Imperial College London

Science and Technology Facilities Council

19/09/25

Design of prototype magnets for FETS-FFA

Ta-Jen Kuo

Supervisor: Jaroslaw Pasternak, Jean-Baptiste Lagrange

Imperial College London, STFC

Imperial College London

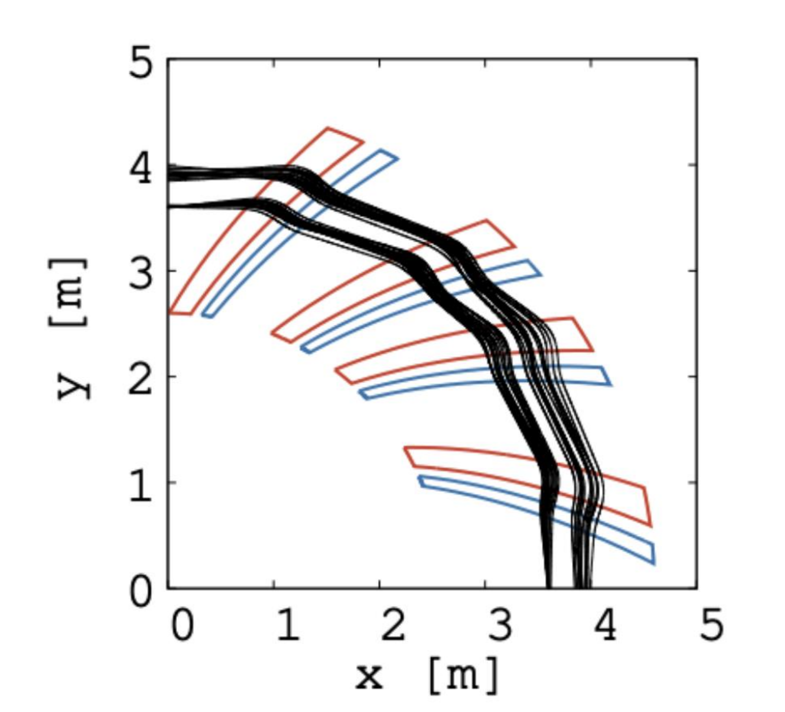
Science and Technology Facilities Council

Content

1. What is FETS-FFA
2. Target field
3. Doublet and coil geometry
4. Optimisating current
5. Adjusting fringe field
6. Final tune result

FETS FFA

- Proof of principle high intensity machine to demonstrate FFA option for the ISIS II upgrade
- Accelerate 3-12 MeV proton
- Zero chromaticity during acceleration
- Change the tune as a function of beam intensity, variable k between 6.2-8.7
- Doublet spiral design, two tuning knobs in tune space, k and F/D ratio



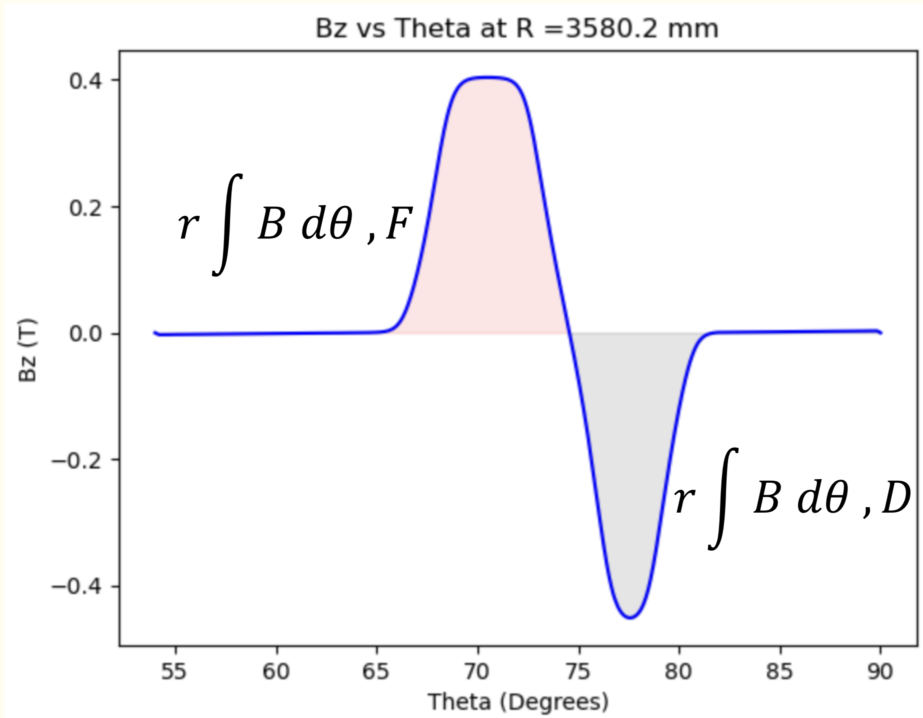
4-fold symmetry

- C shaped magnets due to space constraint for FETS-FFA, not the case for ISIS-II
- 16 cells with 4-fold symmetry to have longer straights
- Optimisation work was done on doublet 4 for different working points
- Tracking in a 16-fold symmetry lattice, will still give us an insight on the tune behaviour

2.Target field

Integrated B field

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



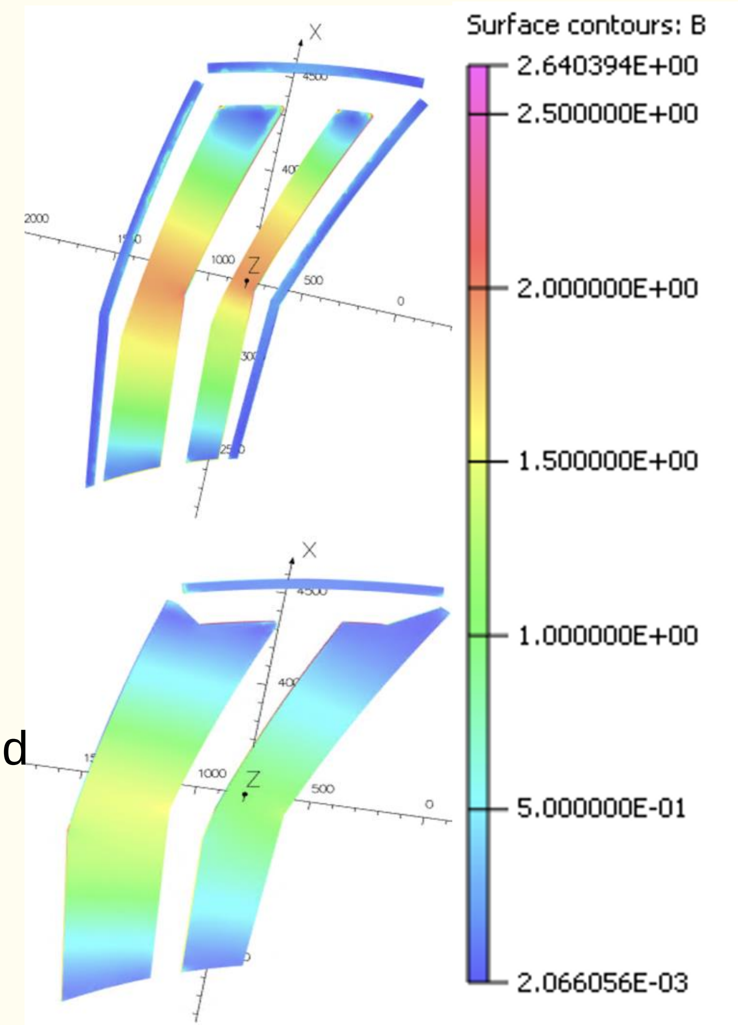
Using where the field crosses zero as a boundary, separate the integral into F and D sections
Each to be optimized for their respective scaling law, same k but different BL_0

