Proposal 2010: Multimat-2

F. Carra on behalf of HL-LHC WP5

HiRadMat Scientific Board 2019
CERN
June 5th, 2020
Outline

- Introduction
  - Scientific background
  - Thresholds of damage for collimator materials
  - Overview of past HiRadMat collimation experiments

- Multimat-2 proposal
  - Goals
  - Experimental setup
  - Beam parameters
  - Instrumentation
  - PIE
  - Timeline

- Conclusions
Introduction to beam damage

- Reflected waves
- Cylindrical waves
- Liquid, gas, plasma

Solid

- Plastic deformation
- Micro-spallation, micro-jetting
- Spallation, fragmentation

Introduction to beam damage

- Damage is triggered by the energy absorbed by the material
- Two parameters controlling the damage:
  - **Energy density peak** $e_p$ (J/cm$^3$) $\rightarrow$ localized effects, the onset of damage, …
  - **Average energy per target section** $\bar{e}_s$ (J/cm$^3$) $\rightarrow$ global response of the target, the damage far from the impact, …

Energy density peak ($e_p$)

\[
T_p = \frac{e_p}{\rho c_p} > T_{lim} \rightarrow \text{DAMAGE}
\]

\[
\varepsilon_p = f(\alpha T_p) > \varepsilon_{lim} \rightarrow \text{DAMAGE}
\]

Average energy on the most loaded section ($\bar{e}_s$)

\[
\bar{e}_s = \frac{\bar{E}_s}{A}
\]

\[
\bar{T}_s = \frac{\bar{e}_s}{\rho c_p}
\]

\[
\varepsilon_s = 2\alpha \bar{T}_s > \varepsilon_{lim} \rightarrow \text{DAMAGE}
\]

Collimator damage thresholds

- **Three damage thresholds** defined for collimator materials.
  - Introduced for metallic (ductile) materials ([MPP Workshop 2013](#)). Extended to graphitic materials in the [MPP Workshop 2019](#).
  - Defined as a function of the effect on the collimator behaviour.

- **Threshold 1**: onset of damage, with no need to activate the 5\(^{th}\) axis.
  - Ductile materials: onset of plasticity.
  - Graphitic materials: crack initiation, local material ablation.

- **Threshold 2**: damage to the surface requiring correction with the 5\(^{th}\) axis.
  - Ductile materials: it usually involves heavy plastic deformation and/or ejecta generation.
  - Graphitic materials: pseudo-plastic deformation, internal delamination, important material ablation, …

- **Threshold 3**: damage cannot be corrected with 5\(^{th}\) axis anymore.
  - Ductile materials: significant material erosion and plastic deformation in the jaw, no more flat surface close to the impact.
  - Graphitic materials: fracture of the blocks jeopardizing the structural integrity, complete block face delamination with loss of the flatness.
Collimator materials

- The evaluation of material response to beam impact is done in two ways:
  - **Numerical simulations** (FLUKA + ANSYS, Autodyn)
  - **Experimental tests** (HiRadMat: on full-scale devices or on simple geometry targets)

- The damage thresholds are estimated using a combination of the two techniques.

- Past HiRadMat experiments on collimator materials and devices:
  - HRMT-09 (2012): TCT collimator (Inermet180)
  - HRMT-14 (2012): Collimator material samples (cylinders and half-moons)
  - HRMT-23 (2015): LHC and HL-LHC collimator jaws (CFC, MoGr, CuCD)
  - HRMT-21 (2017): Rotatable collimator (Glidcop)
  - HRMT-36 (2017): Collimator material samples (rods, uncoated and coated)

*Green*: tests on material samples; *Red*: tests on collimator sub-assemblies; *Blue*: tests on full collimators.
Scientific Publications (1/2)

- **HRMT-09 “TCT”**

- **HRMT-14 “Samples”**

- **HRMT-21 “RotCol”**
Scientific Publications (2/2)

HRMT-23 "Jaws"

