Lecture III

Magnetic Design
General Principle

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Superconducting Magnet Design (1)

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

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

•The superconducting magnets should be well protected. If the magnet quenches (conductor looses 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 Kelvin) for the entire series of magnets in the machine. It should be able to handle the heating caused by beam, including that by synchrotron radiations or decay particles.

Superconducting Magnet Design (2)

- The magnet cost should be minimized.
- There are very large Lorentz forces in the superconducting magnet. 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 conductor. In high field magnets, the design of mechanical structure plays a major role.
- The magnet should be designed in such a way that they are easy to manufacture.
- They must meet the field quality (uniformity) requirements.

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

Coil Aperture

- Usually comes from accelerator physicists
- But also depends on the expected field errors in the magnet
- A 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

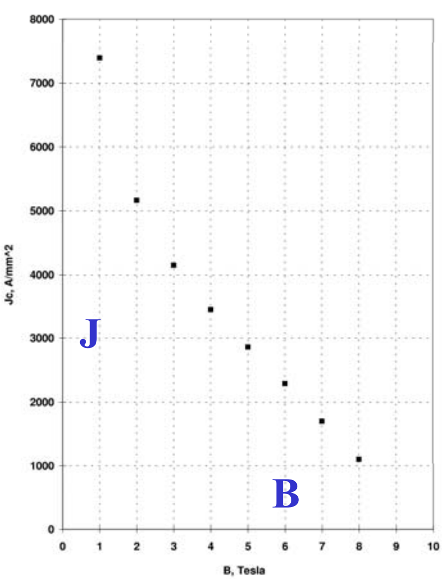
Field must be uniform in the magnet aperture
Very uniform : Desired relative errors (typical value): $\Delta B/B \sim 10^{-4}$

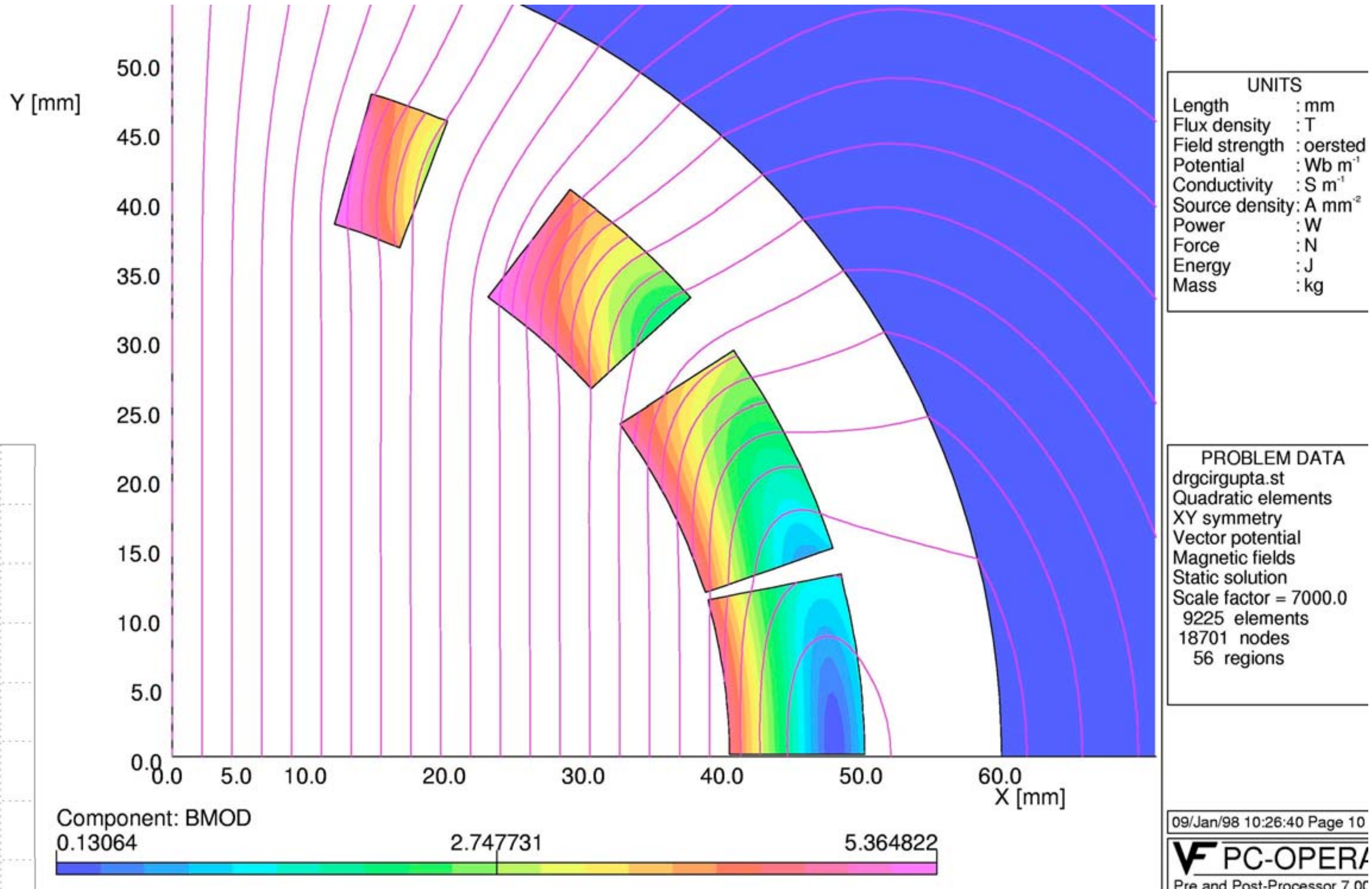
Things that must be done to achieve the required field uniformity:

