# Accelerator and optimization issues for a 100 TeV pp collider

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# Abstract

Physics at higher energies needs luminosity rising as $\gamma^2$, but pile up will set practical limits to the luminosity per bunch. Thus we need higher bunch repetition i.e shorter bunch spacing. Current limitations will then imply fewer protons per bunch. To maintain the average luminosity, lower $\beta^*$s and/or lower beam emittances are be required. Coherent Electron Cooling could achieve the required lower emittances.

A magnet and linear cost model is described, based on SSC and other estimates. Using the model we find that there is a cost minimum with dipole bending fields of the same order as in the LHC ($\approx$ 8.3 T). If 20 T dipoles are used, the machine cost appears to be about a factor of three higher: a transformational difference. These conclusions are not significantly changed by component and/or tunnel costs differing by a factor of two.

Synchrotron radiation is a serious problem. Higher temperature beam screens will drive up the magnet bore size and thus cost, and perhaps hurt the vacuum. The use of open mid-plane dipoles and a remote synchrotron absorber is suggested.

More R&D is needed on cost estimation, parameter choice, and low emittance proton sources, including the use of Coherent Electron Cooling. Study of synchrotron radiation screening, including open plane dipoles, is a priority. Very high field quadrupoles and dipoles are still needed for the IPs, but their cost there is not a major problem.

# 1) INTRODUCTION

There have been several studies[1, 2, 3, 4, 5] of hadron colliders with energies above the LHC[6], some of them extensive and detailed. What will be presented here contains much from these studies, but also adds some new ideas that need developing.

The talk is in three parts:

- Consideration of luminosity and pile up requirements, leading into a discussion of the need for cooling.
- An estimation of the bending field strengths that would, given a green site, minimize the overall cost.
- A discussion of the synchrotron radiation, leading up to a proposal using open mid-plane dipoles.

To illustrate these ideas, a speculative parameter list is given in the first appendix.

# 2) LUMINOSITY

$$\mathcal{L} \ \propto \ \frac{\gamma \ I}{\beta^*} \Delta\nu \qquad I \ \propto \ (f \ N_p) \qquad \Delta\nu \ \propto \ \left(\frac{N_p}{\epsilon_\perp}\right)$$

where $f$ = bunch frequency, $N_p$ = protons per bunch, $\epsilon_\perp$ = normalized rms transverse emittance, $\beta^*$ = IP Courant-Snyder function, $\Delta \ \nu$ = beam-beam tune shift, and $I$ = beam current

Fundamental cross sections fall with $1/\gamma^2$, so lumiosity should rise as $\gamma^2$. Going from LHC at 14 TeV to 100 TeV we need:

$$\mathcal{L}_{100} \ \geq \ 1 \ 10^{34} \ \times \ \left(\frac{100}{14}\right)^2 \ = \ 5 \ 10^{35} \quad (\mathrm{cm}^{-2}\mathrm{s}^{-1})$$

With fixed $I$ and $\Delta\nu$ this requires

$$\beta^*_{LHC} = 55(\mathrm{cm}) \quad \rightarrow \quad \beta^*_{this} \approx 5.5(\mathrm{cm})$$

(c.f. $\beta^*$=5 (mm) in 3 a TeV muon collider lattice[8].)

Being 10 times the luminosity discussed at CERN[2] this would be transformational. But radiation at the IP will be "interesting"[7].

# Required Luminosity per Bunch Crossing

Again:

$$\mathcal{L} \propto \frac{\gamma\ I}{\beta*} \Delta\nu \qquad I \propto (f\ N_p) \qquad \Delta\nu \propto \left(\frac{N_p}{\epsilon_\perp}\right)$$

With the luminosity goal of $5\ 10^{35}\ \mathrm{cm}^{-2}s^{-1}$ and an LHC like bunch spacing ($\approx 25ns$), the event pile up is excessive ($\approx\ 1700$). Only by increasing $f$ by 10 (bunch spacing 2.5 ns) and decreasing $N_p$ by $1/10$ can the pile up be constrained with a fixed current $I$.

To keep the total luminosity at the goal, we must, and now can, reduce emittance $\epsilon_\perp$ from 3.75 $\mu m$ to 0.43 $\mu$m. These and more parameters are given in the Appendix 1.

With such little bunch separation, electron cloud formation will be a challenge. However, the low bunch charge and proposed extraction of synchrotron radiation (see section 4.) should help.

# Luminosity Evolution

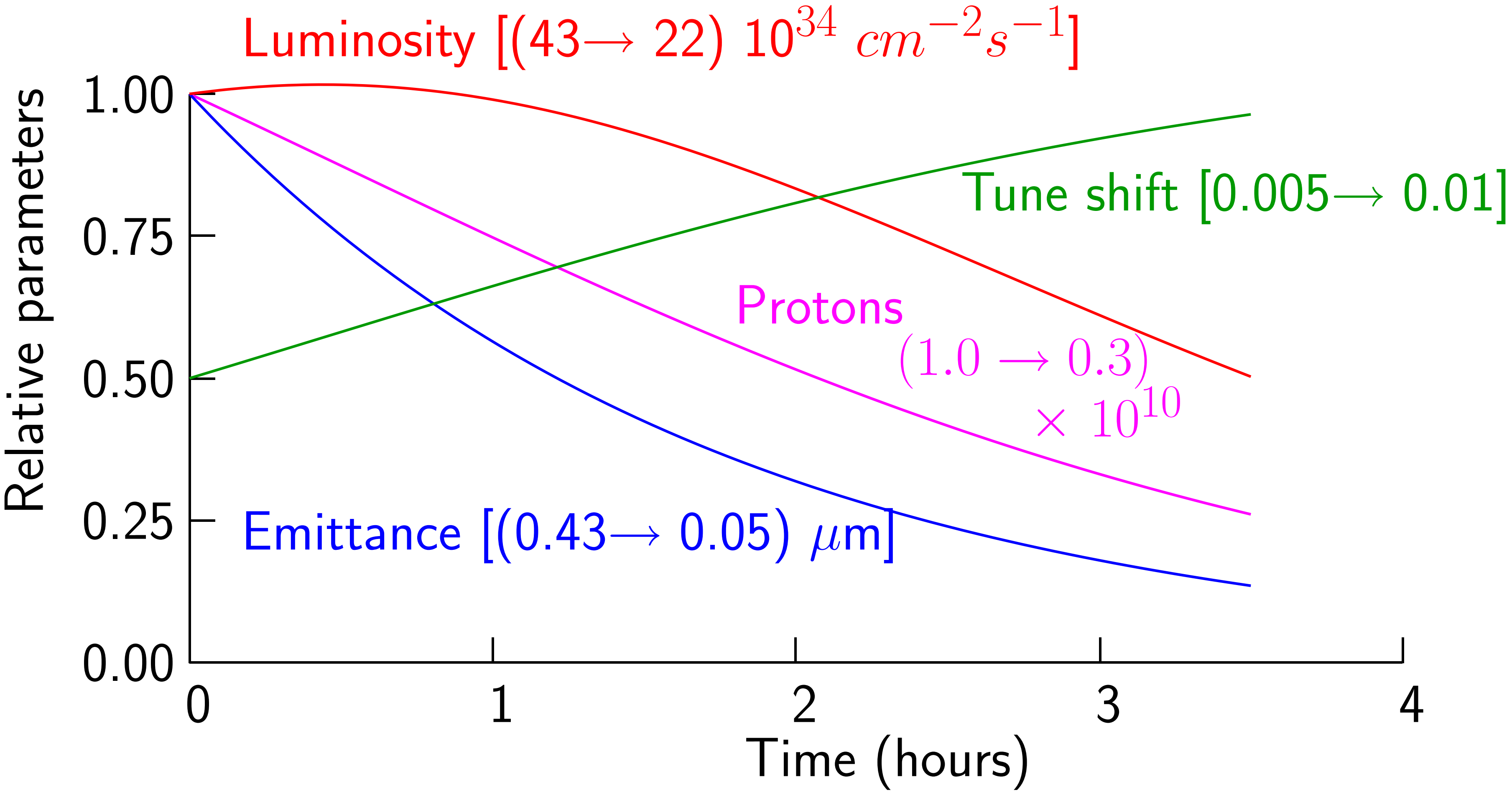
At 100 TeV there is significant synchrotron damping. With appropriate parameters, Intra Beam Scattering (IBS) can be weak enough so that the transverse emittance $\epsilon_\perp$ falls with time.

With the speculative parameters given in Appendix 1, the luminosity initially rises a little, before particle loss takes over and the luminosity falls (see the next slide).

The beam-beam tune shift, however, rises monotonically, requiring a smaller initial tune shift e.g. $\Delta\nu = 0.005$, which is about half of its acceptable level of $\Delta\nu = 0.01$. No other luminosity leveling is required.

See the next slide.

# Beam parameters vs. time



- Warning: This calculation did not include the rise in IBS from the changes in $N_p$ and $\epsilon_\perp$ during the cooling, and has other approximations.
- More than 70% of protons are used in 3.5 hours.

# Beam Lifetime

For a given luminosity and energy, the lifetime increases as the magnetic field falls ($\tau_{life} \propto 1/B$), because there are more stored protons in the larger ring, for the same rate of loss.

Nevertheless, with our luminosity goal, the useful lifetime is only about 3.5 hours (as shown in the previous slide).

For efficiency, we need a turn around time of the order of 1 hour.

With increased rf, an acceleration in 30 minutes appears feasible.

With lower field dipoles (see the next section), using only NbTi with very fine filaments, such a ramp rate seems plausible. It would be more difficult with $Nb_3Sn$ or HTS.

# Initial Emittances and Cooling

In the parameters in Appendix 1 we require an initial normalized transverse emittance of 0.43 (mm mrad). This is much less than that in the LHC (3.75 mm mrad), and is probably not achievable without cooling.

But cooling to such an emittance appears within the capability of Coherent Electron Cooling that will soon be tested at RHIC.

