Beam losses and damage potential of the FCC-ee beams

Anton Lechner (SY/STI)

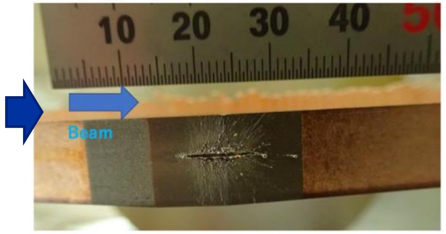
30/05/2024

Introduction

- **Beam losses can be of different origin (some are regular, some are accidental)**
  - Beam-beam (e.g. radiative Bhabha, Beamstrahlung, …)
  - Beam-gas scattering
  - Touschek scattering, intra-beam scattering, …
  - Hardware failures, timing errors (e.g. beam transfer&extraction failures, cavity failures …)
  - Matter entering the beam (dust) or aperture restrictions (obstacles)
  - Instabilities
  - ….

Superfast losses in SuperKEKB (origin still under investigation)

Damaged jaw



Not to forget synchrotron radiation, which can be more important for these effects than beam losses (depends on location)

Main concerns:

- Detector background
- long-term radiation damage
- single event effects in electronics
- ***quenches of final focus***
- ***machine and detector damage***

Machine protection topics

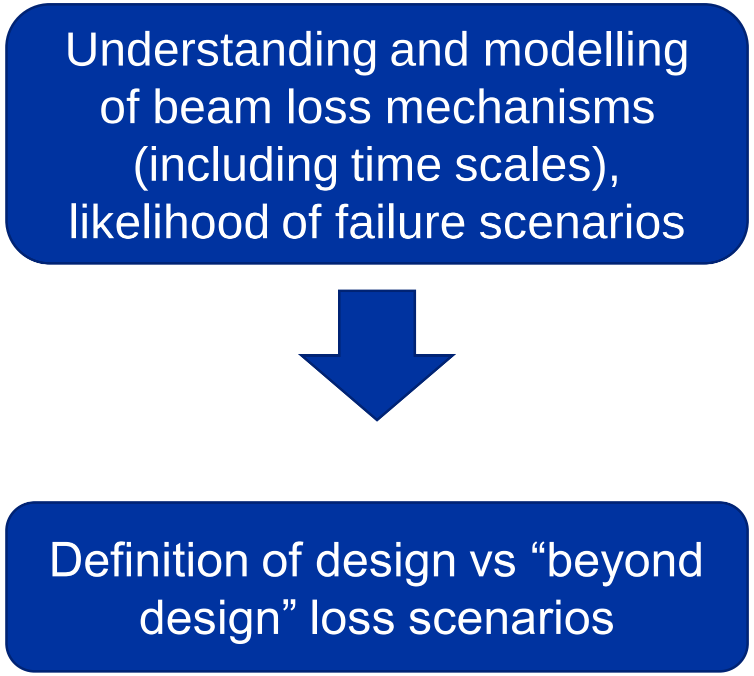
Protection absorbers
Collimation system
Beam Loss Monitor system
Beam interlock system
Beam dump system
…

System design requirements – many open questions

- **Beam loss monitor system**
  - Time resolution? response time? spatial resolution? pattern recognition? → which kind of beam loss scenarios?
  - Operating conditions – how to detect beam losses on top of synchrotron-induced radiation fields? Cross-talk between booster and collider?
- **Beam abort system**
  - Required reaction time? All gaps in filling scheme as abort gaps? *Do we need multiple beam dump systems (per beam) at different locations? (this was a recurring question ...)*

1 turn is 300 μs!

- **Passive protection systems**
  - How to cope with the small beam emittance (material robustness)? Local vs global protection (aka protection absorbers vs collimation system), protection absorbers upstream of experiments?
- **Active mitigation systems**
  - Mitigation of beam instabilities?

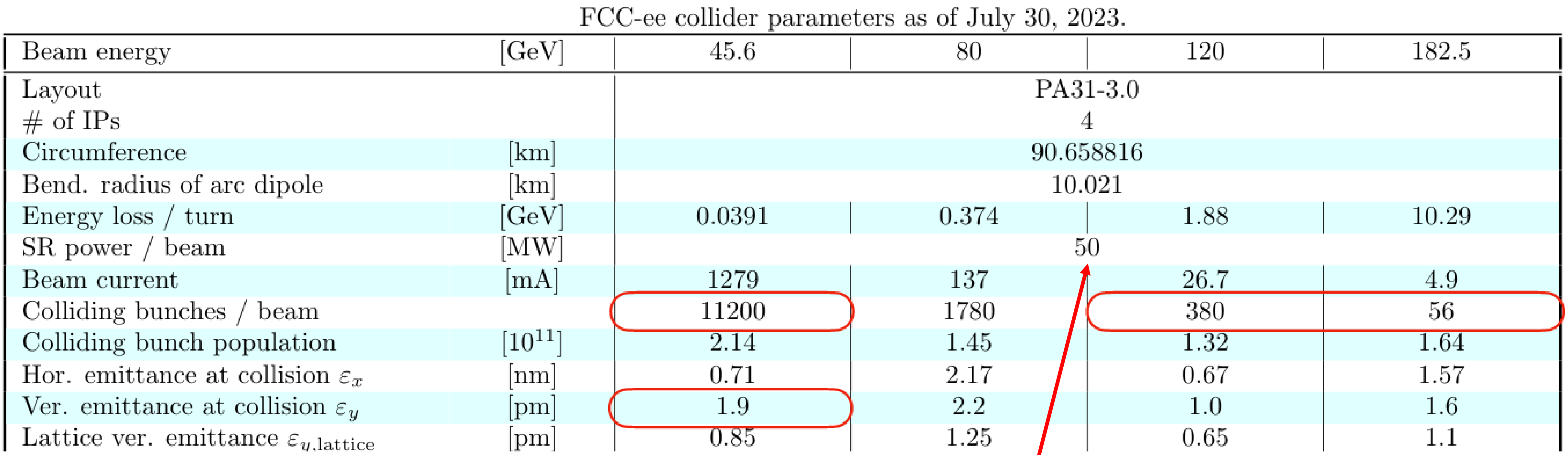


Understanding and modelling of beam loss mechanisms (including time scales), likelihood of failure scenarios

Definition of design vs “beyond design” loss scenarios

Can start from high-level considerations: How destructive are the FCC-ee beams?