- Optimize conductor geometry
- Conductor must be placed accurately (~25 micron)
- Deal with non-linear magnetization of iron
- Reduce persistent currents (or use external correctors)

Field in the Superconducting Coil in RHIC Dipole

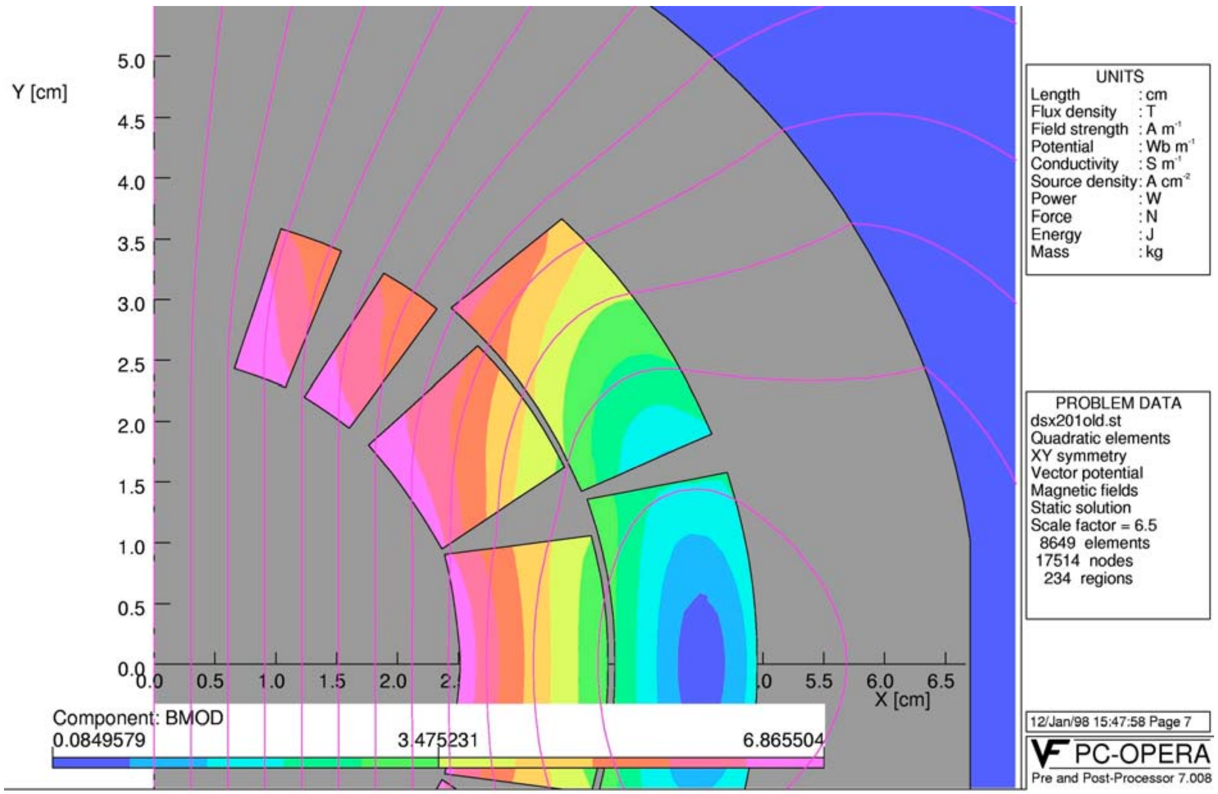
Note that the field is high in pole block and it is much lower on other blocks, particularly on the outside.





