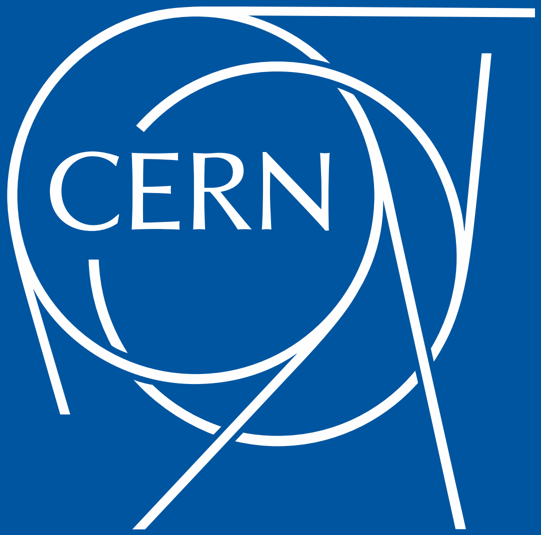
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Overall machine protection

(in session FCC-hh INJ: Collider beam transfer and injector II)

Yuancun NIE
CERN, TE-MPE

Acknowledgments:
R. Schmidt, D. Wollmann, J. Uythoven, E. Renner, V. Raginel, A. Verweij, R. Denz, M. Zerlauth, A. Siemko, C. Zamantzas, R. Bruce, C. Fichera, F. Carra, A. Bertarelli, N.A. Tahir, et al.

Another talk: Beam impact and machine protection challenges
(12th April, in session Special technologies: Machine Protection, Circuits and Powering)
Poster: FCC machine protection requirements and architecture

Outline

I. Introduction

II. Beam impact up to 50 TeV

III. Machine protection architecture

IV. Specific requirements and strategies

V. Summary and conclusions

I. Introduction

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

- Beam-related machine protection (this talk)

- Considerations for magnet protection:
  - Powering of magnet circuits

    Multiple circuits per arc and/or energy extractors distributed along the tunnel

    [see talk: Marco Prioli, Circuit layout and protection, 12th April, Special Technologies]

  - Energy extraction and quench protection

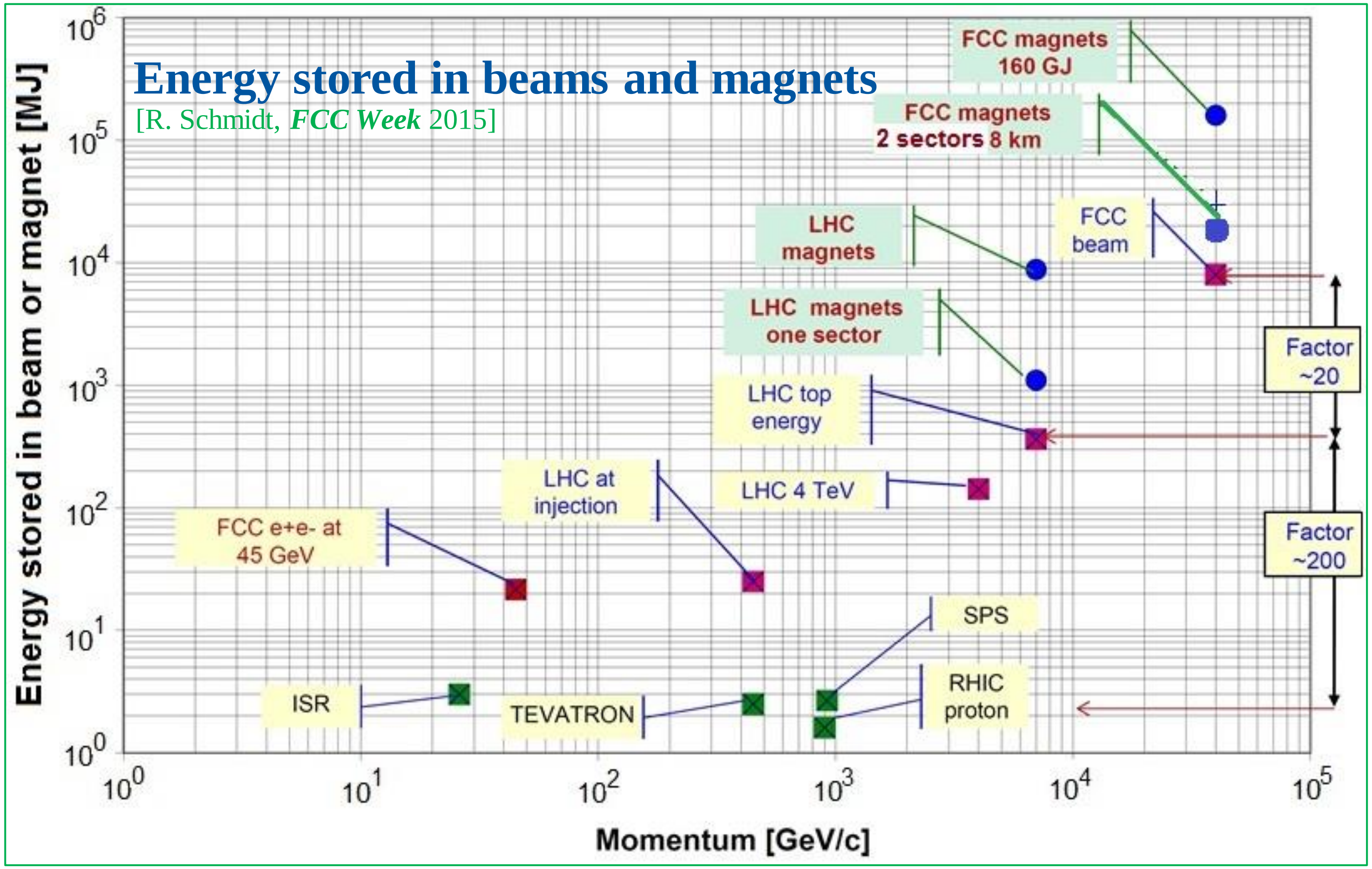
    Two distinct methods are proposed for the extraction of energy from the main dipole circuits: discharging the energy into passive resistors, and active energy extraction and recuperation.

