Design studies for the FCC-hh beam dump

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FCC Week 2017
May 31\textsuperscript{st}, 2017
Introduction

- Graphite - the natural choice for high-energy proton dumps

Graphite:
+ low Z and density
+ high thermal shock resistance
+ high melting point

This talk:
- Dilution requirements for safely absorbing FCC beams in a LHC-like Graphite dump
- Consequences of irregular beam aborts → mitigation with low-density Carbon foams/powders?

A. Lechner (FCC Week 2017)
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This talk:
- Dilution requirements for safely absorbing FCC beams in a LHC-like Graphite dump
- Consequences of irregular beam aborts → mitigation with low-density Carbon foams/powders?
Even with large $\beta$:
- O(few) bunches can induce critical stresses
- O(10s) bunches can provoke phase transition
(if all on the same spot)

Figures on the left: dose in 3 m long Graphite ($1.83 \text{ g/cm}^3$) for one nominal proton bunch ($\sigma=400 \mu\text{m}$) - HL-LHC (top) and FCC (bottom).
**Max. energy density/temp. by single bunch → spot size**

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### (HL-)LHC vs FCC: single proton bunch on Graphite

1 proton bunch, Graphite (1.8 g/cm³)

### Table: Energy Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (TeV)</td>
<td>7</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>$\epsilon_n$ ($\mu$m-rad)</td>
<td>3.75</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>$\text{ppb} \times 10^{11}$</td>
<td>1.15</td>
<td>2.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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### Figures on the left:

Graphite R4550 (1.83 g/cm³) for one nominal proton bunch ($\sigma = 400 \mu$m) -

- HL-LHC (top) and FCC (bottom).

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**Even with large $\beta$:**

- O(few) bunches can induce critical stresses
- O(10s) bunches can provoke phase transition (if all on the same spot)

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Max. temperature (deg C)

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Higher-density Graphite segment (1.8 g/cm³)
Higher material density at upstream end gives rise to a steeper shower build-up and hence reduces the overall dump length
Note: the presence of the higher-density graphite has only a small effect on the maximum energy density in the low-density segment if the beam is diluted across the dump face

Lower-density Graphite segment (1.0 g/cm³)
Lower material density in the region of the shower maximum reduces the max. energy density and temperature

Higher-density Graphite segment (1.8 g/cm³) + possibly other materials (tbd)
Higher material density gives rise to better attenuation of the longitudinal shower tails and hence reduces the dump length

Total core length expected < 10-12m
Core radius depends on sweep pattern (+ a certain margin to jacket)
FCC-hh: optics parameters + bunch spot sizes at the dump

Distance dilution kickers - dump: \( \sim 2.5 \text{ km} \)

- **Optics parameters at dump:**
  
<table>
<thead>
<tr>
<th>( \beta_x )</th>
<th>( \beta_y )</th>
<th>( D_x )</th>
<th>( D_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 km</td>
<td>240 km</td>
<td>0.13 m</td>
<td>2.7 m</td>
</tr>
</tbody>
</table>

- **25 nsec beam (10600 bunches):**
  
<table>
<thead>
<tr>
<th>( \varepsilon_{x,y} )</th>
<th>( l_b )</th>
<th>( \sigma_x^* )</th>
<th>( \sigma_y^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 ( \mu \text{m-rad} )</td>
<td>( 1 \times 10^{11} )</td>
<td>1.36 mm</td>
<td>3.15 mm</td>
</tr>
</tbody>
</table>

- **5 nsec beam (53000 bunches):**
  
<table>
<thead>
<tr>
<th>( \varepsilon_{x,y} )</th>
<th>( l_b )</th>
<th>( \sigma_x^* )</th>
<th>( \sigma_y^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44 ( \mu \text{m-rad} )</td>
<td>( 0.2 \times 10^{11} )</td>
<td>0.61 mm</td>
<td>1.41 mm</td>
</tr>
</tbody>
</table>

**Note:**

- The large \( \beta \)-functions at the dump do not relax much dilution requirements (the optics is mainly motivated by the available kicker aperture)

* Without dispersion contribution. 

\( \Rightarrow \) see talk of F. Burkart for details.
FCC-hh: spiral dilution pattern

Assumption: frequency modulation of dilution kickers such that $\Delta d = \text{const}$ when spiralling inwards

Tentatively assumed filling scheme for 25 nsec: Trains of 80b separated by 425 nsec gaps (5 nsec: trains of 400b separated by 425 nsec).
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Assumption: frequency modulation of dilution kickers such that \( \Delta d = \text{const} \) when spiralling inwards.
FCC-hh: which bunch and branch separation is required?

