Energy deposition in collimator/dump materials: challenges due to the energy increase to 50 TeV

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Introduction

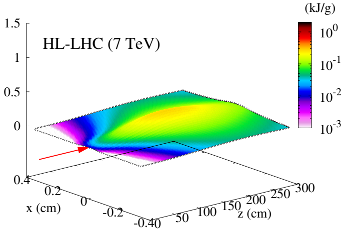
- In the LHC, a range of devices/absorbers is directly exposed to the beam* (or the beam halo):
  - Collimators (halo cleaning, protection etc.)
  - Injection protection devices
  - Protection devices in case of dump failures
  - Dump

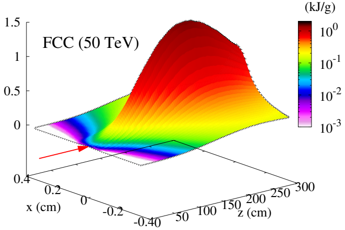
  → evidently, in one or another form also required for the FCC-hh (see [1-3])

- What are the implications for such devices/materials if the beam energy increases from 7 TeV to 50 TeV?
  - The aim of this presentation is to derive first estimates of the deposited energy/power
  - Main focus is on light absorber materials presently used in the LHC

[1] M. Fiascaris, "Collimation system design".
[2] W. Bartmann, "Injection and extraction".
[3] W. Bartmann, "Beam Dump concepts and design".

* During regular operation and/or in case of accidental beam losses.

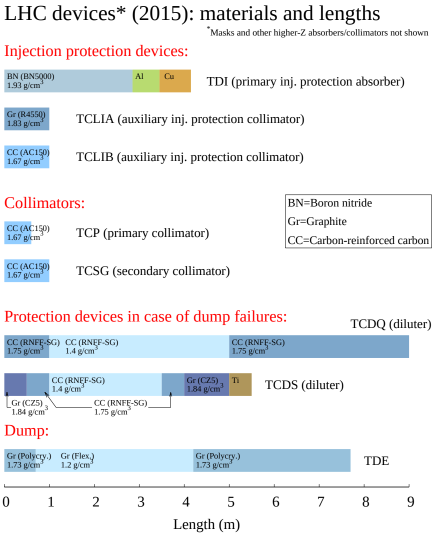




Figures: Energy density in 3 m-long Graphite (1.83 g/cm^3) for one nominal proton bunch (σ=400μm), comparing HL-LHC (top) and FCC (bottom).

- Light materials are typically used for robustness reasons:
  - present LHC devices (except the TDI) rely on different grades of Graphite and CfC
  - densities between ∼1.2 and ∼1.9 g/cm^3
  - in some cases (e.g. injection failures) already challenging to find suitable materials for HL-LHC beams

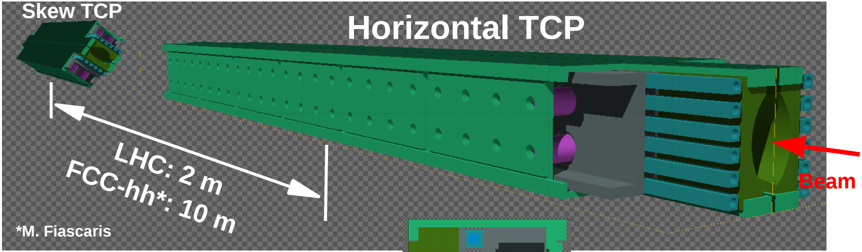
- Outline of the presentation:
  - Power deposition in primary collimators during halo cleaning
  - Energy deposition by a single 50 TeV bunch lost on an absorber
  - Basic considerations about the beam dump (sweep)

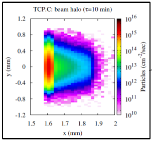


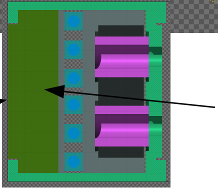
Contents

Collimation layout and halo cleaning

- First FCC-hh collimation layout design → see M. Fiascaris talk:
  - Similar system as in the LHC, with the present collimator lengths and materials e.g. 3 primary collimators (TCPs) made of CfC, but further apart
  - Optics scaled from LHC to have similar collimator gaps (in mm)





