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Roadmap to determine the damage limits of superconducting magnets for instantaneous beam losses

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Acknowledgments:

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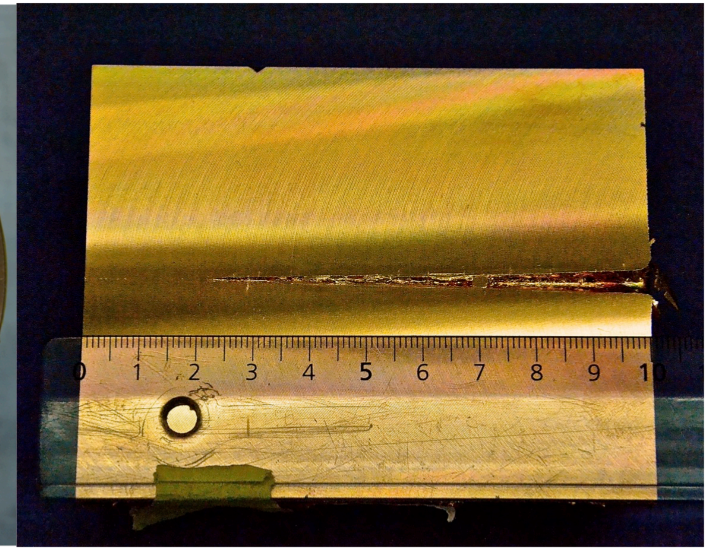
Outline

- Introduction: Quench and damage limits due to beam losses.
- Critical parts and failure modes in Nb-Ti cables.
- LHC failure scenarios.
- Planned damage tests with and without beam.
- Summary.

Introduction - Material damage levels due to direct beam impact





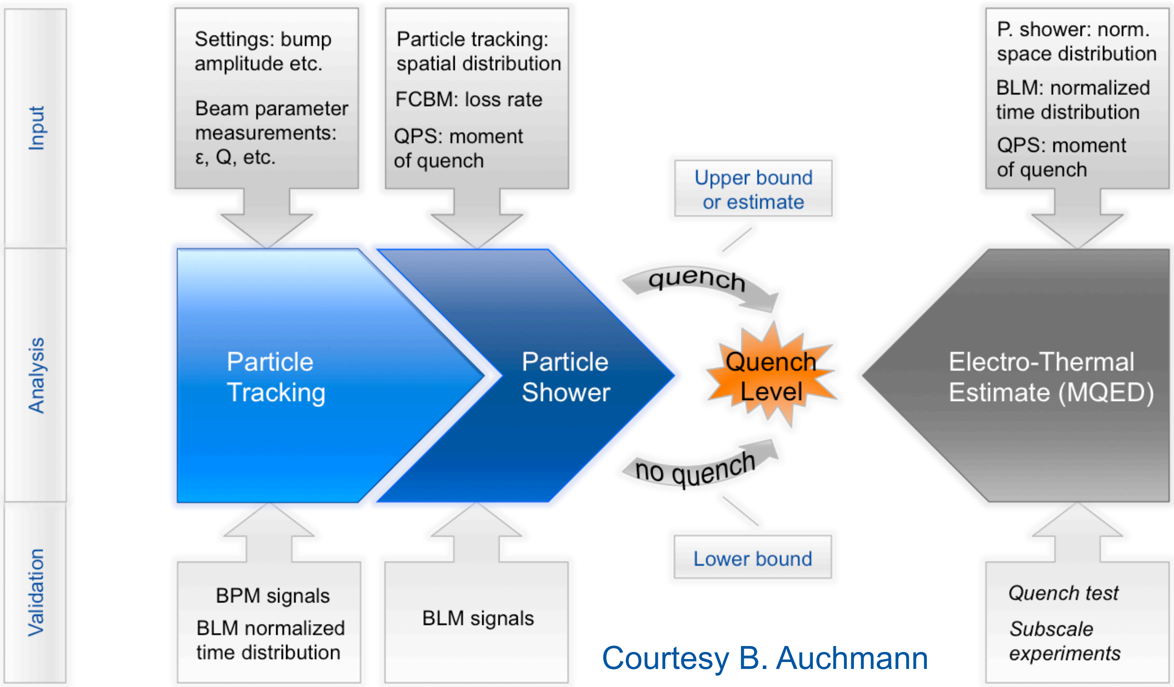
Courtesy F. Burkart


- **Benchmark experiment** to verify Hydrodynamic tunneling (HiRadMat, CERN): 144b (1.15e11p/bunch) @ 440GeV into copper.
- Peak energy deposition (~100kJ/cm^3)
- Maximum **penetration depth 85cm**.
- **LHC beam** (7TeV, 3e14p, 360MJ) → **20m**

