Unit 9
Iron effect and grading design

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Based on P. Ferracin USPAS lecture in 2009-2015 with H. Felice, S. Prestemon
And course at Milano Bicocca University 2015-2017
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All the units will use International System (meter, kilo, second, ampere) unless specified

PLAN OF THE LECTURES

- Part 1 – From beam dynamics to magnet specifications
  - Unit 1: The energy and specifications for cell dipole and quadrupole
  - Unit 2: The luminosity and specifications for insertion region magnets
  - Appendix A: Beam optics from stable motion to chaos
- Part 2 – Principles of electromagnets
  - Unit 3: Multipolar expansion of magnetic field
  - Unit 4: How to generate pure multipole field
- Part 3 – Basics of superconductivity
  - Unit 5: Elements of superconductivity
  - Appendix B: Maxwell and scales in atomic physics
  - Unit 6: Instability and margins

PLAN OF THE LECTURES

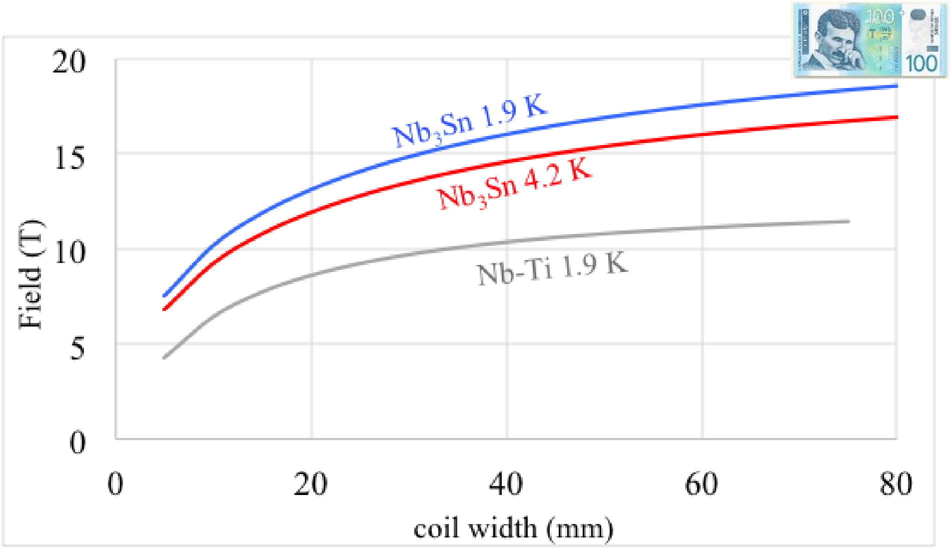
- Part 4 – Magnet design
  - Unit 7: Strand, cable and insulation
  - Unit 8: Short sample field/gradient of sector coils and sensitivity to parameters
  - Unit 9: Grading the current density and iron effect

  - Unit 10: Forces
  - Unit 11: Structures
  - Unit 12: Protection

  - Appendix C: Review of magnet designs
  - Appendix D: A digression on cost, and two case studies, from Terminator to FCC

QUESTIONS

- Efficiency: the last Teslas are expensive … are there techniques to save conductor ?



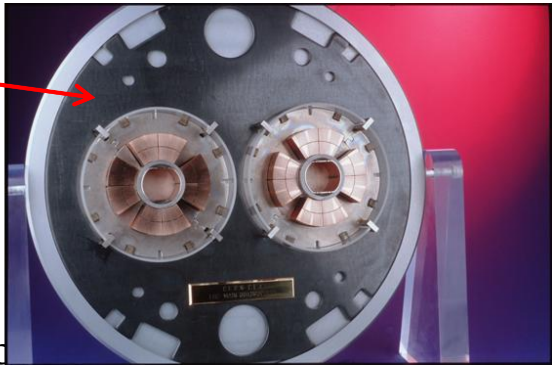
- What is the effect of iron ? Does it help in having higher short sample fields ?
- What happens in coil heads ?

CONTENTS

- The role of iron
- Grading techniques
- A few words on coil ends

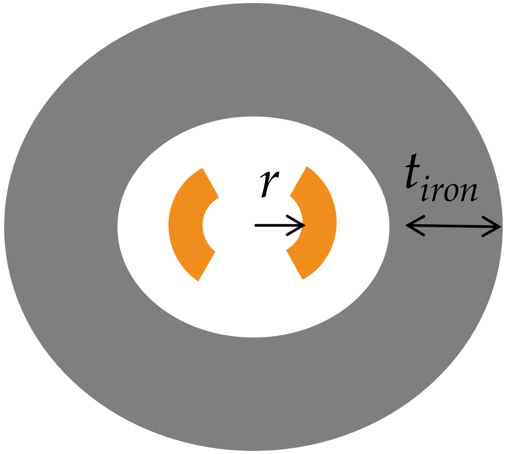
IRON YOKE - GENERICS

- An iron yoke usually surrounds the collared coil – it has several functions
  - Keeps the return magnetic flux avoiding fringe fields
  - The iron can contributing (Unit 11) to the mechanical structure
    - RHIC magnets: no collars, iron holds the Lorentz forc[e]
    - LHC dipole: very thick collars, iron gives small 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 current density, reducing stress and easing 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* (thin coils)



IRON YOKE – WHAT THICKNESS

- A rough estimate of the iron thickness necessary to avoid fields outside the magnet



$$rB \sim t_{iron} B_{sat}$$

  - The iron cannot withstand more than 2 T
  - Shielding condition for dipoles:
    - 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

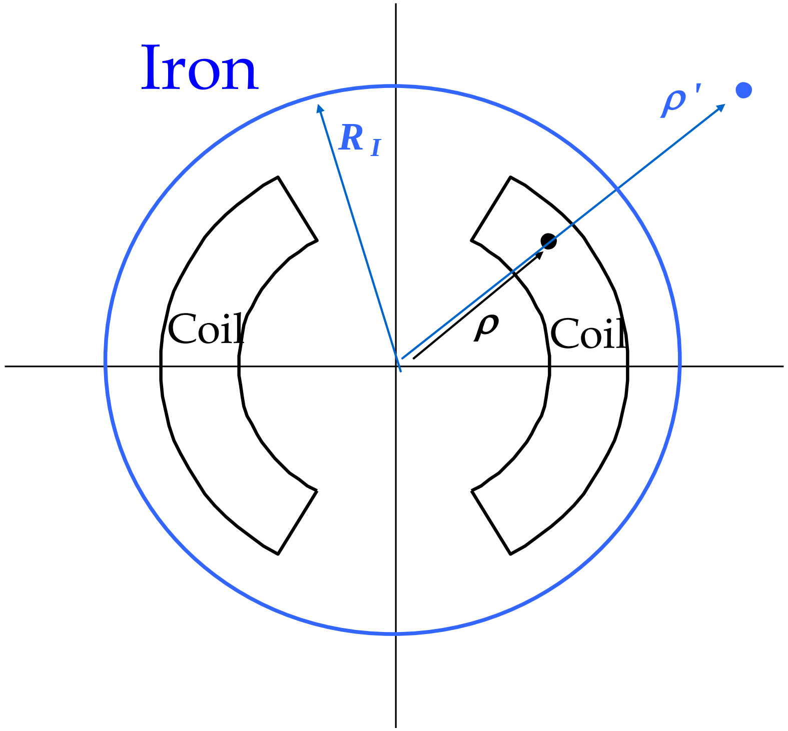
$$t_{iron} \sim \frac{rB}{B_{sat}} = \frac{28*8.3}{2} \sim 100 \text{ mm}$$

