Higher Gradient Quads for Collider IP

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Physics and Detectors

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- Motivation
- Super-conductor properties
- Cos theta quadrupole optimization
- Aside on "block" design
- Grading super-conductor current density (p9)
- Use of exotic magnetic materials
- Application to Collider final focus
- Conclusion

Motivation

Luminosity

$$\mathcal{L} = n_{\text{turns}}\, f_{\text{bunch}} \frac{N_\mu^2}{4\pi\sigma_\perp^2}$$

$$\mathcal{L} \propto \frac{< B > P_{\text{beam}}\ N}{\epsilon_\perp\ \beta^*}$$

- We may have trouble getting $N = 2\ 10^{12}$
- We may have trouble getting $\epsilon\ =\ 25\ 10^{-6}$ m
- We may have trouble getting 7% cooling transmission

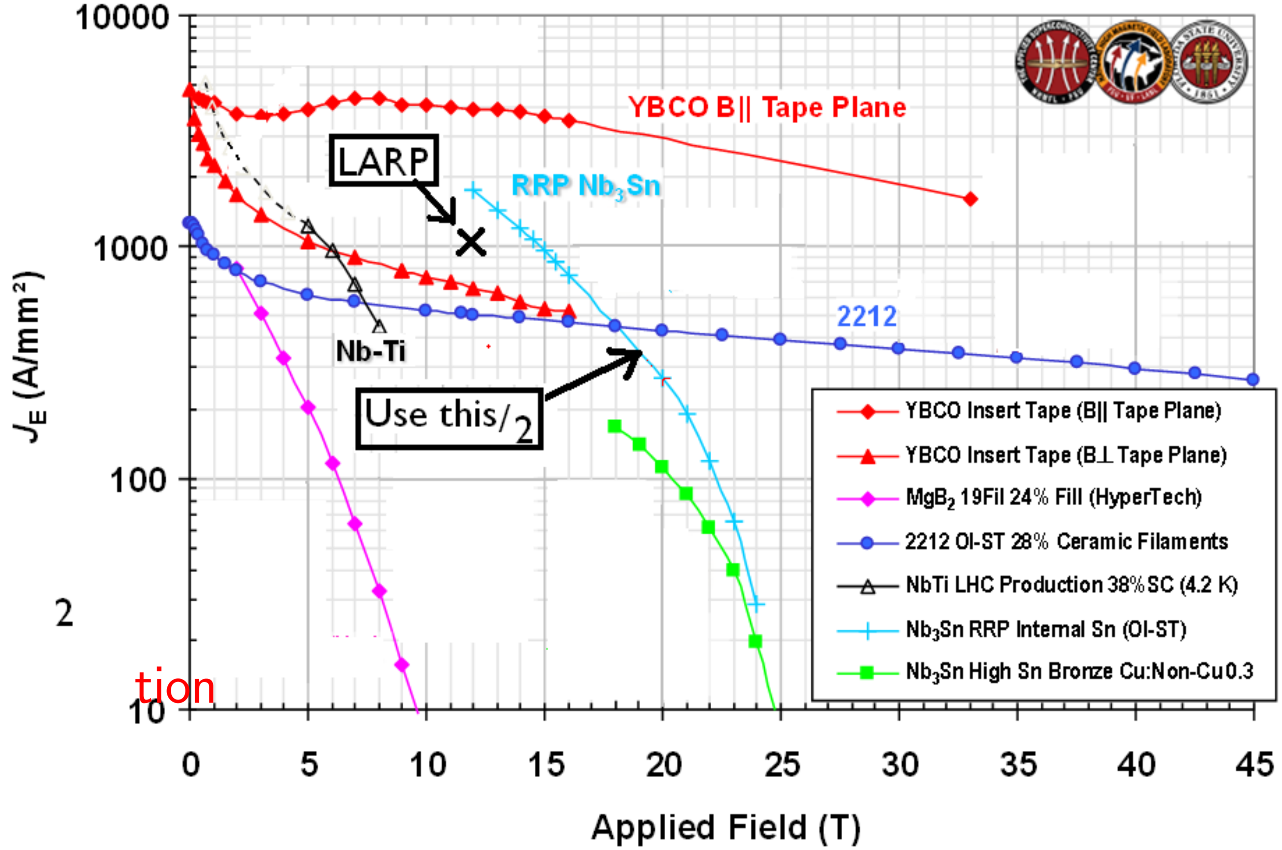
- Look for other ways to recover Luminosity
  - More proton power (Chuck)
  - Lower β^* $<<<<<<$

Advances in SC Quadrupole Design

Design of HQ – a High Field Large Bore Nb_3Sn Quadrupole Magnet for LARP

H. Felice, G. Ambrosio, M. Anerella, R. Bossert, S. Caspi, D. Cheng, D. Dietderich, P. Ferracin, A. K. Ghosh, R. Hafalia, C. R. Hannaford, V. Kashikhin, J. Schmalze, S. Prestemon, G.L. Sabbi, P.Wanderer, A.V. Zlobin

Above magnet now under construction uses conductor performance:



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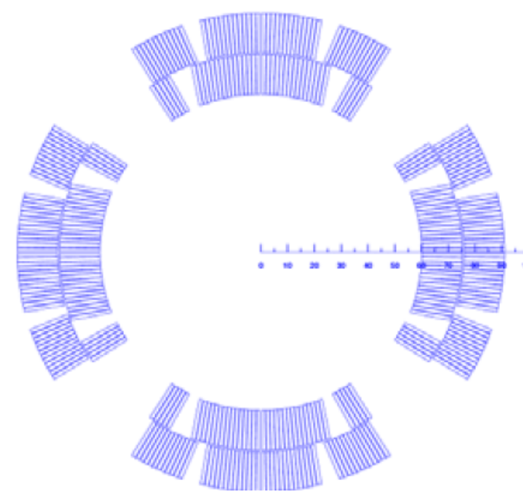
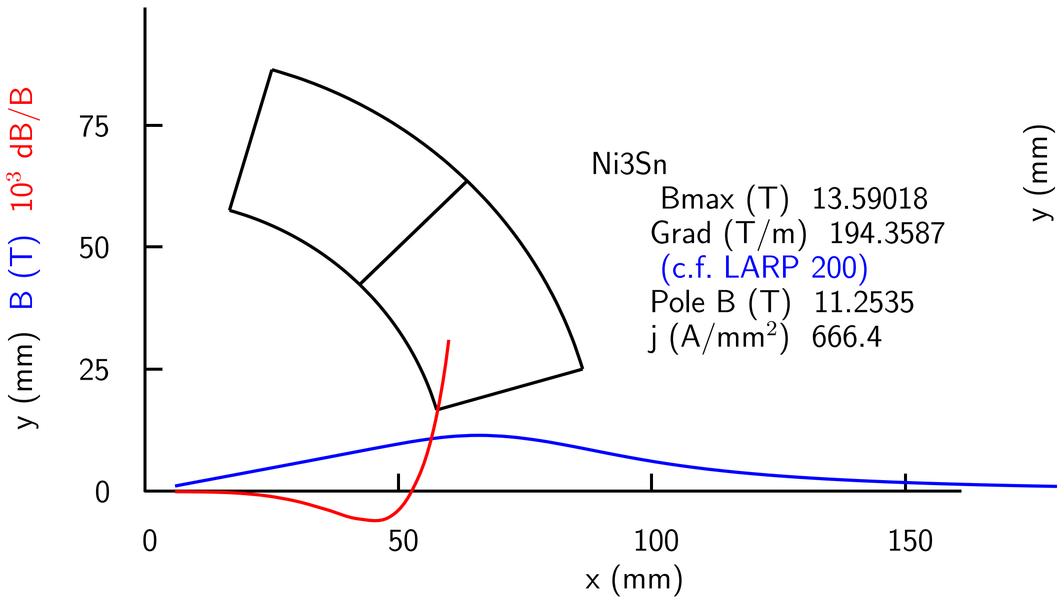
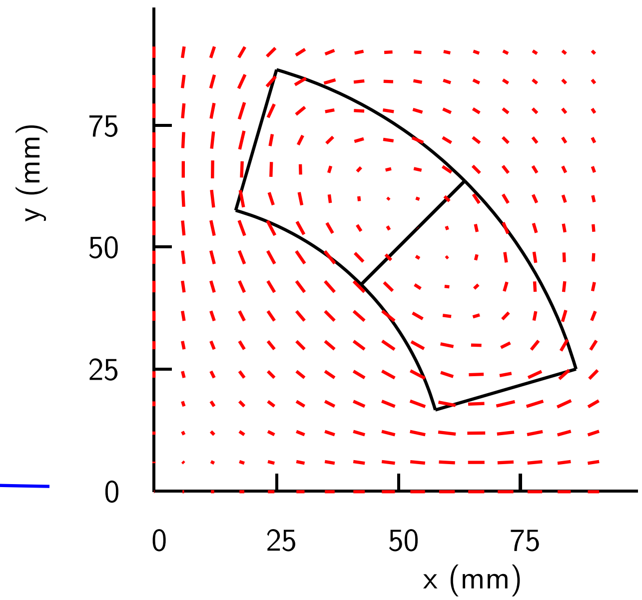


LARP Quad Cross sec-

tion

Reproduce LARP Design

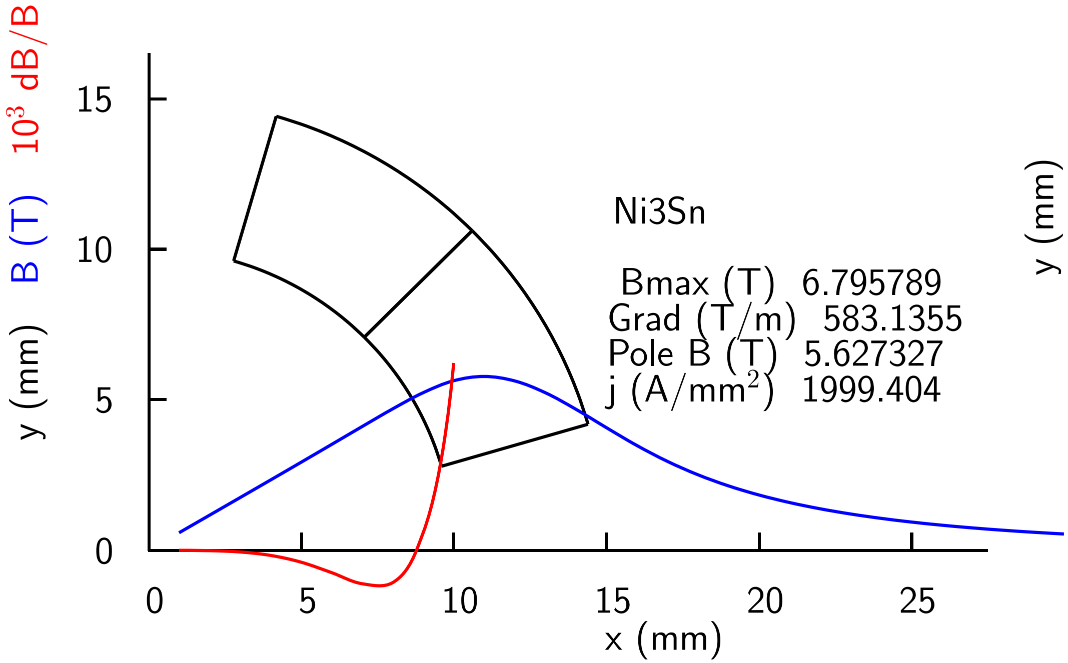




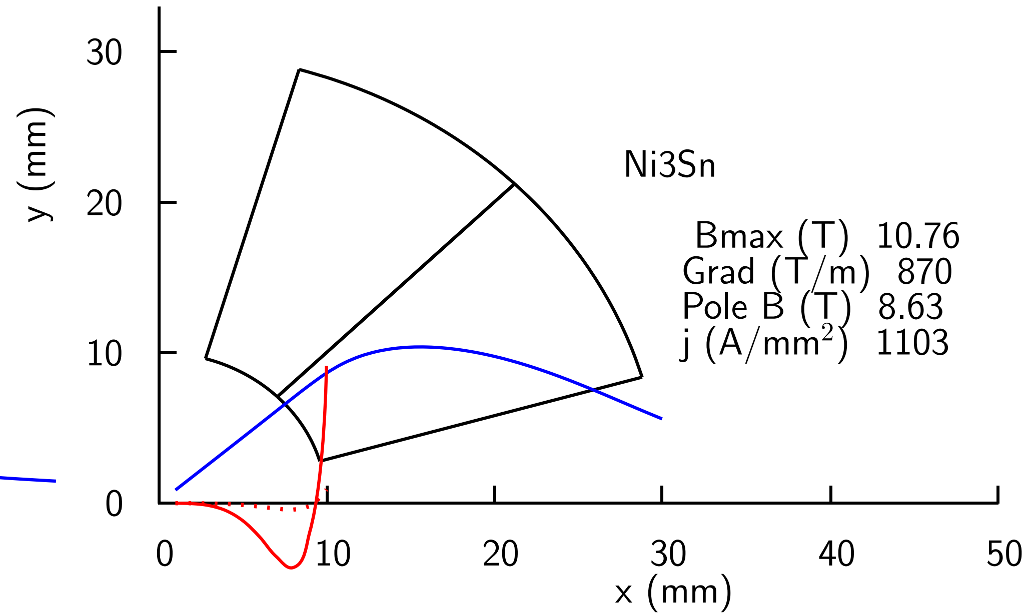
- Gradient found of 194 T/m
  c.f. LARP's 203 T/m   Good enough agreement
- Adding wedges would give required field quality
  but would not significantly change the fields

