FLUKA simulations on residual gas production in IR7 collimators

9th HiLumi Annual Meeting 16/10/2019

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On behalf of FLUKA and collimation teams
Motivation

- **Radiation damage** incurred by high energy protons and secondary shower particles on beam-intercepting devices like collimators during operation
- Estimate quantities using FLUKA that can be related to changes in important physical properties of collimator material:
  - Embrittlement/creep/swelling/corrosion
  - Fracture toughness reduction
  - Fatigue response
  - Thermal/electrical conductivity reduction
- Damage effects are dependent upon irradiation parameters including energy, intensity, material properties, …
- Simulations used to estimate quantities for real accelerator environment which can serve as input for irradiation experiments
  - Displacements in crystal lattice quantified by DPA
  - Void formation/embrittlement caused by H, He residual gas production inside collimator jaw material, (expressed as atomic parts per million per DPA, appm/DPA)
● Inelastic nuclear interactions of GeV, TeV energy hadrons (primary and secondary) with target nuclei considered as a two-step process:
  ○ **Fast phase**: nucleon-nucleon collision, primary interacting with single nucleon in target nucleus, production secondary fast nucleons and pions producing a cascade in direction of the beam, further collisions (range cm, m)
  ○ (Intermediate phase: pre-compound)
  ○ **Slow phase**: de-excitation of target nuclei in an isotropic fashion (range < 100 μm for charged particles)
    ■ Evaporation of nucleons/ nucleon clusters, residual H, He nuclei

● Recoils produced by elastic and inelastic interactions, energy loss through:
  ○ Electronic stopping (inelastic) for high energies
  ○ **Nuclear stopping** (elastic, NIEL) for lower energies, all shower particles can contribute to DPA, at low energy dominated by heavy recoils
  ○ Atomic displacement cascade forms, function of target material, threshold energy, primary energy
Radiation damage

- The displacement per atom (DPA) quantity is a measure of the amount of radiation damage incurred during irradiation, can be used to relate radiation damage to change of macroscopic material properties.
- Cannot be measured experimentally, can only be measured indirectly (so far)
- Indirect through study of macroscopic effects (electric and thermal conductivities, radiation hardening, swelling…)
- Quantitative interpretation:
  - 3 dpa means each atom in the material has been displaced from its site within the structural lattice an average of 3 times
  - 0.01 DPA implies 1 out of 100 atoms has been displaced.

<table>
<thead>
<tr>
<th>FLUKA material name</th>
<th>Density [g/cm³]</th>
<th>atoms/cm³</th>
<th>DPA threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC</td>
<td>AC150GPH</td>
<td>1.67</td>
<td>8.37E22</td>
</tr>
<tr>
<td>MoGR</td>
<td>MG6403Fc</td>
<td>2.55</td>
<td>1.13E23</td>
</tr>
</tbody>
</table>
Optics and collimator settings

- HL-LHC v1.2
- 2 σ retraction
- 7 TeV proton beam
- Beam 2 only
- No misalignments
- Assuming all primary protons are lost on horizontal TCP.C
- ~ 1E17 protons lost during HL-LHC

<table>
<thead>
<tr>
<th></th>
<th>TCP.C6R7 (H)</th>
<th>TCP.B6R7 (S)</th>
<th>TCS.6R7</th>
<th>TCP.D6R7 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from IP7 [m]</td>
<td>203</td>
<td>202</td>
<td>201</td>
<td>205</td>
</tr>
<tr>
<td>161</td>
<td>162</td>
<td>161</td>
<td>161</td>
<td>161</td>
</tr>
<tr>
<td>Half gap [mm]</td>
<td>1.77</td>
<td>1.52</td>
<td>1.28</td>
<td>1.09</td>
</tr>
<tr>
<td>σ</td>
<td>7.7</td>
<td>7.7</td>
<td>5.7</td>
<td>5.7</td>
</tr>
<tr>
<td>β_x [m]</td>
<td>40.2</td>
<td>143.0</td>
<td>87.6</td>
<td>159.4</td>
</tr>
<tr>
<td>β_y [m]</td>
<td>226.9</td>
<td>82.9</td>
<td>82.9</td>
<td>78.4</td>
</tr>
</tbody>
</table>

