Simple Scaling Estimations for a Large Aperture Superconducting QD0 Magnet

World Year of PHYSICS 2005
www.physics2005.org

prepared by

Brett Parker, BNL/SMD

For a new project like the ILC we need to watch out for human bias factors that give overly optimistic IR magnet parameters. Starting from state-of-the-art designs for LHC IR quads and accounting for important differences with the present ILC IR provides guidance on what we may reasonably use in our designs.

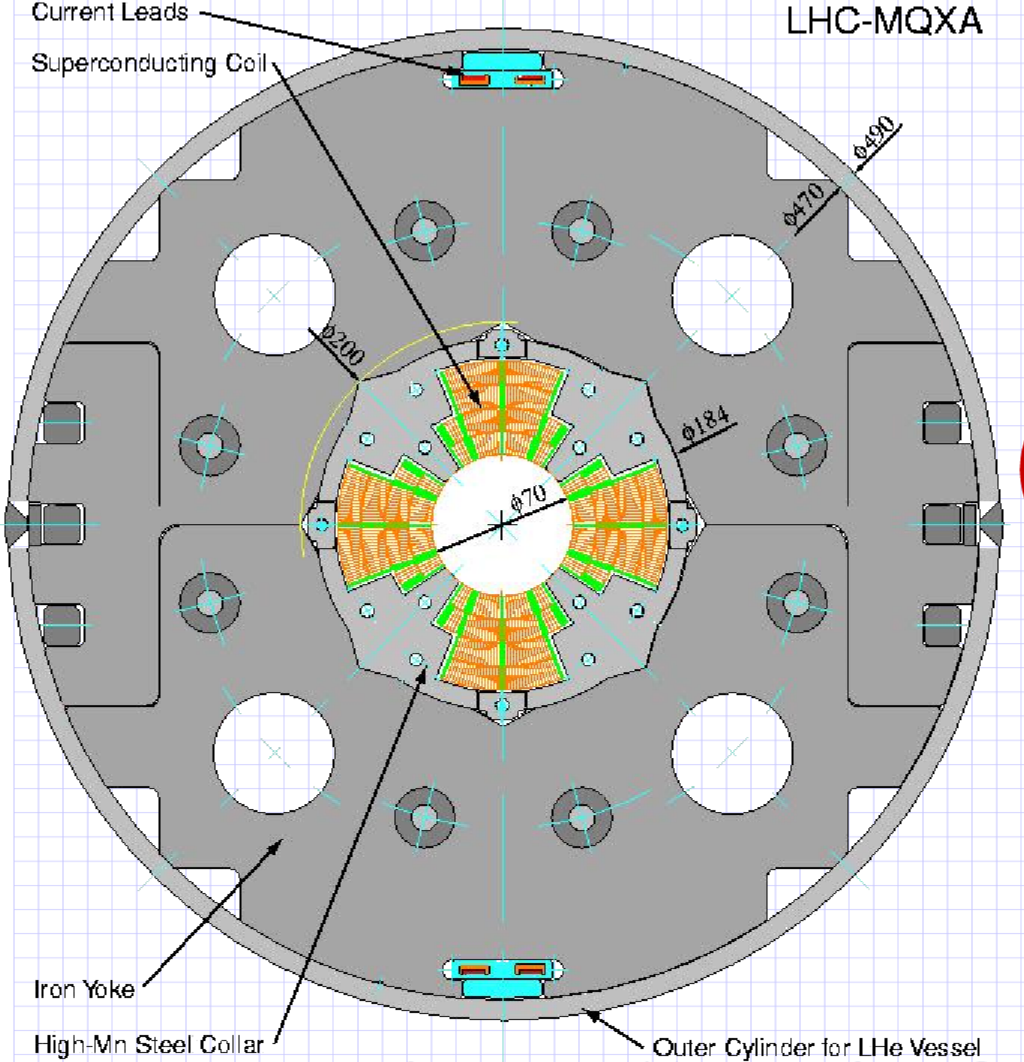
International Linear Collider

BROOKHAVEN NATIONAL LABORATORY

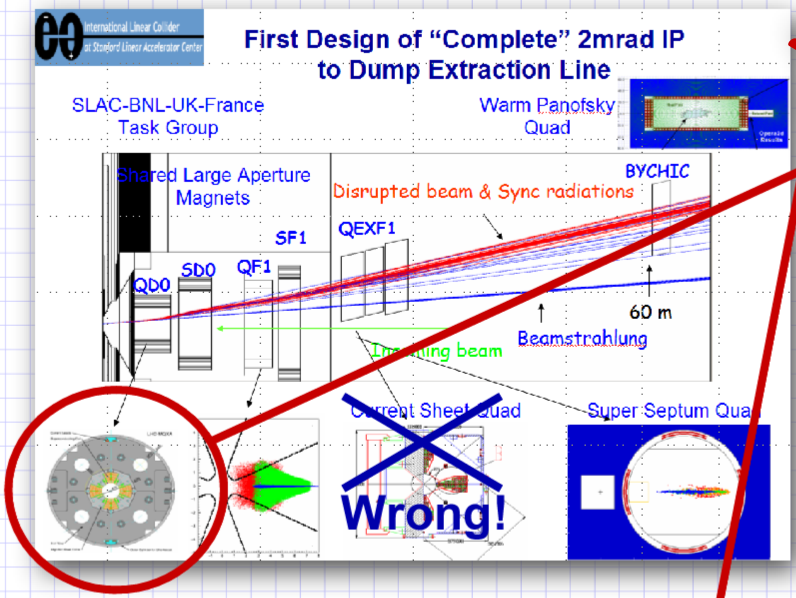
Superconducting Magnet Division

Can we use an LHC IR quadrupole as starting point for the ILC QD0 design?

http://cry3-dts.kek.jp/~lhcirq/LHC/drawings/lhc-mqxa-design.jpg

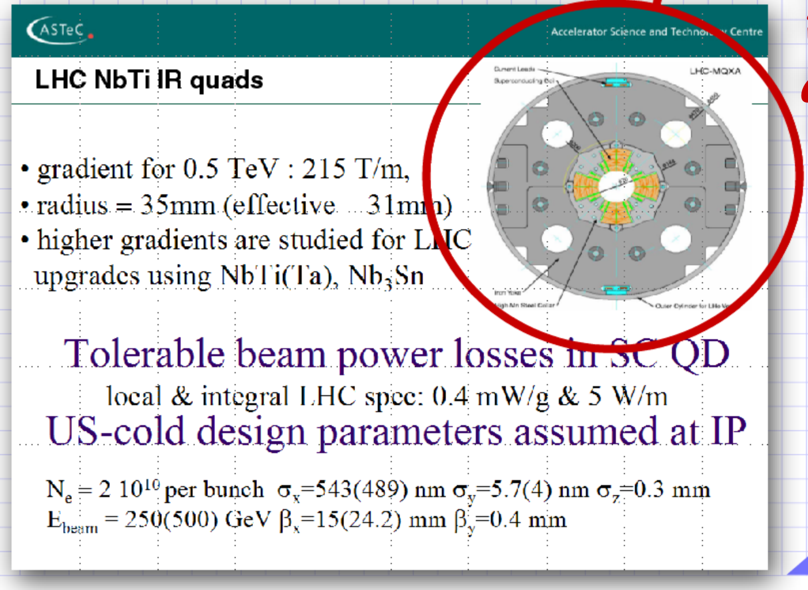


Cross Section of Inner Cold Mass for KEK Produced LHC-MQXA IR Quadrupole.


