The role of SC Magnets for High Energy Physics

Lucio Rossi
CERN

John Adams Lecture
CERN, 3 Dec 2012
Content

- Magnets and Accelerators
- Superconductivity
- Basics of SC Accelerator Magnets
- Short history of SC Magnets for Hadron colliders/synchrotron
- The present LHC
- The road to future
  - HiLumi LHC
  - HiEne LHC
  - Fast Cycling Magnets
- Spin-off
The first accelerator magnets: The Cyclotron in Berkeley in the 1930s
Particle bending in Accelerators for Nuclear and Particle Physics

Low Energy Physics (Cyclotrons, Synchrocyclotrons): fill the magnetic volume with particle orbits

High Energy Physics (synchrotrons, colliders): minimum field volume along the beam path
THE MAIN COMPONENTS OF THE LHC ACCELERATOR

- Focusing MAGNET (quadrupole)
- Bending MAGNET (dipole)
- Accelerating CAVITY
- Vacuum CHAMBER

Injection

Collisions
Large size and high field: $E_{beam} \approx 0.3BR$

- $B_{dip} \approx 8.3\ T$
- $R_{dip} \approx 3\ km$
- $L_{dip} \approx 15\ m \times 1232$
- $L_{tunnel} = 27\ km$

- 1500 tonnes of top quality SC cables
- 15000 MJ of magnetic energy

- 1800 Power Converter from 60 A to 24 kA
- 1800 HTS Leads 11 kW@1.9 K

LHC!
SC: an enabling technology

Superconducting LHC
- Tunnel: 27 km
- Cryoplant power at the plug: 40 MW
- Average power (cryo always on): 1 x 40 = 40 MW

Vacuum in the beam pipe is a big plus

Normalconducting LHC
- Tunnel 120 km
- Dissipated power at collision: ~2,200 MW
- Average power (0.4 coefficient): 900 MW
Not only bending... and needed also in linacs and transfer lines

**Quadrupoles for focussing**

Higher order: Sextupoles (hexapoles), octu-, deca-, dodeca-poles...

Lees used for beam lines
Usually duty cycle 10% or less
Cryogenics is always on, so less interesting,
Unless constrained on radius or high duty cycle

SC is an enabling technology
- Voltage accelerator
- Cyclic accelerators
- Phase stability
- Strong focusing
- Colliders
- Superconductivity
  - (Plasma acceleration?)

Modified from Ph. Lebrun
The start: K.H. Onnes (1,2,3...)  
Onnes and van der Waals (standing) in front of the first He liquifier in 1013  
Heino Kammerligh Onnes in Leiden (NL), first liquifies Oxygen in 1894, then loses to Dewar the race for first H liquifaction, 1898, finally wins over him the first He liquifaction in 1908
(real) Long term planning

No paper by Onnes for 10 years...

He founded a school for technicians lasted 70 y.
Cutting edge physics: $R = R(T)$

Idea: split the dewar of LHe production and make measurements in a separated cryostat: new technology $\rightarrow$ He transfer

His Physical hypothesis was that resistivity would become null when approaching absolute zero temperature.

Other models (lord Kelvin) said that $T \rightarrow 0$ K freezing of electrons, $R \rightarrow \infty$.
After years of patient work in Leiden everything is ready

Set up of 8 April 2011: use of Hg, as sample, because by distillation it could be very pure
The log book, found only in 2009…
Experiment of 23 May 1911: theory demonstrated?

Experiment of 23 May 1911

They increased the temperature from 3.0 K

HKO’s notebook says:
At 4.00 [K] not yet anything to notice of rising resistance.
At 4.05 [K] not yet either.

Notebook entry of May 26: no short circuit!
Reality is always exceeding our expectation... but not serendipity!

Experiment of 26 October 1911 with the historic plot showing the resistance jump at 4.20 K.
Today superconductors

Recent compilation by C. Senatore (UniGE)
Only few with good critical field

Critical Surface concept

Recent compilation by C. Senatore (UniGE)

Nb-Ti critical surfacte (from MN Wilson textbook)
Critical surface of modern Nb$_3$Sn

By C. Senatore (UniGE)
### Practical 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 LHe</td>
</tr>
<tr>
<td>$B_{c2} \geq 10$ T</td>
<td>200</td>
<td>Needs factor 2 over $B_{op}$</td>
</tr>
<tr>
<td>$J_c \geq 1$GA/m$^2$ @ $B \geq 5$</td>
<td>20</td>
<td>$J_{coil} \sim J_c/10$</td>
</tr>
</tbody>
</table>

| Technical Superconductors               | 2      | Nb-Ti and Nb$_3$Sn                           |

