CERN

# Damage levels of superconducting magnet components

## Status of studies and first experimental results

V. Raginel, D. Kleiven, K. Kulesz, D. Wollmann

# Outline

- Motivations and goals
- Damage mechanisms and consequences
- Experimental road map
- Experimental results
- Next experiments

# Motivations from HL-LHC ultra-fast failure

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

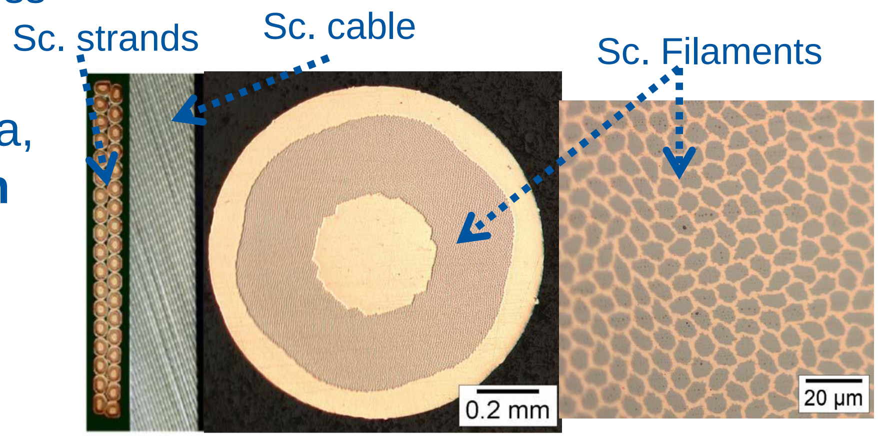
- Studies of **injection and extraction failures** with HL-LHC bunch intensities show that despite beam absorber a peak energy density up to **~ 100 J/cm$^3$ in sc. magnets** can be reached. **Is it safe?**

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

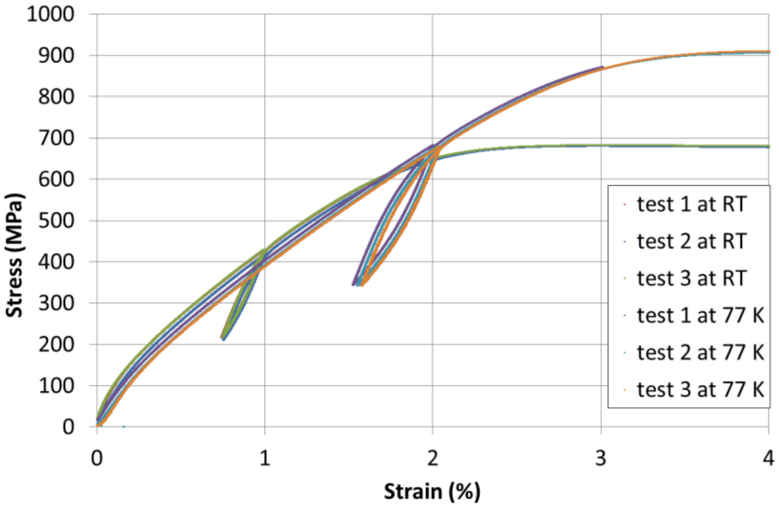
⇒ **What are the damage mechanisms?**

# Reduction of cable $I_c$ due to thermo-mechanical stress

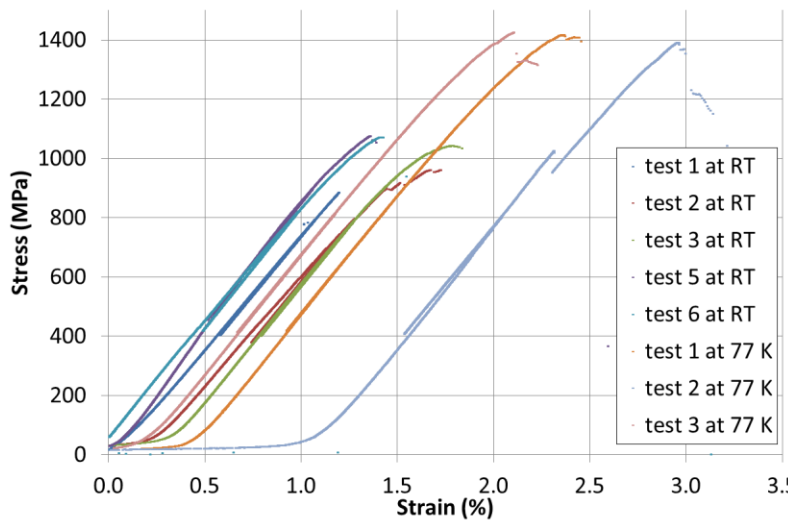
Beam losses → Fast heating → Mechanical stress




- **Nb-Ti filaments breaking** ($\sigma_{RT}$= 1 GPa, $\sigma_{77K}$= 1.4 GPa) leading to a **reduction of the $I_c$** of the sc. cable




