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Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Superconducting Magnets for Particle Accelerators

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Outline of the presentation

1. Introduction
2. Importance of Accelerator Magnets
3. Superconductivity
4. Design of Superconducting Magnets
5. Construction of Superconducting Magnets
6. Present scenario and future work

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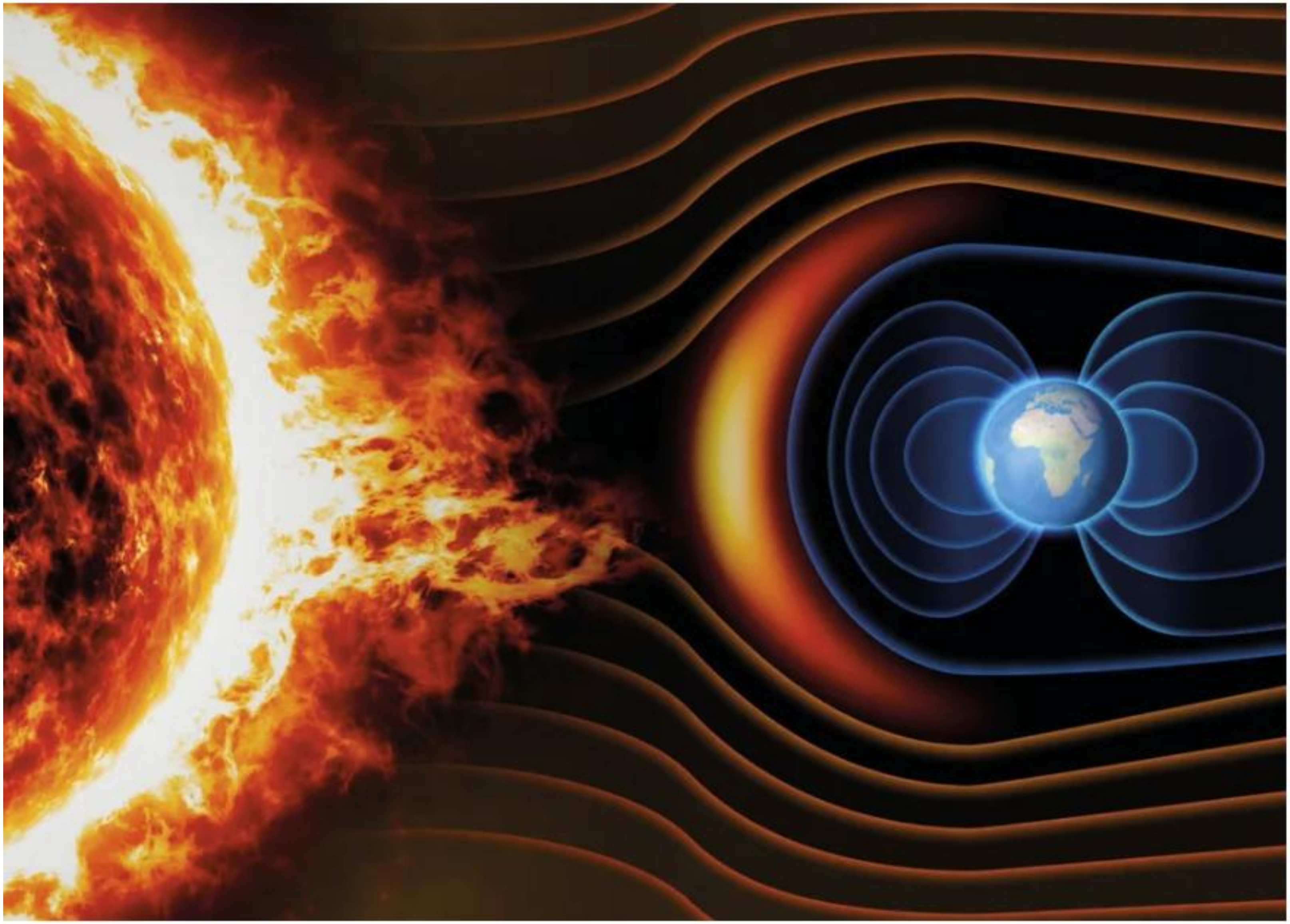
How crucial is the magnetic field!



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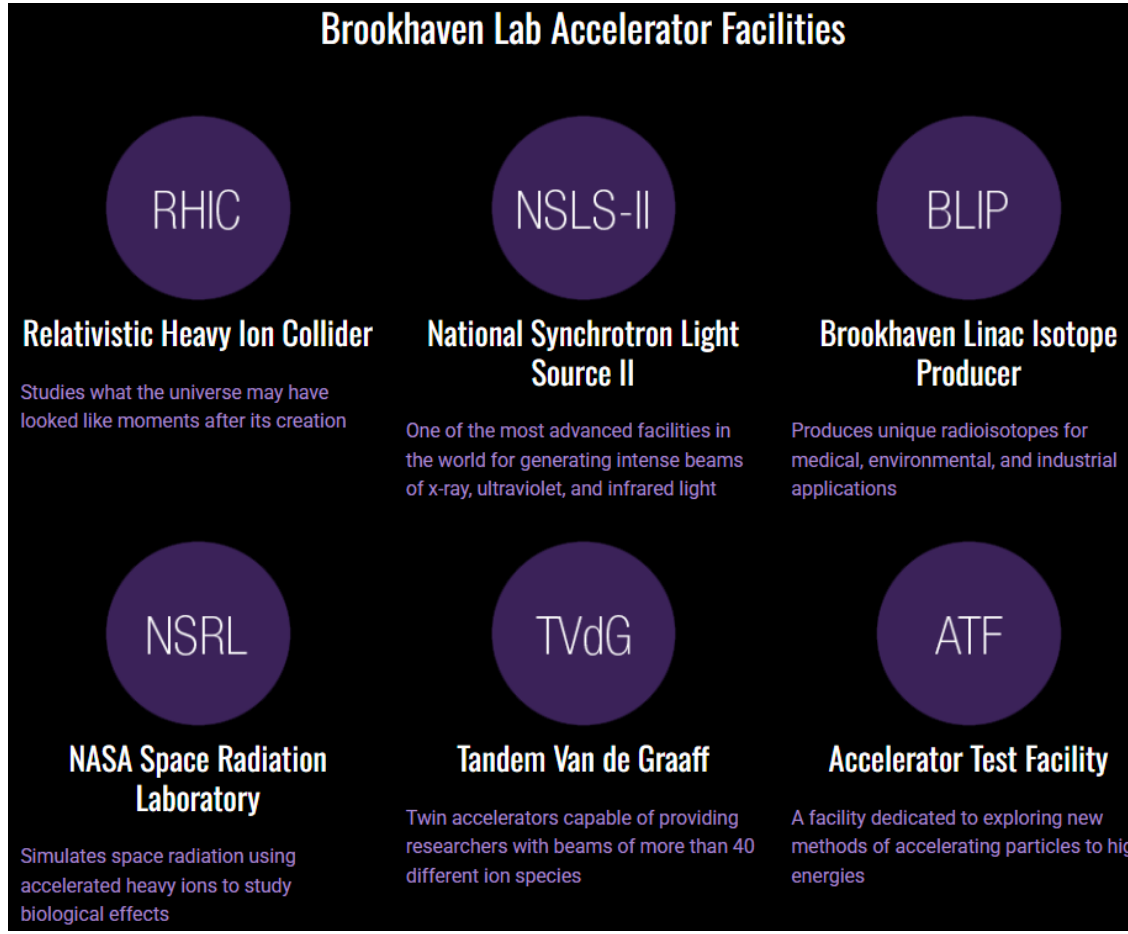
Scales of Magnetic Field

Value	Item
0.1 - 1.0 pT	human brain magnetic field
24 μT	strength of magnetic tape near tape head
31-58 μT	strength of Earth's magnetic field at 0° latitude (on the equator)
0.5 mT	the suggested exposure limit for cardiac pacemakers by American Conference of Governmental Industrial Hygienists (ACGIH)
5 mT	the strength of a typical refrigerator magnet
0.15 T	the magnetic field strength of a sunspot
1 T to 2.4 T	coil gap of a typical loudspeaker magnet
1.25 T	strength of a modern neodymium-iron-boron ($Nd_2Fe_{14}B$) rare earth magnet.
1.5 T to 3 T	strength of medical magnetic resonance imaging systems in practice, experimentally up to 8 T
9.4 T	modern high resolution research magnetic resonance imaging system
11.7 T	field strength of a 500 MHz NMR spectrometer
16 T	strength used to levitate a frog
36.2 T	strongest continuous magnetic field produced by non-superconductive resistive magnet
45 T	strongest continuous magnetic field yet produced in a laboratory (Florida State University's National High Magnetic Field Laboratory in Tallahassee, USA)
100.75 T	strongest (pulsed) magnetic field yet obtained non-destructively in a laboratory (National High Magnetic Field Laboratory, Los Alamos National Laboratory, USA)
730 T	strongest pulsed magnetic field yet obtained in a laboratory, destroying the used equipment, but not the laboratory itself (Institute for Solid State Physics, Tokyo)
2.8 kT	strongest (pulsed) magnetic field ever obtained (with explosives) in a laboratory (VNIIEF in Sarov, Russia, 1998)
1 to 100 MT	strength of a neutron star
0.1 to 100 GT	strength of a magnetar

What are particle Accelerators?

- A **particle accelerator** is a machine that uses electric and magnetic fields to speed up charged particles, such as protons or electrons, to very high energies.
- These high-energy beams are used for scientific research, like smashing particles together to **study fundamental physics**, and for **industrial, medical, and commercial applications**, including **cancer therapy**, **food sterilization,** and the **manufacturing of computer chips.**



All these at Long Island !

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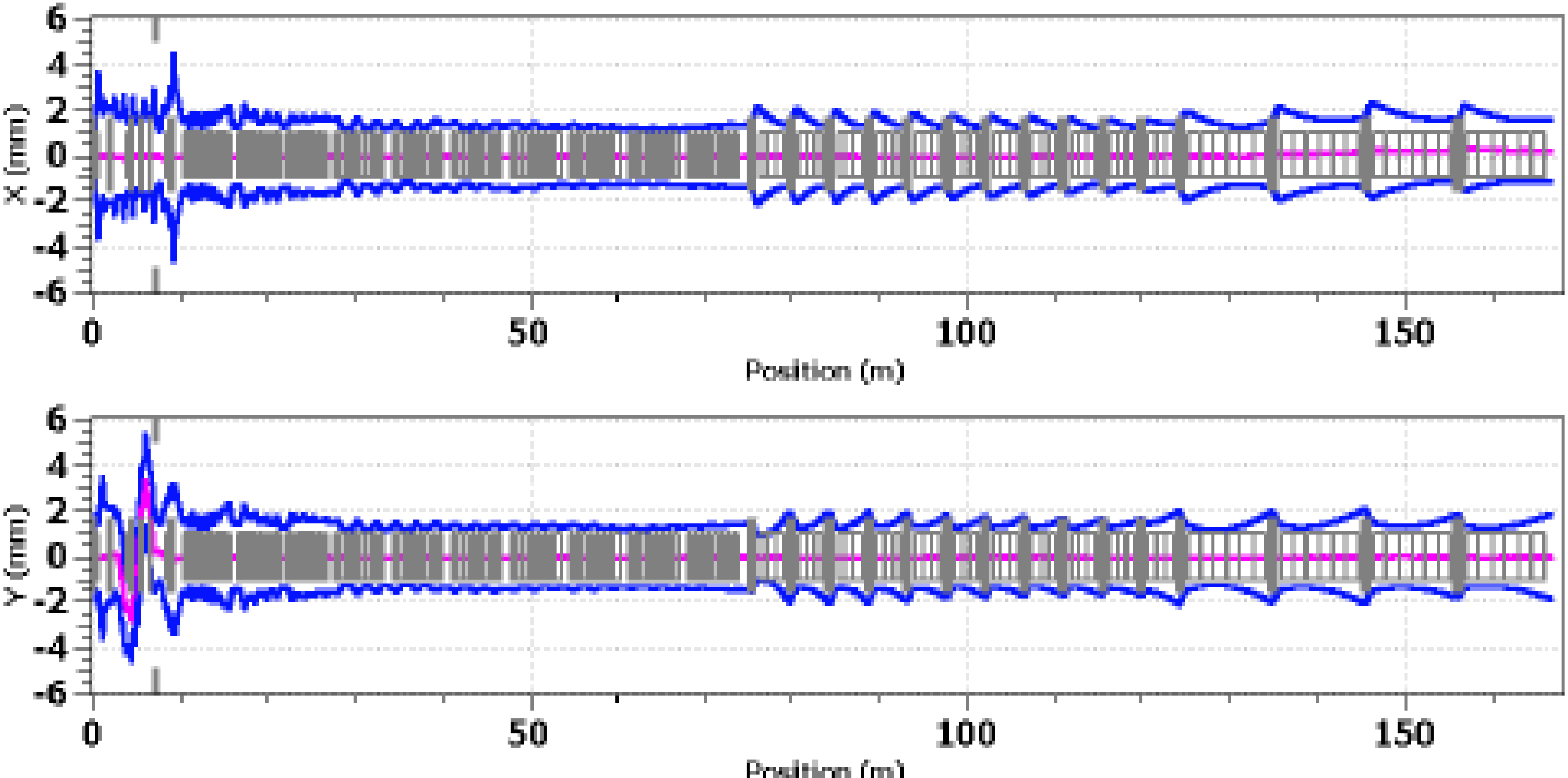
Typical Linear Particle Accelerator

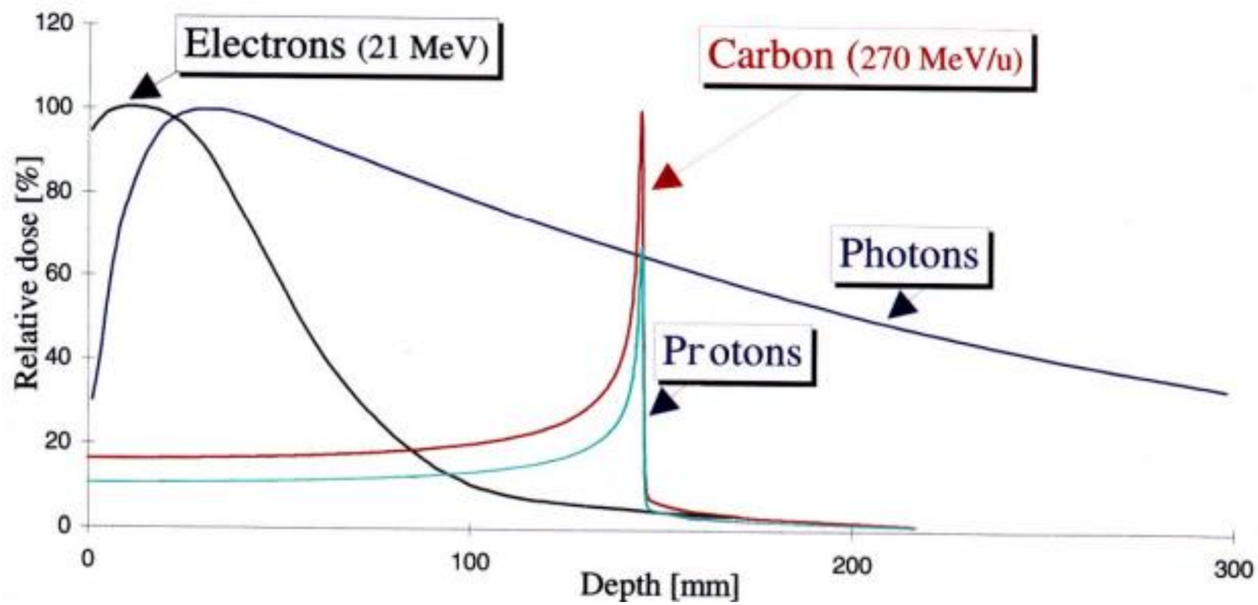
Ion Source → LEBT → RFQ → MEBT → LINAC →

$$F = q\,(\overrightarrow{E} + \vec{v} \times \overrightarrow{B})$$



Particle Accelerators in Medical sciences

Cancer treatment using Hadron Therapy

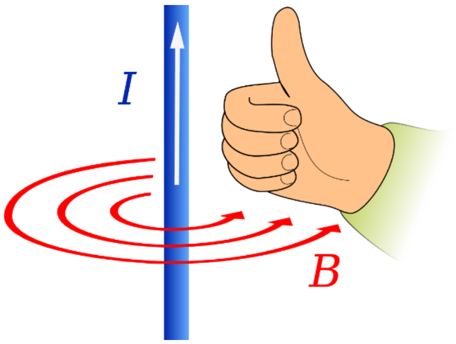


Radiopharmaceuticals

- **Diagnostic**:
    - **FDG:** Used in PET scans for cancer, heart, and brain disease diagnosis.
    - Gallium-68 (Ga-68): Used in imaging for neuroendocrine tumors.
- **Therapeutic**:
    - Lutetium-177 (Lu-177): Used in targeted therapies for cancers like prostate and neuroendocrine tumors.
    - Actinium-225 (Ac-225): A potent alpha-emitter used in targeted alpha therapy for certain cancers, such as acute myeloid leukemia and metastatic castration-resistant prostate cancer.
    - Astatine-211 (At-211): Another alpha-emitter being developed for targeted cancer therapy, particularly for blood-borne cancers like leukemia and lymphoma.

Magnetic Field

1. A magnetic field is a vector field that describes the magnetic influence of electrical currents and magnetized materials.



2. Magnetic field is omnipresent. From human brain to neutron star; magnetic field ranges from as low as pT to 100 MT neutron star.

3. ***Hans Christian Oersted*** proved electric current produces magnetic field in 1820, thereafter ***Andre-Marie Ampere*** formulated mathematical form to represent the magnetic forces between current carrying conductors in 1826.

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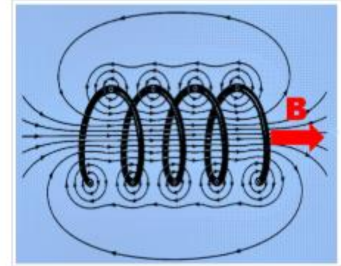
Magnets for MRI

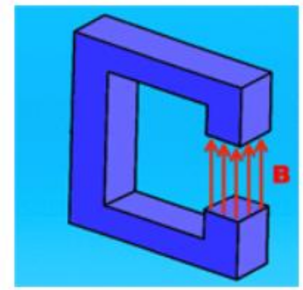
GE Signa 1.5T superconducting scanner



Magnetic field created by solenoid

Closed bore (cylindrical) configuration with superconducting solenoidal design. The coils are bathed in liquid helium allowing a stable, homogeneous field to be created, typically 1T and higher.

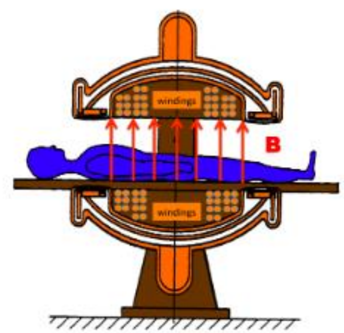
Fujifilm Aperto 0.4T permanent magnet scanner



C-shaped permanent magnet

Most **open bore** scanners utilize permanent magnets in a C-shaped or horseshoe configuration. These operate at field strengths typically ranging from 0.064T to 1.0T.

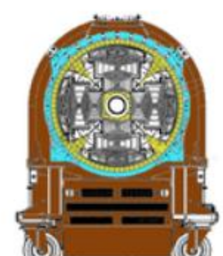
Fujifilm Oasis 1.2T HFO superconducting scanner



Dipolar electromagnet design

The third design is a **dipolar electromagnet** configuration with coils on either side of the patient. These coils can be superconductive or resistive and range from 0.5T to 1.2T.