3.Geometry of doublet and coils

Different iron connections

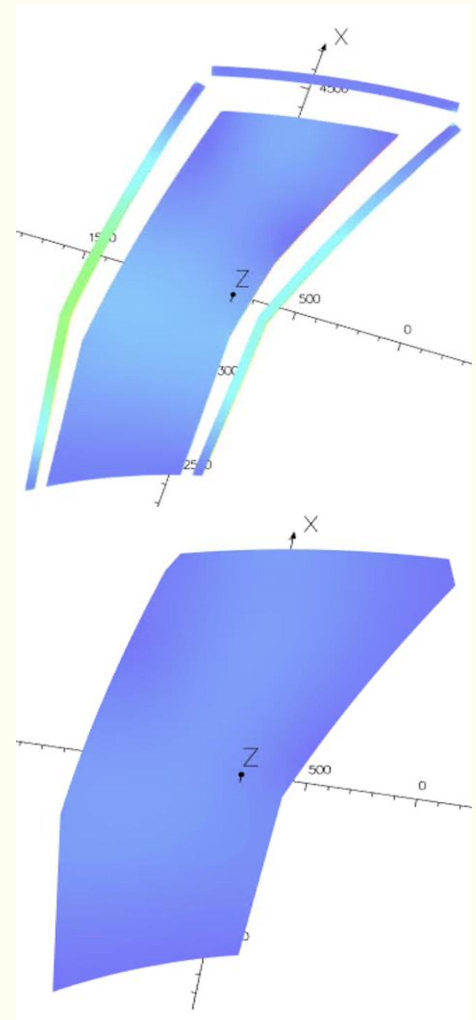
All separated

Pole connected with clamp

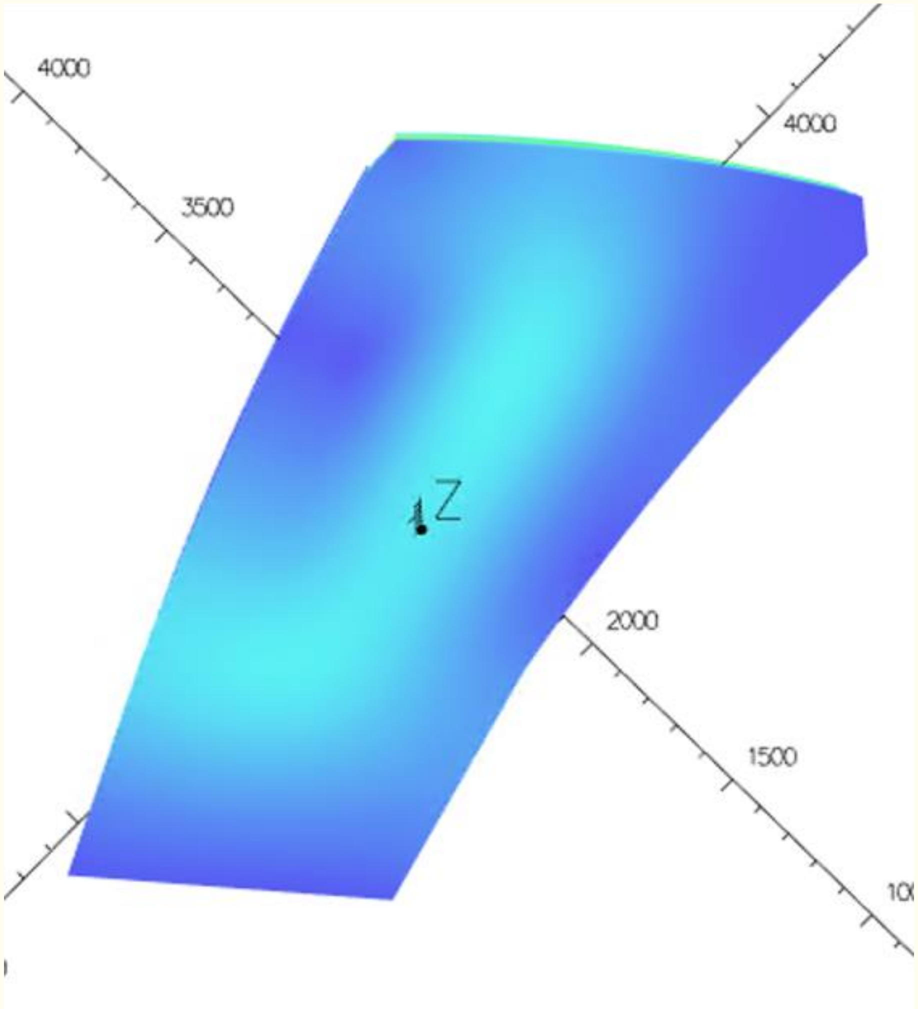


FD connected

All connected



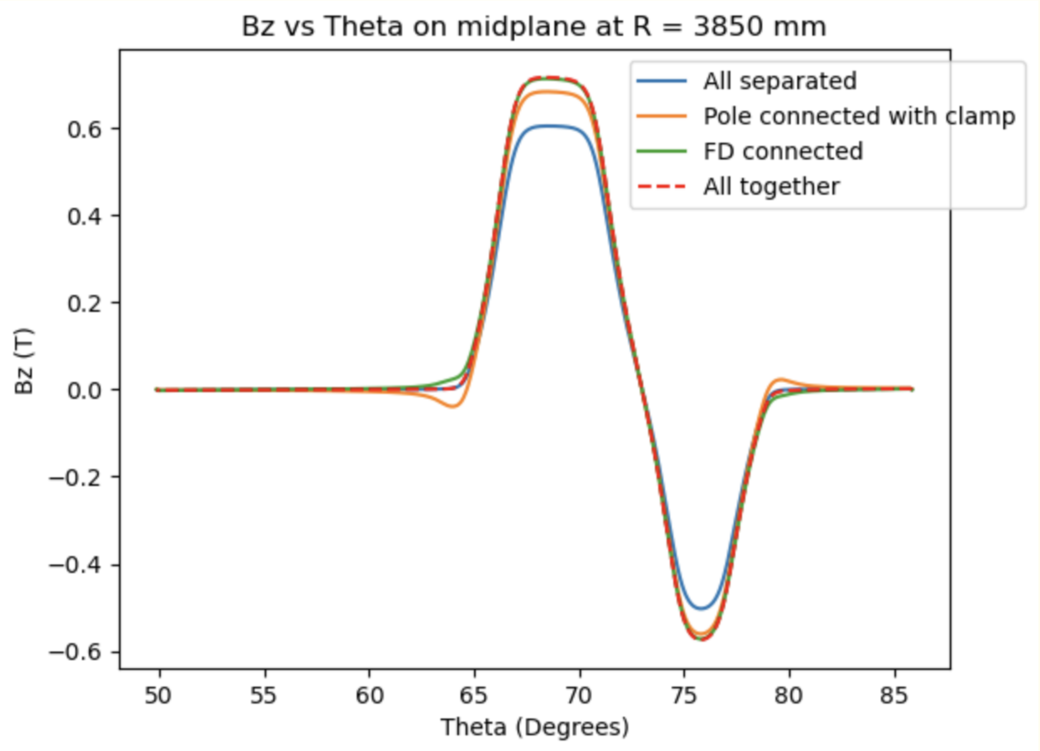
Flux return in all connected doublet



Yoke height can be reduced
flux returning between F and D
Pole making it more current efficient.

Field profile of different connections

(All with the same current setting)



Chose the all connected set up as the final shape

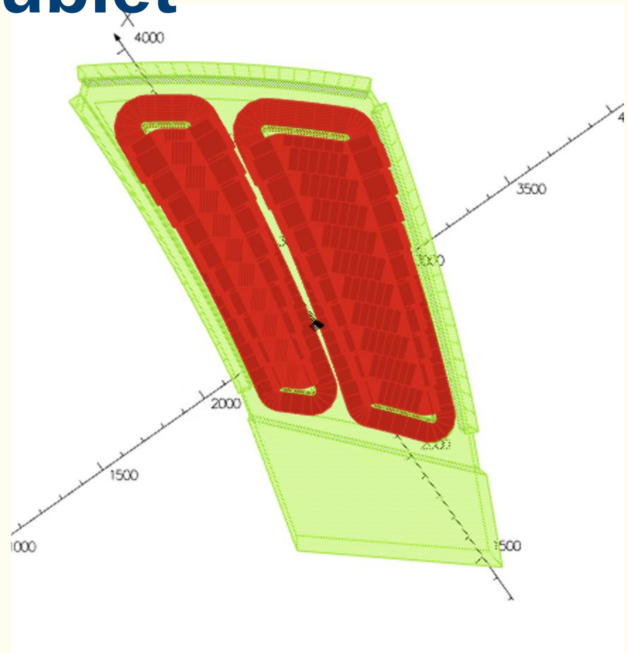
Reduced return yoke height: 700mm to 300mm

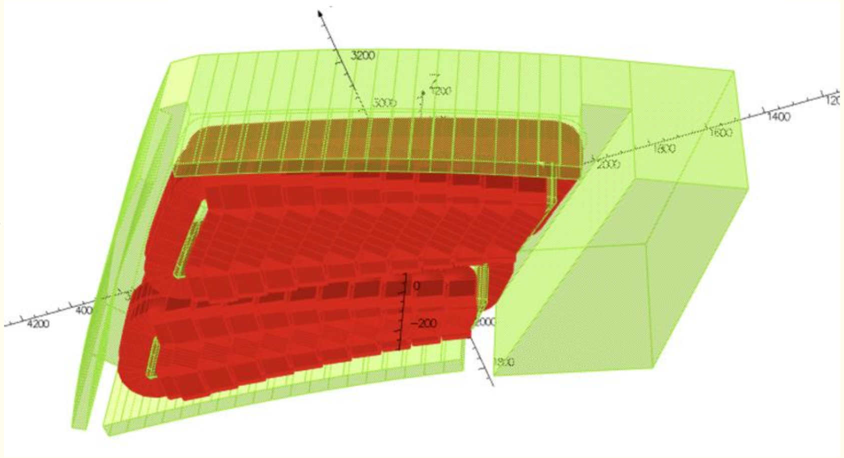
Reduced weight of doublet: 19 tonnes to 15 tonnes

Reduced power consumption of doublet: 39kW to 35 kW

Geometry of the doublet

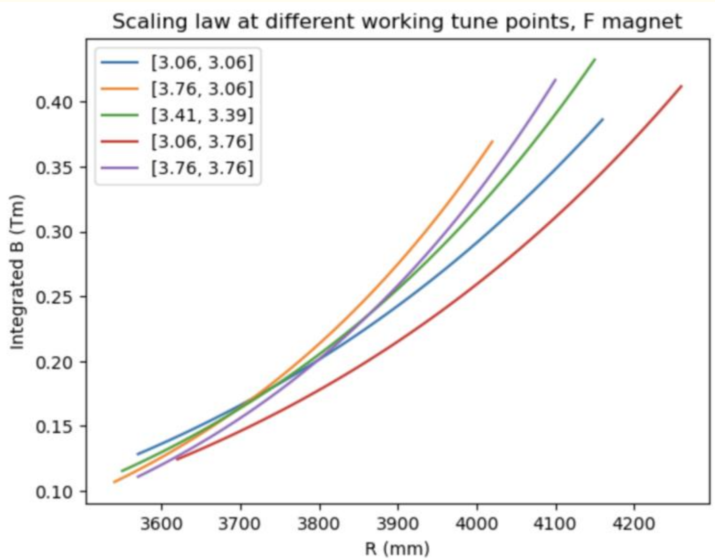
- Doublet spiral, two poles and clamps share a common yoke
- F magnet: 4.5 degrees opening angle
- D magnet: 2.5 degrees opening angle
- Opening angle between F/D: 3.55 degrees to accommodate thickness of trim coils
- Opening angle between pole and clamp: 1.92 degrees
- Radially dependent trim coils to be optimized together due to strong cross talk