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

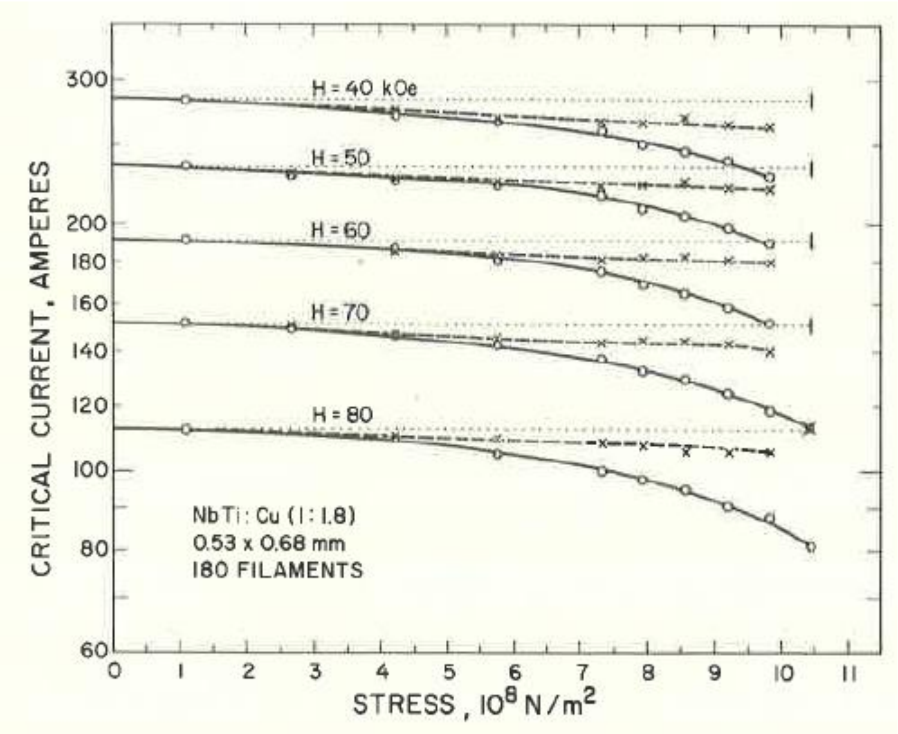



Engineering stress versus strain of Nb-Ti filaments tested at RT and at 77 K.

# Reduction of cable $I_c$ due to thermo-mechanical stress

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

$\Rightarrow$ $I_c$ of Nb-Ti has a low dependency to stress compare to $Nb_3Sn$.



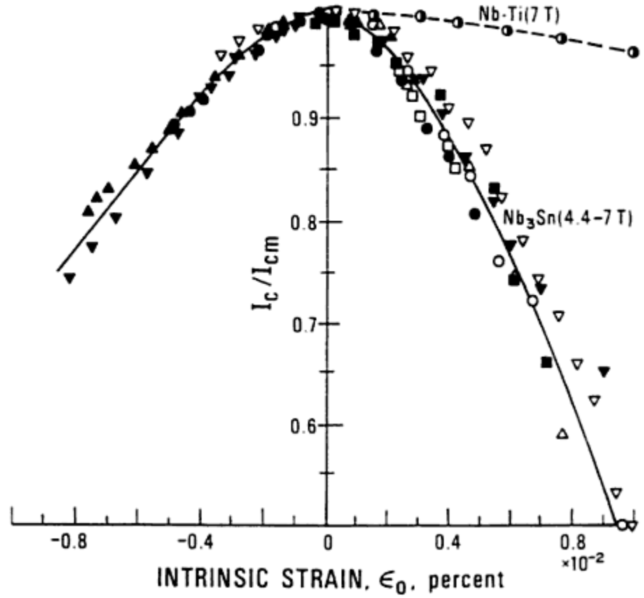
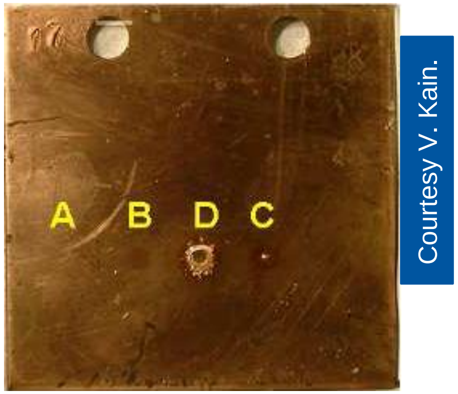



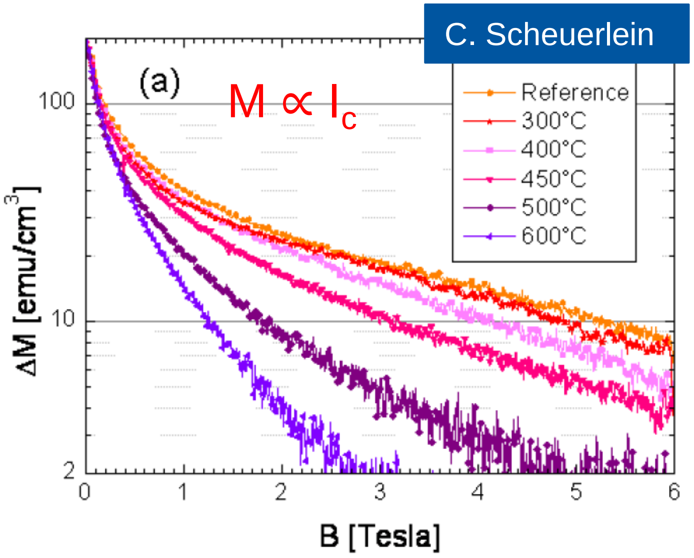

**Figure 44** Effect of uniaxial strain on the critical current of both ductile (Nb–Ti) and brittle ($Nb_3Sn$) superconductors at low magnetic fields. △, Rupp (1977); ○, △, □, ▽, Ekin (1976, 1978); ◑, Ekin et al. (1975); ■, Easton and Schwall (1976). (From Ekin, 1978.)

* 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

# Reduction of cable $I_c$ induced by temperature

- **Melting of copper matrix** (~6 kJ/cm³)
- **Variation of the α-Ti precipitate size** (T>400°C for several minutes)

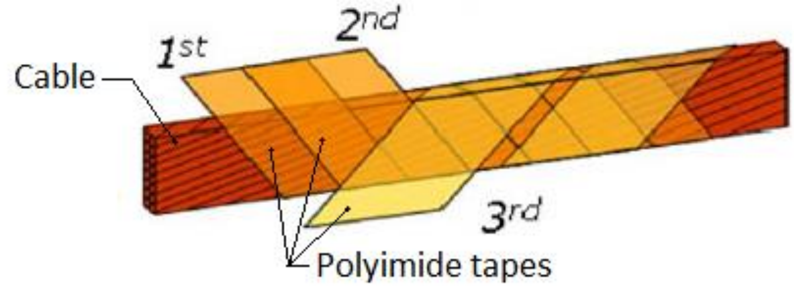


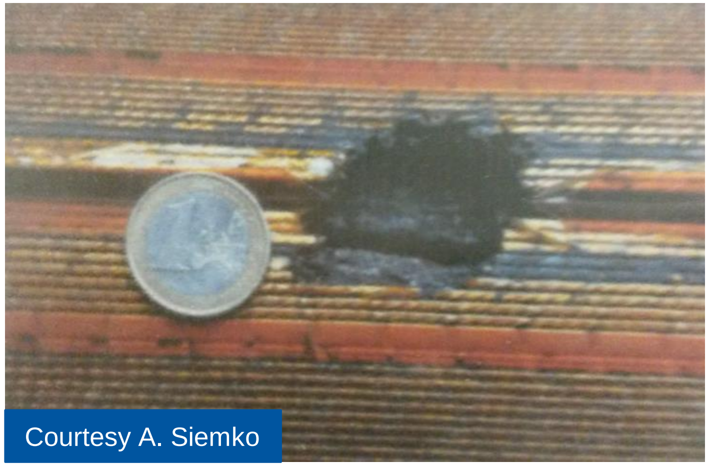

Variation of the Nb-Ti/Cu strand magnetization (ΔM) at 4.2 K in magnetic field up to 6 T after different HT's

