Overview

- Why superconductors? A motivation
- Superconducting magnet design
  - Magnetic field and field quality
  - Margins and stability
  - Forces and mechanics
  - Quench protection
- A brief history of superconducting HEP magnets
- The making of a superconducting LHC magnet
- Towards higher fields
  - High field LTS magnets
  - Outlook of HTS magnets
- Other superconducting magnet systems

Part I

Part II
Overview

- A brief history of superconducting HEP magnets
- The making of a superconducting LHC magnet
- Towards higher fields
  - High field LTS magnets
  - Outlook of HTS magnets
- Other superconducting magnet systems
Magnet engineering is born!

- **G. Yntema, 1954:** Nb wire on an iron-core, produced 0.71 T ("I saw no reason why a magnet could not be made with superconducting windings, so I gave it a try")

  

- **J. Hulm, 1955:** Nb-wire air-core solenoid, produced 0.6 T

- **S. Autler, 1960:** Nb wire on an iron-core, produced 1.4 T for a solid state MASER

- **J.E. Kunzler, September 19, 1960:** first patent for a Superconducting Magnet Configuration (Patent 3,129,359, April 14th, 1964)
Cold worked Nb wires (Yntema, 1954): 1000 A/mm² at 0.5 T and 1.7 K

Mo₃Re wires (Kunzler, 1959): 500 A/mm² at 1.5 T and 1.5 K

Nb₃Sn wires (Kunzler, 1961): up to 1000 A/mm² at 9 T and 1.5 K

NbTi wires (Berlincourt, 1962): from 440 A/mm² at 3T and 4.2 K to 100 A/mm² at 10 T and 4.2 K

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Setting the scene

- International Conference on High Magnetic Fields, hosted by MIT, Boston, 1961:
  - J.E. Kunzler (Bell Labs) Nb$_3$Sn magnet achieves 68 kGauss, barely surpassing the 60 kGauss reported by J. Hulm (Westinghouse) and T. Berlincourt (Atomics International) in NbZr solenoids.

- The *scotch bet* (Tanenbaum vs. Kunzler):
  - A bottle of scotch for every 3 kG above 25 kG.
  - The *first 10 T solenoid* was built by Kunzler’s group 2 crates of scotch later.
Dealing with flux-jumps

"Those tiny, primitive magnets were, of course, terribly unstable" (J. Hulm, ASC 1982)
The 1968 *Woodstock* of superconducting accelerators

- A six weeks summer study organized and hosted by BNL in 1968
- The *crème de la crème* addresses material and engineering issues of superconducting accelerators
First ideas are discussed

- **Issues addressed at the 1968 Summer Study**
  - Stability and stabilization strategies
  - Flux-jump instability, filamentary superconductors
  - AC loss, coupling and the need of twisting
  - **Potential for the use in superconducting synchrotrons**
The ISR’s

- The Intersecting Storage Rings (ISR) was the world first hadron collider
- It ran from 1971 to 1984 with maximum center-of-mass energy of 31+31GeV
- Held the record luminosity ($1.4 \times 10^{32} \text{ 1/cm}^2 \text{ s}$) for hadron colliders till 2004
- **Hosted the first accelerator SC quadrupole magnets**
ISR low-\(\beta\) quads

- **1973** – Study launched on low-beta (high-luminosity) insertions using superconducting quadrupole magnets
- **1976** – First prototype of a superconducting quadrupole tested
- **1985** – Manufacture of 8 quadrupoles (4 of L=1.15 m, 4 of L=0.65 m) begins at Alsthom. They are installed at intersection I8 of the ISR, enhancing luminosity by a factor 7
From strands to cables


W.B. Sampson, Proc. 1968 Summer Study, BNL, 998-1001, BNL 50155 (C-55), 1968

Exotic new products derived from research on superconductivity have been predicted to revolutionize things ranging from railroads to power lines, but it is now virtually certain that the first major activity superconductivity will revolutionize will be that of accelerator building.
Isabelle