International Linear Collider at Stanford Linear Accelerator Center

First Design of "Complete" 2mrad IP to Dump Extraction Line

SLAC-BNL-UK-France Task Group


ASTeC

Accelerator Science and Technology Centre

LHC NbTi IR quads

- gradient for 0.5 TeV : 215 T/m,
- radius = 35mm (effective 31mm)
- higher gradients are studied for LHC upgrades using NbTi(Ta), Nb_3Sn

Tolerable beam power losses in SC QD

local & integral LHC spec: 0.4 mW/g & 5 W/m

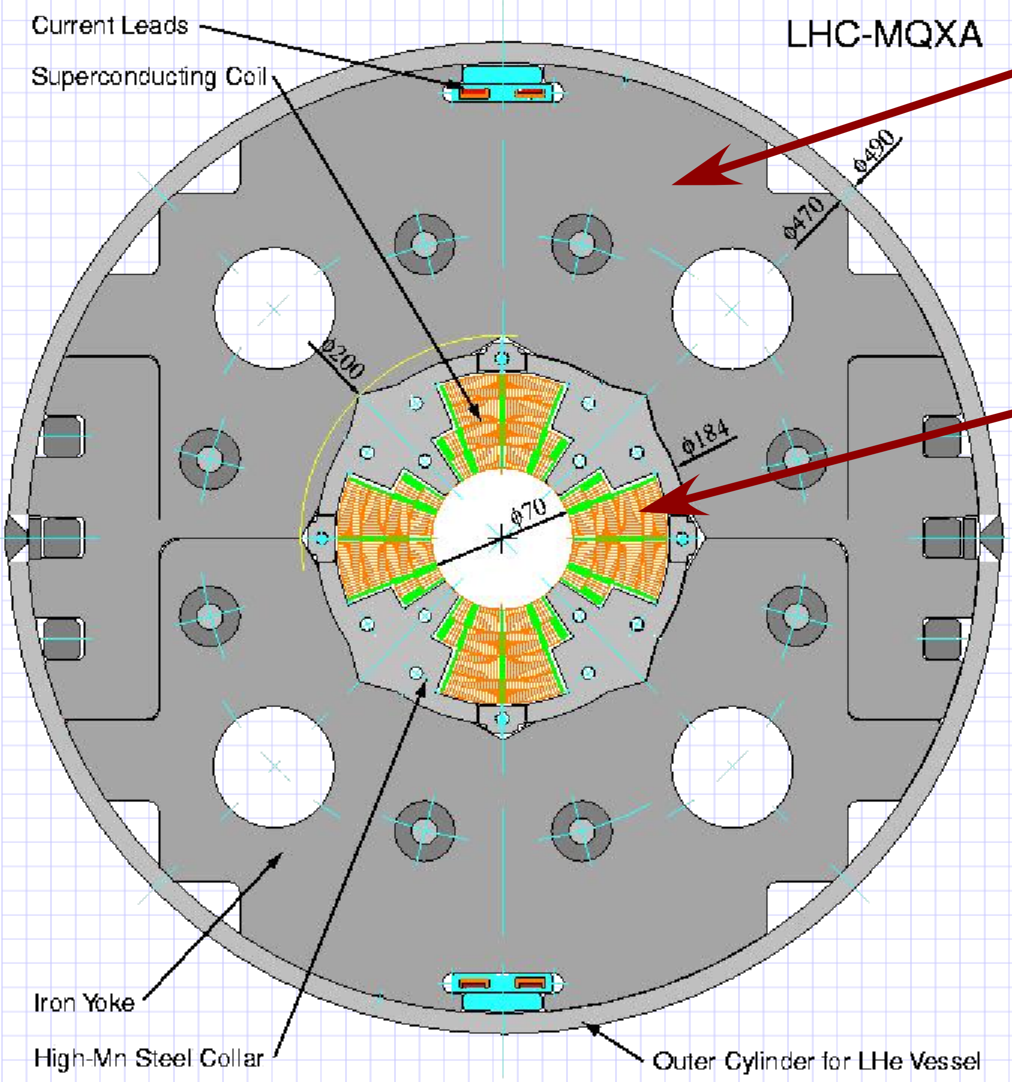
US-cold design parameters assumed at IP

$N_e = 2\ 10^{10}$ per bunch σ_x=543(489) nm σ_y=5.7(4) nm σ_z=0.3 mm

E_{beam} = 250(500) GeV β_x=15(24.2) mm β_y=0.4 mm

Yes
see
earlier
talks

But what are some important LHC-MQXA design features?



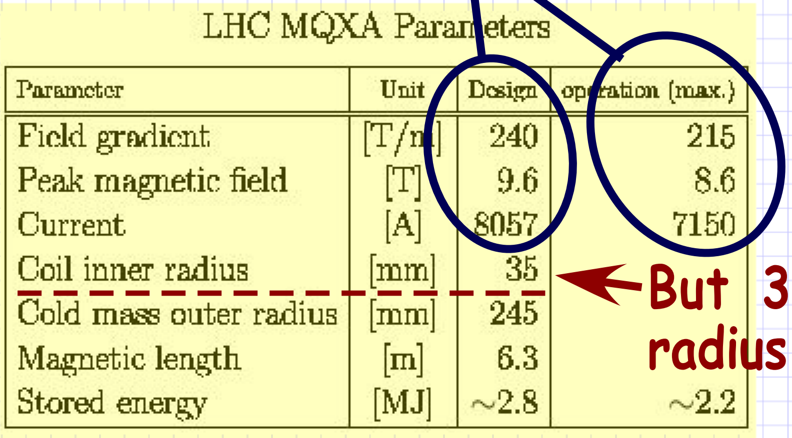
Cross Section of Inner Cold Mass for KEK Produced LHC-MQXA IR Quadrupole.