FCC-ee beam parameters*



FCC-ee collider parameters as of July 30, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.88	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1279	137	26.7	4.9
Colliding bunches / beam		11200	1780	380	56
Colliding bunch population	[10^{11}]	2.14	1.45	1.32	1.64
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.67	1.57
Ver. emittance at collision ε_y	[pm]	1.9	2.2	1.0	1.6
Lattice ver. emittance $\varepsilon_{y,\text{lattice}}$	[pm]	0.85	1.25	0.65	1.1

Beware: table not up to date, beam parameters changed again yesterday (*tradeoff between number of bunches and bunch intensity for W, ZH, ttbar*)

By design ➡ **Intensity limited by SR power**

K. Oide, FCCIS WP2 Workshop 2023, Rome, https://indico.cern.ch/event/1326738/

Energy density of stored beam: FCC-ee vs HL

Collider beam parameters:

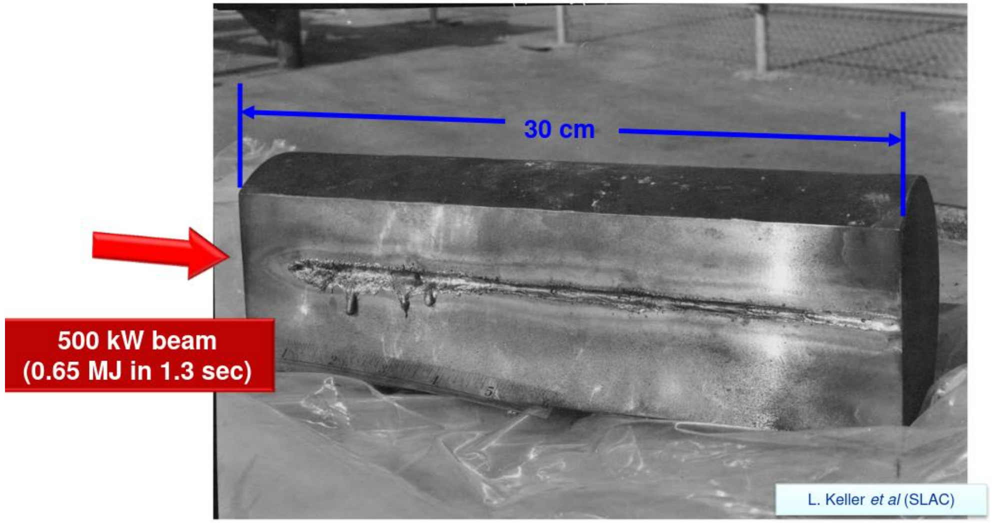
	FCC-ee (Z)	FCC-ee (W)	FCC-ee (ZH)	FCC-ee (ttbar)	HL-LHC*	
Beam particles	e-/e+				p	
Energy E	45.6 GeV	80 GeV	120 GeV	182.5 GeV	450 GeV	7000 GeV
Beam intensity I	11200b x 2.14x10^{11} ppb =2.4x10^{15}	1780b x 1.45x10^{11} ppb =2.6x10^{14}	380b x 1.32x10^{11} ppb =5x10^{13}	56b x 1.64x10^{11} ppb =0.9x10^{13}	2760b x 2.2x10^{11} ppb =6.1x10^{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)**

Destructive potential of FCC-ee beams

- FCC-ee beams: **high intensity (at Z)** and **small emittance** → significant destructive potential in case of accidental beam losses
- The risk of damage strongly depends on the actual loss scenario (i.e. particle loss distribution and loss duration)
- Nevertheless, can get a first feeling about the damage potential by studying a generic impact scenario (one bunch on a block of copper)
- Note: the energy density of the beam itself does not give the full picture → when comparing to HL beams need to consider also the **different shower development** of EM and hadronic showers (at largely different particle energies)



L. Keller *et al* (SLAC)

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

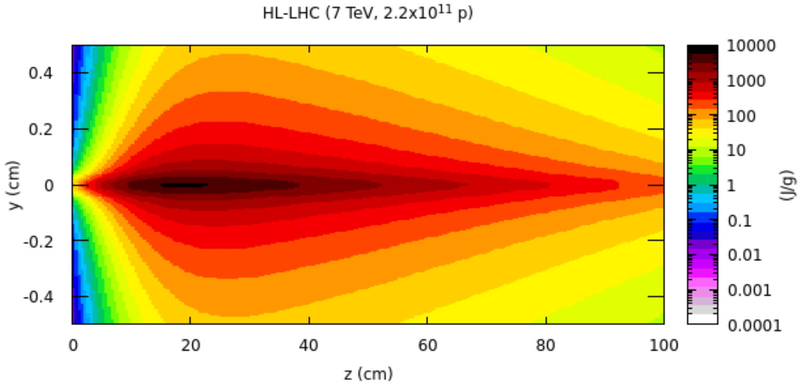
This was a slow beam loss (0.65 MJ in 1.3 s) with a large beam spot size (2mm).

