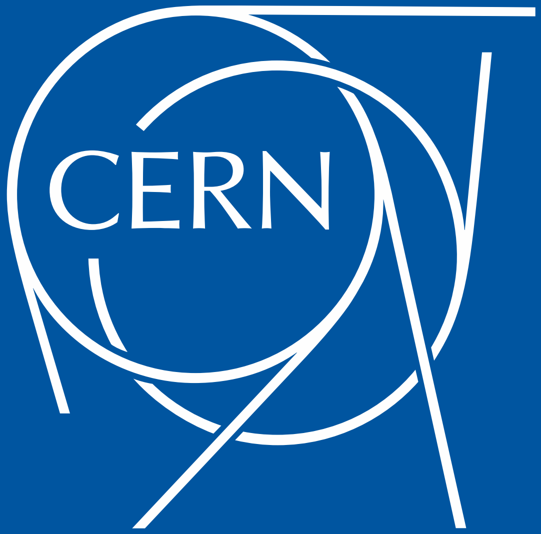

CERN

Beam-related machine protection of the future circular collider (FCC-hh)

Yuancun NIE
TE-MPE-PE

Acknowledgments:
R. Schmidt, D. Wollmann, M. Jonker, V. Raginel, A. Verweij, et al.

Outline

I. Importance of machine protection

II. General protection strategy for LHC and possibly for FCC-hh

III. Classification of FCC-hh failure mode and strategy

IV. Specific requirement of FCC-hh

V. Summary

I. Importance of machine protection

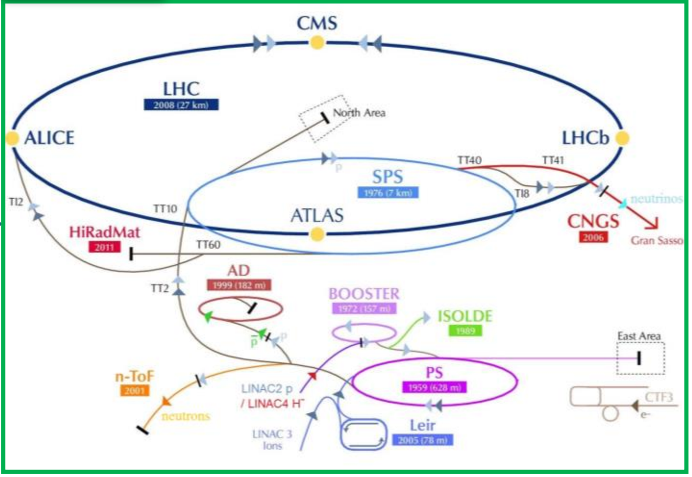
FCC CDR: by the end of 2018!

Tevatron:6km, 2TeV (pp-) LHC:27km, 14TeV (pp) FCC:100km, 100 TeV (pp)

1930's

!

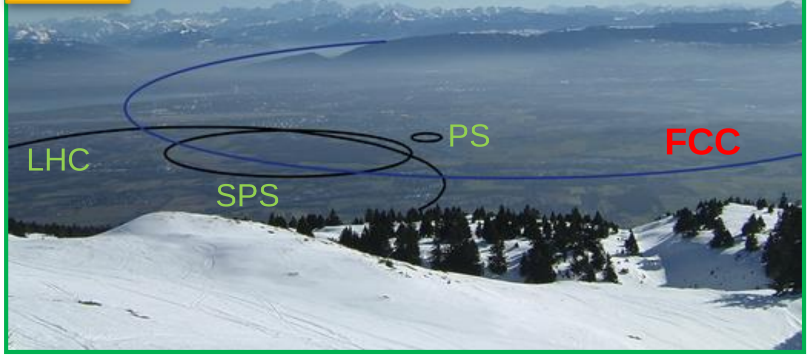
nowadays



?

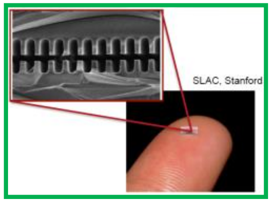
2030's

>110 Institutes; >30 Countries; > 20 Companies



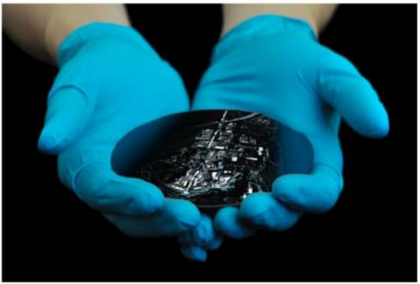
?

2040's



Laser?

Stanford ~~Linear~~ Accelerator Center

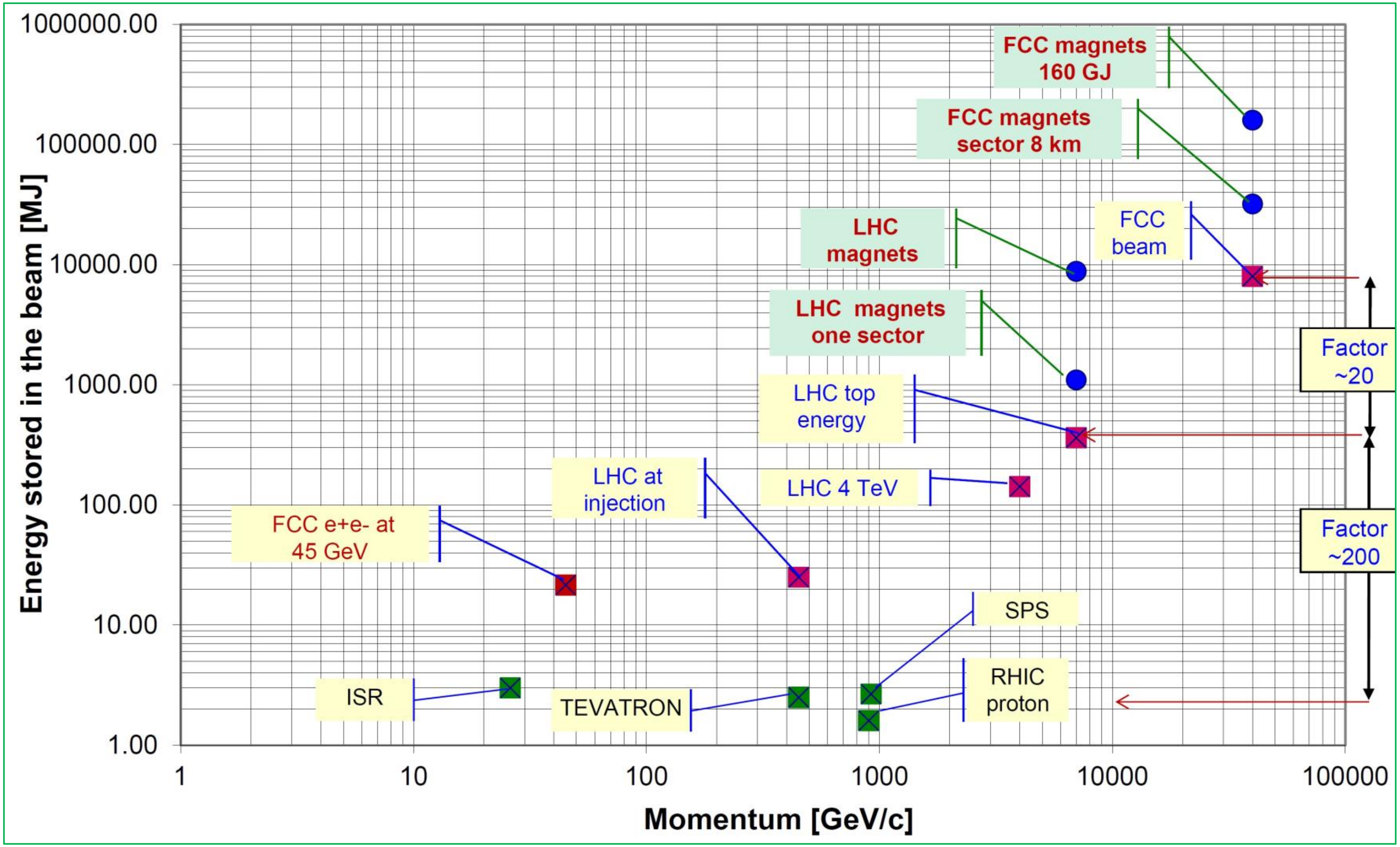


[E. A. Peralta, et al., *Nature* 2013]

