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

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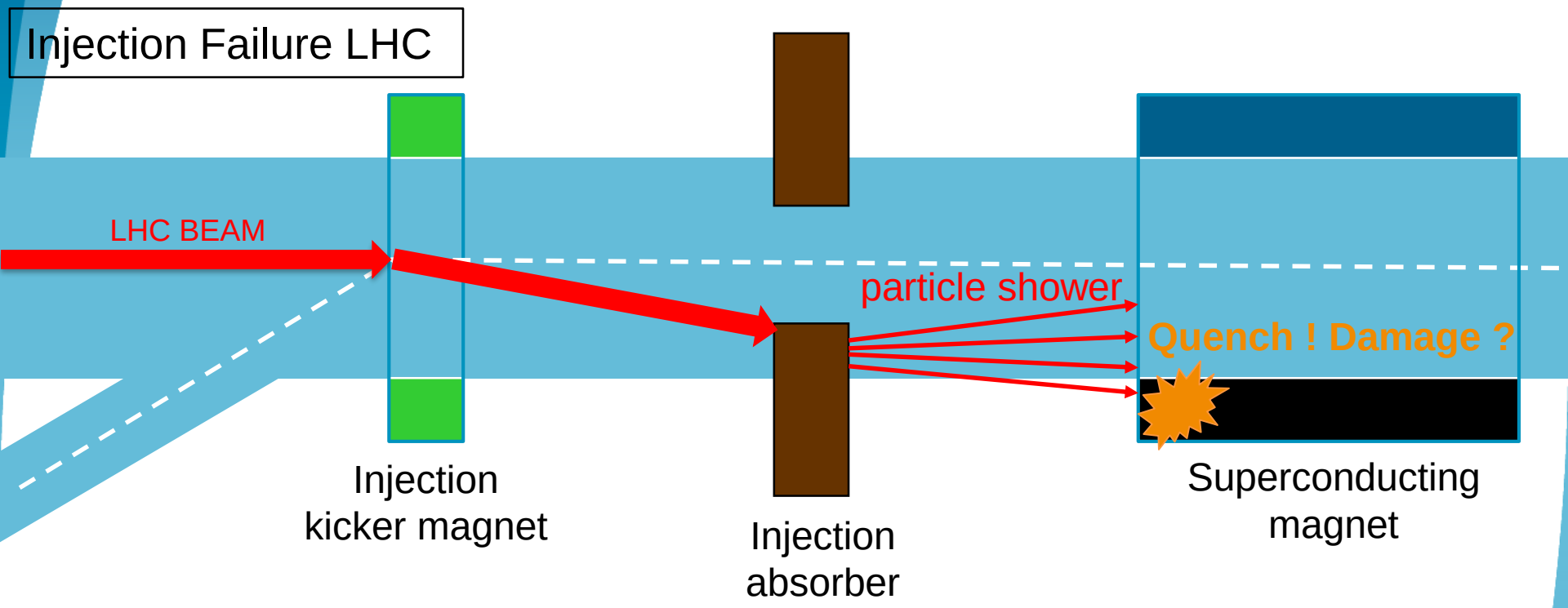
Motivation of the study – HL-LHC ultra-fast failure



- One such event per year in today's LHC. No damage.
- **For HL-LHC beam, peak energy deposition of 100 Jcm^{-3} in the D1 magnet without mask** [1] **– similar in Q5 in case of asynchronous beam dump** [2].

⇒ **Will the magnets survive?**

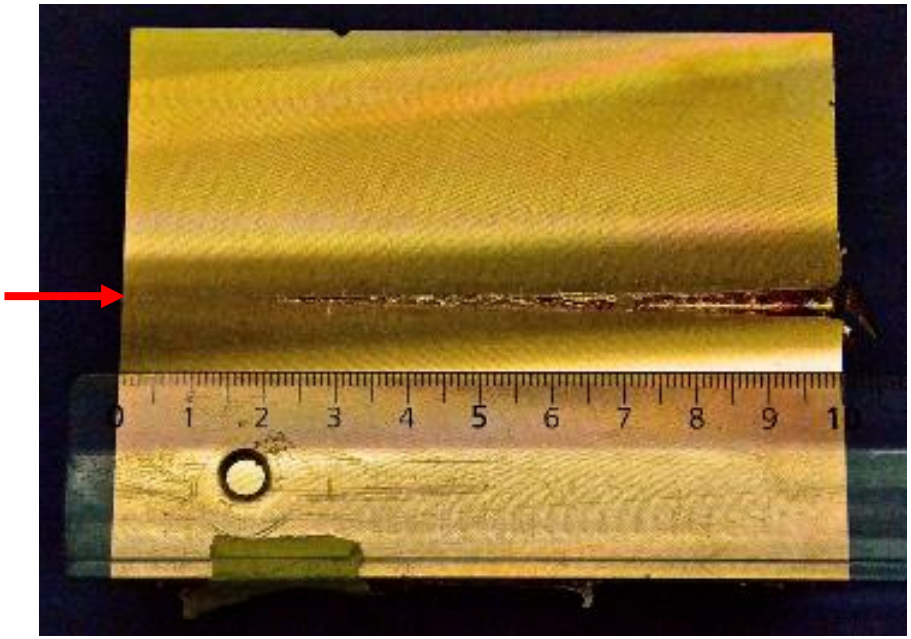
⇒ **What are the damage mechanisms and limits of superconducting magnets ?**

