Lecture III

Magnetic Design
General Principles

Ramesh Gupta
Superconducting Magnet Division
Brookhaven National Laboratory

US Particle Accelerator School
Arizona State University
Phoenix, Arizona
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Superconducting Magnet Design (1)

A few of many things that are involved in the overall design of a superconducting magnet

• The magnet should be designed in such a way that the conductor remains in the superconducting phase with a comfortable margin.

• Superconducting magnets should be well protected. If the magnet quenches (conductor loses its superconducting phase due to thermal, mechanical, beam load, etc.), then there should be enough copper in the cable to carry the current to avoid burn out.

• The cryogenic system to cool and maintain the low temperature (roughly at 4 Kelvins) for the entire series of magnets in the machine. It should be able to handle heating caused by the beam, including that by synchrotron radiation or decay particles.

Superconducting Magnet Design (2)

- The magnet cost should be minimized.
- There are very large Lorentz forces in superconducting magnets. They roughly increase as the square of the field. The coil should be contained in a well design support structure that can contain these large forces and minimize the motion of the conductor. In high field magnets, the design of the mechanical structure plays a major role.
- The magnets should be designed in such a way that it is easy to manufacture.
- It must meet the field quality (uniformity) requirements.

Overall Magnetic Design (First cut - 0^{th} order process)

Coil Aperture

- Usually comes from accelerator physicists
- But also depends on the expected field errors in the magnet
- Feedback between accelerator physicists and magnet scientists may reduce safety factors in aperture requirements

Design Field

- Higher field magnets make machine smaller
  - Reduce tunnel and infrastructure cost
  - But increase magnet cost, complexity and reduce reliability
- Determines the choice of conductor and operating temperature

Find a cost minimum with acceptable reliability.

What is involved in the magnetic design of superconducting (SC) magnets?

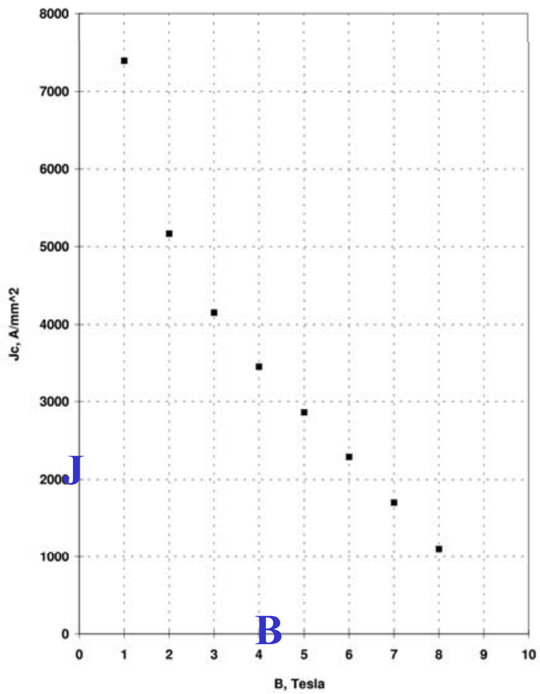
Everywhere in the magnet, the conductor must remain below the critical surface, while the field is maximized in the magnet aperture

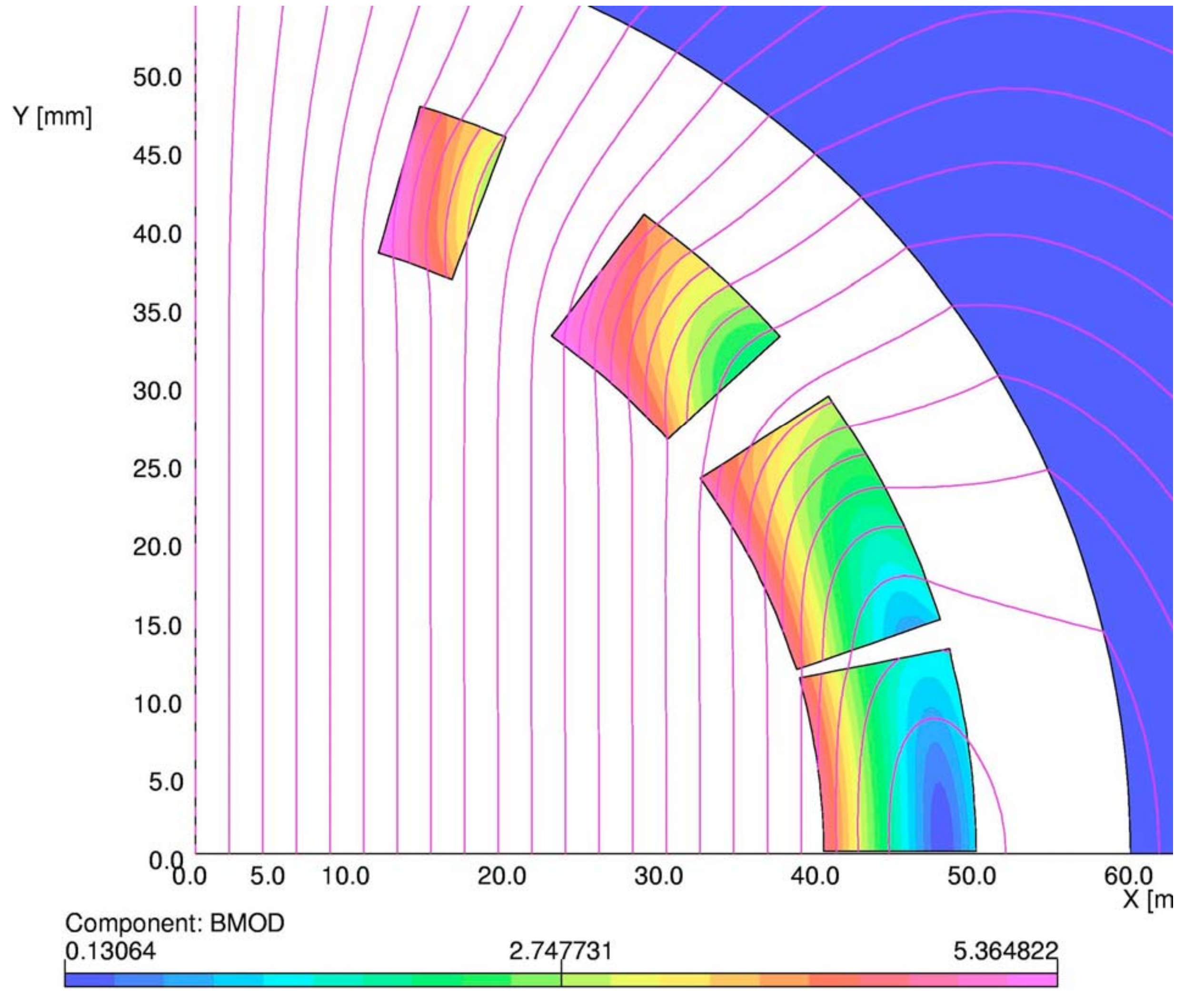
Field must be uniform in the magnet aperture (~2/3 coil radius)
Very uniform : Desired relative errors (typical value): $\Delta B/B \sim 10^{-4}$

Things that must be done to achieve the required field uniformity:
- Optimize conductor geometry
- Conductor must be placed accurately (~25 microns)
- Deal with non-linear magnetization of iron
- Reduce persistent currents (or use external correctors)

