Unit 11
Electromagnetic design
Episode III

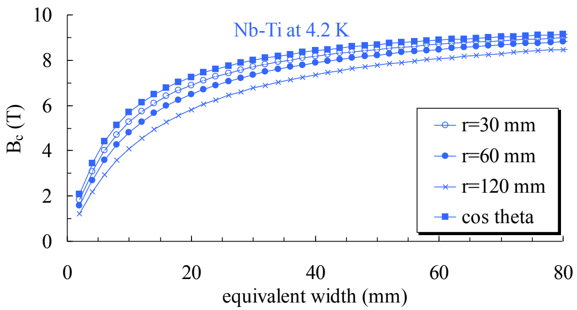
Soren Prestemon and **Steve Gourlay**

Lawrence Berkeley National Laboratory (LBNL)

With significant re-use of material from the same unit lecture by Ezio Todesco, USPAS 2017

QUESTIONS

- Where can we operate the magnet ? How far from the critical surface ?
- Efficiency: the last Teslas are expensive … are there techniques to save conductor ?

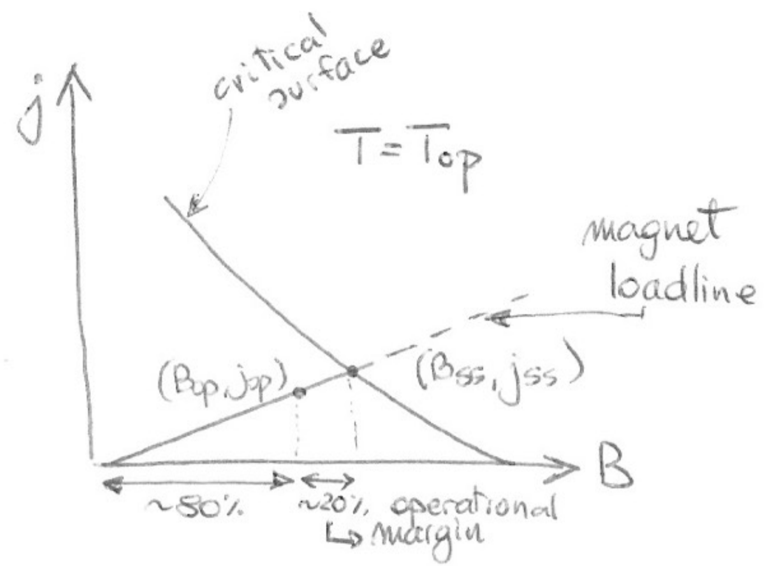


- What is the effect of iron ? Does it yield higher short sample fields ?
- What happens in coil ends ?
- Are there other possible lay-outs ?

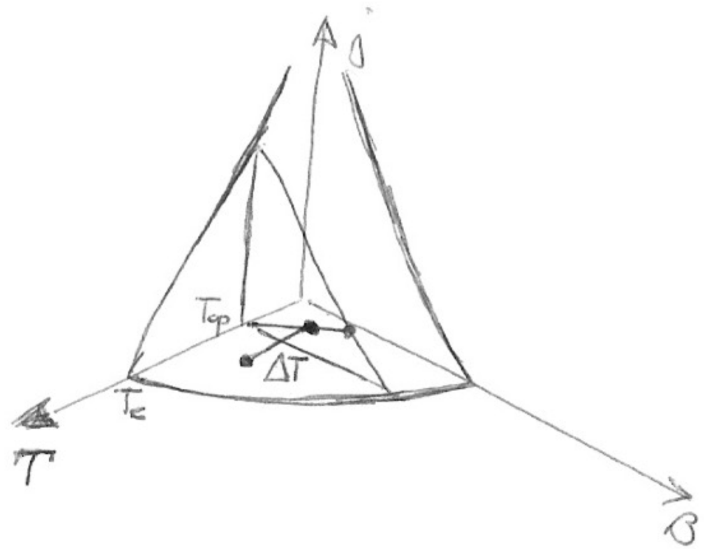
CONTENTS

Margin and operational risk

- Magnets have to work at a given distance from the critical surface, i.e. they are never operated at short sample conditions
  - At short sample, any small perturbation quenches the magnet
  - One usually operates at a fraction of the loadline which ranges from 60% to 90%



Loadline with 20% operational margin



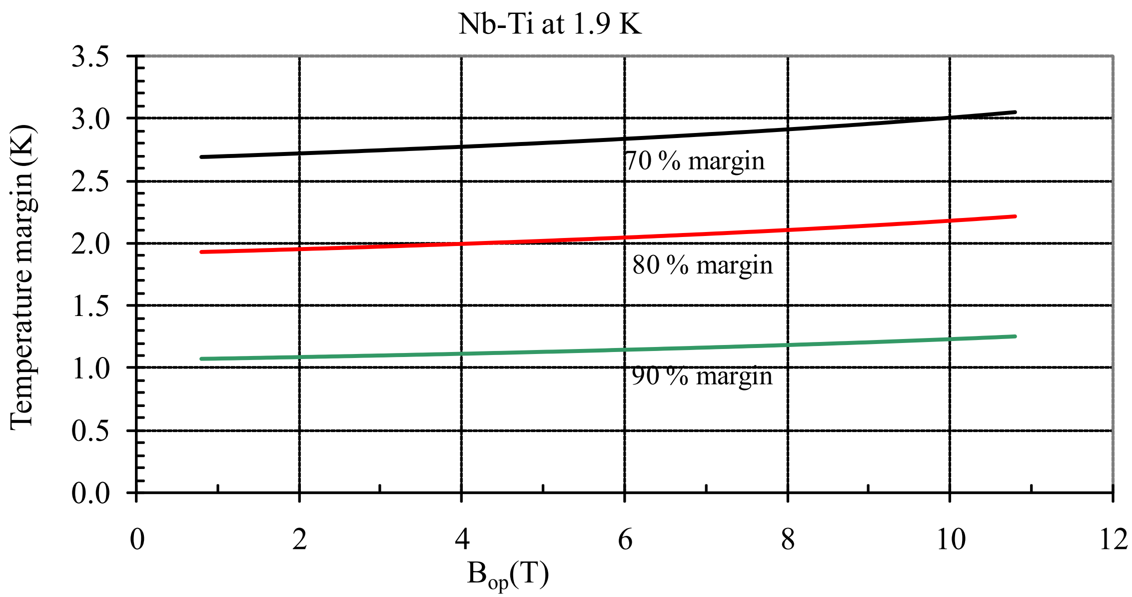
Operational margin and temperature margin

- This fraction translates into a temperature margin

Temperature margin is a common figure of merit

- How to compute the temperature margin ?
  - One needs an analytic fit of the critical surface $j_{ss}(B,T)$
  - The temperature margin ΔT is defined by the implicit equation

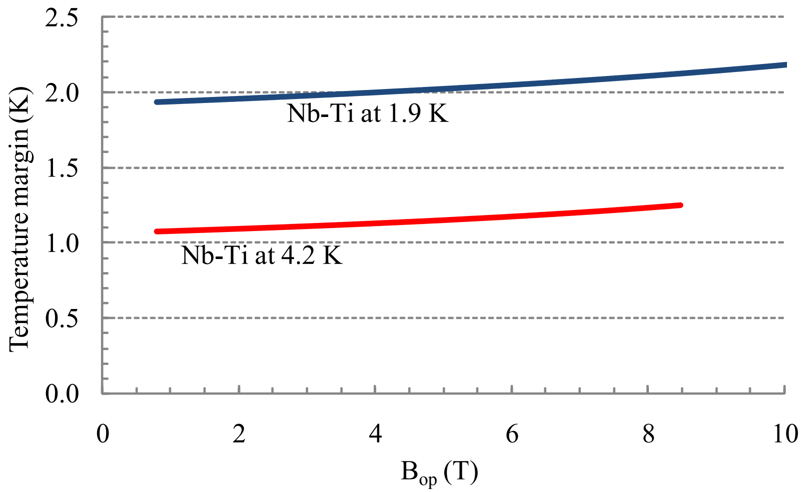
$$j_{ss}(B_{op}, T_{op} + \Delta T) = j_{op}$$



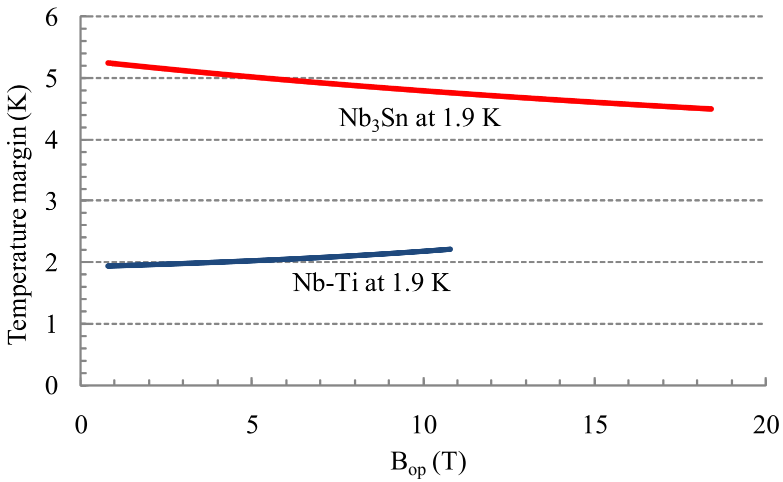
- Nb-Ti at 1.9 K at 80% of the loadline has about 2 K of temperature margin

Examples of temperate margin and role of superconductor

- Some parametric analysis
  - Nb-Ti at 4.2 K loses at least 1/3 of temperature margin w.r.t. 1.9 K
    - But the specific heat is larger …
    - But helium is not superfluid …
  - Nb_3Sn has a temperature margin 2.5 times larger than Nb-Ti
    - This is due to the shape of the critical surface
    - At 80%, Nb_3Sn has about 5 K of temperature margin



Temperature margin of Nb-Ti at 1.9 K and at 4.2 K



Temperature margin of Nb-Ti versus Nb_3Sn

Transient vs steady losses

- Two regimes

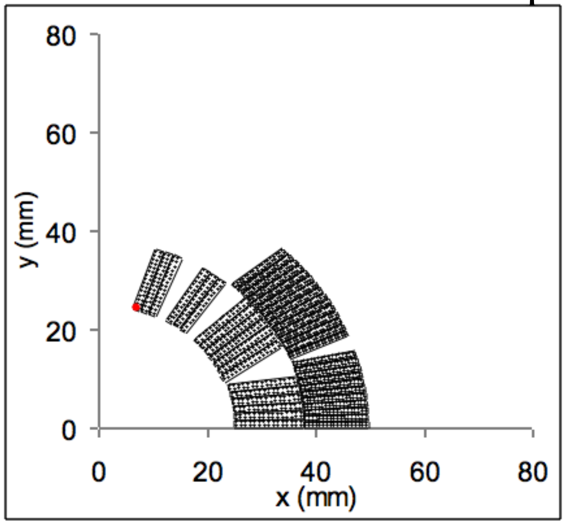
1. Fast losses or fast release of energy (J/cm³)
   - Adiabatic case – all heat stays there
   - Main issue: the conductor must have high enough thermal inertia
   - The deposited energy must not exceed the enthalpy margin
   - Enthalpy margin is the critical parameter
2. Continuous losses (as debris coming from collisions, or losses from the beam) (W/cm³)
   - All heat is removed – stationary case
   - Main issue: the heat must be extracted efficiently
   - The gradient between the heat sink and the coil must not exceed the temperature margin
   - Temperature margin is the critical parameter

How to introduce grading

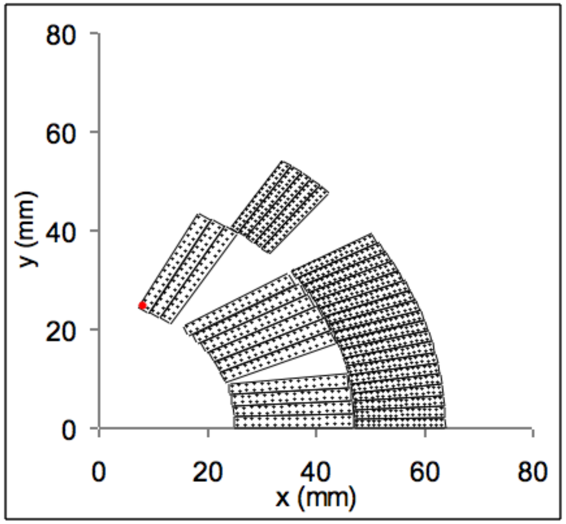
- The idea
  - The map of the field inside a coil is strongly non-uniform
  - In a two layer configuration, the peak field is in the inner layer, and outer layer has systematically a lower field
  - A higher current density can be put in the outer layer

- How to realize it
  - First option: use two different power supplies, one for the inner and one for the outer layer (not common)
  - Second option: use a different cable for the outer layer, with a smaller cross-section, and put the same current (cheaper)
    - The inner and outer layer have a splice, and they share the same current
    - Since the outer layer cable has a smaller section, it has a higher current density

- Examples of graded coils
  - LHC main dipole (~9 T)
    - grading of 1.23 (i.e. +23% current density in outer layer)
    - 3% more in short sample field, 17% save of conductor
  - MSUT - Nb_3Sn model of Univ. of Twente (~11 T)
    - strong grading 1.65
    - 5% more in short sample field, 25% save of conductor



LHC main dipole



MSUT dipole

We can study graded magnets using the tools defined earlier

- Short sample limit for a graded Nb-Ti dipole
  - Each block has a current density $j_1 \ldots j_n$, each one with a dilution factor $\kappa_1 \ldots \kappa_n$
  - We fix the ratios between the current densities

$$\chi_1 \equiv \frac{j_1}{j_1} = 1 \qquad \chi_2 \equiv \frac{j_2}{j_1} \qquad \chi_n \equiv \frac{j_n}{j_1}$$

  - We define the ratio between central field and current densities

$$B = \sum j_n \gamma_{c,n} \equiv j_1 \gamma_c$$

  - We define the ratio between peak field in each block and central field

$$B_{p,n} \equiv \lambda_n B = \lambda_n \gamma_c j_1 = \frac{1}{\chi_n} j_n \lambda_n \gamma_c$$

Grading of dipoles - continued…

- Short sample limit for a graded Nb-Ti dipole (continued I)

$$B = \sum j_n \gamma_{c,n} \equiv j_1 \gamma_c \qquad B_{p,n} = \frac{1}{\chi_n} j_n \lambda_n \gamma_n$$

- In each layer one has $j_{c,n} \leq \kappa_n s (B_{c2}^{*} - B_{p,n})$

  and substituting the peak field expression one has

$$j_{c,n} \leq \frac{\chi_n \kappa_n s}{\chi_n + \lambda_n \kappa_n s \gamma_c} B_{c2}^{*}$$

- All these n conditions have to be satisfied – since the current densities ratios are fixed, one has

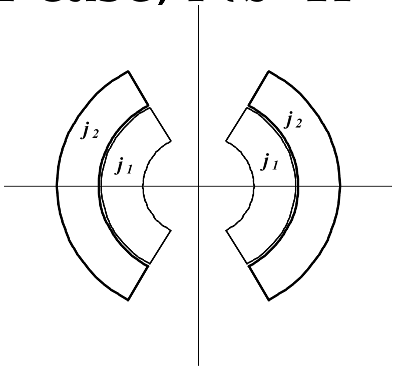
$$j_{c,1} = \frac{j_{c,n}}{\chi_n} \leq \frac{\kappa_n s}{\chi_n + \lambda_n \kappa_n s \gamma_c} B_{c2}^{*} \qquad j_{c,1} = \mathrm{Min}_n \frac{\kappa_n s}{\chi_n + \lambda_n \kappa_n s \gamma_c} B_{c2}^{*}$$

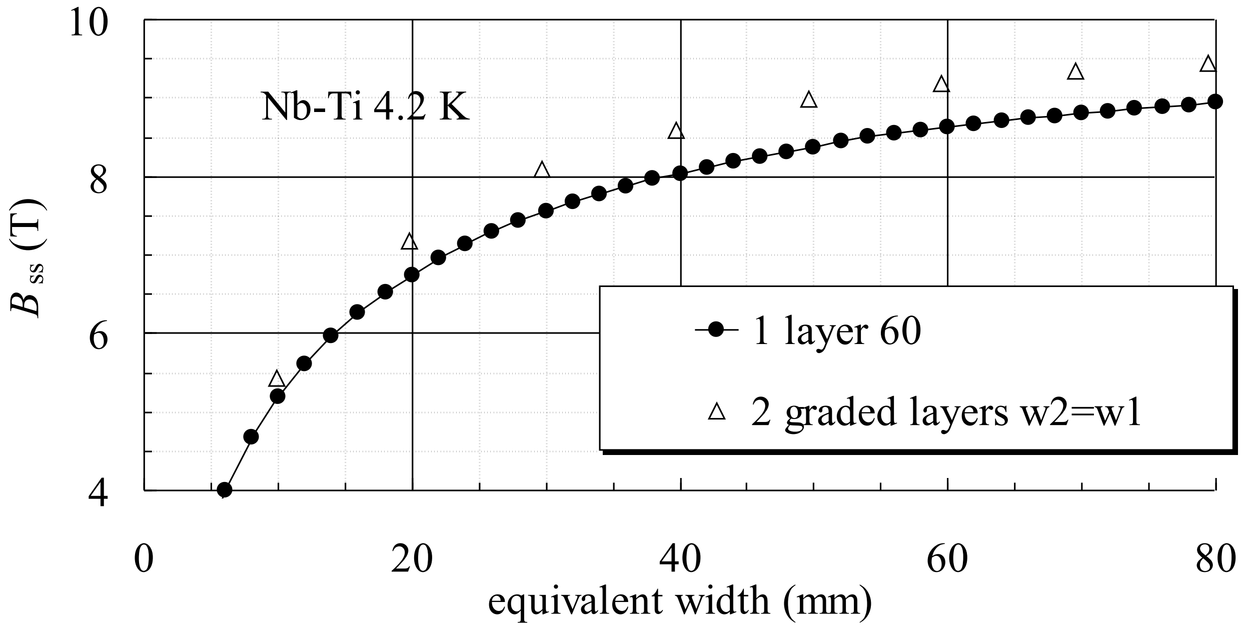
How to calculate the short sample limit

- Short sample limit for a graded Nb-Ti dipole (continued II)
  - The short sample current is
    $$j_{c,1} = \mathrm{Min}_n \frac{s\kappa_n}{\chi_n + \lambda_n s\kappa_n \gamma_c} B^*_{c2}$$
  - and the short sample field is
    $$B_{ss} = \mathrm{Min}_n \frac{s\kappa_n \gamma_c}{\chi_n + \lambda_n s\kappa_n \gamma_c} B^*_{c2}$$
  - Comments
    - The grading factor χ in principle should be pushed to maximize the short sample field
    - A limit in high grading is given by quench protection issues, that limit the maximal current density – in general the outer layer has lower filling factor to ease protection
    - Please note that the equations depend on the material – a graded lay-out optimized for Nb-Ti will not be optimized for Nb_3Sn

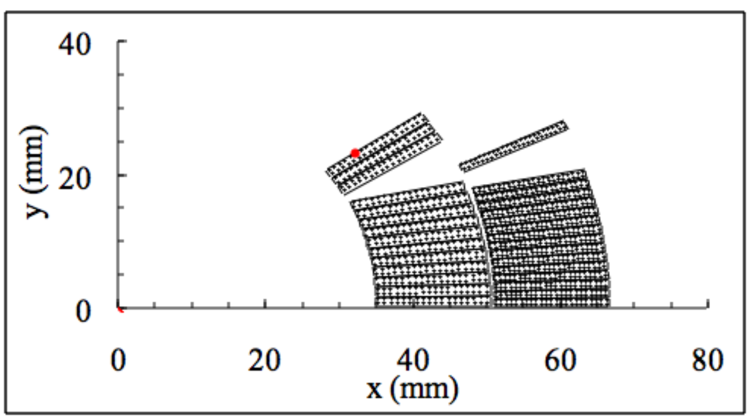
Comparison of single layer vs graded 2-layer

- Results for a two layer with same width sector case, Nb-Ti
  - The gain in short sample field is ~5%
  - But given a short sample field, one saves a lot !
    - At 8 T one can use 30 mm instead of 40 mm (-25%)
    - At 9 T one can use 50 mm instead of 80 mm (-37%)