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

Energy deposition: FCC-ee vs HL (one bunch)

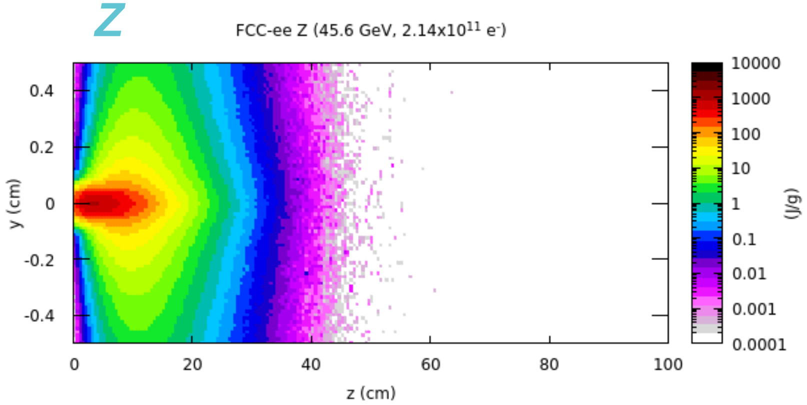
One bunch on a block of copper, assuming ß-functions of 100m in both planes (dispersion contribution neglected)

Horizontal plane (HL-LHC):

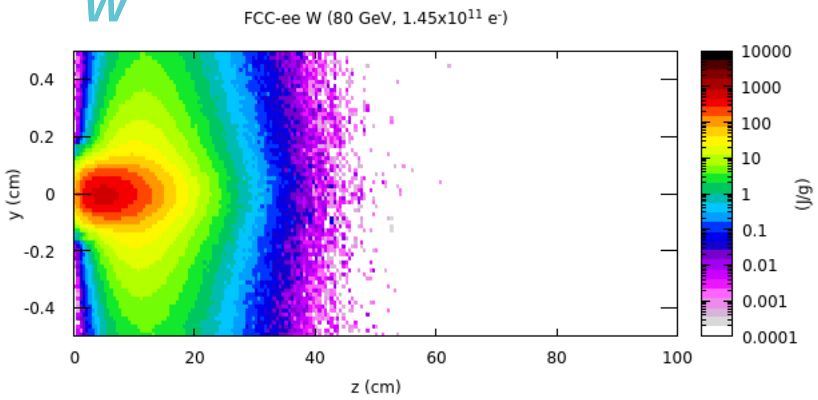


Horizontal plane (FCC-ee):

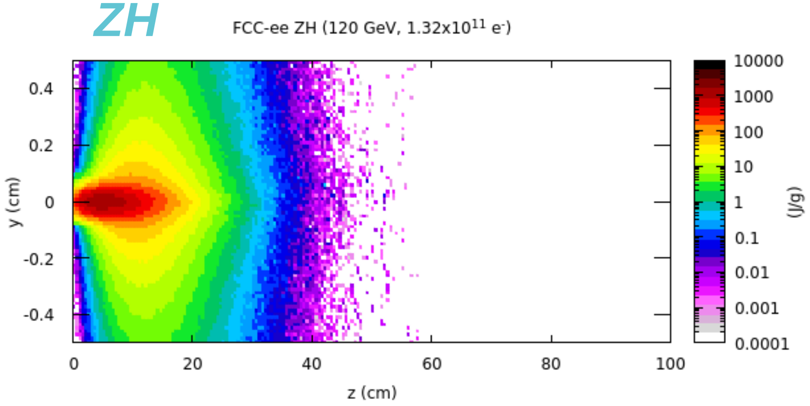
Z



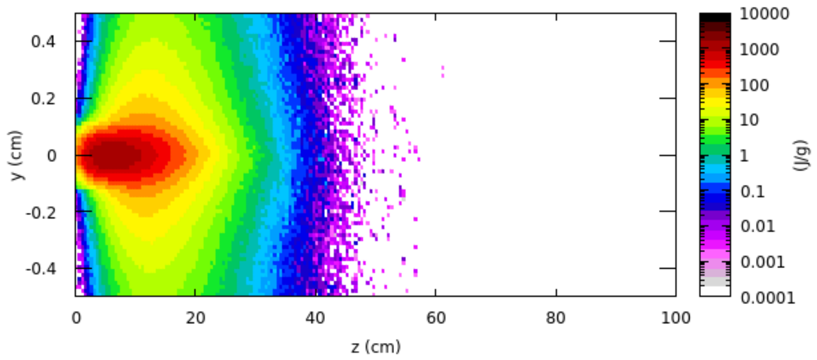
W



ZH



ttbar



Lateral shower width for EM showers:

Well described by Moliere radius:

$$R_M = \frac{E_s^\dagger}{E_c} X_0 = \frac{21\ \mathrm{MeV}}{E_c} X_0$$

= average lateral deflection of electrons with $E = E_c$ after traversing one X_0 (90% of energy deposition within $\sim 1\, R_M$)

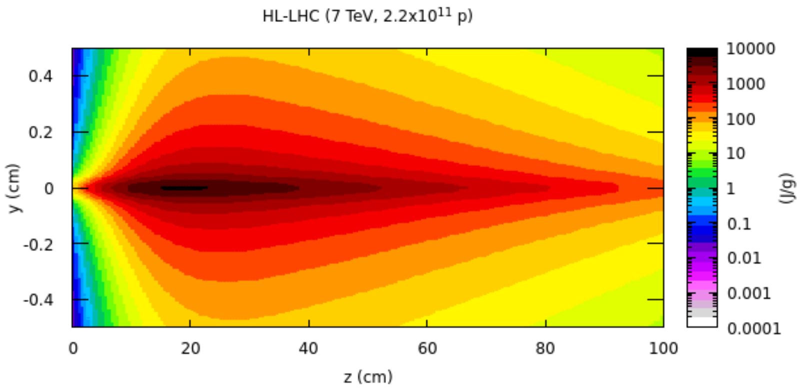
† $E_s = \sqrt{4\pi/\alpha}\, m_e c^2$, where α is the fine structure constant