Field in the Superconducting Coil in the RHIC Arc Dipole Magnet

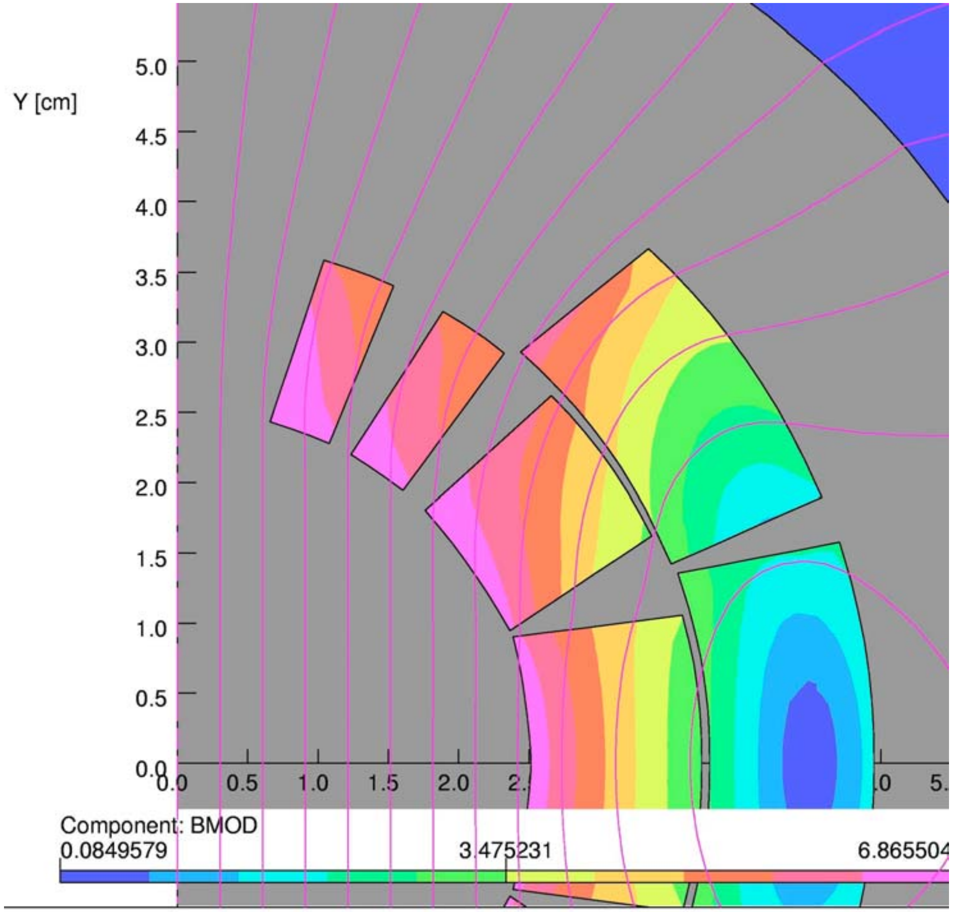
Note that the field is high in the pole block and it is much lower on other blocks, particularly on the outside.





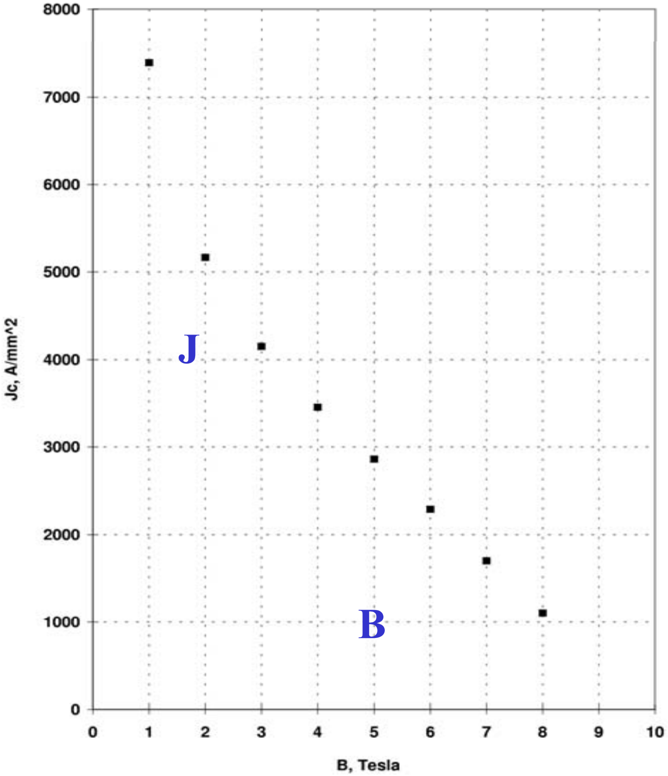
Maximizing Field in the Magnet Aperture: Conductor Grading

Field on the conductor in the two layer SSC dipole



Most of the conductor stays well below the critical surface

Grading for higher field



A higher current density (and hence higher central field) is possible in the outer layer, as the field is lower.

The Maximum Field Available To Beam Vs. The Maximum Field on The Superconductor

- **The peak (maximum) field on the conductor is always more than the field at the center of the dipole.**
- **In a perfectly made superconducting dipole, the central field is limited by the maximum field point in the superconducting coils (not by structure,etc.).**

What happens in a quad, where the field at the center is zero?

- Typical values for a single layer coil design : 115% of B_o
- Typical values for a double layer coil design :
  105% in inner, 85% in outer

