December 2021
MOLLER Collaboration Meeting
Spectrometer Update

Juliette Mammei

Team Acknowledgements

- **JLAB Magnet Group**
  - Mike Bevins *(CAM)**
  - Probir Ghoshal *(Magnet Group Leader)*
  - Dave Kashy *(Principal Mechanical Engineer – Spectrometer Lead)*
  - Eric Sun *(Senior Mechanical Engineer)*
  - Sandesh Gopinath *(Mechanical Engineer)*
  - Randy Wilson *(Mechanical Designer)*
  - Dan Young *(Mechanical Designer)*
- **Physics Collaboration**
  - Juliette Mammei (Experimental Contact)
  - Krishna Kumar
  - **Chandan Ghosh**
  - **Sakib Rahman**
  - **Nazanin Roshanshah**
  - **Ciprian Gal**
  - Kent Paschke
  - and others…

- **MIT Bates REC**
  - James Kelsey (Associate Director Bates)
  - Ernie Ihloff (Principle Research Scientist)
  - Jason Bessuille (Senior Mechanical Engineer)
  - Danielle Petterson (Mechanical Engineer)
  - Designer/ Draftsperson TBD

* Ruben has moved to Princeton

Outstanding questions for physicists (from last meeting)

- Field map and interpolation tests – our current maps are okay
  - Extent – can/should it be smaller than 75 cm in the downstream?
  - Coarseness of grid – probably okay; want to test the limits, optimize
  - Interpolation – default is linear interpolation, investigating cubic as well
- Dose reduction on epoxy
  - Downstream – absolutely possible; just needs to be done
  - Upstream – needs careful design
- Effects of offset coils – needs to be considered in every study (still recommended)
- Tolerable vacuum level determination – beamline backgrounds (Cip's talk)
- Dipole field specification – depends somewhat on some of the things above
- Field measurement system needs
- Continued iteration with JLAB and MIT engineers

Not started
Deprioritized
In progress
Done

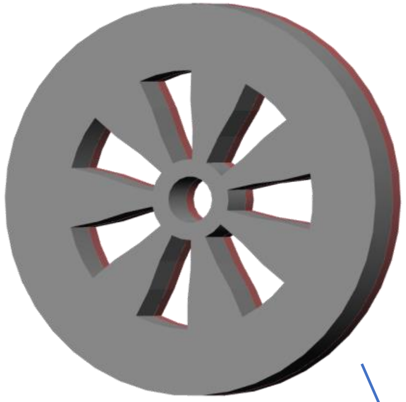
Topics

- Alignment and position tolerances
- Field variation tolerances
- Doses on coil epoxy
  - Upstream
  - downstream

- W collimator leak testing
- Testing downstream window
- …

- Things are gettin’ real, y’all

Open Spectrometer system



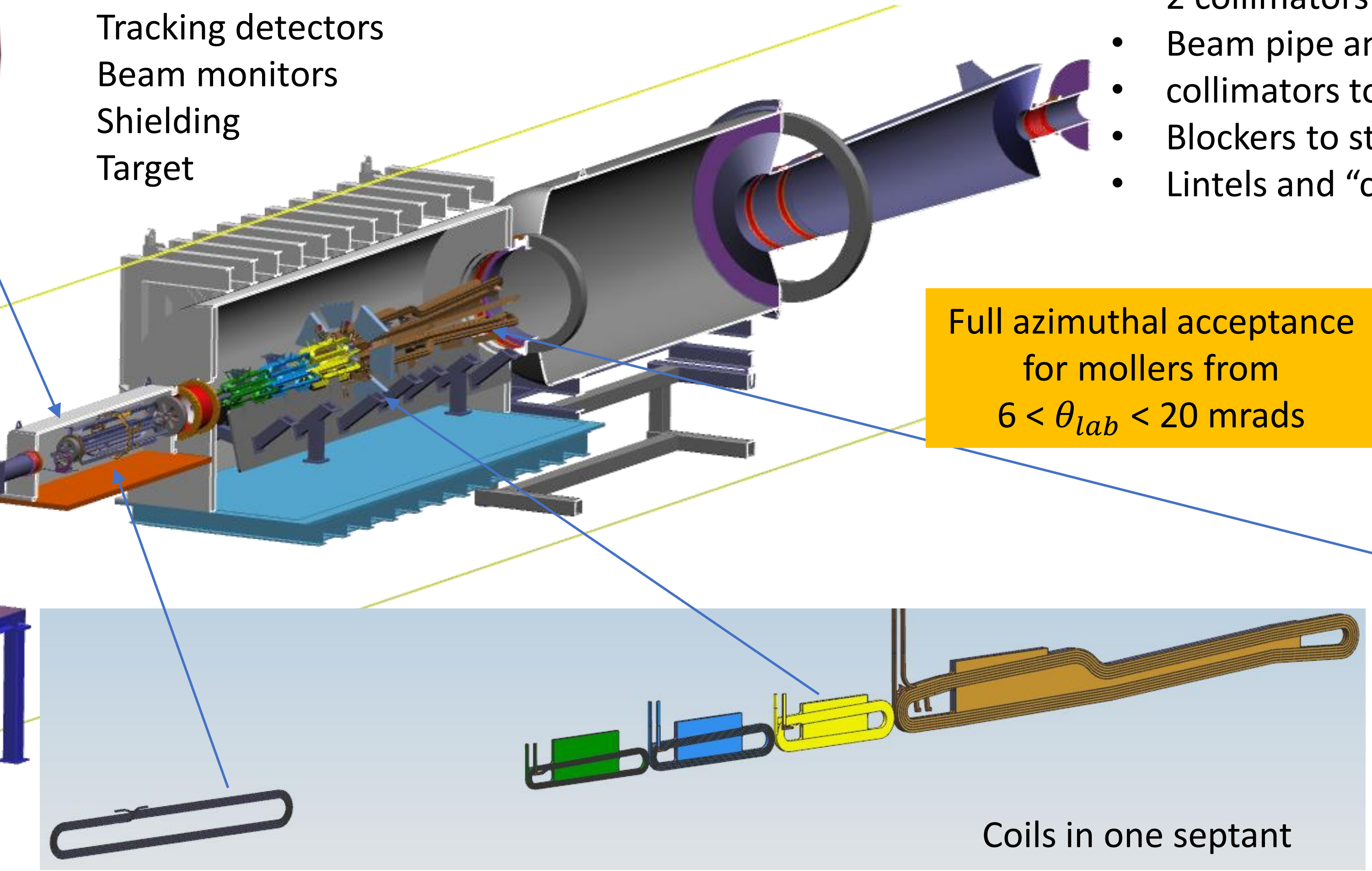
Acceptance defining collimator

Other parts of the experiment

Integrating detectors
Tracking detectors
Beam monitors
Shielding
Target

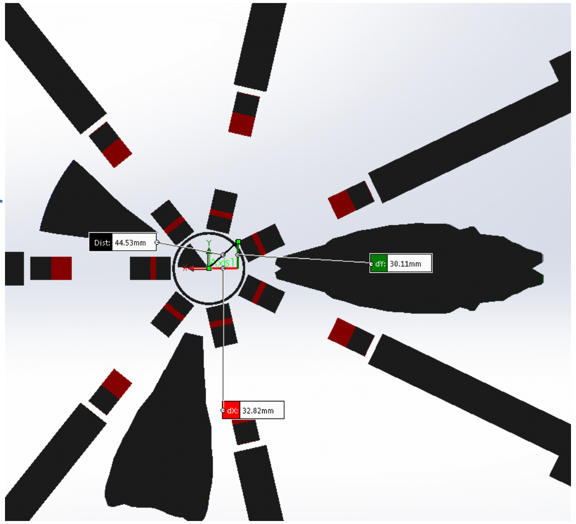
Spectrometer Elements

- Set of resistive toroidal magnets (US and DS)
- 2 collimators to define the acceptances
- Beam pipe and enclosures
- collimators to control backgrounds
- Blockers to study backgrounds
- Lintels and “collars” to shield coils and detectors



Full azimuthal acceptance for mollers from $6 < \theta_{lab} < 20$ mrads

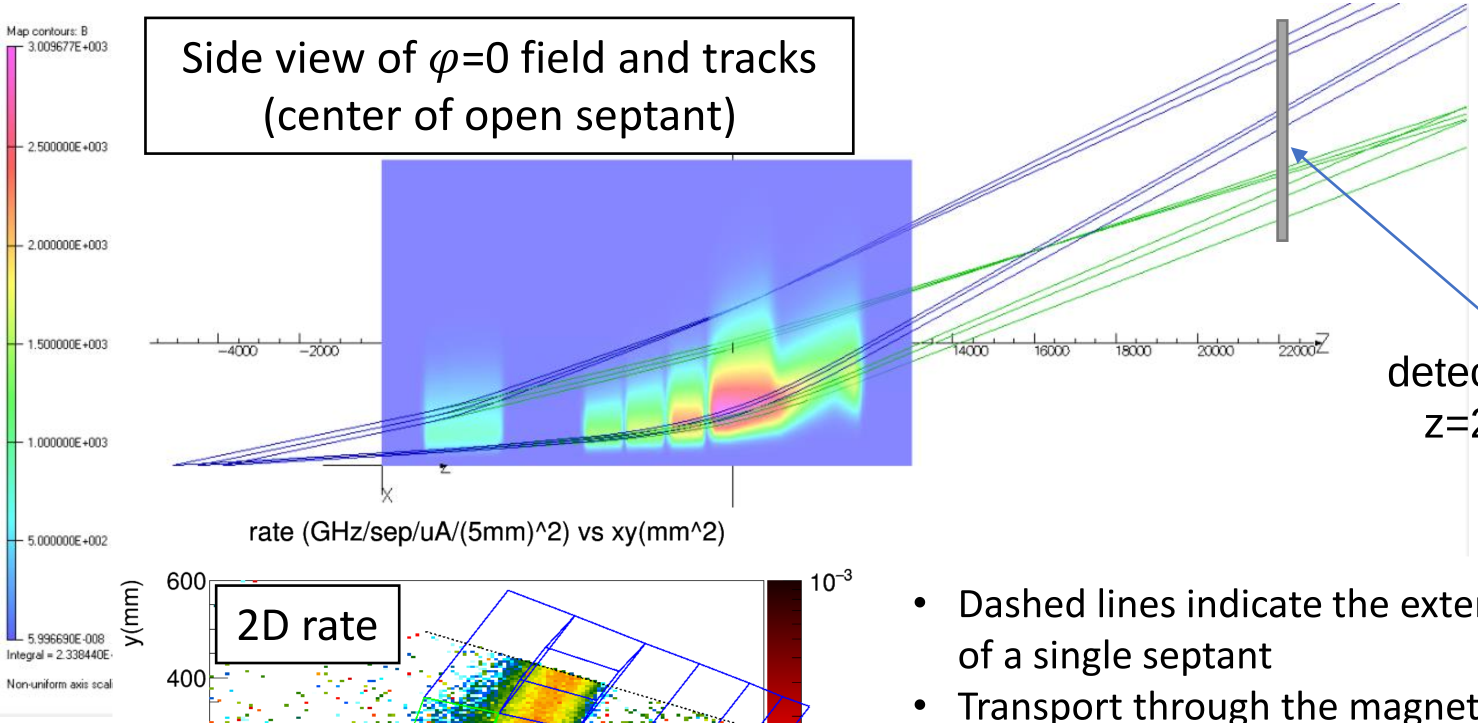
Coils in one septant



particle envelopes along beamline

Jefferson Lab

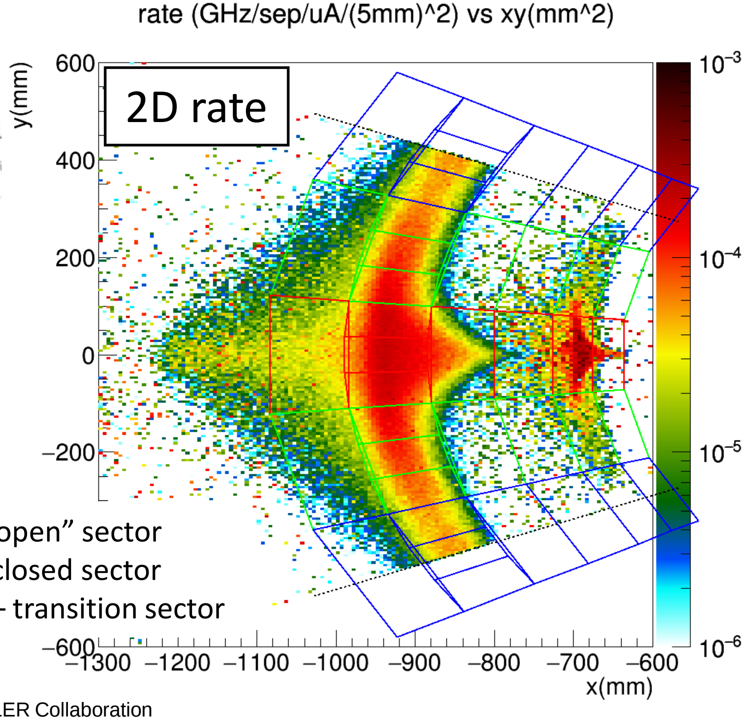
Fields and particle tracks



detector plane
z=2650cm

Tracks are 6 and 21 mrads for both ep and mollers, from 3 different parts of the target

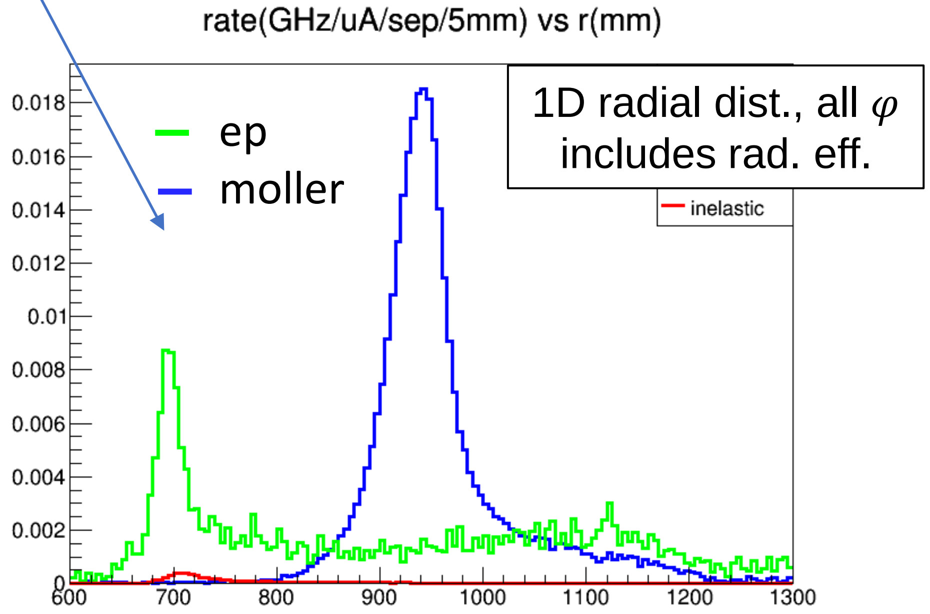
Tracks have energy/angle correlation, but not the radiative effects in the target



Red – “open” sector
Blue – closed sector
Green – transition sector

- Dashed lines indicate the extent of a single septant
- Transport through the magnets causes the moller “envelope” to be azimuthally defocussed
- The add’l segmentation in moller ring allows for monitoring of systematics