    The core strategy for the quench detection system is:

    the concept of a centralized data processing and quench detection.

    [see talks: Tomasz Podzorny, Quench detection system for the FCC era; Vasilios Karaventzas, Proposal on a novel energy extraction system for superconducting magnet chains, 12th April, Special Technologies]

II. Beam impact up to 50 TeV: unprecedented energies



Energy stored in beams and magnets

[R. Schmidt, *FCC Week* 2015]

$$\sigma_{x,y} = \sqrt{\frac{\beta_b \varepsilon_{\mathrm{n,rms}}}{\beta\gamma}}$$

Parameters	LHC (nominal)	FCC-hh (baseline)
Energy of one beam (MJ)	362	**8320 (melt 10 *t* copper)**
Typical beam-energy density (GJ/mm^2)	1	**200 (potentially more destructive)**
Quench limit of dipole magnets (p/m/s)	7.8×10^6	**0.5×10^6 (protection challenge)**

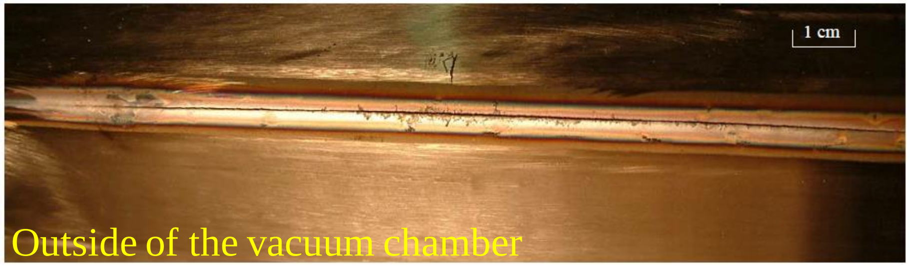
II. Beam impact up to 50 TeV: beam accidents

Beam induced damages at particle accelerators worldwide:

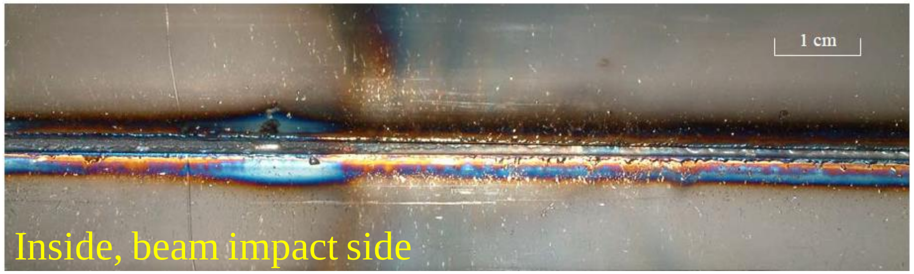
- Damage of SPS-LHC transfer line
- Damage of collimators at Tevatron
- Damage at RHIC (MPC detector)
- Damage of superconducting cavities at SNS
- Damage of radioactive target at J-PARC
- Damage of vacuum chamber at CERN LINAC 4 (few W beam power)
- Damage at XFEL (electron beam)

➢ And many more accidents (not published)

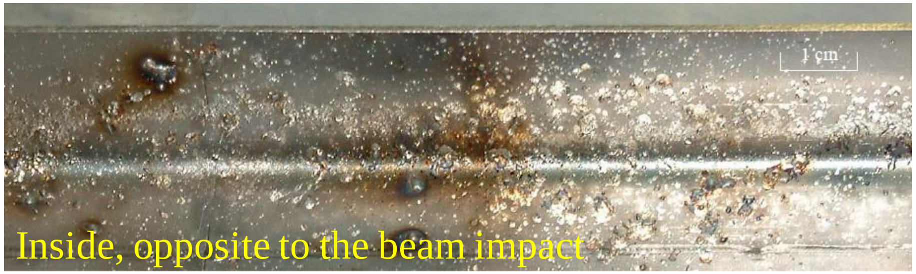
[R. Schmidt, *CERN TE-MPE-PE meeting* 2017]