<table>
<thead>
<tr>
<th>Type of SC</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 develop.</td>
<td>100 tonnes/year (50%ITER) Margin of improvement</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 Labs R&amp;D</td>
<td>100 kg/y? (only one manufacturer)</td>
</tr>
<tr>
<td>YBCO / REBCO</td>
<td>Industry and Labs R&amp;D</td>
<td>1 tonne/y? (&gt; 5 manufacturers)</td>
</tr>
<tr>
<td>MgB2</td>
<td>Industry and Labs R&amp;D</td>
<td>&gt; 1 tonne/y (4-5 manufacturers)</td>
</tr>
<tr>
<td>Picnite</td>
<td>Lab R&amp;D</td>
<td>No production</td>
</tr>
</tbody>
</table>
Acc. SCM: basic shape - theory

Uniform J, coil thickness $t \sim t_0 \cos \Theta$

Uniform thickness, $J \sim J_0 \cos \Theta$

Here inside it is a perfect circle! Two descriptions equivalent for a thin coil

Acc. SCM: basic shape - theory

Approximating the $J_0 \cos \varphi$ with a uniform thickness, uniform J distribution

Here inside it is a perfect circle.

$\varphi = 60^\circ$ for dipole

$\varphi = 30^\circ$ for quads

$\varphi = 20^\circ$ for sext.
Acc. SCM: basic shape
Main dipoles of existing machines
Scaling: for a given $J$ and $R_{in}$ one wants goes up in field

<table>
<thead>
<tr>
<th>Width (radial thickness) $w$</th>
<th>$F$</th>
<th>$\sigma$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\approx B$</td>
<td>$B^2$</td>
<td>$B$</td>
<td>$B^{5/2}$</td>
</tr>
</tbody>
</table>
Trasnsverse field
Magnetic efficiency

- In ideal solenoids the field goes as: \( B = \mu_0 J t \) where \( t \) is the coil thickness.

- In trasverse field the field is less with the same coil thickness:
  - \( B = \frac{1}{2} \mu_0 J t \) (geom cos\( \theta \))
  - \( B = (\sqrt{3}/\pi) J t \) (60° shell)
HEP Accelerator: current density

<table>
<thead>
<tr>
<th>Magnetic system (only dc)</th>
<th>Current density $J_{\text{overall}}$ (A/mm$^2$)</th>
<th>Operating current (kA)</th>
<th>Typical field range (T)</th>
<th>System stored energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive – air cooled</td>
<td>1 - 5</td>
<td>1-2</td>
<td>&lt; 1</td>
<td>0.01</td>
</tr>
<tr>
<td>Resistive – water cooled</td>
<td>10-15</td>
<td>1-10</td>
<td>2</td>
<td>0.05</td>
</tr>
<tr>
<td>SC magnets for particle detectors</td>
<td>20-40</td>
<td>2-20</td>
<td>2-6</td>
<td>5-2500</td>
</tr>
<tr>
<td>SC Tokamaks for fusion†</td>
<td>25-50</td>
<td>5-70</td>
<td>8-13</td>
<td>5-40,000</td>
</tr>
<tr>
<td>SC magnets for MRI</td>
<td>50-200</td>
<td>1</td>
<td>1-10</td>
<td>1-50</td>
</tr>
<tr>
<td>SC laboratory solenoids</td>
<td>100-250</td>
<td>0.1-2</td>
<td>5-20</td>
<td>1-20</td>
</tr>
<tr>
<td>SC Accelerators</td>
<td>200-500</td>
<td>1-12</td>
<td>4-10</td>
<td>1-10,000</td>
</tr>
</tbody>
</table>

†Top figures refer to ITER, under construction

Why not more?
Huge force density: J B
Huge stresses : J B R
Huge energy : protection needs time...
Other configurations: window frame

KEK window frame, for high field, made in coil block. Reached 9.4 T (10.4 on coil) !!!

