Experiments for machine protection: from consequences of beyond-design failures to damage limits of sc. magnets

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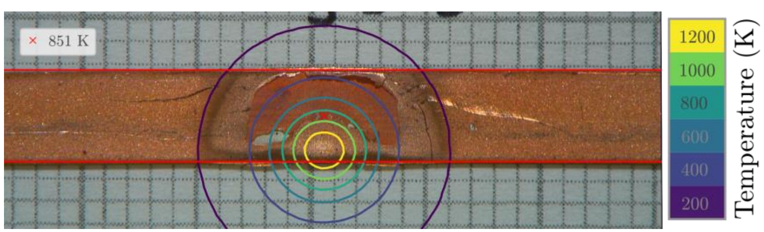
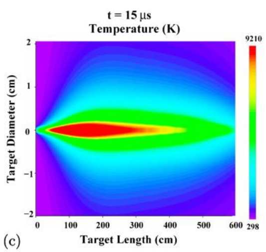
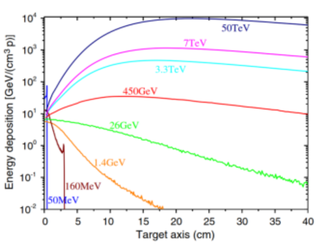






Outline

1) Motivation: Experiments for Machine Protection (MP)
2) Letter of Interest 1: **Damage limits of superconducting materials**
    - *Performed experiments*: Damage tests of Nb-Ti and Nb_3Sn strands at room temperature and at 4.5 K
    - *Proposed experiments*: Damage limits of superconducting coils
3) Letter of Interest 2: **Beyond-design failures and hydrodynamic tunnelling**
    - *Performed experiment*: First proof of hydrodynamic tunnelling
    - *Proposed experiments*: Investigation of hydrodynamic-tunnelling effects and tests of new absorber materials and mechanisms
4) Conclusions

Motivation: Experiments for MP

Stored beam energy

	LHC nominal	HL-LHC standard	FCC-hh
Stored energy per beam	0.36 GJ	0.68 GJ	8.3 GJ
Typical* beam-energy density	1.6 GJ/mm^2	4.4 GJ/mm^2	220 GJ/mm^2

*Assuming: β = 100 m for (HL-)LHC and β = 200 m for FCC.

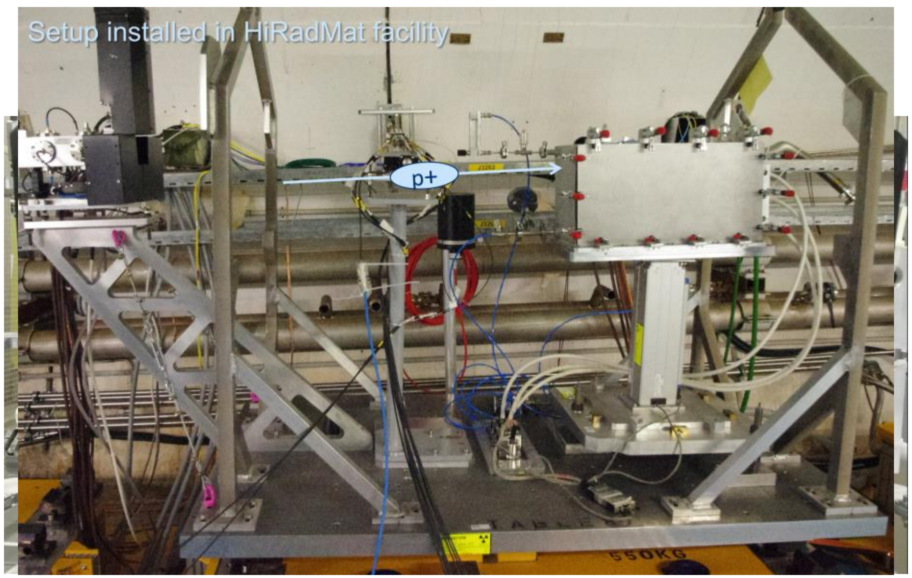
- **The stored beam energy** at LHC, HL-LHC and future machines is a major machine-protection (MP) challenge.
- **Accidental release** of this energy would lead to **high energy deposition** in short time scales.
- Fast (~milliseconds) and ultra-fast (<hundreds of µs) failures can be caused by existing and new equipment in the LHC and HL-LHC.
- **Experimental beam-impact studies** are required to estimate the **failure consequences** and define the **reliability requirements** for the protection elements, whilst optimizing the machine's **physics output**.