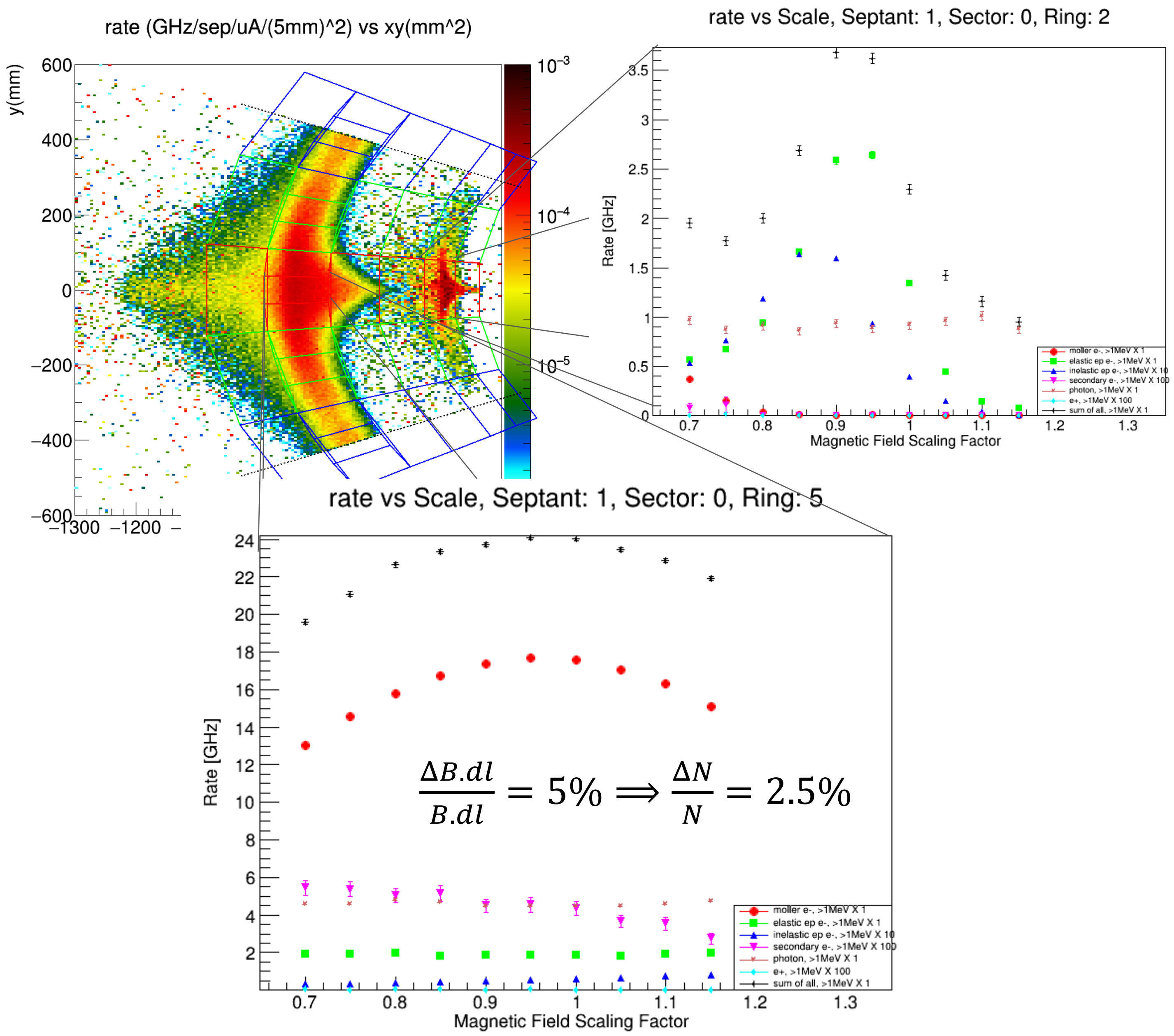
- Require 20% less up to 10% higher current for background determination



Deconvolution

- Although we call the rings moller or ep rings, we actually use more than one ring to determine the moller asymmetry
- We will use the different contributions of the rate and asymmetry for each of the processes in each of the detector tiles to "deconvolute" the asymmetries for each process
- Need measurements to benchmark simulation
  - Tracking system – low current runs
  - Magnet current scans
  - Alternate beam energies?
- Should do further studies to test this procedure to determine if additional systematic measurements are needed
- because the cross-section varies like ~ 1/Q whereas the A_{PV} ~ Q^2

$$\Longrightarrow \frac{\Delta A}{A} = 5\%$$



Tolerance on current variation in PS

A_{PV} ~ 34 ppb ± 0.7 ppb (2%)

Rough estimates of various changes for given $\int \vec{B} \cdot d\vec{\ell}$

Drift in $\int \vec{B} \cdot d\vec{\ell}$	(ppm)	ΔN/N	ΔA/A	Ring Δr (mm)
10^{-4}	100	0.005%	0.01%	0.06
10^{-3}	1000	0.05%	0.1%	0.6
10^{-2}	10000	0.5%	1%	6

our specification for individual detector tile placement is +/- 0.5 mm and the main ring 5 tile has an extent of 160 mm in the radial dimension

If $\int \vec{B} \cdot d\vec{\ell}$ drifts, we would know from tracking runs

How does this affect the Q^2 calibration?

In order to extract the weak charge, we need to know the Q^2

$$A_{PV} = K Q_W^e \langle Q \rangle^2$$

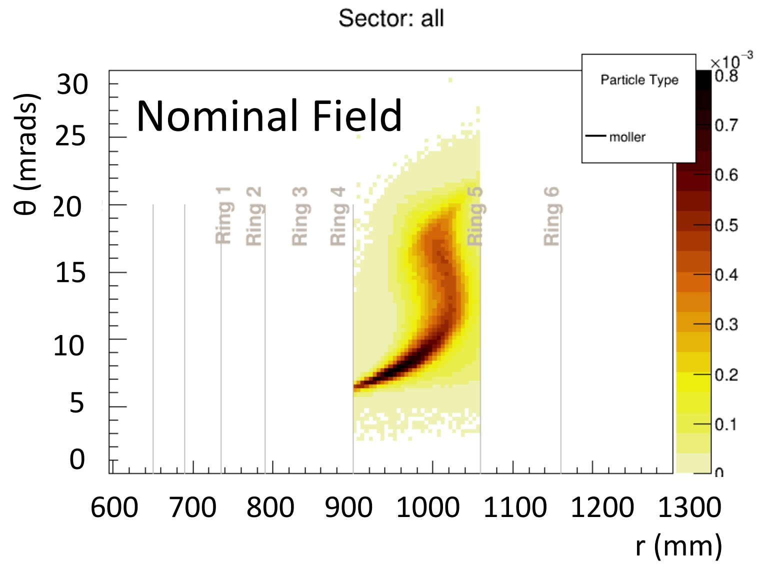
Our error budget for the absolute calibration uncertainty on Q^2 is 0.5%

Q^2 depends on geometrical acceptance, radiative corrections in addition to the spectrometer optics

Confident we can handle ±500 ppm

Need a full deconvolution analysis for 10^{-3}
in parallel with tiling of the main detector array

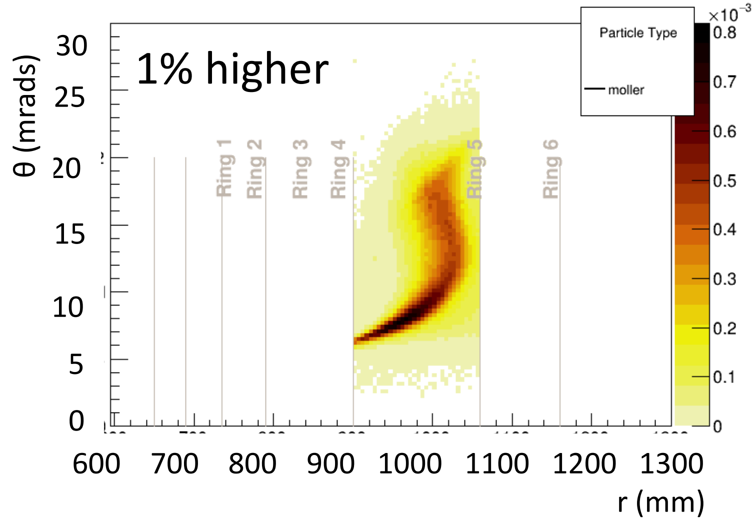
Field Variation Study

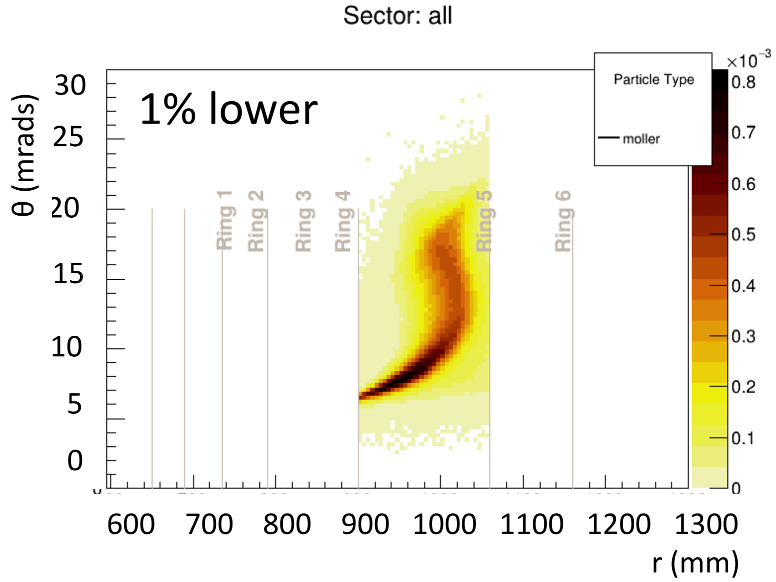


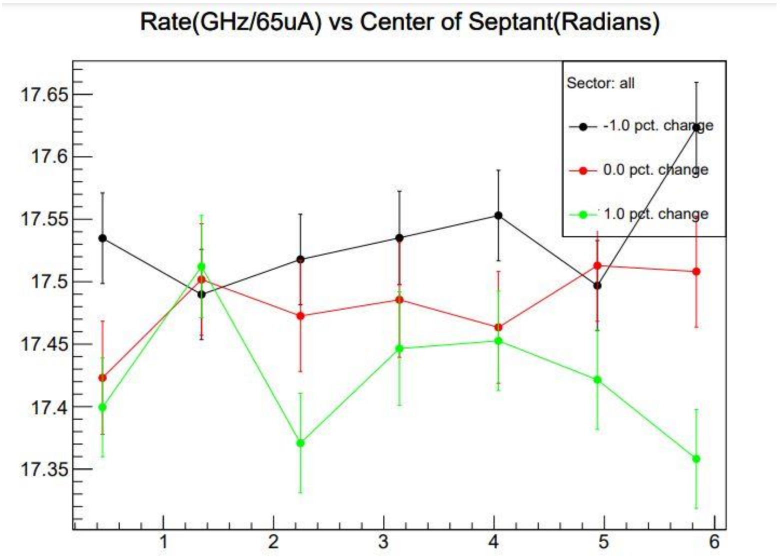
Variation in PS current is linear with field variation

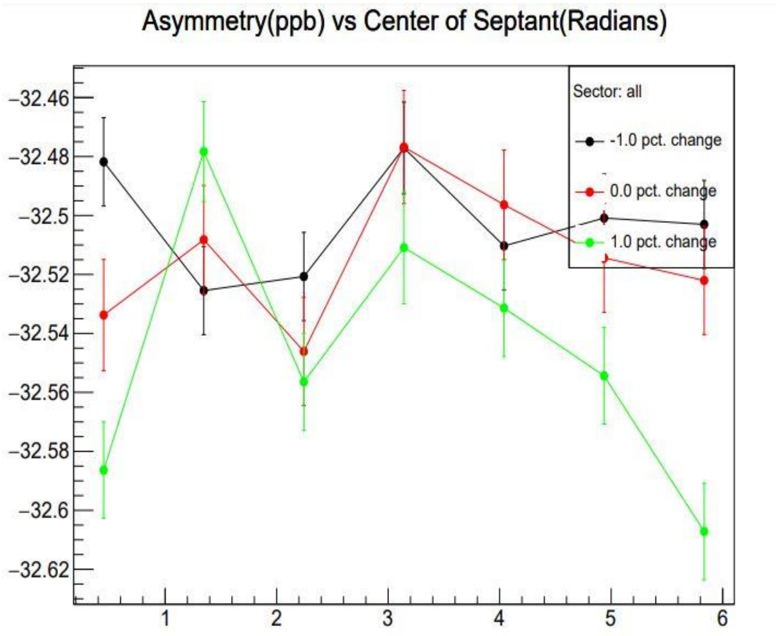
Looked at the effect of field variations ±1%

Need more stats for smaller variations







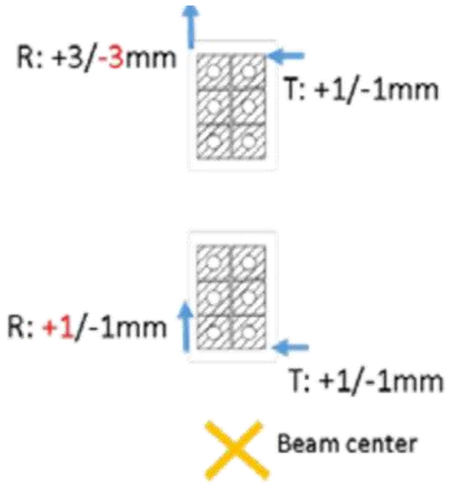


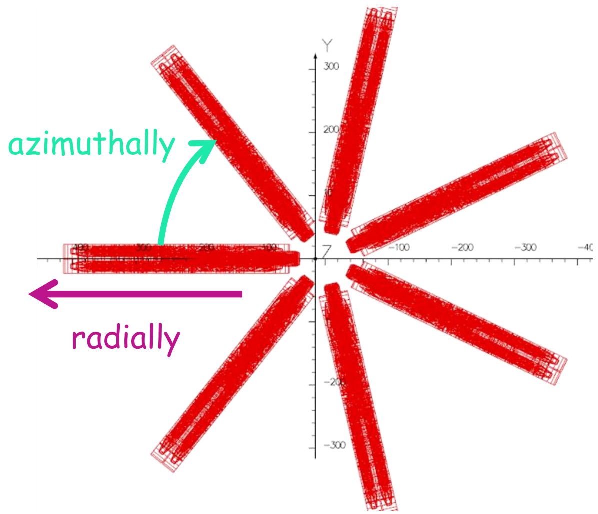
Alignment tolerances

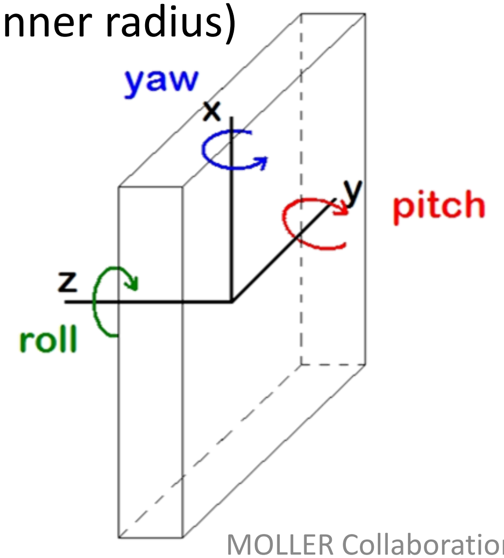
- Tolerances determined by single coil/single offset studies have been verified with "worst-case" multiple coil/multiple offsets within the specified tolerances
- Considerations
  - physics optics (ability to "deconvolute" the asymmetries with desired uncertainty)
    - signal electron focal plane distributions
    - backgrounds
  - clearance with the scattered particle envelopes
  - clean transport to the dump
  - doses on coils (epoxy, especially at inner radius)

