First Experimental Results on Damage Limits of Superconducting Accelerator Magnet Components due to Instantaneous Beam Impact

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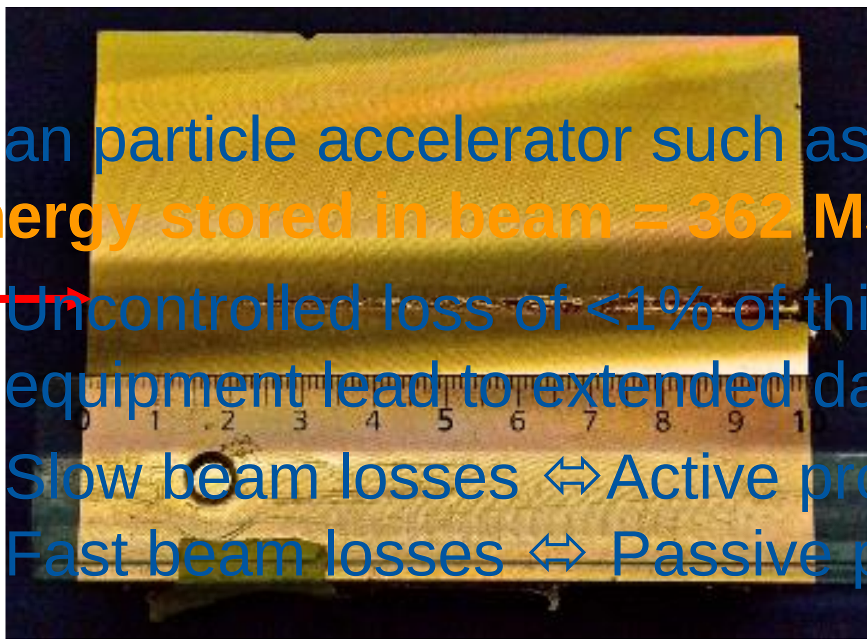
Beam – matter interaction

The fast (µs) interaction of an high energy beam with matter leads to:

- **Temperature rise** leading in the worst cases to phase transition (melting, vaporization, plasma ….).
- **Dynamic stresses** that can lead to extended mechanical damage - deformations, cracks.



Damage experiment on solid copper

Burkart, F., et al. *Journal of Applied Physics* 118.5 (2015): 055902.

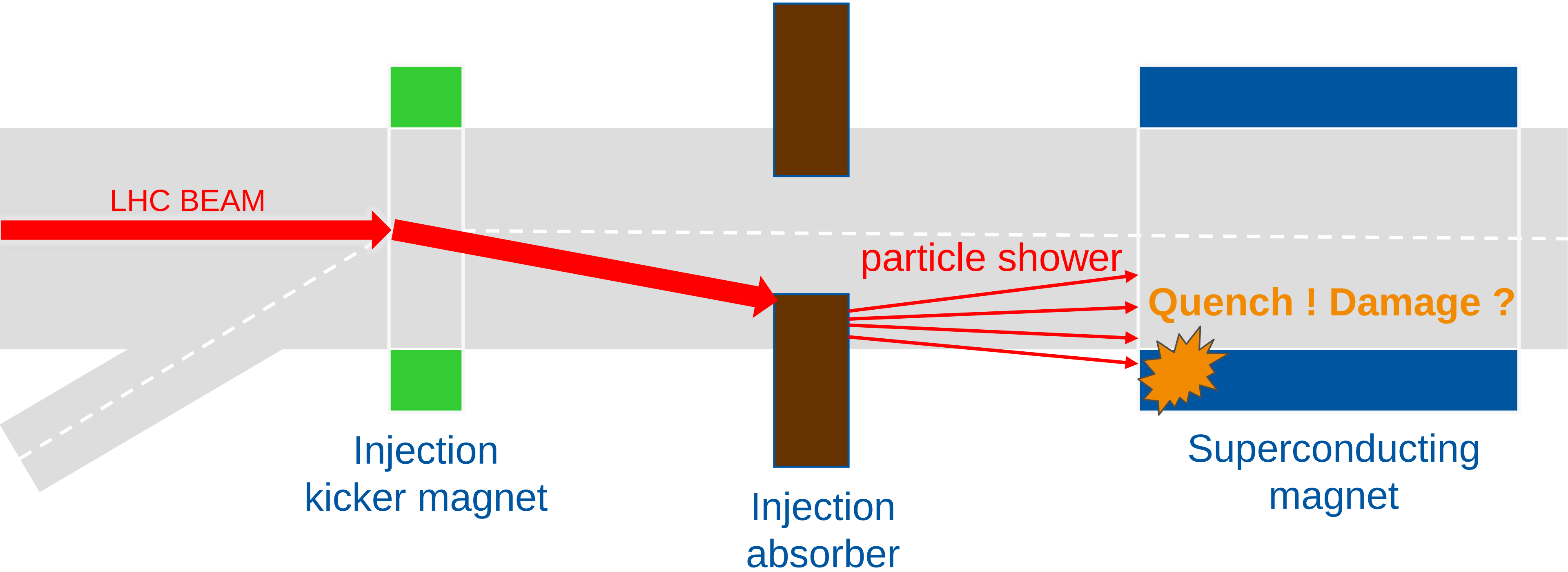
In an particle accelerator such as **LHC, energy stored in beam = 362 MJ**

⇒ Uncontrolled loss of <1% of this energy into accelerator equipment lead to extended damage!

