Magnets for the next generation accelerators at CERN

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Contents

• LHC and magnet technology today
• Upgrade of the LHC ring
  – Luminosity upgrade
  – R&D toward higher fields
• Upgrade of the injector chain
  – PS2 vs PS2+
  – SPS
• (Study for beta beam ring & NbSn Undulator)
• Thanks to E. Todesco, A. Devred, L. Bottura, G. Kirby
30 years of SC Accelerator Magnets

**DIPOLE MAGNETS**

**HERA**
B = 4.7 T  
BORE : 75 mm

**RHIC**
B = 3.5 T  
BORE : 80 mm

**TEVATRON**
B = 4.5 T  
BORE : 76 mm

**LHC**
B = 8.3 T  
BORE : 56 mm

**SSC**
B = 6.6 T  
BORE : 50-50 mm
LHC Main dipoles

- Nb-Ti Sc
- Field 8.3-9 T (9.65)
- Kapton tape as insulation
- Superfluid helium
- $F_x = 180$ MN/m per quadrant
- $F_y = 0.81$ MN/m (70 MPa)
- Stress 150 MPa at collaring
- Energy : 6.93 MJ
- $T_{\text{max}} = 375$ K (adiabatic)
- $T_{\text{op}} = 1.9$ K
- Heat removal: 10 W/m
- $T_{\text{margin}} = 1.5$ K
- Margin for beam losses: 10 mW/cm$^3$
Collider magnets

- Field accuracy (and knowledge!) must be very high (10-100 ppm)
  - At collision (500 millions turns)
  - At injection: large emittance
    « soft »beam field distorsion by persistent current
Specific problems of SC in accelerator magnets - 1

Cryogenic operation with LHe or Hel is still necessary to exploit the higher field and the zero-dissipation regime.
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Critical Current Density, A/mm²
10,000

At 4.2 K Unless Otherwise Stated

Critical Current Density, A/mm²
1,000

Critical Current Density, A/mm²
100

Critical Current Density, A/mm²
10

Applied Field, T

80 90 100

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Specific problem of using SC in accelerator magnets - 2

- Magnetization as results of persistent currents.
- Fine filaments (1-10 μm range). This implies 3-10,000 filaments in a single wire)
LHC Magnets are all tested
LHC Magnets are all tested

Histogram of the number of quenches to reach 8.33 Tesla (11850 A) after thermal cycle

Number of quenches to reach 8.33T

0 1 2 3 4 5 No TC not reached

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Large tooling repatriation: MAR (Magnet Rescue Facility)

- At CERN from Sept 07 we will start install and use the LHC tooling used in Industry.
Reconstitution of short model labo and constitution of a complete MAR
What’s next?

• Upgrade of the LHC ring
  – Luminosity upgrade Phase I
  – Luminosity upgrade Phase II
  – R&D toward higher fields
LHC (peak) luminosity upgrade

Radiation damage limit $\sim 700$ fb$^{-1}$

Improving the peak luminosity should be soon or later a necessity:
- For statistics
- If we reach the luminosity goal we need to replace too-irradiated magnets
- If we don’t reach it for reason related to difficulty in handling the beam current, optics may in part compensate this shortfall.

High quadrupole strength is always a gain (but not at any price).

- The technology of the luminosity upgrade is fully relevant for an eventual energy upgrade.
Gradient versus aperture for Nb-Ti and Nb$_3$Sn

- $B_c \approx 13$T for Nb-Ti,
- $B_c \approx 25$T for Nb$_3$Sn

However for quadrupoles does not work like this.