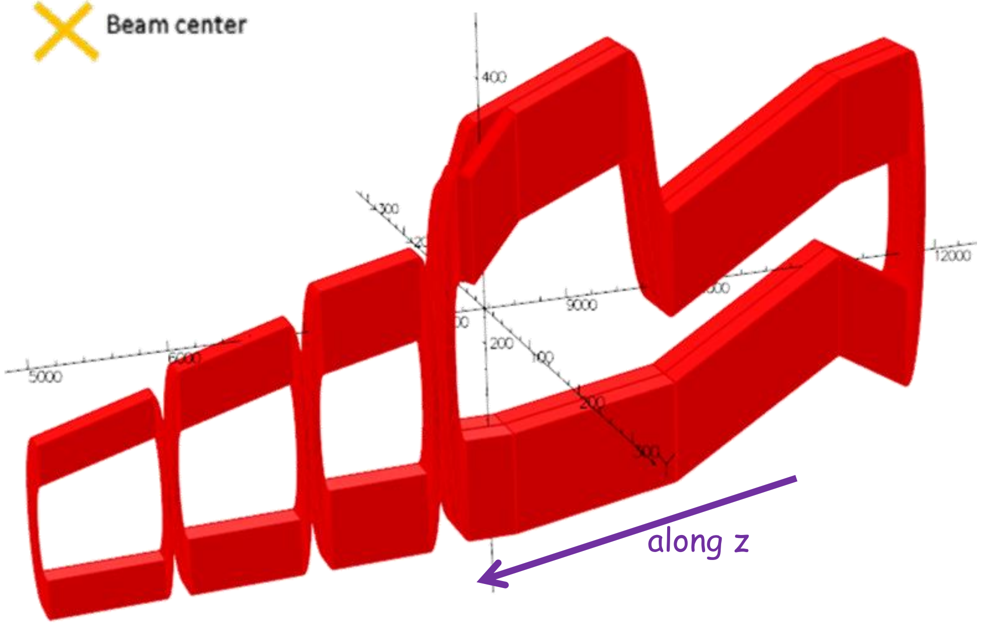
Physics worst case
All coils offset in same direction (without us knowing)
- Least likely (survey, tracking)
- Relatively insensitive

single coil/ single offset tolerances

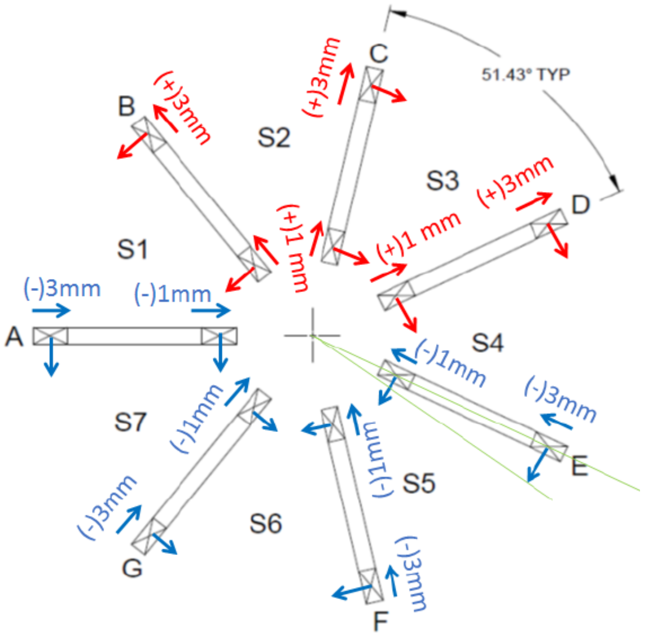




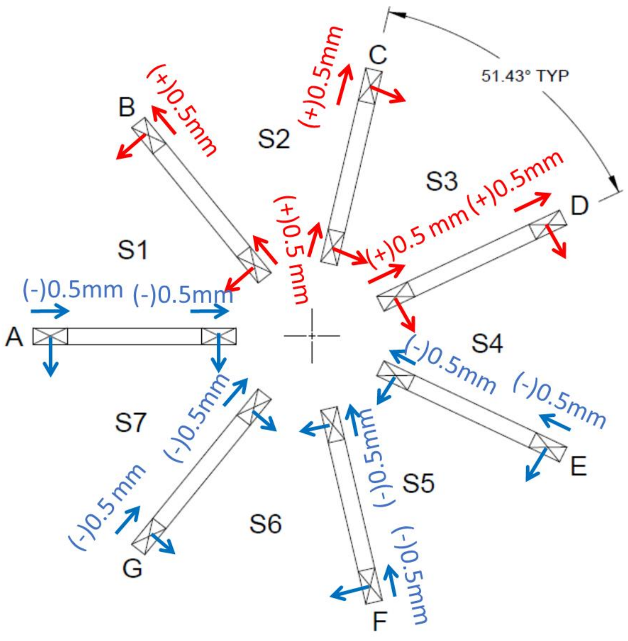




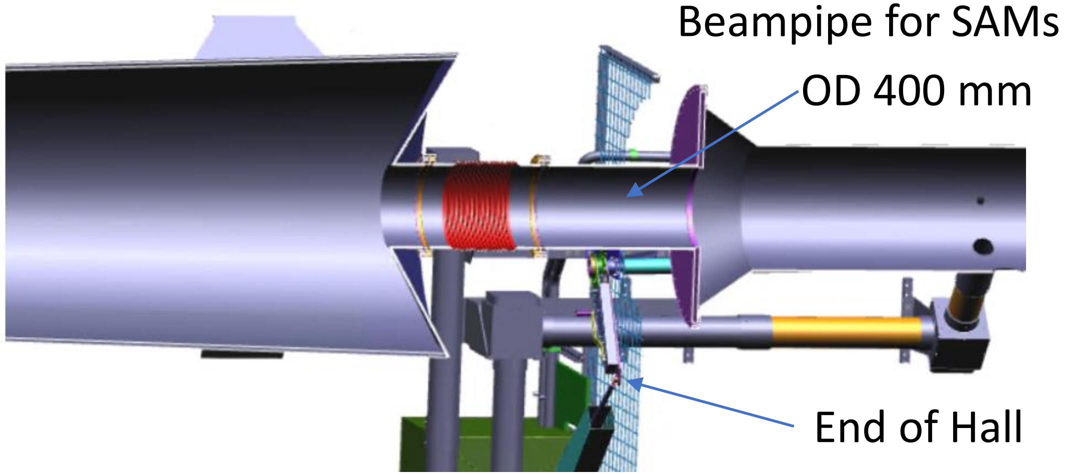
Alignment Tolerance Cases



CASE 1



CASE 2 and 3



BEAM worst case is coils aligned in a "conspiratorial" way within tolerances

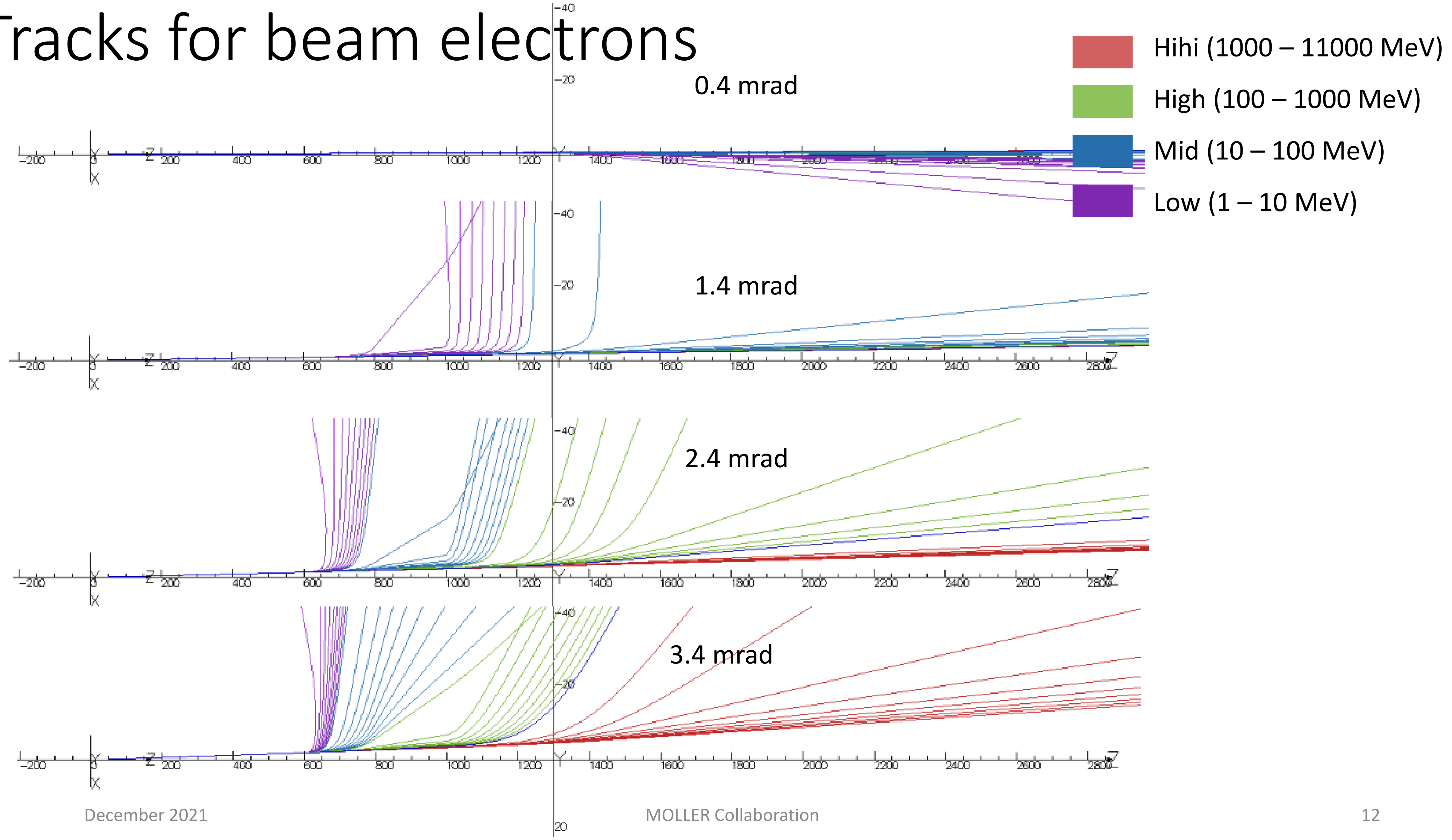
→ induces dipole

- affects beamline shielding (dose on coils)
- backgrounds from end of hall apertures
- Irradiation

Several offset cases considered:

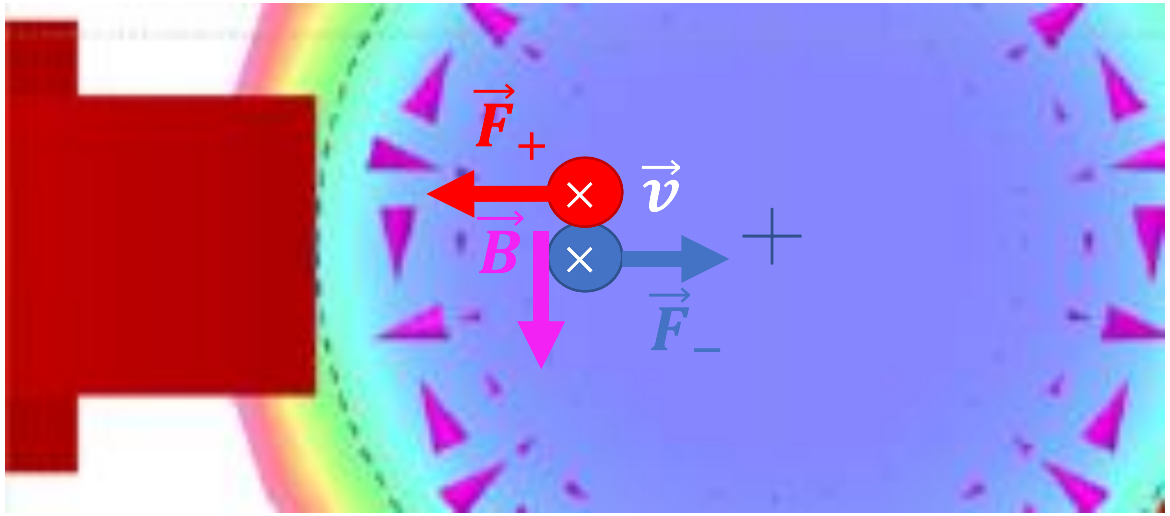
1. All sub-coils offset in same direction to induce maximum dipole within allowed tolerances, including deformations.
2. All subcoils offset without deformation and to ±0.5 mm
3. Same as case 2, but dipole field has different orientations in each subcoil

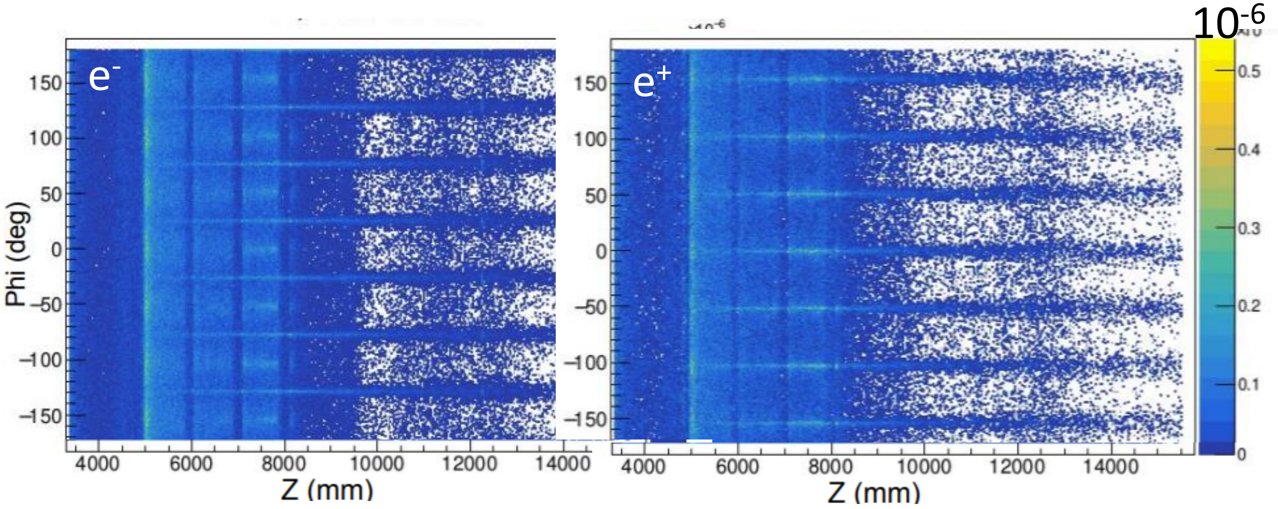
Tracks for beam electrons



Stray fields in beampipe deflect $e^{\pm}$

Looking downstream



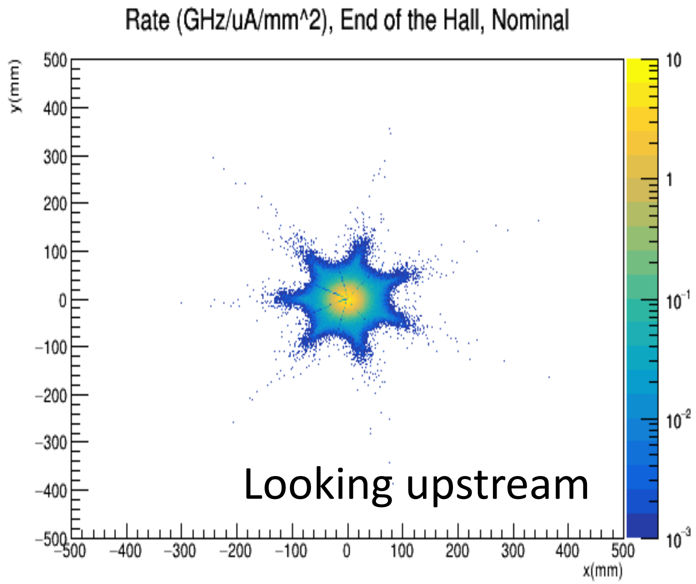


Consider the horizontal coil, in the perfectly symmetric case

- all velocity in the z-direction
- field is vertical along the x axis, (mid-plane of coil)