Massive Magnetic Yoke (But ILC QD0 is in fringe field of detector).

Cooling via He-II @ 1.9°K (Have max current possible from NbTi).

Thick 4-Layer Conductor Pack (Coil structure already fairly complicated).

Max Operation Gradient is 90% of "Design Value" (Need some margin).



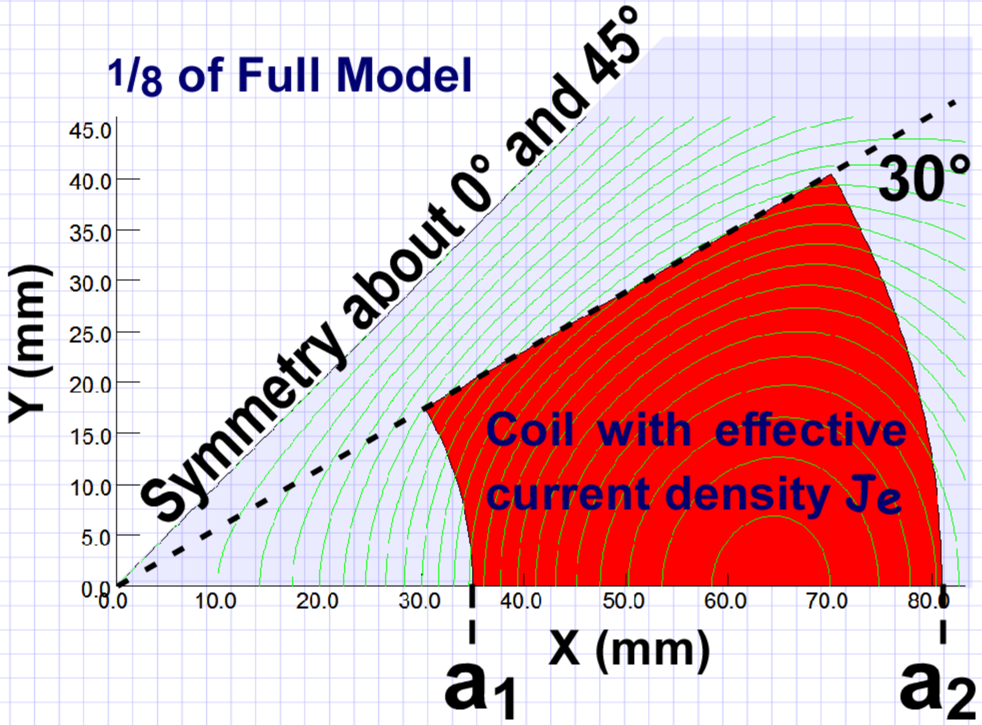
LHC MQXA Parameters

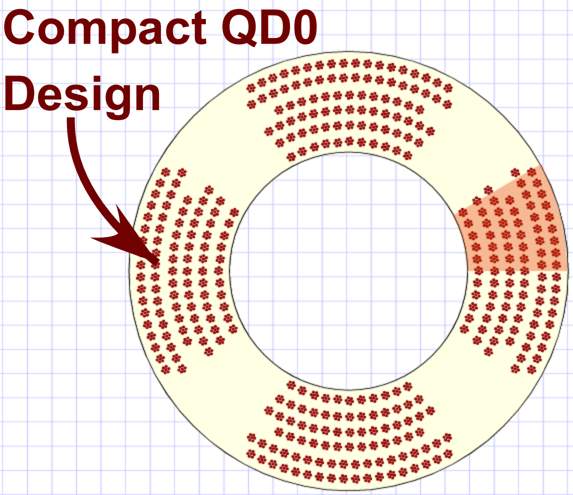
Parameter	Unit	Design	operation (max.)
Field gradient	[T/m]	240	215
Peak magnetic field	[T]	9.6	8.6
Current	[A]	8057	7150
Coil inner radius	[mm]	35	
Cold mass outer radius	[mm]	245	
Magnetic length	[m]	6.3	
Stored energy	[MJ]	~2.8	~2.2

But 31 mm radius bore.

For quadrupole with no magnetic yoke, use simple formula to estimate transfer function.

For a cos(2θ) current distribution, $G = \sqrt{3}\,\mu_o\,J\,\ln(a_2/a_1)\,/\,\pi$
$= 0.693\,J\,\ln(a_2/a_1)$
(J in A/mm² for G T/m)





a_1 = 13.3 mm
a_2 = 21.4 mm
I_o = 731 A
N/pole = 44
NI = 32.164 kA

Wedge Area = $\pi/12\,(21.4^2 - 13.3^2)$
= 73.58 mm²

For J_e = 437 A/mm²

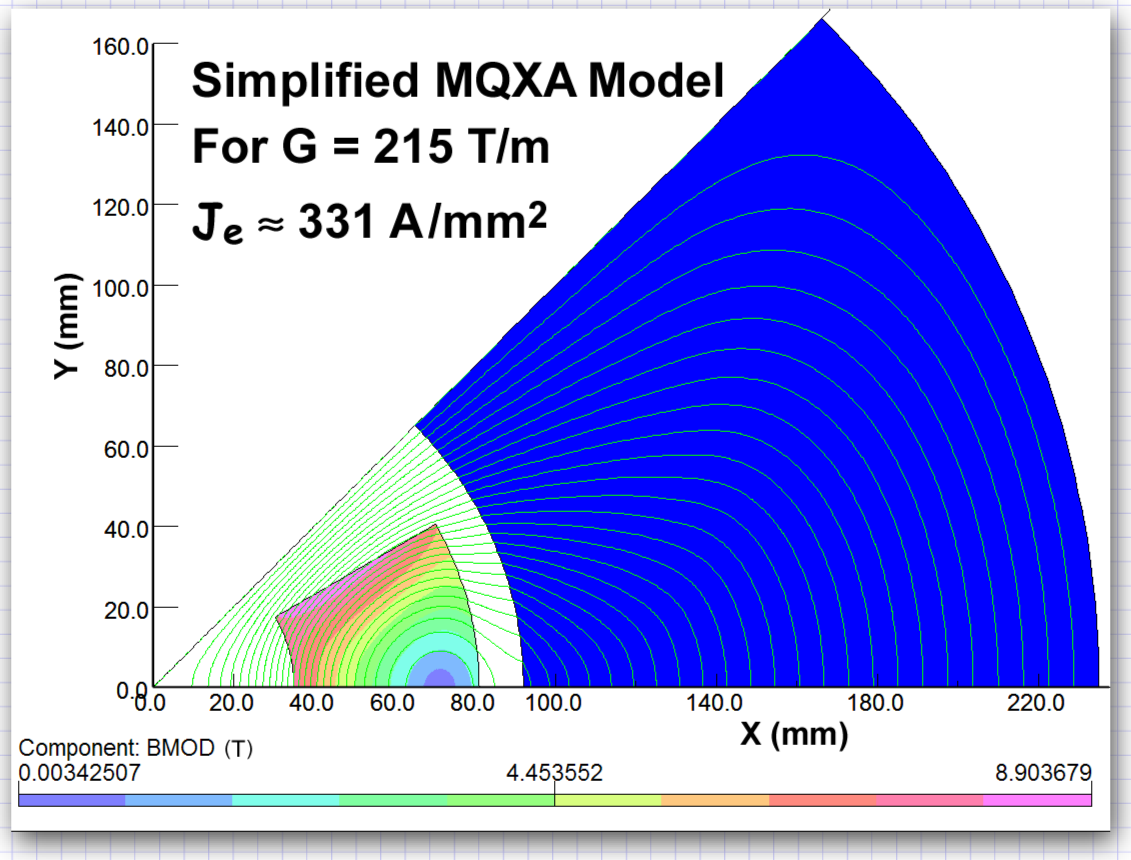
In fact the above simplified coil geometry approximates cos(2θ) fairly well.