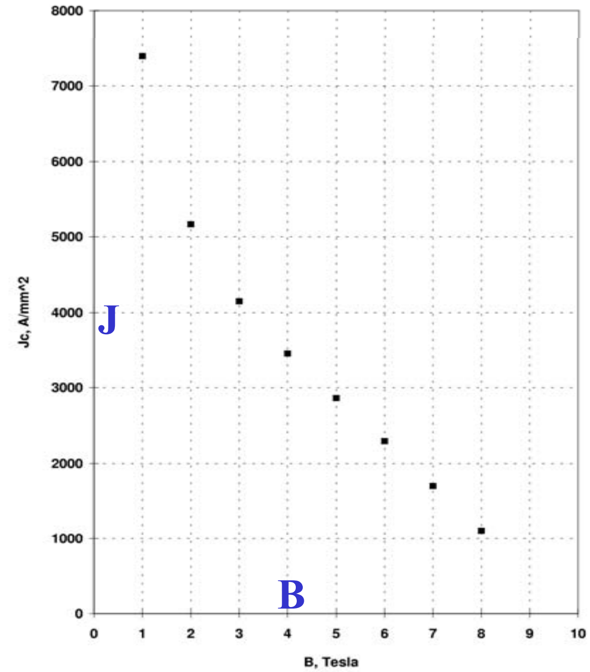
Maximizing Field in the Magnet Aperture: Conductor Grading

Field on the conductor in two layer SSC dipole



Most of the conductor stays well below 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.

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

In a perfectly made superconducting dipole, the central field is limited by the maximum field point in the superconducting coils.

- 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

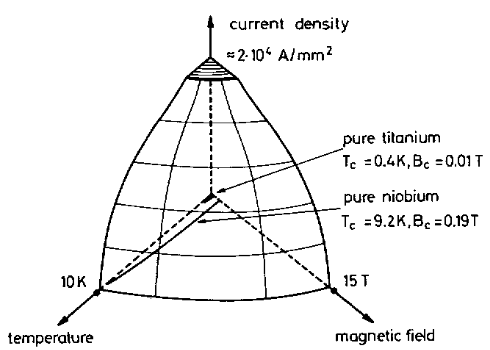
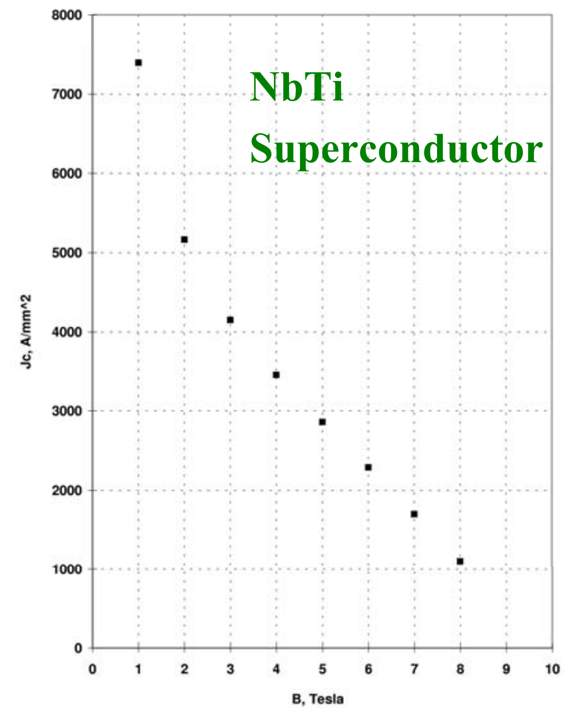
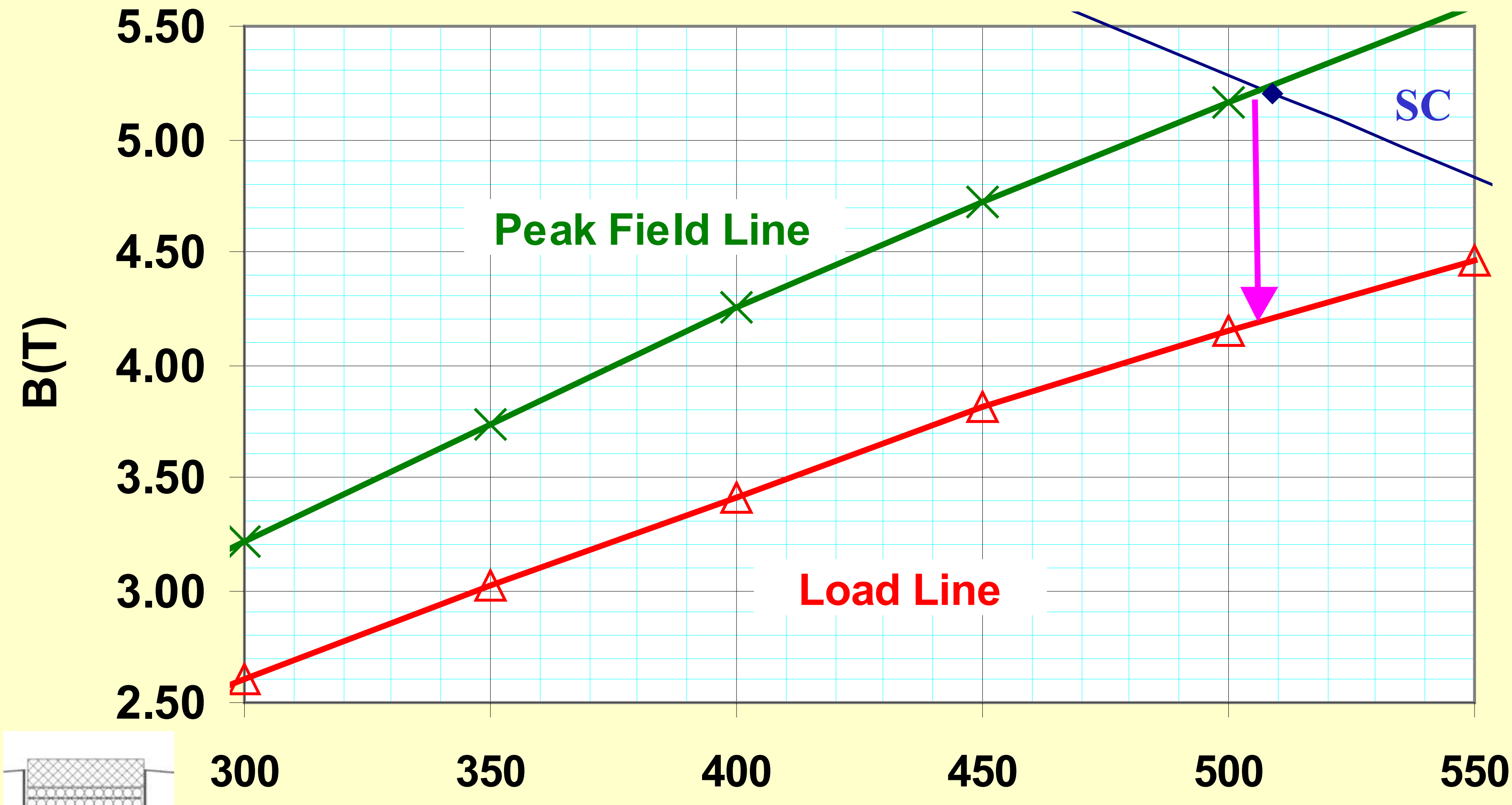
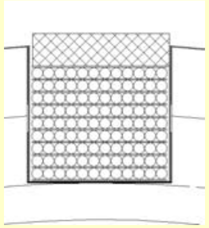


