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Studies on beam related machine protection of the FCC-hh

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Introduction: Machine protection of the Future Circular Collider (FCC), especially the circular proton-proton collider (FCC-hh), is very challenging due to unprecedented energies stored in the magnets and circulating beams. We post preliminary considerations of beam related machine protection of the FCC-hh. Response time of the machine protection system from failure detection to beam dump execution was estimated. Different operation and failure scenarios were classified depending on beam lifetime. A few top critical equipment failures that could potentially lead to very fast (within a few turns) beam losses were studied based on experiences from the Large Hadron Collider (LHC) and specific beam dynamics analysis. Furthermore, interactions of multi-TeV protons with solid copper and graphite targets were simulated using FLUKA, in order to assess beam impacts of lost protons on different accelerator components.

Table 1: Relevant Parameters of LHC and FCC

Parameters	LHC (nominal)	FCC-hh (baseline)
Proton energy (TeV)	7	50
Bunch intensity	1.15×10^{11}	1.0×10^{11}
No. of bunches per beam	2808	10600
Ring circumference (km)	26.66	97.75
Time per turn (μs)	89	326
One beam energy (MJ)	362	8500
Typical beam energy density (GJ mm^{-2})	1	200
Quench limit (p m^{-1} s^{-1})	7.8×10^{6}	0.5×10^{6}
Tune Q_x	64.31	111.31
/ Q_y	/ 59.32	/ 108.32
RMS emittance (nm)	0.50	0.04
/ Norm. emittance (μm)	/ 3.75	/ 2.2
β* (m)	0.55	1.1
/ min. RMS beam size (μm)	/ 16.6	/ 6.8
Peak luminosity (10^{34} cm^{-2} s^{-1})	1	5
Beam intensity lifetime (h)	46	19

Table 2: Beam Losses and Protection Strategies for Different Operation and Failure Scenarios

Beam Lifetime	Beam Power Lost		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 failure 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)

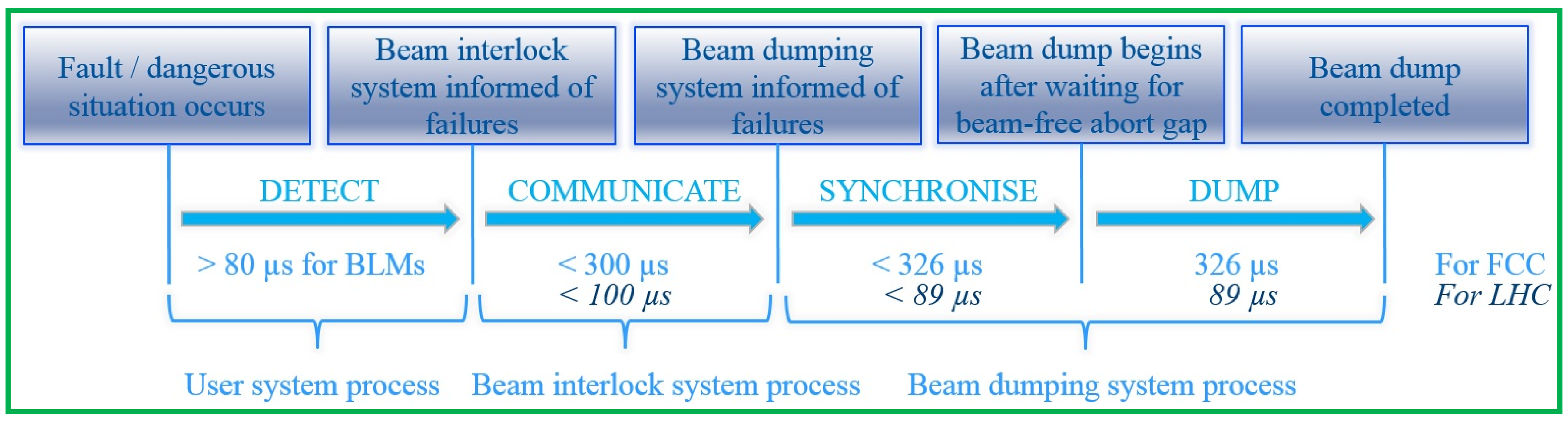

Fig.1: Execution process of a beam dump after failure detection.

