Damage levels of superconducting magnet components

Status of studies and first experimental results

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6th HL-LHC Collaboration Meeting, Paris, France

Outline

- Motivations and goals
- Damage mechanisms and consequences
- Experimental road map
- Experimental results
- Conclusion and next steps

Motivations from HL-LHC ultra-fast failure

Ultra-fast failure < 270 us (3 LHC turns)

- Studies of **injection and extraction failures** with HL-LHC bunch intensities show that despite beam absorber a peak energy density up to **~ 100 J/cm^3 in sc. magnets** can be reached. **Is it safe?**

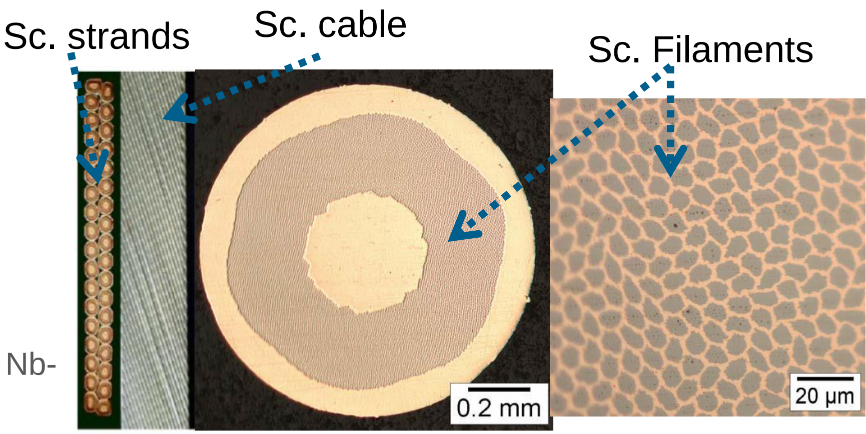
⇒ **What is the damage limit of sc. magnets in case of ultra-fast beam losses?**

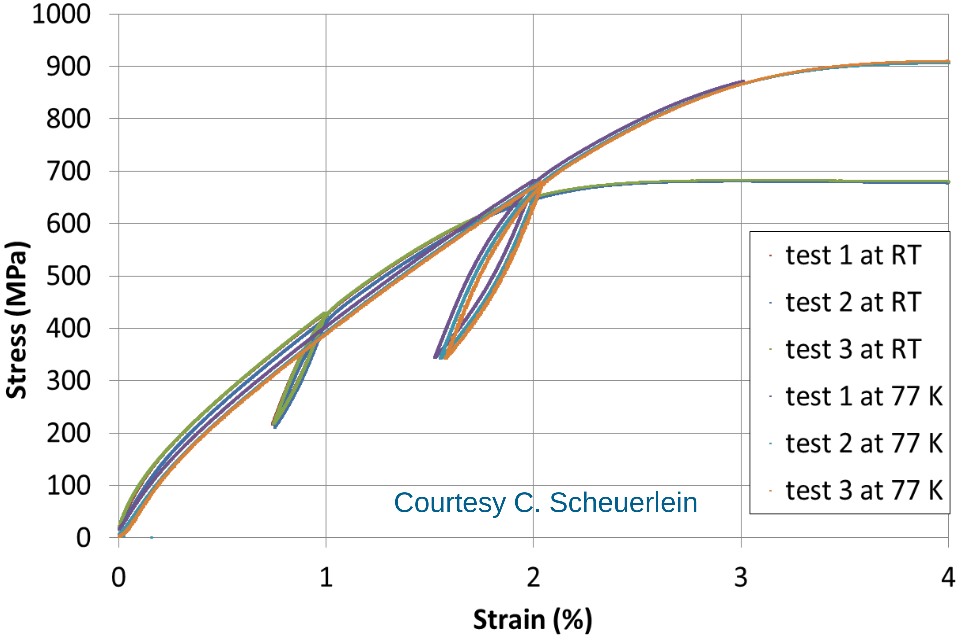
⇒ **What are the damage mechanisms?**

Yield and tensile strength in Nb-Ti wires

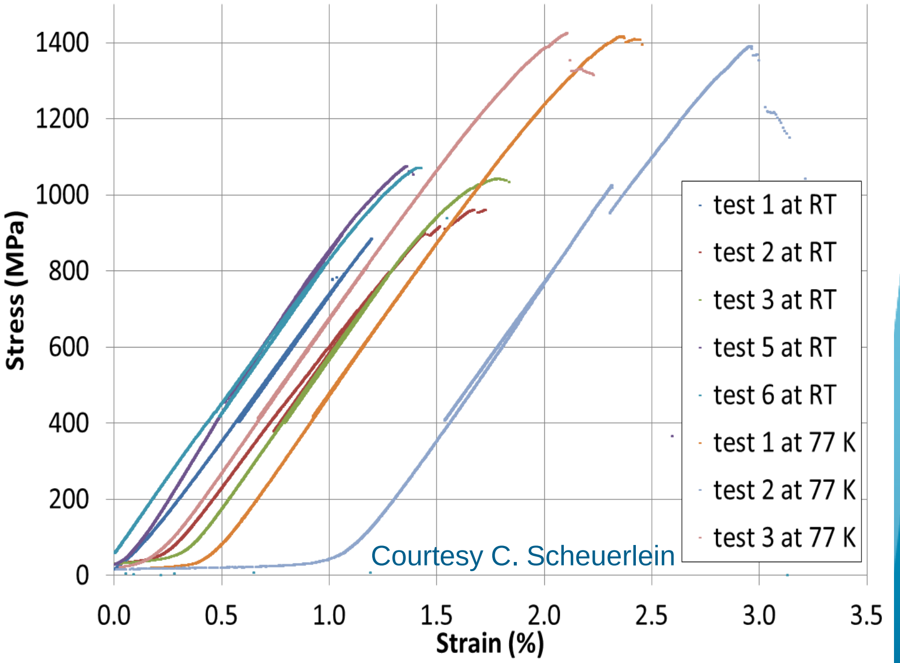
Beam losses → Fast heating → Mechanical stress

