Superconductivity for particle accelerators

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CAS Course on Advanced Accelerator Physics
Warsaw, 27 September-9 October 2015

Contents

• Superconductivity in a nutshell
• Superconductivity and accelerators
• Superconducting magnets for accelerators
• Superconducting RF cavities for accelerators
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• Some ongoing and future projects
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• Superconductivity in a nutshell
Onnes’ measurement of electrical resistivity of mercury at low temperature

At a time when the atomic theory was not established, measuring electrical resistivity vs temperature was a way to explore the scattering of charge carriers and thus the structure of metals.

To study properly the effect of temperature, the sample must be free from impurities.

Mercury, a metal in the liquid state at room temperature, could be easily purified by distillation (it boils at 357 ºC).

H.K. Onnes produced « wires » of mercury by filling glass tubes with connection electrodes: the « wires » get solid upon cooling at -39 ºC.

Discovery of superconductivity (1911)

Heike Kamerlingh Onnes

Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium.

Nobel Lecture, December 11, 1913

Thus the mercury at 4.2K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity.
A superconductor shows zero resistance

The current induced in a ring of superconducting material flows without losses almost indefinitely. Measurements showed a typical time constant for current decay of 100'000 years, i.e. a few billionths per hour!

Onnes immediately tries to use superconductivity for building high-field magnets...

dendum 2.) There is also the question as to whether the absence of Joule heat makes feasible the production of strong magnetic fields using coils without iron. For a current of very great density can be sent through very fine, closely wound wire spirals. Thus we were successful in sending a current of 0.8 amperes, i.e. of 56 amperes per square millimetre, through a coil, which contained 1,000 turns of a diameter of 7/20 square mm per square centimetre at right angles to the turns.

...but stumbles upon their « critical field »!

after this lecture was given and produced surprising results. In fields below a threshold value (for lead at the boiling point of helium 600 Gauss), which was not reached during the experiment with the small coil mentioned in the text, there is no magnetic resistance at all. In fields above this threshold value a relatively large resistance arises at once, and grows considerably with the field. Thus in an unexpected way a difficulty in the production of intensive magnetic fields with coils without iron faced us. The discovery of the
Discovery of the Meissner effect (1933)

Walther Meissner

A superconductor excludes magnetic field from its interior (perfect diamagnet)

Application of a magnetic field above a limit value $B_c$ destroys superconductivity

The superconducting state only exists in a limited domain of temperature and magnetic field

Vortex lattice of type-II superconductors (1954)

Field penetrates locally without destroying superconductivity

Lev Shubnikov
Alexei Abrikosov
Type II superconductors are practical materials

- The superconducting state only occurs in a limited domain of (low) temperature, magnetic field and current density, limited by the «critical surface» of the material.

- The working point must remain below the «critical surface» of the superconductor.

- Operating at lower temperature increases the working range in the magnet design plane $(J_c, B)$.

- In practice, operate at temperature well below $T_c$.

Using superconductivity

Critical surface of Nb-Ti

Ph. Lebrun  
CAS Accelerator Physics Warsaw 2015
Microscopic theory of superconductivity (1957)

BCS theory of superconductivity

- Three major insights:
  - Effective forces between conduction electrons can sometimes become attractive in a solid rather than repulsive, due to electron-phonon coupling
Three major insights:
- Effective forces between conduction electrons can sometimes become attractive in a solid rather than repulsive, due to electron-phonon coupling
- This attractive interaction between two electrons outside an occupied Fermi surface can form a stable bound state (\textit{"Cooper pair"}), however weak the attractive force
- The many-particle wave function describing the pairing of all electrons near the Fermi surface has the form of a coherent state. The density of states shows an energy gap $2\Delta$ at the Fermi level, corresponding to the binding energy of a pair

The width of the gap depends on temperature; its value at zero temperature is proportional to the critical temperature.

