WP6: Design & Integration Progress

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With contributions from Ken Long, Ta-Jen Kuo, & Clive Hill

LhARA Fortnightly

26th March 2024

Outline

- Standard parameterised source
- Gabor lens tracking performance
- Stage 1 proposed accelerator updates
- Engineering & integration update
- FFA magnet design

Promised to bring "standard" source distribution

- **M. Maxouti & N. Dover:**
  - **Standard parameterisation:**
    - **"exponential" energy spectrum with h/e cut off**
    - **Gaussian, pointing θ, flat ϕ**

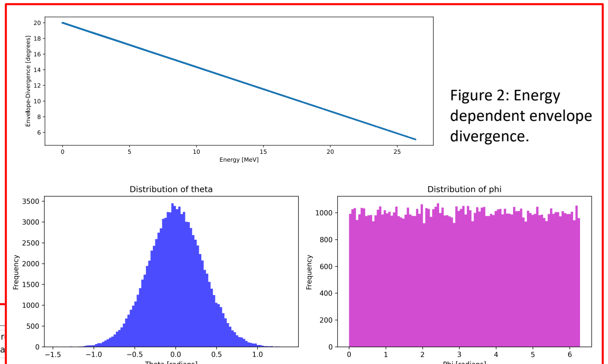
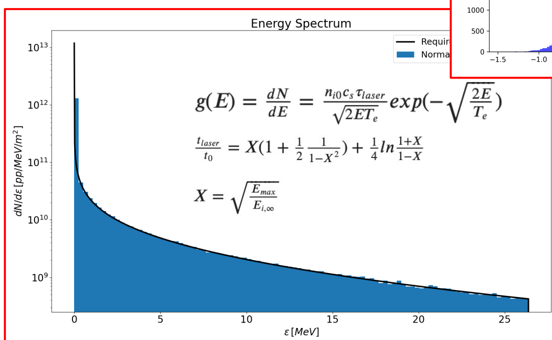


Figure 2: Energy dependent envelope divergence.

M. Maxouti



[4] J. Fuchs, P. Antici, *et al.*, "Laser-driven proton scaling laws and new paths towards energy increase," *Nature Physics* **2** (01, 2006) .

[5] J. Schreiber, F. Bell, *et al.*, "Analytical Model for Ion Acceleration by High-Intensity Laser Pulses," *Physical review letters* **97** (08, 2006) 045005.

[6] P. Casolaro, L. Campajola, G. Breglio, S. Buontempo, M. Consales, A. Cusano, A. Cutolo, F. Di Capua, F. Fienga, and P. Vaiano, "Real-time dosimetry with radiochromic films," *Scientific Reports* **9** (03, 2019) .

5 Source

A variety of options for the generation of the particle distribution at source are included in the package (see section **??**. The principal, and the default, option ios the target-normal sheath acceleration (TNSA) model presented in [4]. This model is summarised in this section.

5.1 Energy distribution

The typical energy spectrum produced in target-normal sheath acceleration falls rapidly with energy before dropping rapidly to zero above a maximumm "cut off" energe $\varepsilon_{\rm max}$. The model energy spectrum of the TNSA model presented in [4] is given by:

$$\frac{dN}{d\varepsilon} = \frac{n_{e0} c_s t_{laser} S_{sheath}}{\sqrt{2\varepsilon T_e}} exp(-\sqrt{\frac{2\varepsilon}{T_e}}) \, ; \tag{35}$$

where N is the number of protons or ions produced per unit solid angle, ε is the ion energy in Joules, n_{e0} and T_e are the hot electron density and temperature respectively, c_s is the ion-acoustic velocity, $t_{\rm laser}$ is the duration of the laser pulse, and $S_{\rm sheath}$ is the effective area over which the TNSA mechanism takes place. The variables and the units in which they are expressed are presented in table 1.

Equation 35 is based on time-limited fluid models which are unable to predict the cut-off energy, $\varepsilon_{\rm max}$, accurately. The cut-off energy is taken to be that given by the model described in [5] where the time over which the laser pulse creates the conditions necessary for acceleration. The energy cut-off is given by:

$$\varepsilon_{max} = X^2 \varepsilon_{i,\infty} \, ; \tag{36}$$

where X is obtained by solving:

$$\frac{t_{laser}}{t_0} = X \left(1 + \frac{1}{2} \frac{1}{1 - X^2} \right) + \frac{1}{4} \ln \left(\frac{1+X}{1-X} \right) \, ; \tag{37}$$

where t_0 is the time over which the ion acceleration may be treated as ballistic and $\varepsilon_{i,\infty}$ is given in table 1.

To generate the energy spectrum, a practical approach is taken:

- Equation 35 is normalized.
- A random number is generated between 0 and 1 for the y-axis.
- If the number falls below the equation it gets accepted, otherwise the loop is repeated.
- If accepted, the corresponding x-value (energy) is calculated and returned.

5.2 Angular Distribution

The angular distribution of the particles at the source has been approximated with a Gaussian distribution [6]. The following approach has been used to generate it:

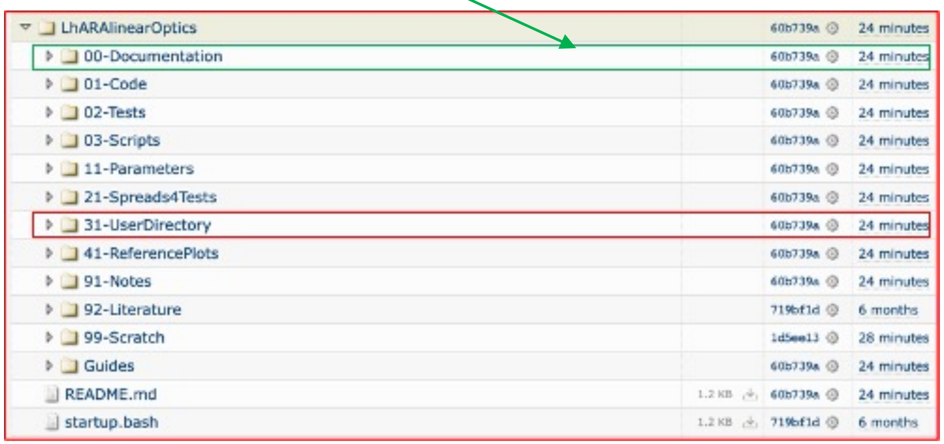
- The maximum divergence angle of the protons has been calculated based on the particle's energy.
- A linear equation has been used that generates a maximum divergence angle of 20 degrees for the low energies, down to 5 degrees for the cut-off.
- A gaussian distribution with a FWHM equal to the divergence angle has been used for each particle.
- A divergence angle is returned that falls within that distribution.

A beam diameter of 10 microns has been used.

Code & example comparison

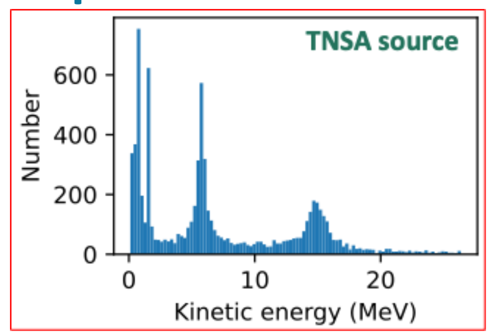
CCAP/LhARA repository:

Some, rudimentary documentation



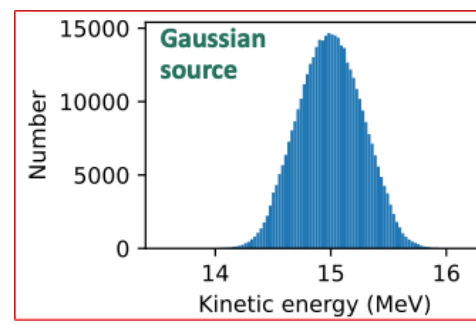
Example comparison:

- TNSA vs Gaussian energy spectrum
- Energy distribution at entrance to 1st dipole



Momentum selection in arc selects 15 MeV peak

Important for, e.g.:
- Radiation protection studies
- Dose distribution evaluation