Similar concept developed in Nb3Sn at BNL by Sampson (1 inch) in NbSn
Other configuration: Coil block

Common Coil

Block with stress management

Intercepting plates and laminar spring

Many designers, P. McIntyre (Texas A&M), stress management
Other configuration: canted solenoid

New
Canted-Cosine-Theta (CCT)
With stress interception

First proposed as double helix by D. Meyer and R. Flasck MSU, 1970!
Revived by S. Caspi LBNL and team of NHMFL, & AML (Advanced Magnet Lab)

Direction of current

Seminar by S. Caspi
Tuesday 11 December at 14.00
Transverse field: Forces

In solenoids, forces are self supported (till the limit of the winding!)

In transverse field the lateral forces are not supported at all
The longitudinal (along beam) forces are poorly supported

Large forces kept from outside means movements with –inevitably – friction (stick and slip, resin fracture, flux change, etc.). Thicker the coil and farther is restrain from $J_B$ peak
Timeline Record Field (solenoids)

Recent compilation by M. Bird (NHMFL, FSU)

Records in 1990
- 68T/1msec, MIT
- 40T/1 sec, Amsterdam
- 31T Hybrid, Grenoble
- 24T/50mm, Grenoble
- 20T, IGC

MagLab Records
- 100T/1msec, 2012
- 60T/1 sec, 1998
- 45T Hybrid, 2000
- 36T/32mm, 2009
- 35T=31T+4T HTS (HTS Test Coil, 2011)

MagLab technology has been adopted by ~20 labs worldwide

Recent compilation by M. Bird (NHMFL, FSU)
Dipoles vs solenoids in time: a comparison

Factor 2 due to Coil «efficiency» and to force-stress management
Load line and stability

- \( J_{op}/J_c \) = Current margin
- \( \Delta T = T_{CS} - T_{op} \) = Temperature margin
- \( LL = J_{op}/J_{max} \) = Margin on load line
- Energy margin

\( B = t \cdot J \)

Graph showing various curves and points labeled with different parameters.
Current density: the hierarchy - 1

High $J_c$ (superconductor and metallurgical properties)

- It is the primary factor
- LHC dipole design at 93% of $I_{\text{max}}$, operated at 86% (80%)
- 10% variation matters on performance because energy margin $\Delta H \approx (I_c-I_{\text{op}})^3$

Low stabilizer content

- Stabilizer necessary, for stability AND protection:
  7 MJ energy for LHC dipoles
  (Energy density...)
- $\text{Cu/Nb-Ti} \approx 1.3-2$  $\text{Cu/Nb}_3\text{Sn} \approx 1$
- Uniformity of stabilizer: cost...
Result: $J_{\text{critical}} \rightarrow J_{\text{engineering}}$
Current density: the hierarchy - 2

High compaction cable (cabling machine!)

- Rutherford cable have only 10-12% void, can be compressed transversally (making only 5-6% voids) and keystoned 1°

Insulation

- Very thin: 0.25 mm cable to cable (cabel not solid, movement and friction)

  1st Layer with overlap (to provide enough surface current path: 200V/cm & to avoid punch through)

  2nd Layer with or w/out spacing and glue on 1 or 2 sides
Packed coil based on sophisticated Superconductor.
Field quality of conductor dominated magnets

Coil geometry dominates at medium-high fields: 20-100 μm!

• Field errors expressed always in unit of 10^-4 of the main field components
• Except dipole all components increase with Radius
• Usually one use 2/3 of the magnet apertures, so it is the natural ref. radius

\[ B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n)z^{n-1} \]

From MN Wilson
Magnet structure

Warm iron: quick cool down - warm up but high heat load. Collar must take all forces.

Cold iron: big cold mass but much more compact for force restrain and alignment.
Quench detection and protection

- Following a quench
- Dump energy outside, on an external resistor
- Buy time to do so
  \[ \tau = \frac{L}{R}, \text{ but } V = R I \]
  \[ \Delta T = RI^2 \Delta t/mC \]
  - Discharge at low voltage and fast
- With \( J_{Cu} \approx 400-1000 \text{ A/mm}^2 \)
  time is \( \sim 30-300 \text{ ms} \)

\[ \int_{T_{op}}^{T_{hot}} \frac{C}{\rho} dT = \frac{1}{A_{cu} A_{tot}} \int_0^\infty I_{op}^2 dt \]

- Stored energy
- 7 MJ in a 15 m long LHC dipoles
- \( \sim 1 \text{ GJ in an LHC sector (154 dipoles): 8 independent dipole circuits + 16 for quads (less than 10% of dipole energy)} \)
- \( \sim 1.2 \text{ GJ in ATLAS SC magnets} \)
- \( \sim 2.5 \text{ GJ in CMS solenoid!} \)
First magnets: MIT conf. on HF magnets, 1961

- 4.3 T NbZr solenoid
- 5.5 T NbZr solenoid
- 2.5 T superferric racetrack with Nb$_3$Sn or NbZr windings
- 1.5 T MoRe solenoid

Magnets in cryostats for the first

courtesy of MN Wilson

http://indico.cern.ch/event/superconductivity
Strong effort in Europe for a SC SPS and a big deception!(by J. Adams...)