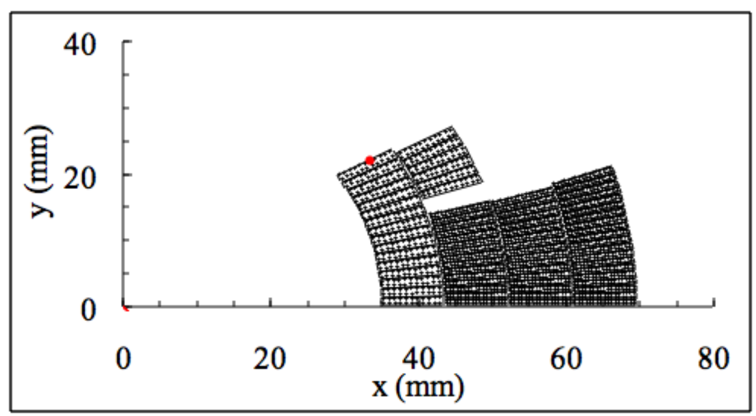




- Similar strategy for quadrupoles – gain of 5-10% in G_{ss}
  - LHC MQXB – quadrupole for IR regions
    - grading of 1.24 (i.e. +24% current density in outer layer)
    - 6% more in short sample field, 41% save of conductor
  - LHC MQY – quadrupole close to IR regions
    - Special grading (grading inside outer layer, upper pole with lower density) of 1.43
    - 9% more in short sample field, could not be reached without grading



LHC MQXB



LHC MQY

Some basic comments concerning the use of iron

- An iron yoke usually surrounds the collared coil – it has several functions
  - Keep the return magnetic flux close to the coils, thus avoiding fringe fields
  - In some cases the iron is partially or totally contributing to the mechanical structure
    - RHIC magnets: no collars, plastic spacers, iron holds the Lorentz forces
    - LHC dipole: very thick collars, iron give little contribution
  - Considerably enhance the field for a given current density
    - The increase is relevant (10-30%), getting higher for thin coils
    - This allows using lower currents, easing the protection
  - Increase the short sample field
    - The increase is small (a few percent) for "large" coils, but can be considerable for small widths
    - This action is effective when we are far from reaching the asymptotic limit of B^*_{c2}

How to size the iron - for shielding

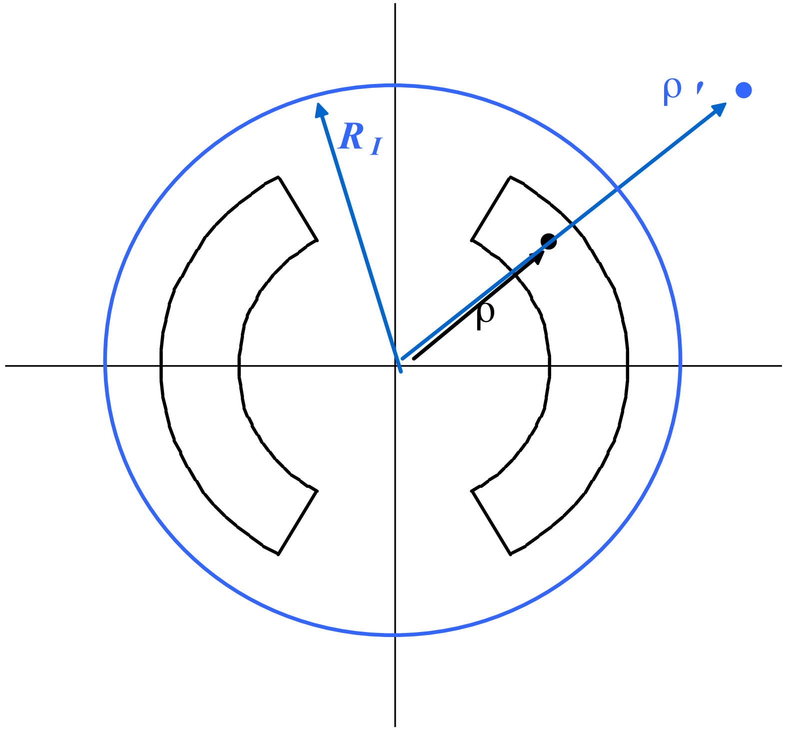
- A rough estimate of the iron thickness necessary to avoid fields outside the magnet
  - The iron cannot withstand more than 2 T (see discussion on saturation, later)
  - Shielding condition for dipoles: $$rB \sim t_{iron} B_{sat}$$
    - i.e., the iron thickness times 2 T is equal to the central field times the magnet aperture – One assumes that all the field lines in the aperture go through the iron (and not for instance through the collars)
    - Example: in the LHC main dipole the iron thickness is 150 mm

$$t_{iron} \sim \frac{rB}{B_{sat}} = \frac{28 * 8.3}{2} \sim 100 \text{ mm}$$

  - Shielding condition for quadrupoles: $$\frac{r^2 G}{2} \sim t_{iron} B_{sat}$$

We can analyze the influence of iron using image currents

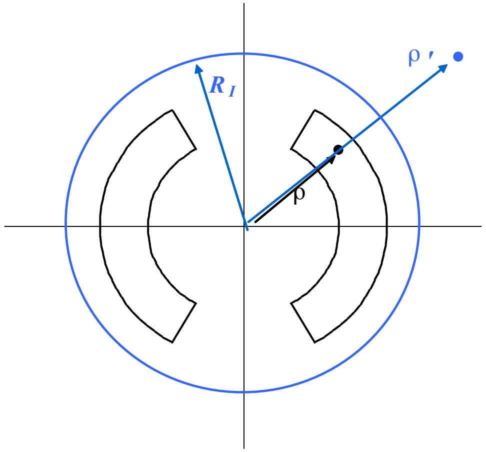
- The iron yoke contribution can be estimated analytically for simple geometries
  - Circular, non-saturated iron: image currents method
  - Iron effect is equivalent to add to each current line a second one
    - at a distance $$\rho' = \frac{R_I^2}{\rho}$$
    - with current $$I' = \frac{\mu - 1}{\mu + 1} I$$
  - Limit of the approximation: iron is not saturated (less than 2 T)



- Remarks on the equations

$$\rho' = \frac{R_I^2}{\rho} \qquad I' = \frac{\mu - 1}{\mu + 1} I$$

  - When iron is not saturated, one has μ>>1 and then $I' = I$
  - Since the image is far from the aperture, its impact on high order multipoles is small
  - The impact of the iron is negligible for
    - Large coil widths
    - Large collar widths
    - High order multipoles
  - The iron can be relevant for
    - Small coil widths, small collar widths, low order multipoles, main component
  - At most, iron can double the main component for a given current density (i.e. can give a Δγ=100%)
    - This happens for infinitesimally small coil and collar widths



Iron influence on main field

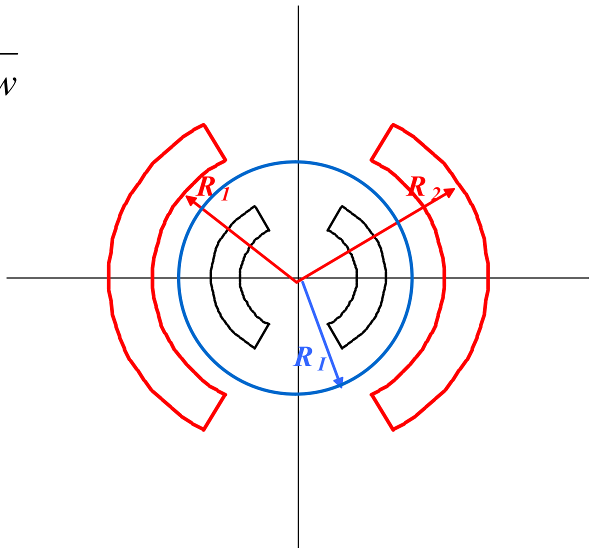
$B = \gamma_c J_E$

- Estimate of the gain in main field $\Delta\gamma$ for a sector coil

$$B_1 = kjw \qquad \Delta B_1^{iron} = kj'(R_2 - R_1) \qquad R_1 = \frac{R_I^2}{r+w}$$

k is just a temporary transfer function term…

$$\frac{\Delta B_1^{iron}}{B_1} = \frac{j'(R_2 - R_1)}{jw} \qquad R_2 = \frac{R_I^2}{r}$$



the current density has to satisfy the integral condition

$$j\left[(r+w)^2 - r^2\right] = \frac{\mu - 1}{\mu + 1} j' \left[R_2^2 - R_1^2\right]$$

and one obtains

$$\frac{\Delta B_1^{iron}}{B_1} = \frac{\mu - 1}{\mu + 1} \frac{(r+w)r}{R_I^2}$$

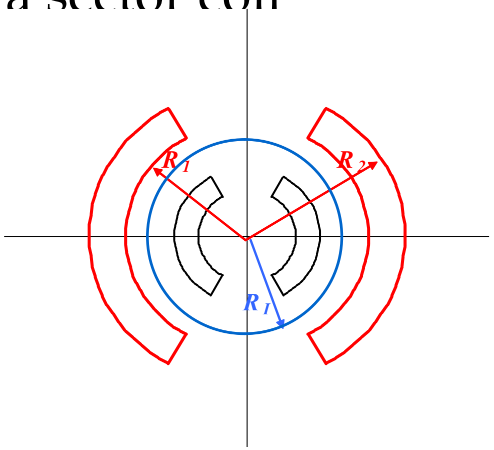
- For higher order multipoles
  - The relative contribution becomes very small

$$\frac{\Delta B_n^{iron}}{B_n} = \frac{\mu - 1}{\mu + 1} \left[\frac{(r+w)r}{R_I^2}\right]^n$$

Examples of iron enhancement to main field

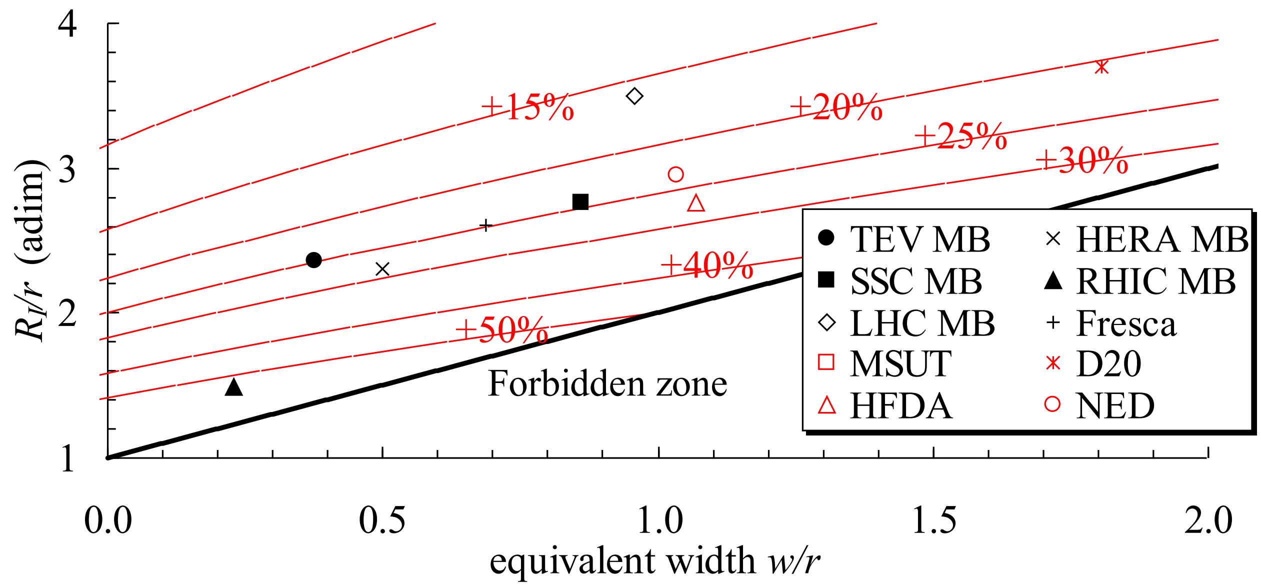
- Estimate of the gain in main field for fixed current in a sector coil

$$\frac{\Delta B_1^{iron}}{B_1} = \frac{\mu - 1}{\mu + 1}\frac{(r + w)r}{R_I^2}$$



Examples of several built dipoles

- Smallest: LHC ~16% (18% actual value)
- Largest: RHIC ~55% (56% actual value)



Influence of iron on short sample field

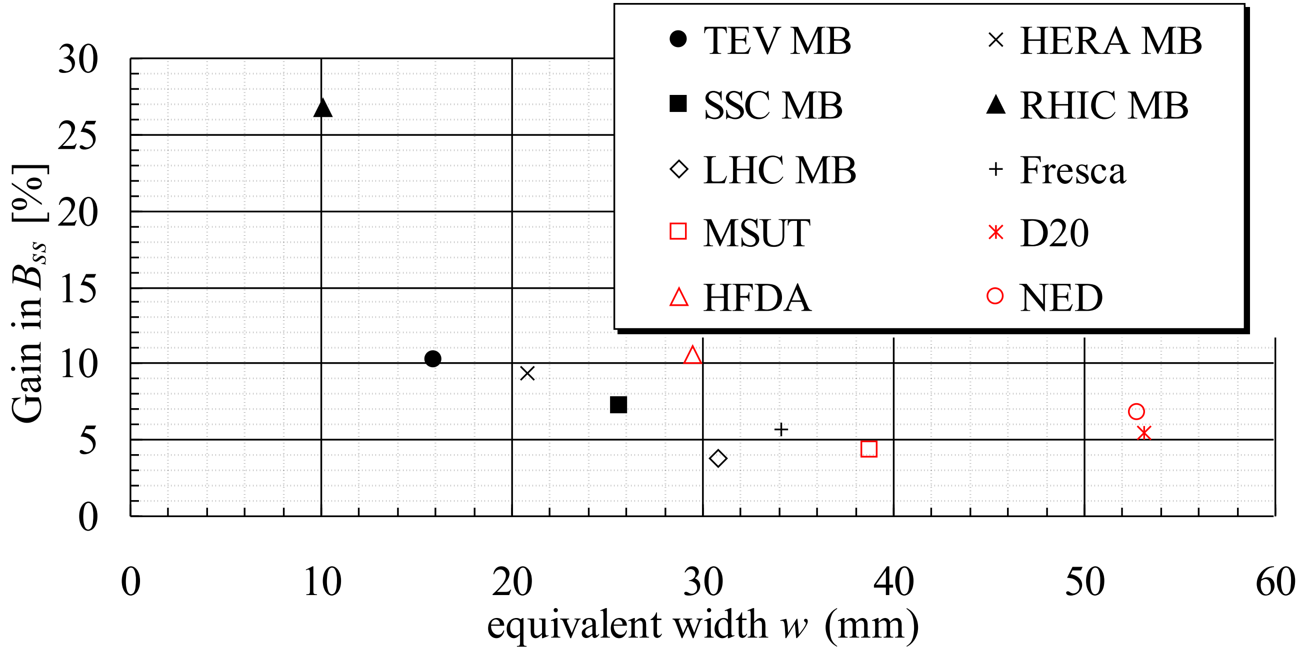
- Impact of the iron yoke on dipole short sample field, Nb-Ti

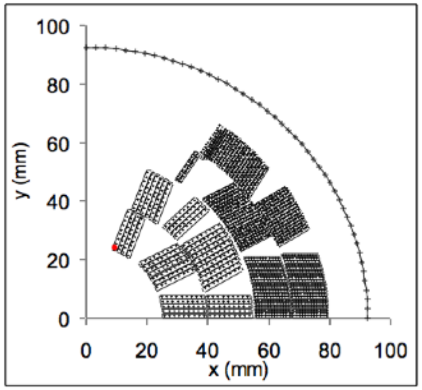
$$B_{ss} = \frac{\kappa s \gamma_c}{1 + \lambda \kappa s \gamma_c} B^*_{c2}$$

- The change of γ_c is the change of B for a fixed current, previously computed
  - Two regimes:
    - for $\lambda\kappa s\gamma_c$<<1 the increase in γcorresponds to the same increase in the short sample field ("thin coils")
    - for $\lambda\kappa s\gamma_c$>>1 no increase in the short sample field ("thick coils")
    - Please note that the "thin" and "thick" regimes depend on filling ratio κ and on the slope *s* of the critical surface
  - For the Nb_3Sn one has to use the corresponding equations
    - Phenomenology is similar, but quantitatively different

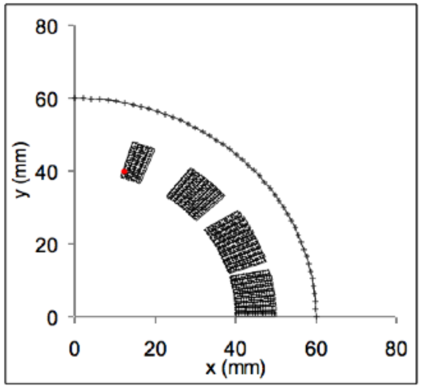
Examples of iron influence

- Impact of the iron yoke on short sample field
  - Large effect (25%) on RHIC dipoles (thin coil and collars)
  - Between 4% and 10% for most of the others
    (both Nb-Ti and Nb_3Sn)





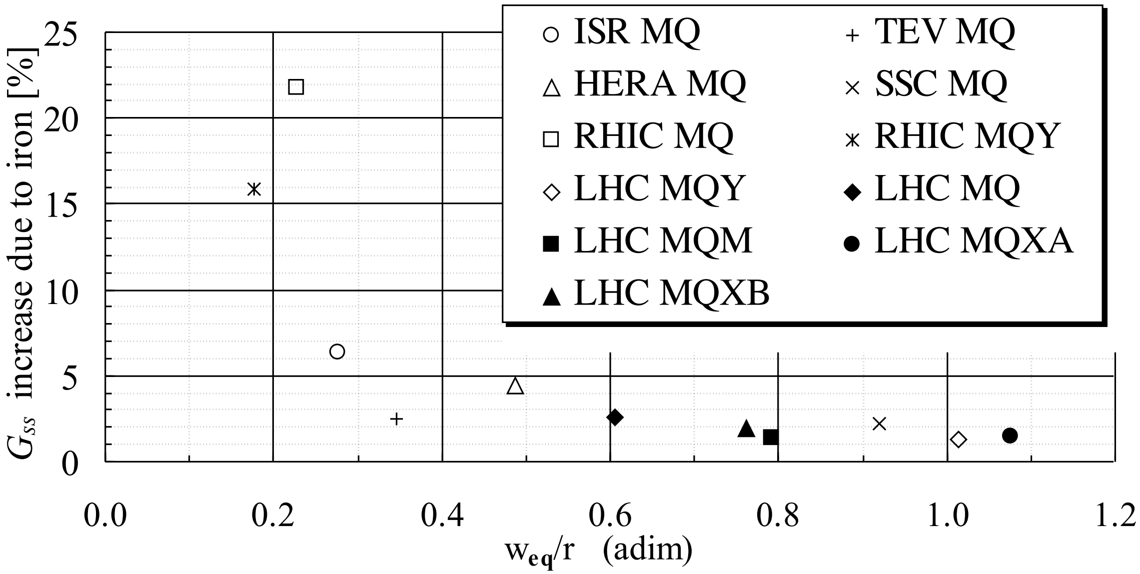
D20 and yoke

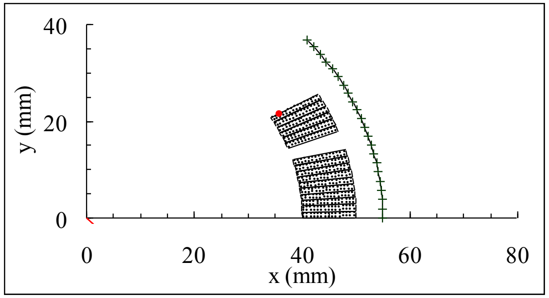


RHIC main dipole and yoke

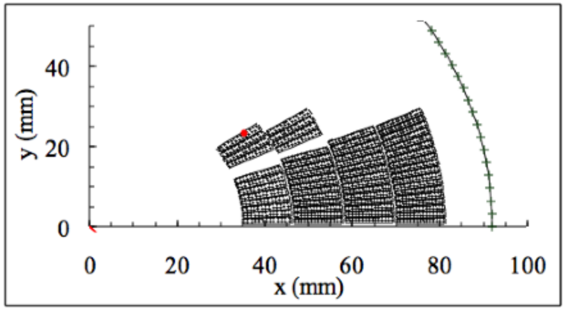
Influence of iron on quadrupole field strength

- Similar approach can be used in quadrupoles
  - Large effect on RHIC quadrupoles (thin coil and collars)
  - Between 2% and 5% for most of the others
  - The effect is smaller than in dipoles since the contribution to B_2 is smaller than to B_1





