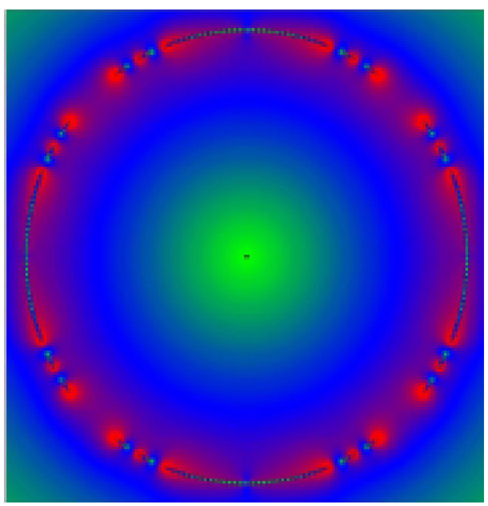
BROOKHAVEN NATIONAL LABORATORY

SLAC Presentation
December 2001

Superconducting Magnet Division

Superconducting Magnets for the NLC: A Design Odyssey

Brett Parker will be your guide today...



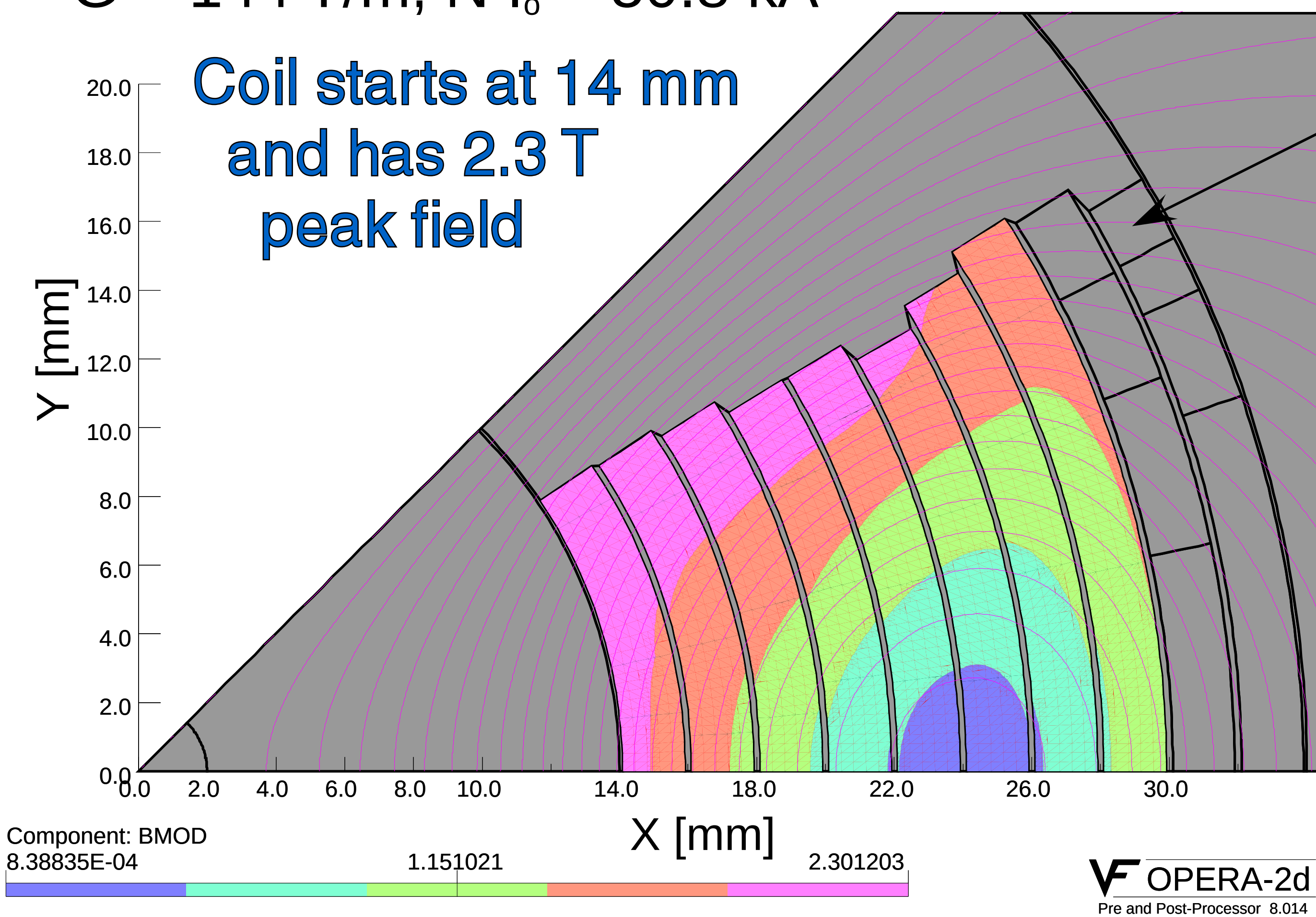
DESY GO Coil Field Map

However it takes a team to make things work:

M. Anerella, J. Escallier, G. Ganetis, A. Ghosh, M. Harrison, A. Jain, LX. Jia, A. Marone, J. Muratore, R. Thomas, P. Thompson, P. Wanderer, KC. Wu + ...

14 mm Coil Toy Model Quadrupole Design

G = 144 T/m, $N \cdot I_o$ = 50.8 kA



Design codes, Wire2dopt, Coilgen and Coilfield, which use actual wire centers for field calculations, were used; however, to keep to a manageable number of files the layers are grouped four at a time and represented by a single layer at the average layer radius. Within a layer conductor center-to-center spacing is varied smoothly to change the effective current density and thus better approximate a cos(2θ) distribution.

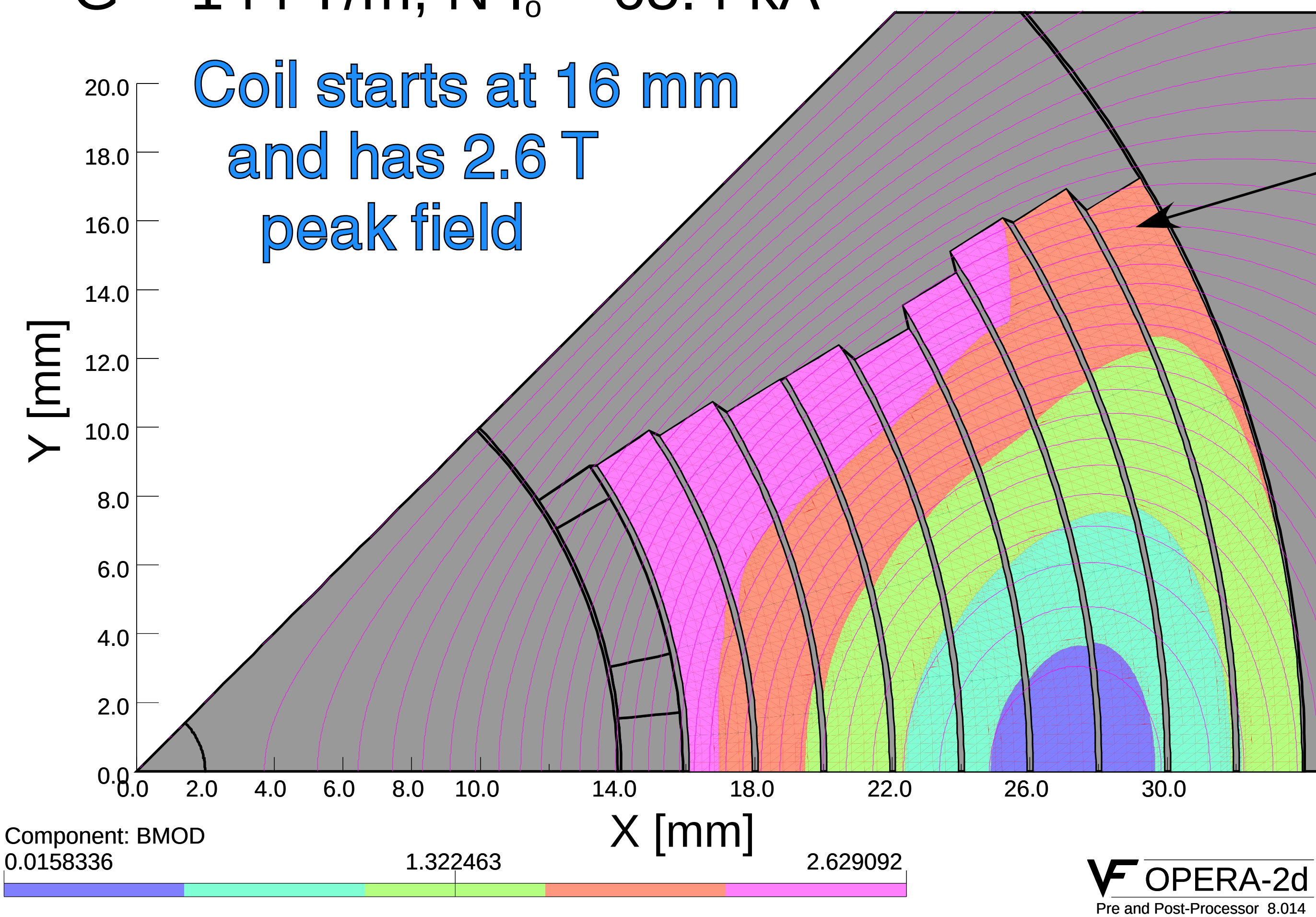
Keeping to smallest possible coil radius minimizes peak field, stored energy etc. and gives best transfer function.