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Impact distribution and scoring mesh

- Primary collimators: mesh size determined by impact distribution ("touches") on horizontal collimator (TCP.C)
  - Distribution in X: 5 μm bins between 0 and 0.4 mm.
Scoring

- Primary collimators: mesh size determined by impact distribution (“touches”) on horizontal collimator (TCP.C)
  - assuming all primary protons are lost on TCP.C (~ 1E17 protons lost during HL-LHC lifetime)
  - X: 5 μm bins between 0 and 0.4 mm (in cleaning plane).
  - Y: 50 μm bins between -1 and 1 mm
Scoring

- Primary collimators: mesh size determined by impact distribution ("touches") on horizontal collimator (TCP.C)
  - Assuming all primary protons are lost on TCP.C (~1E17 protons lost during HL-LHC lifetime)
  - X: 5 μm bins between 0 and 0.4 mm (in cleaning plane).
  - Y: 50 μm bins between -1 and 1 mm
  - Z (longitudinally): 1 cm bins between -30 and 30 cm
- Secondary collimators: mesh size required to be larger due to shower development, jaws impacted by secondary particles
  - X: 400 μm bins between 0 and 2 cm.
  - Y: 400 μm bins between -2.5 and 2.5 cm
  - Z: 1 cm bins between -50 and 50 cm
- Residual gas production:
  - $^1$H, $^2$H, $^3$H scored separately, summed for analysis
  - $^3$He, $^4$He scored separately, summed for analysis
Previous results

- DPA studies on primary and secondary collimators (CFC and MoGR)
- Beam 1 geometry and touches
- v1.2 optics

Left jaw

Right jaw
Previous results

- DPA studies on primary and secondary collimators (CFC and MoGR)
- Beam 1 geometry and touches
- v1.2 optics
## Previous results

<table>
<thead>
<tr>
<th>1E17 protons lost</th>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC</td>
<td>0.05 - 0.1</td>
<td>1 - 2 \cdot 10^{-4}</td>
</tr>
<tr>
<td>MoGR</td>
<td>0.3</td>
<td>4 - 5 \cdot 10^{-4}</td>
</tr>
</tbody>
</table>
Primary collimators
Primary collimators

- Assuming 1E17 protons all lost on horizontal TCP.C
  - 5 μm x 50 μm x 1cm mesh

<table>
<thead>
<tr>
<th>DPA peak values</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC</td>
<td>~ 0.085</td>
<td>~ 0.12</td>
</tr>
<tr>
<td>MoGR</td>
<td>~ 0.15</td>
<td>~ 0.18</td>
</tr>
</tbody>
</table>
Primary collimators

- Assuming 1E17 protons all lost on horizontal TCP.C
  - 5 μm x 50 μm x 1 cm mesh
  - All H, He species scored on most impacted jaw (right) only

<table>
<thead>
<tr>
<th>ppm peak values</th>
<th>4He</th>
<th>1H</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC</td>
<td>~120</td>
<td>~25</td>
</tr>
<tr>
<td>MoGR</td>
<td>~140</td>
<td>~40</td>
</tr>
</tbody>
</table>
Primary collimators

- Assuming 1E17 protons all lost on horizontal TCP.C

<table>
<thead>
<tr>
<th>appm/DPA</th>
<th>He</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC</td>
<td>1000 - 3000</td>
<td>400 - 1000</td>
</tr>
<tr>
<td>MoGR</td>
<td>1000 - 2000</td>
<td>400 - 1000</td>
</tr>
</tbody>
</table>
Primary collimators: Run 2 results

- Present layout features CFC primary collimators
- Integrated intensity measurements estimate betatron induced proton losses amount to $7.1 \times 10^{15}$ for Run 2 in Beam 2

