Accidental bunch impact on FCC collimators made of carbon: energy density estimates

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Acknowledgements to F. Burkart, W. Bartmann, E. Renner, F.X. Nuiry, M. Frankl

FCC collimation meeting

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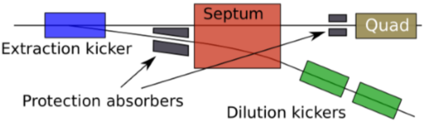
Introduction

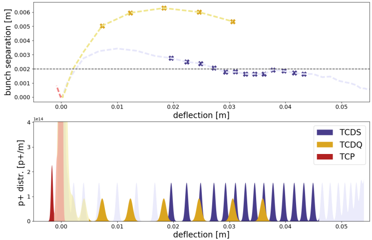
- **In case of fast failures like extraction kicker malfunctions bunches can impact on collimators in the betatron cleaning insertion**
- **For example, spontaneous trigger of extraction kicker - in this case the # of bunches escaping the extraction region depends on various parameters:**
  - # number of extraction kickers
  - kicker rise-time + time delay between spontaneous trigger and next bunch
  - asynchronous beam dump or delayed dump until abort gap arrives
  - half gap of extraction protection devices

FCC extraction protection layout:



Figures courtesy of F. Burkart and E. Renner.

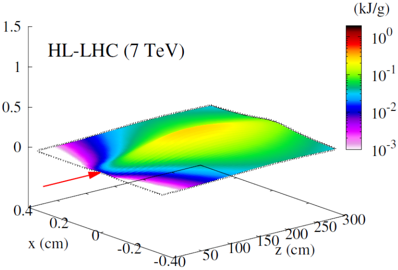
Spontaneous trigger+asynchronous beam dump (300 kickers, 1.15 μsec rise-time)

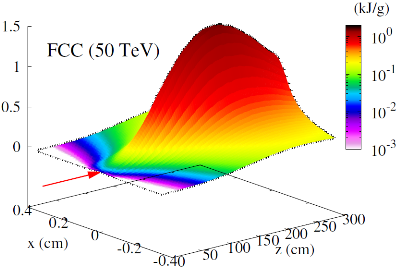


Accidental bunch impact on a collimator

- **The shower-induced peak energy density depends on:**
  - Proton **energy E**
  - The **number of impacting protons N_b** and the **impact distribution (x,x',y,y')**
  - The collimator **material**, **density**, **length**
- **In this presentation:**
  - We assume that entire bunches with **nominal bunch intensity I_b** and a **given transverse bunch size** ($\sigma = \sigma_x = \sigma_y$) impact on a carbon collimator with a **given impact parameter (d)**

⇒ *In reality the impact distribution can be a more complicated since bunches might only be partially intercepted by extraction protection devices and/or particles might be scattered out of extraction protection devices*





Case studies

- **Part 1 (7 TeV and 50 TeV) :**
  - Bunch impact on a long† absorber made of carbon with ρ=1.83 g/cm^3 (a la Graphite R4550/R7550 used in TCDIs, TDI)
  - Large impact parameter

† *long enough to contain the shower maximum (several meters)*

- **Part 2 (50 TeV):**
  - Bunch impact on a 0.3, 0.6 and 1 m long collimators made of carbon with ρ=1.67 g/cm^3 (a la CfC AC150K used in present TCPs, TCSGs, TCLIBs)
  - 1 σ impact + large impact parameter
- **Note:**
  - In all cases, **only the energy deposition in the absorber material** has been studied
  - Additional limitations may arise from the energy deposition in other jaw components (backstiffener, cooling pipes, clamps, etc.)
  - No studies were carried out for beam line components downstream of the impacted absorber/collimator

“Damage limit” of collimators made of carbon?