[*Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop* 2017, CERN]

I. Importance of machine protection

Energy stored in beams and magnets [R. Schmidt, ***FCC Week*** 2015]



I. Importance of machine protection

Relevant LHC and FCC parameters [F. Zimmermann, ***IPAC***-2014]

Parameters	**LHC (nominal)**	**FCC-hh (baseline)**
Proton energy (TeV)	7	50
Bunch intensity	1.15×10^{11}	1.0×10^{11}
Bunches per beam	2808	10600
Circumference (km)	26.66	97.75
Time per turn (μs)	89	326
Beam energy (MJ)	**362**	**8500**
Typical beam energy density (GJ/mm^2)	**1**	**200**
Quench limit (p/m/s)	**7.8×10^6**	**0.5×10^6**
Tune Q_x / Q_y	64.31 / 59.32	111.31 / 108.32
RMS emittance (nm) / Norm. emittance (μm)	0.50 / 3.75	0.04 / 2.2
β^* (m) / min. RMS beam size (μm)	0.55 / 16.6	1.1 / 6.8
Peak luminosity L (10^{34} cm^{-2}s^{-1})	1	5
Beam intensity lifetime (h)	46	19

I. Importance of machine protection

Total beam energy is impressive [R. Schmidt, ***CAS*** 2011/***FCC Week*** 2015]

LHC vs. FCC

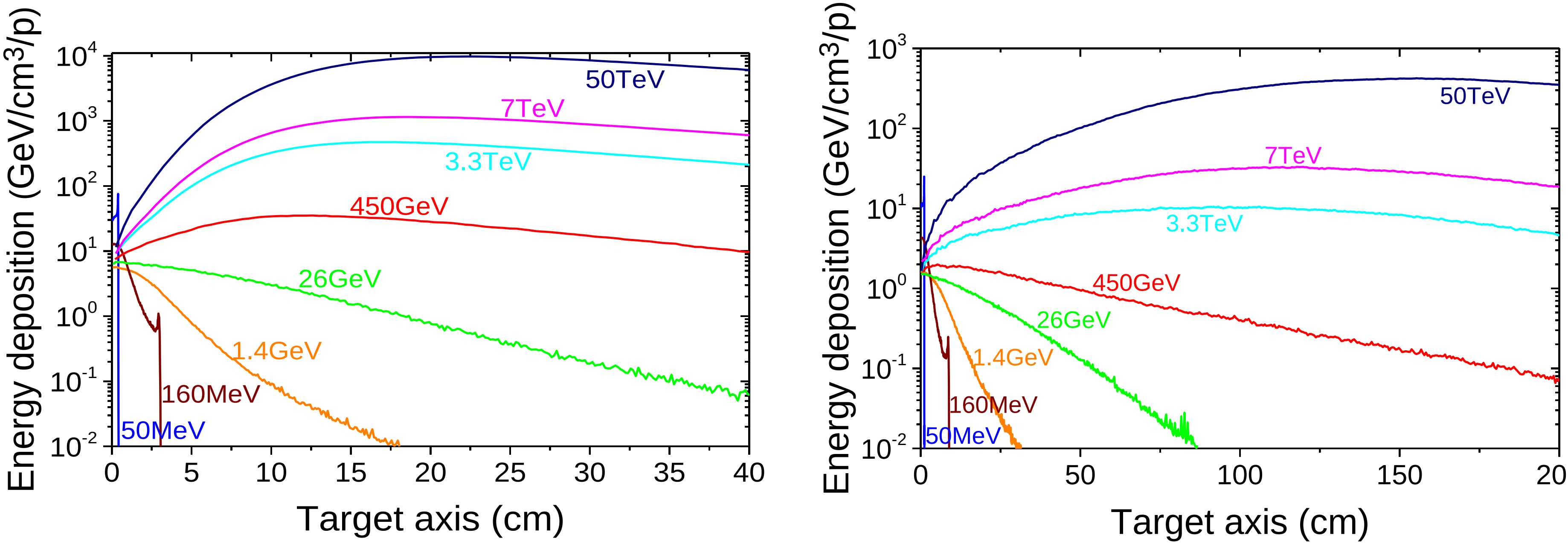
LHC beam energy:
200 m train at 155 km/h
i.e., 360 MJ:
90 kg TNT/8 L gasoline/15 kg chocolate!

FCC beam energy:
20 times LHC, equivalent to kinetic energy of A380 at nominal speed (850 km/h)

- ➢ can melt 10 tons of copper

I. Importance of machine protection

Moreover, the energy normally concentrates on square submillimeters! → potentially destructive



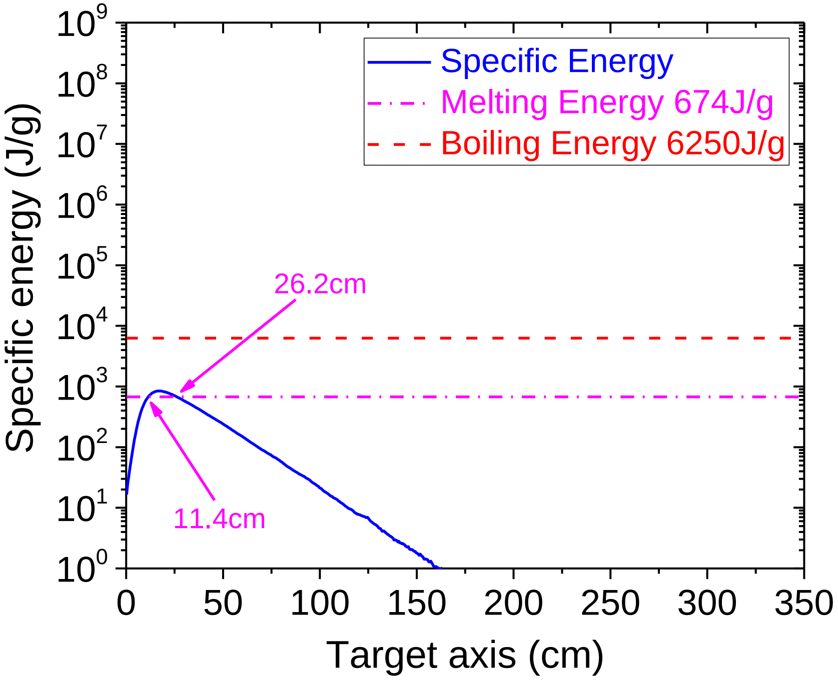
Energy deposition per proton in copper (left) and graphite(right)

