THE FCC-EE BEAM DUMPING SYSTEM

Alexander Krainer

Contributors:
Marco Calviani, Antonio Perillo-Marcone, Anton Lechner, Wolfgang Bartmann, Yann Dutheil, Rebecca Ramjiawan

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union’s H2020 Framework Programme under grant agreement no. 951754.
Table of contents

Recap of the proposed semi-passive beam dumping system

The HiRadMat experiment HRMT56-HED

Current Status

Next steps and open questions
Challenges concerning the FCC-ee beam

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>Z, New Layout (4 IPs)</th>
<th>ZH</th>
<th>t(\bar{t})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV/pp]</td>
<td>45.6</td>
<td>45</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>Bunch population [10^{11}]</td>
<td>1.7</td>
<td>2.76</td>
<td>1.8</td>
<td>2.2</td>
</tr>
<tr>
<td>Bunches / beam</td>
<td>16640</td>
<td>8800</td>
<td>328</td>
<td>59</td>
</tr>
<tr>
<td>Stored energy / beam [MJ]</td>
<td>20.6</td>
<td>17.5</td>
<td>1.13</td>
<td>0.36</td>
</tr>
<tr>
<td>Horizontal emittance (\varepsilon_x) [nm]</td>
<td>0.27</td>
<td>0.71</td>
<td>0.63</td>
<td>1.34</td>
</tr>
<tr>
<td>Vertical emittance (\varepsilon_y) [pm]</td>
<td>1.0</td>
<td>1.42</td>
<td>1.3</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Defocusing triplet

![Diagram of Kicker, Septum, and Defocusing triplet]
Peak Energy Deposition, with triplet, no dilution

assuming a 6 m long 1.0 g/cm³ graphite block
Passive Beam Diluter Concept

- Dilution of the beam by multiple coulomb scattering and Bremsstrahlung energy losses

- Bremsstrahlung-induced shower build-up contributes to the energy deposition in the Spoiler.
A semi-passive beam dumping system

- Multiple spoilers to decrease the peak load

- High density (1.7-1.8 g/cm³) graphite
- 3 cm thick
- 30 cm diameter
  - Corresponding to ~15 σ horizontally
- Aluminium support
The FCC-ee Beam Dump Core

- Similar approach as the current LHC Dump
- Multiple sections with different densities for the Dump core
- Design and material choice to be optimized following the findings of the HiRadMat High Energy Dumps Experiment

Graphite
- High density (1.8 g/cm³)
- Low density (1.1 g/cm³)

High density absorber with triplet and 3 spoilers

Peak energy deposition along the Dump

Peak adiabatic temp. increase along the Dump
Peak energy deposition on the Spoiler

- Spoiler spacing to reach similar peak energy deposition
Thermomechanical simulations

• Energy deposition from FLUKA
• Finite Element Analysis
• LS-Dyna tight-coupled thermomechanical simulations
• Detailed material model with all relevant properties
Thermomechanical simulations

The Christensen Failure Criterion

• For brittle materials, the von-Mises stress is not a good indicator for material failure.
• Here the Christensen criterion is a much better representation for likelihood of material failure. (The Theory of Materials Failure, Richard M. Christensen)

$\left(\frac{1}{T} - \frac{1}{C}\right)(\sigma_1 + \sigma_2 + \sigma_3) + \frac{1}{2TC} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] \leq 1$

$\sigma_i < T$

Where $C$ is the maximum compressive strength and $T$ is the maximum tensile strength

Values $> 1$ show material failure

For SGL R7550, isotropic graphite (conservative estimate)
$C = 120 \text{ MPa}$
$T = 40 \text{ MPa}$
Thermomechanical simulations

Christensen Failure Criterion in LS-Dyna

max value: 0.33
HiRadMat HRMT56-HED

- High Energy Dumps experiment
- Finished 1st week of November 2021
- Multiple targets for testing:
  - Sigraflex material of the existing LHC Dump
  - Material candidates for the HL-LHC Dump
  - Materials for the TCDQ and TCDS for the HL-LHC upgrade
  - Material test for the FCC-ee Spoiler
- In total 35 different targets
- Key experiment for insights into high energy impacts on graphite materials.
HRMT56 FCC-ee Spoiler setup

• Experimental verification of the validity of the simulations.
  • Especially important since testing with an FCC-ee style beam is not possible.

• HiRadMat beam parameters were chosen to reproduce the mechanical stresses expected from an impact with the FCC-ee beam.
  • A proton beam of $\sigma = 2.2 \text{ mm} \times 0.25 \text{ mm}$ was used for the experiment.
  • 450 GeV, 288 bunches, $\sim 1.2 \times 10^{11}$ protons/bunch

• To increase the deposited energy in the target, a pre-target material is used to create shower build-up.