1967: '...superconductor diameter about $5 \times 10^4 \text{ cm}$...' PF Smith JD Lewin: Superconducting Proton Synchrotrons: NIMs 52 p298

Rutherford cable

1970s: GESSS collaboration (Karlsruhe, Rutherford, Saclay)

proposed superconducting magnets for the CERN SPS

D1 Karlsruhe
courtesy of MN Wilson
CERN North Area Beam line:
use of Sc magnets in 1978

Superconducting magnets (two MBS dipoles (CESAR) of 150 mm bore and 4.5 T, and one quadrupole (CASTOR) of 90 mm bore and 54 T/m) installed in hall EHN1

J. Pérot (CEA Saclay) & D. Leroy (CERN)
courtesy of Ph Lebrun
Use on SC magnets in accelerator (proton colliders): ISR I8

1965 ISR model dipole
1977 sc low-β quadrupole

| TABLE 1 |
|-----------------|---------------------|
| Nominal gradient | $\frac{\partial B}{\partial r} = 40 \, \text{Tm}^{-1}$ |
| Sextupole component | $\frac{\partial^2 B}{\partial r^2} = 31 \, \text{Tm}^{-2}$ |
| Maximum dodecapole component | $\frac{\partial^5 B}{\partial r^5} = 10^5 \, \text{Tm}^{-5}$ |
| Peak field in the windings | 5.1 T |
| Nominal current | 1500 A |
| Warm bore diameter | 173 mm |
| Inner diameter of main coils | 232 mm |
| Outer diameter of main coils | 309 mm |
| Inner diameter of steel yoke | 352 mm |
| Outer diameter of steel yoke | 632 mm |
| Outer magnet diameter | 672 mm |
| Magnetic length | 1250 mm |
| Physical length | 1500 mm |
| Stored energy | 500 kJ |
1981 ISR SC low $\beta$ Quads: the first magnets in routine operation

### TABLE 1

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</tr>
<tr>
<td>Inner diameter of steel yoke</td>
<td><strong>352 mm</strong></td>
</tr>
<tr>
<td>Outer diameter of steel yoke</td>
<td><strong>632 mm</strong></td>
</tr>
<tr>
<td>Outer magnet diameter</td>
<td><strong>672 mm</strong></td>
</tr>
<tr>
<td>Magnetic length</td>
<td><strong>1250 mm</strong></td>
</tr>
<tr>
<td>Physical length</td>
<td><strong>1500 mm</strong></td>
</tr>
<tr>
<td>Stored energy</td>
<td><strong>500 kJ</strong></td>
</tr>
</tbody>
</table>

Lumi boost by factor 6.5 in I8
Record Lumi: $1.4 \times 10^{32}$ cm$^{-2}$s$^{-1}$
Handing over the «baton» to USA

Despite large effort in beam lines magnets, SC low-β ISR, late SC low beta insertion of LEP, and R&D magnets (P0 and early LHC works), with the choice for a resistive SPS and LEP, the spotlight definitively migrated to USA from mid-seventies to early nineties.

Two labs fought the «good» battle:
- BNL (Isabelle → CBA)
- Fermilab (Energy Doubler → Energy Saver → Tevatron)

Then a project looked like the Big Brother: SSC
BNL: Isabelle 200+200 GeV p-p at 4 T
Hunting for Z and W bosons

ISA
Later
ISAblle

...later
CBA

J. P. Blewett, 1971!
Isabelle «upgrade» 200+200 GeV (4T) to 400+400 GeV (5 T): kiss of death!

Figure 10. Cross section of 4½-m dipole.

Sp-pbarS by C. Rubbia in 1981-83 took away its main goal: Isabelle/CBA cancelled in 1983...
Tevatron and the role of R.R. Wilson

- The hero of this story is Bob Wilson who was the founding father of FERMILAB. In 1968 Fermilab was authorized: 200 GeV and $250 M. Some talk of SC magnets, but too risky. Space left in tunnel for a second ring to be built later.