HRMT-36 "Multimat"
- M. Portelli et al. (2020). Thermomechanical Characterisation of Copper Diamond and Benchmarking with the MultiMat experiment. Submitted to Shock and Vibration.
HRMT-36 “Multimat” – Overview

- Test on 16 target stations, including coated and uncoated material targets (rods) and electronic devices
- Specimen geometry chosen to:
  - Generate easily detectable uniaxial signals
  - $e_p$ enhanced by squeezing the beam (30-50% above HL-LHC)
  - $\bar{e}_s$ (factor 2-3 above HL-LHC!) enhanced reducing target section (~10% of collimator jaw section)

<table>
<thead>
<tr>
<th>#</th>
<th>Material</th>
<th>Density [g/cm$^3$]</th>
<th>Coated</th>
<th>Coating Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IT180</td>
<td>18.0</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Ta10W</td>
<td>16.9</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Ta2.5W</td>
<td>16.7</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>TZM</td>
<td>10.0</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>CuCD IFAM</td>
<td>5.40</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>CuCD RHP</td>
<td>5.40</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>SiC</td>
<td>3.21</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>MG-6403Fc</td>
<td>2.54</td>
<td>✓</td>
<td>5µm TiN</td>
</tr>
<tr>
<td>9</td>
<td>ND-7401-Sr</td>
<td>2.52</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>MG-6530Aa</td>
<td>2.50</td>
<td>✓</td>
<td>2µm Cu</td>
</tr>
<tr>
<td>11</td>
<td>MG-6541Fc</td>
<td>2.49</td>
<td>✓</td>
<td>8µm Mo</td>
</tr>
<tr>
<td>12</td>
<td>TPG</td>
<td>2.26</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>TG-1100</td>
<td>2.19</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>R4550</td>
<td>1.90</td>
<td>✓</td>
<td>2µm Cu</td>
</tr>
<tr>
<td>15</td>
<td>CFC AC150K</td>
<td>1.88</td>
<td>✓</td>
<td>8µm Mo</td>
</tr>
<tr>
<td>16</td>
<td>Ti6Al4V (AM)</td>
<td>1.62</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>CFOAM</td>
<td>0.40</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Al 6082-T651 (UoHud)</td>
<td>2.70</td>
<td>×</td>
<td></td>
</tr>
</tbody>
</table>
HRMT-36 “Multimat” – Coatings

Graphite (R4550) with 2 µm Cu + 0.5 µm Ti coating – CO2 blasting

\[ E_{\text{MAX}} = 7.68 \text{ kJ/cm}^3 \text{ (bulk)} \]

\[ E_{\text{MAX}} = 15.3 \text{ kJ/cm}^3 \text{ (coat.)} \]

\[ \sigma_{\text{real}} = 0.29 \times 0.26 \text{ mm} \]

\[ \sigma_{\text{nom}} = 0.25 \text{ mm}, \ \text{impact} - 150 \mu m \]

\[ \sigma_{\text{nom}} = 0.25 \text{ mm}, \ \text{impact} - 500 \mu m \]

\[ E_{\text{MAX}} = 6.11 \text{ kJ/cm}^3 \text{ (bulk)} \]

\[ E_{\text{MAX}} = 14.3 \text{ kJ/cm}^3 \text{ (coat.)} \]

\[ \sigma_{\text{real}} = 0.29 \times 0.31 \text{ mm} \]

\[ \sigma_{\text{nom}} = 0.25 \text{ mm}, \ \text{impact} - 150 \mu m \]

\[ \sigma_{\text{nom}} = 0.25 \text{ mm}, \ \text{impact} - 500 \mu m \]

\[ E_{\text{MAX}} = 3.72 \text{ kJ/cm}^3 \text{ (bulk)} \]

\[ E_{\text{MAX}} = 13.9 \text{ kJ/cm}^3 \text{ (coat.)} \]

\[ \sigma_{\text{real}} = 0.29 \times 0.23 \text{ mm} \]

\[ \sigma_{\text{nom}} = 0.25 \text{ mm}, \ \text{impact} - 150 \mu m \]

\[ \sigma_{\text{nom}} = 0.25 \text{ mm}, \ \text{impact} - 500 \mu m \]

\[ E_{\text{MAX}} = 3.72 \text{ kJ/cm}^3 \text{ (bulk)} \]