- **Copper in Nb-Ti cable reaching elastic limit** at σ_{RT}= 0.68 GPa, σ_{77K}= 0.9 GPa
- **Nb-Ti filaments breaking** (σ_{RT}= 1 GPa, σ_{77K}= 1.4 GPa)
- < 100 MPa elastic regime; < 870 MPa at 77 K (< 570 MPa at RT) plastic regime of the copper; > 870 MPa at 77 K (> 570 MPa at RT) Nb-Ti and copper in the plastic regime.





Engineering stress versus strain of the Nb-Ti/Cu 02R wires acquired with the H&P set-up at RT and at 77 K

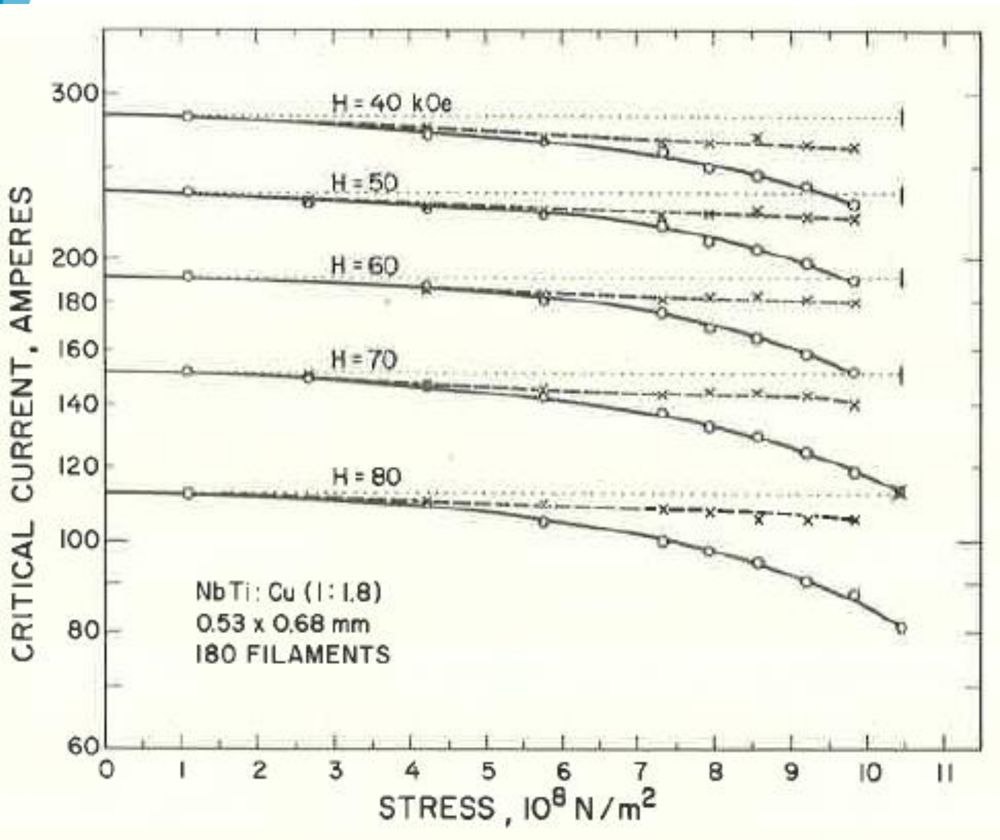


Engineering stress versus strain of Nb-Ti filaments tested at RT and at 77 K.

Critical current (I_c) as function of stress in Nb-Ti and Nb_3Sn wires

- **Plastic deformation of copper matrix inducing permanent stress on the Nb-Ti filaments**.

⇒ I_c of Nb-Ti has a low dependency to stress compare to Nb_3Sn.