The BCS theory predicts the critical temperature from properties of the solid

$$k_B T_c = 1.13 \hbar \omega_D \exp\left(-\frac{1}{U_D(\varepsilon_F)}\right)$$

Hence, critical temperature of BCS superconductor increases with
- Energetic phonons (Debye energy)
- Strong electron-lattice interaction (bad normal conductors)
- High electron density of states at Fermi level
First « high-field » superconducting magnet (1960)

Patent filed in 1960 by J. Kunzler, of Bell Laboratories (registered in 1964)

1.5 T reached with magnet wound from molybdenum-rhenium alloy wire

Discovery of Nb-Ti alloys (1961)

The solid solution alloys formed by testes for superconductivity down to row 4 of the periodic table, two transition points being equal to 4.2 and 6.0, each having a maximum at 6.0. Similar maxima of the periodic table, thus confirmed normal density of states function, N(E) of these peaks lying at about the same constant. The relationship of $\gamma$, to $\Delta (T)$ data are also presented for alloys with

In this case, the form of the relationship

Fig. 6. Transition temperature versus composition for titanium-niobium alloys prepared by different types of heat treatment.
A very frequent phenomenon... at low enough temperature

Towards higher temperatures?
Discovery of « high » temperature superconductors
(1986)

Possible High $T_c$ Superconductivity in the Ba–La–Cu–O System

J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

Metallic, oxygen-deficient compounds in the Ba–La–Cu–O system, with the composition $\text{Ba}_x\text{La}_{y-x}\text{CuO}_z$ have been prepared in polycrystalline form. Samples with $x=1$ and $y>0$, annealed below 900 °C under reducing conditions, consist of three phases, one of them a perovskite-like mixed-valent copper compound. Upon cooling, the samples show a linear decrease in resistivity, then an approximately logarithmic increase, interpreted as a beginning of localization. Finally an abrupt decrease by up to three orders of magnitude occurs, reminiscent of the onset of paramagnetic superconductivity. The highest onset temperature is observed in the 30 K range. It is markedly reduced by high current densities. Thus, it results partially from the percolative nature, but possibly also from 2D superconducting fluctuations of double perovskite layers of one of the phases present.

« High » temperature superconductors
Compactness through higher fields

- **Circular Accelerators**
  \[ p \approx 0.3 \, B \, r \]
  \([\text{GeV/c}]\) \([\text{T}]\) \([\text{m}]\)
  -> superconducting bending and focussing magnets
  - high-energy hadron synchrotrons
  - compact electron synchrotrons
  - LHC \((r = 2.8 \, \text{km}), \, B = 8.33 \, \text{T}\) for \(p = 7 \, \text{TeV/c}\)

- **Linear Accelerators**
  \[ p = f \, E \, L \]
  \([\text{MeV/c}]\) \([\text{MV/m}]\) \([\text{m}]\)
  -> superconducting acceleration cavities
  - high-energy linacs
  - E-XFEL \((L = 1.6 \, \text{km}), \, E = 23.5 \, \text{MV/m}\) for \(p = 17.5 \, \text{GeV/c}\)
Evolution of hadron colliders

- SppS
- ISR
- HERA proton ring
- Tevatron
- RHIC
- LHC

- Larger diameter
- Stronger magnetic field
- Limit of NC magnets

Fermi’s 1954 concept for the « Ultimate Accelerator » was not superconducting!

- Ebeam = 5000 TeV
- B = 2 T
- R = 8000 km ~ 5000 miles

E. Fermi, APS Lecture, Columbia University, 29 January 1954
Superconductivity in accelerators for higher magnetic fields

Magnet power consumption

- Normal conducting (copper)
  - Power dissipation per unit length: \( P/L \sim \rho_{Cu} jB \)
  - Total power dissipation: \( P \sim \rho_{Cu} jB r \sim \rho_{Cu} jB \)
- Superconducting
  - Total power (refrigeration): \( P \sim C \sim r \)

\( \rightarrow \) independent of magnetic field

<table>
<thead>
<tr>
<th>Magnetic field</th>
<th>Normal conducting (1.8 T, limited by iron saturation)</th>
<th>Superconducting (LHC) 8.1 T, limited by critical surface of Nb-Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field geometry</td>
<td>Defined by pole pieces</td>
<td>Defined by windings</td>
</tr>
<tr>
<td>Current density in windings</td>
<td>10 A/mm²</td>
<td>400 A/mm²</td>
</tr>
<tr>
<td>Electromagnetic forces</td>
<td>20 kN/m</td>
<td>3400 kN/m</td>
</tr>
<tr>
<td>Electrical power from grid</td>
<td>10 kW/m</td>
<td>2 kW/m</td>
</tr>
</tbody>
</table>
Superconductivity in circular accelerators for lower power consumption