- R. Schmidt et al., *First experimental evidence of hydrodynamic tunneling of ultra–relativistic protons in extended solid copper target at the CERN HiRadMat facility*, Physics of Plasmas (1994-present) 21, 080701 (2014)
- F. Burkart et al., *Experimental and simulation studies of hydrodynamic tunneling of ultra-relativistic protons*, In Proceedings of IPAC15

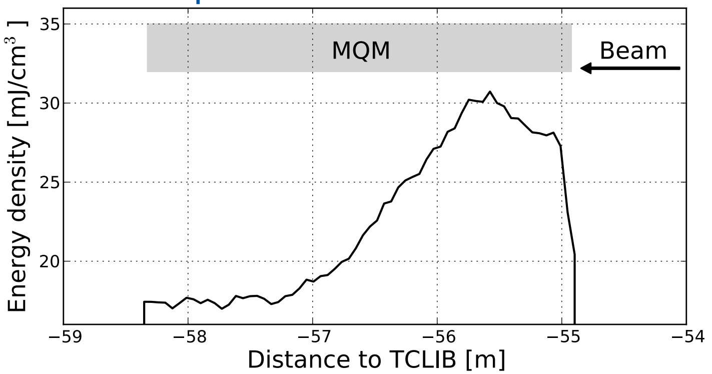
Introduction – Quench levels

- Studied extensively **quench levels** with beam in LHC: @ 450GeV and 3.5/4TeV for different loss scenarios during LHC run1.
- **Quench levels are strongly dependent in loss duration and loss distribution (i.e. loss scenario)**



Courtesy B. Auchmann

Example: Loss duration 0-50us



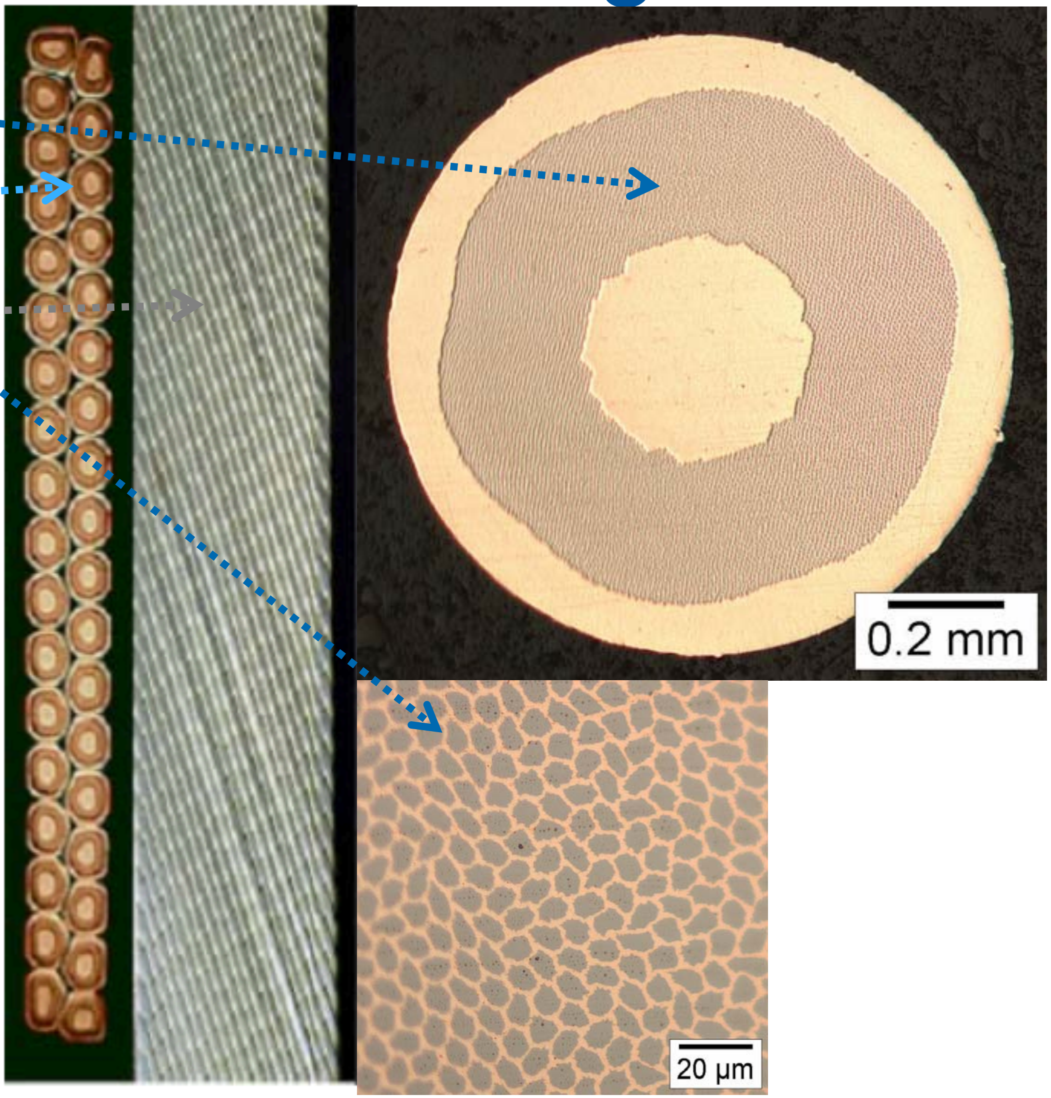
For more details:
- Proceedings of Beam Induced Quench workshop, CERN, 09.2014, to be published.
- B. Auchmann et al., *Testing Beam-Induced Quench Levels of LHC Superconducting Magnets in Run 1*, PR-STAB, submitted 02.2015