# Insulation degradation due to temperature

- 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

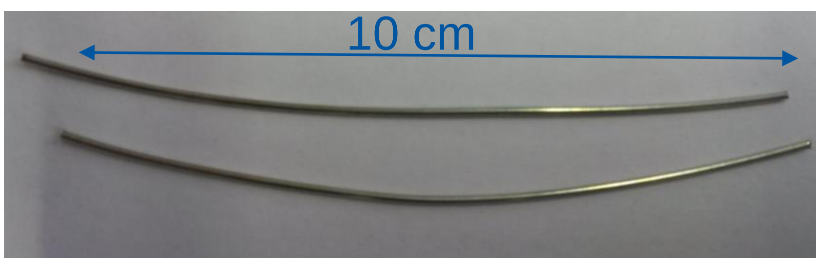
1. Heat stacks of cables in furnace (hours) ✓
2. Heat insulation by a short current pulse in a heater (ms)

Sc. strand degradation due to temperature

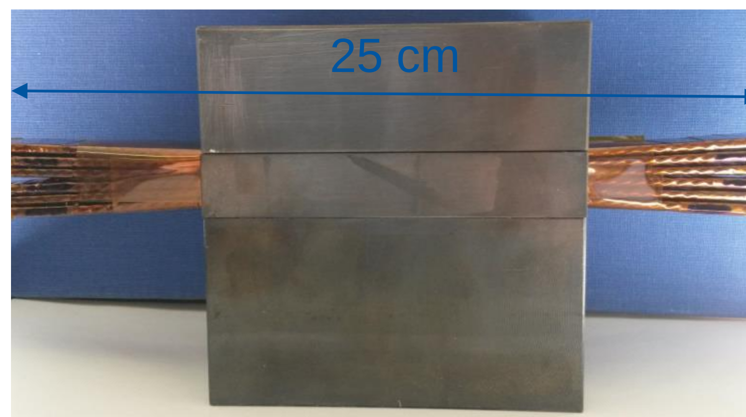
3. Heat a single strand by a current pulse and measure critical current (ms)

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



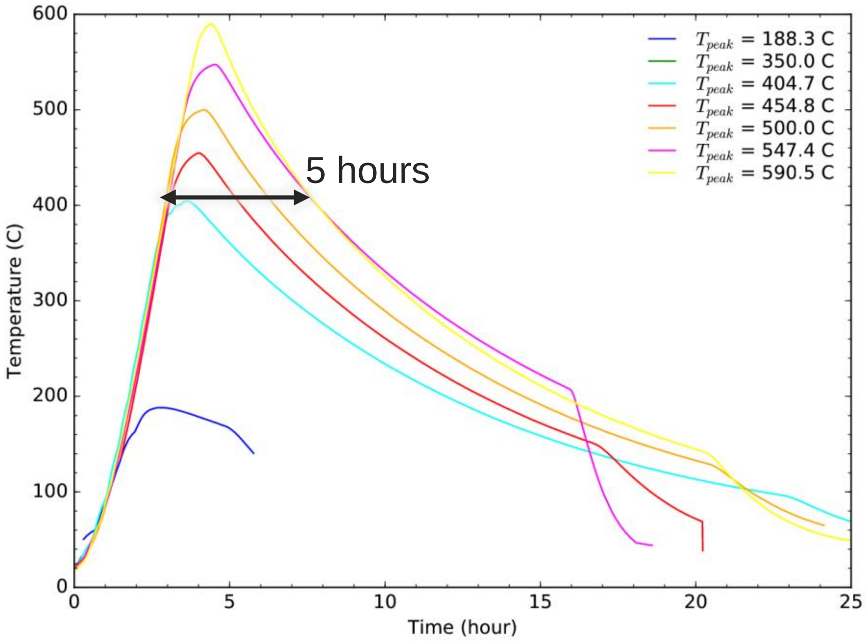
Nb-Ti strands (1 mm ø)



Stack of 6 Nb-Ti cables

# Degradation of insulation due to temperature

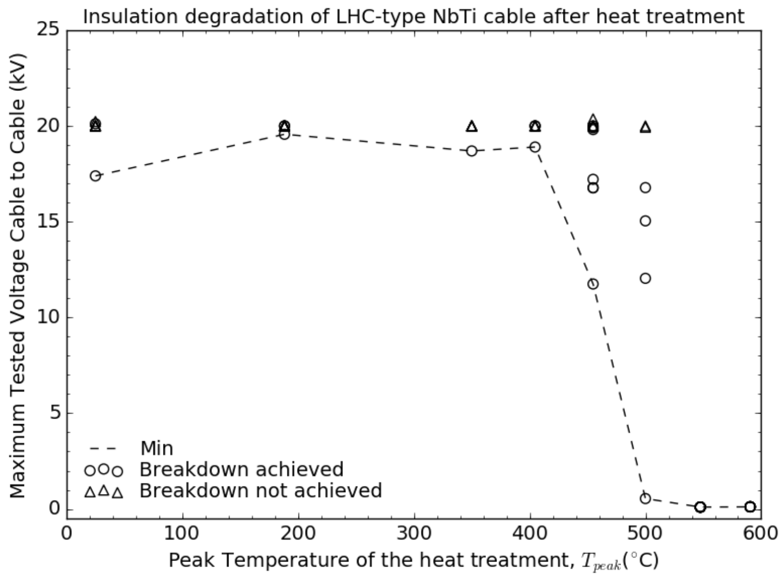
- Cable stacks heated in furnace between 200°C and 600°C in an inert atmosphere.
- Measurement of the breakthrough voltage cable to cable after heat treatment