Promaxo 0.064T single-sided scanner



Conical Hallbach array of rare-earth magnets (yellow)

Very low field scanners utilize arrays of small permanent rare-earth magnets in a **Hallbach configuration**. This reduces fringe fields and permits a single-sided magnetic field.

[MR magnet types - Questions and Answers in MRI]

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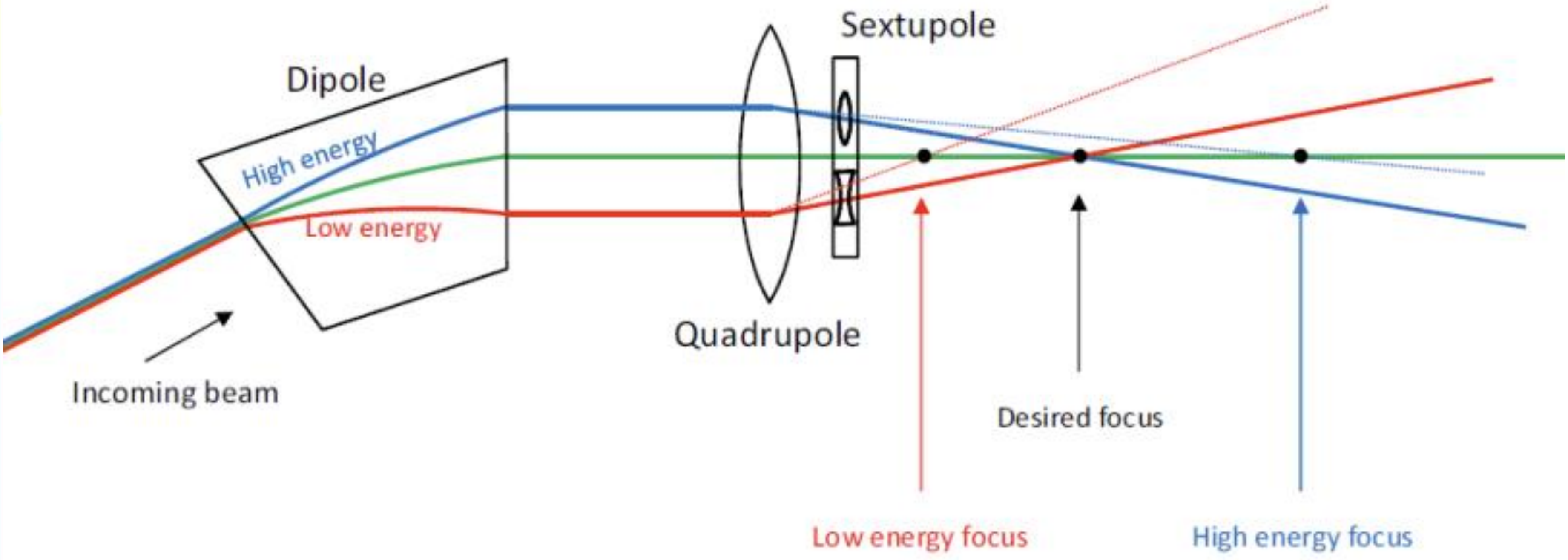
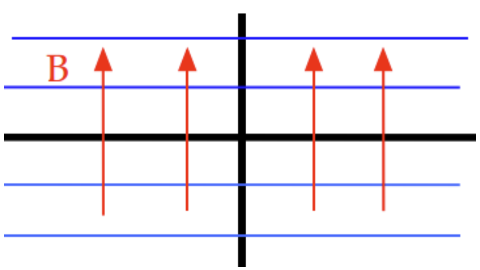
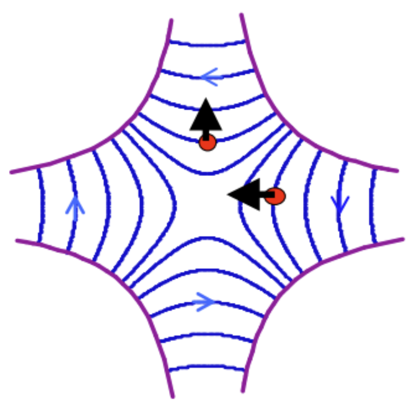
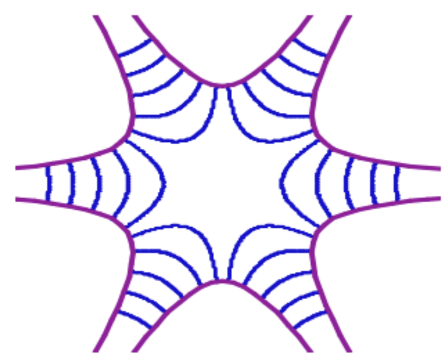
Typical scenario in a particle Accelerator









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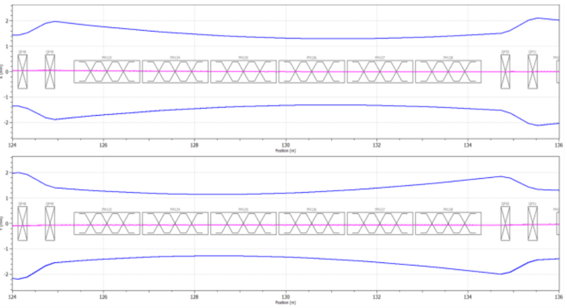
Development cycle of Accelerator Magnet

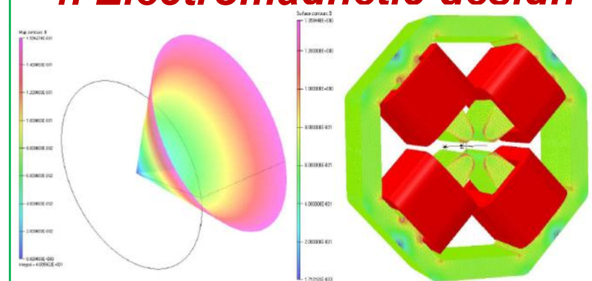
1. Beam Dynamics Design

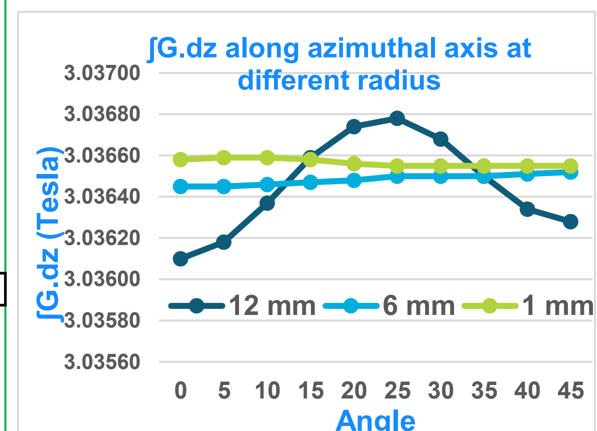


2. Drawing Functional Requirement Specification Application Basic physics requirement

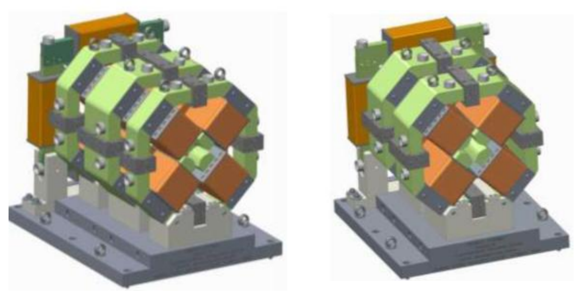
3. Drawing Technical Requirement Specification Interface Specifications Limitations on size/power consumption Acceptance criteria

4. Electromagnetic design



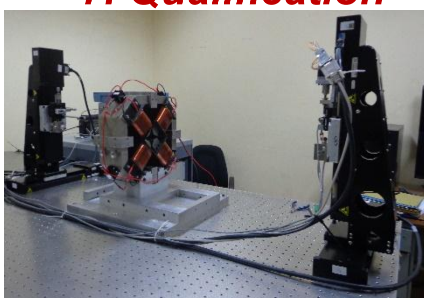


5. Engineering design

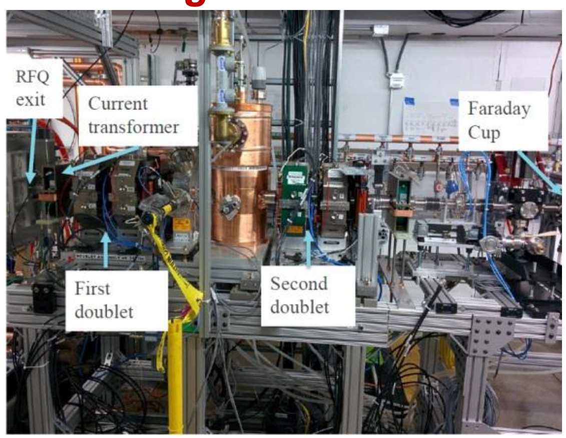


6. Series Fabrication

7. Qualification



8. Integration in Beam



Beam Line Magnets in Particle Accelerators

Transport Line

a. Quadrupole Magnet
b. Solenoid Magnets
c. Dipole magnets
d. Sextupole Magnets
e. Kicker magnets

Accelerator

a. Quadrupole Magnet
b. Solenoid Magnets
c. Dipole magnets
d. Sextupole Magnets

Special magnets

a. Undulators
b. Wigglers
c. Septum

Magnet Technology
(Realization of Magnets)

- ❑ Permanent Magnets
- ❑ Electromagnets : NC/SC

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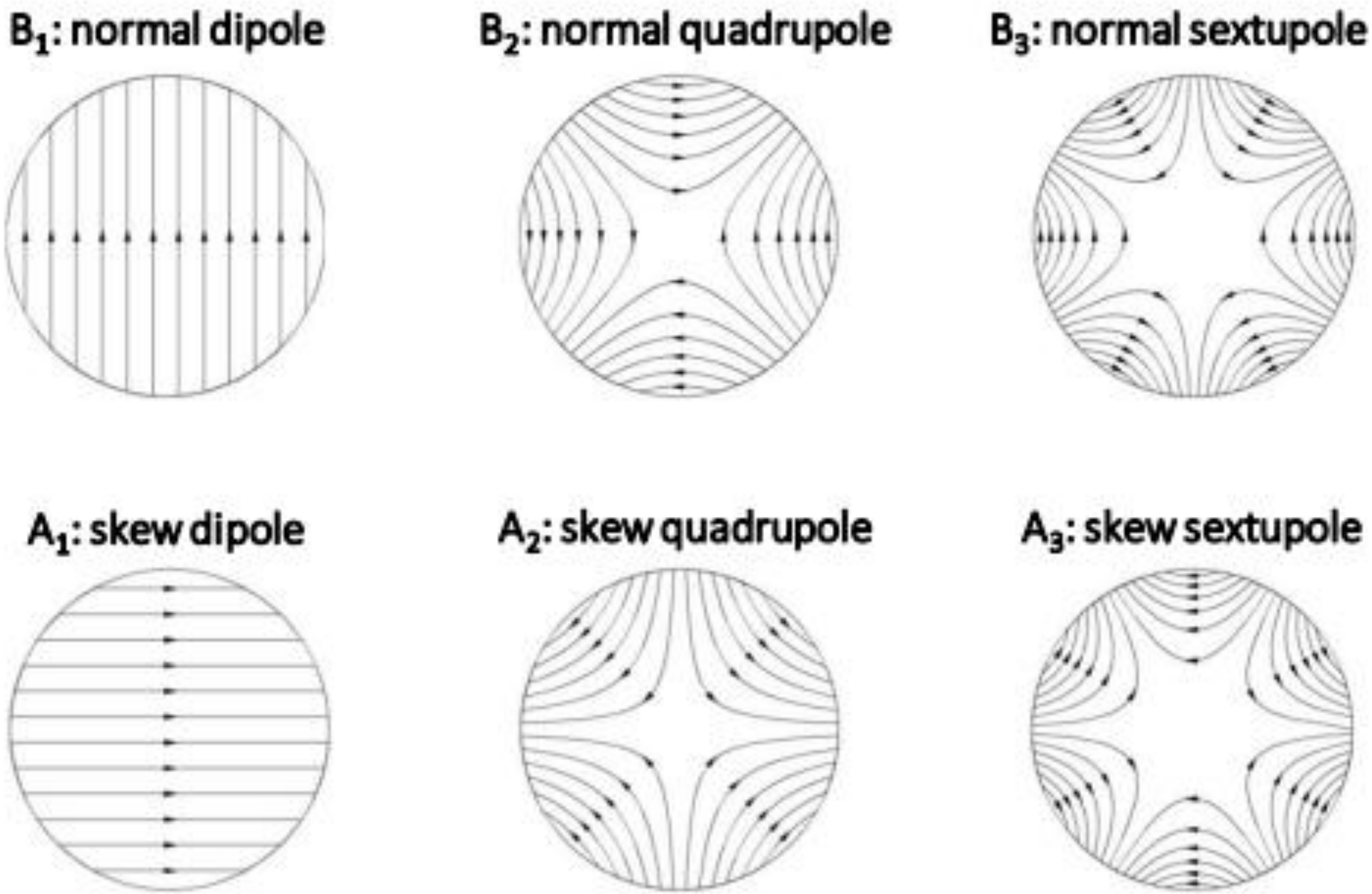
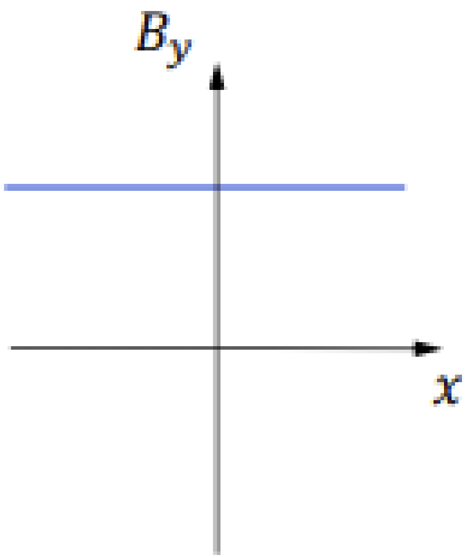
Field distribution in multi-pole magnets

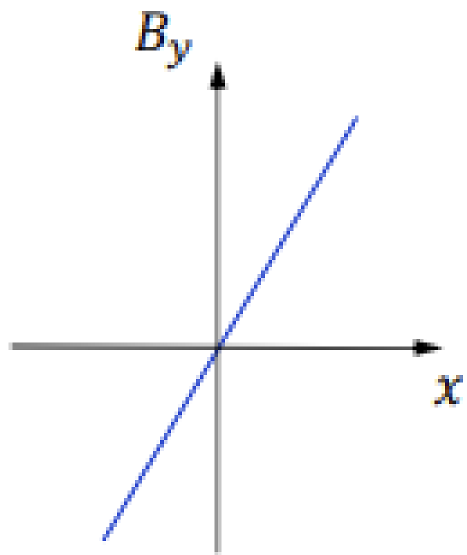


Field profile in horizontal axis

$$B_y(x) = \sum_{n=1}^{\infty} B_n \left(\frac{x}{R}\right)^{n-1} = B_1 + B_2\frac{x}{R} + B_3\frac{x^2}{R^2} + \cdots$$

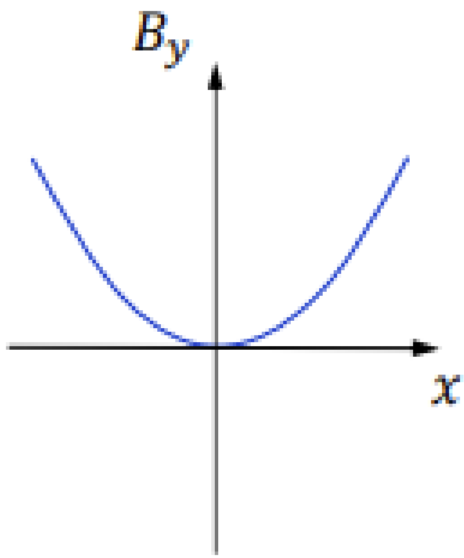


B_1: dipole



B_2: quadrupole

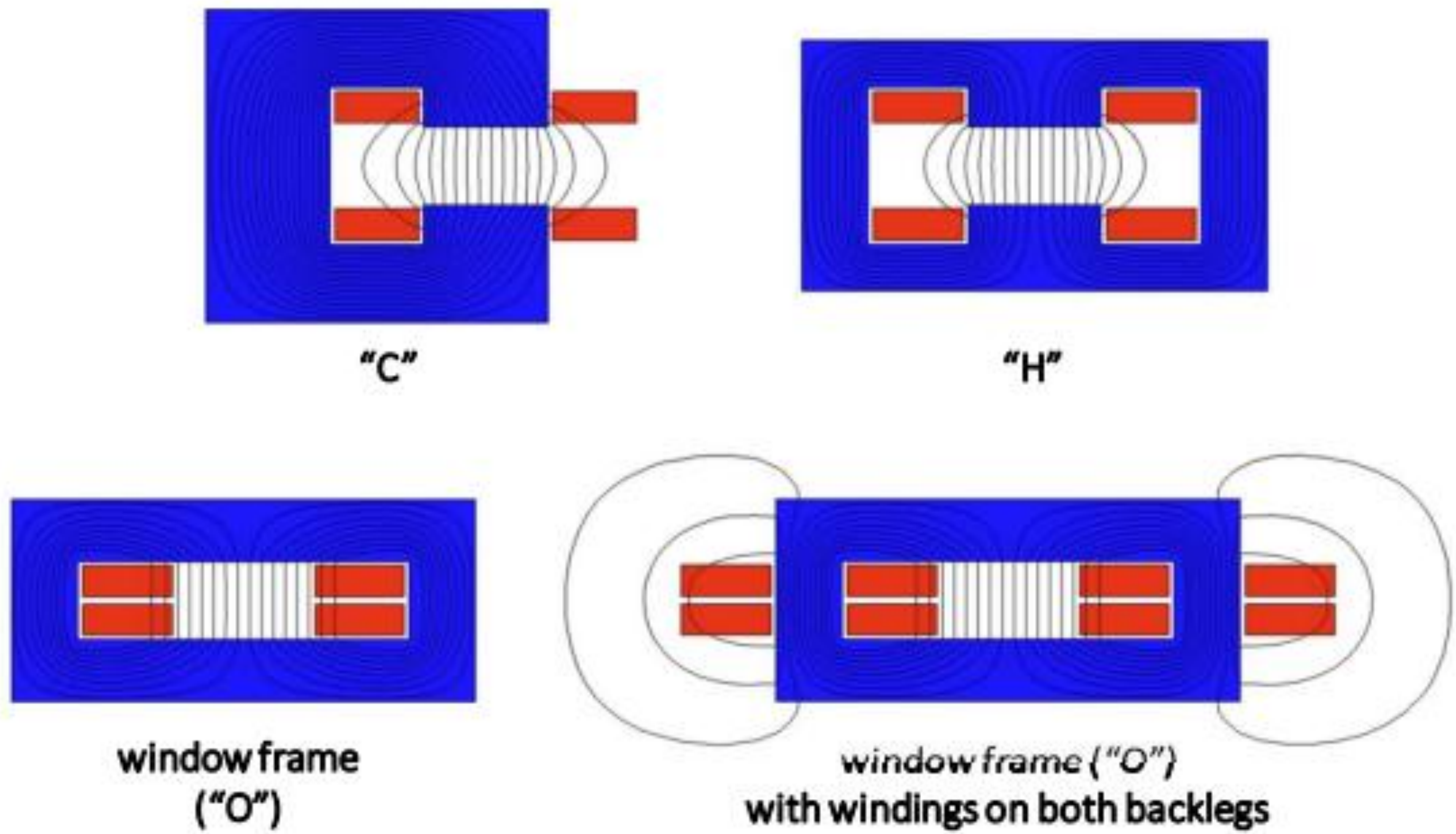
$$G = \frac{B_2}{R} = \frac{\partial B_y}{\partial x}$$