Field lines and |B| in coil are shown for $^1/_8$ model.

Gradient is uniform to better than one unit (±0.01%) inside 7.5 mm radius.

16 mm Coil Toy Model Quadrupole Design

G = 144 T/m, N·I_o = 65.4 kA



This coil needs many more turns to achieve about the same operating current as the 14 mm model and has 14% higher peak field.

For this geometry each layer eliminated from inside requires two outside layers to be added to reach same operating point!

Field lines and |B| in coil are shown for $^1/_8$ model.

Gradient is uniform to better than one unit (±0.01%) inside 7.5 mm radius.

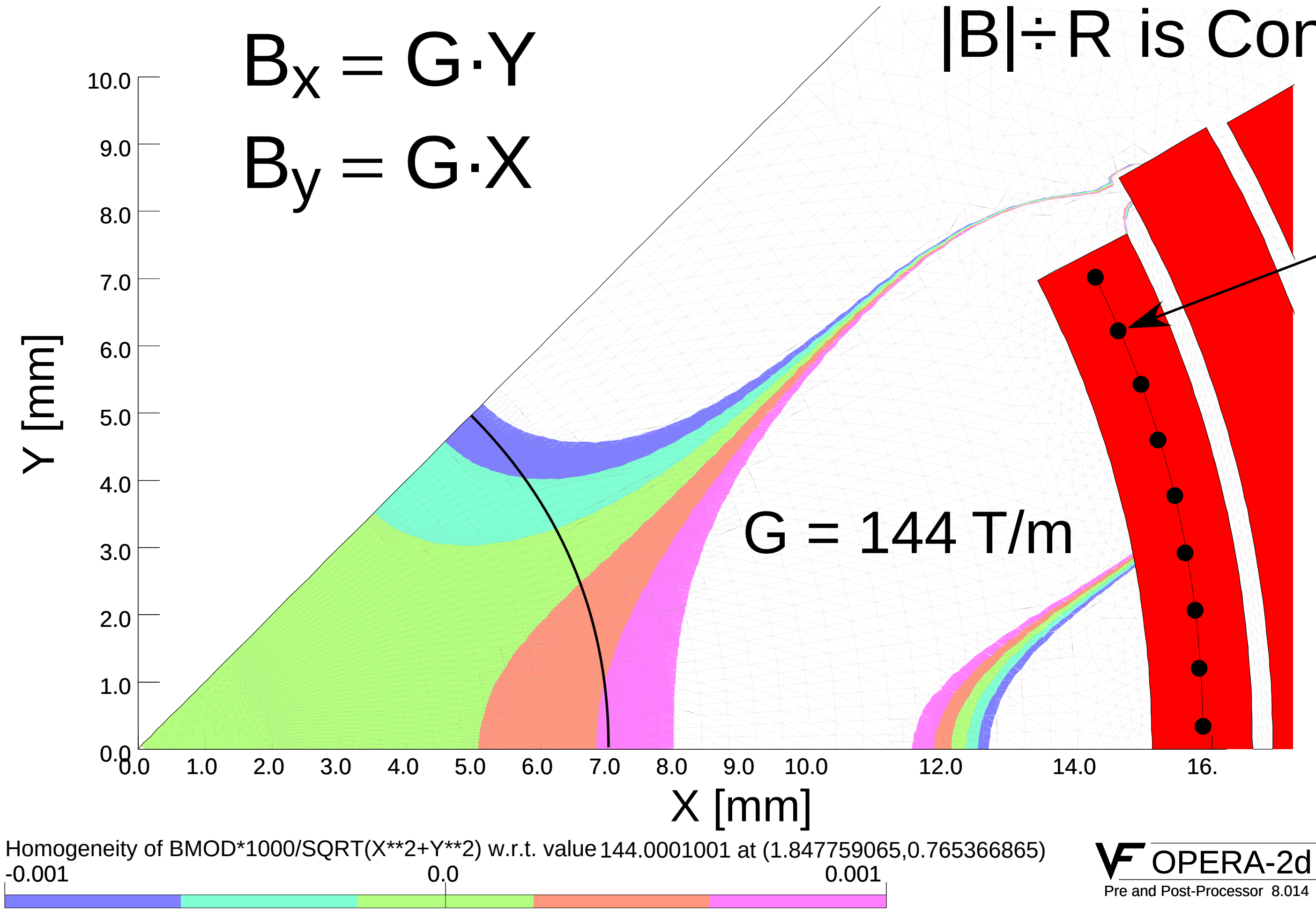
Field Uniformity Inside Quadrupole Coil

Inside the coil:

$$B_x = G \cdot Y$$

$$B_y = G \cdot X$$

For an Ideal Quad
$|B| \div R$ is Constant



Coil design codes, Wire2dopt, Coilgen and Coilfield use actual wire centers for field calculations. By design the gradient is uniform to better than 1×10^{-4} inside a circle of radius 5 mm using only a fixed conductor spacing. With care gradient can be made uniform to close to this level at 7.5 mm radius, but with some loss of transfer function.

For simple coil shown, gradient is uniform to better than 0.1% inside 7 mm radius.

Field Quality: Its Hard Not To Be Good

Even for a simple coil design with uniform turn spacing in the straight section and in the ends the field quality comes out much better than requested.

Harmonics for 2216 mm Long
8 Double Layer Coil at R=5 mm

n	b_n	a_n
1	-0.002	0.002
2	10000.000	-1.482
3	0.001	-0.000
4	0.004	0.078
5	0.000	0.000
6	-0.370	-0.000
7	-0.000	-0.000
8	-0.000	-0.000
9	-0.000	-0.000
10	-0.057	0.000
11	-0.000	0.000
12	0.000	-0.000
13	-0.000	0.000
14	0.000	0.000
15	0.000	-0.000
16	0.000	-0.000
17	0.000	0.000
18	0.000	0.000
19	-0.000	-0.000