Figure 2.11: Sketch of the critical surface of NbTi. Also indicated are the regions where pure niobium and pure titanium are superconducting. The critical surface has been truncated in the regime of very low temperatures and fields where only sparse data are available.



Load line

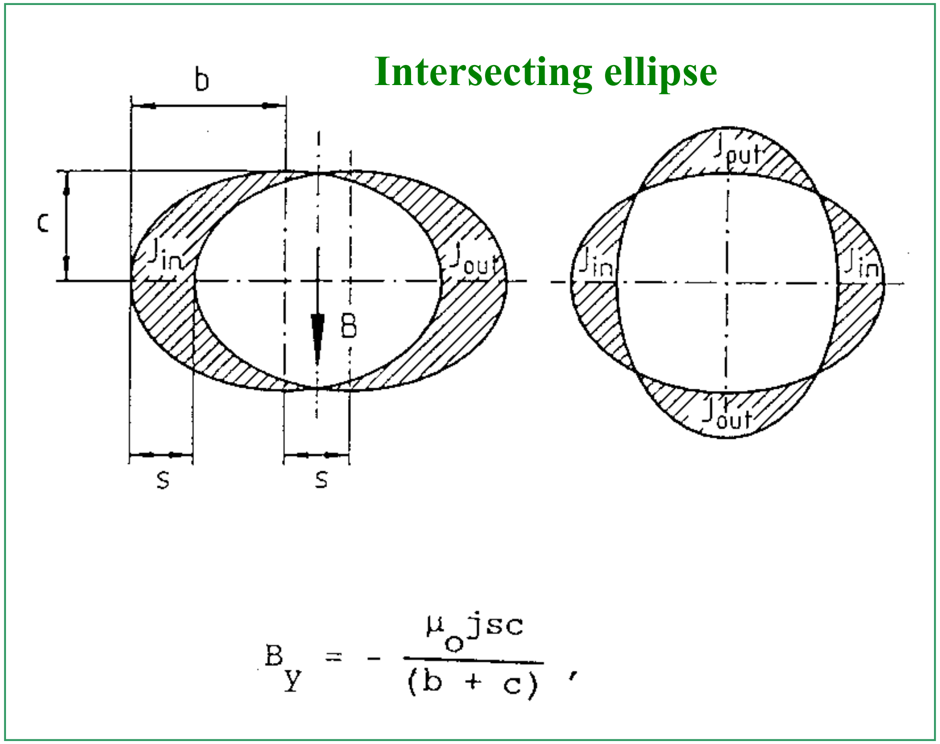

5.50
5.00
4.50
4.00
3.50
3.00
2.50
B(T)
SC
Peak Field Line
Load Line
300
350
400
450
500
550
I(A)