[1] A. Lechner et all, Protection of superconducting magnets in case of accidental beam losses during HL-LHC injection, In Proceedings of IPAC15
[2] B. Auchmann et all, Quench and Damage Levels for Q4 and Q5 Magnets near Point 6, CERN EDMS 1355063, 2014

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

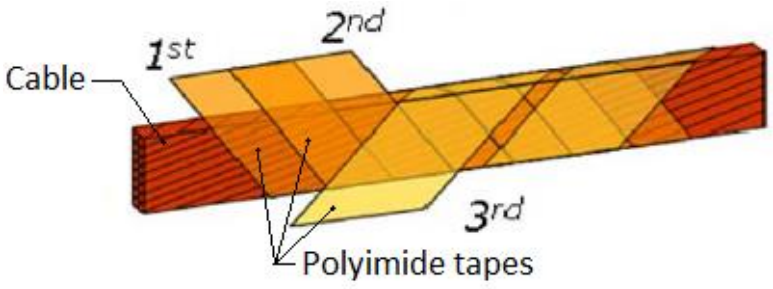
Burkart, F., et al. *Journal of Applied Physics* 118.5 (2015): 055902.

Magnets most sensitive parts

Polyimide insultation

⇒ Decomposition of the polyimide when expose to high temperature

- ❑ Reduction of the dielectric strength

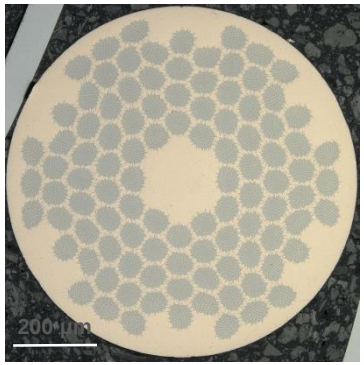


Fessia, P., et al. *IEEE Transactions on Applied Superconductivity* 20.3 (2010): 1622-1625.

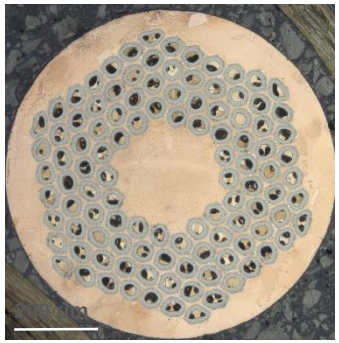
Nb-Ti and Nb_3Sn superconducting cables

⇒ Reduction of the J_c induced by:

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



Nb-Ti strands (LHC dipole)

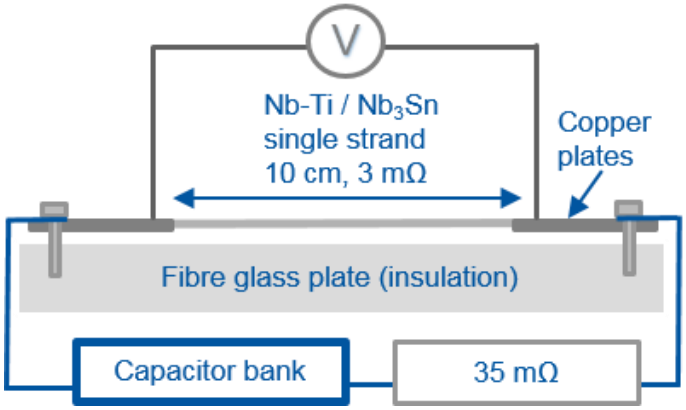


Nb_3Sn RRP type (HL-LHC triplet)

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
  - Identification of degradation mechanisms via microscopic analysis