- **1963** – Summer Study at BNL considers storage rings for a colliding beam accelerator
- **1970** – Idea revived by J. Blewett
- **1972** – Fitch Committee recommends that BNL develops the concept for an *Intersecting Storage Accelerator + BELLE* (ISABELLE)
- **1973** – Design study at Brookhaven completed for a 200+200 GeV proton collider
- **1978** – Groundbreaking

Isabelle

- **1979** – Successful test of model magnet, reaching 5 T
- Energy raised from 200 to 400 Gev, requiring nominal dipole field from 4 to 5 T (*single layer, large braided cable*)
- Construction started before completion of the supporting magnet R&D

“Isabelle’ braid

A.D. McInturff, , Superconducting Magnets at Brookhaven National Laboratory, World Electrotechnical Congress, Moscow, USSR, 6/21-25/77
From Isabelle, to CBA, into oblivion

- Technical difficulties in magnet performance experienced in 1981
- Machined renamed to Colliding Beams Accelerator
- Production cost increases, timeline slips
- Questions on competitiveness vs. new 20 TeV concept (SSC)

Project cancelled by DOE in 1983, after spending > 200 M$, large part of which in civil engineering (tunnel)
The energy *doubler* and *saver* at NAL

Robert R. Wilson, March 9th, 1971, in Washington, D.C.:

"It appears now that such a possibility [500 GeV] may become feasible in the concept of what I like to call an 'energy doubler.' It is a small-bore superconducting magnet that can be mounted 'pickaback' on the present main ring magnet. If successful, it should be of modest cost and should enable us to achieve higher energies -- as much as 1,000 BeV. Just as important, though, is that operation above the 200 BeV level would cost much less using the superconducting magnet than it would using our present copper and iron magnets... I would hope, too, that ... the Committee will challenge me to build as extensive experimental facilities and attain as high an energy as is possible without exceeding the Congressional authorization of $250,000,000."
Concepts for the doubler


R. Wilson


Main ring

Doubler

Superconducting strand

Dipole magnet concepts
We started out by straightforwardly applying logic and Maxwell's Laws. This attempt only demonstrated the hubris of experimental physicists; there were too many unknown and uncontrollable variables. Our next approach, largely Edisonian, was to build dozens and dozens of supermagnets, each only about one foot long but full scale in cross section. We built on our successes, tried to avoid repeating our failures, and accumulated experience; gradually the magnets improved until by now they are of quite adequate quality for an accelerator or a storage ring. Two rules summarize our experience: Permit little or no motion of the superconductor, and let the helium coolant bathe the superconductor as directly as possible. To this we might add that the superconductor should be as filamed as is practical.

R.R. Wilson, The Tevatron, TM-763, 1978
**The Tevatron!**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection (GeV)</td>
<td>151</td>
</tr>
<tr>
<td>Flat-top (GeV)</td>
<td>980</td>
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<tr>
<td>Length (km)</td>
<td>6.3</td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>4.3</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>76</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>4.2</td>
</tr>
<tr>
<td>Commissioned</td>
<td>1983</td>
</tr>
</tbody>
</table>

Image by courtesy of Fermi National Accelerator Laboratory
Hadron Elektron Ring Anlage

- **1977** – Ch. Llewellyn-Smith, B. H. Wiik: “Physics with large electron-proton colliding rings”.

July 1981

B.H. Wiik
Accelerator technology at HERA


SC magnet testing

Reference magnets
International collaborations and celebrations

International Collaboration in the Construction of the HERA Collider

The electron-proton collider HERA, built at DESY, the German High Energy Physics Laboratory in Hamburg, is the result of an international collaboration with contributions from laboratories and research centres from six countries. These contributions came in the form of components for the HERA storage rings and injection systems, developed and constructed by the participating institutes in collaboration with their local industry. Additionally, skilled staff from five countries were sent to DESY for one to three years to join in the HERA construction.