Outside of the vacuum chamber



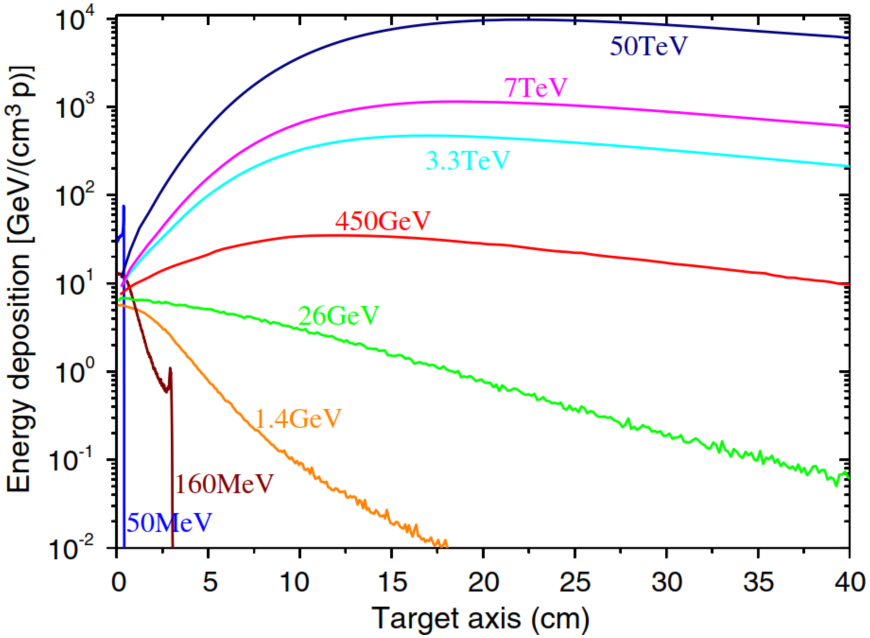
Inside, beam impact side

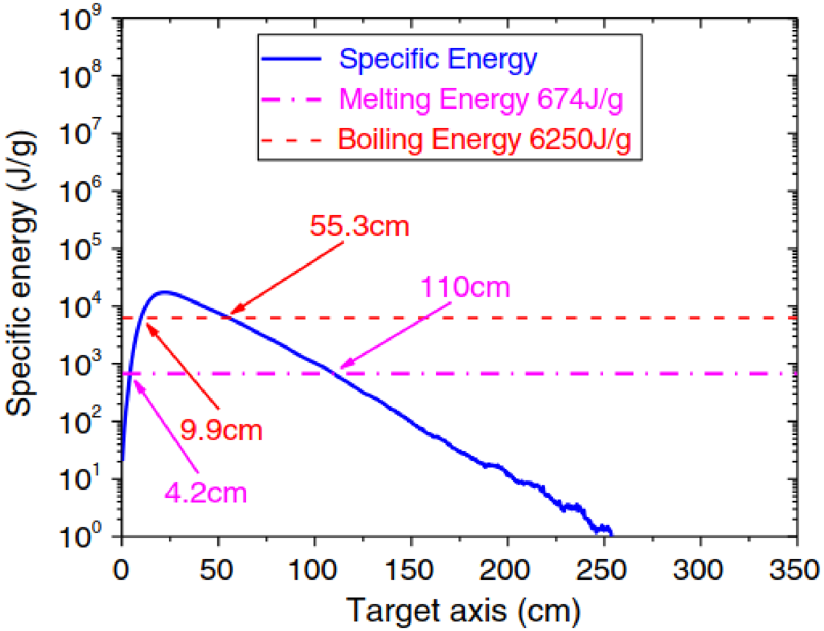


Inside, opposite to the beam impact

In 2004, the full SPS beam (288 bunches, 3.4×10^{13} protons, 450 GeV) was once extracted with wrong angle due to the switching-off 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***]

II. Beam impact up to 50 TeV: energy deposition





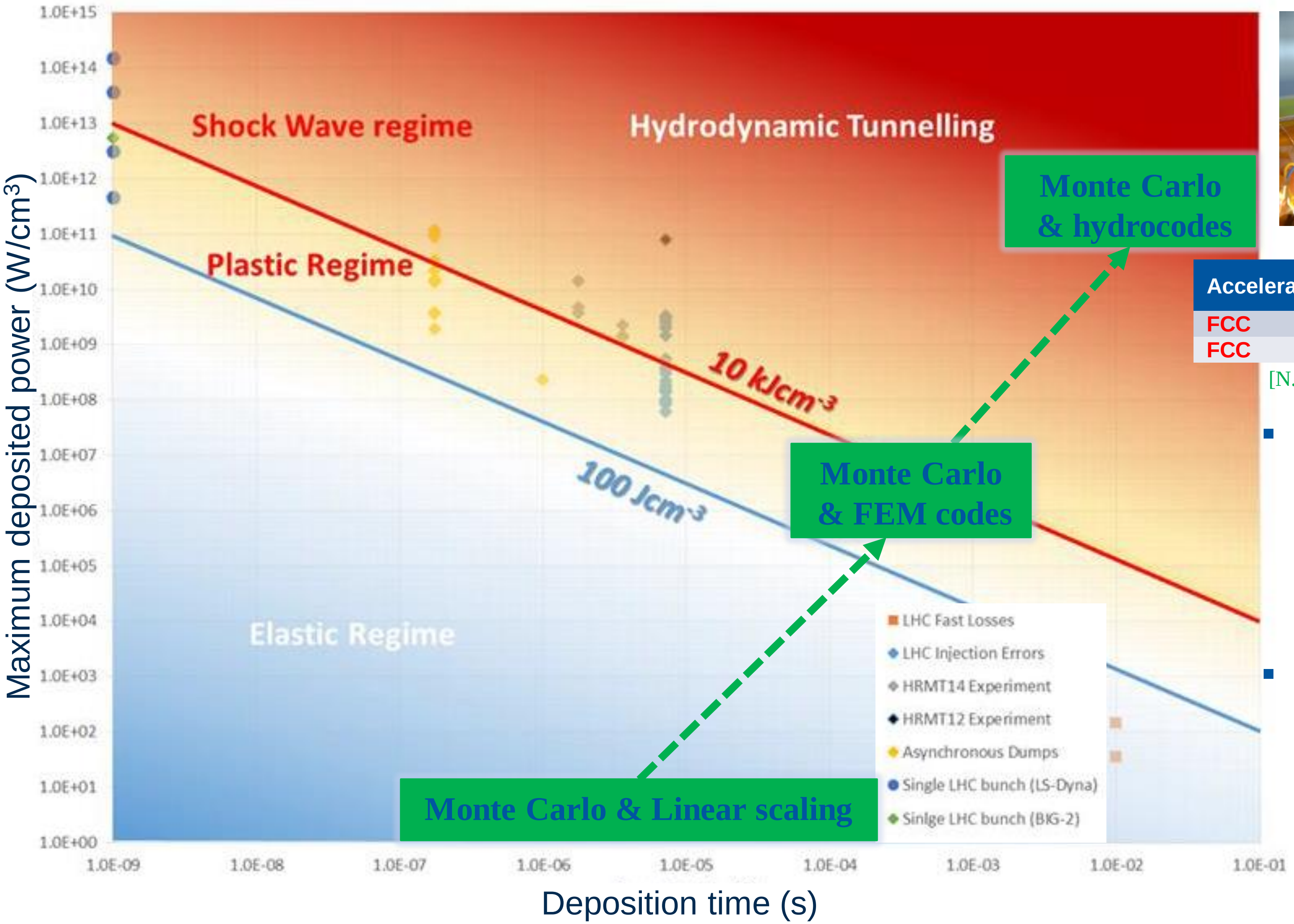
Energy deposition along cylinder axis of copper target ($\sigma_{x,y}$ = 0.2 mm)