⇒ Slow beam losses ⇔ Active protection
Fast beam losses ⇔ Passive protection

Example of one of the most critical LHC beam loss

Injection Failure LHC



- ❑ One such event per year in today's LHC. No damage.

- ❑ **With an increase of beam intensity (HL-LHC), will the magnet survive?**

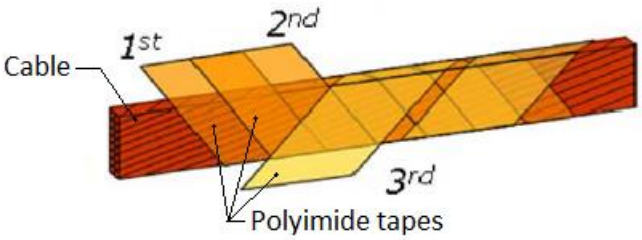
⇒ **What are the damage mechanisms and limits of superconducting magnets ?**

Magnets most sensitive parts

Polyimide insulation

⇒ Decomposition of the polyimide when expose to high temperature

- ❑ Reduction of the dielectric strength

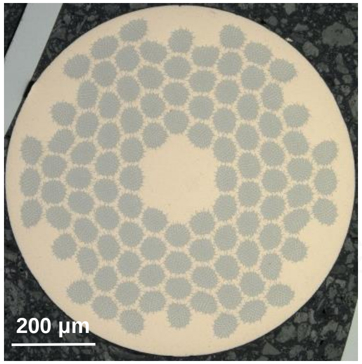


Fessia, P., et al. *IEEE Transactions on Applied Superconductivity* 20.3 (2010): 1622-1625.

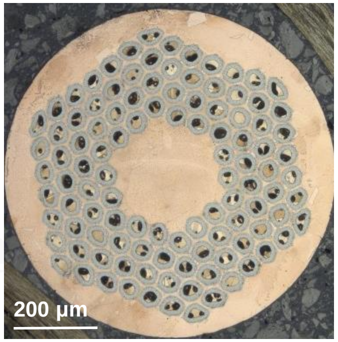
Nb-Ti and Nb_3Sn superconducting cables

⇒ Reduction of the J_c induced by:

- ❑ High temperature
- ❑ Mechanical stress, deformation and cracks



Nb-Ti strands (LHC dipole)

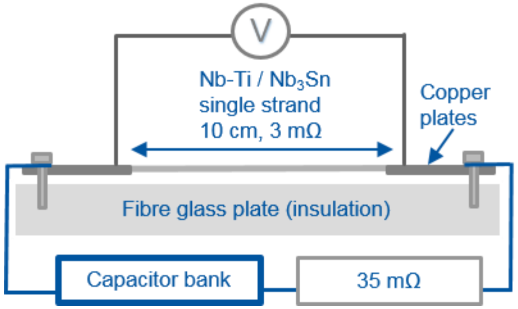


Nb_3Sn RRP type (HL-LHC triplet)

Experimental road map

- **Polyimide insulation degradation due to heating over hours** [1]
  - **Cable stacks heated over hours** in furnace between ~460 K and ~860 K.
  - Polyimide **dielectric strength measured** with high voltage.

- **J_c degradation of Nb-Ti and Nb_3Sn due to heating over seconds** [2]
  - Nb-Ti and Nb_3Sn single strands heated up between ~640 K and ~1250 K using a **capacitive discharge**.
  - Strand were in air at room temperature.
  - **J_c degradation measured** via magnetization measurements