  - Shielding condition for quadrupoles:

$$\frac{r^2 G}{2} \sim t_{iron} B_{sat}$$

IRON YOKE – IMAGE METHOD

- 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)

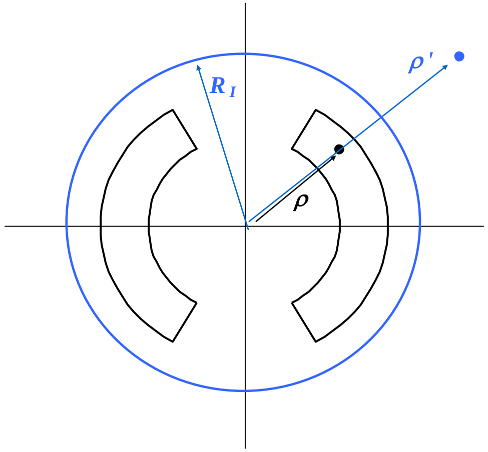


IRON YOKE – IMAGE METHOD

- 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 $\Delta\gamma_c$=100%)
    - This happens for infinitesimally small coil and collar widths

IRON YOKE – IMAGE METHOD

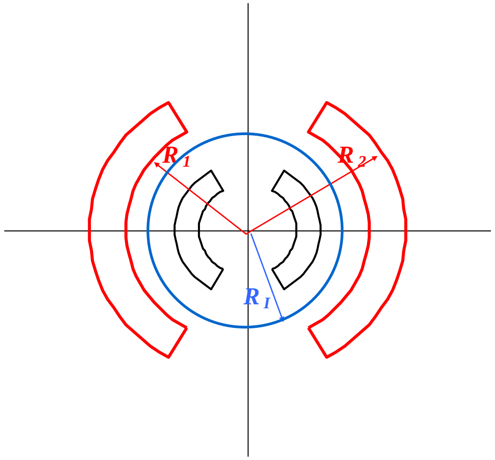
- Estimate of the gain in main field $\Delta\gamma_c$ for a sector coil

$$B_1 = g_c jw \qquad \Delta B_1^{iron} = g_c j'(R_2 - R_1)$$

$$R_1 = \frac{R_I^2}{r+w}$$

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

$$R_2 = \frac{R_I^2}{r}$$



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 after some algebra

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

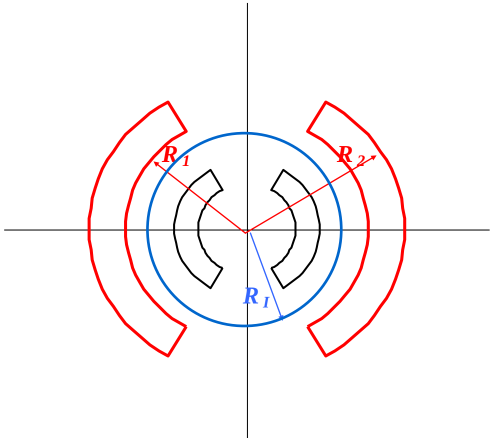
- For higher order multipoles
  - The relative contribution becomes very small

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

IRON YOKE – IMAGE METHOD

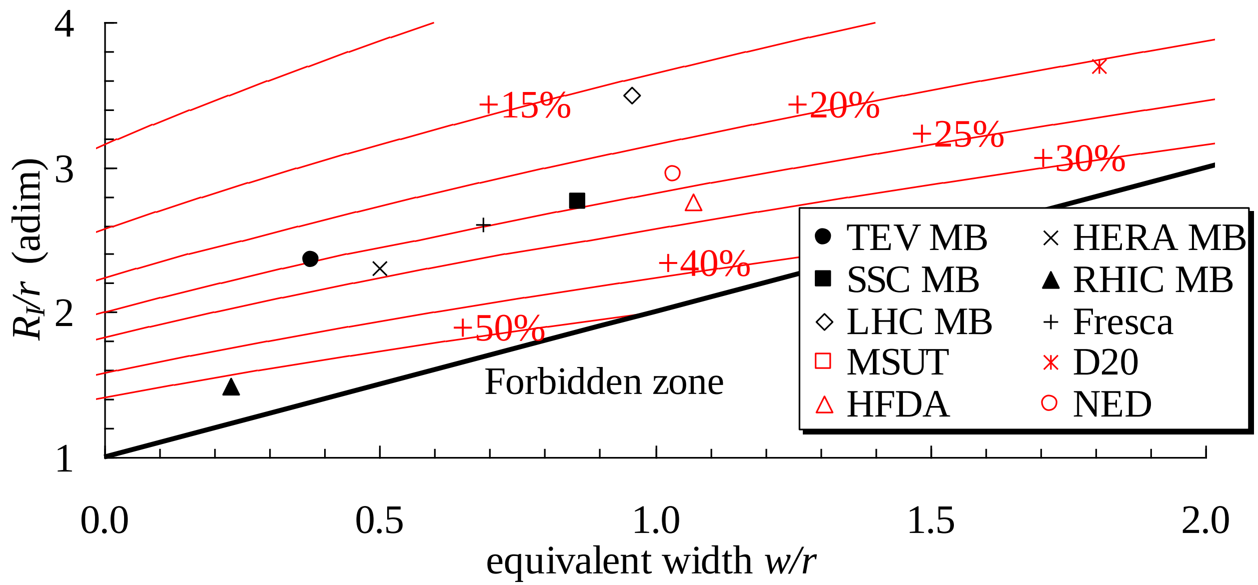
- Estimate of the gain in main field for fixed current in a sector coil