RF cavity power consumption

• Power dissipation in RF cavity
  - Power per unit length \( P/L \sim R_s E^2/\omega \)
  - Q factor of resonator \( Q \sim 1/R_s \)
  - to reduce power dissipation, need high Q at high field
  - superconductivity allows very high Q values
  - the power is however dissipated at low temperature: the electrical consumption must take into account the efficiency of cryogenic refrigeration

SC cavities Nb at 1.5 GHz Example of Q values for cavities at 500 MHz

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Normal conducting (Copper)</th>
<th>Superconducting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>( 4 \times 10^4 )</td>
<td>( 4 \times 10^9 )</td>
</tr>
<tr>
<td>P at 4.2 K [W/m]</td>
<td>-</td>
<td>0.7</td>
</tr>
<tr>
<td>P at 290 K [W/m]</td>
<td>35'000</td>
<td>350</td>
</tr>
</tbody>
</table>
Optimum operation temperature

- Surface resistance of superconductor
  - BCS theory
  - For practical materials
  - Refrigeration (Carnot)

\[ R_{BCS} = \frac{(A\omega^2)}{T} \exp\left(-\frac{BT_c}{T}\right) \]
\[ R = R_{BCS} + R_0 \]
\[ P = P(T_0/T - 1) \]

\[ R_{\text{opt}} = R_{\text{BCS}} + R_0 \]

- Refrigeration (Carnot)

\[ \eta = \frac{T_0}{T_0 - 1} \]

\[ \text{Cavity loss, Carnot efficiency, Cooling power} \]

Limiting energy stored in beam

- Energy \( W \) stored in beam of circular accelerator of circumference \( C \)
  \[ W \approx 3.34 \times 10^8 \times \frac{C}{\text{GeV/c} A \text{ km}} \]

\( \Rightarrow \) For a given beam intensity, beam stored energy is lower for a smaller machine

Example: LHC

\[ p = 7000 \text{ GeV/c} \]
\[ I_{\text{beam}} = 0.56 \text{ A} \]
\[ C = 26.7 \text{ km} \]
\[ W \approx 350 \text{ MJ} \]

\( \Rightarrow \) Enough to heat and melt \( \approx 500 \text{ kg} \) of copper
Low wall impedance for beam stability

- Interaction between the beam and the wall of the beam pipe can be characterized by a transverse impedance

\[ Z_T(\omega) \sim \rho \frac{C}{\omega b^3} \]

\( \rho \) electrical resistivity of wall

\( b \) half-aperture of beam pipe

- This interaction leads to power dissipation and to beam instabilities
  - Important in large accelerators
  - Must be compensated by feedback provided that characteristic time for development of the instability be long enough \( \tau \sim 1/Z_T \)

- In a large accelerator with small aperture, low transverse impedance is achieved by reducing \( \rho \) i.e. with a good electrical conductor (copper) at low temperature

LHC beam screens

LHC beam screens

75 μm Cu co-laminated on 1 mm austenitic steel, cooled < 20 K

Cryopumping of beam vacuum

Saturation pressure of all gases except helium vanish at cryogenic temperature

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Rationale for superconductivity & cryogenics in particle accelerators

Cryogenics
Superconductivity
Compactness

- Cryopumping
- Beam impedance
- Zero resistance
- Limit beam stored energy
- Reduce power consumption
- Beam vacuum
- Beam stability
- Reduce cost

How?  Why?

The Tevatron at Fermilab (Batavia, USA)
The first superconducting particle accelerator

Started operation in 1983 as synchrotron, upgraded as collider (1.8 TeV c.m.)
Circumference 6.3 km
Magnetic field 4.4 T
990 main superconducting magnets, cooled at 4.4 K by supercritical helium
The LHC at CERN
The largest scientific instrument in the world

Started operation 2008
Circumference 26.7 km
Magnetic field 8.3 T
1706 main superconducting magnets, cooled at 1.9 K by superfluid helium

CEBAF at the Jefferson Lab (Newport News, USA)
The first large-scale superconducting RF accelerator

Started operation 1995, upgraded 2014
Two recirculating linacs producing 12 GeV electron beams
1.5 GHz Nb cavities
50 cryomodules cooled at 2 K in superfluid helium
• Superconducting magnets for accelerators

![Critical current density vs applied field of technical superconductors](image)
Engineering current density vs applied field of technical superconductors