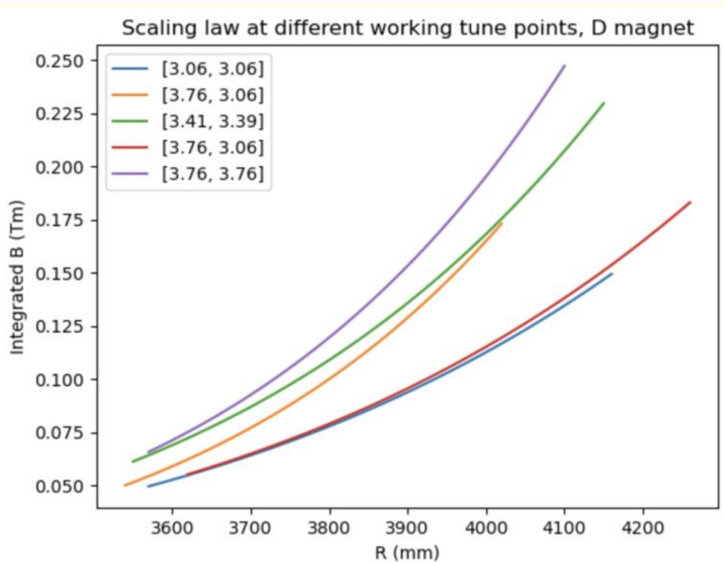




4. Optimisation of current

Working tune points





Good field region

	Qx=3.06	Qx=3.26	Qx=3.46	Qx=3.76
Qz=3.76	GFR [m]: (r_{min}=3.62, r_{max}=4.26) $B_{max F,D}(r_{max})$ [T] = (-1.275, 1.156) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.25922, 0.11516) k=6.3515	GFR [m]: (r_{min}=3.60, r_{max}= 4.21) $B_{max F,D}(r_{max})$ [T] = (-1.345, 1.428) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.28411, 0.14915) k=7.0128	GFR [m]: (r_{min}=3.59, r_{max}= 4.17) $B_{max F,D}(r_{max})$ [T] = (-1.409, 1.618) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.30987, 0.17678) k=7.6089	GFR [m]: (r_{min}=3.57, r_{max}= 4.10) $B_{max F,D}(r_{max})$ [T] = (-1.347, 1.606) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.32911, 0.19514) k=8.5597
Qz=3.46	GFR [m]: (r_{min}=3.57, r_{max}= 4.21) $B_{max F,D}(r_{max})$ [T] = (-1.406, 1.463) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.31147, 0.16005) k=6.0874	GFR [m]: (r_{min}=3.60, r_{max}= 4.21) $B_{max F,D}(r_{max})$ [T] = (-1.415, 1.286) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.30019, 0.13363) k=6.9841	GFR [m]: (r_{min}=3.58, r_{max}=4.15) $B_{max F,D}(r_{max})$ [T] = (-1.352, 1.431) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.30773, 0.16104) k=7.7165	GFR [m]: (r_{min}=3.56, r_{max}= 4.06) $B_{max F,D}(r_{max})$ [T] = (-1.244, 1.336) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.33078, 0.17575) k=8.6172
Qz=3.26	GFR [m]: (r_{min}=3.56, r_{max}=4.16) $B_{max F,D}(r_{max})$ [T] = (-1.231, 1.229) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.29205, 0.14357) k=6.2301	GFR [m]: (r_{min}=3.54, r_{max}= 4.07) $B_{max F,D}(r_{max})$ [T] = (-1.131, 1.091) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.30371, 0.14398) k=6.9705	GFR [m]: (r_{min}=3.55, r_{max}=4.08) $B_{max F,D}(r_{max})$ [T] = (-1.2374, 1.266) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.32208, 0.16255) k=7.6143	GFR [m]: (r_{min}=3.57, r_{max}= 4.08) $B_{max F,D}(r_{max})$ [T] = (-1.353, 1.470) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.34431, 0.18507) k=8.7076
Qz=3.06	GFR [m]: (r_{min}=3.57, r_{max}=4.16) $B_{max F,D}(r_{max})$ [T] = (-1.222, 0.972) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.29126, 0.11261) k=6.2013	GFR [m]: (r_{min}=3.55, r_{max}= 4.09) $B_{max F,D}(r_{max})$ [T] = (-1.194, 1.142) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.31016, 0.14585) k=6.9122	GFR [m]: (r_{min}=3.55, r_{max}= 4.07) $B_{max F,D}(r_{max})$ [T] = (-1.236, 1.168) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.32833, 0.15242) k=7.5978	GFR [m]: (r_{min}=3.54, r_{max}= 4.02) $B_{max F,D}(r_{max})$ [T] = (-1.213, 1.157) $BL_{F,D}(r{=}4m)$ [T.m] = (-0.35179, 0.16488) k=8.7484

JB Lagrange 1

Central tune point [3.41,3.39] and the four working tune points at the Corners of this table was investigated

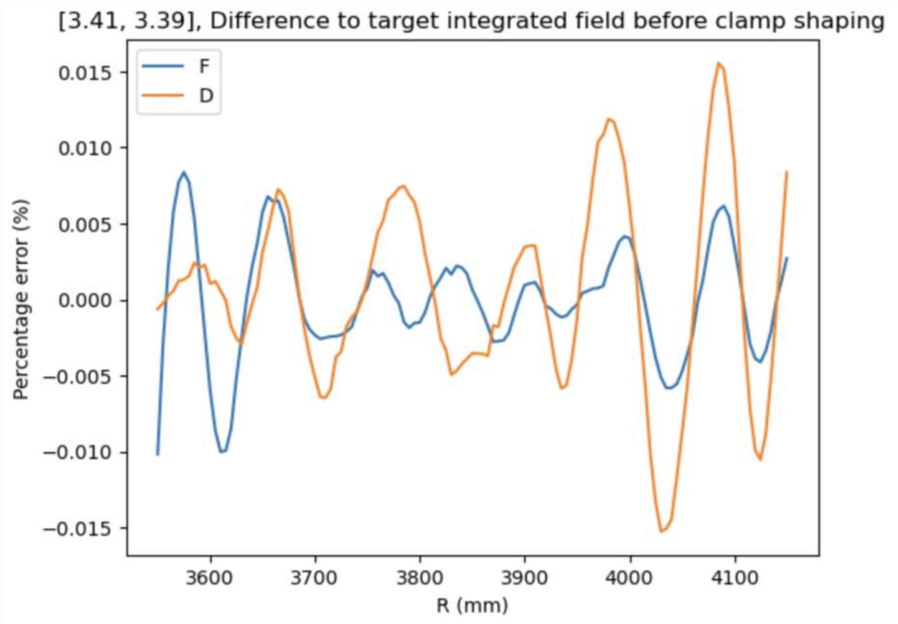
Tune and GFR calculated for 3-12 MeV beam in 4-fold symmetry