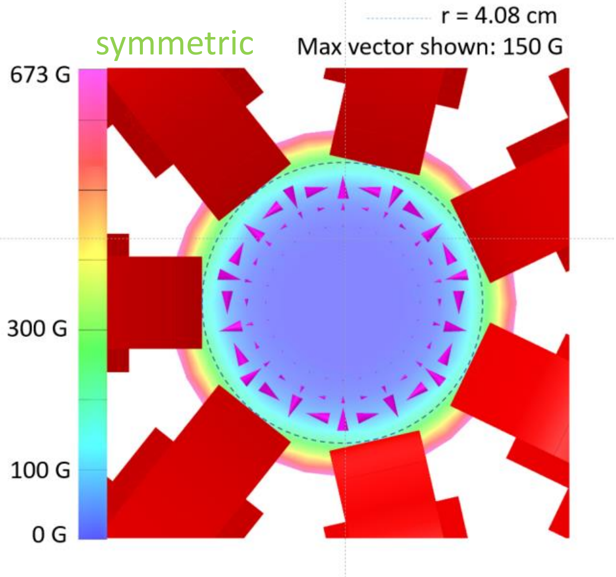
- e^- will be bent to the right
- e^+ will be bent to the left (onto the coil)

- just off the axis,
    - the field direction is dramatically different
    - $e^{\pm}$ would feel both horizontal and vertical components of force
    - dispersed

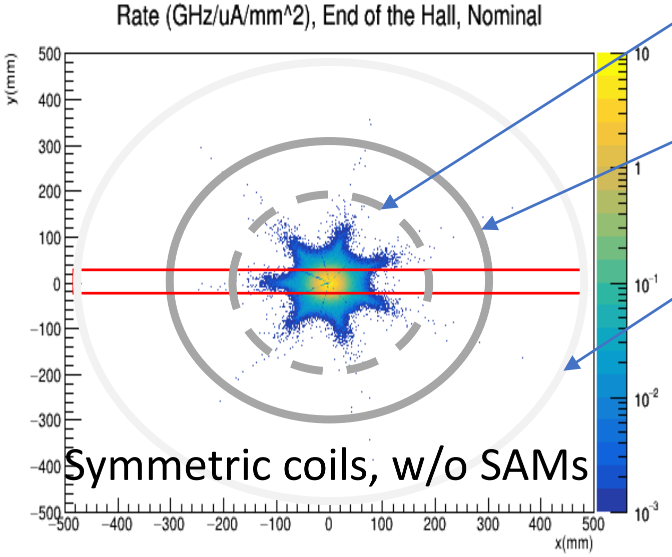


Beam backgrounds - nominal (symmetric) case

Looking downstream



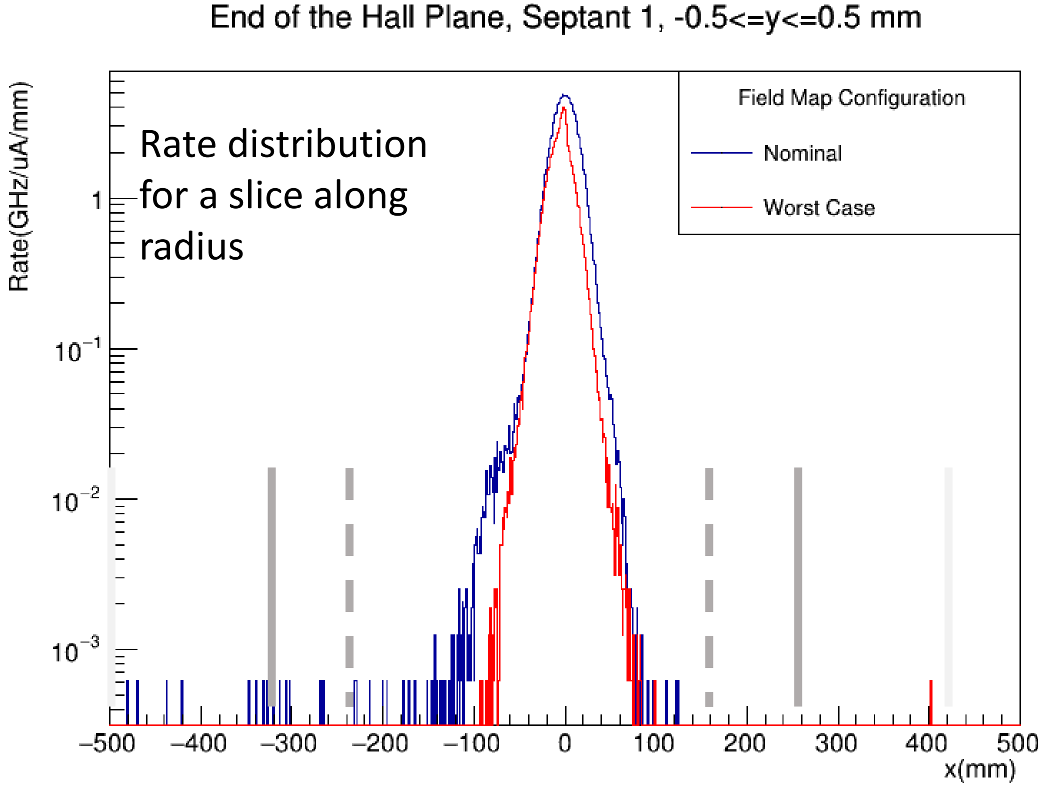
Looking upstream



Beampipe intrusion for the SAMs
(~0.5m upstream)

Limiting aperture in dump tunnel
(~0.5 m downstream)

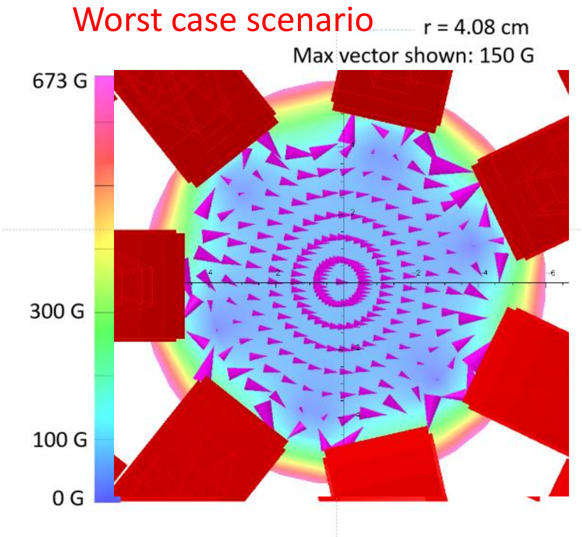
Dump entrance flange
(same z location as plots)



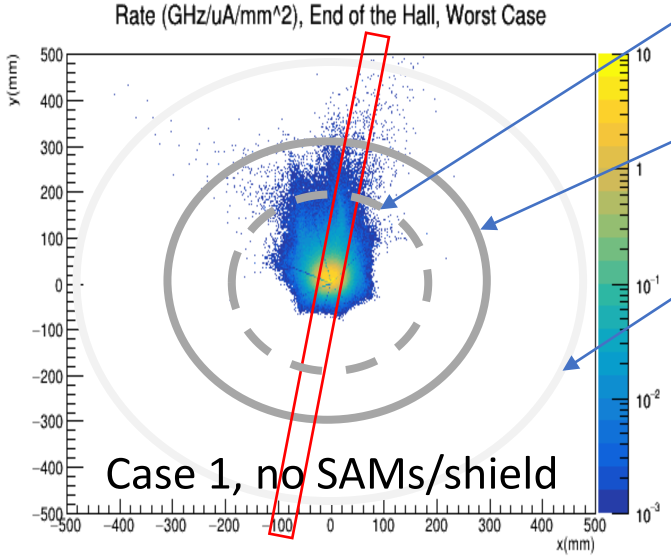
- In the top left plot you see a picture of the ds coils at a particular z location with the magnetic field contours and vectors
- Middle top plot is a 2D rate distribution at the entrance to the dump tunnel
- To the right is a 1D distribution of the rate in horizontal septant (1); the vertical lines indicate the radius of various apertures

Beam backgrounds - worst case

Looking downstream



Looking upstream



Beampipe intrusion for the SAMs
(~0.5m upstream)

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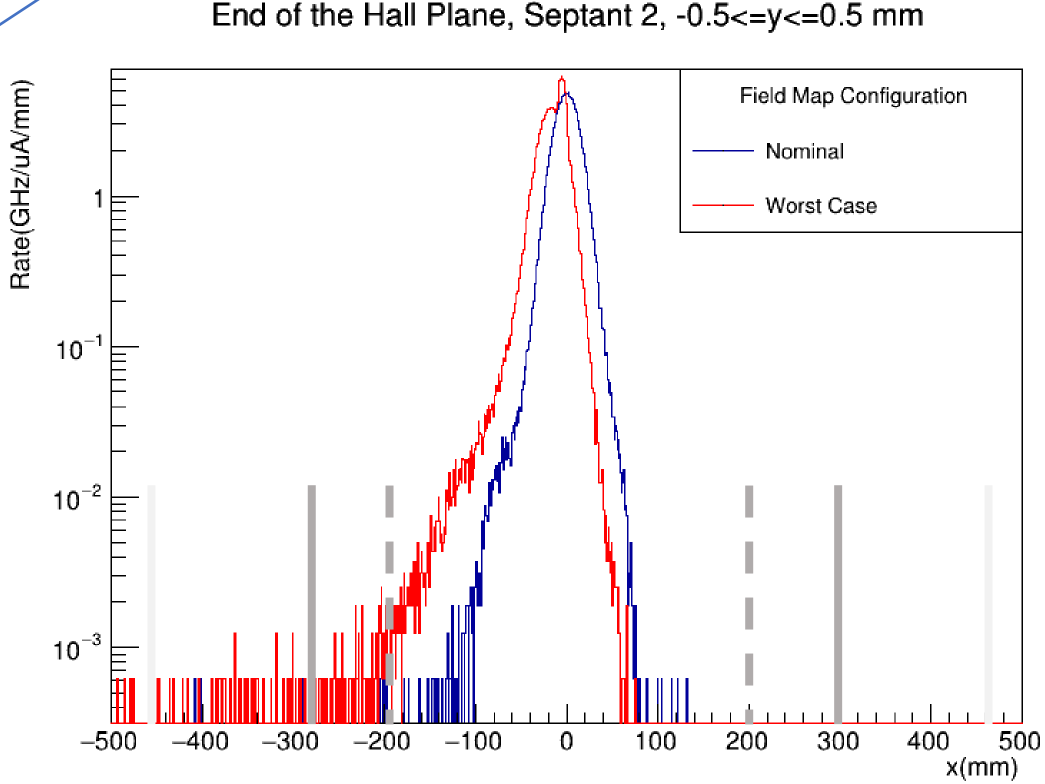
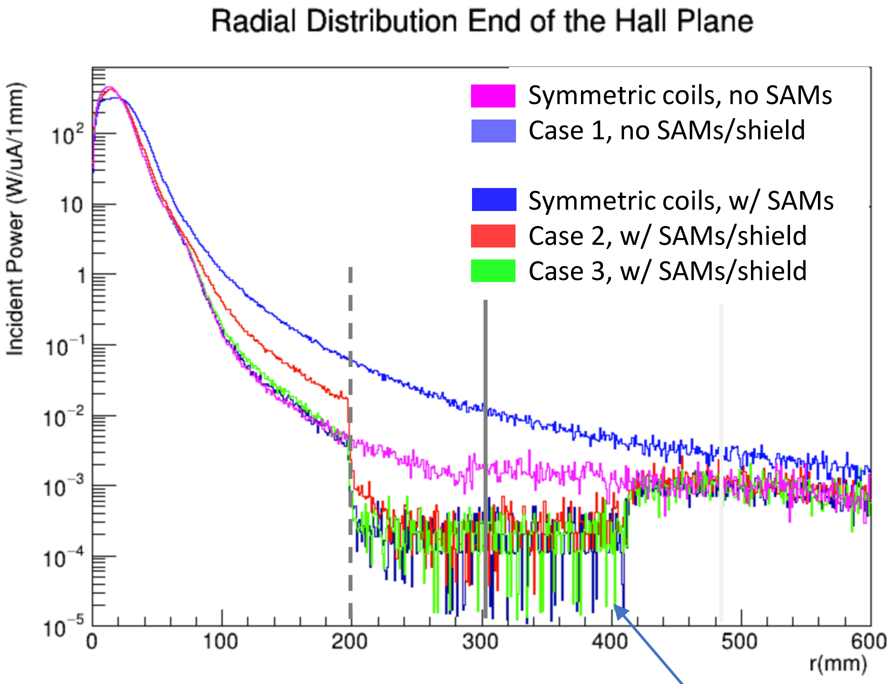
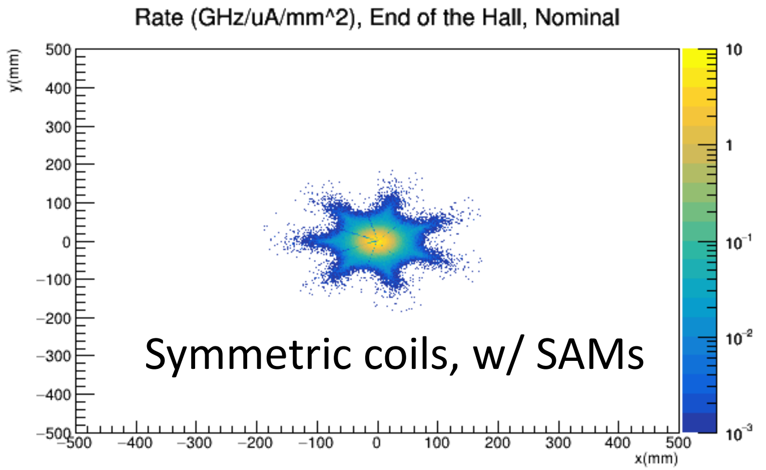
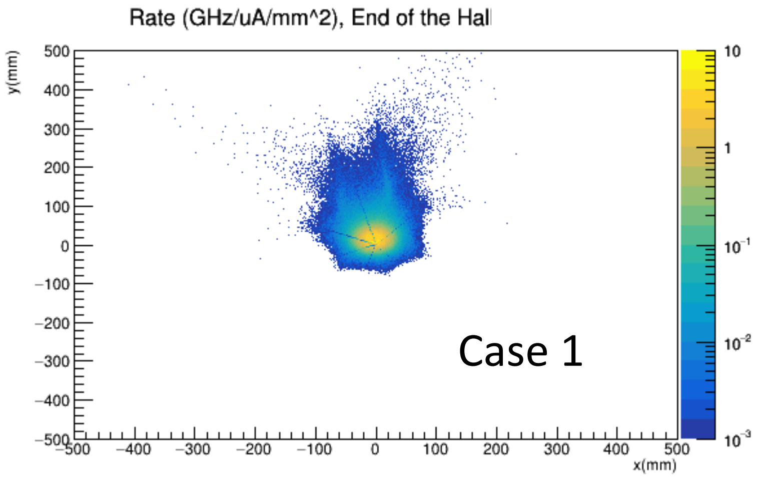