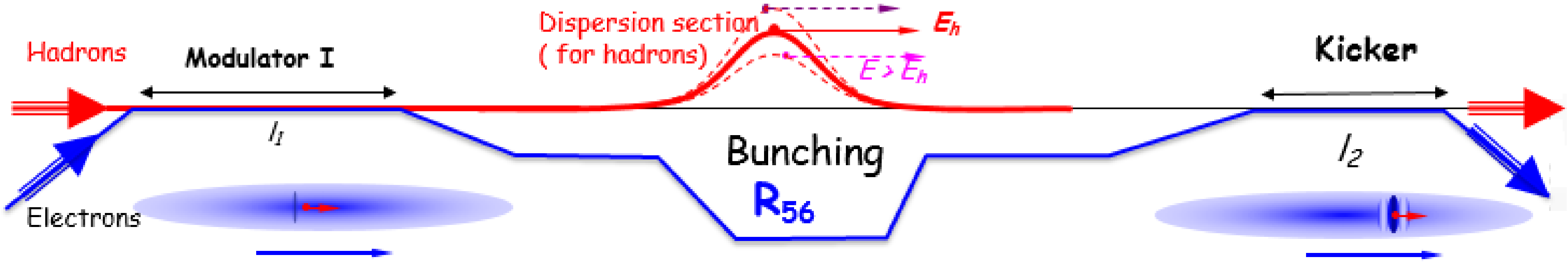
Lower emittances have other advantages:

1. to reduce pole tip fields in IR quads
2. to reduce required apertures in bending dipoles
3. to narrow the vertical extent of the synchrotron radiation

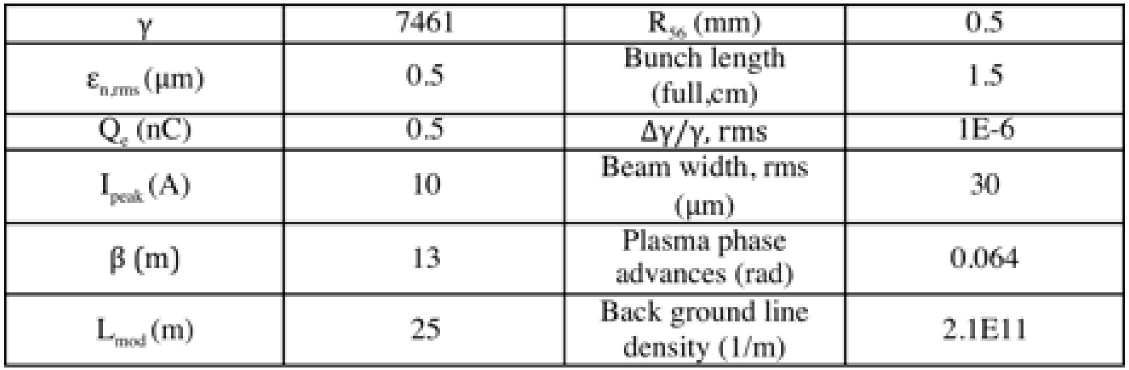
# Coherent Electron Cooling

(using micro-bunching instability, D. Ratner, PRL **111** (2013) 084802)

Micro-bunching amplifier has potential of bandwidth ~$10^{17}$ Hz



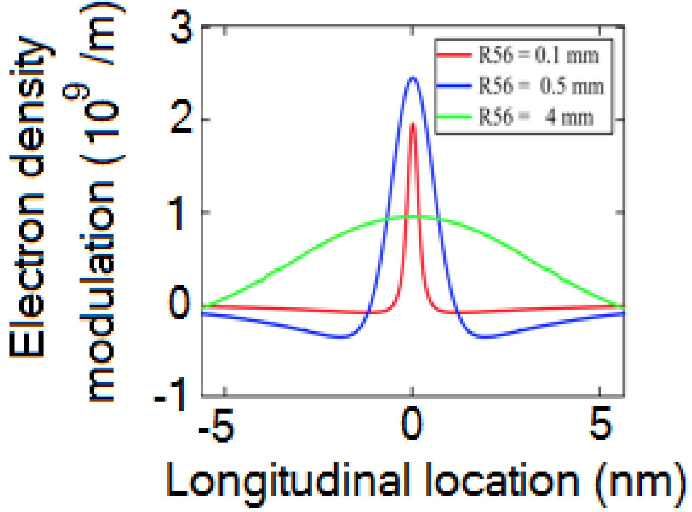
. D. Ratner



| $\gamma$ | 7461 | $R_{56}$ (mm) | 0.5 |
|---|---|---|---|
| $\varepsilon_{n,rms}$ (μm) | 0.5 | Bunch length (full,cm) | 1.5 |
| $Q_e$ (nC) | 0.5 | $\Delta\gamma/\gamma$, rms | 1E-6 |
| $I_{peak}$ (A) | 10 | Beam width, rms (μm) | 30 |
| β (m) | 13 | Plasma phase advances (rad) | 0.064 |
| $L_{mod}$ (m) | 25 | Back ground line density (1/m) | 2.1E11 |

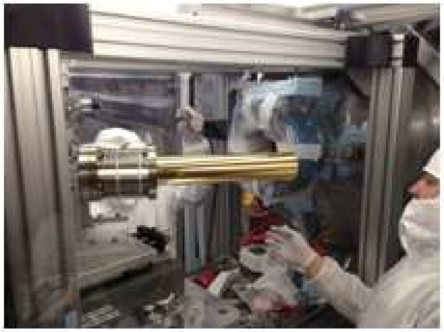
Table 1: parameters applied in generating Fig. 1-6.

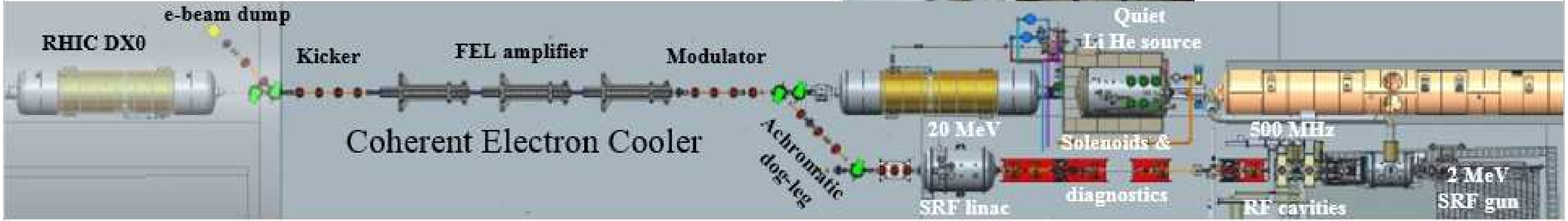
Gang Wang, 2013

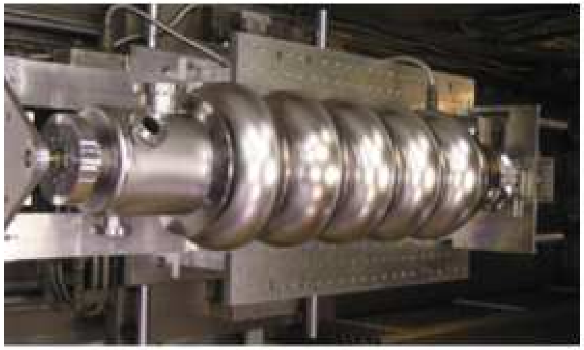


This shows enough bandwidth to cool our beams

# Demonstration in RHIC







# 3) BENDING FIELD AND RING SIZE

## Raising the average bending field:

- Decreases the ring circumference and related 'linear' costs:
  - Tunnel
  - Survey & installation
  - Quadrupole, monitors and spools
- But increases the cost per unit of magnet length because:
  - More super-conductor gives increased average coil radius
  - Required super-conductors are more expensive
  - Supports must hold greater forces $\propto \; B^2 \times <radius>$
  - More Fe needed to contain the flux[1]
- There has to be a field giving a minimum total cost
- We have updated earlier studies[9, 10] to address this question.

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[1] The CERN 20 T magnet design[1] does not contain the flux

# Magnet model

- Current densities vs. B by fits to NHMFL data[11]
- Assume degradations, packing factors, & margins from LHC[6]
- Determine a cos theta coils thickness
- Add Fe to return all[2] the flux assuming $B_{sat} = 2$ T
- Spaces for cryogenic insulation taken from LHC
- Cost super-conductor per kgm using HE-LHC[1] costs

  NbTi at 200 $/kgm  $Nb_3Sn$ at 4× NbTi  HTS(2212) at 15× NbTi
- Cost structures $\propto$ weight escalated from SSC[12]
- Cost cryogenics $\propto$ cold surface area$/T(K)$, scaled from SSC[12]
- Add linear costs based on escalated SSC[12]
- Iron & stainless steel, including manufacture, proportional to weights as determined from SSC[12] study

Detailed assumptions are in Appendix 2.

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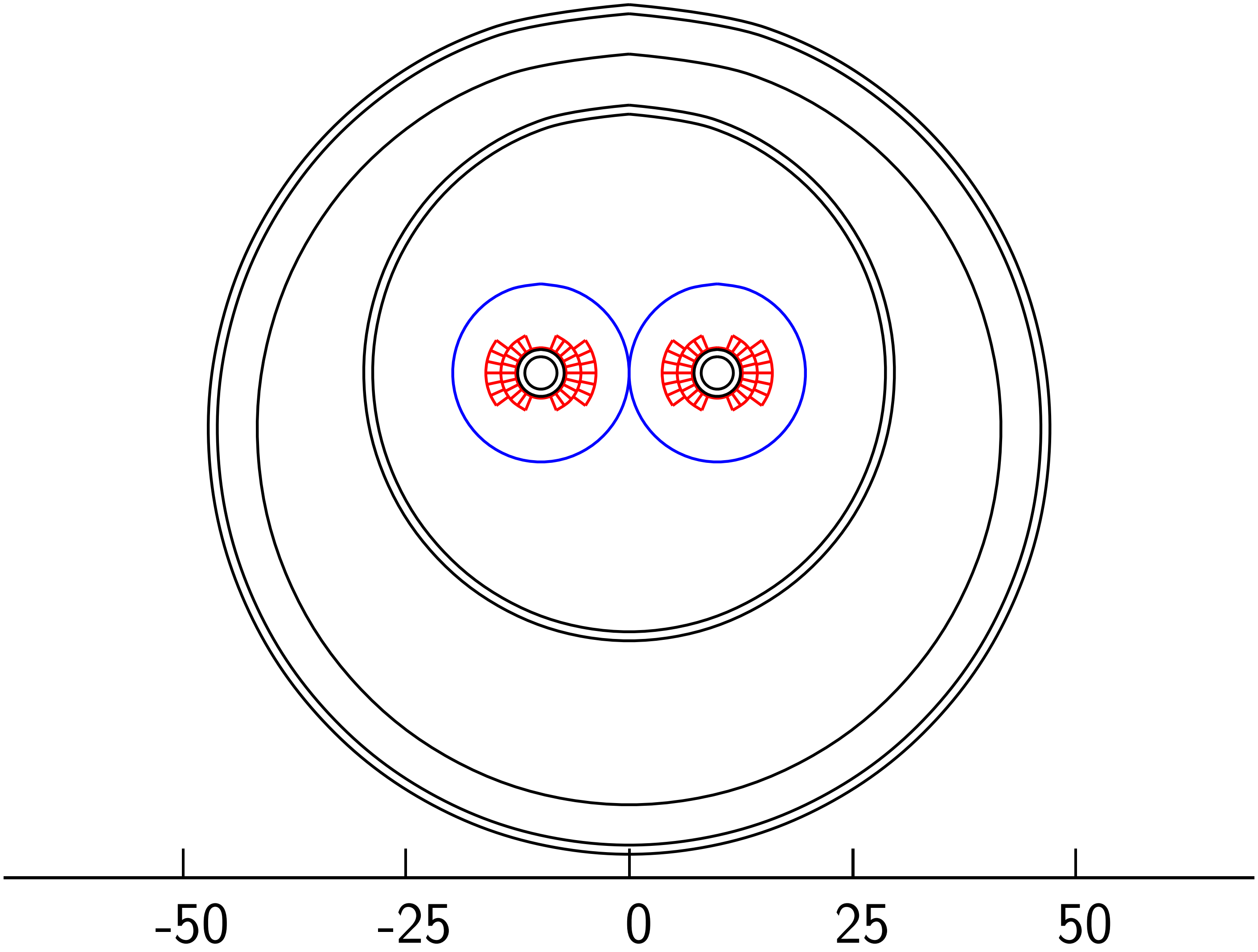
[2] If specified. See previous footnote