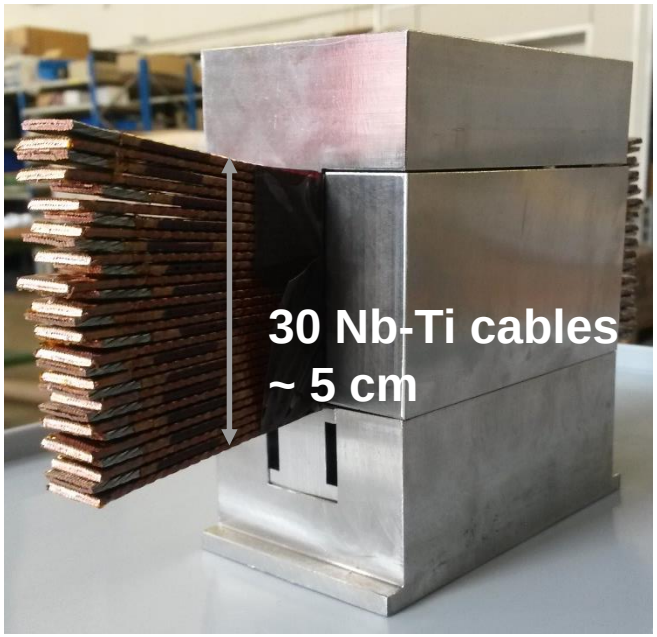


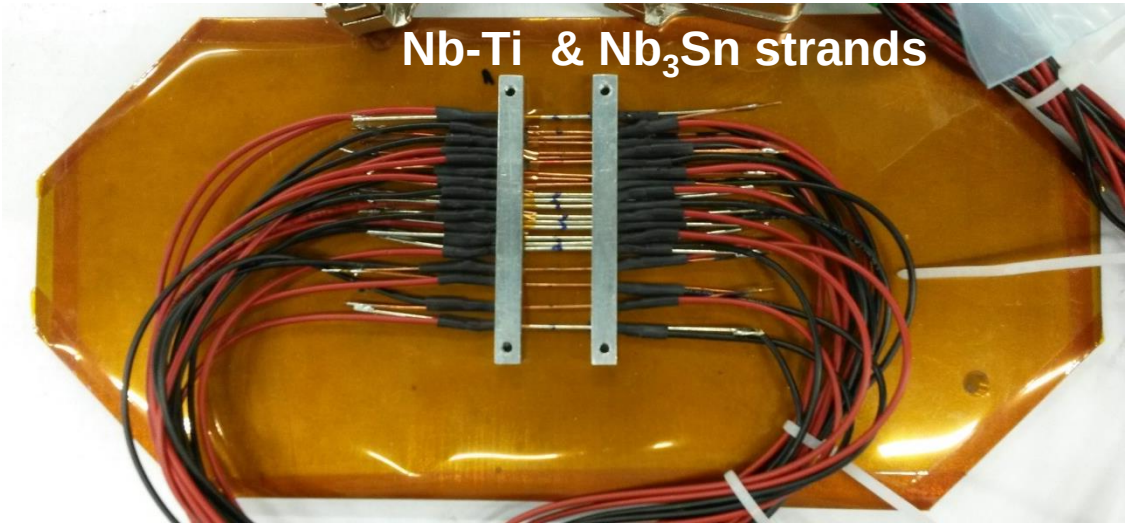
- **Degradation** of polyimide insulation and of Nb-Ti & Nb_3Sn critical current density **induced by** impact of a 440 GeV proton **beam**

[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

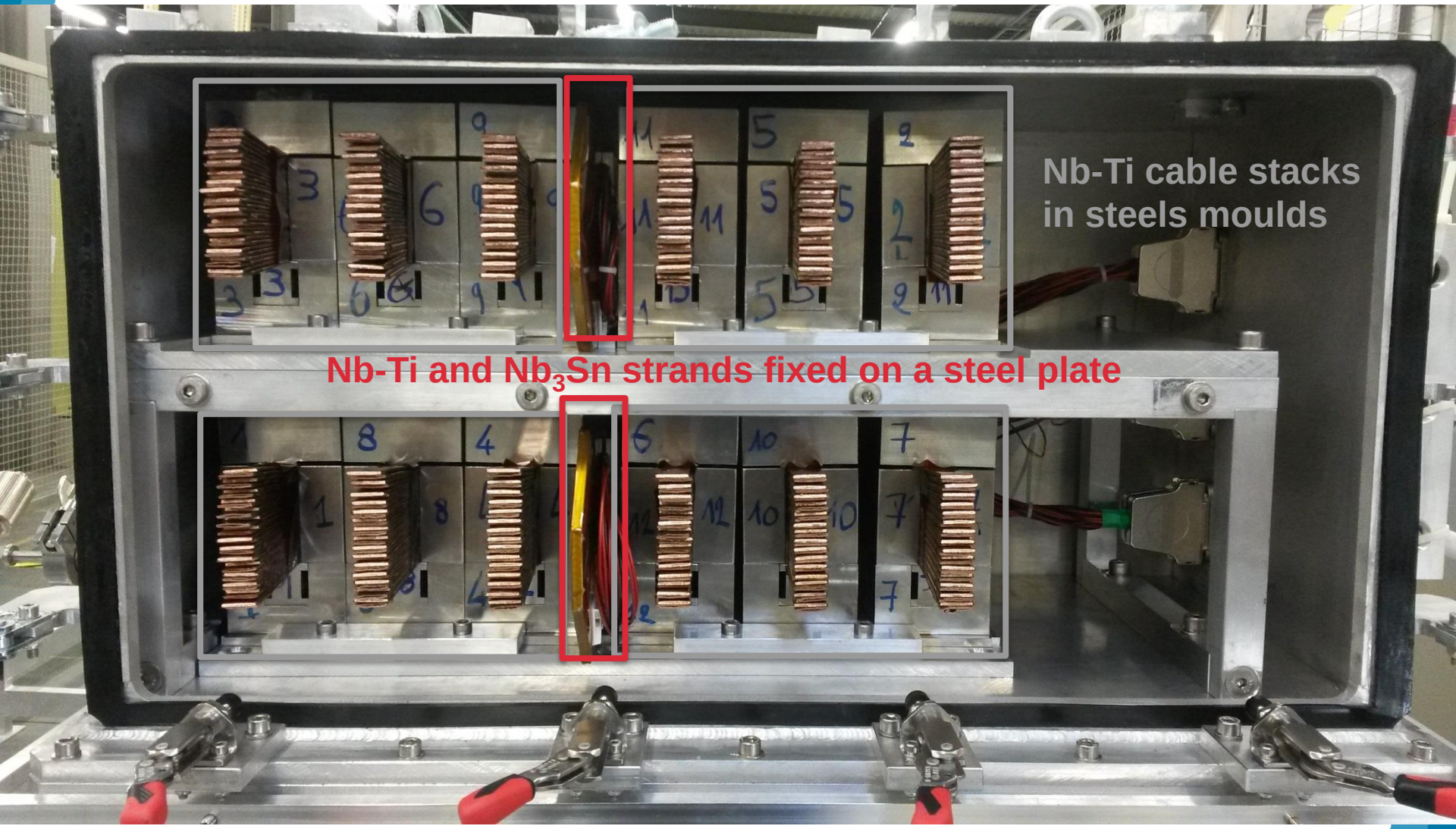
- At CERN HiRadMat facility sending 440 GeV proton beam pulses on:



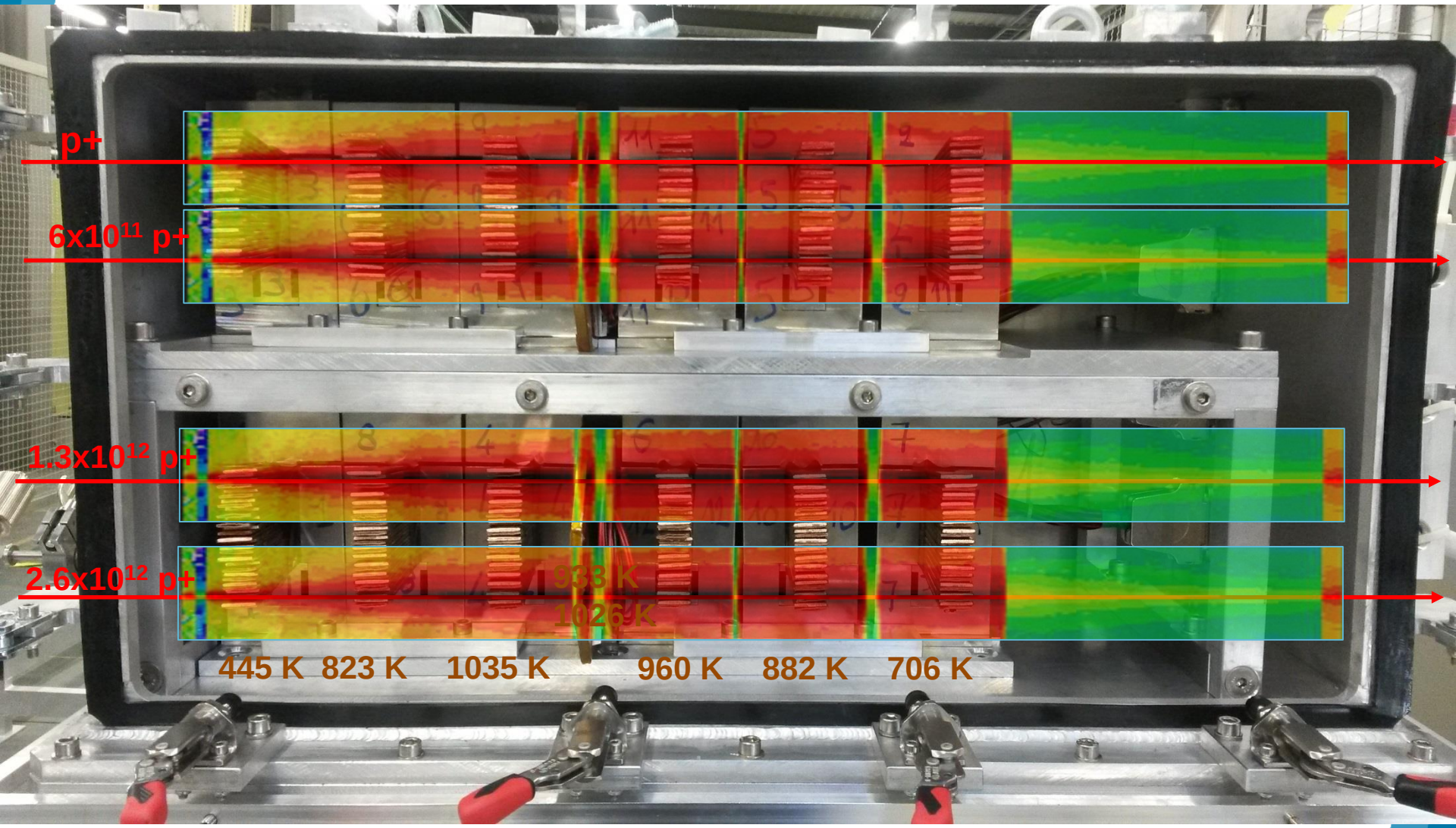


- Samples at room temperature within an inert atmosphere (Argon).