- 1971. AEC gave approval for a study to see if the energy doubler magnets would fit within the $250 M budget. Wilson had $20M “left over” which he considered was his! He proposed a ring of magnets with 3” aperture that would receive beam at 150 GeV from the Main Ring and accelerate it to 1000 GeV.

- March 1972 Main Ring had first beam.

- Sept. 1972 Wilson formed an “informal working group” under Paul Reardon: William B. Fowler, Bruce Strauss, D. Edwards, Henry Hintenberger, Ernie Malamud, Donald Miller, Rae Stiening, Lee Teng, Donald Young, and Boyce McDaniel to consider the technical questions associated with building the doubler.

Courtesy of A. Tollenstrup
Tevatron: engineering of <Rutherford and insulation: buy SC by tons

- Overlapping wrap of .001” kapton film for insulation
- .023” strand with 2100, 8 micron NbTi filaments
- Glass tape impregnated with uncured epoxy resin.

After the coil is wound, it is placed in a precision form and the epoxy is cured by heating.
1. MAKE A MAGNET
2. CUT SLICE and cut slot in COLLAR
3. APPLY F TO RESTORE ORIGINAL DIMENSION.

X vs F gives the preload and the elastic properties of the coil package. Can be measured both at room temp and cold.

Concentric tube and rod go out of cryostat to a rotary transformer and monitors coil motion.

By A. Tollenstrup
More than 700 6-m-long dipoles: it required new techniques

Invention: Laminations/tooling

Laminated tooling for forming the magnet coil.

From: Tim Nichols
Tevatron: the commitment of a laboratory for its future

Lab director winding a prototype (however this it didn’t work...). Courtesy A. Tollenstrup
SC magnets of Tevatron extended Fermilab leadership for ~30 years...

1983: 512 GeV beam
1984: 800 GeV beam
1985: 1.2 TeV p-pbar collision (c.o.m.)
1986: 900 GeV beam
1986: 1.8 TeV collisions
1992-1996: Collider Run I at 1.8 TeV
180 pbarn
1997: fixed target program, 980 GeV
2001-2011: Collider Run II at 1.96 TeV
10 fb
UNK: 3 TeV synchrotron (3+3 later)
21 km tunnel: remained a dream

- 2000 dipoles, about 5 m long, 5 T (6 T reached)
- 100-300 mT/s of B ramp
- 1994 project stop (ex-Soviet Union crisis)
HERA @ Desy: $p$ ring 820 (920) GeV colliding $e^-$ at 30 GeV (SC cavities)

Using features developed at BNL and CERN P0

416 5.1 T dipoles, 75 mm aperture, 8.8 m long. First Cold iron collared coil. Free standing Aluminum collars for first time to help control the preload.

Designed and prototyped in the laboratory, manufactured all by industry (following ISR route): opening the way for RHIC and LHC
The way out of BNL: RHIC

On the ashes of the 200 M$ spent for Isabelle (mainly in civil engineering, i.e. tunnel!), BNL re-built its future. Approved during SSC, it was low field-low cost machine for heavy ions (100 GeV p equivalent).

3.5 T field
Low cost was really a challenge
Plastic collar (spacer)
Yoke as collars
Field careful design and correction/trim
Perfection in SC and its measurements
Field measurements to steer production
SC Magnets in the RHIC tunnel
The Big battle for (future) leadership

SSC vs. LHC

- Initial attempt of CERN to play a significant role in SSC was dismissed
- LHC: 7.7+7.7 TeV p-p
- Compensated by a 10 times more luminosity
- Super Superconducting Collider: 20+20 TeV p-p
SSC on green field: optimization study

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

6.5 T, high field, two-in-one option, (by BNL and LBNL) resurrected from the waning days of ISABELLE/CBA

3T superferric low field option (by TAC)
Choice: 6.6 T, 4.4 K «single aperture»

NEW generation cables with fine filaments and high Jc (→ LHC)
Full polyimide insulation
Tapering keys of the austenitic steel collars
Coil end design
Many study on quench and instrumentation development
Change aperture form 40 mm to 50 mm was the opening to cost escalation
However training was a serious issues: the margin was only 0.6 K!
The strategy of CERN (Rubbia)