RHIC MQ and yoke



LHC MQXA and yoke

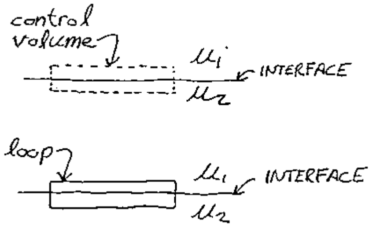
Influence of iron is strongly field-dependent

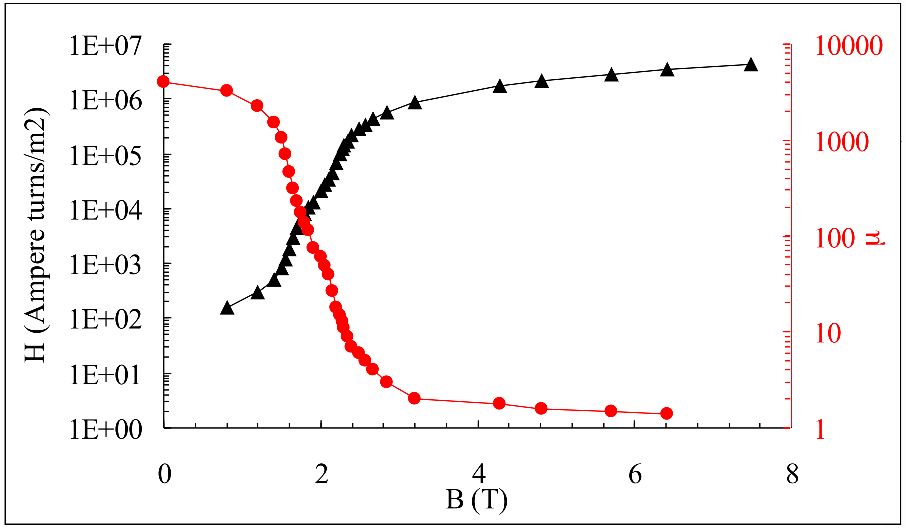
- Iron saturation: B-H curve $B = \mu\mu_0 H$
  - for B<2 T, one has $\mu \gg 1$ ($\mu \sim 10^3$-10^4), and the iron can give a relevant contribution to the field according to what discussed before
  - for B>2 T, $\mu \to 1$, and the iron becomes "transparent" (no effect on field)

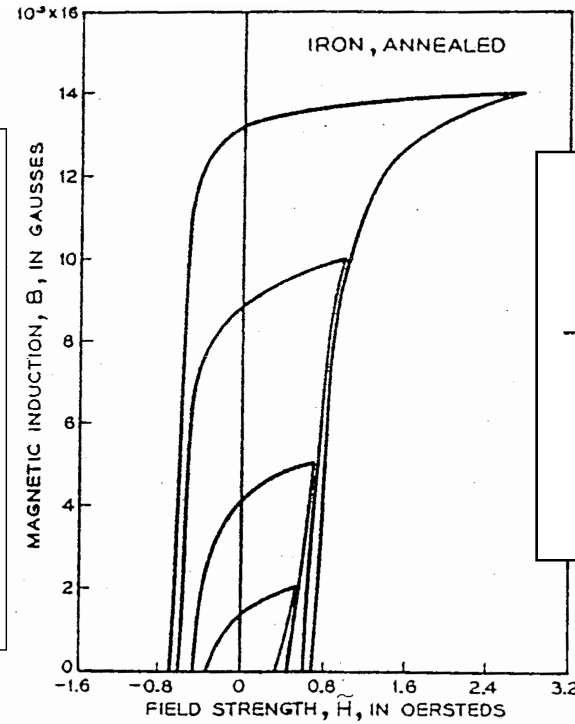
Continuity across an interface:

$\vec{\nabla} \cdot B = 0 \Rightarrow \Delta B_\perp = 0$

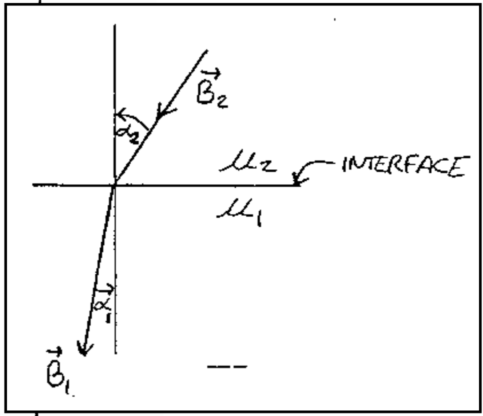
$\vec{\nabla} \times H = 0 \Rightarrow \Delta H_\parallel = 0$





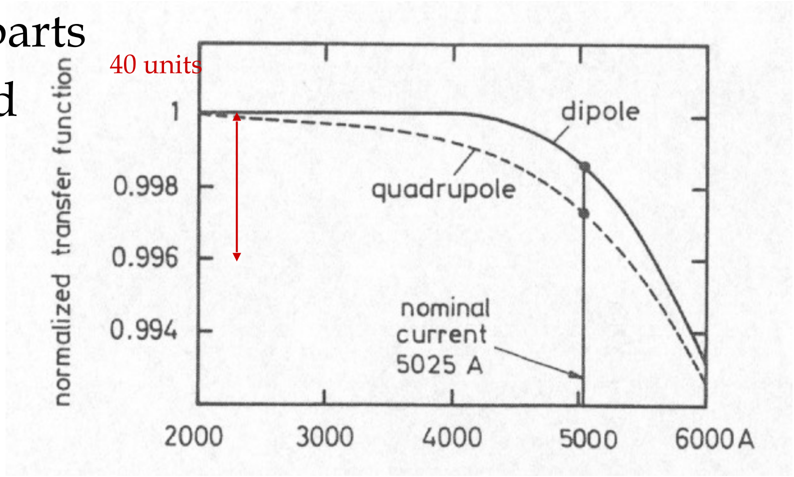


Upper halves of hysteresis loops of ordinary annealed iron



Iron saturation complicates modeling and analysis

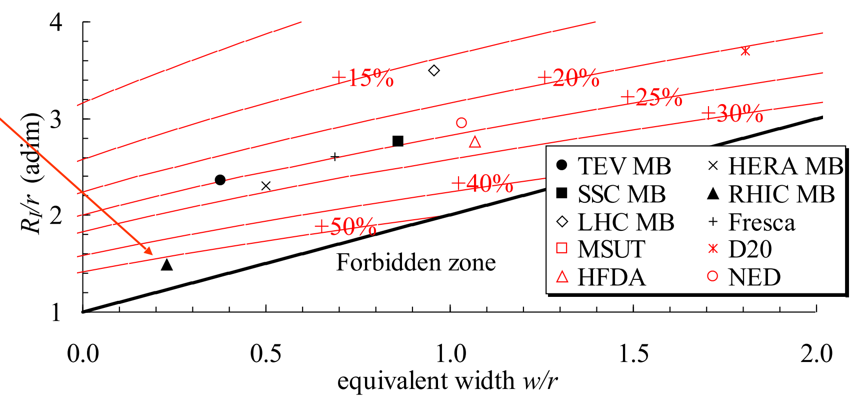
- Impact on calculation
  - When iron saturates → image current method cannot be applied, finite element method is needed (Poisson, Opera, Ansys, Roxie, …)
  - Accuracy of model is good (error less than 10% if B-H well known)
- Impact on main component and multipoles
  - The main field is not ∝ current → transfer function *B/i* drops
  - Since the field in the iron has an azimuthal dependence, some parts of the iron can be saturated and others not → variation of b_3
- It was considered critical
  - Led to warm iron design in Tevatron
  - Today, even few % of saturation seem manageable in operation



Impact of yoke saturation in HERA dipole and quadrupoles, From Schmuser, pg 58, fig. 4.12

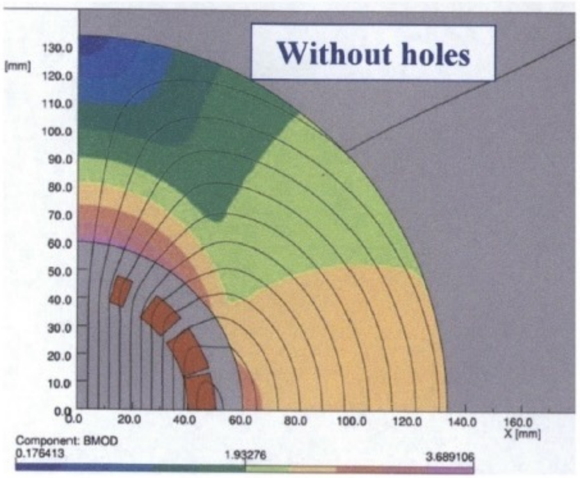
Optimization of iron yoke to compensate for saturation effects

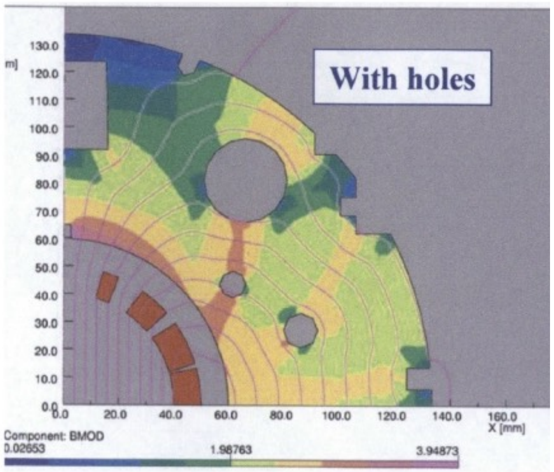
- Corrective actions: shaping the iron
  - In a dipole, the field is larger at the pole – iron will saturate there first
    - The dependence on the azimuth of the field in the coil provokes different saturations, and a strong impact on multipole
  - One can optimize the shape of the iron to reduce these effects
    - Optimization of the position of holes (holes anyway needed for cryogenics) to minimize multipole change
    - RHIC is the most challenging case, since the iron gives a large contribution (50% to γ, i.e. to central field for a given current)



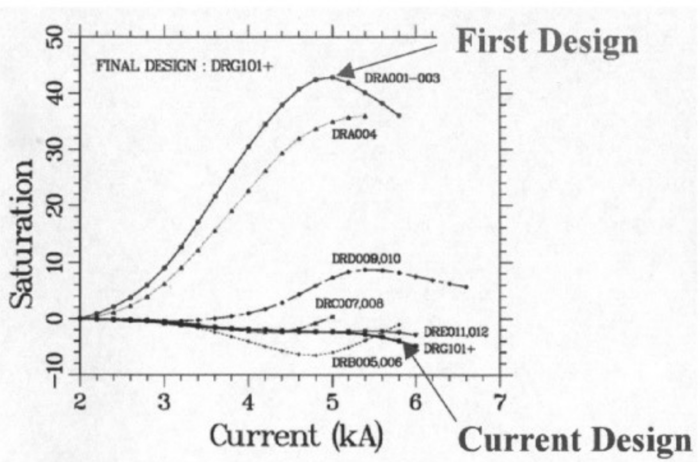
Examples of iron shaping - RHIC

- Corrective actions: shaping the iron – the RHIC dipole
  - The field in the yoke is larger on the pole
  - Drilling holes in the right places, one can reduce saturation impact on b_3 from 40 units to less than 5 units (one order of magnitude), and to correct also b_5





Field map in the iron for the RHIC dipole, with and without holes
From R. Gupta, USPAS Houston 2006, Lecture V, slide 12

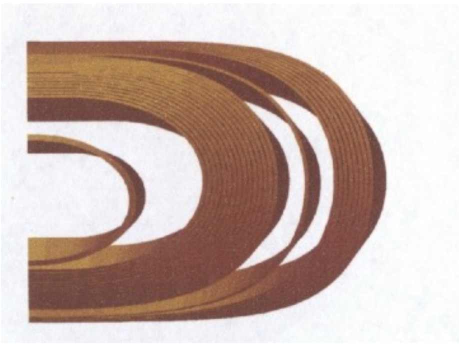


Correction of b3 variation due to saturation
for the RHIC dipoles, R. Gupta, ibidem

- A similar approach has been used for the LHC dipole
  - Less contribution from the iron (20% only), but left-right asymmetries due to two-in-one design [S. Russenschuck, C. Vollinger, ….]
- Another possibility is to shape the contour of the iron (elliptical and not circular)

Magnet end design is a critical issue

- Main features of the coil end design
  - ++Mechanical: find the shape that minimizes the strain in the cable due to the bending (constant perimeter)
    - In a cos(θ) magnet this strain can be large if the aperture is small
    - In a racetrack design the cable is bent in the ‘right’ direction and therefore the strain is much less
    - It is important to have codes to design the end spacers that best fit the ends, giving the best mechanical support – iteration with results of production is usually needed



End of a cosθ coil
[S. Russenschuck, World Scientific, Fig. 32.13]

End spacers supporting the ends of a cosθ coil
[S. Russenschuck,World Scientific, Fig. 32.13]

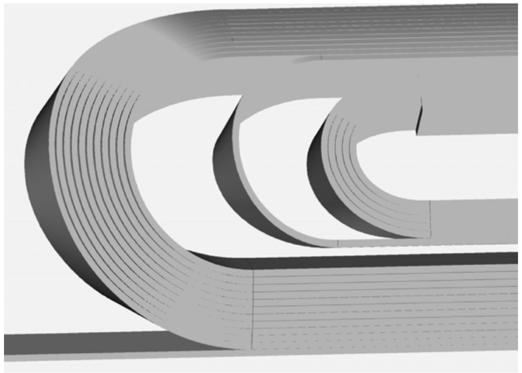
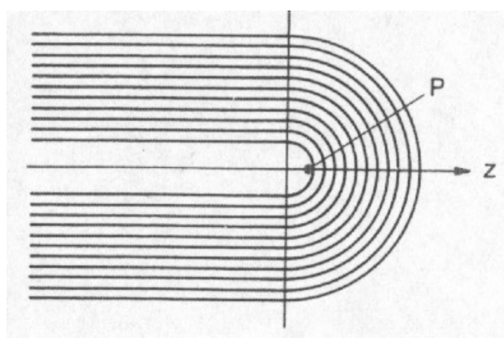


Fig. 2. Typical turns generated by BEND loaded into the CAD ProE program.

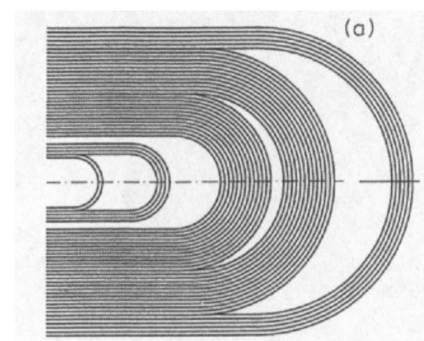
Caspi, Ferracin TAS Vol 16, 2006

Figure of merit for end design

- Main features of the coil end design
  - + Magnetic: find the shape that allows to avoid a higher field in the ends
    - Due to the coil return, the main field in the ends is enhanced (typically several %)
    - On the other hand, the ends are often the most difficult parts to manufacture
    - It is common to reduce the main field in the ends by adding spacers - this makes the design a bit more complicated



Simple coil end with increased field in P
[Schmuser,pg. 58]

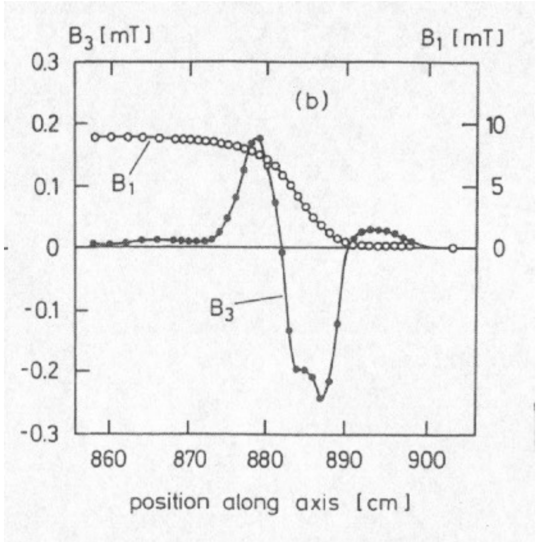


Coil end with spacers to decrease the main field in the end
[Schmuser,pg. 58]

Magnet end design influences field quality

- Main features of the coil end design
  - +/- Magnetic: take care of field quality (especially if the magnet is short)
    - In general a coil end will give a non-negligible contribution to multipoles
    - Two possibilities
      - Leave it as it is and compensate the coil end with the straight part so that the multipoles integral over the magnet is optimal (cheap, simple)
      - Optimize the end spacer positions to set to zero the integral multipoles in each the head (more elegant, complicated)
    - In the plot pseudo-multipoles are shown, extracted as Fourier coefficients
      - The scaling with the reference radius is not valid
      - They are not unique – if you start from radial or tangential expression, B_x or B_y you get different things
      - They give an idea of the behavior of the field harmonics, and way to get a compensation
    - The real 3d expansion can be written

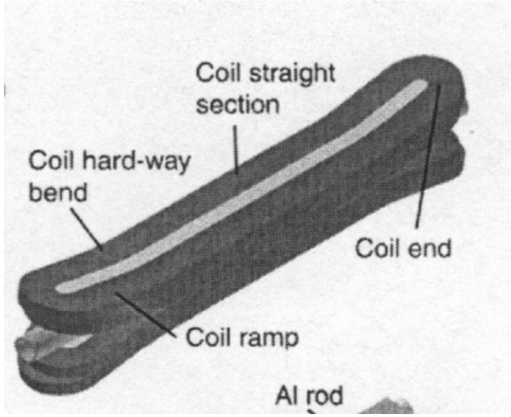
(see A. Jain, USPAS 2006 in Phoenix: "Harmonic description of 2D fields", slide 4)

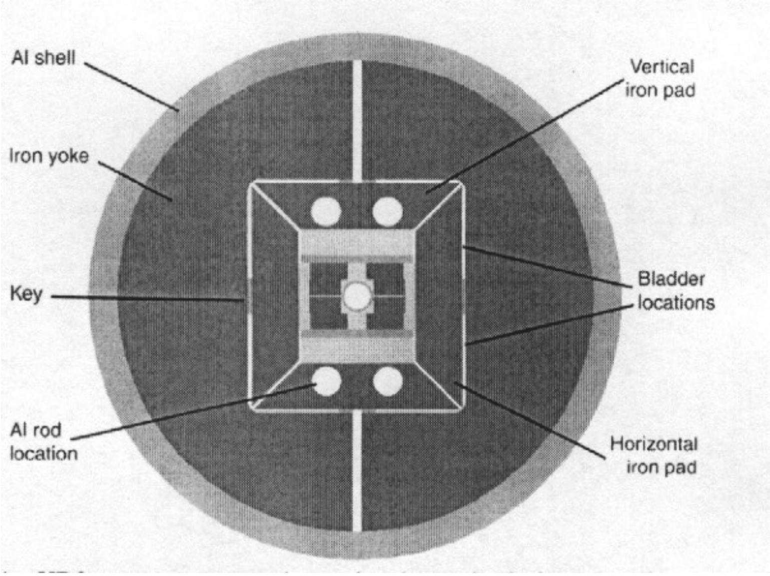


Main field and pseudo-multipoles in coil end optimized to have null integrated b_3 [Schmuser,pg. 58]

Lets look at other design concepts again…

- Block coil
  - Cable is not keystoned
  - Cables are perpendicular to the midplane
  - Ends are wound in the easy side, and slightly opened
  - Internal structure to support the coil is needed
  - Example: HD2 coil design





HD2 design: 3D sketch of the coil (left) and magnet cross section (right)
[from P. Ferracin et al, MT19, IEEE Trans. Appl. Supercond. **16** 378 (2006)]

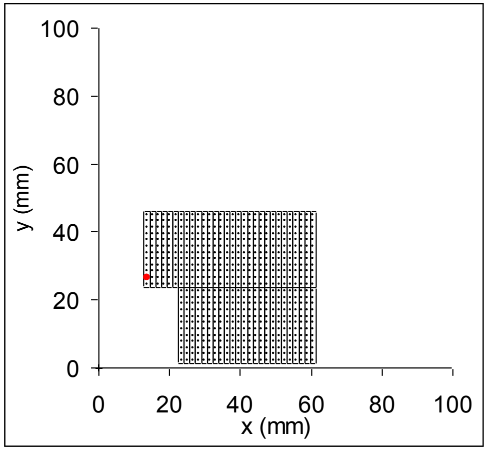
Flared-racetrack example

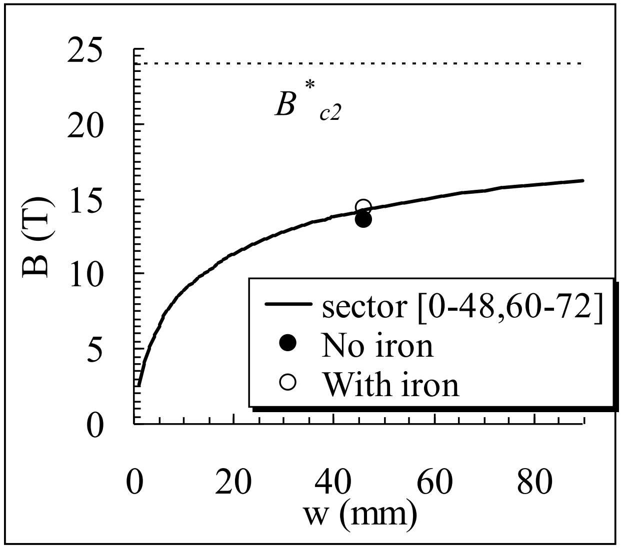
- Block coil – HD2
  - Two layers, two blocks
  - Enough parameters to have a good field quality
  - Ratio peak field/central field not so bad:

    1.05 instead of 1.02 as for a cosθ with the same quantity of cable
  - Ratio central field/current density is 12%

    less than a cos(θ) with the same quantity of cable
  - Short sample field is around 5% less

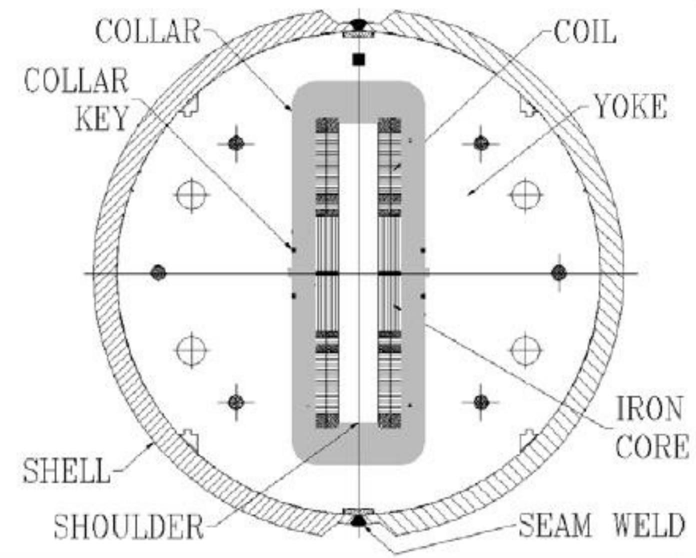
    than what could be obtained by a cosθ with the same quantity of cable
  - Reached 87% of short sample

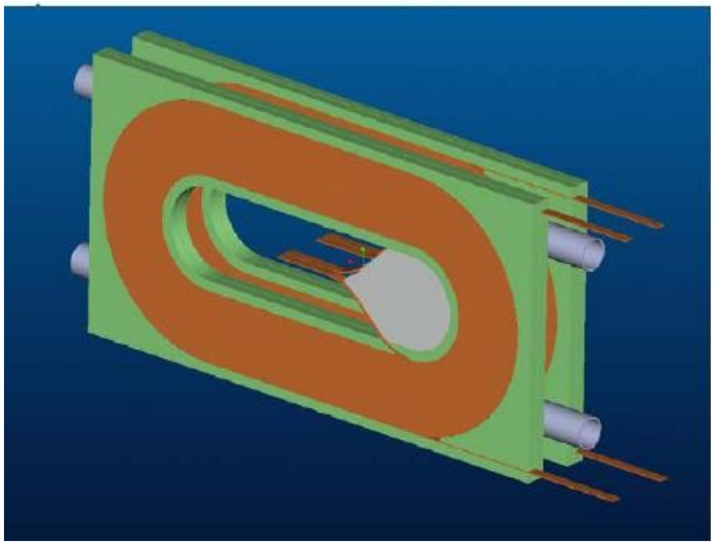




Common coil example

- Common coil
  - A two-aperture magnet
  - Cable is not keystoned
  - Cables are parallel to the mid-plane
  - Ends are wound in the easy side

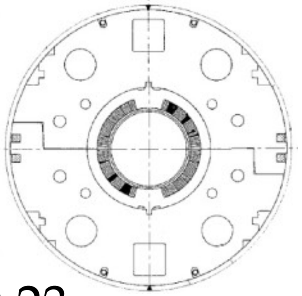




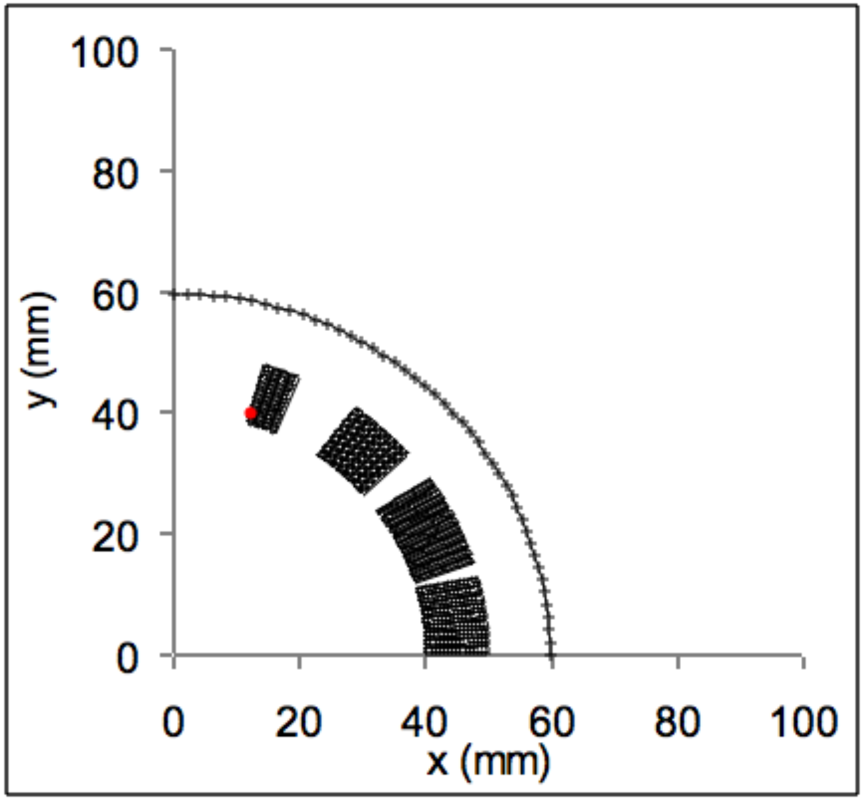
Common coil lay-out and cross-section
R. Gupta, *et al.*, "React and wind common coil dipole", talk at *Applied Superconductivity Conference 2006,* Seattle, WA, Aug. 27 - Sept. 1, 2006.

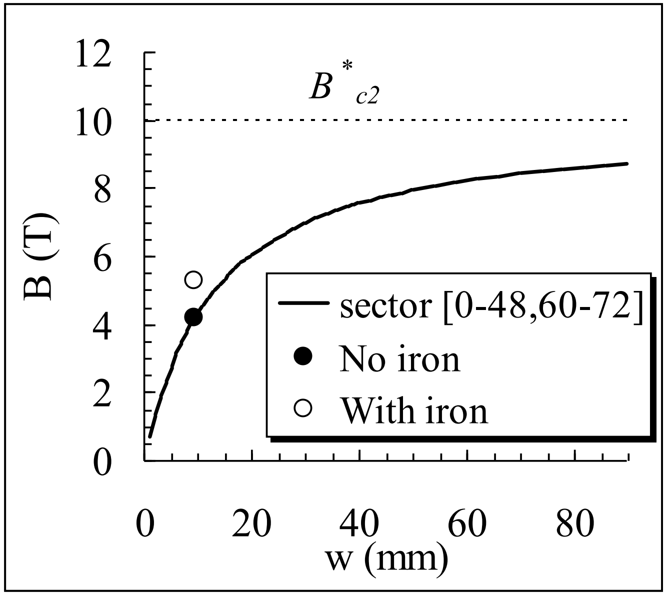
RHIC MB

- Main dipole of the RHIC
- 296 magnets built in 04/94 – 01/96



- Nb-Ti, 4.2 K
- w_{eq}~9 mm   κ~0.23
- 1 layer, 4 blocks
- no grading

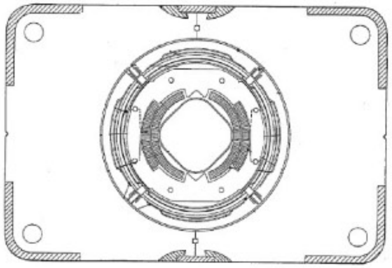




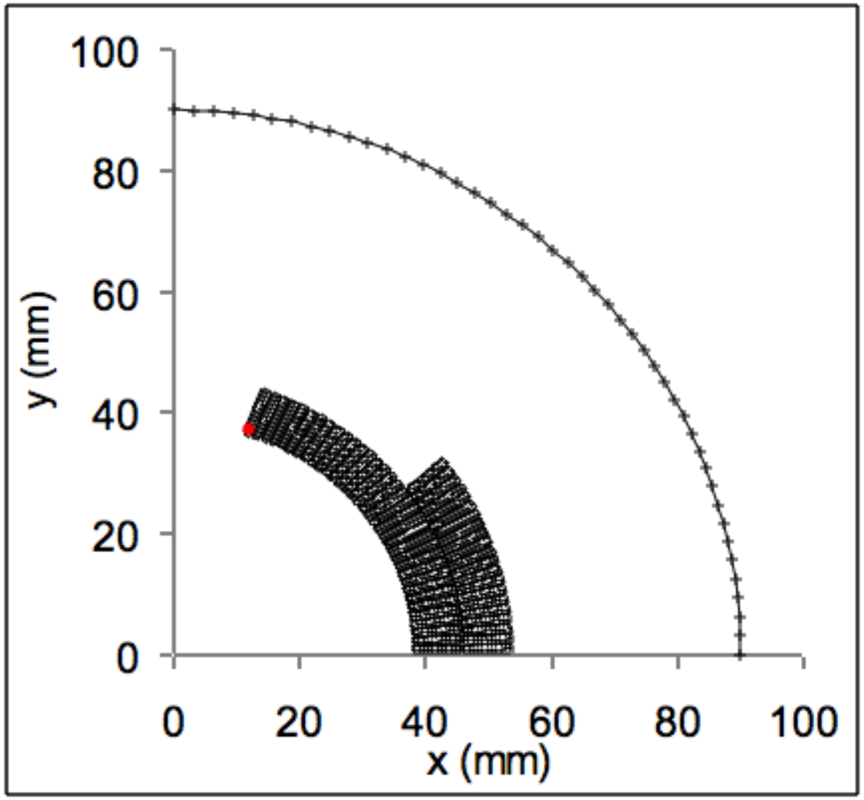
Example dipole layouts - Tevatron

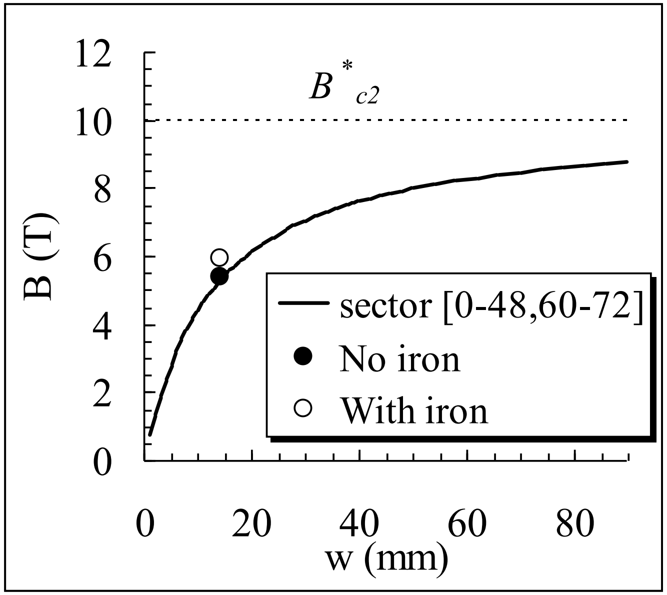
Tevatron MB

- Main dipole of the Tevatron
- 774 magnets built in ~1980



- Nb-Ti, 4.2 K
- w_{eq}~14 mm   κ~0.23
- 2 layer, 2 blocks
- no grading

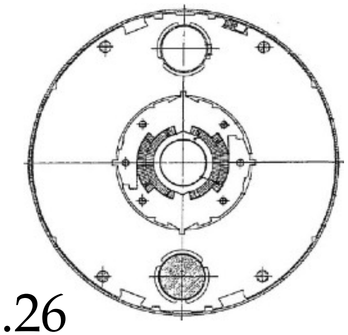




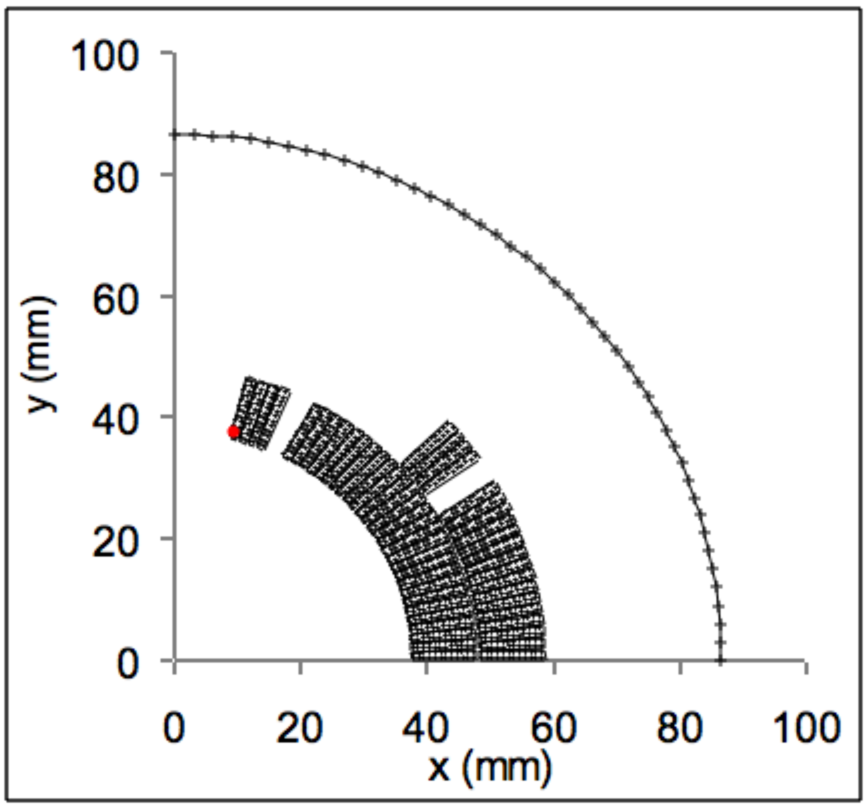
Example of dipole layouts - HERA

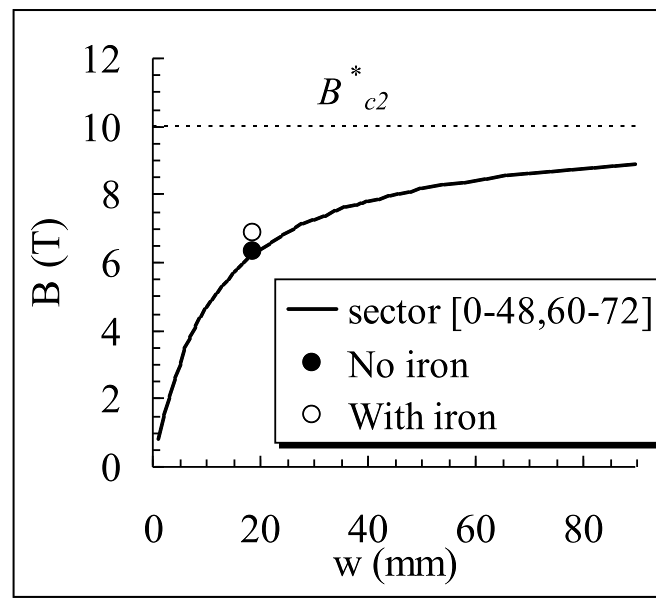
HERA MB

- Main dipole of the HERA
- 416 magnets built in ~1985/87



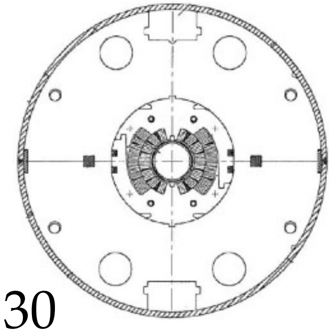
- Nb-Ti, 4.2 K
- w_{eq}~19 mm κ~0.26
- 2 layer, 4 blocks
- no grading