B_3: sextupole

$$B'' = \frac{2B_3}{R^2}$$

Availability of options (example of normal conducting dipole magnet)



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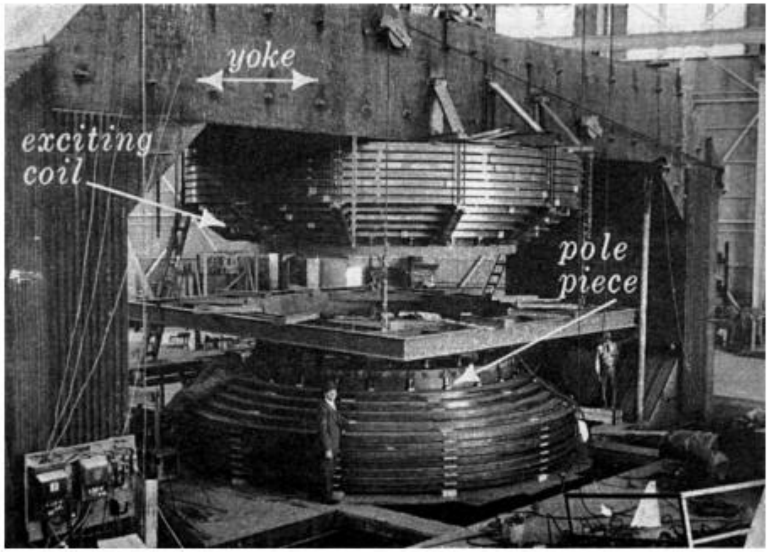
Magnet Technology (Realization of Magnets)

- ❑Permanent Magnets
- ❑Electromagnets
- ❑Iron Dominated
- ❑Coil Dominated
- ❑Resistive
- ❑Superconducting
- ❑Static
- ❑Cycled/ramped/slow
- ❑Fast pulsed



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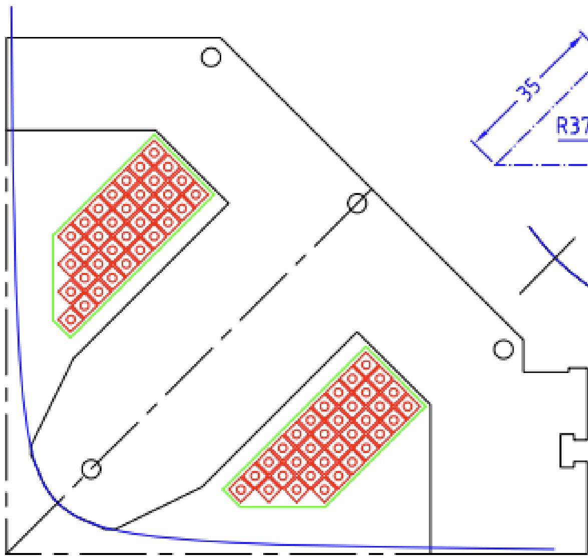
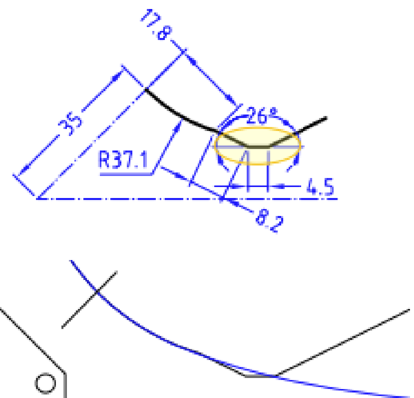
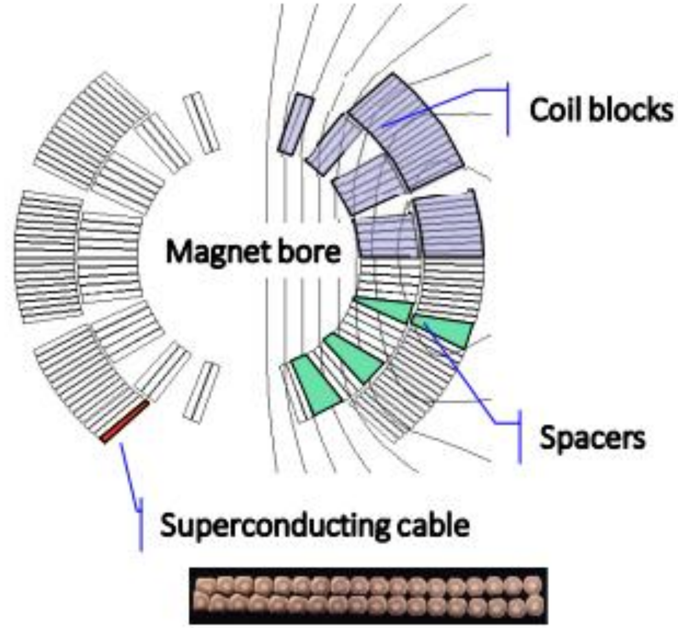
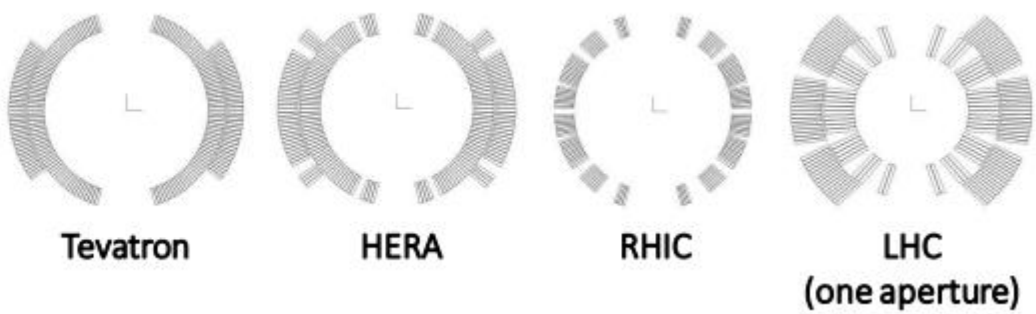
Iron Dominated versus Coil Dominated magnets









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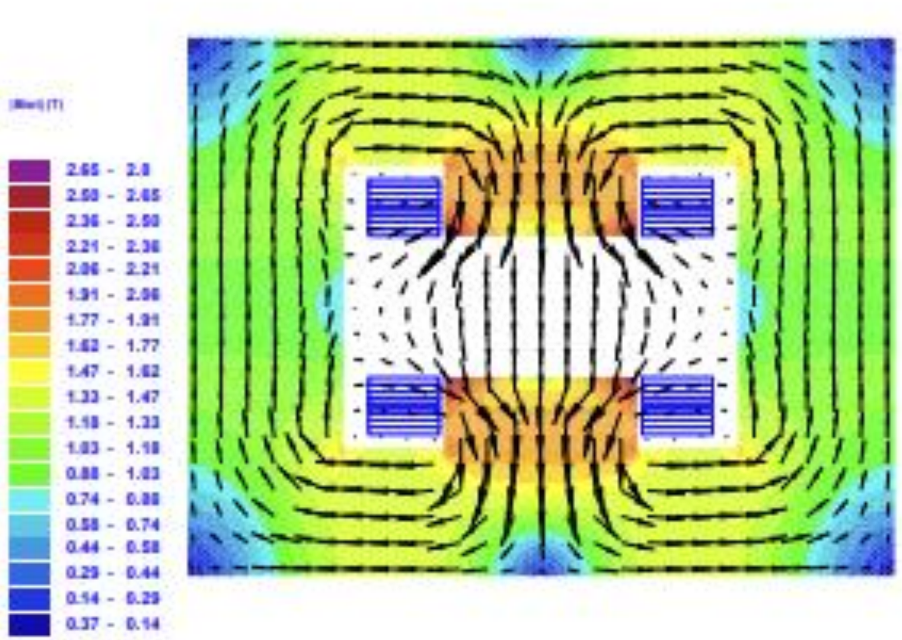
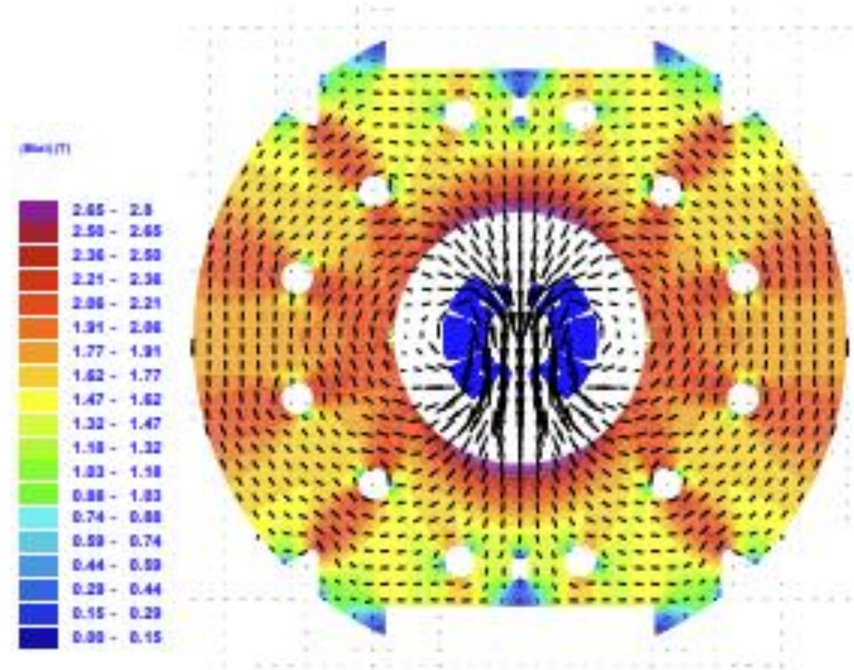
Normal conducting versus Superconducting





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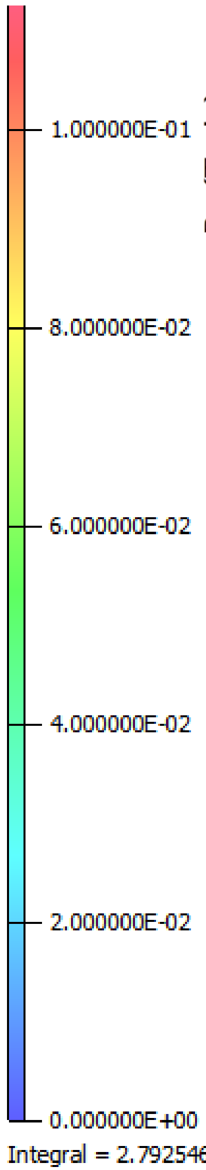
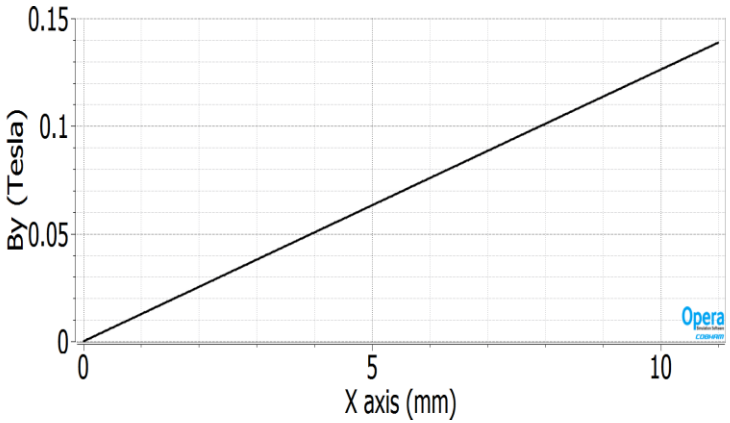
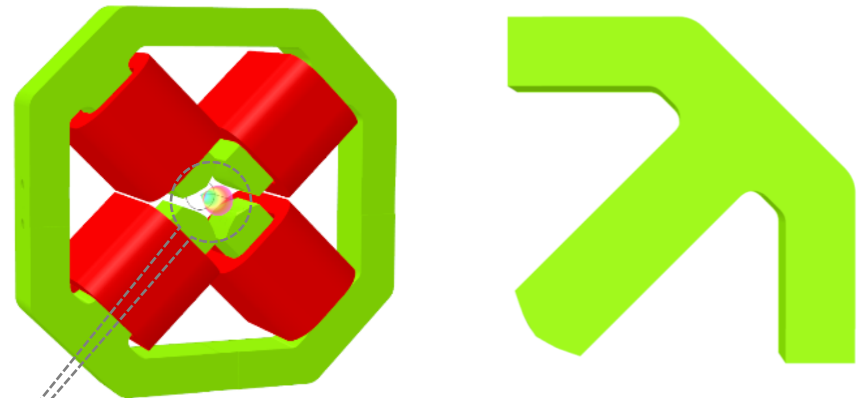
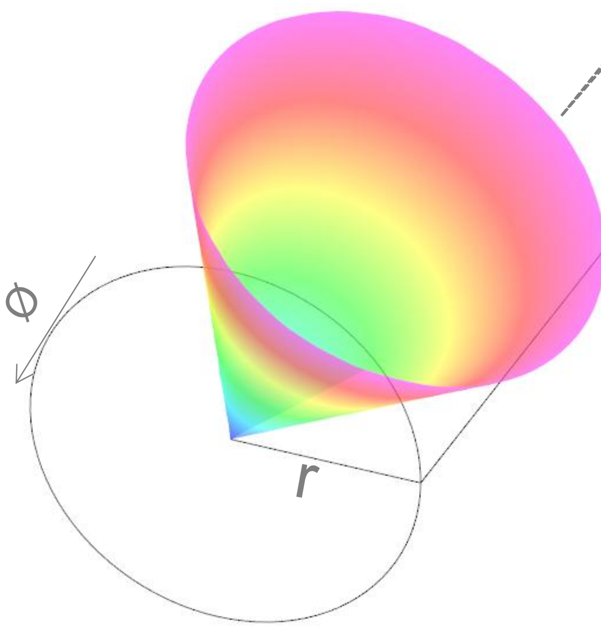
Magnetic profile of Quadrupole Magnet









$$B_x = Gy$$

$$B_y = -Gx$$

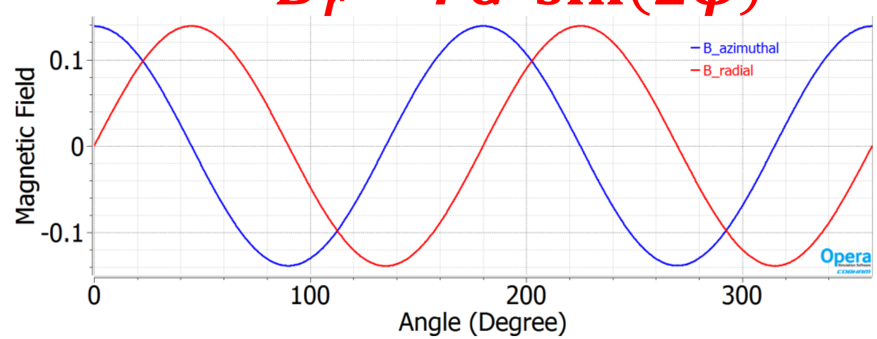
$$|B| = G\sqrt{(x^2 + y^2)}$$

Transforming into cylindrical Coordinates

⇩

$$B_\phi = rG\ \cos(2\phi)$$

$$B_r = rG\ \sin(2\phi)$$



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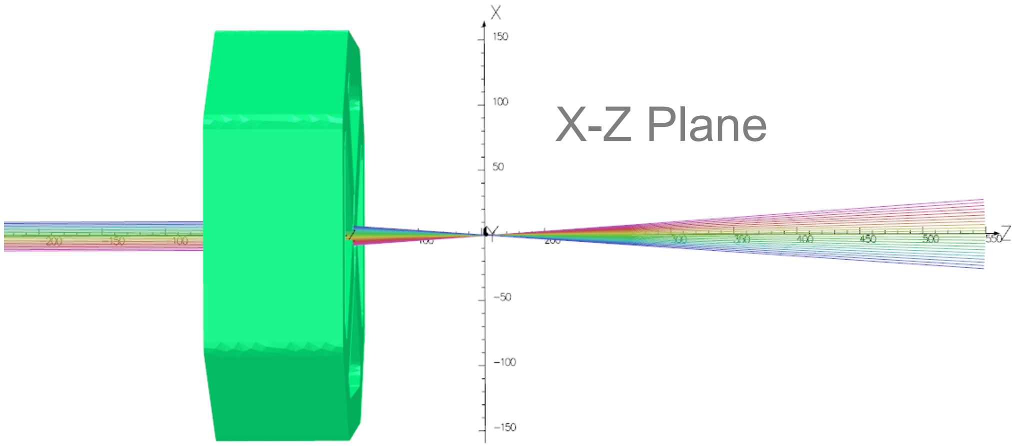
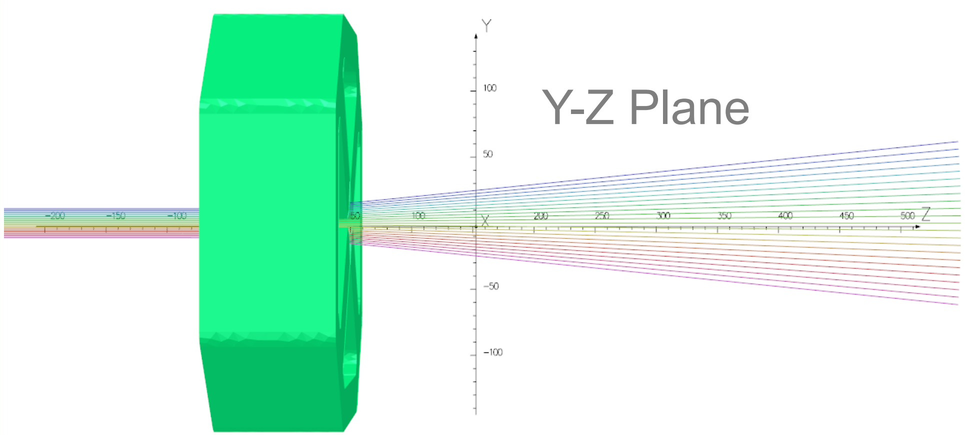
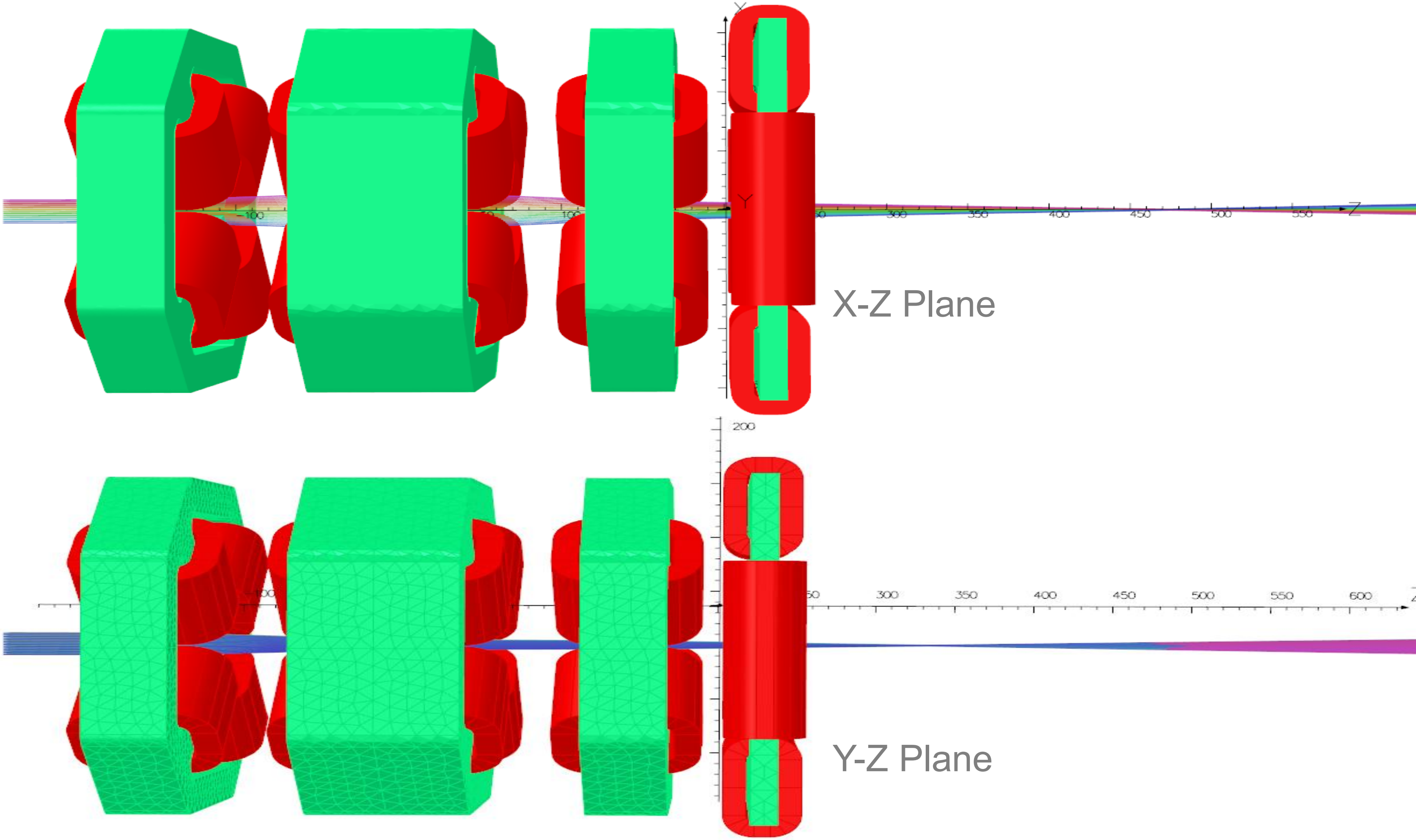
Beam Transmission through A Quadrupole Singlet