EM shower length increases with log(E) and is proportional to X_0

Energy deposition: FCC-ee vs HL (one bunch)

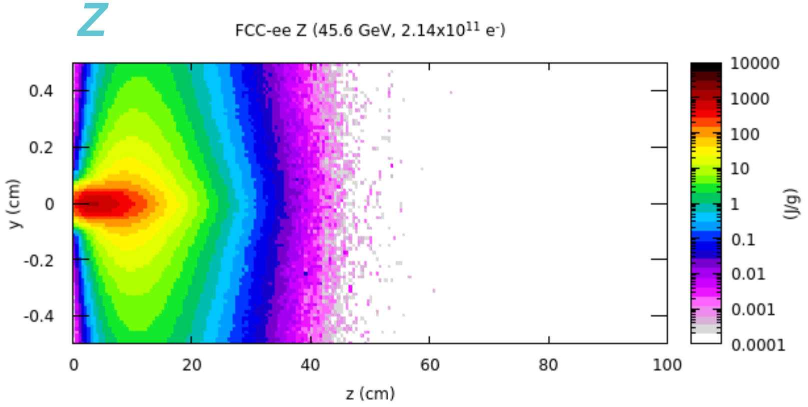
One bunch on a block of copper, assuming ß-functions of 100m in both planes (dispersion contribution neglected)

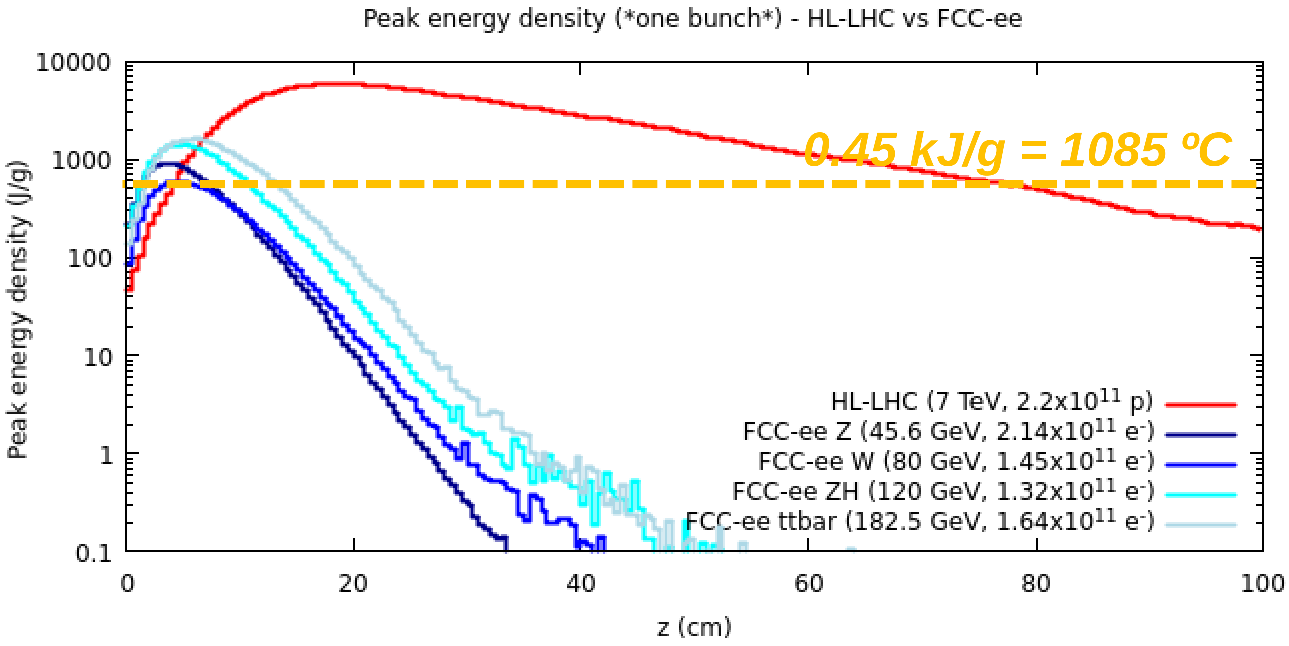
Horizontal plane (HL-LHC):



Horizontal plane (FCC-ee):

Z





Max energy density by one bunch in Cu for the assumed optics function:

HL-LHC	FCC-ee (Z)	FCC-ee (W)	FCC-ee (ZH)	FCC-ee (ttbar)
5.8 kJ/g	0.9 kJ/g	0.6 kJ/g	1.4 kJ/g	1.6 kJ/g

The energy deposition density by one FCC-ee bunch in copper is 4-10 times lower than for one HL-LHC bunch, but one can nevertheless reach the melting point

Considerations for HEB-to-FCC-ee transfer

- **FCC-ee beams@Z have the potential to damage protection absorbers**
  - Need large transverse spot size at absorber locations, i.e. large ß-functions
  - Larger emittances can also help if affordable by the injection process
  - *In addition, we limited the intensity for the booster-to-collider beam transfer at Z mode from 10% to 1% of the collider intensity*
  - Nevertheless the FCC-ee injection trains have a higher energy density than HL-LHC injection trains