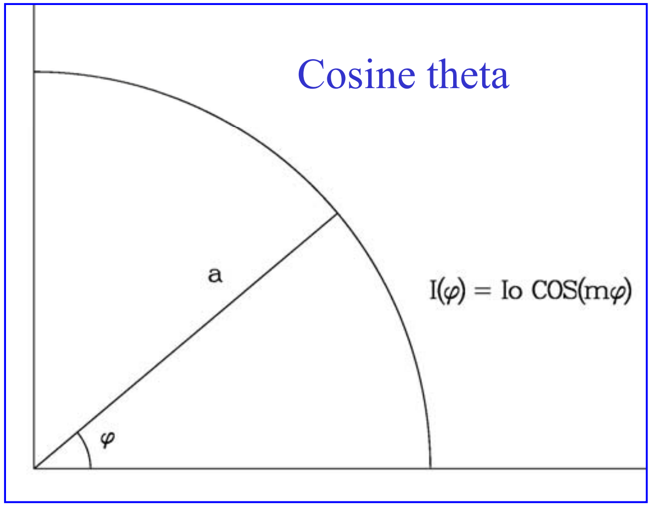


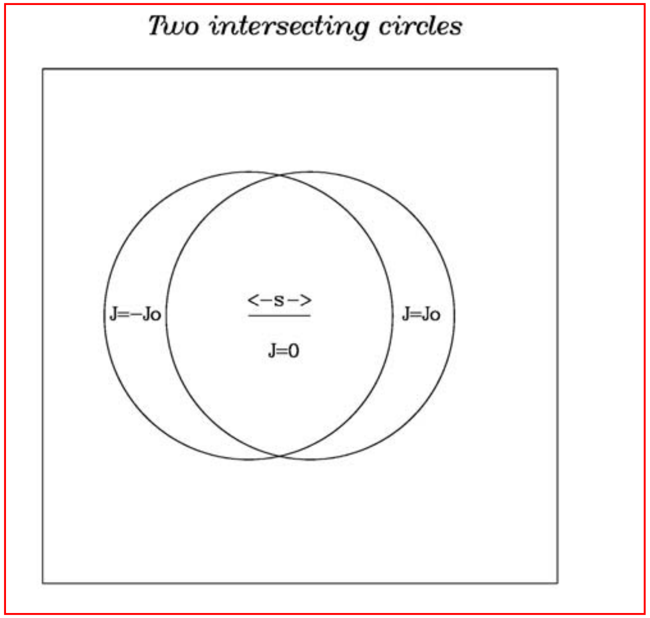
Designs for Ideal Fields

Here are some current distributions, those 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.







Dipole from Intersecting Circles

Home Assignment:

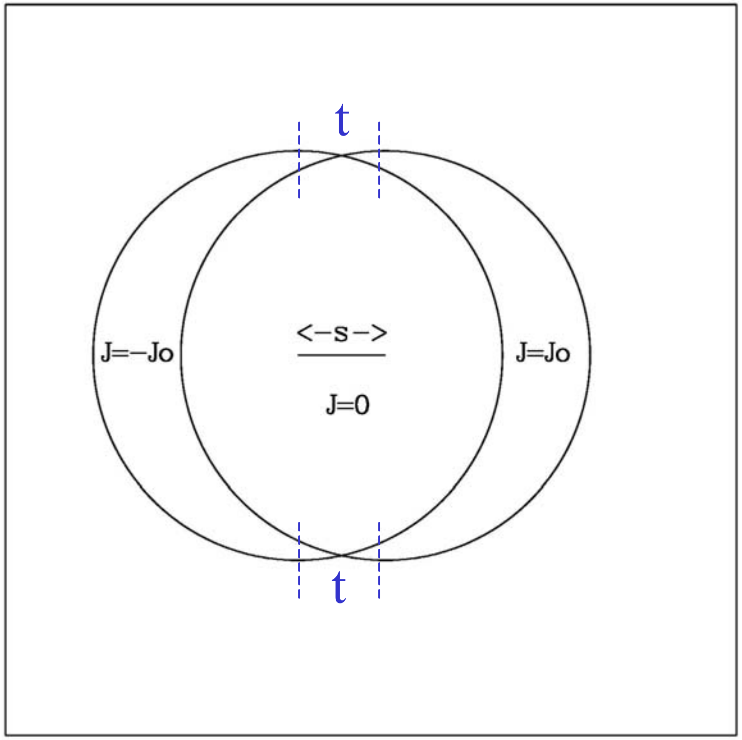
Prove, without using complex variables, that the geometry shown on the right produces a pure dipole field in the current free region. (I.I. Rabi, 1984, Rev. Sci. Inst. & Method).