The contributions in detail are:

Canada
TRIUMF Laboratory, Vancouver
Design and construction of the 80 metre beam transport system to take the 50 MeV negative hydrogen ions from the linear accelerator "LINAC III" to the proton synchrotron "DESY II".

Chalk River Nuclear Laboratory AECL, Chalk River
Design, construction and test of the 52 Mega-Hertz radiofrequency systems for the proton acceleration in PETRA II and the take over of the proton bunches injected into HERA.

France
CEN Laboratory, Saclay
In collaboration with DESY, design of the superconducting quadrupole magnets for the proton storage ring, development of the production tools and prototype construction, technical responsibility for the whole series production of 246 quadrupoles in two production lines, and as a French contribution the supply of 126 quadrupoles manufactured by French industry.

Israel
Weizmann Institute of Science, Rehovot
Design, construction and test of the transition sections of the main current leads which connect the 4.5 K coil and the room temperature current leads for the superconducting magnets of the proton storage ring.

Italy
Istituto Nazionale di Fisica Nucleare INFN, Roma
Delivery of 232 superconducting 16 metre long bending magnets, manufactured completely by Italian industry - this amounts to half of the total number of superconducting dipole needed for the proton storage ring.

Netherlands
National Institute for High Energy Physics Nikhef, Amsterdam
Development of superconducting correction elements in co-operation with DESY and Dutch industry, delivery of about 450 correction quadrupole and sextupole coils and 250 correction dipoles manufactured by Dutch industry.

United States
Brookhaven National Laboratory BNL, Upton
Quality control (short sample tests) of single wires and of the total quantity of all superconducting cable for the dipole and quadrupole magnet coils, and correction elements.

PR China, CSFR, former GDR, Poland, United Kingdom
Physicists, engineers and technicians from five countries were sent to DESY to collaborate in the HERA construction, most of them on a rotating basis (their stay in Hamburg was normally between one and three years). About 50 people from P.R. China, 3 from Czechoslovakia, 3 from Germany GDR, 40 from Poland, and 3 from United Kingdom worked at DESY at the same time. They were engaged in nearly all the proton aspects of the project, for example: H injection system (source, r.f. quadrupole, and linear accelerator), vacuum system for the proton ring, test of the superconducting magnets, proton beam abatement system, design of the proton r.f. system, beam orbit calculation, and in the development of superconducting r.f. cavities for the electron ring.
The *sine-qua-non* accelerator

- **July 1983** – HEPAP recommendation of “...exploiting our superconducting magnet technology with an energy goal of 10 to 20 TeV per beam...”
- **1984** – National Reference Designs Study (RDS) for a 20 TeV proton machine, hosted by LBNL, DOE recommends proceeding with R&D
- **1984** – Central Design Group (CDG) formed at LBNL
- **1987** – Site selection process
- **1989** – Superconducting Super Collider (SSC) Laboratory established in Texas
- **1991** – Major construction start. Seventeen shafts sunk and 23.5 km (14.6 mi) of tunnel by late 1993
6.5 T, high field, two-in-one option, (by BNL and LBNL) resurrected from the waning days of ISABELLE/CBA

5T medium field option (by FNAL), based on the Tevatron cos-θ coils

3T superferric low field option (by TAC)
From SSC to Desertron to oblivion

- **1987** – Heated debate on cost. Estimate of 4.4 B$ strongly supported by the Texas representative at Congress
- **1993** – Cost projection reaches 12 B$, similar to the ISS. Strong criticism triggered an audit from DOE
- **October 1993** – Congress cancels the project, after 2 B$ were spent in the program
A phoenix from the ashes

- **1983** – At the meeting of the U.S. Nuclear Science Advisory Committee (NSAC) in Aurora (NY) a physics quorum pledged for a heavy ion collider in the CBA tunnel
- **1984** – First proposal submitted
- **1991** – Funding released to start construction of the Relativistic Heavy Ion Collider (RHIC)
Magnet technology at RHIC

Arc dipole

Nested correctors
RHIC!