# Model dimensions of an LHC like magnet

From this model for 8.4 T at 1.8 degrees, with collar:



This cross section is essentially identical to the LHC dipoles[6]

# Inputs for New Parametric Study

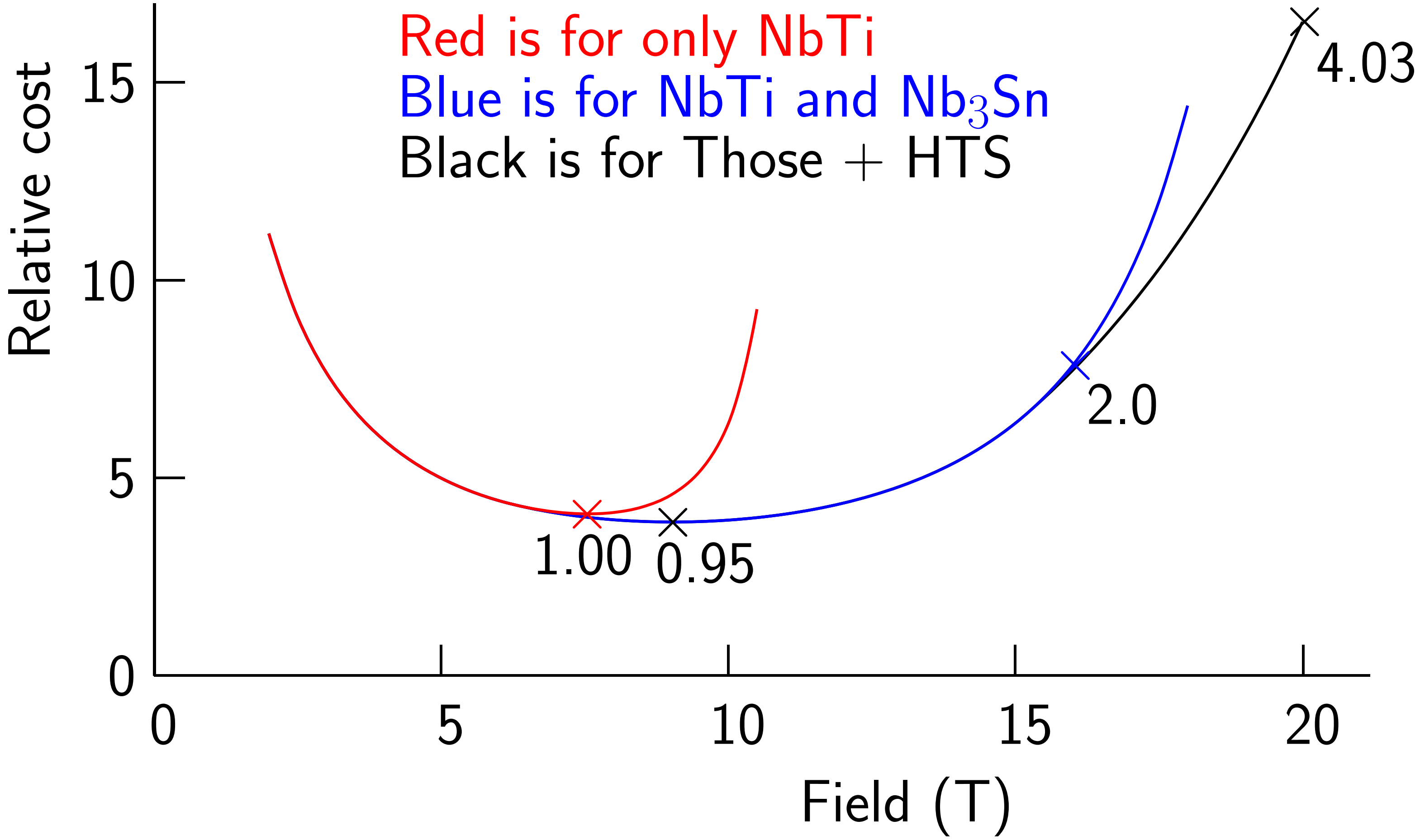
- Two-in-one magnets without collars
  Four 2-in-1 magnets for the SSC were built without collars[15]
- Allow 'graded' conductors with NbTi, $Nb_3Sn$, or BSCCO HTS
- Relative thickness of each chosen to minimize cost

# Approximations

- Force estimates here were based on Cos theta coils, even though, for many reason, the higher field magnets would use block designs as assumed by CERN[1], but estimates for 20 T are within 20%.

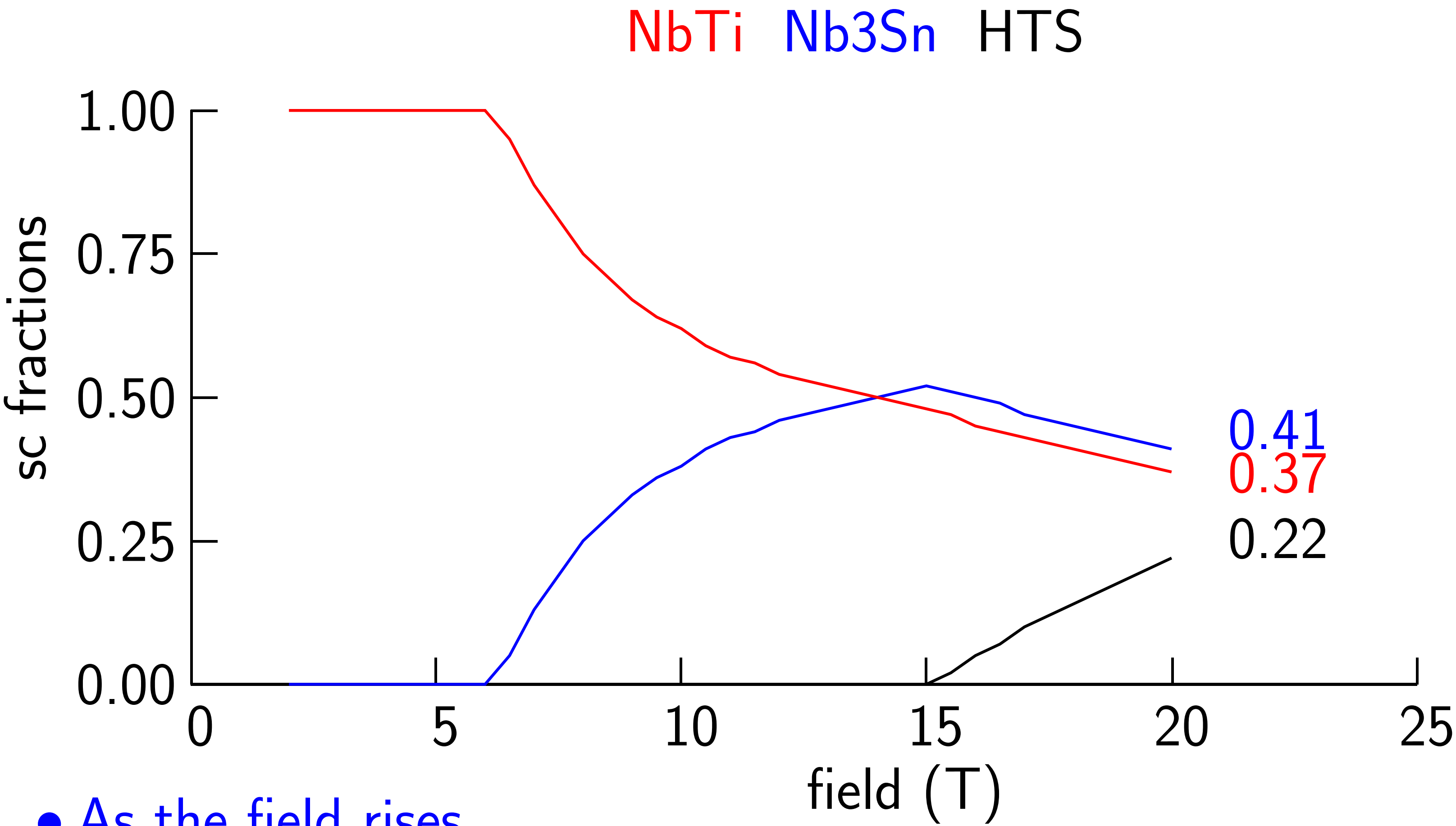
- There are many other approximations. Costs are only approximate.
- They are useful to identify trends, and to motivate further study and R&D.