How will the component of 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 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/mm²*.

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}).

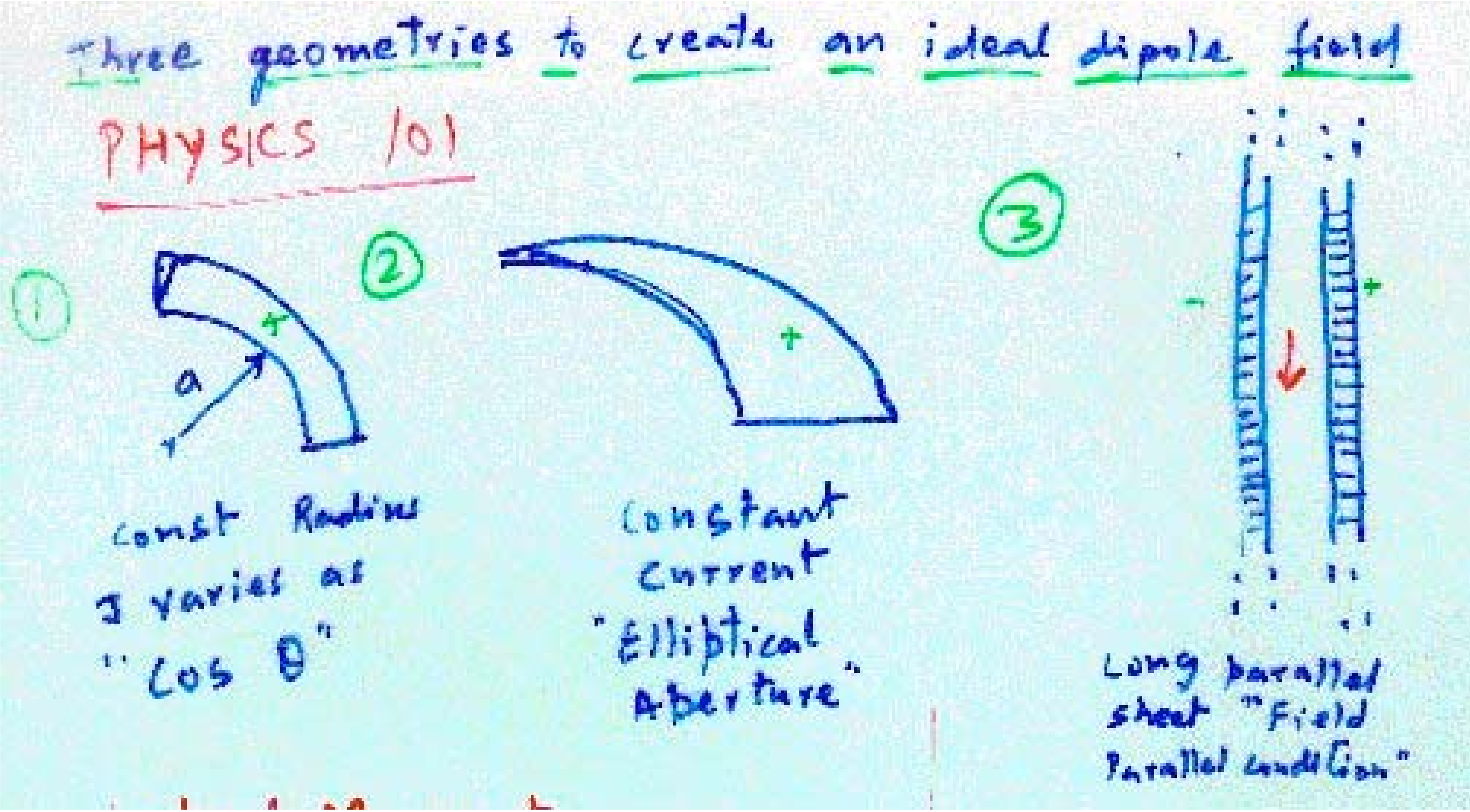
Class Problem: Compute the required conductor with for a 5 T dipole. Assume that the current density in the coil is 500 A/mm^2.

How does the required conductor width varies with aperture?

How does the required conductor volume varies with the aperture?