1. Quadrupole Singlet focuses in one axis and defocus in other axis.
2. As per nomenclature, Quadrupole which focus in X axis is called " focusing Quadrupole"; one which focuses in Y axis is called "defocusing quadruple"
3. For focusing in both axis simultaneously, for "focusing" and "defocusing" quadruple are required. This configuration is called **"Doublet"**
4. For smooth beam transmission, three Quadrupoles are used where side quads are half and opposite in strength compared to central quad. This is called **Triplet**

Electromagnetic Design of Doublet and Triplet Quadrupole Assembly



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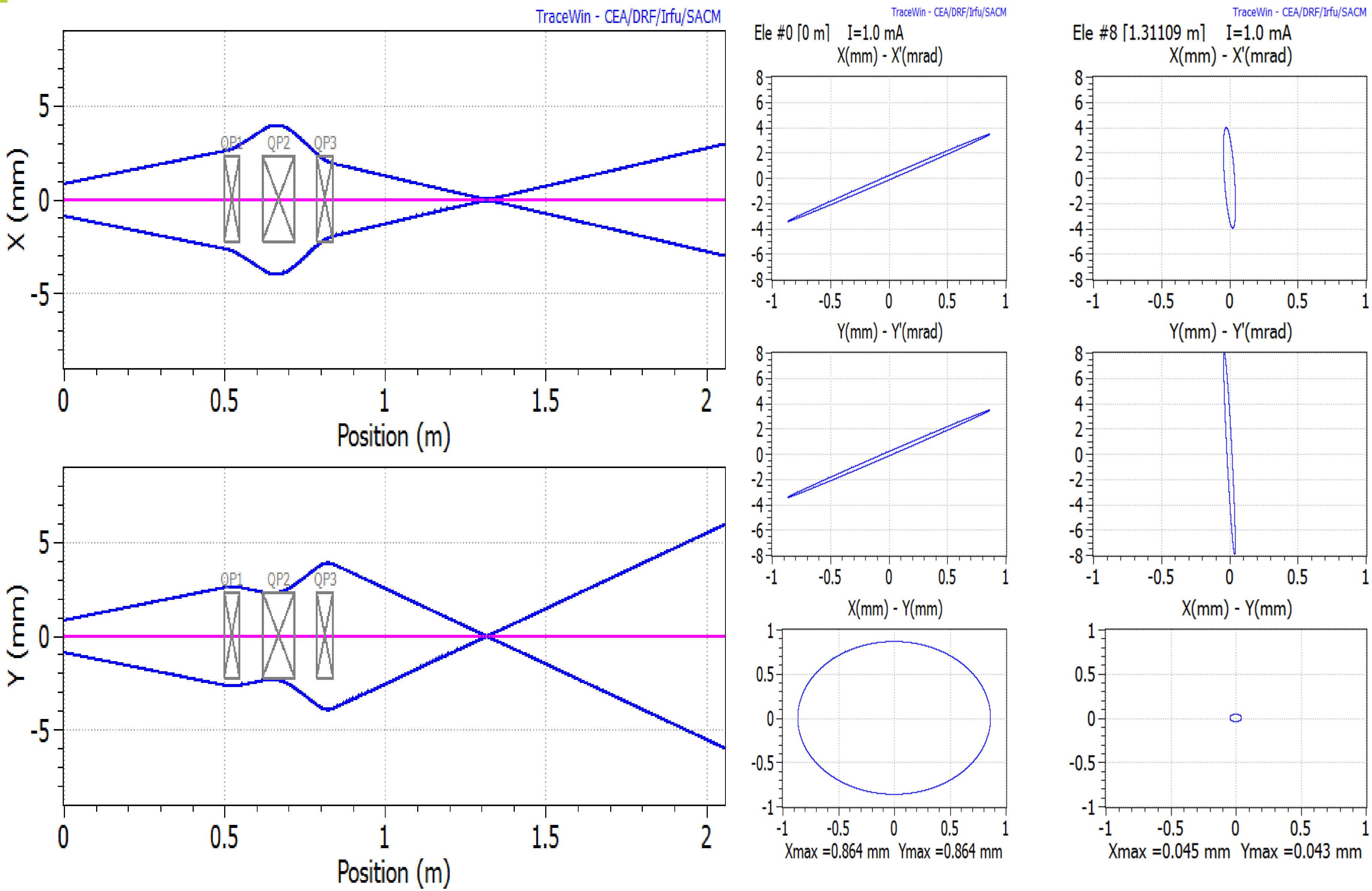
Electromagnetic Design of Doublet and Triplet Quadrupole Assembly



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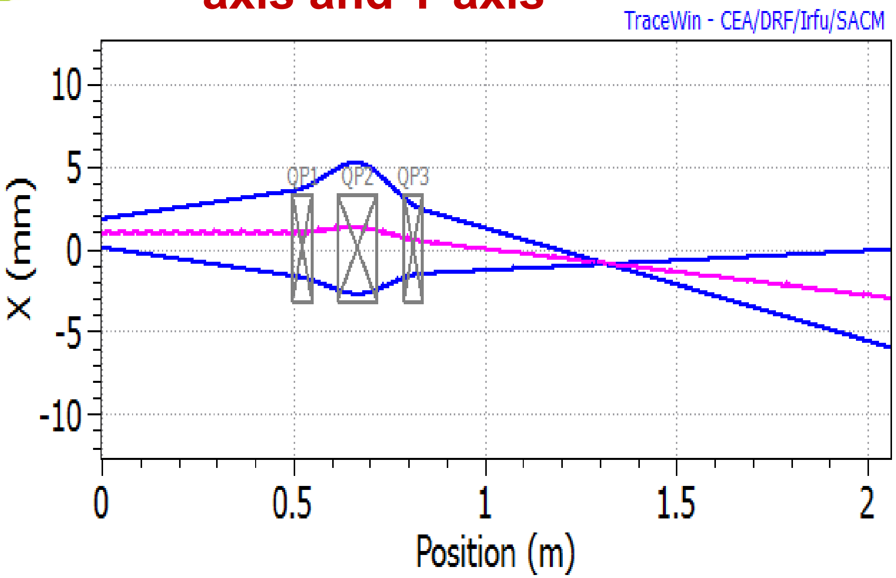
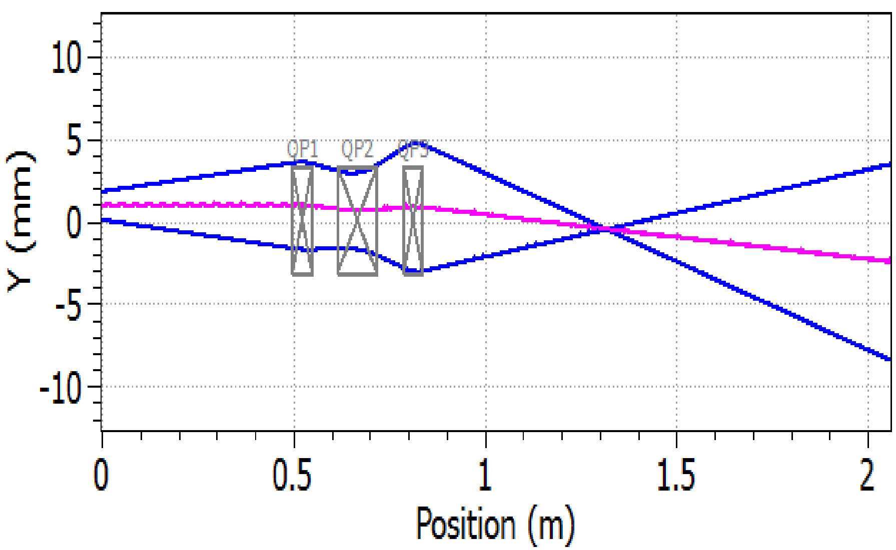
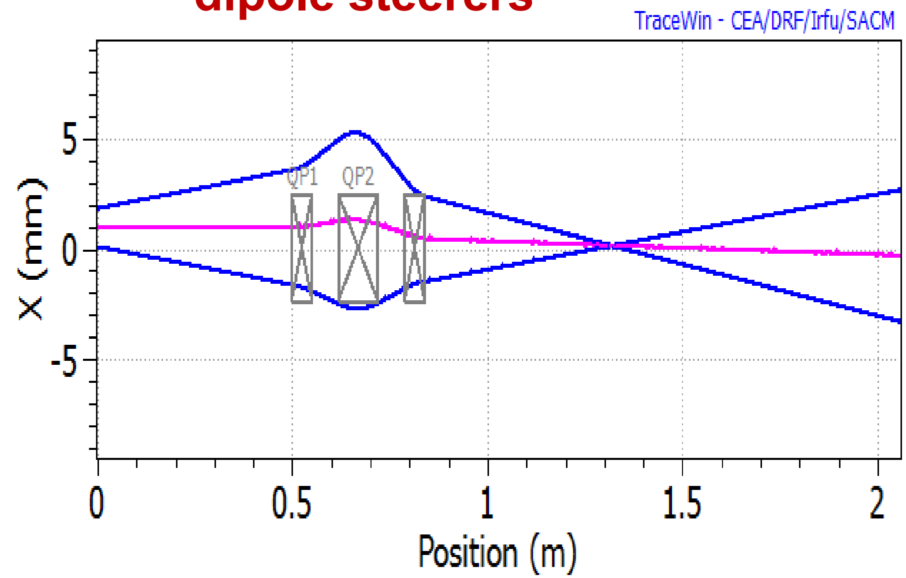
Significance and application of Dipole Correctors

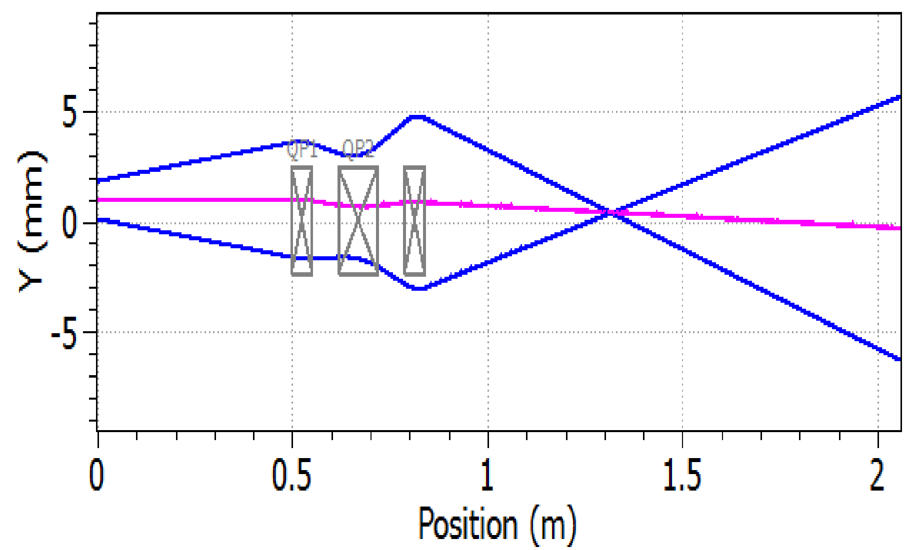
Beam off-orbit by 1 mm in X-axis and Y-axis





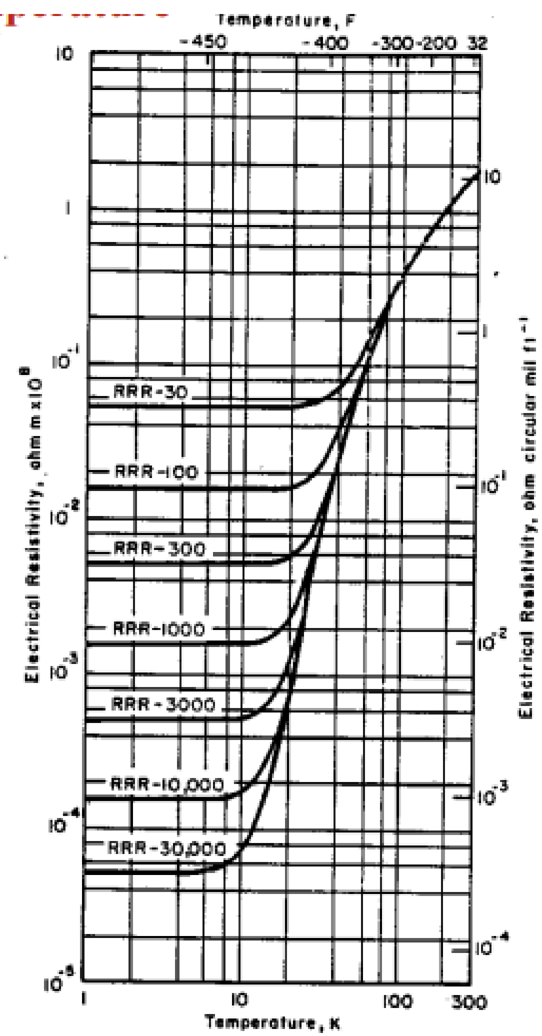
Beam orbit corrected by dipole steerers



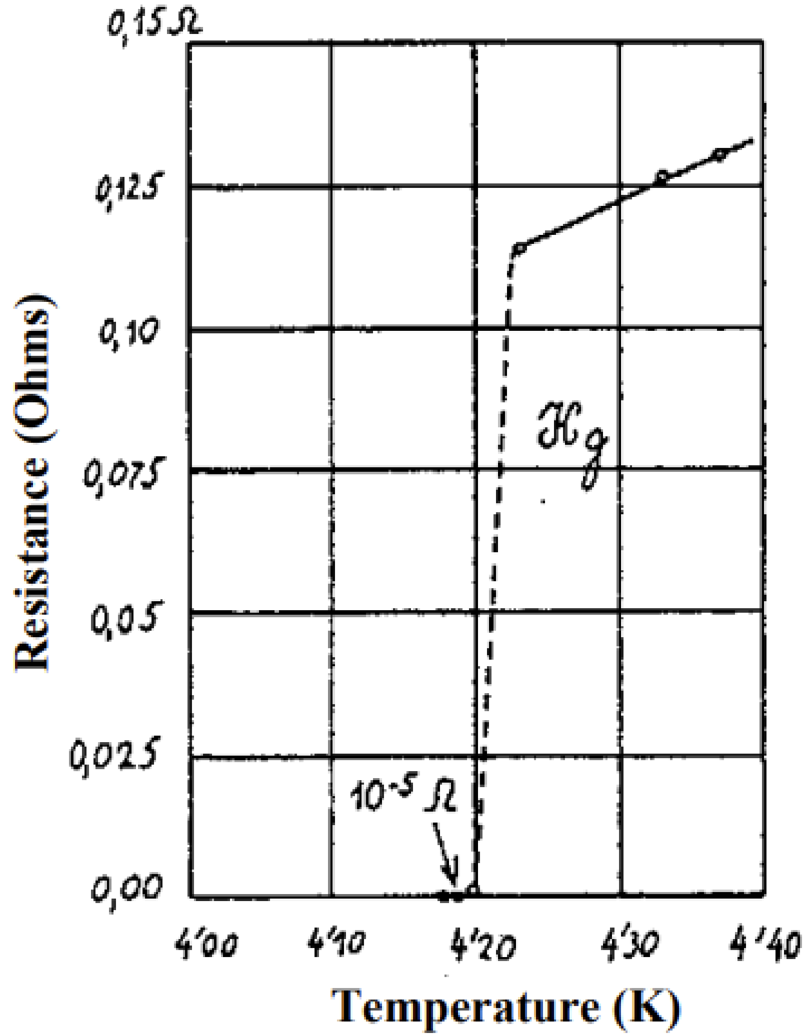


Superconductivity

RRR=ρ(273K)/ρ(~4K)
High purity copper has larger RRR



ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER



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Normal Conductor

Super Conductor

London Penetration Depth and Coherence Length

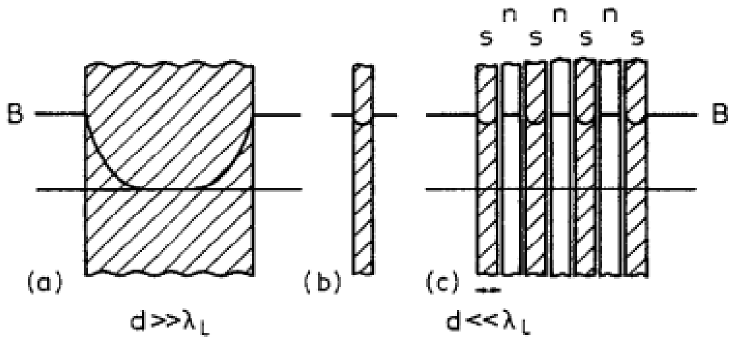


Figure 14: Attenuation of field (a) in a thick slab and (b) in thin sheet. (c) Subdivision of a thick slab into alternating layers of normal and superconducting slices.