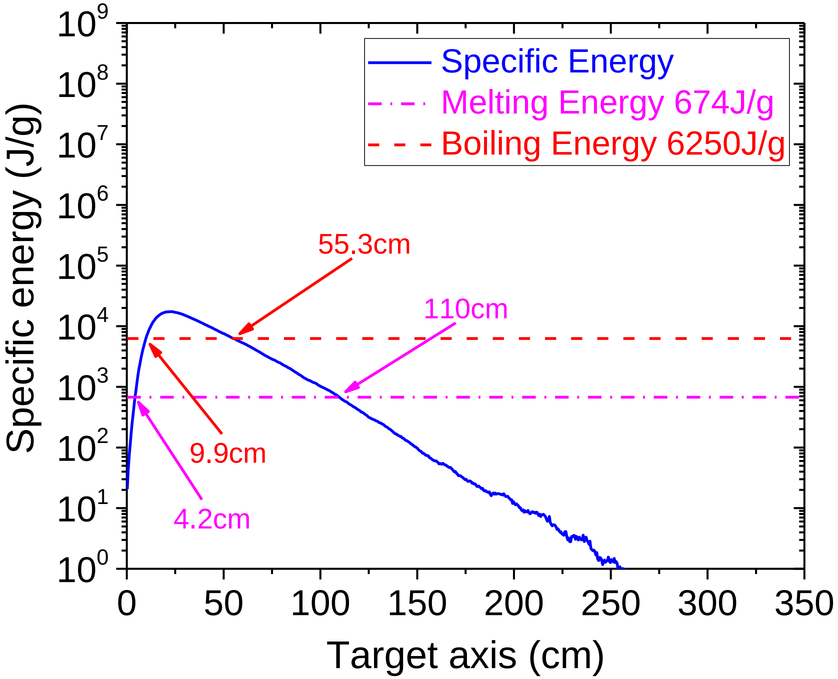
- From 50 MeV to 50 TeV, three beam sizes have been studied for each energy (the case of $\sigma_{x,y} = 0.2$ mm is shown here)
- **The integral study provides a reference for quick assessment of beam impact on component in FCC-hh and its injector chain, in the case of less-severe beam loss.**

[**Y. Nie**, et al., ***Phys. Rev. Accel. Beams*** 2017; ***CERN-ACC-2017-0054***]

I. Importance of machine protection

Impact of one proton bunch on copper (melting/evaporation)!





3.3 TeV (FCC injection):

One bunch, bunch intensity 1.0×10^{11} p^+,

$\sigma_{x,y}$= 0.2 mm

Peak specific energy: 844 J/g > 674 J/g

50 TeV (FCC top energy):

One bunch, bunch intensity 1.0×10^{11} p^+,

$\sigma_{x,y}$= 0.2 mm

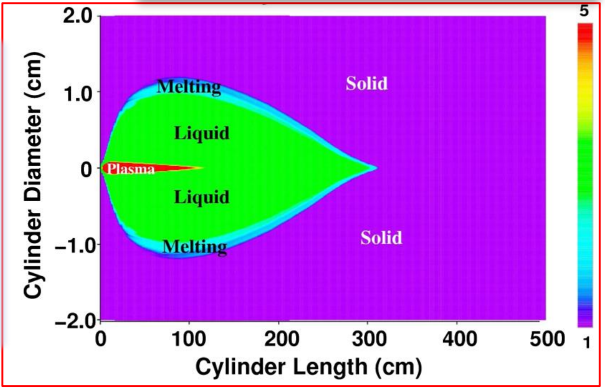
Peak specific energy: 17390 J/g > 6250 J/g >> 674 J/g

I. Importance of machine protection

i. FLUKA&BIG2, FCC beam in copper

[N.A. Tahir, et al, PRAB 2016]

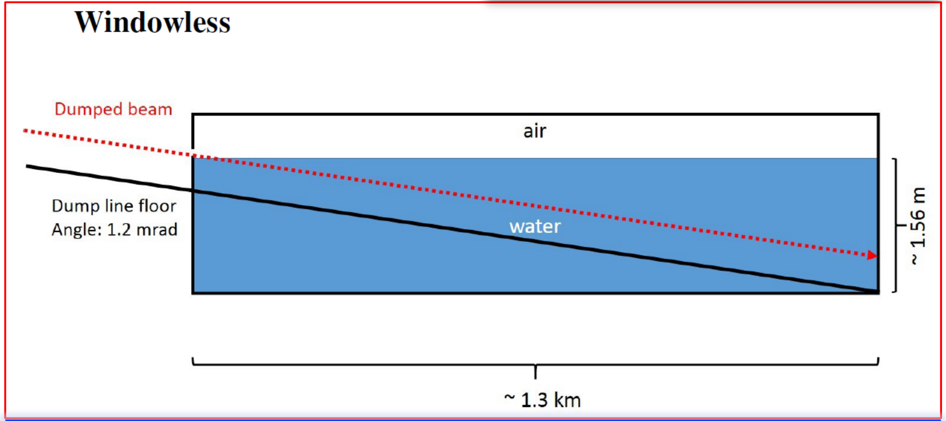
Physical state of the Cu target irradiated by 50 bunches (40TeV, 50×10^{11} protons, $\sigma_{x,y}$=0.2mm)



Hydrodynamic tunneling of 10600 bunches:
290 m @ 40 TeV; 350 m @ 50 TeV!

ii. FLUKA&BIG2, FCC water beam dump

[N.A. Tahir, FCC Week 2017]

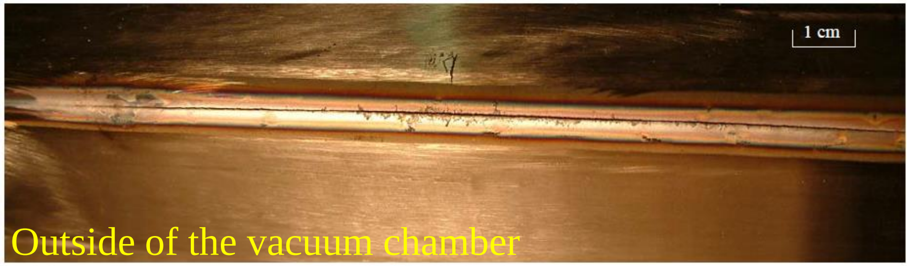


In simulation: 50TeV, 10600 bunches, $\sigma_{x,y}$=0.4mm→ 1.3km
How about σ_x=3mm & σ_y=1.3mm or other beam sizes?

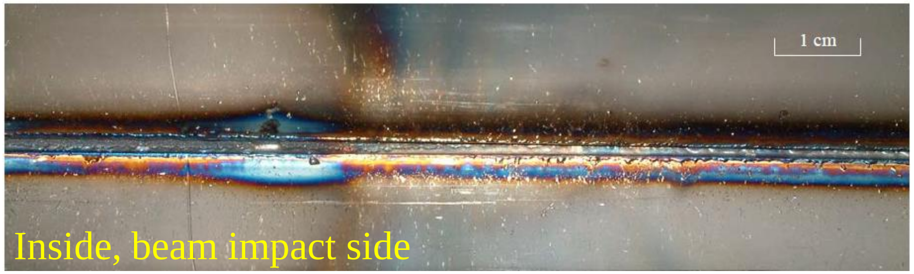
- In the worst case, the entire beam (or a large number of bunches) is lost at the same point, which could happen during injection/extraction → **hydrodynamic tunneling** due to the successive density drop along the target/beam axis.
  - LHC beam (7 TeV, 2808b, $\sigma_{x,y}$=0.2 mm) in copper: 35 m.
  - FCC beam (50 TeV, 10600b, $\sigma_{x,y}$=0.2 mm) in copper: 350 m.
- Now, hydrodynamic tunneling can alternatively be simulated coupling FLUKA & Autodyn.
  - Many other cases to be studied: FCC beam in graphite, water, …

