FCCee Machine Protection Considerations

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Anton Lechner**

With thanks to the other members of the FCC Machine Protection Task Force:
Chiara Bracco, Roderik Bruce, Xavier Buffat, Andy Butterworth, Brennan Goddard, Belen Salvachua

FCC week 2025
19 – 23 May, Vienna

Machine Protection

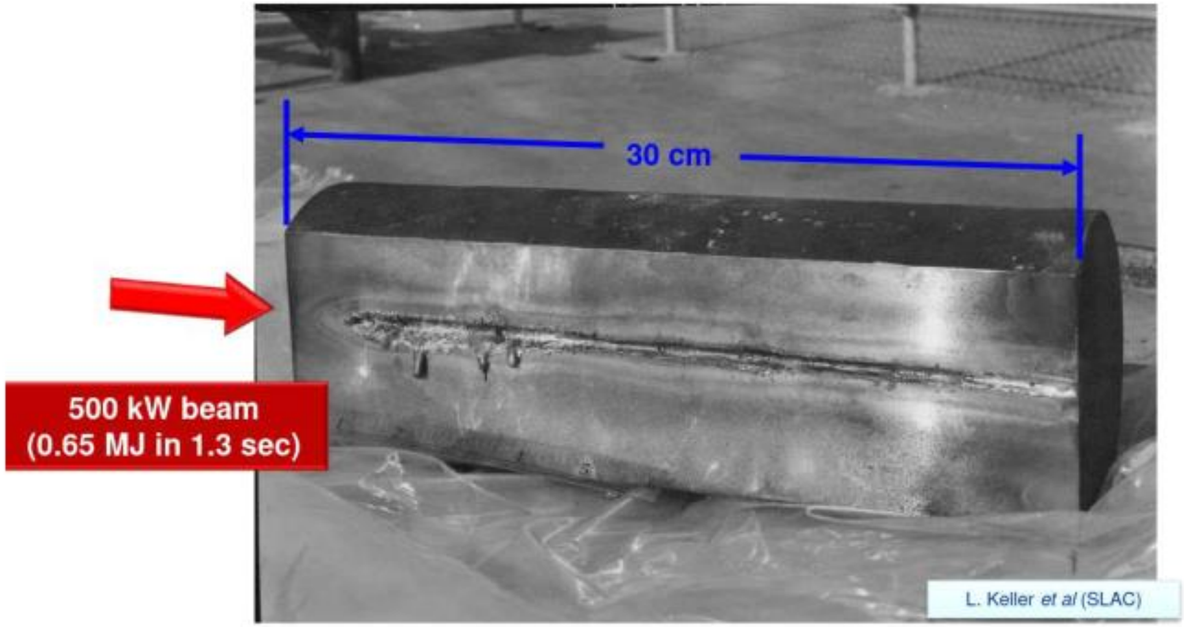
Is important because:

The beams are very bright:
serious damage of the collider leading to important downtime and costs

There are many ways to lose the beams:
a complete inventory of failure scenarios needs to be made

Loss processes tend to be very fast:
the design of the machine protection system is not evident

- Need to define the detection system
- Need to define the transmission system
- Need to define the beam abort system



Damage of a copper block in a 18 GeV electron beam test at SLAC (1971).

This was a slow beam loss (0.65 MJ in 1.3 s) with a large beam spot size (2mm).

For comparison: stored beam energy in FCC-ee (Z) is 17.5 MJ, with a MUCH smaller spot size (=higher energy density)

Energy density of stored beam: FCC-ee vs HL

Collider beam parameters:

	FCC-ee (Z)	FCC-ee (W)	FCC-ee (ZH)	FCC-ee (ttbar)	HL-LHC*	
Beam particles	e-/e+				p	
Energy E	45.6 GeV	80 GeV	120 GeV	182.5 GeV	450 GeV	7000 GeV
Beam intensity I	11200b x 2.14×10^{11} ppb $=2.4\times10^{15}$	1780b x 1.45×10^{11} ppb $=2.6\times10^{14}$	380b x 1.32×10^{11} ppb $=5\times10^{13}$	56b x 1.64×10^{11} ppb $=0.9\times10^{13}$	2760b x 2.2×10^{11} ppb $=6.1\times10^{14}$	
Stored energy E_s	17.5 MJ	3.3 MJ	1.0 MJ	0.3 MJ	**44 MJ**	**681 MJ**
σ_x (for ß$_x$=100m)**	270 μm	470 μm	260 μm	400 μm	650 μm	160 μm
σ_y (for ß$_y$=100m)**	**14 μm**	**15 μm**	**10 μm**	**13 μm**	650 μm	160 μm
$E_s/(\sigma_x\sigma_y)$ (for ß$_{x/y}$=100m)	4600 MJ/mm^2	470 MJ/mm^2	380 MJ/mm^2	60 MJ/mm^2	100 MJ/mm^2	27000 MJ/mm^2

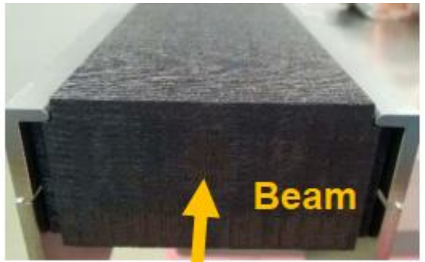
**Assuming a normalized emittance of 2 μm rad (neglecting for simplicity emittance growth and intensity loss in the ramp)*

*** Dispersion contribution neglected*

Stored beam energy only 0.05-2.5% of HL-LHC beams, but energy density of FCC-ee beams is between **0.2-17% of HL beams (7 TeV)**

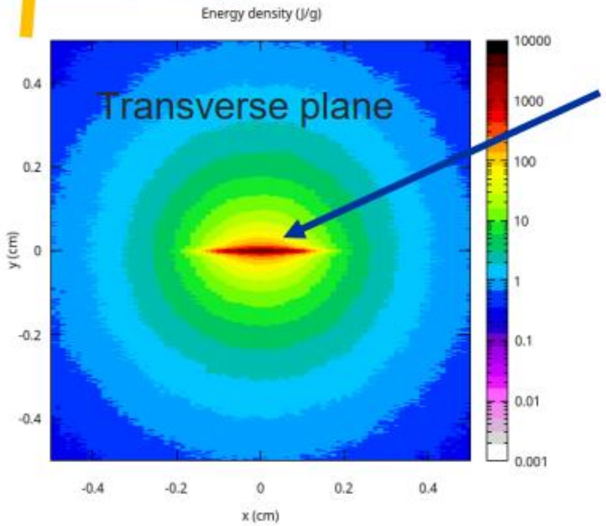
Energy deposition by an FCCee injection train in graphite/CfC absorber block

The energy density of the beam itself does not give the full picture → when comparing to HL beams, one needs to consider also the different shower development of lepton and hadronic showers (at largely different particle energies)



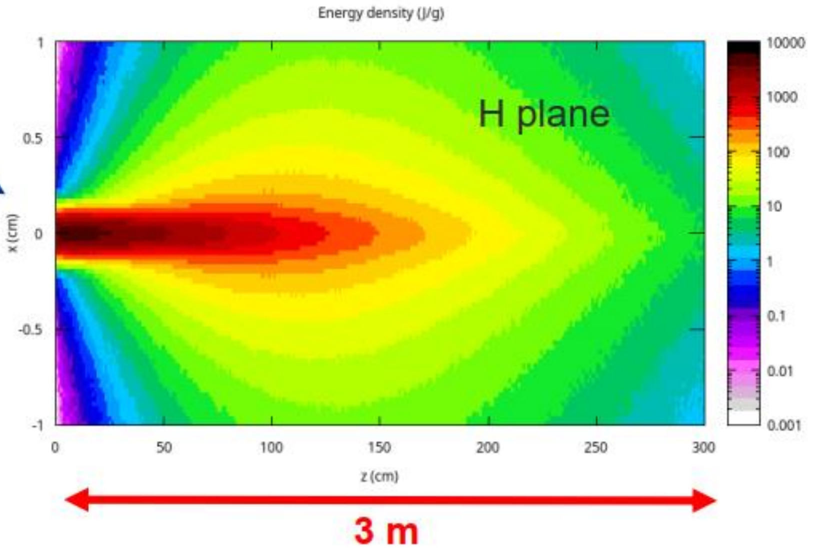
Example (Z pole, 45.6 GeV):

- *Injection train with **0.5%** of collider intensity (**1.2×10^{13} e-**)*
- *All bunches impact on same spot on graphite/CfC absorber (1.8 g/cm^3)*
- *Geometric emittances of **0.26 nm/0.53 pm***
- *Local beta functions of **1km** in both planes*