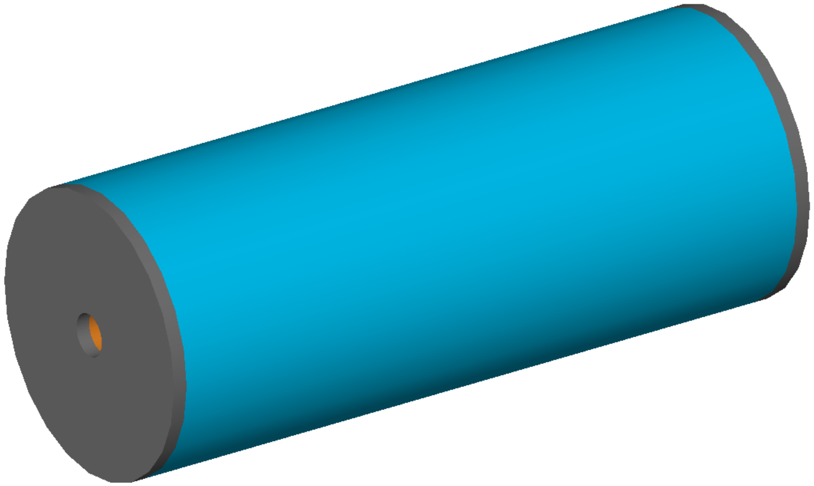
UserAnal framework

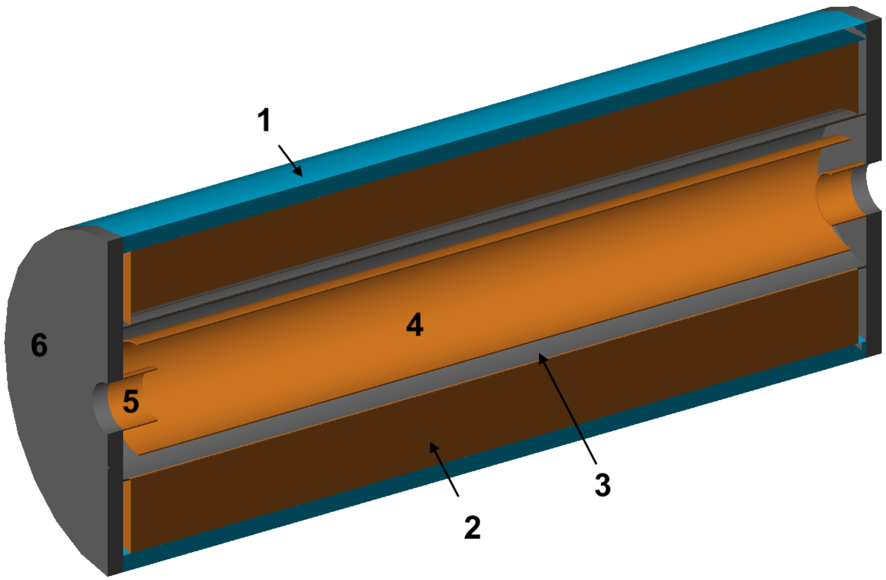
```
readBEAMsim: start
    ----> Initialise:
        ----> HOMEPATH: /Users/kennethlong/KL-GIT/CCAP/00-Repository/lhara/LhARAlinearOptics/31-UserD
        ----> Check input and output files:
            ----> Input file: LhARABeamLine-Params-LsrDrvn-Gabor.dat
                  Output file not implemented.
    <---- Initialisation complete.
    ----> Read data file:
        ----> Read data file:
<---- return after init.
        ----> Read event  10
        ----> Read event  20
        ----> Read event  30
        ----> Read event  40
        ----> Read event  50
        ----> Read event  60
        ----> Read event  70
        ----> Read event  80
        ----> Read event  90
        ----> Read event  100
    <---- 100 events read
<---- Data-file reading done.
User analysis:
LhARA:1:Source:Source : z, s, trace space: 0.0 0.0 [ 0.       0.03503  0.       -0.03619  0.       -0.07
LhARA:1:Interface:Drift:1 : z, s, trace space: -999999.0 0.05 [ 0.00175  0.03503 -0.00181 -0.03619 -0.
LhARA:1:Source:Source : z, s, trace space: 0.0 0.0 [ 0.       -0.00273 -0.       0.02938  0.       -0.06
LhARA:1:Interface:Drift:1 : z, s, trace space: -999999.0 0.05 [-0.00013 -0.00273  0.00147  0.02938 -0.
LhARA:1:Interface:Aperture:Circular:1 : z, s, trace space: -999999.0 0.05 [-0.00013 -0.00273  0.00147
LhARA:1:Interface:Drift:2 : z, s, trace space: -999999.0 0.1 [-0.00027 -0.00273  0.00294  0.02938 -0.2
LhARA:1:Source:Source : z, s, trace space: 0.0 0.0 [ 0.       -0.00014  0.       0.00005  0.       -0.08
LhARA:1:Interface:Drift:1 : z, s, trace space: -999999.0 0.05 [-0.00001 -0.00014  0.       0.00005 -0.
LhARA:1:Interface:Aperture:Circular:1 : z, s, trace space: -999999.0 0.05 [-0.00001 -0.00014  0.
LhARA:1:Interface:Drift:2 : z, s, trace space: -999999.0 0.1 [-0.00001 -0.00014  0.00001  0.00005 -0.2
LhARA:1:Interface:Aperture:Circular:2 : z, s, trace space: -999999.0 0.1 [-0.00001 -0.00014  0.00001
LhARA:1:Capture:Drift:1 : z, s, trace space: -999999.0 0.25 [-0.00003 -0.00014  0.00001  0.00005 -0.69
LhARA:1:Capture:Gabor lens:1 : z, s, trace space: -999999.0 1.107 [ 0.00001  0.04954 -0.       -0.01829
LhARA:1:Capture:Drift:2 : z, s, trace space: -999999.0 1.257 [ 0.00744  0.04954 -0.00275 -0.01829 -3.4
LhARA:1:Capture:Drift:3 : z, s, trace space: -999999.0 1.4069999999999998 [ 0.01487  0.04954 -0.00549
LhARA:1:Capture:Gabor lens:2 : z, s, trace space: -999999.0 2.264 [ 0.00043  9.23849 -0.00016 -3.4112
LhARA:1:Capture:Drift:4 : z, s, trace space: -999999.0 2.4139999999999997 [ 1.38621  9.23849 -0.51184
LhARA:1:Source:Source : z, s, trace space: 0.0 0.0 [-0.       0.00022 -0.       -0.00041  0.       -0.08
LhARA:1:Interface:Drift:1 : z, s, trace space: -999999.0 0.05 [ 0.00001  0.00022 -0.00002 -0.00041 -0.
LhARA:1:Interface:Aperture:Circular:1 : z, s, trace space: -999999.0 0.05 [ 0.00001  0.00022 -0.00002
LhARA:1:Interface:Drift:2 : z, s, trace space: -999999.0 0.1 [ 0.00002  0.00022 -0.00004 -0.00041 -0.2
LhARA:1:Interface:Aperture:Circular:2 : z, s, trace space: -999999.0 0.1 [ 0.00002  0.00022 -0.00004 -
LhARA:1:Capture:Drift:1 : z, s, trace space: -999999.0 0.25 [ 0.00006  0.00022 -0.00011 -0.00041 -0.69
LhARA:1:Capture:Gabor lens:1 : z, s, trace space: -999999.0 1.107 [-0.00002 -0.08077  0.00003  0.15243
LhARA:1:Capture:Drift:2 : z, s, trace space: -999999.0 1.257 [-0.01213 -0.08077  0.0229   0.15243 -3.4
LhARA:1:Capture:Drift:3 : z, s, trace space: -999999.0 1.4069999999999998 [-0.02425 -0.08077  0.04576
LhARA:1:Source:Source : z, s, trace space: 0.0 0.0 [-0.       -0.05358  0.       0.06061  0.       0.04
LhARA:1:Interface:Drift:1 : z, s, trace space: -999999.0 0.05 [-0.00268 -0.05358  0.00303  0.06061  0.
LhARA:1:Source:Source : z, s, trace space: 0.0 0.0 [ 0.       0.00018 -0.       -0.0002   0.       -0.08
LhARA:1:Interface:Drift:1 : z, s, trace space: -999999.0 0.05 [ 0.00001  0.00018 -0.00001 -0.0002  -0.
LhARA:1:Interface:Aperture:Circular:1 : z, s, trace space: -999999.0 0.05 [ 0.00001  0.00018 -0.00001
LhARA:1:Interface:Drift:2 : z, s, trace space: -999999.0 0.1 [ 0.00002  0.00018 -0.00002 -0.0002  -0.2
LhARA:1:Interface:Aperture:Circular:2 : z, s, trace space: -999999.0 0.1 [ 0.00002  0.00018 -0.00002 -
LhARA:1:Capture:Drift:1 : z, s, trace space: -999999.0 0.25 [ 0.00005  0.00018 -0.00005 -0.0002  -0.69
```

- **Placeholder, but:**
  - Provides example of looping through particle instances
  - Trace space at each element:
    - Source, nozzle, …
    - Transformation to lab will be provided
      - Source distribution felt to be most valuable
- **Source distribution comparison**
  - Initial beam profile
  - Beam transport performance
  - Model losses

BDSIM Gabor Lens

- Example Geometry
  - Anode & electrode geometry to be updated

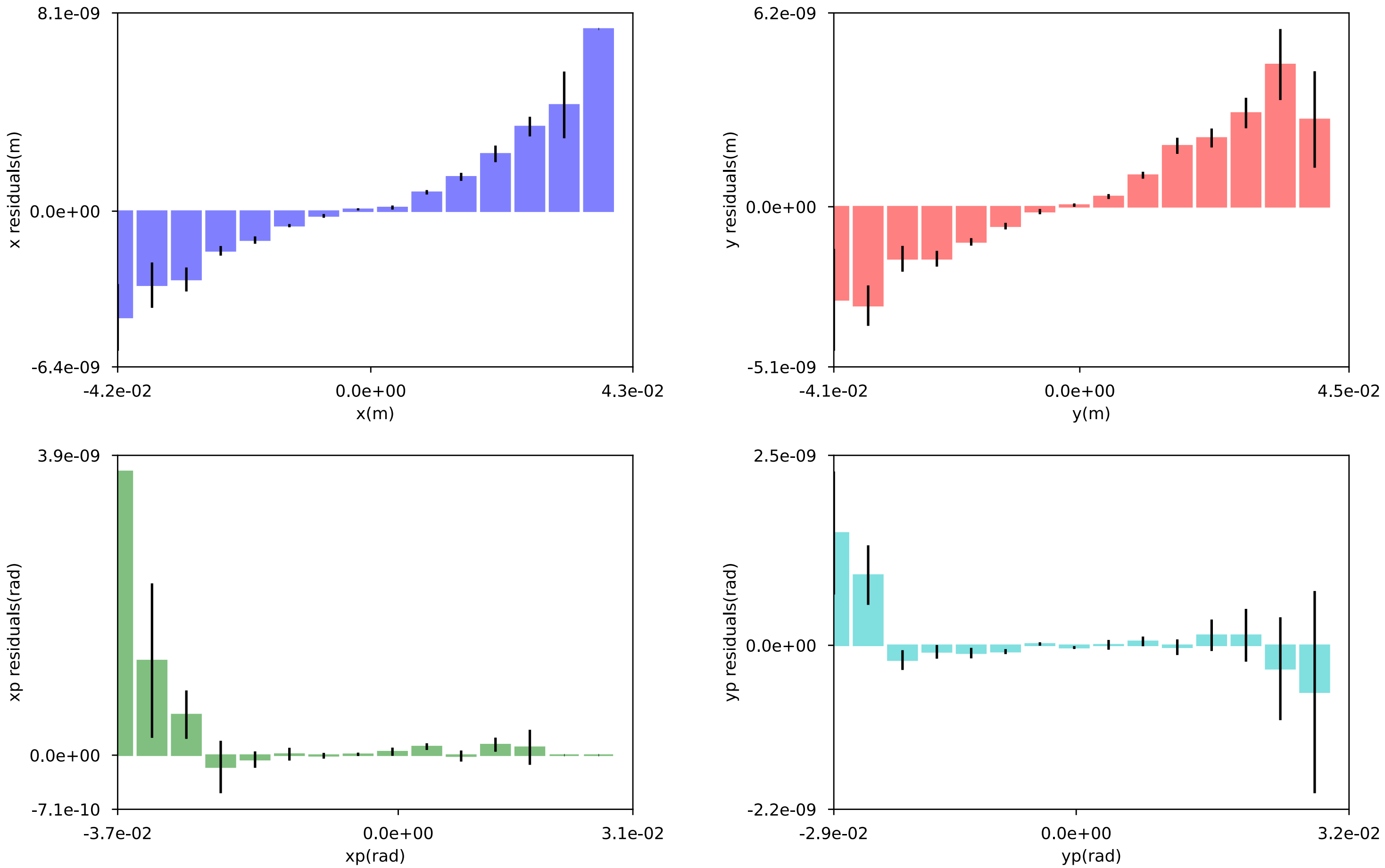




- Geometry:
  1) Outer tube (variable, default iron)
  2) Solenoid coils (copper)
  3) Vacuum tube
  4) Anode (copper)
  5) Electrode (copper)
  6) End caps (stainless steel)

- Anode & electrode:
  - User defined radius, length, and aperture
- EM field
  - Radial plasma (electric) field only
  - Future-proofed to later allow addition of confinement fields
  - Restricted to ± anode radius

BDSIM Gabor Lens: Tracking



- Good particle tracking residuals compared to external field map

BDSIM Element: Parameterised Strength

- Currently based on B [T]: solenoid equivalent field strength
  - Used in field map generation – useful for tracking comparisons

- R-matrix:

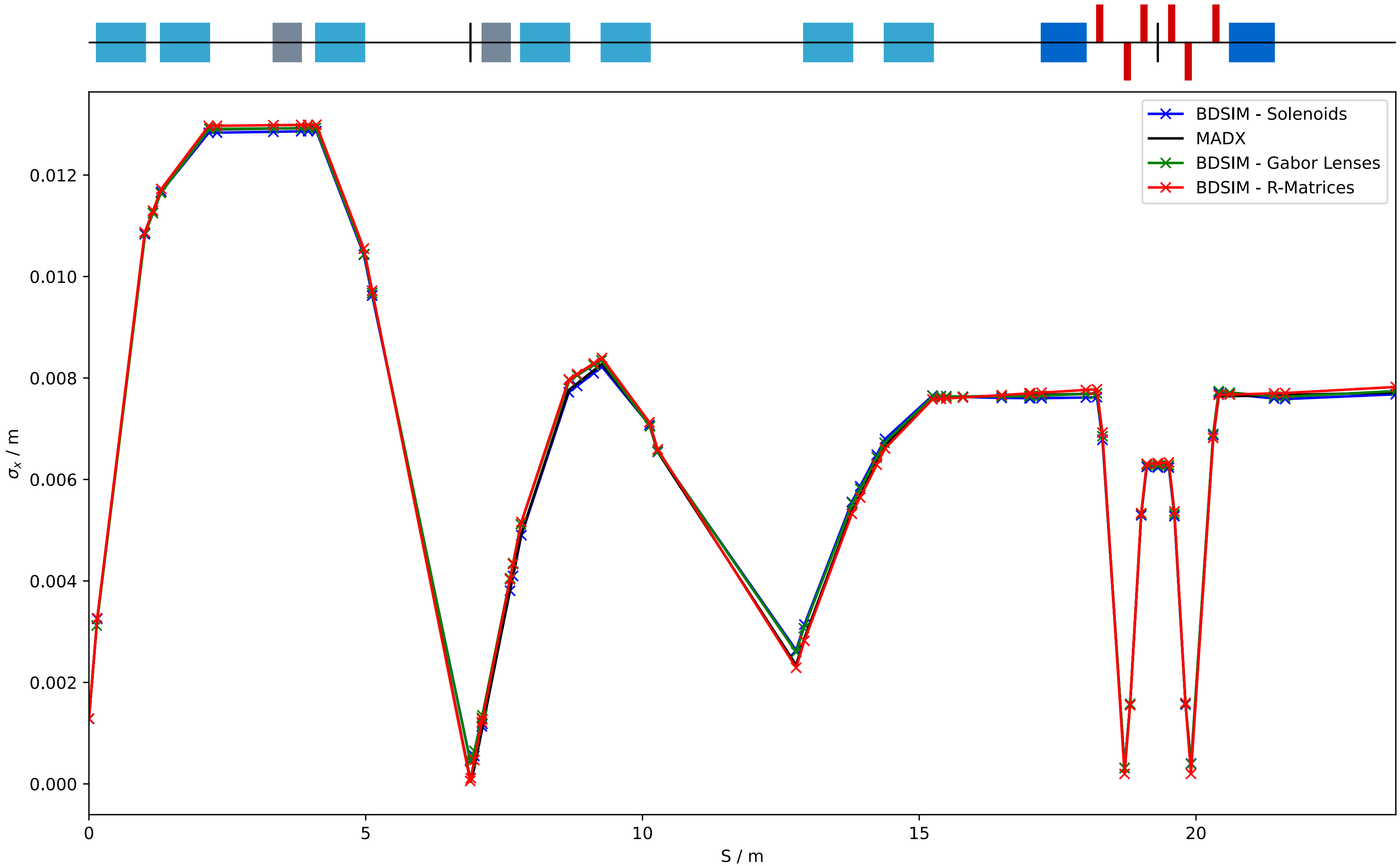
$$R_{GL} = \begin{pmatrix} \cos(\omega L) & \frac{\sin(\omega L)}{\omega} & 0 & 0 & 0 & 0 \\ -\omega\sin(\omega L) & \cos(\omega L) & 0 & 0 & 0 & 0 \\ 0 & 0 & \cos(\omega L) & \frac{\sin(\omega L)}{\omega} & 0 & 0 \\ 0 & 0 & -\omega\sin(\omega L) & \cos(\omega L) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{L}{\beta_0^2\gamma_0^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\omega = \sqrt{k}$$

$$\boxed{k_G = \frac{e}{2\epsilon_0}\frac{m_p\gamma}{p^2}n_e}$$

- Kg strength allowed (definition via B_{sol} still permitted)
  - Dependant on manually defined constants – CLHEP preferred

LhARA Tracking Performance



- Minor Gabor lens strength adjustments required

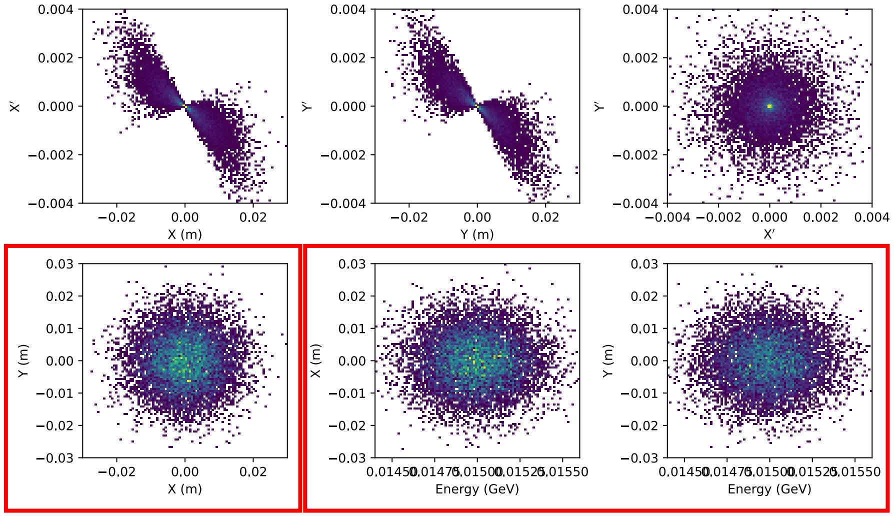
Gabor Lens Strength Updates

- Tweaks only to **some** Gabor lens fields needed.
  - Unsure why - investigating
- Manual iteration, cumulatively.

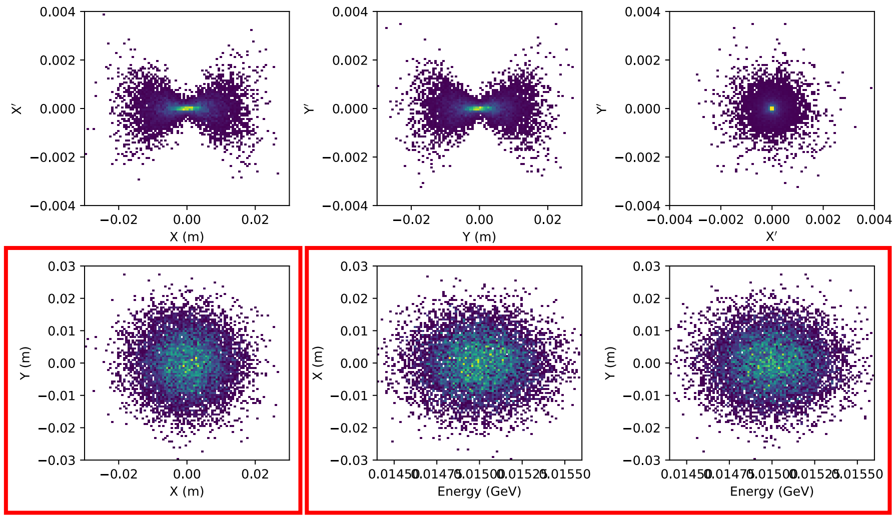
Solenoid / Gabor Lens	Solenoid (Design parameters)		Gabor Lens (simulation optimized)		
	KS	B [T]	B [equivalent]	ΔB/B (%)	Kg
1	2.4917	1.4000	1.3850	**1.07**	1.5433
2	1.0187	0.5724	0.5724	**0**	0.2636
3	1.4486	0.8139	0.8120	**0.23**	0.5304
4	1.7889	1.0051	1.0051	**0**	0.8126
5	1.6043	0.9014	0.8750	**2.929**	0.6160
6	1.2448	0.6994	0.6994	**0**	0.3936
7	1.1660	0.6551	0.6450	**1.54**	0.3347

End Station Phase Space

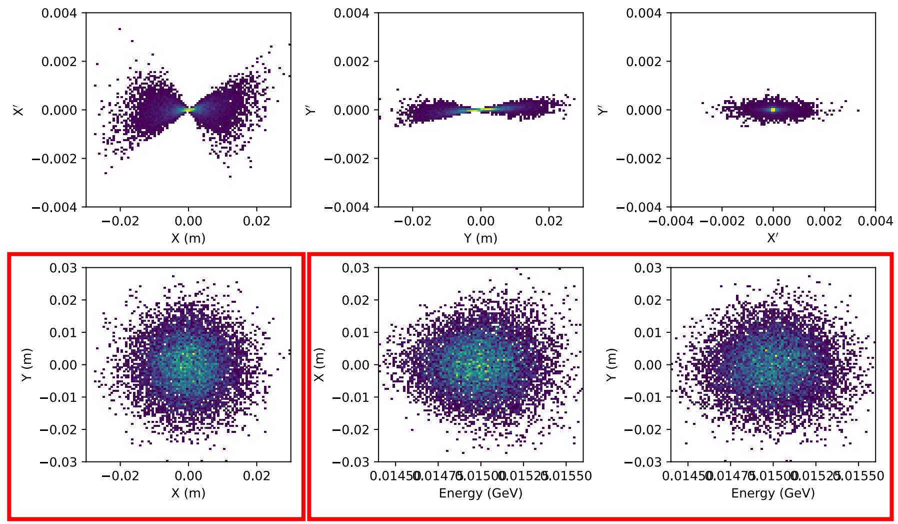
Gabor Lens



Solenoid



R-Matrix

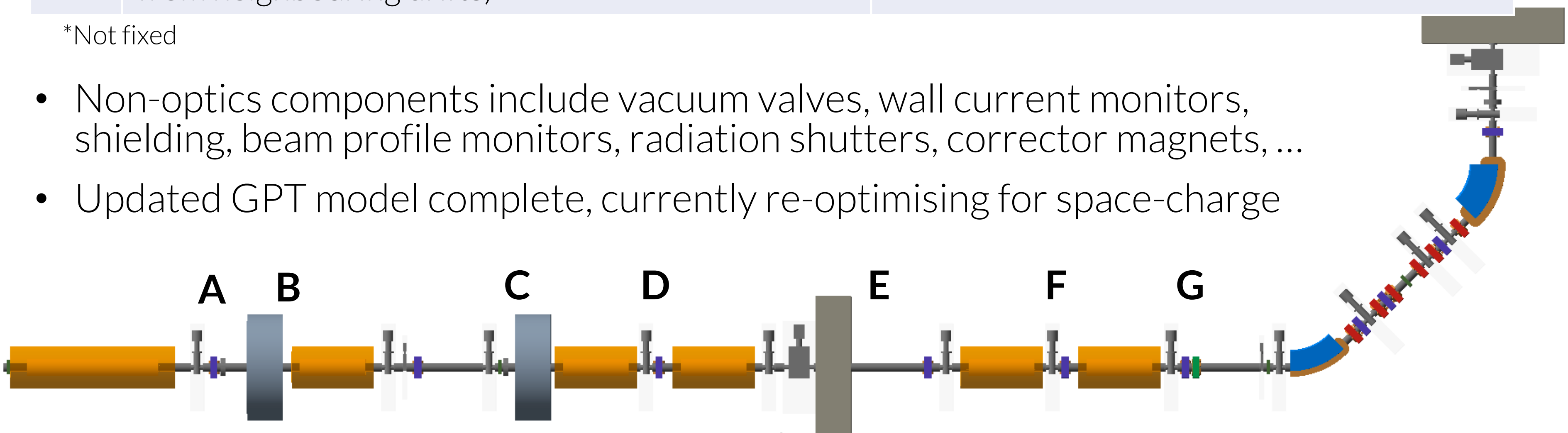


Proposed Stage 1 Changes

	Update	Reason
A	**+1.0185m*** between **GL2 & RF CAV 1**	Non-optics components
B	**+ 0.127m*** between **RF CAV 1 & GL3**	Practical space allowance
C	**RF CAV 02** moved upstream by **0.0546m***	Practical space allowance
D	**+ 0.2m** between GL4 and GL5	Non-optics components
E	**+ 0.4m** between GL4 and GL5	Non-optics components, Wien filter
F	**+ 0.2m** between GL6 and GL7	Non-optics components
G	**Octupole** moved downstream by **0.15m***	Practical space allowance
-	**All collimators** now **0.05m*** long (space taken from neighbouring drifts)	Practical space allowance