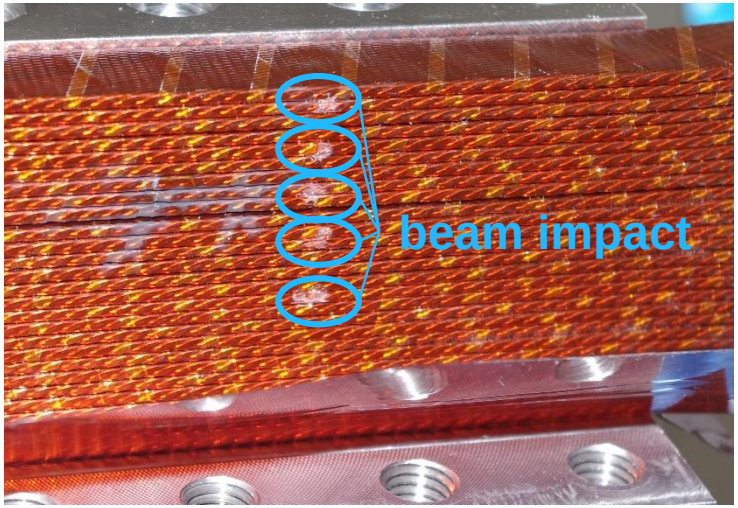
Experimental setup



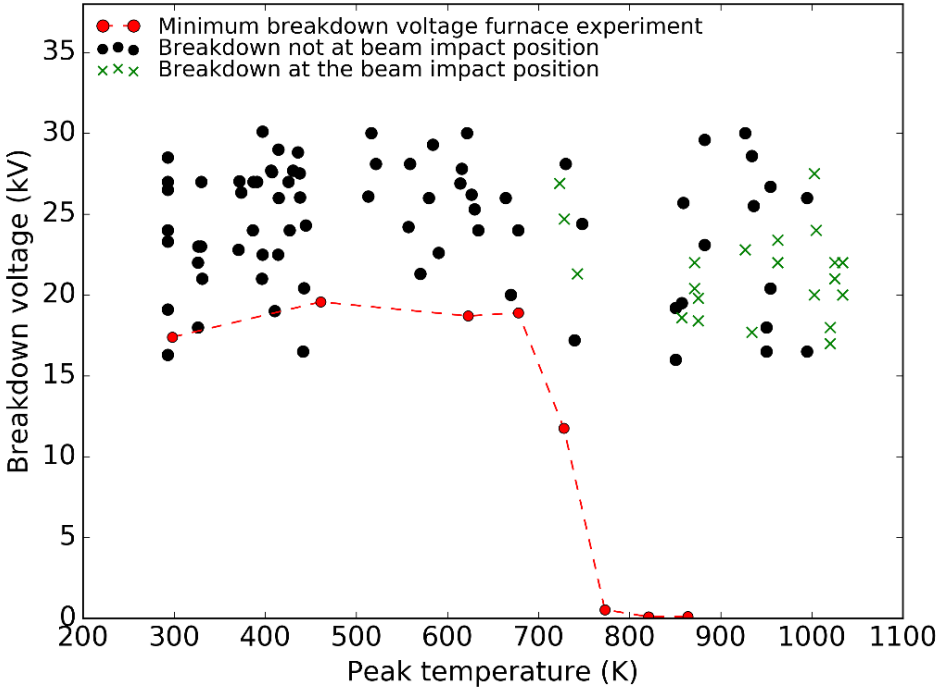
Experimental setup



Polyimide insulation degradation



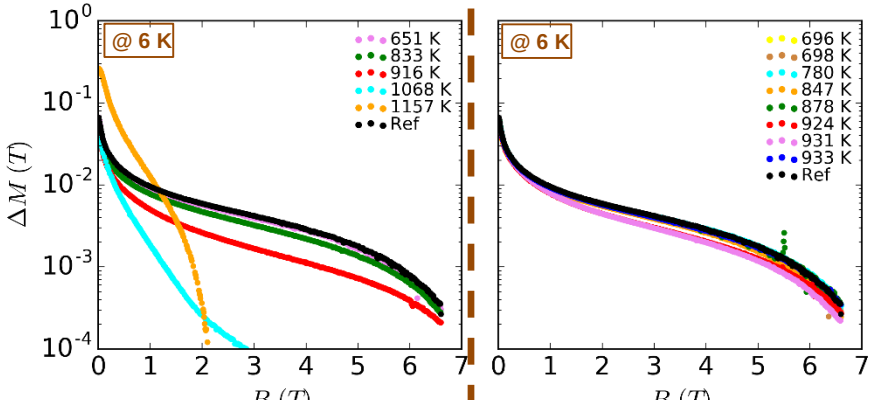
Side view of a Nb-Ti cable stack after beam impact

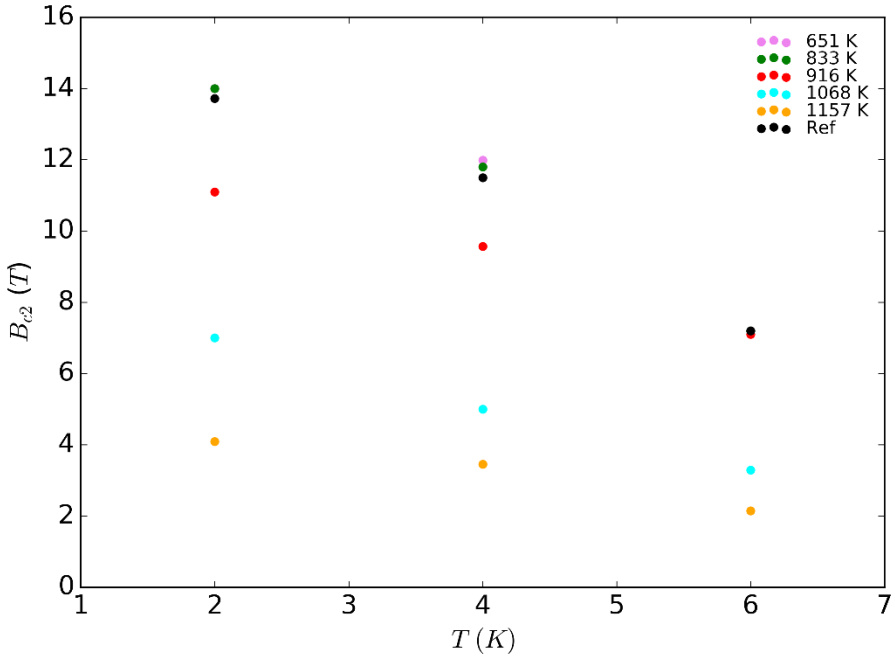


- **Degradation due to chemical decomposition** as function of temperature and exposure time.
- **No degradation measured after beam impact** – temperature up to ~1050 K (2.5 kJ cm^{-3}) for few ~ms
  - **Weakening of the insulation** at the point of the beam impact was observed for **T > 850 K (1.9 kJ cm^{-3}).**

J_c degradation of Nb-Ti

Capacitive discharge | **Beam impact**





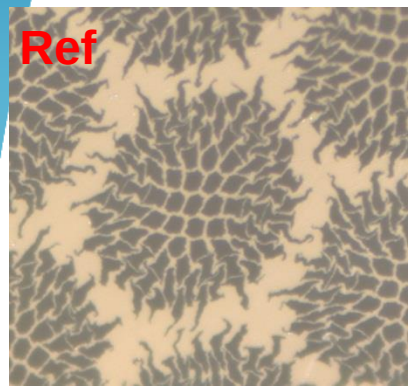
- **Capacitive discharge, ΔM degradation** ($\propto J_c$) above **651 K**
- After **beam impact, ΔM degradation** above **878 K (2.2 kJ cm^{-3})**
- F_p decrease and F_{pmax} shifts toward lower b.