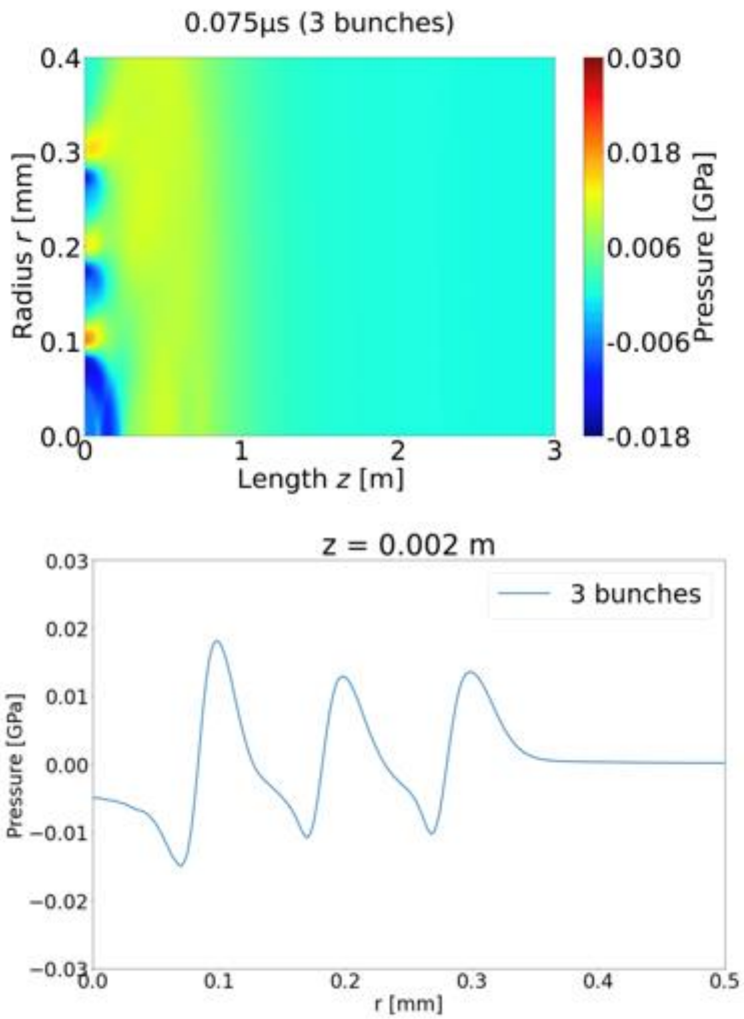


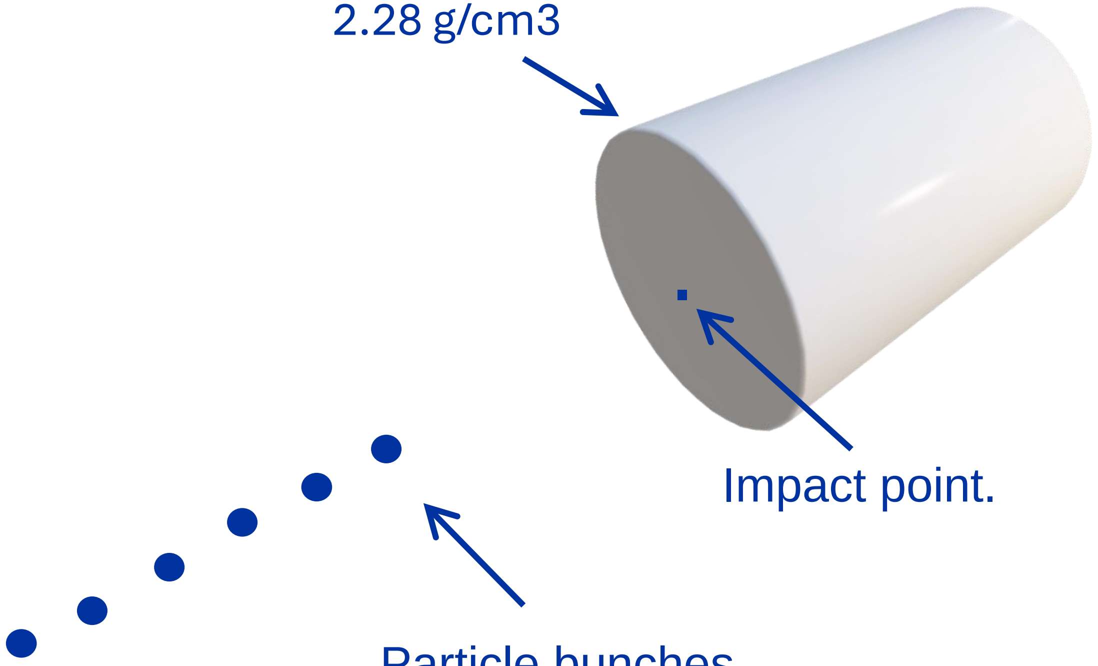
4.3 kJ/g (2650 °C)

Quite high…



Coupling FLUKA and ANSYS simulations for many bunches impacting at the same position (‘tunnelling’)





Graphite target,
2.28 g/cm3

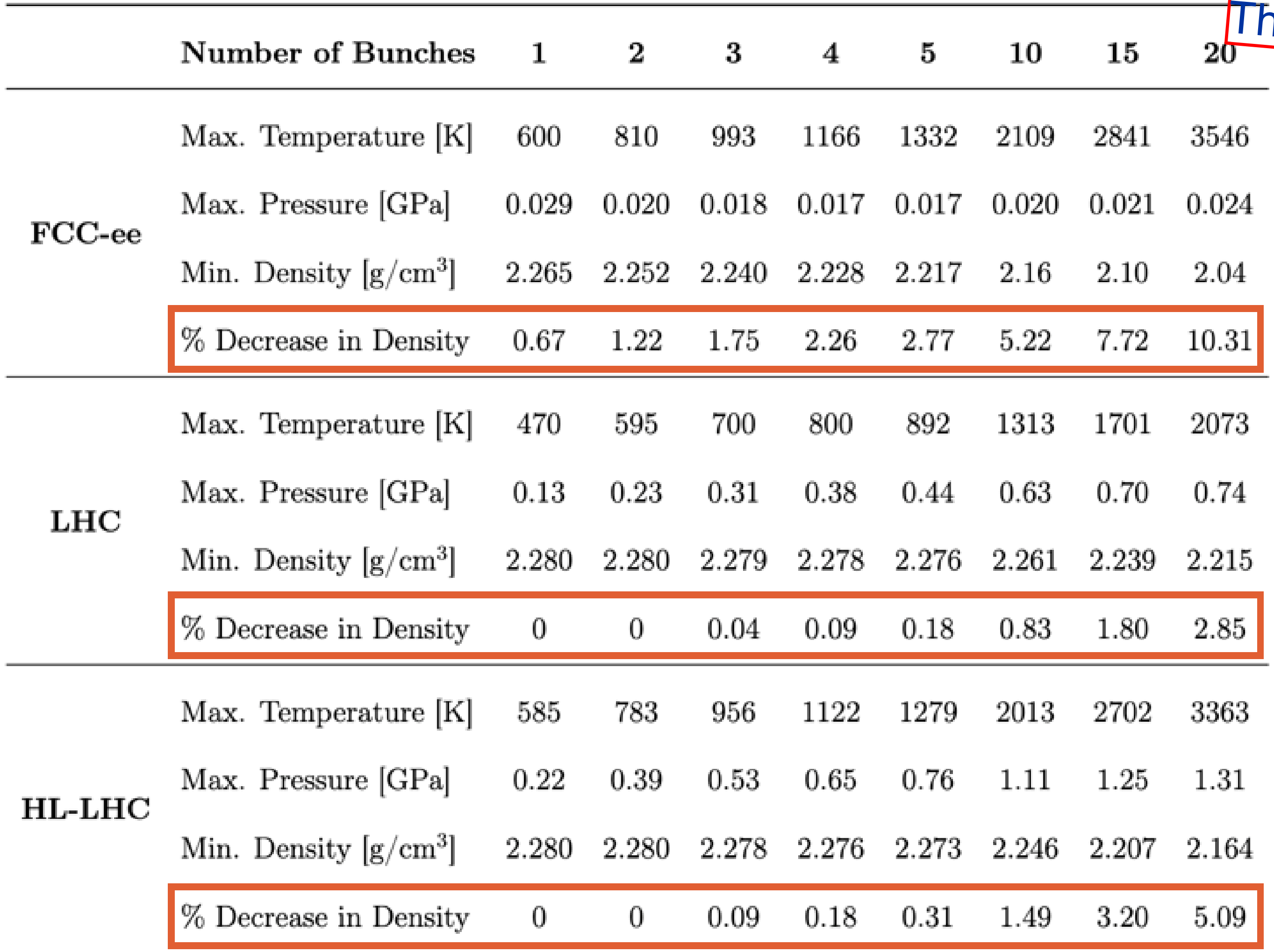
Impact point.

Particle bunches
with 2.14e11 e^-/e^+

Ingrid M. Hjelle
CERN-THESIS-2024-357

Coupling FLUKA and ANSYS simulations for many bunches impacting at the same position (tunnelling)

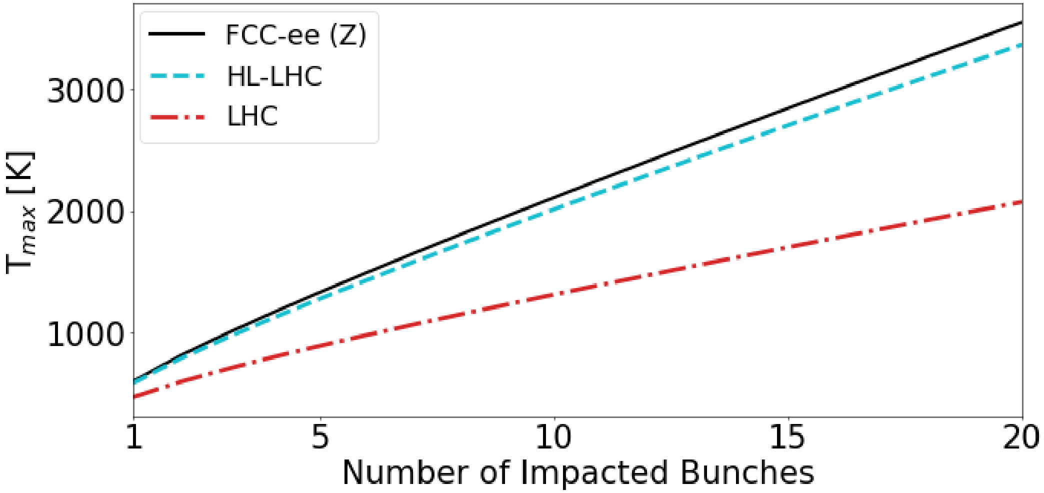
There will be many more bunches !!



	Number of Bunches	1	2	3	4	5	10	15	20
FCC-ee	Max. Temperature [K]	600	810	993	1166	1332	2109	2841	3546
	Max. Pressure [GPa]	0.029	0.020	0.018	0.017	0.017	0.020	0.021	0.024
	Min. Density [g/cm^3]	2.265	2.252	2.240	2.228	2.217	2.16	2.10	2.04
	% Decrease in Density	0.67	1.22	1.75	2.26	2.77	5.22	7.72	10.31
LHC	Max. Temperature [K]	470	595	700	800	892	1313	1701	2073
	Max. Pressure [GPa]	0.13	0.23	0.31	0.38	0.44	0.63	0.70	0.74
	Min. Density [g/cm^3]	2.280	2.280	2.279	2.278	2.276	2.261	2.239	2.215
	% Decrease in Density	0	0	0.04	0.09	0.18	0.83	1.80	2.85
HL-LHC	Max. Temperature [K]	585	783	956	1122	1279	2013	2702	3363
	Max. Pressure [GPa]	0.22	0.39	0.53	0.65	0.76	1.11	1.25	1.31
	Min. Density [g/cm^3]	2.280	2.280	2.278	2.276	2.273	2.246	2.207	2.164
	% Decrease in Density	0	0	0.09	0.18	0.31	1.49	3.20	5.09

Simulation of the initial impact of an approximated round FCC-ee beam (σ = 0.5 mm) has similar maximum energy deposition and temperature rise as the impact of the HL-LHC beam.