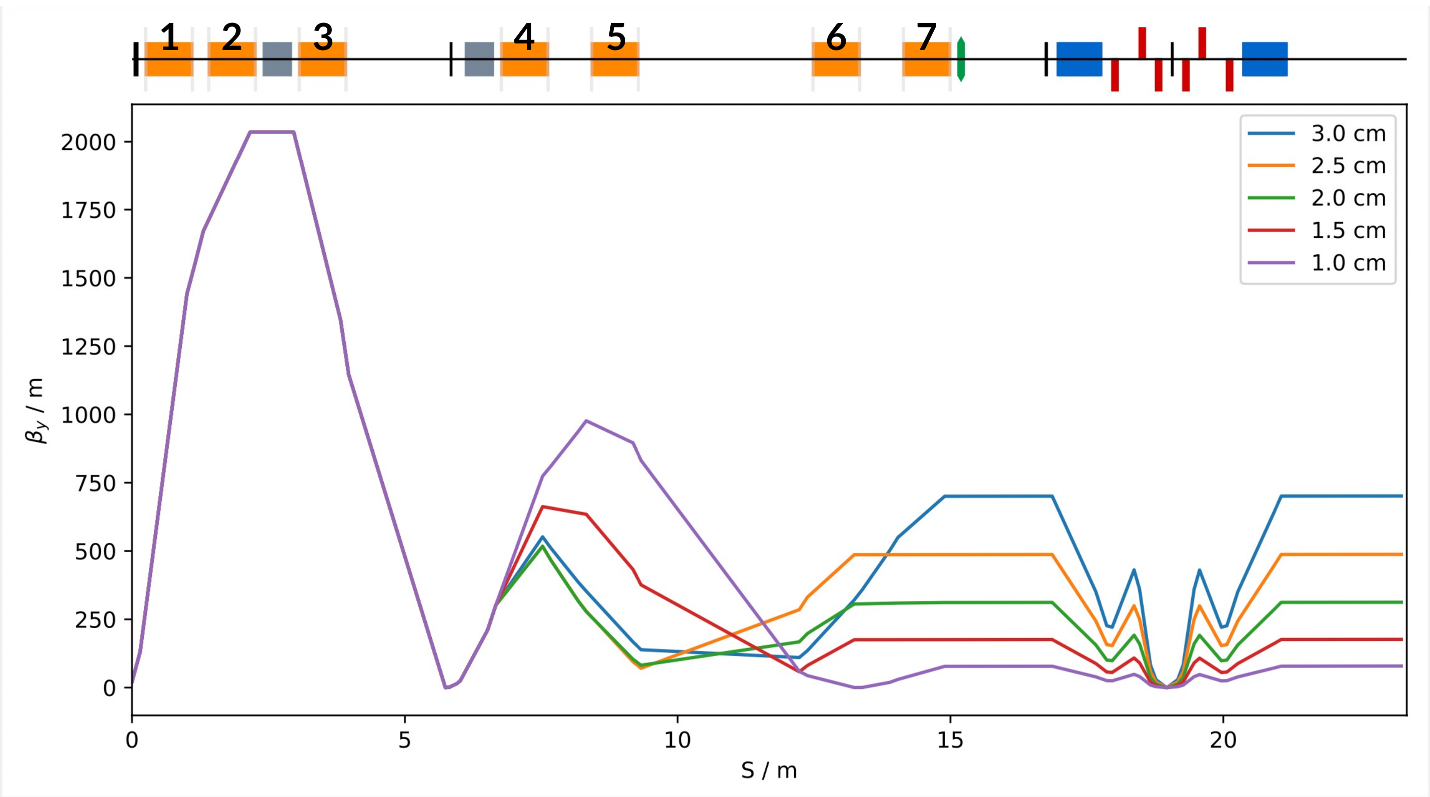
*Not fixed

- Non-optics components include vacuum valves, wall current monitors, shielding, beam profile monitors, radiation shutters, corrector magnets, …
- Updated GPT model complete, currently re-optimising for space-charge



S1 Optics Tests: Extra Drift Space

- **+ 0.2m** between GL4 and GL5
- **+ 0.4m** between GL4 and GL5
- **+ 0.2m** between GL6 and GL7
- Solutions found for original 5 spot sizes
  - Sensitive to initial conditions



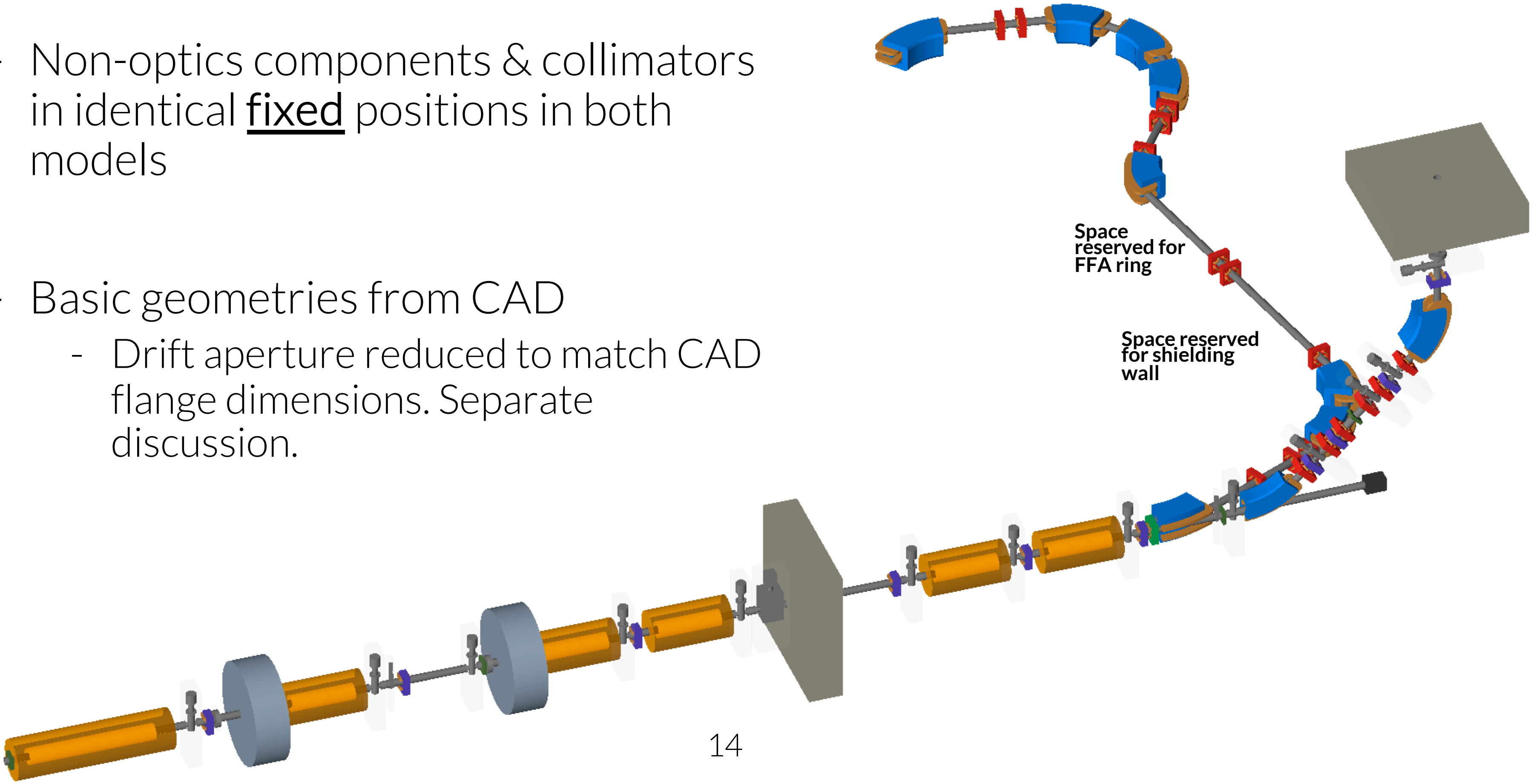
Parallel Optics & Survey Models

- Separate models for optics tracking & geometry survey

- Gabor lenses 1 & 2 combined into a single component
    - Considered separate in tracking simulations

- Non-optics components & collimators in identical <u>fixed</u> positions in both models

- Basic geometries from CAD
    - Drift aperture reduced to match CAD flange dimensions. Separate discussion.



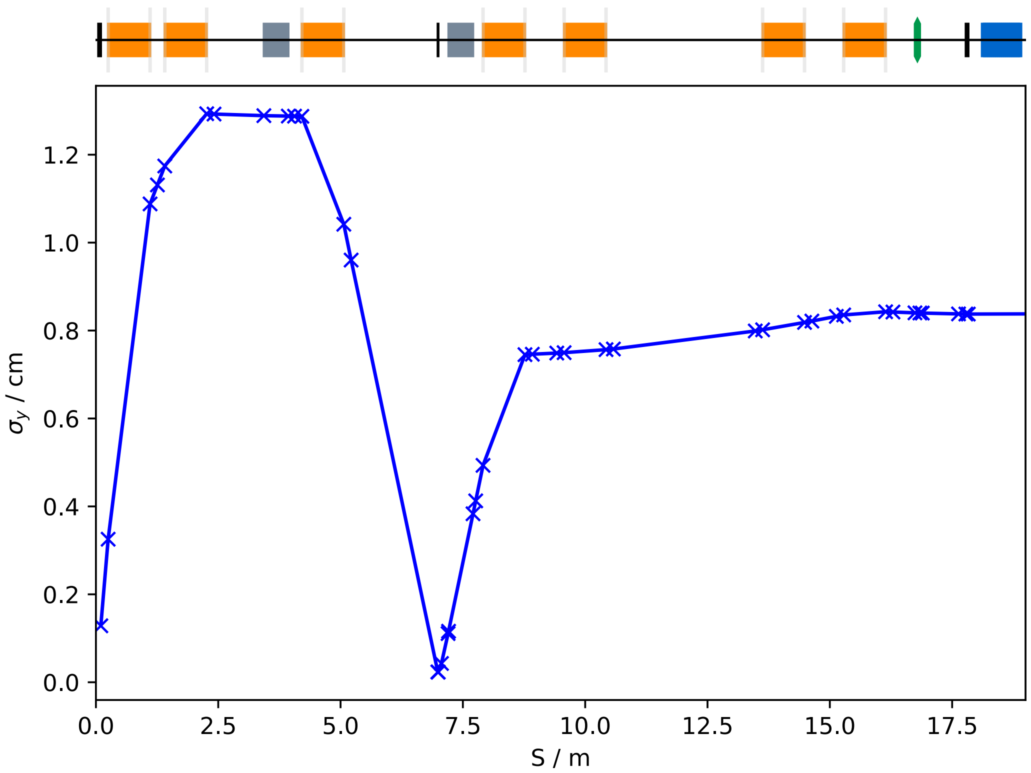
Stage 1 Optimisation

- Emittance growth introducing difficulties optimising for injection line conditions
  - Emittance ~2.7e-6, beta of 50m = 1 sigma beam radius of 1.16 cm.
  - Prioritise alpha = 0
- Solution: beam at start of switching dipole:

```
Alpha x: 0.094
Alpha y: 0.104
 Beta x: 25.092
 Beta y: 26.463
 Emit x: 2.822e-06
 Emit y: 2.707e-06
```