Results relative to a sector coil for $\phi \sim 100$ mm

- Nb-Ti: $G \phi/2 \sim 10$ T
- Nb$_3$Sn: $G \phi/2 \sim 15$ T
- Nb$_3$Sn: 50% more than Nb-Ti

Gain in $\beta^*$ versus technology and $I^*$ (distance to IP)

- Comparison of lay-outs giving the same chromaticity
  - For each technology, apertures and triplet length optimized
  - Both technologies used at the limit
  - Aperture set at the minimum requirement (energy deposition ?)
  - For the same chromaticity,
  - Nb$_3$Sn gives 30% more
Understanding the gain in Nb$_3$Sn

- Nb$_3$Sn gives improvement in $G$ of a factor $\alpha = 1.5$ \[ \hat{G} = \alpha G \]
- Constant integrated gradient: triplet length decreases with $\alpha$ \[ \hat{I}_t = \frac{I_t}{\alpha} \]
- Chromaticity proportional to $\beta_m$ \[ Q' = \int G\beta ds \propto \beta_m \int G ds \]
- Equal chromaticity, constant int. $G \Rightarrow$ equal $\beta_m$
- Using the empirical fit for $\beta_m$
  \[ \beta_m = \frac{l^2 + al_z}{\beta^*} \]

- We obtain the gain in $1/\beta^*$
- For +50% in $G$, +35% in $1/\beta^*$
Scope of phase 1

- The LHC will have difficulty to reach nominal luminosity $10^{34}$, not to mention ultimate (in the baseline configuration) $2.3 \times 10^{34}$
- A change of the triplet (just it!) it is certainly one way to recover and also to improve: for example a big advantage from an aperture increase of the triplet
- The luminosity may saturate quickly $\Rightarrow$ the change must be fast and be feasible for 2012.
- The scope is to be able to reach 2 and pass $10^{34}$ with a $\beta^*$ $\sim$ 20 cm.
Phase 1: exploring the range 130 mm aperture?
EU-FP7
SLHC proposal

- Model and prototype for a 130 mm wide NbTi quadrupole.
- Based on existing Sc cable left over from LHC main dipole production
- Some other material like iron and collar steel is left over from LHC production
- Main tooling adapted from existing LHC tooling.
- Time scale June 2008-june 2010
- From 2010 till 2012 production of 16 magnets (8 and 9 m long, same Xsect).
- New shielding scheme (Mokhoff) and new more porous insulation scheme (Tommasini) might be implemented.
- Substitution vs. modifications of D1 and cryogenics must be addressed in a more detailed study
- The Program is NOT in the CERN plan today but we are confident it will next year.
Upgrade Phase II

- The scope is going from 2 to $10 \times 10^{34}$
- Based on Nb$_3$Sn superconductor magnets, and on many other new equipments in the whole machine and experiments
- Because of the luminosity gain, a 6 months shutdown will be acceptable (or even 1 year if required by experiments)
- Carefully prepared it will probably require to revisit the machine-detector interface and the whole Interaction Region.
- It will probably (possibly) contain a new scheme like the Early Separation Scheme with "moderate’crab cavities. This will make best use of the larger reach in $\beta^*$, up to 11 cm
R&D - 3 NED conductor

- We achieved significant milestones but progress are slow. Task should be completed by 2007-08. SMI first conductor is being cabled and has sold the business to EAS (former VAC). Alstom has still to show the capability to attain 2500 A/mm²

Alstom/NED
(workability program milestone)
1.25 mm; 78x85 μm sub-element
740 A (∼1500 A/mm²) @ 4.2 K & 12T

SMI/NED
1.26 mm; 288 x 50 μm tube
1400 A (∼2500 A/mm²) @ 4.2 K & 12T
Conductor study

- Building a comprehensive model to understand the deformation (INFN-GE).

- Understand Reaction parameter

Influence of temperature ramp rate on void formations in internal tin wire
Current distribution
(V-H test)
Current distribution
(V-H test)
Quench due to a Flux Jump
(V-H test)
Quench due to a Flux Jump
(V-H test)
Design issue for the NED dipole

NED is dipole for 15 (12) T in 88 mm bore

NED Magnet Zoo
(Courtesy F. Toral, CIEMAT)
HF Program next 4 years

- White Paper approved
- Some 18 MCHF (material) for HFM in 2008-2011
- Technology R&D and associated study (heat deposition, heat removal, etc.)
- Quadrupole development for LHC up
  - 1 m long model by 2010
  - 6 m long magnet by 2011 (2012)
  - Schedule based on LARP success
- Dipole development: NED and beyond
Area where Nb$_3$Sn can play a role in the LHC up (or consolidation)