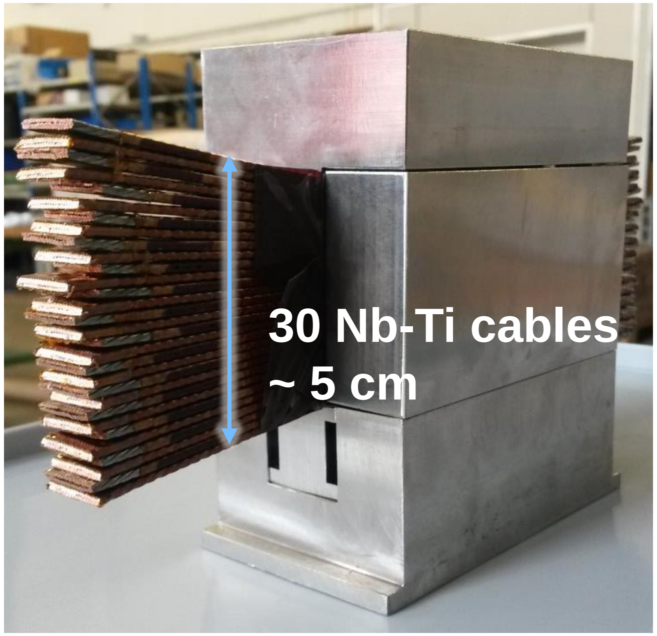


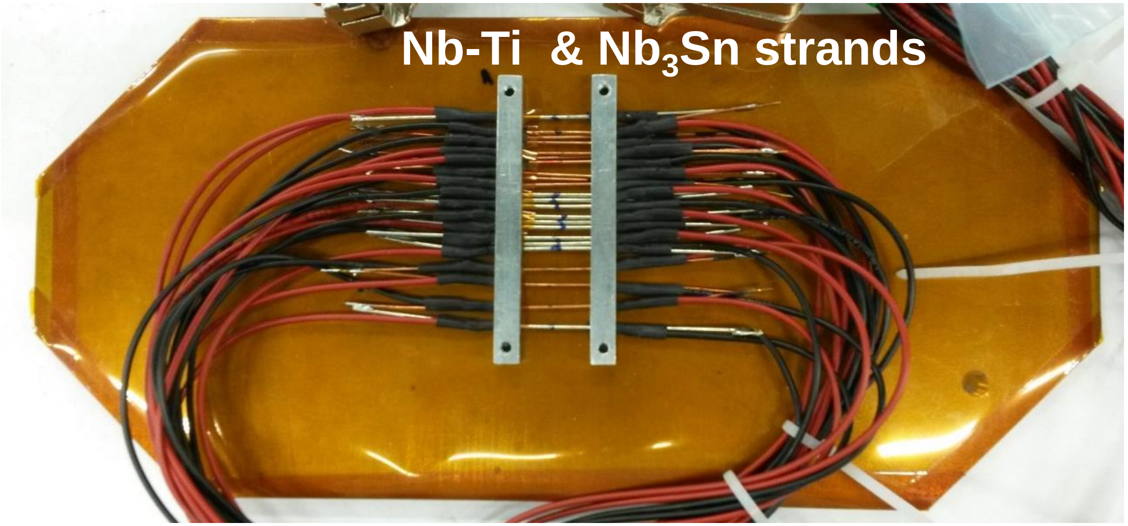
- **Degradation of polyimide insulation and of Nb-Ti & Nb_3Sn critical current density** induced **by interaction with 440 GeV proton beam pulses**

[1] V. Raginel, et al, "Degradation of the insulation of the LHC main dipole cable when exposed to high temperatures", IPAC'16
[2] V. Raginel, et al, "Change of critical current density in Nb-Ti and Nb3Sn strands after millisecond heating", IPAC'17

Beam Experiment: Samples

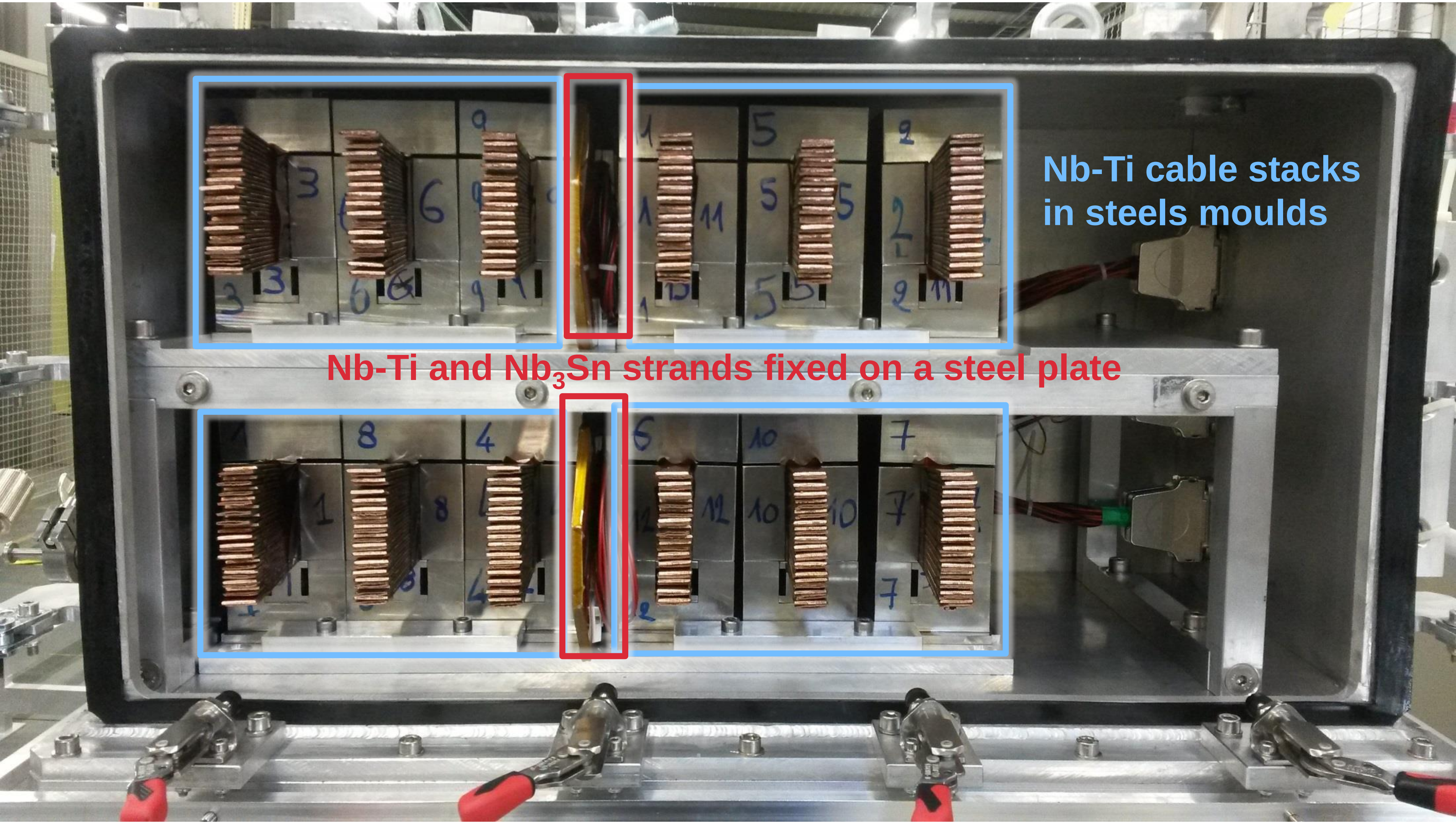
- At CERN HiRadMat facility shooting 440 GeV proton beam pulses on:



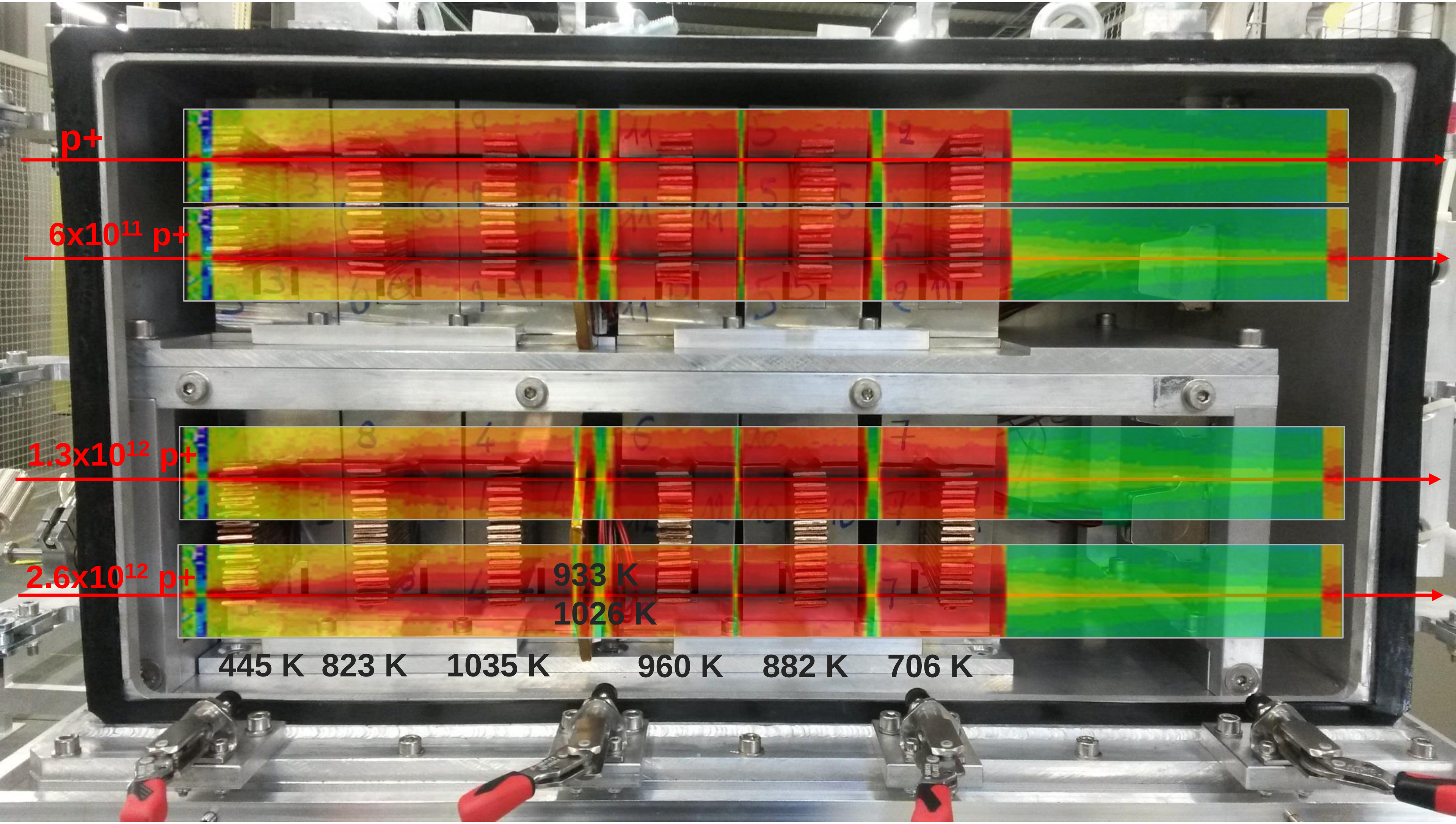


- Samples at room temperature within an inert atmosphere (Argon).