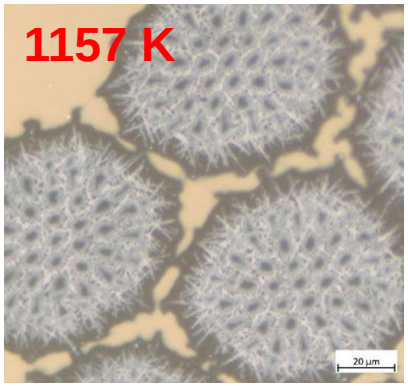
⇒ **Change of pinning behaviour**

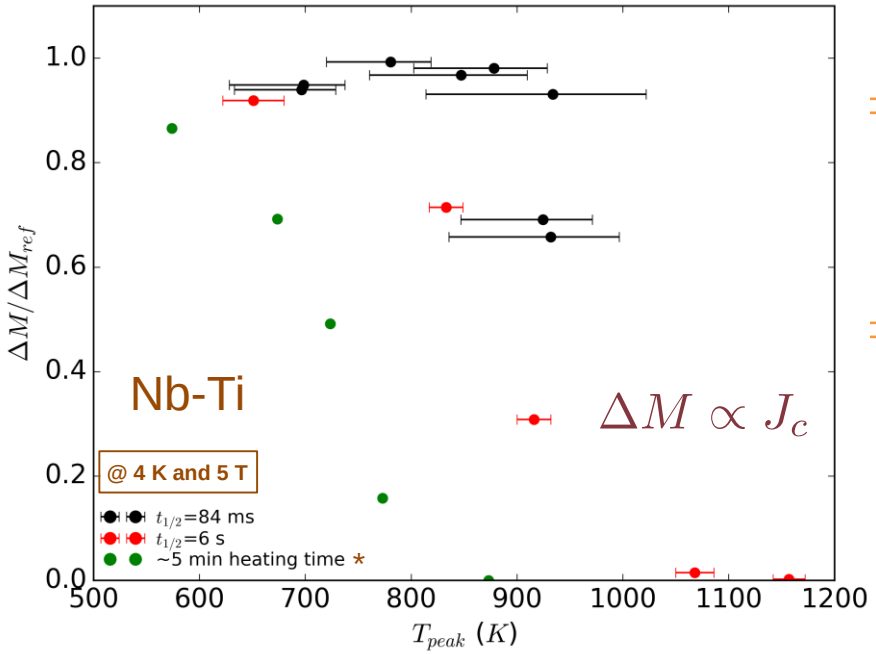
- Decrease of $B_{c2}(T)$ for T ≥ 916 K in discharge case. No decrease for beam case.

⇒ **Variation of Ti content in filaments**

J_c degradation of Nb-Ti







- At T=1157 K (discharge case), **filament merging** is observed
- **J_c decreases 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

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

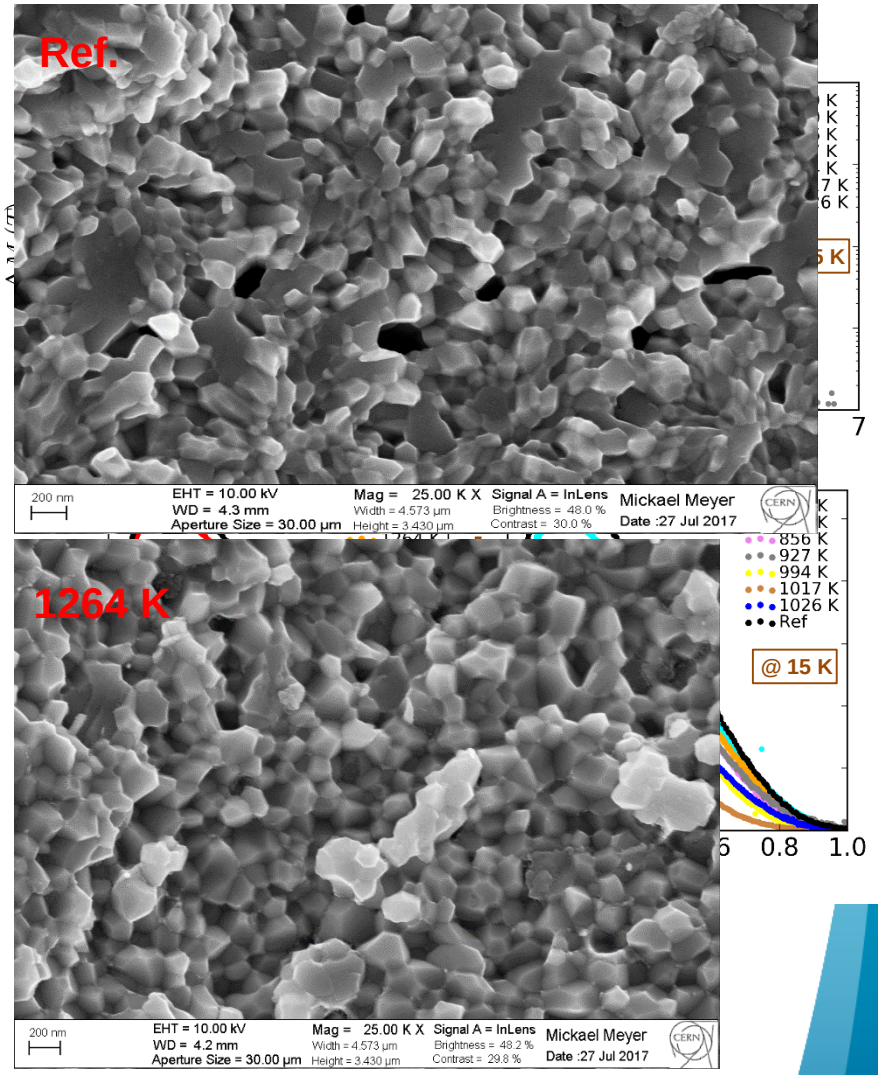
J_c degradation of Nb_3Sn

- Capacitive discharge, J_c degradation for **T > 823 K**
- All samples degraded 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

