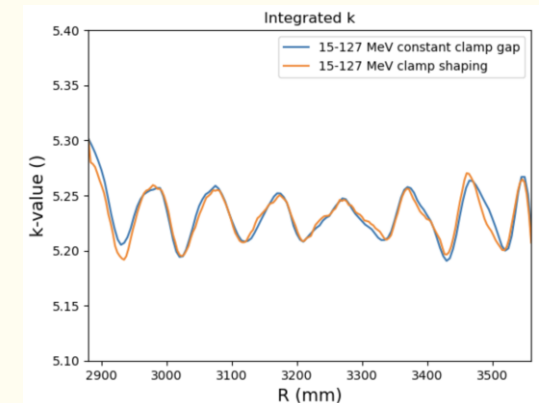
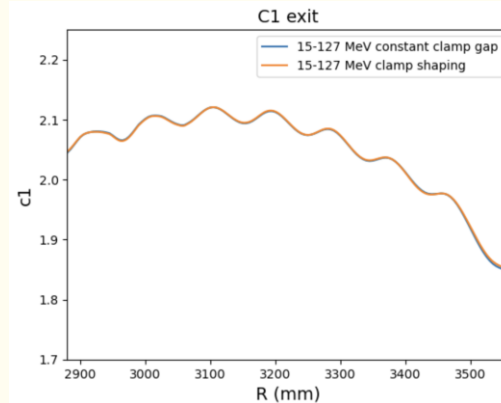
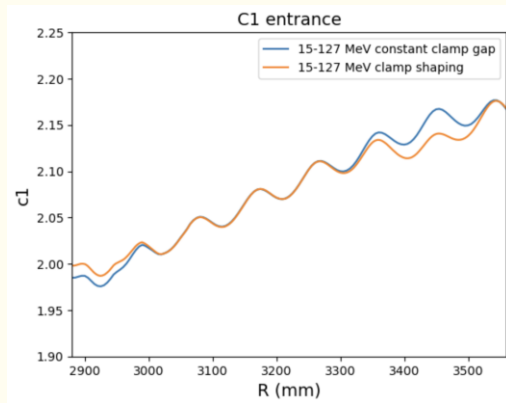