- With a flagship project running: LEP
- With an upgrade that bought 5 years more of physics: LEP200
- CERN could continue R&D on HF magnets
- From safety commission(!) R. Perin could led magnet R&D

- Use of 2-1 concept pushed at its extreme: LHC TWIN Dipole
- 8-10 T by HE II cooling

Computed magnetic flux map at $B_0=10$ Tesla
Evolution of X-section in time

J. Adams & G. Brianti (right)
Two routes: Nb-Ti and Nb₃Sn

- High field dipole in Nb-Ti (HERA strands). CERN (Perin & Leroy) Ansaldo (Spigo)
  - 8.55 T first quench, reached 9.3 T at 1.6 K

- Nb₃Sn CERN-Elin dipole (Asner-Wenger & Zerobin)
  - Reached 9.7 T: Previously a coil in mirror configuration broke first the 10 T barrier
But the route was signed...

Continous progress in $J_c$ of fine filaments Nb-Ti
Definitive step achieved by SSC

$\text{Nb}_3\text{Sn}$ 5 to 10 time more expensive
HE II Cryogenics was working in Tore Supra!
TAP proto and MTA models successful

Work on high field concept (R. Perin, D. Leroy, M. Bona)
- Develop large cable size with small filam. and properties
- Test appropriate coil-collar design
- Test 2-1 final structure
- All in 1 m long models
- 4 model orders in Industry!

Test rapidly the 2-1 concept on long magnet and HE II cryostat
- Use of HERA coils meanwhile Industry was ending HERA dipole production
- TAP prototype all in Industry (Ph. Lebrun, J. Vlogaert)
Putting all together 1989-94
First LHC prototypes (CERN-INFN-CEA)

First LHC coils arriving!

SSC stop on October 21, 1993
Cost was escalating to 14 B$ (from 4.4 B$ initial).
Spent 2 B$ for civil and tech.

Test INFN-1: June 1994: incredibly good!
String1: 3 dipoles 1 Quads by end of year
Approval by Council of LHC: December 1994
The base: SC cable!

Multiple suppliers helped, however only a few were really critical for the project.

Precision to the μm!

- was shown with images of Cu wedges in the Dipole X-Section.
- Rutherford cable was labeled.
- Key information in boxes:
  - Mid-thickness: ±6 μm
  - Key-stone angle: ±0.05 deg
  - Width: 0/+80 μm
- Accurate positioning for quench for field accuracy
- Winding
- Curing at 185 °C
- 3-D: ends. Quasi-impregnation
20-100 μm over 15 m of composite
It has also helped to detect a number of defects.
It has also been used to detect subtle electrical shorts.

Courtesy of E. Todesco and C. Vollinger

Introduced first to steer the FQ toward beam dynamics targets.
To get it right we need model that predict position and deformation at the level of 10-20 micron
The twin design is ... complex!

Shrinking cylinder (also helium shell)
Austenitic steel collars
Superconducting coils
Cold bore tube and beam screen
Iron yoke (lamination)
Superconducting bus bars

Stress at Coil Pole (MPa)

- Cylinder welding
- After cool down
- Magnet energization

P. Fessia and L. Rossi
Good geometry for aperture
Sorting helped!

Laser Tracking measurements
Field Quality, improved by sorting
A successfully collaboration
Laboratory - Industry

P. Fessia
and L. Rossi
Quench and training

- 1-2 quench to pass nominal field 8.33 T, 0.86 of $I_{\text{quench}}$
- Further 4-5 quenches to reach ultimate design field of 9 T at 0.93 $I_{\text{quench}}$; actually half of the dipole reached 9 T with 0-2 quenches (bonus magnets)
- For first 30 magnets and then for the 10% worst magnets of the 1200 remaining dipoles we did a thermal cycle
- Almost all the re-tested dipole went over the nominal current with no quench
- Only 2.5% rejected (half for Electrical NC, half for quench, only 1 lost)
But not all is bright

We pushed magnet to high field in only one sector (1/8 of the machine) reason: symmetric quenches (SEE LATER) and lack of time
In a sector we had the time to push to 11200 or 7.7 T (95% of nominal field ) above 7.4 T we found unexpected training, i.e. lack of memory.
Mainly one family of magnets, that were the best at acceptance test to 9 T !!
To push LHC to its nominal we need 3-4 months of dedicated time