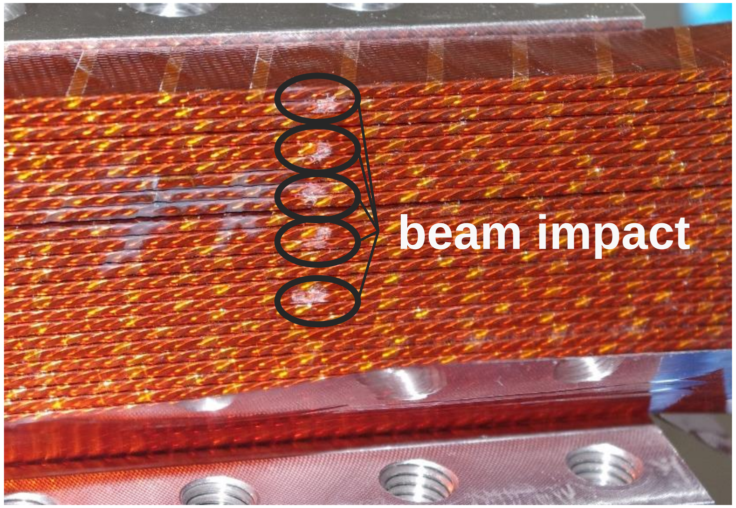
Experimental setup



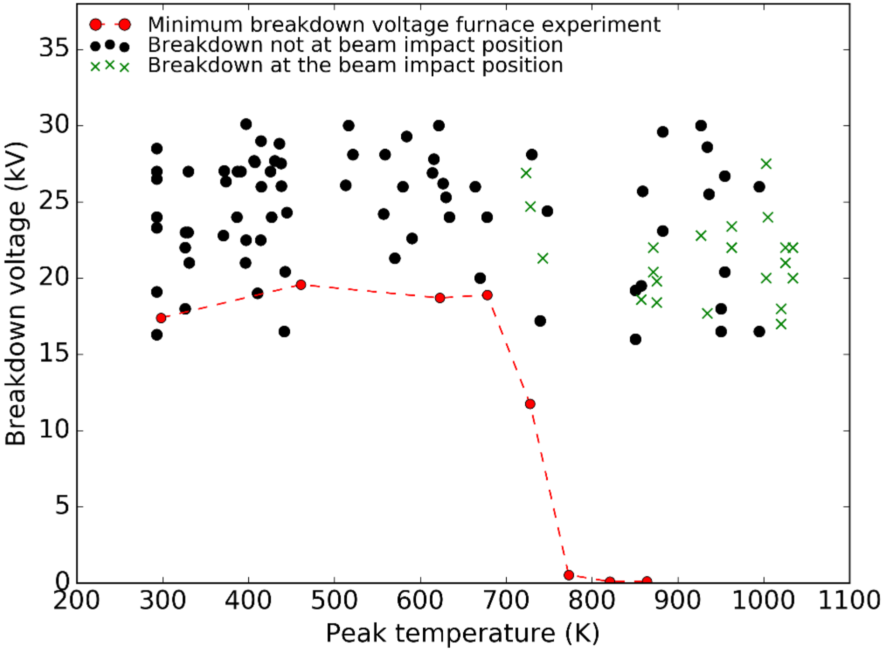
Experimental setup



Polyimide insulation degradation



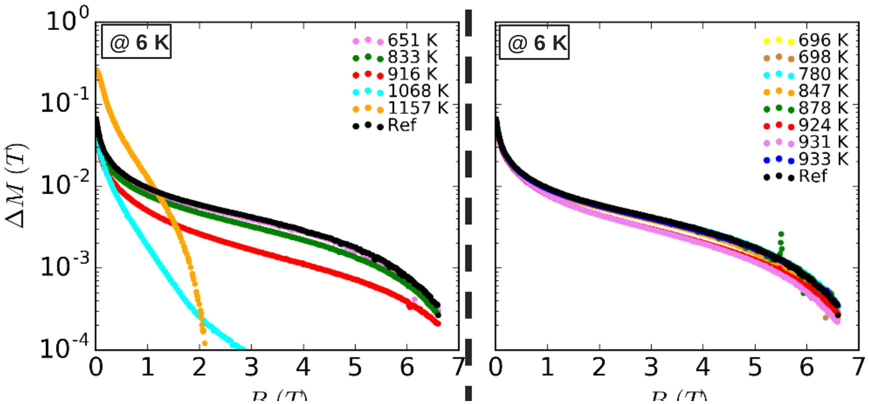
Side view of a Nb-Ti cable stack after beam impact