Allowed Harmonics

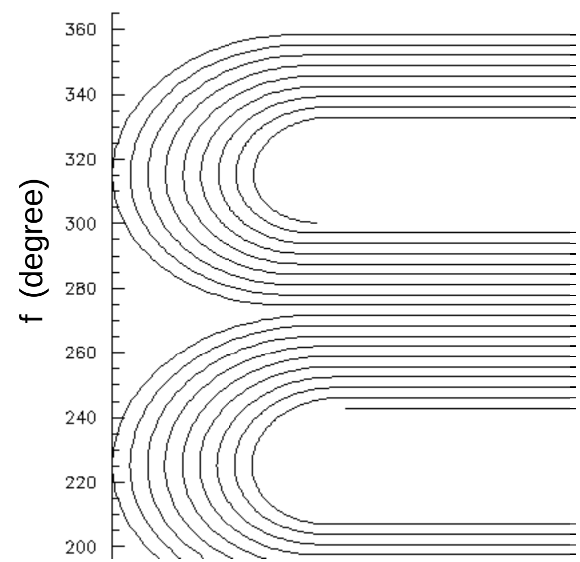
Winding Terms

Tube & Offset Errors

$$ITF = 1.3125\ \mathrm{T/A}$$

$$TF_{cen} = 0.5965\ \mathrm{T/(m \cdot A)}$$

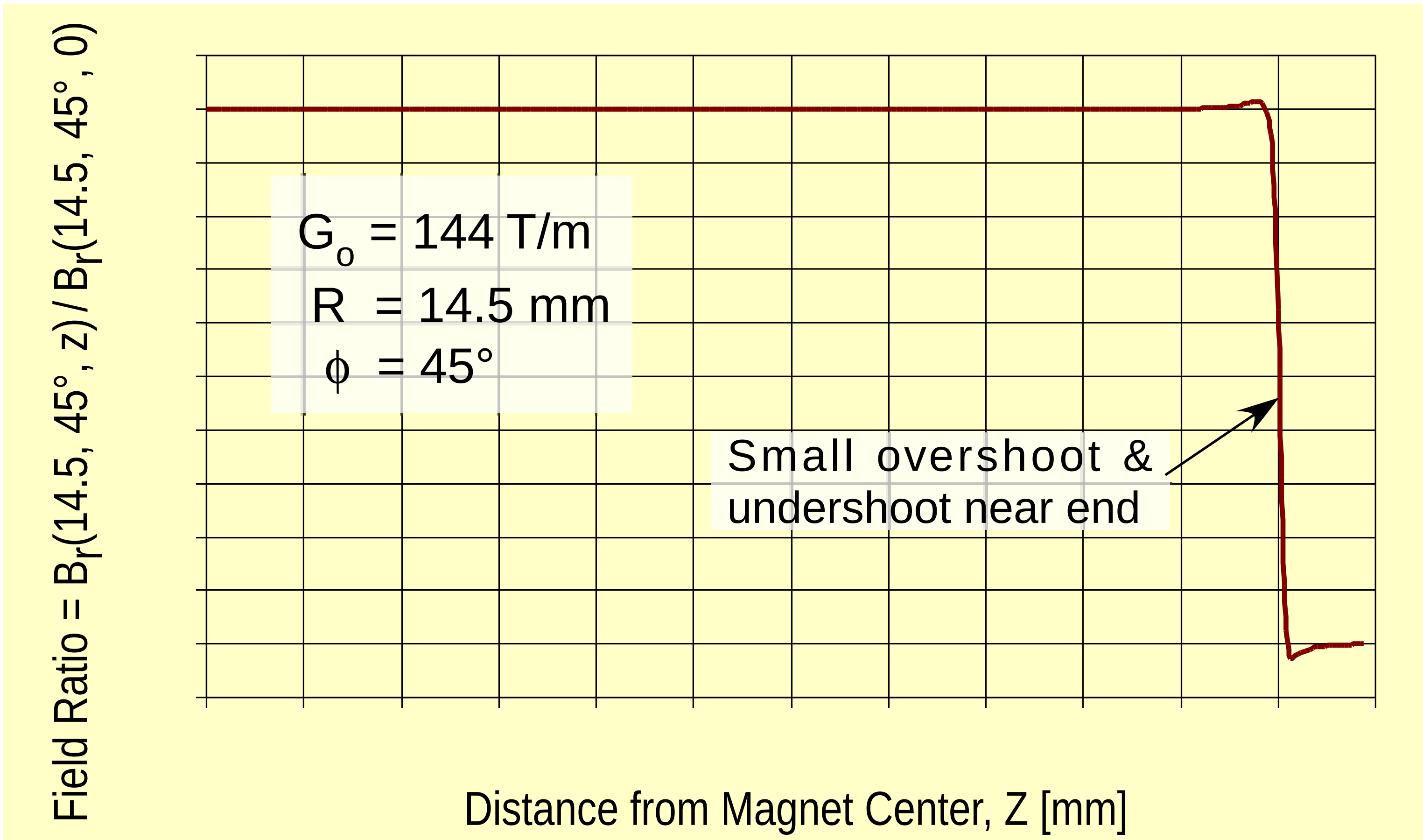
$$L_{mag} = 2.200\ \mathrm{m}$$



Winding Pattern

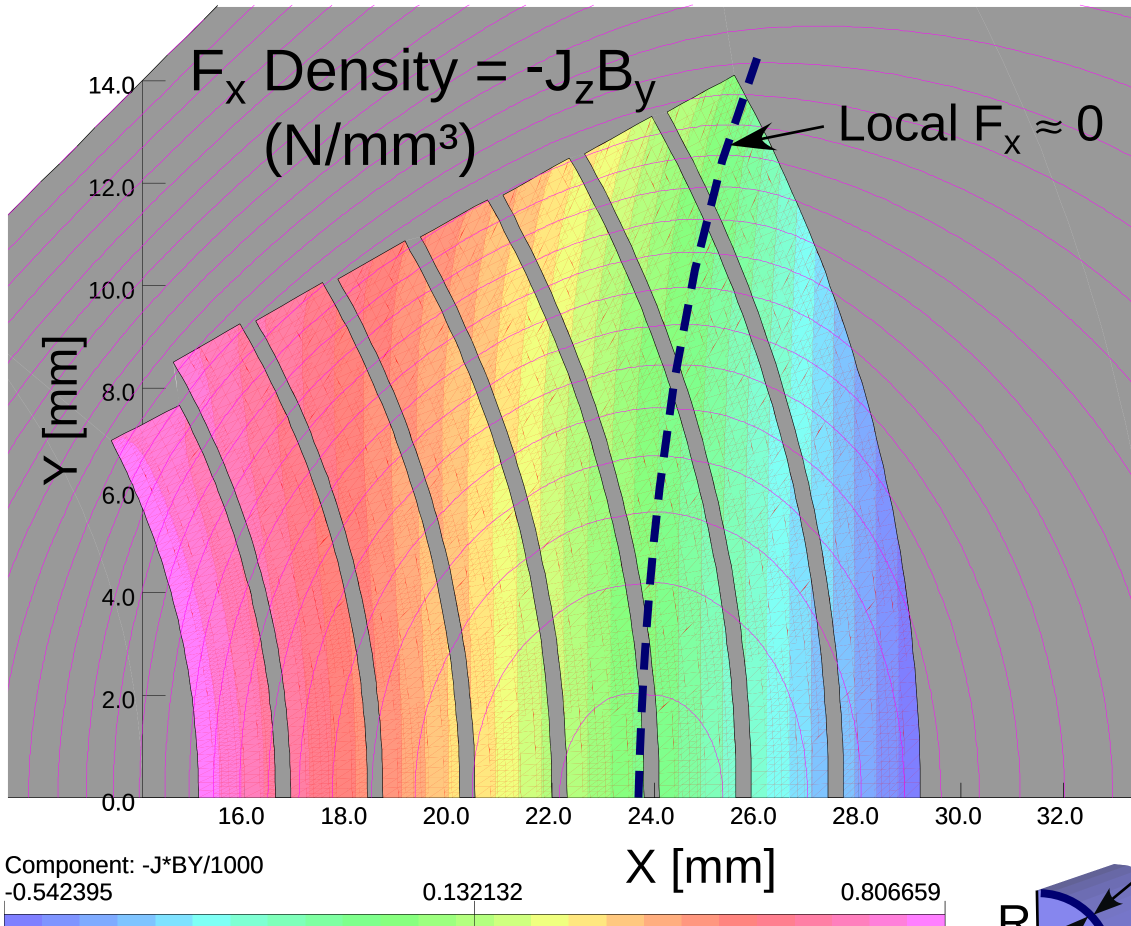
Field Uniformity Along Quadrupole Length

Make scan of radial field at constant radius, 0.5 mm inside coil, and constant angle 45°, e.g. along pole region, as a function of distance from magnet center...



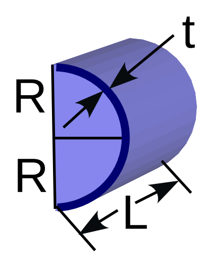
The result is constant, at the percent level, until the coil stops.