Injection (GeV) 12/n
Flat-top (GeV) 100/n
Length (km) 3.8
Dipole field (T) 3.5
Aperture (mm) 80
Temperature (K) 4.3-4.6
Commissioned 2000

Image by courtesy of Brookhaven Accelerator Laboratory
Labouring for Half a Century (LHC)

- **1984** – Concept and preliminary studies
- **1988** – Model magnets demonstrate feasibility
- **1990** – R&D program launched
- **1994** – Project approved by the CERN council
- **1996-1999** – Transfer of technology to industry
- **1998** – Start civil engineering
- **1998 – 2001** – Main contracts signed
- **2003** – Start tunnel installation
- **2005-2007** – Magnet installation
- **2007** – First sector test
- **2008-2030** – Physics

Personal Note: joined CERN 1995
LHC Origins
ECFA – Lausanne 1984

Synopsis of hadron collider options for the LEP tu
Earlier traces of the *two-in-one* concept

John P. Blewett, 1971

SSC high field

Assembly work at BNL


SSC vs. LHC

G. Brianti had various reasons for *headaches* in the race of the two projects:

- The existing LEP tunnel imposed a given radius and cross sectional space to the new accelerator – *Field*!
- The missing factor in energy (8.5+8.5 TeV for LHC vs. 20+20 TeV for SSC) needed to be compensated by a higher luminosity (design value of $10^{34}$ 1/cm² s for LHC vs. $10^{33}$ 1/cm² s for SSC) – *Aperture and quality*!

R&D focus was the key!

- **High field**: aim at 8 to 10 T bore field
- **Two-in-one**: to gain space in the crammed tunnel space for the widest possible magnet bore
LHC twin-aperture dipole magnets

Concept perfected (design), demonstrated (models and prototypes) and realized on a large industrial scale

R. Perin  C. Wyss  L. Rossi
The LHC superconducting magnet zoo

By courtesy of S. Russenschuck (CERN)
LHC!

- Injection: $450 \text{ GeV}$
- Flat-top: $7 \text{ TeV}$
- Length: $26.7 \text{ km}$
- Dipole field: $8.3 \text{ T}$
- Aperture: $56 \text{ mm}$
- Temperature: $1.9 \text{ K}$
- Commissioned: 2008
September 10th, 2008...

First turn!
...September 19th, 2008...

Unprotected quench of defective joint

Arcing in an interconnection

Over-pressure

Magnet displacement
...back to work in 2009...

1. 14 quadrupole magnets replaced
2. 39 dipole magnets replaced
3. 54 electrical interconnections fully repaired. 150 more needing only partial repairs
4. Over 4 km of vacuum beam tube cleaned
5. A new longitudinal restraining system is being fitted to 50 quadrupole magnets
6. Nearly 900 new helium pressure release ports are being installed around the machine
7. 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid
…November 30th, 2009…

LHC surpasses a proton beam energy of 1 TeV
Overview

- A brief history of superconducting HEP magnets
- The making of a superconducting LHC magnet
- Towards higher fields
  - High field LTS magnets
  - Outlook of HTS magnets
- Other superconducting magnet systems
LHC dipole

LHC DIPOLE CROSS SECTION

$B_{\text{nominal}}$ current
11850 (A)

stored energy
$\approx 10$ (MJ)

cold mass
$\approx 35$ (tonnes)
Superconducting dipole magnet coil

Ideal current distribution that generates a perfect dipole

Practical approximation of the ideal distribution using Rutherford cables
Technical coil windings

LHC arc dipole

Magnet bore

Coil blocks

Spacers

Superconducting cable

LHC arc quadrupole
Twin coil principle

Combine two magnets in one
Save volume, material, cost
LHC dipole coils
Fine cables

LHC *inner* cable

LHC Nb-Ti strand

LHC outer cable cross section

7500 km of superconducting cables with tightly controlled properties (state-of-the-art production)
Coil winding

10 \( \mu \text{m} \) precision!