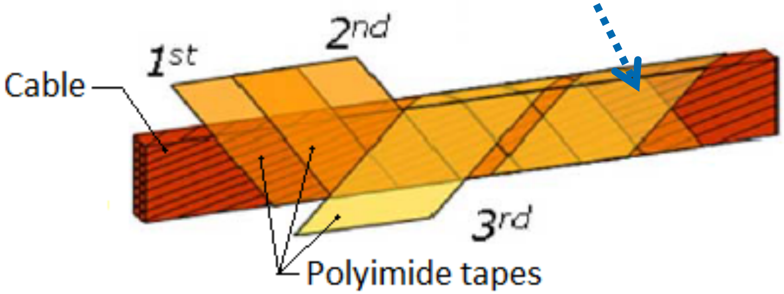
What happens in-between?

- What is the **damage limit** of sc. magnets in case of **instantaneous beam impact** (ns to tens of us)?
- Is *LHC safe beam* (~5e11p @ 450GeV, ~1e10 @ 7TeV) **safe for LHC sc. magnets**?
- Which are the **critical elements** of the sc. magnet?

Identify critical parts of sc magnet

- Sc. filaments
- Sc. strands
- Cables
- Insulation
- Bonding agent between turns





Failure modes of sc. magnets

- Damage of superconductor by **melting of copper** matrix (~6kJ/cm^3).
- **Reduced I_c** → e.g. damage of sc. filaments → unknown!
- **Insulation** damage (disintegration of Kapton > 400C) → inter-turn short (reduced performance, or replacement required), short to ground (magnet replacement required), short to quench heater.
- Breaking of **bonding between turns** (curing of magnet at 195C) → loss of performance due to detraining.
- Damage of epoxy in potted coils (cracking due to thermal strain or exceeding of glass transition temperature @ 113C for CTD-101A) → loss of performance due to detraining.

- Peak temperature during **quench ~300K**.