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Number</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconductor</td>
<td>20 000</td>
<td>SC is not a rare phenomenon</td>
</tr>
<tr>
<td>$T_c \geq 10$ K</td>
<td>2 000</td>
<td>Need factor 2 over $L_{He}$</td>
</tr>
<tr>
<td>$B_{c2} \geq 10$ T</td>
<td>200</td>
<td>Needs factor 2 over $B_{op}$</td>
</tr>
<tr>
<td>$J_c \geq 1$ GAm$^2$ @ $B \geq 5$</td>
<td>20</td>
<td>$J_{coil} - J_{c/10}$</td>
</tr>
<tr>
<td>Technical superconductor</td>
<td>2</td>
<td>Nb-Ti and Nb$_3$Sn</td>
</tr>
</tbody>
</table>

Practical superconductors

<table>
<thead>
<tr>
<th>Type</th>
<th>Status</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-Zr</td>
<td>Dismissed</td>
<td>First SC magnet</td>
</tr>
<tr>
<td>Nb-HF</td>
<td>Dismissed</td>
<td>Used in Homer (KIT)</td>
</tr>
<tr>
<td>V$_{3}$Ga</td>
<td>Dismissed</td>
<td>Small coil test</td>
</tr>
<tr>
<td>Nb-Ti</td>
<td>Mature</td>
<td>$&gt; 2000$ tonnes/year</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>Industry development</td>
<td>$100$ tonnes/year (50% ITER)</td>
</tr>
<tr>
<td>Bi-2223</td>
<td>Industry R&amp;D</td>
<td>$500$ kg/y? (1-2 manufacturers)</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>Industry and Lab R&amp;D</td>
<td>$100$ kg/y? (only one manufacturer)</td>
</tr>
<tr>
<td>YBCO / REBCO</td>
<td>Industry and Lab R&amp;D</td>
<td>$1$ tonne/y? (&gt; 5 manufacturers)</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>Industry and Lab R&amp;D</td>
<td>$&gt; 1$ tonne/y? (4-5 manufacturers)</td>
</tr>
</tbody>
</table>

L. Rossi
Superconducting accelerator magnets

In a superconducting magnet, the field level and geometry is basically given by the current distribution in the coils.

To match the geometry of the beam tubes, the coils are saddle-shaped & elongated. In the LHC, two sets of coils create opposite fields in the neighbouring apertures.

Producing the field: current distributions

Two intersecting ellipses with uniform current density generate uniform dipole and quadrupole fields → “cos θ” geometry.

In practice, this can be approximated by current sheets, leading to “block” or “layer” coil designs.
“Rutherford” superconducting cable

- Invented at the Rutherford Laboratory (UK) in the 1970s
- Challenge: produce a high-current (>kA) conductor for superconducting magnets
- Constraints
  - Small-diameter filaments for thermal stability and low remanent magnetization
  - Transposed wires for electromagnetic decoupling and low AC losses
  - Flat, keystoned, high-precision geometry for winding cos θ coils
  - Dielectrically rigid, mechanically resistant insulation with helium porosity

Keystoned cable made of ~1mm strands

Manufacturing of superconducting wires & cables
Field of single-layer dipole coil

Average current density in coil

\[ B = \frac{\mu_0 \sqrt{3}}{\pi} j_{\text{tech}} w \]

Coil width

Superconducting cos θ dipoles in Nb-Ti

Coil width vs field

- Nb-Ti at 4.2 K
- Nb-Ti at 1.9 K
- RHIC
- TeVatron
- HERA
- SSC
- LHC
Load lines of LHC main dipole

Current grading permits the outer cable, which sees a lower field, to operate at higher current density.

Inter-layer splice in graded coil
Field quality in superconducting magnets
Conductor placement

• In superconducting magnets, the field quality is determined by the positioning precision of a finite number of conductors and not by the geometry of the iron yoke, so it can never be as good as in conventional "iron-dominated" magnets
• As a consequence, the « good field » region is substantially smaller than the magnet aperture
• Dynamic aperture = aperture inside which particle orbits are stable
• Dynamic aperture is estimated by computer « tracking » of particle orbits around virtual machines with distributed random and systematic imperfections
• Tracking results are used to define maximum systematic and random deviations of each field multipole

\[
B_y + iB_x = B_1 \sum_{n=1}^{\infty} (b_n + i a_n \frac{x + iy}{r_{ref}})^n
\]

• The field is periodical over a rotation of 2\(\pi\); it can therefore be represented as a Fourier series, with the field errors as higher harmonics ("multipoles")

