Proposal 1602 – Cable Stack
HiRadMat Scientific board

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Outline

• Scientific Motivation
• Project Damage Limit of Sc. Magnets
• Goals of the Cable Stack experiment
• Experimental Set up and Beam parameters
• Post irradiation analysis
• Safety and Radio Protection
Scientific motivation
Sc. Magnet Damage Limit Project

- **Goal:** Measure the damage limit of LHC superconducting magnet components due to instantaneous beam impact
  
  - LHC Nb-Ti magnets
  
  - **Ultra-fast** beam losses (μs): injection and extraction failure cases with highly brilliant beams after LHC injector upgrades.
  
  - Beam impact leads to **spot heating** causing **thermo-mechanical stresses** and performance degradation.
Example of failure cases - injection

- Injection Kicker (MKI) kicks the circulating beam
- Beam intensity: $2.2 \times 10^{11}$ p per bunch (HL-LHC)
- Maximum energy density $\sim 100 \text{ J/cm}^3 (> 100 \text{ K})$ in separation dipole (D1)

What is the damage limit of sc. magnet components due to ultra-fast beam losses?

A. Lechner et al., Protection of superconducting magnets in case of accidental beam losses during HL-LHC injection, In Proceedings of IPAC15
Example of failure cases – extraction

- Asynchronous beam dumps
- Beam intensity: $2.2 \times 10^{11}$ p per bunch (HL-LHC)
- Maximum energy density ~$100 \text{ J/cm}^3$ in Q5

B. Auchmann et al., Quench and Damage Levels for Q4 and Q5 Magnets near Point 6, CERN EDMS 1355063, 2014
Known limits

**Lower bound**
- Quench of a magnet $\sim \text{mJ/cm}^3$
- Accidental beam losses during injection in 2011. MKI kicked circulating beam, 176 bunches were lost in the machine.
  - Peak energy density in D1 coils $\sim 6 \text{ J/cm}^3$

**Upper bound**
- Melting of copper with energy densities of $6 \text{ kJ/cm}^3$
Critical Components

- Degradation of the cable insulation: Polyimide films

- Degradation of the superconducting properties of Nb-Ti cable/strand ($I_c$)
Experimental plan

Insulation degradation

1. **Heat stacks of cables** in an oven to different peak temperatures and measure dielectric strength of the insulation

2. Heat **insulation** by a short current pulse and measure dielectric strength – on-going

Sc. strand degradation

3. Heat a single strand by a current pulse and measure critical current – on-going

Experiment with beam

4. Shock heating in cable stacks and strands due to beam impact in HiRadMat at RT to derive reduction of dielectric strength and critical current as function of hot spot temperature.

5. Shock heating in cable stacks, strands and coil samples due to beam impact in HiRadMat liquid He temperature to derive reduction of dielectric strength and critical current as function of hot spot temperature

→ HiRadMat SextSC experiment.
Degradation of insulation when exposed to heat treatment

- No degradation of the insulation below 400°C.
- Variation of the breakdown voltages within each measurement set due to inhomogeneity in the samples as expected in LHC magnets due to the significant length of the used cables.

Results of the dielectric strength measurements after heat treatments at different peak temperature

Side view of the cable stacks before and after the heat treatment with different peak temperatures

Temperature profiles of the cable stacks during the heat treatment in an oven filled with Argon
Weight loss model and extrapolation to ms time scale

The degradation of the dielectric strength is directly correlated to weight loss.

\[
\frac{d\omega}{dt} = k_0 \, e^{-\frac{(E_a/RT)}{\omega_f}} \left( 1 - \frac{\omega}{\omega_f} \right)^n \omega_f
\]

\( \frac{d\omega}{dt} \) is the reaction rate
\( \omega_f \) is the weight loss after a full degradation,
\( R \) is the ideal gas constant,
\( T \) is the temperature in Kelvin
\( k_0, E_a \) and \( n \) are fitting parameters

⇒ Extrapolation from long heating time (hours) to short heating time (us, ms)
⇒ 950°C heating for ms time scale is equivalent to heating at 500°C for several hours.
Degradation of critical current ($I_c$) of Nb-Ti strands

- Significant $I_c$ degradation after 5 minutes at 400°C, due to variation of the α–Ti precipitate size.
- Verification of the degradation of $I_c$ for ms heating.

