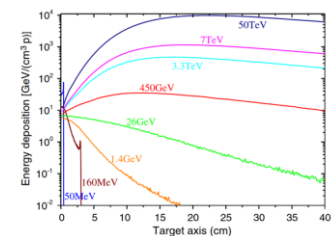
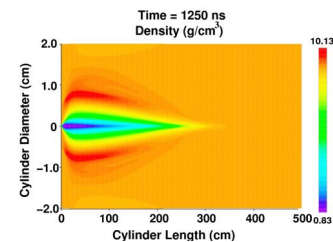
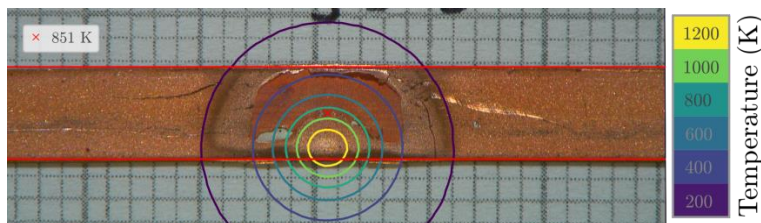




# Status of studies on beam impact & machine protection challenges

A. Apollonio, Y. Nie, R. Schmidt, J. Schubert, A. Siemko, J. Uythoven, A. Verweij, A. Will, C. Wiesner, D. Wollmann, M. Zerlauth, CERN, Geneva, Switzerland



# From LHC to FCC: MP Challenges



- Increased beam energy
  - → increased stored energy in beams and magnets
- Increased size
  - → increased number of elements
  - → increased communication and reaction time
- New equipment types → new failure cases

*This presentation is focused on FCC-hh.*

# Outline

- 1) Stored beam energy and damage potential
- 2) Beam-impact studies and damage experiments
- 3) Beam-related failures: classification and mitigation strategies
- 4) Interlock system, reaction time, and availability
- 5) Conclusions

# Major Challenge: Stored energy

Stored energy in the **FCC-hh magnet system**: **~160 GJ** (LHC: ~9 GJ)

- *Not part of this talk. → See A. Verweij, Status of FCC main magnet circuit layouts, powering and protection, FCC Week 2019, THU 16.10h*

Stored energy in the **FCC-hh beams**: **8.3 GJ per beam**

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

*Note: Red arrows in the original image indicate scaling factors: 0.36 GJ to 8.3 GJ is x23, and 1.6 GJ/mm² to 220 GJ/mm² is x140.*

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




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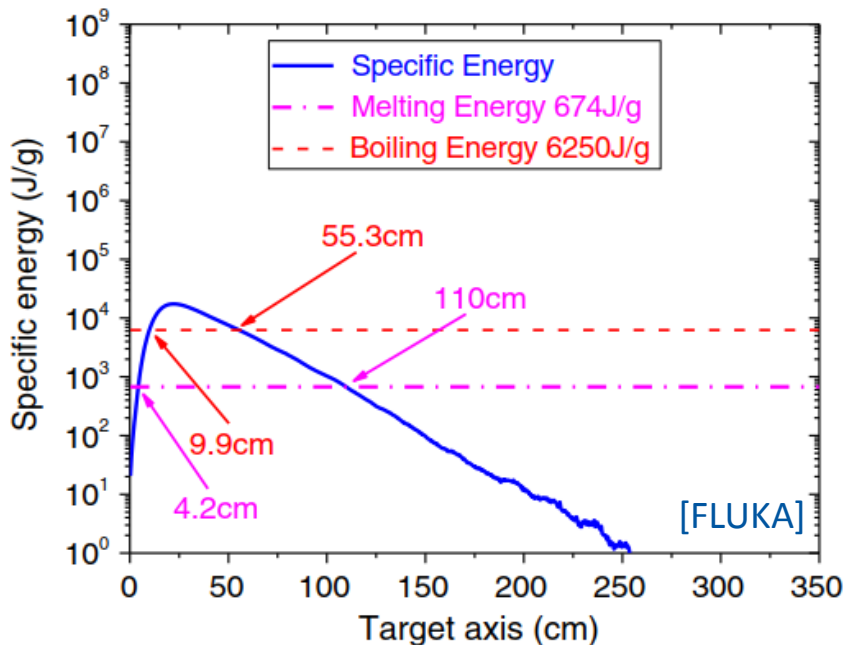


\*Assuming:  $\beta = 100$  m for (HL-)LHC and  $\beta = 200$  m for FCC.

- **Unprecedentedly high stored beam energy** → fast reacting and ultra-reliable interlock and extraction system with high redundancy required.
- **Beam-impact studies** → estimate the failure consequences and define the reliability requirements for the protection elements.