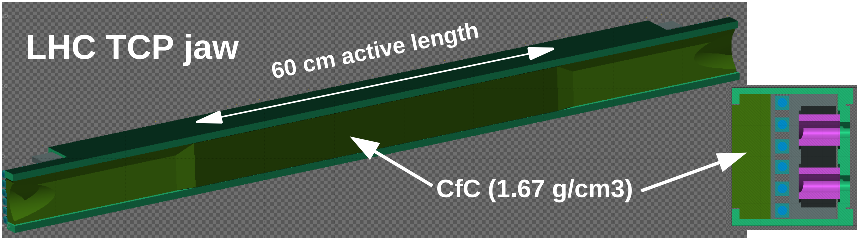


CfC(AC150K)
1.67 g/cm3

Calculating the power deposition in collimators

- Halo cleaning:
  - Only a fraction of the impacting power is deposited in the TCP jaws
- Highest load of all collimators in LHC → skew TCP:
  - is the most downstream TCP
  - is exposed to showers from other TCPs
- Getting a first estimate of the total power deposition in jaws for FCC:
  - Same collimator design assumed as in LHC
  - Starting point of shower simulations: inelastic collisions in jaws from multi-turn tracking simulations with SixTrack (courtesy of P. Garcia Ortego and M. Fiascaris)

→ Total power not too much dependent on mean impact parameter of halo particles



First power deposition estimates for primary collimators assuming τ =0.2 h

	LHC	HL-LHC	FCC-hh
Energy	7 TeV	7 TeV	50 TeV
Bunch intensity	1.15×10^{11}	2.2×10^{11}	1.0×10^{11}
Bunches	2808	2748	10600
Proton loss rate (τ=0.2 h)	4.5×10^{11} sec^{-1}	8.4×10^{11} sec^{-1}	1.5×10^{12} sec^{-1}
Power loss (τ=0.2 h)	503 kW	941 kW	11786 kW
Distance betw. TCPs	2 m	2 m	10 m
Power deposition in horizontal TCP (most impacted jaw)			
Entire jaw	1.6 kW	3.0 kW	13 kW
CfC block (AC150)	0.6 kW	1.2 kW	5.2 kW
Power deposition in skew TCP (most impacted jaw)			
Entire jaw	7.7 kW	15 kW	121 kW
CfC block (AC150)	3.2 kW	6.0 kW	45 kW

→ For the same beam lifetime, the power loss increases by a factor 12 from HL-LHC to FCC

→ Simulation predicts an 7-8 fold increase of the power deposition in the skew TCP from HL-LHC to FCC if one assumes the scaled layout presented by M. Fiascaris

→ Results depend on layout specifics (collimator length, distance betw. collimators etc.)

→ For LHC, the power load to secondary collimators is equal or smaller compared to the skew primary: to be studied for FCC.

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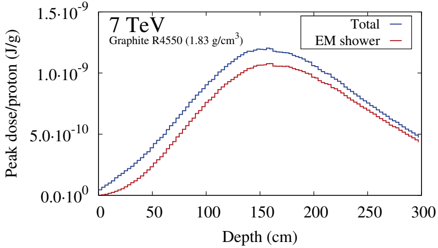
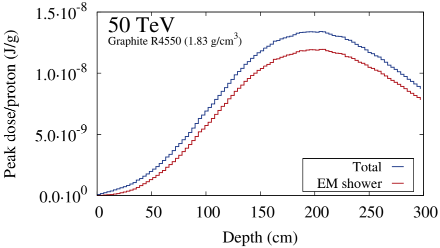
Energy deposition: contribution of electromagnetic showers at LHC and FCC energies

- At each inelastic proton-nucleus collision, about 1/3 of the energy goes into π^0's
- π^0's give rise to EM showers ($\pi^0 \rightarrow \gamma\gamma$)
  - concentrated along the core of the overall shower development
- At LHC and FCC top energy and for typical beam sizes, they yield the dominating contribution to the peak energy density
  - not only in heavy materials, but also in lighter absorbers (where X_0 can be a few tens of cm)

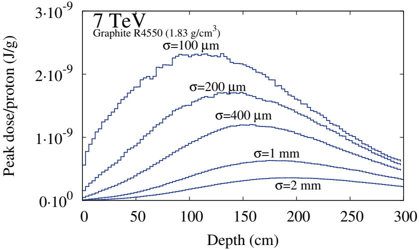
Figures: longitudinal peak dose induced by round beam (400 μm) in Graphite (1.83 g/cm^3).