Specific energy of one nominal bunch (50 TeV, 1.0×10^{11} p, $\sigma_{x,y}$ = 0.2 mm)
Peak specific energy:
17390 J/g > > 6250 J/g (boiling energy)

- @ 50 TeV, scaling linearly from energy deposition per proton, one nominal bunch has the potential to evaporate copper at the location of the maximum energy deposition!

[Y. Nie, et al., ***Physical Review Accelerators and Beams*** 2017]

II. Beam impact up to 50 TeV: different regimes



HiRadMat-12 experiment at SPS

[F. Burkart, et al, ***J. Appl. Phys.*** 2015]

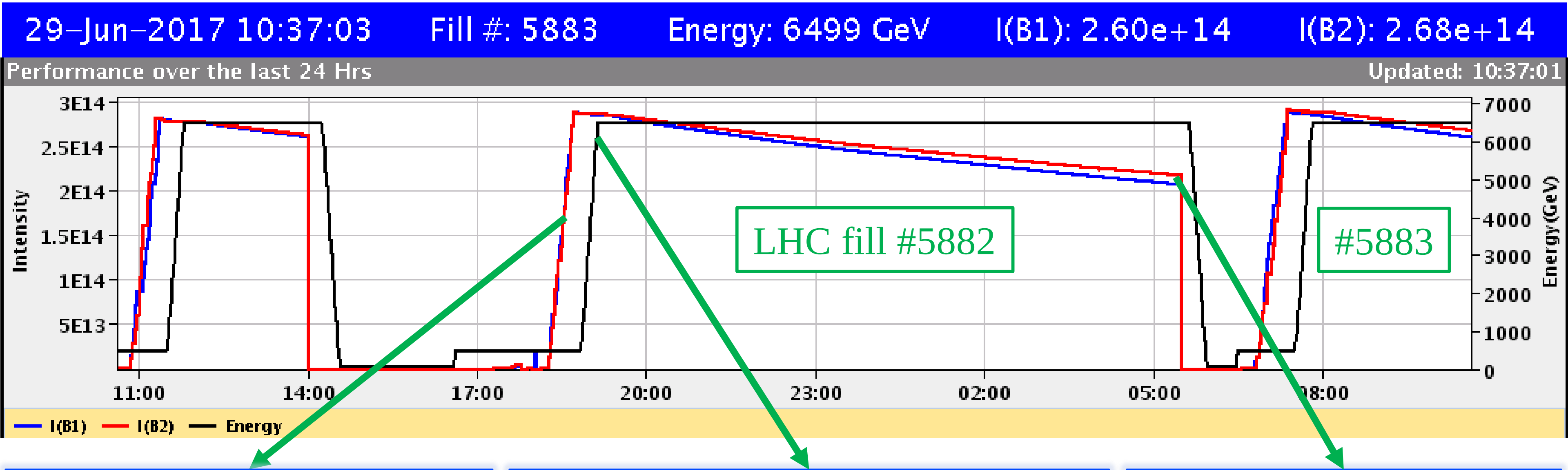
Accelerator	RMS beam size	Target material	Tunneling range
FCC	0.2 mm	copper	350 m
FCC	0.4 mm	water	1300 m

[N.A. Tahir, et al, ***PRAB*** 2016; ***FCC Week*** 2017]

- Accelerator components are usually designed to work in the **elastic regime**. → Linear scaling from energy deposition per proton is practical.
- Hydrodynamic tunneling is the **extreme situation** which would be likely if a large number of bunches was lost at the same place. (“Risk” = Probability * Consequences)

Mechanical responses in different regimes [A. Bertarelli, ***Joint Accelerator School*** 2014]

III. Machine protection architecture: protection through operational cycle



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

Injection of trains of 144b, each set = 1.2 MJ: (FCC: 80b, 4.2MJ)

- 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, energy of one beam from 20 MJ to 300 MJ: (FCC: 10400b, 3.3TeV to 50TeV, 550MJ to 8320MJ)