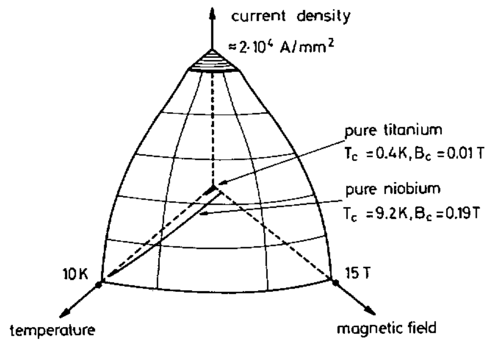
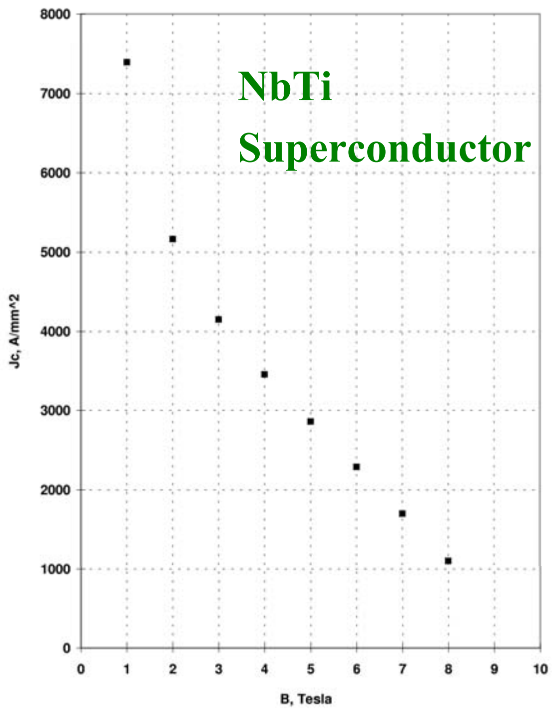
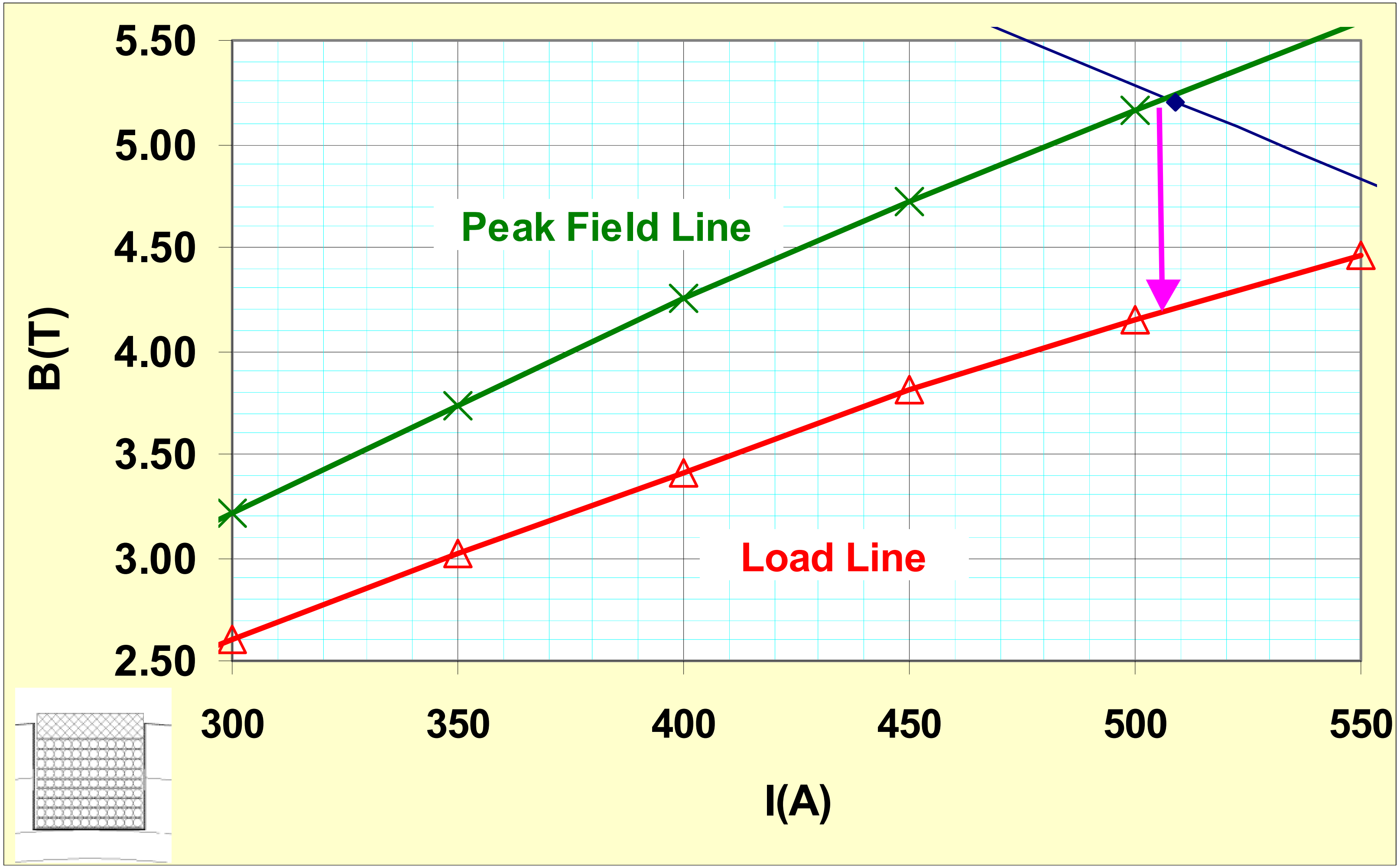


Figure 2.11: Sketch of the critical surface of NbTi. Also indicated are the regions where pure niobium and pure titanium are superconducting. The critical surface has been truncated in the regime of very low temperatures and fields where only sparse data are available.



Load line Vs. Peak Field Line

Peak field line corresponds to the maximum field on the conductor (determines how much current one can put in), and Load line refers to the field in the aperture (determines field available to beam)

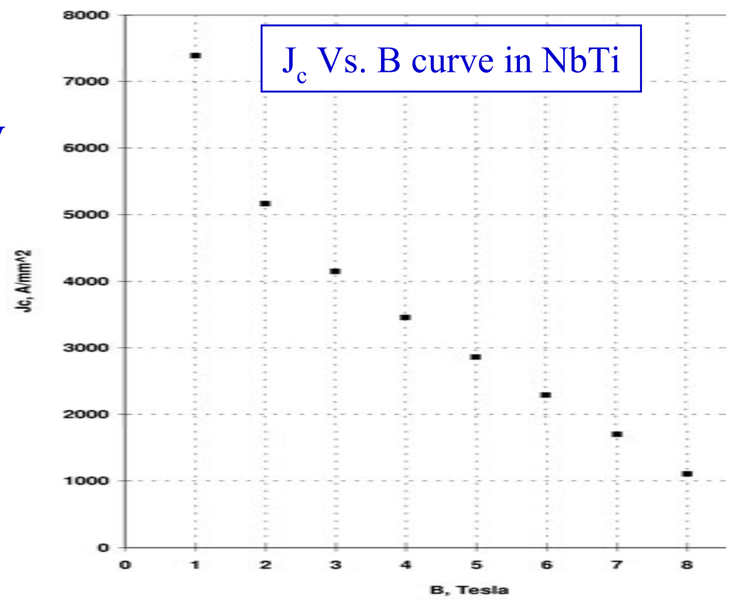


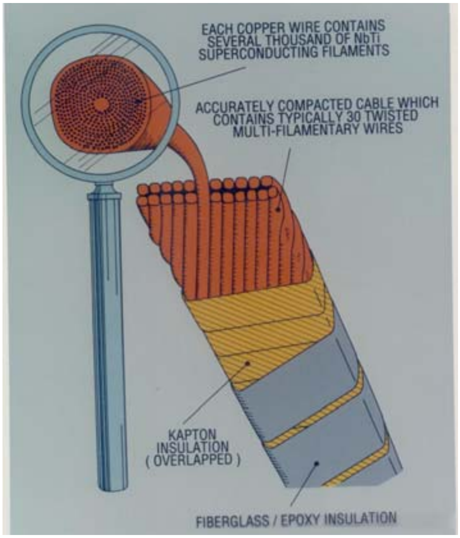
Current Density in Superconductor Vs. Available Current Density in Coils

Even though the superconductor may be capable of carrying a current density of 3000 A/mm^2 or so, only a fraction of that is available to power the magnet.

Here is why?

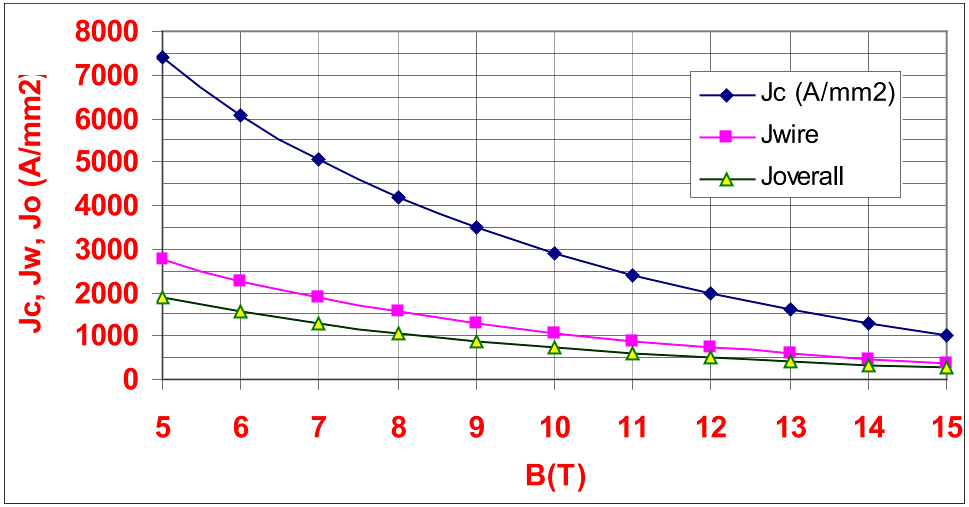
- There should be enough copper within the wire to provide stability against transient heat loads and to carry the current in the event the superconductor turns normal.
- Usually the copper content is more than superconductor. In most medium field NbTi production magnets, the maximum current density in copper is 1000 A/mm^2 or less at the design field. In high field Nb_3Sn R&D magnets, we are allowing it to be twice that (or even more).
- The trapezoidal "Rutherford cable" is made of several round wires. The fill factor may be 90% or so.
- The coil consists of many turns. There must be a turn-to-turn insulation taking ~15% of the volume.