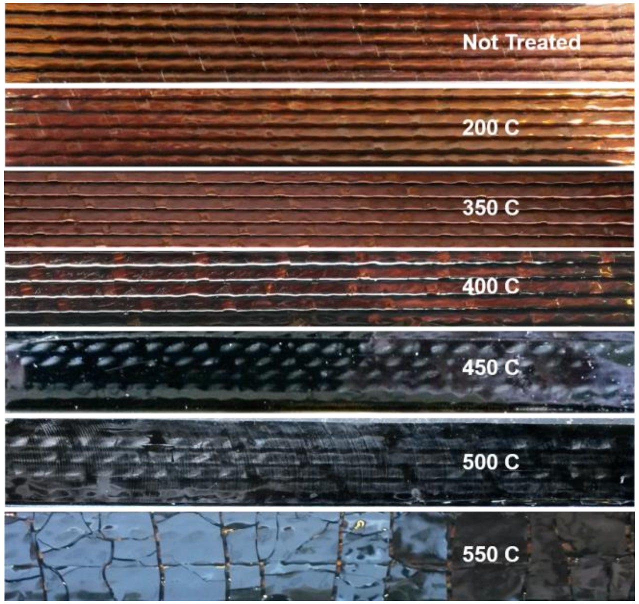

Temperature profiles of the cable stacks during the heat treatment in an oven filled with Argon

# Experimental results

- **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 and extrapolation

- 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

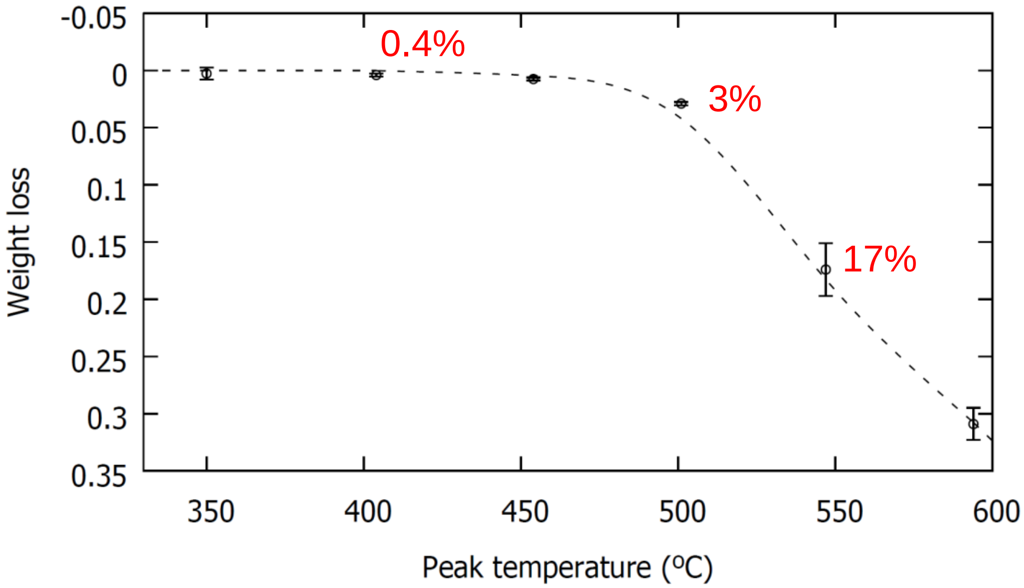
$$\frac{dw}{dt} = -k_0 \exp\left(-\frac{E_a}{RT}\right)\left(1 - \frac{w}{w_f}\right)^n w_f$$

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

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

$k_0$, $E_a$ and $n$ are fitting parameters

$w_f$ is the weight loss after full degradatio[n]



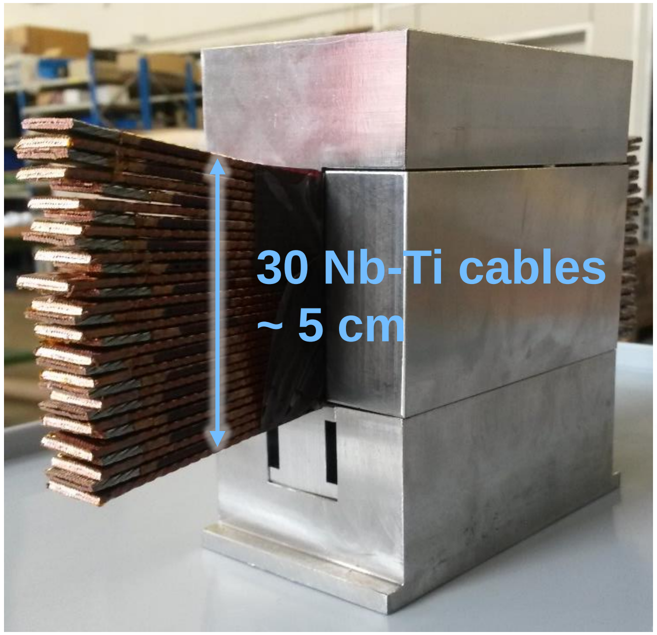

⇒ Extrapolation from long heating time (hours) to short heating time (us, ms)