I. Importance of machine protection

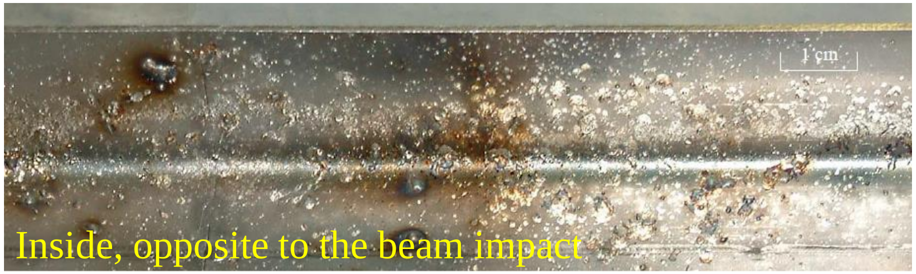
Severe beam accident not often, but did happen



Outside of the vacuum chamber



Inside, beam impact side



Inside, opposite to the beam impact

In 2004, the full SPS beam (288 bunches, 3.4×10^{13} protons, 450 GeV) was once extracted with wrong angle due to switch-off of the septum. Vacuum chamber (stainless steel) of one magnet was severely damaged. Both the vacuum chamber and the magnet had to be replaced. [B. Goddard, et al, ***AB-Note-2005-014 BT***]

HiRadMat experiment at SPS

Damage of a beam with an energy of 1.5 MJ [F. Burkart, et al, ***J. Appl. Phys.*** 2015]

II. General protection strategy for LHC and possibly for FCC-hh

- **Machine Protection: Methods and technologies to identify, mitigate, monitor, and manage the technical risks** associated with the operation of accelerators with high power beams or sub-systems with large stored energy, **if failure modes can result in substantial damage to accelerator systems or significance interruption of operations**.

[R. Schmidt, et al., ***New Journal of Physics*** 2006]

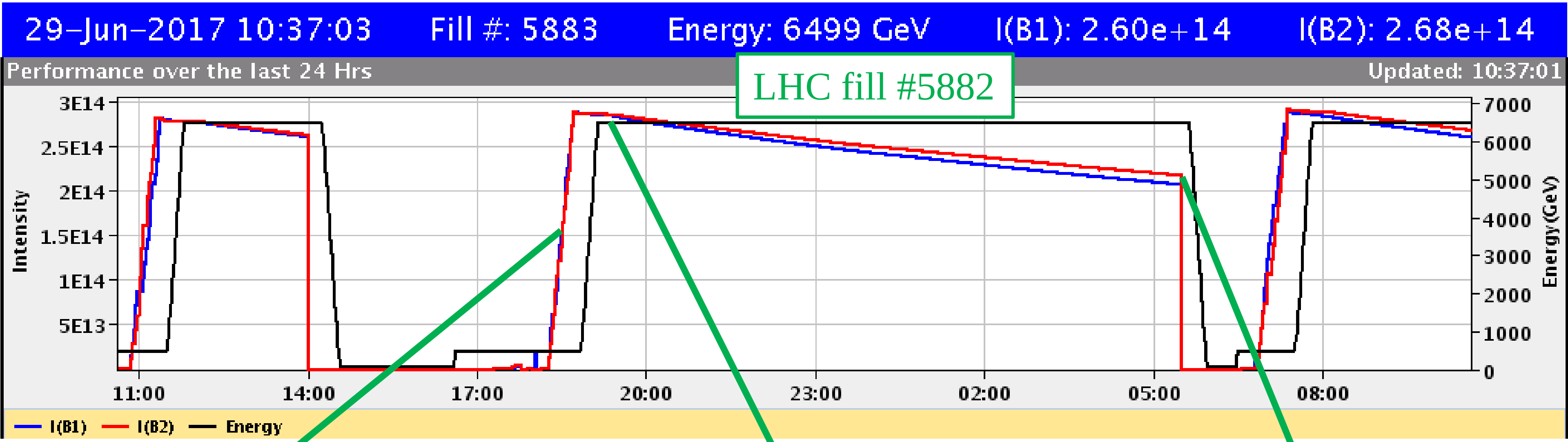
- Machine protection (≠ interlock system) includes an ensemble of hardware systems + software + commissioning and operational procedures + …

- Requirements for the protection systems:
  - **Protect equipment from damage, superconducting magnets from quench**
  - **Protect the beam (dump only when necessary → availability → luminosity)**
  - **Provide the evidence (diagnostics data in a failure, causes, functionalities)**

- We focus on beam-related machine protection:
  - **Analysis of failure modes leading to beam losses**
  - **Protection strategies based on failure scenarios (beam power matters a lot)**

II. General protection strategy for LHC and possibly for FCC-hh

Courtesy of R. Schmidt



29-Jun-2017 10:37:03 Fill #: 5883 Energy: 6499 GeV I(B1): 2.60e+14 I(B2): 2.68e+14

Performance over the last 24 Hrs Updated: 10:37:01

LHC fill #5882

Injection of sets of 144b, each set = 1.2 MJ:

- Transfer line collimators
- Injection absorbers (90° downstream of the injection kicker)
- Injection inhibit if necessary

Ramp 2556b from 450 GeV to 6.5 TeV and then circulate, one beam energy from 20 MJ to 300 MJ:

- Beam cleaning system (multi-stage collimators)
- Beam dump if failure

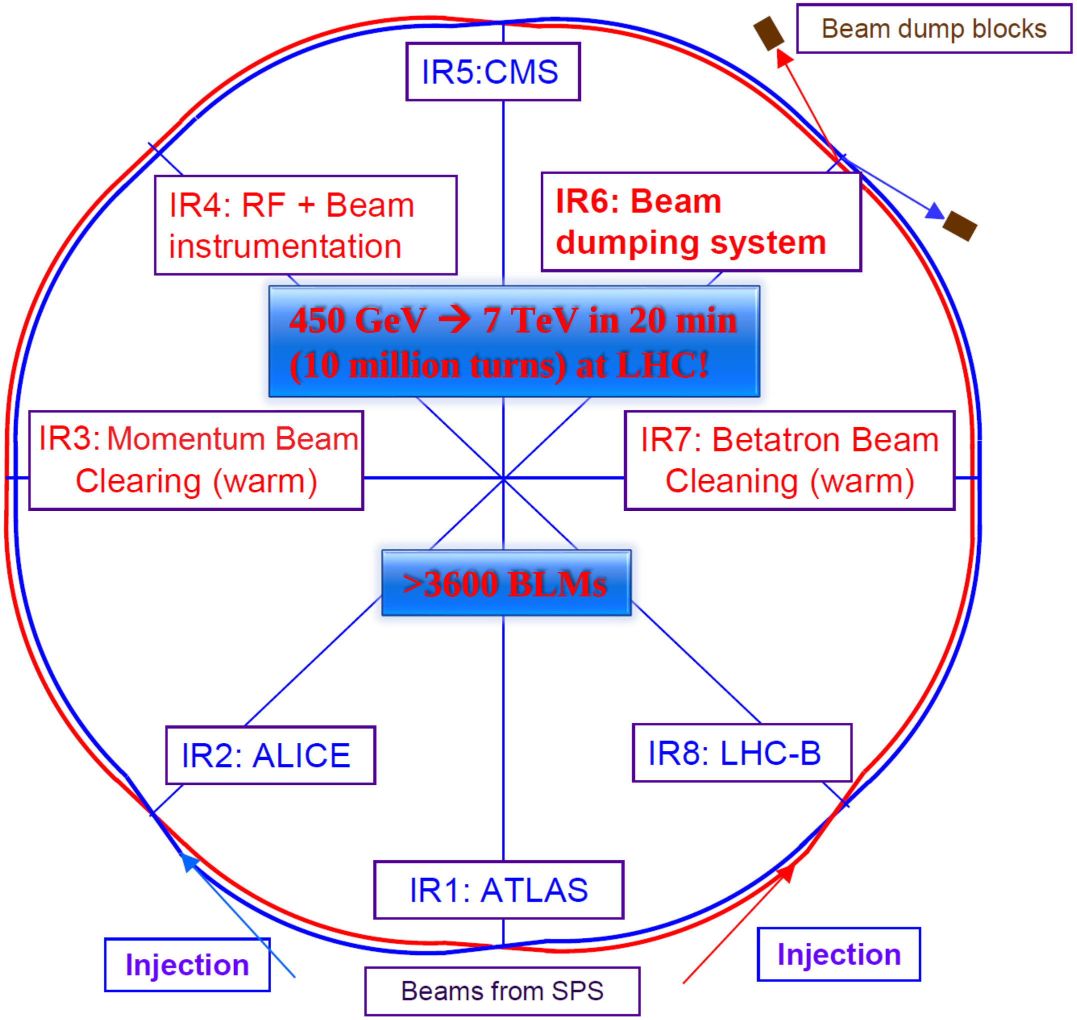
End of fill: what to do with the two beams of 300 MJ each?