	Energy	Assumed train intensity	Stored energy	Geom. emittances
SPS to HL-LHC	450 GeV	6.6×10^{13} p (288b, 2.3×10^{11} ppb)	4.78 MJ	4.4 nm
HEB to FCC-ee (**Z**)	45.6 GeV	2.4×10^{13} e+/e-	0.175 MJ	0.26 nm / 0.53 pm (booster emittances*)

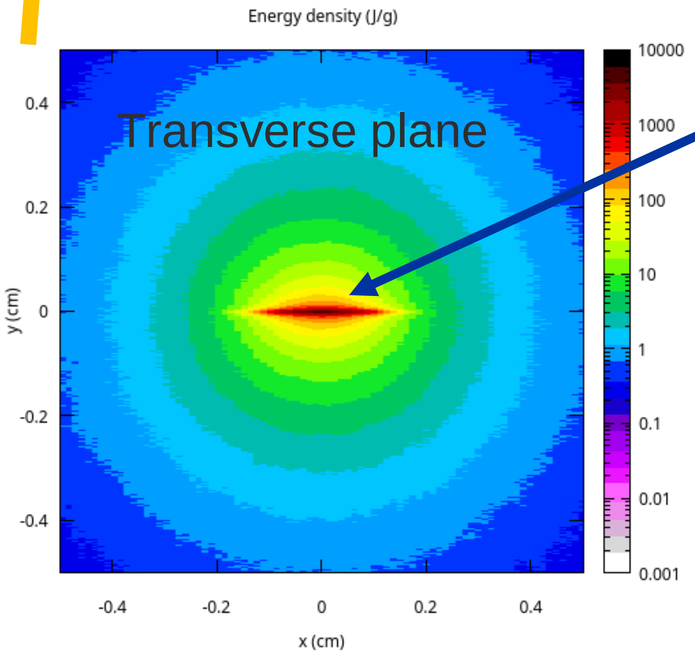
For the same ß-functions, the FCC-ee train energy density (MJ/mm^2) is ***>10 times higher than HL-LHC (will depend on emittance)***

**Emittances from Antoine's talk at the FCCIS WP2 workshop in Rome (Nov 2023); vertical emittance was calculated assuming a coupling of 0.001.*
BUT: these emittances are still changing!

Energy deposition by FCC-ee injection train in graphite/CfC absorber block

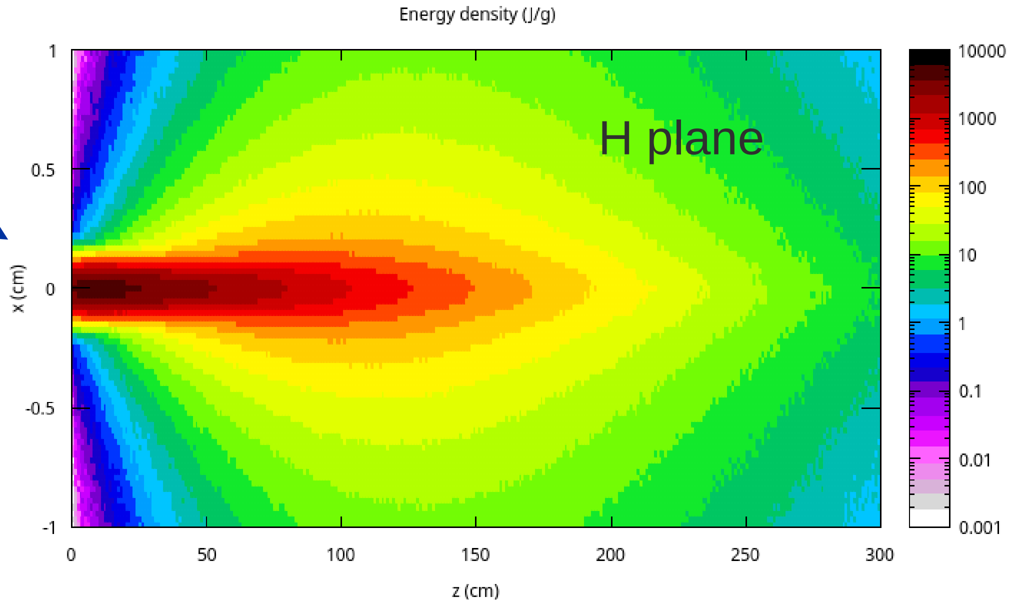
Example (Z pole, 45.6 GeV):

- *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 ºC)