- Note field at all angles
- So YBCO is not suitable

Optimize radial thickness



Small dR/R=0.5
Grad=583

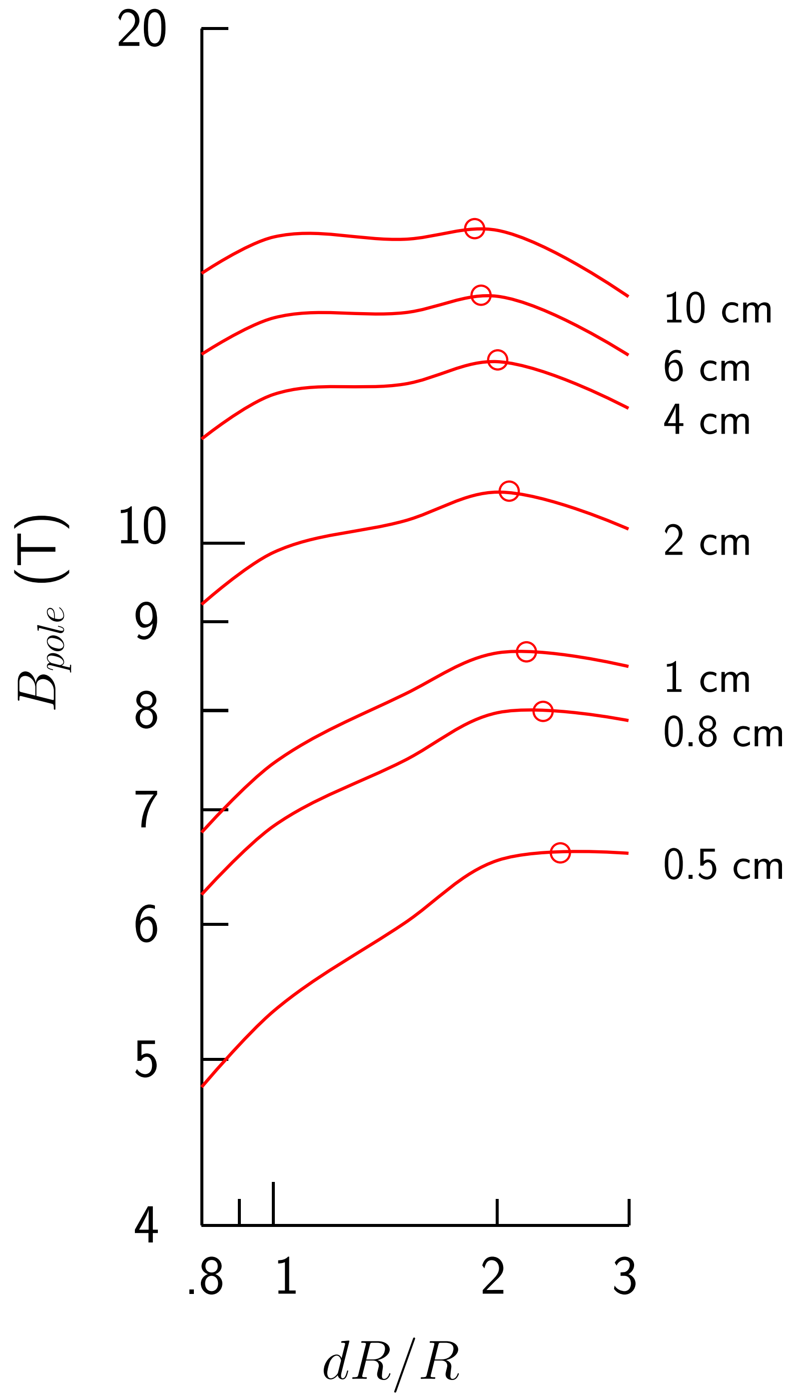


Large dR/R=2.0
Grad=870

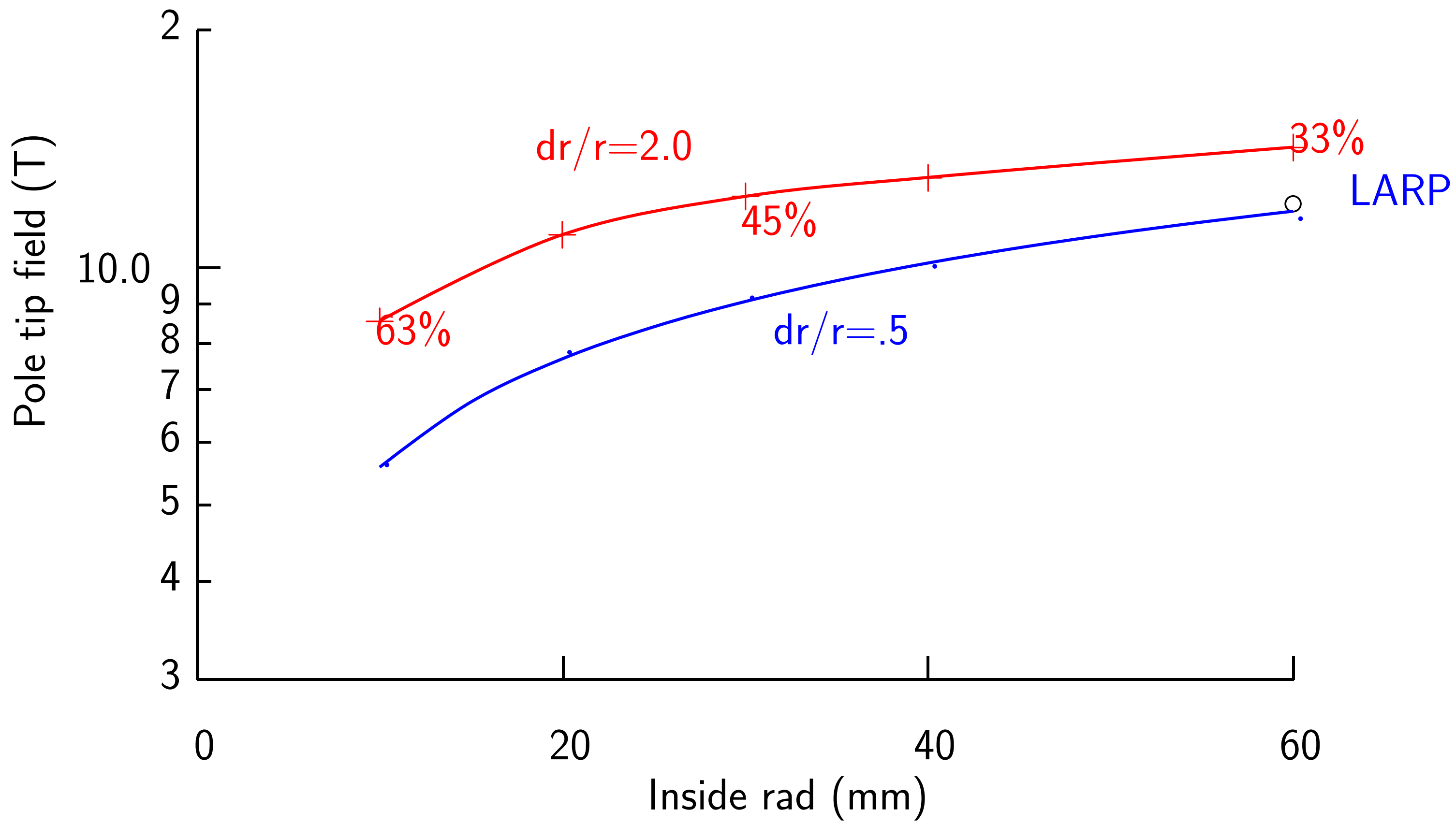
- Max fields higher in dR/R=2.0, current densities lower, but gradient still higher
- dR/R=0.5: Radial width of conductor (0.5 cm) much less than LARP (3 cm)
- dR/R=2.0: Radial width of conductor (2 cm) still less than LARP (3 cm) but key-stoning is more severe and will need R&D