Goals of the HRM Cable Stack experiment

Study the **damage mechanisms** induced by the impact of high intensity proton beams for time scales comparable to LHC injection and dump failures:

- **Degradation of the superconducting properties** due to strain/stress induce by the thermal-shock.
- **Degradation of critical current** due to the variation of $\alpha$-Ti precipitate size when sc. cable is exposed to high temperature.
- **Degradation of the insulation** due to high temperature
- **Identification of other mechanisms**
- **Verify structural integrity of steel** after energy deposition up to 2.5 kJ/cm3 due to instantaneous beam impact in preparation of HiRadMat SextSC experiment.
Cable stacks as pre-experiment for SextSc

The experiment at room temperature will give essential inputs to optimize the following experiment planned to be done at cryogenic temperature.

- **Simpler setup** at room temperature.
- Energy deposition in **μs time scales** and verification of damage models.
- **Optimization** (number of shots and samples).
- Validation of **mechanical robustness** of proposed cryostat solution via stainless steel plate.

Extension to environment as in LHC (cryogenic) required.
Experimental Setup - Samples

- **12 Nb-Ti cable stacks** (30 Rutherford cables, 5 cm height) in steel molds with 100 MPa pre-stress.

- **34 Nb-Ti strands horizontally fixed on a stainless steel plate.**

- **2 stainless steel plates** (5 mm thick)

Steel mold with cable stack in yellow

Sc. strands (orange) fixed on steel plates
Peak Temperature – Design choice

<table>
<thead>
<tr>
<th>Peak Temperature (°C)</th>
<th>Energy Density in Cu/Nb-Ti (kJ/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>950</td>
<td>3.2</td>
</tr>
<tr>
<td>850</td>
<td>2.8</td>
</tr>
<tr>
<td>750</td>
<td>2.5</td>
</tr>
<tr>
<td>650</td>
<td>2.2</td>
</tr>
<tr>
<td>550</td>
<td>1.9</td>
</tr>
<tr>
<td>400</td>
<td>1.2</td>
</tr>
<tr>
<td>300</td>
<td>0.9</td>
</tr>
<tr>
<td>200</td>
<td>0.6</td>
</tr>
<tr>
<td>100</td>
<td>0.3</td>
</tr>
<tr>
<td>50</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Minimum six samples for each peak temperature taking into account inhomogeneity of the cable insulation.

No degradation expected
**Experimental Setup – General Assembly**

- **Cable stacks**
- **Aluminium container filled with Argon (1.2 atm)**
- **Steel plate with sc. strands**
- **Vertical movable pillar (re-used from HRM24)**

**Instrumentation**
- **Beam position measurement externally**
- **Resistance** measurement of the single strands to derive **peak temperature**.
- Temperature sensor to monitor the **steady state temperature** of the strands.
• Beam characteristics $\sigma_x = \sigma_y = 1$ mm, $E = 440$ GeV
• Beam pulse list:
  6 x 6 bunches, 6 x 12 bunches, 6 x 24 bunches
  ➢ **Total intensity:** 252 bunches, $2.9 \times 10^{13}$ protons
Post irradiation analysis

After cool down for 3 - 6 months:

- **High voltage tests** on the cables stacks – degradation of insulation (CERN – b.112)
- **Magnetization measurements** on single strands – degradation of the sc. properties. (University of Geneva)
- **Structural analysis** of the steel plate with microscope. (CERN – b.599)
Safety and Radio Protection

• Beam intensity and size chosen to **rule out any structural damage** of the container. **No melting** of the samples is expected.

• Radiological Risk: the experiment has been designed to include **as little material as possible**.
### Residual dose

<table>
<thead>
<tr>
<th>Cooling Period</th>
<th>Aluminium box (Total intensity consider)</th>
<th>Moulds/Stacks (½ intensity considered)</th>
<th>Single Stands (24 bunches considered)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum residual dose rate at 40 cm (µSv/h)</td>
<td>Maximum residual dose rate at contact (µSv/h)</td>
<td>Maximum residual dose rate at contact (µSv/h)</td>
</tr>
<tr>
<td>1 day</td>
<td>&lt; 300</td>
<td>1.0 x 10^4</td>
<td>1.0 x 10^5</td>
</tr>
<tr>
<td>1 week</td>
<td>&lt; 60</td>
<td>5.5 x 10^2</td>
<td>1.6 x 10^4</td>
</tr>
<tr>
<td>3 months</td>
<td>&lt; 8</td>
<td>5.5 x 10^1</td>
<td>1.2 x 10^3</td>
</tr>
<tr>
<td>6 months</td>
<td>&lt; 3</td>
<td>3.2 x 10^1</td>
<td>5.5 x 10^2</td>
</tr>
</tbody>
</table>