Quite high…

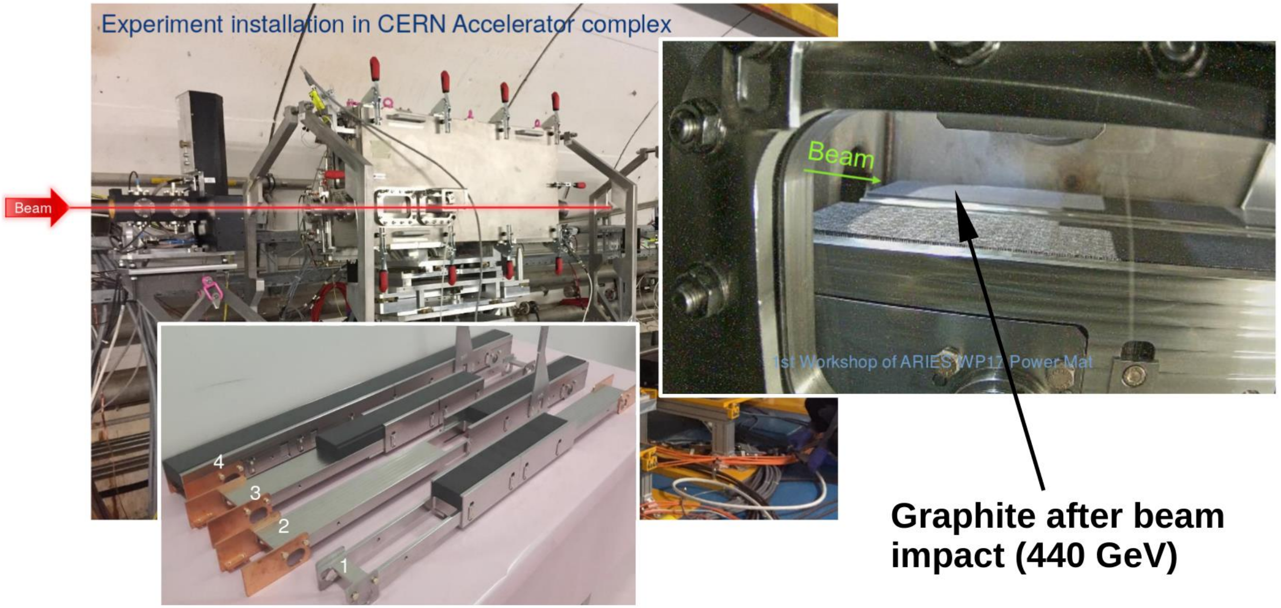


3 m

Material tests in HiRadMat

Pictures show HRMT-28 (F.X. Nuiry et al.)

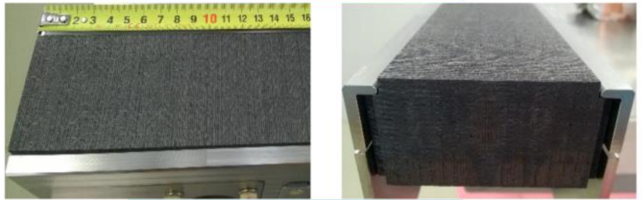
Different graphite and 3D CfC grades (from different manufacturers) were tested in HiRadMat (440 GeV p) in the past 10 years



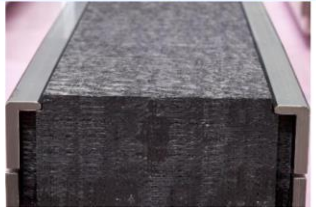
Graphite after beam impact (440 GeV)

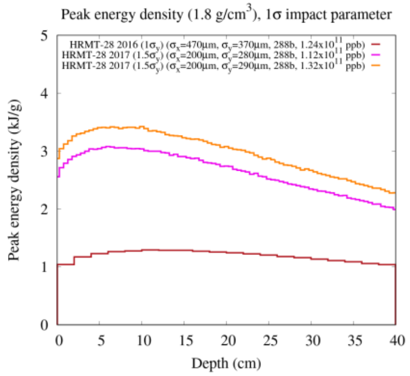
3D CC

Before impact

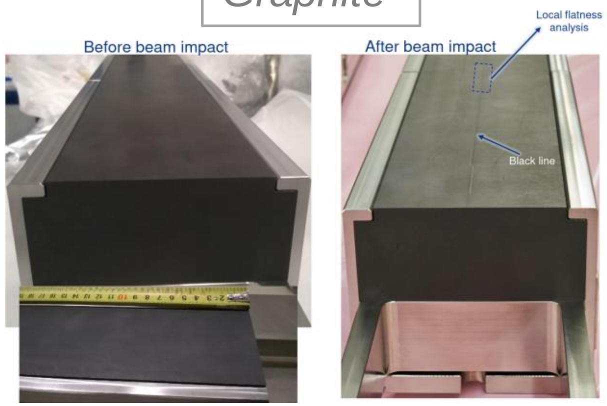


After impact





Graphite



In HRMT-28, a peak energy density of almost **3.5 kJ/g (2300 ºC)** was achieved in Graphite (1.83 g/cm^3) without visible damage

Can take this as a tentative material limit (note: this is only a very rough criterion → for a more precise answer, stresses need to be assessed on a case-by-case basis, in particular for the flat FCC-ee beams)

Conclusions

- The small-emittance beams in FCC-ee pose a challenge for machine protection, in particular in combination with a high beam-intensity as in Z operation
- The overall destructive potential is less than for HL-LHC beams, but nevertheless even a single bunch can induce temperatures higher than the melting point of copper
- Beam transfer from the HEB to the collider is delicate for machine protection (at Z, the injection trains have a higher energy density than HL injection trains → challenging for absorber materials)
- It will be crucial to compile a list of failure scenarios, in order to derive specifications for systems

home.cern

Protection absorbers for SPS-to-LHC beam transfer

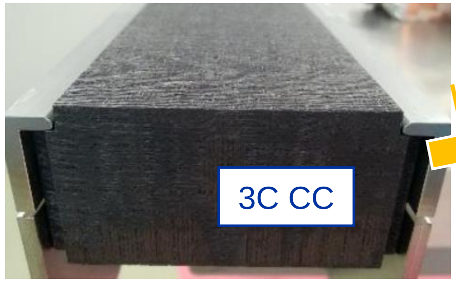
Absorber materials → must resist to high energy densities (kJ/g/pulse)