Table 3: Studied Failure Scenarios That Could Potentially Lead to Very Fast Beam Losses at FCC-hh (based on FCC-hh lattice in October 2016)

Magnet Name	Failure Scenario	l	B_0	α_0 or k	β	τ or σ_t	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
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)	30.8 m	86 T/m	5.1×10^{-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	6.3 m	357 T/m	2.1×10^{-3} m^{-2}	350 m (max.)	> 8.6 ms	Less critical
Warm dipole in collimation insertion	Powering failure of MBW.A6R3.B1	9.1 m	1.45 T	0.079 mrad	718 m	> 270 ms	Need to be careful
Warm quadrupole in collimation insertion	Powering failure of MQWA.D4R3.B1	8.3 m	29 T/m	1.7×10^{-4} m^{-2}	1068 m	> 23 ms	Less critical

Summary and Future Works

- **Preliminary considerations of beam related machine protection of the FCC-hh have been reported.**
- **A few top critical equipment (magnet) failures that could potentially lead to very fast (within a few turns) beam losses have been described. Further efforts are being made to complete this list.**
- **Such studies may provide inputs for the powering design of magnets.**
- **In addition to the response time of the machine protection system, robustness and reliability of the protection components are rather critical, in order to withstand beam impact of up to 50 TeV protons which are potentially destructive.**
- **For energy deposition of protons in solid copper and graphite materials, an integral FLUKA simulation covering all typical beam energies and beam sizes of the FCC-hh and its injector chain has been performed. The study provides a reference for quick assessment of beam impacts on copper and graphite targets, in case of beam loss.**

References

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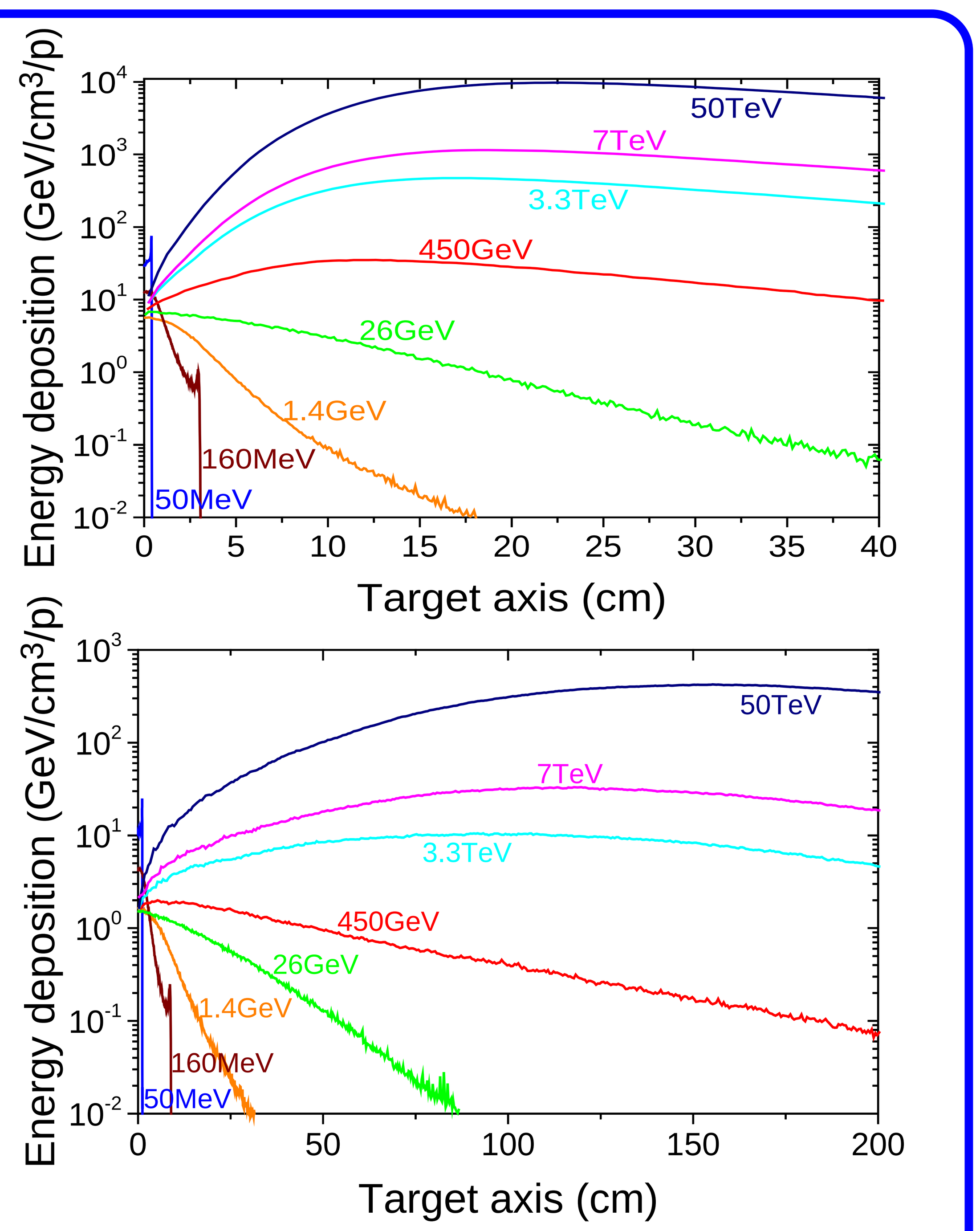