# Damage Potential and Safe Beam

Specific energy for **one nominal FCC bunch** impacting a copper target



50 TeV,  $1e11$  p<sup>+</sup>,  $\sigma = 0.2$  mm

**At 50 TeV:**

- One bunch of  $1e11$  protons ( $\sigma=0.2$  mm) is sufficient to evaporate copper.
- $2e9$  protons ( $\sigma=0.1$  mm) are sufficient to melt copper.
- → **Safe beam intensity** for machine setup and commissioning defined as  **$5e8$  protons**.
- → Defines required **dynamic range for MP-relevant beam instrumentation**.

[Y. Nie, et al., *PRAB* 20 (081001), 2017]

# Damage Potential: Hydrodynamic Tunnelling

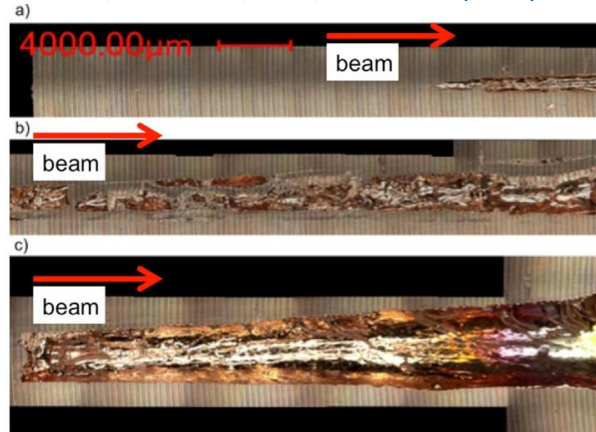
**Hydrodynamic tunnelling:** Density reduction due to first impacting bunches → increased penetration depth for next bunches.



## Experiment at HiRadMat, CERN

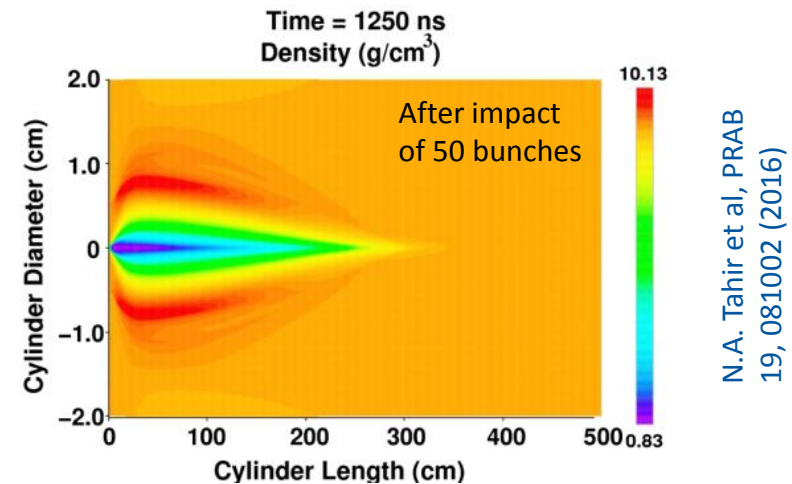
440 GeV, 144b,  $\sigma = 0.2$  mm,  
1.5e11 p<sup>+</sup>, 1.5 MJ beam energy

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



→ First experimental proof of hydrodynamic tunnelling

## Simulated hydrodynamic tunnelling effect for a 40 TeV proton beam impacting on copper.



N.A. Tahir et al, PRAB  
19, 081002 (2016)

A 50 TeV beam (10600b, 1e11p<sup>+</sup>,  $\sigma=0.2$ mm) would penetrate an estimated ~350 m into copper.

→ Highly reliable extraction, dilution and dump system required.

→ See also FCC Week 2019: S. Gilardoni, THU, 14.30h and A. Chmielinska, TUE, 17.15h.

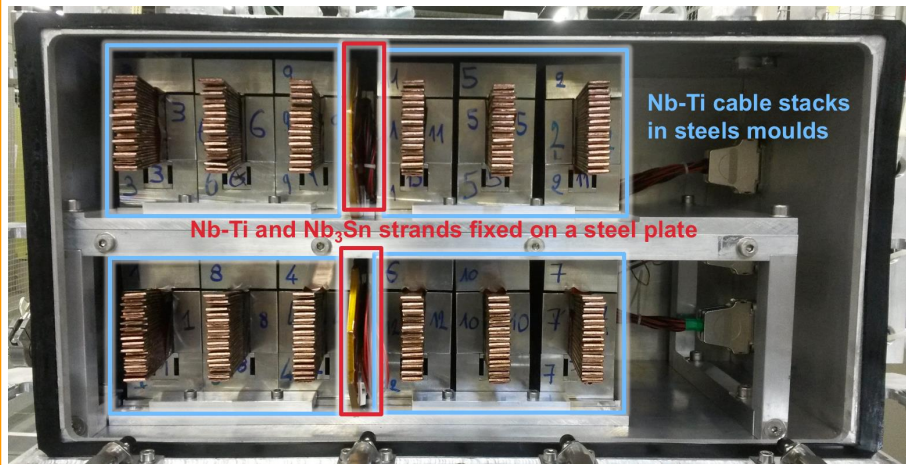
→ For beyond-design failures, hydrodynamic tunnelling can become relevant and, thus, has to be studied as part of the risk assessment.