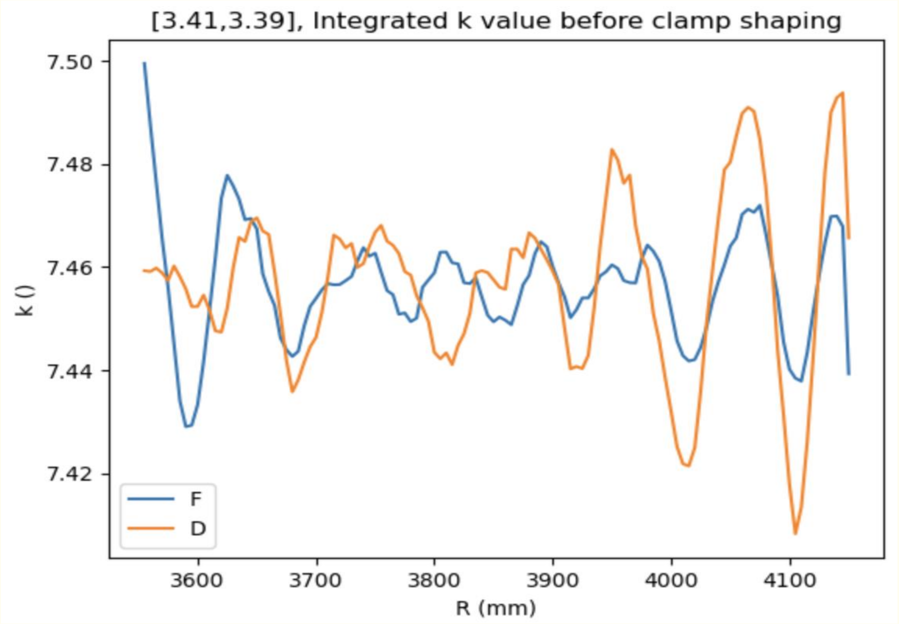
Imperial College London

UKRI Science and Technology Facilities Council

Field error, [3.41,3.39] working point

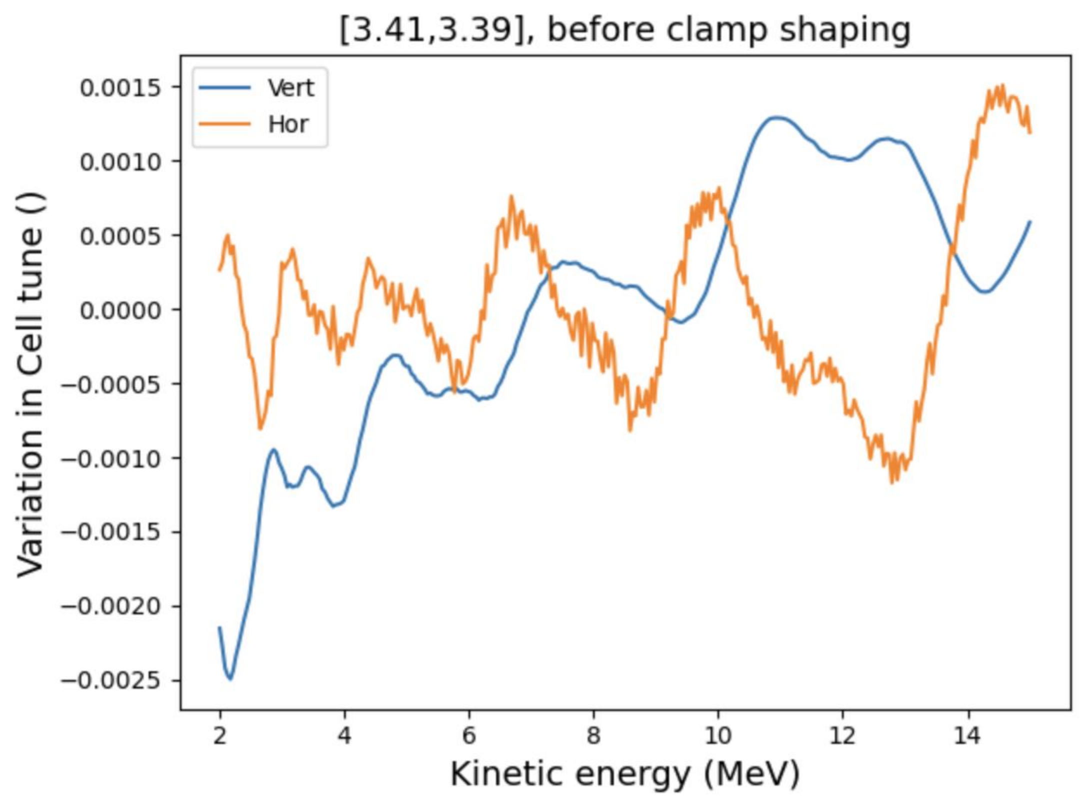
Target k: 7.456





Oscillation in residuals due to the discretization of trim coils
Amplitude and phase of oscillations to be investigated

Cell tune variation, [3.41,3.39]



Target cell tune variation: +/- 0.000625, such that ring tune variation is +/- 0.01
10 percent of space charge tune shift

5. Adjusting fringe field

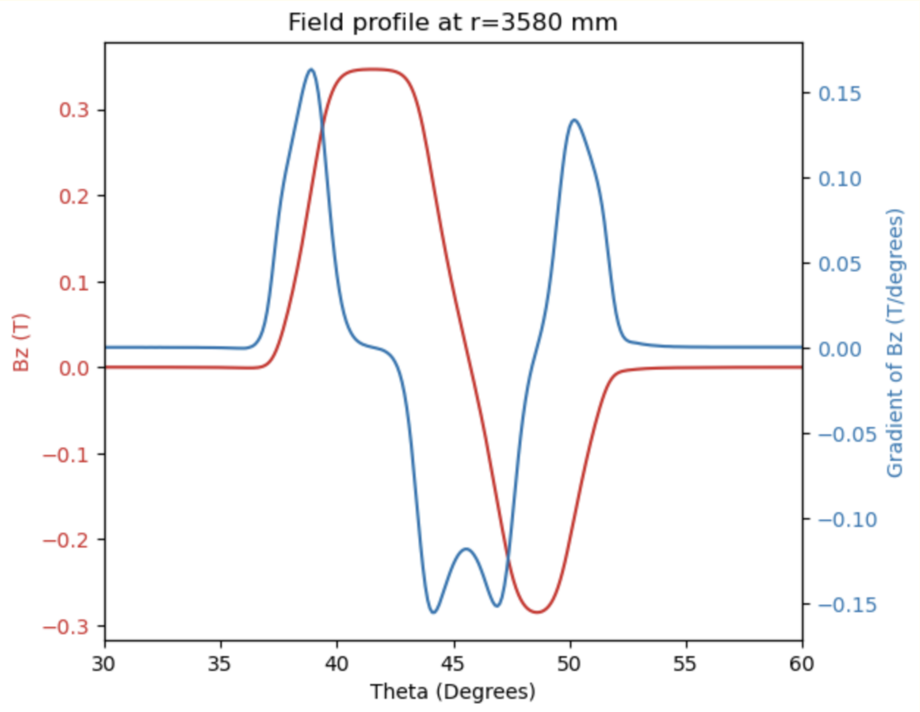
Imperial College London

UKRI Science and Technology Facilities Council

Spiral angle

Using the angle of the centre of moment θ_{COM} on the longitudinal gradient G of the field along a constant radius

$\theta_{COM} = \frac{\int G\,\theta\,d\theta}{\int G\,d\theta}$, where $G = \frac{\partial B_z}{\partial \theta}$, the gradient of the field with respect to theta.



Spiral angle $\xi = \arctan(r\frac{d\theta_{Com}}{dr})$

Introduce spiral angles for

- entrance F $\xi_{F\ en}$
- between F and D $\xi_{F/D}$
- exit D $\xi_{D\ ex}$

Imperial College London | UKRI Science and Technology Facilities Council

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

$$B = \frac{B_{0,F}}{(1+\exp(F_{en}))(1+\exp(F_{ex}))} + \frac{B_{0,D}}{(1+\exp(D_{en}))(1+\exp(D_{ex}))}$$

$$F_{en}(\theta) = C1_{F\ en}\frac{r_0}{\lambda_0}(\theta_{EFB\ F\ en} - (\theta - tan\xi_{F\ en}\ln\frac{r_0}{\lambda_0}),\ F_{ex}(\theta) = C1_{F\ ex}\frac{r_0}{\lambda_0}((\theta - tan\xi_{F/D}\ln\frac{r_0}{\lambda_0}) - \theta_{EFB\ F\ ex})$$

$$D_{en}(\theta) = C1_{D\ en}\frac{r_0}{\lambda_0}(\theta_{EFB\ D\ en} - (\theta - tan\xi_{F/D}\ln\frac{r_0}{\lambda_0}),\ D_{ex}(\theta) = C1_{D\ ex}\frac{r_0}{\lambda_0}((\theta - tan\xi_{D\ ex}\ln\frac{r_0}{\lambda_0}) - \theta_{EFB\ D\ ex})$$

Independent Parameters

λ_0: Gap height of the pole
$\xi_{F\ en,F/D,D\ ex}$: Spiral angles from the previous equations

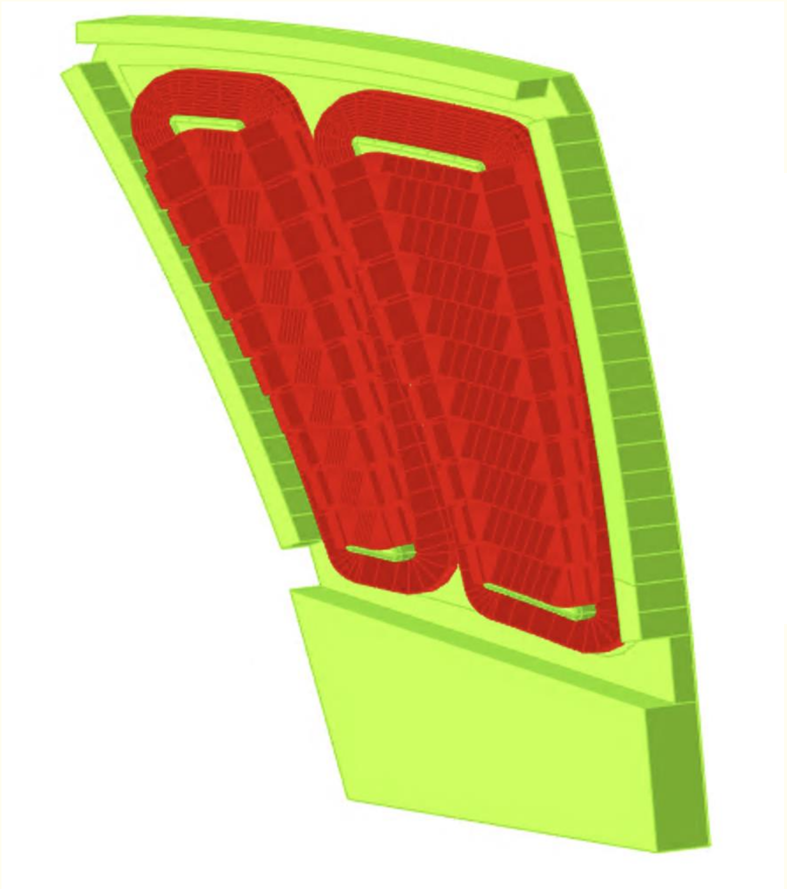
Parameters to fit
$B_{0,F/D}$:Maximum field of F and D magnet
$C1_{F/D\ en,ex}$: Describes the fringe field length
$\theta_{EFB\ F/D\ en,ex}$: Describes the effective field boundaries