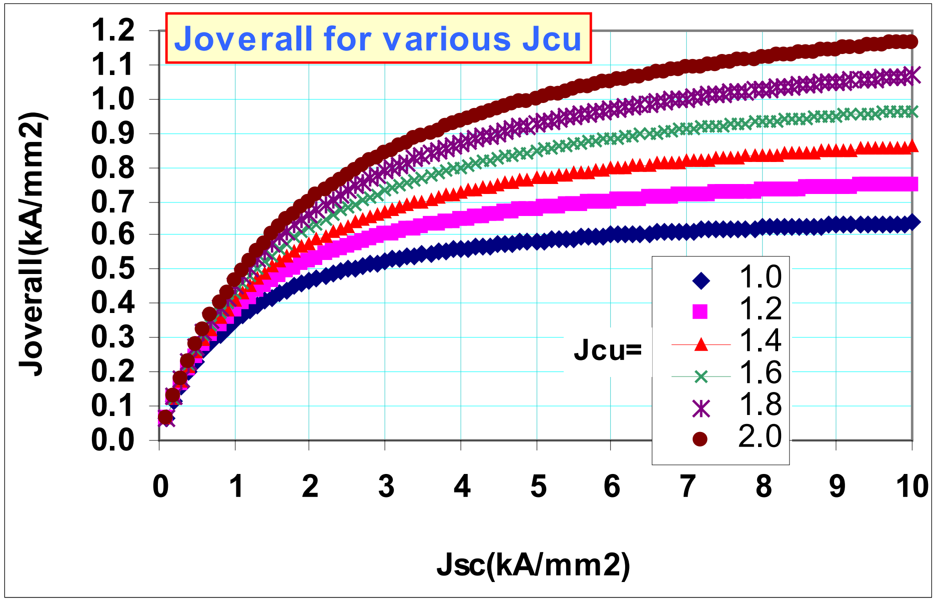


Usable Current Densities in Coils

The example on the right is for a Nb_3Sn superconducting cable with Cu/Sc ratio fixed at 1.7. Note that the overall current density in the coil is only ¼ of the superconductor current density.



In the example on the right, the overall current density is computed to keep the current density in copper at a given value (see legends, values in kA/mm^2).

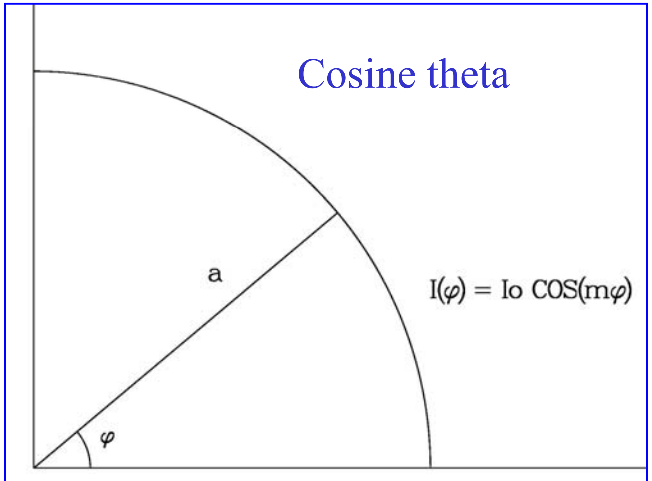


Designs for Ideal Fields

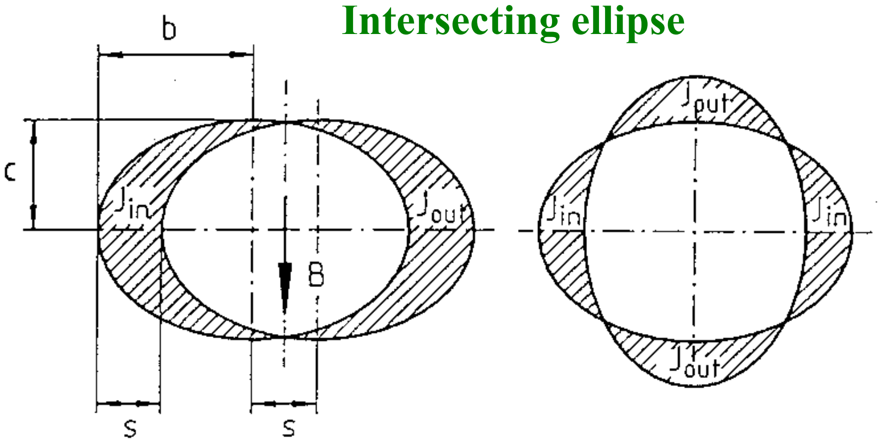
Here are some current distributions, that produce an ideal field.

Ideal field is the one where only one multi-pole (dipole, quadrupole, etc.) is present and all other harmonics are theoretically zero.

Cosine theta

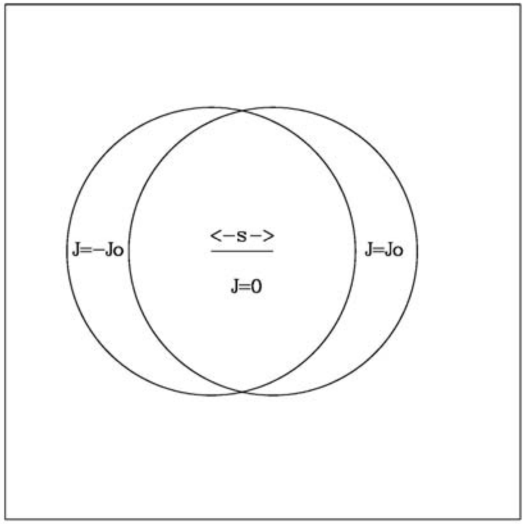


Intersecting ellipse



$$B_y = -\frac{\mu_o jsc}{(b+c)},$$

Two intersecting circles



Dipole from Intersecting Circles

Home Assignment:

Prove, without using complex variables, that the geometry shown on the right produces a pure dipole field in the current free region. (I.I. Rabi, 1984, Rev. Sci. Inst. & Method).

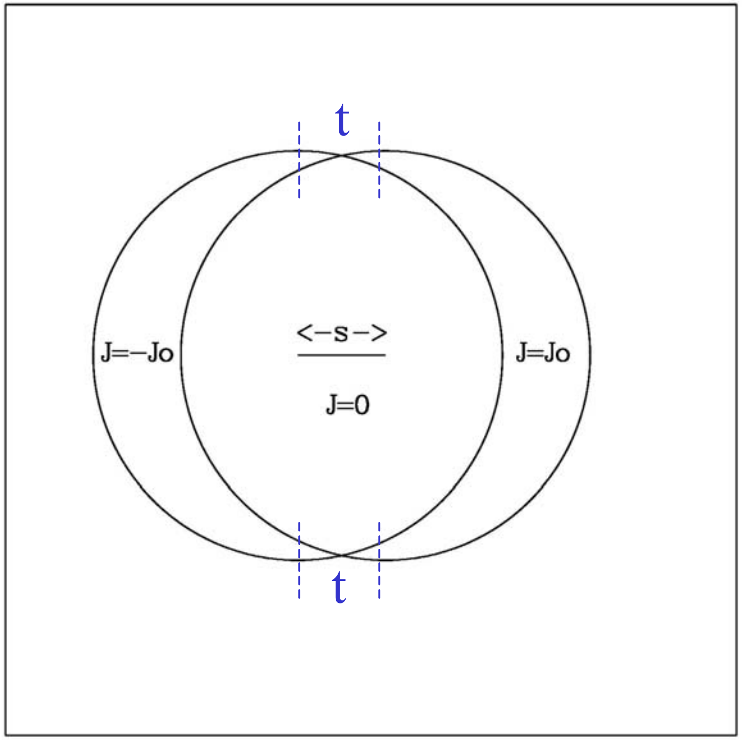
How will the components of the field (Hx, Hy) and the magnitude will fall outside the current region as a function of (x,y) and (r,θ)? Assume that the radius of the circle is *"a"*.