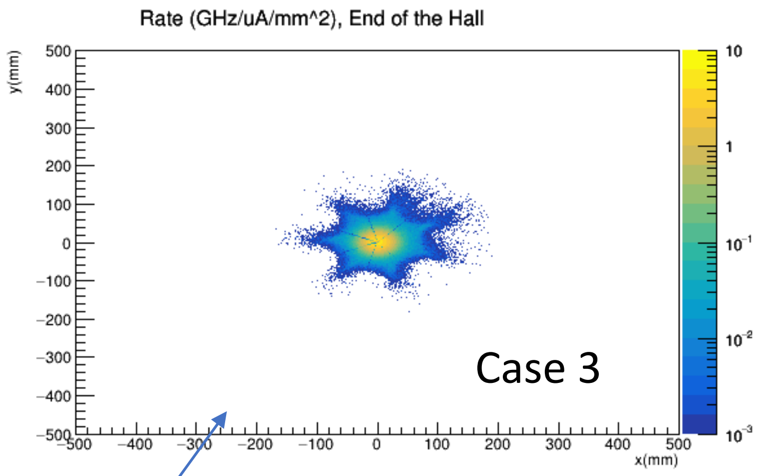
- In the top left plot in the worst case scenario there is an induced dipole field > 100 G over most of the area inside the coils
- In this particular orientation, the electrons are bent upward into septant 2
- To the right is a 1D distribution of the rate in the worst septant (2); even in the worst-case scenario the beam is mostly clearing

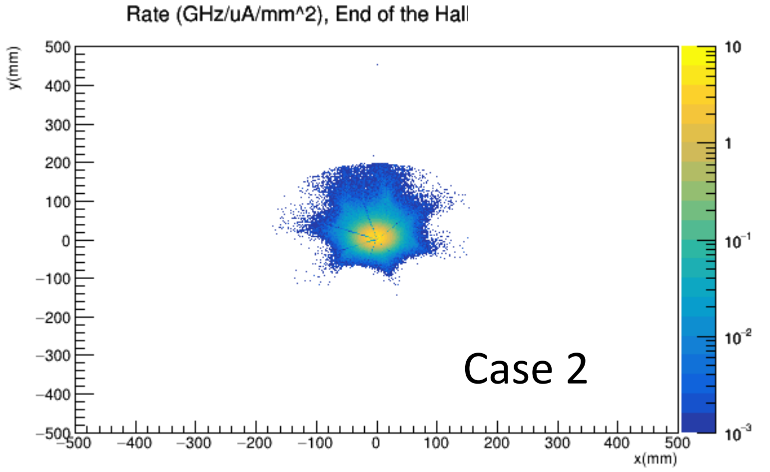
Comparison of cases











Total Beam Power 715 kW

Integrated Power from 200 mm < r < 600 mm

Symmetric coils, no SAMs	38.1 W
Case 1, no SAMs/shield	260 W
Symmetric coils, w/ SAMs	13.4 W
Case 2, w/ SAMs/shield	17.8 W
Case 3, w/ SAMs/shield	14.2 W

Most likely

worst case is 10^{-4} of total beam power
order of magnitude lower for most likely case

Estimates of tolerable doses on epoxy

- Initially, Ruben estimated a max dose of 70 MGy with a 15% reduction in the shear strength of the epoxy
- Unfortunately the irradiations were done at very low temperatures, with thermal cycling
- Depending on how you extrapolate over the doses and the temperatures, there is a large range of allowable doses
- Initially trying to achieve a factor of 2x smaller than the 70 MGy, or 35 MGy
- With older geometry had managed to achieve 37 MGy

- After changes to the upstream collimators, re-evaluation of the hot spot with simply adding a shield plate+wedge results in a dose of 70 MGy

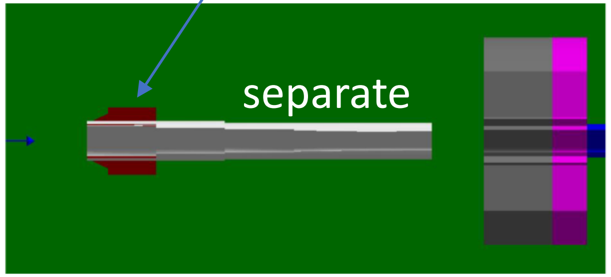
Collimators/ coil shielding

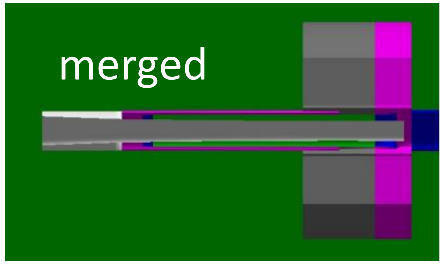
Upstream region

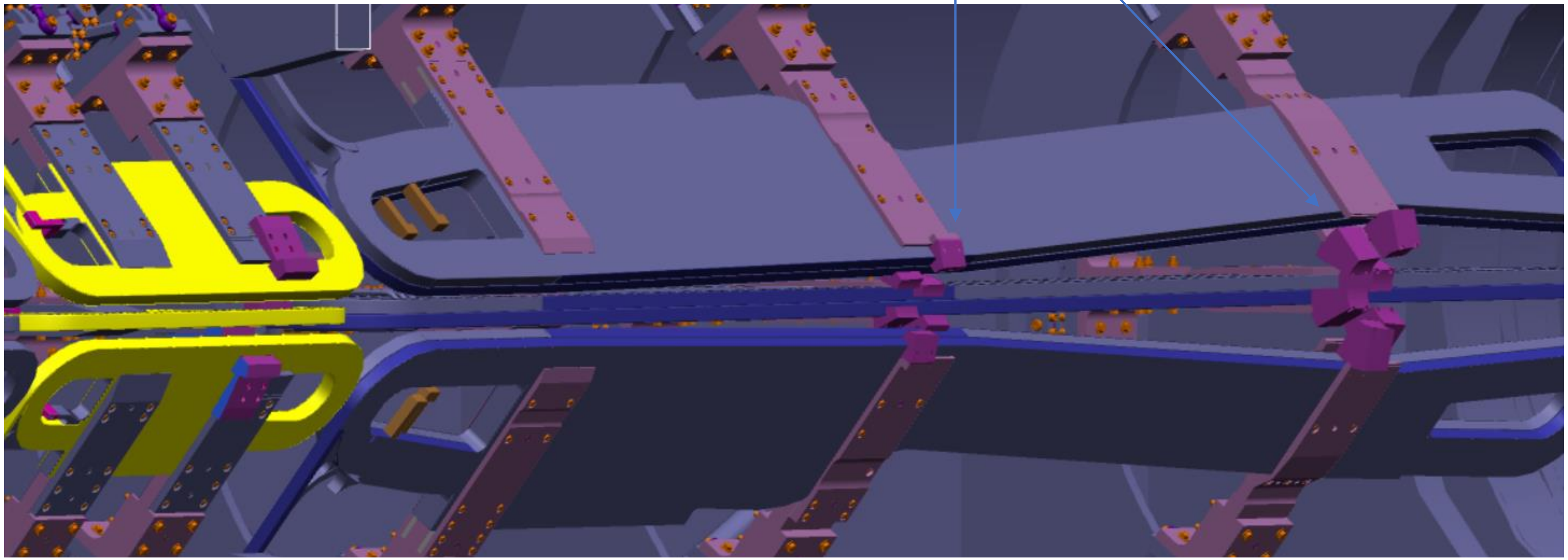
- cols 1+2 merged
- eliminate fins (were a source of dose on the us coil)
- Upstream region shielding (wedges and 2-bounce)

Downstream region

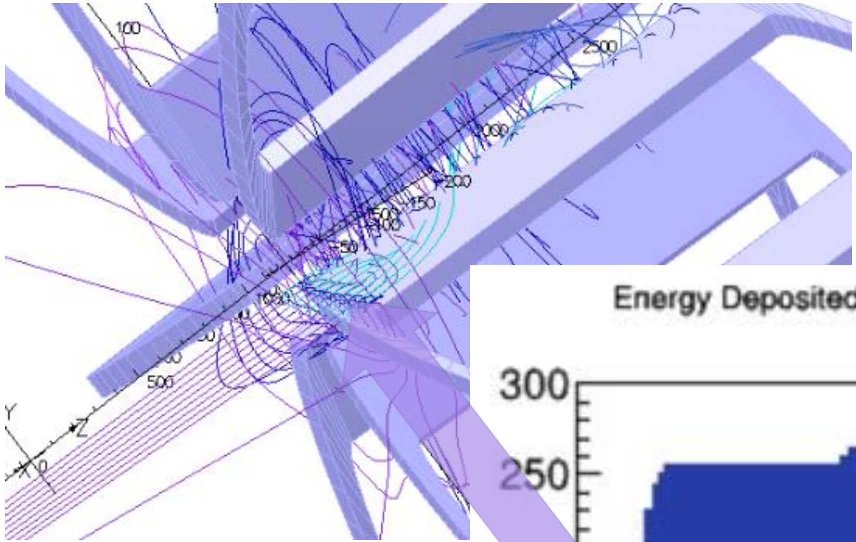
- sculpt coll4, adjust coll 5,6
- use the bulkheads to support the lintels and collimators
- split collimator 6 ⇒ 6 a, b







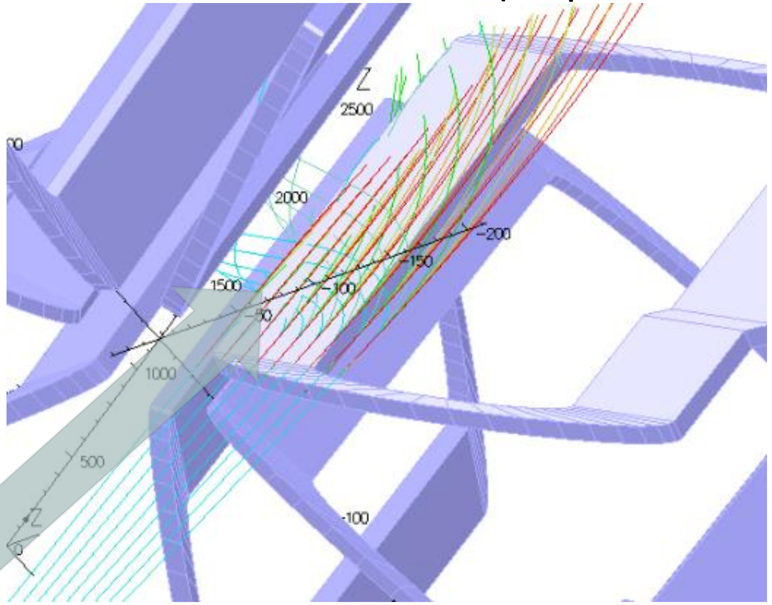
Doses on the epoxy in US torus



Colored by energy (MeV)
0.1 purple
50 cyan
300 green
700 orange
1100 red

$\phi = 12°$
$6 < \theta < 22$ mrad
(steps of 2)

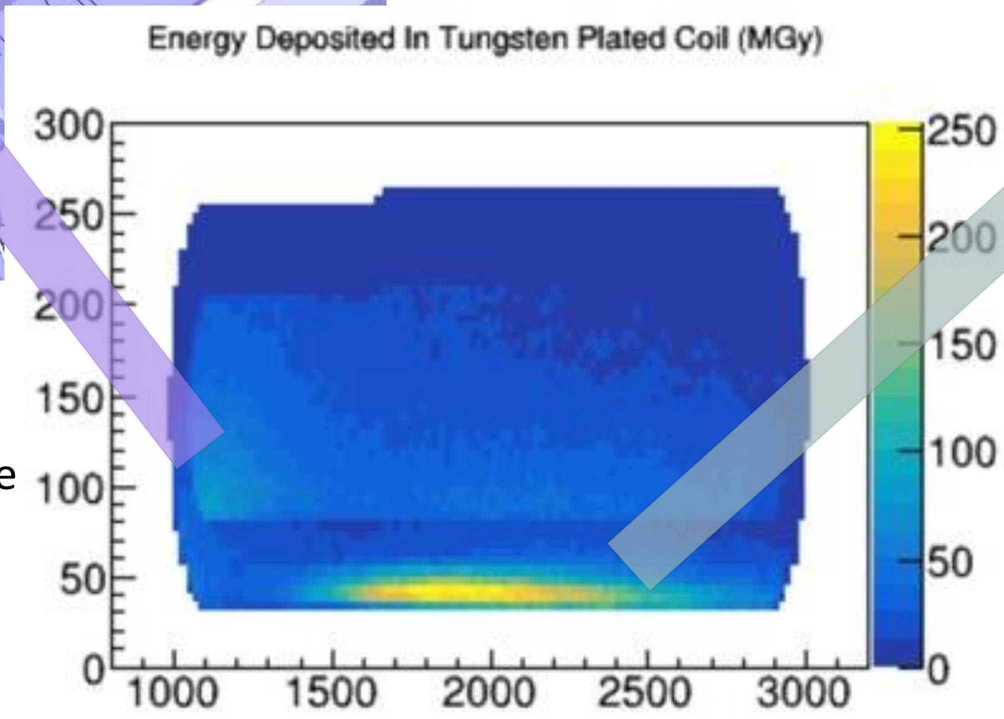
50 < E < 1100 MeV (steps 200 MeV > 100)