Letter of Interest 1: Study the **damage limits of superconducting coils**

Damage limits of superconducting strands

Previous experiments: Beam-induced **degradation of superconducting strands** has been measured at CERN's HiRadMat facility (2016 and 2018).

Room-temperature experiment (09/2016):
- Nb-Ti & Nb_3Sn strands
- Up to **2.6e12 p^+** per shot at 440 GeV
- Hotspots **up to ~1150 K** reached in strands



Cryogenic experiment at 4.5 K (08/2018):
- Nb-Ti, Nb_3Sn strands & YBCO tapes
- **3e12 p^+** per shot at 440 GeV
- Hotspots **up to ~1250 K** reached in strands

Experimental Results: RT & Cryogenic

Nb-Ti strands:

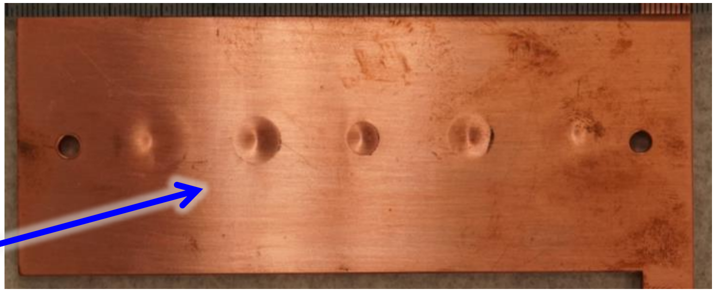
J_c degradation for hotspot **temperatures > 880 K** (2.2 kJ/cm^3)

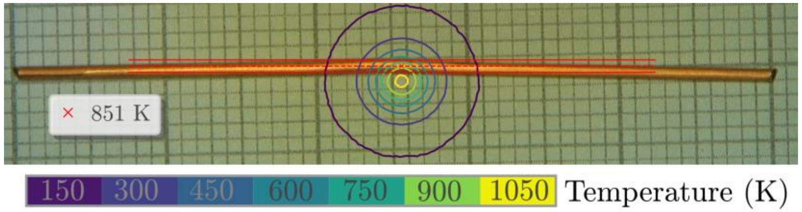
Nb_3Sn strands:

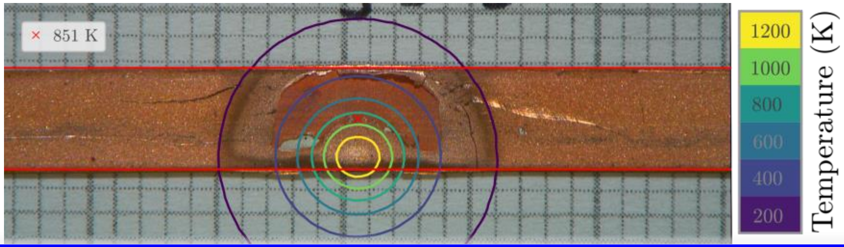
J_c degradation observed in **all impacted samples** (T ≥ 700 K, 1.4 kJ/cm^3)

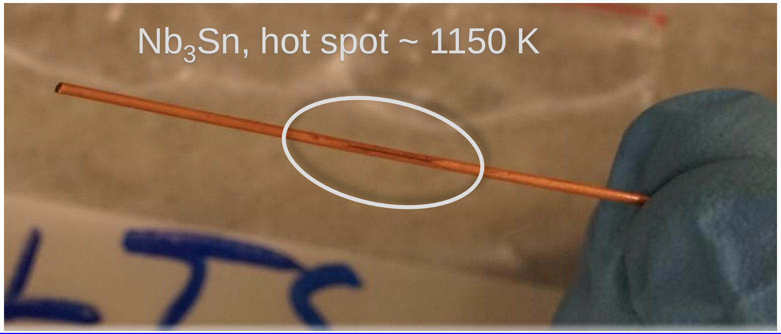
- Nb-Ti strands: **no visible deformation up to 1100 K**.
- Nb_3Sn strands: **plastic deformation** from $T_{hotspot}$ **≥ 640 K.**
- YBCO tapes: **decolourisation** for $T_{hotspot}$ **≥ 720 K**.
- Detailed analysis and **critical transport current (I_c) measurements** ongoing in collaboration with University of Geneva.