- Extraction and dump
    - Synchronous
        - Graphite block (dilution)
    - Asynchronous
        - Passive absorbers + block

Interlock systems, beam monitors (BLMs, BPMs…), hardware detections (FMCM…), etc

More challenging for FCC (each nominal beam: 8500 MJ!)

II. General protection strategy for LHC and possibly for FCC-hh



Beam dump blocks

IR5:CMS

IR4: RF + Beam instrumentation

IR6: Beam dumping system

450 GeV → 7 TeV in 20 min (10 million turns) at LHC!

IR3: Momentum Beam Clearing (warm)

IR7: Betatron Beam Cleaning (warm)

>3600 BLMs

IR2: ALICE

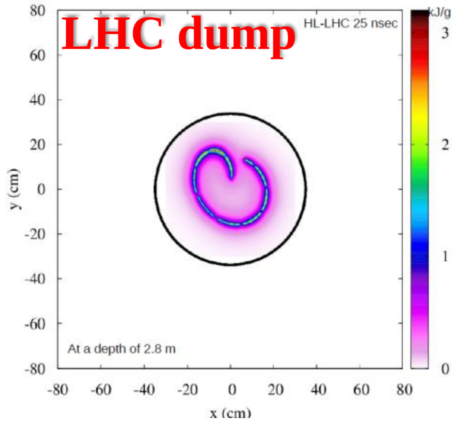
IR8: LHC-B

IR1: ATLAS

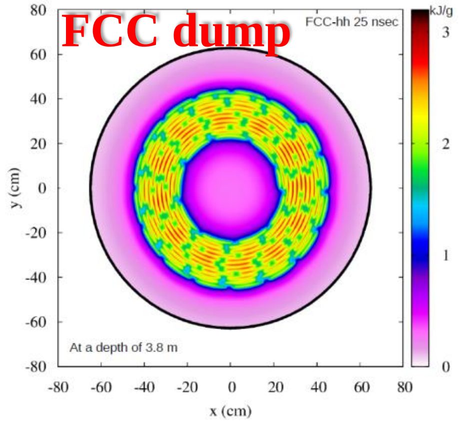
Injection

Injection

Beams from SPS



LHC dump



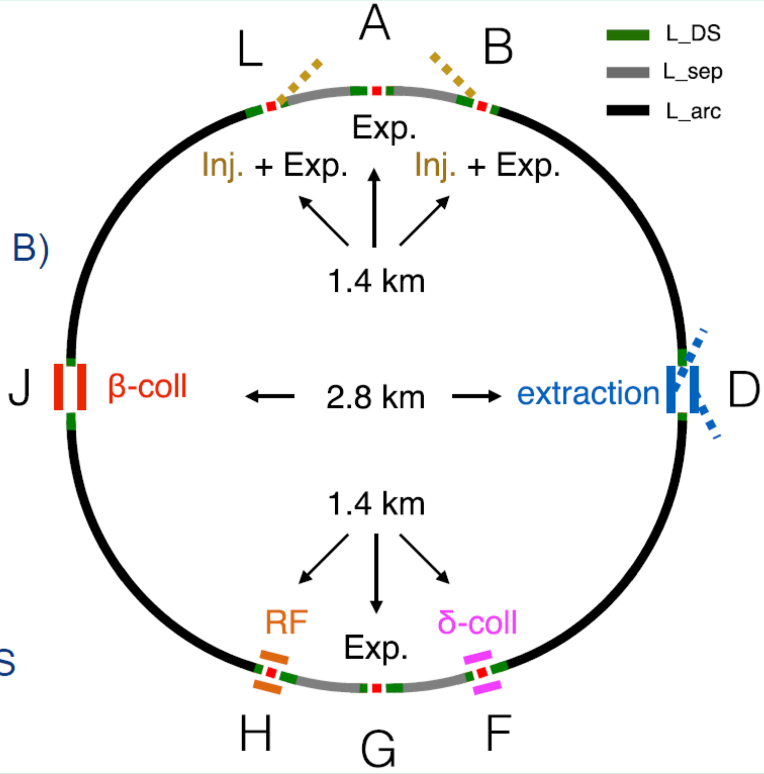
FCC dump

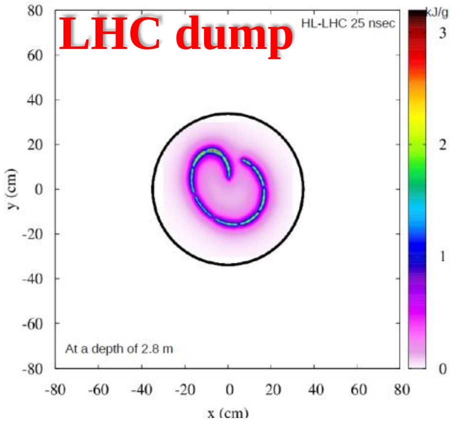
[R. Schmidt, ***JAS*** 2014; A. Lechner, ***FCC Week*** 2017; M. Benedikt, ***FCC Week*** 2017]

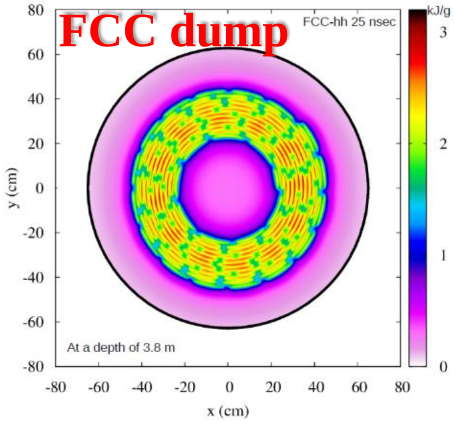
II. General protection strategy for LHC and possibly for FCC-hh

FCC-hh layout for CDR preparation

- Two high-luminosity experiments (A & G)
- Two other experiments combined with injection (L & B)
- Two collimation insertions
    - Betatron cleaning (J)
    - Momentum cleaning (F)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Compatible with LHC or SPS as injector