For different R

- Optimum always near $dR/R = 2$
- But Large dR/R more useful at low radii

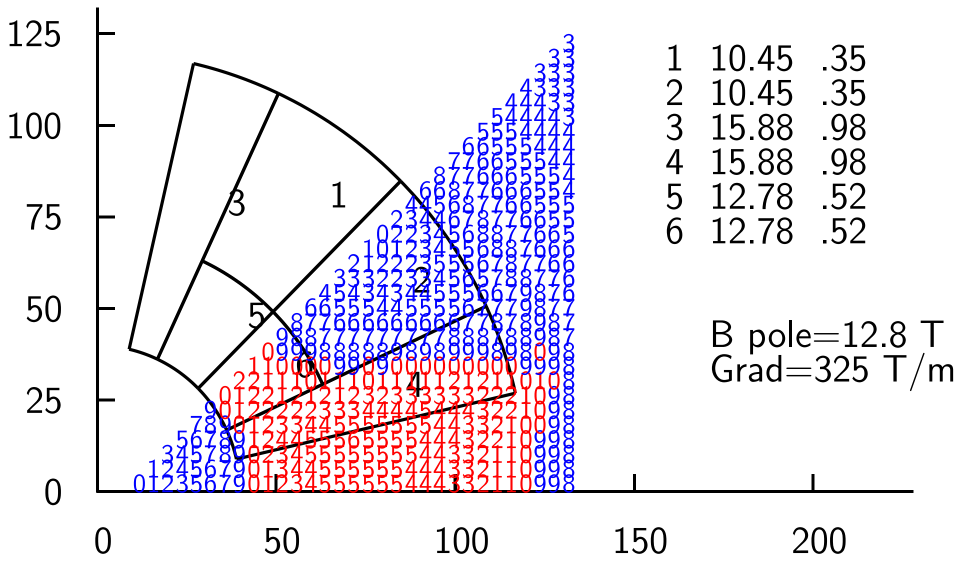


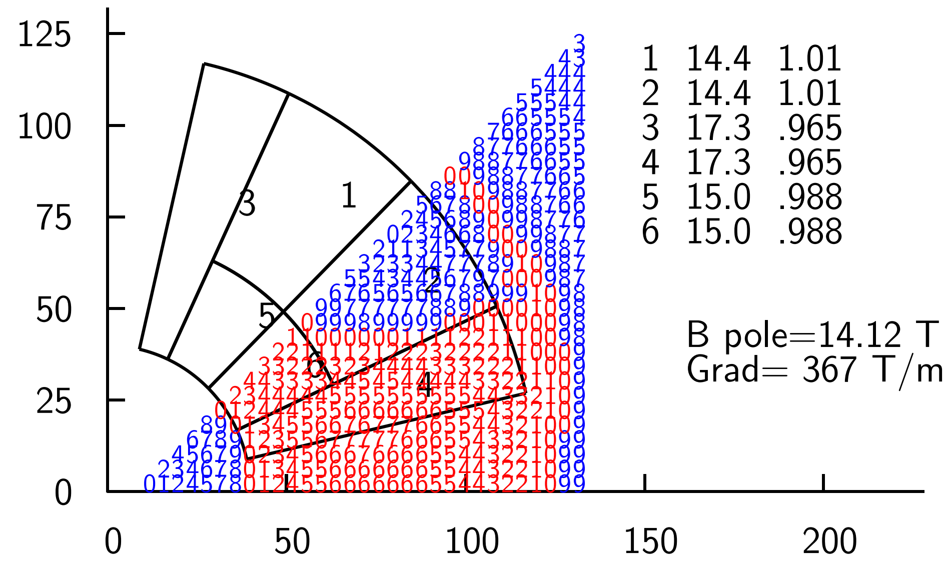
B_{pole} and Gradient vs. R



- Huge gains if radius reduced

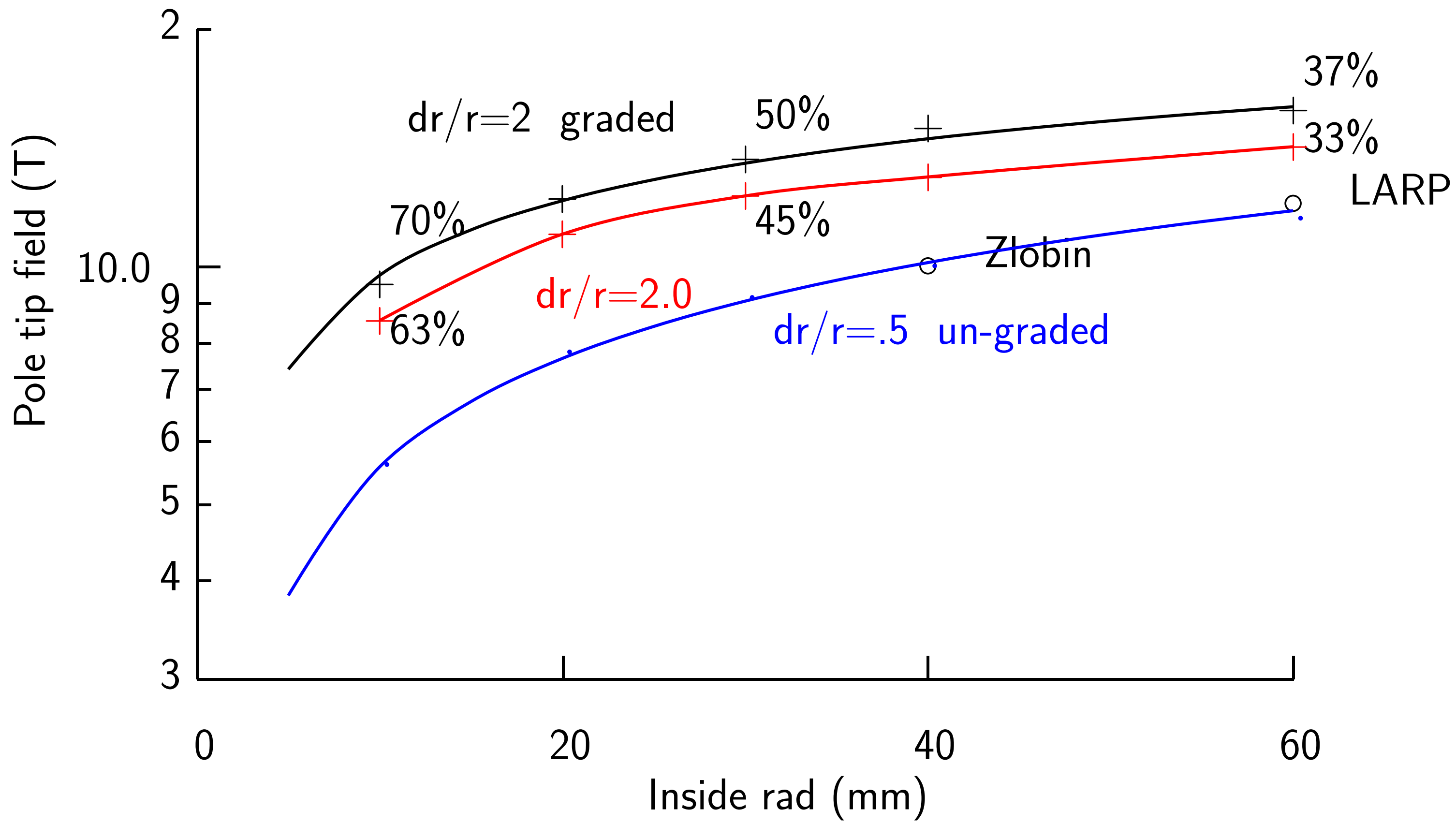
Grading super-conductor current densities