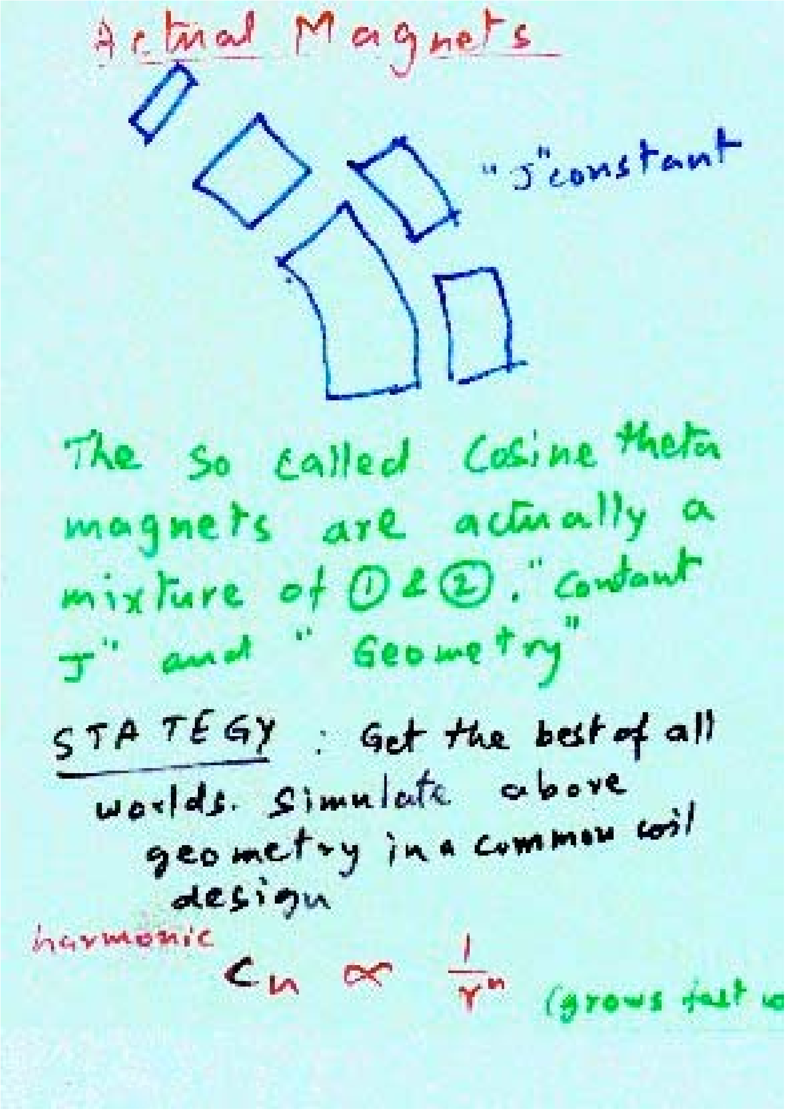
Always check the B-J-T surface of the superconductor, the operating point must stay well within.

Field Quality optimization from 1st Principle



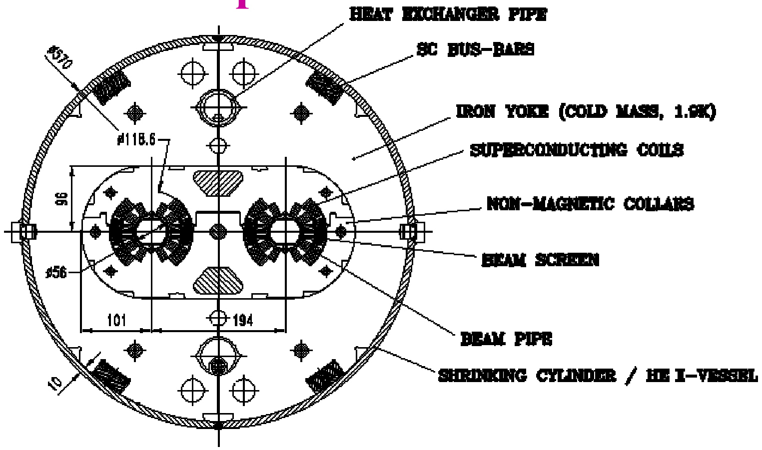
Field Quality optimization from 1st Principle

- Cosine Theta
- Elliptical Coil
- Boundary condition
  - Field Parallel :
    - Conductor dominated,
  - Field Perpendicular :
    - Iron dominated