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



Estimate of several built dipoles

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



IRON YOKE - DIPOLES

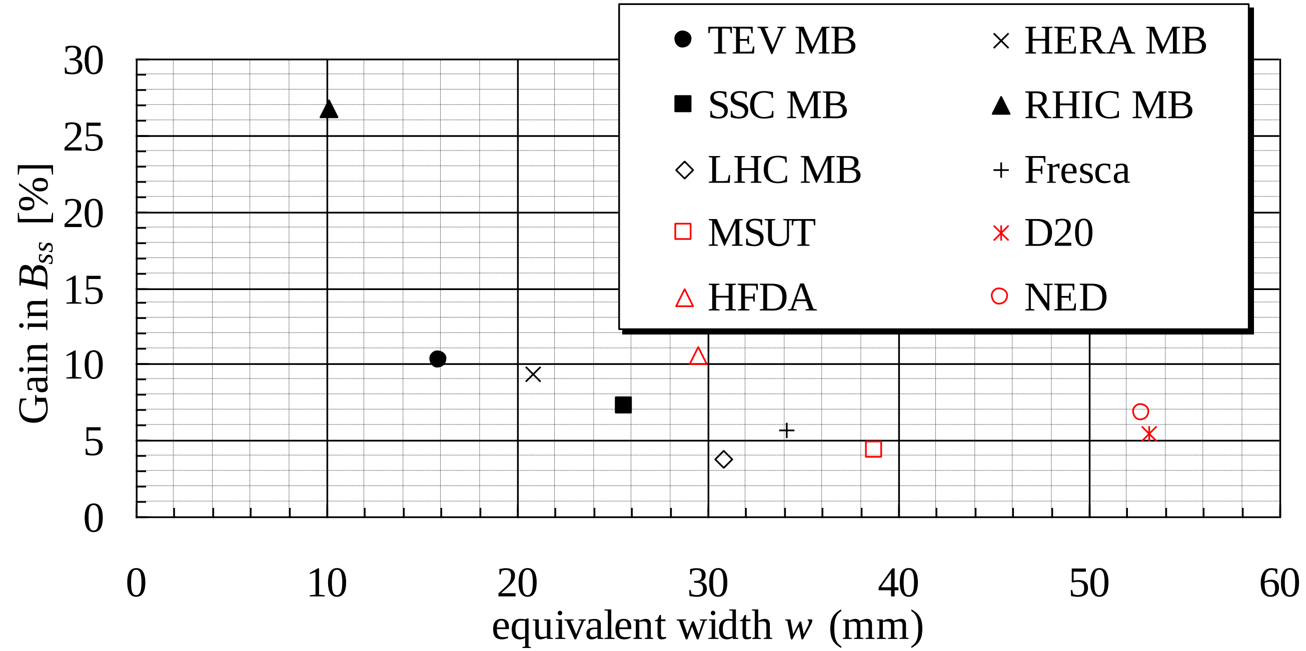
- Impact of the iron yoke on dipole short sample field, Nb-Ti

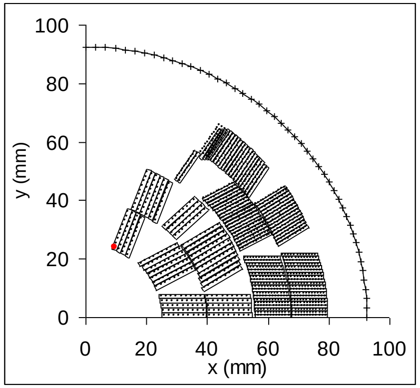
$$B_{ss} = \frac{X}{1+X} b \qquad\qquad X = \gamma_c \left(1 + \frac{(r+w)r}{R_I^2}\right) \kappa s w$$

- The change of γ_c is the change of B for a fixed current, previously computed
  - Two regimes:
    - for X<<1 the increase in γ corresponds to the same increase in the short sample field ("thin coils")
    - for X>>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

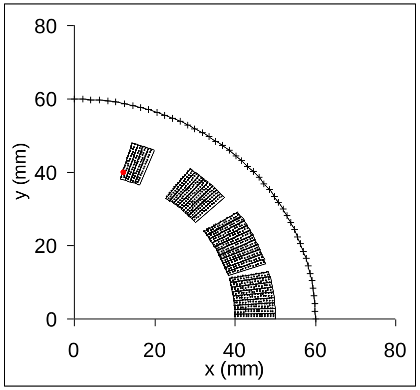
IRON YOKE - DIPOLES

- 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)