- Tables show fraction of short sample currents by block
- Without 'grading' inner blocks run far bellow maximum
- Adjusting densities by choice of cable thickness brings all blocks to same level
- Field and gradient gain is 10-15 %

Fields vs radius with grading & dr/r=2.0



- Gain from grading ≈ 10% independent of radius
- Gain including dr/r=2 greatest for small radii

Use of exotic materials for pole tips

Holmium

only becomes ferromagnetic below 20K and saturates at about 4 Tesla.

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http://en.wikipedia.org/wiki/Holmium~~
http://www.stanfordmaterials.com/ho.html
Phys. Rev. 109 (1958) 1547
http://prola.aps.org/pdf/PR/v109/i5/p1547\_1
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Dysprosium

Becomes ferromagnetic below 85K and saturates at maybe 3.5 Tesla

Physica B211 (1995) 345 "Magnetically aligned polycrystalline dysprosium as ultimate saturation ferromagnet for high magnetic field polepieces"

http://dx/doi.org/10.1016/0921-4526(94)01059-A

Gadolinium

Saturates at 3.2 T at 80 deg K

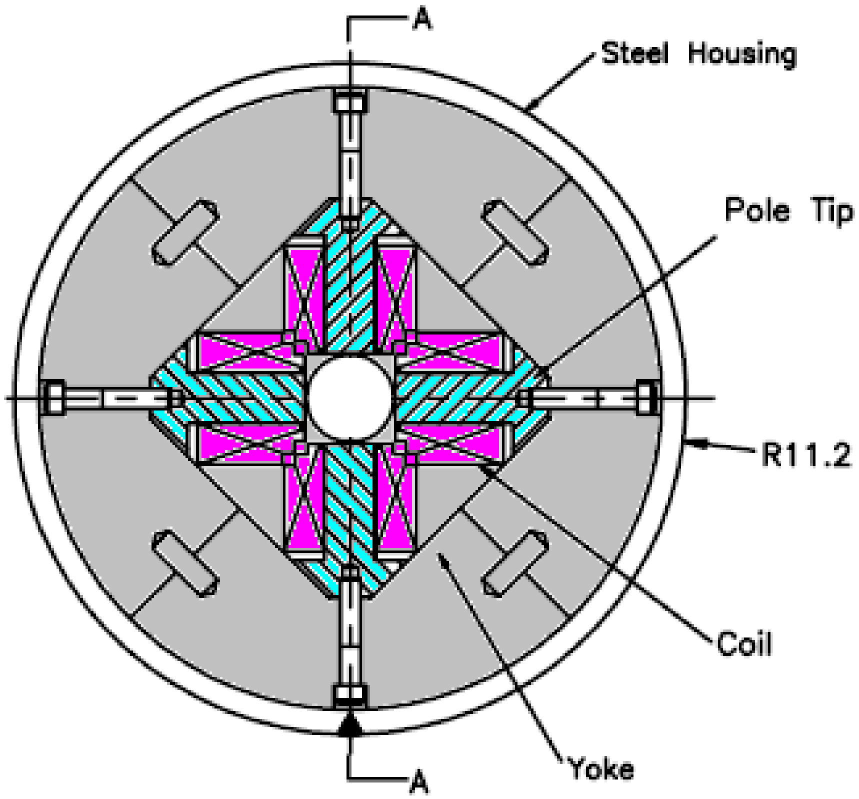
http://en.wikipedia.org/wiki/Gadolinium $130/kilogram

The Curie point is described as a phase transition.

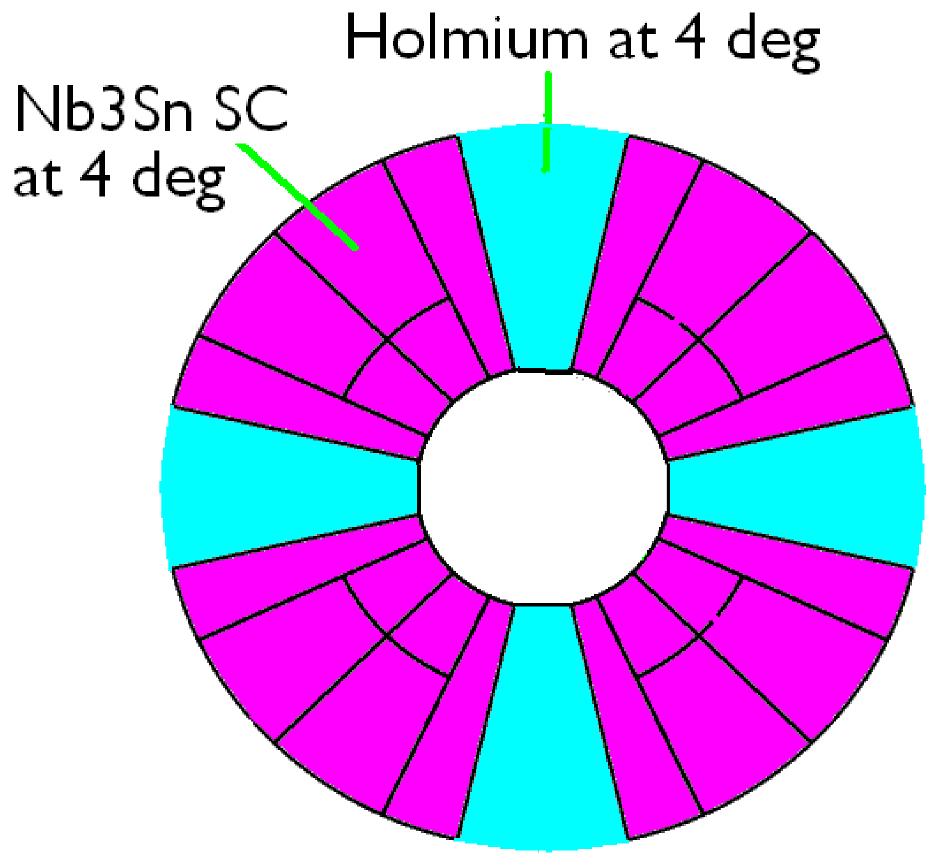
http://en.wikipedia.org/wiki/Ferromagnetic

