Superconducting Magnets for Accelerator Science

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Item

- Introduction: Accelerator and Magnet
- Superconducting Magnet for Accelerator
  - Collider • Large Accelerators
  - Light Source • Medical • Small Accelerators
- Future Possibilities
- Summary
• Introduction: Accelerator and Magnet
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Particle Accelerator?

- Accelerate Charged Particle by
- By Electric Field

\[ F = q \times E \]

*F*: Force

*q*: Charge

*E*: Electric Field \((E = \frac{V}{d})\)
**Synchrotron**

- Confine Charged Particle in Circular Orbit
- Re-use Accelerating Electric Field
- Change Magnetic Field According to Particle Momentum

\[
F = q \times v \times B \frac{m \times v \times v}{r}
\]

\[
\mathbf{r} = \frac{m}{q} \times \frac{v}{B} = \frac{p}{qB}
\]

\[
B\mathbf{r} = \frac{p}{q} : \text{rigidity}
\]
LHC: Large Hadron Collider

8 of 2.45 km arc + 8 of 545 m straight section
Make bending field
Uniform Current in Rod

\[ B_\theta (r) = \frac{\mu_0 \pi r^2 j}{2 \pi r} = \frac{\mu_0 r j}{2} \]
\[ B_x (x, y) = -\frac{\mu_0 r j}{2} \sin \theta = -\frac{\mu_0 y j}{2} \]
\[ B_y (x, y) = \frac{\mu_0 r j}{2} \cos \theta = -\frac{\mu_0 x j}{2} \]

\[ I = \pi r^2 j \]
Make Bending Field Uniform Current in Rod

Left rod \( (J = +j) \)

\[
B_x(x, y) = -\frac{\mu_0 y j}{2} \\
B_y(x, y) = \frac{\mu_0 (x + d/2) j}{2}
\]
Make Bending Field
Two current rod

Left rod \((J = + j)\)
\[
B_x(x, y) = -\frac{\mu_0 y j}{2} \\
B_y(x, y) = \frac{\mu_0 (x + d/2) j}{2}
\]

Right rod \((J = - j)\)
\[
B_x(x, y) = \frac{\mu_0 y j}{2} \\
B_y(x, y) = -\frac{\mu_0 (x - d/2) j}{2}
\]
10 Make Bending Field Uniform Field

Left rod \((J = +j)\)

\[
B_x(x, y) = -\frac{\mu_0 yj}{2}
\]

\[
B_y(x, y) = \frac{\mu_0 (x + d/2)j}{2}
\]

Right rod \((J = -j)\)

\[
B_x(x, y) = \frac{\mu_0 yj}{2}
\]

\[
B_y(x, y) = -\frac{\mu_0 (x - d/2)j}{2}
\]

Overlay area \((J = 0)\)

\[
B_x(x, y) = 0
\]

\[
B_y(x, y) = \frac{\mu_0 j d}{2}
\]
Make Bending Field
LHC Bending Magnet

\[ B_y(x, y) = \frac{\mu_0 j d}{2} \]

- \( j = 400 \text{ A/mm}^2 \)
- \( d = 3 \text{ cm} \)
- \( B_y = 8.3 \text{ T} \)

Actual Coil
- Inner Cable
  - Width: 15.1 mm
  - Thickness: 1.9 mm
  - Turn no.: 15*2
  - \( J = 400 \text{ A/mm}^2 \)

- Outer Cable
  - Width: 15.1 mm
  - Thickness: 1.48 mm
  - Turn no.: 26*2
  - \( J = 520 \text{ A/mm}^2 \)
12 Normal conducting magnet?

- Joule Heating: \( W = VI = RI^2 \) → Limit actual current density: 10 A/mm\(^2\)
- \( 1/40 \) of \( J \): 40 times larger coil? Noway.
- Real normal conducting magnet: Use iron yoke magnet circuit
- Iron saturation: limit field to 2 T

![Diagram of magnetic field](image)

\[ H = NI \]
\[ B \sim \mu_0 NI/g \]
\[ P = \varrho i (NI)L \sim \varrho jBLg/\mu_0 \]

LHC by normal conducting
Need 5 times larger size
10 times more energy consumption

\( 0.05 \text{(gap)} \times 0.1 \text{(width)} \times 1 \text{(length)} \text{m} & 2\text{T} \sim 15\text{kW (@ 10A/mm}^2\text{)} \sim 7\text{kW/Tm} \)
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• Future needs

• Summary
1895 Crookes tube: first electron accelerator
1911 Discovery of Superconductivity
1930 Cockcroft & Walton circuit: first radioactive decay
1931 Cyclotron (Lawrence)
1933 Discovery of Meissner effect
1947 Electron Synchrotron
1952 Proton Synchrotron
1957 BCS theory, Type II superconductor
1961 6T Superconducting Magnet
1983 Superconducting Synchrotron TEVATRON
Superconducting Collider: BNL vs FNAL

1970 ~ early 1980s
Strong competition
Between 2 US Lab.