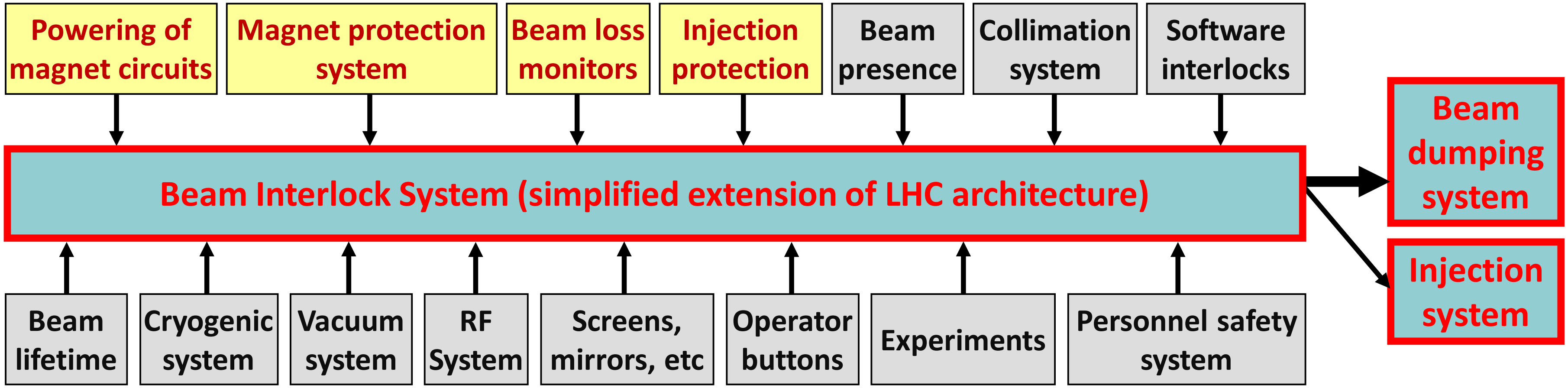
- Continuous cleaning (multi-stage collimators)
- Beam dump in case of any failure in the machine

End of fill: what to do with the two beams of 300 MJ each? (FCC: 8320MJ)

- Extraction and dump
  - Synchronous (Graphite block)
  - Asynchronous (additional absorbers)

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

III. Machine protection architecture: Beam Interlock System



Powering of magnet circuits

Magnet protection system

Beam loss monitors

Injection protection

Beam presence

Collimation system

Software interlocks

Beam Interlock System (simplified extension of LHC architecture)

Beam dumping system

Injection system

Beam lifetime

Cryogenic system

Vacuum system

RF System

Screens, mirrors, etc

Operator buttons

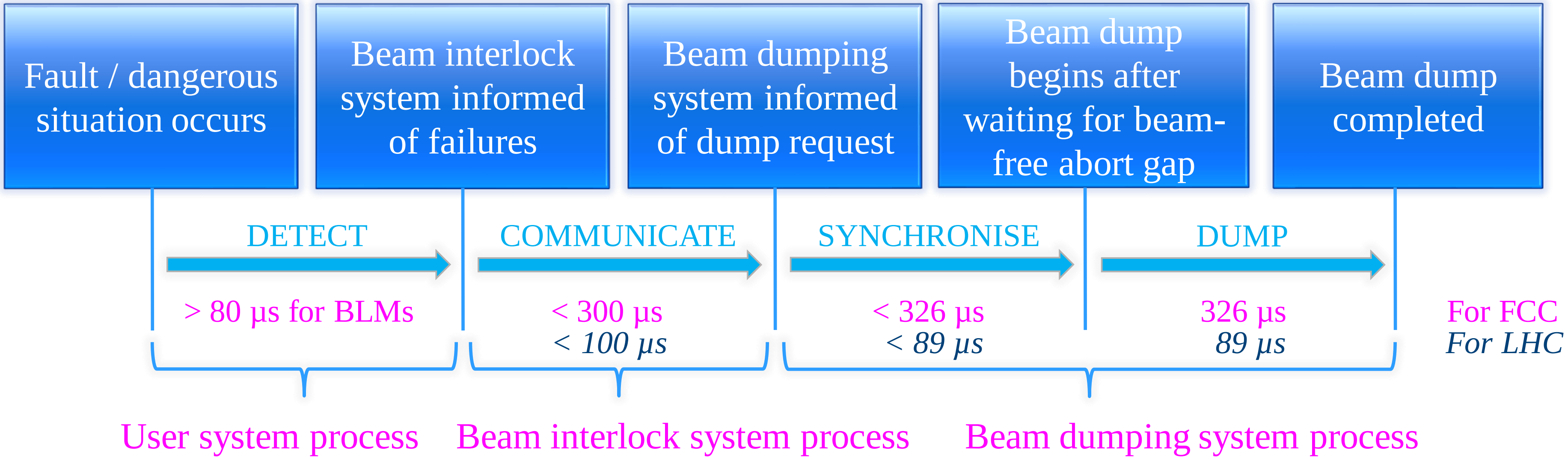
Experiments

Personnel safety system

- Scaling from LHC, the number of elements that should be capable of triggering a beam dump for the FCC-hh is estimated to exceed 100 000!

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

III. Machine protection architecture: reaction time of the system



Fault / dangerous situation occurs

Beam interlock system informed of failures

Beam dumping system informed of dump request

Beam dump begins after waiting for beam-free abort gap

Beam dump completed

DETECT	COMMUNICATE	SYNCHRONISE	DUMP	
> 80 µs for BLMs	< 300 µs	< 326 µs	326 µs	For FCC
	< 100 µs	*< 89 µs*	*89 µs*	*For LHC*

User system process

Beam interlock system process

Beam dumping system process

- With a machine protection system similar to the LHC, the FCC would require up to three turns' to dump the beam synchronously after the detection of a failure, i.e. ~1 ms.