Test: Get G = 144 T/m, the right answer.

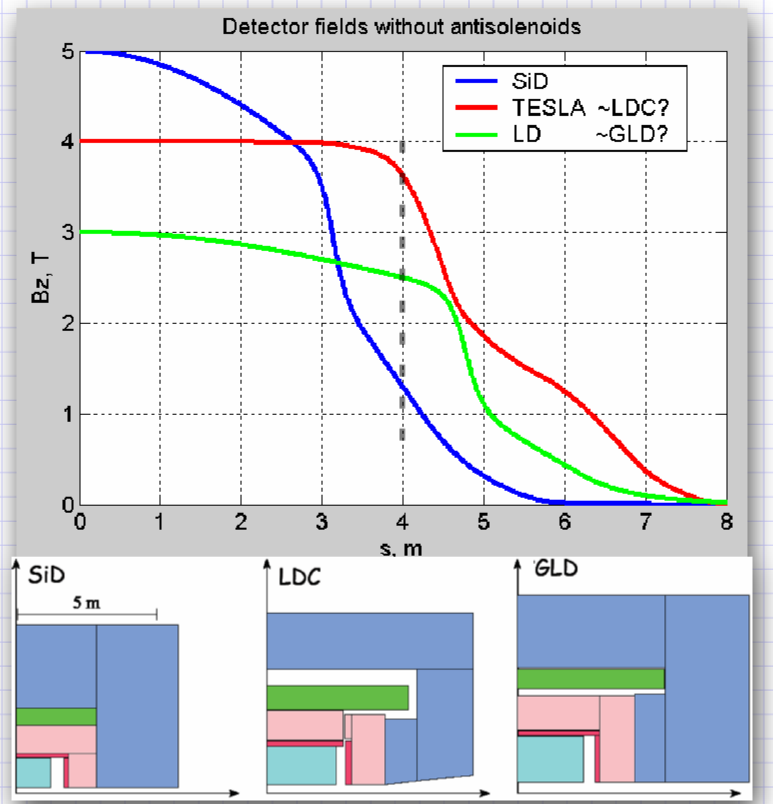
International Linear Collider

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

First lets calibrate our simplified coil model using the LHC-MQXA design.



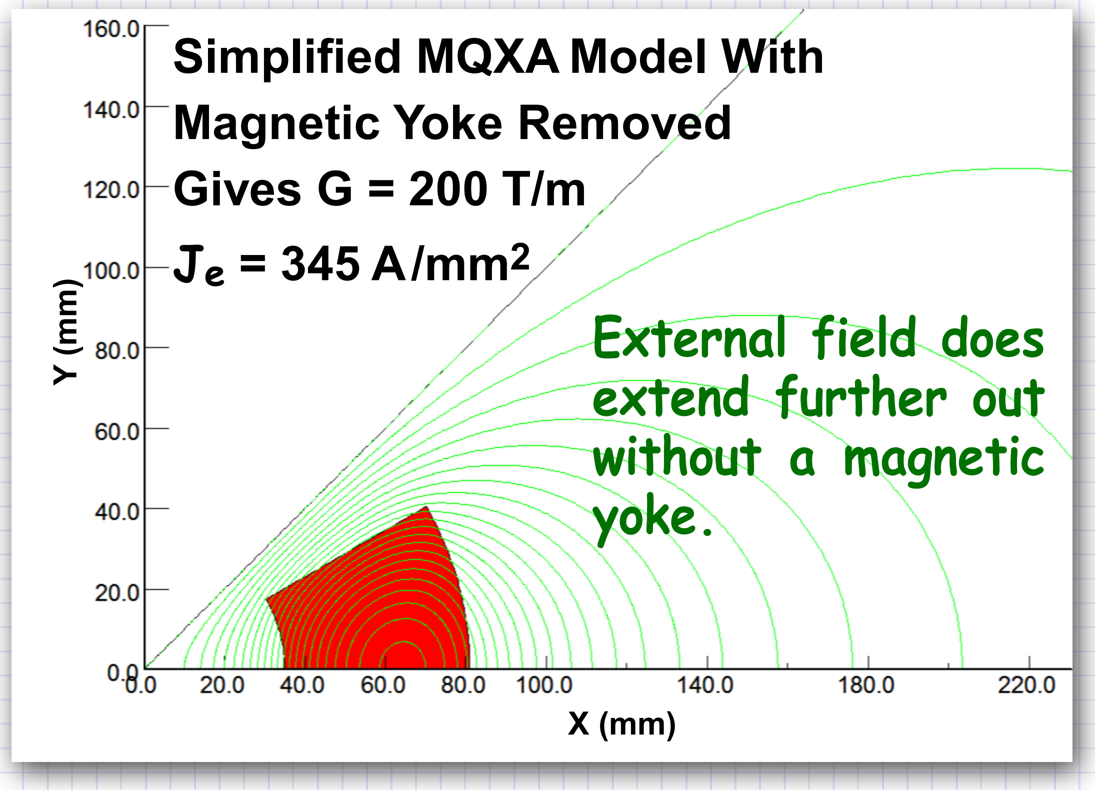
Note: With L*=4 m, QD0 sits in a 1.3-3.7 T background field so its yoke must be non-magnetic.



Simplified coil has somewhat worse harmonics and higher peak field but is adequate for our purposes and is amenable to scaling.