However the density is depleted faster, and the pressure waves differ with amplitudes ~10 times lower.



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Needed: Machine Protection

Not talking about Equipment Protection here….
Slides below refer for a large part to presentations made at the Machine Protection Task Force meetings (Indico)

Define the failure scenario’s

Failure mechanism and its impact
Timescale
Likelihood
Defence mechanism

Define the specific protection systems

Detection of the failure at the source
Detection of the effects on the beam
Transmission of beam abort request
Beam abort

Failures

- **Hardware related failures**
  - Injection and extraction
  - Powering failures
  - Collimation system
  - Radio frequency
  - Transverse feedback
- **Beam related failures**
  - Beam instabilities
  - Beam dust interaction
  - Synchrotron radiation damage
- **Protection related failures**
  - Failure of protection systems
  - Synchrotron light absorber

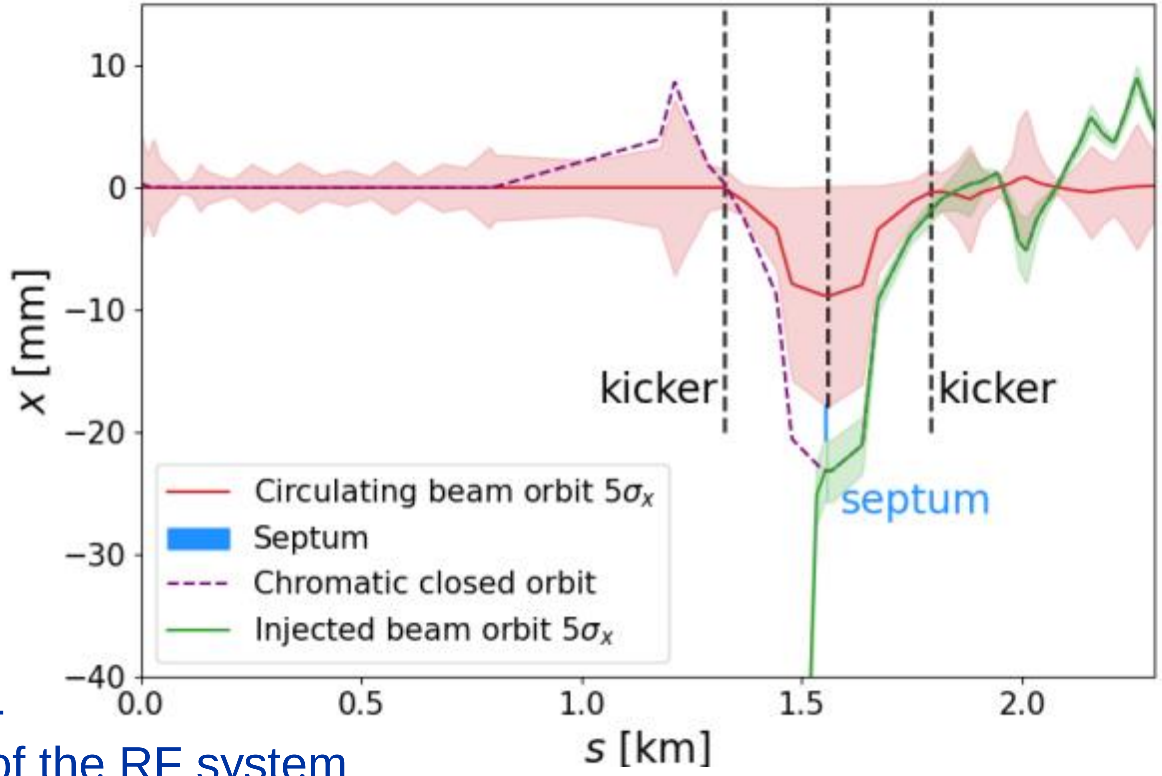
Detection & Protection

- **Definition of critical aperture**
  - Collimation system
- **Beam instrumentation**
  - Beam Loss Monitors (BLMs)
  - Beam Position Monitors (BPMs)
  - Beam Current Change Monitor (BCCM)
- **Other detection systems**
  - Fast Magnet Current change Monitor (FMCM)
  - Warm magnet Interlock Controller (WIC)
- **Beam Interlock System (BIS)**
  - BIS and Safe Machine Parameter System (SMP)
- **Beam dumping system**

Injection from Booster to Collider

Top-up injection:

- Two kickers are placed with 180° phase advance between them (π-orbit-bump) to create a closed bump to bring the stored beam trajectory close to the injection septum
- The bump is constant for up to a single turn (304 μs) while off before and after (rise and fall in 0.6 μs abort gap) ➔ possible affecting all circulating bunches (up to 11200, 17.5 MJ) in case of kicker failures and up to 88 bunches (Z-mode) in case of loss of synchronization ➔ oscillations and losses



Presented at Task Force meeting by Chiara Bracco June ’24

The abort gap length has been reduced to 600 ns because of the RF system

Is it better to have a slow rising injection bump over many turns?

Impedance issues, radiation damping times

Inject on a flat machine (one vote on Tuesday)

Do we need highly segmented bumper systems?

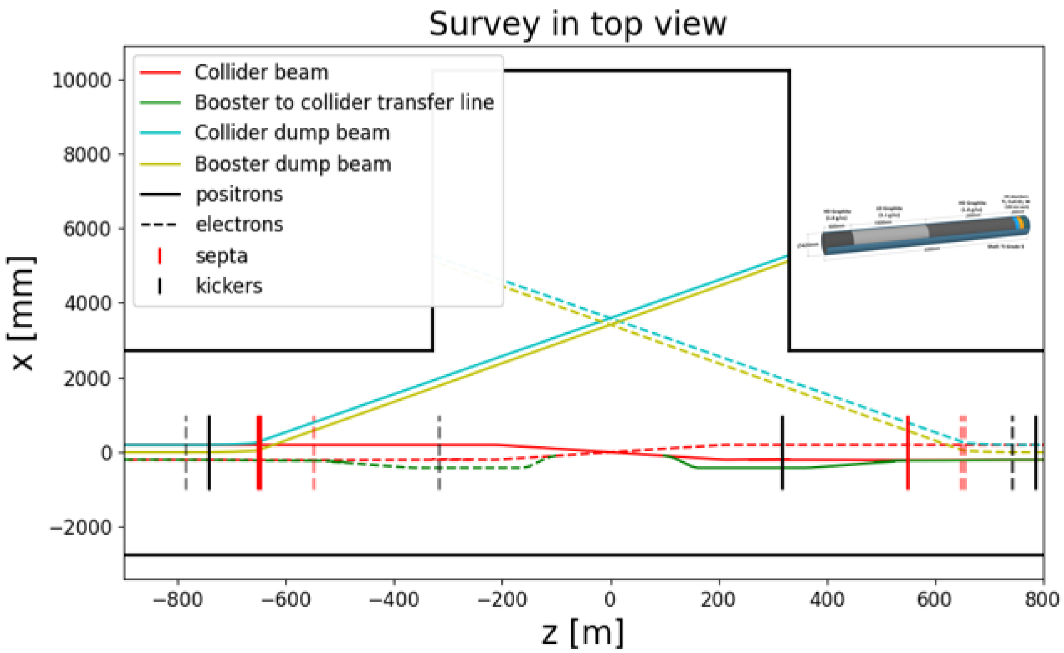
Synchronisation issues

Passive absorbers for single turn failures – reduction of injection intensity

See also presentation Yann Dutheil, ‘Top-up injection status and studies’ on Tuesday

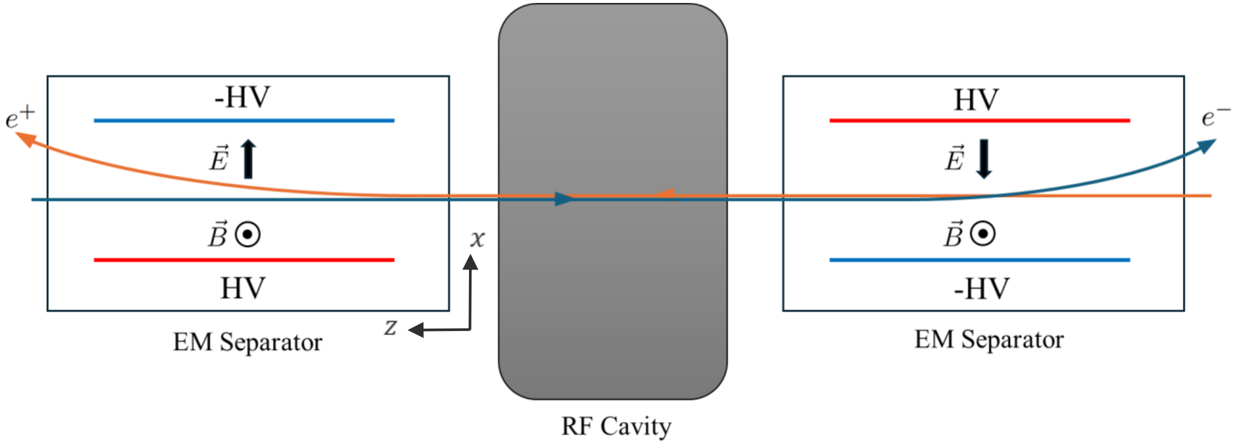
Extraction of the collider

- **Has to be extremely reliable**
  - This means that system will normally have to be redundant (like LHC can extract with 14/15 magnets)
  - Has to pulse at the correct strength and at the right moment, synchronised with abort gap
- **Number of abort gaps – for kicker risetime – affect the reaction time between beam dump request and last particle extracted from the machine**
- **Based on lumped inductance kickers and low power DC septa**
- **Passive dilution using a spoiler looks sufficient to reduce energy density at the dump**
- **For both injection and extraction, use passive (sacrificial?) absorbers in case of failures**
- **List of failure modes to be established**