IV. Specific requirements and strategies: magnet failures

- **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**

$$\Delta B_{\text{error}}(t) = B_0\left(1-e^{-t/\tau}\right)$$

- **Quench → approximately Gaussian-decay:**

$$\Delta B_{error}(t) = B_0\left(1-e^{-\frac{t^2}{2\sigma_t^2}}\right)$$

  - **Typical time constant σ_t for a quench is >100 ms.**

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

α_0 is nominal deflecting angle

where $\cos(\Delta\psi+\pi Q_x)\sim 0.83$ if $\Delta\psi = 90°$

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

Details 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 up to 1.5 σ or tune change is up to 0.01, within 2 ms after magnet failure.

IV. Specific requirements and strategies: failure modes

Magnet Name	Failure Scenario	Time Constant
Separation dipole 'D1' in IRA / IRG	**Powering failure of all the 4 MBXA magnets**	***> 20 s***
Low-β triplet quadrupoles	**Quench of 1 magnet (MQXC.3RA)**	***> 140 ms***
Main dipole	Quench of 1 magnet	*> 55 ms*
Main quadrupole	Quench of 1 magnet	*> 9 ms*
Normal conducting dipole in collimation insertion	Powering failure of MBW.A6R3.B1	*> 270 ms*
Normal conducting quadrupole in collimation insertion	Powering failure of MQWA.D4R3.B1	*> 23 ms*

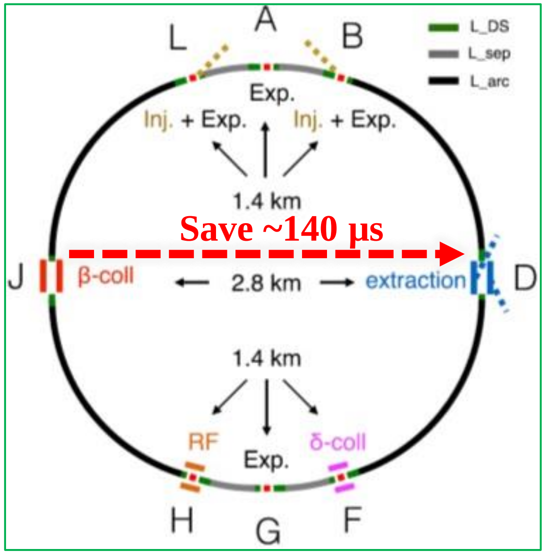
- **Powering failure or quench of magnets**
  - A beam displacement of up to 1.5 σ during 2 ms is just acceptable. If it is faster, the damage limit of collimators might be exceeded before the beam is dumped.
- **Phase/voltage jump of crab cavities**
- **Unidentified falling objects (UFOs) causing beam instability (e.g. in the LHC 16L2 events)**
- …

[Y. Nie, et al., ***IPAC*** 2017;
Y. Nie, et al., Concept of beam-related machine protection for the FCC-hh, *to be published*]

IV. Specific requirements and strategies: make reaction time shorter

Requirements for the machine protection system:

- **Reaction time (around 1 ms if extending the LHC design)**
  - **Shorten detection time** of the failure from 80 µs to 1 µs by using faster detectors (e.g. diamond BLMs)
  - **Ensure minimum time for signal transmission** from BLMs at collimators to beam dump
  - **Shorten synchronization time** by using multiple beam-free abort gaps



- **Reliability**
  - The likelihood of a missed dump should not exceed one occurrence in a 1000 year → redundant design!
- **Availability**
  - Possibly introduce a voting logic on redundant interlock channels to balance availability and reliability

IV. Specific requirements and strategies: other potential strategies

- **Slow down influence on beam during equipment failures:**
  - For critical normal conducting magnets, with respect to the powering failure, ensure the required time constant ($\tau = L/R$) during the design of powering circuits.
- **Avoid beam (e.g. UFO) induced quenches by detecting beam losses inside superconducting magnets**
  - Fast BLMs (e.g. diamond BLMs) behind the beam screens distributed over the magnets
  - A continuous optical fibre close to the beam aperture to detect beam losses
  - A superconducting cable with lower quench threshold than that of the magnets, in the cryostat (close to the beam aperture)
- **Hollow electron lens** [G. Stancari, et al., ***PRL*** 2011]
  - From the experience of LHC, transverse beam halo population is more than that indicated by a Gaussian distribution. (5% in tails above 3.5 σ, not 0.22% if Gaussian) [M. Fitterer, et al., ***IPAC*** 2017]
  - To have more margin avoiding damage to accelerator components before the beam is dumped, the halo population could be reduced via an electron lens.
  - Meanwhile, few witness bunches with uncleaned/less-cleaned halo would provide early detection of abnormal beam losses.