# Calculated Relative Costs vs. Field



- Results are for Temp=1.8 K   Costs are always higher for 4.2 K
- The minimum cost is at relatively low fields (≈ LHC's 8.3 T).
- With 20 T, the total cost is 4 times the minimum
- With 16 T, the total cost is 2 times the minimum

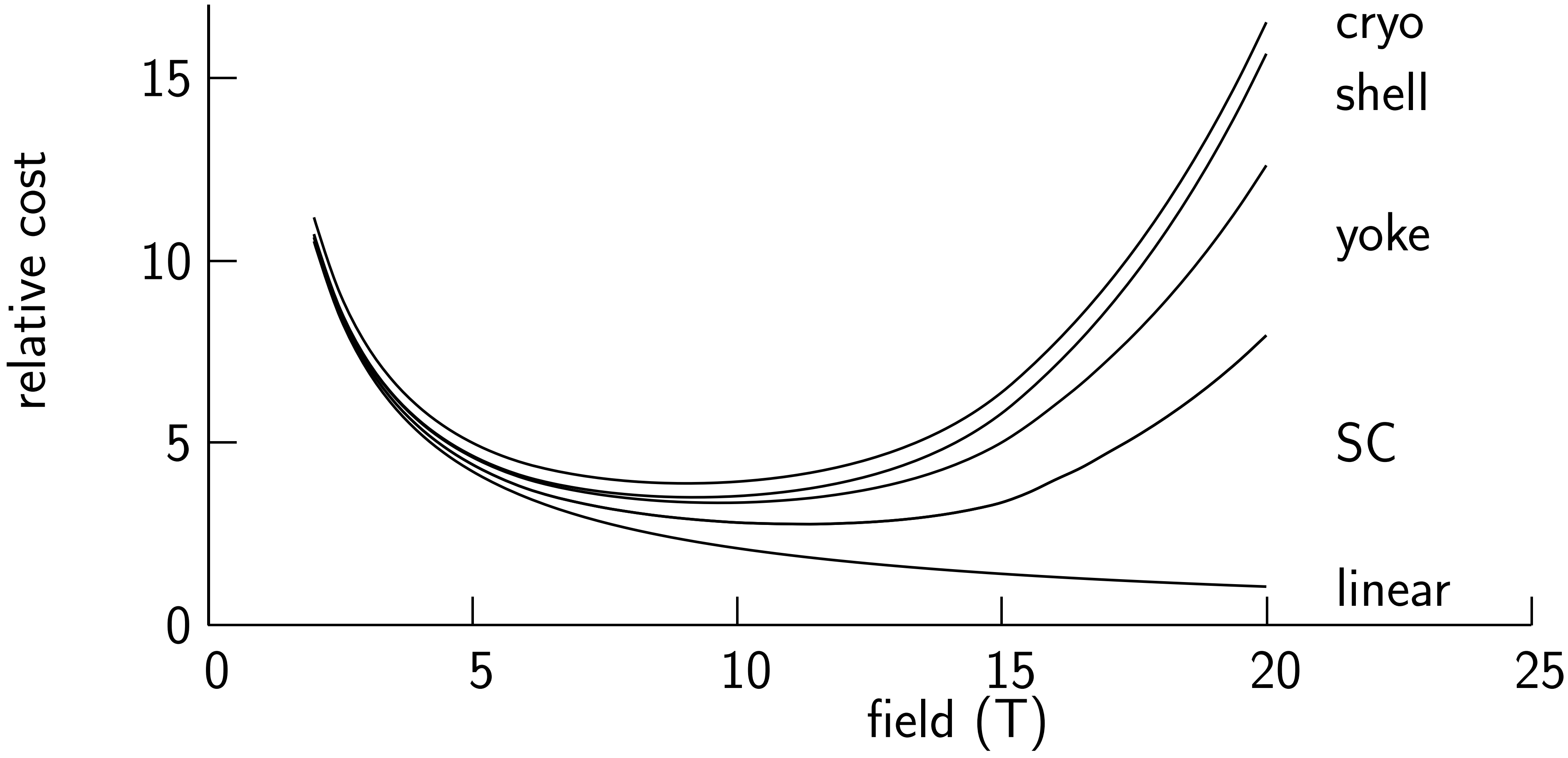
# Fractions of each Super-conductor



- As the field rises
- First $Nb_3Sn$, then HTS, for inner coils
- Giver lower overall cost despite their higher cost per kgm

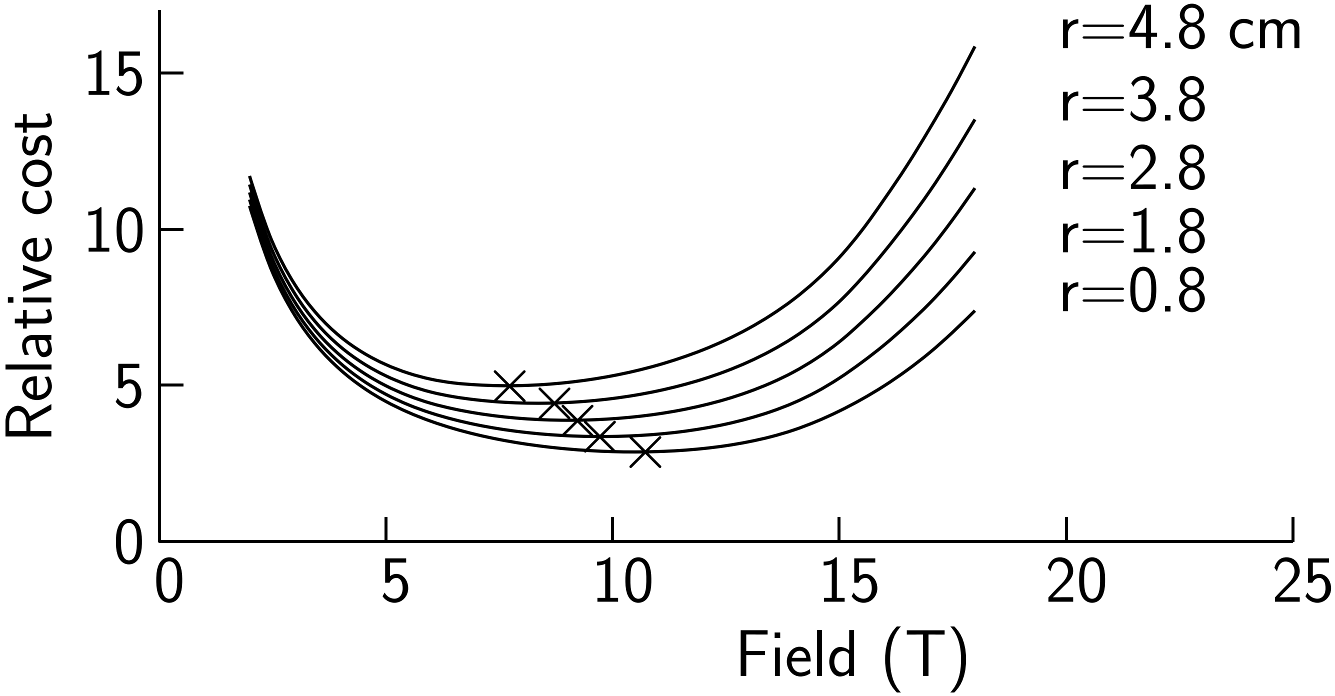
# Relative costs of components

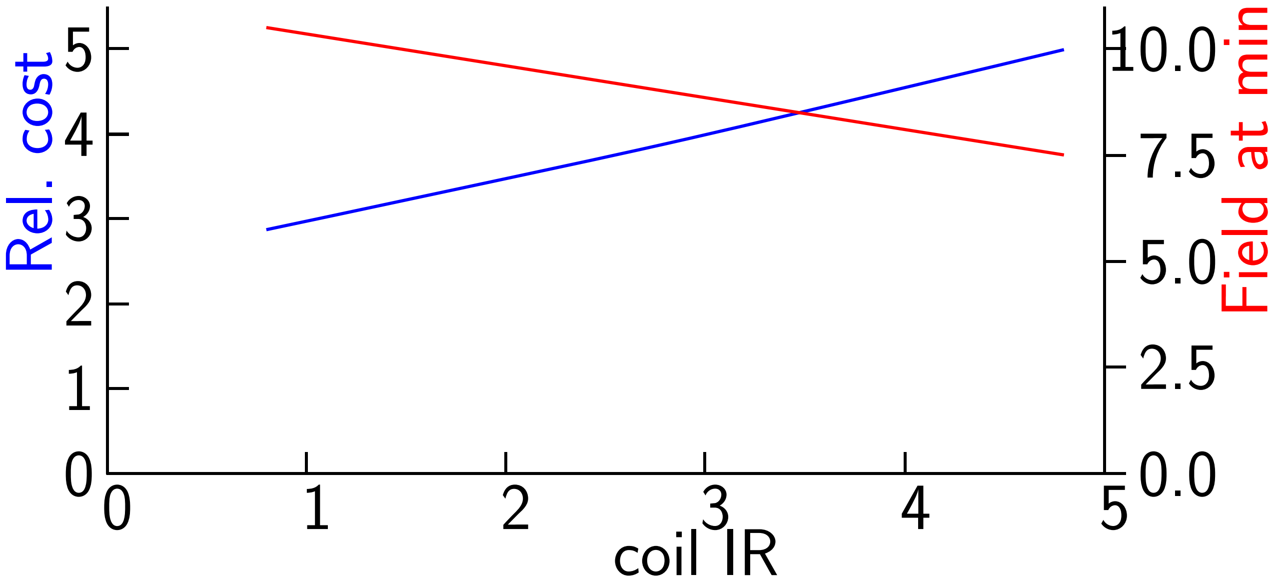
The plot is of the accumulated costs. The labeled part costs are thus represented by the spaces between the lines.



- The largest single cost at 20 T is for super-conductor

# Dependence on Aperture





Smaller apertures reduce costs and shift min fields higher

# Resistive wall Impedance concerns

The transverse resistive wall impedance:

$$Z_{\perp}(\omega) = \frac{\mu \, R Z_o}{\mu_o \, b^3} \delta_s$$

where $R$ is the circumference$/2\pi$, $b$ is the pipe radius, and $\delta_s$ is the skin depth.

The pipe should be lined with high RRR copper, and be as cold as possible to reduce the skin depth $\delta_s$. The impedance always sets a the minimum for the pipe radius $b$.

The most serious instability from this impedance appears to be the Transverse Mode Coupling at injection energy. A Fermilab study[3] suggested several amelioration strategies (coalescing bunches at higher energies, positive feedback, and an rf quadrupole) and argued that a beam pipe radius as small as 8 mm could be possible.