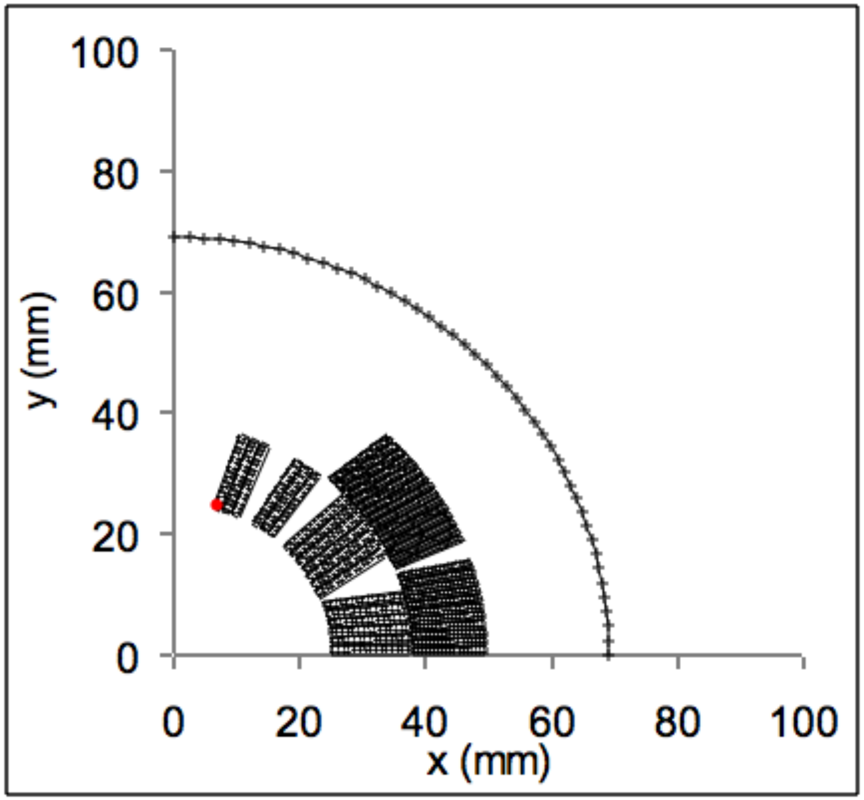


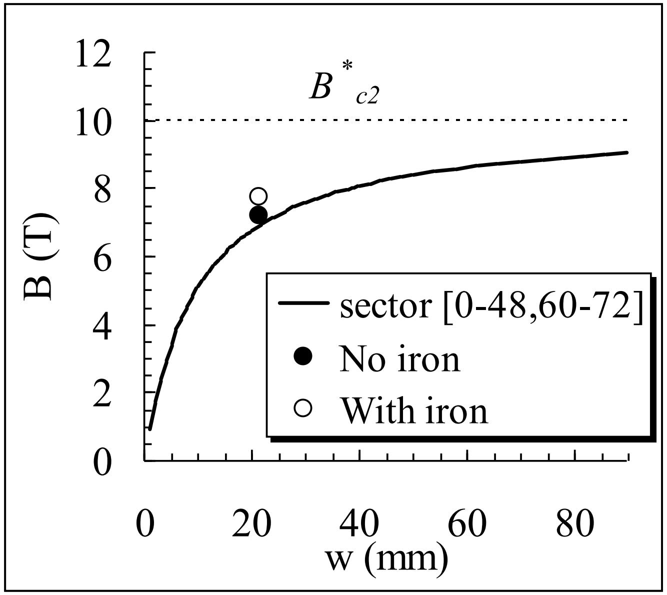
SSC MB

- Main dipole of the ill-fated SSC
- 18 prototypes built in ~1990-5



- Nb-Ti, 4.2 K
- w_{eq}~22 mm   κ~0.30
- 4 layer, 6 blocks
- 30% grading

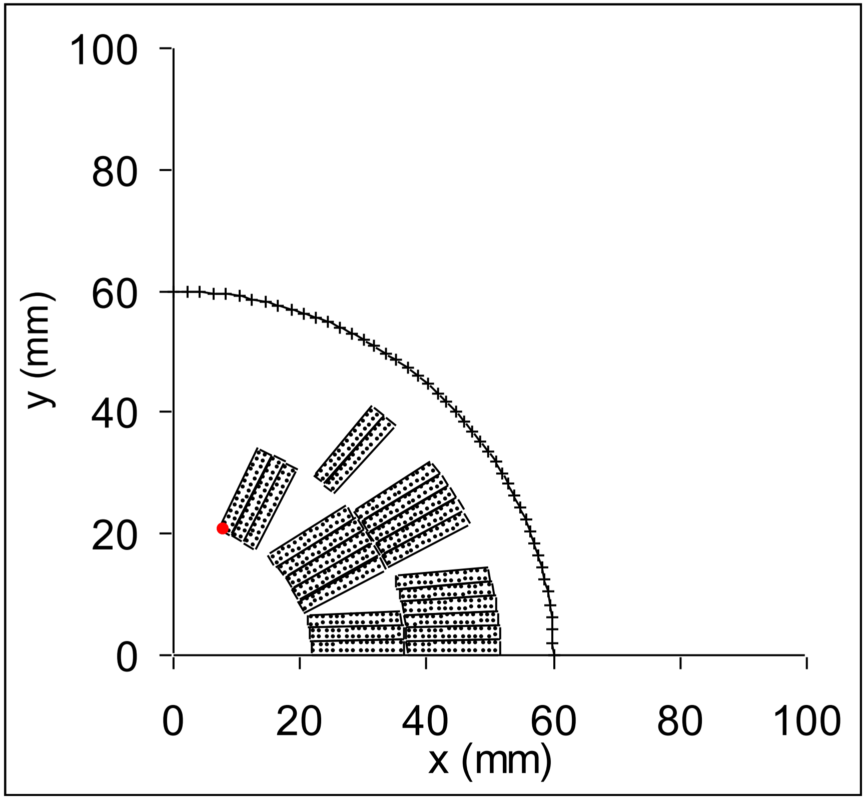




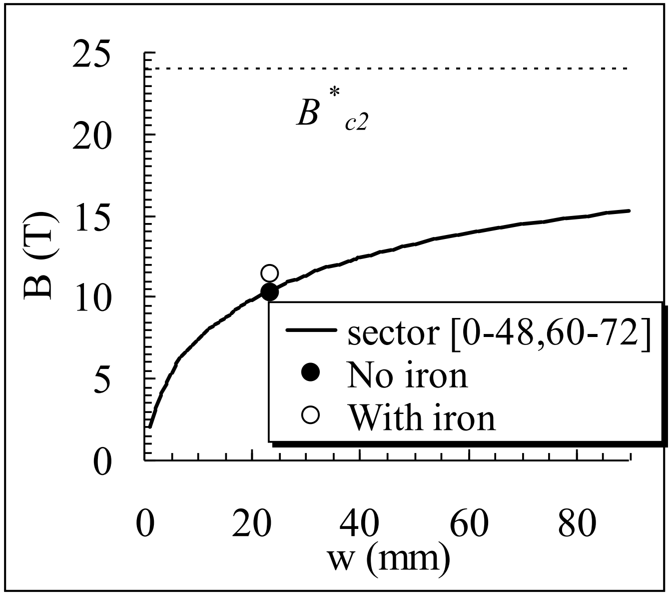
Example dipole layouts - HFDA

HFDA dipole

- Nb_3Sn model built at FNAL
- 6 models built in 2000-2005



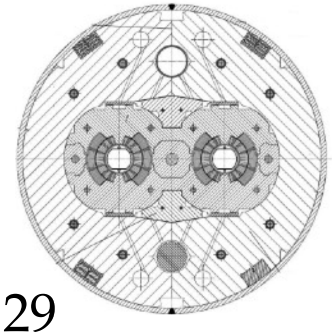
- Nb_3Sn, 4.2 K
- j_c~2000 to 2500 A/mm² at 12 T, 4.2 K (different strands)
- w_{eq}~23 mm κ~0.29
- 2 layers, 6 blocks
- no grading



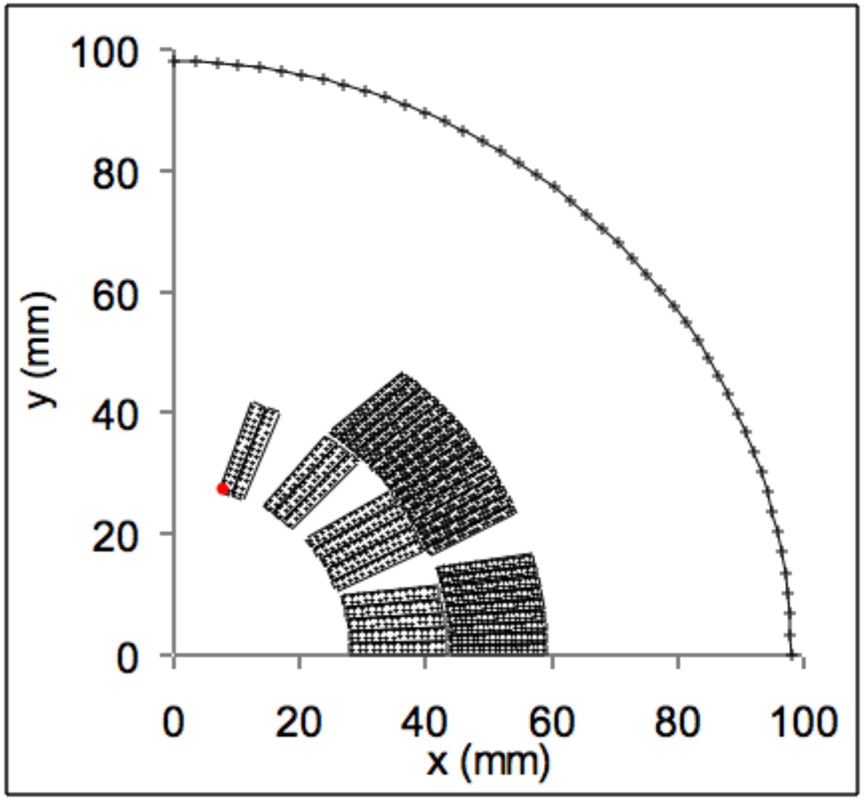
Example dipole layouts - LHC MB

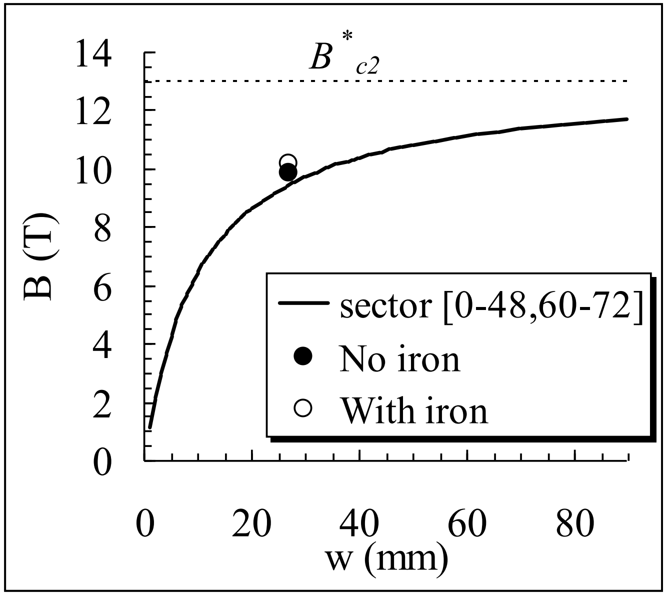
LHC MB

- Main dipole of the LHC
- 1276 magnets built in 2001-06



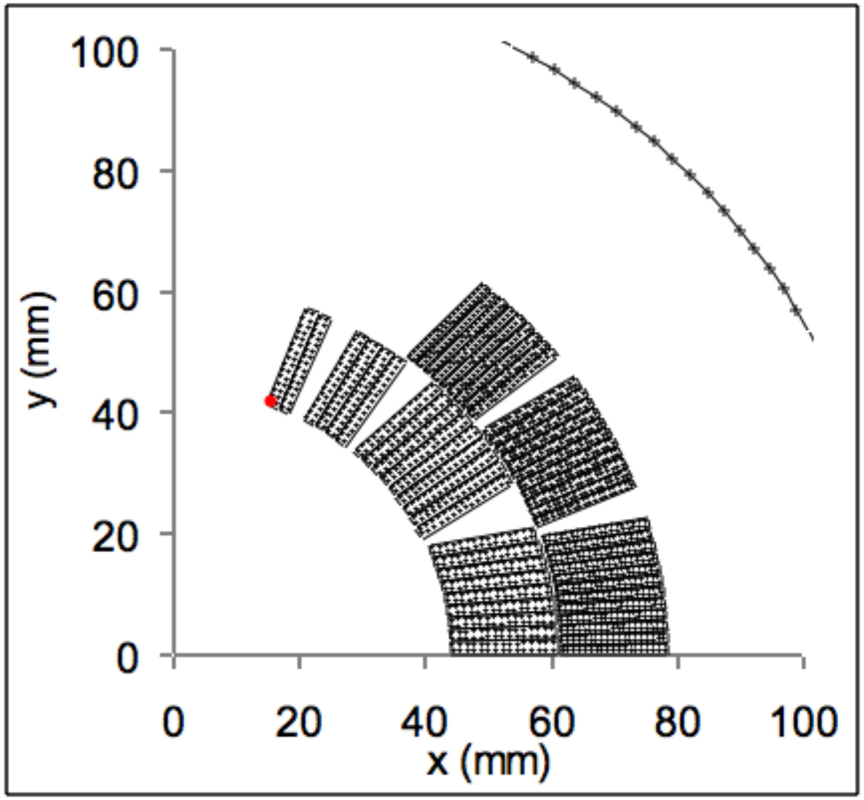
- Nb-Ti, 1.9 K
- w_{eq}~27 mm   κ~0.29
- 2 layers, 6 blocks
- 23% grading



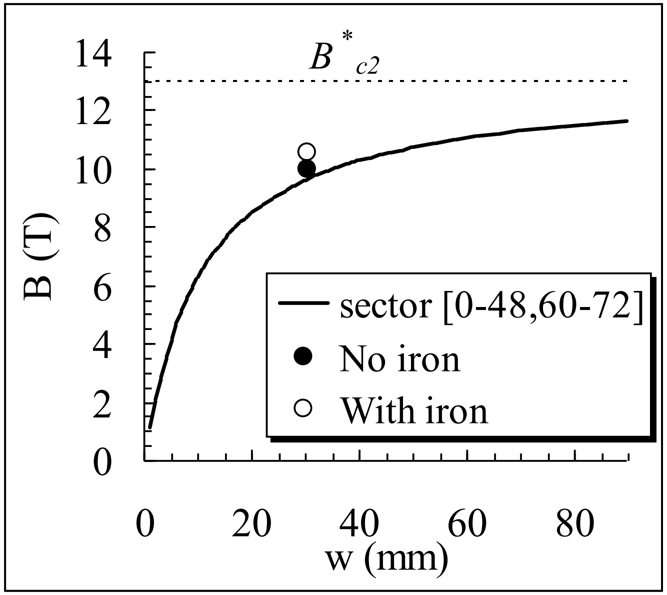


FRESCA

- Dipole for cable test station at CERN
- 1 magnet built in 2001



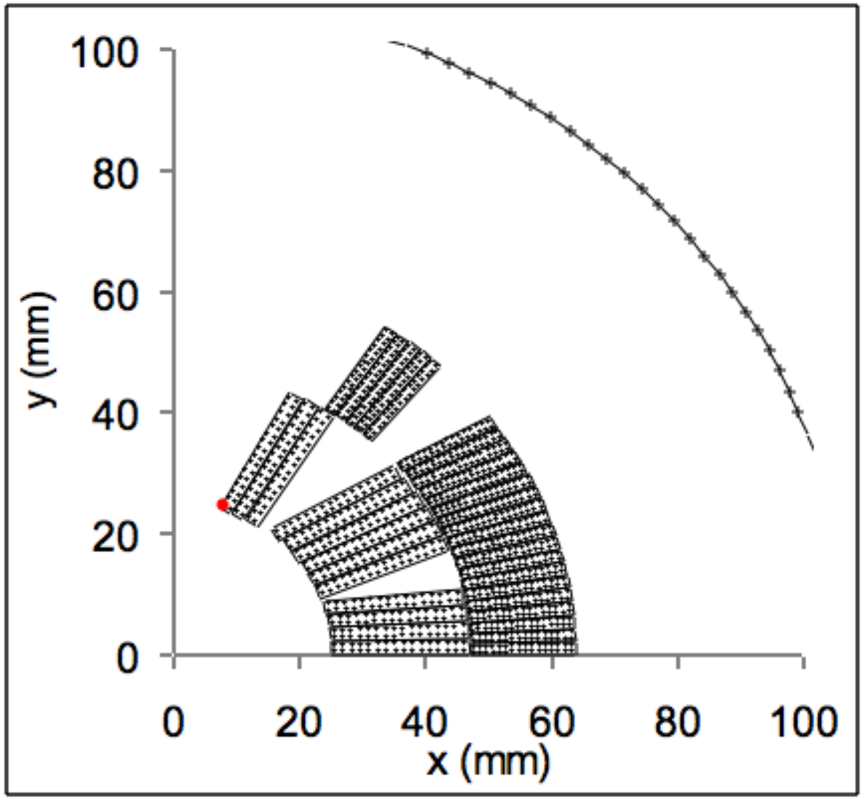
- Nb-Ti, 1.9 K
- w_{eq}~30 mm κ~0.29
- 2 layers, 7 blocks
- 24% grading

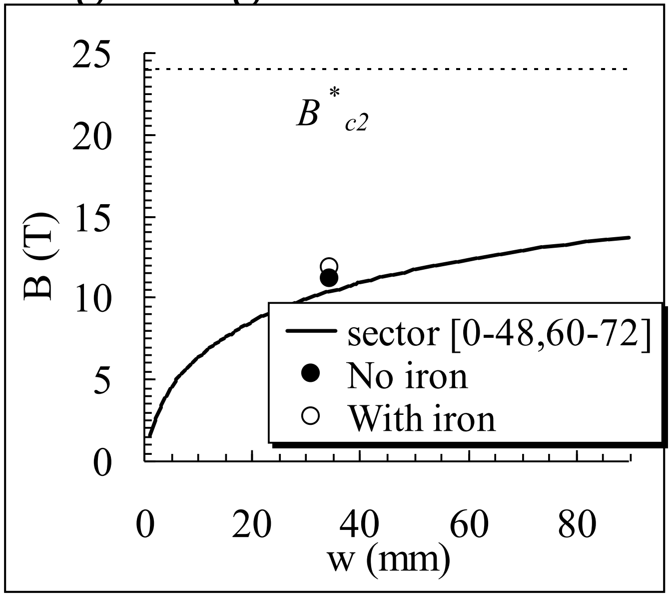


MSUT dipole

- Nb_3Sn model built at Twente U.
- 1 model built in 1995

- Nb_3Sn, 4.2 K
- j_c~1100 A/mm² at 12 T, 4.2 K
- w_{eq}~35 mm κ~0.33
- 2 layers, 5 blocks
- 65% grading

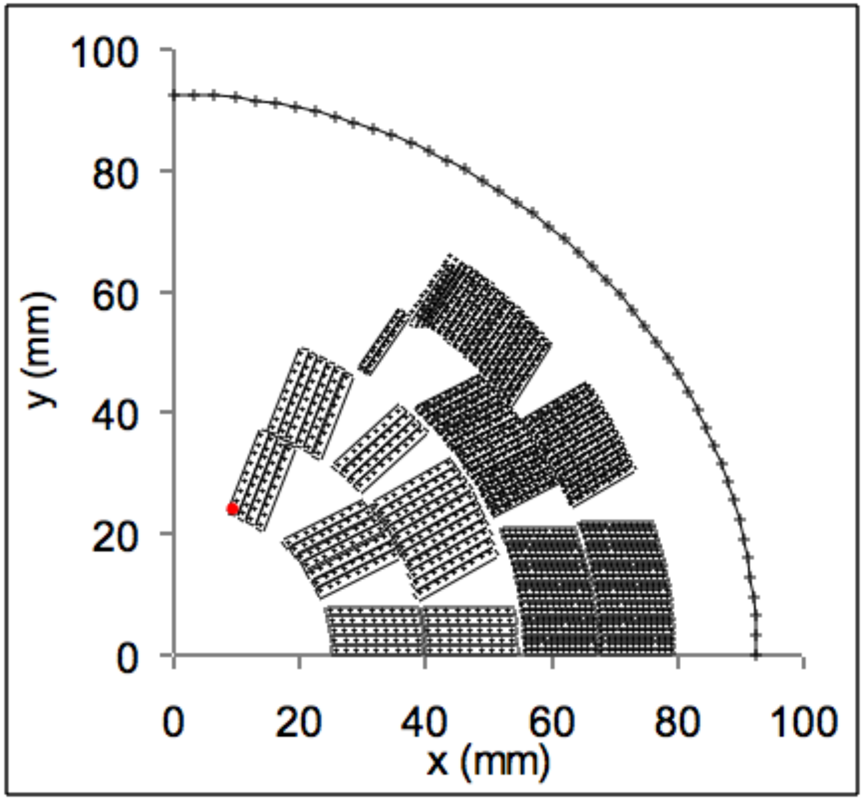


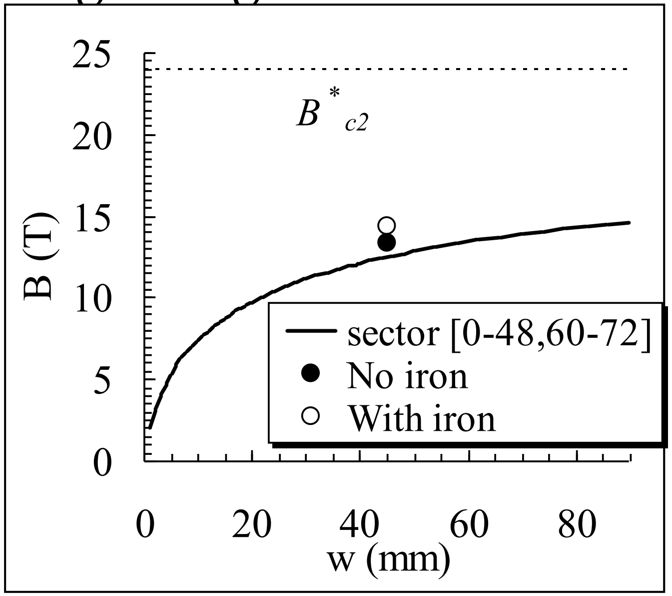


D20 dipole

- Nb_3Sn model built at LBNL (USA)
- 1 model built in ~1998

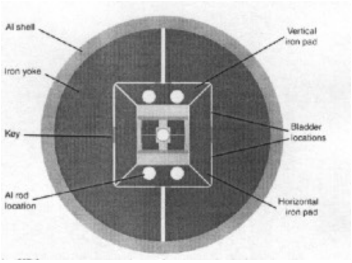
- Nb_3Sn, 4.2 K
- j_c~1100 A/mm² at 12 T, 4.2 K
- w_{eq}~45 mm   κ~0.48
- 4 layers, 13 blocks
- 65% grading