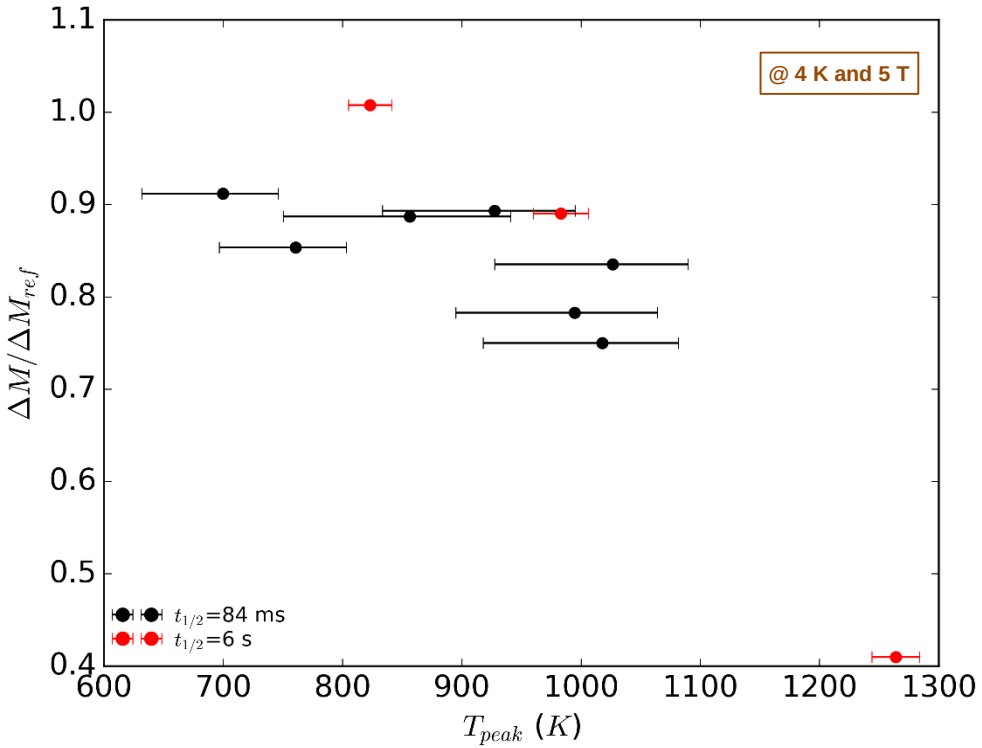


J_c degradation of Nb_3Sn

Contrary to Nb-Ti, **J_c decreases 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

Polyimide insulation

- **No degradation** induced by beam up to 1050 K, however observation of a **weakening for T > 850 K (1.9 kJ cm^{-3})**
- **Chemical decomposition** due to exposure to high temperature

Nb-Ti strands

- **J_c degradation** for peak temperatures above **900 K (2.2 kJ cm^{-3})** in case of (single) **beam impact**
- Degradation dominated by **diffusion** processes

Nb_3Sn strands

- **J_c degradation due to beam impact** observed in all samples
  – lowest peak temperature **700 K** (**1.4 kJ cm^{-3})**
- Grain growth is excluded. Further investigations to identify degradation mechanism
- Probably caused by **stresses and cracks** induced by the fast heating and high **thermal gradients**

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

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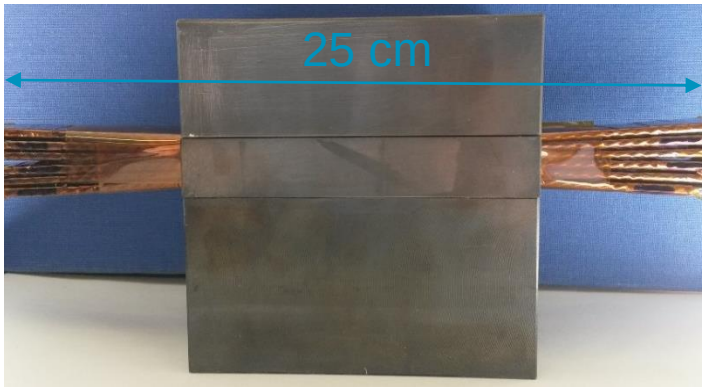
Thank you for your attention!

Questions?

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