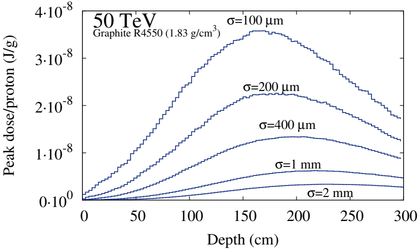




Energy deposition: increase of the peak energy density from 7 TeV to 50 TeV

- The transverse momentum of hadrons produced in nuclear collisions (incl. π^0's) is more or less invariant with energy
  - hence, their angular opening narrows with energy
  - this in turn leads to a greater overlap of the EM components of the shower
- For the same physical beam size, the max. energy density scales more than just with the ratio of beam energies ($50/7 \approx 7$), e.g. in Graphite/CfC:
  - $\sigma = 100\,\mu$m: factor $\sim$15–16 increase
  - $\sigma = 1$ mm: factor $\sim$9–10 increase
- Evidently, one needs to consider in addition that beams are smaller compared to HL-LHC if β-functions remain similar





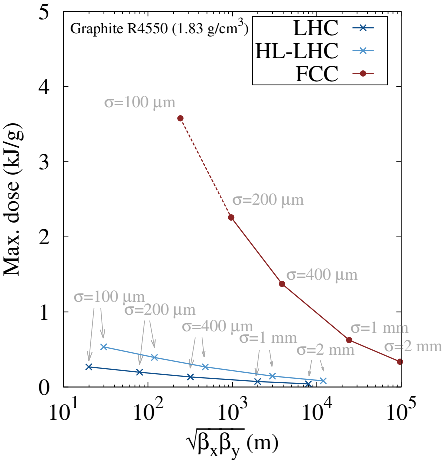
Figures: longitudinal peak dose induced by diff. round beams in Graphite (1.83 g/cm^3).

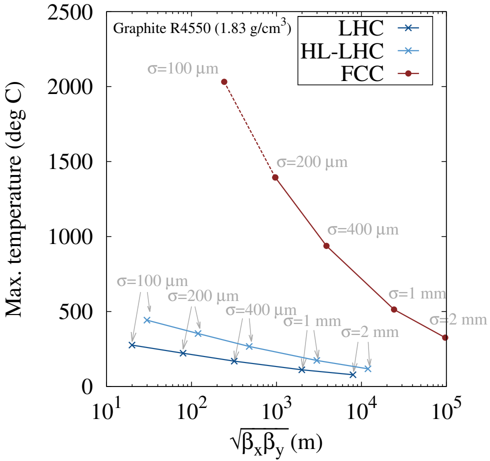
FCC vs (HL-)LHC: dependency on β-function at absorber location

1 proton bunch, Graphite ($1.83\,g/cm^3$)

(Dispersion contribution to beam size neglected)

	LHC	HL-LHC	FCC
E (TeV)	7	7	50
ϵ_n (μm·rad)	3.75	2.5	2.2
ppb ($\times 10^{11}$)	1.15	2.2	1.0





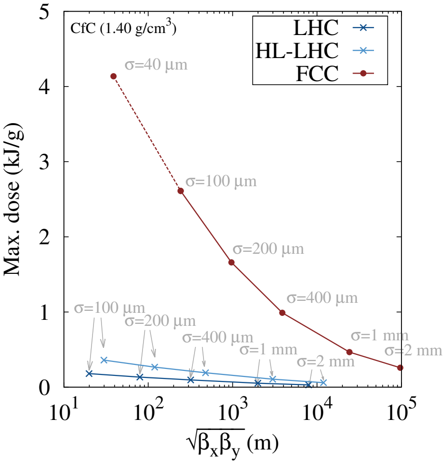
→ For small spot sizes could expect some (localized) material damage from 1 bunch.

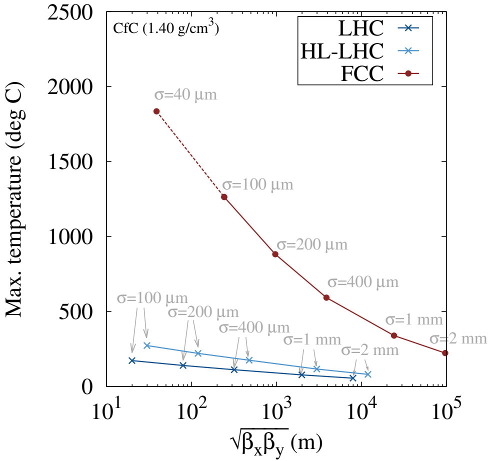
FCC vs (HL-)LHC: dependency on β-function at absorber location

1 proton bunch, CfC (1.4 g/cm^3)

(Dispersion contribution to beam size neglected)

	LHC	HL-LHC	FCC
E (TeV)	7	7	50
ϵ_n (μm·rad)	3.75	2.5	2.2
ppb ($\times 10^{11}$)	1.15	2.2	1.0





→ For small spot sizes could expect some (localized) material damage from 1 bunch.