Information from A. Seryi

Simplified coil model for LHC-MQXA done without a magnetic yoke.



Simplified MQXA Model With Magnetic Yoke Removed Gives G = 200 T/m

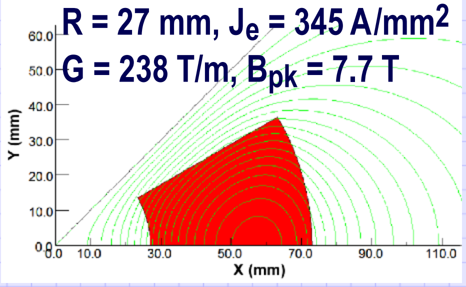
J_e = 345 A/mm^2

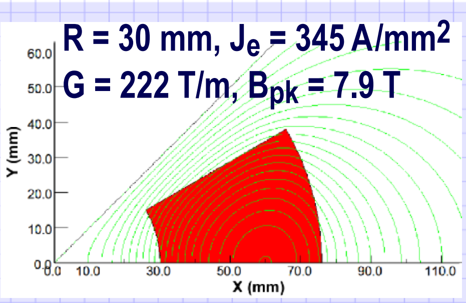
External field does extend further out without a magnetic yoke.

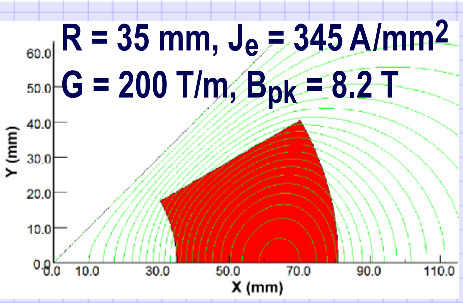
With a non-magnetic yoke and 331 A/mm^2 the gradient drops to 192 T/m. But since the peak field also goes down, we can increase J_e to make up some of this difference. Final result is 200/215 = 93% of the gradient with a magnetic yoke. At 4.8 T the inner yoke is so saturated that it does not contribute much to the transfer function; however, it does help to reduce the external field significantly.

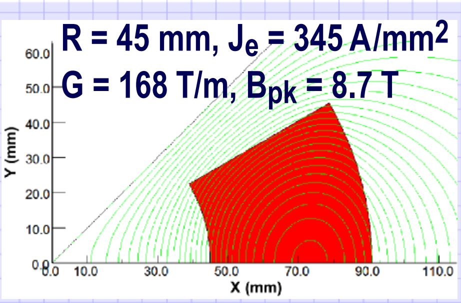
Since original MQXA coil was quite complicated, when scaling to larger apertures do not increase the number of coil layers but keep the coil thickness constant. Due to logarithmic dependence on radius ratio for thick coils results are not very sensitive to this assumption.

Several calculations using simplified coil model for different coil inner radii.