Coil Self Force for QD0 at G = 144 T/m



Layer #	Net F_x (N/mm)
1-2	8.2
3-4	8.3
5-6	7.0
7-8	5.4
9-10	3.3
11-12	0.7
13-14	-2.4
15-16	-6.1
Total =	24.4

Force / unit length = $\int J \times B \, ds$



Support Tube:
let t = 2 mm

P = F/A = F/(2RL)

HoopStress = P·(R/t)

= (F/L) · 1/(2t)

= 48.8/4 = 12 N/mm²

= 12 MPa

= 12 · 0.145 = 1.7 kpsi

Note: 1/8 model has net downward vertical force which is cancelled by bottom half coil.

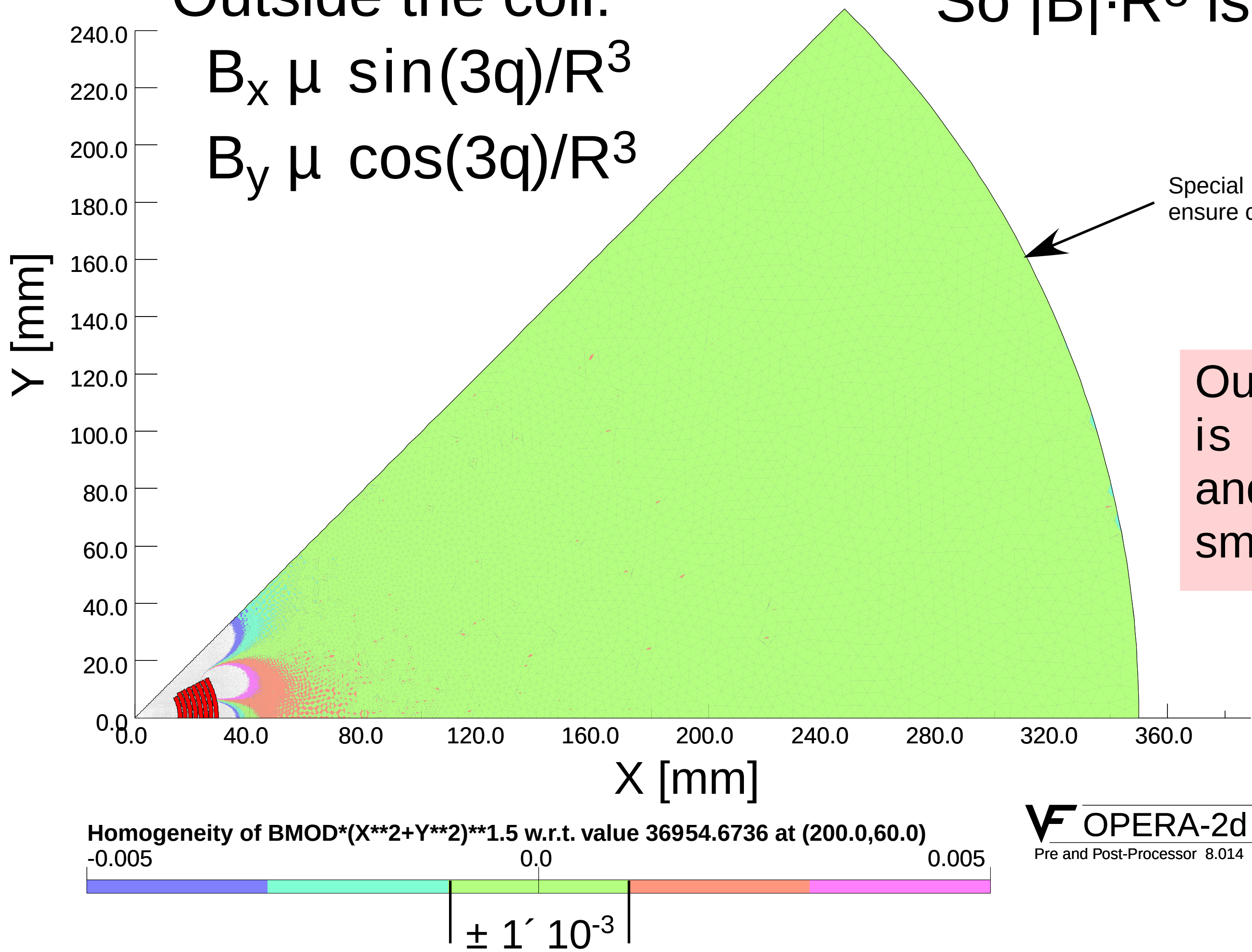
External B-Field From Quadrupole Coil

Outside the coil:

B_x µ sin(3q)/R^3

B_y µ cos(3q)/R^3

So |B|·R^3 is Constant

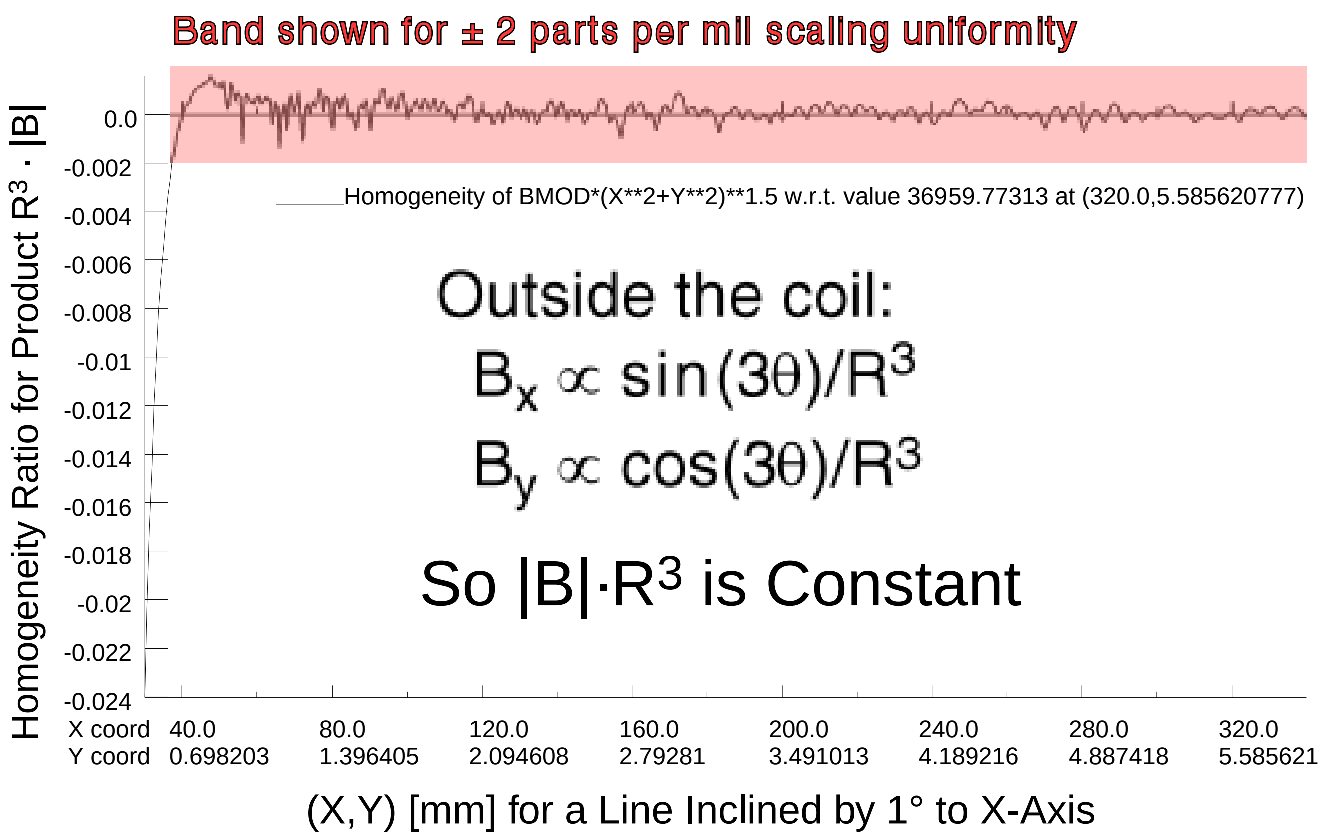


Outside coil the field is quite predicable and quickly becomes small in magnitude.