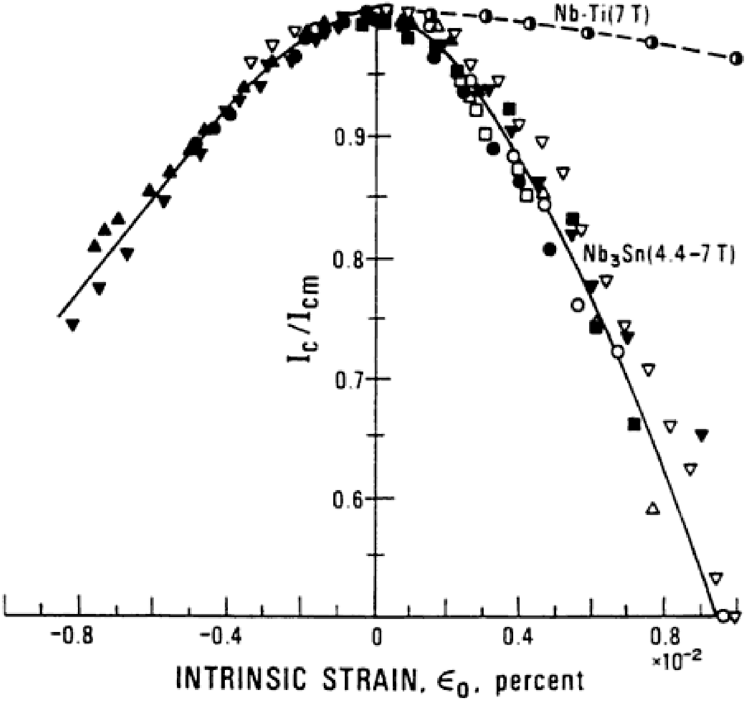


Figure 44 Effect of uniaxial strain on the critical current of both ductile (Nb–Ti) and brittle (Nb_3Sn) superconductors at low magnetic fields. △, Rupp (1977); ○, △, □, ▽, Ekin (1976, 1978); ◑, Ekin et al. (1975); ■, Easton and Schwall (1976). (From Ekin, 1978.)

* J.W. Ekin, F.R. Fickett, A. F. Clark, Effect of Stress on the Critical Current of NbTi Multifilamentary composite wire, Proc. Int. Cryogenic Materials Conf., 1975; (1977), Adv. Cryog. Eng., 22:449

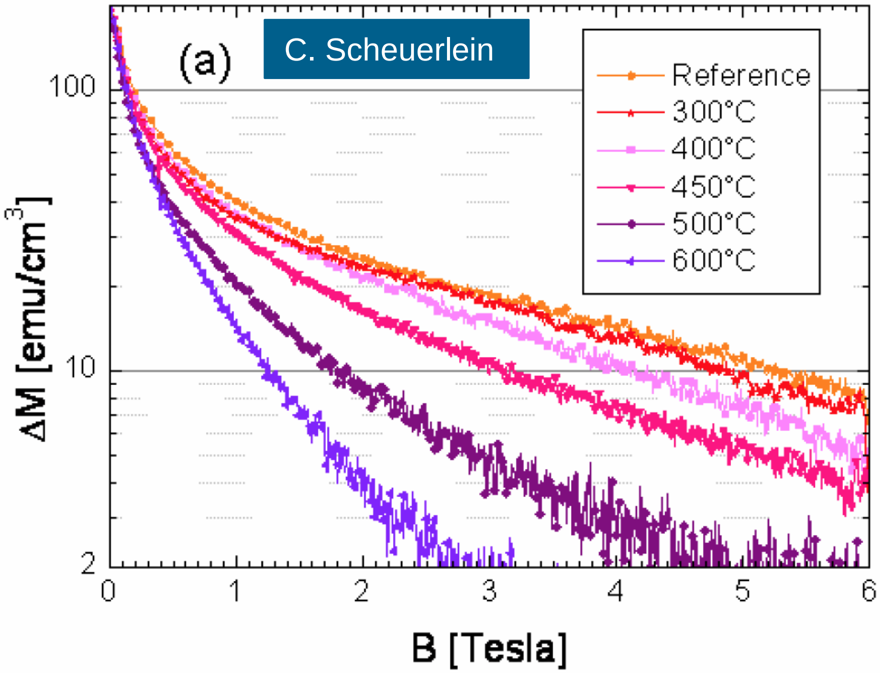
* K. Osamura, Composite superconductors, CRC Press, 1993

Known effects reducing critical current in Nb-Ti wires

Courtesy V. Kain.

- **Melting of copper matrix** (~6 kJ/cm^3)

- **Variation of the α-Ti precipitate size** (T>400°C for several minutes)

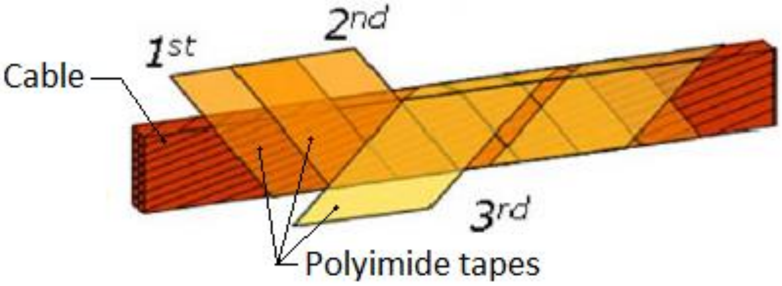


C. Scheuerlein

Variation of the Nb-Ti/Cu strand magnetization (ΔM) at 4.2 K in magnetic field up to 6 T after different heat treatments

Insulation degradation due to high temperatures

- Reduction of the dielectric strength of polyimide films for T > ~400°C



- Failure modes:
  - **inter-turn short** (fatal for magnet in case of quench)
  - **short to ground** (prevent operation and require most probably a replacement of the damage magnet)