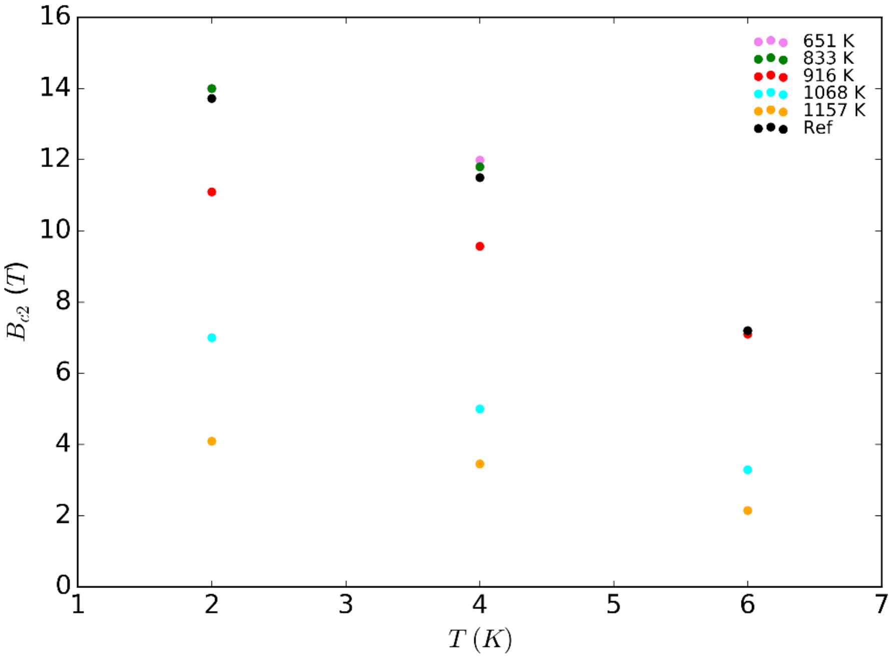


- **Degradation due to chemical decomposition** as function of temperature and exposure time.
- **No degradation measured after beam impact** – temperature up to ~1050 K for few ~ms
  - **Weakening of the insulation** at the point of the beam impact was observed for **T>~850 K.**

J_c degradation of Nb-Ti

Capacitive discharge | **Beam impact**





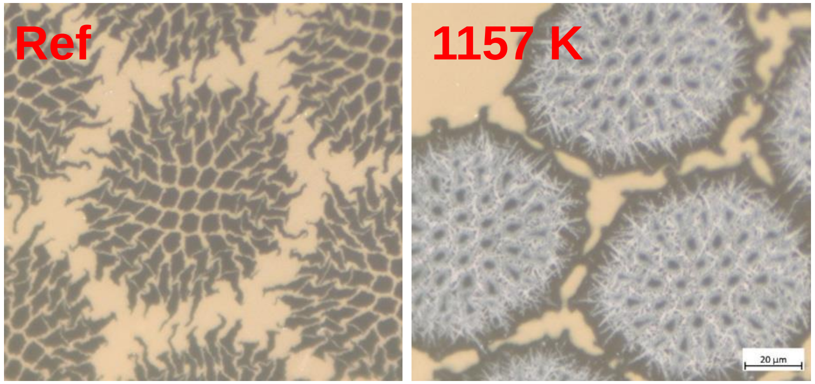
- **Capacitive discharge, ΔM degradation** (∝ J_c) above **651 K**
- After **beam impact, ΔM degradation** above **878 K (2.2 kJ cm^{-3})**
- F_p decrease and F_{pmax} shifts toward lower b.