Beam impact marks on sample holder









V. Raginel, et al., *First Experimental Results on Damage Limits of Superconducting Accelerator Magnet Components Due to Instantaneous Beam Impact*, IEEE Trans. Appl. SC, Vol 28(4), June 2018

V. Raginel, *Study of the Damage Mechanisms and Limits of Superconducting Magnet Components due to Beam Impact,* CERN-THESIS-2018-090

A. Oslandsbotn, A. Will, D. Wollmann, Beam Impact on Superconductor short samples of Nb3Sn, Nb-Ti and YBCO, 2018, EDMS 2068064

A. Will, et al., Beam impact experiment of 440GeV/p Protons on superconducting wires and tapes in a cryogenic environment, IPAC2019

Proposed Experiments at HiRadMat I

1) Study the damage limit of dedicated superconducting **sample coils (Nb-Ti, Nb_3Sn)** at cryogenic temperatures.
2) Study the damage limit of **HL-LHC Nb_3Sn triplet** short prototype coils at cryogenic temperatures.

Experimental wish-list:

- Use of liquid helium (4.2 K) to allow **in-situ** measurement of **degradation** of critical current.
- Shot intensities from **10^{10} to ~$3x10^{12}$ protons**, allowing to verify the models for quench and **damage limits** in case of **transient beam losses** and reaching peak hot-spot temperatures in the coils of **up to 1200 K**.

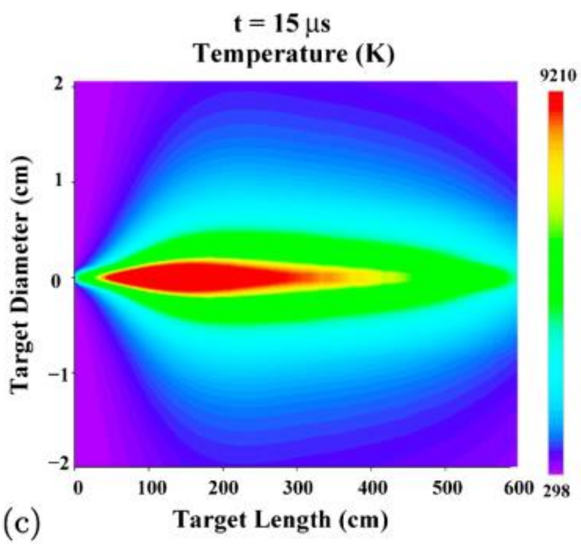
→ Better knowledge of quench/damage limits will allow to optimize machine-protection settings (e.g. beam-loss limits) and design choices for passive absorbers.

Letter of Interest 2: **Beyond-Design Failures and Hydrodynamic Tunnelling**

Beyond-Design Failures

- **Beyond-design failure cases** at (HL-)LHC and future machines can lead to localized impact of numerous bunches → **hydrodynamic-tunnelling effect** has to be considered to **estimate the failure consequences**.
- Hydrodynamic tunnelling: Material density is reduced by first impacting bunches → penetration depth of subsequent bunches is (significantly) increased.
- Simulation requires **coupling of energy-deposition codes and hydro codes**.

Simulated point impact of LHC beam



7 TeV, 2808b, 1.15e11 ppb, σ = 0.2 mm

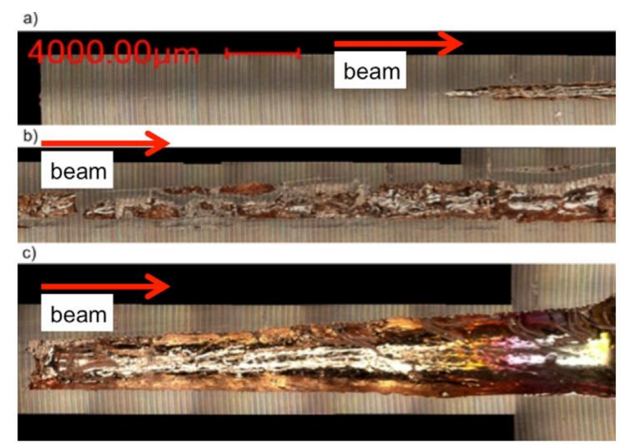
[N. A. Tahir et al., PRSTAB 15, 051003 (2012)]

→ Full LHC beam would penetrate ~25 m into a carbon target

Experiment at HiRadMat, CERN

440 GeV, 144b, σ = 0.2 mm, 1.5e11 p^+, 1.5 MJ beam energy

N.A. Tahir, **F. Burkart**, et al., NIM B 427 (2018) 70–86



→ **First experimental proof of hydrodynamic tunnelling**

Proposed Experiments at HiRadMat II

1) Continue the numerical and experimental study of **hydrodynamic-tunneling effects** for copper or other machine-relevant materials, such as graphite or tungsten.
   - → Benchmark the numerical models and study the Equation of State for these materials.
2) Study **new absorber materials and mechanisms**
   - Future high-energy machines will pose demanding requirements to the different kinds of beam-intercepting devices.
   - Traditional materials or mechanisms might reach their limits, while non-standard approaches, such as using foams, powders, non-solid materials, still present numerous challenges.
   - → long-term machine-protection interest to **assess the feasibility and limitations of these approaches**.