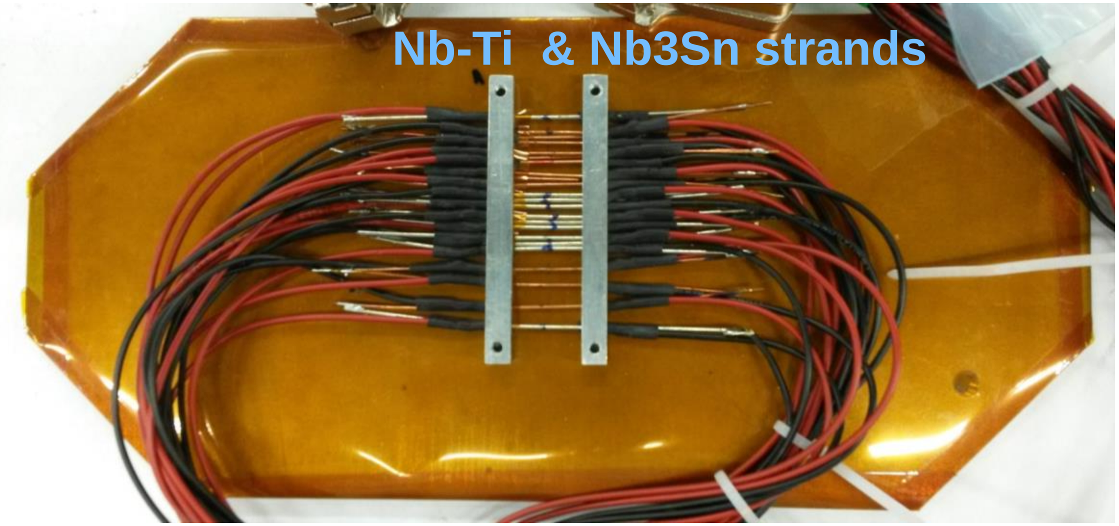
⇒ **950°C** heating for **ms time scale** is equivalent to heating at **500°C for several hours**.

# 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 $Nb_3Sn$ strands** to study the degradation of sc. properties

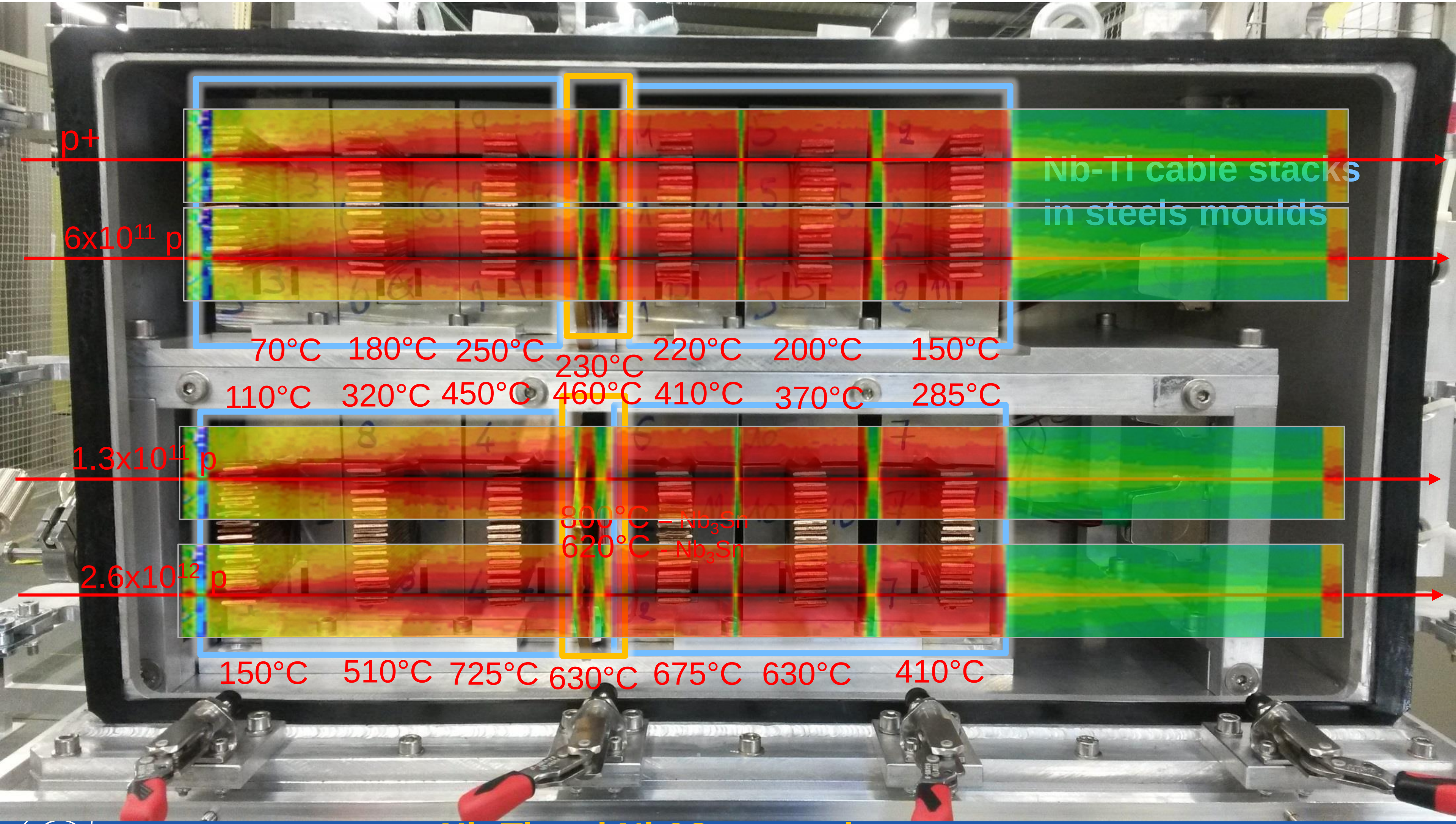
Samples are within an inert atmosphere**.**