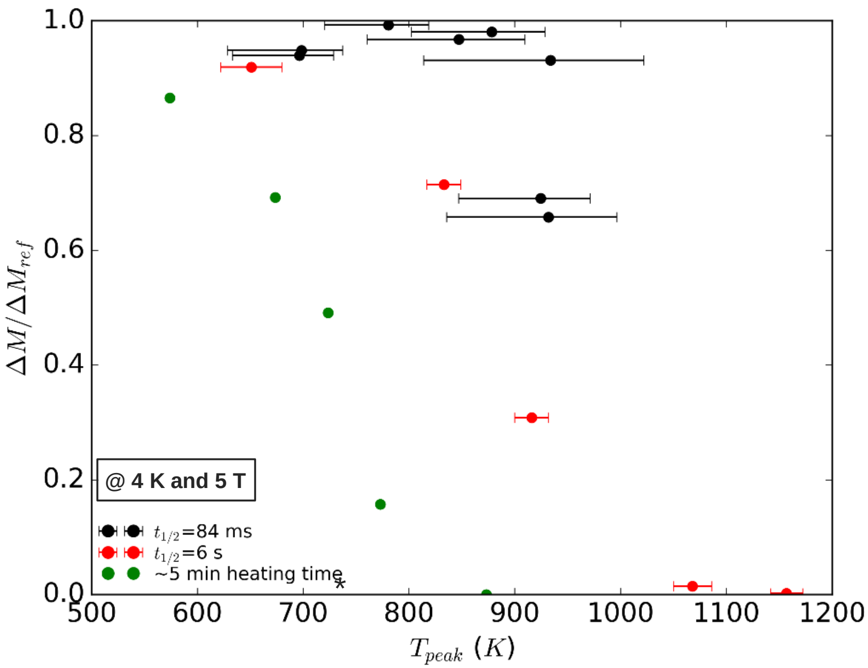
⇒ **Change of pinning behaviour**

- Decrease of B_{c2}(T) for T ≥ 916 K in discharge case. No decrease for beam case.

⇒ **Variation of Ti content in filaments**

J_c degradation of Nb-Ti





* C. Scheuerlein et all., Journal of Physics: Conference Series, vol. 234, no. 2. IOP Publishing, 2010

- **At T=1157 K (discharge case), filament merging is observed**
- For same temperature, ΔM goes down with increasing exposure time.

⇒ Diffusion process
+ change of pinning behaviour

⇒ **Degradation of J_c caused by variations of α-Ti precipitates size and spacing**

⇒ If higher temperature or longer exposure time, Ti diffuses outside filaments to form Cu-Ti compound
=> B_{c2}(T) reduction, filament merging

J_c degradation of Nb_3Sn

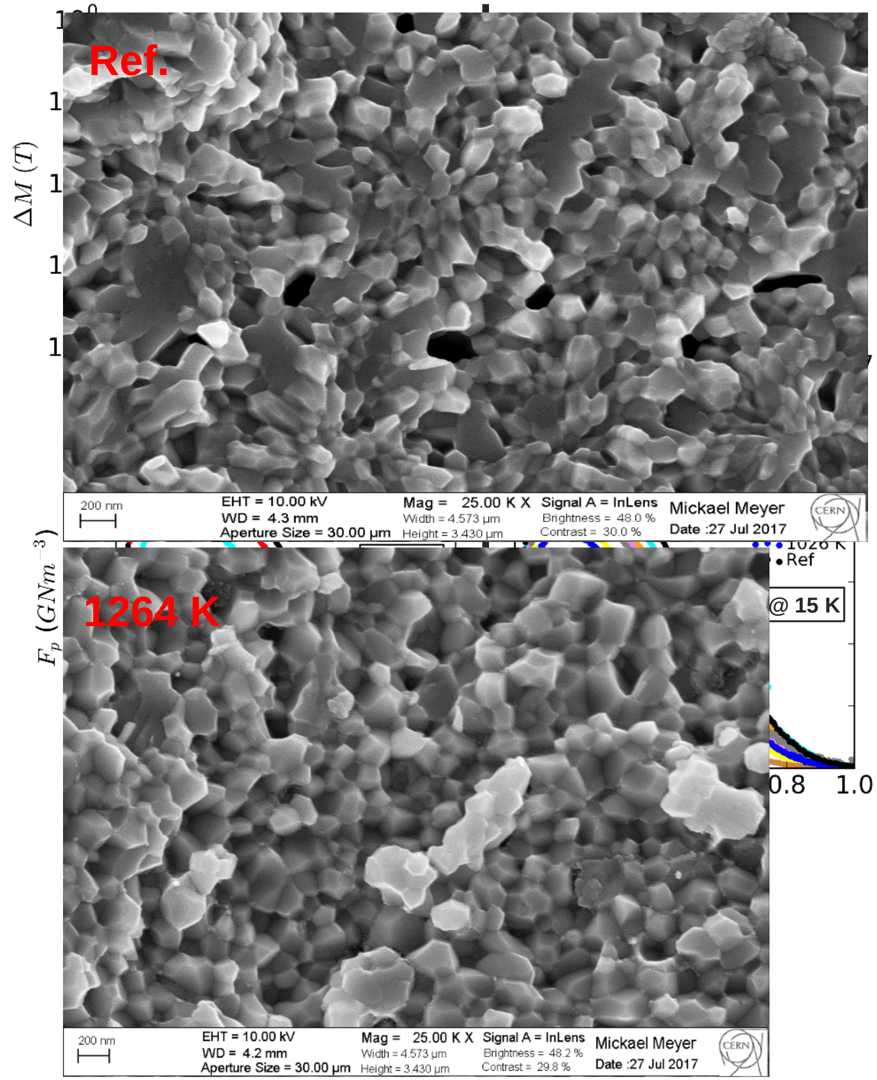
- **Capacitive discharge, ΔM degradation** for **T > 823 K**
- All samples degrade after **beam impact ,T ≥ 699 K (1.4 kJ cm^{-3})**
- F_p decrease and no shift of F_{pmax}

⇒ **No change of pinning behaviour**

⇒ **No grain growth** observed (SEM analysis)

- Decrease of B_{c2}(T) not observed, however Tin content measurements are planned