<table>
<thead>
<tr>
<th>Quadrupoles</th>
<th>Field</th>
<th>Aperture (mm)</th>
<th>Radiation load</th>
<th>e.m. Forces</th>
<th>Peak field</th>
<th>Radiation Hardness</th>
<th>Heat removal</th>
<th>Temperature margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-beta insertion</td>
<td>&gt;140 T/m</td>
<td>&gt;130</td>
<td>high</td>
<td>large</td>
<td>&gt;9 T</td>
<td>increased</td>
<td>very good</td>
<td>large</td>
</tr>
<tr>
<td>slim dipole in front</td>
<td>8 T</td>
<td>70</td>
<td>high</td>
<td>large</td>
<td>&gt;9 T</td>
<td>increased</td>
<td>very good</td>
<td>large</td>
</tr>
<tr>
<td>of Q1</td>
<td>4 T-6 T</td>
<td>&gt;130</td>
<td>high</td>
<td>as lhc</td>
<td>9 T</td>
<td>increased</td>
<td>very good</td>
<td>large</td>
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<tr>
<td>Dogleg dipole</td>
<td>5 T</td>
<td>&gt;56</td>
<td>high</td>
<td>as lhc</td>
<td>9 T</td>
<td>increased</td>
<td>very good</td>
<td>large</td>
</tr>
<tr>
<td>Dispersion</td>
<td>12 T</td>
<td>&gt;56</td>
<td>high</td>
<td>large</td>
<td>&gt;12 T</td>
<td>increased</td>
<td>very good</td>
<td>large</td>
</tr>
<tr>
<td>Suppressor dipole</td>
<td>4-6 T</td>
<td>large</td>
<td>high</td>
<td>?</td>
<td>9 T</td>
<td>increased</td>
<td>very good</td>
<td>large</td>
</tr>
<tr>
<td>Muon decay ring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Cycling (or pulsed) Magnets

- SPS upgrade will require $1.8 \text{T} \rightarrow 4.5 \text{T}$, with $\text{dB/dt}$ about $2 \text{T/s}$
- $2/3$ of the 6 km long tunnel
- The 6 km long inj. lines needs same field
- However the upgrade of SPS has been postponed in favor of the PS renewal: PS2
- At present the baseline magnet for PS2 is 70 mm gap, $1.8 \text{T} \Rightarrow \text{normal conducting}$
First draft of NC dipole

However the weight is 15 tonnes

A Sc solution may be 2.5 tonnes with saving in construction cost. However operation cost seems higher for Sc option.
Conductor development (1-3 \(\mu m\)) & simple magnet design (2-3 \(T\))
Similar R&D in Europe (very relevant for the SPS up)

- FAIR at GSI (Darmstadt, D)
  - SIS-100 (2 T, 4 T/s, Superferric, Nuclotron magnets)
  - SIS-300 (4.5 T, 1 T/s, cos-theta magnets)
- DiSCoRap at INFN (Milano, Genova, Frascati, l) R&D on a 5...6 T, 1...1.5 T/s dipole for SIS-300
R&D target

- Target: produce and test a representative model of a PS2+ dipole $B_{\text{max}} = (1.8) \ 2.3 \ T$
  - $\frac{dB}{dt}_{\text{max}} = (1.5) \ 2.3 \ T/s \ (B_{\text{max}} \text{ in } 1 \ s)$
  - $Q_{\text{AC}} < (10) \ 5 \ W/m \ (\text{average over } 2.4 \ s \ \text{cycle})$, room for beam losses
  - Good field region ($10^{-4}$ homogeneity):
    - Injection ($3.5 \ \text{GeV}$): $\pm 42 \ mm \times \pm 30 \ mm$
    - Extraction ($50 \ \text{GeV}$): $\pm 42 \ mm \times \pm 14 \ mm$
  - Address fatigue issues at $> 100 \ MCycles$ lifetime
  - Address magnet protection issues
  - Address radiation damage issues
- With this choice:
  - The R&D complements the on-going work for FAIR at GSI and INFN
  - *R&D is scalable “also possibly for an SPS2+ in the future”*
The cost estimate in perspective