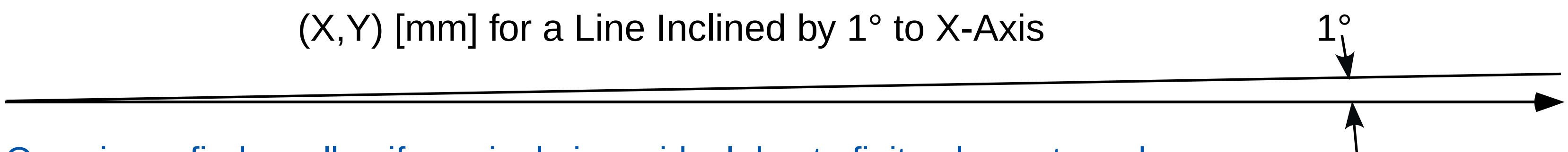
Regions of uniform scaling shown for $^1/_8$ model.

Simple scaling works at the 0.1% level over the entire green area.

External B-Field From Quadrupole Coil

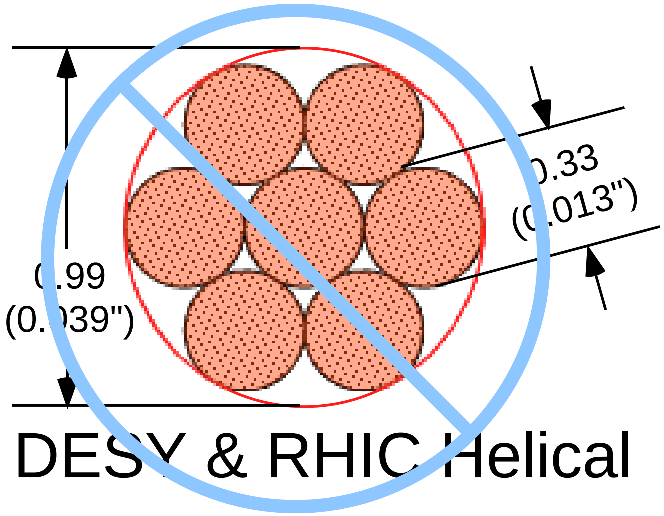


R	|B|
(mm)	(T)
40	0.5774
80	0.0722
120	0.0214
160	0.0090

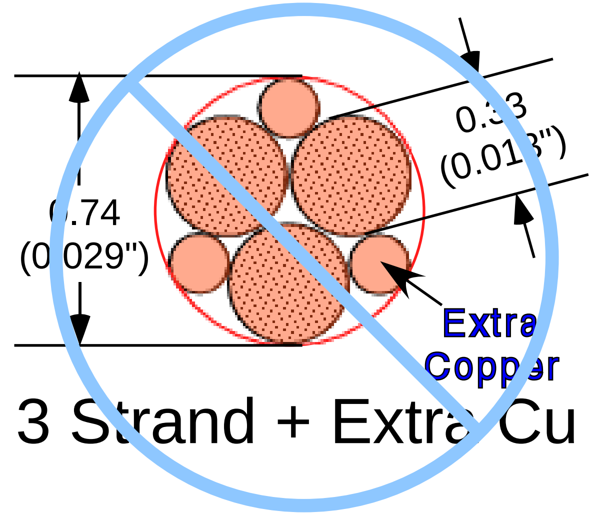


On axis we find small uniform ripple in residual due to finite element mesh.

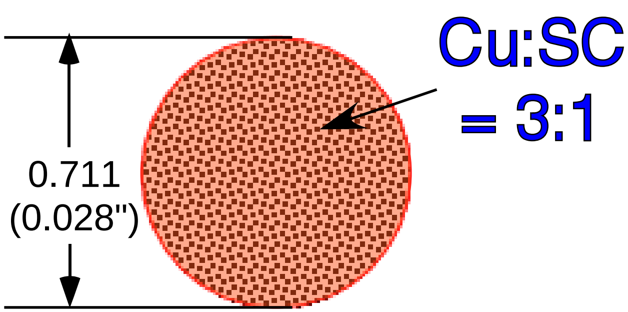
Choosing the Conductor: Some Options



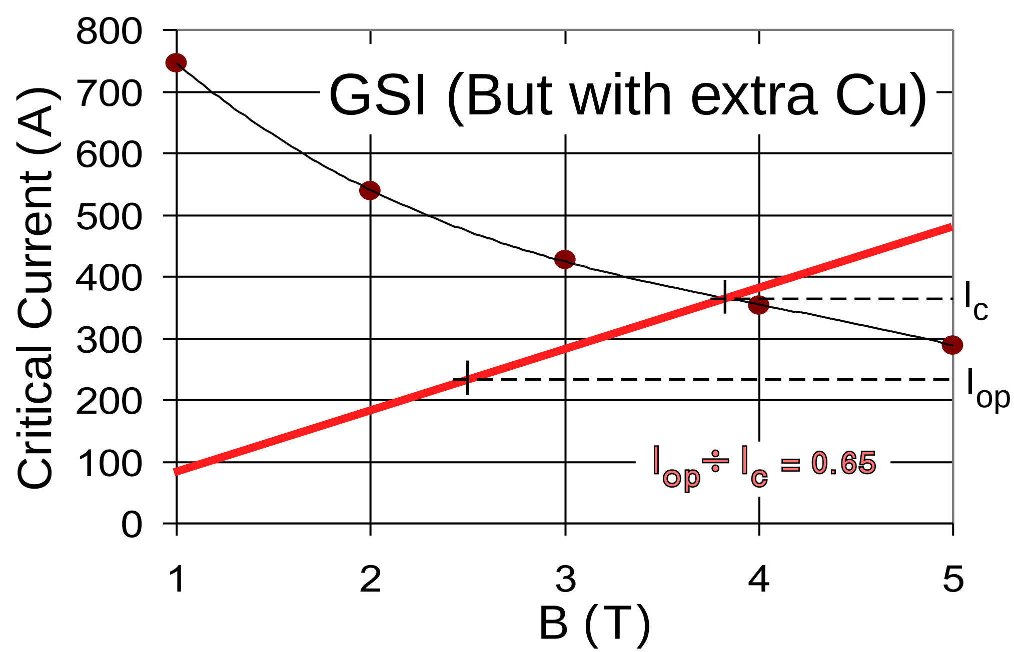
DESY & RHIC Helical



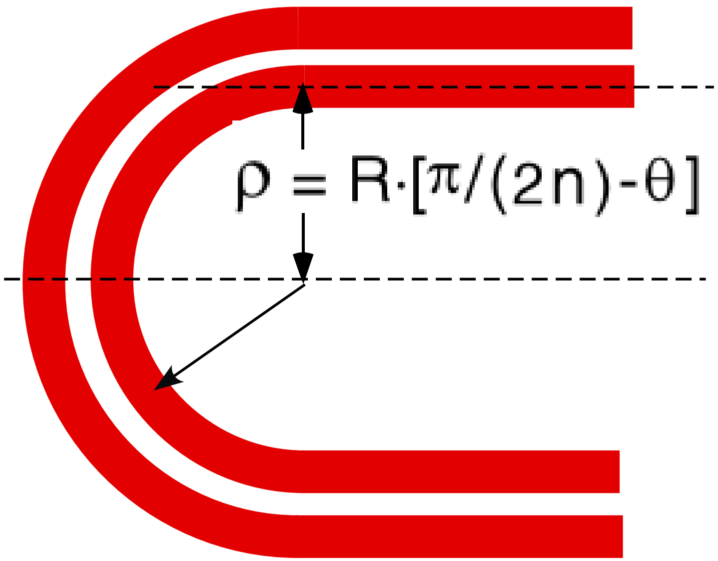
3 Strand + Extra Cu



GSI (But with extra Cu)