Experimental wish-list:

- 288 bunches per pulse.
- 1.2e11 protons/bunch (ideally LIU bunch intensities).
- Variable beam sigma, e.g. between 0.25 mm (or smaller) and 2.0 mm, to adjust the energy density.

Conclusions

- **Beam-impact studies** are essential for machine protection
  - to estimate the **failure consequences,**
  - and define the **reliability requirements** for the protection elements,
  - whilst optimizing the machine's **physics output**.
- HiRadMat is a **unique facility** for experimental beam-impact studies.
- CERN's TE-MPE group has conducted 3 beam damage experiments at HiRadMat in recent years and the continuation of these tests has high priority.
- **Future experiments** are proposed to
  - **study the damage limits of superconducting sample and prototype coils**,
  - **study the consequences of beyond-design failures**, including the effect of hydrodynamic tunnelling, and **test new absorber materials and mechanisms**.

Thank you for your attention!

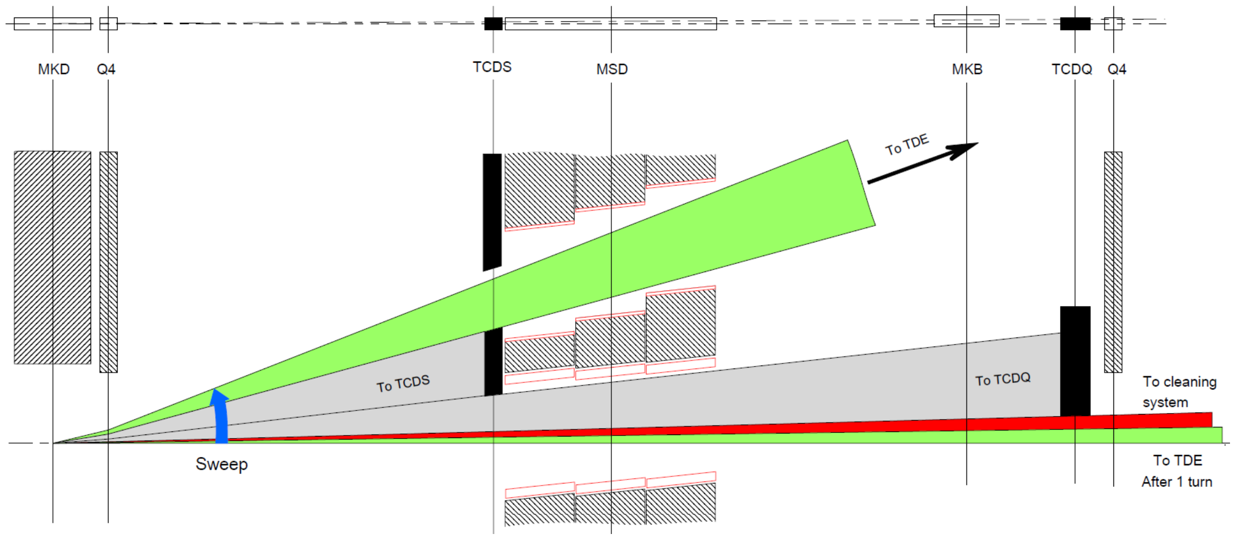
LHC Risk Matrix

HL-LHC/ LHC risk matrix		Recovery						
		∞	year	month	week	day	hours	minutes
		S7	S6	S5	S4	S3	S2	S1
Frequency	1 / hour							
	1 / day							
	1 / week							
	1 / month							
	1 / year							
	1 / 10 years							
	1 / 100 years							
	1 / 1000 years							

Risk matrix: J. Uythoven/M. Blumenschein

LBDS failure cases

“Acceptable (Design) Fault Cases”	“Unacceptable (Beyond Design) Fault Cases”
Asynchronous beam dump	MKDs not firing upon request
One missing extraction kicker (MKD)	Wrong energy information in BETS → beam can impact on machine/TCDQ
Missing dilution kicker	Complete dilution failure with high-intensity beam
…	…



[See LHC Design Report, Chap. 17]