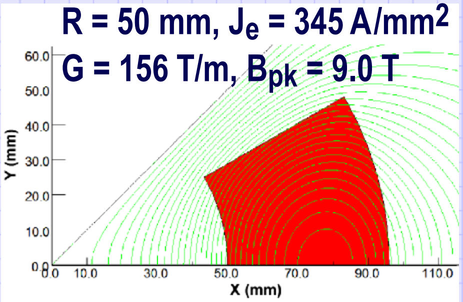

R = 27 mm, J_e = 345 A/mm^2
G = 238 T/m, B_{pk} = 7.7 T

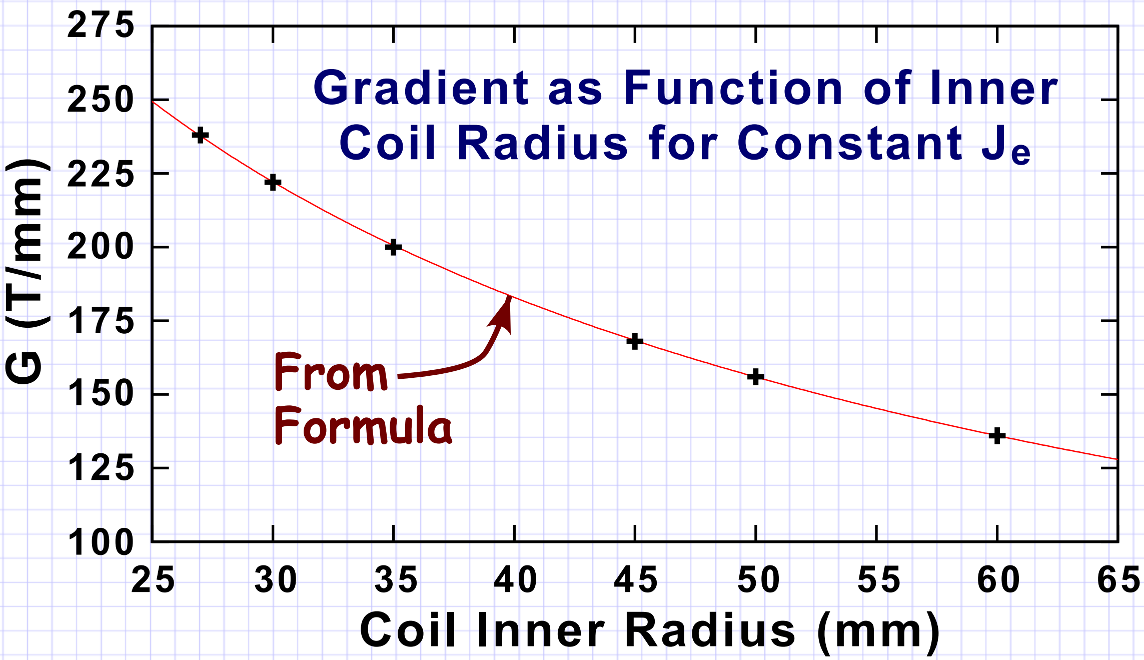

R = 30 mm, J_e = 345 A/mm^2
G = 222 T/m, B_{pk} = 7.9 T


R = 35 mm, J_e = 345 A/mm^2
G = 200 T/m, B_{pk} = 8.2 T

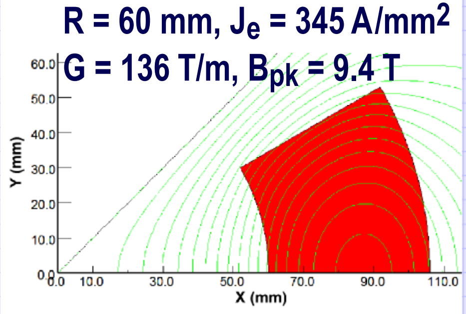

R = 45 mm, J_e = 345 A/mm^2
G = 168 T/m, B_{pk} = 8.7 T

Here with constant J_e, $G \approx 239 \ln(1+46/R)$ in T/m


R = 50 mm, J_e = 345 A/mm^2
G = 156 T/m, B_{pk} = 9.0 T

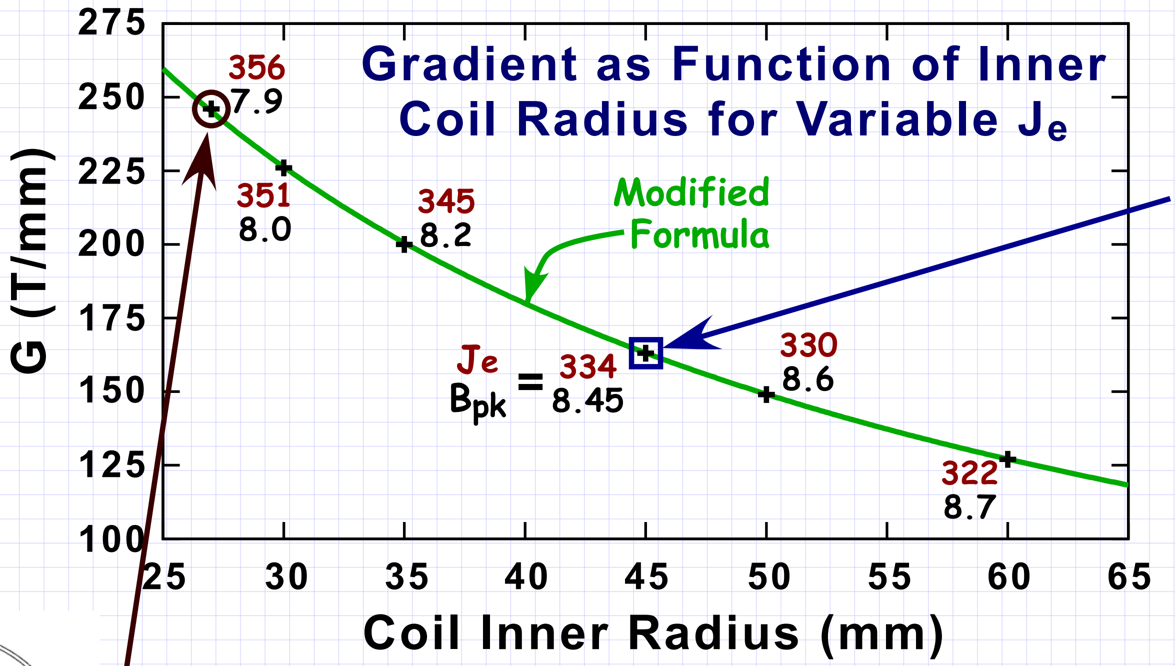

Gradient as Function of Inner Coil Radius for Constant J_e

From Formula

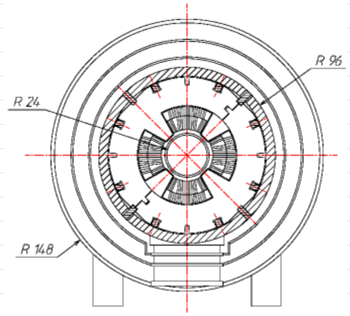

R = 60 mm, J_e = 345 A/mm^2
G = 136 T/m, B_{pk} = 9.4 T

Revised calculation accounting for dependence of current density on B_{pk}.

J_e was tuned at 35 mm radius but changing the radius also causes a change in B_{pk}. Use variable $J_e = 345. - 42\ln(R/35)$ to approximately account for this.

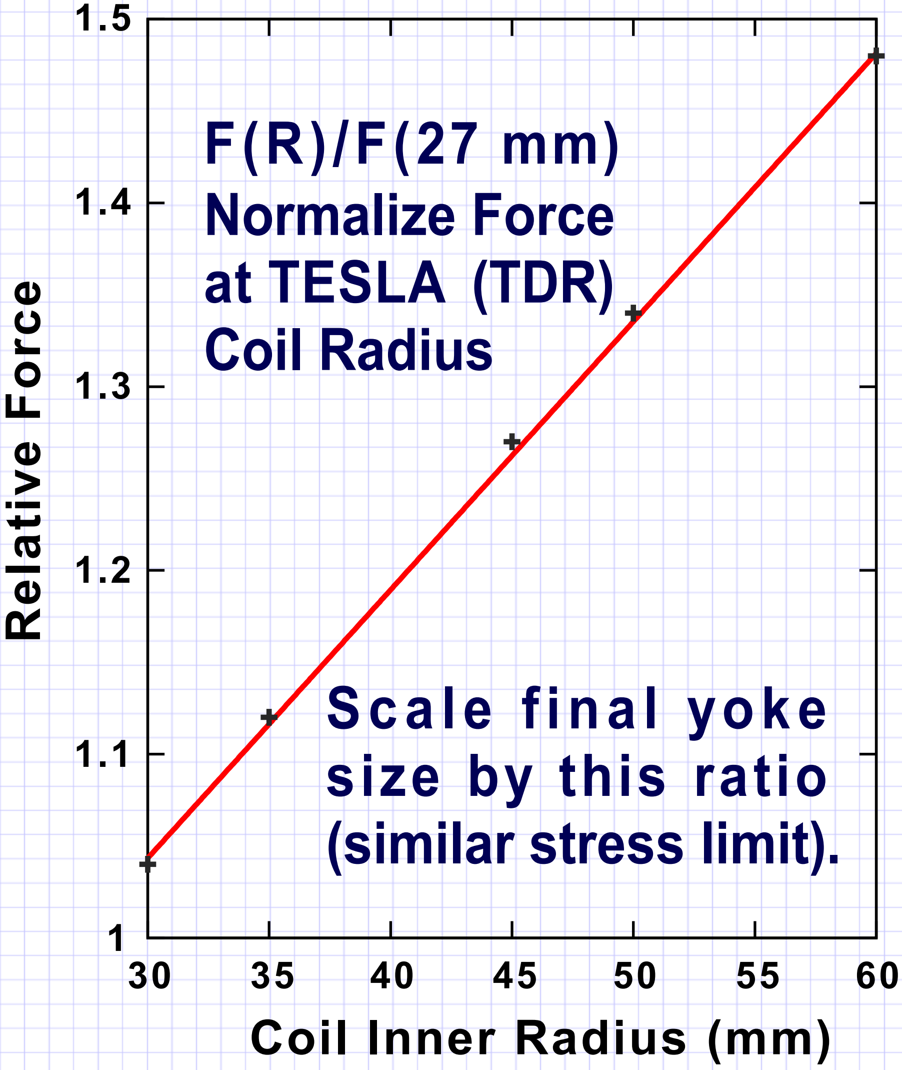


For a 45 mm inner coil radius G = 163 T/m.