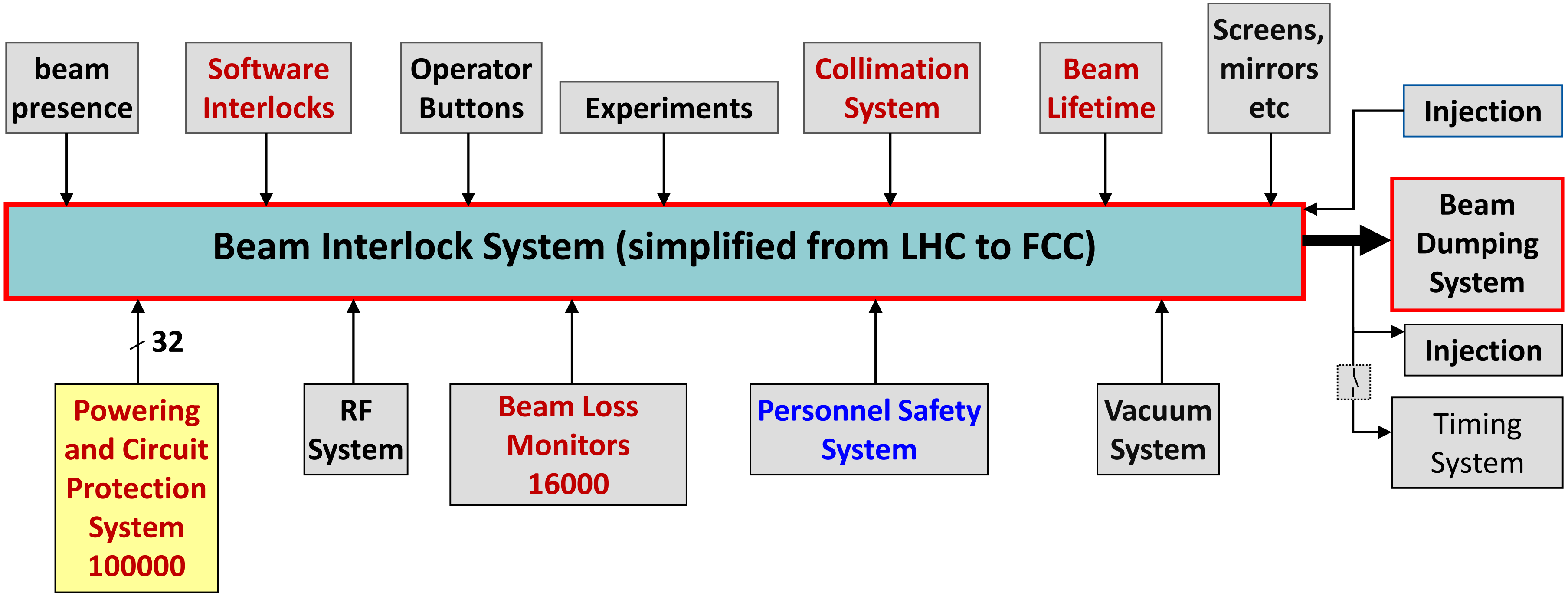


[R. Schmidt, ***JAS*** 2014; A. Lechner, ***FCC Week*** 2017; M. Benedikt, ***FCC Week*** 2017]

II. General protection strategy for LHC and possibly for FCC-hh

• Definition of aperture by collimators.	**Beam Cleaning System**
• Passive protection by beam absorbers and collimators for specific failure cases.	**Collimator and Beam Absorbers**
• Early detection of equipment failures generates dump request, possibly before beam is affected.	**Powering Interlocks** **Fast Magnet Current change Monitor**
• Active monitoring of the beams detects abnormal beam conditions and generates beam dump requests down to a single machine turn.	**Beam Loss Monitors** Other Beam Monitors
• Reliable operation of beam dumping system for dump requests or internal faults, safely extracting beams onto the external dump blocks.	**Beam Dumping System** **Stop beam at source**
• Reliable transmission of beam dump requests to beam dumping system. Active signal required for operation, absence of signal is considered as beam dump request and injection inhibit.	**Beam Interlock System**

II. General protection strategy for LHC and possibly for FCC-hh



beam presence

Software Interlocks

Operator Buttons

Experiments

Collimation System

Beam Lifetime

Screens, mirrors etc

Injection

Beam Interlock System (simplified from LHC to FCC)

Beam Dumping System

Injection

Timing System

32

Powering and Circuit Protection System 100000

RF System

Beam Loss Monitors 16000

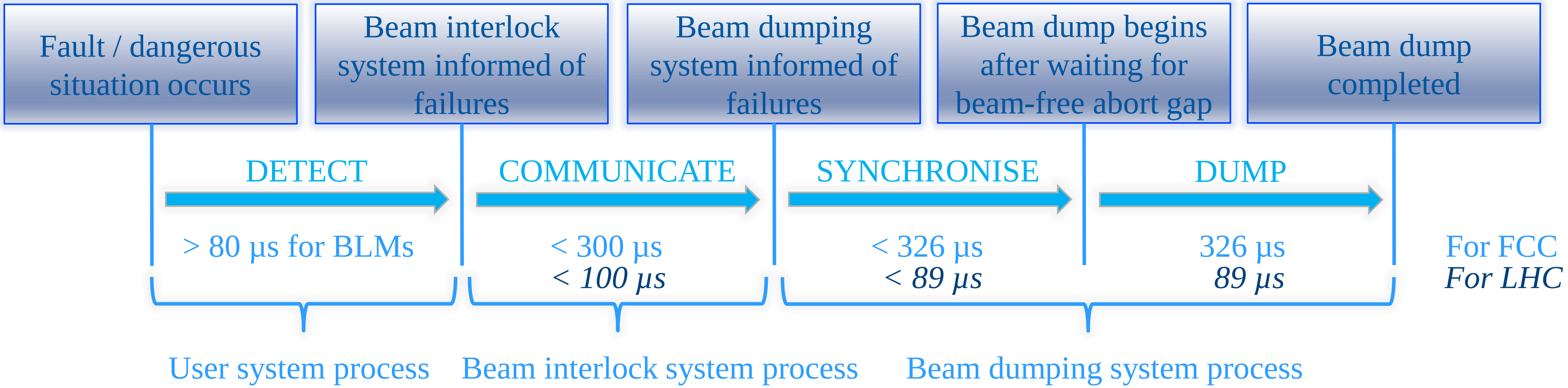
Personnel Safety System

Vacuum System

Scaling from LHC, the number of interlock channels will exceed 100000 for FCC!

[B. Todd, ***PhD Thesis*** 2006; A. Alonso, ***PhD Thesis*** 2009; R. Schmidt, ***FCC Week*** 2015]

III. Classification of FCC-hh failure mode and strategy



Fault / dangerous situation occurs

Beam interlock system informed of failures

Beam dumping system informed of failures

Beam dump begins after waiting for beam-free abort gap

Beam dump completed

DETECT: > 80 µs for BLMs

COMMUNICATE: < 300 µs; *< 100 µs*

SYNCHRONISE: < 326 µs; *< 89 µs*

DUMP: 326 µs; *89 µs*

For FCC

For LHC

User system process

Beam interlock system process

Beam dumping system process

- LHC Machine Protection System (MPS)
  - After failure detection, about **3** turns' time is needed to dump the full beam completely.

- **For FCC, the time needed is most likely similar in terms of 'number of turns'**
  - **which is about 1 ms (1 gap, 1 dump)**
  - **but depends on how many beam-free abort gaps & beam dump systems we have.**
  - **2 gaps→ -0.5 turn; 2 dumps→ -0.625 turn; 2 gaps & 2 dumps→ -1.125 turns**

III. Classification of FCC-hh failure mode and strategy

Beam lifetime	Beam power into environment		Scenario	Strategy & Remark
	LHC	FCC		
100 h	1 kW	23 kW	Optimum operating conditions	(Possible) upgrade of the collimation system after some years of operating experience
10 h	10 kW	236 kW	Acceptable operating conditions (expected during early operation)	Operation acceptable, collimators must absorb large fraction of beam energy
12 min	500 kW	11806 kW	Particular operating conditions (during change of optics, tuning, collimator aperture setting, etc)	Operation only possible for short time (~ 10 seconds), collimators must be very efficient
1 s	362 MW	8500 MW	Fast beam loss (standard equipment failures)	Detection of failure, beam must be dumped rapidly
A few ms (multi turns)	~100 GW	~ TW	**Very fast beam loss** (fast equipment failures, e.g., magnet powering failures or quenches)	Detection of hardware failures or beam losses, beam dump as fast as possible
1 turn	4 TW	26 TW	Single-passage beam loss (failures at injection or during beam dump, potential damage of equipment)	Beam dump not possible, passive protection relies on collimators, absorbers (sacrificial materials) (TE-ABT-BTP)