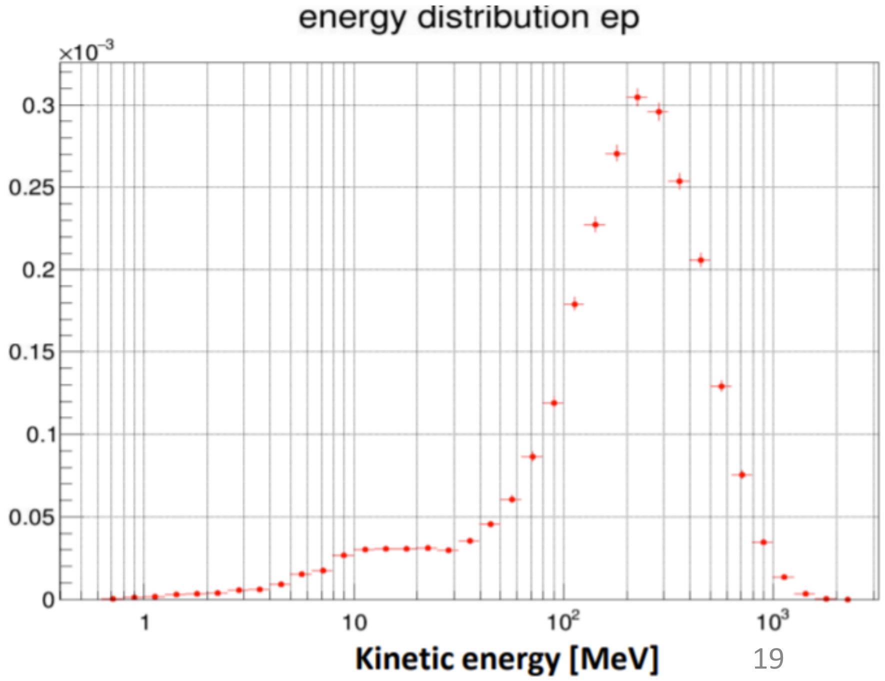
E = 0.1, 1, 10, 50 MeV

lowest energy e^+ bent immediately into the nose

higher energy e^+ bent in stripe near the bottom

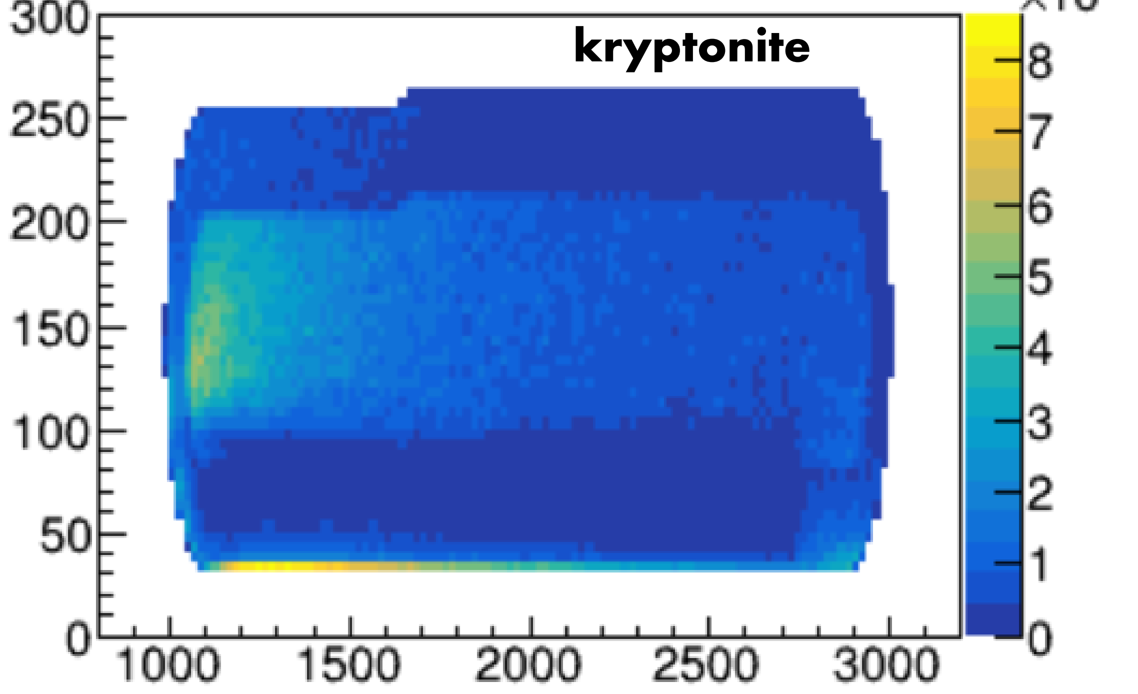


with no shielding on the side of the coils, the highest dose on the upstream torus is **250 MGy** over the lifetime of the experiment



Comparison of the Kx and W plate+wedges

Power Deposited in the Epoxy (W/μA/(5x20x2)mm³)



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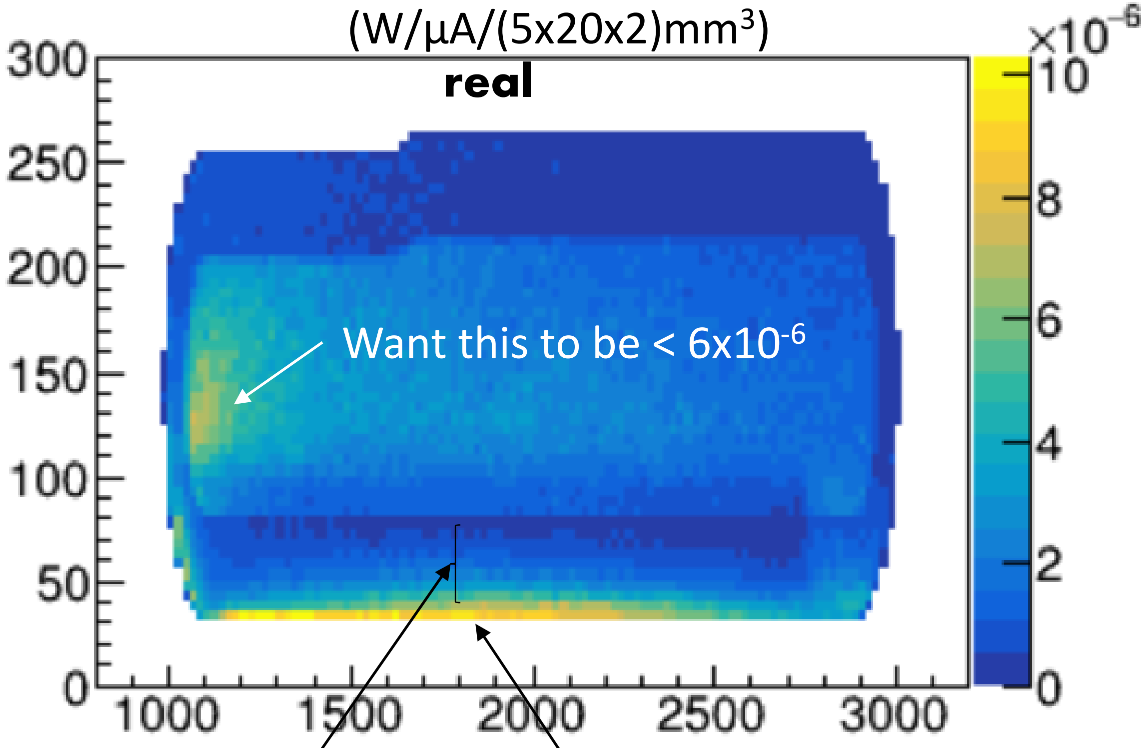


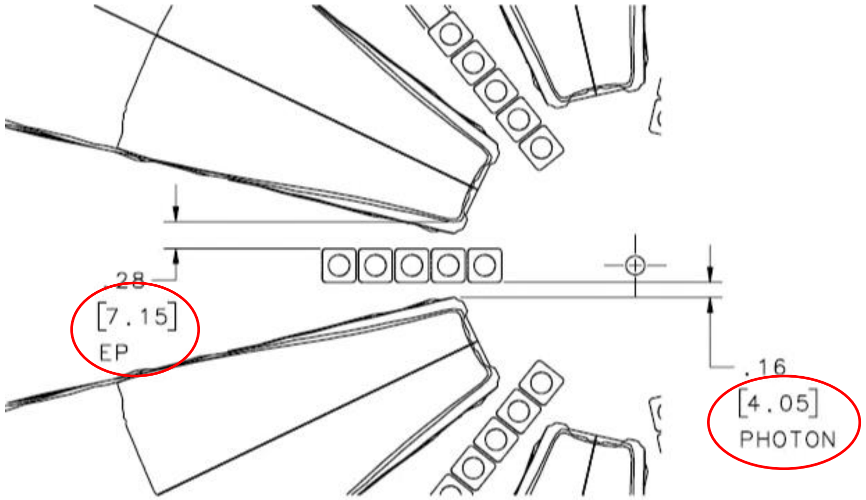
Want this to be < 5×10^{-6}

Want this to be < 25×10^{-6}

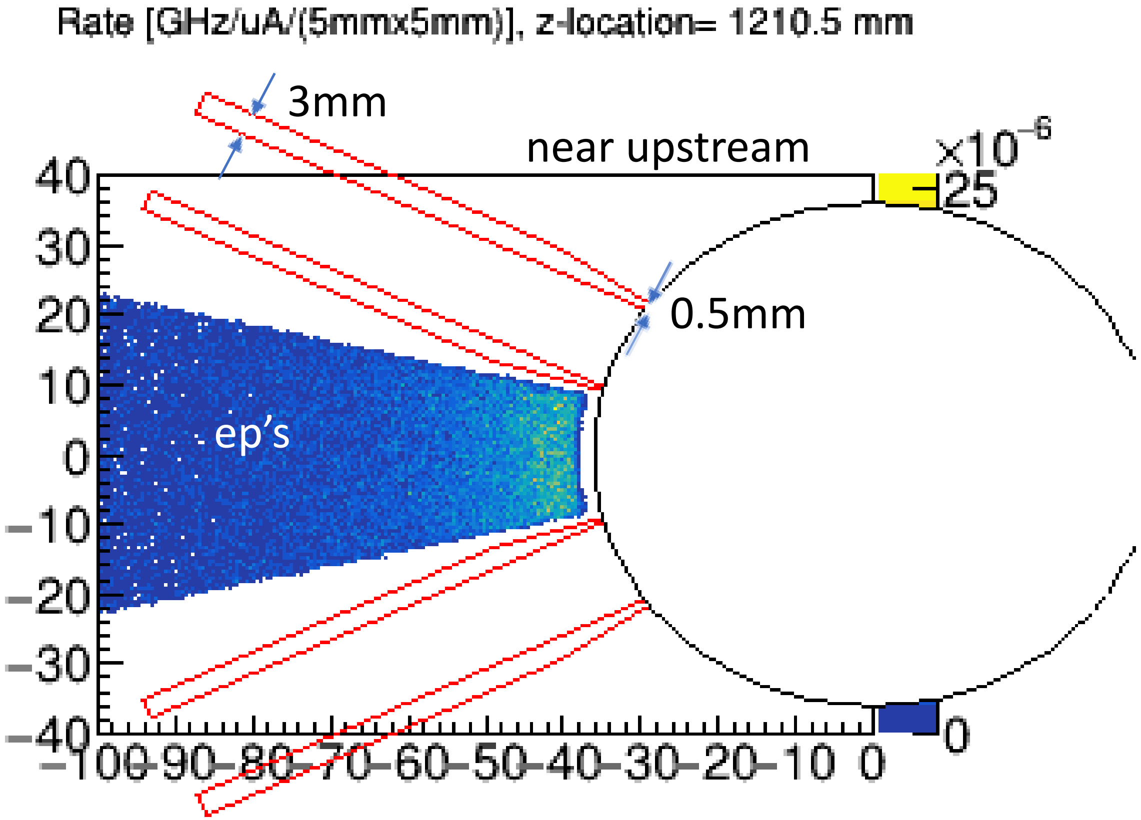
Based on this, we think there is still some dose originating from the beamline, but also still a significant amount through the side

Plate+wedge shield for us torus

Downstream end



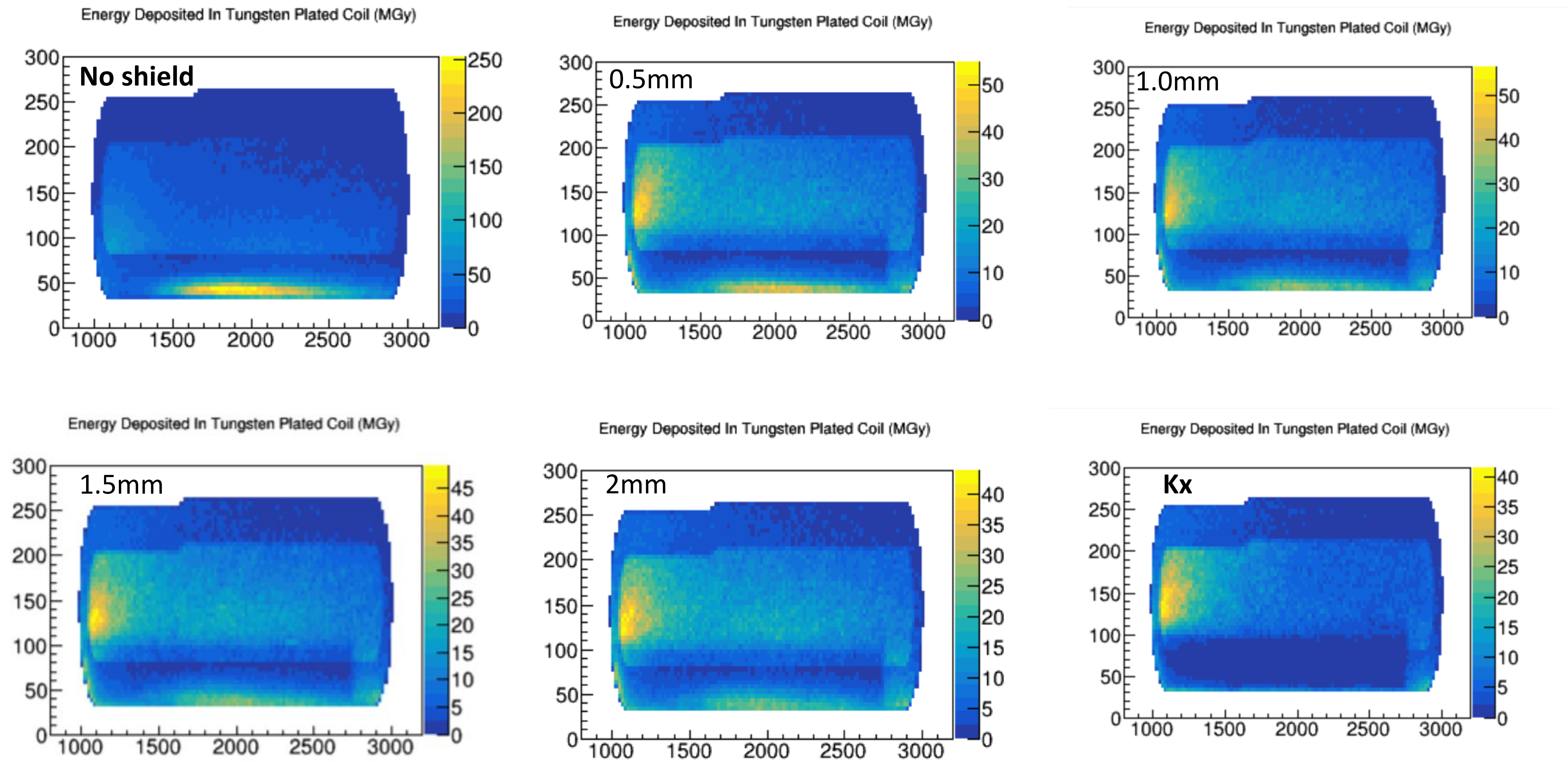
	Value (mm)
conductor thickness	9
epoxy thickness	1
alignment tolerance	1
clearance	1.2
flatness/sag	0.5
keystoning	0.2
Total beyond cond.:	3.9



gain some space as you go downstream, but where we need it is upstream

can increase the thickness if you make the conductor thinner – is it worth it?