• This material needs higher density than the target as well as a high melting point to survive the beam impact.
  • Titanium – Carbide (TiC) and Titanium-Diboride (TiB2) proved to be the best options
HRMT56 FCC-ee Spoiler setup

- TiC
- SGL R7550 isostatic graphite
- Arianne Group S332 3D carbon/carbon
HRMT56 FCC-ee Spoiler setup
HiRadMat HRMT-56

- FCC target 1 iso. graphite
- FCC target 2 Carbon/Carbon
FCC-ee Spoiler material candidates

Requirements

- Low Z material
- High melting point
- High specific heat
  - Over a wide temperature range
- Mechanical strength

Isotropic Graphite (SGL R7550)

Carbon/Carbon Composites (AG S332)
HRMT56 / LS-Dyna simulation

max value: 0.34
Similar to the FCC-ee Spoiler simulation
Instrumentation for the FCC target

• Out of plane displacement is correlated to strain

• Laser Doppler Vibrometer for live surface velocity measurement

• Surface displacement and velocity are simulated and can be directly compared

• Gives good indication if material model and simulations are correct

• Post irradiation examination to verify material survival (i.e. micro tomography, raman spectroscopy, etc.)
Current Status

• Dump beamline ~70 m from Spoilers to Beam Dump.

• Overall extraction line length depends mainly on requirements for separation from the main ring.

• Extraction does not need a dedicated external tunnel.

• Dilution and beam dumping can be done with a (semi) passive system
Next steps and open questions

• Specify location in the lattice
• Evaluate radiation field around spoilers and dump
  • Determine the required separation of dump and main ring
  • Access requirements and shielding requirements
• Post irradiation examination of HRMT56-HED
  • Optimize spoiler design
  • Optimize dump absorber design
• What about injection/extraction protection?
  • Booster beam abort system?
  • Extraction protection like in the LHC?
Thank you for your attention.
BACKUP
HRMT56 FCC targets

Pre-Target
Titanium-Carbide (TiC)
Density of $\sim 4.84 \text{ g/cm}^3$
Melting point of $\sim 3100 \, ^\circ\text{C}$

Targets
Scaled Model of the FCC-ee Spoiler design
Isotropic Graphite and Carbon/Carbon are tested
Instrumentation for HRMT56

• To verify that the simulations correctly reproduce the thermal expansion and resulting stresses on the surface of the target, special instrumentation is needed.

• Strain gauges do not have a good enough resolution and cannot be placed directly in the beam trajectory.

• To measure this during and after the beam impact directly at the impact spot is possible by using a Laser Doppler Vibrometer (LDV).

• The LDV can measure with a time resolution of 0.4 ns (2.5 MHz) and a displacement resolution of less than 1 nm.
No triplet, passive protection by the Spoiler

- Spoilers get destroyed
- Dump should survive
- Hydrodynamic tunneling not considered

Peak energy deposition along the Dump

<table>
<thead>
<tr>
<th>s [cm]</th>
<th>no spoiler</th>
<th>3x3 cm spoiler</th>
<th>no triplet</th>
</tr>
</thead>
<tbody>
<tr>
<td>7000</td>
<td>5000</td>
<td>4000</td>
<td>3000</td>
</tr>
<tr>
<td>7100</td>
<td>4500</td>
<td>3500</td>
<td>2500</td>
</tr>
<tr>
<td>7200</td>
<td>4000</td>
<td>2500</td>
<td>1500</td>
</tr>
<tr>
<td>7300</td>
<td>3500</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>7400</td>
<td>3000</td>
<td>1500</td>
<td>500</td>
</tr>
<tr>
<td>7500</td>
<td>2500</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>7600</td>
<td>2000</td>
<td>500</td>
<td>0</td>
</tr>
</tbody>
</table>

Peak adiabatic temp. increase along the Dump

<table>
<thead>
<tr>
<th>s [cm]</th>
<th>no spoiler</th>
<th>3x3 cm spoiler</th>
<th>no triplet</th>
</tr>
</thead>
<tbody>
<tr>
<td>7000</td>
<td>5000</td>
<td>4000</td>
<td>3000</td>
</tr>
<tr>
<td>7100</td>
<td>4500</td>
<td>3500</td>
<td>2500</td>
</tr>
<tr>
<td>7200</td>
<td>4000</td>
<td>2500</td>
<td>1500</td>
</tr>
<tr>
<td>7300</td>
<td>3500</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>7400</td>
<td>3000</td>
<td>1500</td>
<td>500</td>
</tr>
<tr>
<td>7500</td>
<td>2500</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>7600</td>
<td>2000</td>
<td>500</td>
<td>0</td>
</tr>
</tbody>
</table>