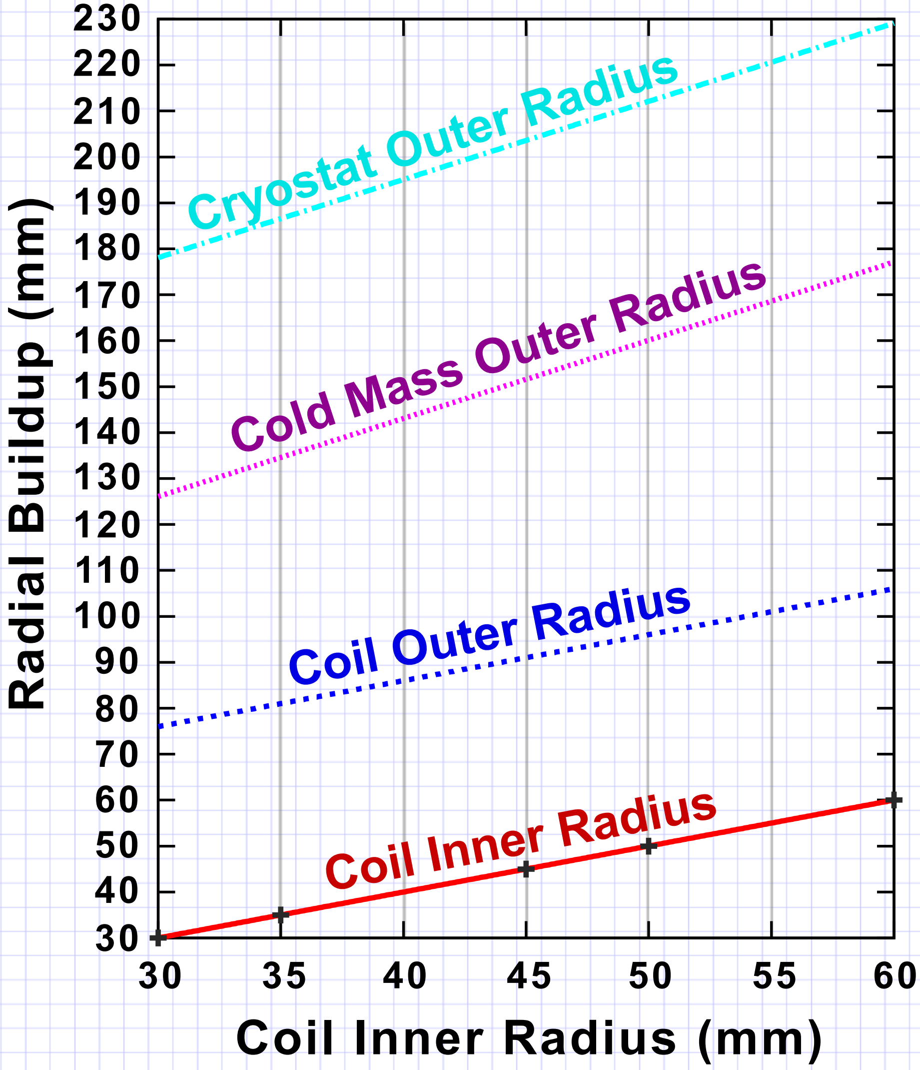
From this TESLA TDR figure we see that the inner coil radius is ≈ 27 mm and our scaled gradient is close to the 250 T/m TDR value.

Simple Model: Rescaling TESLA TDR design with the inner coil aperture.



F(R)/F(27 mm)
Normalize Force at TESLA (TDR) Coil Radius

Scale final yoke size by this ratio (similar stress limit).



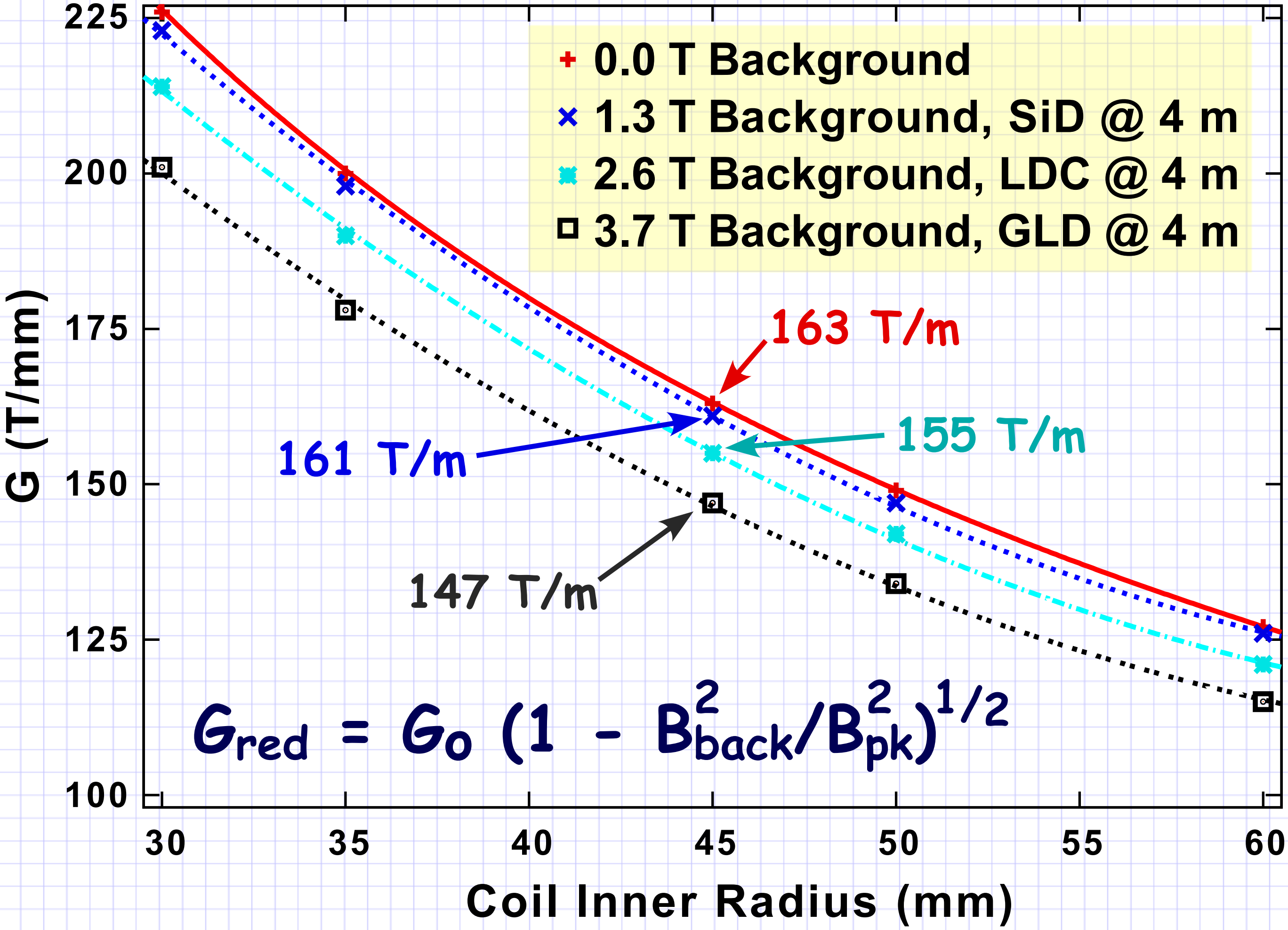
Magnet Size: Scale TDR yoke according to force & add fixed cryostat.