Use of Holmium for pole within conductors

e.g. Argonne NIM A313 (1992) 311;
http://accelconf.web.cern.ch/AccelConf/p95/ARTICLES/FAQ/FAQ09.pdf
Rad=1.5 cm   Bpole=5.25 T   Grad-350 T/m



Argonne Design

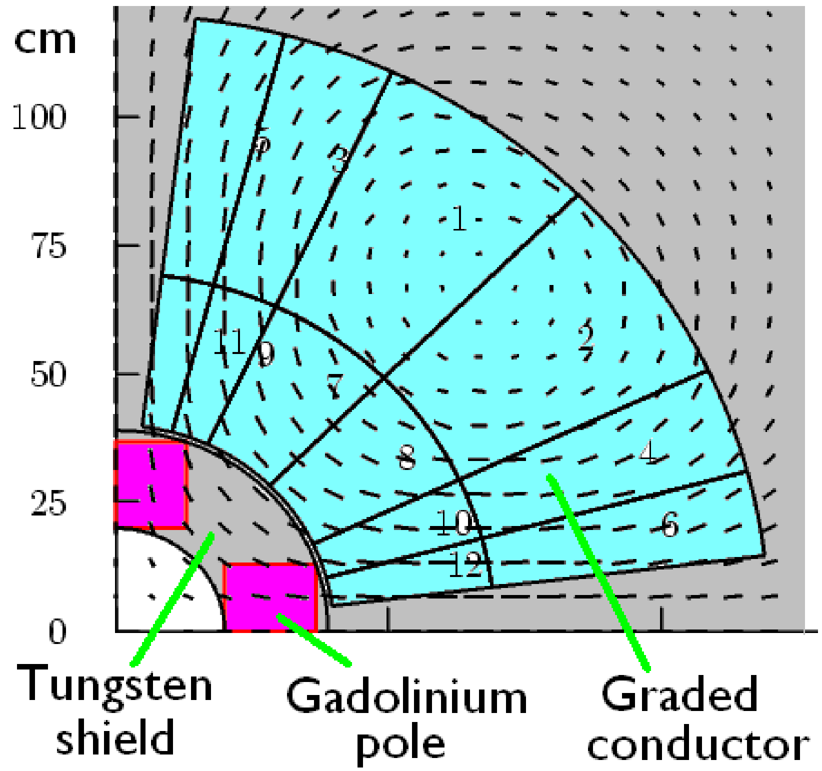


For our design: 0-5% gain

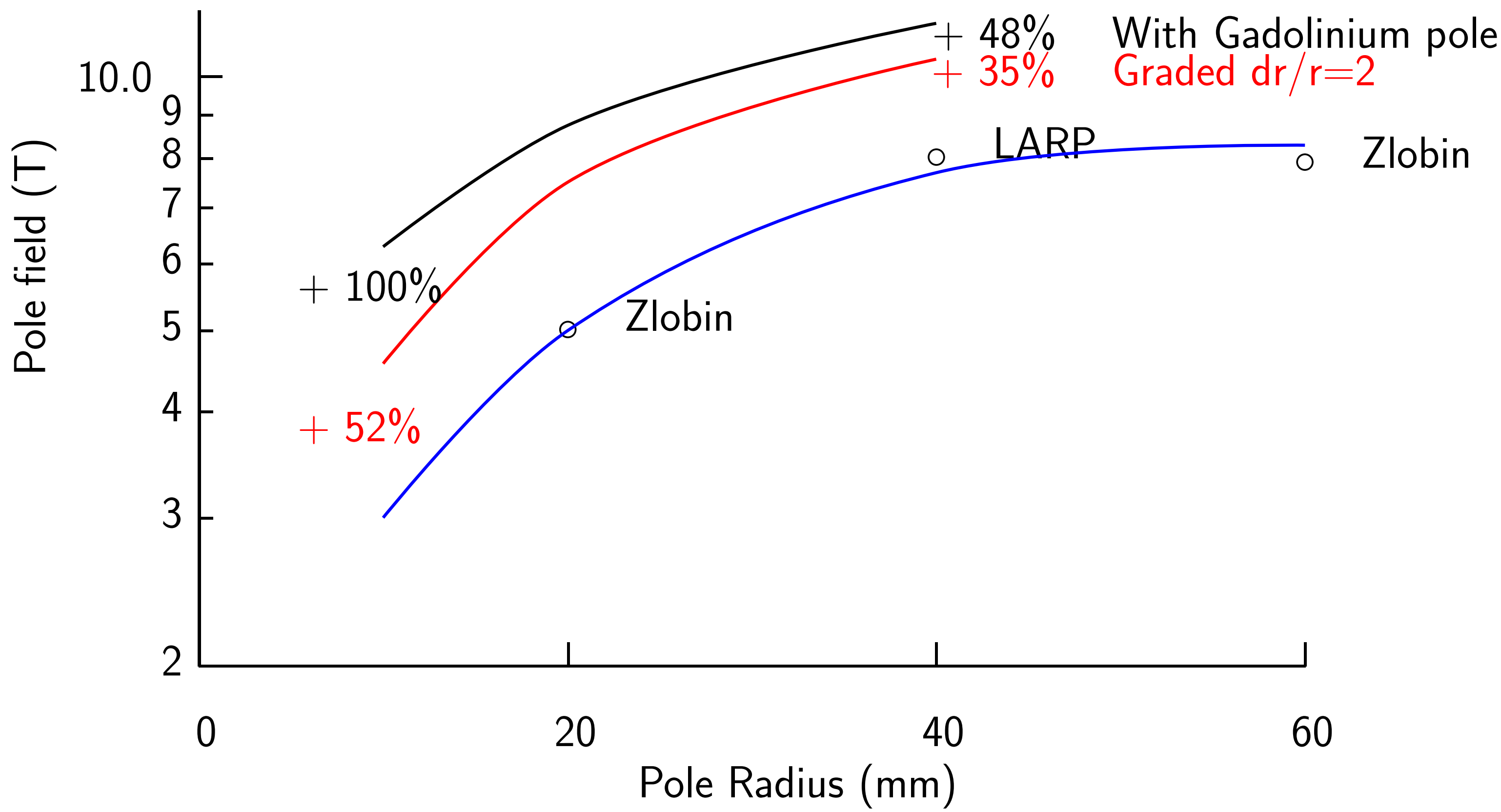
Use of Exotics if inner shield required

- Because of decay electron halo, we may need some shielding - assumed 2 cm
- Having ferromagnetic poles passing through this shielding would add significantly to the gradient
- The shielding, and poles, can not be at 4 deg for the heat load
- 70-80 degrees is probably ok
- That rules out Holmium, but leaves Gadolinium and Dysprosium as possibles