Coil winding machine

Cable insulation

Stored coils
Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet.
Collaring and yoking
Magnet assembly

Alstom
Noell
Ansaldo
Cold mass
Cryo-magnets and tests

Magnet reception, cryostating, preparation for cold test and “stripping” for installation

Magnet powering tests and magnetic measurements
Magnet installation

Descent in the tunnel

Magnet transport and installation
Interconnection

65’000 electrical joints
Induction-heated soldering
Ultrasonic welding
Very low resistance
HV electrical insulation

40’000 cryogenic junctions
Orbital TIG welding
Weld quality
Helium leaktightness
Large scale use of HTS

Warm end (300K)

BSCCO 2223

50 K

4.2 K
Finally, in the tunnel!
Overview

- A brief history of superconducting HEP magnets
- The making of a superconducting LHC magnet
- **Towards higher fields**
  - High field LTS magnets
  - Outlook of HTS magnets
- Other superconducting magnet systems
Dipole field generated by a current distribution with constant current density $J$ over a sector of inner radius $R_{in}$, outer radius $R_{out}$, coil width $w = R_{out} - R_{in}$ and opening angle $\varphi$:

$$B = \frac{2}{\mu_0} J w \sin(\varphi)$$

First challenge: $J_c$

$$A_{coil} = 2 \left( w^2 + 2 R_{in} w \right) \mu_0 \frac{1}{J^n}$$

$n \approx 1...2$

In the range of typical magnet designs considered $n \approx 1.5$

<table>
<thead>
<tr>
<th>$B$ (T)</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J$ (A/mm$^2$)</td>
<td>300</td>
</tr>
<tr>
<td>$w$ (mm)</td>
<td>76</td>
</tr>
<tr>
<td>$A_{coil}$ (mm$^2$)</td>
<td>20,000</td>
</tr>
</tbody>
</table>

$A_{coil} \mu M_{coil} \mu COST$

| 16 |
| 600 |
| 38 |
| 7000 |

Factor 2

Factor 3
Challenge #1: Jc

600 A/mm²
Challenge #2: Abolish training!
Lorentz forces in the plane of a thin coil of radius $R_{in}$ generating a dipole field $B$ (thin shell approximation), referred to a coil quarter

$$F_x = F_y \frac{4}{3^2} \frac{B^2}{2\mu_0} R_{in}$$

Progression of $F_x$:

- LHC MB(8.33T) $\approx$ 1.7 MN/m
- LHC MBH(11T) $\approx$ 3.2 MN/m
- FRESCA2(13T) $\approx$ 7.6 MN/m
- FCC MB(16T) $\approx$ 8 MN/m
- HE-LHC MB(20T) $\approx$ 10 MN/m
Old structures, new structures

mid 1970’s, FNAL: Collared coils

1998, TAMU: Stress management

2002, LBNL: Bladder and keys

2014, LBNL: CCT

2017, FNAL: SM cos(θ)

1975, MIT: CICC
Challenge#3: Structures and stress

\[ F \mu B^2 \left\{ w \mu \frac{B}{J} \right\} \xrightarrow{\text{reduce J}} \frac{F}{w} \mu JB \]

![Graph showing peak stress vs bore field](image)

- Stress limited reducing J
- Unconstrained scaling
- FCC
- QXF
- 11T
- HE-LHC
- LHC
Protection at high fields

\[ E/l = \frac{B^2 R_{in}^2}{1 + \frac{2}{3} \frac{w}{R_{in}} + \frac{1}{6} \frac{w}{R_{in}}} \]

\[ V/l = \frac{2E/l}{I_{op}} \]