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\[ \sigma_{\text{real}} = 0.29 \times 0.31 \text{ mm} \]

\[ \sigma_{\text{nom}} = 0.25 \text{ mm}, \ \text{impact} - 150 \mu m \]

\[ \sigma_{\text{nom}} = 0.25 \text{ mm}, \ \text{impact} - 500 \mu m \]
However, in anisotropic materials, transversal strains are much higher than longitudinal ones. Transversal strains are those leading to potential failure of the material! A future experiment shall better investigate this failure mode (limited number of transverse strain gauges in Multimat).
HRMT-36 “Multimat” – PIE

- On top of observing the onset of damage related to $e_p$ (upstream samples), onset of damage related to $\bar{e}_s$ (downstream) also identified
- Sample section ~1/10 of collimator block section $\rightarrow$ increased $\bar{e}_s$
- Appearing on samples with $\bar{e}_s$ 2.5 higher than HL-LHC accidents
- Samples with $\bar{e}_s$ equal to HL-LHC $\rightarrow$ below onset of damage

MoGr sample n. 8
(highest average energy density per section)

Carra (CERN), 5 June 2020
Multimat: success from several points of view!

- Demonstration of prototypes of HL-LHC collimators technological solutions (materials and coatings)
- Derivation, for the first time, of a robust strength model with damping for the graphitic materials, and refinement of the constitutive model of metals and CuCD
- Individuation of failure mode for anisotropic graphitic materials, strongly dependent on longitudinal/transversal stress coupling
- For the first time we exceeded the maximum HL-LHC energy per section, observing the damage threshold $e_p$ and $e_s$

From Multimat to Multimat-2: Goals

- What is still missing?
- Validation of material specific industrial grades and coatings used in series production
- Derivation of the strength model for the graphitic materials, better characterizing the transversal stress domain, by increasing the dedicated instrumentation
- Define a failure model for the anisotropic graphitic materials, better characterizing the thresholds of damage for the materials, via dedicated target stations
Multimat-2 Exp. Setup – Test bench

- Multimat was designed with an **openable tank**, to be re-used for next, similar experiments. **Up to 16 target stations** can be installed under inert gas atm.
- We will therefore adopt the same test bench, only replacing the targets
- **Faster, cheaper!** Bulk of the preparation work will be the local instrumentation on the targets
- Test bench is currently in the storage b. 954 ([CR-025436](#)), already disassembled (February 2019)
- **Total collective dose during disassembling:** 26 µSv
Multimat-2 Exp. Setup – Targets

- **Targets**: slender rods, indicative size 10x10x200 mm³
- Main objective is to validate the HL-LHC Baseline (industrial solution adopted for LS2 collimator production) and Plan B/C under the HL-LHC accident scenarios (beam injection error)
  - **Baseline**
    - Primary collimators: MoGr grade NB-8404Ng produced by Nanoker
    - Secondary collimators: MoGr NB-8404Ng coated with a 5 Mo layer by DTI via HIPIMS technique
  - **Plan B/C**
    - Secondary collimators: isotropic graphite equivalent to SGL R7550, coated with Mo or Cu via HIPIMS
- Possibility of adding further target stations of the same materials, with different cross section (to explore thresholds of damage)
- Possibility to test other materials of interest for Beam Intercepting Devices (BID), also in the scope of ARIES and IFAST (European projects) → possible contribution coming from those programs
### Multimat-2 Beam Parameters