# Beam-Impact Studies: Superconductors

Beam-induced degradation of superconducting material has been measured at CERN's HiRadMat facility.

## Room-temperature experiment (09/2016):

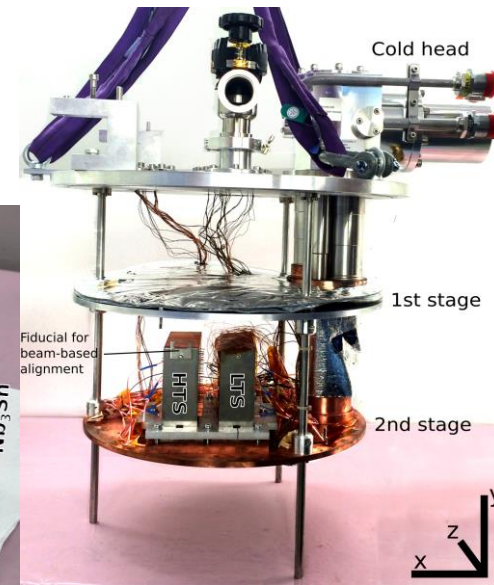
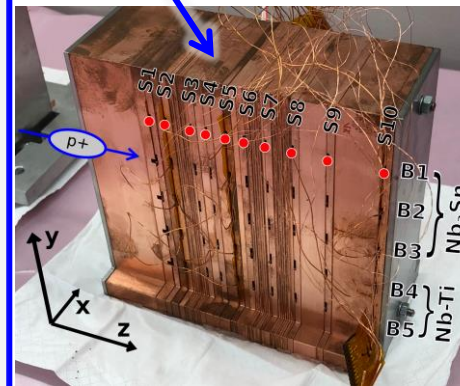
- Nb-Ti & Nb<sub>3</sub>Sn strands
- Up to  $2.6e12$  p<sup>+</sup> per shot @ 440 GeV
- Hotspots up to **~1150 K** reached in strands



## Cryogenic experiment @ 4.5 K (08/2018):

- Nb-Ti, Nb<sub>3</sub>Sn strands & YBCO tapes
- $3e12$  p<sup>+</sup> per shot @ 440 GeV
- Hotspots up to **~1250 K** reached in strands

### Copper sample holders



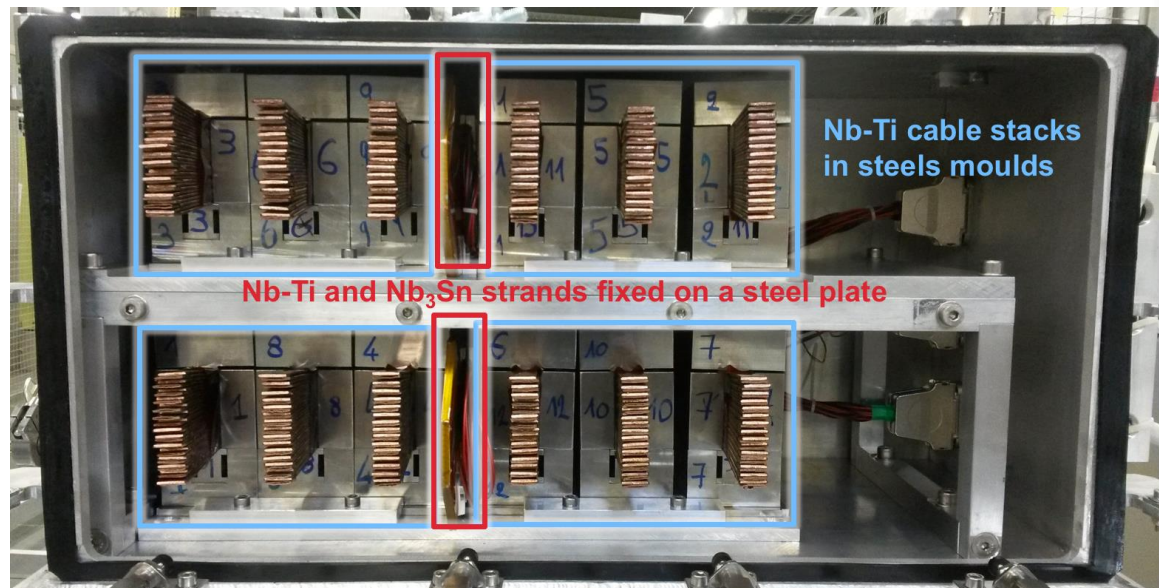
# RT Experiment: Results

## Nb-Ti strands:

- $J_c$  degradation for hotspot temperatures **> 880 K** ( $2.2 \text{ kJ/cm}^3$ )