A simple exercise:

\[ J_{Cu} \approx 1000\ldots1250 \text{ (A/mm}^2\text{)} \]
\[ dT/dt \approx 1000\ldots2000 \text{ (K/s)} \]
\[ \tau_{(300 \text{ K})} \approx 0.15\ldots0.3 \text{ (s)} \]
\[ I_{op} \approx 15 \text{ (kA)} \]
\[ E/l \approx 1000 \text{ (kJ/m)} \]
\[ V/l \approx 500\ldots1000 \text{ (V/m)} \]

It is not possible to protect accelerator magnet strings using an external dump.
Challenge#4: Ultimate protection limit

\[ \frac{E}{l} \mu B^2 \]

\[ A_{\text{coil}} \mu \frac{B^n}{J} \]

\[ e \frac{E}{l} \mu J^n B^2 n \]

Typical energy densities \( e \):

- LHC MB(8.33T) \( \approx 50 \text{ MJ/m}^3 \)
- LHC MBH(11T) \( \approx 85 \text{ MJ/m}^3 \)
- FRESCA2(13T) \( \approx 100 \text{ MJ/m}^3 \)

- FCC MB(16T) \( \approx 200 \text{ MJ/m}^3 \)

In the range of typical magnet designs considered \( n \approx 1.5 \)
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Stability (and no training) in HTS

\[ H(T) = \int_0^T C(T) \, dT \]

![Graph showing stability and training in HTS](image)
HTS challenges

- HTS materials have spectacular critical fields (100 T, and higher) and engineering current densities (1000 A/mm² at 4.2 K and 20 T, and higher)
  ✔
- Stability is large enough (100...1000 mJ/cm³) to withstand any foreseeable and unforeseeable internal and external perturbation
  ✔
- We could build them right away?
Challenge #1: Quench detection

- Quench propagation speed

\[ v_{\text{adiabatic}} = \frac{J_{\text{op}}}{C} \sqrt{\frac{k_{st}}{T_J - T_{op}}} \]

Example LTS:
- \( J_{\text{op}} \approx 100 \times 10^6 \text{ (A/mm}^2) \)
- \( C \approx \rho \times c_p = 10^4 \times 10^{-1} \text{ (J/m}^3 \text{ K)} \)
- \( \eta \approx 10^{-9} \text{ (}\Omega \text{ m)} \)
- \( k \approx 100 \text{ (W/m K)} \)
- \( T_J - T_{op} \approx 2 \text{ (K)} \)
- \( v \approx 22 \text{ m/s} \)

Example HTS:
- \( J_{\text{op}} \approx 100 \times 10^6 \text{ (A/mm}^2) \)
- \( C \approx \rho \times c_p = 10^4 \times 10 \text{ (J/m}^3 \text{ K)} \)
- \( \eta \approx 10^{-9} \text{ (}\Omega \text{ m)} \)
- \( k \approx 10 \text{ (W/m K)} \)
- \( T_J - T_{op} \approx 10 \text{ (K)} \)
- \( v \approx 3 \text{ cm/s} \)

The detection of a quench is a major challenge in HTS magnets.
Challenge #2: Wires and cables

BSCCO-2212

HT at 900 °C, 50…100 bar

REBCO

2…10 mm tapes, cannot be folded

CORC cable

Roebel cable
Challenge #3: Stress

**BSCCO-2212 wire**

**REBCO Roebel cable**

- **Impregnated cable**
  - 75 MPa
  - 100 MPa
  - 400 MPa

- **Bare cable**
Challenge #4: Material availability

- Cost of material is usually compared on the basis of identical unit current carrying capacity:

\[ C \text{ [EUR/kA m]} = 10^3 \frac{c\text{[EUR/kg] } \rho\text{[kg/m}^3\text{]} / J_E\text{[A/m}^2\text{]}}{}} \]

- Nb-Ti: \( C \approx 0.5 \text{ EUR/kA m} \) (5T, 4.2K)
- Nb\(_3\)Sn: \( C \approx 10 \text{ EUR/kA m} \) (12T, 4.2K)
- REBCO: \( C \approx 100...400 \text{ EUR/kA m} \) (20T, 4.2K)
- BSCCO-2212: \( C \approx 250 \text{ EUR/kA m} \) (20T, 4.2K)

