Magnets for Accelerators
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Magnets are Essential Technology for Accelerators
SuperConducting (SC) magnets are essential for large accelerators

• Synchrotrons and storage rings
  – Bending-Dipoles
  – Focusing-Quads
  – Chromaticity- Sextupoles
  – Resonant Extraction-Octupoles
  – Correctors- Fix the fields due to imperfect magnet construction

• SC Accelerators Tevatron, RHIC, HERA, LHC
Growth of LHE Refrigeration tracks accelerator progress
Superconductor Improvement
Driven by accelerators, medical equipment and fusion
FNAL Tevatron
Worlds first SC Synchrotron
FNAL Tevatron Dipole
HERA

Hadron-Electron Ring Accelerator
HERA Dipole

Justierung
Adjustment

Aufhängesband für Strahlungsschild
Suspension band for shield

Aufhängesband für Magnet
Suspension band for magnet

Strahlungsschild
Radiation shield

Stangen für Querstabilisierung
Rods for lateral stabilisation

Justierung
Adjustment

SL DIPOL HERA
SC DIPOLE HERA
RHIC
Relativistic Heavy Ion Collider
RHIC Dipole

[Diagram of RHIC Dipole]
SC magnets are essential for compact cyclotron accelerators

- SC Cyclotrons
  - Research
  - Beam Therapy cyclotrons
  - PET isotope production
- SC Synchro-cyclotrons
  - Compact Neutron sources-security
  - Compact beam therapy

K500 SC Cyclotron at MSU with Harold Hilbert
250 MeV Cyclotron for proton therapy super ferric-sector focused
MEVION 250 MeV SC Synchro-cyclotron for single patient beam therapy installations

Cyclotron is in gantry
SC Synchro-Cyclotron installations for cancer therapy
Proton and Gamma Therapy
exploiting the Bragg Peak
Magnet Technology and Field

- Resistive (copper and iron) 0 to 2 Tesla
- Superferric (SC coils and iron) 1 to 3 Tesla
- Mixed (copper and SC coils and iron) to 5 Tesla
- SC Magnets(NbTi, 4.2 Kelvin) 0 to 6 Tesla
- SC Magnets( NbT1, 1.8 Kelvin) 0 to 9 Tesla
- SC Magnets( Nb3Sn, 4.5 Kelvin) 10-20 Tesla
- For Higher fields our children will use High Temperature Superconductors (HTS)
Low field accelerator magnets

Resistive and Superferric

Resistive Magnet
FNAL Main Injector

SuperFerric Dipole

Iron yoke

Water cooled copper coils

 Beam tube

SC coils with Helium Vessel

cryostat
4 to 7 Tesla Accelerator magnets
2 layer collared coils

Tevatron Dipole
warm iron yoke

HERA Dipole
Cold iron Yoke
LHC Dipole 9 Tesla
2 in 1 design

- 2 layer NbTi
- 1.8 Kelvin
- 9 Tesla
- Cold iron yoke
- 2 in 1 design
  opposite fields
- 1792 2 in 1 dipoles required
- 8000 SC magnets in all
Nb3Sn Sc magnets 4 layer
10-15 Tesla

D20 coil cross section

D20 SC magnet
Common coil 2 in 1 SC magnet design
13 to 16 Tesla

BNL RD3 SC common coil magnet

Common coil configuration
2-in-1 over/under magnet
Magnetic Design Tools I

JLAB uses TOSCA extensively

- Vector Fields (VF) – TOSCA- the gold standard
  - Pre-processor-simple modeling tool
  - Modeler- advanced 3D CAD modeling tool
  - OPERA- 3D Non-Linear(NL) FEA solver
  - OPERA-2D  NL Solver for axi-symmetric problems
  - ELEKTRA- Time dependant fields, circuits, cavities,
  - QUENCH- semi 3D SC magnet time dependant quench simulation coupled with Elektra and OPERA

- Not cheap (license ~ 20K$ /annual fee ~5 K$)
Magnetic Design Tools II
JLAB has license—does not use yet!!

• ROXY- CERN product
  – Inexpensive ~ 1500
  – Training cost $15,000
  – Full 3D coil simulator
  – Excellent optimization—variation of parameters allows search for best solutions
  – Not fully non-linear
  – Outputs a TOSCA input file for final result check
Magnetic Design Tools III
JLAB uses ANSYS- Hall D solenoid -engineering

• ANSYS
  – Full service engineering FEA code family
  – Engineers and designers like this because it is all integrated
  – Magneto-statics is “just as good as Tosca”!
  – Contains full stress analysis FEA
  – Supported by 3D CAD and Drafting
  – Definitely not cheap!
Cosine Theta Dipoles

So called perfect geometry
VF TOSCA has “canned” cos theta coils
Cosine Theta Dipoles
TOSCA easily extracts multipoles and outputs normal and skew amplitudes

- Linear to 1 in 10,000
- Allowed Multipoles controllable up to n=20 (42 pole) and beyond
- Non allowed multipoles suppressed by symmetry (no odd, no skew)
- Current dominated
- Non saturated iron adds ~20%
Controlling Multipoles in cosine dipoles
SSC dipole study by R. Gupta and P. Thompson ca 1994

• Variations of the *six current blocks* and 4 wedges
  – block radial position of 0.05 mm
  – thickness of the wedges of 0.05 mm
  – pole angle of typically 0.075°.

• Effects on Multipoles of any ONE of the above!!
  – $B_2(\text{sex})$ of about 50% of the nominal value
  – $B_4(\text{dec})$ of about 100% of nominal value.

• Tolerances +/- 0.025 mm!!
Magnet Forces in Dipoles

5 KA, 5 Tesla, 50 turns dipole
Radial force $\sim 1 \times 10^6$ Nt/m
Azimuthal $\sim 0.25 \times 10^6$ Nt/m
Z force/m $\sim$ same as radial

Force collar to withstand forces and pre-load coil against motion
Magnetic forces
Magnetic Forces from TOSCA input to 3D FEA-real solutions

• Radial force supported by collars
• Azimuthal force compresses the coil and if this force exceed the pre-load the first turn next to the “pole” could move triggering a quench
• Solution is to pre-load the force collars to exceed this force and prevent conductor motion
• Requires very large and expensive 300 ton presses for magnet assembly
• Oh and lots of R&D too
Robotic Winding LHC Dipoles
LHC Curing press
Finished coils for LHC
Now easy to handle
LHC Corrector coils
Collars on coils
Collars and end plate (LHC dipole)
Adding the iron yoke and shell
LHC Dipole inside its stainless shell
Complete Magnet
Making connections
electrical and cryogenic
Current leads and cryo feeds
LHC test stand
Summary

• Magnets are essential accelerator components
• Low Temperature Superconducting (LTS) technology and Liquid Helium refrigeration will dominate large scale magnetic installations for HEP and Fusion for the near future
• Next generation accelerators may use Nb3Sn and common coil magnets to reach 15 Tesla
• Our kids and grand kids will use HTS magnets