## Nb<sub>3</sub>Sn strands:

- $J_c$  degradation observed in **all impacted samples** ( $T \geq 700 \text{ K}$ ,  $1.4 \text{ kJ/cm}^3$ )



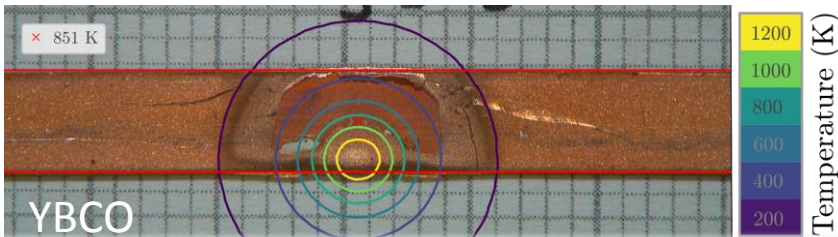
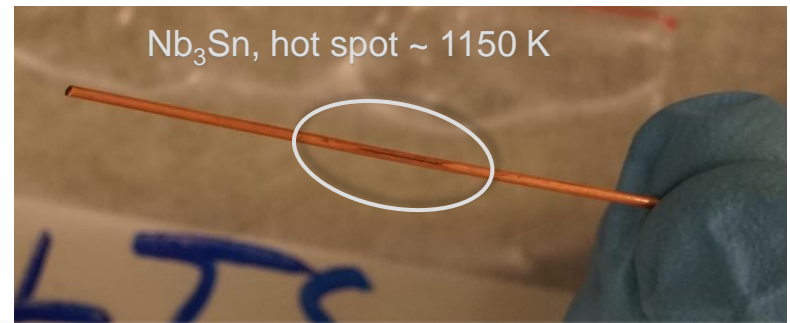
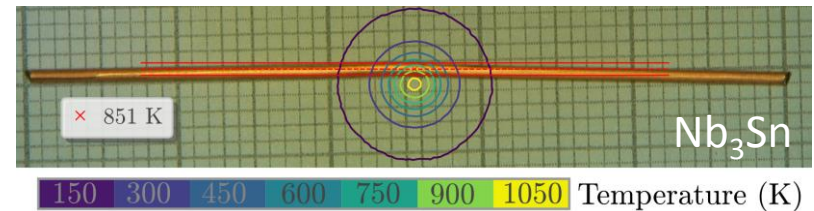
V. Raginel, et al., *First Experimental Results on Damage Limits of Superconducting Accelerator Magnet Components Due to Instantaneous Beam Impact*, IEEE Trans. Appl. SC, Vol 28(4), June 2018

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

# Cyrogenic Experiment: First Results

- Clear **beam impact marks** on copper blocks of sample holder.
- **Nb-Ti strands**: no visible deformation up to **1100 K**.
- **Nb<sub>3</sub>Sn strands**: **plastic deformation** observed for  $T_{\text{hotspot}} > 550 \text{ K}$ .
- **YBCO tapes**: **partial welding** to sample holder for  $T_{\text{hotspot}} > 700 \text{ K}$ .
- Detailed analysis and **critical transport current ( $I_c$ ) measurements** ongoing in collaboration with University of Geneva.