Courtesy A. Siemko

Experimental plan

Insulation degradation due to temperature

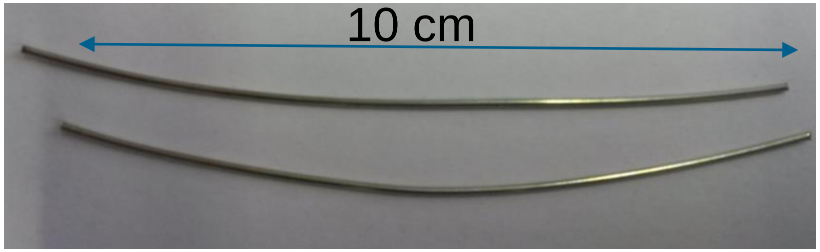
1. Heat stacks of cables in furnace (hours) ✓
2. Heat insulation by a short current pulse in a heater (ms) → Dec. 2016 / Jan 2017

Sc. strand degradation due to temperature

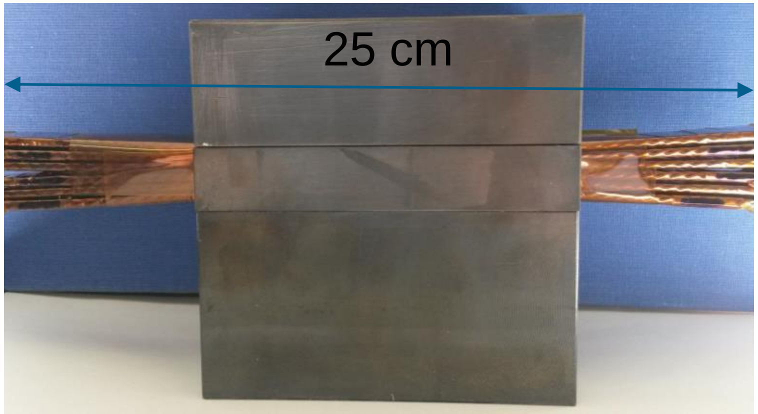
3. Heat a single strand by a current pulse and measure critical current (ms) → end Nov. 2016

Experiments with beam (all degradation mechanisms – µs to ms)

4. Expose stacks of cables and strands to a proton beam, at room temperature ✓
5. Expose stacks of cables and coils to a proton beam at cryogenic temperatures → end 2017



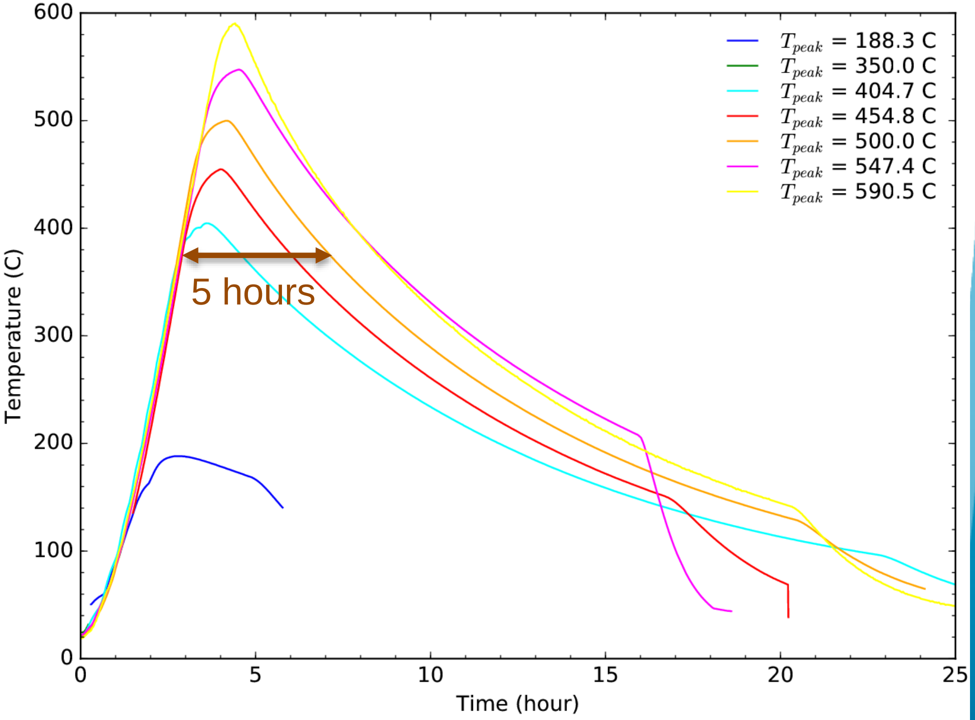
Nb-Ti strands (1 mm ø)