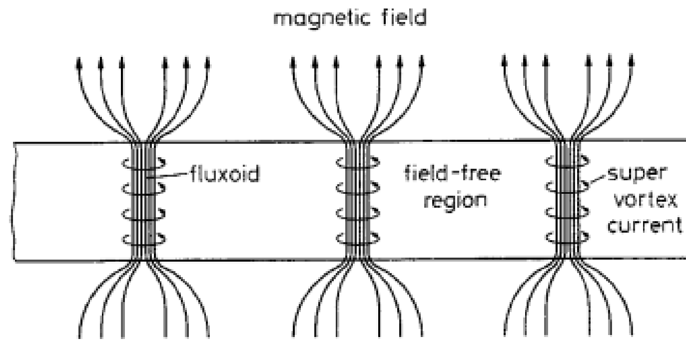
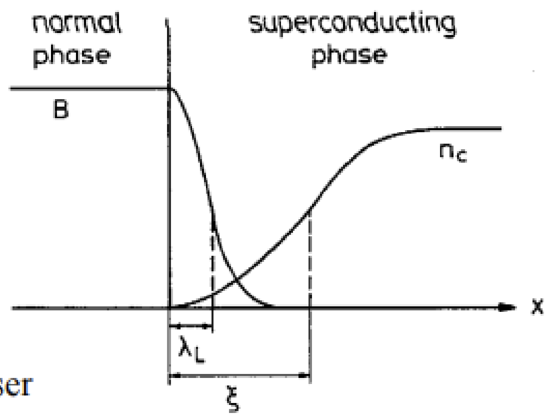


Figure 13: Flux tubes in a type II superconductor.

material	In	Pb	Sn	Nb
λ_L [nm]	24	32	≈ 30	32
ξ [nm]	360	510	≈ 170	39



Courtesy: Schmuser

Figure 15: The decay of the magnetic field and the rise of the Cooper pair density at a normal-superconductor interface.

Ginzburg-Landau Parameter

$$\kappa = \lambda_L/\xi$$

$$\text{type I:} \quad \kappa < 1/\sqrt{2}$$
$$\text{type II:} \quad \kappa > 1/\sqrt{2}.$$

- **"London Penetration Depth" tells how field falls**
- **"Coherence Length" tells how does cooper pair density increases**

Nb is type II superconductor

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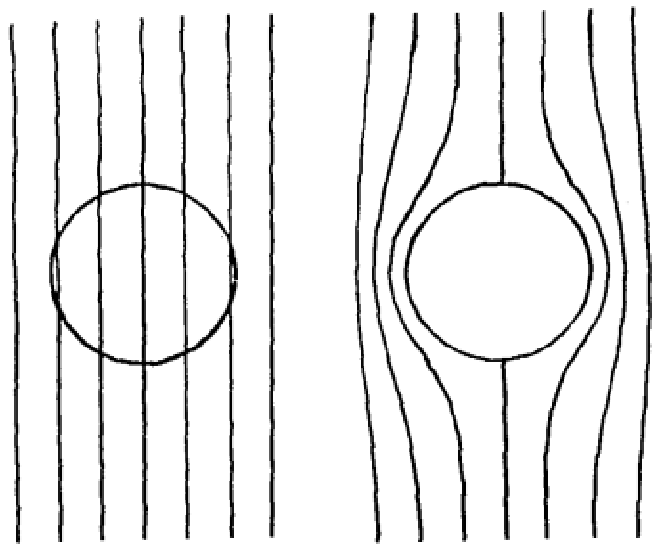
Meissner Effect

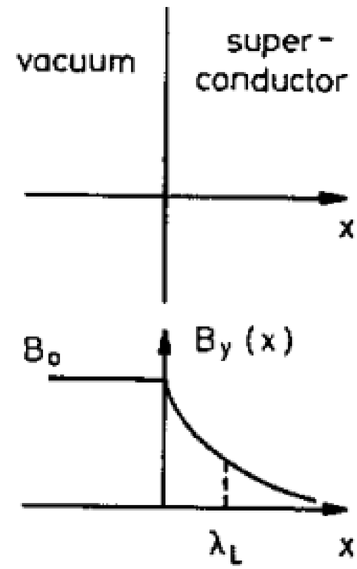
They exclude the magnet flux lines from going through it.

Meissner and Ochsenfeld (1933)

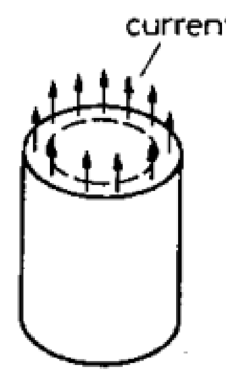


Normal Conductor Superconductor

Courtesy: Wilson

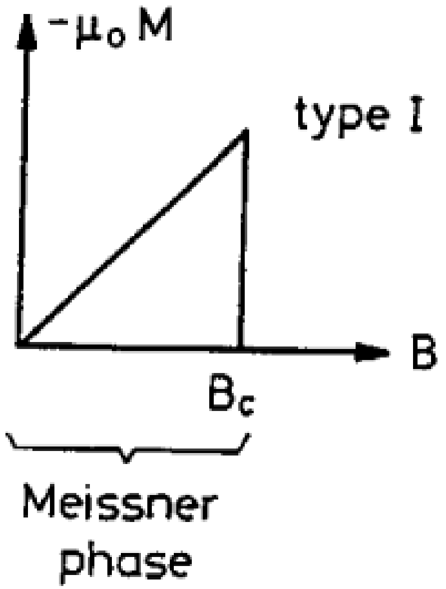


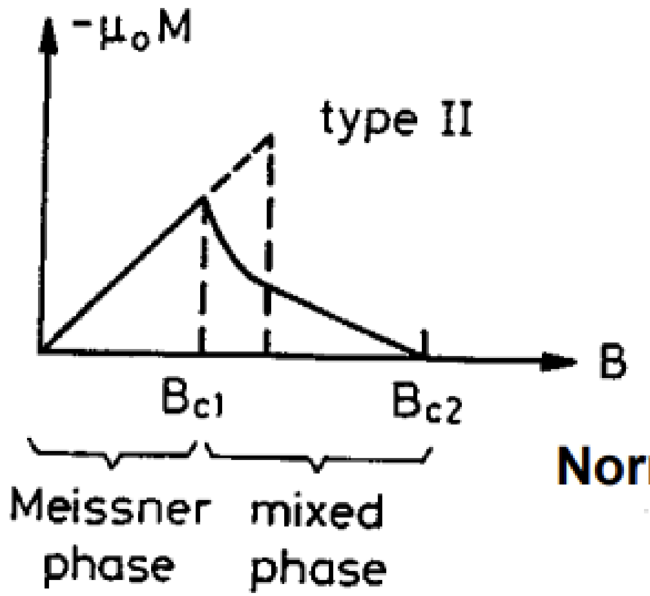
Attenuation of magnetic field and
shielding currents in Type I superconductors



Courtesy: Schmuser

Types of Superconductors

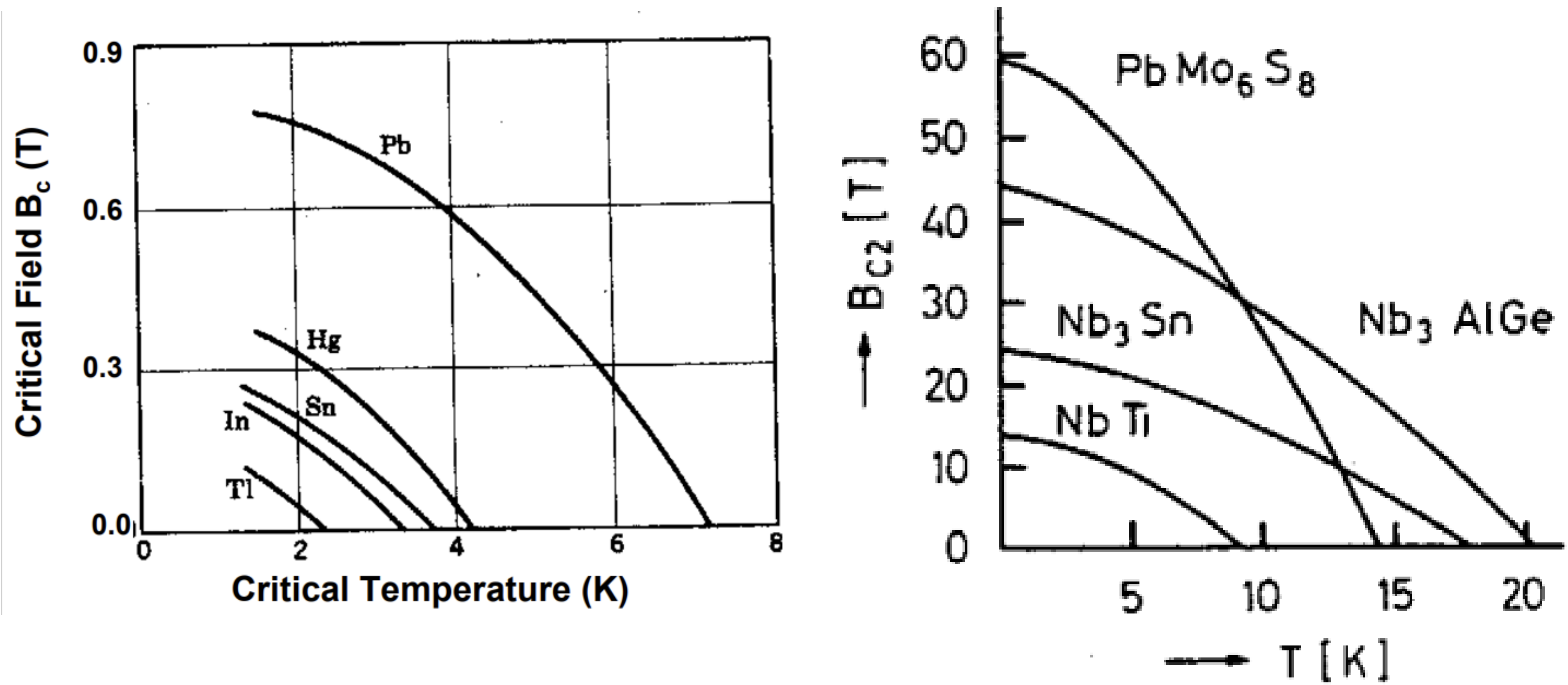




- Type I: Also known as the "soft superconductors".
- Completely exclude the flux lines. Allow only small field (< 0.1 T). Not good for accelerator magnets.

Type II: Also known as the "hard superconductors".
Completely exclude flux lines up to Bc1 but then part of the flux enters till Bc2 Important plus: Allow much higher fields. Examples: NbTi, Nb3Sn

Critical Surface if Type I and Type II Superconductor



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Critical Surface

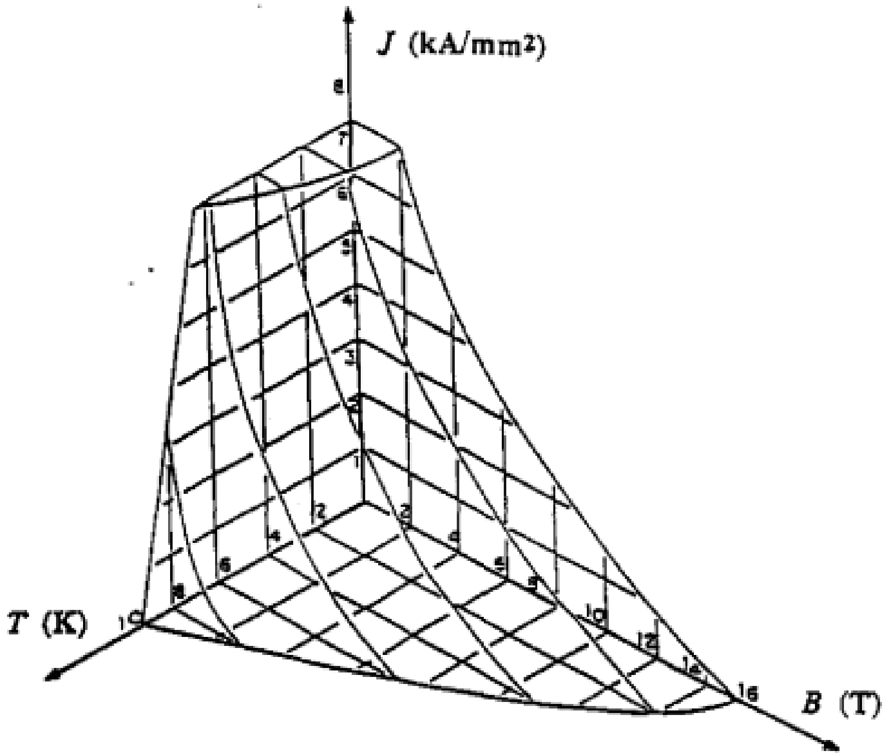
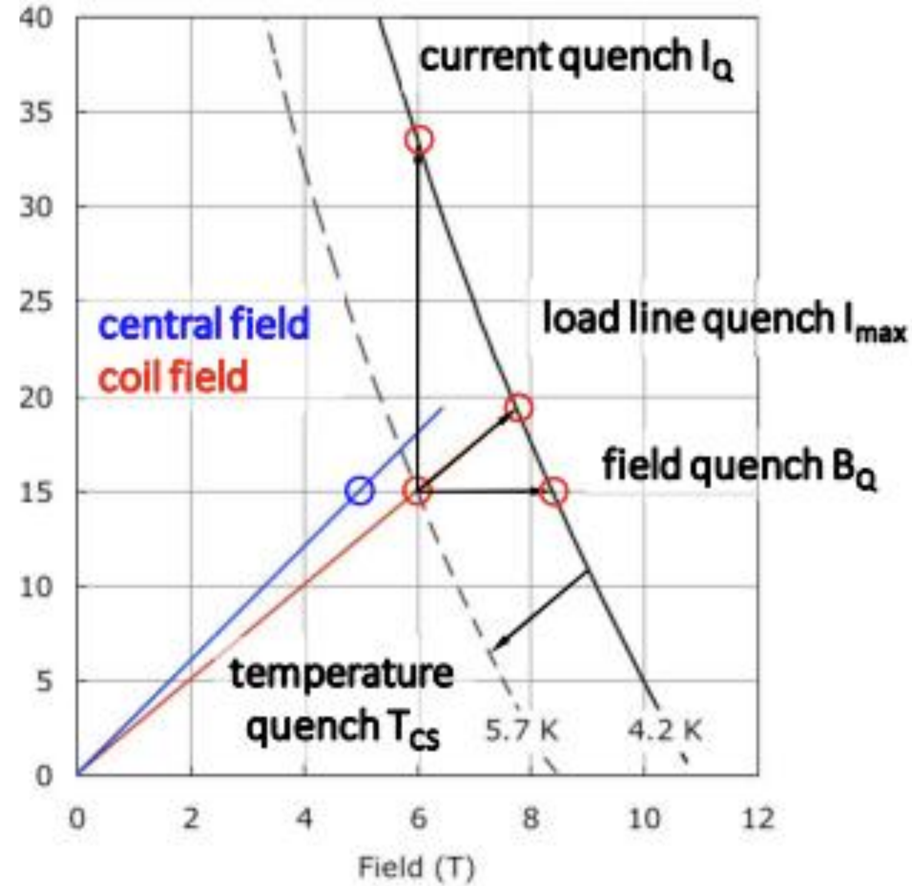
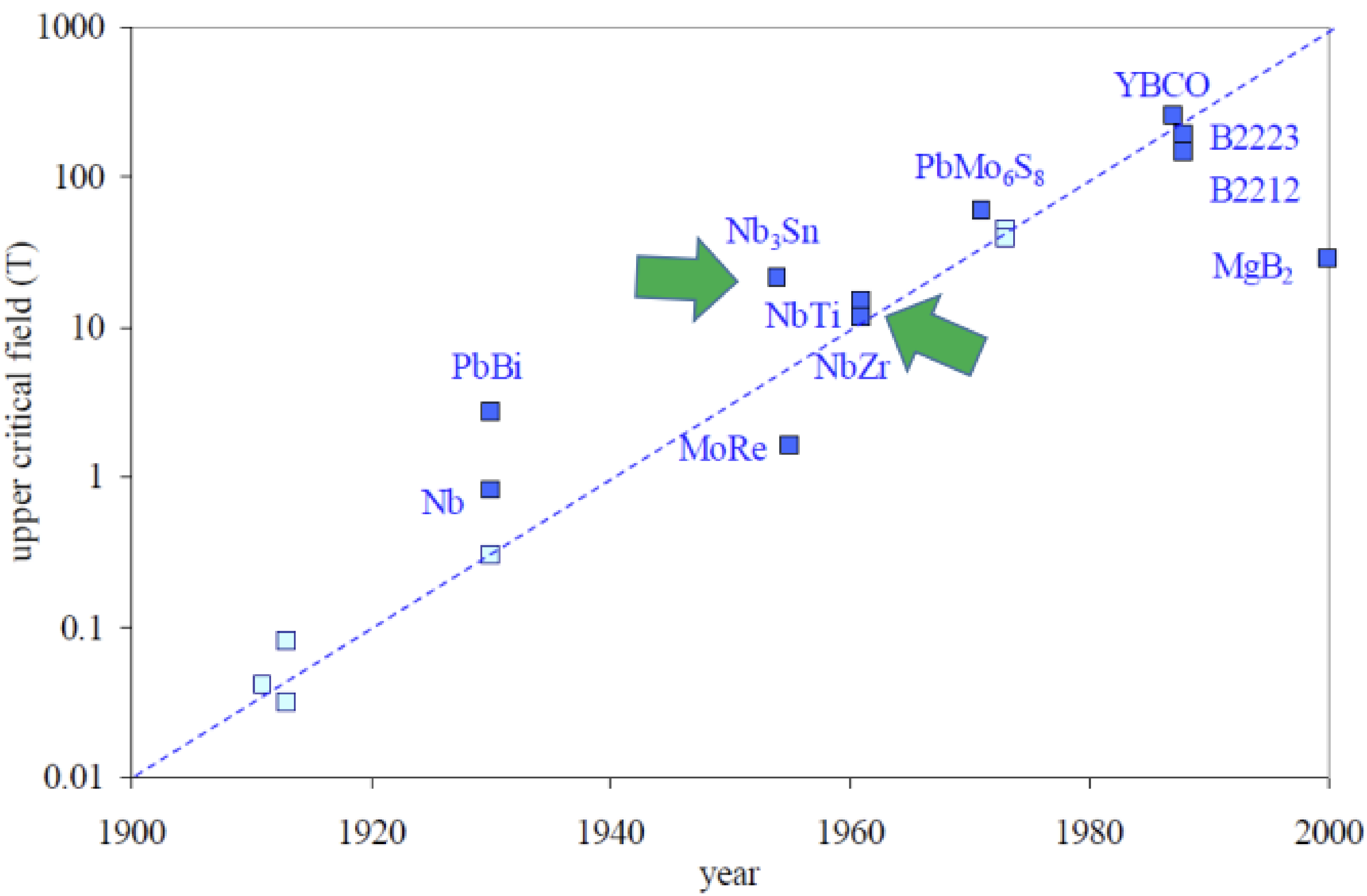


Figure 1. NbTi critical surface.