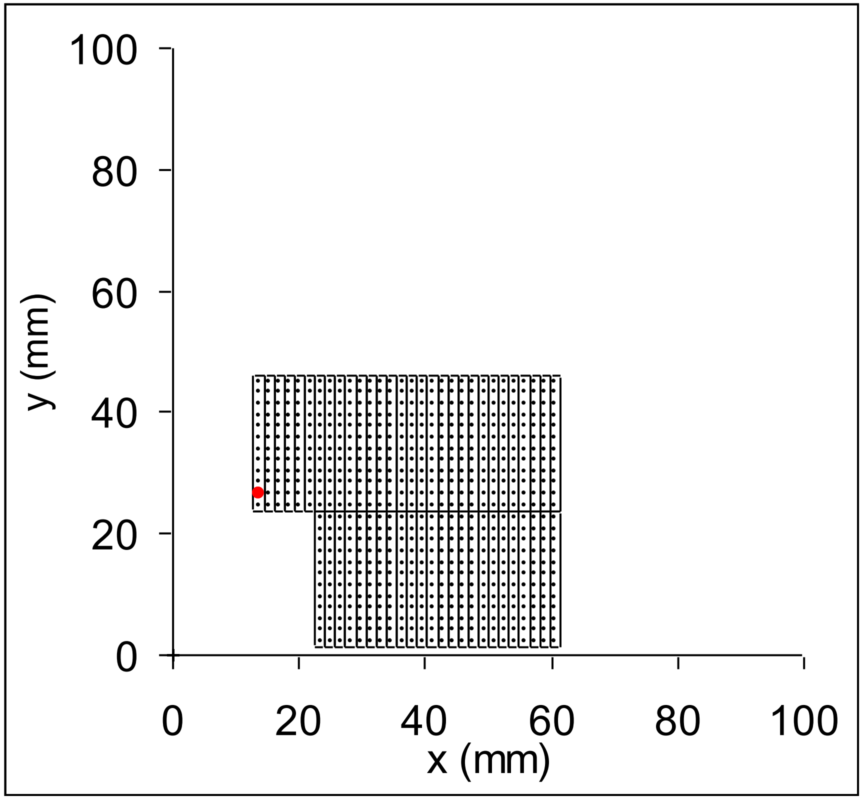


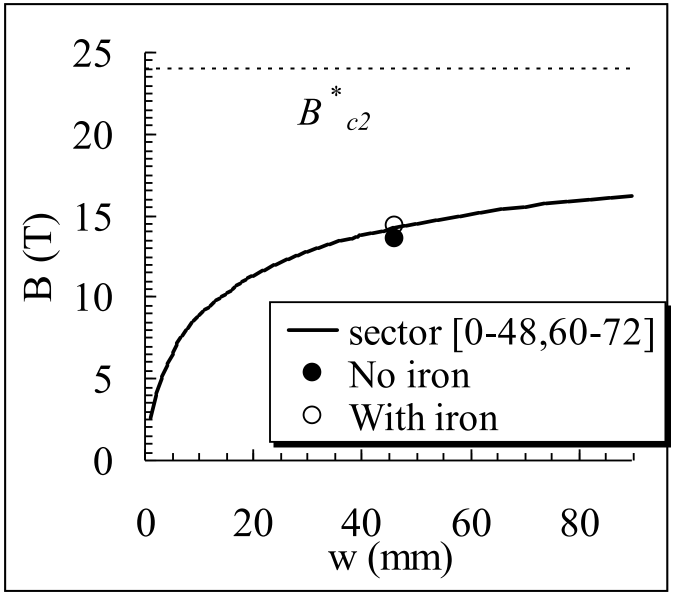
HD2

- Nb_3Sn model being built in LBNL
- 1 model to be built in 2008



- Nb_3Sn, 4.2 K
- j_c~2500 A/mm² at 12 T, 4.2 K
- w_{eq}~46 mm   κ~0.35
- 2 layers, racetrack, no grading

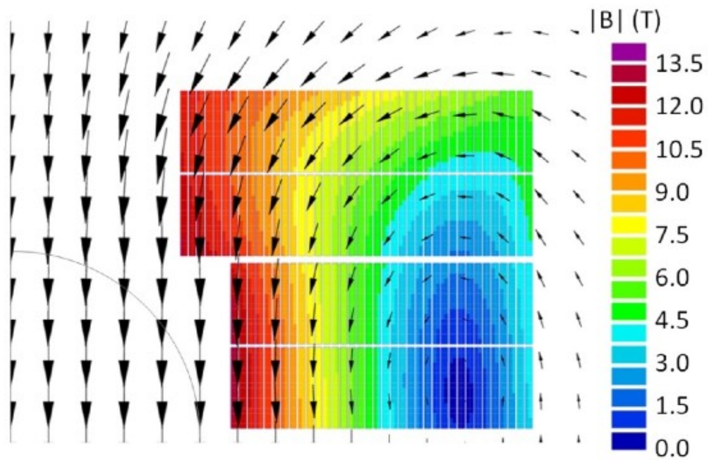


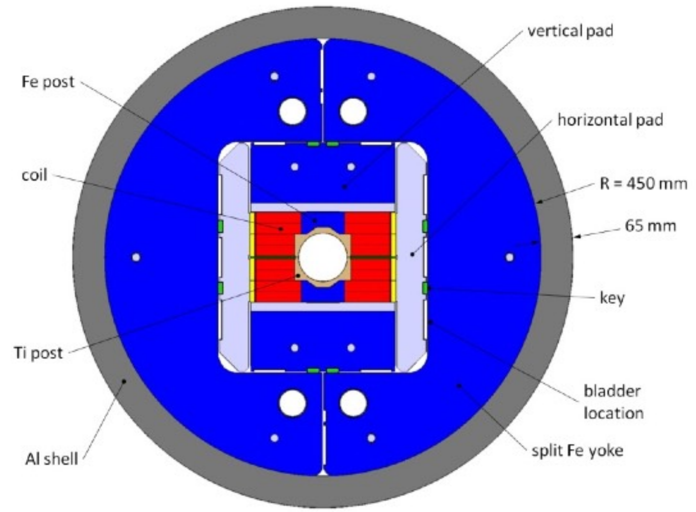


Fresca2 dipole

- Nb_3Sn test station founded by UE
- cable built in 2004-2006
- Operational field 13 T
- To be tested in 2014

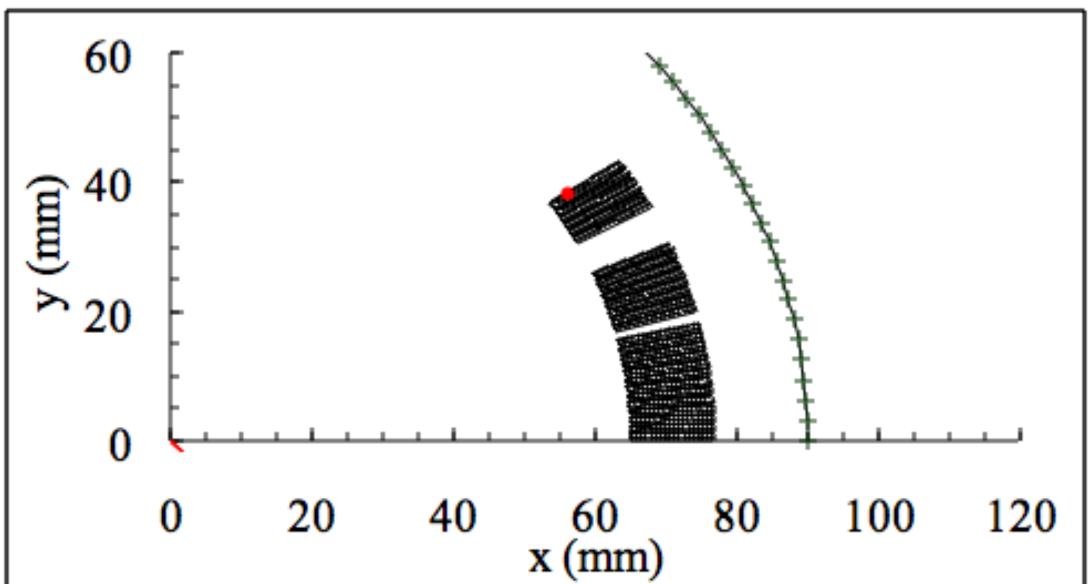
- Nb_3Sn, 4.2 K
- j_c~2500 A/mm² at 12 T, 4.2 K
- w_{eq}~80 mm κ~0.31
- Block coil 4 layers

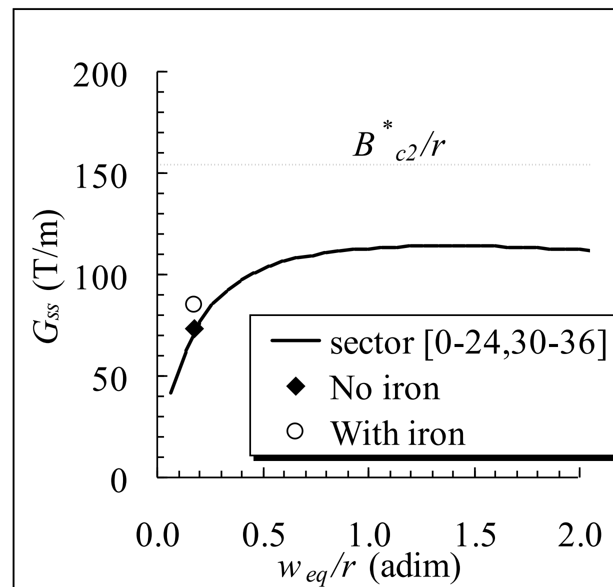




RHIC MQX

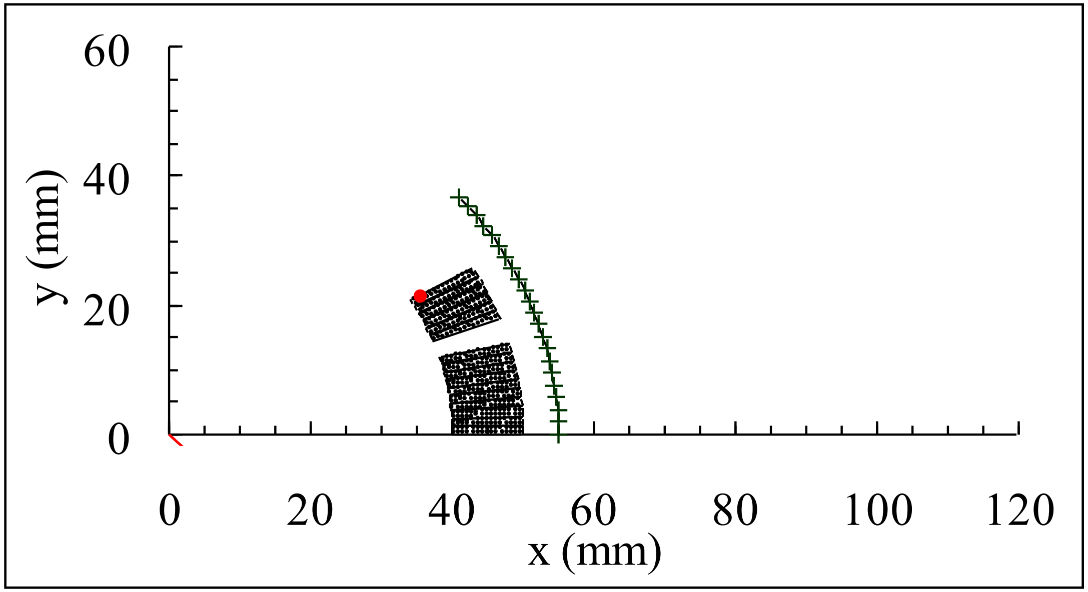
- Quadrupole in the IR regions of the RHIC
- 79 magnets built in July 1993/ December 1997
- Nb-Ti, 4.2 K
- w/r~0.18 κ~0.27
- 1 layer, 3 blocks, no grading

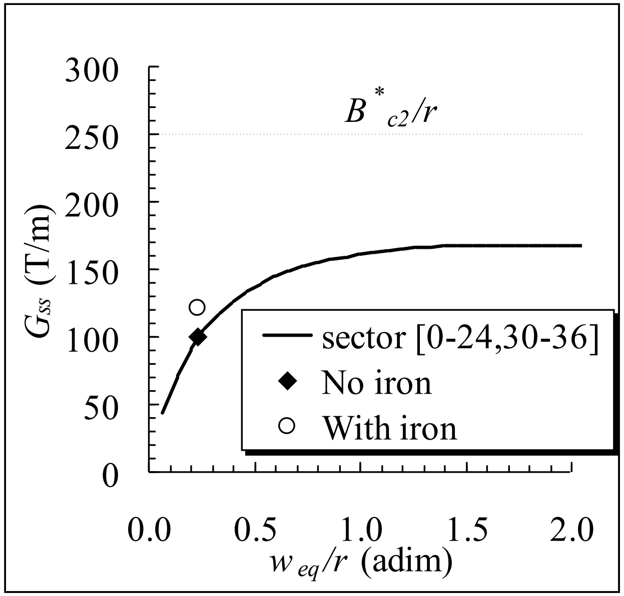




RHIC MQ

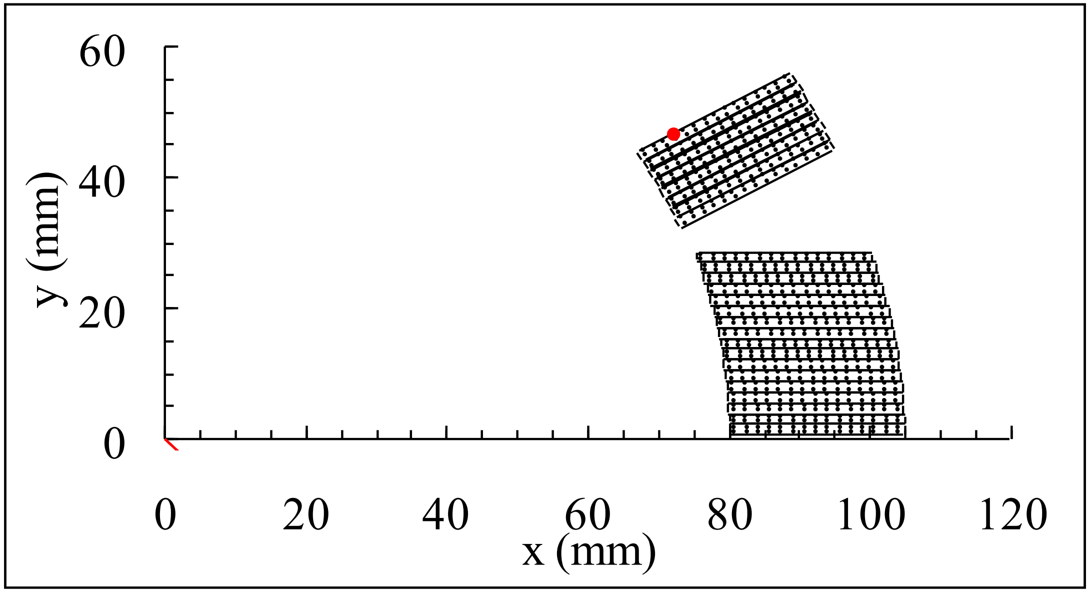
- Main quadrupole of the RHIC
- 380 magnets built in June 1994 – October 1995
- Nb-Ti, 4.2 K
- w/r~0.25   κ~0.23
- 1 layer, 2 blocks, no grading

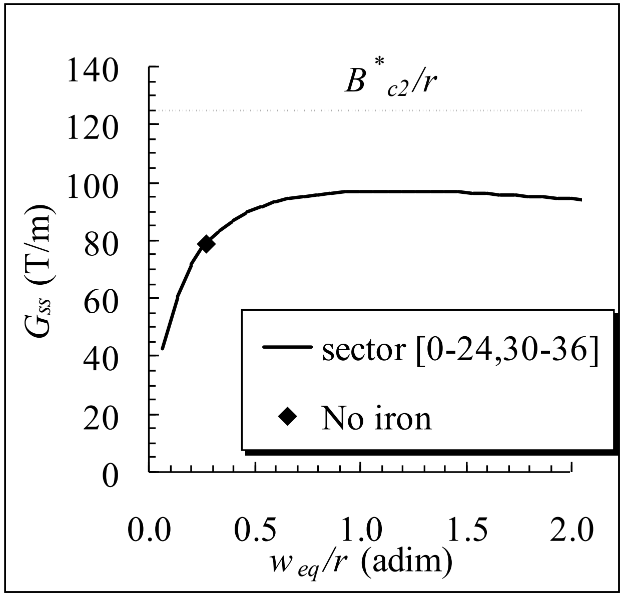




LEP II MQC

- Interaction region quadrupole of the LEP II
- 8 magnets built in ~1991-3
- Nb-Ti, 4.2 K, no iron
- w/r~0.27 κ~0.31
- 1 layers, 2 blocks, no grading

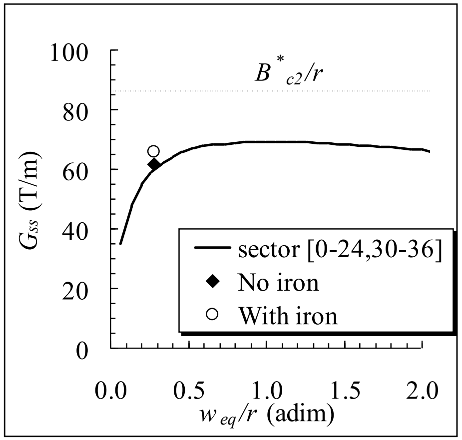


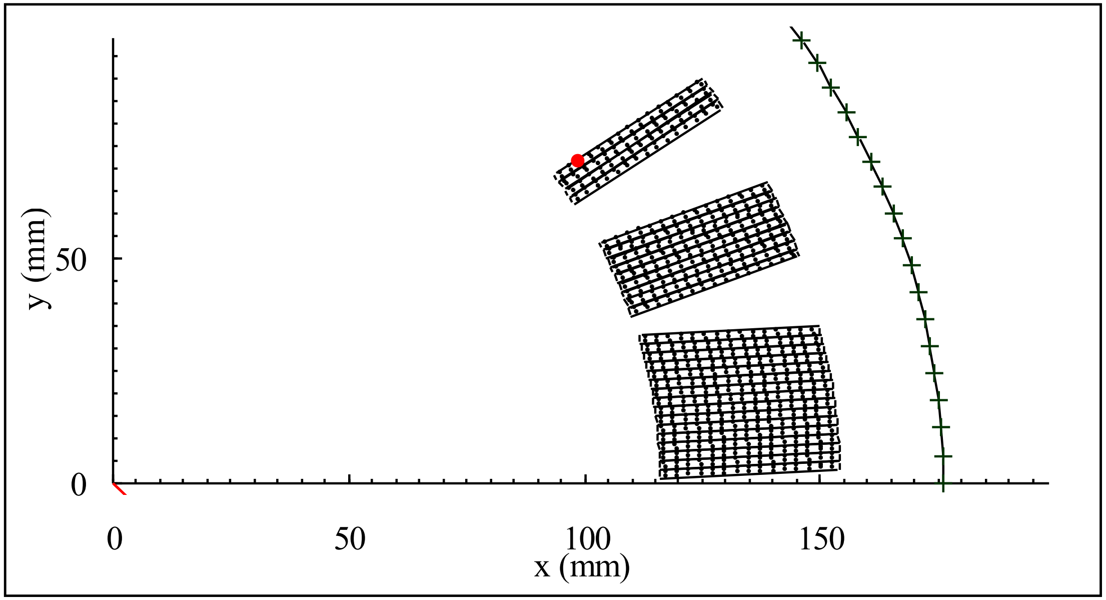


Review of quadrupole layouts - ISR

ISR MQX

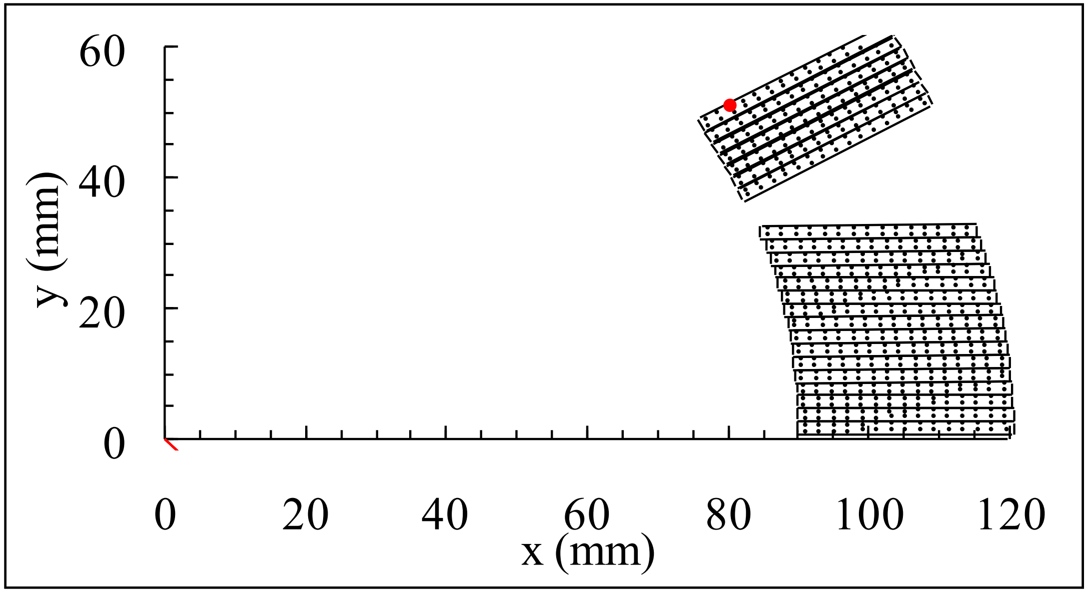
- IR region quadrupole of the ISR
- 8 magnets built in ~1977-79
- Nb-Ti, 4.2 K
- *w/r*~0.28 κ~0.35
- 1 layer, 3 blocks, no grading