<table>
<thead>
<tr>
<th>Multimat-2 beam parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle type</td>
<td>Protons</td>
</tr>
<tr>
<td>Bunches/pulse</td>
<td>1 to 288</td>
</tr>
<tr>
<td>Intensity/bunch</td>
<td>Up to 1.2E11 p (higher intensity, if available, would be very welcome)</td>
</tr>
<tr>
<td>Spot size</td>
<td>Down to 0.25 mm</td>
</tr>
<tr>
<td>N. pulses</td>
<td>~250 including pilot bunches</td>
</tr>
<tr>
<td>Integral intensity</td>
<td>~2E15 p</td>
</tr>
</tbody>
</table>

- **Energy density peak equivalent to HL-LHC (or higher)** by squeezing the spot size, with the max beam intensity available ($\sigma=0.25$ mm $\rightarrow \frac{e_{p,\text{Multi2}}}{e_{p,\text{HL}}} = 1 \div 1.5$ depending on the material).
- **Maximum average energy equivalent to HL-LHC** (or higher) by decreasing the target cross-section ($B \times H = 10 \times 12$ mm$^2$ $\rightarrow \frac{\bar{e}_{s,\text{Multi2}}}{\bar{e}_{s,\text{HL}}} = 2 \div 3$ depending on the material).
Multimat-2 Instrumentation

- Similar principles of Multimat, but implementing the lessons learnt (e.g. more strain gauges dedicated to transverse wave propagation, to better investigate longitudinal/transversal stress coupling)
- **Local instrumentation**: strain gauges, temperature probes, rad-hard camera. Possibly optical fibres. BTV/BPKG system to monitor beam spot size and impact position.
- **Remote instrumentation**: laser-Doppler vibrometer
Multimat-2 – PIE

- **Procedures well established** from previous collimation experiments
- After irradiation, the following examination steps will be taken:
  - Remote observation of impacted jaws through rad-hard camera.
  - Close-by observation through viewports at the end of experiment.
  - After appropriate cool-down time, rapid opening of the tank, dismounting of target stations and removal of single specimens in a bunker (*e.g.* in b. 867)
  - After RP approval: Metrology, NDT and analysis of specimens. If appropriate, cutting and destructive testing of specimens
Multimat-2 – Timeline

- Test-bench is available, however it will need some tests to confirm operability
- Possibly some components to be produced (e.g. supports)
- Samples must be manufactured, coated and instrumented
- Also considering the gradual restart of CERN activities, a reasonable timeline for running the experiment could be the 2nd half of 2021
- Running the experiment in 2021 would allow participation of ARIES WP17 people through TA
Conclusions

- Past experiments in HiRadMat led to **important results for the collimation project**, helping to validate technical solutions under the beam accident conditions, and to determine the thresholds of damage for the main components.
- Those experiments also produced **significant advancements in the scientific knowledge of the tested materials**, helping to characterize the material behaviour and derive constitutive models, leading to a relevant number of scientific publications.
- In order to validate the HL-LHC collimation solutions for series production, and to better explore novel aspects of the response of the absorber composites under beam impact, we propose a **new experiment on material targets**.
- The new experiment, named Multimat-2, will make use of the existing Multimat setup, **with big savings in terms of cost, time and manpower**.
- We could be ready for the 2<sup>nd</sup> half of 2021. This slot would also allow participation of people through the ARIES Transnational Access. Possibility of additional contribution from ARIES and IFAST also to the sample production.
Thanks for your attention!
Backup slides
Collimator damage thresholds and accidental scenarios

- Damage triggered by $e_p$ (values in the table are in kJ/cm$^3$)
- For the thresholds not yet observed experimentally, the “>” symbol is used to indicate the most intense peak sustained by the material without reaching that threshold.