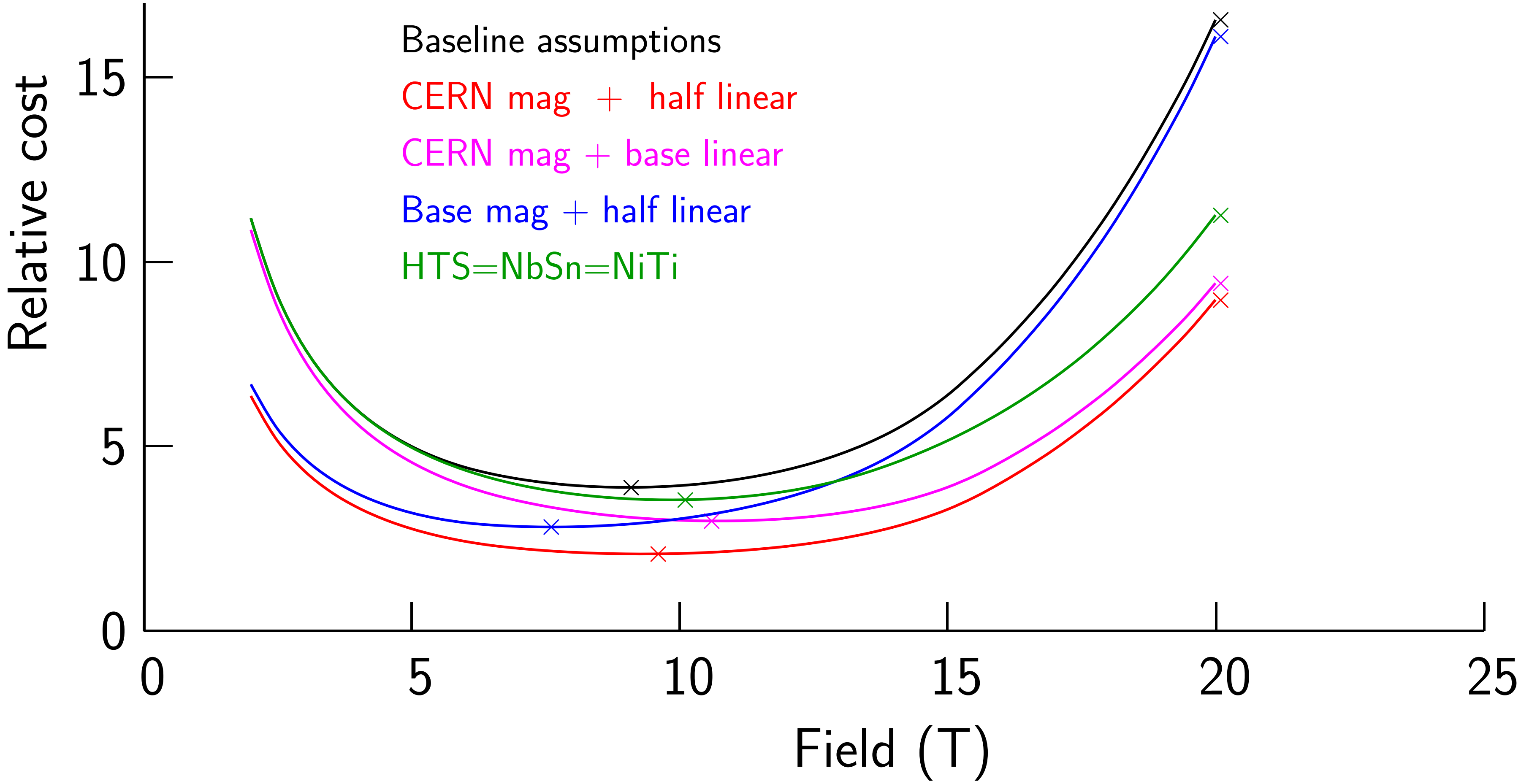
Perhaps 1.2 cm is a reasonable choice.

# Sensitivity to Assumptions

Examining the scatter using different component cost estimates will give us a sense of the sensitivity to those assumptions.

- The CERN[1] dipole assumes a yoke of only about half the diameter needed to return all the flux. This raises possible difficulties with other instrumentation in the tunnel, but reduces its cost by almost a factor of two.
- In addition, CERN assumed a smaller (4.4 cm vs. 5.8 cm) coil inside diameter.
- Tunnel costs vary with location[4, 1]. Let me consider a factor 2 lower.
- Permuting these magnet and tunnel costs explores sensitivity to such factor of two errors.
- Also, to see dependence on $Nb_3Sn$ and HTS costs, we try setting both of these to equal that of NbTi - a wildly optimistic hope!

# Cost estimates for the five cases



Combining these 5 simulations, we get averages with rms errors:

20 T cost/minimum = 3.1 ± 0.6 Field at min = 9.3 ± 1

# Ring Circumference

If we have a 'green' site, and no geological constraints then

- Cost minimum is at fields of order 8.3 T (LHC's field)
- The cost is then about 1/3 of that at 20 T
- For 100 TeV this implies a tunnel circumference of ≈ 190 km
- The McIntyre[4] proposal of 4.5 T appears low, but he is making the same point.

190

is ~~80-100~~ km too big?

*"Of course, it should not be the size of an accelerator, but its costs which must be minimized."*

Gustav-Adolf Voss,
builder of PETRA,
5. October 2013

Figure modified from slide in Frank Zimmermann talk[13]

# 4) SYNCHROTRON RADIATION

For the 14 TeV LHC[6], the beam current is 0.584 A and the synchrotron power per m[6] is ≈ 0.2 W/m per beam Assuming this current & a 20 T field for 100 TeV, the power is

$$\frac{dP}{dL} \propto \left(\frac{dP}{dL}\right)_{HL-LHC} \gamma^2 \; B^2 \;\approx\; 0.2\,(100/14)^2 \; \left(\frac{20}{8.4}\right)^2 \;\approx\; 90\,W/m$$

The Total power for both rings is

$$P \;=\; 2\,\frac{dP}{dL}\,L \;\approx\; 2\;90\;(0.65\;84) \;\approx 10MW$$

In an LHC like magnet, this power is absorbed by a beam screen inside the magnet bore at a temperature at or below 20 K. The wall power needed to cool it would then be, assuming 50% of Carnot efficiency :

$$10\;10^6 \times (300/20)/0.5 \;\approx\; 300MW$$

An unacceptable power.

# Synchrotron Radiation with 8.4 T vs. 20 T

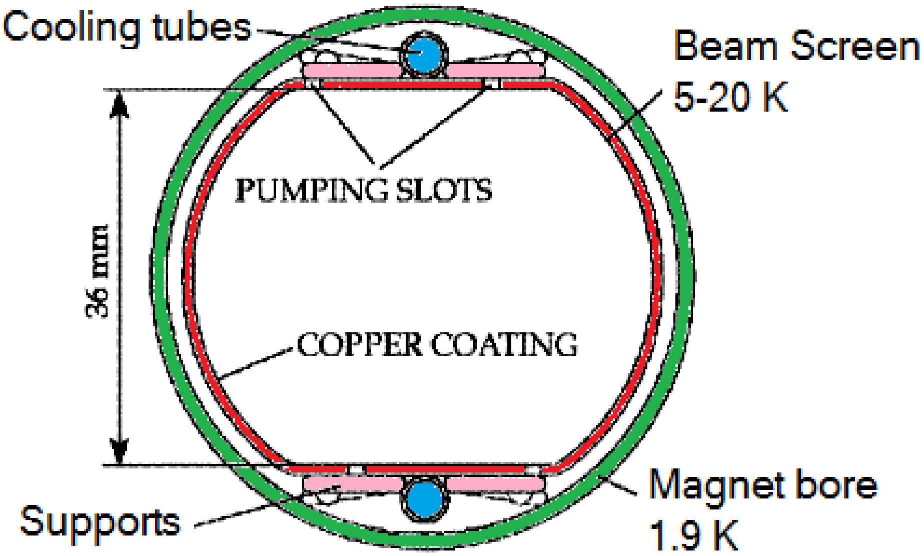
Now $dP/dL \approx$ 16 W/m (vs. 92), but the wall power is still a significant 125 MW (vs. 300).

Having a beam shield running at 77 K would help, but shielding this from the 1.8 K bore would probably need more than the LHC's ≈1 cm: decreasing the beam pipe or increasing the coil ID and cost.

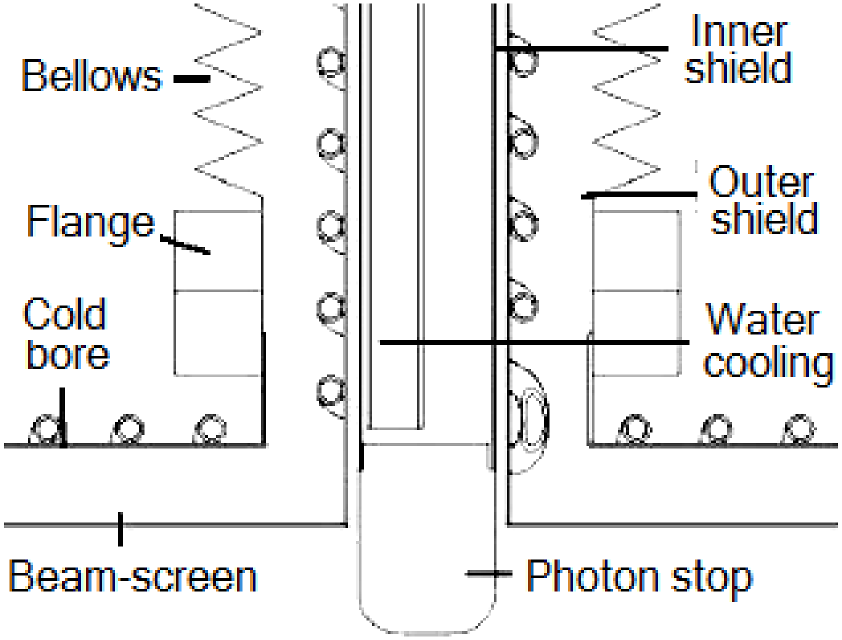
This raises the subject of open mid-plane dipoles, allowing the synchrotron radiation to be absorbed away from the beam center. Such magnets have been discussed[14] even for 13.5 T, and they will become even more practical at lower fields, when the inward forces ($\propto B^2$) are less.

And the 100 MW power discussed for an initial electron-positron collider would, for the same energy and the 2.35 × larger ring, be reduced to 42 MW; simplifying the rf and beam pipe cooling.