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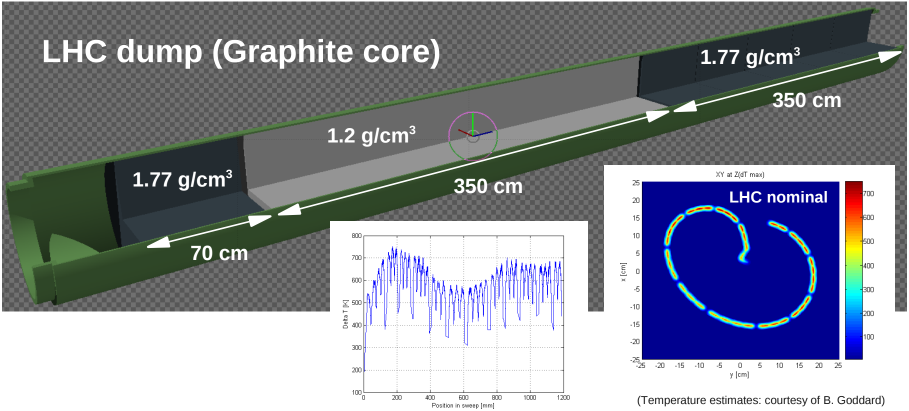
Can the materials of the present LHC dump cope with 50 TeV beams?

- Or in other words: can the beam be sufficiently diluted?
  - Local temperature increase should remain below a predefined limit (roughly 1500°C, otherwise one could risk localized fracture)



(Temperature estimates: courtesy of B. Goddard)

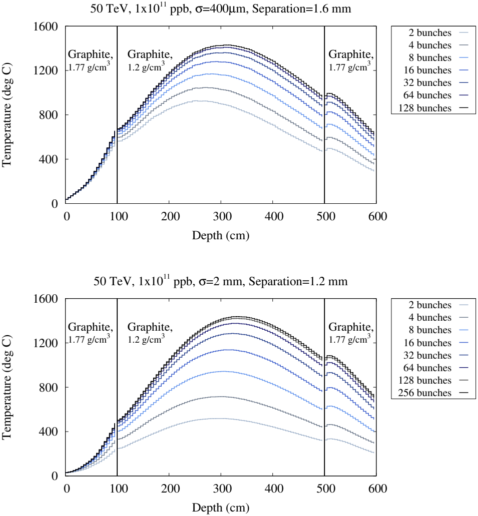
Some (very basic) considerations about a sweep for different βs at the dump block

For which lateral bunch separation levels the temperature off at an acceptable value?

- β-functions of a few km like at LHC (σ=few 100 μm)
  - → neighbouring bunches need to be separated by at least 1.6–1.8 mm
- β-functions of 100 km (σ=2 mm)
  - → limited gain, required separation still around 1.2–1.5 mm
- Even with very large β-functions, one would probably need a minimum* sweep path length of roughly 20 m for 10600 bunches

* Note:

- The results only reflect contributions of neighbouring bunches, for a more complete picture one needs to take into account the full sweep pattern (i.e. contribution of far tails)
- The indicated path length only represents a minimum value based on the maximum acceptable temperature. In practical terms the sweep length might be quite longer, e.g. due to variations in the sweep speed etc.
- Estimated sweep path length tentatively includes gaps in the filling scheme.



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Summary and conclusions (1/2)

- How much power deposition do we expect in primary collimators for short beam lifetimes?
  - For beam lifetimes of 0.2 h, the power deposition in a single jaw can exceed 100 kW
  - Power load could still be acceptable for the presently used CfC $\rightarrow$ see talk of A. Bertarelli [1]
  - Present study presented only a first glance of the expected power loads (and results are to some extent layout specific)
  - Further studies would be needed (in particular, load to downstream coll.)
- Can we safely intercept a single 50 TeV bunch with absorber materials presently used in the LHC?
  - Yes, if the beam spot size is at least a few hundred μm (in both planes)
  - For smaller sizes, the peak temperature induced by a single bunch in Graphite or CfC can easily exceed 1000°C and stresses can be beyond material limits

[1] A. Bertarelli, "Evolution and limits of the present collimation materials studies".

Summary and conclusions (2/2)

- Can the materials of the present LHC dump cope with 50 TeV beams?
  - At a first glance, yes, if the sweep path length is at least 20 m
  - Evidently, there are many open questions to be adressed:
    - → Practical implementation of such a sweep? Which pattern? Transverse size of the dump core?
    - → Contributions of tails from neighbouring portions of the sweep pattern need to be investigated
    - → Eventually, dilution failures need to be studied (allowing for certain failure modes might require a significantly increased sweep path length)
- Conclusion:
  - FCC beams are certainly challenging even for the most robust materials presently used in the LHC
  - Evidently, the main issue are accidental beam losses:
    - → How to handle failure scenarios like asynchronous beam dumps?
    - → Do we need sacrificial absorbers for such failure modes?
  - Eventually, robustness requirements for materials will also depend on the (acceptable) failure modes