- **HiRadMat-28 (TCDI&TDI, F.X. Nuiry et al.):**
    - Peak dose of around **3.4 kJ/g** ($>$**6 kJ/cm**^{3}) achieved in Graphite with ρ=1.83 g/cm^3 without visible damage
    - In this presentation, I tentatively use this value as material limit (one could equally use results from other tests like HRM-23 (MME), but I didn't have the values at hand)
- **A word of caution:**
    - The adopted dose limit allows only for a **very approximative assessment** if an absorber material can sustain the impact
    - For a more detailed assessment, **thermo-structural studies** would be necessary to evaluate the stresses generated by the shower-induced temperatures and temperature gradients inside the absorbers

Contents

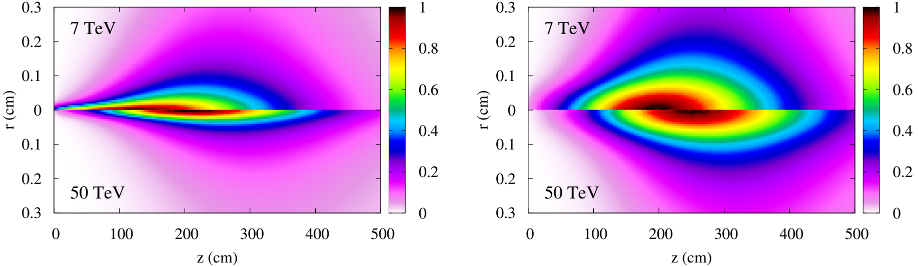
1) Bunch impact on a long* Carbon absorber (1.8 g/cm^3): 7 TeV vs 50 TeV (* long enough to contain the shower max., i.e. several meters)

2) Bunch impact on 0.3, 0.6 and 1 m Carbon collimators (1.67 g/cm^3): 50 TeV

Conclusions

Proton-induced showers: 7 TeV vs 50 TeV

r-z energy density maps[†] *for protons impacting on Graphite*



$\sigma_{x,y}$ = 100 μm

$\sigma_{x,y}$ = 400 μm

[†] *normalized to the maximum value.*

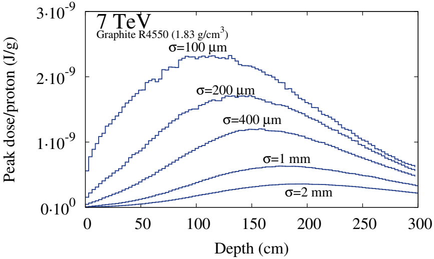
Some basic remarks:

- the depth where the energy density is max., $d_{\varepsilon,max}$, increases with transv. bunch size ($\sigma_{x,y}$)
- $d_{\varepsilon,max}$ increases moderately with energy (remember: shower length $\propto \log(E)$)
- the transverse momentum of hadrons produced in nuclear collisions is more or less invariant with energy → **shower opening angle decreases with increasing energy**

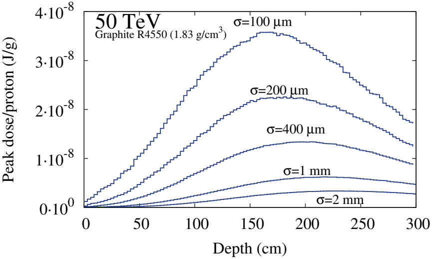
Longitudinal peak dose profile (per proton) in Graphite

Material density ρ=1.83 g/cm^3

E = 7 TeV



E = 50 TeV



Maximum energy density:

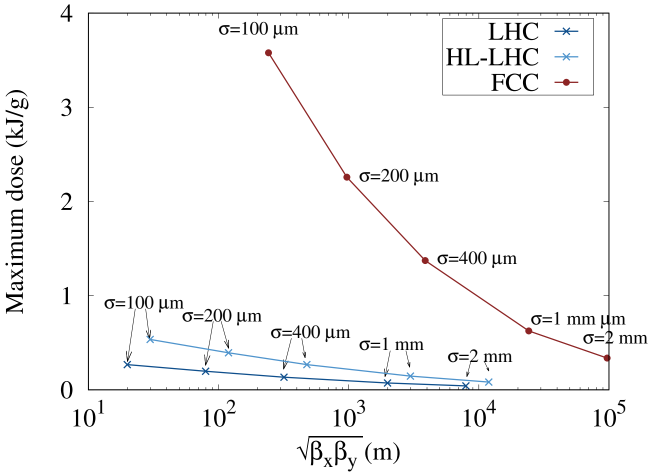
- for a given transverse proton density (i.e. a given σ), the maximum energy density increases by more than the simple ratio of beam energies (50/7≈7)
- For example: energy density increase in Graphite with ρ=1.83 g/cm^3:
  - σ=100 μm → **roughly a factor of 15 increase**
  - σ=1 mm → **roughly a factor of 9 increase**