# Beam Screens



LHC Beam Screen

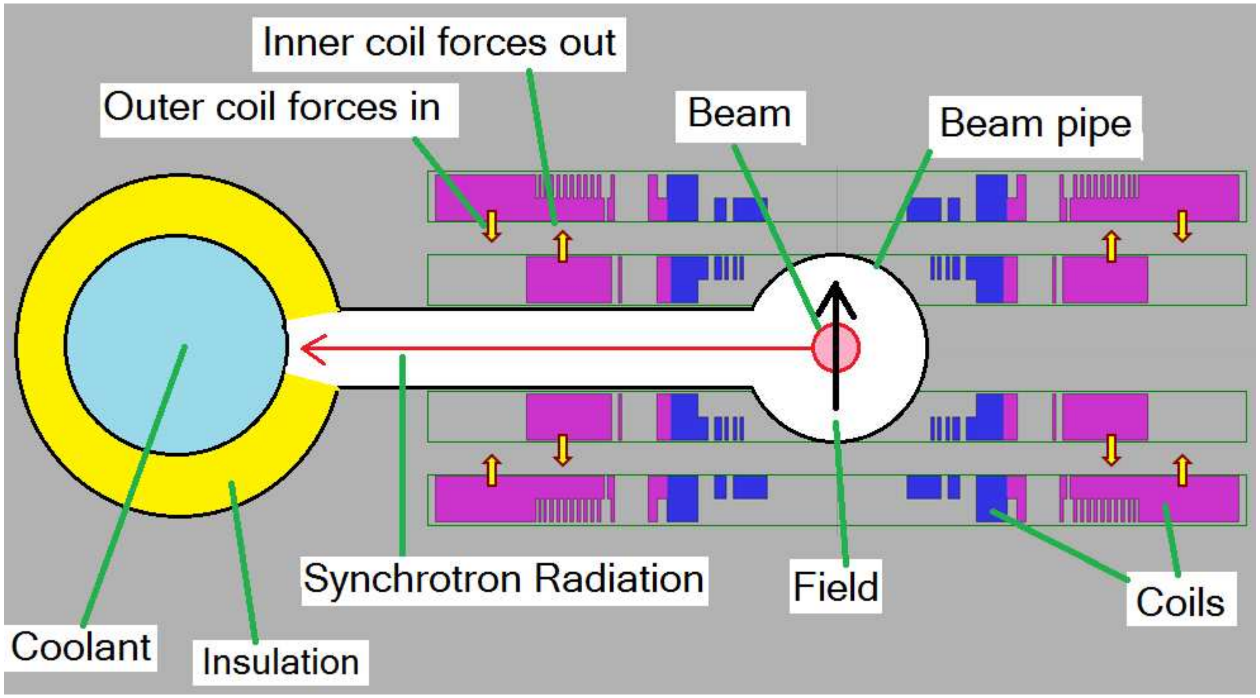


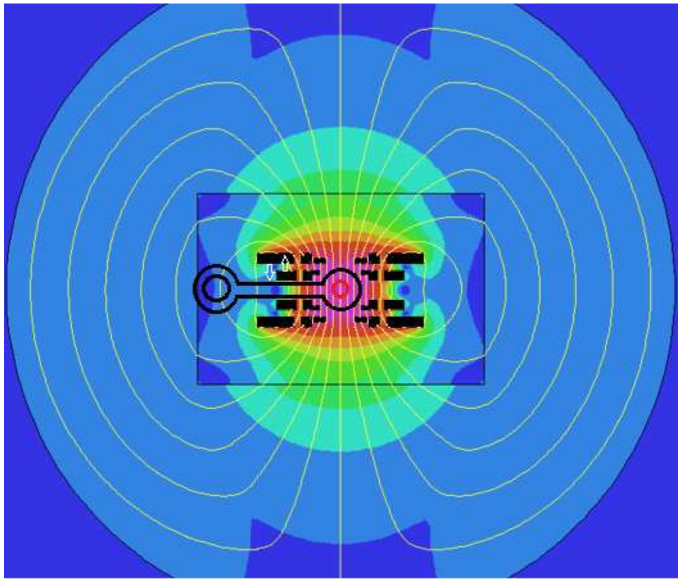
Bauer Photon Stop

- An LHC like screen at 70-80 K and would probably use up more space.
- The Bauer et al[3] Photon Stops every feq meters could take the load. But there are questions about their impedance and beam vacuum effects.
- The other alternative is to use an open mid-plane dipole:

# Open Mid-plane Dipoles

R. Gupta's design[14] for 13.5 T





- Coils shown give very good field uniformity
- The sketched idea allows cooling at 77 K, or room temperature, and has space for good thermal insulation to the 1.8 K yoke
- The open plane design will be easier at lower dipole fields.
- Also need open mid plane quads, skew[16], or combined function

# 5) CONCLUSION

- A luminosity at or above our goal of $(5\ 10^{35}\ \mathrm{cm}^{-2}s^{-1})$ is needed and, with a lower $\beta^*$ and transverse emittance, may be attainable.
- Luminosity per beam cross, and thus pile-up, can be controlled by using smaller bunch spacing and fewer protons per bunch.
- Proton cooling is probably required to reduce the initial transverse emittances.

- The cost of a 100 TeV collider can probably be reduced by using moderate field dipoles and a larger ring. This also increases the beam life-time.

- Synchrotron radiation is intense, and open plane dipoles may be the best way to capture it.

- These ideas need R&D to refute or confirm their promise, establish a firm parameter set, and demonstrate an open mid-plane dipole.

# Needed R&D

- Lattice design giving the required 5.5 cm $\beta^*$
- IBS calculations with the real lattice
- Time evolution with SR during acceleration and operation
- Minimum beam pipe diameter from:
  - Impedance and stability considerations
  - Electron clouds with short bunch separation
  - Compare beam screen, photon stops, and remote SR capture
  - Beam emittance
- Proton production, accumulation, cooling and injection concepts
- Open mid-plane dipole magnet design, including focus elements
  And build a short demonstration model
- Costs of tunnel, related linear items, focus elements
- Refine magnet cost, and total cost optimization

Work should be done in collaboration with IHEP and CERN

# Appendix 1. Beam Parameters

| | | LHC | FCC-hh | This |
|---|---|---|---|---|
| Energy (c of mass) | TeV | 14 | 100 | 100 |
| Dipole Field $B$ | T | 8.3 | 20 | 8.3 |
| Circumference | km | 26.7 | 80 | 190 |
| Luminosity | $10^{34}\mathrm{cm}^{-2}s^{-1}$ | 1 | 5 | 43* |
| Init. Protons/bunch | $10^{10}$ | 11.5 | 9.7 | 1 |
| Bunch sep. | ns | 25 | 25 | 2.5 |
| Number of bunches | $10^{3}$ | 2.8 | 10.6 | 204 |
| Bunch length $\sigma_z$ | cm | 7.5 | 7.5 | 5.5 |
| $\beta^*$ at IP | cm | 55 | 110 | 5.5 |
| Initial norm rms emittance $\epsilon_\perp$ | $\mu$m | 3.75 | 2.15 | 0.43 |
| IP Beam radius $\sigma_\perp$ | $\mu$m | 16.6 | 6.6 | 0.67 |
| Crossing angle $\theta_{cross}$ | $\mu$rad | 363 | 73 | 145 |
| Dipole filling fraction | % | 66 | 65 | 66 |

* Hour-glass effect $\approx 0.75$

.

| | | LHC | FCC-hh | Proposed |
|---|---|---|---|---|
| Initial beam-beam $\Delta\nu$ | | 0.01 | 0.01 | 0.005 |
| Final beam-beam $\Delta\nu$ | | | | 0.01 |
| Total cross section $\sigma$ | mb | 111 | 153 | 153 |
| Events/crossing | | 27 | 171 | 171 |
| SR trans. damping $\tau_{\perp}$ | hr | 12.9 | 0.32 | 1.8 |
| SR long. damping $\tau_{\parallel}$ | hr | 25.8 | 0.64 | 3.6 |
| Initial trans. IBS rise $\tau_{IBS\perp}$ | hr | 103 | 157 | 9 - 20 * |
| Initial long. IBS rise $\tau_{IBS\parallel}$ | hr | 206 | 396 | 100 |
| Life-time $\tau_{life}$ | hr | 40 | 16 | 4 |

* Depending on approximations used

|  |  | LHC | FCC-hh | Proposed |
|---|---|---|---|---|
| Injection Energy | TeV | 0.45 |  | 3.3 |
| Tune $\nu_x \approx \nu_y$ |  | 63 |  | 85 |
| Arc: maximum $\beta$ | m | 183 |  | 950 |
| Arc Injection beam rms radius $\sigma_\perp$ | mm |  |  | 0.4 |
| SR Energy loss/turn | MeV | 0.006 | 5.9 | 2.5 |
| Turn around time | hr | 5 | 5 | 1 |
| Acceleration time | hr |  |  | 0.5 |
| rf freq. | MHz | 400 | 400 | 400 |
| rf Voltage | MV | 16 | 22 | $\leq$ 54 |