Beam  
impact  
marks on  
sample  
holder



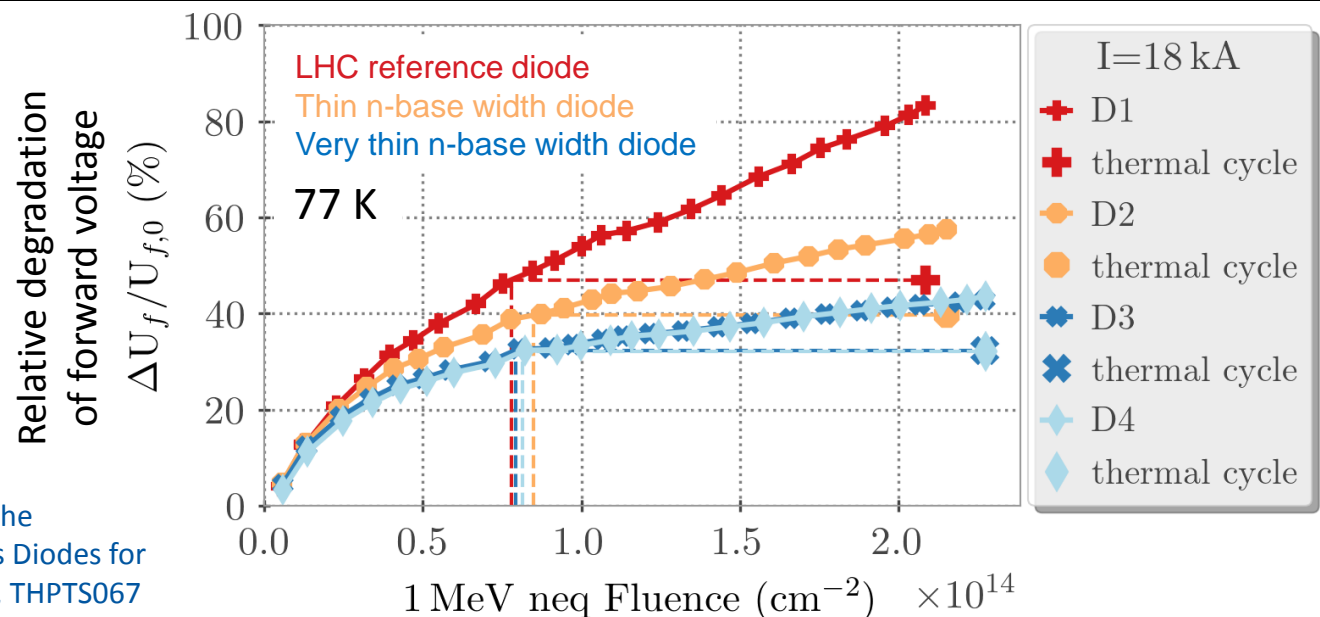
A. Oslandsbotn, A. Will, D. Wollmann, Beam Impact on Superconductor short samples of Nb<sub>3</sub>Sn, Nb-Ti and YBCO, 2018, EDMS 2068064

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

# Radiation Damage of Cold Bypass Diodes



- Bypass diodes are **important part of the quench protection** of the main magnets. They are exposed to beam-induced radiation.
- **Three different cold diode types** irradiated over **8 months** in CERN's CHARM facility at 77 K and 4 K. In total,  $\sim 11$  kGy and  $\sim 2.2 \times 10^{14}$  1MeV neq/cm<sup>2</sup> reached.
- **Regular in-situ measurement** of forward voltage  $U_f$  up to 18 kA, ...
- Very thin n-base width diodes show **significantly improved radiation tolerance** as compared to LHC diodes.
- Annealing @ RT allows to reduce effect of radiation damage by > 60%.



D. Wollmann et al, Characterisation of the Radiation Hardness of Cryogenic Bypass Diodes for the HL-LHC Inner Triplet Circuit, IPAC19, THPTS067

# Beam-Related Failures: Overview

Beam lifetime	Beam power lost		Failure classification	Failure scenarios	Machine-protection strategy
	LHC	FCC			
~1 s	~360 MW	~8 GW	<b>Slow failures</b>	<ul style="list-style-type: none"> <li>Powering failures</li> <li>Magnet quenches</li> <li>RF failures</li> </ul>	<ul style="list-style-type: none"> <li>Detection of hardware failure. If properly detected, enough time to dump the beam.</li> </ul>
A few ms (tens of turns)	~100 GW	~ TW	<b>Fast failures</b>	<ul style="list-style-type: none"> <li>UFOs</li> <li>Fast equipment failures</li> <li>Failures of magnets* with short time constant and at positions of large <math>\beta</math>, ...</li> </ul>	<ul style="list-style-type: none"> <li>Fast detection of hardware failure and of beam losses.</li> <li>Fast reaction time of the interlock and dump systems.</li> </ul>
1 turn to a few turns	< 4 TW	< 26 TW	<b>Ultrafast failures</b>	<ul style="list-style-type: none"> <li>Single passage losses during extraction and injection</li> <li>Missing beam-beam kick</li> <li>Ultrafast equipment failures, e.g. phase jumps of crab cavities, quench protection equipment firing on the circulating beam, ...</li> </ul>	<ul style="list-style-type: none"> <li>Use passive protection. Might require novel materials or sacrificial absorbers.</li> <li>Reduce probability, time scale and consequences of equipment failure.</li> </ul>