Fringe field parameters, 127 MeV extraction energy

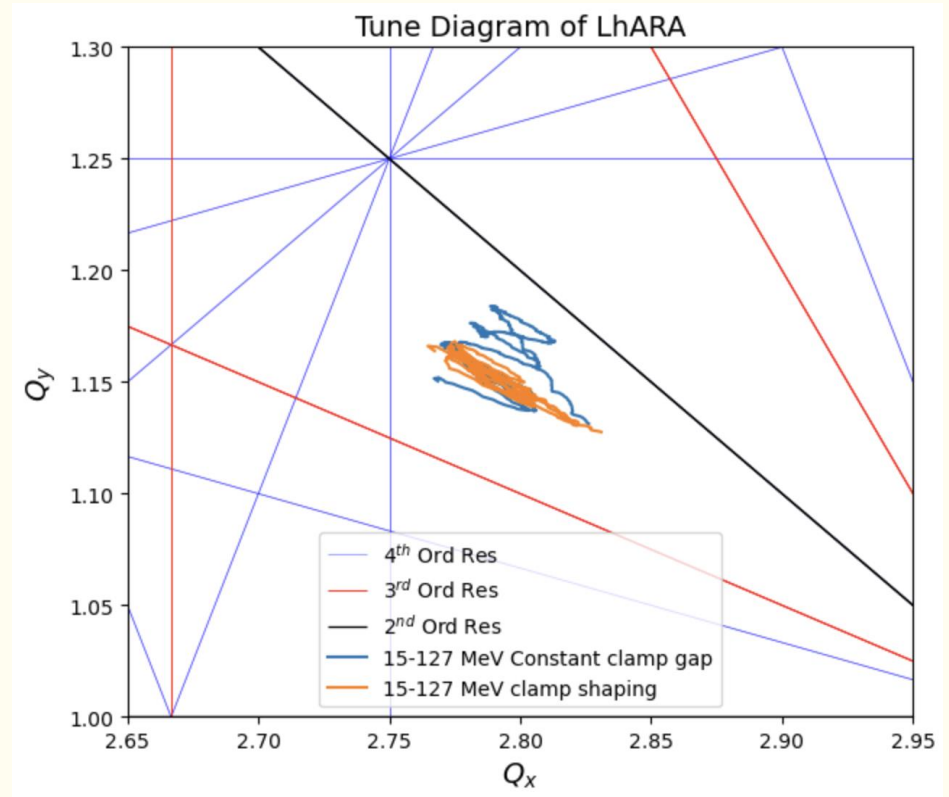
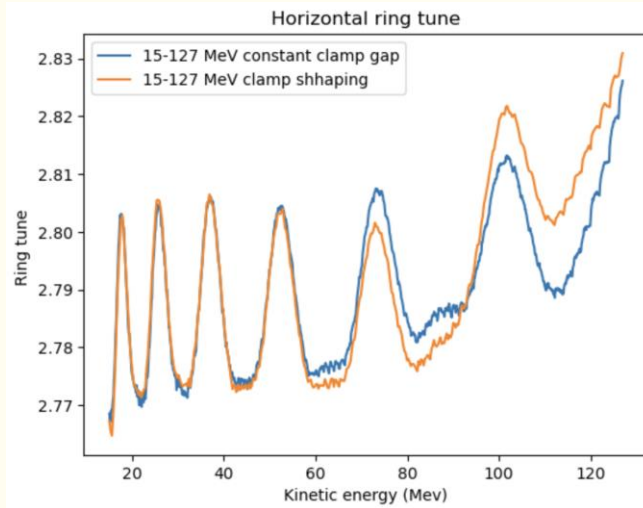
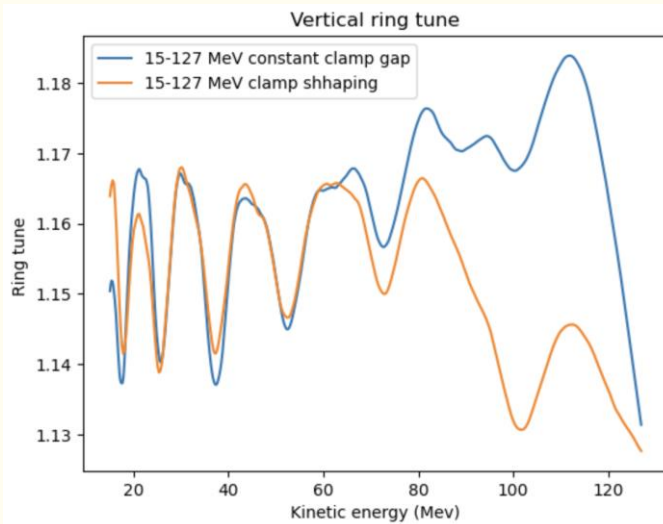
Clamp shaped with tune as target