Stack of 6 Nb-Ti cables

Degradation of insulation due to temperature

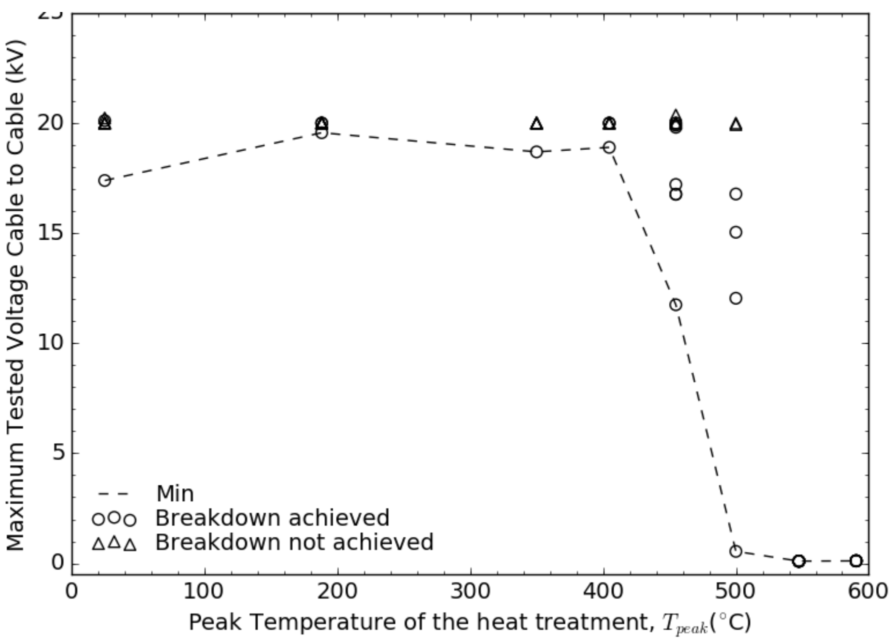
- Cable stacks heated in furnace between 200°C and 600°C in inert atmosphere (Argon).
- Measurement of the breakthrough voltage cable-to-cable after heat treatment.



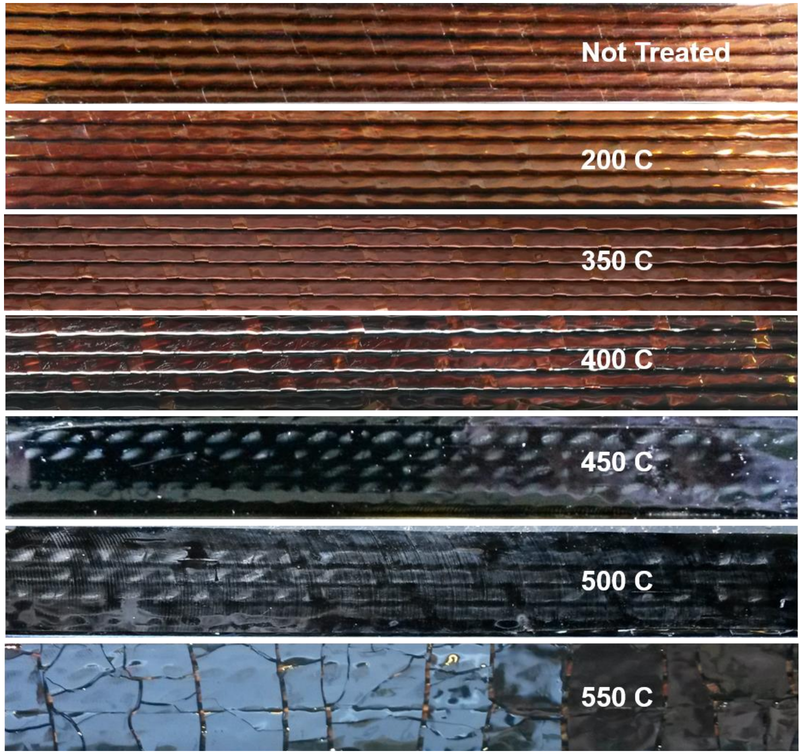
Temperature profiles of the cable stacks during the heat treatment in an oven filled with Argon

Experimental results – insulation degradation

- **Significant degradation** of polyimide insulation when **heating > 400°C**
- Lowest breakthrough voltage considered as worst case scenario.



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

Weight loss model & extrapolation of degradation

- Weight loss can be used as an indicator for the degradation of the insulation dielectric strength:

⇒ **Below 0.4% weight loss, no degradation of dielectric has been observed.**

- A model of the weight loss (w) has been developed

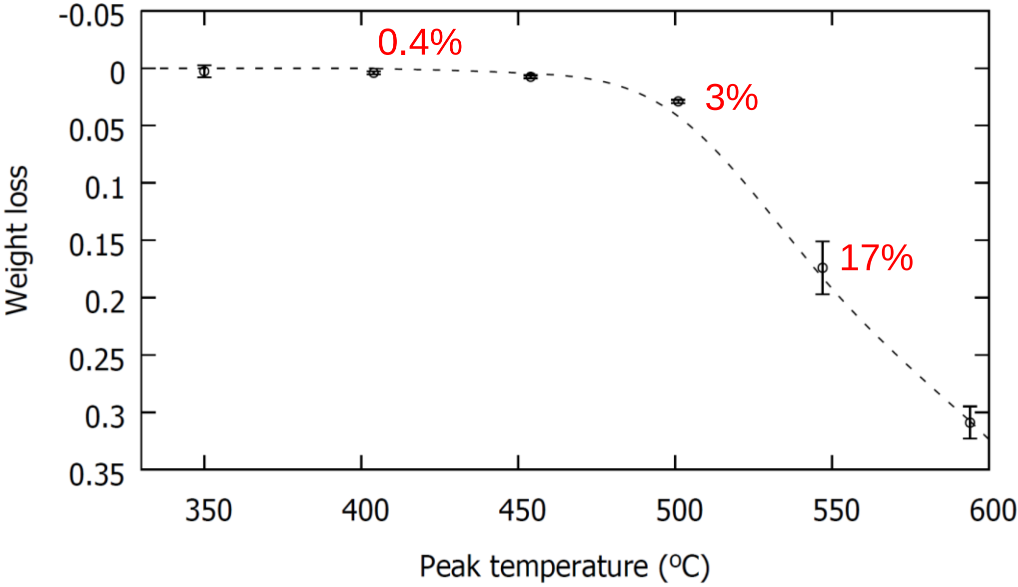
$$\frac{dw}{dt} = -k_0 \exp\left(-\frac{E_a}{RT}\right)\left(1-\frac{w}{w_f}\right)^n w_f$$

$$w = \frac{(m_0 - m)}{m_0}$$

$\frac{dw}{dt}$ is the reaction rate

k_0 , E_a and n are fitting parameters

w_f is the weight loss after full degradation



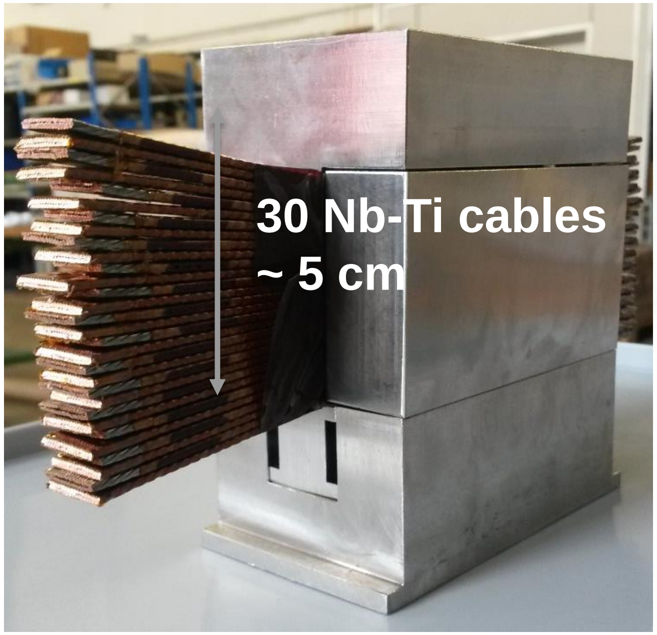
⇒ Extrapolation from long (hours) to short time scales of heating (us, ms).

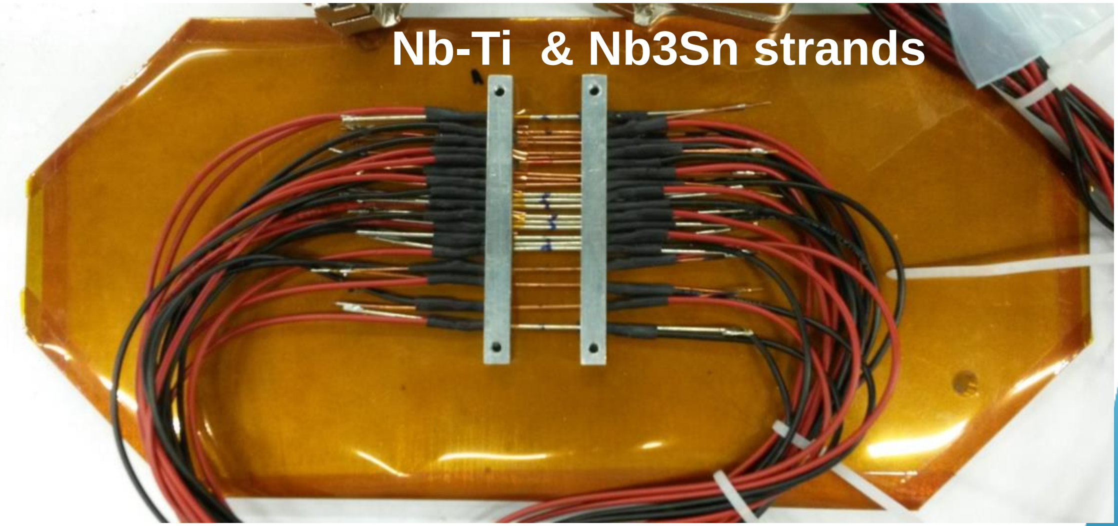
⇒ **950°C** heating for **ms time scale** is equivalent to heating at **500°C for several hours**.