Analysis by E. Todesco
Beam Screen (BS): The red color is characteristic of a clean copper surface. BS with some contamination by super-isolation (MLI multi layer insulation). BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.
Finally with great satisfaction...
The light is nothing without eyes

- Magnetic fields needed for
  - electric charge identification
  - momentum spectrometry
    - $p = mv = q \rho B; \quad \phi = q/p \quad B L$
    $\Rightarrow BL$ is often the comparison parameter

- If momentum analysis is done by tracking inside the field volume:
  - $\Delta p/p \propto 1/BL^2 \Rightarrow$ large volume better than high field
  - Field homogeneity appreciated but NOT critical
    (field knowledge of 0.1% usually suffices)
Large Sc: 35 A/mm² overall

Special Al alloy developed by KEK for Atlas inner solenoid

Al alloy reinforced by e-beam, welding, developed by ETHZ-CERN for CMS
ATLAS Magnetic structure

ECT: 2 end-cap toroids
~ 4T on surface
(8 coils each)

Inner solenoid (2 T, superconducting)

BT: barrel toroid, 8 coils
~ 4 T on surface

Physicists want the magnetic field, NOT the structures as this scatters particles, → light, low density materials, as thin as possible …….
CMS sketch

- 14 m long
- 223 ton - cold mass weight
- 12500 ton – total weight
- 3.5 inner coil radius
- 4 T (4.3 T of $B_{peak}$) @ 19.5 kA
- 4.6 K
- 2.6 GJ of stored energy
Magnet need powering! HTS CLs

HTS IN THE LHC MACHINE

Powering of the LHC magnets
About 3 MA of rated current through 1800 circuits
3286 current leads

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Current rating (A)</th>
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<tbody>
<tr>
<td>64</td>
<td>13000</td>
</tr>
<tr>
<td>298</td>
<td>6000</td>
</tr>
<tr>
<td>820</td>
<td>600</td>
</tr>
<tr>
<td>2104</td>
<td>60-120</td>
</tr>
</tbody>
</table>

$J_c = 12500 \text{ A/cm}^2$ @ 77 K self field

A. Ballarino
Luca Bottura  alternate current timeline...: what is next?
Pulsed magnets for fast synchrotron
Led by GSI, FAIR project

- SIS100: 2 T dipole rated fro 2-4 T/s (based on Nuclotron technology)
- May be useful for PS2+
INFN-GSI collaboration for SIS-300

Full scale curved dipole built in Italy (INFN-GE, INFN-LASA and LNF)
Reached 4.5 T nominal at first quench, at INFN-LASA Milan
Continuous ramp rate of 300 mT/s demonstrated in vertical pool boiling
Should reach 1 T/s in horizontal supercritical helium
Similar good results at Protvino: a 6 T 1-m-long straight model
The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, infrastructures


**LEP**
- Construct.
- Physics
- Upgr

**LHC**
- Design, R&D
- Proto
- Construct.
- Physics

**HL-LHC**
- Design, R&D
- Construct.
- Physics

**HE-LHC**
- Design, R&D
- Proto
- Construct.
- Physics
HE-LHC magnetic parameters

- \( E_{\text{beam}} \approx 0.3 \times R \times B \) (TeV, km, T)
- \( L_{\text{dipole field}} \approx \frac{2}{3} L_{\text{tunnel}} \)
- LHC (\( R_{\text{tunnel}} = 4.25 \) km):
  - \( 0.3 \times 2.8 \text{km} \times 8.33 \text{T} = 7.0 \) TeV
  - \( 0.3 \times 2.8 \text{km} \times 4.76 \text{T} = 4.0 \) TeV
  - \( 0.3 \times 2.8 \text{km} \times 7.74 \text{T} = 6.5 \) TeV
- \( \text{HE-LHC} \)
  - \( 0.3 \times 2.75 \text{km} \times 20 \text{T} = 16.5 \) TeV
  - \( 0.3 \times 2.75 \text{km} \times 16 \text{T} = 13.2 \) TeV
- Choice of magnet aperture
  \( \Rightarrow \) injection energy is critical

- The magnetic field is mainly determined by:
  - \( \rightarrow \) Superconductor \((B_c, J_c)\)
  - \( \rightarrow \) Coil thickness (~Aturns)
  - \( \rightarrow \) Mechanics (ability to keep the huge e.m. forces)

However other parameters play a key role:
- Magnetic design (optimization)
- Stability and Protection
- Magnet aperture
Luca Bottura hyper-optiomsitic view: toward quadratic growth?