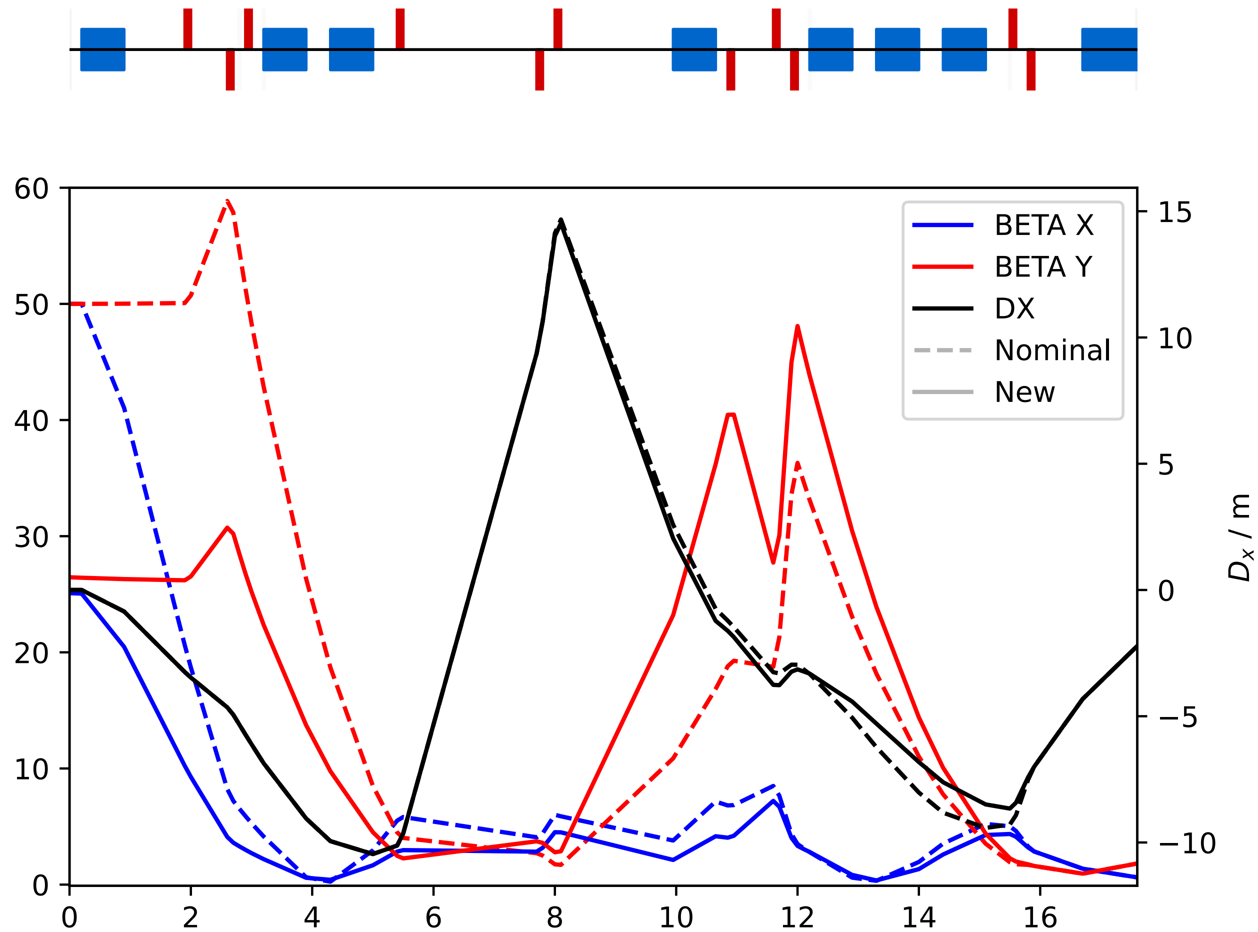
- Solenoids 5 & 6 **off**

- Solenoid 4 KS = 1.95
  - Field = 1.096 T
- Solenoid 7 KS = 0.4
  - Field = 0.225 T

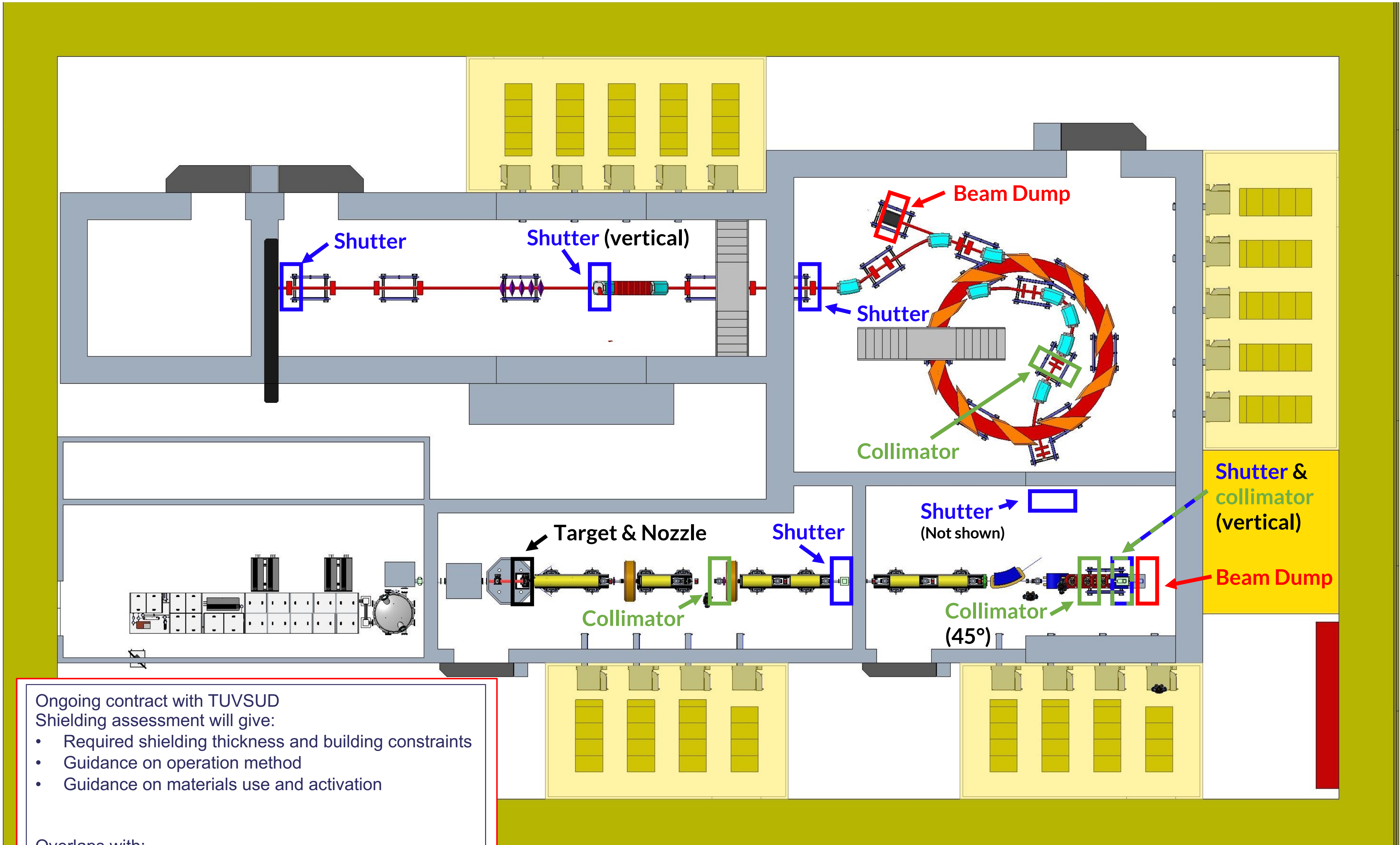


Injection Line: MADX Optimisation

- Able to meet conditions at injection septum
- Vary last 7 quads only
  - Constraint of 9.55 T/m.
- Solution found:
  - Small changes to field gradients
  - Confident we can handle minor shifting of quad (engineering)



Radiation Modelling: Loss Map



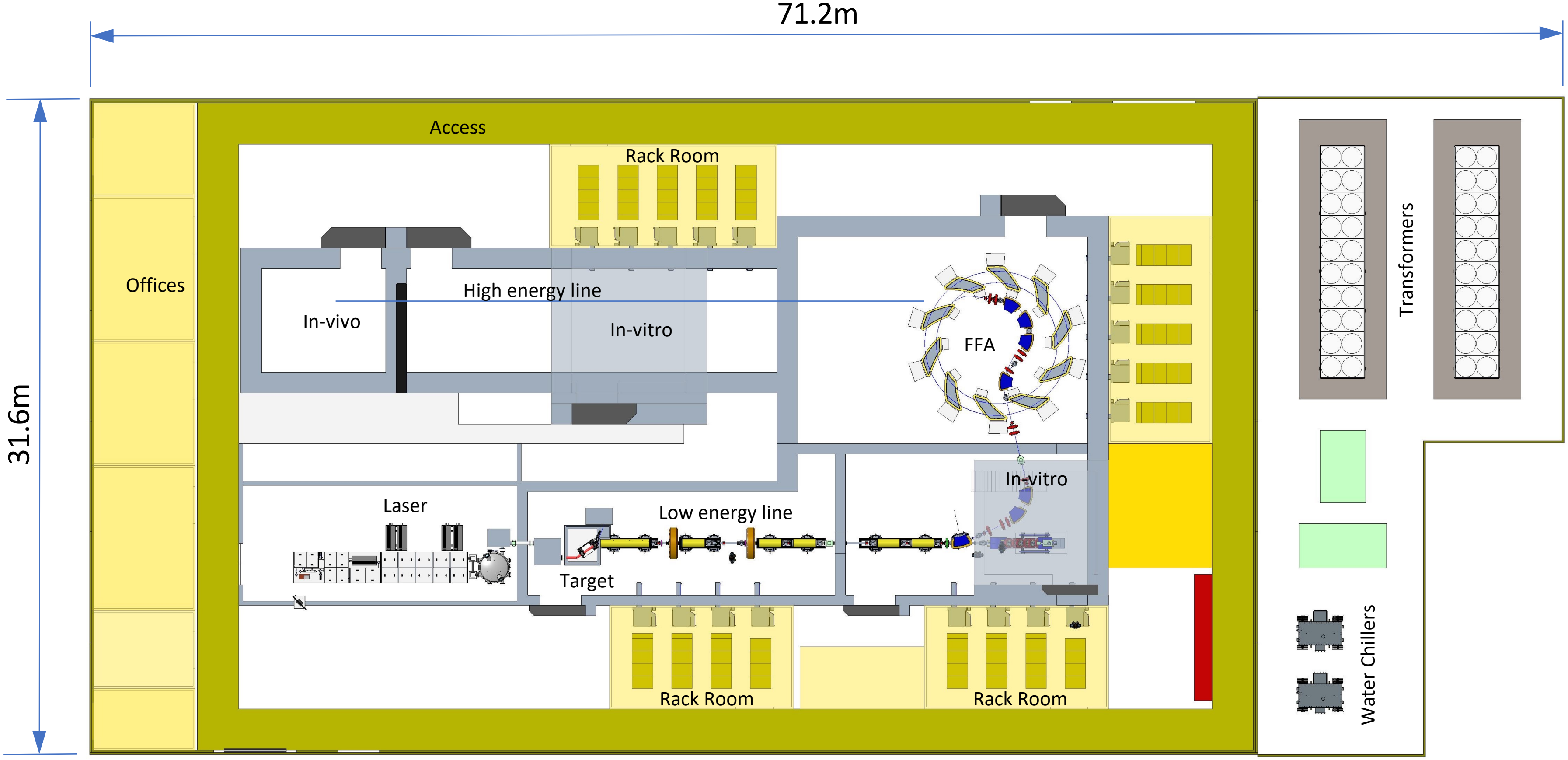
Ongoing contract with TUVSUD
Shielding assessment will give:

- Required shielding thickness and building constraints
- Guidance on operation method
- Guidance on materials use and activation

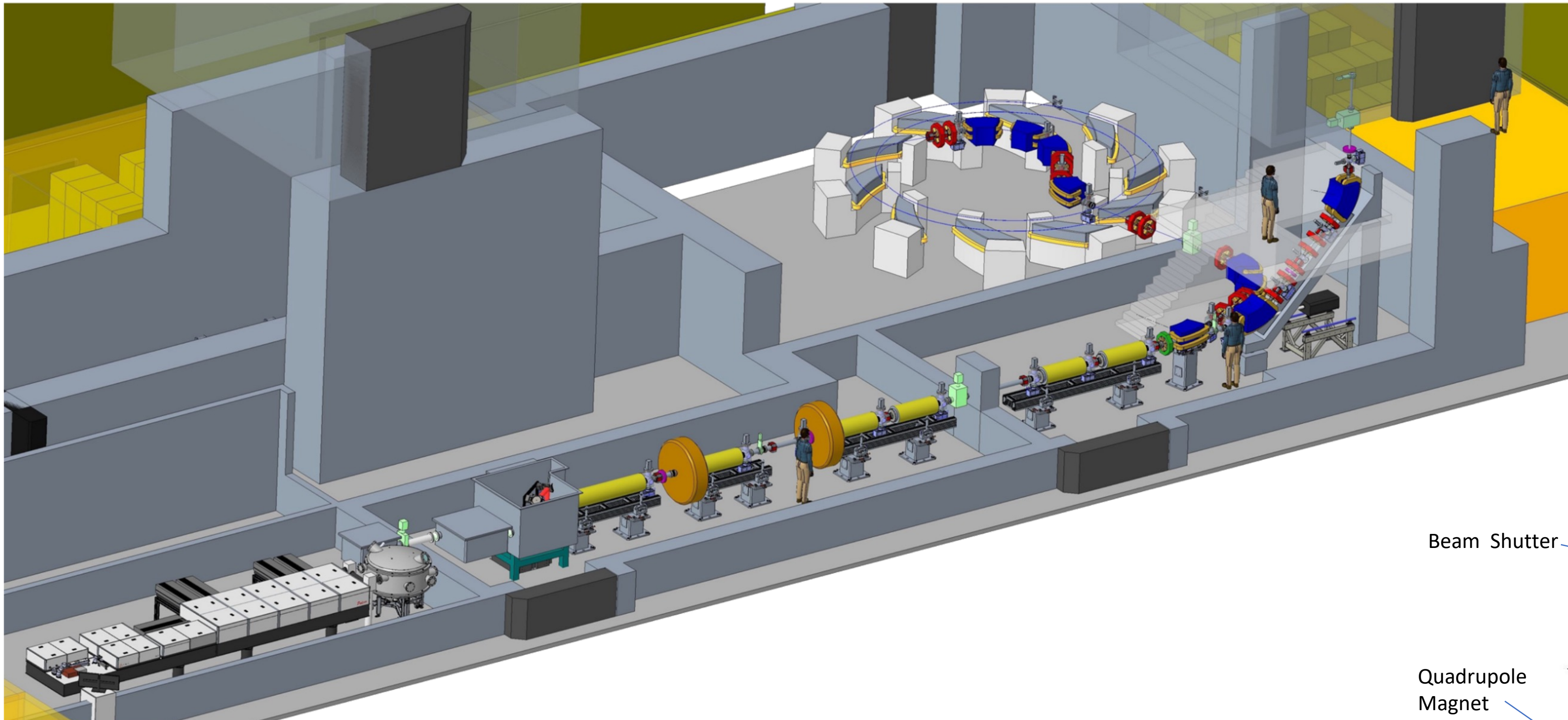
Overlaps with:

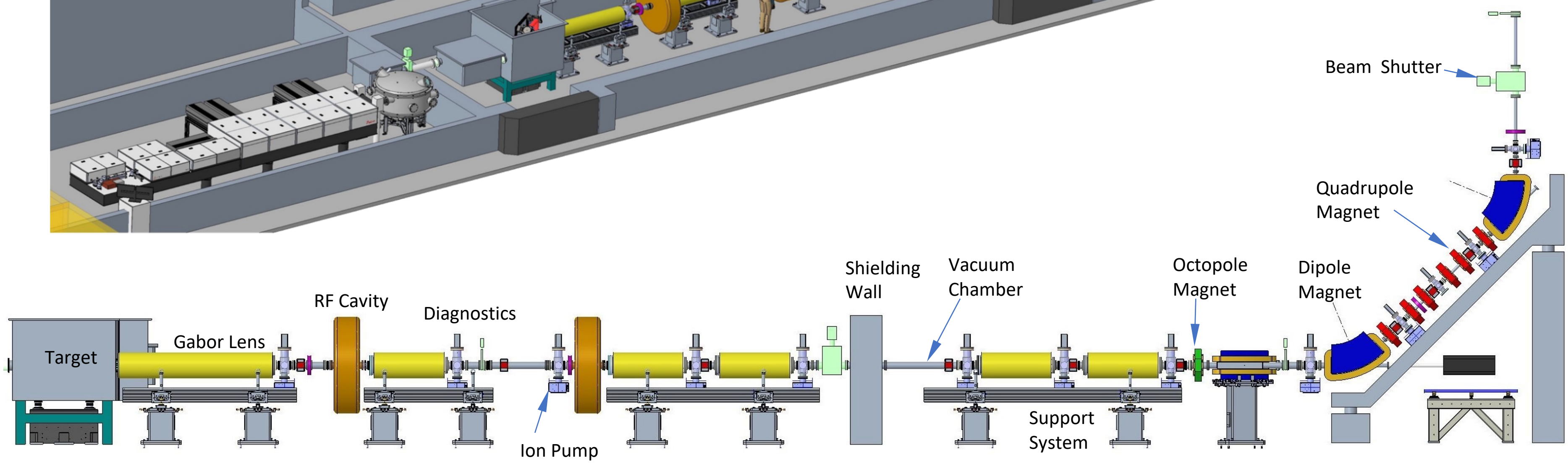
- Source modelling, definition and experiments
- Development of Stage 1 Gabor lens design
- Stage 2 FFA design