Estimating the Tightest Bend Radius



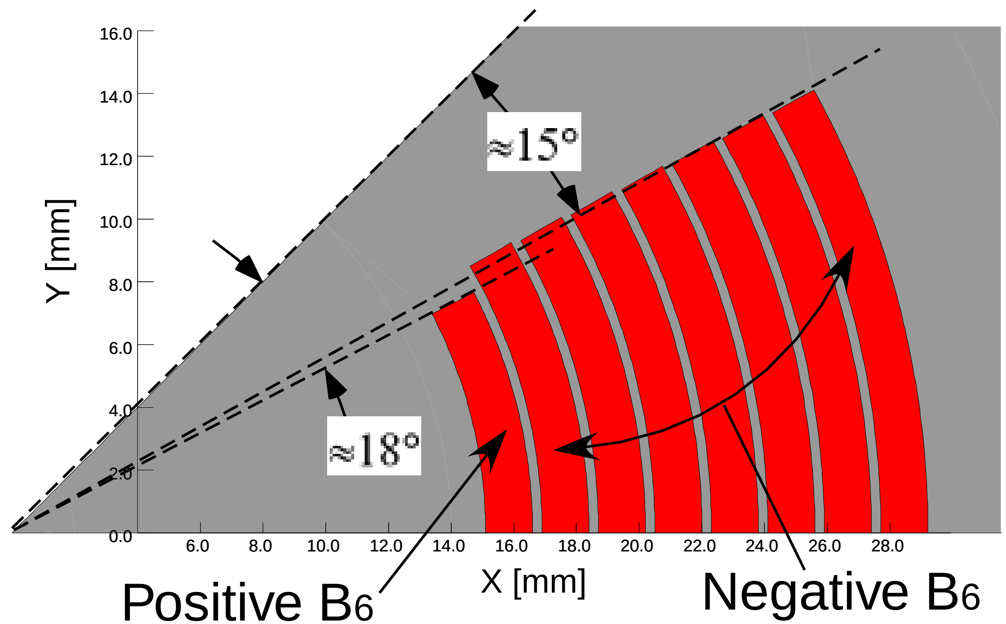
Imagine laying a winding layer out flat...

Then it becomes obvious that the bend radius is a function both of coil layer radius and the angle between the last winding and the pole.

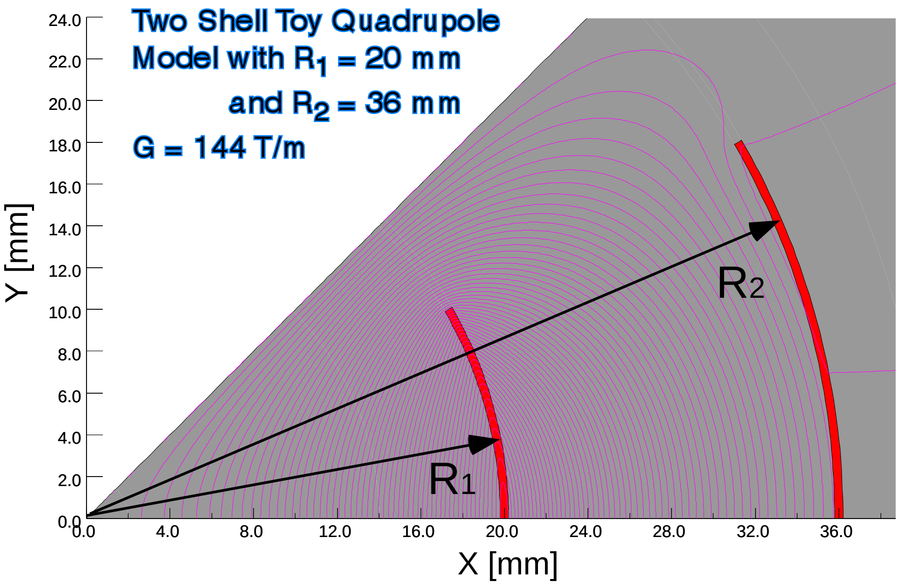
For a quadrupole coil $n=2$.

15 mm @ 18°
or 17 mm @ 15°

give $\rho \approx 4.5$ mm
for the coil shown



External Shielding: Facts of Life Part1



For thin shell currents distributed as cos(nq) and N·I Amp·turns, the condition for external shielding is:

$$(N\cdot I)_2 = -\ (N\cdot I)_1 \cdot (R_1/R_2)^n$$

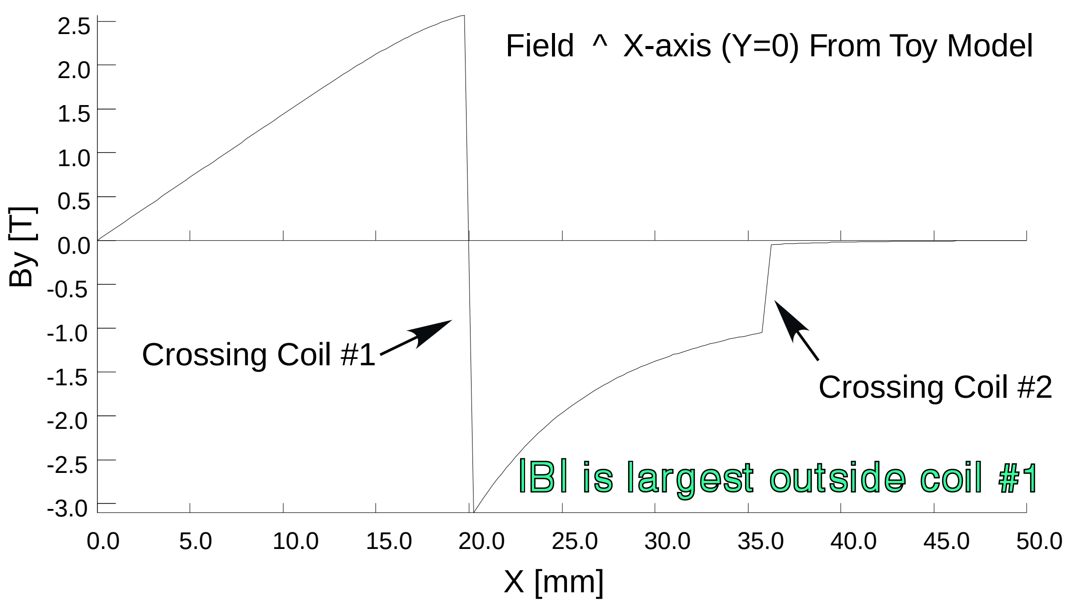
Where n=1 dipole, n=2 quadrupole etc.

Note: a shield coil reduces magnet strength by a factor, f, where

$$f = 1 - (R_1/R_2)^{2n}$$

Thus it is very painful to shield a dipole and merely difficult to shield a quadrupole.

But shielding a thick coil requires even more current than indicated by the simple formula!

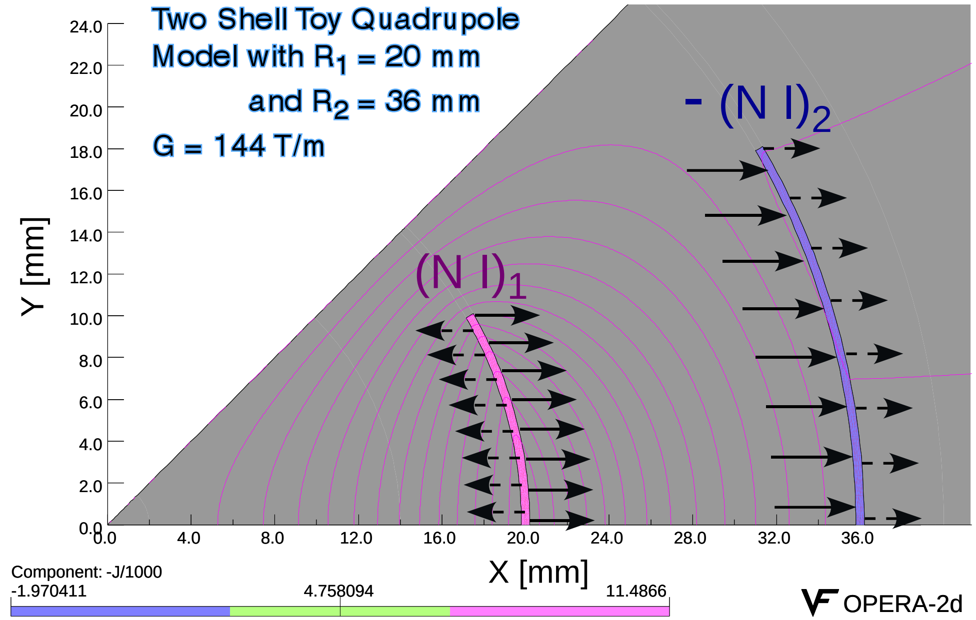


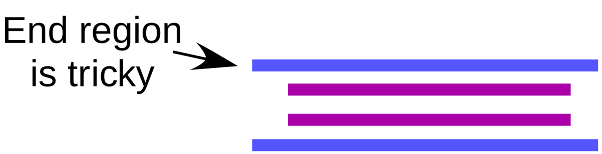
External Shielding: Facts of Life Part2

With shielding, the outward force is largest on outer shell.