V. Summary and Conclusions

- Challenges of machine protection for FCC (especially for FCC-hh) arise from its unprecedented energies stored in the magnets and the beams.
- FCC will profit from successful LHC experience in machine protection. LHC has been operating since nearly 10 years without beam accidents.
- However, novel strategies have been being proposed for specific challenges:
  - reducing the reaction time by using fast diamond BLMs, a shorter traveling path of the dump request and multiple abort gaps
  - controlling the time constant of field decay in critical magnet failures
  - avoiding beam/UFO induced quenches by detecting beam losses inside the cryostat
  - cleaning the beam halos by using the e-lens

V. Summary and Conclusions

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  - controlling the time constant of field decay in critical magnet failures
  - avoiding beam/UFO induced quenches by detecting beam losses inside the cryostat
  - cleaning the beam halos by using the e-lens

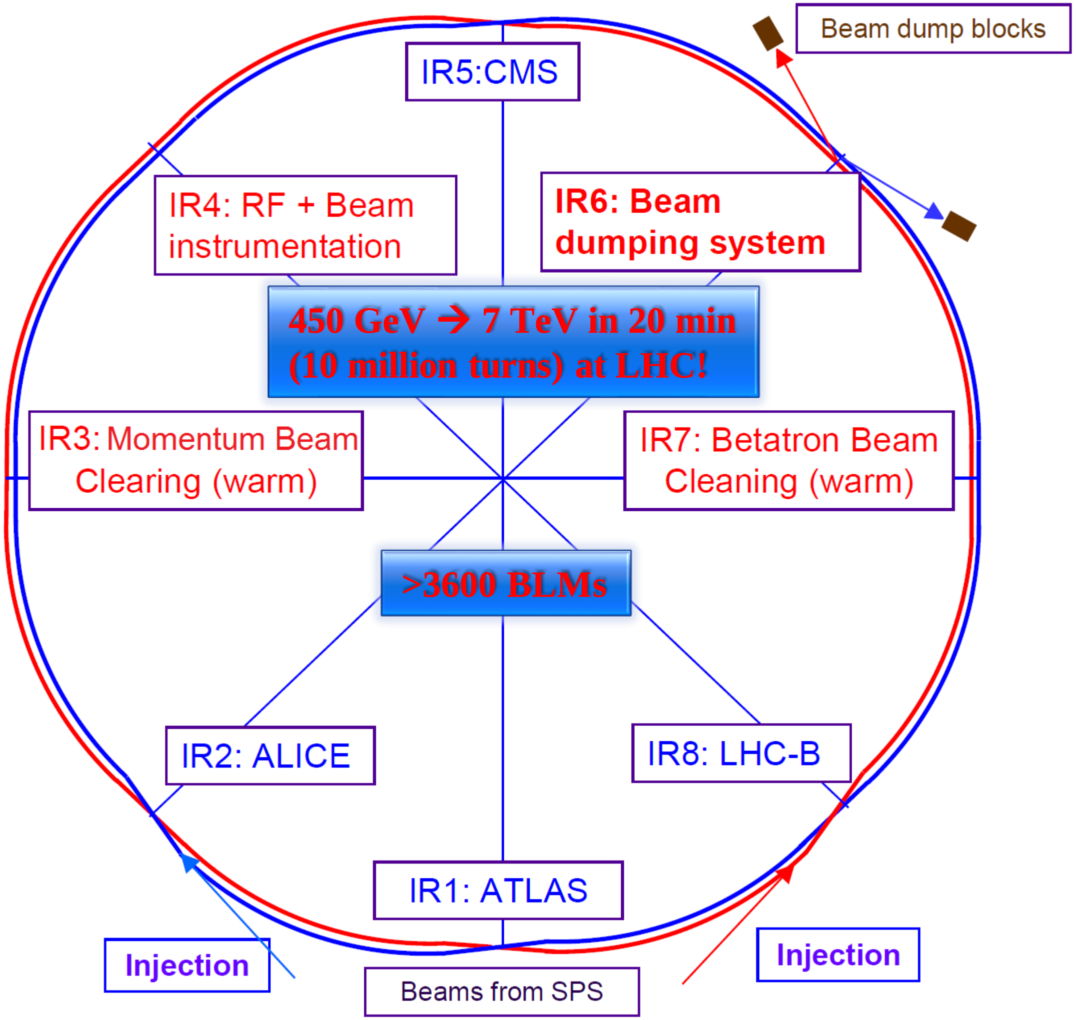
Thank you very much!

Backup

III. Machine protection architecture: strategies for different scenarios

Beam lifetime	**Beam power lost**		**Operation or failure scenario**	**Remark and basic strategy**
	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	230 kW	Steady beam loss, acceptable operating conditions (expected during early operation)	Operation acceptable, collimators must absorb large fraction of beam energy
12 min	500 kW	116 MW	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	8320 MW	Slow failures (powering failures, magnet quenches, RF failures, …)	Detection of failure, beam must be dumped rapidly
A few ms (tens of turns)	~100 GW	~ TW	Fast failures (UFOs, fast equipment failures, e.g., magnet failures at the highest beta function or with short time constant)	Fast detection of hardware failures or beam losses, beam dump as fast as possible
1 turn or a few turns	up to 4 TW	up to 26 TW	Ultrafast failures (Single-passage beam losses during injection and extraction; ultrafast equipment failures, e.g., phase jump of crab cavity, leading to dramatic beam losses in 3 turns)	No time to extract the beam in a controlled way, passive protection with collimators and absorbers (made of novel or sacrificial materials) is required, sometimes asynchronous dump must be executed