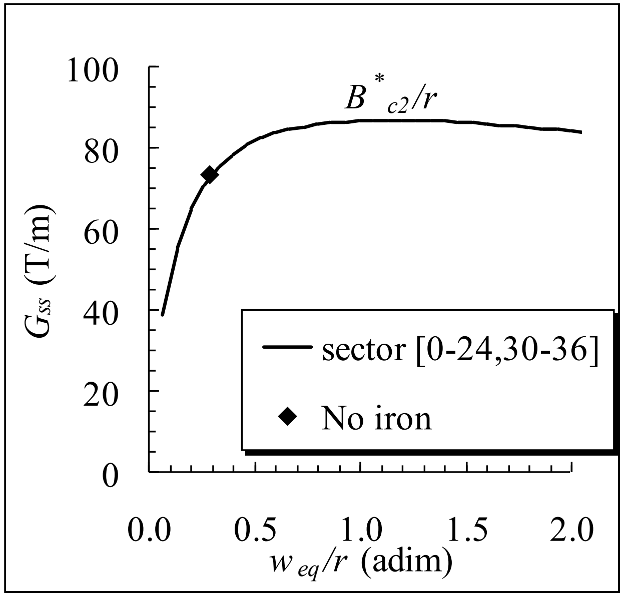




LEP I MQC

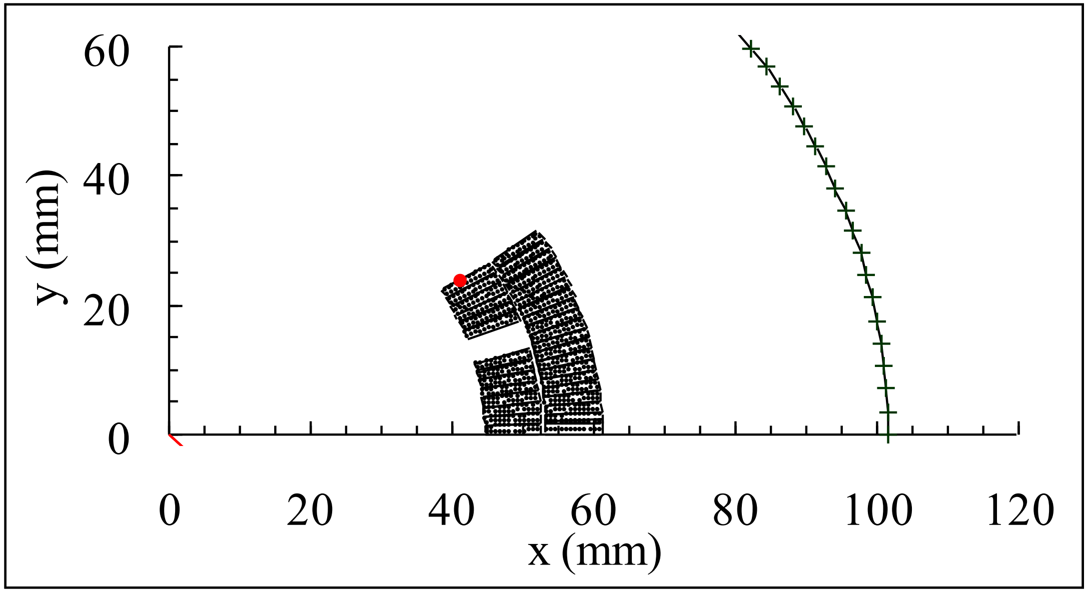
- Interaction region quadrupole of the LEP I
- 8 magnets built in ~1987-89
- Nb-Ti, 4.2 K, no iron
- *w/r*~0.29   κ~0.33
- 1 layers, 2 blocks, no grading

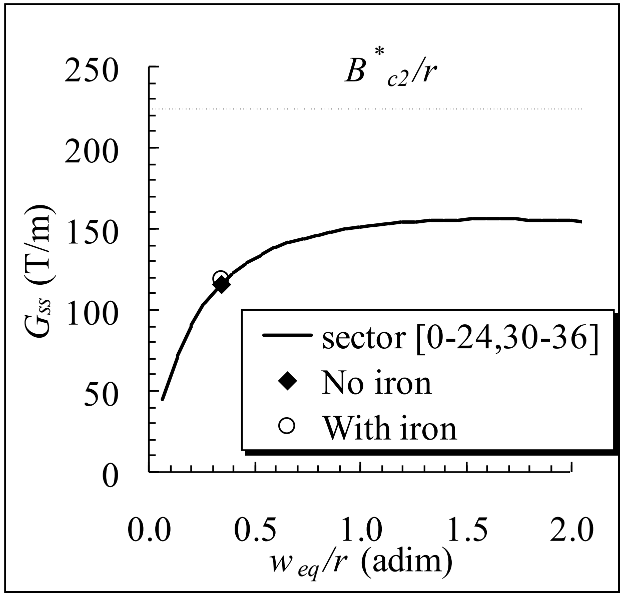




Tevatron MQ

- Main quadrupole of the Tevatron
- 216 magnets built in ~1980
- Nb-Ti, 4.2 K
- w/r~0.35 κ~0.250
- 2 layers, 3 blocks, no grading

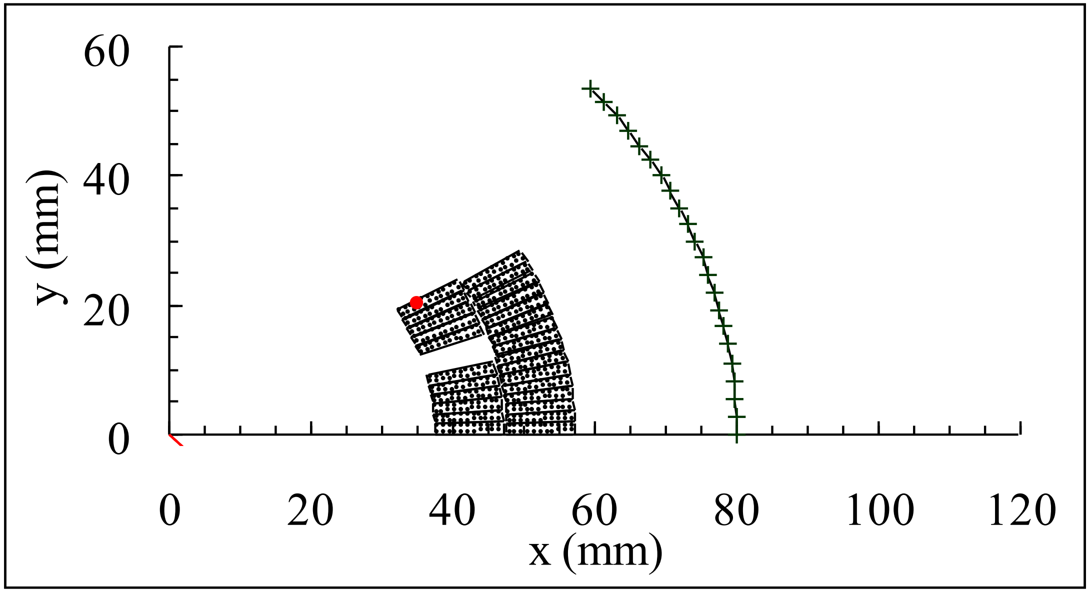


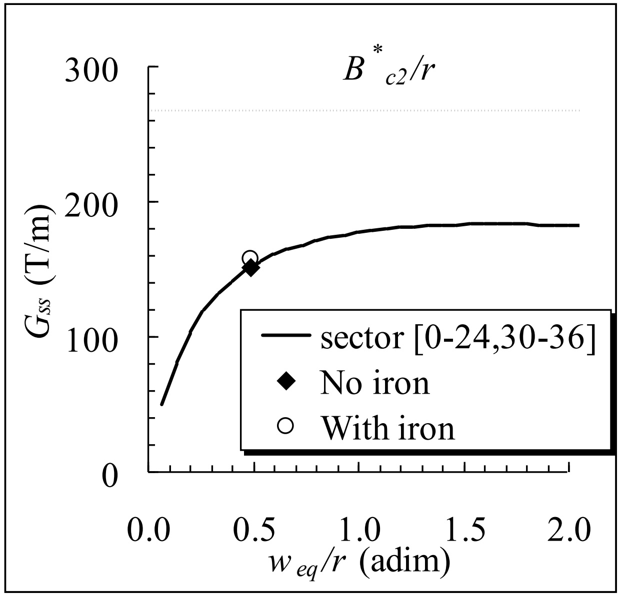


HERA MQ

- Main quadrupole of the HERA

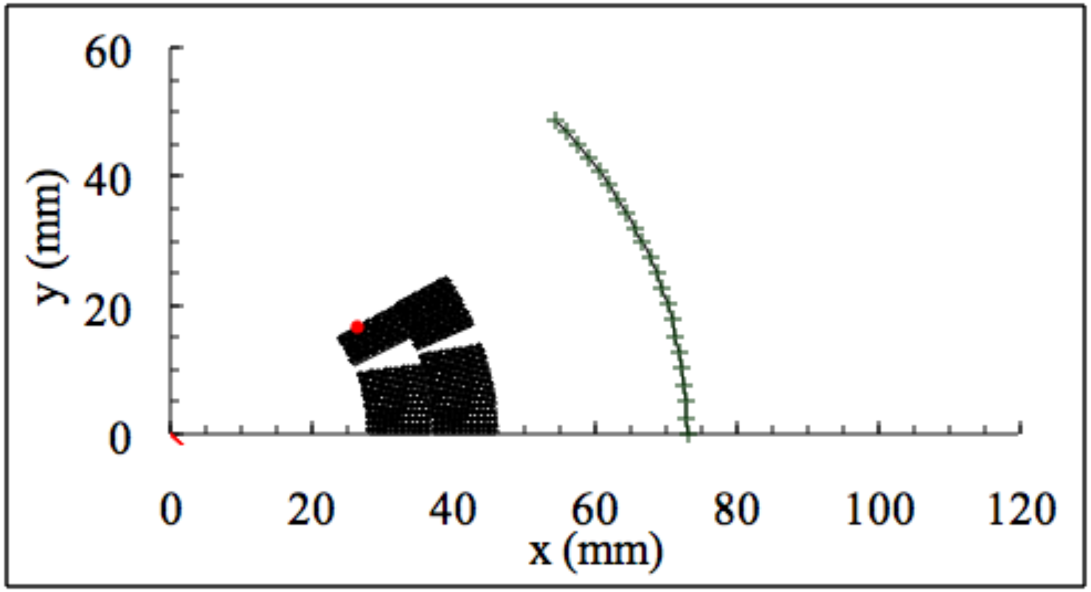
- Nb-Ti, 1.9 K
- w/r~0.52 κ~0.27
- 2 layers, 3 blocks, grading 10%

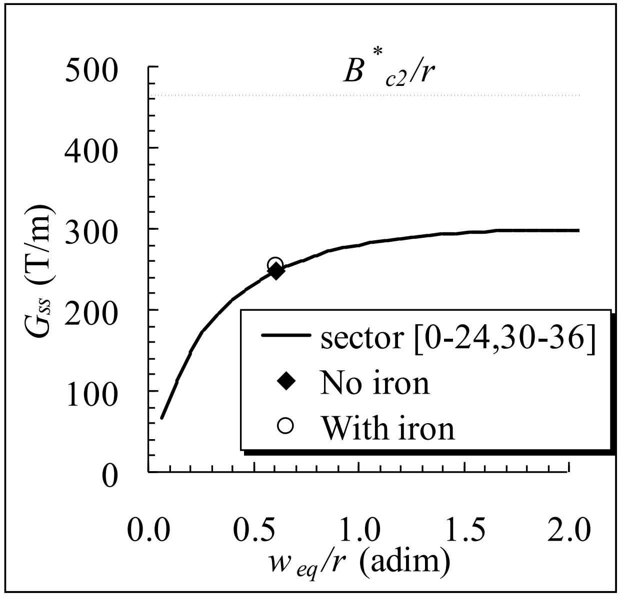




LHC MQM

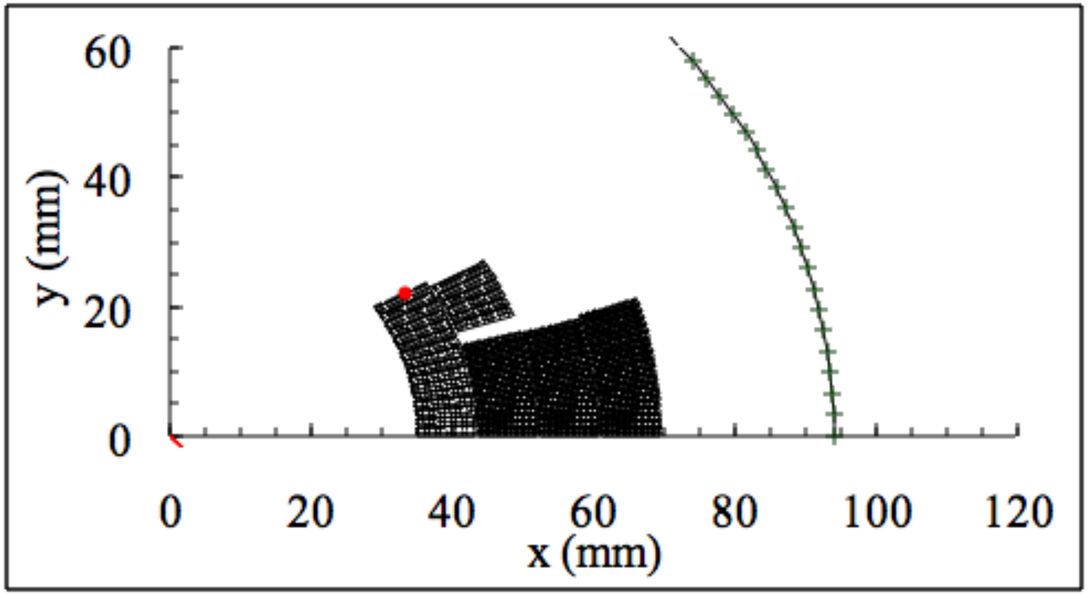
- Low- gradient quadrupole in the IR regions of the LHC
- 98 magnets built in 2001-2006
- Nb-Ti, 1.9 K (and 4.2 K)
- w/r~0.61 κ~0.26
- 2 layers, 4 blocks, no grading

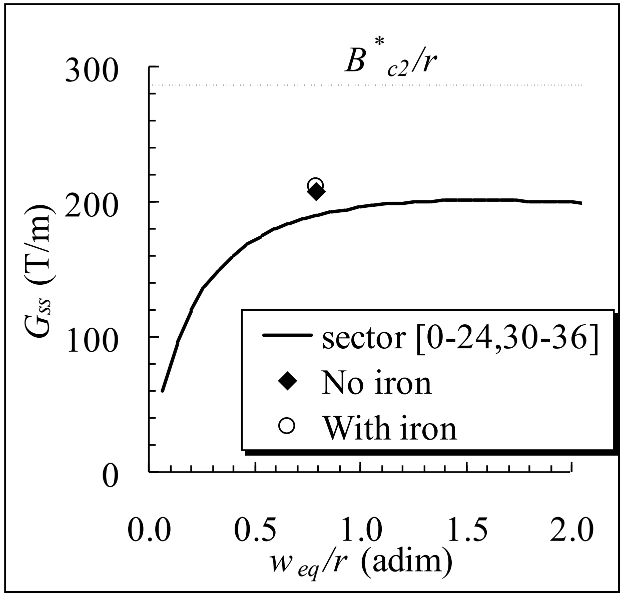




LHC MQY

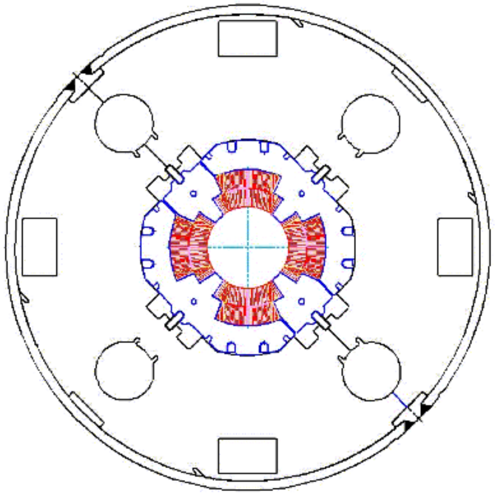
- Large aperture quadrupole in the IR regions of the LHC
- 30 magnets built in 2001-2006
- Nb-Ti, 4.2 K
- w/r~0.79   κ~0.34
- 4 layers, 5 blocks, special grading 43%

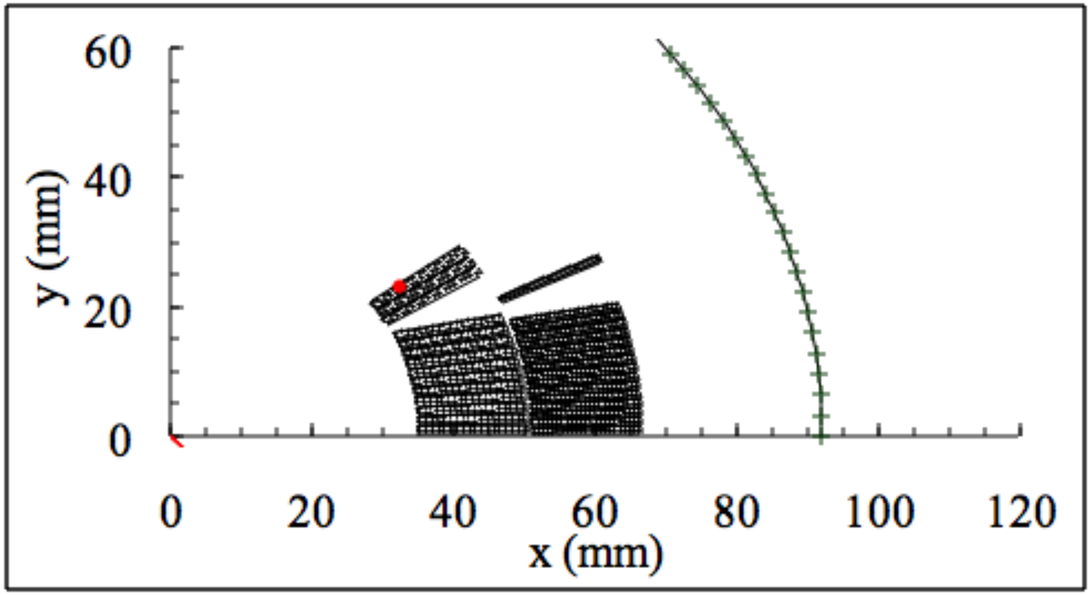


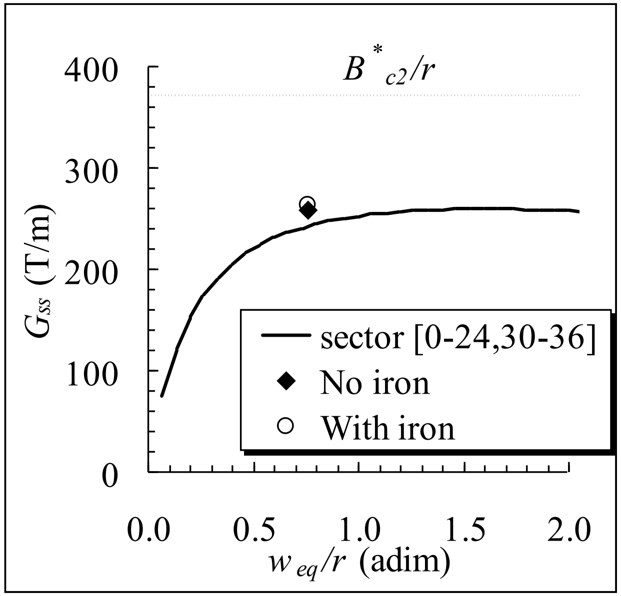


LHC MQXB

- Large aperture quadrupole in the LHC IR
- 8 magnets built in 2001-2006
- Nb-Ti, 1.9 K
- w/r~0.89 κ~0.33
- 2 layers, 4 blocks, grading 24%