\*For a detailed discussion see Y. Nie, FCC Week 2018

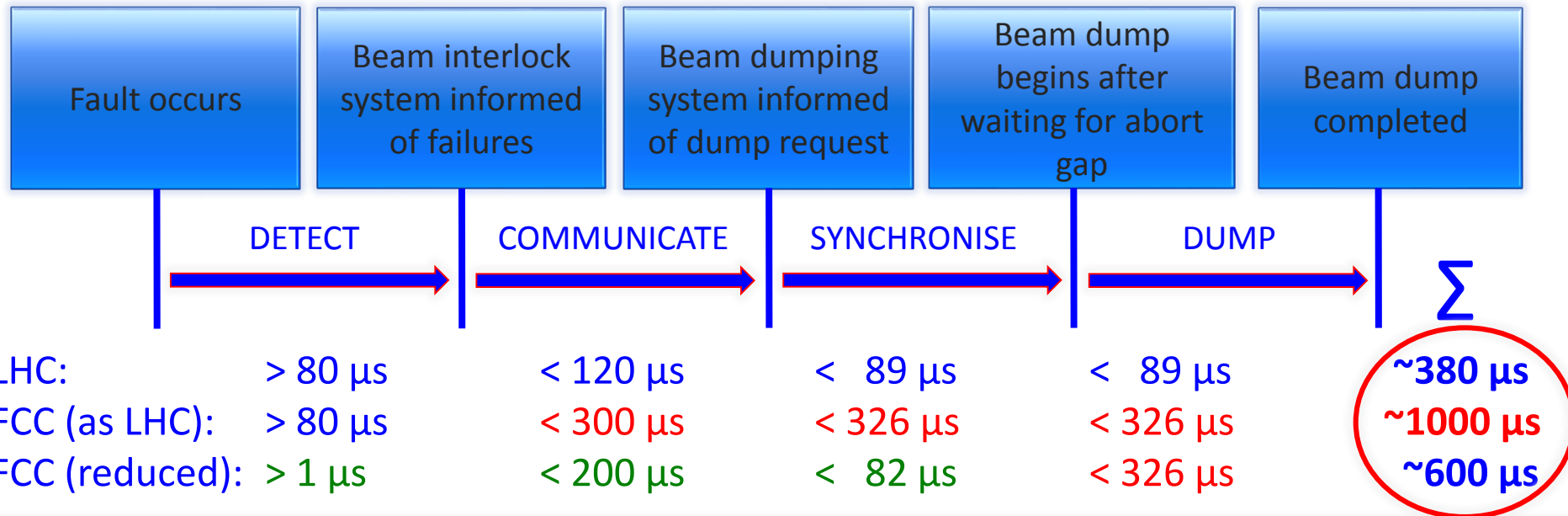
# Fast Failures: How to gain time?

- Assumed **acceptable beam displacement**: 1.5 sigma within 2 ms.
- Criticality of fast failures can be decreased by
  - **Reducing failure speed**
    - Example: **controlled increase of the decay time constant** ( $\tau=L/R$ ) for magnet power converters to avoid that beam losses build up too fast in case of failures.
  - **Increasing time until loss onset**
    - **Reduce transverse tail population**, e.g. by using a hollow electron lens.\*
  - **Reducing reaction time of Machine Protection System (MPS)**
    - See next slide

\*Note: witness bunches with normal population are still required for early detection of abnormal beam losses.

# MPS: Strategy and Reaction Time

MPS for FCC-hh will be based on the successful strategy adopted for LHC.

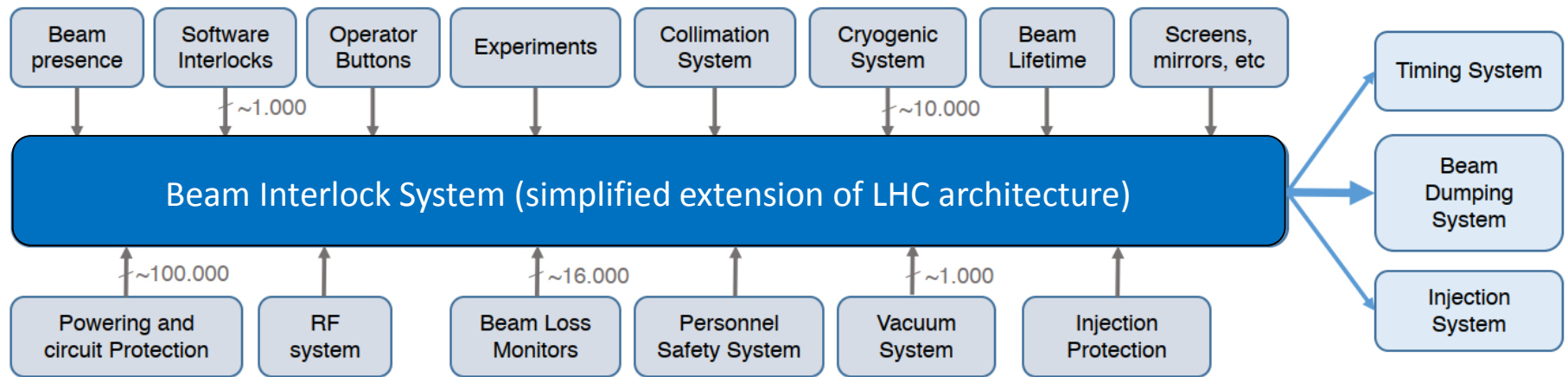


## Options to reduce total reaction time of the Machine Protection System (MPS):

- **1) Detection time:** Use **faster detectors** (diamond, silicon, Cherenkov fibers), equipped with faster read-out electronics.
- **2) Communication time:** Use **direct signal path** (instead of a path following the arcs).
- **3) Synchronisation time.** Use **multiple particle-free abort gaps** (e.g. 4).
- **4) Beam extraction time:** Would only be possible by installing **additional extraction and dump systems**. Not proposed.