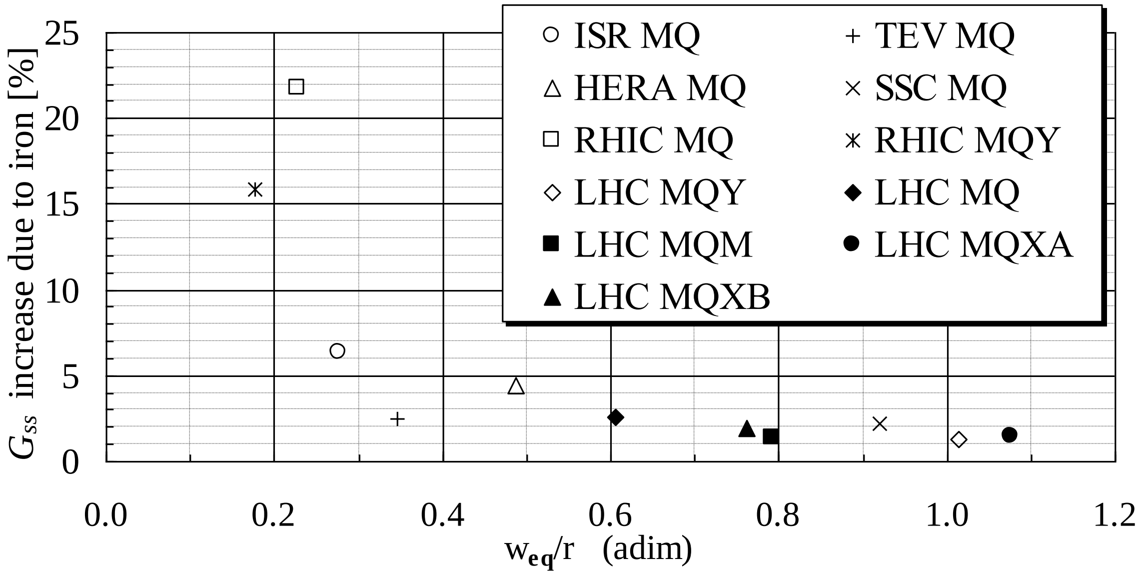
D20 and yoke

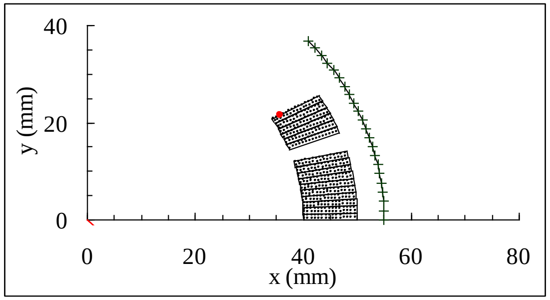


RHIC main dipole and yoke

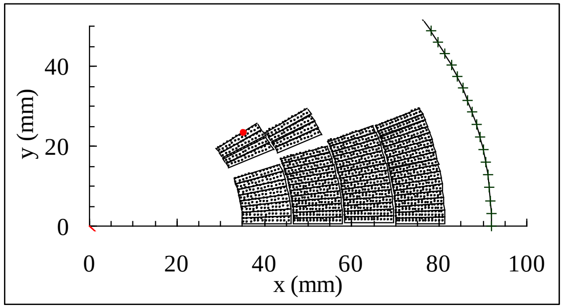
IRON YOKE - QUADRUPOLES

- 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





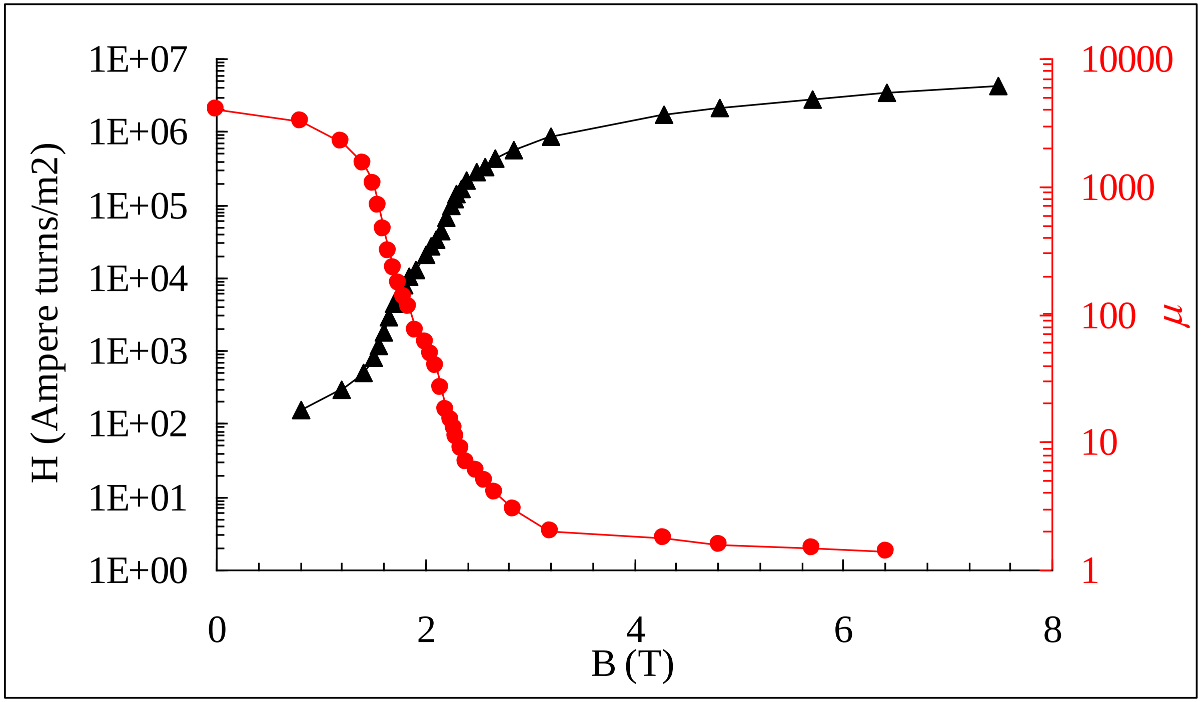
RHIC MQ and yoke



LHC MQXA and yoke

IRON YOKE - SATURATION

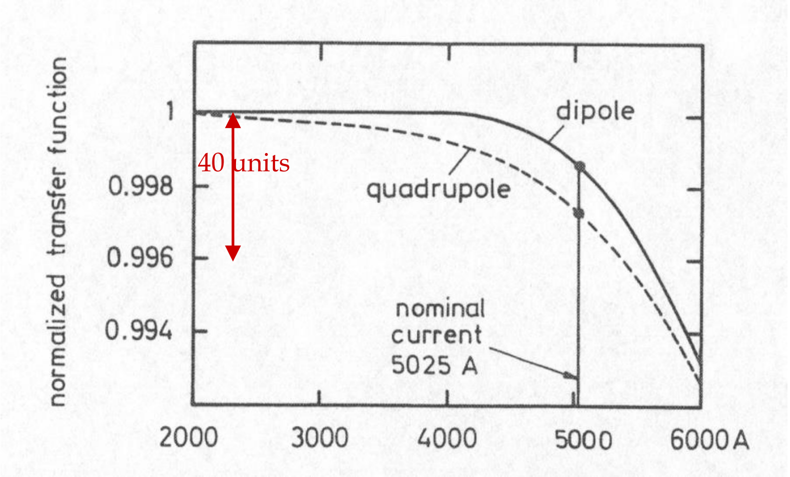
- Iron saturation: B-H curve $B = \mu\mu_0 H$
  - for B<2 T, one has $\mu >> 1$ ($\mu \sim 10^3$-10^4), and the iron can give a relevant contribution to the field according to what discussed before
  - for B>2 T, $\mu \to 1$, and the iron becomes "transparent" (no effect on field)



IRON YOKE - SATURATION

- 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 of several (tens) of units – in worse cases 1-10%
  - 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 are manageable in operation

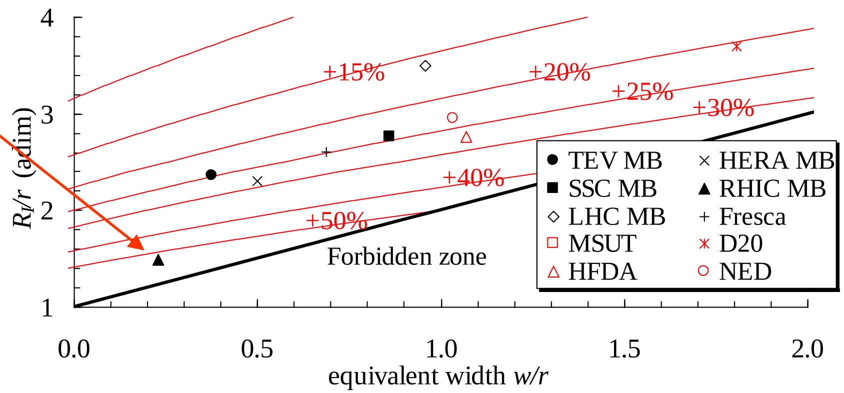
(saturation is compensated via current fine tuning)