International Linear Collider

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

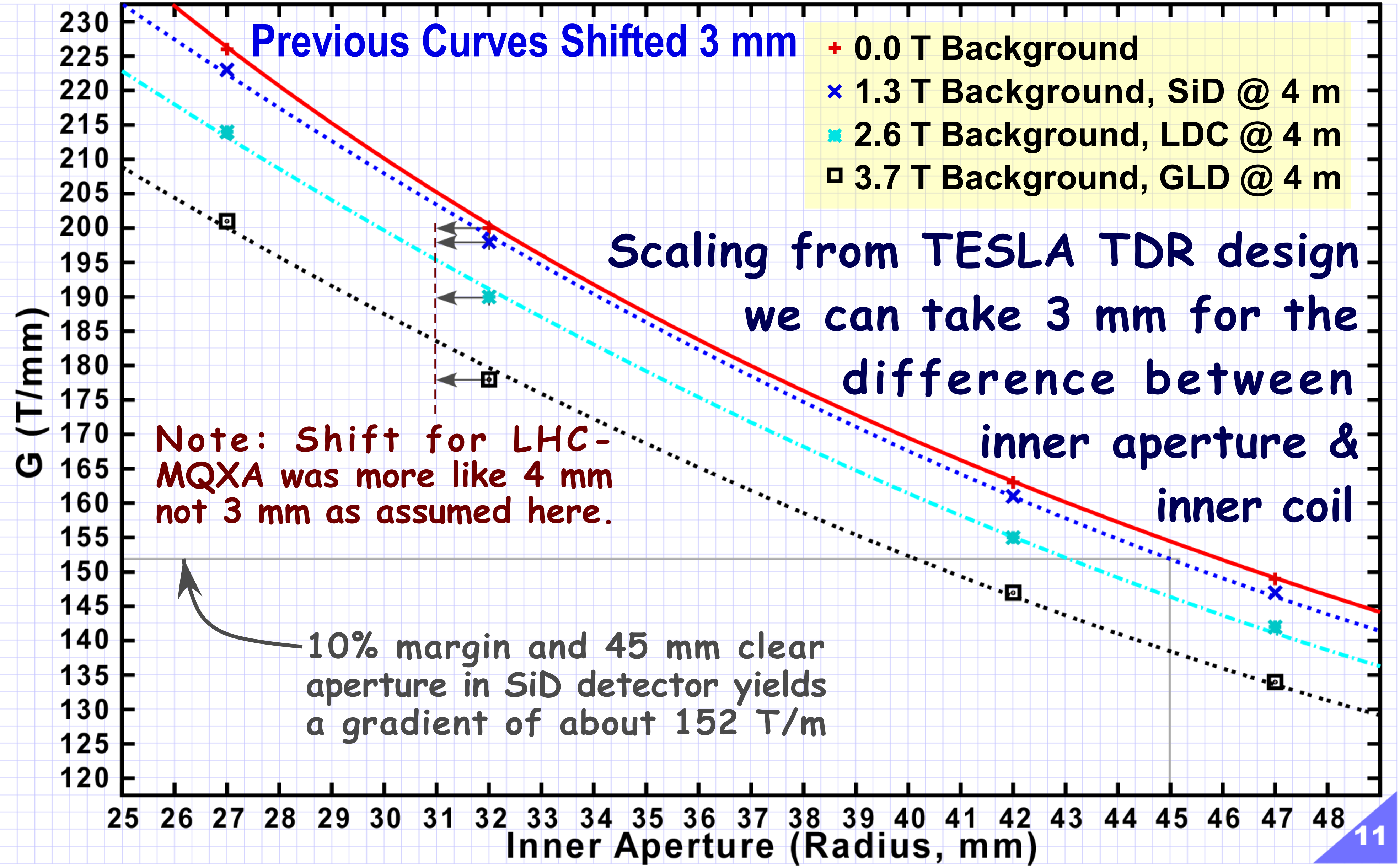
Adjusting gradient to account for different background field assumptions.



$$G_{red} = G_0\,(1 - B^2_{back}/B^2_{pk})^{1/2}$$

Assume: Go to same total peak field with/without longitudinal background field added in quadratue and scale the gradient accordingly.

Same calculation as before, but as a function of aperture, not coil radius.



Previous Curves Shifted 3 mm

Scaling from TESLA TDR design we can take 3 mm for the difference between inner aperture & inner coil

Note: Shift for LHC-MQXA was more like 4 mm not 3 mm as assumed here.

10% margin and 45 mm clear aperture in SiD detector yields a gradient of about 152 T/m

Some final comments.

Yes, it is possible to use Nb_3Sn or HTS at higher fields but for higher gradients we will need even thicker coils. Since these conductors are brittle and sensitive to strain we should start dedicated R&D programs (i.e. don't just assume LHC upgrade in 2015 will solve all ILC challenges).

Too simple a scaling law, i.e. "≈8 T field at the coil radius" sometimes underestimates a "state-of-the-art coil" but if important considerations are left out, it is very easily to over-estimate the achievable gradient.

Even the simple coil model considered here is not a perfect substitute for doing a good point design; still... expect gains of no more than 10-15% compared to simple estimate (primarily due to peak field a bit too high).

For QD0 the background field from the solenoidal detector can have a major impact on the design. The present compact quadrupole design has contingency built in that will account for this uncertainty (and a prototype will be measured soon); the large aperture designs are much closer to the edge (thus more sensitive to such assumptions).