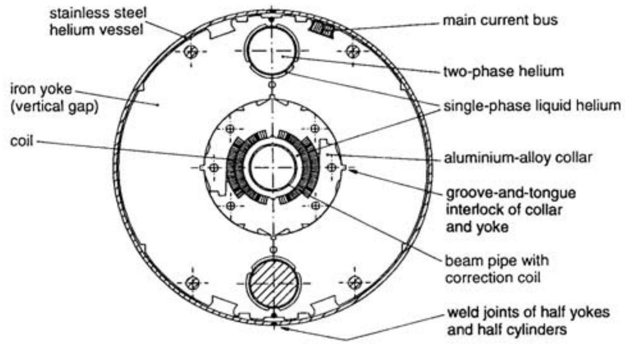


Present Magnet Design and Technology

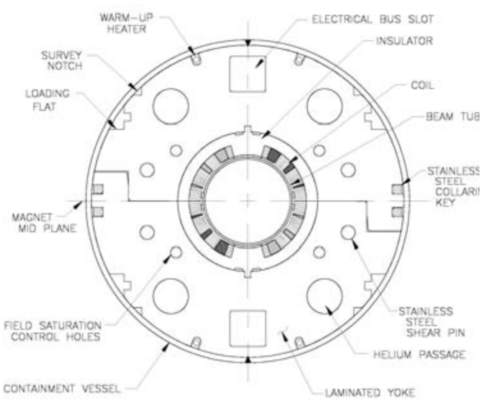
LHC Dipole



HERA Dipole



RHIC Dipole



Tevatron Dipole

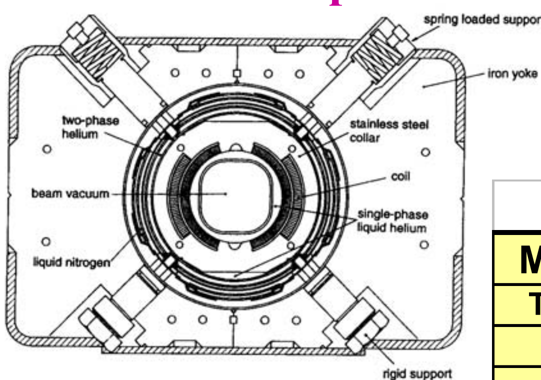


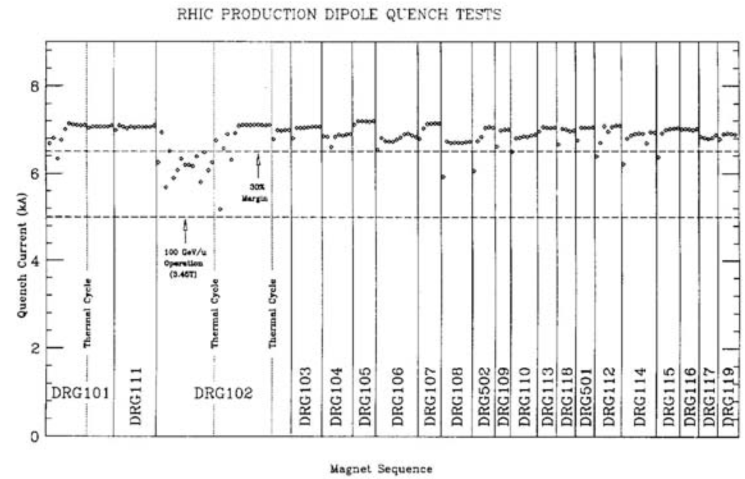
Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979)

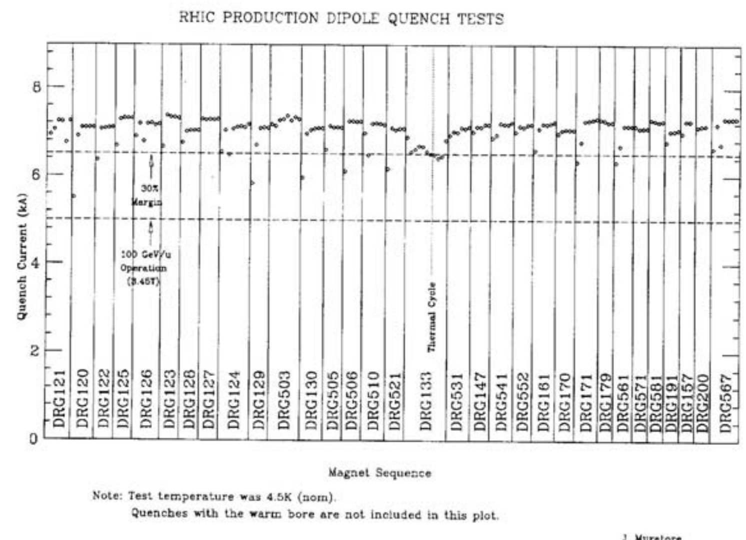
- All magnets use NbTi Superconductor
- All designs use cosine theta coil geometry

	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

Must Allow Comfortable Margin

- In a large series production, there will be some magnets, if not most, that will not be able to reach the ideal field performance (short sample).
- 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.





Quench performance of RHIC magnets

SUMMARY

This was an introduction to the magnet design.

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