Beam experiment at room temperature

- In the HiRadMat facility shooting a **440 GeV proton beam on:**
  - **LHC Nb-Ti Cable stacks** to study the degradation of the insulation
  - **Nb-Ti and Nb$_3$Sn strands** to study the degradation of sc. properties

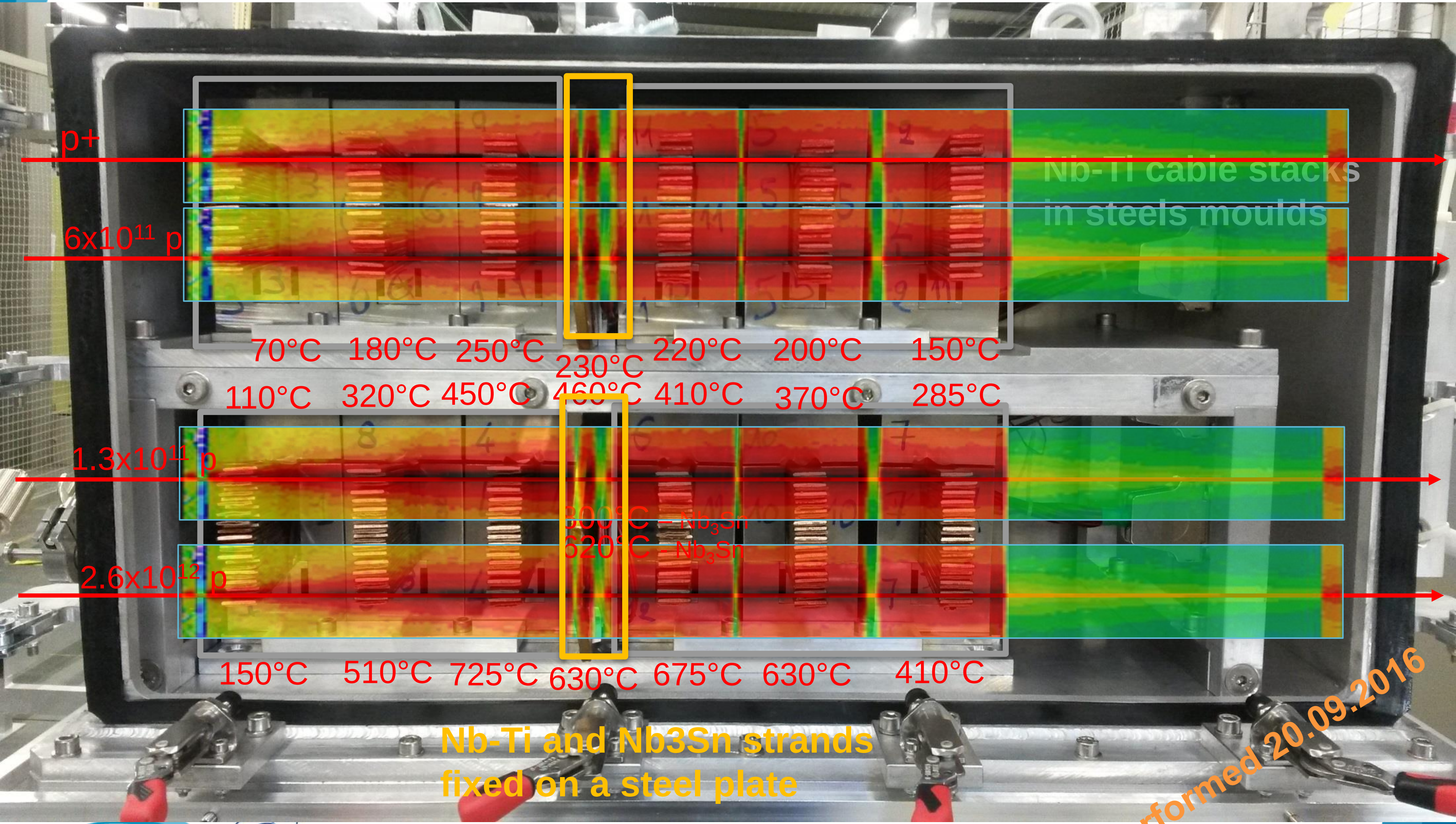
  Samples kept in inert atmosphere**.**





Experimental setup and peak temperatures

Beam pulse list: 6 x $6\text{x}10^{11}$ protons, 6 x $1.3\text{x}10^{11}$ protons, 6 x $2.6\text{x}10^{12}$ protons