- Little or no gain from Holmium pole because gradient limited by conductor far from pole
- But significant gain from Gadolinium through shield

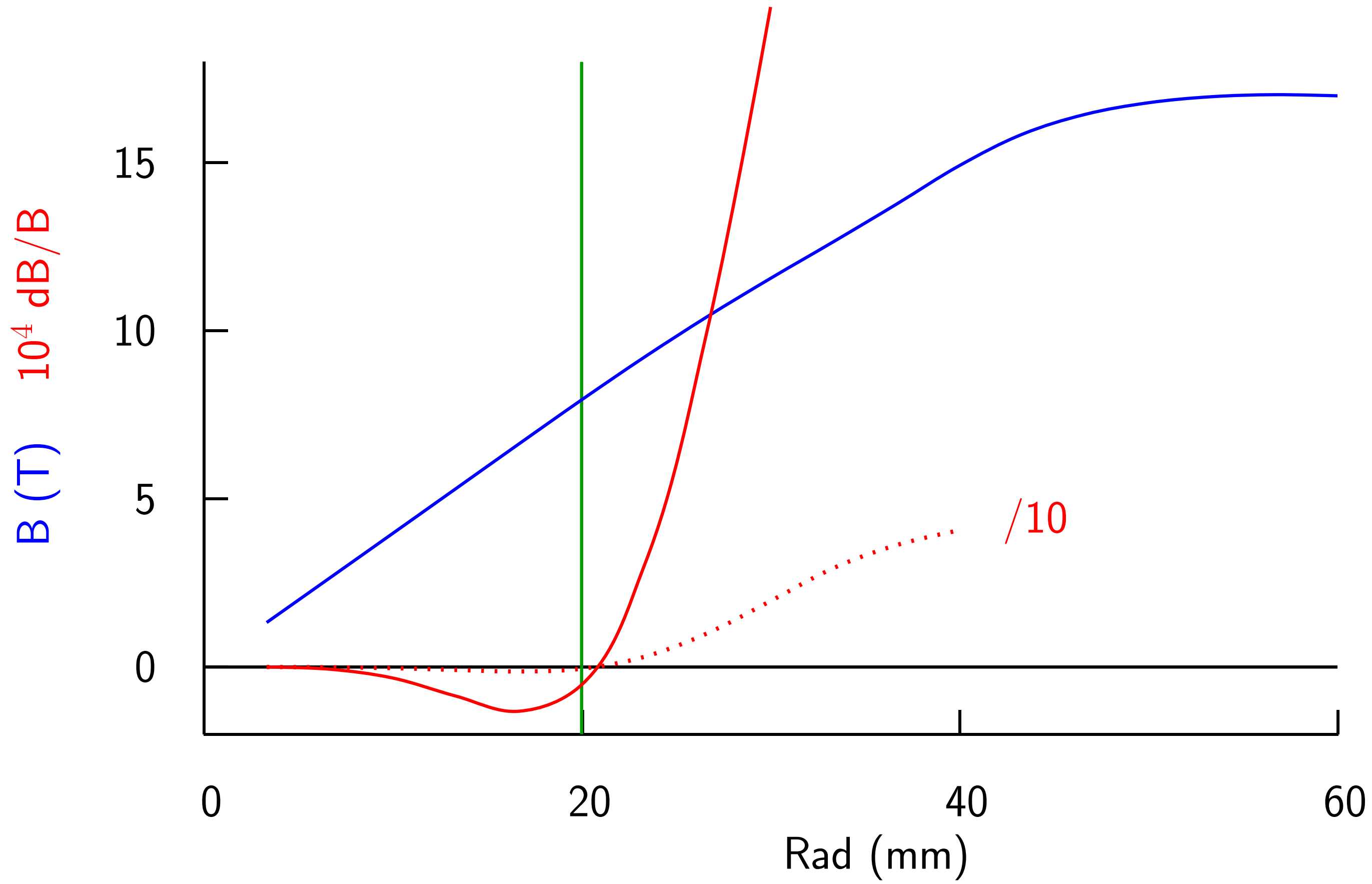


Fields vs radius with 2 cm shield



- Gain now a factor of 2 for 10 mm
- Gain a factor of 1.5 for 30 mm

field quality



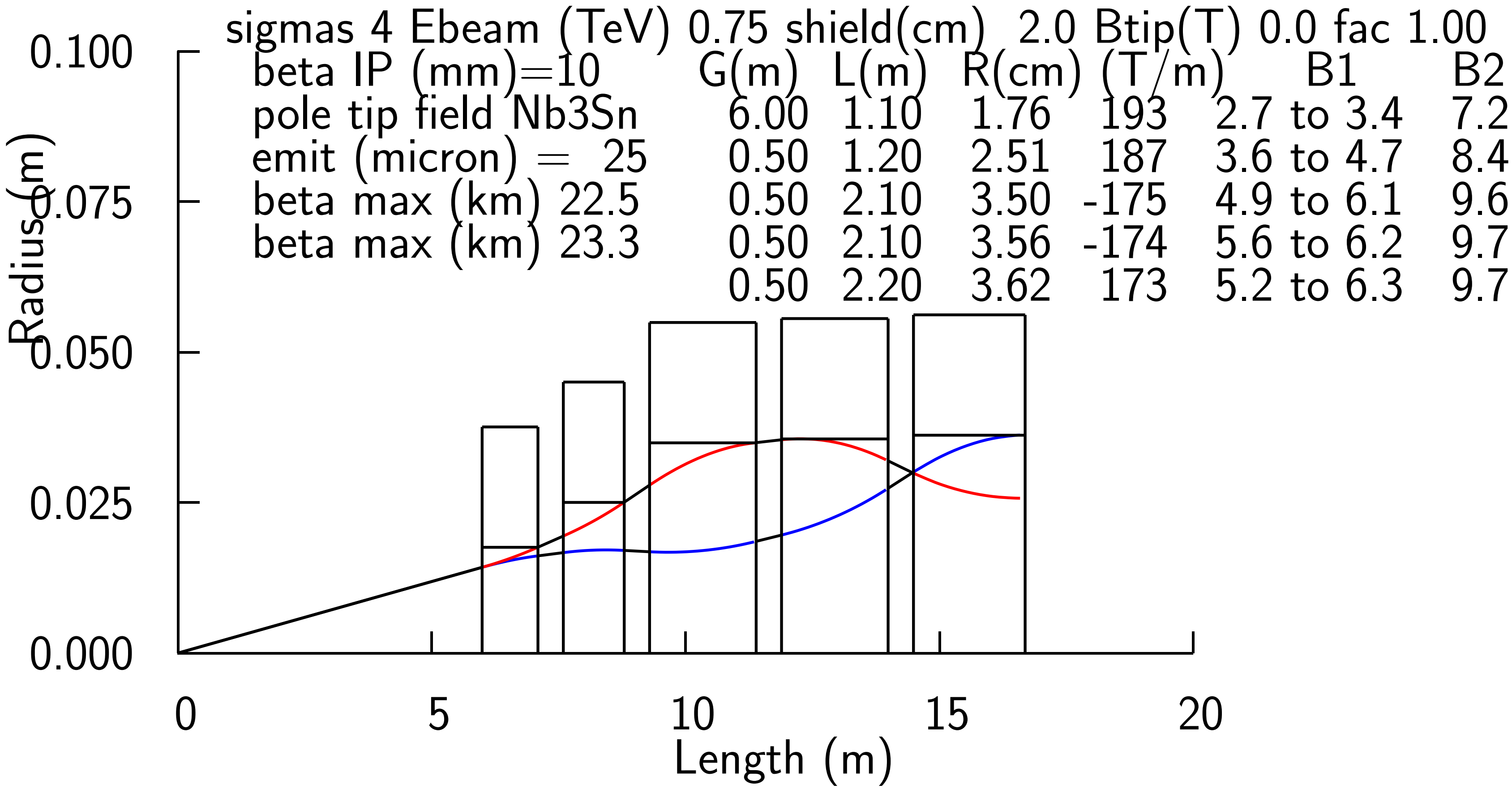
- Seems ok ($dB/B < 10^{-4}$) with square pole end
- Could be improved with pole shaping