- In the plot are the various CERN options. Our target of today (blue) will requires some increase wrt allocation(+ 1.5 MCHF)
- Resources will be likely taken from HFM program. However a plan must be worked next months also in agreement with PS2 strategy.
R&D work breakdown themes

- Design and procure NbTi wire with
  - $J_c > 2500 \text{ A/mm}^2$
  - $D_{\text{eff}} < 3 \mu\text{m} \ (Q_n \text{ for a } 3 \text{ T bi-polar cycle } < 80 \text{ mJ/cm}^3 \text{ of NbTi})$
  - $\tau < 1 \text{ ms}$

- Design and produce a cable for pulsed operation
  - Define targets for $R_e$ and $R_a \text{ TBD (100 } \mu\Omega \text{ or larger) to have negligible AC loss and stable pulsed operation. Surface coating options vs. central core for cable production}$
  - Choose a cable insulation scheme for heat removal and test
  - Develop the joint technology for pulsed operation (AC loss and current distribution)

- Design and produce a 1-m long magnet model (re-usable for coil test purpose)
  - Low-loss iron and coil components (spacers, collars)
  - Verify heat transfer from coil (and heat removal from magnet ?)
  - Demonstrate quench detection and magnet protection scheme
  - Simulate fatigue at large number of cycles

- Test and instrumentation R&D (both for cable and magnet losses and AC field)
NbTi wire procurement

ITER-like specification box:
$J_c(4.2 \text{ K}, 5 \text{ T}) > 2500 \text{ A/mm}^2$
$Q_n(+/3) < 80 \text{ mJ/cm}^3 \text{ NbTi}$
NbTi wire procurement

ITER-like specification box:

\[ J_c(4.2 \text{ K}, 5 \text{ T}) > 2500 \text{ A/mm}^2 \]

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\[ D_{\text{eff}} < 3 \mu\text{m} \]
NbTi wire procurement

ITER-like specification box:

$J_c(4.2 \, \text{K}, \, 5 \, \text{T}) > 2500 \, \text{A/mm}^2$

$Q_n (+/- \, 3) < 80 \, \text{mJ/cm}^3 \, \text{NbTi}$

$D_{\text{eff}} < 3 \, \mu\text{m}$

$D_{\text{eff}} < 2 \, \mu\text{m}$
NbTi wire procurement

ITER-like specification box:
$J_c(4.2 \text{ K, } 5 \text{ T}) > 2500 \text{ A/mm}^2$
$Q_h(+/- 3) < 80 \text{ mJ/cm}^3 \text{ NbTi}$

$D_{\text{eff}} < 3 \text{ \mu m}$

$D_{\text{eff}} < 2 \text{ \mu m}$

A wire procurement program is the first action to be pursued as soon as the R&D is approved

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Thermally Enhanced insulation

State-of-the-art
- Overlap is present between tapes of first layer, nominally no channels.

Enhanced
- Overlap is present between first and third layer: finite dimension channels determined by thickness of second layer tapes

First Layer
(2 tapes 11 mm wide, 50.8 µm thick, 50% overlap)

Second Layer
(1 tape 9 mm wide, 68.6 µm thick, 2 mm space)

Third layer (1 tape 9 mm wide, 55 µm thick, 1 mm space, 40% overlapped to first layer)

First layer
(1 tape 9 mm wide, 25.4 µm thick, 1 mm space)

Second layer
(4 tapes 2.5 mm wide, 75 µm thick, 1.5 mm space)

M. La China, D. Tommasini
Enhanced Heat Tr of 3 to 5
Heat transfer study (for LHC first)

Region to be investigated in detail

D. Ritcher
Possible roadmap

- The horizon for magnet R&D related to the LHC is changing, objectives should be adapted accordingly.