ISABELLE/CBA (BNL) 3.8km, 400GeV
(Magnet: 5.28T)

TEVATRON (FNAL): 6.3km, 1TeV
(Magnet: 4.4T, 6.1m, 774台)
Superconducting Collider HERAとRHIC

1992年：DESY/HERA: 6.3km (4.7T, 8.8m, 416台)

1998年：BNL/RHIC: 3.8km (3.5T, 9.7m, 288台)
“Contrary to all the hype, the **SSC will not cure cancer**, will no provide a solution to the problem of male-pattern baldness, and will not guarantee a World Series victory for the Chicago Cubs”. Congress Man Sherwood Boehlert
Large Hadron Collider
LHC

2008年：CERN/LHC: 26.7km (8.3T, 14.2m, 1232台)
LHC International Collaboration MQXA and MQXB

- Focus Beam at Interaction region
  - Japan and US collaborating together to contribute LHC
Electron Positron Colliders
TRISTAN, KEKB, S-KEKB

Interaction Region Superconducting Magnet

SuperKEKB Interaction Region Superconducting Magnet
High Power Accelerator
J-PARC

- J-PARC: Extraction Machine
  - Rapid cycle operation: difficult for Superconducting Magnet
    - AC loss
  - J-PARC RCS (3GeV 1MW): 25 Hz
  - J-PARC MR (30GeV 1MW): ~1 Hz

- Beam Line after extraction
  - fixed energy = fixed field
  - J-PARC Neutrino Facility
J-PARC
Neutrino Facility

• Need SC magnet to save space.

Combined function magnet (2.6T+19T/m, 28 SCFM) optimize schedule and budget
High Power Accelerator
TEVATRON, GSI SIS100, RIKEN SRC

- **TEVATRON** (800GeV ~70kW)
  - Originally extraction machine
  - ZEBRA cable: AC loss
  - Not very fast cycle: 1 min
- **GSI SIS100** (30GeV ~100kW)
  - Superferic; 1.9T, 1Hz(4T/s)
- **RIKEN SRC** (0.4GeV 80kW)
  - Largest cyclotron
  - DC Operation
  - Energy limitation

GSI SIS100 Main Dipole Magnet
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25 Synchrotron Light Source

- Super-Bend
- Traditional
Synchrotron Light Source

- Wiggler
- High Field Wiggler by Superconducting Magnets
Synchrotron Light Source

- High Field Focusing Magnets
Medical Synchrotron for Carbon Therapy

- Extraction type synchrotron
  - Normal conducting magnets

世界初の重イオン加速器治療を行なったLBNLのBevalac

放医研のHIMAC
Medical Synchrotron for Carbon Superconducting Gantry

To reduce size and weight
Small Accelerator
Superconducting Cyclotron

• DC operation: good for superconducting magnet
• High Field = smaller size
  • Smaller beam separation: larger beam loss

Cyclotron to produce radioactive material at the University of Michigan
Superconducting Cyclotron for Proton Therapy Mevion S250
Superconducting Cyclotron for Proton Therapy by IBA
Small Accelerator Application
ECR Iron Source

- Trap plasma via strong solenoid field with sextupole field
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Upgrade Interaction region
- Smaller beam size
- Higher Field Focusing Magnets (Nb₃Sn)
- Club Cavity
- Higher Field Beam Separation Dipole
- Increase Luminosity
Future Possibilities
Future Circular Collider: FCC at CERN

Future Circular Collider (FCC)
Future 100 TeV Machine
At around CERN
100km ring with 16T Nb₃Sn
Or 20T with 20T HTS
Future Possibilities: SPPC at China

**SPPC**
- **100 km in circumference**
- C.M. energy 70-150 (Upgrading) TeV
- **Timeline**
  - Pre-study: 2013-2020
  - R&D: 2020-2030
  - Eng. Design: 2030-2035
  - Construction: 2035-2042

**Main dipoles** \( E[GeV] = 0.3 \times B[T] \times \rho[m] \)
- Field strength: 12-24 (Upgrading) Tesla
- Aperture diameter: 40-50 mm
- Field quality: \( 10^{-4} \) at the 2/3 aperture radius
- Outer diameter: 650-900 mm in a 1.5 m cryostat
- Tunnel cross section: 6 m wide and 5.4 m high

Conceptual design of the SPPC 12-T magnet with IBS and common coil configuration
Future Possibilities: Medical Accelerator Carbon Therapy

- Smaller Accelerator with SCM
Future Possibilities
Synchrotron Light Source

- Superconducting Undulator or Superconducting Focusing Magnets
Summary

• Accelerator and Superconducting Magnet: developed simultaneously

• Superconducting Magnet: Good for Slow Repetition Accelerator
  • Good for Collider and Synchrotron Light Source
  • High Field: limited for NbTi needs new technologies A15 or HTS or IBS

• Not used for high repetition accelerators
  • AC loss, error field due to eddy current etc…
  • But there are needs, such as medical accelerators

• Possibilities for new conductor
  • Nb$_3$Sn or IBS for high field magnet
  • HTS for high field or high temperature
    • High heat load, i.e. high radiation environment, high repetition….

• In any case cost is important issue: chicken or egg