Fig.2: Energy deposition along cylinder target axis in copper (up) and graphite (down). Transverse rms beam size is 0.2 mm.

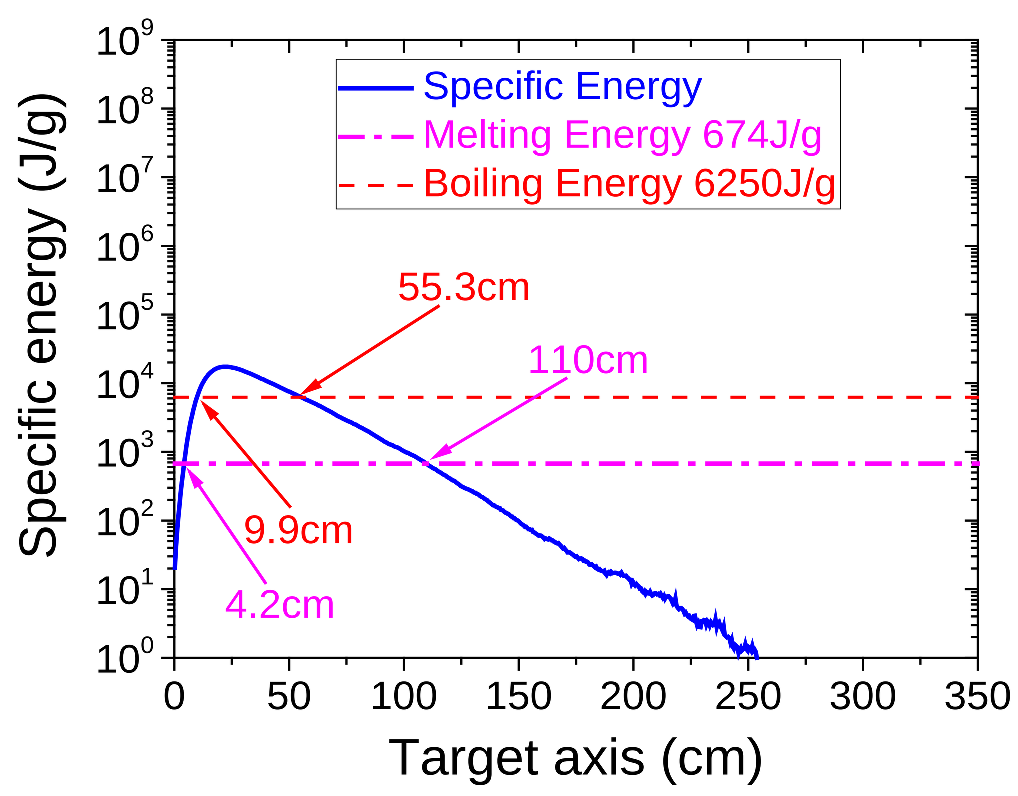

Fig.3: Specific energy deposition of one 50 TeV bunch with 1.0×10^{11} protons in copper.

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