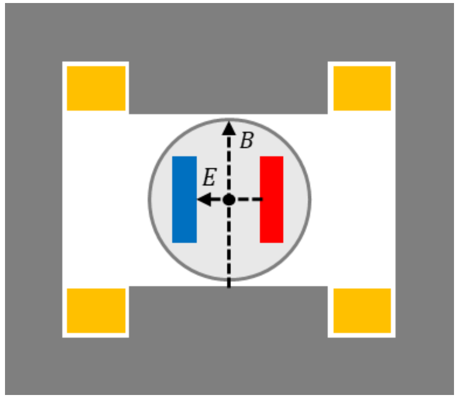


Kickers / Systems	**6/2**
Impedance [Ω]	**10**
Current [kA]	**1.2**
Voltage [kV]	**5**
Element aperture [mm]	**70**
Integrated field [mT.m]	**30**
Effective length [m]	**1**
Physical length [m]	**1.5**
Total kick angle [mrad]	**0.3**
Aperture (beam stay clear) (⌀) [mm]	**60**
Rise / fall time [µs]	**1.100**
Flat top length [µs]	**304**
Flat top quality [%]	**±5**
Repetition rate [Hz]	**0.1**

Electro-Magnetic Separators around the RF cavities



EMS principle using combination of static electric and magnetic fields



EMS cross section showing an outside vacuum dipole magnet and inside vacuum HV electrodes

C. Bracco at Task Force meeting,
L. Porta, presentation yesterday

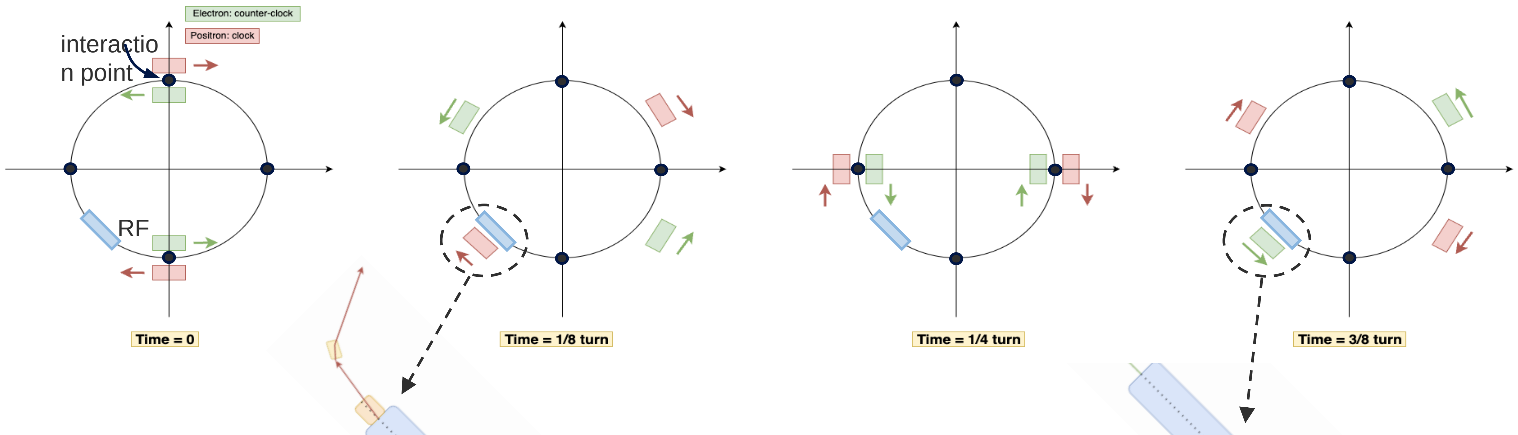
- **Installed upstream and downstream of RF section in H and tt mode.**
- **Used to assure both beams pass through centre of RF cavities, while avoiding synchrotron light hits the cavities.**
- **Failures:**
  - B and E field longitudinal mismatch
  - Synchrotron light on HV electrodes inducing sparks that could give large kicks to the beam (ultra-fast failure) – LEP experience
- **Mitigations:**
  - Fast detection of oscillations (interlock BPMS)
  - Dedicated masks for synchrotron light

Electro-Magnetic Separators around the RF cavities

Kicker System as alternative

L. Porta, presentation yesterday

- **Kicker system has been very recently proposed as an alternative option to EMS**
- **The interest has been triggered by the CEPC project where they have similar approaches [8]**
- **Feasibility analysis is at a very early stage**



Quotes from yesterday's presentation:

A fast-acting system is always a concern for machine protection

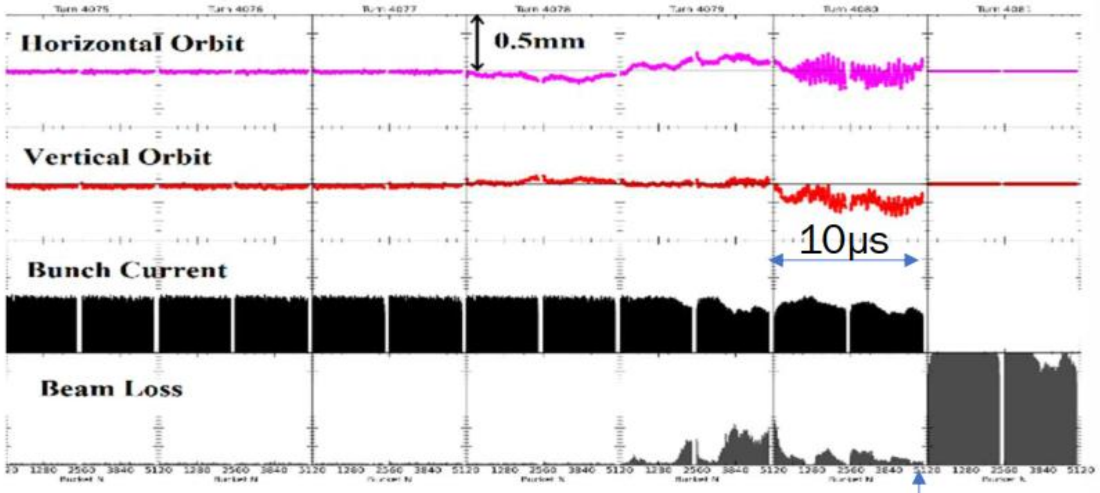
- Risks include mis-kicks, erratic kicks, missing kicks, and synchronization errors

What happens if the separation system fails?

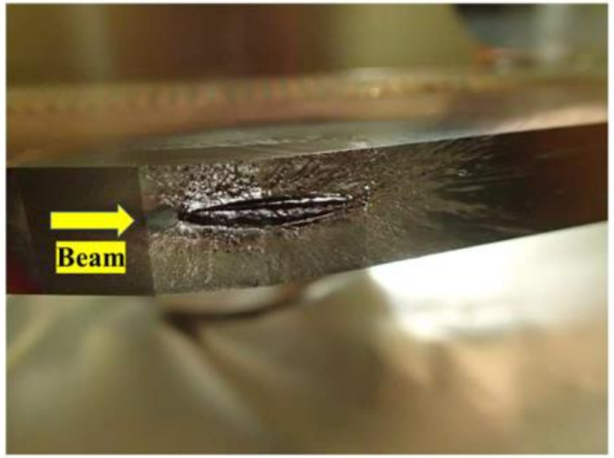
- The beam could hit the septum blade.
- **The beam could end up circulating in the wrong beam pipe.**

Sudden Beam Losses as seen at SuperKEKb

Beam signal measured by
Beam Oscillation Recorder(BOR) & Bunch Current Monitor(BCM)



Abort



10 μs = 1 rev.

Beam loss that occurs suddenly within 1 turn (10μs) without precursory phenomena. ＝ Sudden Beam Loss （SBL）

- A significant percentage of the beam is lost before the abort trigger is applied.

↓

- Damage to collimators and other accelerator components,
- Quench of the final focusing superconducting magnets (QCS),
- Large backgrounds to the Belle-II detector,
- Inability to store high current due to beam abort.

H. Ikeda at Mini SuperKEKb workshop 8/5/2025
Losses occur at the aperture limit, at the collimators

Sudden Beam Losses at SuperKEKb

Extremely important for FCCee – we should really understand it before we build the FCCee

- Beam losses go together with vacuum bursts
- Suspect to be a macro-particle – beam interaction
  Like the LHC UFOs, but different …

Workshop at CERN on Dust Charging and Beam-Dust Interaction at CERN 13th June 2023: https://indico.cern.ch/event/1272104/timetable/

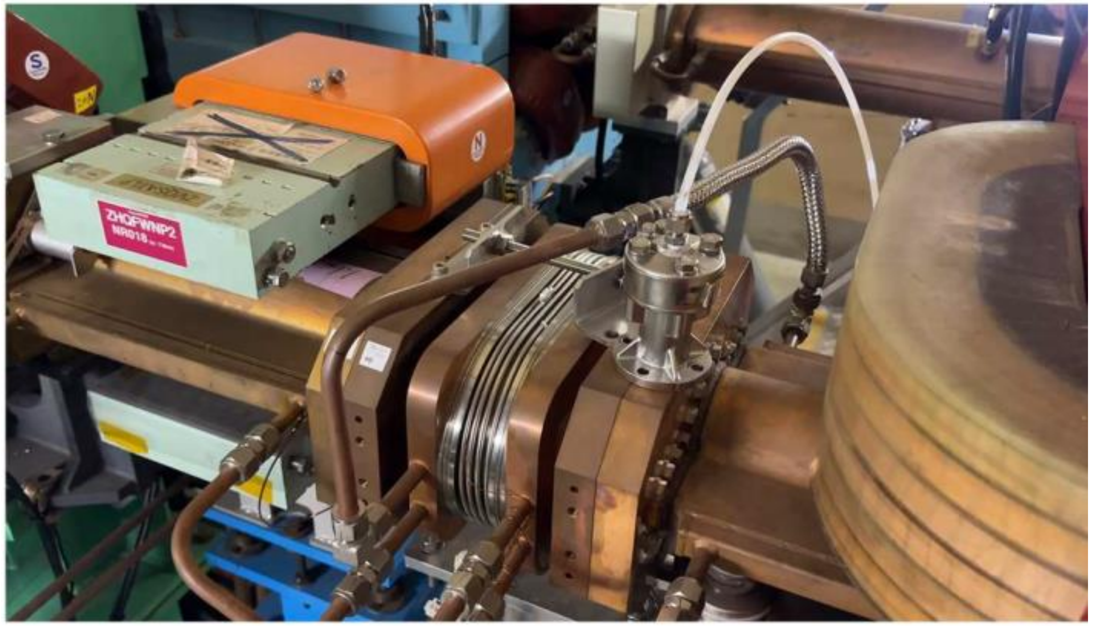
Presentation at the Machine Protection Task Force 27/03/2025