- Note: Cu has a \( C \approx 20 \text{ EUR/kA m} \) at RT
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Magnetic Resonance Imaging (MRI)
NMR spectroscopy

photo courtesy of Oxford Magnet Technology
Motors & generators

Motor with HTS rotor
American Superconductor and Reliance

700 MW generator
NbTi rotor
Hitachi, Toshiba, Mitsubishi
Transformers & energy storage

Toroidal magnet of 200 kJ / 160 kW energy store  
(B = 4 T, dia. = 1.1 m)

HTS Transformer  
630 kVA, 18.7 kV to 0.42 kV

KfZ Karlsruhe
Magnetic separation

- superconducting solenoid, enclosed within iron shield
- stainless steel canister containing ferromagnetic mesh
- pipes feeding the kaolin slurry for separation
Thermonuclear fusion

ITER
International Thermonuclear Experimental Reactor
HEP detectors of the past...

Omega

BEBC
... and HEP of the present (CMS and ATLAS)
SC market

- At present, the vast majority of the use of superconductors is for magnet applications:
  - MRI: 5.5 BUSD/year[^1]
  - NMR, science and research: approximately 1 BUSD/year[^1]

- Large scale projects (HEP, Fusion) represent only a fraction of the total market:
  - Evaluated cost of LHC magnet system (material): 2 BUSD[^2]
  - Quoted cost of ITER magnet system (material): 1.4 BUSD[^3]

Sources:  
[^1]: from market report at Conectus.org, converted from reported 5.3 BEUR in 2013 
[^3]: DOE Assessment of the ITER Project Cost Estimate, reported 1.09 BUSD(2002) escalated to 2013
SC materials

- Nb-Ti: 600 t/year, mostly driven by MRI
- Nb₃Sn: 10 t/year, mostly driven by NMR and laboratory systems
  - LHC required 1300 tons of Nb-Ti (300 t/year peak production)
  - ITER requires 300 tons of Nb-Ti and 600 tons of Nb₃Sn (250 t/year peak production)
- All of HTS (BSCCO, YBCO) and MgB₂ (MTS) is below 1 ton/year
Other uses of superconductivity

The Church of the Latter Day Snakes

founded 1905, revived 1950

We have a big interest in this machine...

How big is this magnet, and can it be concealed beneath a floor...

Does it make much noise...

...we pull back the curtain in the Snake Chamber and I start to rise up from the ground...

...the Natural Law Party... please do not sell them a machine... they are very bonkers...

Does it hurt... because it will be me doing the levitating.

I put in five pounds for you...

This is only the start.

Letter to Prof. Main, University of Nottingham, 14 April 1997
A word of closing

- Superconducting magnet design is a lot about superconductors (materials, wires, cables, and their electric and thermal properties)...
- ... but not only!
  - High field & forces bear mechanical problems that are tough to solve \((B=10 \text{ T} \Rightarrow p_{\text{mag}}=400 \text{ bar})\)
  - Materials at low temperature are not what we are used to (mechanical and magnetic properties, thermal expansion, electrical insulation)
  - **Cooling** is an applied science by itself
Superconducting magnets:

- Proc European Conference on Applied Superconductivity EUCAS, UK Institute Physics
Where to find out more - 2/3

- **Cryogenics**
  - Cryogenics: published monthly by Elsevier

- **Materials - Superconducting properties**
  - Superconductor Science and Technology, published monthly by Institute of Physics (UK).
  - IEEE Trans Applied Superconductivity, published quarterly
Where to find out more - 3/3

- Materials - Mechanical properties
  - Nonmetallic materials and composites at low temperatures, Ed. A.F. Clark, R.P. Reed, G. Hartwig, Plenum Press
  - Nonmetallic materials and composites at low temperatures 2, Ed. G. Hartwig, D. Evans, Plenum Press, 1982