Simulation indicate that post irradiation analysis could be after 3 to 6 months of cool down.
Conclusion

-The goals of the experiment:
  - Validate/extend degradation model derived from long time scale heating for short time scale.
  - Identify other degradation mechanism if any.
  - Prepare for SextSC

- Beam pulses: 6, 12 and 24 bunches; total intensity of 252 bunches \((2.9 \times 10^{13}\text{ protons})\).

- Cool down time before PM analysis: 3 to 6 months

- Post irradiation analysis at CERN (HV test and microscopic analysis) and University of Geneva (magnetization).
Questions ?
Vertical Profile of the Energy Deposition in different mould
Horizontal profile of the energy deposition for strands with different vertical position regarding the beam axis.
Beam characteristics: $E = 440\text{GeV}$, $\sigma_x = \sigma_y = 1\text{mm}$

Proton per bunch: $1.15 \times 10^{11}$

Initial Temperature: 303 K

Max. energy deposited in cable stacks 1 per proton: $1.4\text{ GeV/cm}^3$
Max. energy deposited in cable stacks 2 per proton: $5.2\text{ GeV/cm}^3$
Max. energy deposited in cable stacks 3 per proton: $7.4\text{ GeV/cm}^3$
Max. energy deposited in cable stacks 4 per proton: $6.4\text{ GeV/cm}^3$
Max. energy deposited in cable stacks 5 per proton: $5.8\text{ GeV/cm}^3$
Max. energy deposited in cable stacks 6 per proton: $4.4\text{ GeV/cm}^3$

Max. energy deposited in Steel per proton: $6.4\text{ GeV/cm}^3$
Max. energy deposited in Al per proton: $0.2\text{ GeV/cm}^3$

The graph shows the relationship between the number of protons and the temperature increase ($\Delta T$) for different cable stack configurations and materials (Al, Stainless steel).
Residual dose in proximity of the container

- Figures show spatial distribution of the residual dose rates in $\mu$S/h in the horizontal plane
- Total intensity $\sim 252$ bunches, $1.15\times10^{11}$ p/b

<table>
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<tr>
<th>Cooling Period</th>
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<td>6 months</td>
<td>$&lt; 3$</td>
<td>$3.2 \times 10^{1}$</td>
</tr>
</tbody>
</table>
Residual dose rate within/at contact with 3\textsuperscript{rd} cable stack

- Figures show spatial distribution of the residual dose rates in μS/h in the horizontal plane
- ½ of the total intensity (126 bunches, 1.15E11 p/b)

<table>
<thead>
<tr>
<th>Cooling Period</th>
<th>Maximum residual dose rate within cable stack (μSv/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td>1.0 x 10\textsuperscript{5}</td>
</tr>
<tr>
<td>1 week</td>
<td>1.6 x 10\textsuperscript{4}</td>
</tr>
<tr>
<td>3 months</td>
<td>1.2 x 10\textsuperscript{3}</td>
</tr>
<tr>
<td>6 months</td>
<td>5.5 x 10\textsuperscript{2}</td>
</tr>
</tbody>
</table>
Residual dose rate within/at contact with strand

- Strand exposed to a beam intensity of maximum 24 bunches (1.15E11 p/b)

<table>
<thead>
<tr>
<th>Cooling Period</th>
<th>Maximum residual dose rate within single strand (µSv/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td>2.0 x 10^4</td>
</tr>
<tr>
<td>1 week</td>
<td>2.6 x 10^3</td>
</tr>
<tr>
<td>3 months</td>
<td>2.2 x 10^2</td>
</tr>
<tr>
<td>6 months</td>
<td>1.1 x 10^1</td>
</tr>
</tbody>
</table>

Residual dose after different cooling time along a strand exposed to 24 bunches

After 1 day
- After 1 week
- After 3 months
- After 6 months