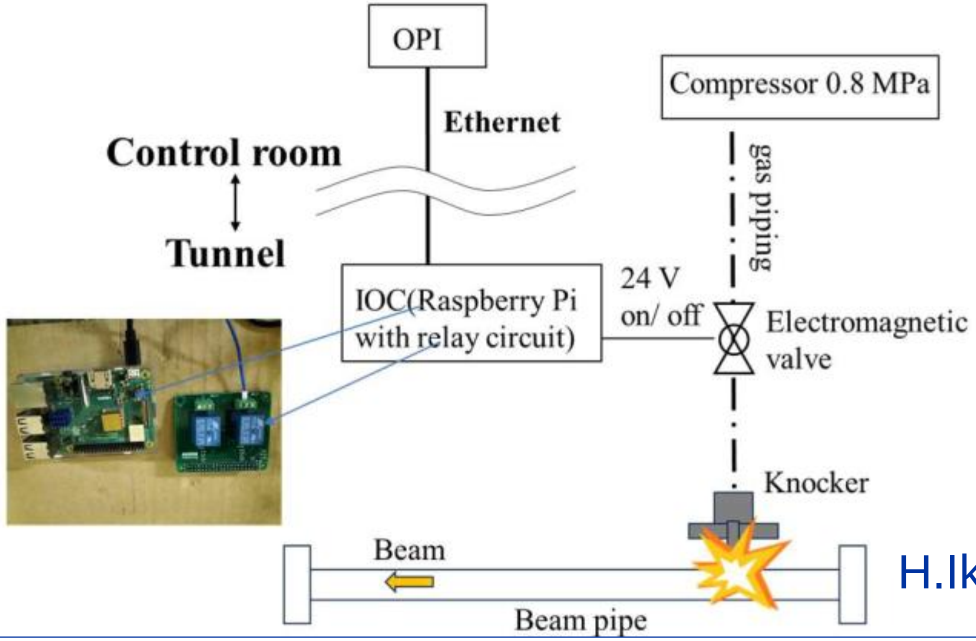
Modelling is important. Difference between 'UFOs' as seen at the LHC – protons – and what is seen at SuperKEKb – electrons

Important for FCCee design

- Requirements on vacuum system
- Requirements on beam diagnostics (BLMs and BPMs), time resolution and sensitivity
- Requirements on delay before dumping the beam

Studies with 'knocker' in the SPS at CERN are being considered





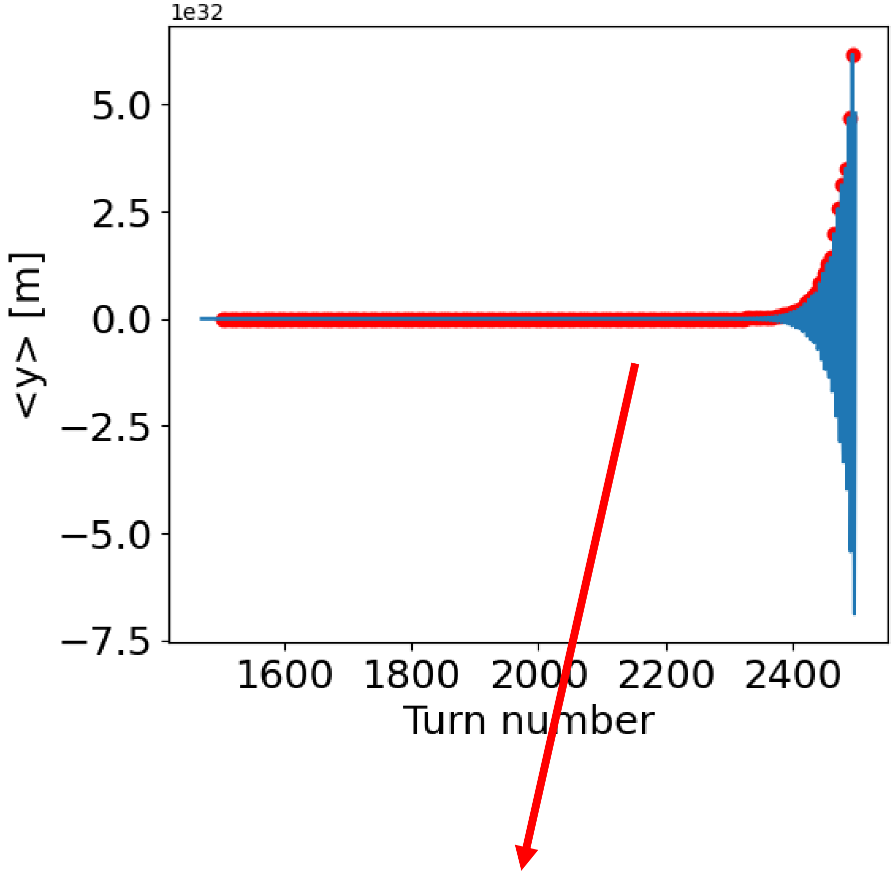
H.Ikeda

Impedance Induced Instabilities

- **Transverse Coupled Bunch Instabilities**
- **Rise time – depending on the tune – around 1.3 ms = O(3 FCC turns)**
- **Need a fast feedback (see later)**
  - That does not fail !!
- **Coupled bunch modes *also* to be damped by feedback**

M. Migliorati, X Buffat

CBI



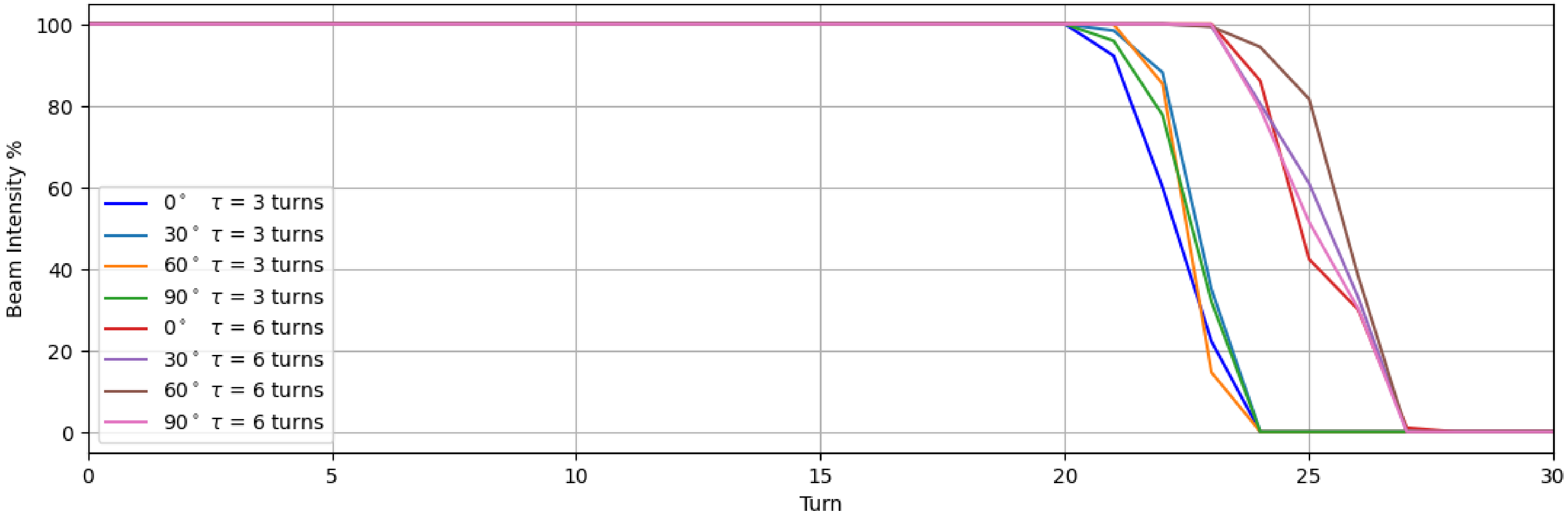
Rise times:

$N_p = 2.0 \times 10^{11} \rightarrow \simeq 8,0$ ms

$N_p = 2.2 \times 10^{11} \rightarrow \simeq 7.6$ ms

Instability Simulations with Collimation System

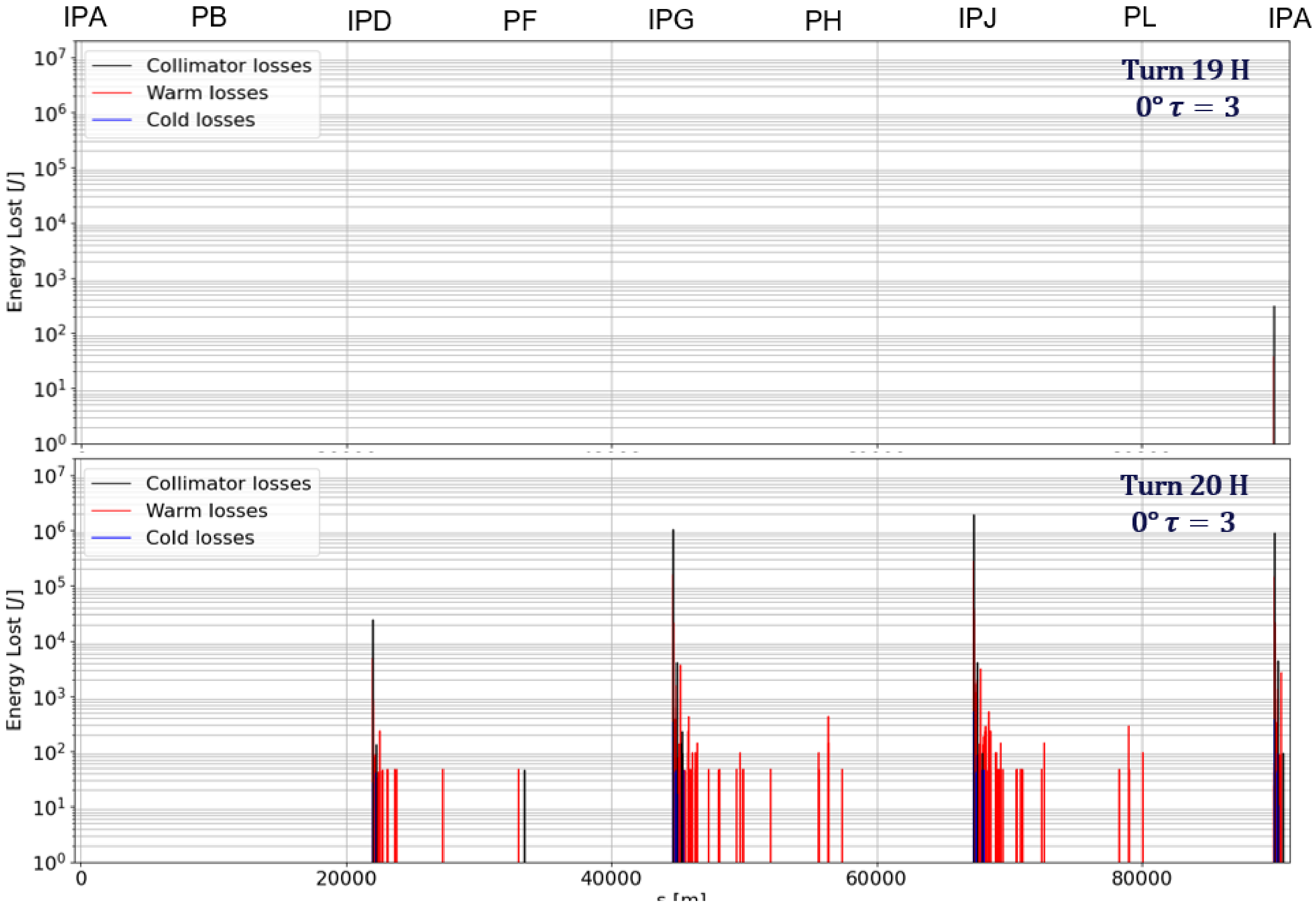
- **The beam must be dumped before any damage to the collimators can occur**
- **Simulations confirm that the beam can be lost in only a few turns**
- **Almost 50% of beam energy lost in one turn, losses of order of MJ in the collimator can be expected**
- **Losses need to be detected in the first turn(s) !**



Giulia Nigrelli in Task Force Meeting,
Result here for H-plane, similar V-plane

Instabilities and losses on collimators

Lossmaps: worst case

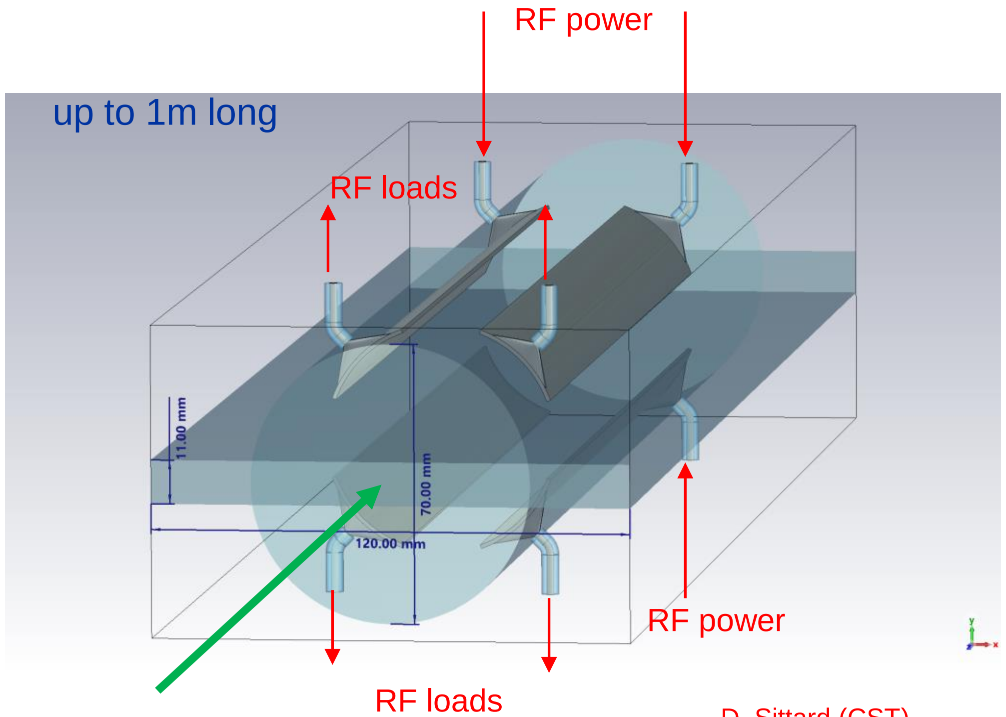


- Primary particles on tertiary collimator → current collimation system in PF cannot intercept this fast losses.
- **From turn 19 ($E_{lost} \sim 400\ J$) to turn 20 ($E_{lost} > 5\ MJ$).**
- Losses in the aperture ($\sim 25\%$ of total losses) coming from secondary particles or scattered primaries.
- Significant losses close to the IPs, more than in the collimator insertion.

Giulia Nigrelli in Task Force Meeting, Result here for H-plane, similar V-plane

Transverse Feedback System & Depolarizer

- **One system for Transverse Feedback and Depolarisation kicker**
- **Transverse feedback to counteract the TMCI (see ←)**
  - Especially at Z energy, due to the larger beam current
  - For the Booster also injection oscillation damping
- **Depolarisation kicker to measure the beam energy at Z and W energies**
- **Both need similar bandwidth, use the same system**
- **If the Transverse Feeback stops working, the beam can be unstable in a few turns**
  - Ideally redundant systems, several locations spread around the ring
  - Independent systems can start to interact and fight each other
- **Need to interlock at the source in case of failure but also interlock on the effects on the beam**



D. Sittard (CST)
W. Höfle at TF

Proposed Stripline Kicker

Transverse Damper Machine Protection Considerations

What can go wrong?

- Excitations not correctly synchronized
- Excitation amplitudes not correct to lead to closed depolarizing bumps
- Any of the other excitations that will certainly be used (AC dipole mode etc.) need to be protected against failures
- Very strong kicks possible comparable or even larger than at LHC injection

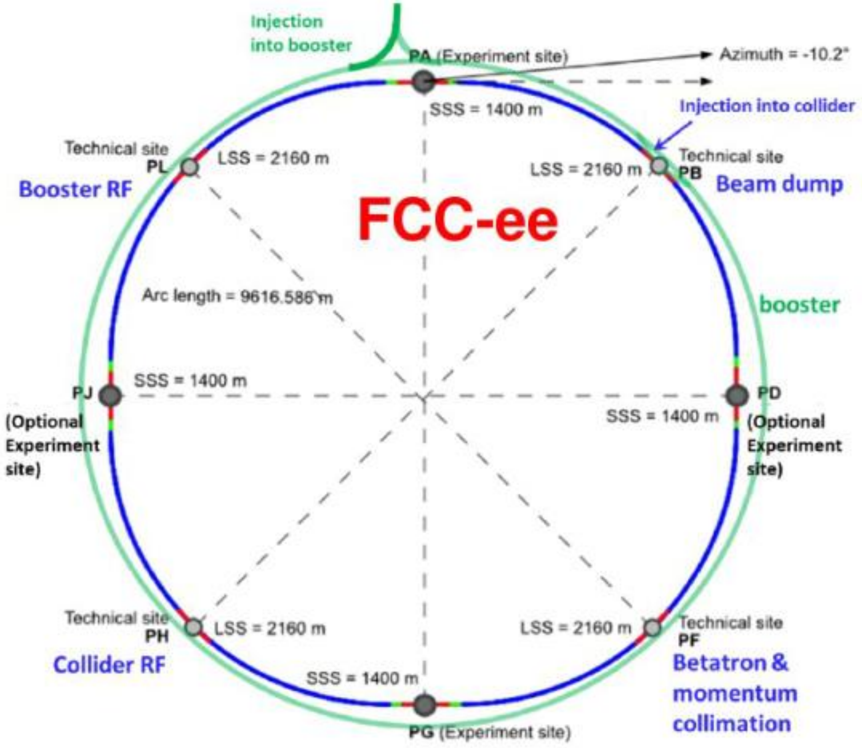
Mitigation

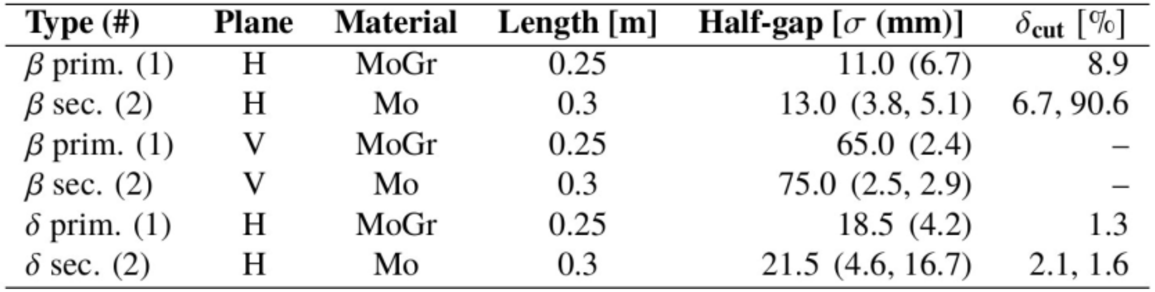
- Protection with BLMs of limited or of no use due to small beam size
- Monitoring of positions at appropriate distance from kickers in phase
- Global monitoring of beam position required turn-by-turn, independent of pick-ups used for TFB
- Interlocks need to be derived from this monitoring