Maximum dose in low-density Graphite segment for 25 nsec beams:

Set of baseline parameters:
- Bunch separation $\Delta d$: 1.8 mm
  (5 nsec: $1.8/5=0.36$ mm)
- Sweep path length: 23.8 m
  (LHC: 1.2 m)
- Branch separation $\Delta r$: 20 mm
- Pattern outer radius: 45.1 cm

(all results shown in the following are for this sweep pattern)
FCC-hh: which bunch and branch separation is required?

Maximum dose in low-density Graphite segment for 25 nsec beams:

Set of baseline parameters:
- Bunch separation \( \Delta d \):
  - 1.8 mm
  - \((5 \text{nsec}: 1.8/5 = 0.36 \text{mm})\)
- Branch separation \( \Delta r \):
  - 20 mm
- Pattern outer radius:
  - 45.1 cm

\((\text{all results shown in the following are for this sweep pattern})\)
LHC vs FCC-hh: sweep pattern and dump radius

- **LHC (core radius = 35 cm):**
  - LHC (2016)

- **FCC-hh (core radius \( \sim 60-70 \) cm):**
  - FCC-hh (concept)
LHC vs FCC-hh: transverse dose distribution

- **LHC (core radius = 35 cm):**
  - At a depth of 2.8 m

- **FCC-hh (core radius ~ 60-70 cm):**
  - At a depth of 3.8 m
FCC-hh: longitudinal peak dose profile (5 & 25 nsec)

Higher-density Graphite segment (1.8 g/cm$^3$)
Low-density Graphite segment (1.0 g/cm$^3$)
Higher-density Graphite segment (1.8 g/cm$^3$)

1.5m 4.5m (tbd)

Diluted beam

Graphite 1.8 g/cm$^3$
Graphite 1.0 g/cm$^3$
Graphite 1.8 g/cm$^3$

1700 deg C
1800 deg C
210 deg C
130 deg C

Single bunch
Full swept beam

Need to check stresses - studies ongoing but challenging

(all values in adiabatic limit)
Failure cases: distortion of dilution pattern

- **Dilution failure:**
  - 10% less dilution in vertical plane (dilution system highly segmented)

- **Asynchronous beam dump:**
  - Beam extracted while dilution kickers still raising
FCC-hh: energy deposition in dump in failure cases (25 nsec)

- **Latent heat:**
  \[ \sim 8.7 \text{ kJ/g} \] [1]

- **Melting:**
  \[ \sim 17 \text{ kJ/g} \] [1]

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FCC-hh alternative dump concept: lower material density

- Higher-density Graphite segment (1.8 g/cm$^3$)
- Low-density Graphite segment (1.0 g/cm$^3$)
- Higher-density Graphite segment (1.8 g/cm$^3$) + possibly other materials (tbd)
- Carbon foam (0.5 g/cm$^3$)

Total core length expected < 10-12m

- 1.5m ($N_\lambda$=4)
- 4.5m ($N_\lambda$=6.6)
- 1.0m ($N_\lambda$=2.7)
- 11m ($N_\lambda$=8.1)

Total core length expected < 16-18m (tbd)
Peak dose reduction wrt baseline concept:
- Regular sweep: -25%
- Asynch. dump: -45%

Further material testing & characterisation required (needed to assess stresses etc.)
Conclusion and outlook

- **Baseline Graphite dump for FCC-hh (LHC-like flexible Graphite with 1g/cm³):**
  - Approximate dimensions:
    - radius of 60-70 cm, length of 10–12 m
  - Simulations of the thermo-mechanical response for regular sweep ongoing
  - Dump will suffer local damage in case of **asynchronous beam dump**
    - might require dump exchange - remote handling desirable
    - mitigation measures under consideration, e.g.
      - anti-damped dilution spiral (to be assessed by kicker experts)
      - delay extraction and allow for $1\sigma$ oscillation of $O(100)$ bunches

- **Alternative directions:**
  - Employ lower-density **Carbon foams** (or even **Carbon powder**) with densities ≤0.5 g/cm³
    - reduces shower-induced energy densities
    - dump length still expected to stay below 20 m
  - Foams already exist but **material characterisation and testing** required to assess their response to beam impact - they have never been used in high-energy proton BIDs or dumps