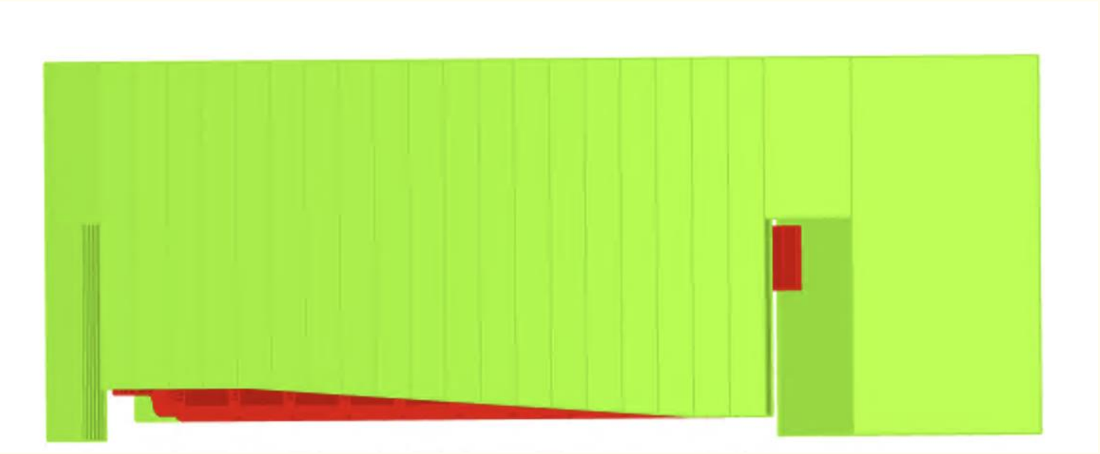
Imperial College London

Science and Technology Facilities Council

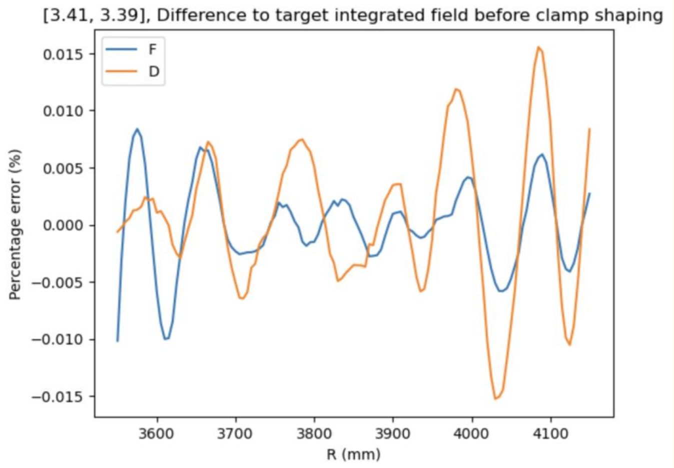
Clamp height optimisation

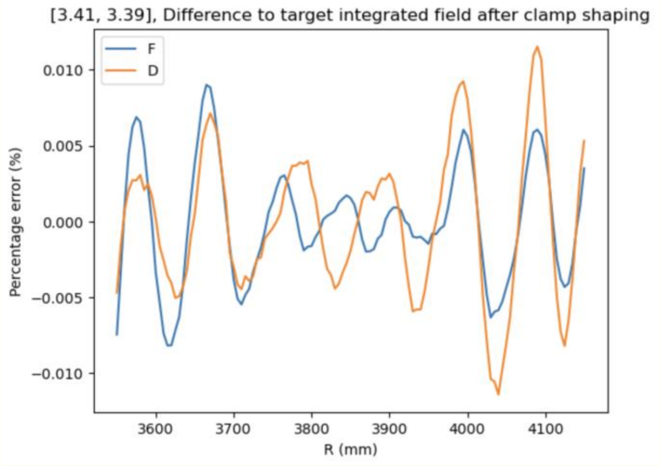
Variation in vertical tune has an increasing trend for every working tune point.
Vary entry clamp gap height linearly and reoptimize current

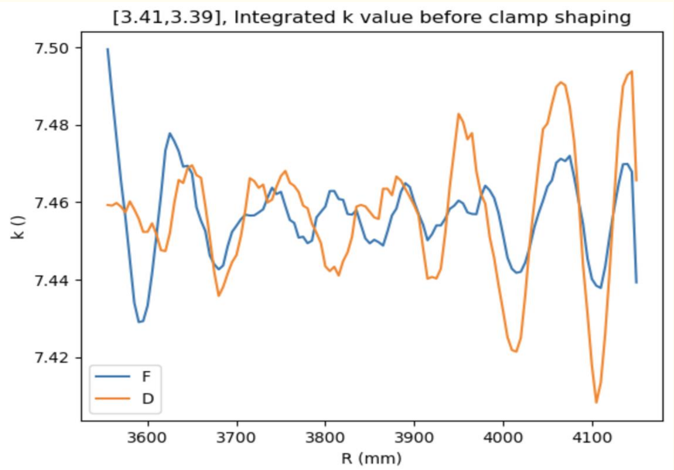


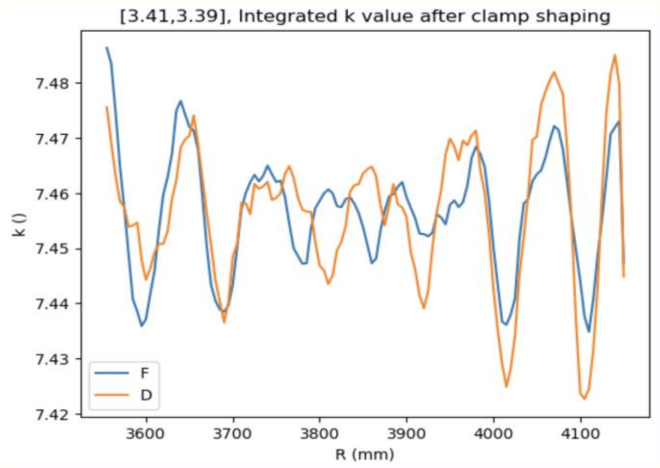


Integrated B field after clamp shaping, [3.41, 3.39]





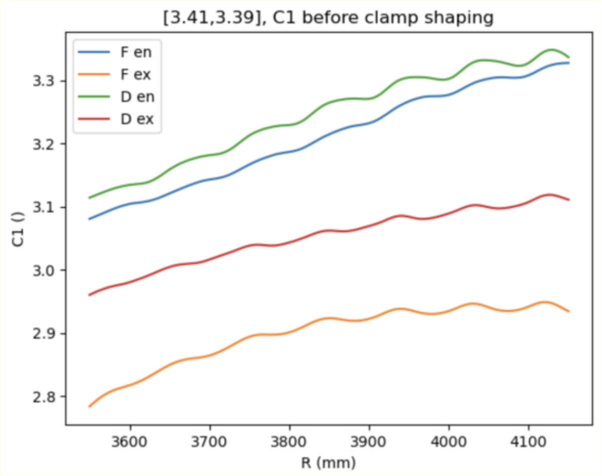


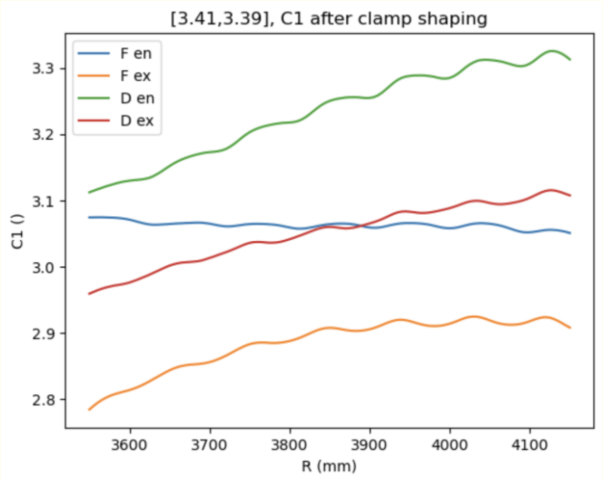


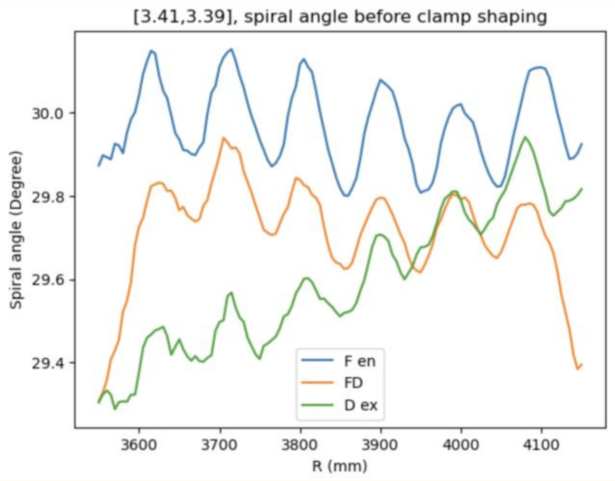
Imperial College London

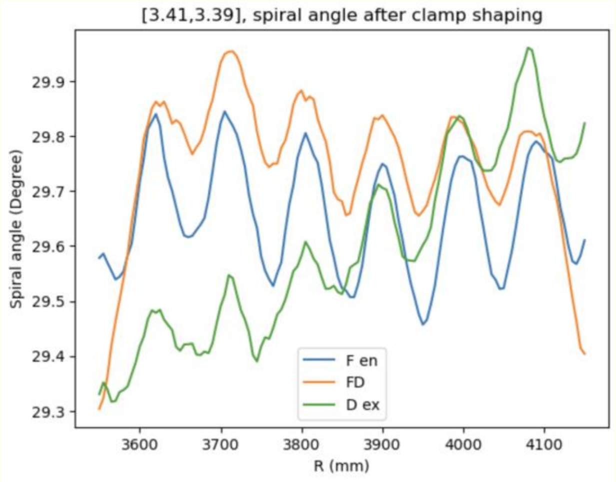
Science and Technology Facilities Council

Fringe field parameters after clamp shaping, [3.41,3.39]