III. Classification of FCC-hh failure mode and strategy

- **Powering failure (power supply trips and voltage goes to zero) → Exponential-decay:**
  - **τ is typically some seconds for normal conducting magnets**
  - **It is much longer (can be up to hours) for superconducting magnets**
- **Quench → approximately Gaussian-decay:**
  - **Typical time constant σ_t for a quench is >100 ms.**

$$\Delta x = \frac{\sqrt{\beta_{\text{magnet}} \cdot \beta_{\text{test}}}}{2\sin(\pi Q_x)} \cdot \left(\alpha_0 \cdot \frac{\Delta B_{\text{error}}}{B_0}\right)$$

$$\Delta Q = \frac{\beta_{\text{magnet}} \cdot l \cdot \Delta k}{4\pi}$$

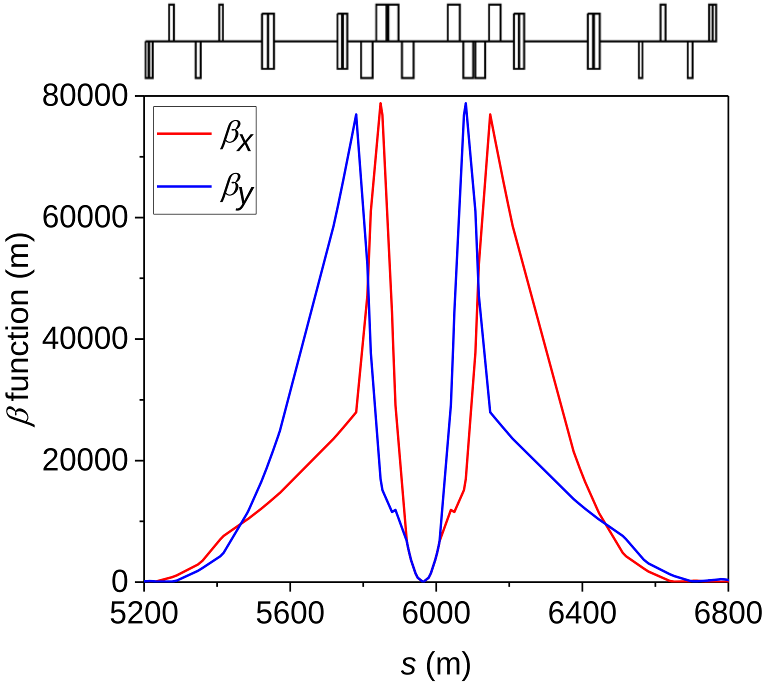
Detail in:
[**Y. Nie**, et al., ***IPAC***-2017]

Beam is influenced faster if the failed magnet is located where the beta function is high, or the magnet has fast field decay!

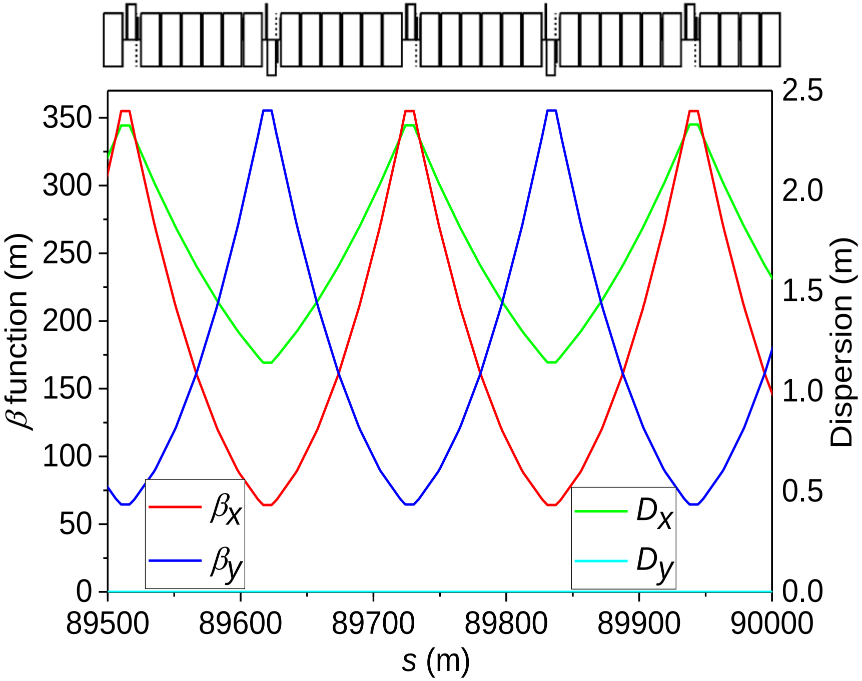
The minimum time constant of field decay can be determined such that beam position is displaced less than 1.5 σ and tune change is less than 0.01, within 2 ms after magnet failure based on analytical estimations.

III. Classification of FCC-hh failure mode and strategy

Separation dipole ‘D1’
low-β triplet quadrupole



Main dipole
Main quadrupole



Interaction region IRA:

- IPA at $s = 5964$ m
- If $\boldsymbol{\beta^*}$ **= 30 cm**, $\sigma_{x,y}$ will be 3.5 μm
- The highest beta function is almost 80 km
- **Optics version May 2016, fcc_hh_0300**

For each FODO cell in the arc:

- 213.89 m long, phase advance 90°
- 12 dipoles, 15.92 T
- deflection angle 12×1.366 mrad

III. Classification of FCC-hh failure mode and strategy

Name	Failure scenario	Magnet length	Nominal field	Nominal deflection or focusing strength	Beta-function at magnet	Time constant requirement of field decay	Comment
Separation dipole 'D1' in IRA / IRG	Powering failure of all the 4 MBXA magnets	12.5 m	4.27 T	0.32 mrad	25 km (left) 61 km (right)	**> 33 s**	Less critical (if SC)
Separation dipole 'D1' in IRA / IRG	Quench of 1 magnet	12.5 m	4.27 T	0.32 mrad	61 km (right)	**> 100 ms**	Need to be careful
Low-β triplet quadrupoles	Quench of 1 magnet (MQXC.3RA)	30.81 m	86 T/m	5.14×10^{-4} m^{-2}	77 km	**> 139 ms**	Need to be careful
Main dipole	Quench of 1 magnet	14.3 m	15.92 T	1.366 mrad	335 m (max.)	**> 55 ms**	Less critical
Main quadrupole	Quench of 1 magnet	6.29 m	357 T/m	2.14×10^{-3} m^{-2}	350 m (max.)	**> 8.6 ms**	Less critical
Warm dipole in collimation insertion	*Powering failure of MBW.A6R3.B1*	*9.09 m*	*1.45 T*	*0.079 mrad*	*718 m*	***> 270 ms***	*Less critical*
Warm quadrupole in collimation insertion	*Powering failure of MQWA.D4R3.B1*	*8.31 m*	*29 T/m*	*1.74×10^{-4} m^{-2}*	*1068 m*	***> 23 ms***	*Less critical*
Combined magnet failure	*More than one magnet fails simultaneously*						*Risk=Consequences* Probability (low); $\Delta\Phi$*
Transverse damper	*Beam deflection*						*Can result in very fast losses?*
Orbit corrector	*Beam deflection*						
RF system / crab cavities	*Debunching / Rotation*						
Vacuum valves / screens / etc	*Aperture reduction / beam pipe obstruction*						
UFOs / vacuum leak / wire scanners / etc	*Beam scattering*						

being completed and finalized!