Field quality in superconducting magnets
Persistent currents

• Eddy currents flow in part of the superconductor filaments to shield the inside from outer field variations
• Quasi-infinite time constant \(\Rightarrow\) «persistent» currents
• Produce remanent magnetization in superconductor filament
• In case of full penetration in round filament, remanent magnetization is

\[
M = \pm \frac{2}{3\pi} \mu_0 J D \lambda
\]

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Field quality in superconducting magnets
Persistent currents

Magnetization of a typical LHC strand

Sextupole in a typical LHC dipole

Obtaining the field quality: corrector magnets

Schematic layout of one LHC cell (23 periods per arc)
Containing the electromagnetic forces

High magnetic field acting on high current generates large electromagnetic forces at right angle, which cannot be resisted by the mechanical strength of the conductor: saddle-shaped coils of accelerator magnets are not self-supporting.

\[ B = 10 \, \text{T}, \, I = 10 \, \text{kA} \Rightarrow 10^5 \, \text{N/m per turn}! \]

⇒ “roman arch” coil geometry to contain the azimuthal component

⇒ external support structure against the radial component

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Mechanical structure of LHC dipole

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Superconductors are basically unstable!

Heat capacity of materials drops at low temperatures
\[ \Delta T = \Delta E / C \]
\( \Delta E \) of few \( \mu \)J on a superconducting strand in the cable generates \( \Delta T \) pushing the operating point beyond the critical surface \[ \Rightarrow \text{resistive transition ("quench") } \]

Temperature margin of superconductor \( \sim 1.5 \text{ K} \)
Specific quench energy \( \sim 10 \text{ mJ/cm}^3 \)
Energy stored inductively in magnet 6.9 MJ
Energy stored in beam 360 MJ

Training of superconducting magnets
LHC dipole

10 T in magnet bore
8.3 T in magnet bore
Typical thermal perturbation spectrum of superconductor in a particle accelerator

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Transient stability of superconducting cable
Helium is an essential element of cable stability

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SC magnets must resist quench
Hot spot temperature after a quench

Assume that quenched section is heated only by Joule effect and adiabatic (no conduction)

\[ J^2(t) \tau(T) dt = \gamma C(T) dT \int_0^T J^2(t) \tau^{-1}(T) \frac{\gamma C(T)}{\rho(T)} dT \]

\[ J_0^2 \tau_0 = U(T_m) \]

To avoid too high hot spot temperature, speed up the quench propagation by any means

1) **Heater**: must be activated fast and reliably (20 ms)

2) "**Quench-back**" inductively propagated

*This goes against having LHe in good contact with the conductor (i.e. against stability)*!

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**LHC magnet circuit protection scheme**

- **Dissipate energy of magnet string by inserting discharge resistor in circuit**
- **Fire heater to spread the quench over maximum coil volume and limit temperature**
- **Free-wheeling diode across power converter**
- **Diode bypasses quenched magnet during current discharge in string**

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Manufacturing of LHC dipole superconducting coils

Assembly of LHC dipole cold masses
• Superconducting RF cavities for accelerators

4-cell, 352 MHz Nb on Cu cavity for LEP2
400 MHz Nb on Cu cavities in LHC tunnel
9-cell, 1.3 GHz Nb prototype cavity for the ILC
Optimizing geometry of elliptical SC cavity

- Optimization strategies
  - Minimize $E_{\text{peak}}/E_{\text{acc}}$ to limit field emission
  - Minimize $H_{\text{peak}}/E_{\text{acc}}$ to stay away from critical magnetic field and reduce risk of quench
  - Increase shunt impedance $R/Q$ to reduce power dissipation

- New cavity shapes
  - «Re-entrant»
  - «Low-loss»

Performance limitations of SC cavities
Degradation of surface resistance by H-related Q disease

- Mechanism
  - Hydrogen dissolved in Nb precipitates as hydrides at cavity surface
  - Depends on quantity of dissolved H, other impurities, cooldown rate

- Cures
  - H degassing in vacuum at high temperature
  - Fast cooldown
Performance limitations of SC cavities
Multipacting

- Mechanism
  - Multiple-impact resonant electron amplification
  - Leads to local heat deposition, Q decrease and X-ray emission
  - Controlled by SEY from surface
- Diagnostics
  - Heat maps
  - X-ray maps
- Cures
  - Numerical simulation codes
  - Conditioning to reduce SEY