Updated Facility Layout

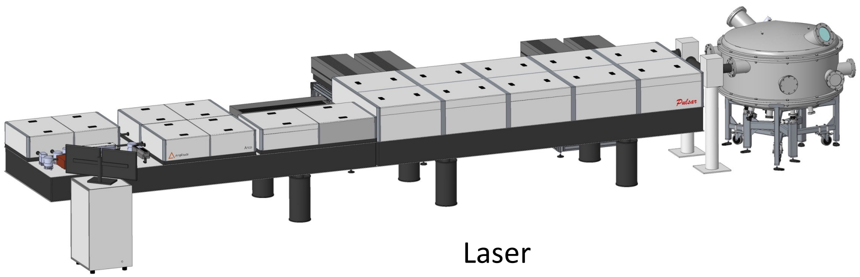


Low Energy Line

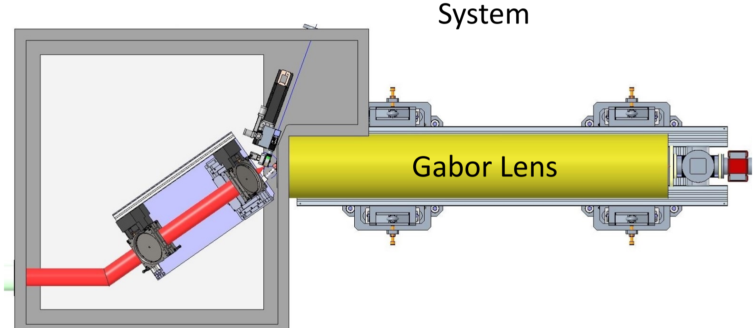




Source and Low Energy Line

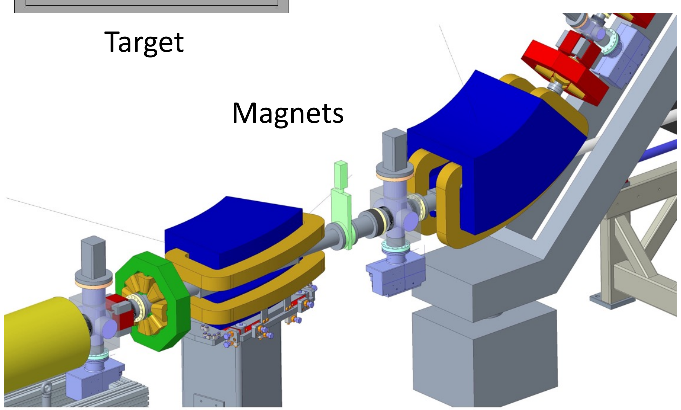


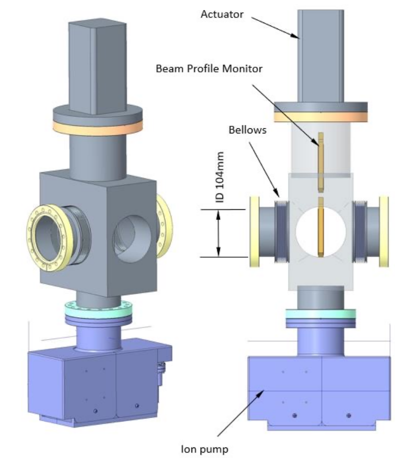
Laser System



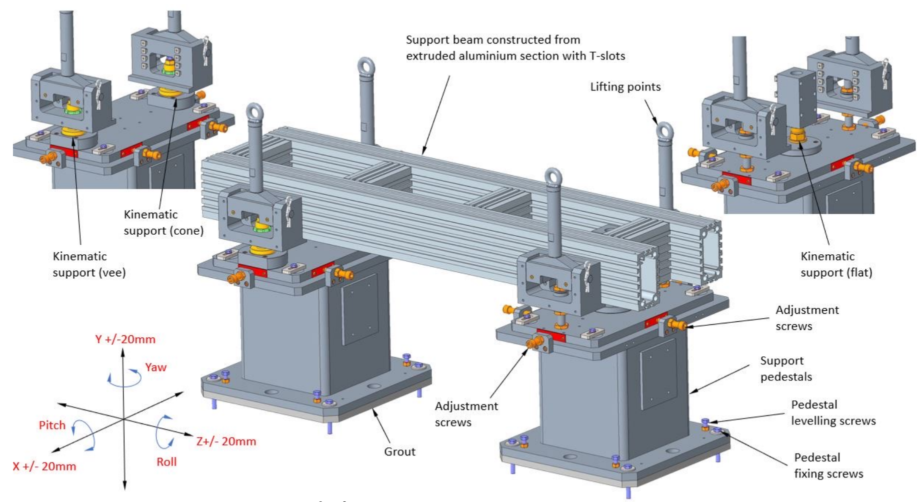
Target

Magnets



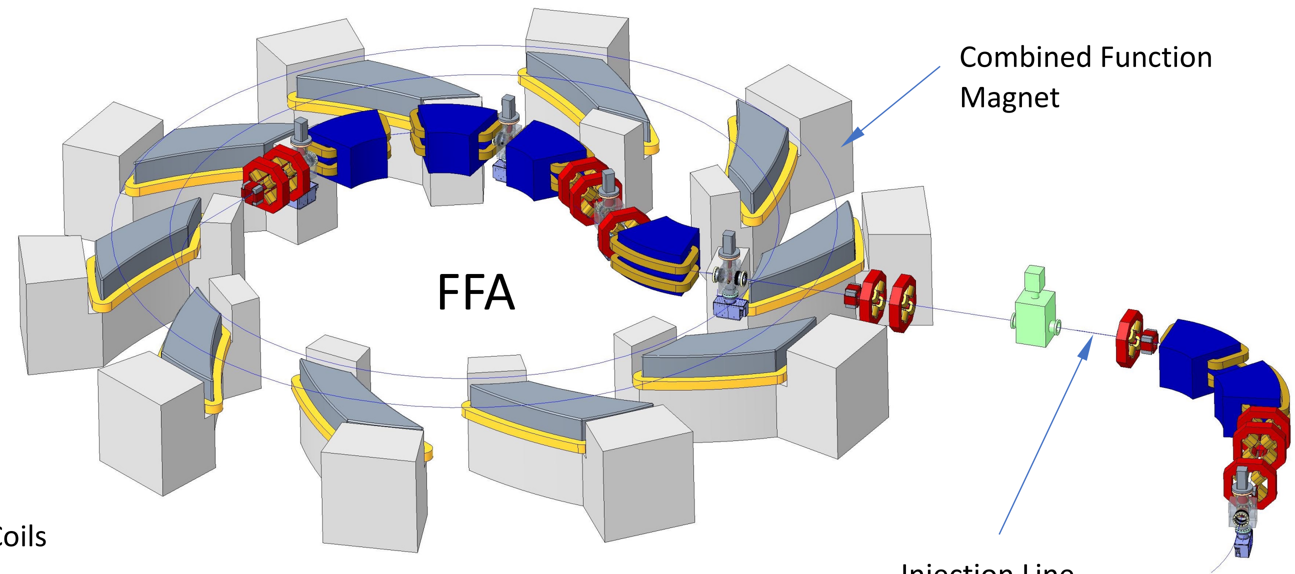


Beam Profile Monitor and Vacuum Pumping

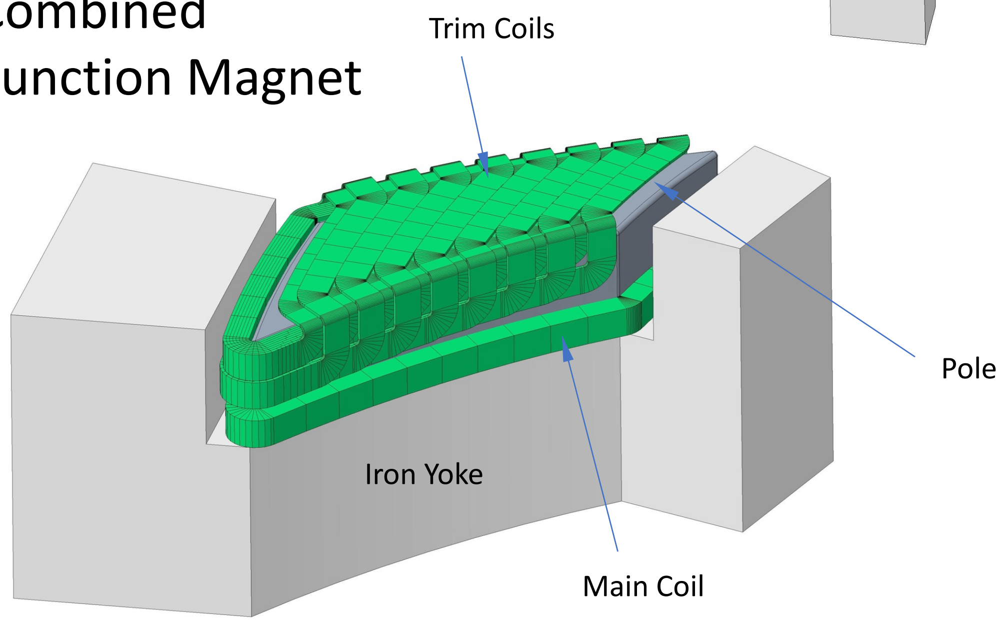


Modular Support System

Injection Line and FFA



Combined Function Magnet



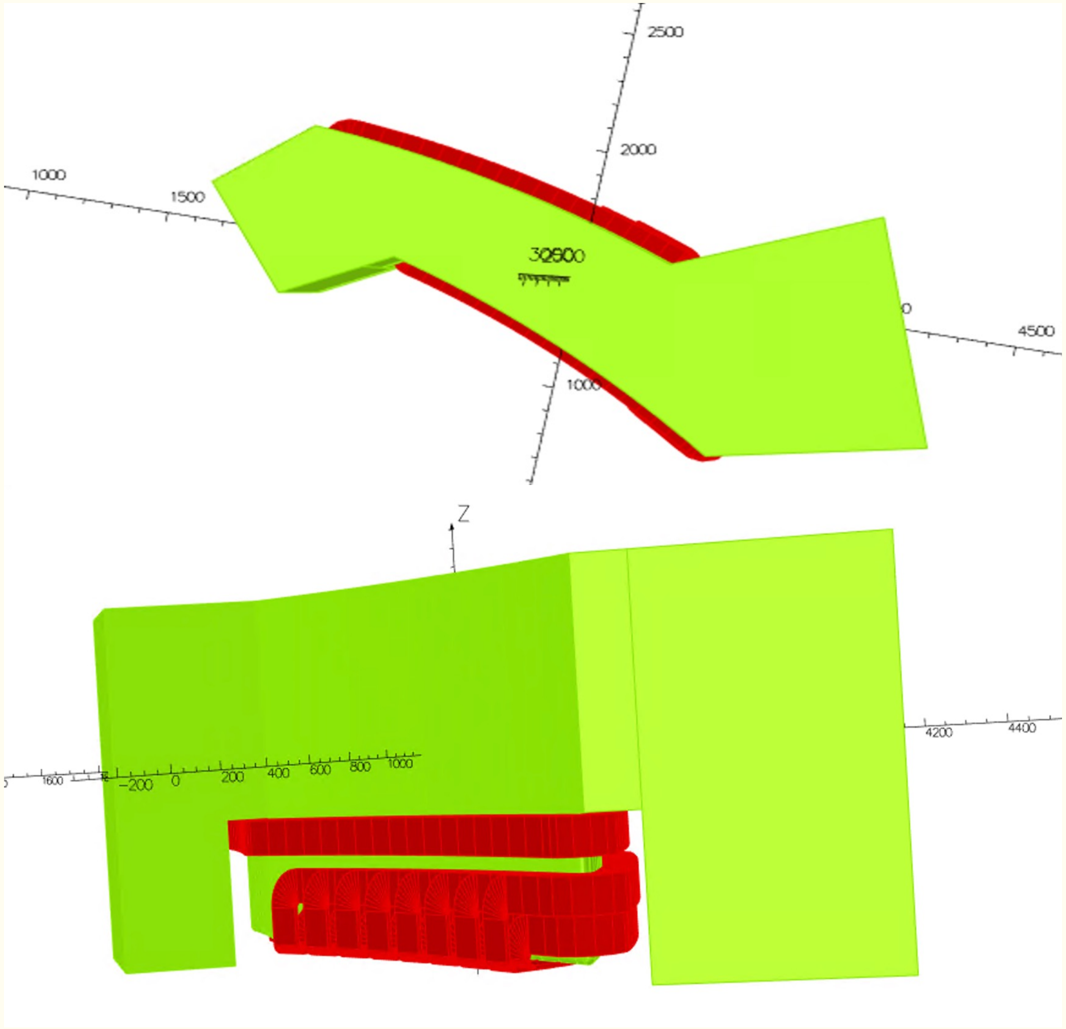
FFA Magnet Design Update

Ta-Jen Kuo

Supervisor: Jaroslaw Pasternak, Jean-Baptiste Lagrange

Imperial College London, STFC

Pictures of the magnet

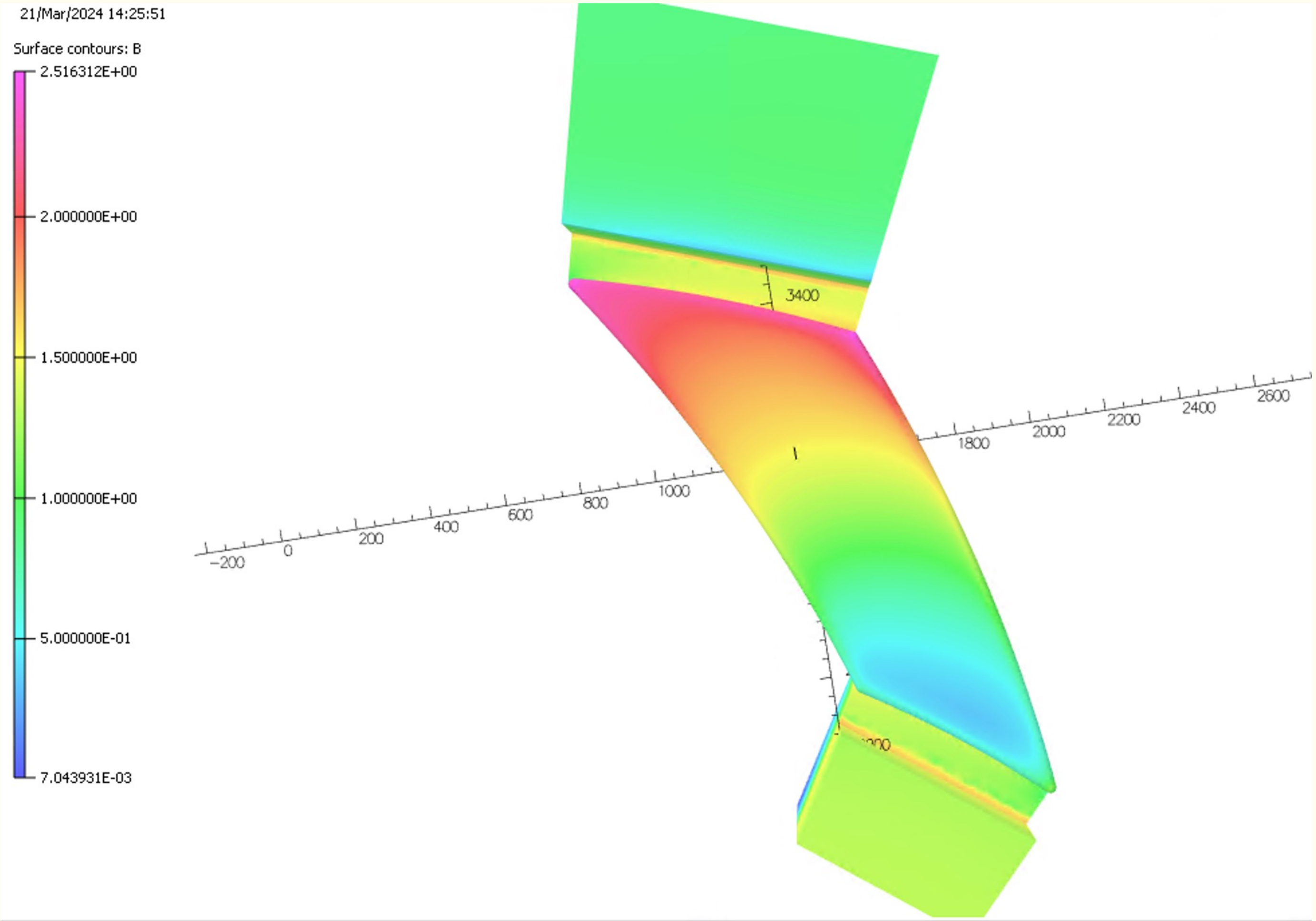


Top View

Conductors shown in red
Iron shown in green

Side View
(Only top half of the magnet shown)