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

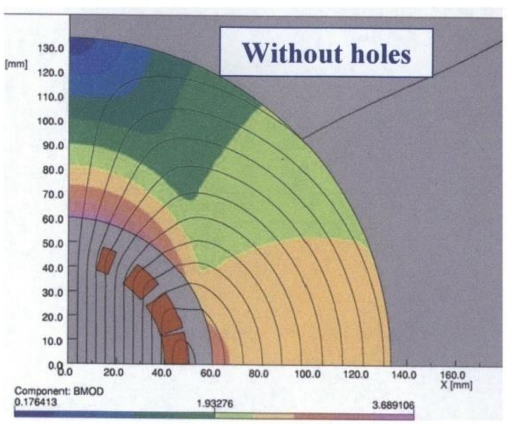
IRON YOKE - OPTIMIZATION

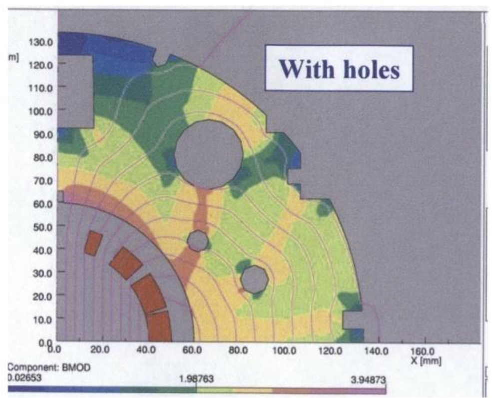
- Corrective actions: shaping the iron
  - In a dipole, the field is larger at the pole – over there, iron will saturate
    - The dependence on the azimuth of the field in the coil provokes different saturations, and a strong impact on multipole
  - One can optimize the shape of the iron to reduce these 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)



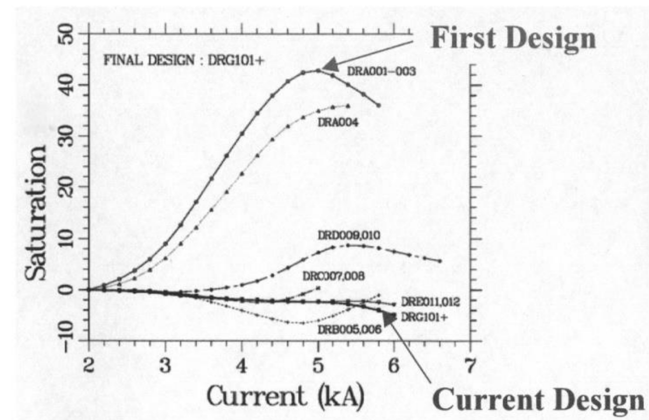
IRON YOKE - OPTIMAZATION

- 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 of 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

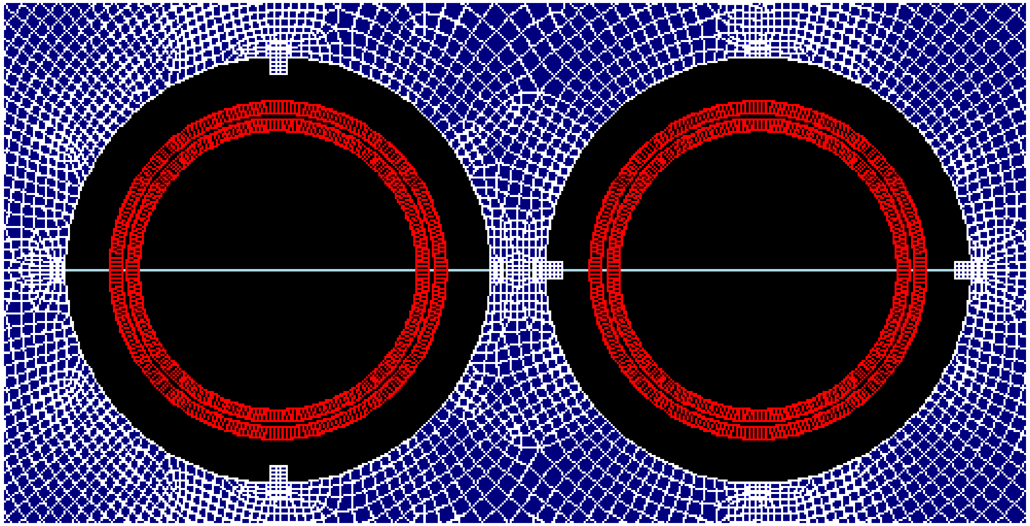


Correction of b3 variation due to saturation
for the RHIC dipoles, R. Gupta, ibidem

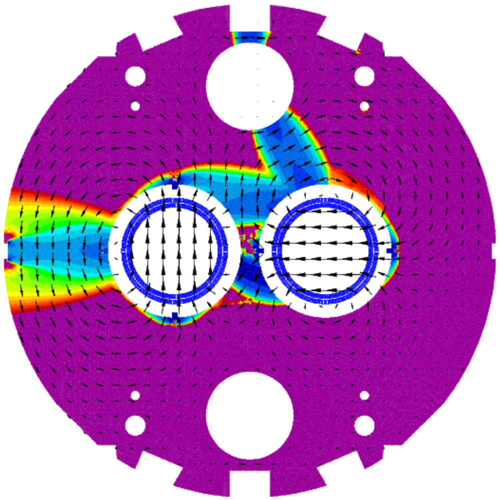
- A similar approach has been used for the LHC dipole
  - Less contribution from the iron (20% only), but left-right asymmetries due to two-in-one design [S. Russenschuck, C. Vollinger, works in IEEE TAS in 2000-2005)
- Another possibility is to shape the contour of the iron (elliptical and not circular)

IRON YOKE EFFECT

- The estimate of the impact of iron saturation, coupled with iron shape and coil design is totally non trivial, even for low fields
  - Ideal tool is ROXIE, using a coupled method to solve the equations
  - Example: the impact of magnetic/non magnetic keys in a low field magnet (D2 correctors in HL LHC, a CCT based design with 2.6 T field): 10 units of b_3 !



The iron keys, of place in the wrong place, can give 10 units of b3
D2 corrector magnet (A. Musso, G. Kirby)