- Peak DPA values in CPC.C (CFC) at 0.008 (left jaw) and 0.006 (right jaw).
**Primary collimators: Run 2 results**

- Present layout features CFC primary collimators
- Integrated intensity measurements estimate betatron induced proton losses amount to $7.1\times10^{15}$ for Run 2 in Beam 2

- Orbit jitter on order of 50 μm, applying shift will not change distribution
Secondary collimators

- CFC primary/secondary and MoGR (+coating) primary/secondary collimators combination simulated
  - 400 μm x 400 μm x 1cm mesh
  - Consistent with previous results
- Large statistical uncertainties for Mo coating scoring
Secondary collimators

- CFC primary/secondary and MoGR (+coating) primary/secondary collimators combination simulated
  - 400 μm x 400 μm x 1cm mesh
  - Overall higher residual gas production in MoGR bulk jaw material compared to CFC

![Graphs showing H, He production in CFC and MoGR collimators](image)
Secondary collimators

- CFC primary/secondary and MoGR (+coating) primary/secondary collimators combination simulated
  - 400 μm x 400 μm x 1 cm mesh
  - appm/DPA result significantly lower for MoGR due to higher overall DPA
BLIP test simulations

- FLUKA simulations performed to estimate BLIP test results
  - DPA and He production for CFC and MoGR capsules
  - Reference calculations of appm/DPA for H (on the same order as He) and $^3$He (~ 20%)
Summary and outlook

- FLUKA simulations performed to assess DPA and gas production in IR7 primary and secondary collimators
  - B2, v1.2 optics, CFC and (Mo-coated) MoGR
  - Results cross-checked and consistent with previous DPA studies
  - appm/DPA reference calculations from BLIP test and simulations

- Outlook:
  - Improve scoring and statistics (coating)
  - Re-evaluate CFC primary / MoGR secondary configuration
  - Use results for/cross check experimental considerations and expected performance in accelerator

<table>
<thead>
<tr>
<th>B2H HL-LHC v1.2</th>
<th>Primary CFC</th>
<th>Primary MoGR</th>
<th>Secondary CFC</th>
<th>Secondary MoGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>He</td>
<td>H</td>
<td>He</td>
<td>H</td>
</tr>
<tr>
<td>DPA (peak)</td>
<td>0.12</td>
<td>0.18</td>
<td>0.0001</td>
<td>0.00034</td>
</tr>
<tr>
<td>appm</td>
<td>45</td>
<td>140</td>
<td>65</td>
<td>160</td>
</tr>
<tr>
<td>appm/DPA</td>
<td>400 - 1000</td>
<td>1000 - 3000</td>
<td>400 - 1000</td>
<td>1000 - 2000</td>
</tr>
</tbody>
</table>

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Fermilab
Backup slides
Backup slides

- appm/DPA in Mo coating on MoGR secondary collimators
H, He production quantity calculation

- H, He production expressed as *appm* or atomic parts per million
- Results in FLUKA normalized per cm$^3$, appm is then expressed with respect to amount of atoms in 1 cm$^3$ of jaw material
- Collimator jaw materials:
  - **CFC**, Fluka material AC150GPH, density $\rho = 1.67$ g/cm$^3$
    - $M(C) = 12.0107$ g/mol
      - $M(C) \cdot N_A \cdot \rho_{CFC} = 8.37E22$ atoms / cm$^3$
  - **MoGR**, Fluka (compound) material MG6403Fc, $\rho = 2.55$ g/cm$^3$
    - $M(Mo) = 95.95$ g/mol, 1.84%
    - $M(C) = 12.0107$ g/mol, 98.09%
    - $M(Ti) = 47.867$ g/mol, 0.07%
      - $M(MoGR) \cdot N_A \cdot \rho_{MoGR} = 1.13E23$ atoms / cm$^3$

Avogadro constant $N_A$; $6.022 \cdot 10^{23}$ mol$^{-1}$