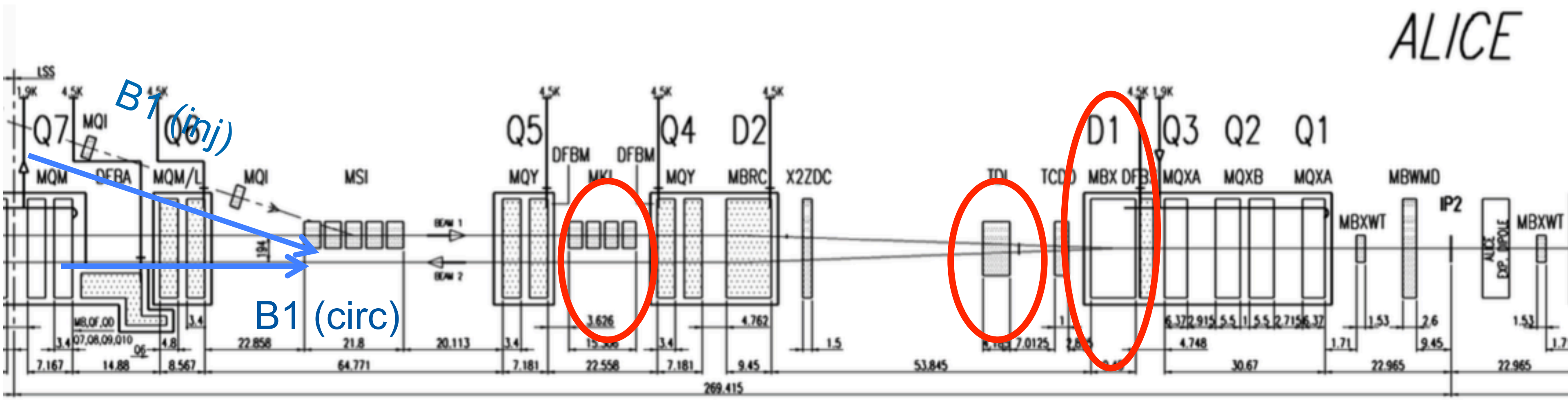
Fast failures in the LHC < 270us (3 turns)

- Injection failures.
- Extraction failures.
- Crab Cavity failures for future HL-LHC?

Injection failure

Injection kicker (MKI) flash-over, erratic firing, no firing

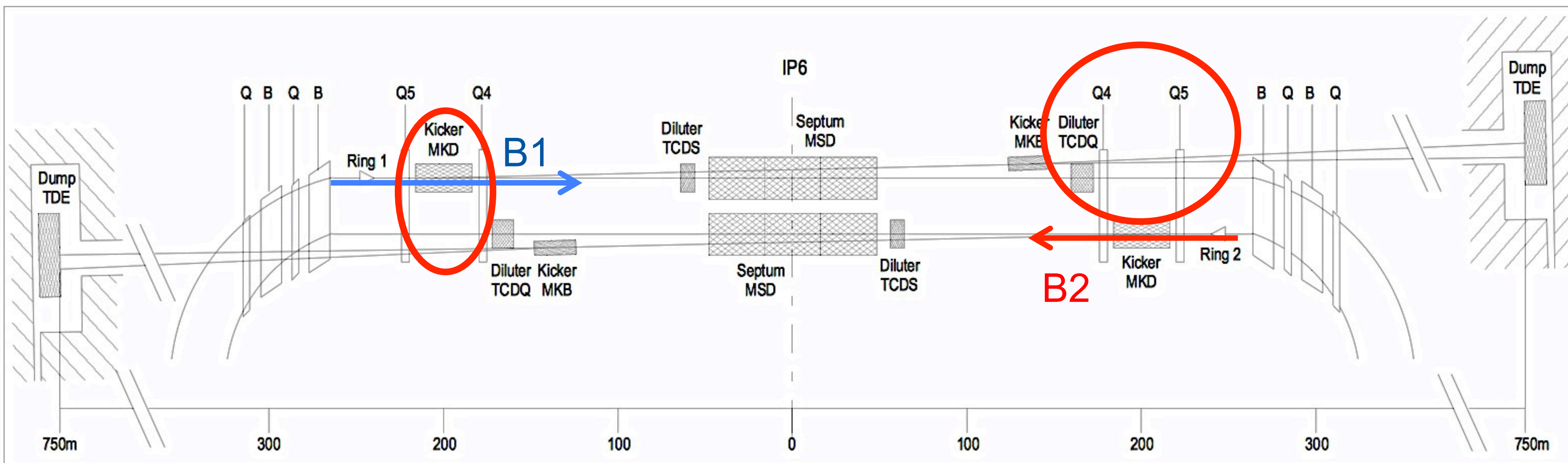
- Injection kicker (MKI) flash-over 28.07.2011 → ~10J/cm^3 peak energy deposition in D1(quench but **no damage**) → damage of 3 non-powered **corrector circuits** in front of Q3.
- **HL-LHC bunch intensities** (2.3e11p) → worst case peak energy deposition: ~30J/cm^3 → ~100J/cm^3 (> 100K) with design margins → Safe?