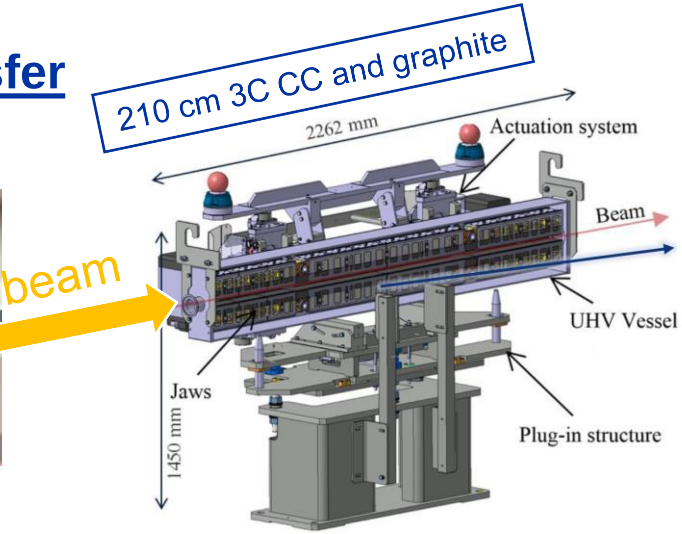
Typical materials used at CERN:

- Isotropic graphite
- 2D reinforced Carbon/Carbon composites
- More recently 3D Carbon/Carbon composites

Often complemented downstream by metals (e.g. TiGr5, CuCr1Zr) for better absorption

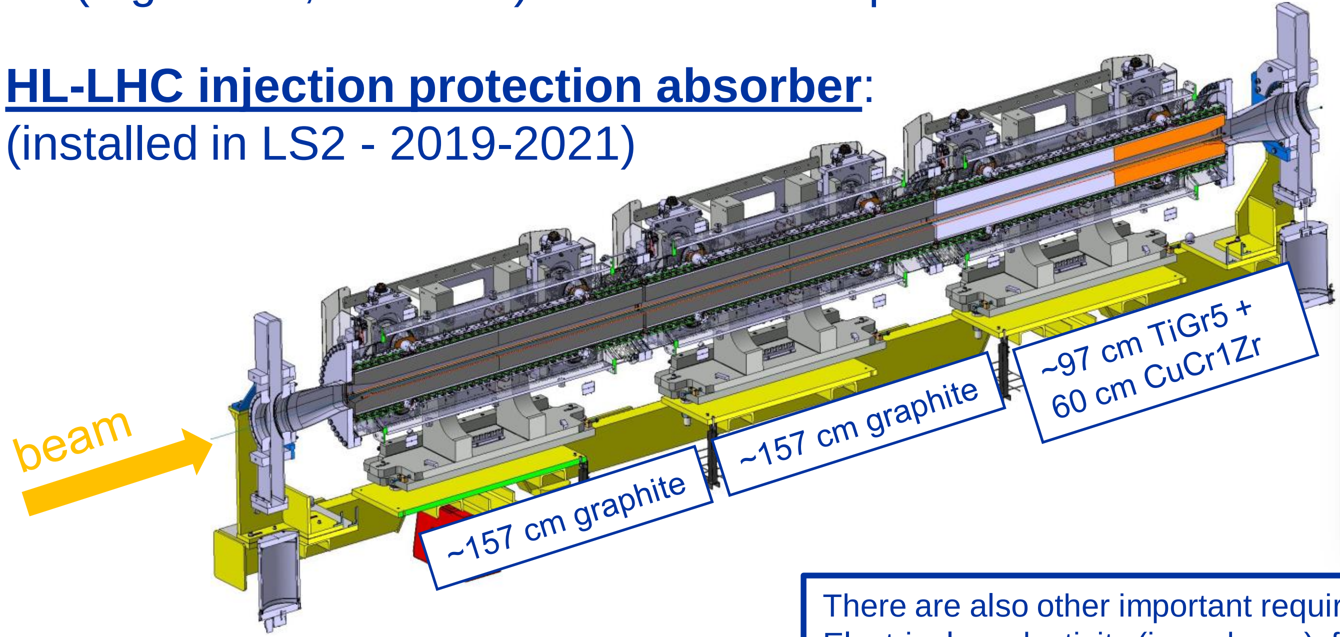
SPS-to-HL-LHC transfer line collimators:

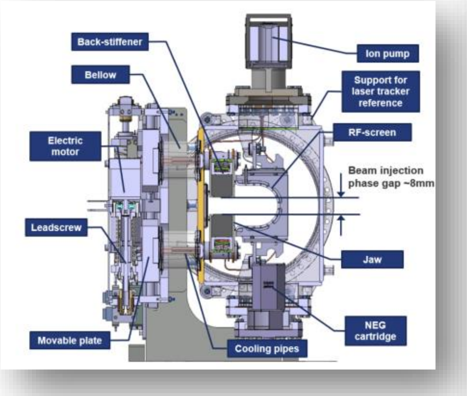


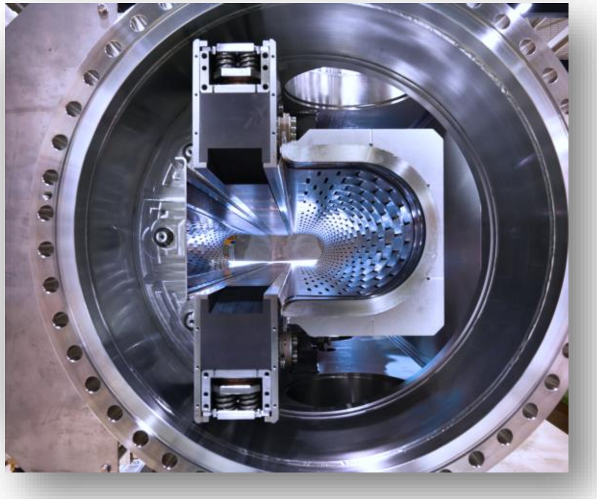


HL-LHC injection protection absorber:

(installed in LS2 - 2019-2021)