W. Höfle at Task Force meeting

Protection: Collimation System

- **Define the aperture of the collider and thus protect the machine**
  - On top: control experimental backgrounds
- **Baseline design is to have PF dedicated to collimation**
- **Plus dedicated synchrotron radiation collimators upstream of the IPs**
- **To be confirmed: Machine Protection prefers a (more) distributed system, to protect against local failures**
  - Failure simulations to be done
  - Put this in the perspective of the sudden beam losses seen at SuperKEKb which damage their collimators





Type (#)	Plane	Material	Length [m]	Half-gap [σ (mm)]	δ_{cut} [%]
β prim. (1)	H	MoGr	0.25	11.0 (6.7)	8.9
β sec. (2)	H	Mo	0.3	13.0 (3.8, 5.1)	6.7, 90.6
β prim. (1)	V	MoGr	0.25	65.0 (2.4)	–
β sec. (2)	V	Mo	0.3	75.0 (2.5, 2.9)	–
δ prim. (1)	H	MoGr	0.25	18.5 (4.2)	1.3
δ sec. (2)	H	Mo	0.3	21.5 (4.6, 16.7)	2.1, 1.6

RF System – will dominate machine operation

Analysis of the failures for the Reverse Phase Operation system have started

- Reverse phase operation allows same hardware for Z, W and ZH mode

A 600 ns abort gap for the beam dump seems feasible

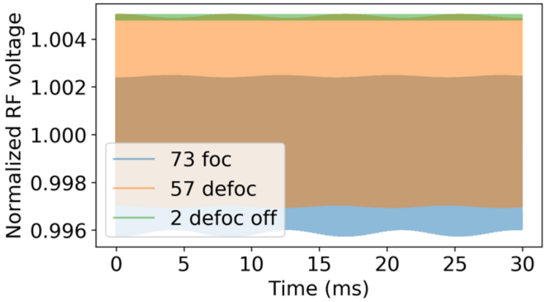
First results show no risk of too high induced voltages if a cavity trips

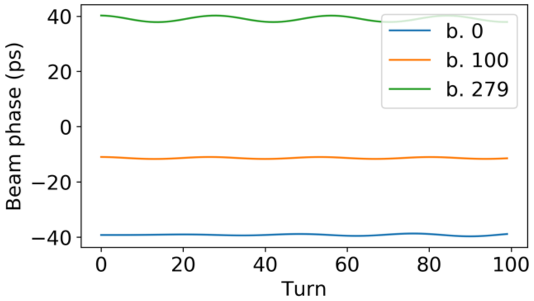
- Don’t need to abort the beam if sufficient cavities remain operational
- Mainly an availability issue, not a machine protection issue

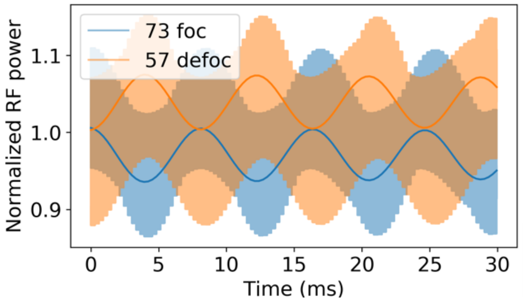
Further analysis needed

2 defocusing cavities trip

Voltage amplitude of tripped cavity increases by 0.5 %
Peak power of other cavities slightly increases
Bunch oscillation amplitude is significantly smaller than the bunch length







I. Karpov at Task Force meeting

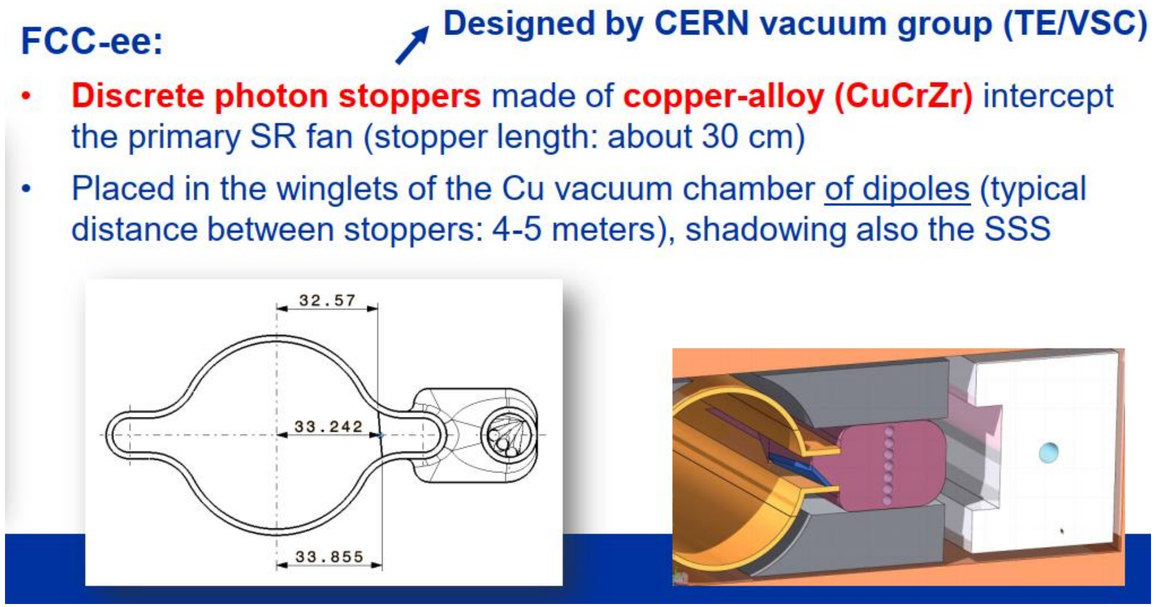
Synchrotron Radiation

What can possibly go wrong?

- **SR photons miss the photon stoppers and impact on the vacuum chamber or other sensitive equipment (e.g. due to machine misalignments, orbit excursions, unexpected SR sources)**
- **Insufficient cooling of photon stoppers (e.g. failure of cooling circuit)**
- **…..**

Some questions for the design phase:

- **Which alignment tolerances for vacuum chambers/SR absorbers?**
- **How can we monitor if SR photons impact on photon stoppers? Temperature monitoring?**
- **Which interlocks are needed? Water flow rate measurement for photon stoppers?**
- **Is all equipment sufficiently protected from SR, in particular in the insertion regions (special SR sources like wigglers, etc.)? Can we accurately model all SR sources?**
- **Do we need additional SR collimators, for example in the technical insertions?**
- **If SR impact on equipment cannot be fully avoided (e.g. beam instrumentation), which design guidelines should be followed?**



FCC-ee:

Designed by CERN vacuum group (TE/VSC)

- **Discrete photon stoppers** made of **copper-alloy (CuCrZr)** intercept the primary SR fan (stopper length: about 30 cm)
- Placed in the winglets of the Cu vacuum chamber of dipoles (typical distance between stoppers: 4-5 meters), shadowing also the SSS

A system, similar the Warm Magnet interlock Controller (WIC), presently used at all accelerators at CERN, might need to be used to interlock the synchrotron radiation absorbers

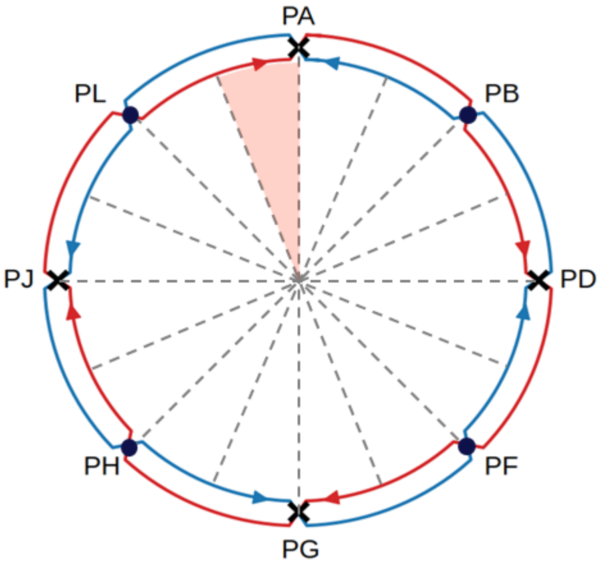
This will be a large distributed interlock system

Main dipoles powering failure

- **Main dipoles powered by half-arc** (175/180 dipoles in series per circuit)
- Loss of a power converter => **Fast decay of the bending magnetic field**

$$\boldsymbol{k_0} \rightarrow \boldsymbol{k_0} * \boldsymbol{e^{-t/\tau}} \text{ with } \tau = \frac{L_{circuit}}{R_{circuit}} = 0.3\ s$$

- ~ 10 turns to lose 1% of the bending magnetic field



× IP (Interaction Point – Experiments)
● IT (Technical Insertion – Injection, Extraction to beam dump, RF, Collimation)

XSuite simulations:

- Single particle tracking
- Impact of tapering
- Synchrotron radiation

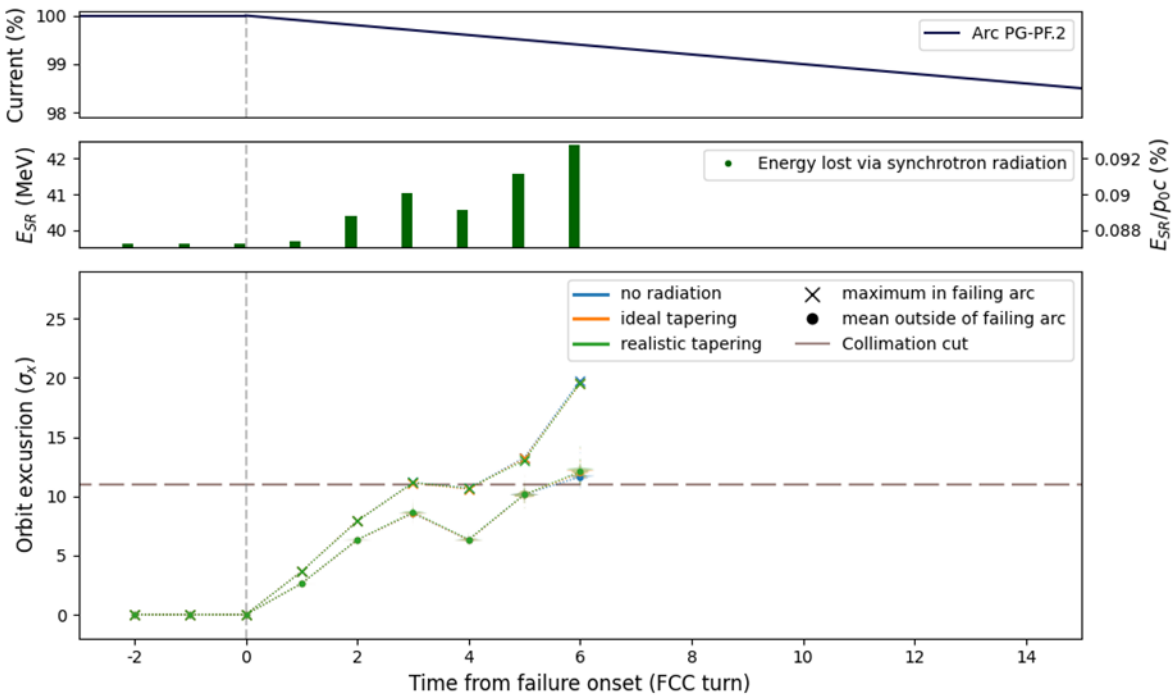
→

Worse case results for Z-pole and $t\bar{t}$ energy

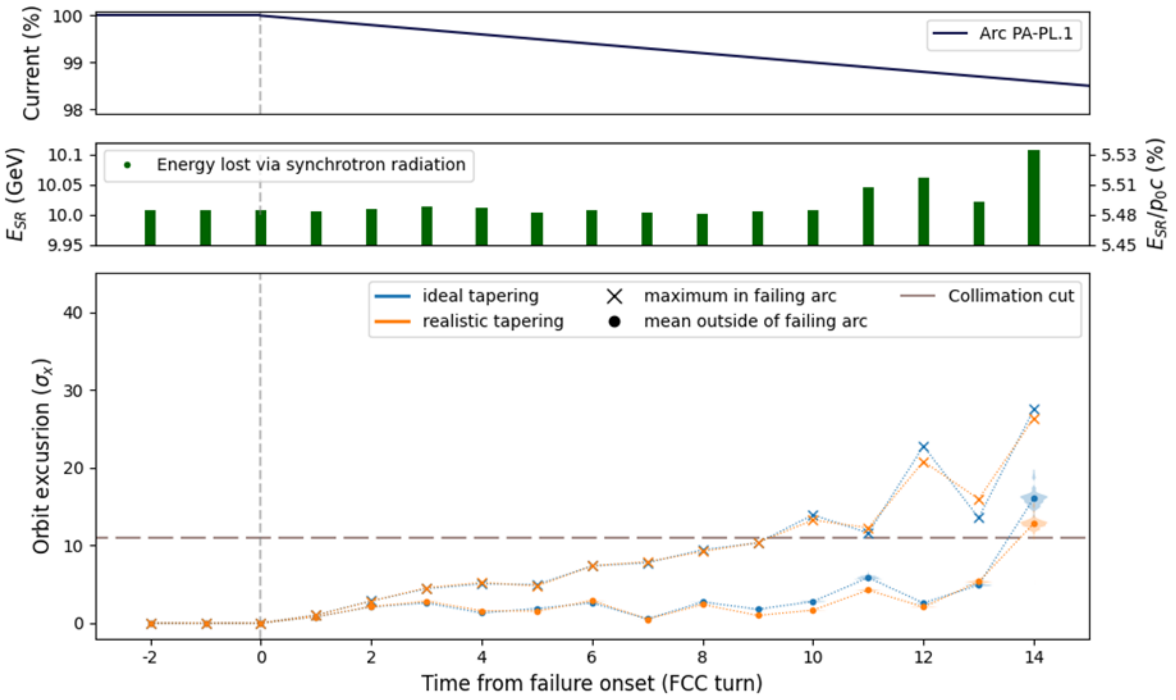
See presentation Delphine Domange, this session

Main dipoles powering failure

Z-pole energy (45.6 GeV) - Arc PG-PF.2 - 6 turns



$t\bar{t}$ energy (182.5 GeV) - Arc PA-PL.1 - 14 turns



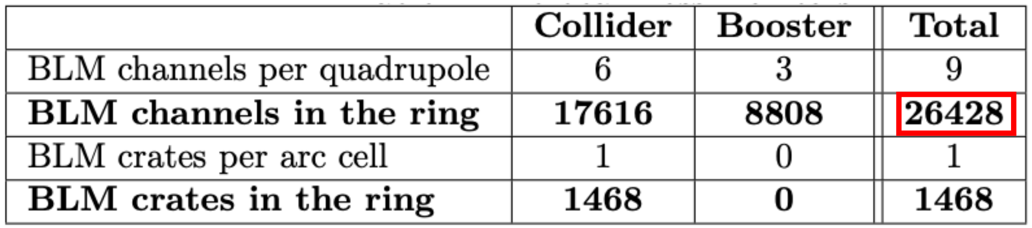
See presentation Delphine Domange, this session

- Fast loss of the particle
- Limited orbit excursion followed by a sudden jump that can be larger than 10σ

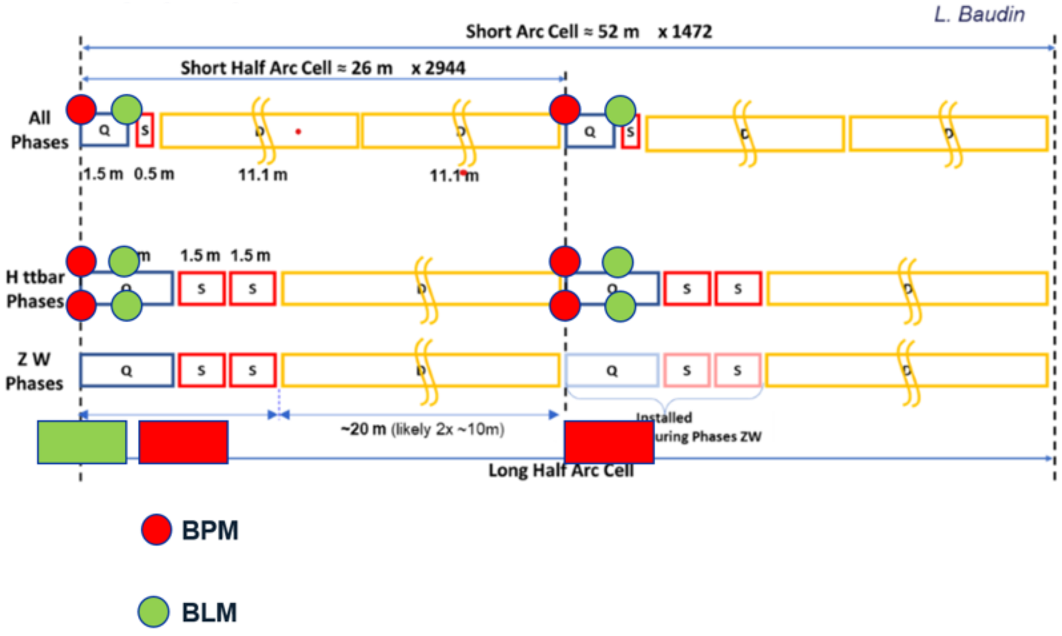
- Detection by BLMs or BPMs might be too slow
- Need to consider Fast Magnet Current Change Monitor – need to be reliable
- Other option is to change time constant of the circuit, add large inductance

Beam Loss Monitors (and Beam Position Monitors)

- **Used as a general and very reliable safety net for the LHC with about 4000 monitors**
- **Also for FCCee foresee a full coverage of the machine**
  - Need to define the spacial coverage → Initial proposal with more than 26'000 BLMs
  - Need to define the sensitivity and dump limit
  - Need to define the required time resolution and reaction time
  - Need to be very reliable if a single BLM can dump the beam
- **Due to very small vertical beam size, part of this functionality might need to be completed by hardware interlocked Beam Position Monitors, distributed over the machine**
- **The electronics needs to be shielded from synchrotron radiation**



	Collider	Booster	Total
BLM channels per quadrupole	6	3	9
BLM channels in the ring	**17616**	**8808**	**26428**
BLM crates per arc cell	1	0	1
BLM crates in the ring	**1468**	**0**	**1468**



See B. Salvachua, later this session

Conclusions on Machine Protection

- **The beams are dangerous, very bright**
- **The environment is hostile with a lot of synchrotron radiation**
- **Several failure modes with a time scale of a few turns have been identified**
- **The inherent delay of dumping a beam is four turns**
  - 1 detection,1 transmission,1 for synchronization to the abort gap,1 to get the last electron/positron out
  - Can gain on detection and number of abort gaps
- **A full inventory of failures needs to be made**
  - Specification of all hardware failure modes that can lead to beam loss and the equipment design aspects
  - A good start has been made in the Machine Protection Task Force, a lot of work still outstanding
  - Sudden beam losses as seen at SuperKEKb need to be understood, model to be applied to FCCee
- **Then a coherent machine protection system can be defined**
  - Detection of the failure by beam diagnostics, besides the detection by the hardware
  - Definition of the Beam Interlock System, Warm Magnet Protection, BLMs, BPMs, Fast Magnet Current Change Monitor etc.
- **The protection system and all other hardware needs to provide a good balance between Protection/Reliability and Availability**
  - FCC work package covering both Availability and Machine Protection
- **All hardware teams to subscribe to a coherent approach across all systems**
- **It will be challenging**

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