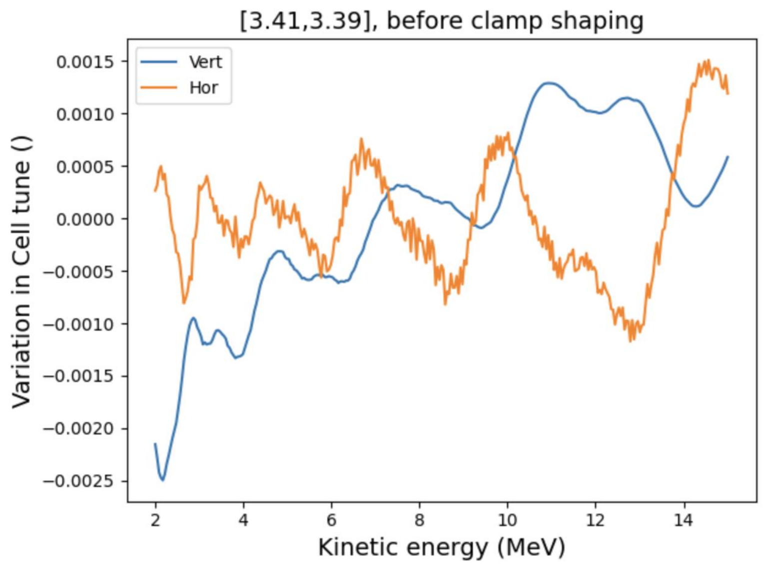


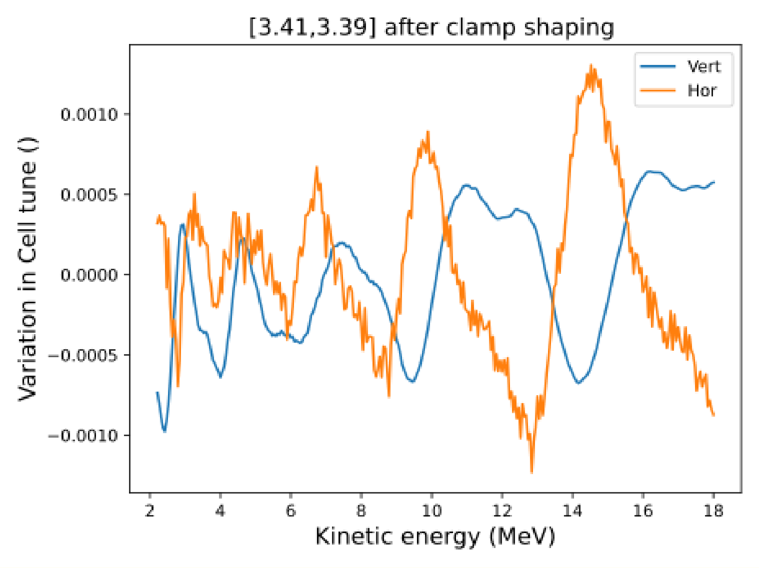




Cell tune variation, [3.41,3.39]

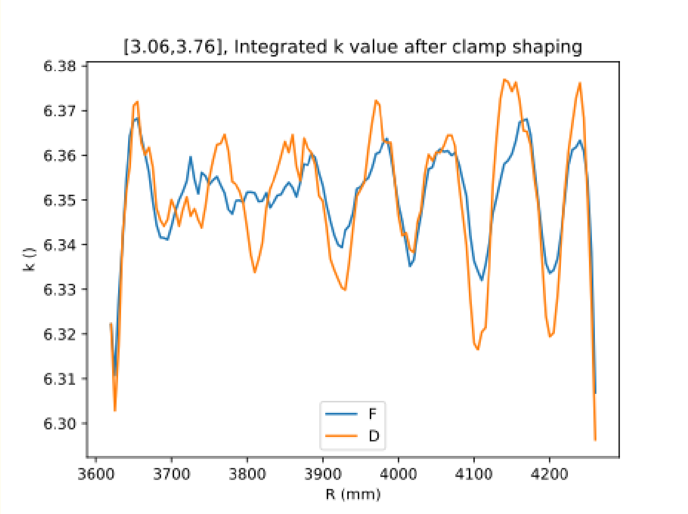
Tracking through the entire GFR, until closed orbit not found