<table>
<thead>
<tr>
<th>Material</th>
<th>Damage threshold</th>
<th>HL LHC - LHC accidental case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>CFC</td>
<td>~1.6</td>
<td>Not observed (&gt; 3.8)</td>
</tr>
<tr>
<td>Graphite</td>
<td>~2.1</td>
<td>Not observed (&gt; 4.1)</td>
</tr>
<tr>
<td>MoGr</td>
<td>≤ 5.7</td>
<td>Not observed (&gt; 7.7)</td>
</tr>
<tr>
<td>Inermet</td>
<td>0.6</td>
<td>2.5</td>
</tr>
<tr>
<td>CuCD</td>
<td>≤ 2.5</td>
<td>3.6</td>
</tr>
</tbody>
</table>

For coatings: the beam injection error provokes a damage equivalent to threshold 3; $E_{max}$ ranging from 12 to 15 kJ/cm$^3$ depending on the coating material and on the substrate.
Collimator damage thresholds and accidental scenarios

- Damage triggered by $\bar{e}_s$ (values in the table are in kJ/cm$^3$)

<table>
<thead>
<tr>
<th>Material</th>
<th>Damage threshold</th>
<th>HL-LHC accidental case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>CFC</td>
<td>Not observed ($&gt;0.27$)</td>
<td>Not observed ($\gg0.27$)</td>
</tr>
<tr>
<td>Graphite</td>
<td>Not observed ($&gt;0.31$)</td>
<td>Not observed ($\gg0.31$)</td>
</tr>
<tr>
<td>MoGr</td>
<td>$\sim0.97$</td>
<td>Not observed ($\gg0.97$)</td>
</tr>
</tbody>
</table>
HRMT-09 (2012)

- Testing of a spare TCT collimator
- Allowed to derive **damage limits for tertiary collimator jaws** (Inermet180)
- Highlighted **additional potential machine protection issues on top of mechanical damage**, due to projection of fragments and dust (UHV degradation, contamination of vacuum chambers, complication of dismounting procedure)

Test of specimens from 6 different materials: Inermet180, Mo, Glidcop, MoCuCD CuCD, and MoGr (very old grade with high density, 5.4 g/cm³)

Allowed characterization of materials of interest for collimators

Tuning of numerical models, with very good benchmarking between measurements and simulations

Test of specimens from 6 different materials: Inermet180, Mo, Glidcop, MoCuCD CuCD, and MoGr (very old grade with high density, 5.4 g/cm$^3$)

Allowed characterization of materials of interest for collimators

Tuning of numerical models, with very good benchmarking between measurements and simulations

### Medium Intensity Samples (Type 1)
- Strain measurements on sample outer surface;
- Radial velocity measurements (LDV);
- Temperature measurements;
- Sound measurements.

### High Intensity Samples (Type 2)
- Strain measurements on sample outer surface;
- Fast speed camera to capture fragment front formation and propagation;
- Temperature measurements;
- Sound measurements.

### Table: Results Summary

<table>
<thead>
<tr>
<th>Case</th>
<th>Bunches</th>
<th>p/bunch</th>
<th>Total Intensity</th>
<th>Beam Sigma</th>
<th>Specimen Slot</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>60</td>
<td>1.5e11</td>
<td>9.0e12 p</td>
<td>2.5 mm</td>
<td>9</td>
<td>316 m/s</td>
</tr>
<tr>
<td>Experiment</td>
<td>72</td>
<td>1.26e11</td>
<td>9.0e12 p</td>
<td>1.9 mm</td>
<td>8 (partly 9)</td>
<td>~275 m/s</td>
</tr>
</tbody>
</table>

Tank opened in May 2015 in b. 109 (CERN), after 2 ½ years of cool-down

Activation was low, but risk of contamination due to radioactive fragments and powders (mostly Cu and W)

Non-destructive and destructive testing campaign
Test on three collimator jaws: CFC (LHC design), MoGr and CuCD (HL-LHC design).

Allowed validation of absorber jaw materials, as well as integral HL design (taperings, BPM, housing, cooling circuit, brazing).

Achieved $\varepsilon_p$ of HL-LHC accidental cases, by squeezing the beam.