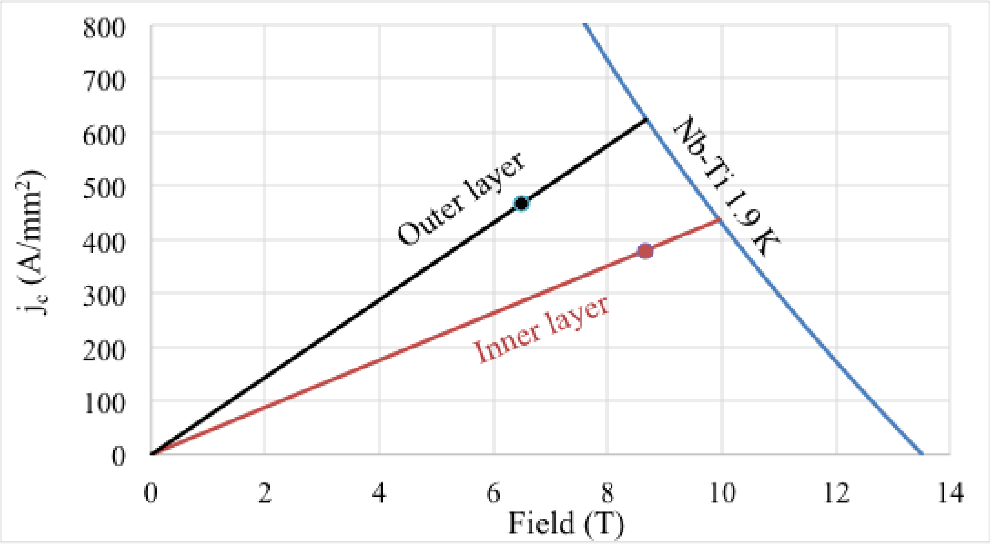
Iron saturation in D2 corrector magnet
(P. Hagen, A. Musso, G. Kirby)

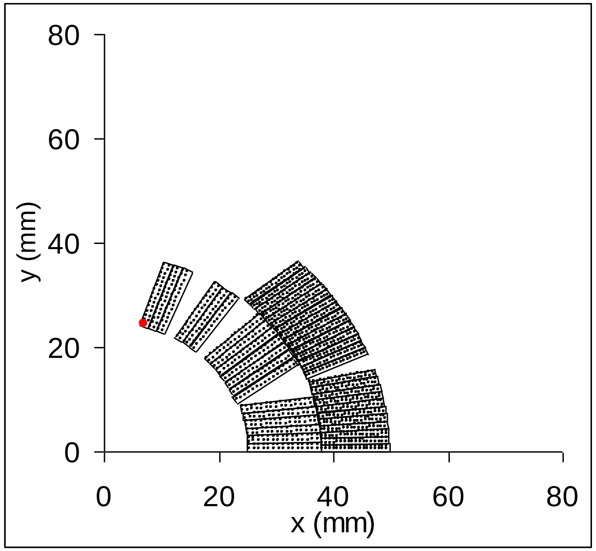
CONTENTS

- The role of iron
- Grading techniques
- A few words on coil ends

GRADING TECHNIQUES

- The map of the field inside a coil is strongly non-uniform
  - Two grading possibilities: first one
    - In the outer layer the peak field can be lower than in the inner layer, therefore larger current density can be used, and thinner coil
    - Example: in the LHC main dipole, 23% larger current density
    - Usually larger loadline margin is used for the outer layer

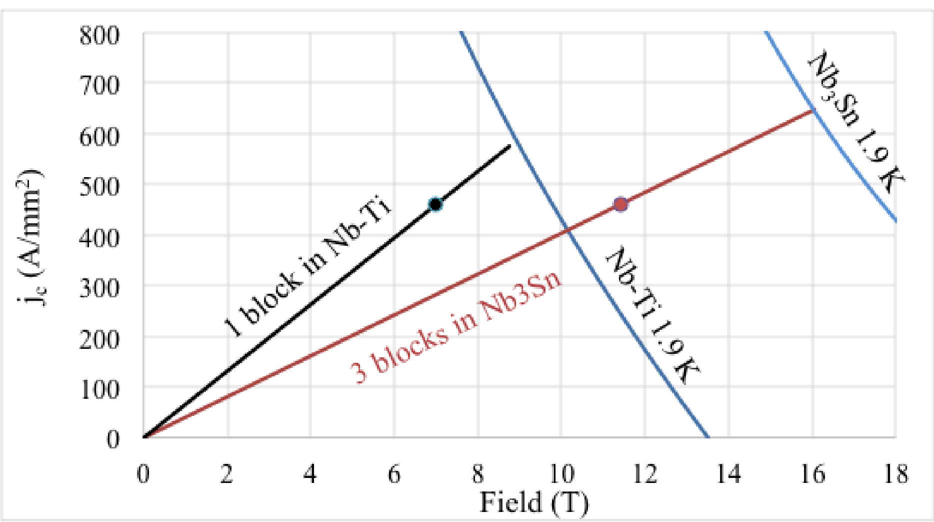


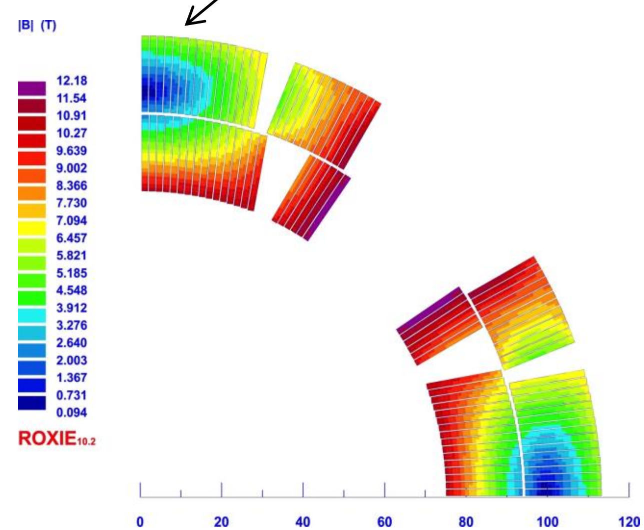


LHC dipole loadlines for peak field in inner and outer layer

GRADING TECHNIQUES

- The map of the field inside a coil is strongly non-uniform
  - Two grading possibilities: second one
    - The same current density is kept, but lower performance material is used for the lower field blocks, saving money
    - For instance, in this magnet Nb_3Sn with peak field 12 T one block has a peak field of 7 T, where Nb-Ti could be used, with a 30% saving at the price of higher complexity (splice between Nb-Ti and Nb_3Sn)

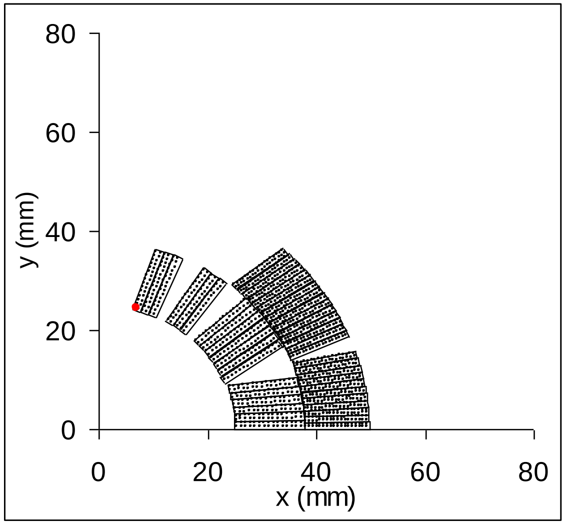




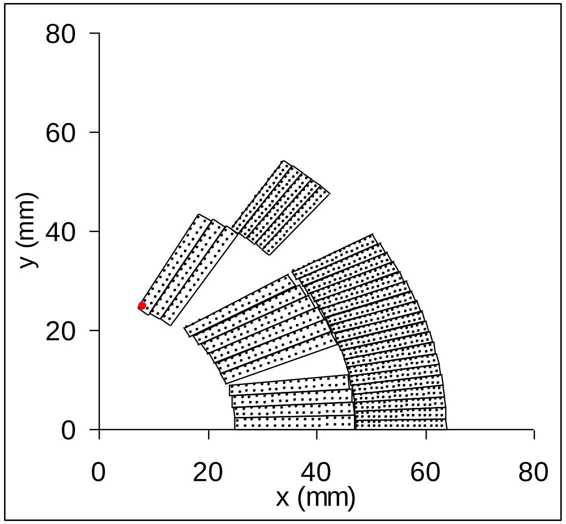
An hypothetical material grading applied to MQXF magnet