Capacitive discharge | Beam impact

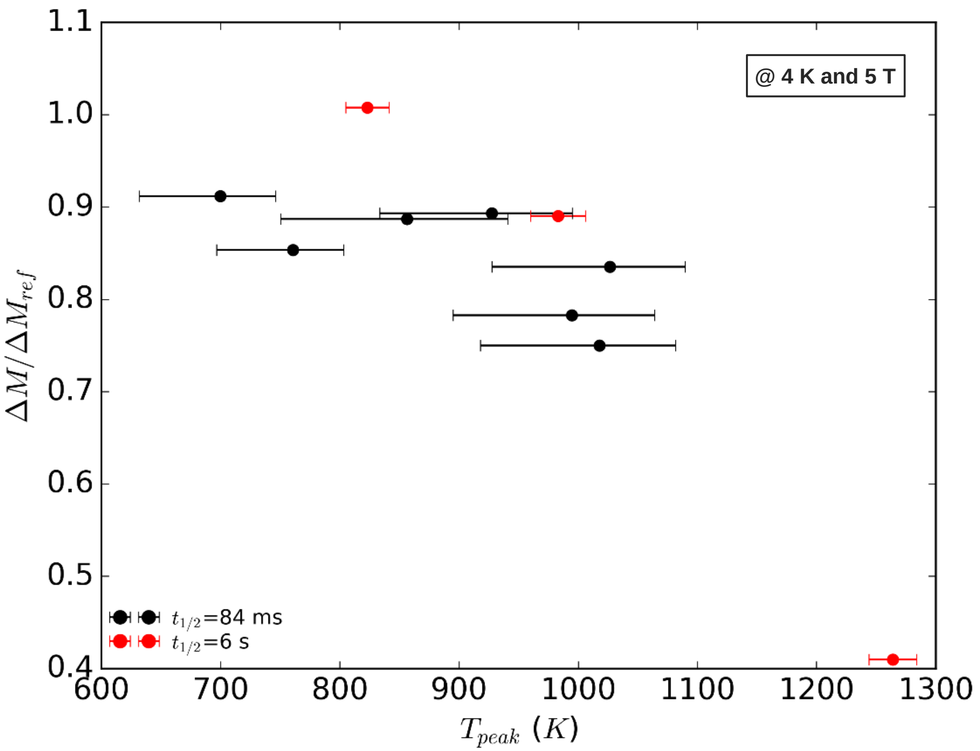


J_c degradation of Nb_3Sn

Contrary to Nb-Ti, for same temperature, **ΔM goes down with decreasing exposure time.**

⇒ Indication **degradation due to beam impact is dominated by stresses and potentially cracks caused by fast heating and high thermal gradients**

⇒ Further investigations to identify the origin:



Conclusions and outlook

Identification of the **damage mechanisms** and **damage limits** of critical **magnet components** due to **instantaneous beam impact** is essential for future increase of beam energy (HL-LHC, FCC)

Polyimide insulation

- **Chemical decomposition due to exposure to high temperature**
- **No degradation induced by beam** up to 1050 K, however **observation of a weakening for T>850 K**
- For long exposure time, degradation for temperatures above 728 K

Nb-Ti strand

- **Degradation dominated by diffusion processes.**
- **J_c degradation** for peak temperatures above **900 K** in case of **beam impact**

Nb_3Sn strand

- Most probable causes are **stresses and cracks induced by the fast heating and high thermal gradient**
- Grain growth is excluded. Further investigations to identify degradation mechanism
- **J_c degradation due to beam impact** observed in all samples – lowest peak temperature **~700 K**
- For second long heating, **J_c degradation for temperatures above 823 K**

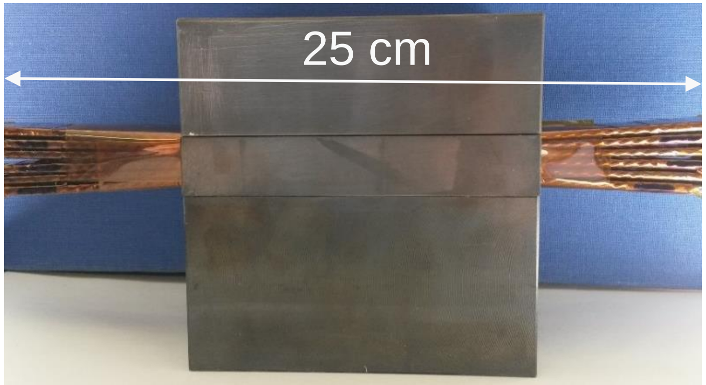
➢ Experimental validation of results with beam at liquid Helium temperature scheduled for mid-2018

Thank you for your attention

Spare slides

Insulation degradation due to hours heating

- **Insulated cable stacks heated over hours in furnace** between 461 K and 864 K in inert atmosphere (Argon).
- Dielectric strength is measured via cable-to-cable **breakdown voltage measurement** after heat treatment.



Stack of 6 Nb-Ti cables