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

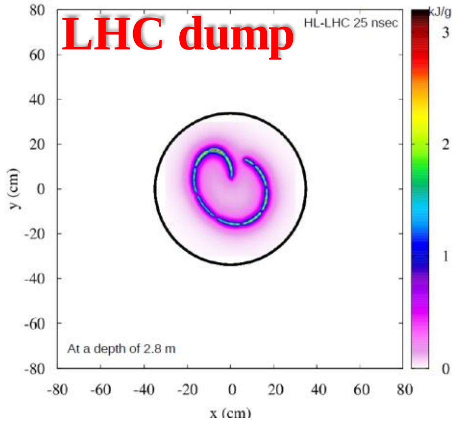
IR8: LHC-B

IR1: ATLAS

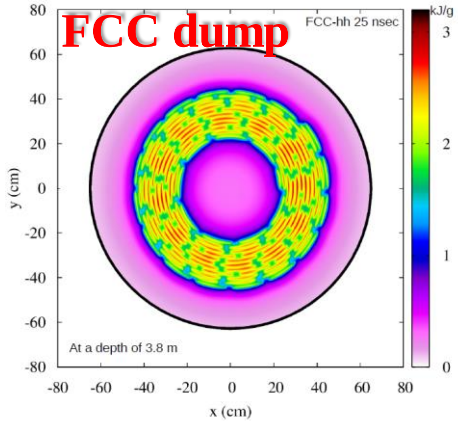
Injection

Injection

Beams from SPS



LHC dump



FCC dump

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

Ultrafast failures of FCC-hh

Studied failure mode	Consequences	Mitigation strategies	Remarks
Wrong deflecting angle of injected beam due to injection kicker failure	Large number of bunches lost at the same place in the accelerator	1) Transfer line collimators 2) injection absorber	See “Injection and extraction” part for more details and other failure modes during injection and extraction
Wrong deflecting angle of beam due to energy-tracking failure or extraction kicker (or septum) failure during extraction	Large number of bunches lost at the same place in the accelerator or dump line	1) Two-sided protection absorbers for septum and other magnets	
Dilution kicker failure	Dump block irradiated by higher-intensity beam without nominal dilution	1) Dump block designed to survive from 90% dilution mode 2) Or, using water dump	
For crab cavities (CCs), voltage/phase changes exponentially with a time constant of $\tau = 2Q_{ext}/\omega$ due to equipment failure, or faster due to quenches or multipacting. In the worst case, phase could jump 90º in one turn	Beam center could be deflected of the order of σ in one turn, leading to significant beam losses in 3 turns	1) Increase Q_{ext} and ω, and the number of CCs per beam per IP side 2) Avoid simultaneous failures of multi-cavities 3) Multi-cavity feedback for field-error compensation 4) Hollow e-lens to deplete halos 5) Make phase advance between CCs and collimators close to 90º	For the fastest CCs failure, probably no time to extract the beam in a controlled way, passive protection and asynchronous dump would be needed
Absence of beam-beam deflection due to the non-simultaneous extraction of the two beams	Fast deflection of the remaining circulating beam, unacceptable losses on some primary collimators if the beam halo is populated	1) Deplete and control the beam halo population using e-lens 2) Monitor the halo population and interlock on it	In the LHC, orbit perturbations up to 0.6 σ have been measured at 4 TeV, and 1.1 σ has been predicted for HL-LHC.
Effect of quench heater firing on the circulating beam	Current discharge induces a magnetic field deflecting the beam quickly	1) Dump the beams before the current discharge if the quench heater is triggered	Orbit distortion of 400 µm was measured in LHC after quench of a dipole. The beam would be deflected in the aperture within one turn for HL-LHC triplet quench heater.

Fast failures of FCC-hh

Studied failure mode	Consequences	Mitigation strategies	Remarks
Powering failure of separation dipole “D1” in IRA/IRG (if NC)	The beam can be displaced quickly from nominal orbit, leading to fast beam losses	1) Time constant of the field decay must >20 s 2) Connect a SC solenoid in series to increase the time constant 3) Detect failure at hardware level (e.g., FMCM) 4) Detect initial influences of the failure on the beam (fast BPM, BLM, etc) 5) Dump beam as fast as possible	One of the fastest failure modes, but can be mitigated by using the SC solenoid to slow down the field decay
Quench of 1 magnet of D1 (if SC)		1) Fast detection of the quench 2) Time constant of the field decay must >100 ms	Need to be careful about the time constant
Quench of 1 magnet of the low-β triplet	Tune change and β-beating, leading to resonances and beam instabilities	1) Fast detection of the quench 2) Time constant of the field decay must >140 ms	Need to be careful about the time constant
UFOs	Beam instabilities and fast beam losses	1) Fast detection of initial effects on the beam and trigger dump 2) Make use of the conditioning effect along the machine run	Lead to significant beam losses in ms at LHC
ADT/orbit corrector misfires	Fast beam deflections	1) Avoid coherent excitation of transverse dampers	
Vacuum valve/screen reduces aperture or obstructs beam pipe	Aperture reduction and fast beam losses	1) Accurate control of these movable devices	
Vacuum leak/wire scanner error scatters the beam	Beam scattering and fast beam losses	1) Fast detection of initial effects on the beam and trigger dump	
Beam instability due to too high beam current/e-clouds	Fast beam losses	1) Fast detection of initial effects on the beam and trigger dump	

Slow failures of FCC-hh

Studied failure mode	Consequences	Mitigation strategies	Remarks
Powering failure of other warm magnets	Change of the closed orbit	1) After detection of failure or abnormal beam parameters, dump the beam rapidly if necessary	Radiation levels should be paid attention to. Normally have enough time for synchronous dump
Quench of 1 main dipole or quadrupole	Change of the closed orbit or optics	1) After detection of failure or abnormal beam parameters, dump the beam rapidly if necessary	
RF accelerating cavity failures	More particle population on the tail due to dephasing	1) After detection of failure or abnormal beam parameters, dump the beam rapidly if necessary	

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