GRADING TECHNIQUES - DIPOLES

- 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



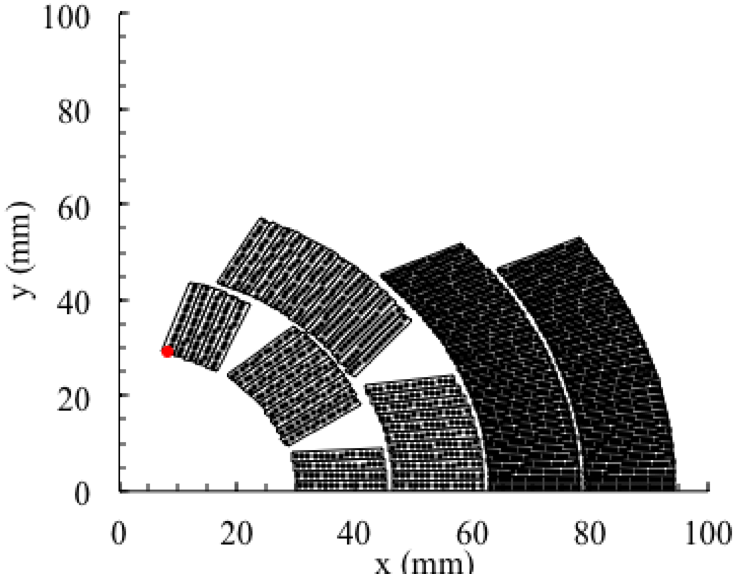
LHC main dipole



MSUT dipole

GRADING TECHNIQUES - DIPOLES

- Examples of graded coils
  - MDPTC1 main dipole (~14 T)
    - Grading of 1.34 (i.e. +34% current density in outer layer)
    - Coil width: 15 mm for each layer
    - Last two layers (30 mm) are equivalent to 30*1.34=40 mm
    - Aperture radius is 30 mm
    - No grading: coil surface
      - $2\pi((30+70)^2-30^2)/3=19000$ mm^2
    - With grading
      - $2\pi((30+60)^2-30^2)/2=15000$ mm^2

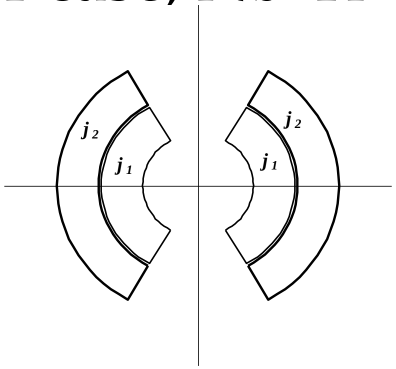


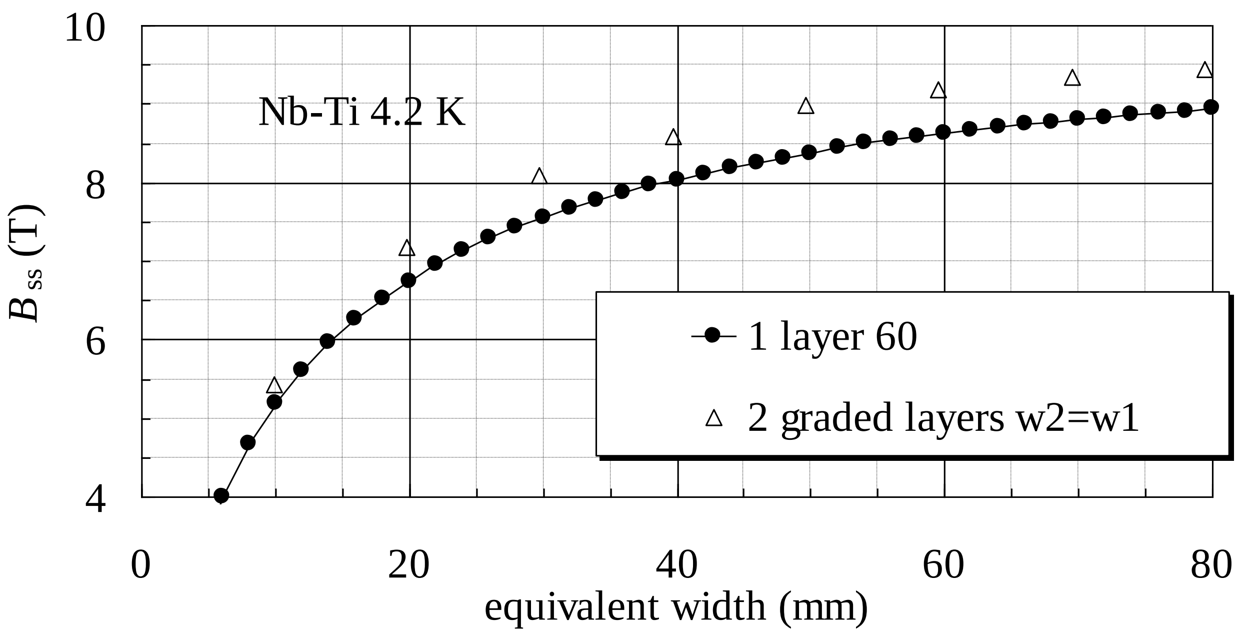
MDPTC1 main dipole (A. Zlobin, et al.)