Opposite currents repel. Thus #2 pushes on #1 reducing inner force but has back action adding to net outer shell force.

Forces are harder to handle at large radius.





- Shielding a thick coil very quickly uses up radial space.
- Must provide for good relative alignment and support.
- Must check complicated interaction with the detector solenoidal field (forces on inner and outer coil).
- Beams are closest at IP end of magnet, but this is the trickiest region for shielding optimization.
- Is shield connected in series or independently powered?

Only ask for shielding if it is absolutely needed. Then look first to put shielding around other beam pipe (not the whole magnet).

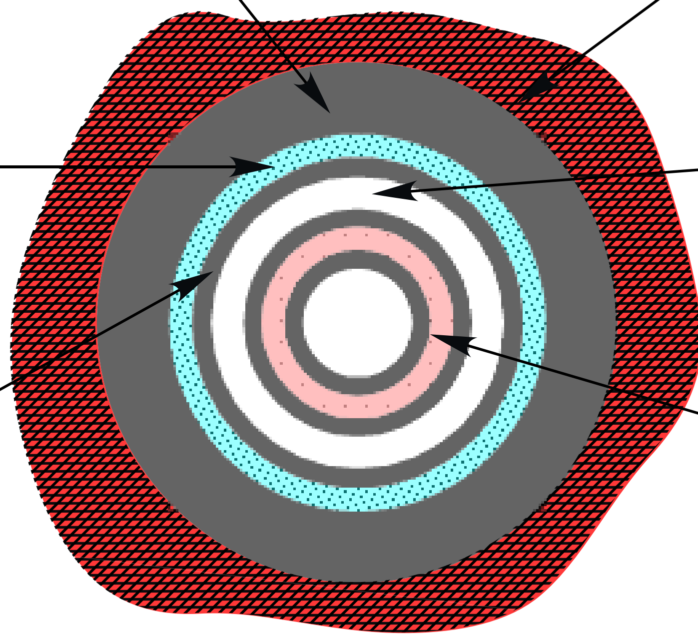
But sometimes it is hard to stay on a strict diet...

For large forces, Andy M. wants at least a 3 mm thick support tube.

If coil starts at 15 mm inner radius...

For helium flow Lin says, "less than 1 mm thickness does not make sense."

Space for insulating vacuum and super-insulation is needed.



0.5 mm for LHe containment wall

Double wall beam tube; must leave space for cooling.

"The thinner you slice it, the more the beef," does not work well for magnet design. Starting at 15 mm, i.e. 50% more than required beam aperture, one quickly concludes that either the coil will have to grow much larger or there is no room for the beam!

Parameters for QD0 Double Coil Solution

$G_1 = 75$ T/m, $N_1 = 80$, $I_1 = 271$ A, $(N \cdot I)_1 = 21.7$ kA·turns/pole

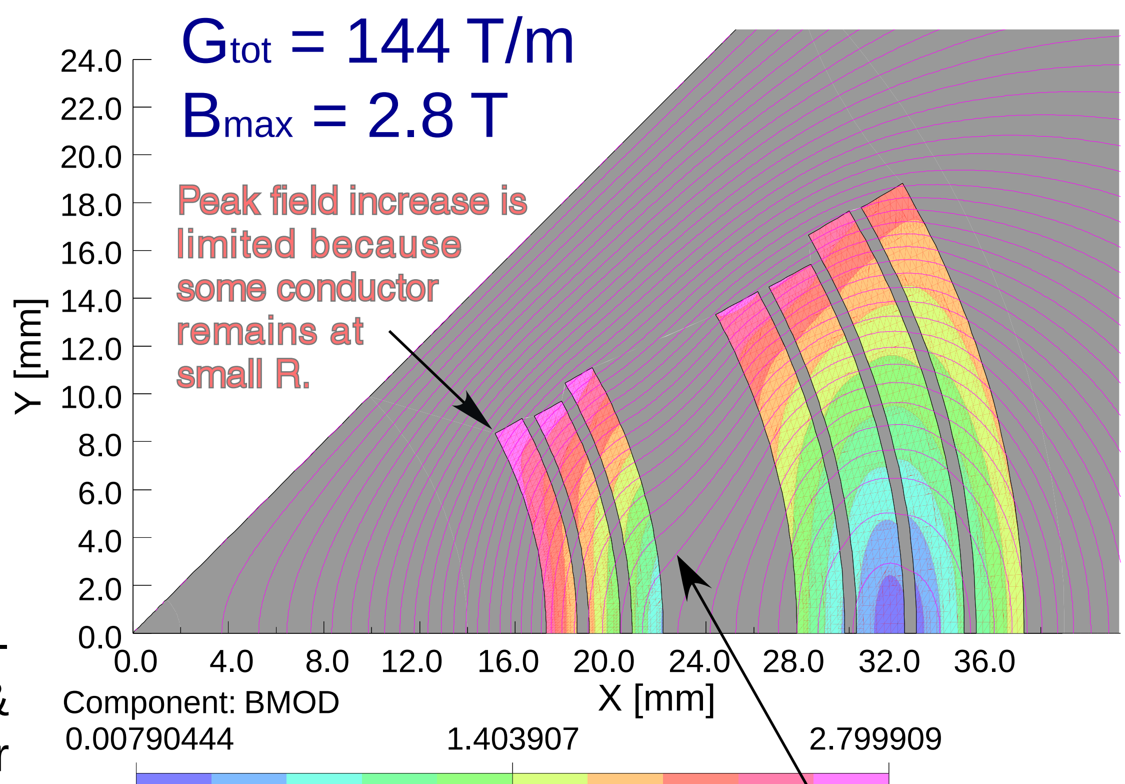
$G_2 = 69$ T/m, $N_2 = 112$, $I_2 = 486$ A, $(N \cdot I)_2 = 54.4$ kA·turns/pole

Inner Coils: RHIC Strand
Single 0.648 mm Wire
Cu:SC is 2.25:1

Outer Coils: Helical Cable
7-Strand, 1 mm Cable
Cu:SC is 2.5:1

With two power supplies & inner/outer segmentation quench protection is easier.

It is possible to shift operating margin between inner & outer coils by adjusting their operating currents.



Can have cooling outside coil & still avoid a long conduction path.