Performance limitations of SC cavities
Field emission

- Mechanism
  - Electron current from high-field emitters on cavity surface, e.g. microparticle contaminants, dust,...
  - Produces Q drop at high field
- Cures
  - Surface cleanliness
    - Assembly in class <100 cleanroom
    - High-pressure rinsing
  - In-situ elimination of emitters
    - RF processing
    - High pulse-power processing
    - Helium processing
Ta defect on Nb located by thermometry and confirmed by radiography

(a) crystal inclusion; (b) drying stain; (c) copper particle; (d) sharp-edged pit; (e) Nb ball; (f) weld hole

Contents

- Superconducting current leads and powering links
Current leads and cables operate in self-field

Bringing the current into the cryogenic environment: cryogenic current leads

Heat transfer processes at work
- Solid conduction
- Joule heating
- Convective cooling by He vapor

Metals are good electrical AND thermal conductors (Wiedemann-Franz-Lorentz law)
Optimal sizing of current lead results from compromise between heat conduction and Joule heating

Superconductors do not follow WFL law
They are perfect electrical conductors with low thermal conductivity
They can make excellent current leads... up to their transition temperature!
⇒ niche application for “high-temperature” superconductors
Current leads using HTS superconductor
The LHC case

<table>
<thead>
<tr>
<th>Resistive (WFL)</th>
<th>HTS (4 to 50 K)</th>
<th>Resistive (&gt; 50 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat leak to liquid helium</td>
<td>1.1 W/kA</td>
<td>0.1 W/kA</td>
</tr>
<tr>
<td>Exergy loss</td>
<td>430 W/kA</td>
<td>150 W/kA</td>
</tr>
<tr>
<td>Electrical power of refrigerator</td>
<td>1430 W/kA</td>
<td>500 W/kA</td>
</tr>
</tbody>
</table>

Sum of currents into LHC ~ 1.7 MA, i.e. need current leads for 3.4 MA total rating (in and out)

Economy ~ 3400 W in liquid helium ~ 5000 l/h liquid helium
⇒ capital: save extra cryoplant
⇒ operation: save ~ 3.2 MW

BSCCO 2223 tapes
Nb-Ti wires

13 kA HTS current lead for LHC

6 & 13 kA leads on electrical feed-box

Water-cooled cables on current lead lugs
SC links using MgB$_2$ wires for HL-LHC

Record current of 20 kA transported at 24 K in MgB$_2$ cable

Contents

- Some ongoing and future projects
**European Spallation Source at Lund, Sweden**

**Long-pulse neutron source**
- 5 MW, 2 GeV proton beam
- 62.5 mA
- 2.86 ms pulse length
- 14 Hz
- Low losses
- High availability > 95%
- High efficiency

**The International Linear Collider (ILC) project**

**Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>500 GeV</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$1.8 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Beam Rep. rate</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>0.73 ms</td>
</tr>
<tr>
<td>Average current</td>
<td>5.8 mA (in pulse)</td>
</tr>
<tr>
<td>Gradient in SCRF acc. cavity</td>
<td>31.5 MV/m $\pm$20% $Q_0 = 1E10$</td>
</tr>
</tbody>
</table>

Damping rings
Polarised electron source
Ring to Main Linac (RTML) (including bunch compressors)
Future Circular Colliders (FCC) study at CERN

Hadron collider:
- 16 T → 100 TeV for 100 km
- 20 T → 100 TeV for 80 km

Quasi-circular tunnel of 80-100 km perimeter

e+ e- collider:
- Collision energy 90 to 350 GeV
- Very high luminosity

Hadron collider:
- 16 T → 100 TeV for 100 km
- 20 T → 100 TeV for 80 km

Quasi-circular tunnel of 80-100 km perimeter

Conceptual design for a 20 T twin dipole
- Nested coils using multiple superconductors

Would yield 33 TeV collision energy in LHC tunnel, 100 TeV in new 80 km tunnel

Magnet design very challenging: 300 mm inter-beam; anticoils to reduce stray flux; multiple powering in the same magnet for field quality

L. Rossi & E. Todesco
Compact SC synchrocyclotron for hadrontherapy
(Still River Systems)

- Provides 250 MeV protons
- 20 t mass allowing integration in gantry
- Cryocoolers at 4.5 K (no liquid helium)

Selected bibliography

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  - Superconductivity in Particle Accelerators, Hamburg (1995) CERN-96-03
  - Superconductivity for Accelerators, Erice (2013) CERN-2014-005

- Reports

- Books