For CuCD, exceeded $\varepsilon_s$ of the HL-LHC accidental case; for MoGr and CFC: we were below (LIU beam needed!).

- F. Carra et al. (2019). Mechanical robustness of HL-LHC collimator designs. Accepted in IPAC19, Melbourne, Australia.
In the case of CFC and MoGr, minor traces visible after the grazing impacts at 144b and 288b (spallation: onset of damage → threshold 1)

- Deeper impacts (even at 288b) → no damage (smaller tensile wave at surface)

- No $\bar{e}_s$-induced damage on downstream blocks

Defect height is in the range of 12-13 µm
Downstream **Glidcop tapering** of CFC jaw **locally melted**

**MoGr no damage detected**
Plastic deformation? Yes \(\rightarrow\) most likely due to a cumulative effect of successive shots with energy equal/above the accidental case scenario
Flatness within the machining tolerance → CFC lower energy absorption
3D topography - MoGr

Block 2

- No spallation takes place → pseudo-plastic expansion

- Defect height is in the range of $12-13 \, \mu m$ and localized in tenth of mm width region

- Surface roughness 1.5 $\mu m$ → considered as mean error of the height measurements
Computed tomography - MoGr

• No internal damages detected
• Agglomerate of molybdenum carbides with disk shape, dimensions few mm
• Small cracks or voids appear in correspondence of carbide agglomerates randomly distributed in the bulk → not attributed to beam effect

Production process not optimized yet at the time of the experiment
Computed tomography - MoGr

- Last block
Test on **SLAC rotatable collimator** (Glidcop)

**Low-impedance secondary collimator** capable of withstanding 7 TeV failures

**Goals:**

- Demonstrate that the rotation functionality works for the design failure at top energy (Asynchronous beam dump: *8 bunches @ 7 TeV*)
- Understand onset of damage for even more demanding scenarios, e.g. LHC injection error: *288 bunches @ 450 GeV*
- Integrity control of the cooling pipes under both impact and jaw rotation
- Check the eventual sticking of the jaws in case of ejecta with LHC-type aperture

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### Beam Pulse List

<table>
<thead>
<tr>
<th>No.</th>
<th>Intensity</th>
<th>Beam spot (mm)</th>
<th>Bunch spacing (ns)</th>
<th>Pulse length (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># bunches</td>
<td>p/bunch</td>
<td>Sigma_x</td>
<td>Sigma_y</td>
</tr>
<tr>
<td>1-25</td>
<td>1</td>
<td>6.00E+13</td>
<td>3.00E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>26</td>
<td>6</td>
<td>1.20E+11</td>
<td>7.20E+11</td>
<td>0.35</td>
</tr>
<tr>
<td>Rotation of 1 facet AC (<em>1.5 hours</em>)</td>
<td>1</td>
<td>6.00E+13</td>
<td>3.00E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>27-51</td>
<td>12</td>
<td>1.20E+11</td>
<td>1.44E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>Rotation of 1 facet AC (<em>1.5 hours</em>)</td>
<td>1</td>
<td>6.00E+13</td>
<td>3.00E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>53-77</td>
<td>24</td>
<td>1.20E+11</td>
<td>2.88E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>Rotation of 1 facet AC (<em>1.5 hours</em>)</td>
<td>1</td>
<td>6.00E+13</td>
<td>3.00E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>78</td>
<td>36</td>
<td>1.20E+11</td>
<td>4.32E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>Rotation of 1 facet AC (<em>1.5 hours</em>)</td>
<td>1</td>
<td>6.00E+13</td>
<td>3.00E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>104</td>
<td>48</td>
<td>1.20E+11</td>
<td>5.76E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>Rotation of 1 facet AC (<em>1.5 hours</em>)</td>
<td>1</td>
<td>6.00E+13</td>
<td>3.00E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>151-155</td>
<td>72</td>
<td>1.20E+11</td>
<td>8.64E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>Rotation of 5 facet AC + 1 facet BD (<em>9 hours</em>)</td>
<td>1</td>
<td>6.00E+13</td>
<td>3.00E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>156</td>
<td>144</td>
<td>1.20E+11</td>
<td>1.73E+13</td>
<td>0.35</td>
</tr>
<tr>
<td>Rotation of 5 facet AC + 5 facet BD (<em>15 hours</em>)</td>
<td>1</td>
<td>6.00E+13</td>
<td>3.00E+12</td>
<td>0.35</td>
</tr>
<tr>
<td>183-207</td>
<td>208</td>
<td>1.20E+11</td>
<td>3.46E+13</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Equivalent total energy**