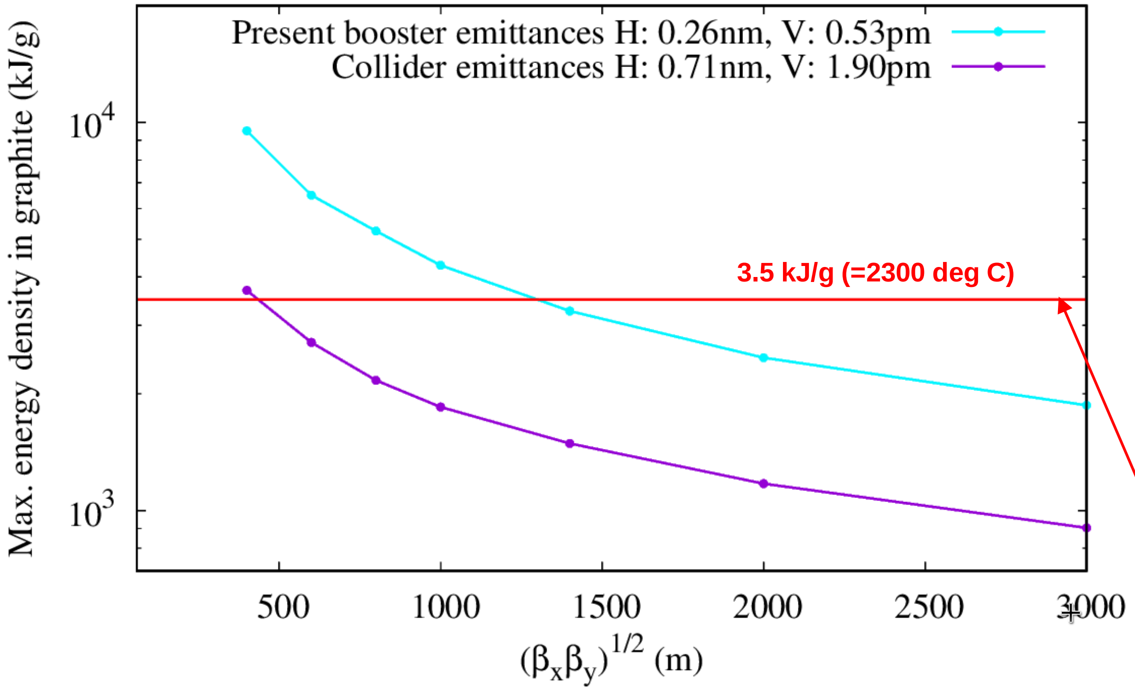


There are also other important requirements for the devices:
Electrical conductivity (impedance), flatness, etc.

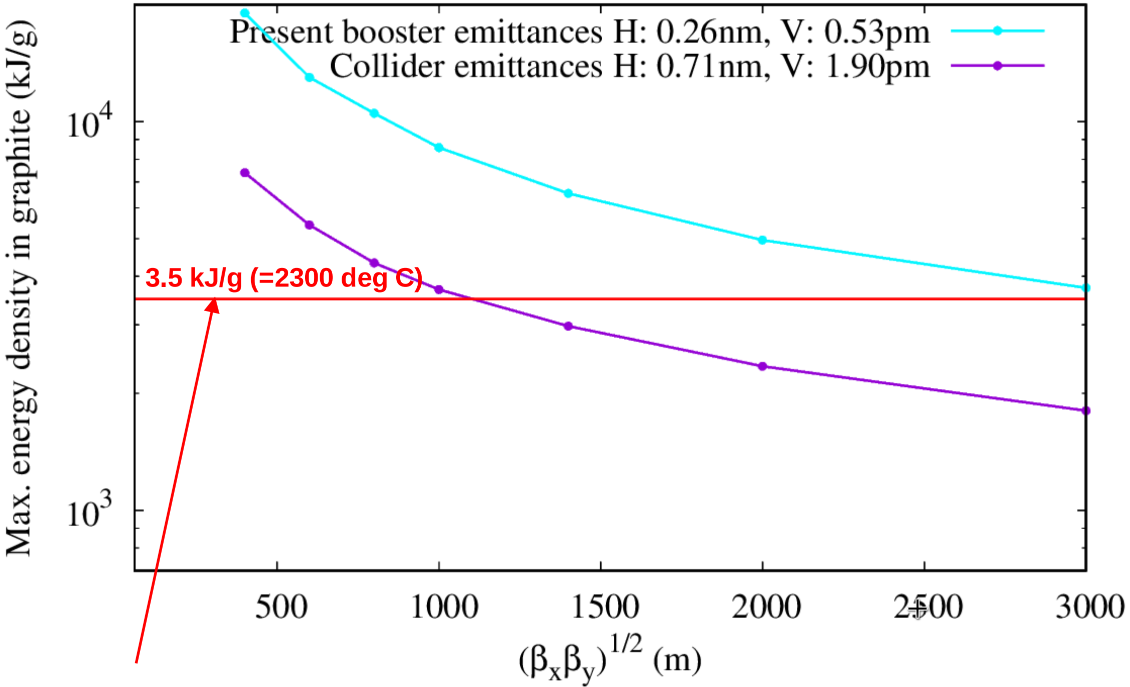
Max. energy density in graphite/CfC (1.8 g/cm^3)

FCC-ee injection train (Z-pole): maximum energy density in block vs local beta-function at absorber location comparing present booster emittances ***(0.26nm, 0.53 pm)*** *with collider emittances* ***(0.71nm, 1.9pm):***

0.5% of collider intensity (1.2 ×10^{13} e-):



1.0% of collider intensity (2.4 ×10^{13} e-):



Just a rough guideline