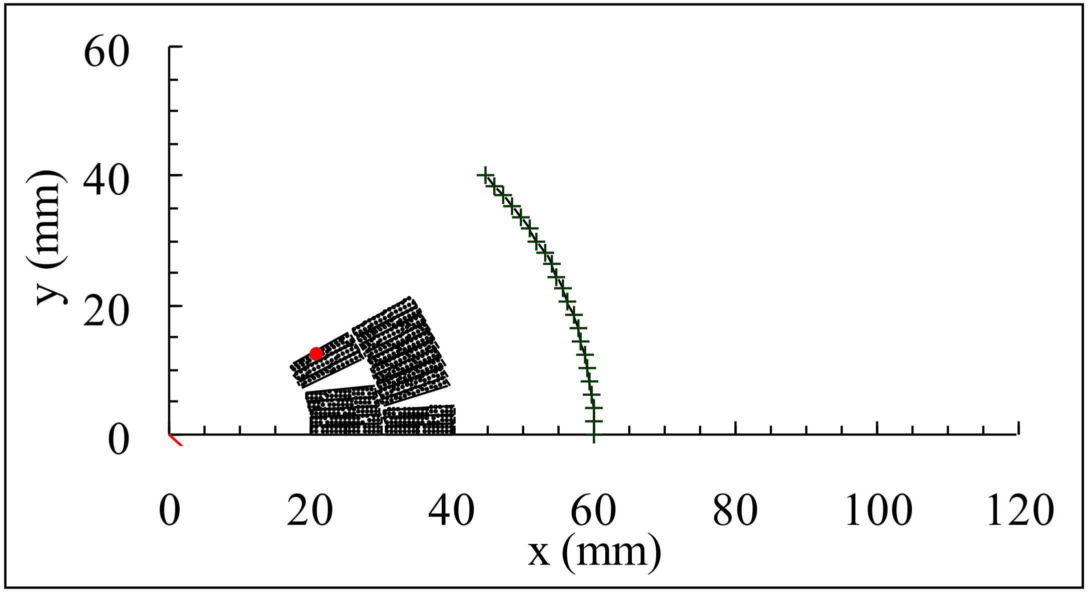


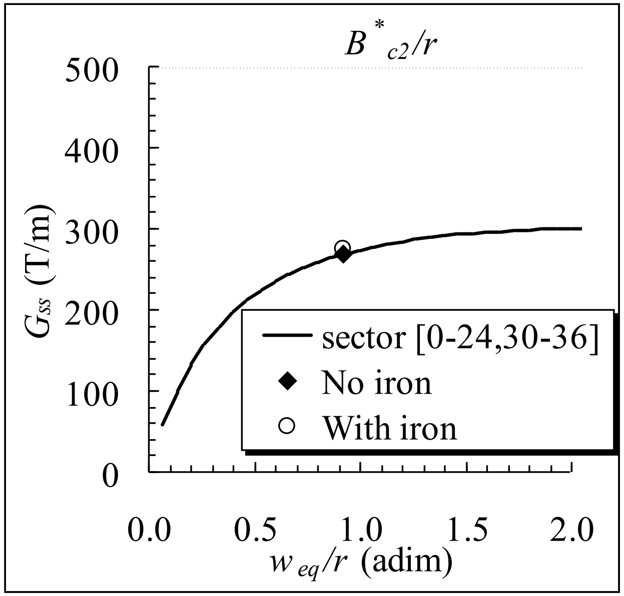


SSC MQ

- Main quadrupole of the ill-fated SSC

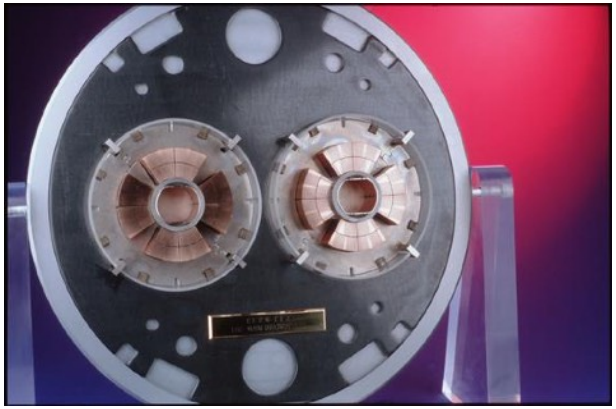
- Nb-Ti, 1.9 K
- *w/r*~0.92 κ~0.27
- 2 layers, 4 blocks, no grading

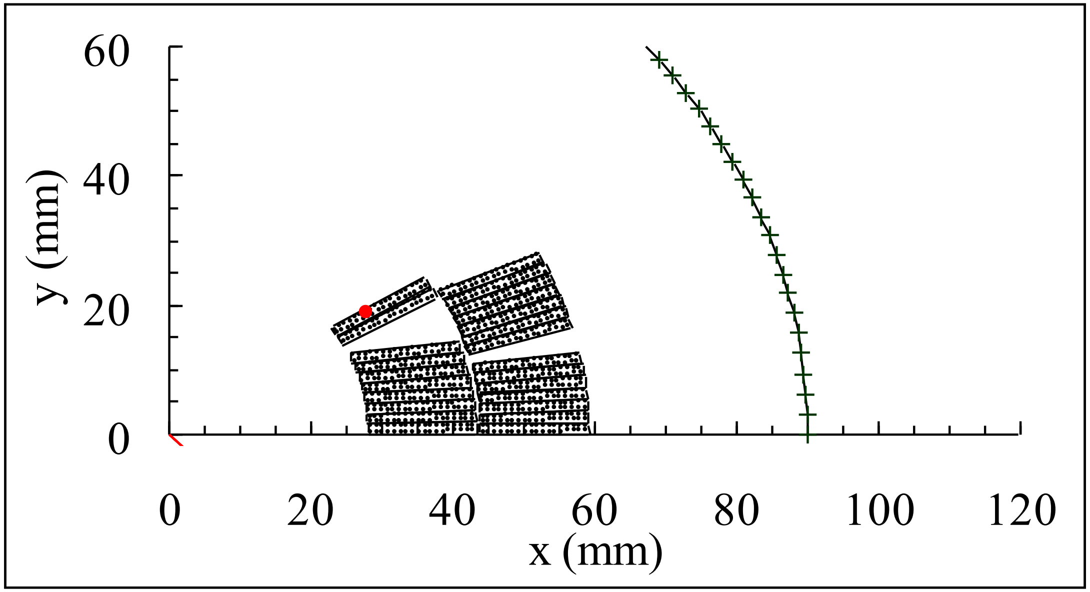


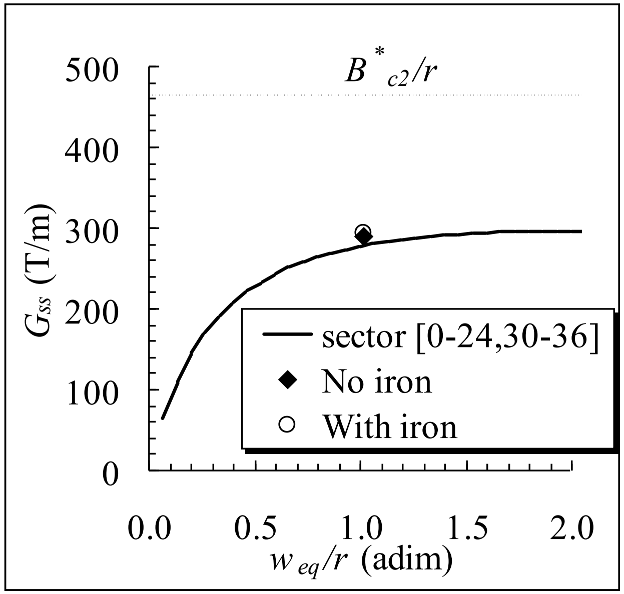


LHC MQ

- Main quadrupole of the LHC
- 400 magnets built in 2001-2006
- Nb-Ti, 1.9 K
- *w*/*r*~1.0 κ~0.250
- 2 layers, 4 blocks, no grading

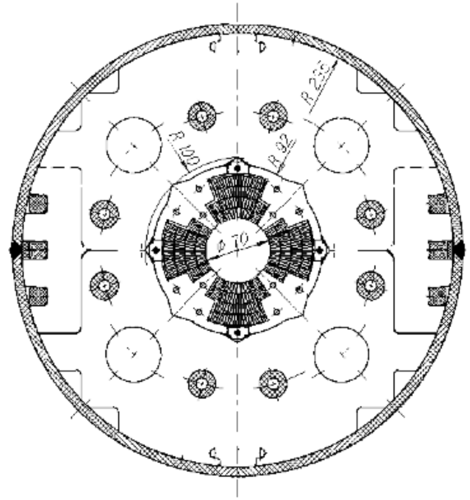


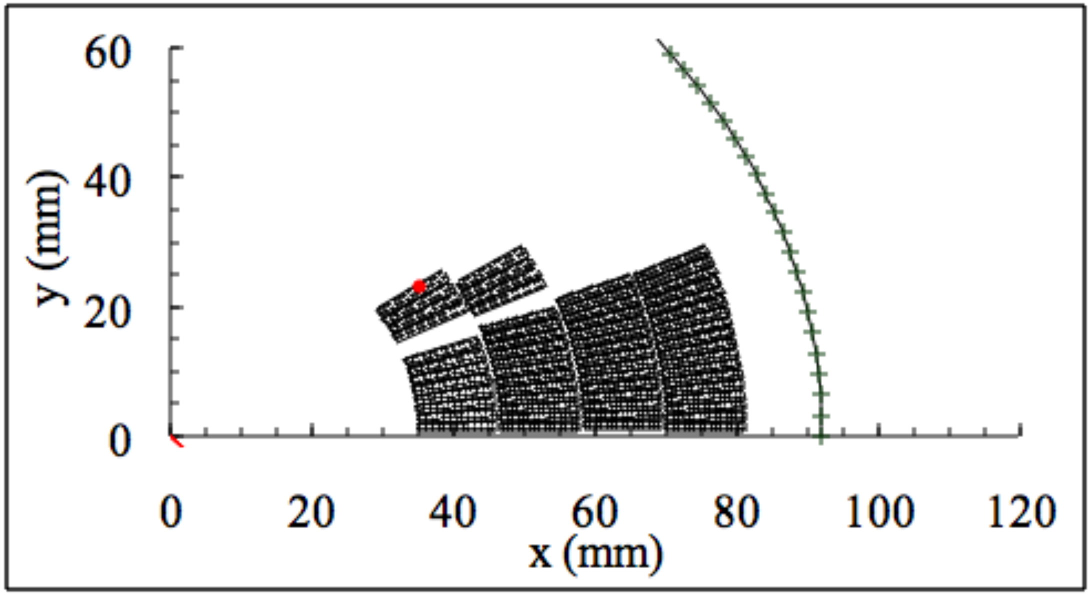


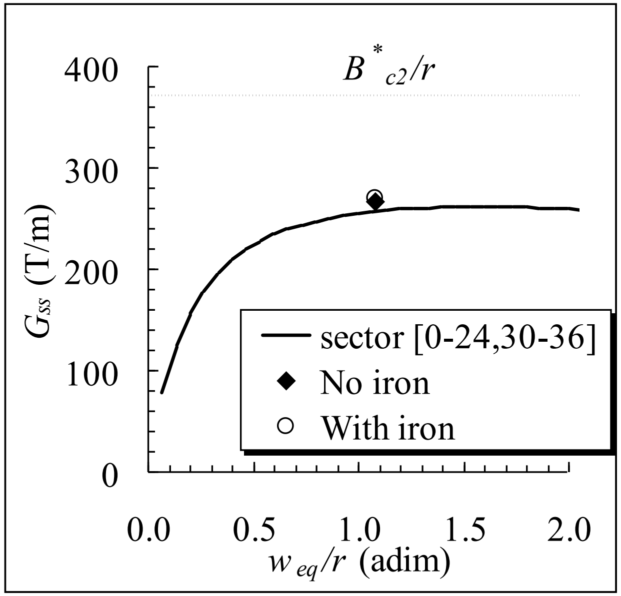


LHC MQXA

- Large aperture quadrupole in the LHC IR
- 18 magnets built in 2001-2006
- Nb-Ti, 1.9 K
- w/r~1.08 κ~0.34
- 4 layers, 6 blocks, special grading 10%

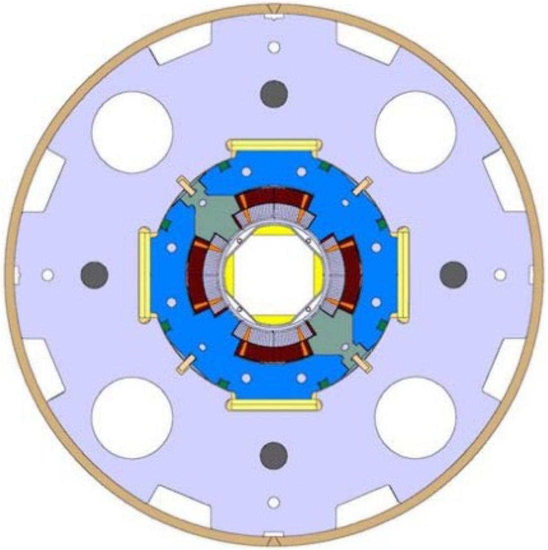


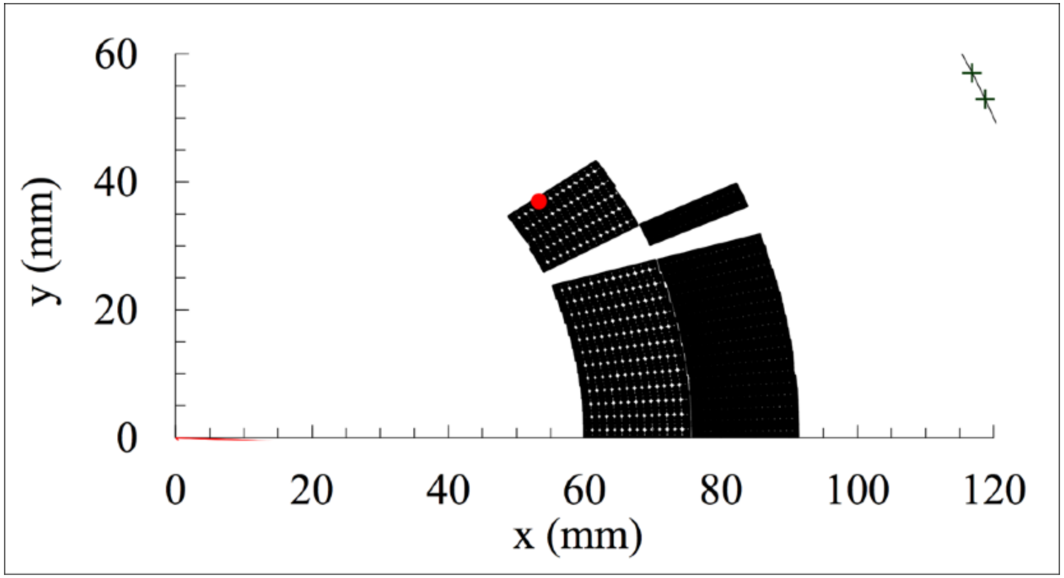




LHC MQXC

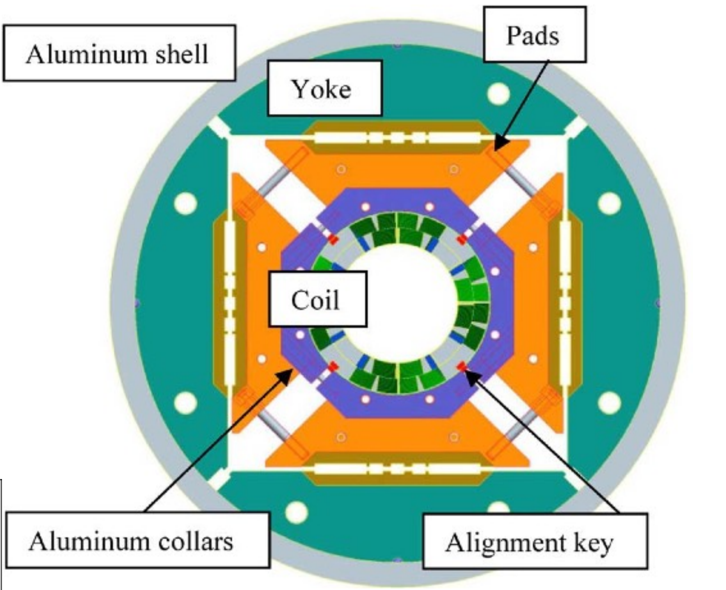
- Nb-Ti option for the LHC upgrade
- LHC dipole cable, graded coil
- 1-m-long model built in 2011-2 to be tested in 2012
- *w/r*~0.5   κ~0.33   2 layers, 4 blocks

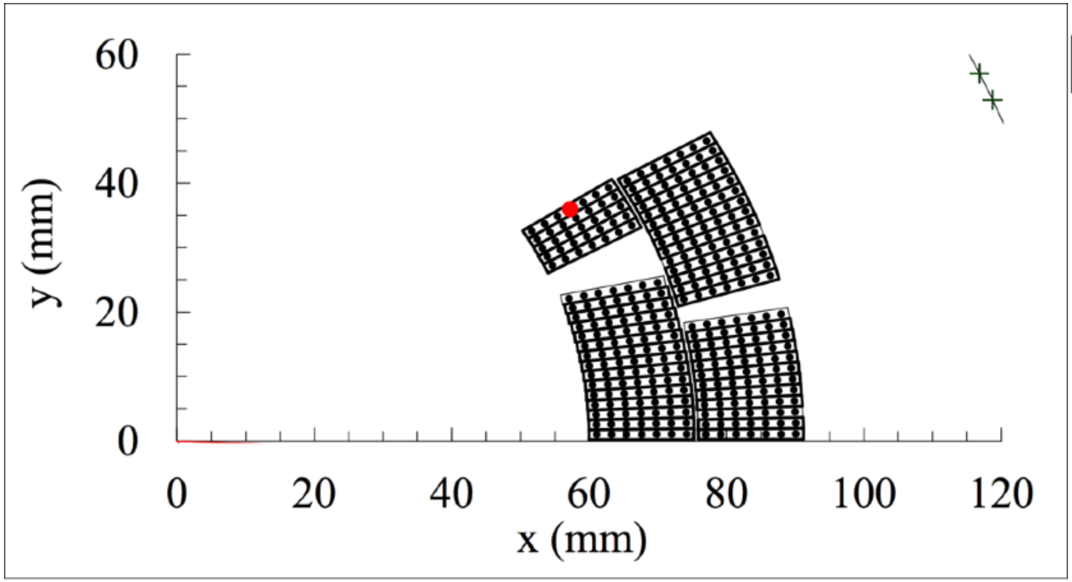




LARP HQ

- 120 mm aperture Nb_3Sn option for the LHC upgrade (IR triplet)
- 1-m-long model tested in 2011, more to come plus a 3.4-m-long
- w/r~0.5 κ~0.33 2 layers, 4 blocks





CONCLUSIONS

- Grading the current density in the layers can give a larger performance for the same amount of conductor
  - 3-5% more in dipoles, 5-10% more in quadrupoles
- The iron has several impacts
  - Useful for shielding, can considerably increase the field for a given current – the impact on the performance is small but not negligible
  - Drawbacks: saturation, inducing field harmonics at high field – can be cured by shaping or drilling holes in the right place
- Coil ends – the design must aim at reducing the peak field
- Other lay-outs: pro and cons
- We shown a gallery of dipole and quadrupole magnetic designs used in the past 30 years

REFERENCES

- Iron
  - M. N. Wilson,
  - P. Schmuser, Ch. 4
  - Classes given by R. Gupta at USPAS 2006, Unit 5
  - R. Gupta, Ph. D. Thesis, available on his web site
  - C. Vollinger, CERN 99-01 (1999) 93-109
- Grading
  - S. Caspi, P. Ferracin, S. Gourlay, "Graded high field Nb3Sn dipole magnets", *19th Magnet Technology Conference, IEEE Trans. Appl. Supercond.,* (2006) in press..
  - L. Rossi, E. Todesco, Electromagnetic design of superconducting quadrupoles Phys. Rev. ST Accel. Beams **9** (2006) 102401.
- Coil ends
  - S. Russenschuck, CERN 99-01 (1999) 192-199
  - G. Sabbi, CERN 99-01 (1999) 110-120
- Other designs
  - Classes given by R. Gupta at USPAS 2006, Unit 10
  - R. Gupta, *et al.*, "React and wind common coil dipole", talk at *Applied Superconductivity Conference 2006*, Seattle, WA, Aug. 27 - Sept. 1, 2006
  - P. Ferracin et al, MT19, IEEE Trans. Appl. Supercond. **16** 378 (2006)
  - Work by G. Ambrosio, S. Zlobin on common coil magnets at FNAL

REFERENCES

- Plus…
  - A whole series of papers about each magnet that has been presented

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