# Experimental setup and peak temperatures

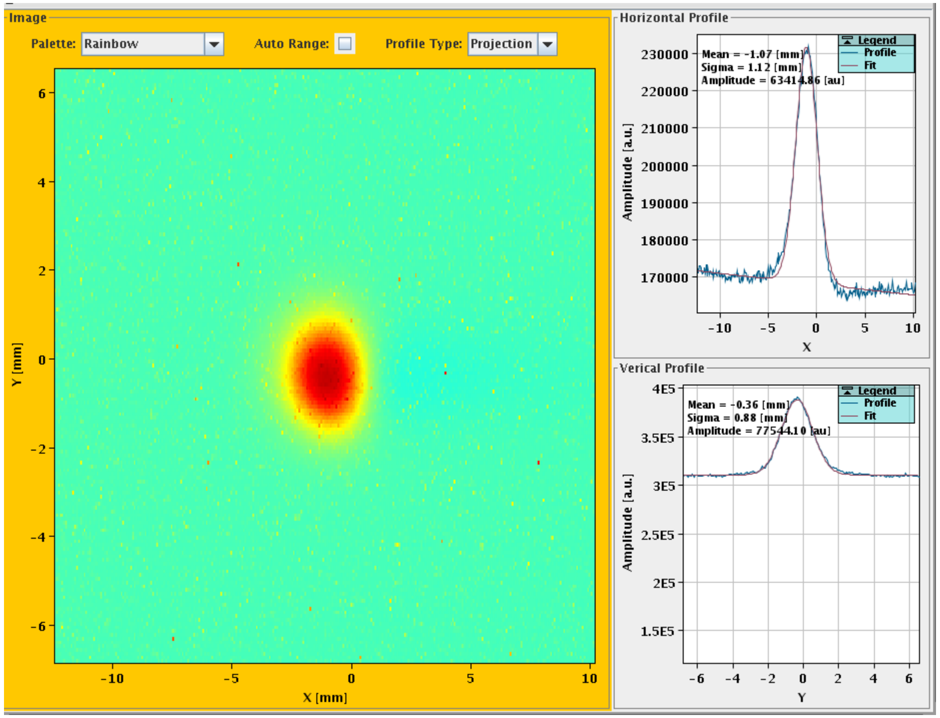
Beam pulse list: 6 x 6x$10^{11}$ protons, 6 x 1.3x$10^{11}$ protons, 6 x 2.6x$10^{12}$ protons



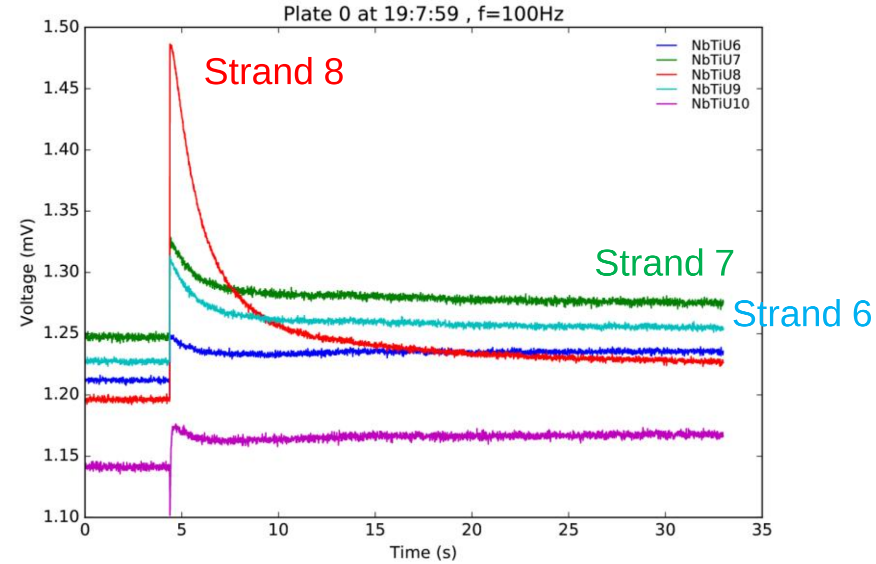

**Nb-Ti and Nb3Sn strands fixed on a steel plate**

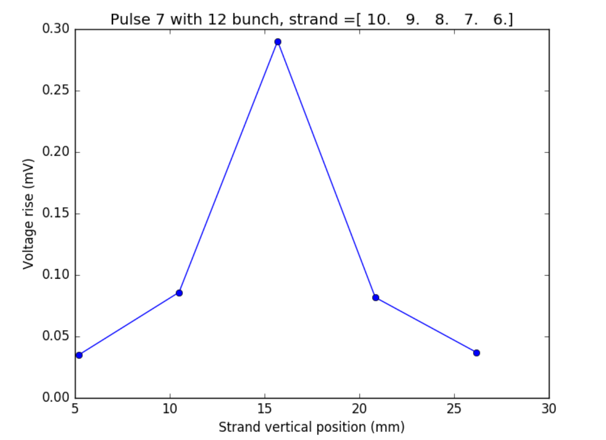
# On-line measurements

## Screen: beam size and position




## Strand voltage: vertical alignment of strands



# Post irradiation analysis

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)

# Conclusions

- The project aims to identify **critical magnet components,** to understand the **damage mechanisms** and to **measure the damage limit of superconducting magnet components.**
- Furnace experiment show a clear **degradation of the insulation above 400°C in the hours timescale**
- The **beam experiment at room temperature** had successfully been **performed**.
  - Peak temperature of **750°C in cable stacks** and **630°C/ 800°C in the strands**.
  - Analysis on the results on going. Measurements on the samples to be done in the coming months.
- More experiments are planned:
  - **Current discharge experiments** to measure degradation of insulation and critical current in the **ms timescale –** (end 2016/beginning 2017)
  - **Beam experiment** at 4 K with coil samples (end 2017)