A. Lechner et al., *Energy deposition studies for fast losses during LHC injection failures*, In Proceedings of IPAC14.
A. Lechner et al., *Protection of superconducting magnets in case of accidental beam losses during HL-LHC injection*, In Proceedings of IPAC15.

Dump failures

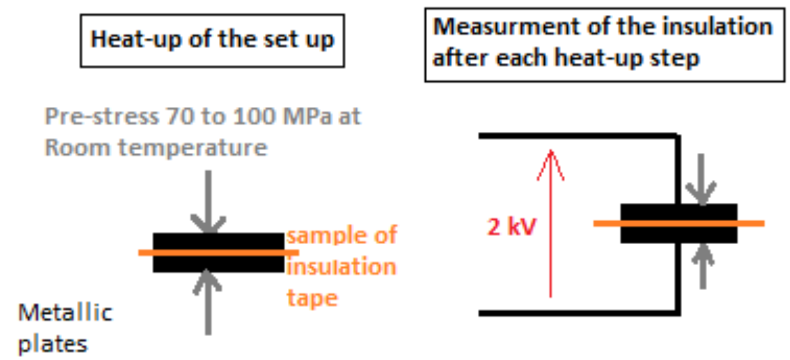
- Asynchronous beam dumps.
- Pre-firing of one Dump kicker (MKD).
- Dump with beam in abort gap.
- Damage of Q4 / Q5 due to showers from Diluter-TCDQ?



Damage tests without beam

Measure damage limit of Kapton insulation

- Measure **degradation of insulation** due to high temperature under stress within inert atmosphere.



- **Insulation tape** and insulated **cable stack clamped** between two plates (or a comparable set-up) providing mechanical stress as experienced in an operating superconducting LHC dipole (70 to 100 MPa).
- **Heat samples step-wise** to temperatures between 200C and 1000C.
- Measurement of the dielectric strength (**break through voltage**) of each samples within inert atmosphere (e.g. nitrogen).

Damage tests of Nb-Ti strands

- **Fast current discharge** (<10 ms) into pre-stressed Nb-Ti strands with increasing peak temperatures.
- Deduce **thermo-mechanical stresses inducing damage** in superconducting strand.
- Measure $\mathbf{I_c}$ **as function of peak temperature**.

Measure mechanical limits of Nb-Ti filaments, strands and cables

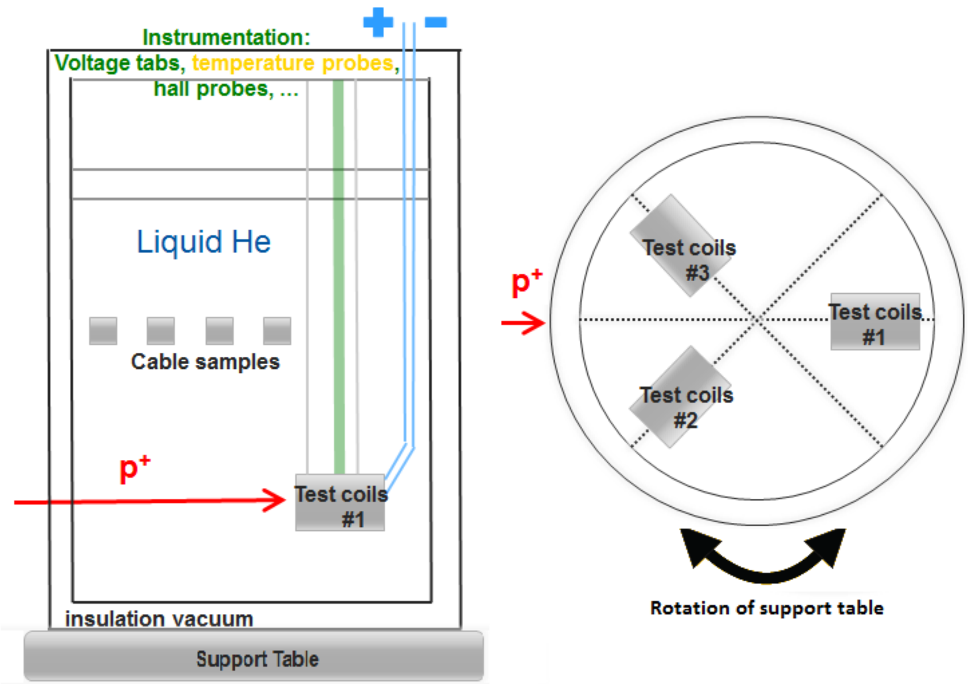
- Determine **tensile, compressive and shear stress limits** at room temperature and at liquid nitrogen temperature.
- Complement existing data where necessary with measurements.
- Measure irreversible **Delta-I_c vs. applied stress**.