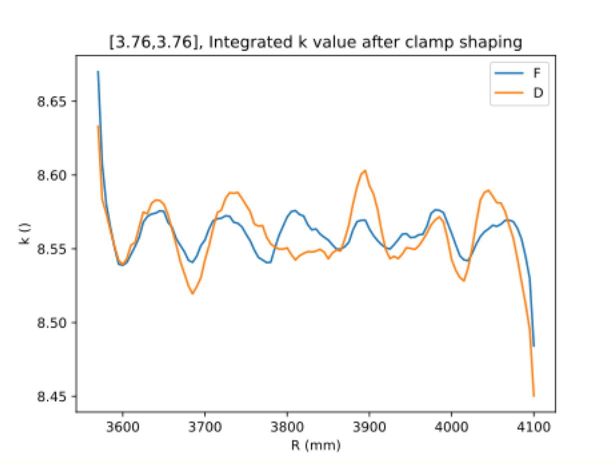


K value

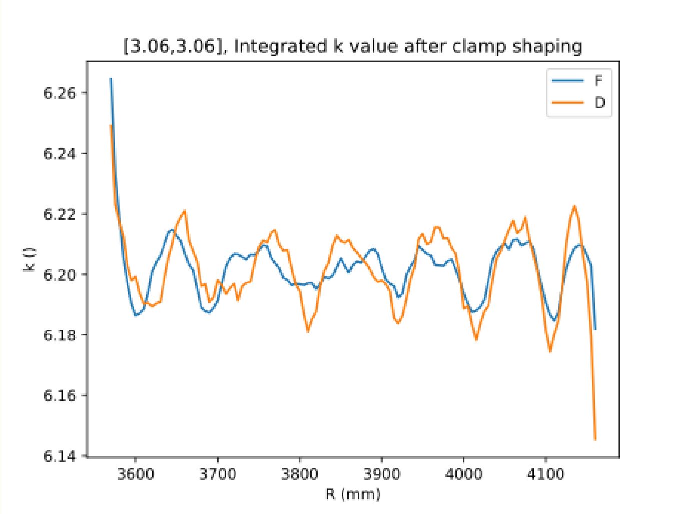
target k=6.3515



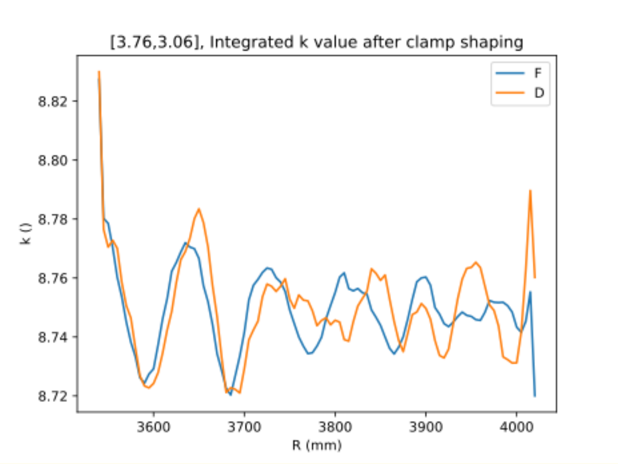
target k=8.5597



target k=6.2013



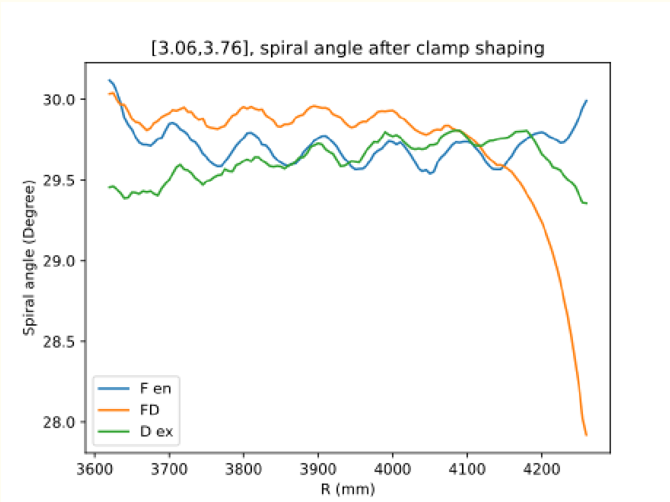
target k=8.7484

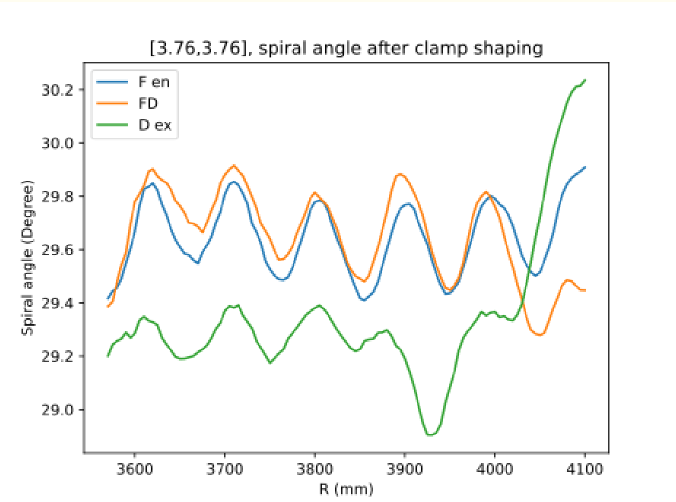


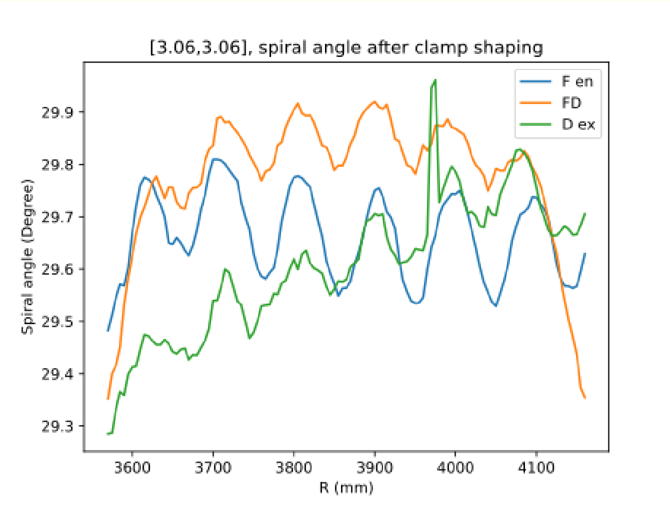
Imperial College London

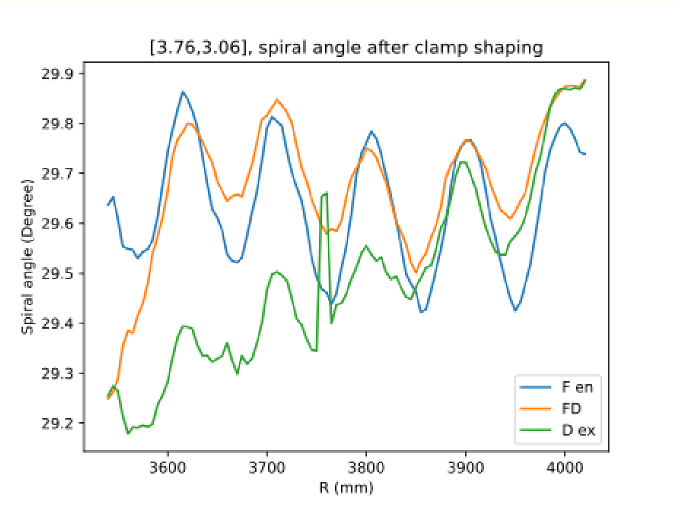
Science and Technology Facilities Council

Spiral angles

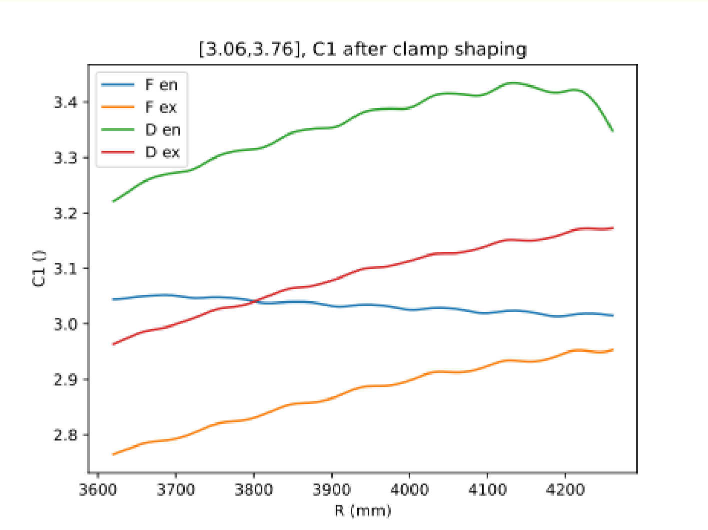


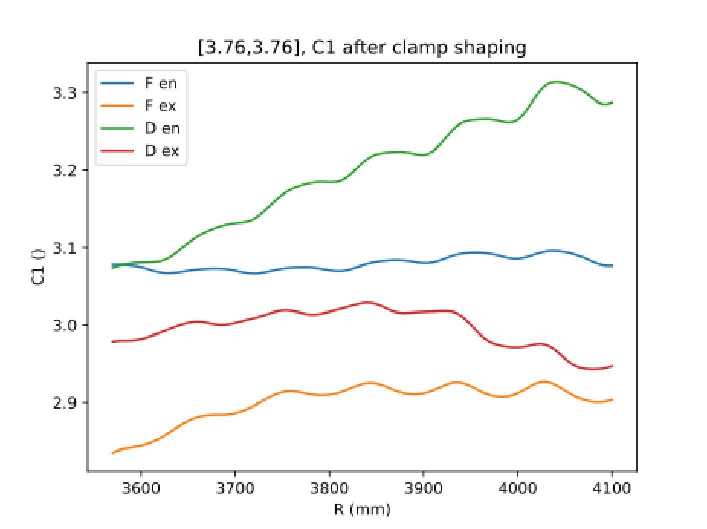


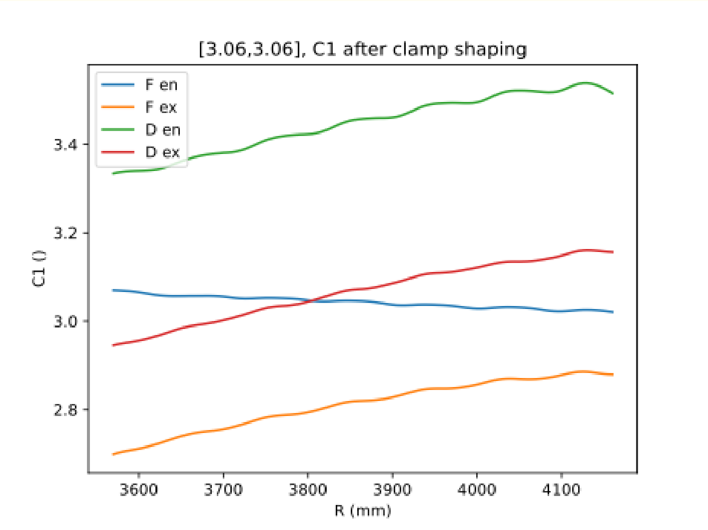


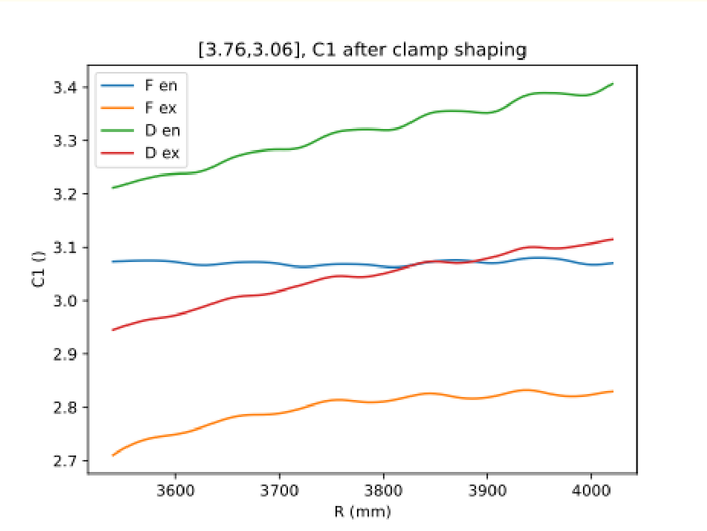


C1s


[3.06,3.76], C1 after clamp shaping
F en
F ex
D en
D ex
C1 ()
3.4
3.3
3.2
3.1
3.0
2.9
2.8
3600
3700
3800
3900
4000
4100
4200
R (mm)


[3.76,3.76], C1 after clamp shaping
F en
F ex
D en
D ex
C1 ()
3.3
3.2
3.1
3.0
2.9
3600
3700
3800
3900
4000
4100
R (mm)


[3.06,3.06], C1 after clamp shaping
F en
F ex
D en
D ex
C1 ()
3.4
3.2
3.0
2.8
3600
3700
3800
3900
4000
4100
R (mm)

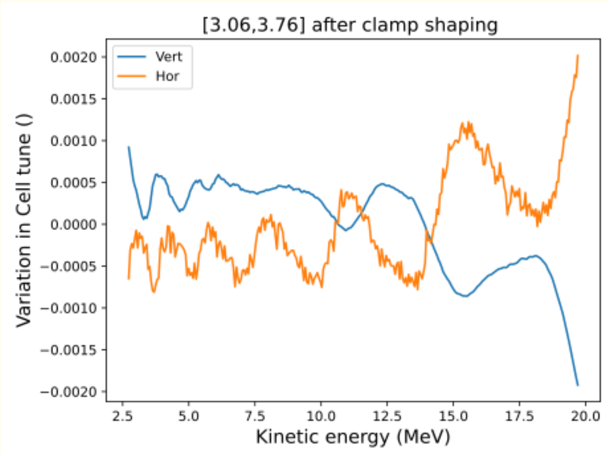

[3.76,3.06], C1 after clamp shaping
F en
F ex
D en
D ex
C1 ()
3.4
3.3
3.2
3.1
3.0
2.9
2.8
2.7
3600
3700
3800
3900
4000
R (mm)