Fringe field parameters calculated for sanity check

Comparing the coefficients before and after clamp shaping

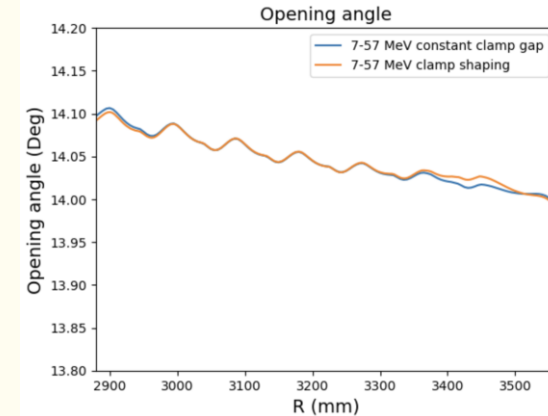
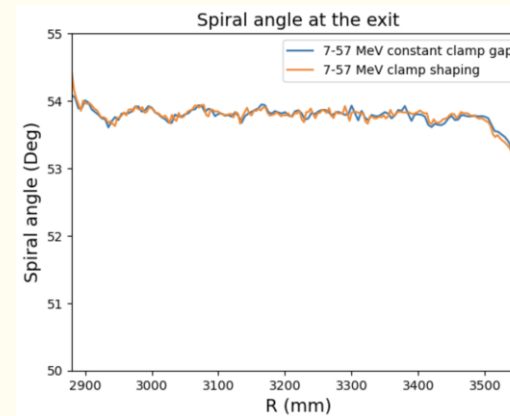
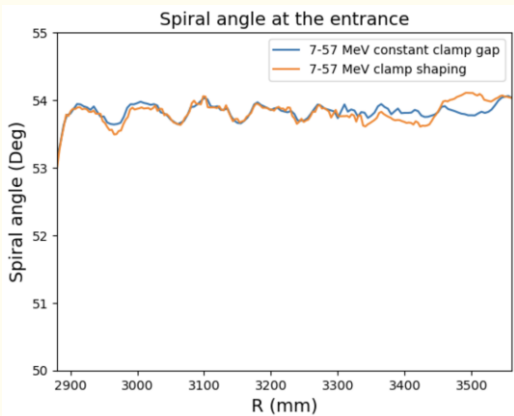
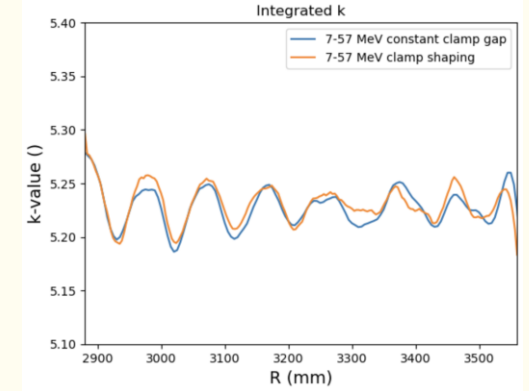
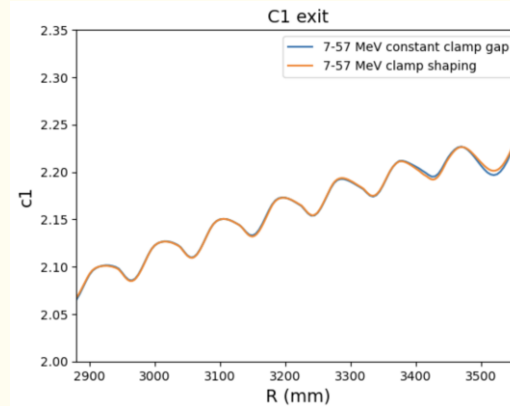
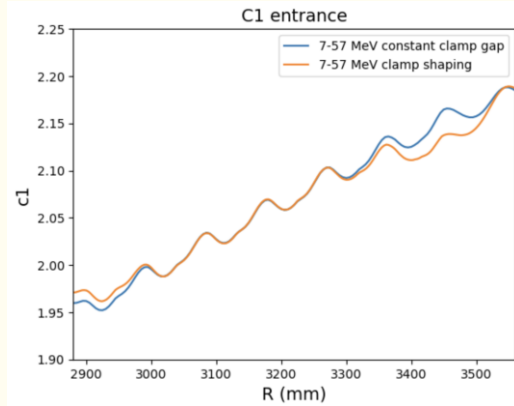