Damage tests with beam

Damage tests with beam in cryogenic environment

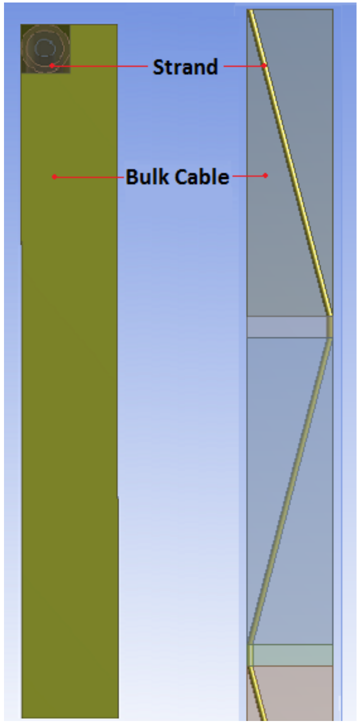
Test in **cryogenic conditions** at the CERN HiRadMat test facility with a **440 GeV proton beam** delivered by the SPS. The beam will be shot on the samples and cause an **instantaneous local heating**.

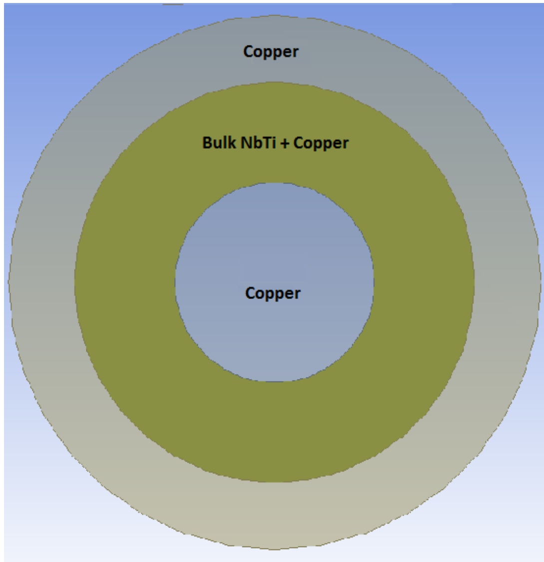
- 3 small coils and several Nb-Ti cable stacks.
- Beam **intensity increasing in steps** - hot spot temperature from 50K to 400K, different temperature gradients.
- **After each shot**, test coils:
  - **Electrical integrity** measured with high voltage measurements.
  - **I_c.**
- Cable stacks: measure I_c and electrical integrity **after removal** from experiment.



Numerical simulations

- FLUKA: derive **energy deposition map** due to beam impact.
- ANSYS Transient module: simulate **dynamic stresses**.
- Study **thermal stresses** in Nb-Ti strands due to different temperature expansion coefficients in Cu-matrix and Nb-Ti.
- Study stresses in Rutherford-cable strands due to **thermal gradients over cable width**.





Summary

- **Damage limits** of sc. magnets due **to instantaneous beam losses** are not know.
- **Increasing bunch intensities** for the (HL-)LHC may cause peak energy depositions into sc. magnets of 100J/cm^3 or more during injection or dump failures.
- Understanding of damage limits is important for definition of safe **operational envelope**, **thresholds** of protection systems and possibly necessary re-designs **passive protection** elements.
- **Experiments** to derive the damage limits of Kapton and Nb-Ti strands **without beam** are in preparation.
- Ultimately a damage experiment with magnets and cable stacks in **LHe using 440GeV protons** is planned in HiRadMat.
- **Numerical studies** of stresses in Nb-Ti strands and Rutherford cables are ongoing.

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