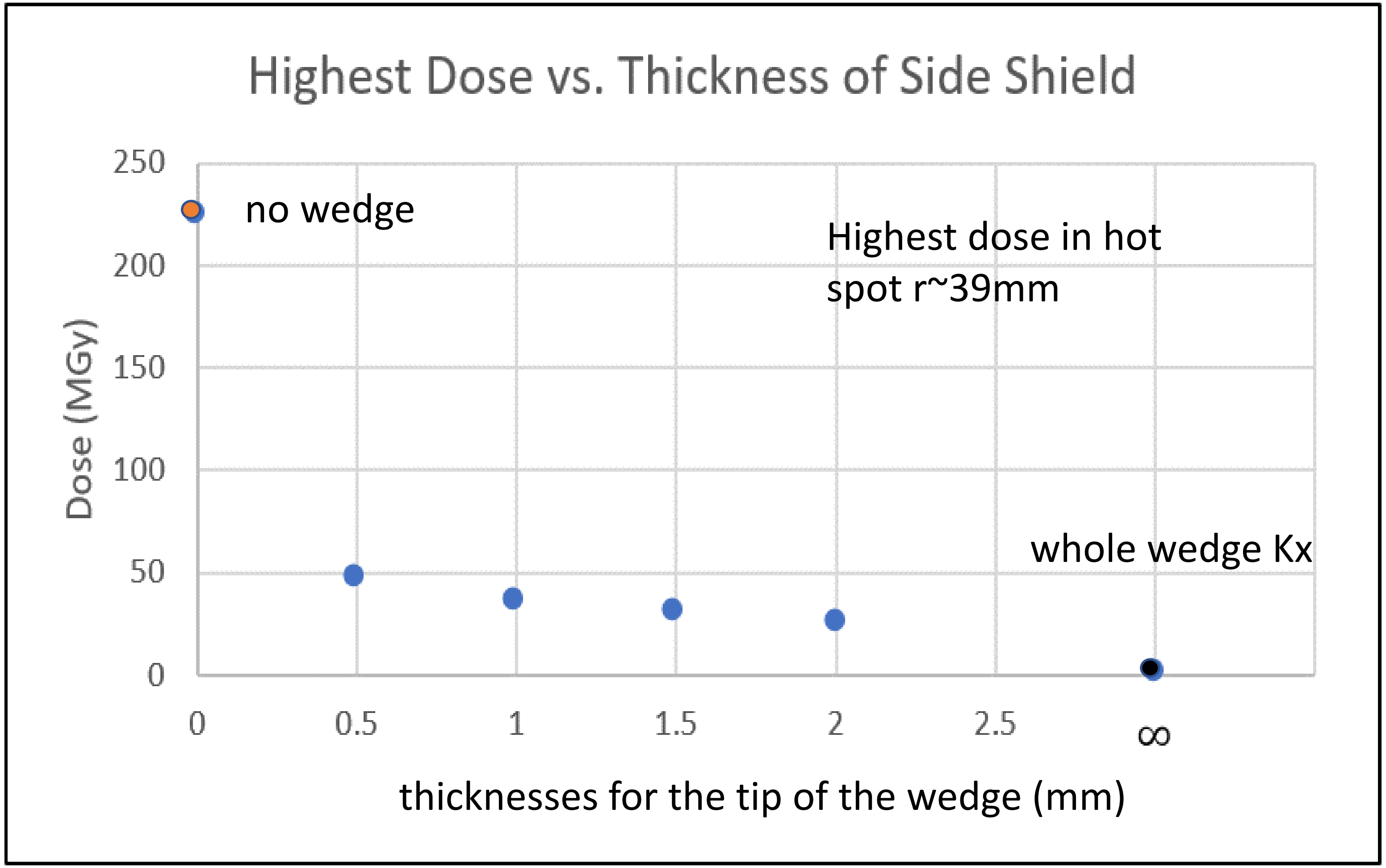
Comparison of wedge tip thicknesses

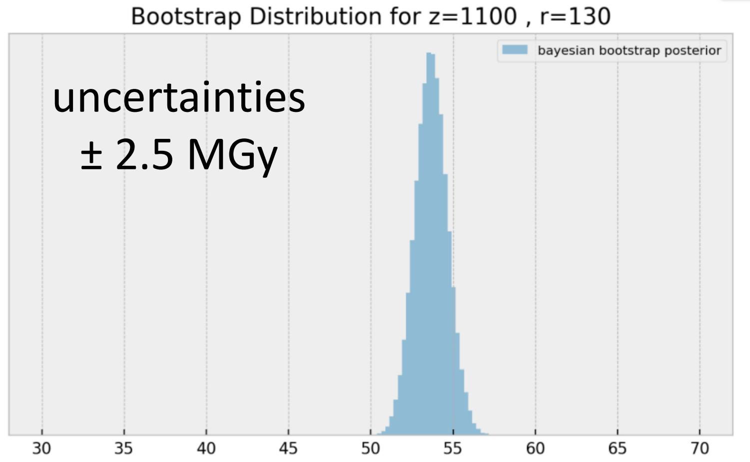


Doses as a function of wedge tip thickness

- Doses from no shield (orange) to kryptonite (black)
- Blue points are showing the effect of the shield with different thicknesses for the tip of the wedge

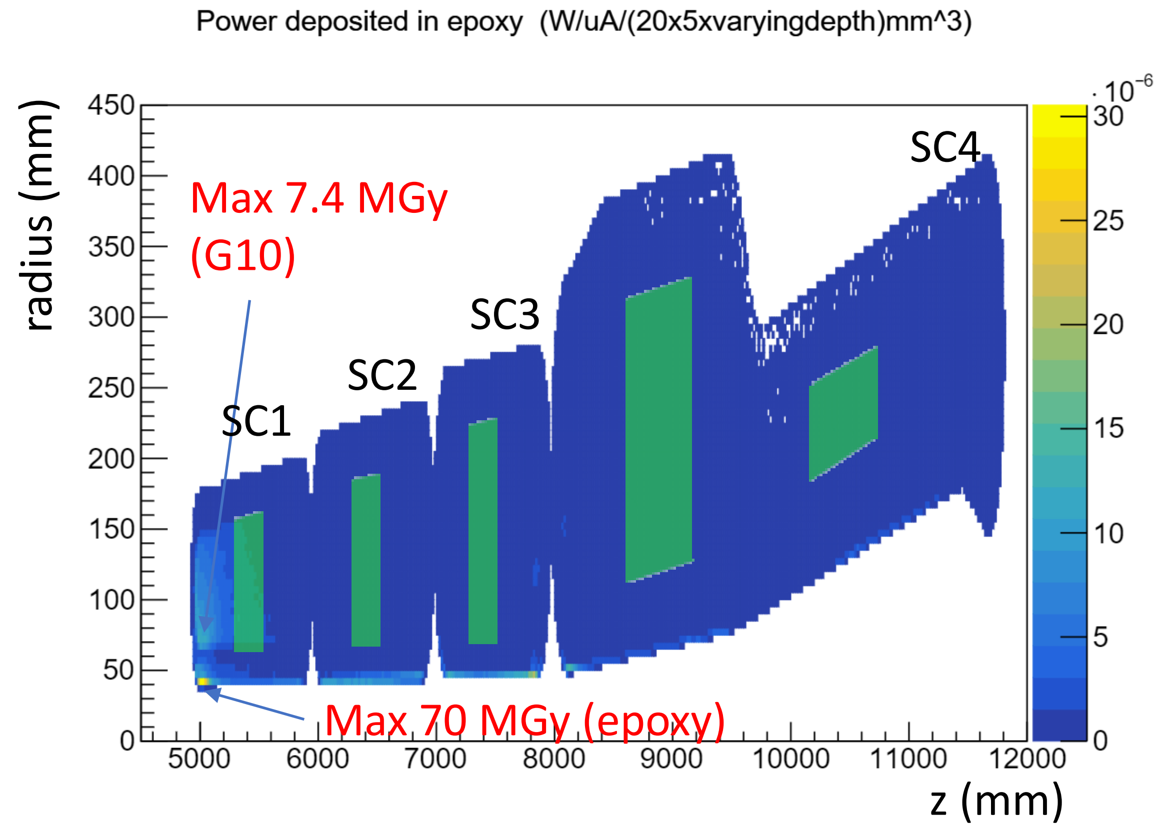
- Plan to add additional points for the tip thickness (0 and 0.25 mm)





In order to have room for the thicker wedge tip, the conductor is thinner (9mm nominal, then 8, 7, 6 mm) to make room on both sides

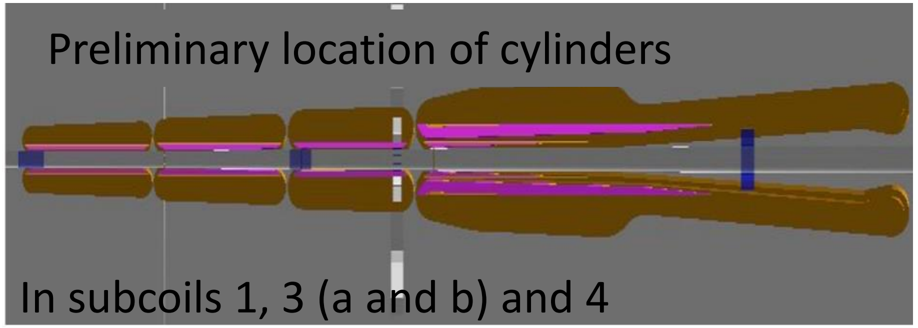
Power deposition in the epoxy – doses



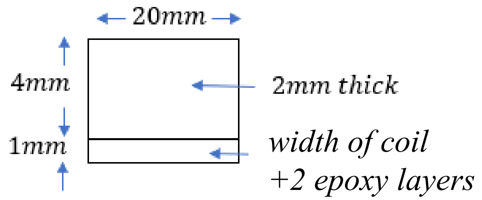
The power deposition in the epoxy (plot to the upper left) is calculated in a volume of G10 in the simulation

- fills the "window"
- surrounds the conductor (1 mm thick)
- volume of epoxy varies from pixel to pixel

There are shields along the beamline (see bottom left picture) that have NOT YET been optimized to reduced the resulting doses

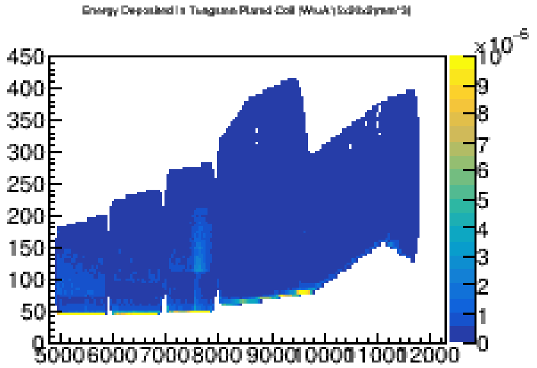


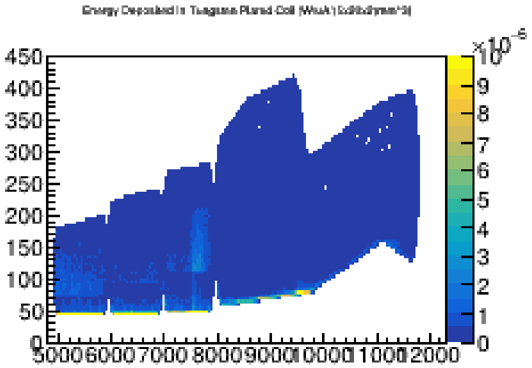
The G10 filler in subcoils 2-4 have maximum doses of < 1MGy

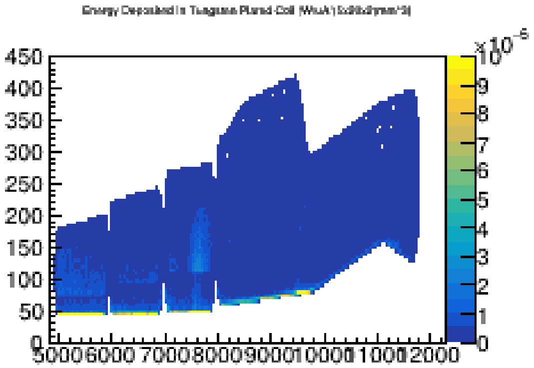


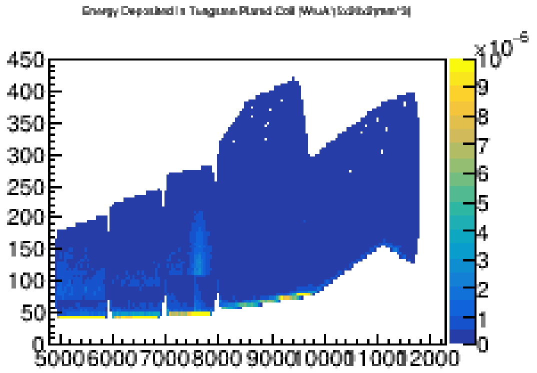
Subcoil	Max Dose (MGy)
1	70
2	34
3	41
4	22