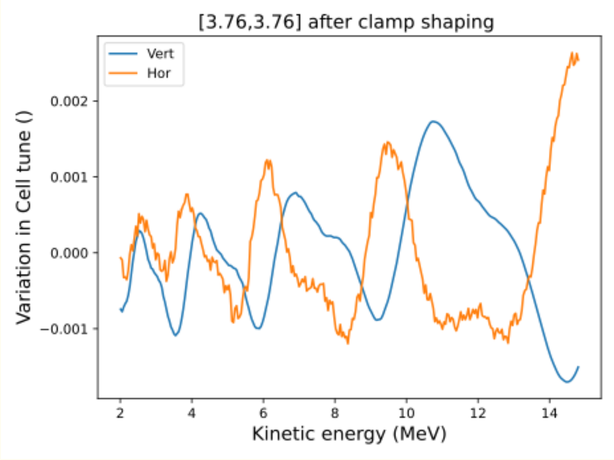
Imperial College London

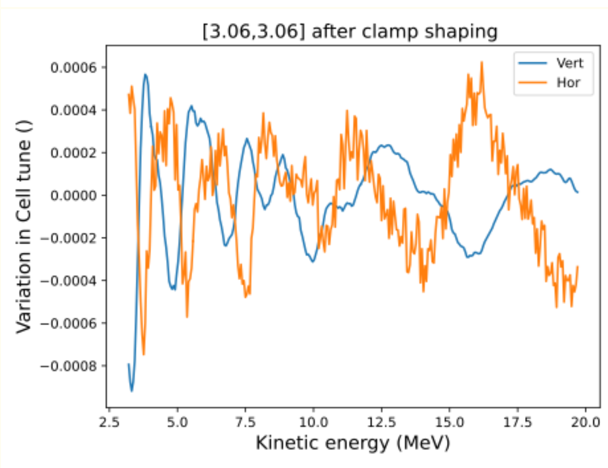
Science and Technology Facilities Council

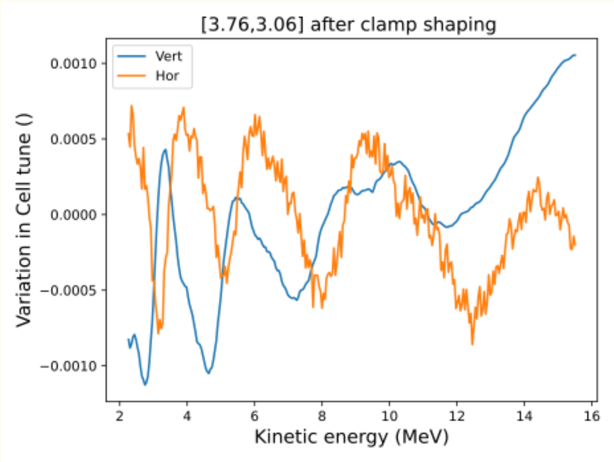
Cell tune

Target cell tune variation +/- 0.000625







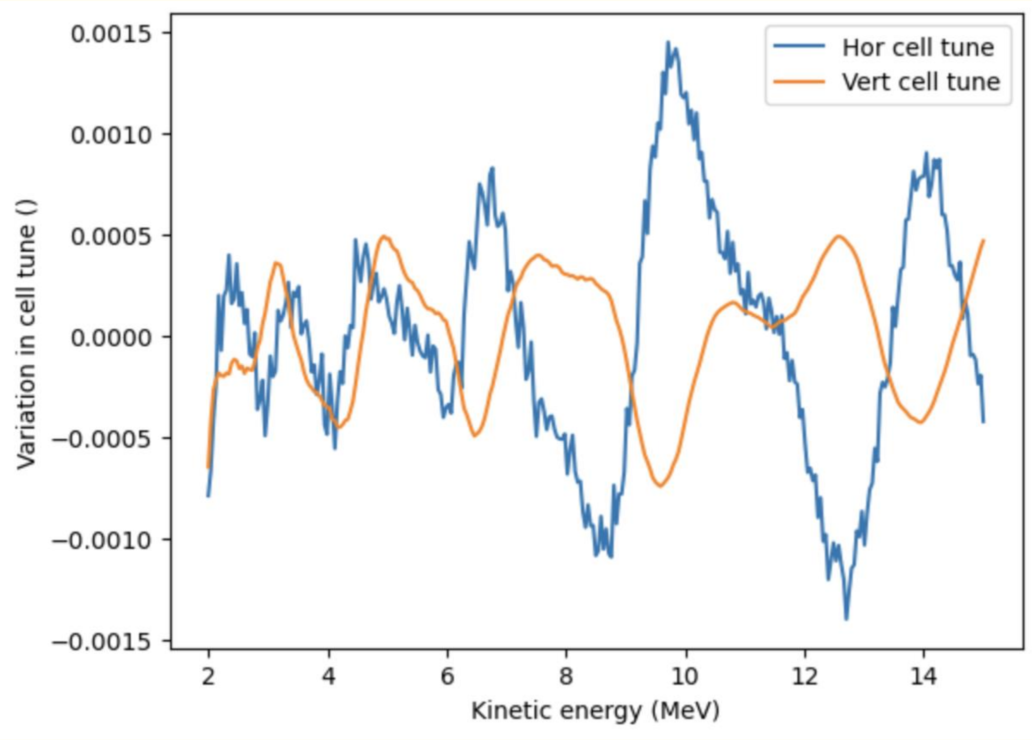


Imperial College London

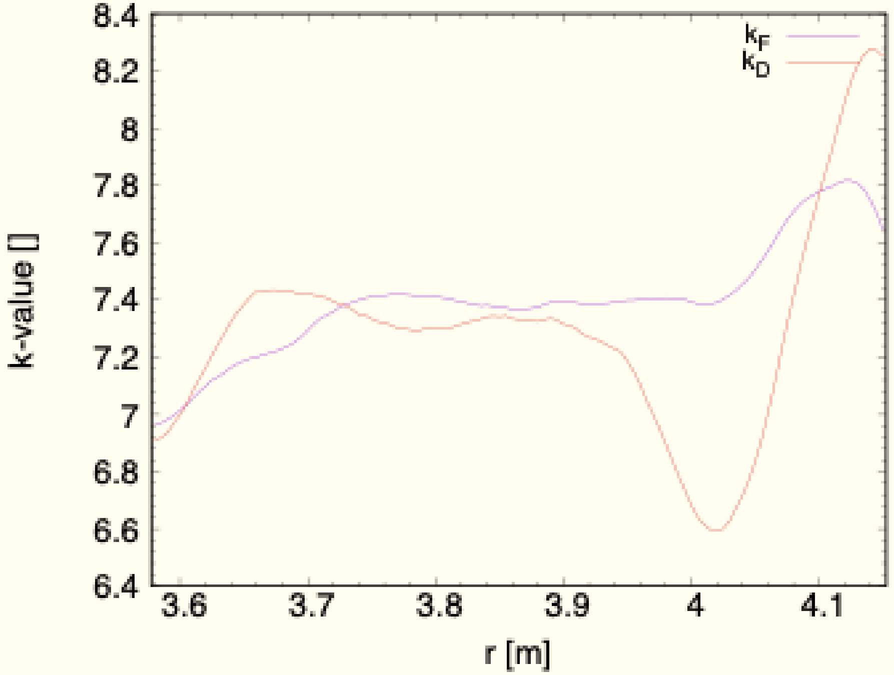
Science and Technology Facilities Council

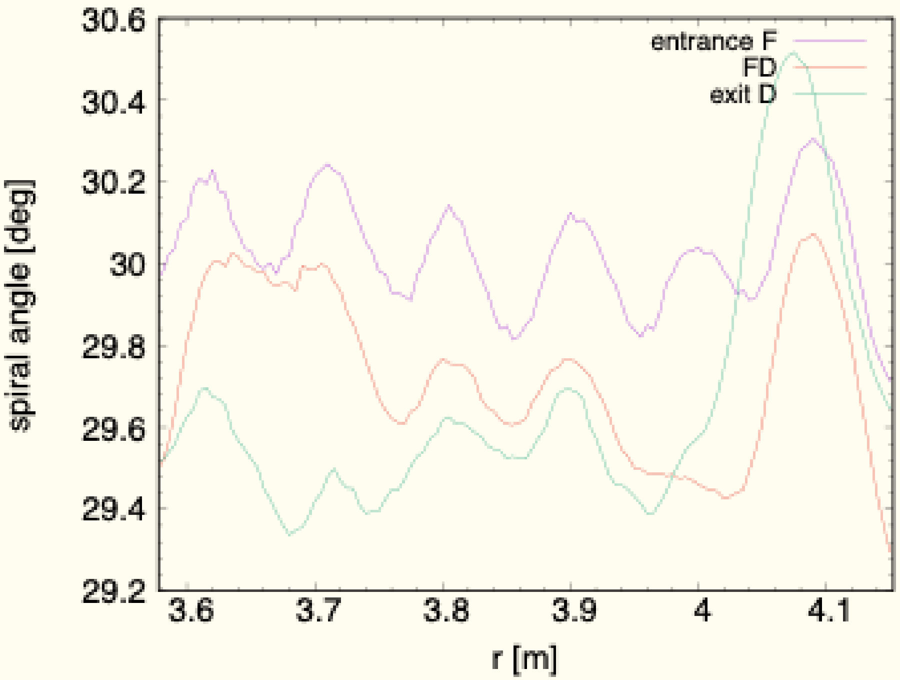
Optimizing with tune as target

Vary the currents with tune as target function to optimize



Optimizing with tune as target





Significantly deviates from the scaling law, could have a big impact on the dynamic aperture that needs to be studied

Imperial College London

Science and Technology Facilities Council

Conclusion

- Variation in horizontal tune oscillate around 0 with amplitude determined by discretization of trim coils
- Increasing trend in the vertical tune flattened by optimizing the clamps.
- Variation in vertical tune can also be flattened by using the tune as the target when optimizing the currents. A Careful dynamic aperture study will be required at all energies
- Variation in cell tune close to the target requirement, two layers of trim coils can be run at different settings to decrease the variation even smaller

Imperial College London

Science and Technology Facilities Council

Prototype radial sector magnet

Smaller in size, without the spiral angle. Coils are designed in the same way and will allow us to test the working principles of trim coils and correction schemes