Make an OPER2D or POISSON model of it and compute field and field harmonics at a reference radius of 50 mm.

Assume a = 100 mm, s = 20 mm, J_o = 500 A/mm^2.

Repeat the same computations with an iron shell around it with an inner radius of 150 mm and outer radius of 300 mm. Do calculations with a fixed μ = 5000, 1000, 100, 10, 2 and 1. Also do a calculations with variable μ with default material No. 2. How does the field fall outside the coil?

Two intersecting circles



Truncate the model at the dashed lines, as shown above, at t=10mm. Compute harmonics and peak field on the conductor.

Coil Design: Starting Parameters

Estimated coil width for generating a dipole field of B_0

$$w \sim 2B_0/(\mu_0 J_0)$$

where J_0 is the operating current density and not the current density in conductor (J_{sc}).

Class Problem: Compute the required conductor for a 5 T dipole.

Assume that the current density in the coil is 500 A/mm^2.

How does the required conductor width vary with aperture?

How does the required conductor volume vary with the aperture?

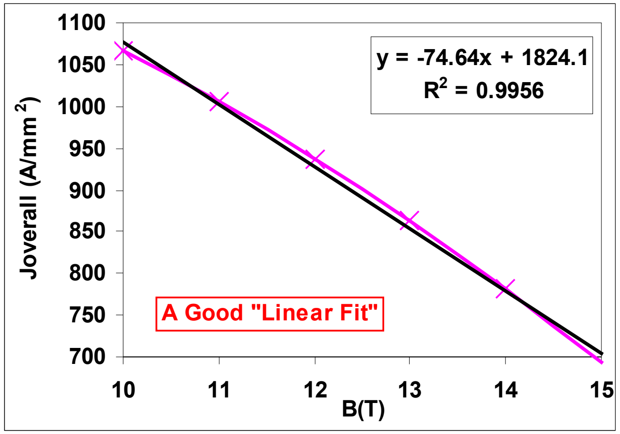
Always check the B-J-T surface of the superconductor, the operating point must stay well within it.

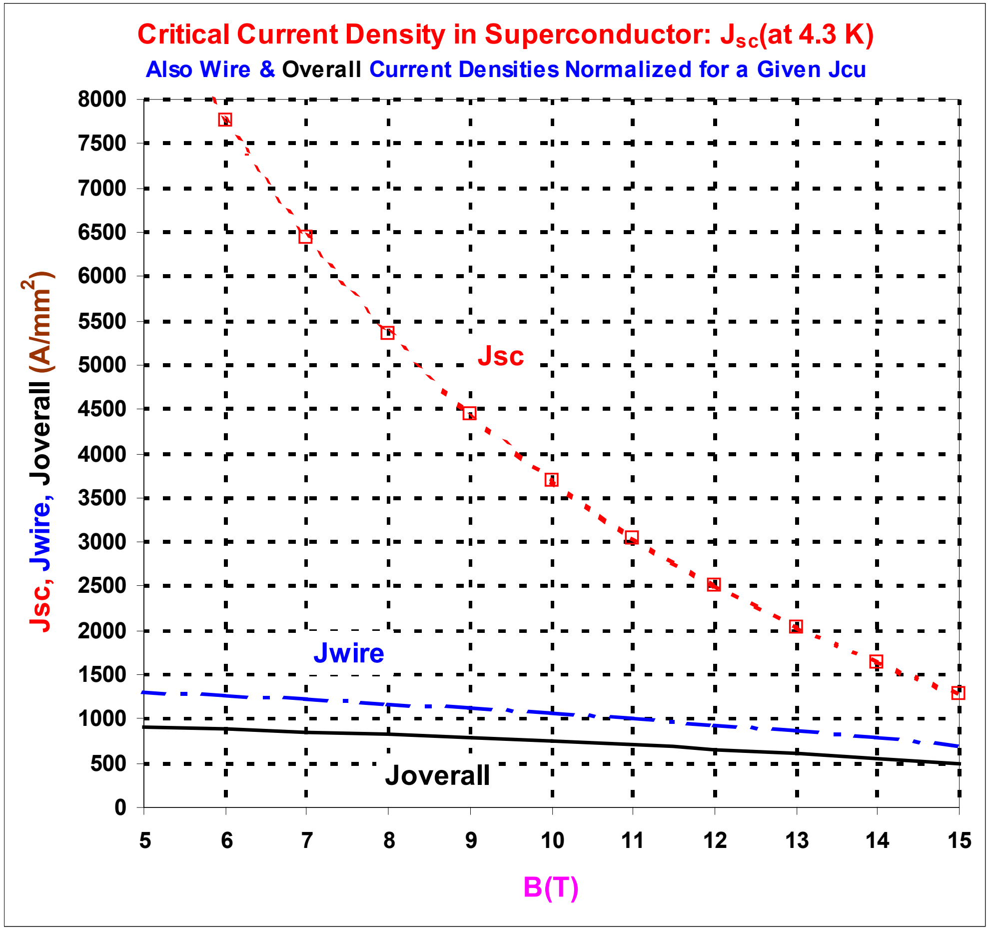
Usable Current Density in Magnet Design (Case study of Nb_3Sn for fixed J_{cu} at quench)

Assignment: Obtain J_{wire} and $J_{overall}$ curves for magnet designs at various short sample fields. Assume the (B_c,J_c) relationship shown below, J_{cu} is 1500 A/mm², fill factor is 90% and insulation takes up 15% of total area in cable.