  - Conductor quantity with grading : -20%

GRADING TECHNIQUES - DIPOLES

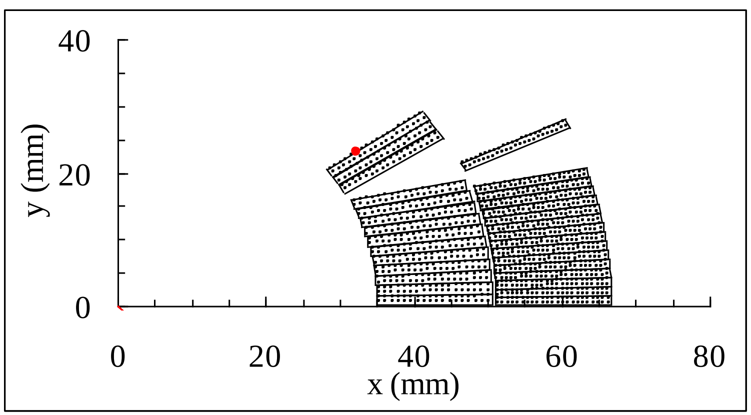
- Results for a two layer with same width sector case, Nb-Ti
  - The gain in short sample field is ~5%
  - But given a short sample field, one saves a lot !
    - At 8 T one can use 30 mm instead of 40 mm (-25%)
    - At 9 T one can use 50 mm instead of 80 mm (-37%)



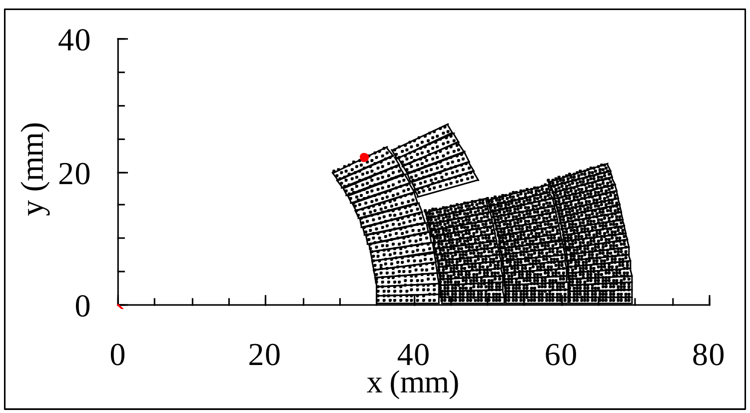


GRADING TECHNIQUES - QUADRUPOLES

- 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 – this is the most amazingly optimized quadrupole
    - 9% more in short sample field, could not be reached without grading



LHC MQXB (J. Kerby, et al, IEEE TAS 1995-2000)



LHC MQY (G. Kirby, R. Ostojic, et al IEEE TAS 1999-2005)

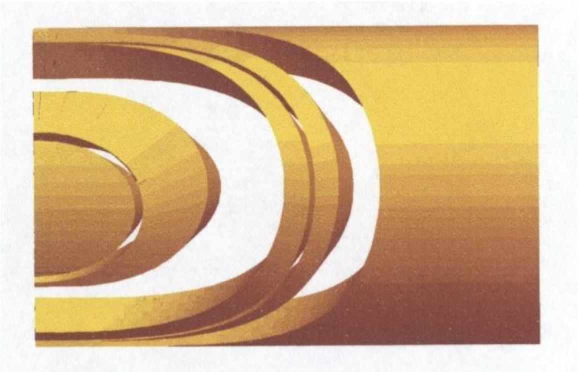
CONTENTS

- The role of iron
- Grading techniques
- A few words on coil ends

COIL ENDS

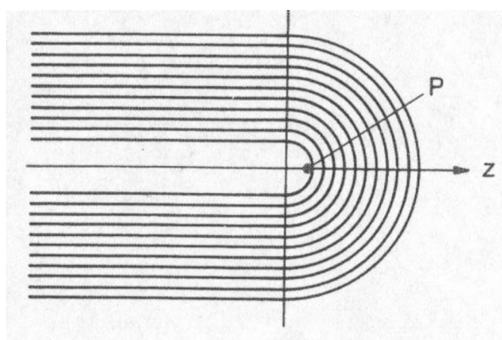
- Main features of the coil end design
  - ++Mechanical: find the shape that minimizes the strain in the cable due to the bending (constant perimeter)
    - In a cosθ magnet this strain can be large if the aperture is small
    - In a racetrack design the cable is bent in the 'right' direction and therefore 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]

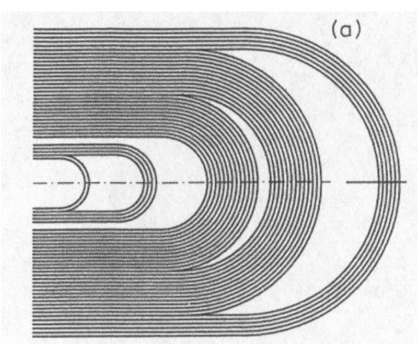


End spacers supporting the ends of a cosθ coil
[S. Russenschuck,World Scientific, Fig. 32.13]

- 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, end are the most difficult parts to manufacture → are the most unstable from a mechanical point of view
    - It is wise 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]

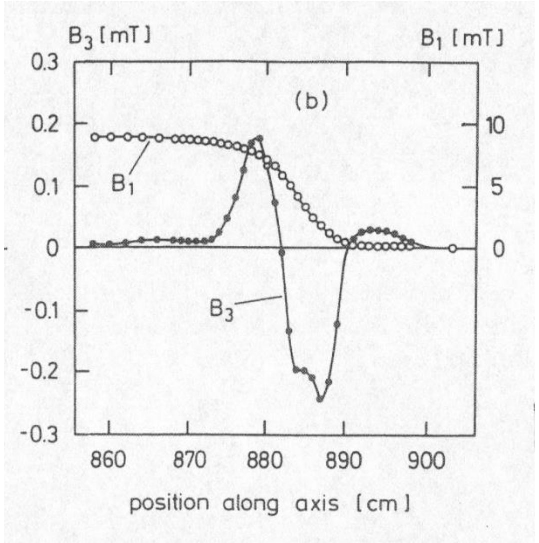


Coil end with spacers to decrease the main field in the end
[Schmuser,pg. 58]

COIL ENDS

- Main features of the coil end design
  - +/- Magnetic: take care of field quality (especially if 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]

CONCLUSIONS

- The iron has several impacts
  - Useful for shielding, but the main role is to increase field for a given current

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

  - Therefore very beneficial for stresses (Unit 10) and protection (Unit 12)
  - Reduction can be considerable for small coil width
  - The impact on the performance (short sample) is small but not negligible
  - Minor drawbacks: saturation, inducing field harmonics at high field – can be cured by power converter (main component) and by shaping or drilling holes in the right place (multipoles)
  - ROXIE is the ideal tool for these computations

CONCLUSIONS

- Grading the current density in the layers can give a larger performance for the same amount of conductor
  - Two types:
    - Higher current density in lower field
    - Cheaper material in lower field (material grading)
  - 3-5% more in dipoles, 5-10% more in quadrupoles
  - Non negligible reduction of cost for large factor X (see Unit 8) magnets
- Coil ends: to be done with complex codes (ROXIE)
  - Nothing much can be said with analytical tools
  - The design must aim at reducing the peak field
  - The design must aim at good windability

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