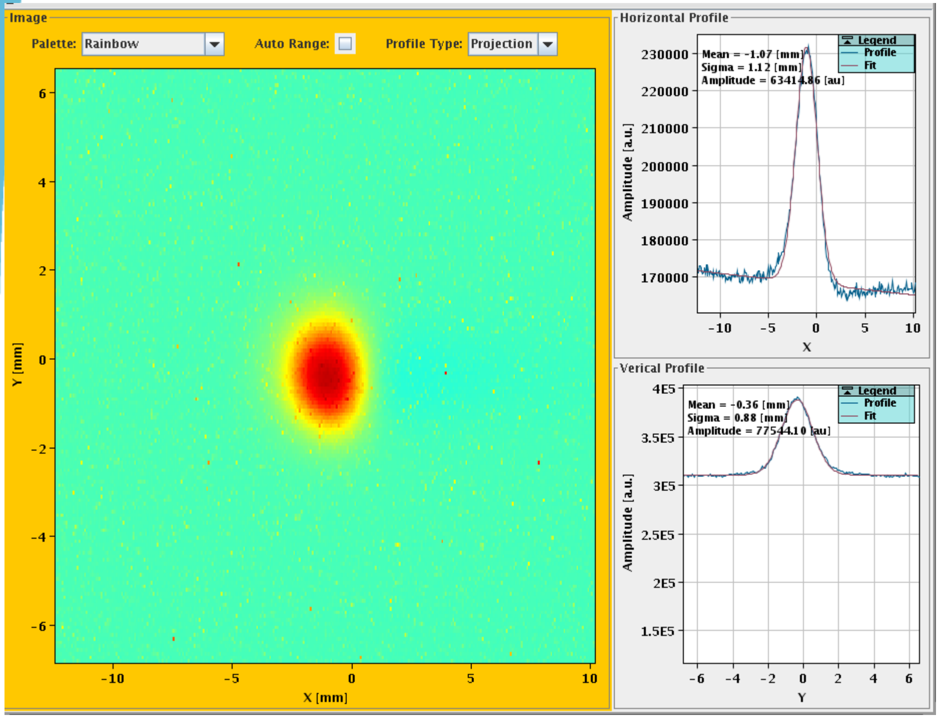
Nb-Ti cable stacks in steels moulds

Nb-Ti and Nb3Sn strands fixed on a steel plate

Performed 20.09.2016

On-line measurements during beam experiment

Screen: beam size and position



Image

Palette: Rainbow

Auto Range: ☐

Profile Type: Projection

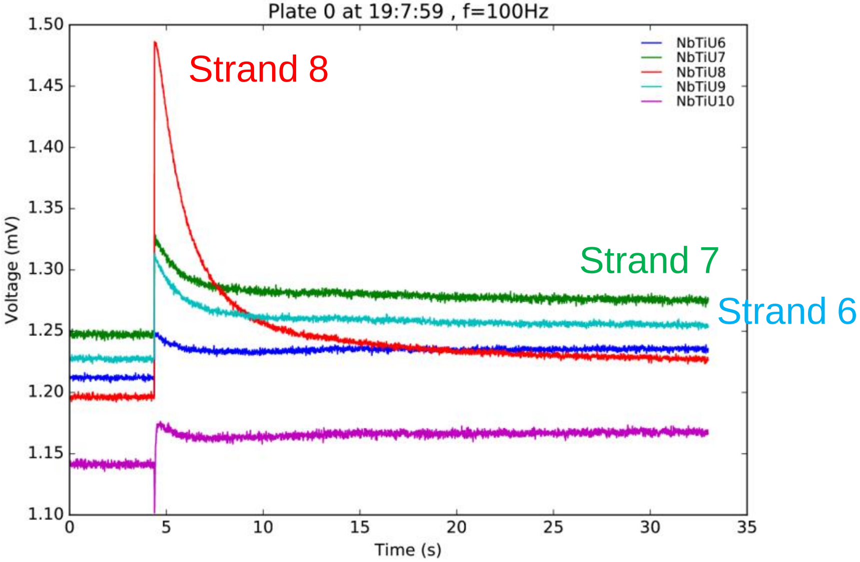
Horizontal Profile

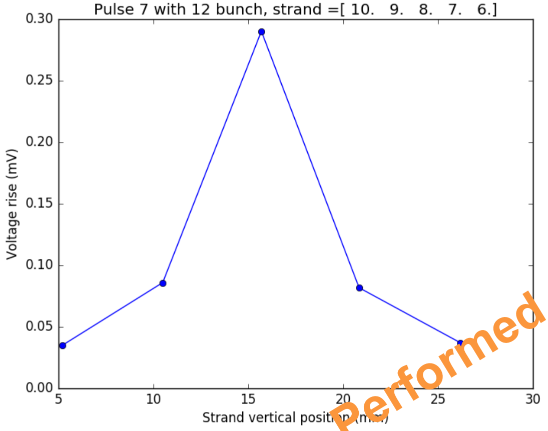
Mean = -1.07 [mm]
Sigma = 1.12 [mm]
Amplitude = 63414.86 [au]

Verical Profile

Mean = -0.36 [mm]
Sigma = 0.88 [mm]
Amplitude = 77544.10 [au]

Strand voltage: vertical alignment of strands





Performed 20.09.2016

Post irradiation analysis

After cool-down of target from **December 2016:**

- **High voltage tests on the cables stacks** – degradation of insulation (CERN – b.112)
- **Magnetization measurements** on the single strands – degradation of the sc. properties. (University of Geneva)

Conclusion

- Identifying the **damage mechanisms** and **damage limits** in critical magnet components due to instantaneous **beam impact** is essential for the HL-LHC project.
- Furnace experiment showed a **clear degradation** of the insulation performance **above 400°C** (couple of hours)
- **First experiment with beam** has been performed successfully (09.2016). **Postmortem analysis** will start after cool down of target in beginning of **December**.
  - Peak temperatures achieved: **750°C in cable stacks** and **630°C/ 800°C in strands**.
- **Future experiments** under preparation:
  - **Current discharge** experiments to measure degradation of insulation and critical current **in ms timescale** – (December 2016 / January 2017)
  - **Beam experiment at lHe temperatures** including full coil samples (end 2017)

Thank you for your attention!