Summary

file	graded conductor	holmium pole	Gadolinium tip	t/R	Bmax T	Grad T/m	gain %
40snh2	no	no	no	0.5	11.7	264	
40snh1	no	no	no	1.0	13.9	305	15
40snh	no	no	no	2.0	15.9	317	20
40snh	yes	no	no	2.0	15.9	365	38
40snhb	yes	yes	no	2.0	13.0	360	36
40snhc	yes	yes	yes	2.0	13.0	424	60

- Many modest gains reach a substantial increase in Gradient
- Gains are greater for smaller radii

Baseline final focus with 2cm shield and 50 cm gaps



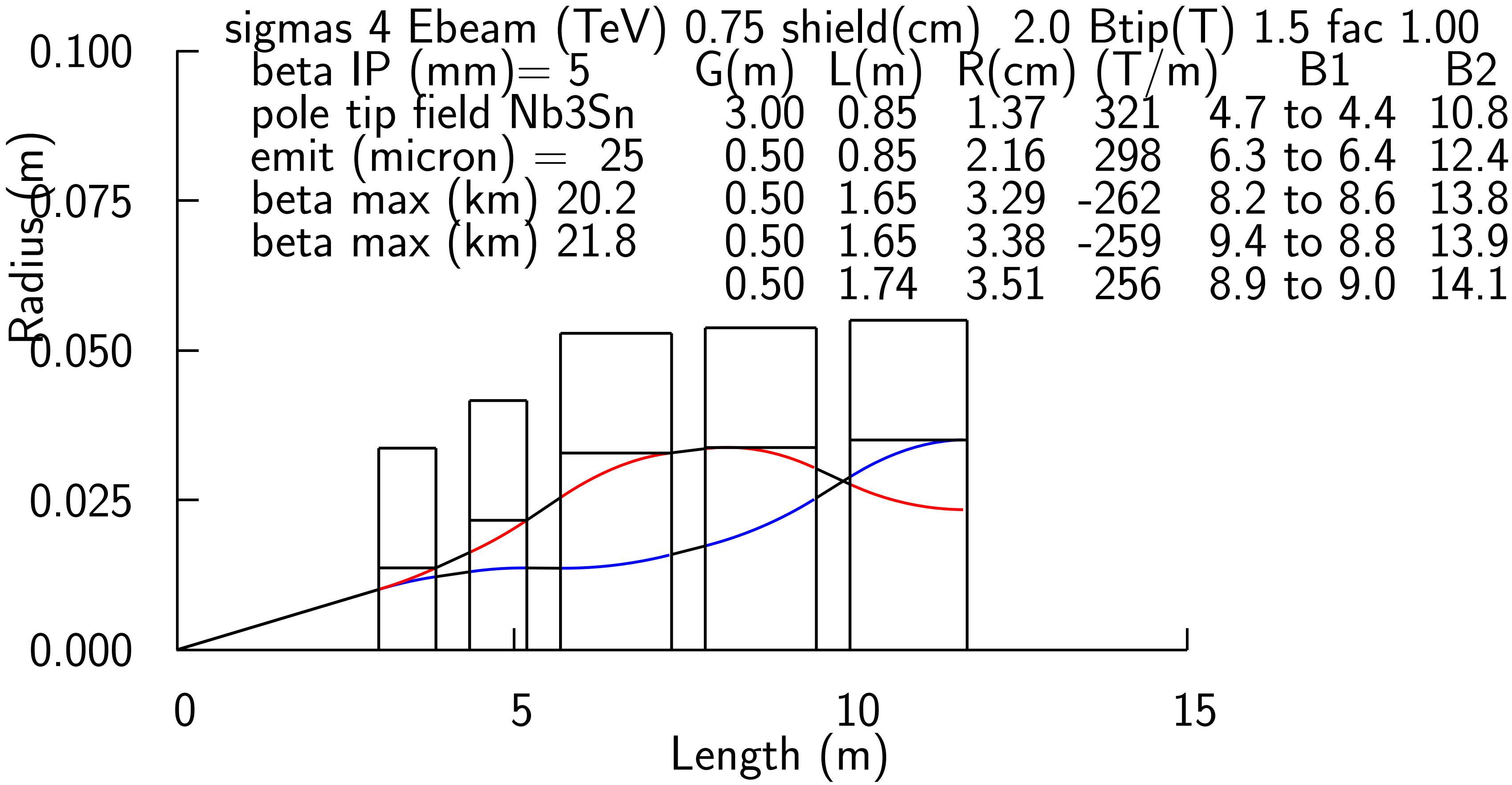
- Betamax=23 km about correct

Betamax with other magnets & distance to first quad

Dist (m)	1	3	6
Baseline		17	25
Optimized		13	18
" + Gadolinium	7.3(16)	10(20)	16

Numbers are for β^* of 10 mm except
Numbers in parentheses are for β^*=5 mm

example with 3 m to first quad including gadolinium



- Betamax=20 km is less than baseline
- But 5 mm beta star gives twice the luminosity,
- or half the background and driver requirements

Conclusion

- 200 T/m Nb_3Sn Quad under construction by LARP Using this material:
- Optimized designs give $\approx$ 20% gradient gains
- With exotic materials give $\approx$ 36% gradient gains
- If shields needed inside quads then gains of $\approx$ 60% achieved

- Use of such quads could lower $\beta*$ in collider ring

- To Do
  - Magnet simulations using code like OPERA for magnet material saturation
  - MARS study of needed shielding