# Beam Interlock System (BIS)

- An estimated **>100 000 elements** will have to be connected to the **Beam Interlock System**.
- Challenging **trade-off between machine protection and high availability** required → study the option of using voting logic (e.g. 2oo3) on the client side to reduce the number of false dumps.



Architecture and client systems of the Beam Interlock System (BIS).

# Availability and Machine Protection

**Challenging trade-off: protect the machine while ensuring high availability and efficiency**

- *Interlocks:*
  - Ensure ultra-high reliability in case of beam dump request → **high degree of redundancy.**
  - Limit number of spurious dumps due to hardware failures → **assess optimization through voting strategies (e.g. 2oo3).**
- *Beam Protection:*
  - Finding optimal **balance between beam losses (potential quenches) and number of preventive dumps** → requiring e.g. understanding of UFOs mechanisms and energy deposition at 50 TeV.
  - Maximize **number of bunches per injection** to reduce filling time → explore limits for quenches of sc materials and material damage as well as allowed energy deposition for injection protection devices.
  - Minimize **risk of asynchronous dumps** by increasing # kickers:
    - Reduce consequences: ensuring insensitivity to spurious firing of one or more kickers.
    - Reduce probability: operate generators with lower voltage to reduce failure rate.
    - Requirement: Avoid common cause failures leading to spurious firing of kickers.
- → Reliability and availability have to be considered from the design phase on – and they don't come for free.

For FCC-ee: see A. Niemi, “FCC-ee machine availability”, WED, FCC Week 2019.

# Conclusions

- Major machine-protection challenges for FCC-hh: **stored energy in magnets and beams** ( $> 8$  GJ per beam).
- Numerical and experimental **beam-impact studies** are essential to estimate the failure consequences and define the reliability and machine protection requirements.
- The Machine Protection System (MPS) for FCC-hh will be based on the successful strategy adopted for LHC. A **fast reacting and ultra-reliable interlock system with high redundancy** of the client systems is required.
- Challenging **trade-off between machine protection and high availability** has to be made.
- Compared to LHC, **improvements in several key areas** are needed:
  - Reduced MPS reaction time.
  - Fast Beam Loss Monitors.
  - Improved control of the time constants for the magnetic field decay.
  - Efficient control and/or monitoring of the transverse beam profile.
- Important challenges, but **no showstopper identified**.

8.3 GJ: A380  
(empty) at  
880 km/h

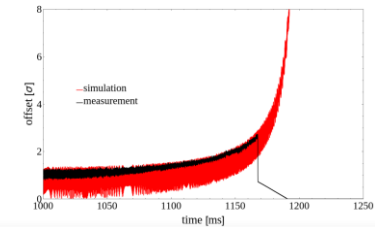


Thank you for your attention!

# Proposed future R&D work

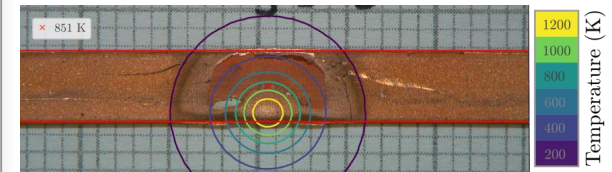
- **Beam-related failures**
  - Study of **new fast and ultra-fast beam-related failure scenarios** and their mitigation measures.
- **Next-generation interlock systems**
  - Study of new technologies for the **beam and related machine interlock systems** and inclusion of new failure scenarios.
- **Beam impact and damage studies**
  - Study the **damage limits of superconducting materials**, including sample coils.
  - Investigation of **hydrodynamic-tunnelling effects** in accelerator materials.
  - Study the feasibility and limitations of **new materials and mechanisms for beam-intercepting devices**.
- **Develop and test radiation-tolerant cold bypass diodes**
- **Availability**
  - Investigate **novel architectures** for reliability and availability critical systems; develop advanced simulation tools and **failure prediction models via machine learning**.