Ring tune, 127 MeV extraction energy

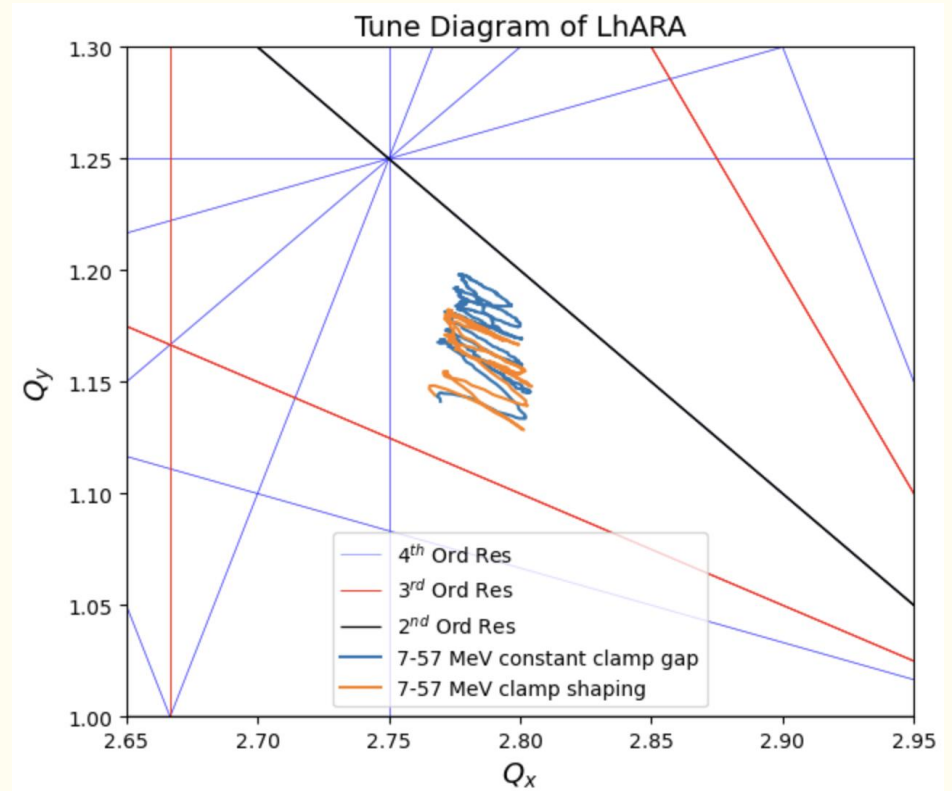
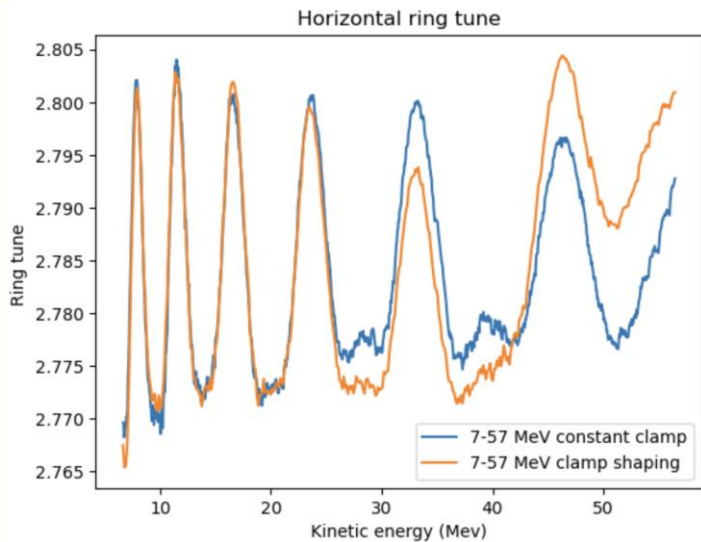
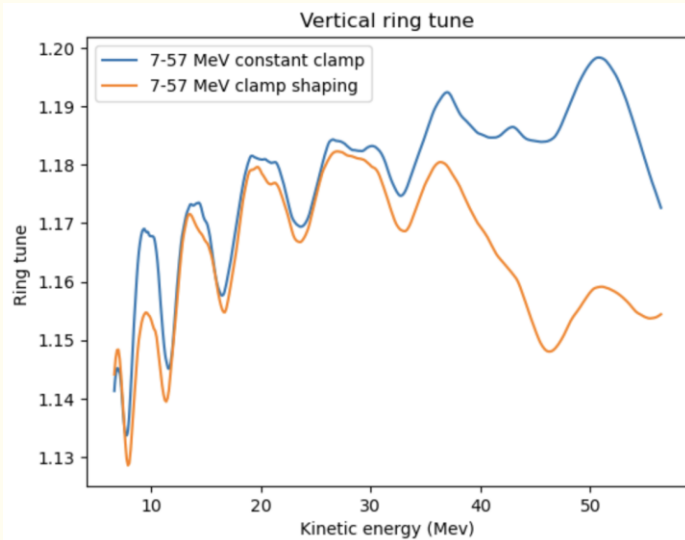


(Not all the resonances plotted are systematic)