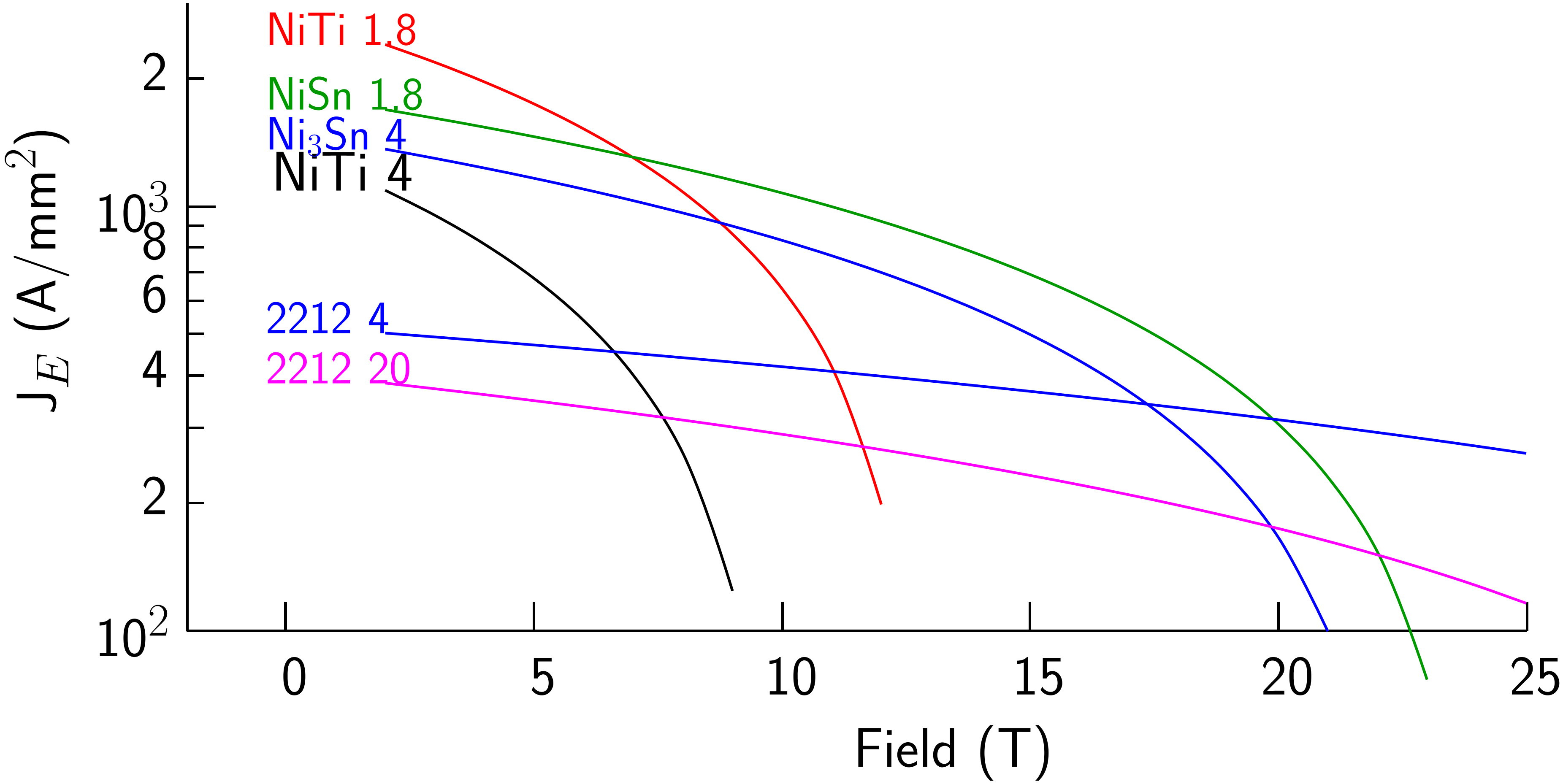
We must again stress that these are speculative parameters and are intended only to stimulate future studies to determine feasibility

# Appendix 2. Costing Input Parameters

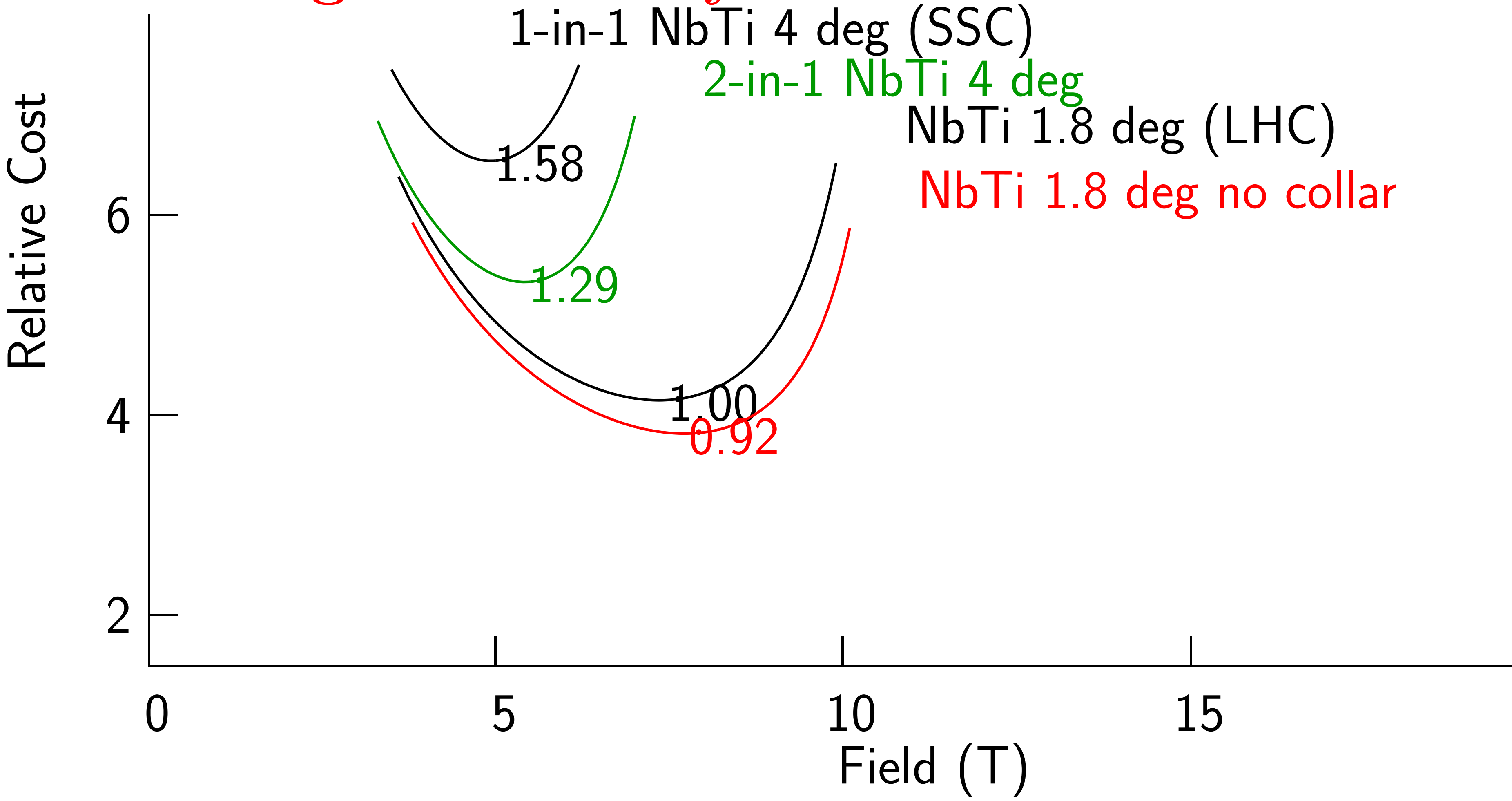
| | | | |
|---|---|---|---|
| | linear costs | k$/m | 40.2 |
| | NbTi cost | $/kg | 200 |
| | Nb3Sn cost | $/kg | 800 |
| | HTS cost | $/kg | 3000 |
| | ss collar cost | $/kgm | 13 |
| | cold yoke iron cost | $/kg | 8 |
| | ss shell cost | $/kg | 13 |
| | cryogenic cost at 4 deg | k$ /m$^2$ | .0335 |
| $j_{Cu}$ | Cu Current density | A/mm$^2$ | 0 |
| $j_{sc}(7)$ | NbTi current density at 7T & 4 deg | A/mm$^2$ | 400 |
| $j_{sc}(7)$ | NbTi current density at 7T & 1.8 deg | A/mm$^2$ | 1300 |
| $j_{sc}(7)$ | NbSn current density at 7T & 4 deg | A/mm$^2$ | 1030 |
| $j_{sc}(7)$ | NbSn current density at 7T & 1.8 deg | A/mm$^2$ | 1304 |
| $j_{sc}(7)$ | BSCCO current density at 7T & 4 deg | A/mm$^2$ | 450 |
| $j_{sc}(7)$ | BSCCO current density at 7T & 20 deg | A/mm$^2$ | 325 |
| $B_{crit}$ | NbTi critical field at 4 deg | T | 9.9 |
| $B_{crit}$ | NbTi critical field at 1.8 deg | T | 12.9 |
| $B_{crit}$ | NbSn critical field at 4 deg | T | 22.5 |
| $B_{crit}$ | NbSn critical field at 1.8 deg | T | 24 |
| $B_{crit}$ | BSCCO critical field at 4 deg | T | 50 |
| $B_{crit}$ | BSCCO critical field at 20 deg | T | 35 |

| | | | |
|---|---|---|---|
| $E$ | Beam Energy | TeV | 100 |
| $Fac_{fill}$ | Fraction of circ of magnets | | .7 |
| $t_{cryo}(4)$ | Cryostat space inner at 4 deg | cm | 8 |
| $t_{cryo}(4)$ | Cryostat space outer at 4 deg | cm | 3 |
| $Fac_{degrade}$ | Cabling degredation | | .9 |
| $Fac_{margin}$ | Field margin fac | | .75 |
| $Fac_{pack}$ | Conductor packing factor | | .66 |
| $Fac_{peak}$ | Peak conductor B / central B | | 1.1 |
| $T_{mid}$ | max pressure in coil | M Pascal | 250 |
| $Fac_{collar}$ | min collar thickness/coil rad | | .4 |
| $T_{collar}$ | max tension in collar | M Pascal | 200 |
| $T_{shell}$ | max tension in shell | M Pascal | 160 |
| $B_{sat}$ | Yoke Sat B | T | 2 |
| $t_{insu1}$ | inner insulation etc. | cm | .2 |
| $t_{insu2}$ | outer insulation | cm | .1 |
| $t_{shield}$ | radiation shield thickness | cm | 1.0 |