Vikas Teotia, Brookhaven National Laboratory

Superconductor discovery



M.N. Wilson, "100 Years of Superconductivity , 50 Years of Superconducting Magnets", CERN Symposium, Dec 2011

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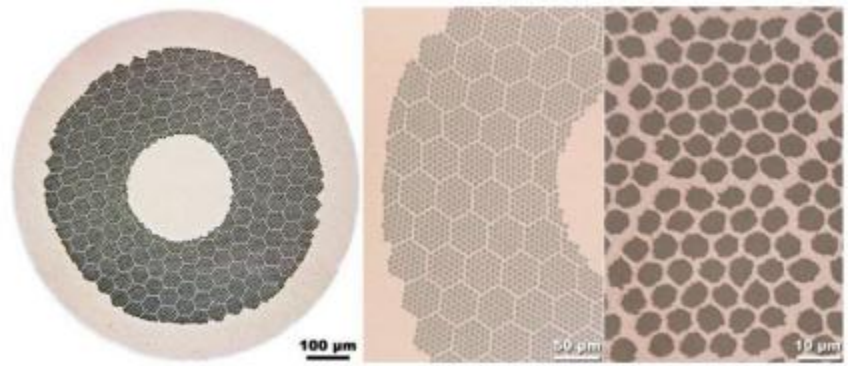
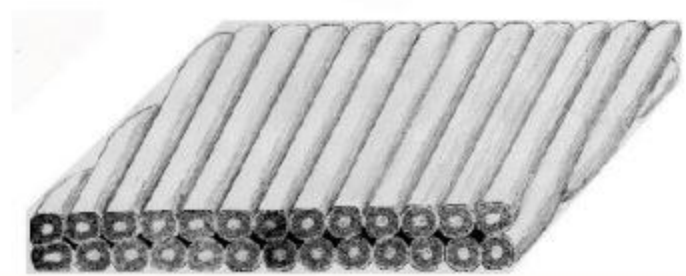
Conductor architecture

Stabilization: solid superconductor wire is replaced with an array of thin superconducting filaments embedded in copper matrix. Should a filament lose superconductivity, current will be redirected into the surrounding copper stabilizer



Twisting filaments along the strand length allows to reduce their stray magnetization

Transposition: superconducting strands forming a cable allow for a uniform current sharing, re-distribution in case of quenching, as well as additional magnetization reduction



"Nb-Ti - from beginnings to perfection", *Peter J. Lee NHMFL, Florida State University* and *Bruce Strauss U.S. Department of Energy*, *in "100 Years of Superconductivity"* ", CRC Press 2011

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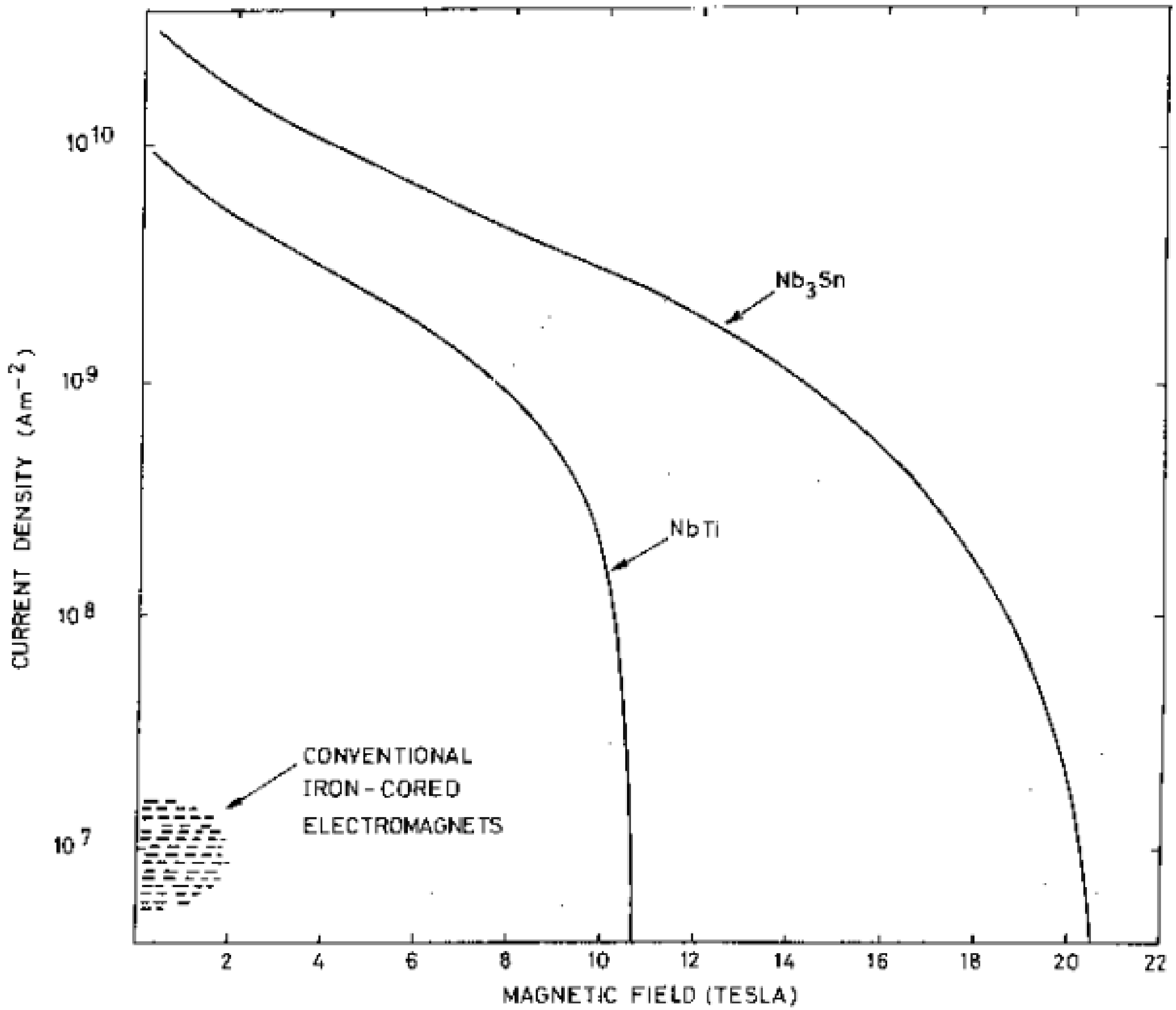
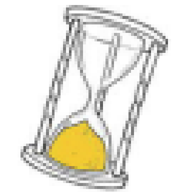
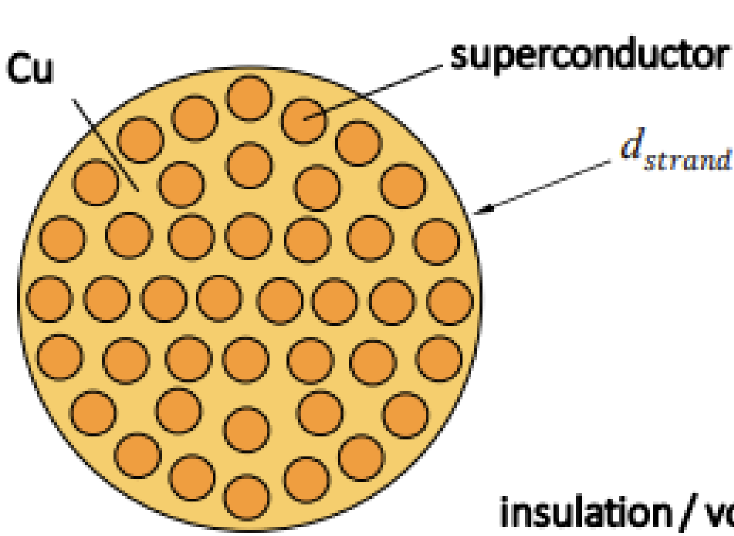
Significant Advantage



Picture is not that glossy!

The overall current density is lower than the current density on the superconductor



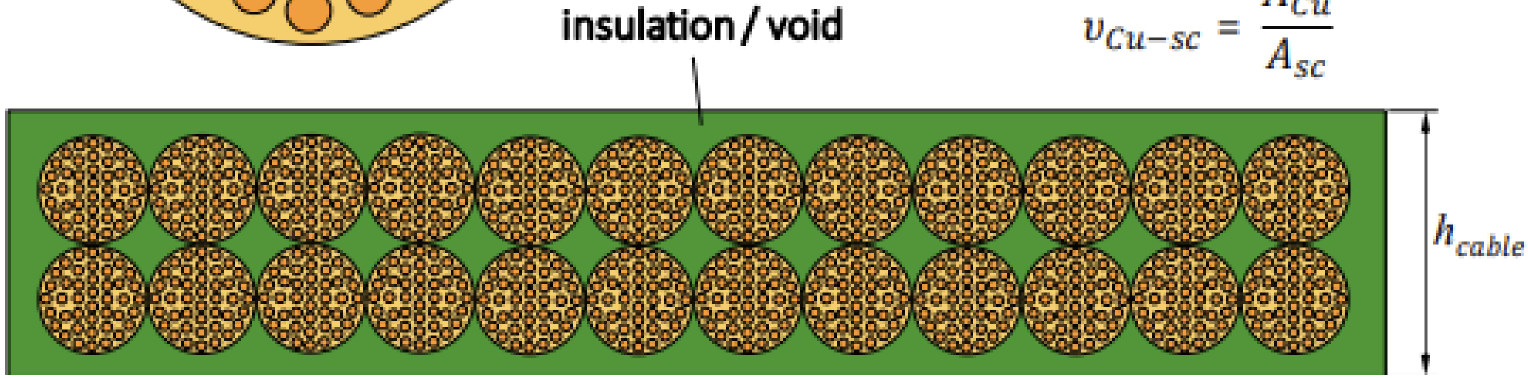


$$j_{overall} = \frac{I}{w_{cable} t_{cable}}$$

$$j_{cond} = \frac{I}{N_{strand} \frac{\pi d_{strand}^2}{4}}$$

$$j_{sc} = (1 + \upsilon_{Cu-sc}) j_{cond}$$

$$\upsilon_{Cu-sc} = \frac{A_{Cu}}{A_{sc}}$$



Power consumption in cryogenics

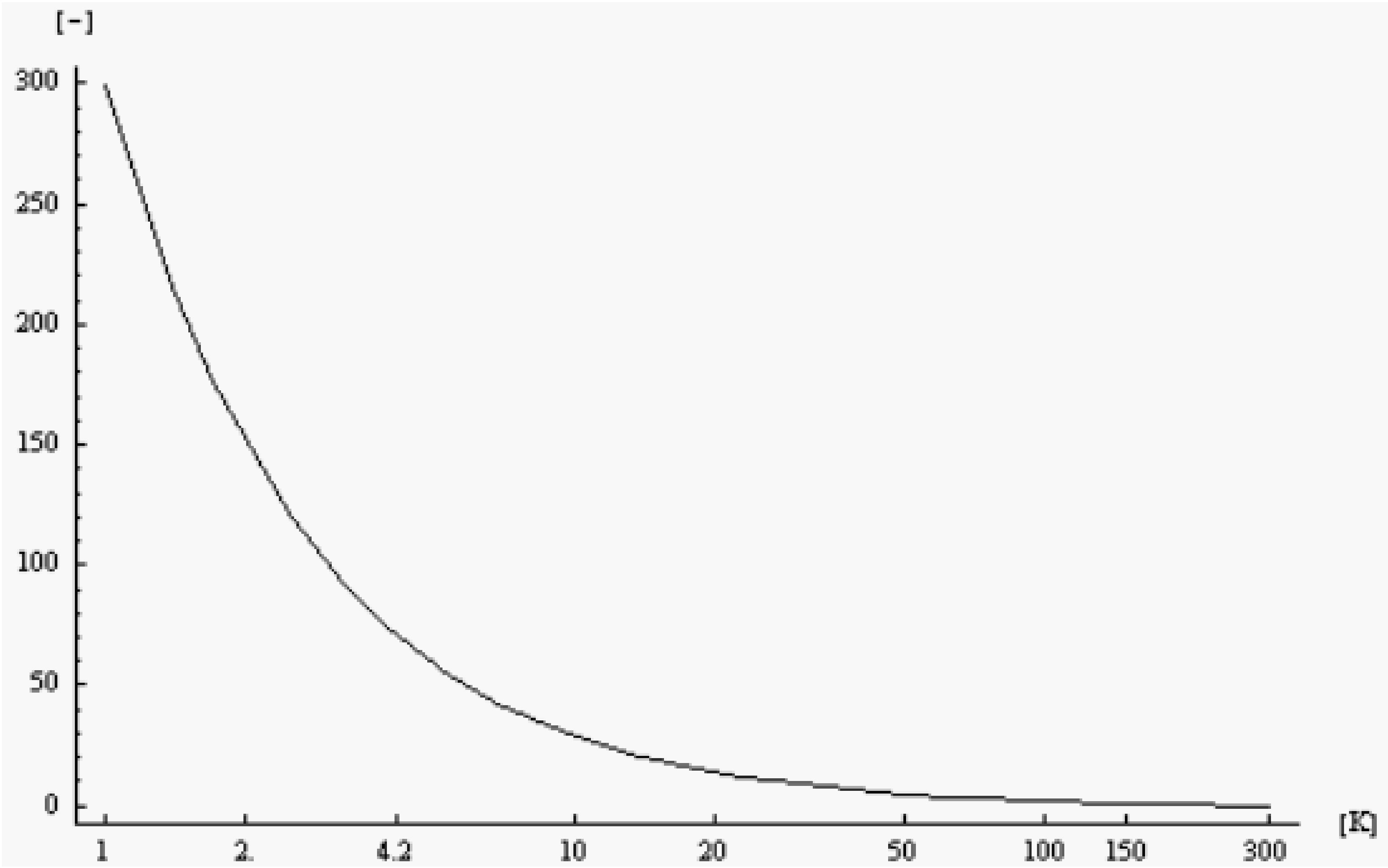


Figure 2: Carnot factor as function of cold temperature for $T_W = 300$ K

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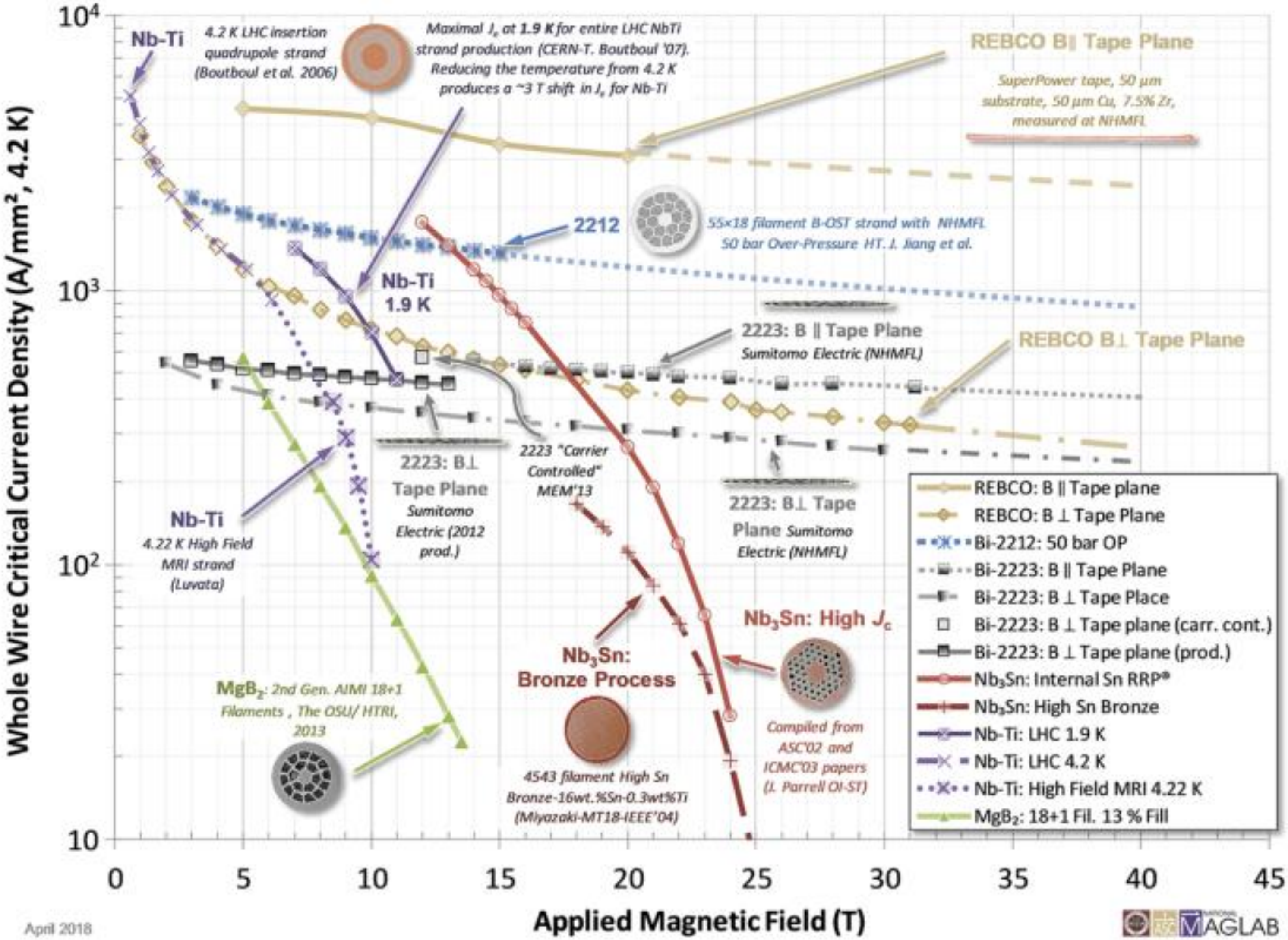
Current Density of different superconductors



Courtesy of Peter J. Lee, Applied Superconductivity Center, Florida State University and the National High Magnetic Field Laboratory
http://fs.magnet.fsu.edu/~lee/plot/plot.htm

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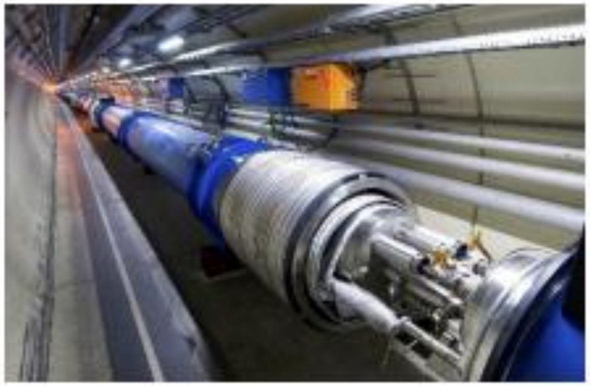
Stored energy of a superconducting magnet

$$E = \frac{LI^2}{2} = \frac{\mu_0}{2}\int B^2 dV$$



The 14-m long LHC dipole has a stored energy of 7 MJ at the design filed of 8.4 T

0.7 MJ is energy of a car (2000 kg) moving at 60 mph

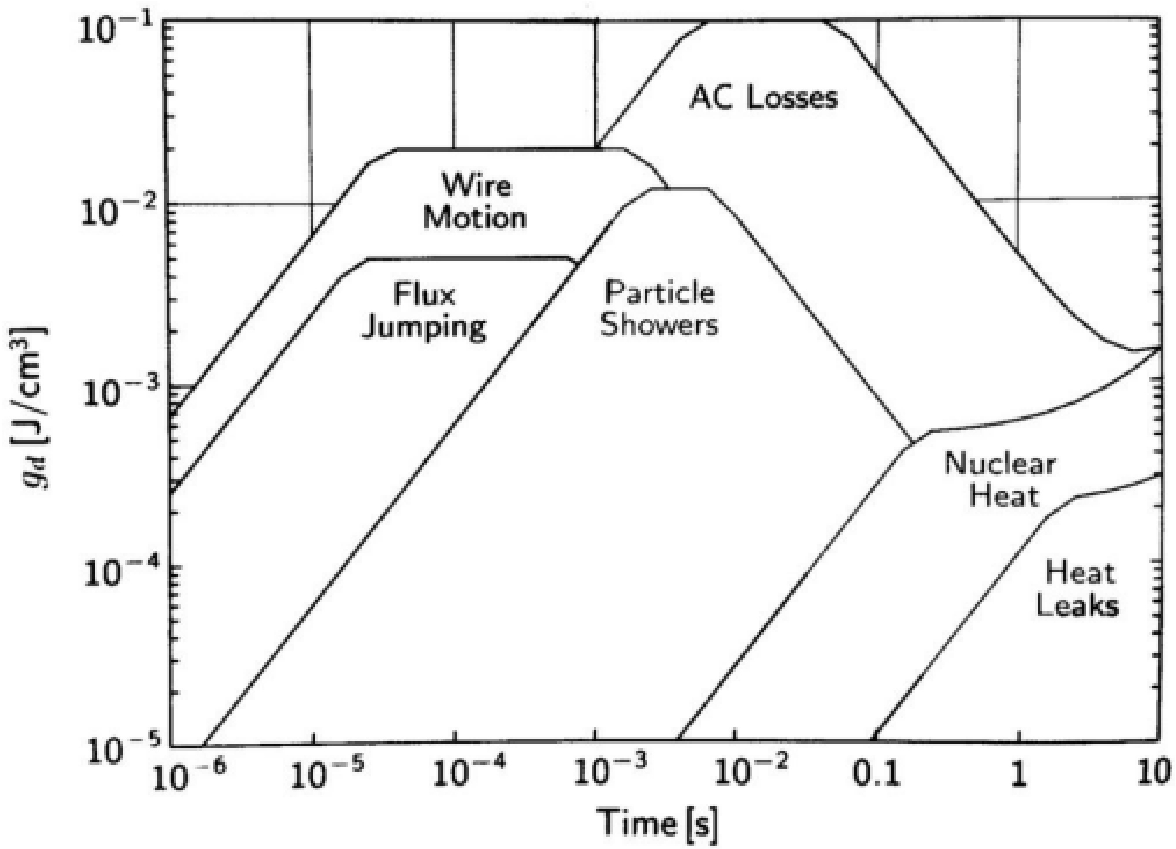
0.7 MJ of energy is sufficient to heat up from 4 K and melt ~1 kg of copper!