Max. dose vs $\sqrt{\beta_x \beta_y}$ induced by a single bunch in Graphite

Material density ρ=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 already from 1 bunch

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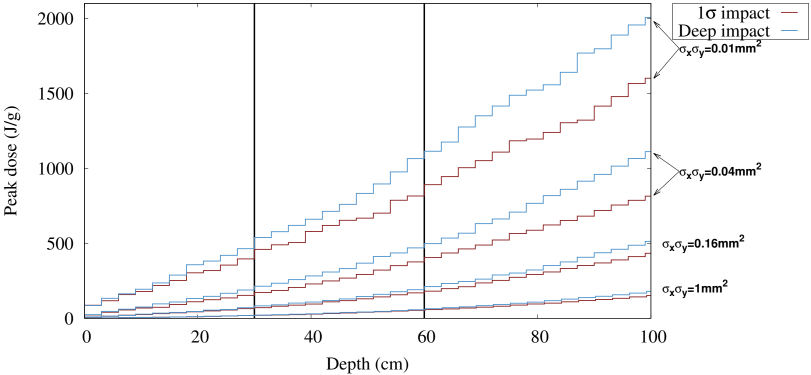
Longitudinal peak dose profile for a FCC bunch in CfC

Material density ρ=1.67 g/cm^3, bunch intensity of I_b=1$\times$10^{11} p



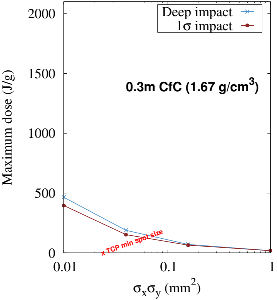
Fraction of impacting protons escaping at the downstream face:

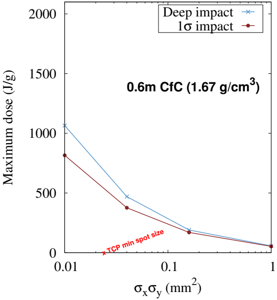
- TCP 0.3 m: **48%**
- TCP 0.6 m: **23%**
- TCSG 1.0 m: **9%**

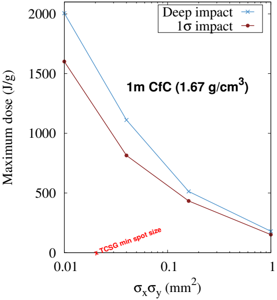
+ showers escaping → would be important to look also at downstream elements

Max. dose vs $\sigma_x\sigma_y$ by a FCC bunch in a CfC collimator

Material density ρ=1.67 g/cm^3, bunch intensity of I_b=1$\times$10^{11} p







Minimum spot sizes at TCPs and TCSGs (simply using the local β-functions):

- $\sigma_x\sigma_y = \varepsilon/(\beta\gamma)\sqrt{\beta_x\beta_y} \to \sigma_x\sigma_y\big|^{TCP}_{min} \approx 0.023\ mm^2,\ \sigma_x\sigma_y\big|^{TCSG}_{min} \approx 0.020\ mm^2$

Acceptable number of bunches on the same spot (using the simple criterion on p.5):

- TCP 0.3 m: **11 bunches**
- TCP 0.6 m: **5 bunches**
- TCSG 1.0 m: **2 bunches**

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- **Summary:**
  - If the spot size is too small, already a single FCC proton bunch might induce damage in a long Graphite absorber
  - Not surprisingly, a short CfC collimator (30 cm) can sustain the impact of around 11 bunches, but half of the protons (!) will be escaping (can induce damage further downstream)
  - If the collimator length is 1 m, damage can be expected for more than 2 bunches
- **Keep in mind:**
  - only the energy depositon in the absorber material was studied, but not in the entire jaw
  - a perfect Gaussian bunch shape was assumed (based on the local β-functions) → to be updated once a more realistic impact distribution is available from tracking simulations
  - we only studied the energy density but not the stresses → the assumed "damage limit" provides only a first rough assessment