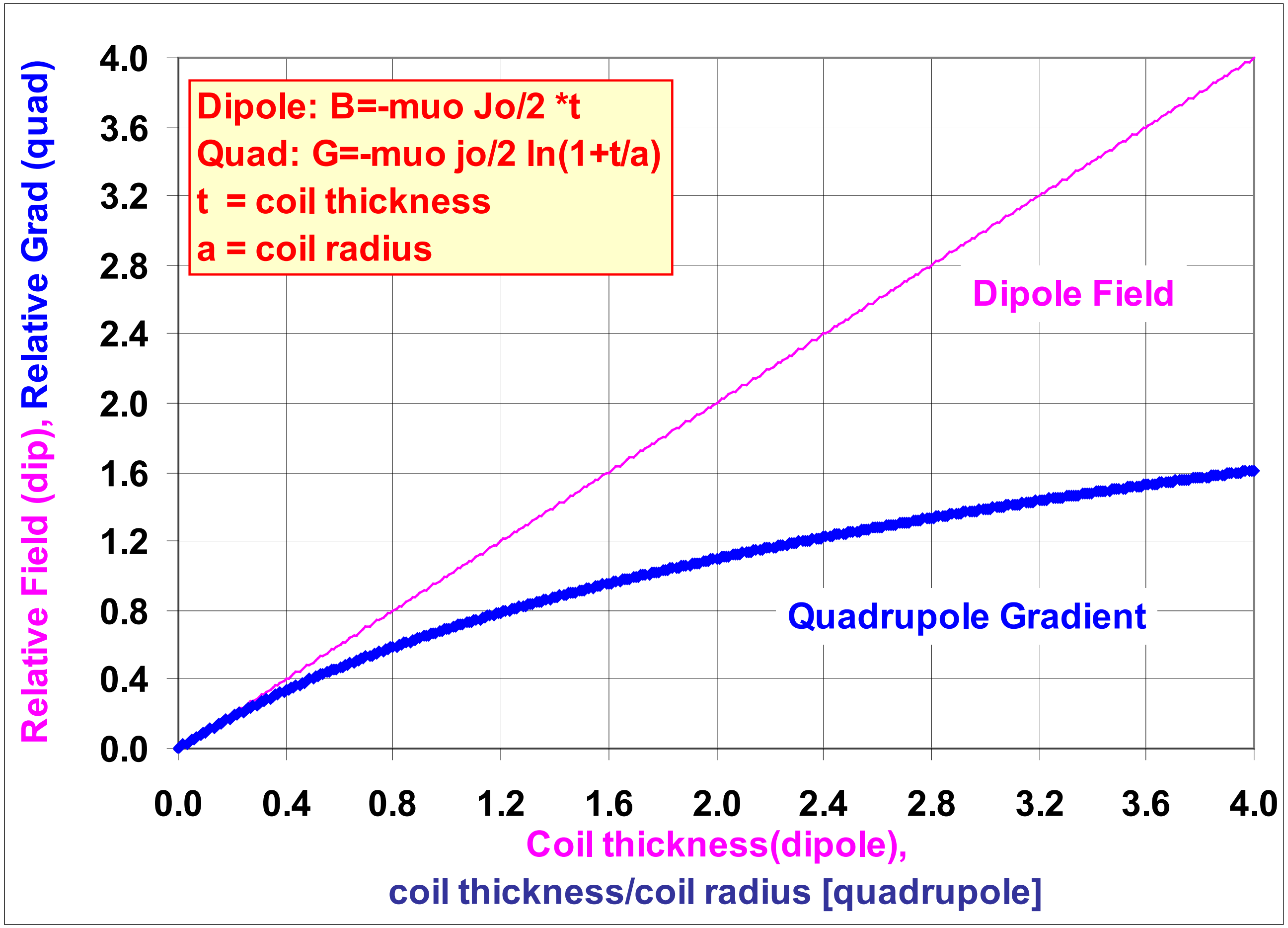
J_{sc}(12T,4.3K)	J_{cu}(A/mm²)
2500	1500

Cu/Sc Ratio	B(T)	J_c(A/mm²)	J_{wire}(A/mm²)	Joverall
6.30	5	9454	1295	911
5.18	6	7766	1257	885
4.29	7	6431	1216	856
3.56	8	5347	1171	825
2.96	9	4446	1122	790
2.46	10	3689	1066	751
2.03	11	3048	1005	708
1.67	12	2500	938	660
1.35	13	2031	863	607
1.09	14	1631	781	550
0.86	15	1289	693	488
	Scaled from TWCA			Insulated





A Guide to Choosing the Maximum Field in Superconducting Magnets



Coil thickness : t

Coil radius : a

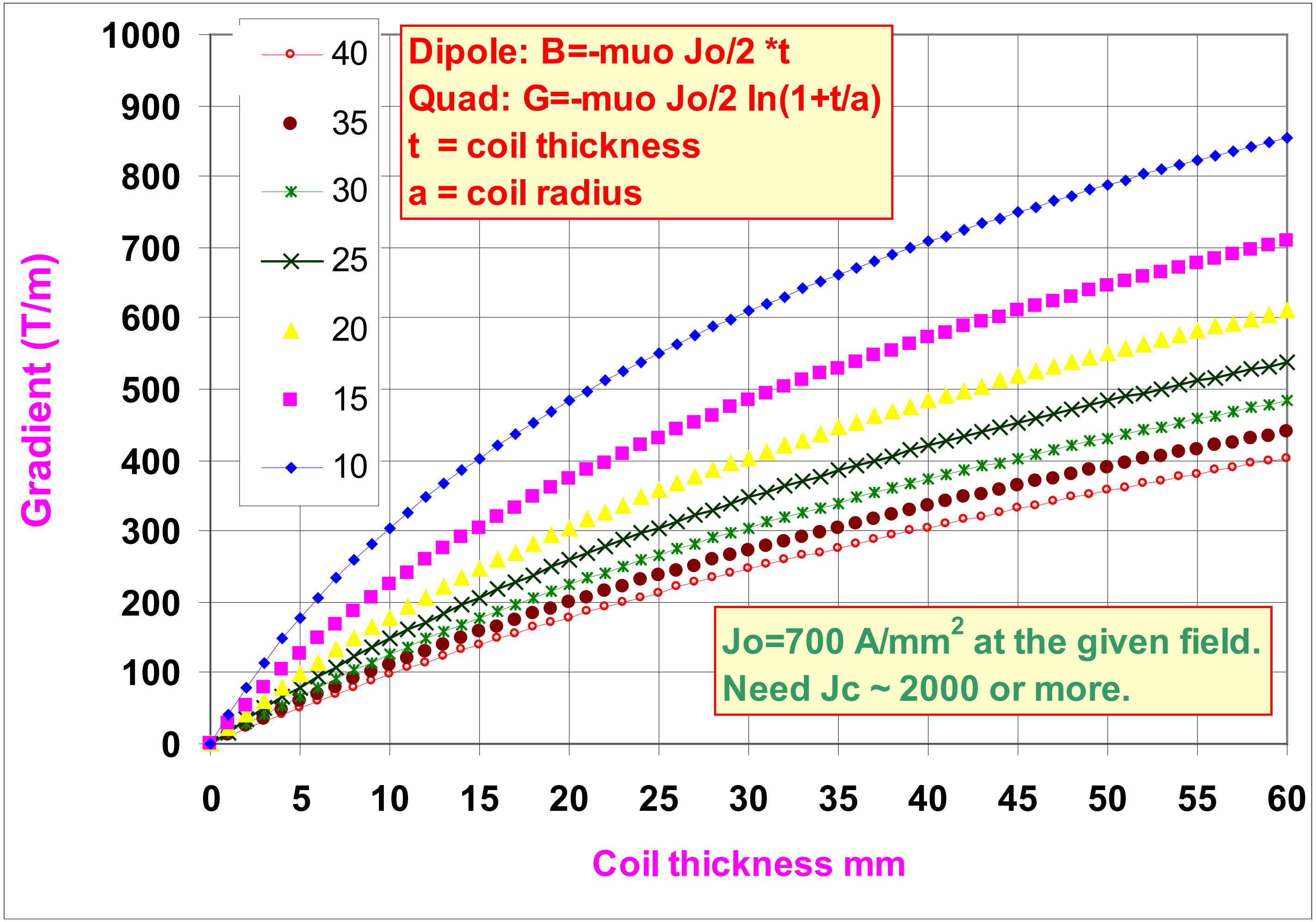
Current density : Jo

Field : B

Gradient : G

To get maximum field keep increasing coil thickness (within practical limit) till you reach the maximum field in the coil where magnet quenches (in quads?)

Quadrupole Gradient for various coil radii



Note: Legends are coil radius, not aperture

The plot scales linearly with Jo (current density in coil)

A reasonable range of Jc is 400-1000 A/mm^2

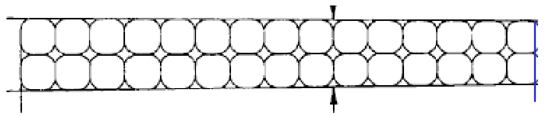
Important number is pole-tip field = Gradient * coil radius

In large aperture magnets, forces become large.