Equivalent He gas release is 254 L / kJ => 177.8 m3 of gas!

What initiates a Quench? Disturbance Spectrum

Quench in a superconductor:

- A sudden, unexpected and unrecoverable transition to the normal state of the superconductor in the device
- which enforces the conversion of the stored energy into mostly heat, which can lead to destruction of the device when not properly controlled



Disturbance spectra of accelerator magnets (Y. Iwasa, "Case Studies in Superconducting magnets", Springer 2009)

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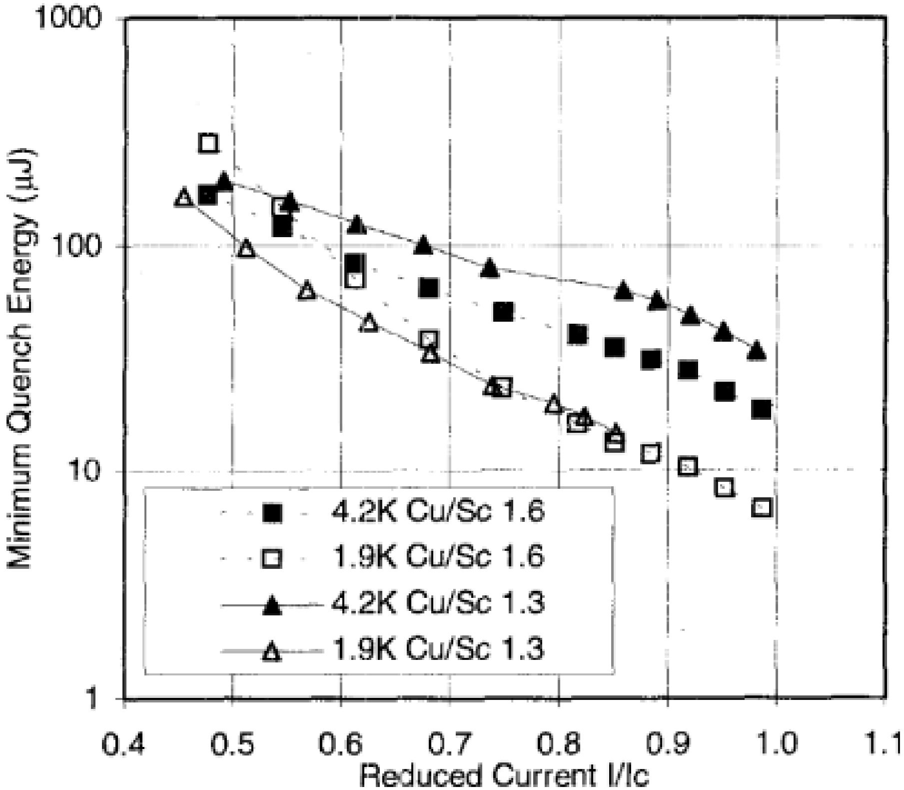
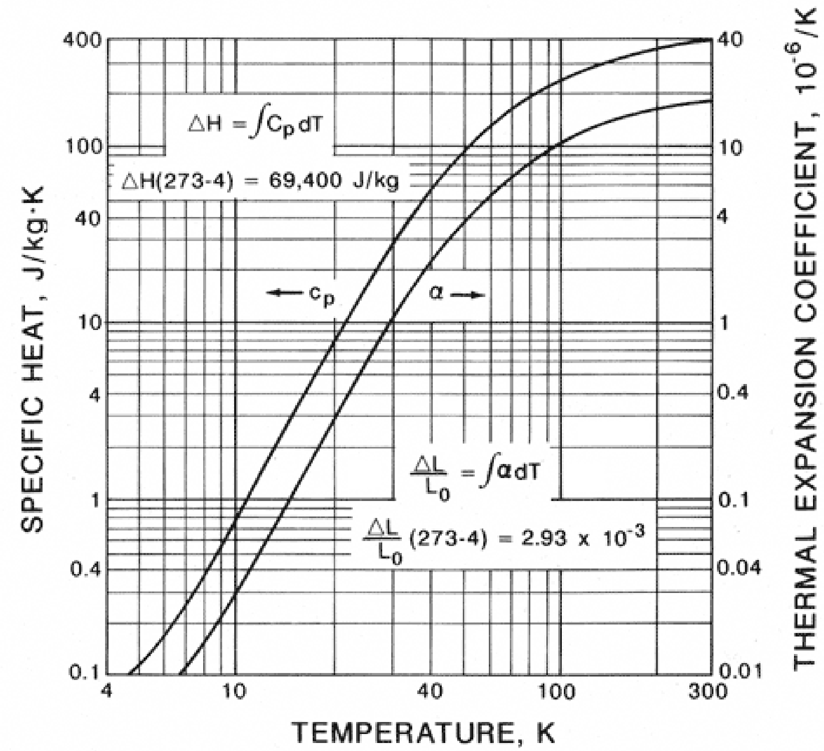
Minimum Quench Energy and specific heat





10 uJ is the kinetic energy of a staple dropped from a 3 cm height….

~10^{11} -10^{12} times less than a stored energy of a typical accelerator magnet!

A.K. Ghosh et al., 1997

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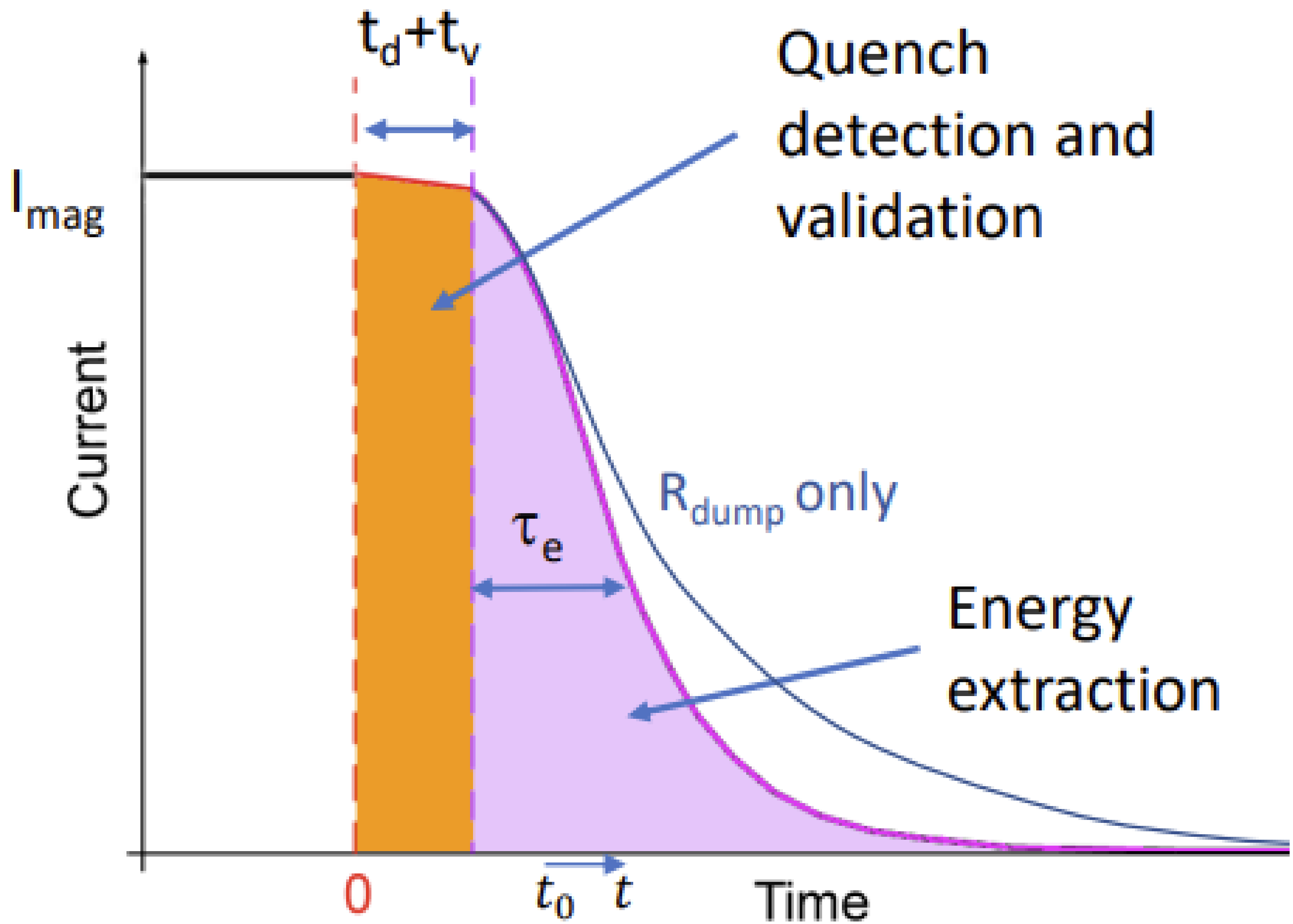
Quench Protection



Once quench occurs

Quench

Normal zone growth

Detection

Power supply switched off

Trigger protection options

Protection heaters | Extraction | Quenchback

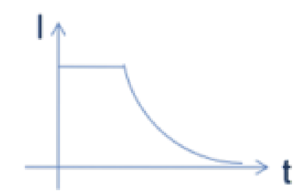
Current decay in the magnet

$\frac{1}{2}LI^2$

Magnetic energy

Converted to heat by Joule heating

$\int_0^{\tau} R(t)I(t)^2\,dt$



The **faster** this chain happens the **safer** is the magnet

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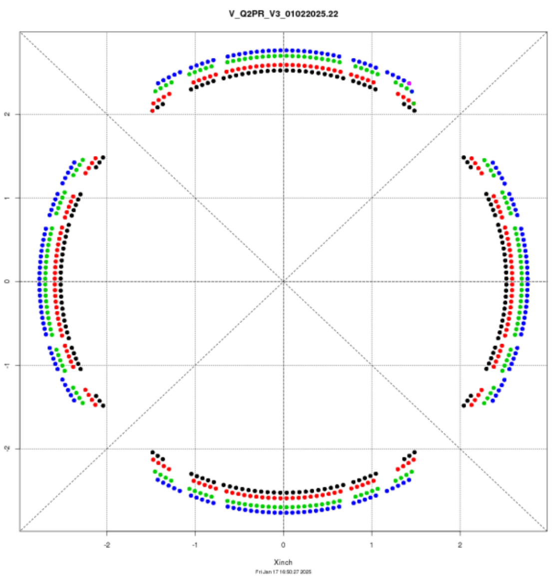
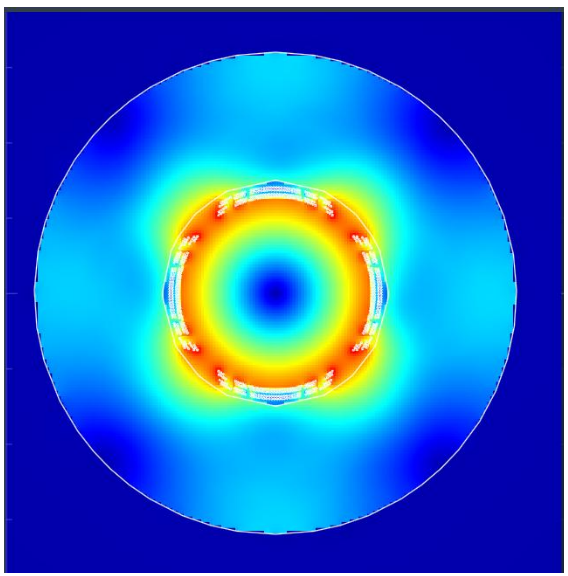
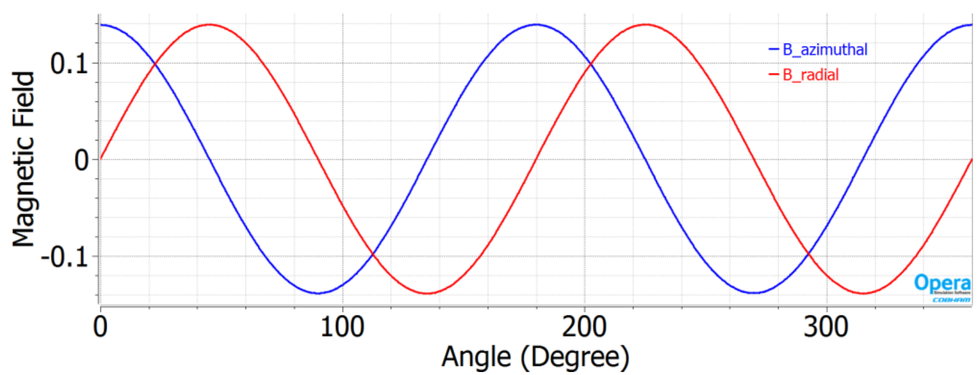
Vikas Teotia, Brookhaven National Laboratory

Electromagnetic Design of Superconducting Magnet





Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A3	-2.90e-04	-0.55		B3	2.46e-04	0.47	
A4	-2.41e-04	-0.46		B4	-1.79e-04	-0.34	
A5	-6.57e-06	-0.01		B5	4.90e-05	0.09	
A6	1.39e-04	0.26		B6	2.38e-03	4.53	
A7	5.91e-05	0.11		B7	6.00e-05	0.11	
A8	2.41e-05	0.05		B8	-2.86e-05	-0.05	
A9	4.61e-05	0.09		B9	-5.45e-05	-0.10	
A10	8.21e-05	0.16		B10	-2.79e-04	-0.53	
A11	4.84e-05	0.09		B11	5.09e-05	0.10	
A12	-1.45e-06	-0.00		B12	8.07e-07	0.00	
A13	4.93e-05	0.09		B13	-5.21e-05	-0.10	
A14	-2.29e-06	-0.00		B14	-2.45e-04	-0.47	
A15	4.97e-05	0.09		B15	5.26e-05	0.10	



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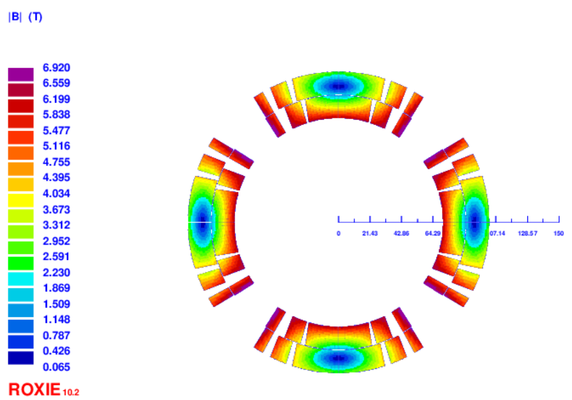
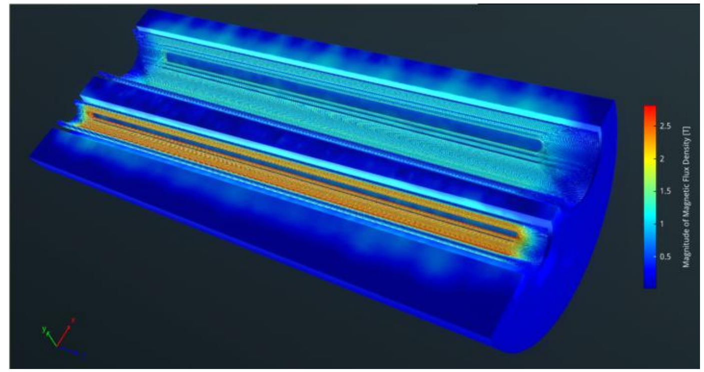
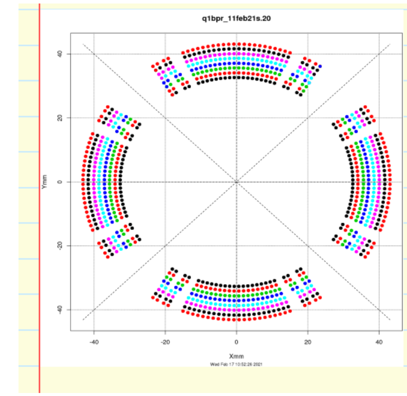
EM design (Collar/Direct Wind magnets)



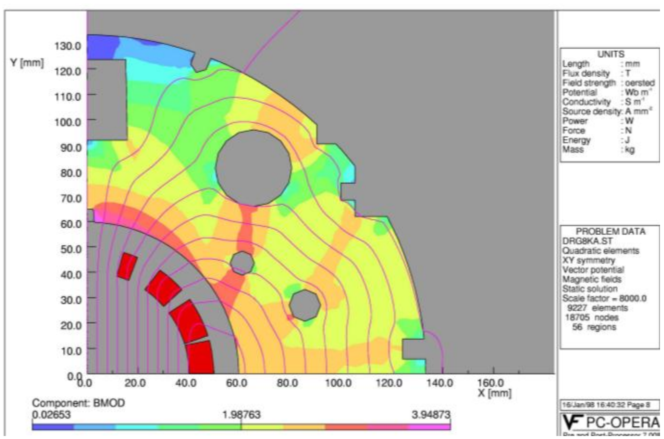
2D analysis (OPERA)



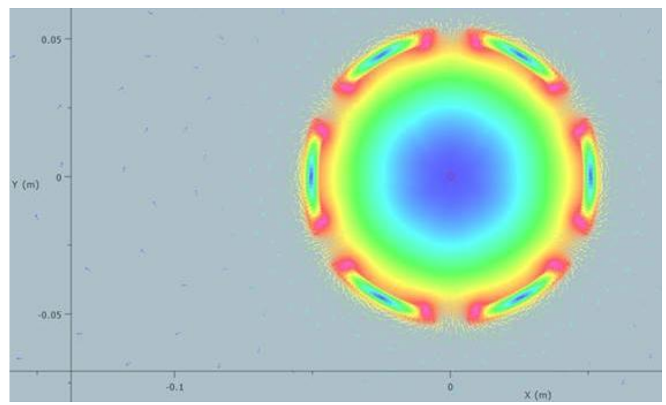
3D analysis (RAT)