The QD0 Double Coil Design Concept

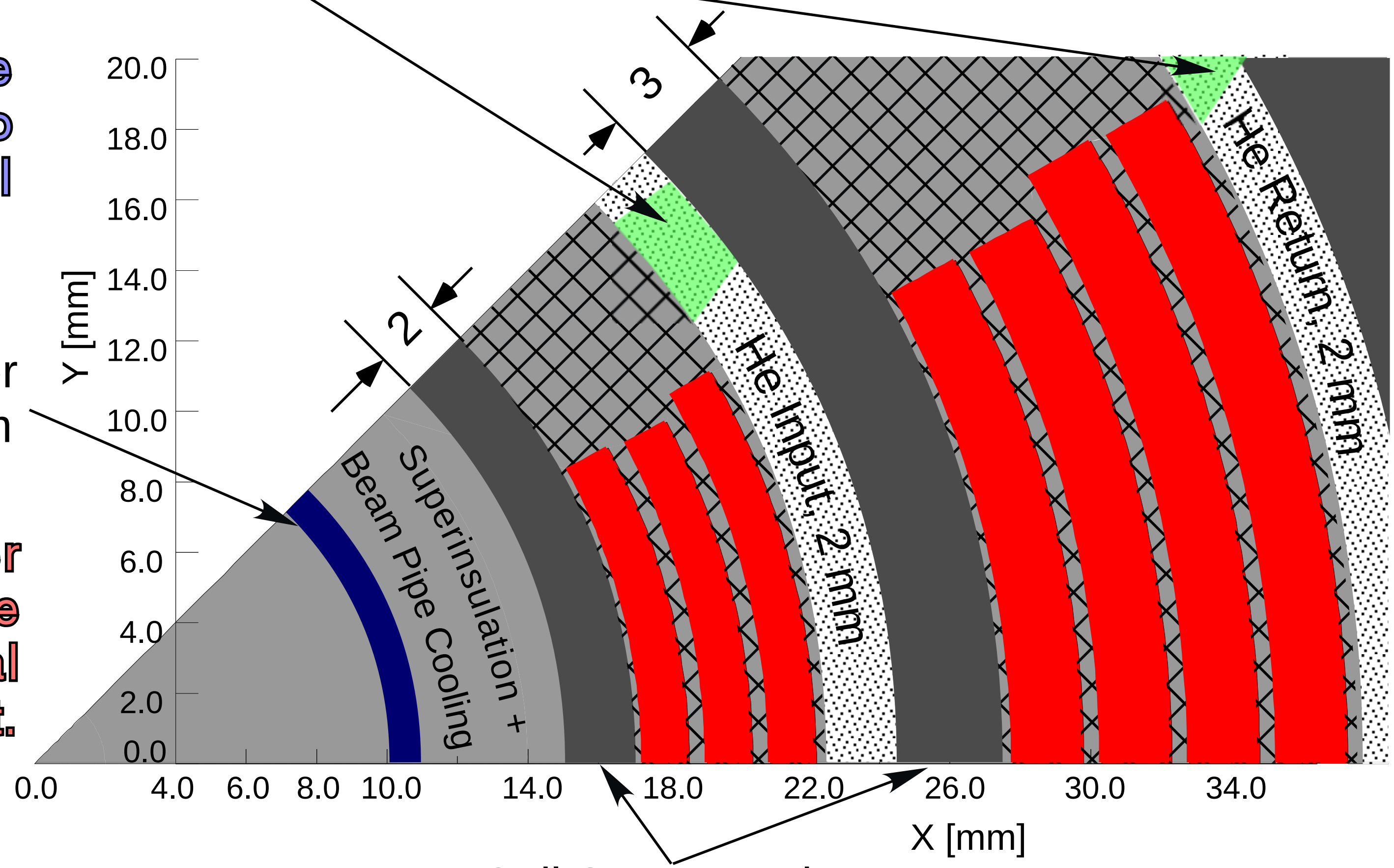
Tight inner bends done with 0.648 mm RHIC strand. For outer coils 1 mm DESY/RHIC 6-around-1 cable is ok.

Bumpers could be used to couple structural elements

Try to limit the inner structure to keep inner coil radius small.

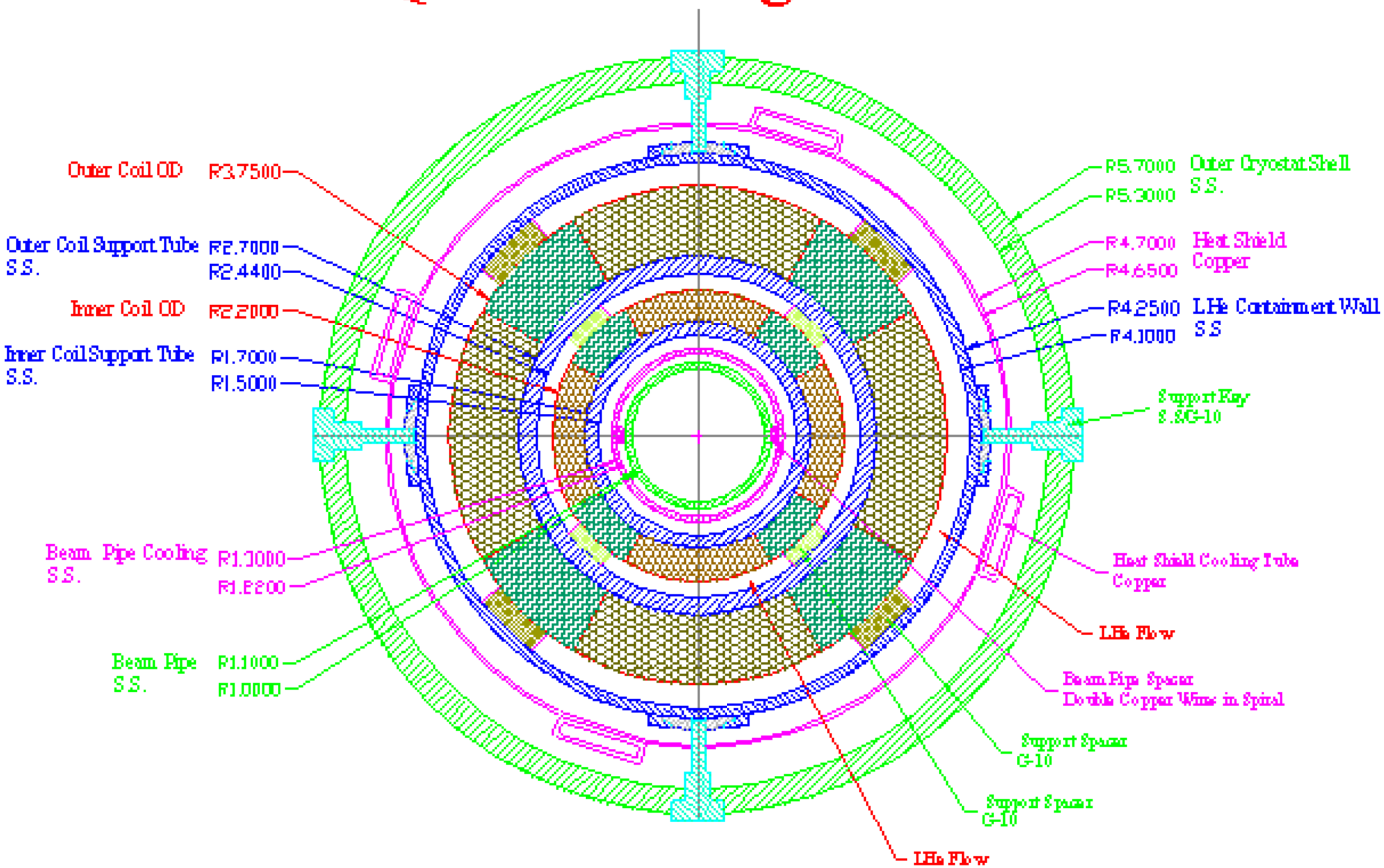
Beam pipe inner radius is 10 mm

Inner and outer coils each give about half total 144 T/m gradient.



Coil Support Tubes

QD0 Cooling Scheme

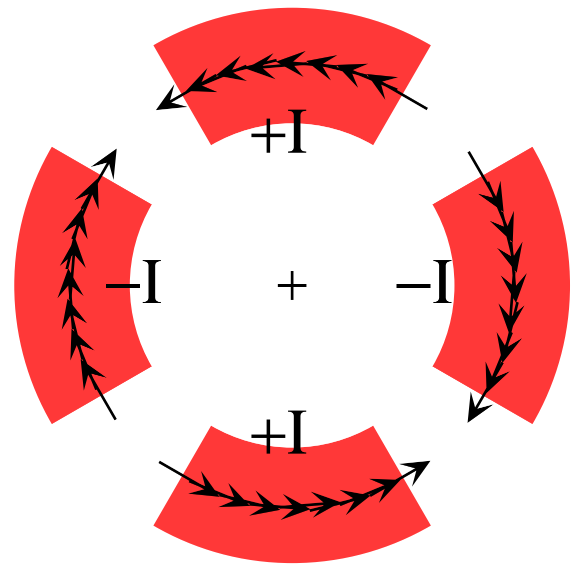


Coil Forces Due to Solenoid's Radial End Fields*

Note: dipole currents flow oppositely on each side yielding net local horizontal or vertical force. With quadrupole symmetry the net local force is zero.

Radial fields at solenoid ends cause a quadrupole coil to try to go out of round.*

But QD0 is offset, tilted and partially inside the aperture of the detector solenoid flux return. Estimating the magnitude and direction of the coil forces is not trivial.



Coil Force Diagram

*Here radial field and quadrupole coil are assumed to have same center.