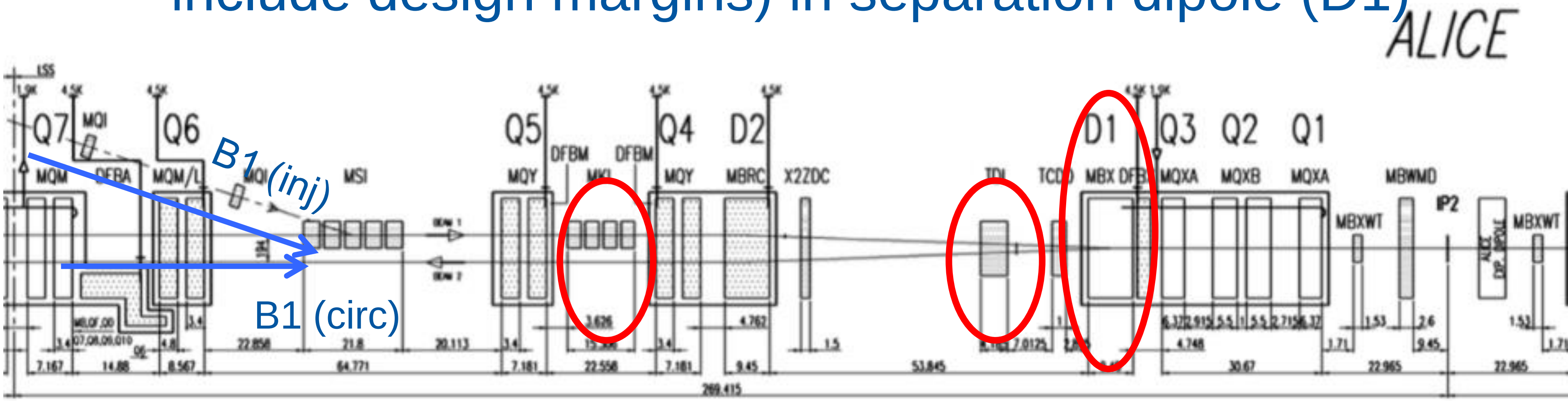
# Extra slides

# Superconducting magnets ? Instantaneous beam impact ?

- LHC Nb-Ti magnets: Main Dipoles, Quadrupoles, Correctors… but also $Nb_3Sn$
- Instantaneous beam impact: ultra-fast beam losses in µs time (e.g. injection and extraction failure cases).
- Despite efficient absorber, beam can impact sc. magnets leading to temperature rise and thermo-mechanical stresses.

# Example of failure cases - injection

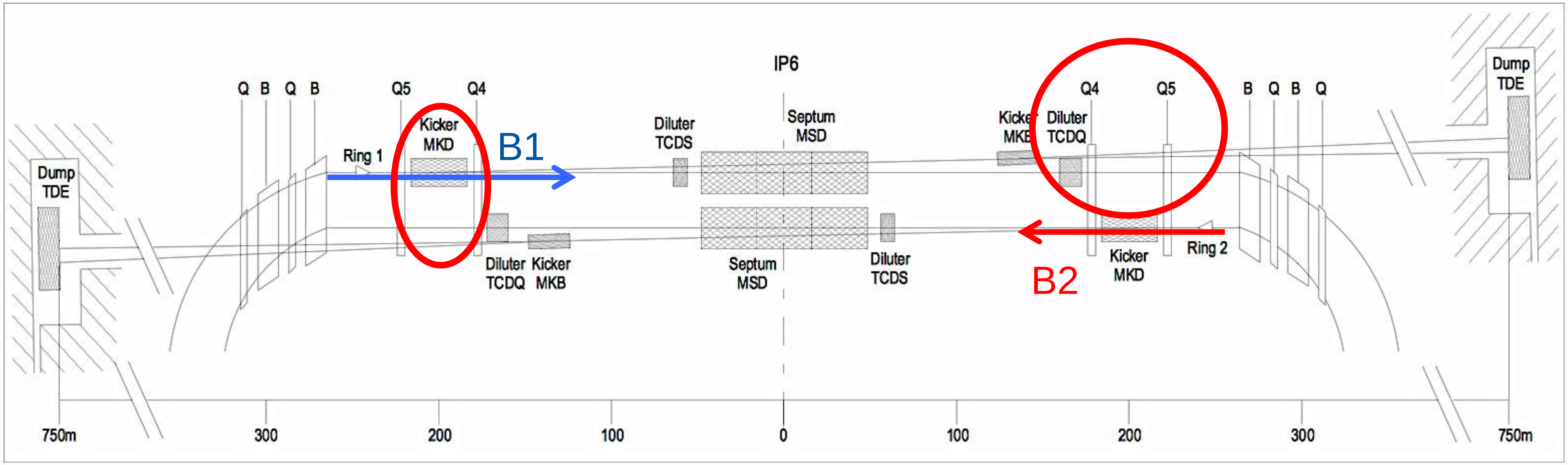
- Injection Kicker (MKI) kicks the circulating beam
- Beam intensity : $2.2 \times 10^{11}$ p per bunch (HL-LHC
- Maximum energy density **~100 J/cm³** (> 100 K – include design margins) in separation dipole (D1)




A. Lechner et all, Protection of superconducting magnets in case of accidental beam losses during HL-LHC injection, In Proceedings of IPAC15

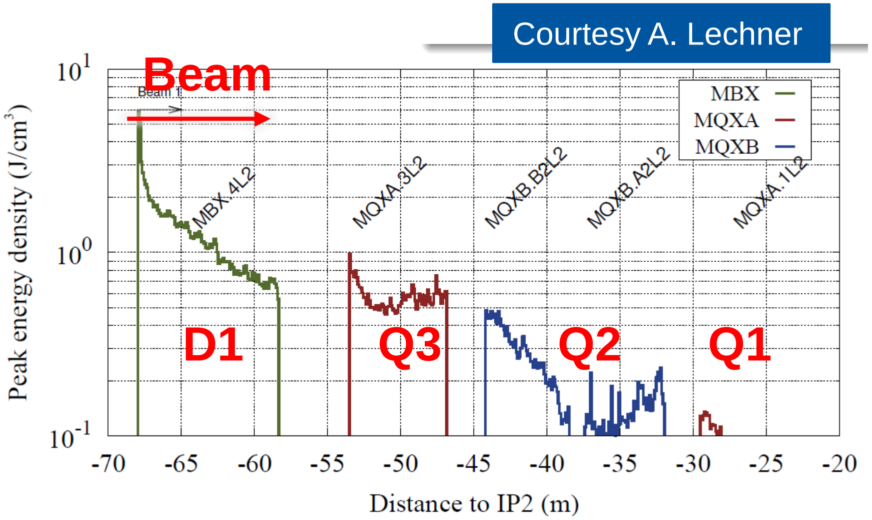
# Example of failure cases – extraction

- Asynchronous beam dumps
- Beam intensity : 2.2x10$^{11}$ p per bunch (HL-LHC
- Maximum energy density **~100 J/cm3** in Q5




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

# Known limits




## Lower bound

- Accidental beam losses during injection in 2011.

