Dilution requirements for the FCC-hh dump


FCC Week 2018
April 12th, 2018
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
- Brief outlook: achievable dose reduction by using lower-density Graphite/C foam grades
HL-LHC beams: already challenging

→ LHC: 6 V + 4 H dilution kickers

Longitudinal peak temperature profile for standard HL-LHC 25 sec beams:

Figures by M.I. Frankl, bunch patterns by C. Wiesner

→ HL-LHC: additional dilution kickers under study:
(HL-)LHC vs FCC-hh: single proton bunch on Graphite

### Table: Energy and Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</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>ppb ($\times 10^{11}$)</td>
<td>1.15</td>
<td>2.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Figure 1**: Dose in 3 m long Graphite (1.83 g/cm$^3$) for one nominal proton bunch ($\sigma = 400 \mu$m) - HL-LHC (top) and FCC (bottom).

**Even with large $\beta$**:
- $O$(few) FCC bunches can induce critical stresses
- $O$(tens) FCC bunches can provoke phase transition (if all on the same spot)

**Max. energy density/temp. by single bunch $\rightarrow$ spot size**

A. Lechner (FCC Week 2018)
FCC-hh dump concept (LHC-like Graphite dump)

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

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

Total core length expected < 10-12m
Core radius depends on sweep pattern (+ a certain margin to jacket)

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

Metallic jacket

1.5m ($N_\lambda = 4$)
4.5m ($N_\lambda = 6.6$)
(tbd)
Spiral dilution pattern

Dilution pattern: spiralling inwards (picture shows 2017 pattern)

LHC (core radius = 35 cm):

- Frequency modulated (≤ 50 kHz)
- Bunch separation \( \Delta d \) 1.8 mm
- Branch separation \( \Delta r \) 2 cm
- Total sweep length 24 m
- Outer spiral radius 45 cm
- \( \beta_x / \beta_y \) 45 km/240 km

FCC-hh (min. core radius 70-80 cm):

- Frequency constant (50 kHz)
- Bunch separation \( \Delta d \) 1.8–4.3 mm
- Branch separation \( \Delta r \) 2 cm
- Total sweep length 39 m
- Outer spiral radius 55 cm
- \( \beta_x / \beta_y \) 170 km/170 km

New sweep pattern 2018:

→ larger spiral footprint (requires larger dump radius of min. 70-80 cm)
→ reduced temperature in dump and less challenging for kickers
LHC vs FCC-hh: transverse dose distribution

- **Updated sweep pattern**
  - FCC week 2017 → FCC week 2018:
    - Max. temp: 1700°C → 1400°C
    - leaves more margin for failure cases

*Graphite 1.8 g/cm³*
*Graphite 1.0 g/cm³*
*Graphite 1.8 g/cm³*

2017 sweep pattern (1700 deg C)
2018 sweep pattern (1400 deg C)

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**LHC (25 nsec, 2017):**

- 1000 deg C

**FCC-hh (2017 sweep pattern):**

- 1700 deg C

**FCC-hh (2018 sweep pattern):**

- 1400 deg C

Dilution patterns by E. Renner and F. Burkart
FCC-hh: effect of bunch brightness on energy deposition in dump

- **Beginning of a fill (largest bunch intensity):**

<table>
<thead>
<tr>
<th>$\varepsilon_{x,y}$</th>
<th>$l_b$</th>
<th>$\sigma_x = \sigma_y$</th>
<th>$l_b / (\sigma_x \sigma_y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 $\mu$m-rad</td>
<td>$1 \times 10^{11}$</td>
<td>2.6 mm</td>
<td>$1.5 \times 10^{10}$ p/mm$^2$</td>
</tr>
</tbody>
</table>

- **After about 2.6h (with collisions) [1] (highest proton density):**

<table>
<thead>
<tr>
<th>$\varepsilon_{x,y}$</th>
<th>$l_b$</th>
<th>$\sigma_x = \sigma_y$</th>
<th>$l_b / (\sigma_x \sigma_y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.26 $\mu$m-rad</td>
<td>$0.33 \times 10^{11}$</td>
<td>0.9 mm</td>
<td>$4.0 \times 10^{10}$ p/mm$^2$</td>
</tr>
</tbody>
</table>

- Synchrotron radiation damping: **bunch brightness increases with time** (by more than a factor of two)

- Because of dilution, peak temperature depends **much stronger on bunch intensity than brightness**

→ **transv. emittance damping not harmful for dump**

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FCC-hh: impact of H-V frequency mismatch on energy deposition

- A frequency mismatch between H and V dilution kickers distorts the sweep pattern → higher temperatures in dump
- A mismatch of a few permille acceptable

Sweep patterns by E. Renner
FCC-hh: impact of frequency offsets of individual kicker modules

- Assumed random frequency offsets on individual kicker modules (Gaussian distributed, with RMS as specified in the figures)
- Affects mainly inner part of the sweep pattern
- Random offsets of a few permille acceptable

Sweep patterns by E. Renner
Failure cases: distortion of dilution pattern

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

- **Asynchronous beam dump:**
  - Beam extracted while dilution kickers still raising

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Dilution patterns by E. Renner.

A. Lechner (FCC Week 2018)
FCC-hh: impact of extraction/dilution failures on energy deposition

Asynchronous beam dump:

- Old sweep pattern FCC week 2017: >8 kJ/g (local damage expected)
- New sweep pattern FCC week 2018: dump core functionality should not be compromised

* The properties of the low-density Graphite sheets are being better characterised within HL-LHC.

A. Lechner (FCC Week 2018)

April 12th, 2018
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)

Lower density Graphite of C foam (0.5 g/cm$^3$)

Total core length expected < 10-12m

Total core length expected < 16-18m
FCC-hh alternative dump concept: energy deposition

- Peak dose reduction wrt baseline concept:
  - Regular sweep: -25%
  - Asynch. dump: -43%

- Further material testing & characterisation required (needed to assess stresses etc.)

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Graph. 1.8 g/cm³
Carbon foam 0.5 g/cm³
Graph. 1.8 g/cm³

Asynch. beam dump (1350 deg C)
Regular sweep (1100 deg C)
Conclusion and outlook

- **Baseline Graphite dump for FCC-hh (LHC-like flexible Graphite with 1g/cm$^3$):**
  - Approximate dimensions:
    - **min. radius of 70-80 cm** → shower load on containment jacket to be checked, Graphite radius challenging for manufacturing
    - **length of 10–12 m**
  - With present sweep pattern, dump functionality expected not to be compromised **in case of asynchronous beam dumps**
  - **Dilution system remains challenging** (see previous talk of E. Renner)
  - Dilution frequency must be well matched between H and V planes (within a few permille), large frequency offsets of individual kicker modules (of more than a percent) must be avoided

- **Alternative directions to reduce to some extent the dilution requirements:**
  - Employ lower-density **Graphite variants or C foams** with densities ≤0.5 g/cm$^3$ (or even lower)
    - reduces shower-induced peak dose (few 10%)
    - dump length still expected to stay below 20 m
  - Materials 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