Measured and simulated beam orbit offset during Crab Cavity ramp at the CERN SPS



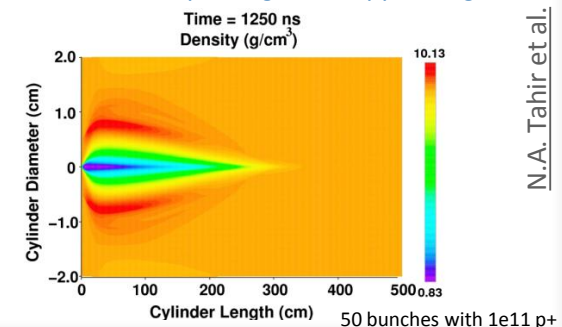
B. Lindstrom et al.

Damaged YBCO tape due to a 440 GeV proton beam impact.



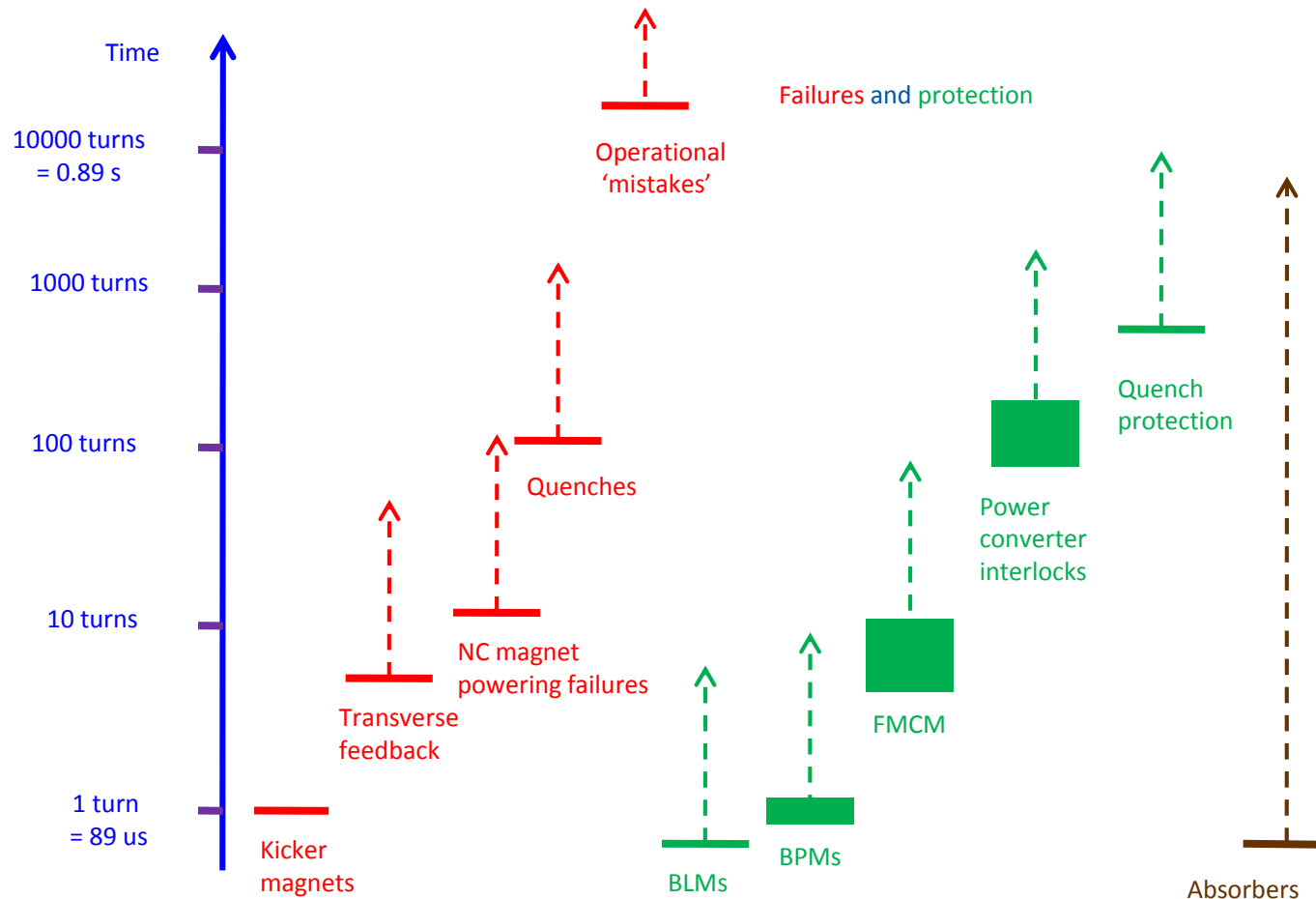
A. Will et al.

Hydrodynamic tunneling effect for a 40 TeV proton beam impacting on a copper target.



N.A. Tahir et al.

# Beam-Related Failures: Time Scales



# LHC Risk Matrix

HL-LHC/ LHC risk matrix		Recovery						
		$\infty$	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