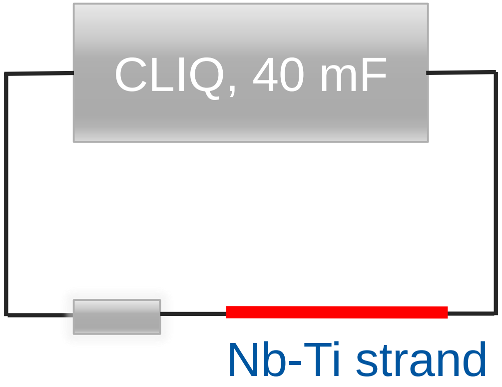
  Peak energy density in **D1 coils ~ 6 J/cm³**

## Upper bound

- Disintegration of polyimide insulation foils for T > ~400°C
- **Melting of copper** with energy densities of **6 kJ/cm³**

# Degradation of sc. properties due to temperature
## - ms timescale

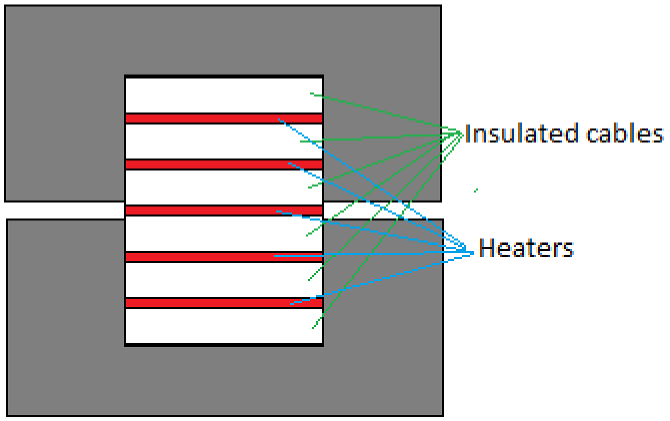
- **Current discharge** (t~ 20 ms) in **sc. strands** to achieve peak temperature rise from **250°C to 1000°C**




- **Magnetization measurement** on ~18 strands (before and after discharge)
- Experiment planned for December 2016

# Degradation of insulation due to temperature
- ms timescale

- **Stack of cable with a steel strip inserted between cable.**



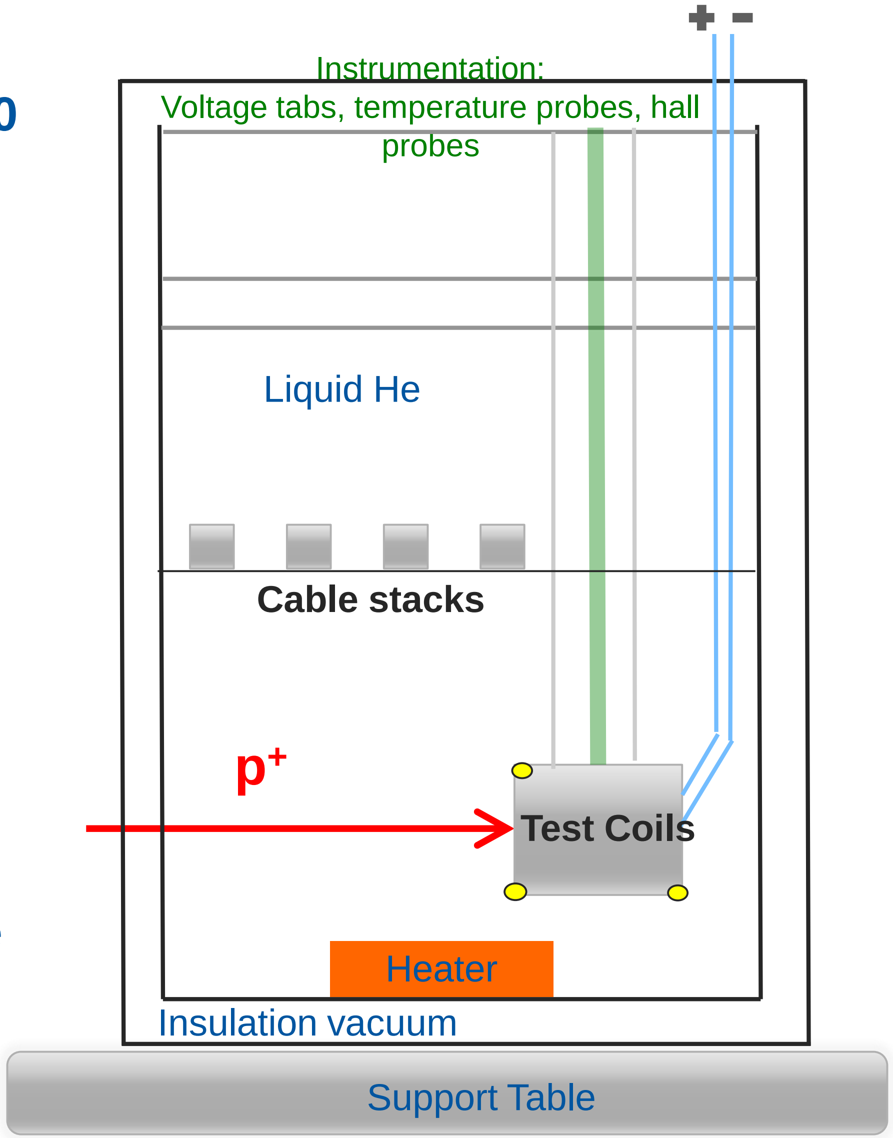

- **Fast current discharge** (~100 ms) in strip **inducing a fast heat pulse** into the **insulation** in inert atmosphere.
  - Measure I and V during the discharge to deduce the temperature of the strip

- **High voltage tests** after the discharge to **measure the degradation of the insulation**.

# Beam experiment in cryogenic environment

- At the HiRadMat facility shooting a **440 GeV proton beam on cable stacks, strands and test coils.**
  - **Cryogenic conditions (4.2K)**
  - **On-line monitoring** of the coils (electrical integrity and critical current)

- Goals:
  - **Extend the results of the previous beam experiment to cryogenic temperature** (LHC environment).
  - Test on sample coils to investigate other damage mechanisms (mechanical stability, ...)



# 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).

Extension to environment as in LHC (cryogenic) required.