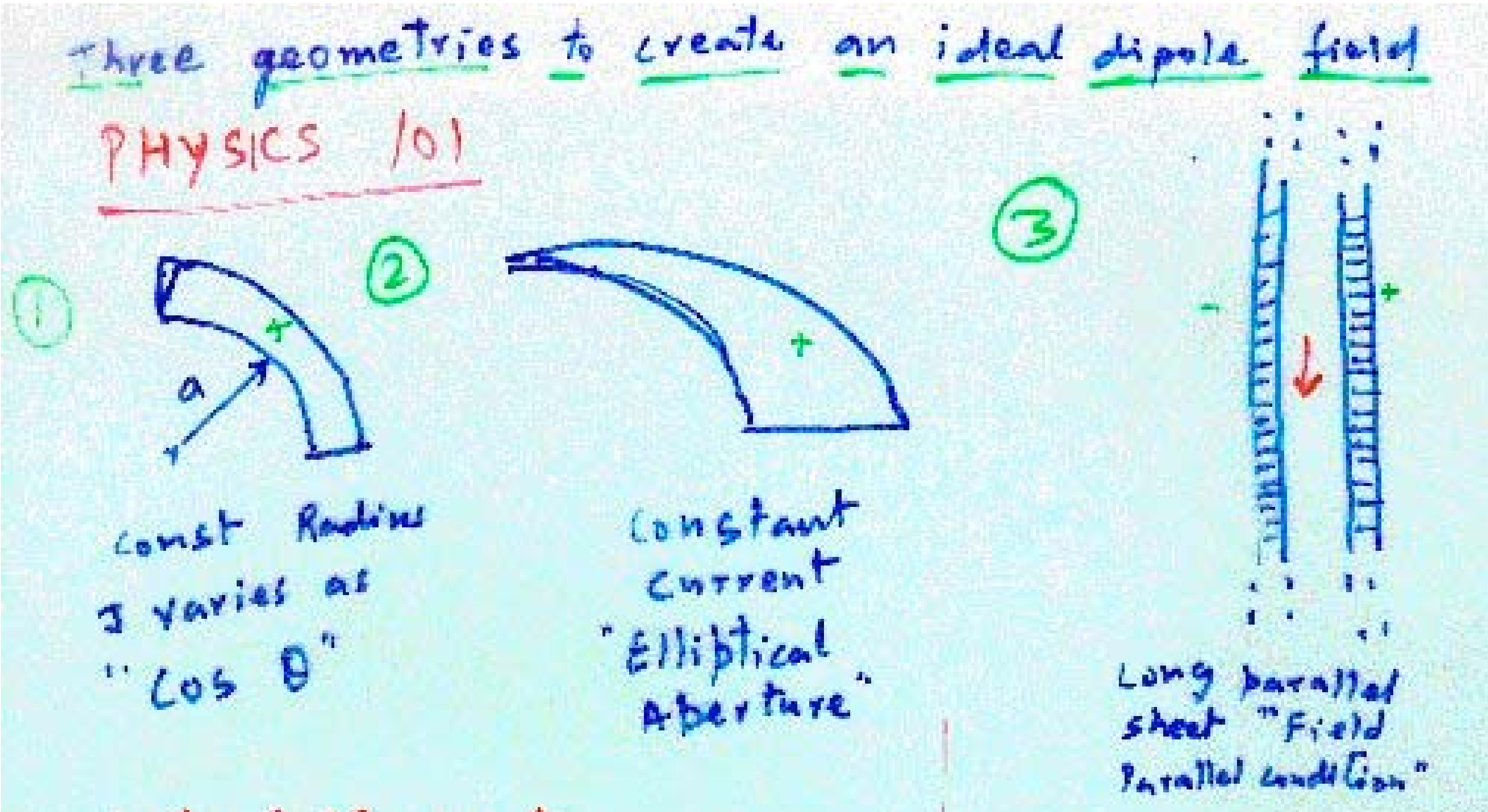
Assignment

Assume that a rectangular cable (Non-Keystone, Rutherford cable) is made of 30 wires (strands). The diameter of each wire is 1 mm. The width of the insulated cable is 17 mm and the thickness is 2 mm. The insulation on each side of the cable is 0.2 mm. The critical current density of the superconductor at 12 T is 2500 A/mm^2. The wire has 40% superconductor and you can assume that the rest is copper.

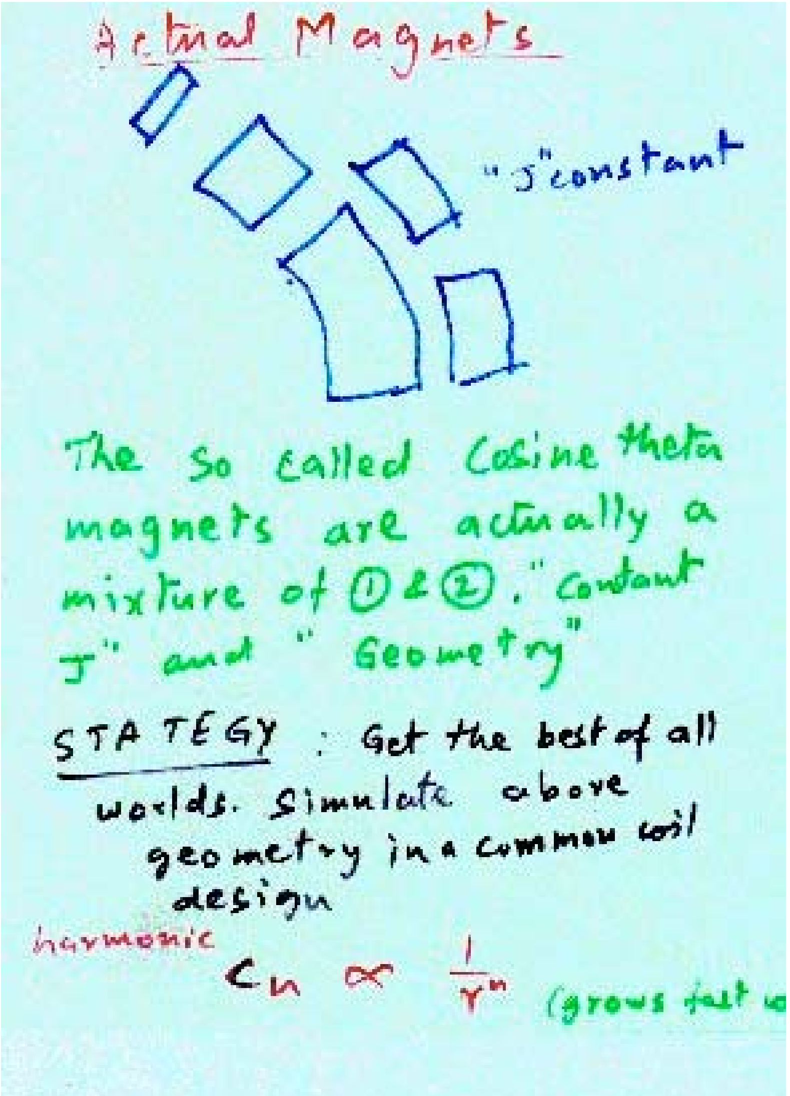
The magnet made with this cable operates at 12 T. Compute the current density in wire, in insulated cable and in bare cable (cable without insulation) at 12 T. What will be the current density in copper if the magnet quenches (looses its superconductivity) at 12 T?