# Assumed Engineering Current Densities

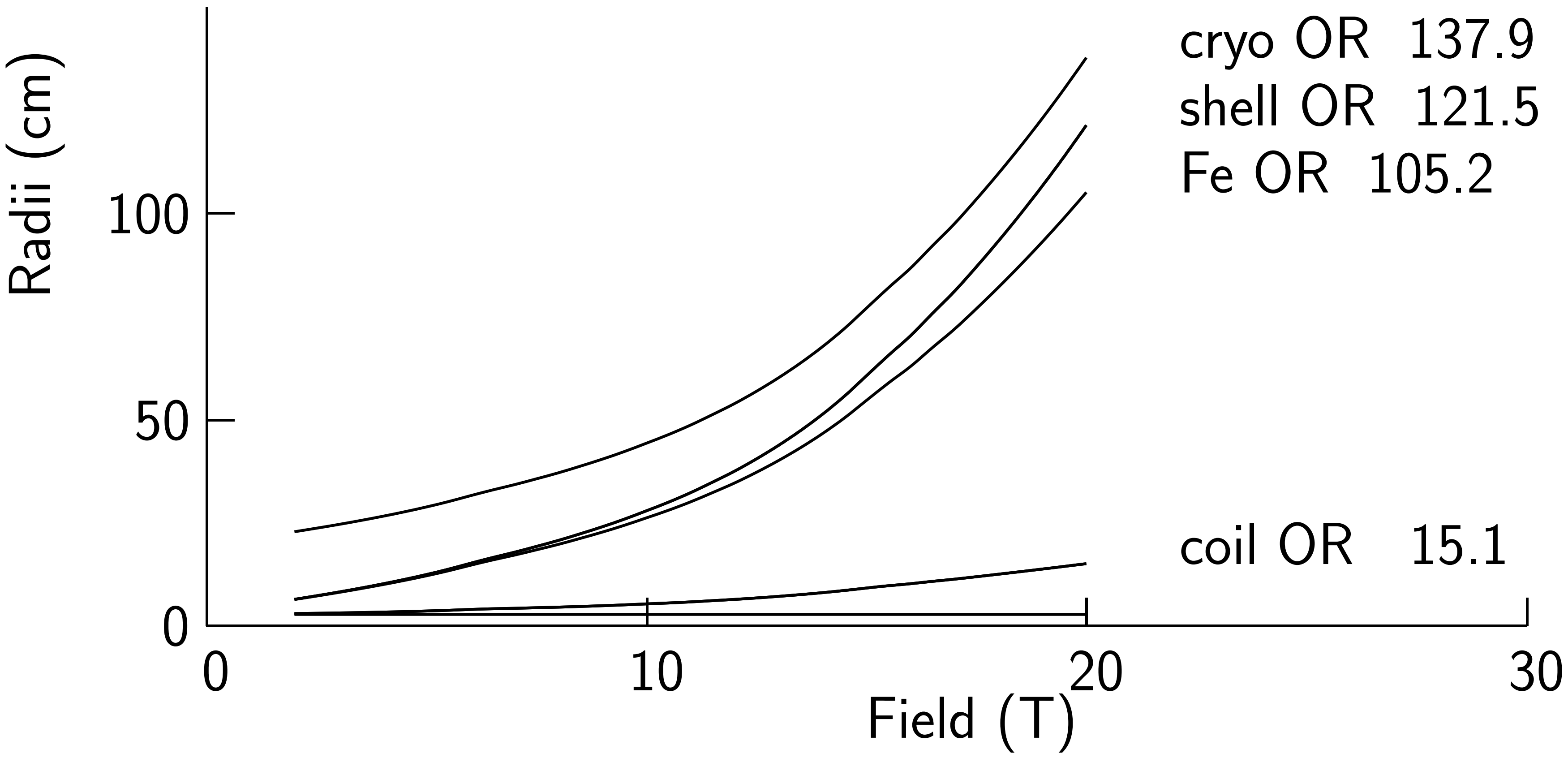


# Other designs with only NbTi



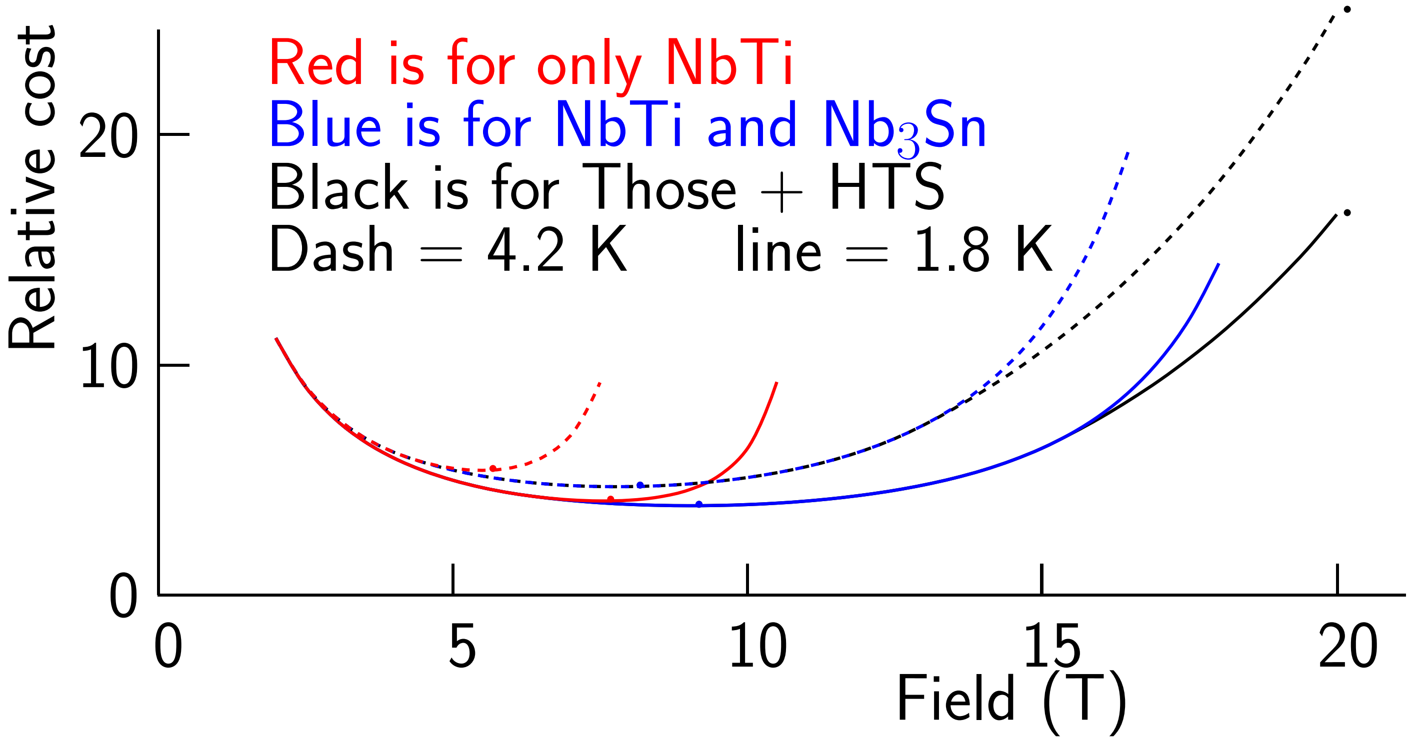
- Two-in-one is cheaper than separate magnets
- 1.8 K design cheaper than 4 K - true for all cases studied
- Using iron instead of a ss collar also reduces cost
- LHC is close to, but not quite at, minimum

# Radii of magnet parts

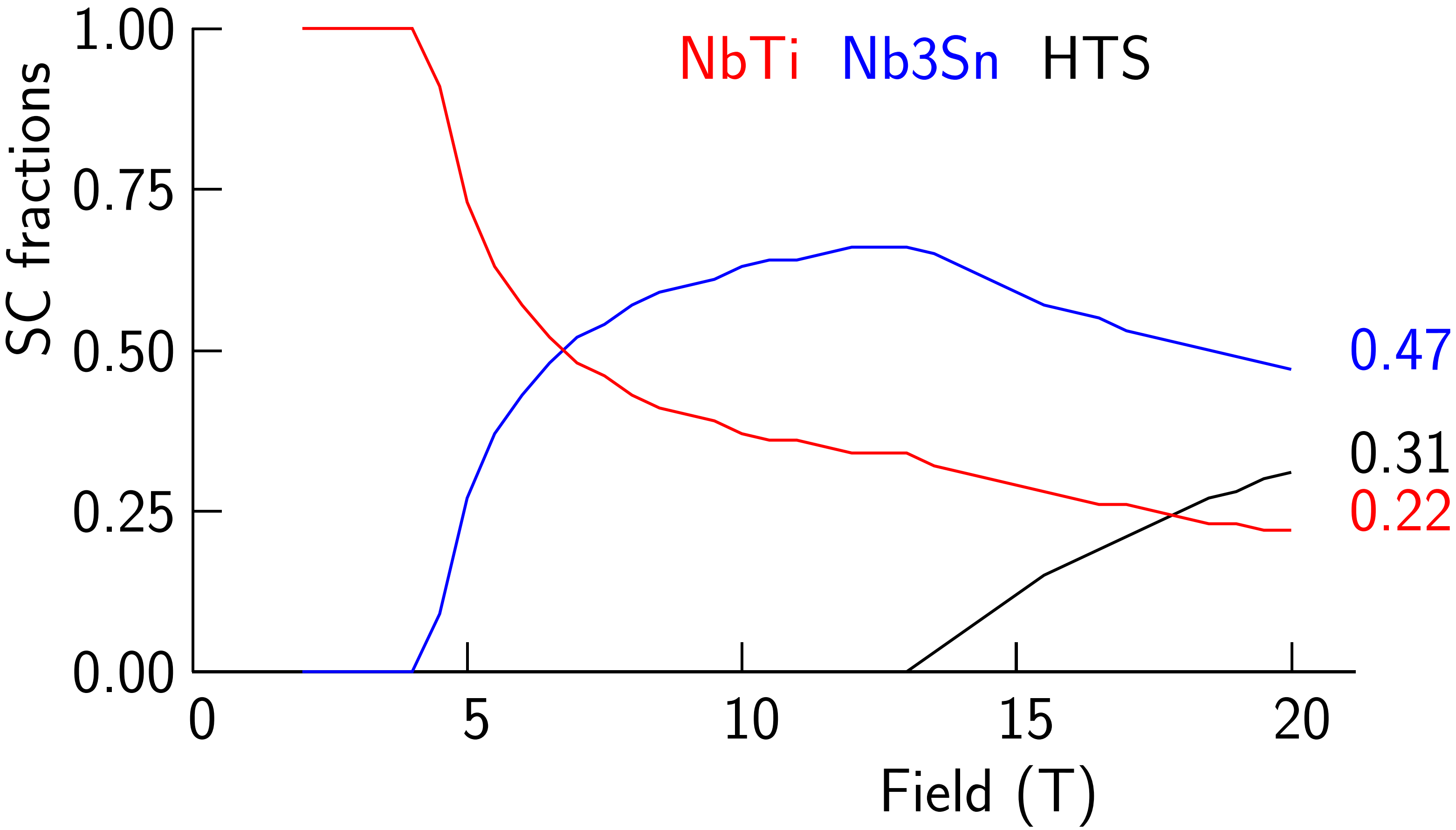


- The coils become large at high fields
- The Fe yokes & magnet O.R. become large to return the flux
- The ss Shells get thick because of large forces

# Vs. Temperature



# Fractions at 4.2 K



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