Saturation level of pole face

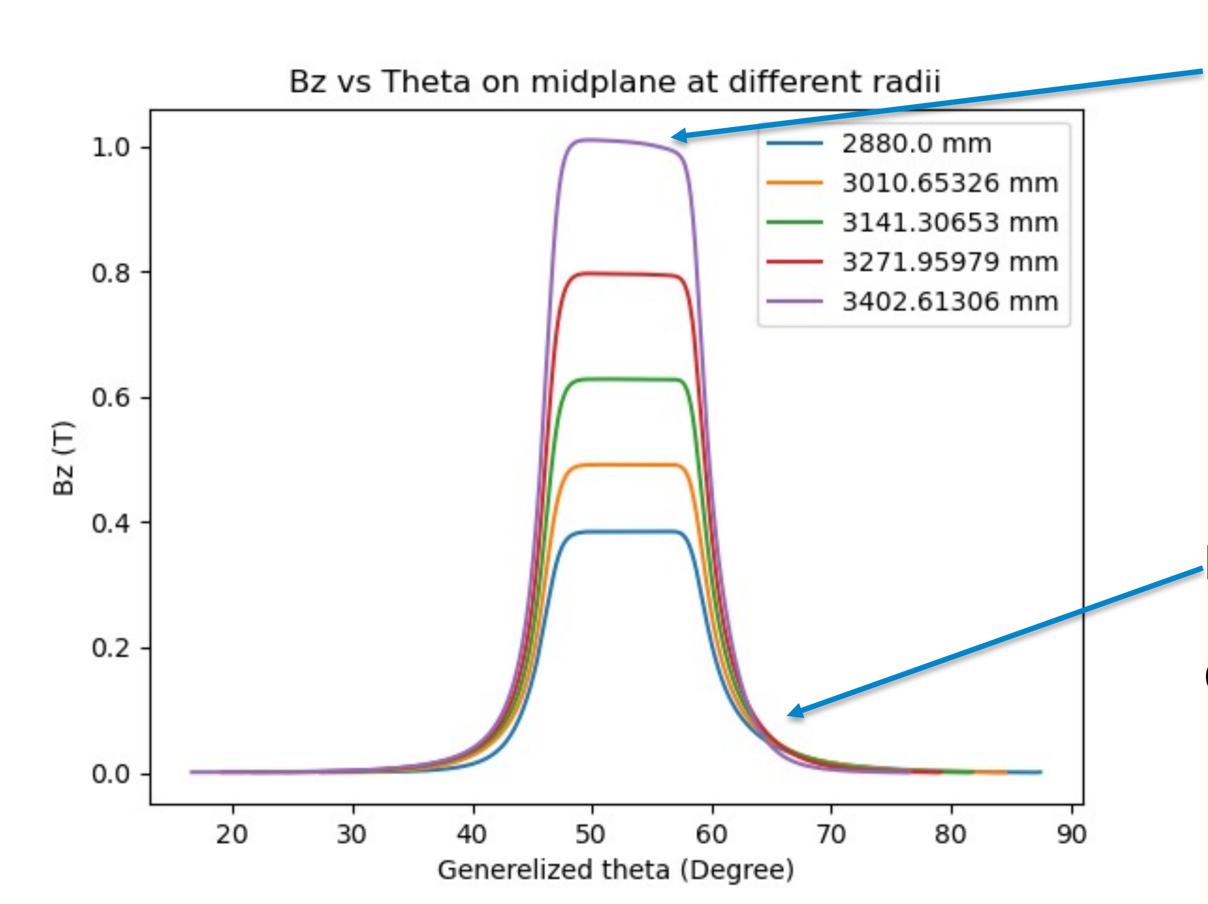


Reaches 2.5 T at the outer radii of the pole

Imperial College London

UKRI Science and Technology Facilities Council

Bz vs theta at different radii



Flat top of field slanted at higher Radii due to saturation

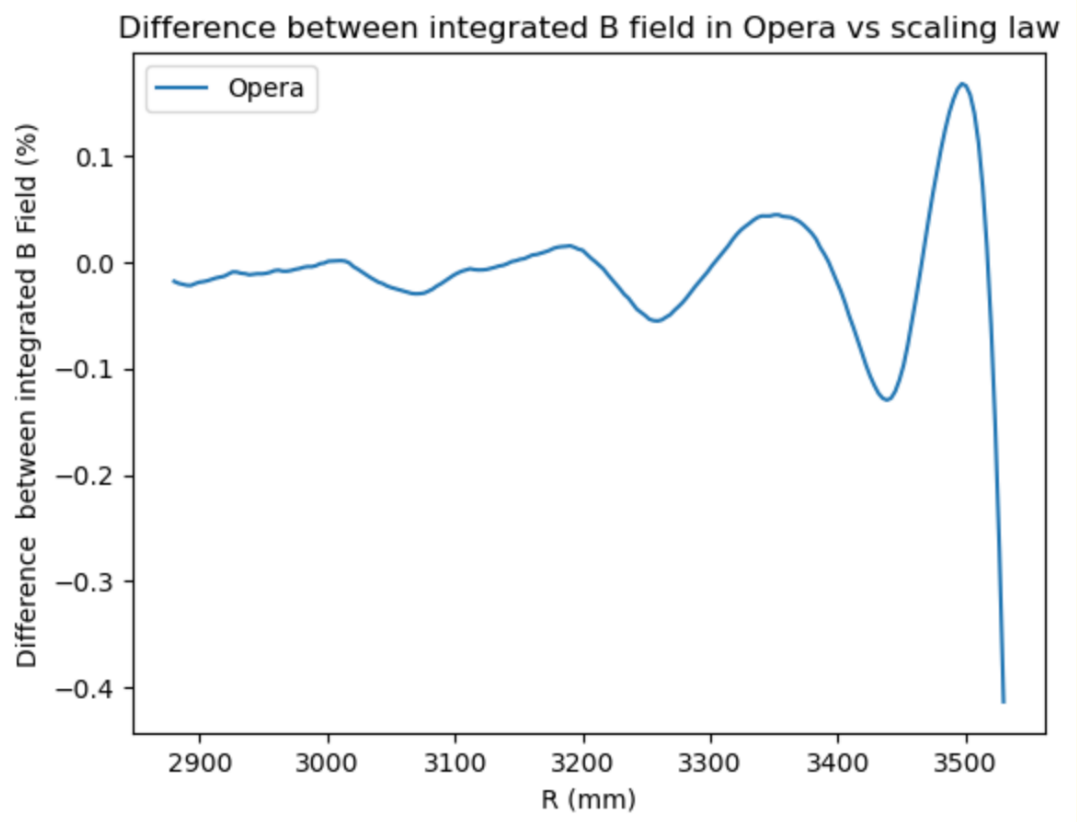
Fringe field extent not constant

Clamps yet to be added

Integrated B Field

k-value=5.33, r_0 = 3.477m , B_0 = 1.405T, BL_0 = 1.044 Tm (Assuming hardedge model)

The integrated B field scales as: $BL = BL_0\,(\frac{r}{r_0})^{k+1}$, $where\ BL = r\int B_z\,d\theta$



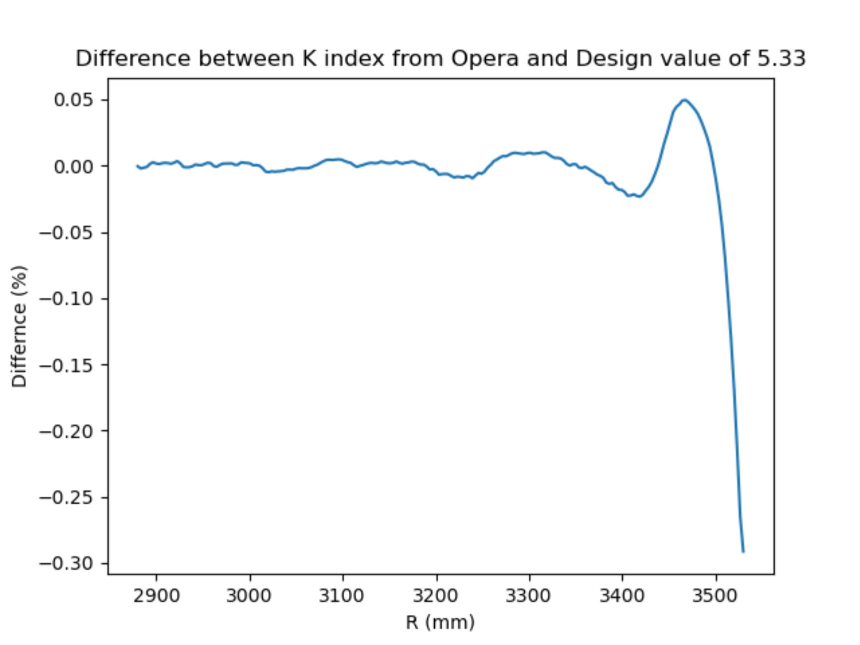
Coil Number	Current Values (Ampere turn)
0	13627.21
8	5224.76
7	3300.79
6	2894.24
5	2373.35
4	2082.01
3	1767.40
2	1500.71
1	1180.91

Optimisation hasn't fully converged and is still running

Integrated B Field

k-value=5.33, r_0 = 3.477m , B_0 = 1.405T, BL_0 = 1.044 Tm (Assuming hardedge model)

$$k_{int} = \frac{r}{BL}\frac{\partial\, BL}{\partial\, r} - 1$$



Optimisation hasn't fully converged and is still running

Power estimation for current

Trim			Main		
Coil width	0.01	m	Coil width	0.07	m
Coil height	0.0925	m	Coil height	0.095	m
Coil area	0.000648	m^2	Coil area	0.004655	m^2
Cu Resistivity	1.68E-08	Ohm.m	Cu Resistivity	1.68E-08	Ohm.m

Trimcoil	Length (m)	Current (AT)	Resistance (Ohm)	Power (W)
0	4.373703	13627.21185	1.58E-05	2.93E+03
1	2.250419	5224.757091	5.84E-05	1.59E+03
2	2.457649	3300.792678	6.38E-05	6.95E+02
3	2.664915	2894.239131	6.91E-05	5.79E+02
4	2.872519	2373.352598	7.45E-05	4.20E+02
5	3.079622	2082.013079	7.99E-05	3.46E+02
6	3.286786	1767.402379	8.53E-05	2.66E+02
7	3.494767	1500.712623	9.07E-05	2.04E+02
8	3.70176	1180.915984	9.60E-05	1.34E+02
9	2.639757	5224.757091	6.85E-05	1.87E+03
10	2.847212	3300.792678	7.39E-05	8.05E+02
11	3.054371	2894.239131	7.92E-05	6.64E+02
12	3.261559	2373.352598	8.46E-05	4.77E+02
13	3.469103	2082.013079	9.00E-05	3.90E+02
14	3.67647	1767.402379	9.54E-05	2.98E+02
15	3.883487	1500.712623	1.01E-04	2.27E+02
16	4.090869	1180.915984	1.06E-04	1.48E+02
				Total Power (W)
				1.20E+04

12kw for a half of the magnet

12 x 2 x 10 magnets = 240 kW Overall

Summary

- Standard parameterised source developed, comparisons ongoing
- Gabor lens tracking performance comparable to solenoids
- Stage 1 accelerator updates proposed without impacting optics configurations
- Engineering & integration updated
- FFA magnet design underway

Thank you

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