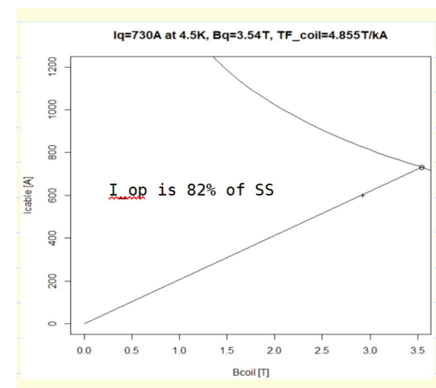
2D analysis (BNL Software)



Yoke Optimization (OPERA)



2D analysis (OPERA)



QUENCH margin

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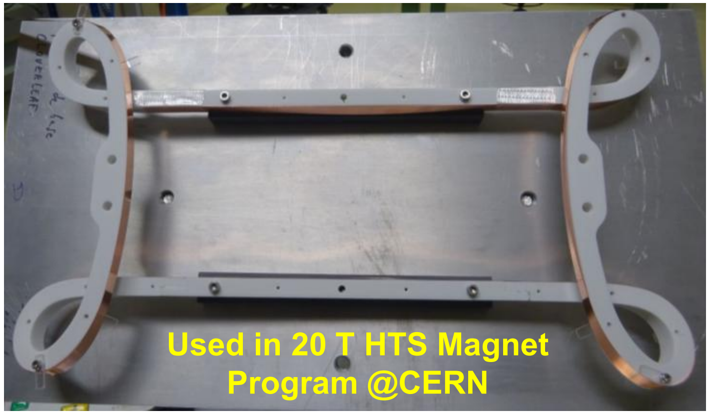
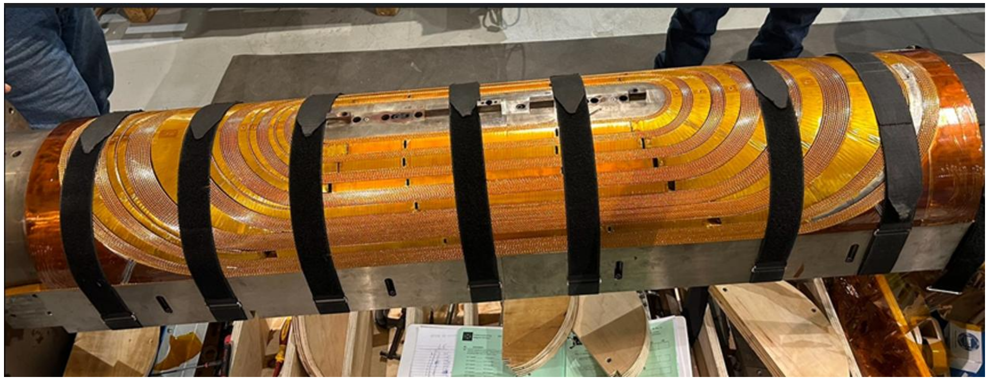
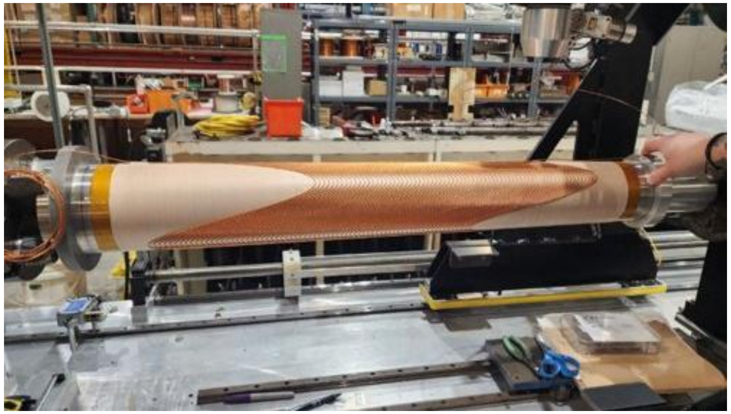
Superconducting coils





Collared Magnet

HTS coil



Double Helical Direct Wind Magnet

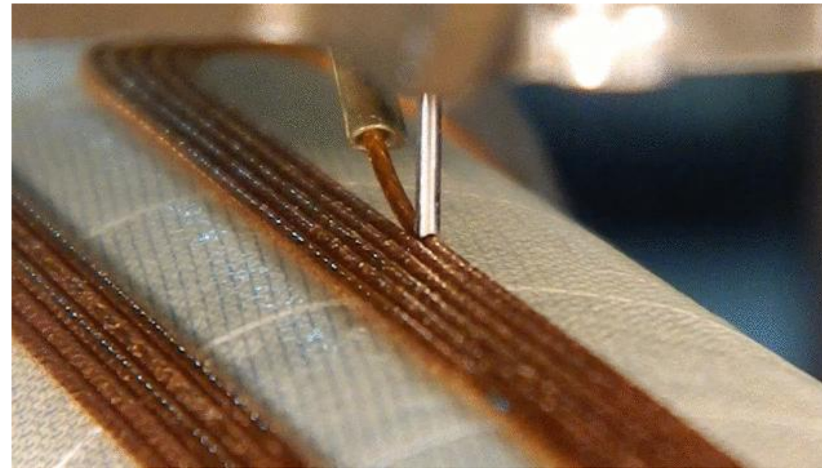
Giorgio Ambrosio (FNAL), Jesse Schmalzle, Mike Anerella (BNL), others, in celebration of final AUP coil

BNL's Direct Wind Technology

We place superconductor (round wire or cable) on a support tube under computer control.

- General purpose, e.g. no need for costly tooling.
- Very good field quality made possible via harmonic corrections based upon magnetic measurements.
- Compact coils (force management without collars).
- Vary aperture along length (wind on tapered tubes).
- Vary field along length (SuperKEKB, EIC, FCC-ee).
- Technology appropriate for doing "one-off magnets."
- Used for decades in accelerators around the world.

BNL's unique, world class magnet technology.



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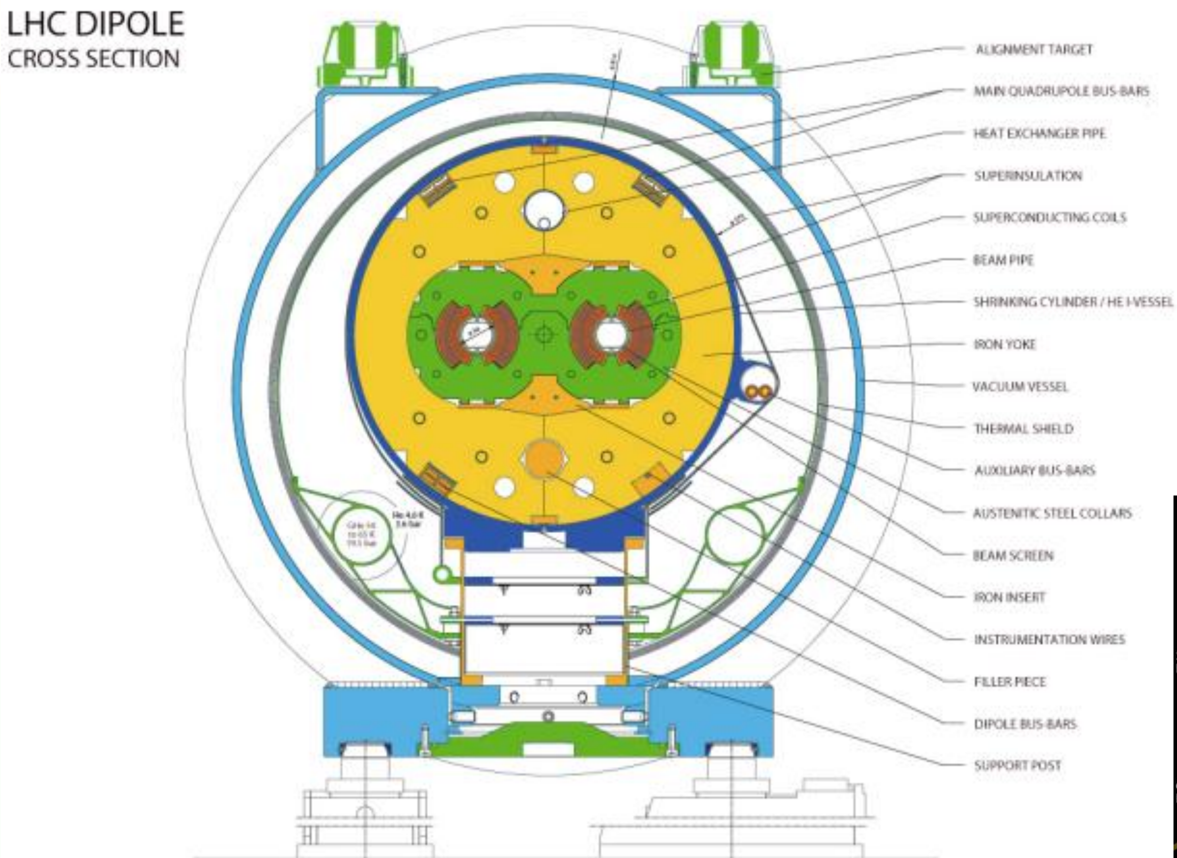
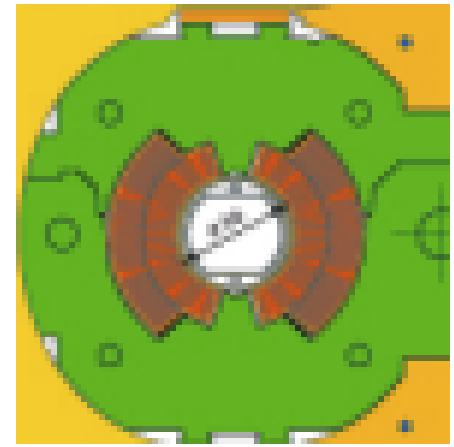
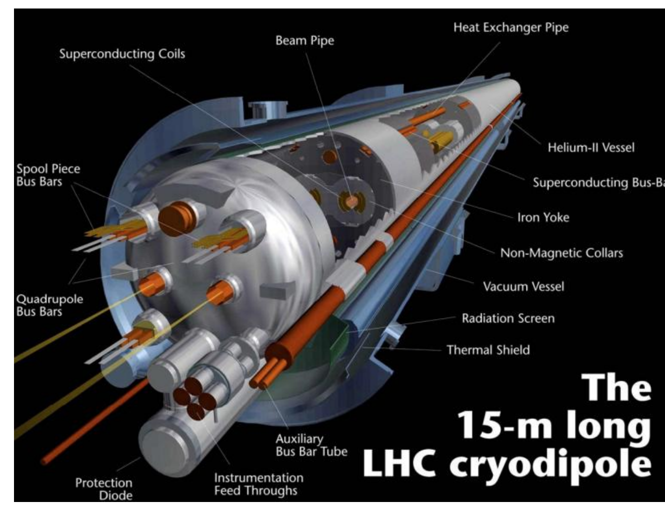
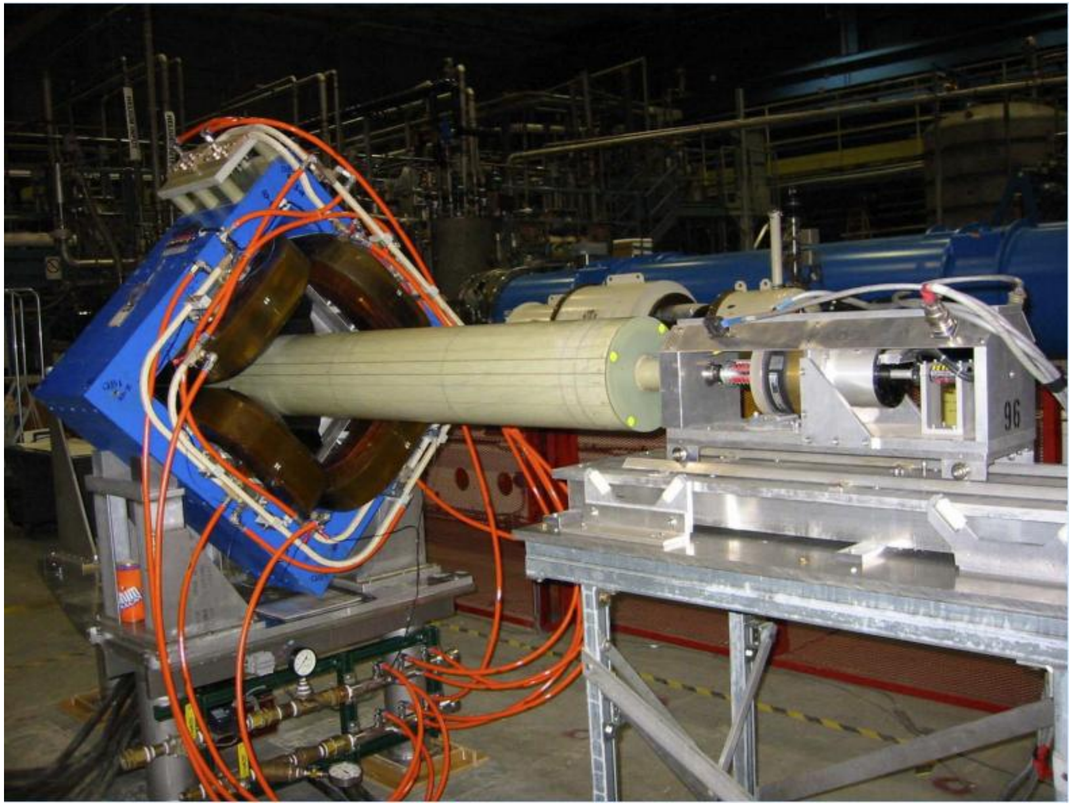
Cryostat Design

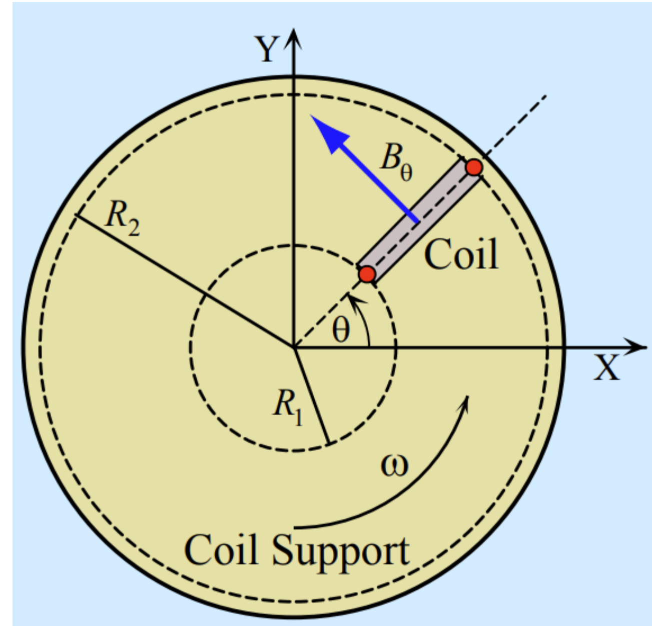


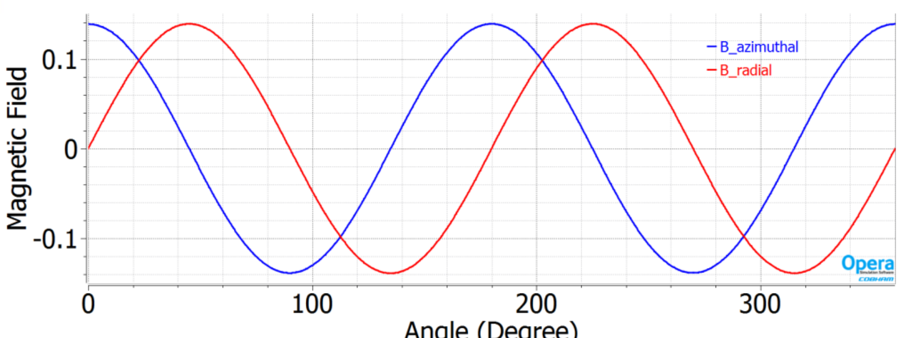


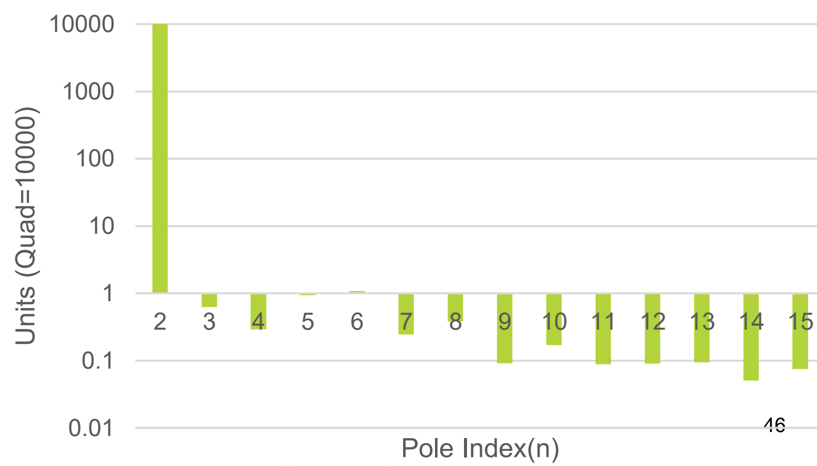


Magnetic Measurements









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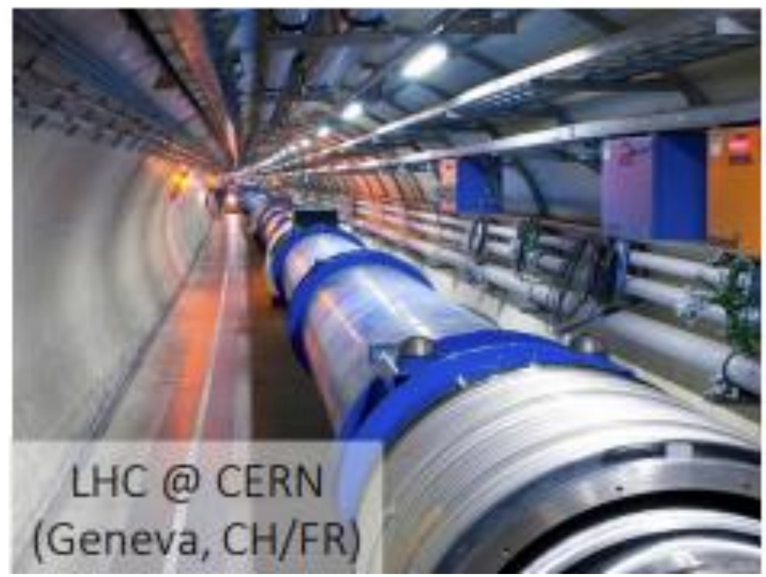
Some snaps


Tevatron @ FNAL
(Chicago, IL, USA)


RHIC @ BNL
(Upton, NY, USA)


HERA @ DESY
(Hamburg, D)


LHC @ CERN
(Geneva, CH/FR)

Summary

- • In circular machines, the size of the machine is determined by the field in the magnet (Circumference ∝ 1/B).
- • High field superconducting magnets may reduce the overall accelerator system cost (tunnel, facilities, vacuum system, etc.).
- • Superconducting magnets may also reduce the operating cost as there is no Joule heating.
- • But the superconducting magnets themselves are much more expensive than the conventional warm magnets. In addition, one must also consider the additional cryogenic costs (both installation and operational).
- • Use superconducting magnets only if there is a substantial savings, because they also bring the complexities (magnet protection, cryogenic system, etc.). In high energy colliders (specially in hadron colliders), the superconducting magnets tend to minimize the cost of building and operating the machine.
- For Building future machines like FCC, Muon Colliders even high strength and high ramp rates magnets are needed.
- Lot of efforts on taping the potential of HTS for future accelerator magnets

Thanks for your attention!

vteotia@bnl.gov