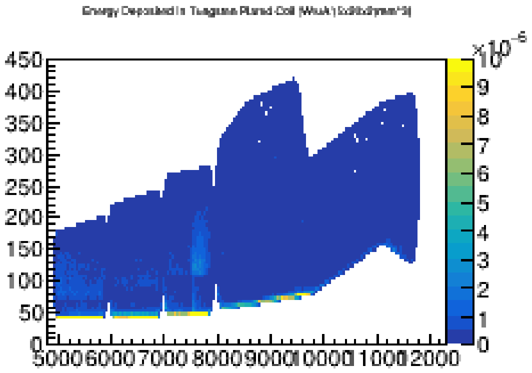
Symmetric coil configuration

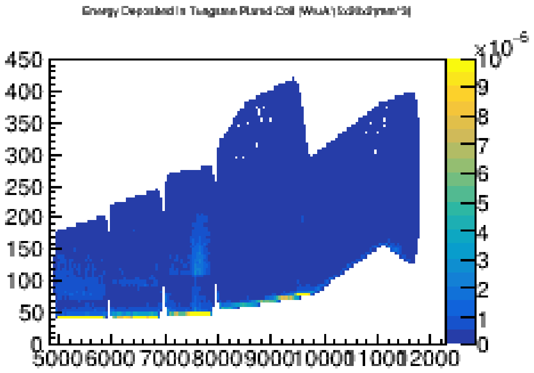


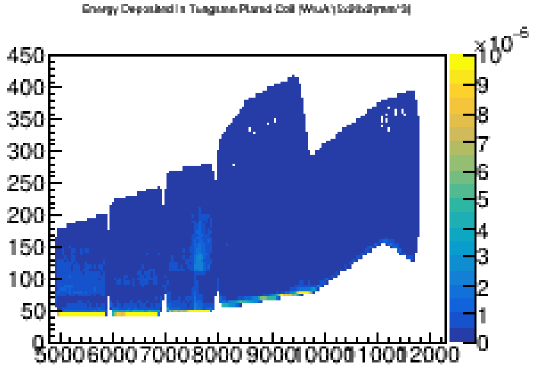






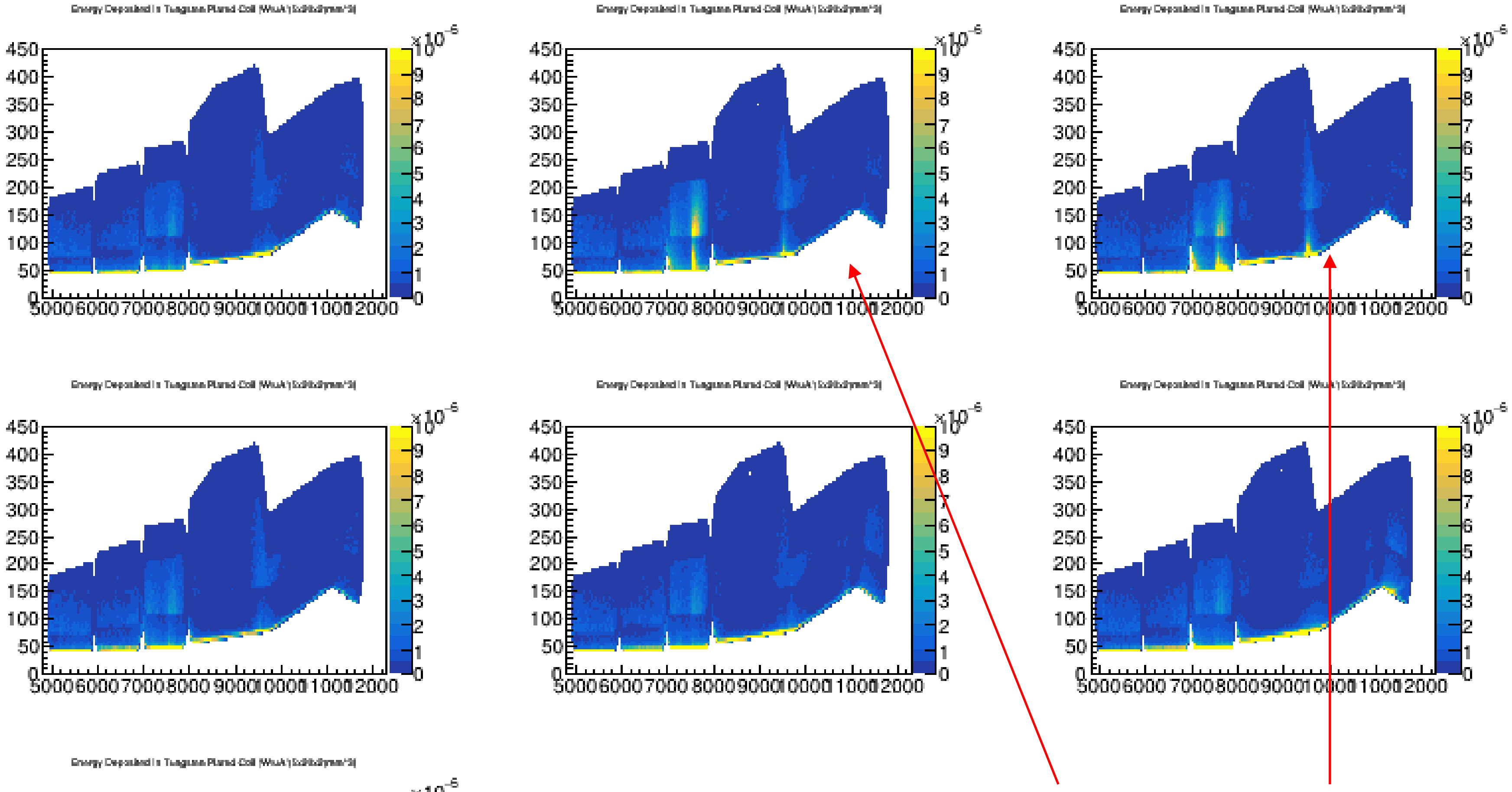


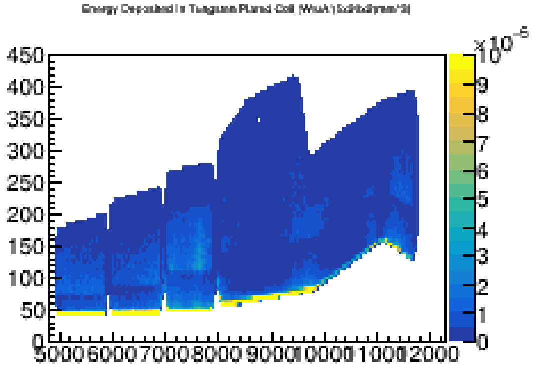




Some hot spots at nose and near collimator 5

Worst case coil configuration

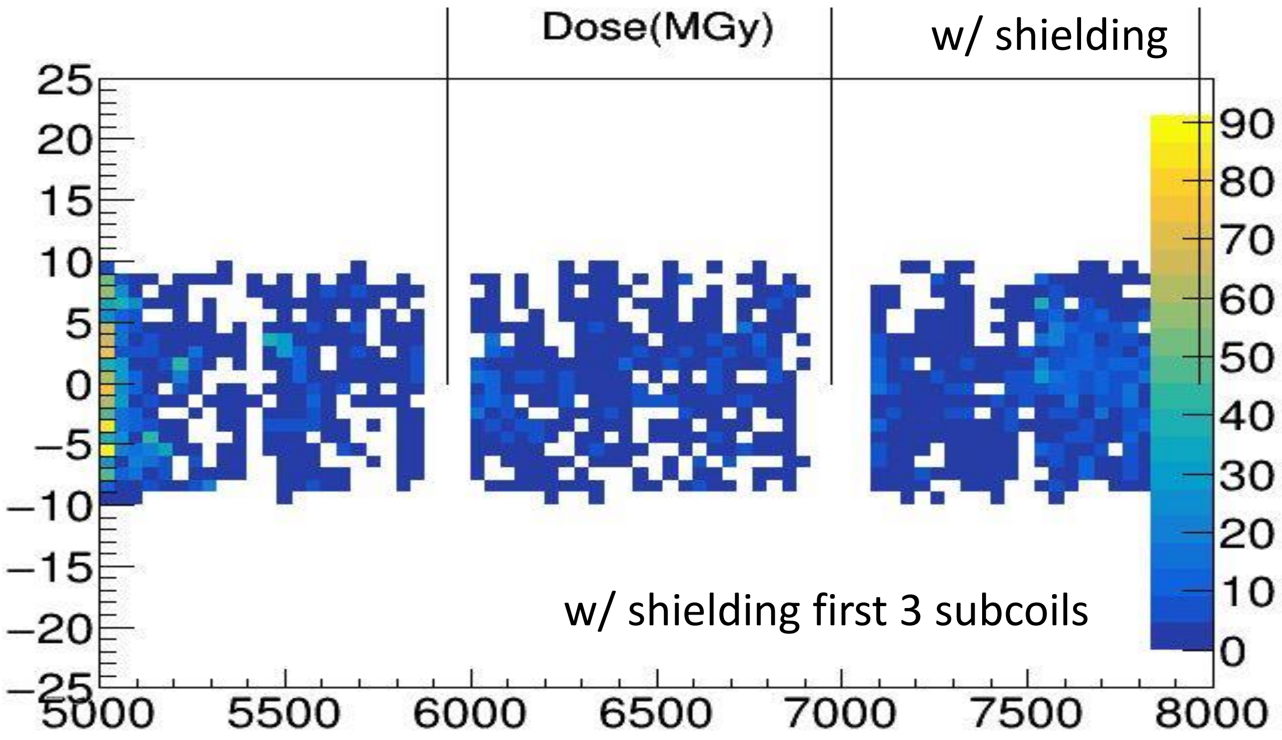


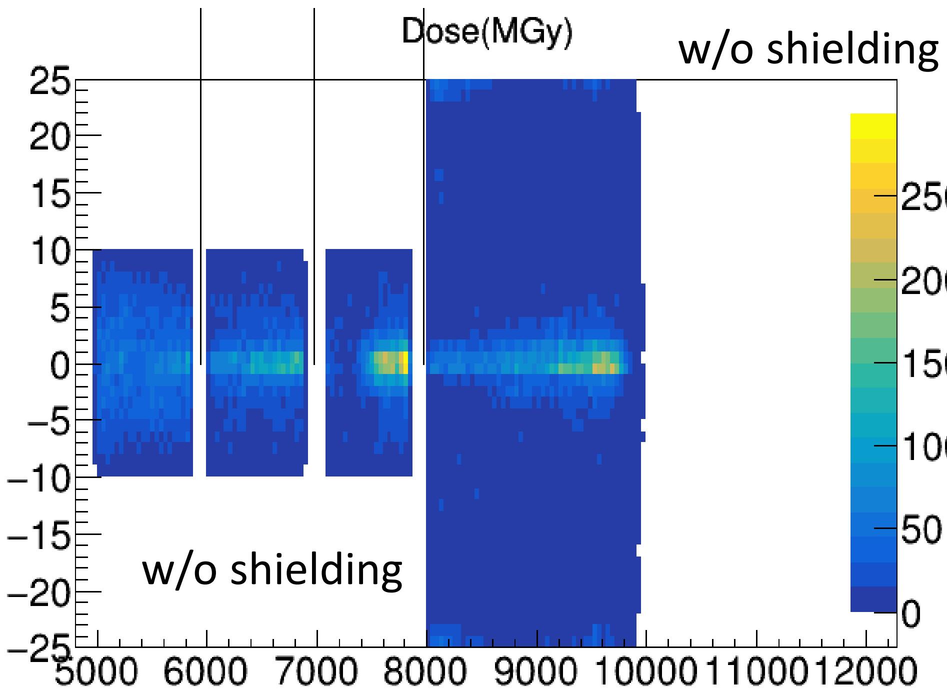


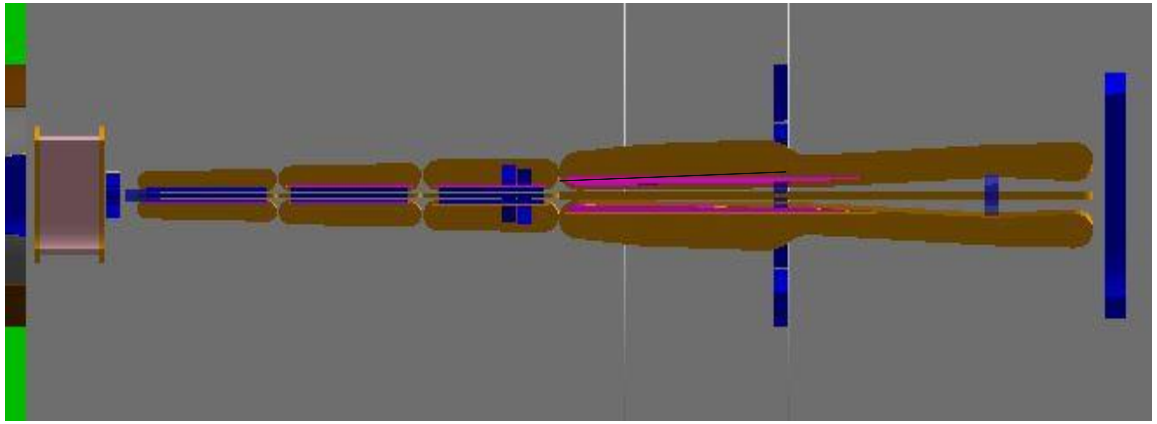
Worst septants (as expected) are 2 and 3

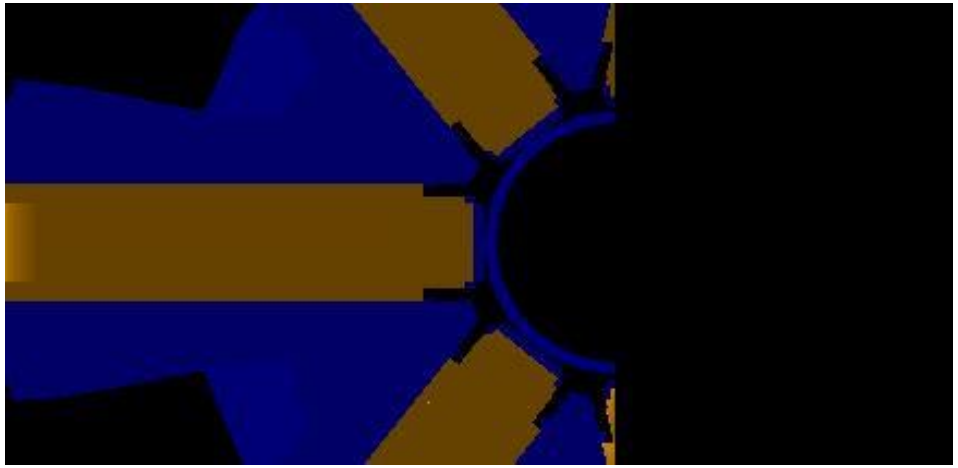
Need to make sure shielding works in this case

Downstream Problems





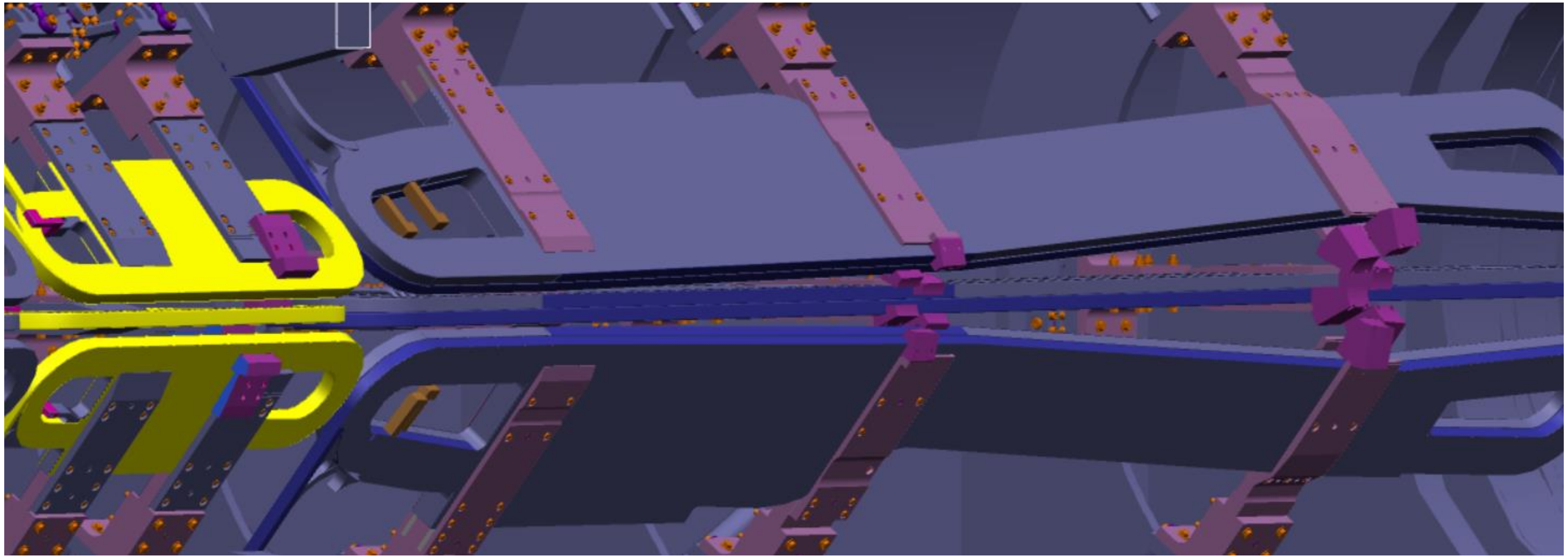




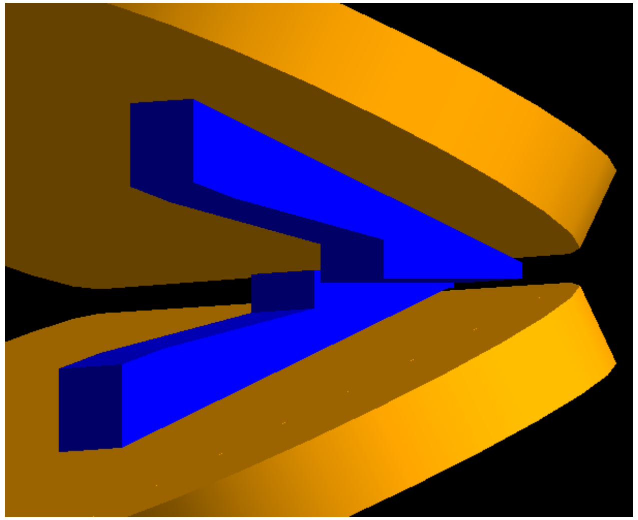
Collimators 5 and 6a,b

There used to be a 2-bounce shield along the length of the whole DS torus

Now using the multiple collimators described by Chandan to shield the main detectors



Collimator 5



Need to add shielding for the downstream that works for both the symmetric and worst-case field maps

Will likely be attached to the coils in a similar way as the collimators (depending on the weight)

Conclusions

- Clean transport down beamline (will have to consider doses on SAMs/intrusions)
- Doses on epoxy
  - upstream have been minimized as much as possible without narrowing the conductor
  - downstream coils is being minimized
  - Need results of epoxy radiation tests to know what dose to aim for
- Position tolerances have been verified with “worst-case” configurations
- Studies looking at background or radiation shielding should
  - use the “beam” generator
  - run sims with the worst-case maps to make sure the design is robust
- More “to do”
  - Field map and interpolation tests
  - Dipole field specification – depends somewhat on some of the things above
  - Field measurement system needs