- **Onset of plastic damage:** estimated to be around 2E12p @ 440GeV (141kJ)
- **Intermediary shots**
  - Design failure at 7Tev: 15E12p @ 440GeV (1MJ)
  - HL-LHC injection error: 3.5E13p @ 440GeV (2.4MJ)
HRMT-21 (2017)

• Simply-supported slender bars (length 120 or 247 mm) of square cross section:
  ⇒ generate easily detectable and separable, mostly uniaxial signals
  ⇒ Reach/exceed $\bar{U}_{\text{max}}$ and strain / stresses of HL-LHC (factor 2-3 higher!) thanks to sample section ~1/10th of BIDs section

• Beam impacts targets with variable offsets.
  • Zero offset. Excites longitudinal vibration (5÷50 kHz).
  • Intermediate offset. Additionally excites lateral oscillations (100÷2000 Hz).
  • Grazing impact. Probe coating strength. Surface damage

<table>
<thead>
<tr>
<th>Material [Sub-Coat]</th>
<th>$U_{\text{max}}$ Coating [kJ cm$^{-3}$]</th>
<th>$U_{\text{max}}$ Substrate [kJ cm$^{-3}$]</th>
<th>$U_{\text{max}}$ HL-LHC (BIE) [kJ cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG6541Fc - Mo</td>
<td>13.85</td>
<td>6.11</td>
<td>6.09</td>
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<tr>
<td>MG6530 - Cu</td>
<td>15.31</td>
<td>7.68</td>
<td>-</td>
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<tr>
<td>AC150K - Mo</td>
<td>14.27</td>
<td>3.72</td>
<td>2.55</td>
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<tr>
<td>R4550 - Cu</td>
<td>12.30</td>
<td>4.15</td>
<td>-</td>
</tr>
</tbody>
</table>

Failure expected for most loaded MoGr samples

$U_{\text{max}} \sim 10^4$ J cm$^{-3}$ reached in grazing shot
CFC AC150k

- Anisotropic material
- 288b, $1.27 \times 10^{11}$ p/b
- $\sigma = 0.5$ mm, no offset
- $\text{CTE}_z < 0 \Rightarrow \text{Tension}$

**Results**

- Longitudinal strain at $z = l/2$ with linear-elastic constitutive model and no damping (Th. = -283µε)

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Isotropic Graphite R4550

- Isotropic material
- 288b, $1.25 \times 10^{11}$ p/b
- $\sigma = 0.5$ mm, no offset
- Deposition time $\tau = 7.95$ µs is close to the radial waves propagation period $\tau_r = 7.88$ µs \Rightarrow Weak coupling with radial waves \Rightarrow Very regular, step-like compressive waves
CuCD (RHP)

- Composite isotropic material
- 1b, $1.43 \times 10^{11}$ p/b, $\sigma = 0.5$ mm, 3.1 mm offset
- Elasto-plastic const. model, $\zeta = 8\%$ (Rayleigh)
- Axial wave
- Bending oscillations

Inermet IT180

- Homogeneous isotropic material
- 288b, $2.03 \times 10^{11}$ p/b, $\sigma = 2$ mm, no offset
- Plasticization for more intense pulses (up to 24b)
- Permanent deformation