[**Y. Nie**, et al., ***IPAC***-2017/***FCC Week*** 2017]

IV. Specific requirement of FCC-hh

Fast and very fast beam losses → how to save time?

Detection:

- **Detect failure at hardware level (FMCM, …) and dump before beam is influenced**
- **Detect initial consequences on beam (beam orbit movement monitor, fast beam loss monitor, fast beam current change monitor)**
- **Fast BLM: ns-resolution at aperture limitations (Diamond/silicon detectors); Cherenkov fibre**

Communication:

- **During transmission of the dump request (from interlock system to dump system), use a straight path instead of along the arc (?)**

Synchronization:

- **More than one abort gap (the second gap can save 0.5 turn's time)**
- **Loss of luminosity**

Dump:

- **More than one dump system (the second dump can save 0.6 turn's time)**
- **Increase too much cost?**

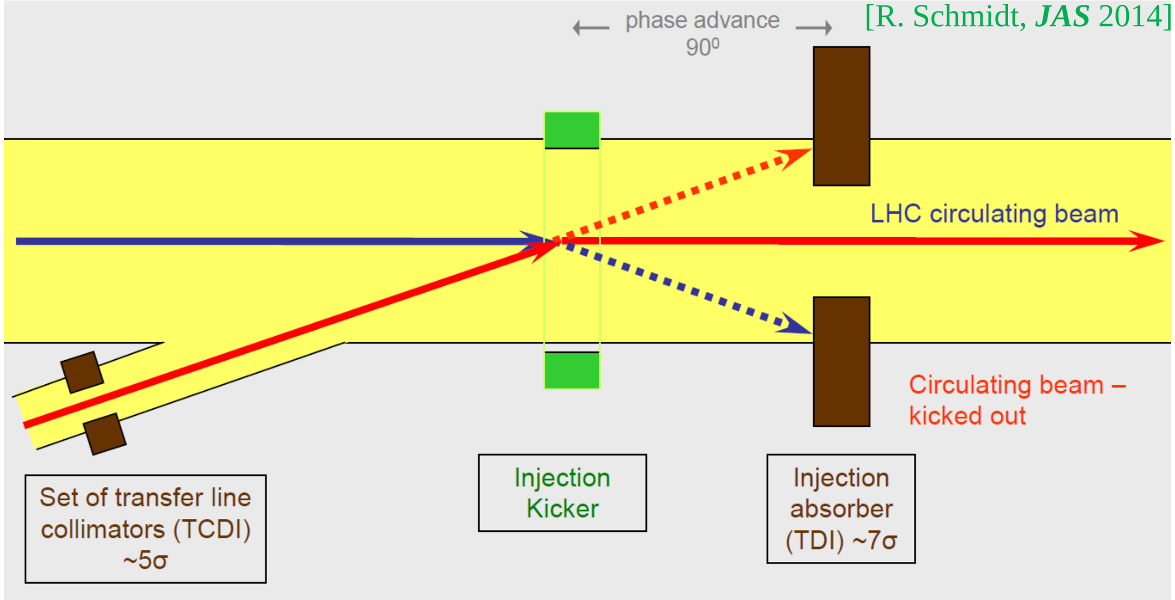
IV. Specific requirement of FCC-hh

Fast and very fast beam losses → how to protect accelerator from beam?/others

- Use beam intercepting devices made of advanced materials:
  - **50 TeV proton is much more destructive than 7 TeV one**
  - **New materials for collimators, absorbers, windows and so on?**
  - **E-Lens**
- Avoid beam induced magnet quenches
- Slow down influence on beam during equipment failure:
  - **For critical warm magnets regarding powering failure, connecting them with a superconducting solenoid in series would increase the time constant for orbit changes and relax the parameters for the protection system.**
  - **How about the time constant of a quench?**
- Reliable operation of monitoring, interlock and dumping system to make sure the beam can be dumped in time onto the beam dump block which is the only device that can withstand the entire beam energy.

IV. Specific requirement of FCC-hh

Single-passage beam loss (to be safe during injection)



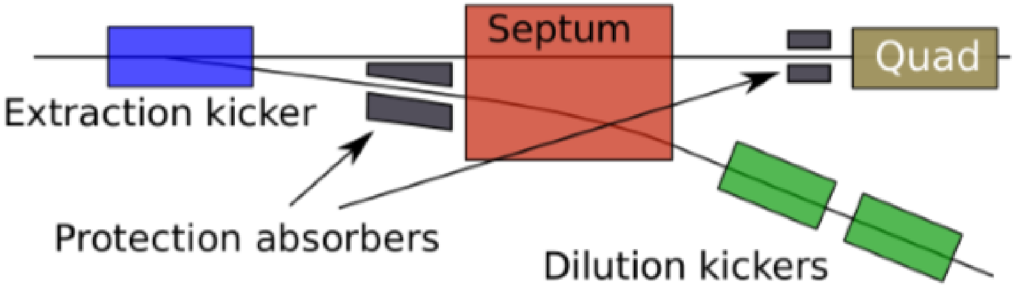
As designed for LHC, injection absorbers help in case of kicker malfunction for injected / circulating beam, however, for FCC:

Injection pattern (in sets of 3.3 TeV bunches…) ⟷ **Injection absorber (limit of material, geometry…)**

Absorber design limits the number of bunches that can be injected at once to be 80 (W. Bartmann)

IV. Specific requirement of FCC-hh

Single-passage beam loss (to be safe during extraction)



Figures courtesy of F. Burkart and E. Renner

- At LHC, in case of asynchronous dump, TCDS and TCDQ (single-sided graphite absorber) will protect the septum and quadrupole.
- For FCC, one may install absorbers from two sides in order to avoid a large orbit offset that would compromise the TCDQ functionality.
  - **Spontaneous trigger of extraction kicker → asynchronous beam dump (300 kickers, 1.15 μs rise time)**

[W. Bartmann, F. Burkart, et al., ***FCC Week 2017***]

IV. Specific requirement of FCC-hh

Failure in the beam dumping system

- Dilution kicker failure (e.g., 80% working point) → beam impact on graphite block (hydrodynamic tunneling might be significant, radiation degradation)
- Water beam dump block without dilution → larger beam size (~*cm*) to allow the existence of a window that can survive after all bunches passing through it
  - **Coupling simulation of FLUKA and a hydrocode (BIG2, Autodyn, …)**
- If the beam dumping system is unavailable when a beam dump is requested:
  - **To drive a sacrificial dump block in the beam (to be replaced after irradiated by the entire beam)**
  - **Massive absorbers around the beam (outside the collimators) that protect the accelerator (but not the collimators).** [J. Uythoven, et al., ***EPAC***-2004]
  - **Very challenging design for such destructive beams…**
- If the beam dumping system becomes unavailable during stable beam operation:
  - **“Dump” the beam in another safe way, e.g., slow scrape using collimators**

V. Summary

- FCC-hh machine protection is very **challenging**. Basic **concept** of beam-related machine protection has been studied to the most possible extent based on current knowledge and LHC experience. **Specific requirements** have been pointed out.

- A preliminary list of **very fast failure modes** has been made. The parameters are to be finalized referring the lattice design (e.g., D1 from "SC" to "NC"?). More items are being implemented (warm magnets in collimation insertions, RF, UFO…). **Time constant requirement** of magnet field decay has been proposed.

- Up to **50 TeV** proton beam is potentially destructive in case of uncontrolled energy release. Protection systems must be very reliable. Of great importance is the study on **beam-matter interactions**. Further FLUKA simulations (coupling a hydrocode or not) are crucial.

- Preparation of the FCC **CDR** (in chapter: *FCC-hh machine protection?*) will start soon on the basis of this summary and its modified version.

CERN

www.cern.ch