Field Quality optimization from 1st Principles



Field Quality optimization from 1st Principles



Ideal Cosine Theta Design:

- **Vary current distribution**
- **Keep radius (radial width) constant**

Elliptical Coil Geometry

- **Vary radial width**
- **Keep current density constant**

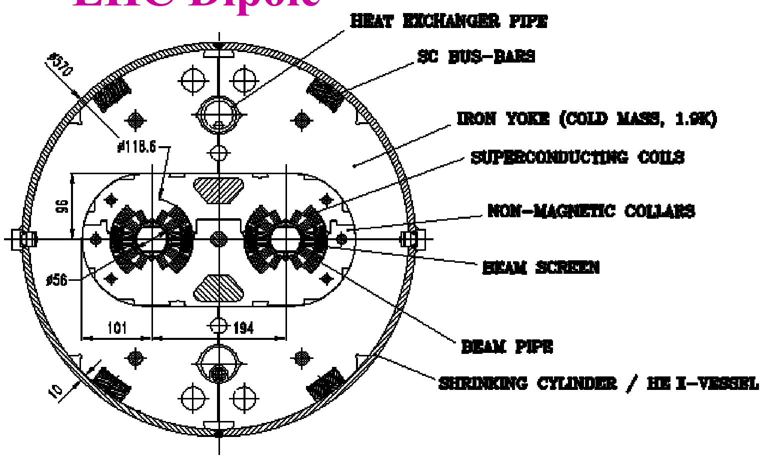
Most accelerator magnet are referred to as cosine theta magnets.

• However, they use constant current density (except for grading).

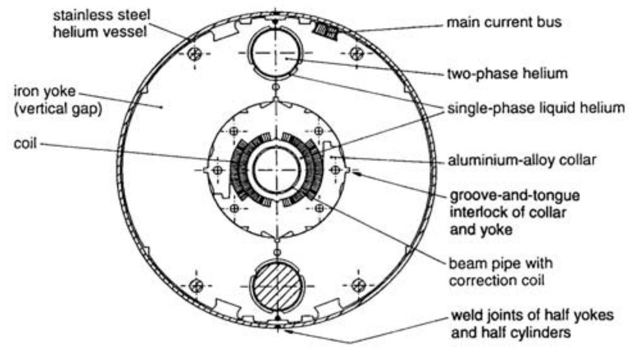
• They look like having a cosine theta distribution packing density of turns.

Present Magnet Design and Technology

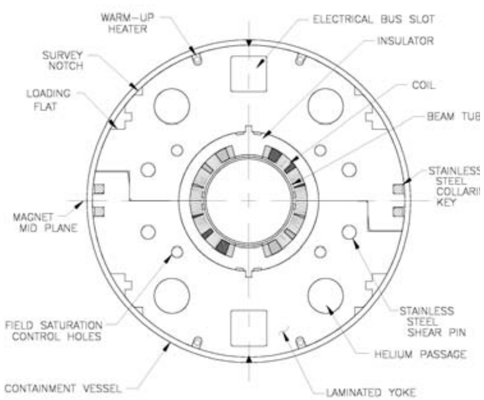
LHC Dipole



HERA Dipole



RHIC Dipole



Tevatron Dipole

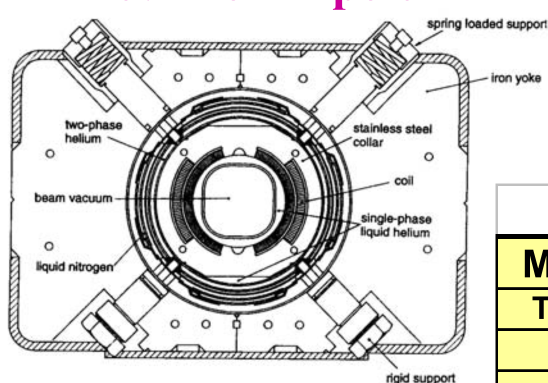


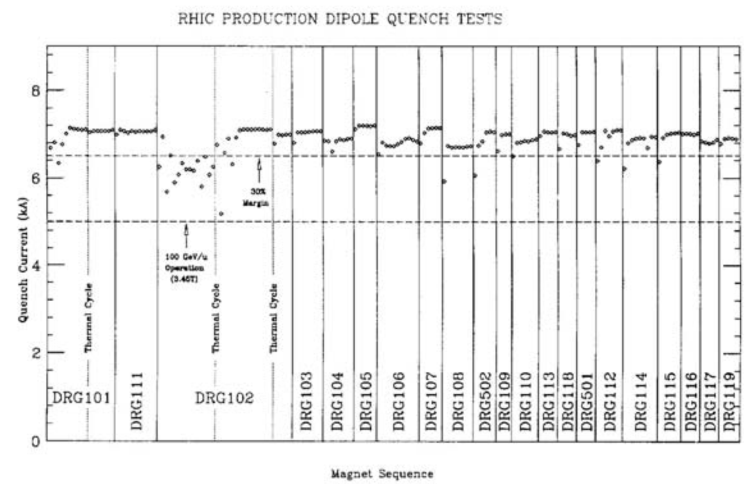
Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979)

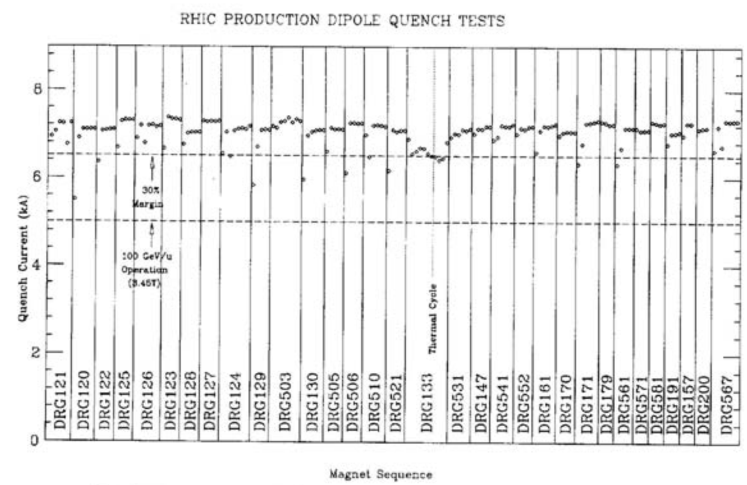
- All magnets use NbTi Superconductor
- All designs use cosine theta coil geometry

	Dipoles			
Machine	B(T)	Aper(mm)	Length(m)	Number
Tevatron	4	76.2	6.1	774
HERA	4.68	75	8.8	416
~~**SSC**~~	~~6.7~~	~~50~~	~~15~~	~~7944~~
~~**UNK**~~	~~5~~	~~70~~	~~5.8~~	~~2168~~
RHIC	3.5	80	9.7	264
LHC	8.3	56	14.3	1232

Quench Performance of RHIC Production Magnets

- In a large series production, there could be some magnets that may not be able to reach the field as determined by the conductor spec/performance.
- Superconducting magnets for accelerators are, therefore, designed with some operating margin.
- RHIC magnets have over 30% margin. This means that theoretically, they are capable of producing over 30% of the required/design field.
- A successful design, engineering and production means that most magnets reach near the short sample current (as measured in the short sample of the cable) or field in a few quenches.
- Also, it is desirable that most reach the design operating field without any quench. Remember, the cost of cold test is high and it is desirable that we don't have to test all magnets cold.





Note: Test temperature was 4.5K (nom).
Quenches with the warm bore are not included in this plot.

J. Muratore

SUMMARY

This lecture was an overall introduction to the magnet design.

The next few lectures will go into more details of designing magnets - with an emphasis on designing magnets with good field uniformity.