We are poising ourselves to break the 20 T barrier

Diagram showing the increase in magnetic field from 1980 to 2040, comparing HTS, Nb₃Sn, and Nb-Ti technologies.
What has been done?
Less than linear... but we’ll catch up

Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) the practical limits is around 20 T. Such a challenge is similar to a 40 T solenoid (μ-C)
Do we have SC? For 12-15 T almost...

- Recent 23.4 T (1 GHz) NMR Magnet for spectroscopy in Nb$_3$Sn (and Nb-Ti). 15-20 tons/year for NMR and HF solenoids. Experimental MRI is taking off.
- ITER: 500 t in 2010-2015! It is comparable to LHC!
- HEP ITD (Internal Tin Diffusion):
  - High Jc., 3xJc ITER
  - Large filament (50 µm), large coupling current...
  - Cost is 5 times LHC Nb-Ti

Seminar A. Devred, Thursday Amphi bldg. 30 h14.00
Can we go beyond 16 T? HTS!!!

- Round wire, isotropous and suitable to cabling!
- HEP only users (good < 20K and for compact cable)
- Big issue: very low strain resistance, brittle
- Production ~ 0,
- cost ~ 2-5 times Nb3Sn (Ag stabilized)

- DOE program 2009-11 in USA let to a factor 2 gain. We need another 50% and more uniformity, eliminating porosity and leakage
- CERN-DOE collaboration
The holy graal of Magnet community: YBCO

- An old type of cabling (Roebel) suitable for tapes has been recently revisited (Karlsruhe, New Research Industry NZ)
- Here a first 2 m long test cable done at CERN
Think wide...

- Canted Solenoid Coil
- S. Caspi
- Block Coil
- Hybrid Cos9 Block Coil
- P. McIntyre

- Shrinking cylinder (also helium shell)
- Austenitic steel collars
- Superconducting coils
- Cold bore tube and beam screen
- Iron yoke (lamination)
- Superconducting bus bars

- Beam bore diameter – 40 mm
- Winding bore diameter – 87 mm
The first strawman design...

Magnet design: 40 mm bore (depends on injection energy: > 1 Tev)
Very challenging but feasible: 300 mm inter-beam; **anticoils to reduce flux**
Approximately 2.5 times more SC than LHC: 3000 tonnes!
**Multiple powering in the same magnet for FQ (and more sectioning for energy)**
Certainly only a first attempt: $\cos \theta$ and other shapes will be also investigated

L. Rossi and E. Todesco
How long will it take?

- 9 T - 1 m single bore
- 10 T-1m Nb3Sn dipole
- 9 T -10 m long prototype
- 9 T-15 m final prototype
- Last LHC dipole

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>LHC study</td>
</tr>
<tr>
<td>1987</td>
<td>Decision for Nb-Ti</td>
</tr>
<tr>
<td>1990</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>Industry contracts Nb-Ti</td>
</tr>
<tr>
<td>2000</td>
<td></td>
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<tr>
<td>2006</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>LHC start-up</td>
</tr>
</tbody>
</table>
The HE-LHC possible timeline

Full profit of the HiLumi program

- US 16 T small dipole
- EuCARD 13 T large dipole + 18 T small insert
- LARP 11 T long quad US 13 T Quads FP7-HiLumi
- EU FP6-CARE-NED
- US basic programs and LARP R&D
- EU FP6-CARE-NED
- HTS for HE-LHC: yes or no
- Industry contracts, start construction
- Final delivery Magnets HE-LHC
- HE-LHC start-up

2005 2010 2020 2025 2030 2035
HiLumi: LARP effort
The effort starts to be CERN-LARP
Hi LUMI LHC We are not far!

Fermilab-CERN 11 T Dipole under way
Great hope for a first NbSn Magnet in accelerator (role like ISR quad)
Above Linca4: Injector re-design SPS+! (maybe a PS2+ as well?)

New injectors optimization
The big leap forward: 80 km tunnel
As better solution for a HE-LHC

For TLEP, then for a superHE-LHC
Optimization could be at 16 T field level: collision
energy 80 TeV c.o.m.
Or 100 TeV for 20 T dipoles
Much better new infrastructure. However many costs go linearly, or more, with length. Magnet stored energy, beam energy also a concern

Whatever solution, a vigorous Magnet R&D will enable to go beyond LHC energy