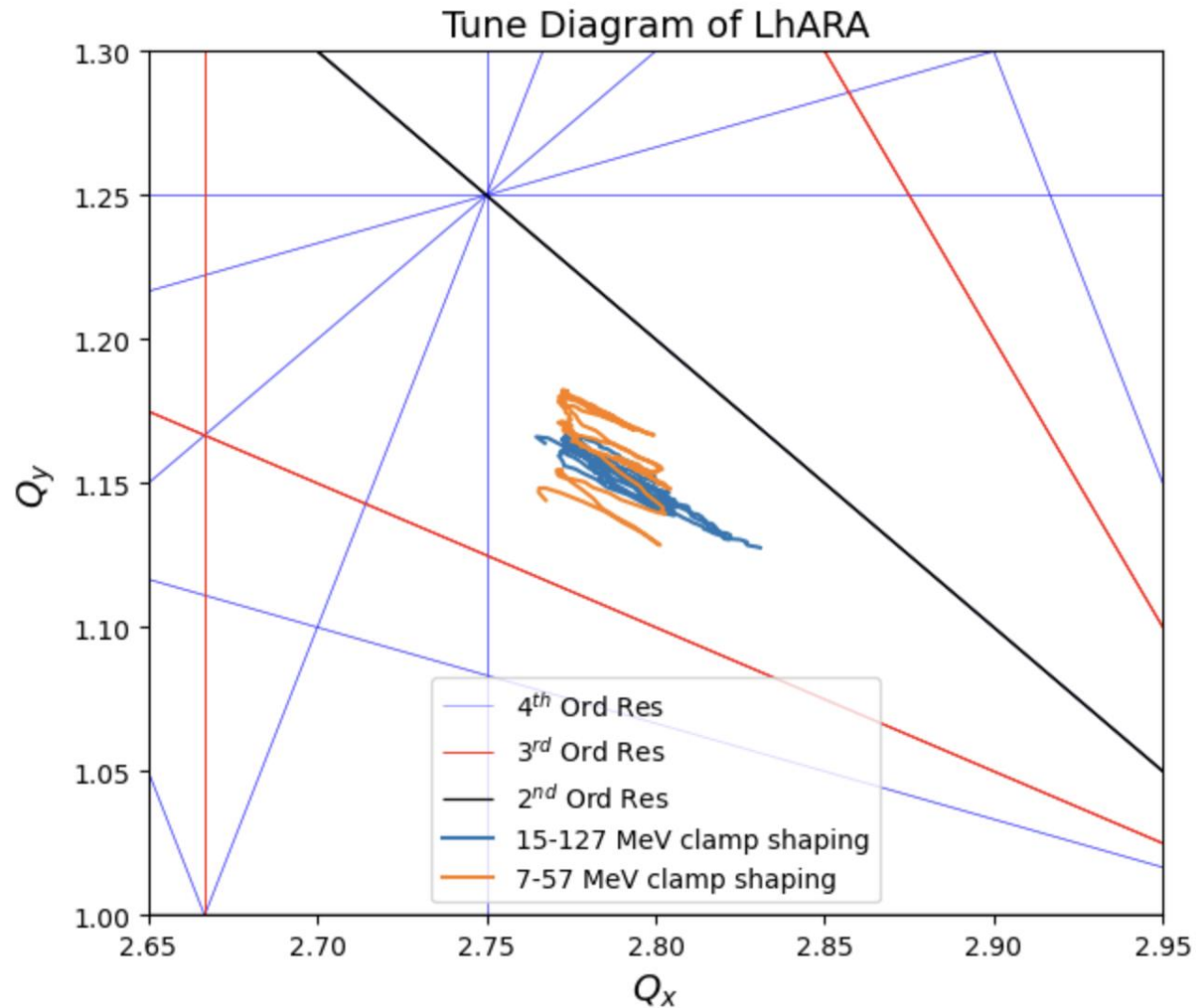
Fringe field parameters, 57 MeV extraction energy



Ring tune, 57 MeV extraction energy



Final results



Conclusion

- +/- 0.035 variation in k achieved with the trim coils set up
- Clamp shape optimized to reduce vertical tune variation at 127 MeV extraction energy
- Working tune for two different extraction energies (57, 127 MeV) stay at the same point
- Tune spread in both cases are small enough to avoid any resonance up to fourth order