PSB ABSORBER/SCRAPER
Thermo-mechanical simulations

J. Maestre and I. Lamas
OUTLINES

- INTRODUCTION
- DESIGN PREVIEW
- SCENARIOS AND BEAM PARAMETERS
- THERMO-MECHANICAL SIMULATIONS
  - ASSUMPTIONS
  - MODEL DESCRIPTION AND SET UP
  - INITIAL PRESFITTING OF THE HOUSING AND GRAPHITE BLOCK
  - THERMAL SIMULATIONS
  - MECHANICAL SIMULATIONS
- CONCLUSIONS
IN THE CONTEXT OF THE LHC INJECTOR UPGRADE PROJECT, THE PS BOOSTER KINETIC INJECTION IS PLANED TO INCREASE THE ENERGY FROM 50 MeV TO 160 MeV

NOWADAYS, THERE IS A SO-CALLED WINWDOS BEAM SCOPE (WBS) DEVICE INSTALLED IN THE SECTION 8L2.

THE WBS CONSISTS ON A 40 mm THICK GRAPHITE MASK. THE FUNCTION IS DOUBLE
- TO PROTECT THE DOWNSTREAM DEVICES FROM POSSIBLE ENERGY LOSSES
- TO SCRAPE AND SHAVE THE BEAM, LIMITING THE BEAM SIZE

AT THIS LEVEL OF ENERGY THE PROTONS CANNOT BE STOPED AND A NEW DEVICE MUST BE DESIGN TO ACCOMPLISH THE NEW OPERATION REQUIREMENTS

THE NEW ABSORBERS/SCRAPERS WILL BE INSTALLED BETWEEN THE DEFOCUSING AND THE SECOND FOCUSING QUADRUPOLE MAGNET

THE THERMO-MECHANICAL ANALYSIS OF THE NEW DEVICE IS SHOWS IN THIS DOCUMENT

Fig. : New design of the PSB-absorber/scraper

BR.DBSV/H8L4 will be removed for the new PSB-absorber/scraper
DESIGN PREVIEW

- Low Z-material are considered for the design of the PSB-absorber-scraper. Carbon graphite have been shown to be optimal. Simulations reveal that a block of 130 mm of graphite is enough to stop 160 MeV protons.
- The control of each PSB-absorber/scrapper is independent per each rings.
- 2 Mask are installed per ring:
  - A Fixed mask (major aperture limitation): it is always in the beam line
  - A movable mask (smaller aperture). The mask can be in or out of the beam line depending of the operational requirements.
- One mask is able to stop the 160 MeV protons.
- An extension chamber is introduced instead of the movable mask in order to reduce the impedance.

Fig : movable mask out

Fig : movable mask in
<table>
<thead>
<tr>
<th>SCENARIOS AND BEAM PARAMETERS</th>
<th>From the technical specification EDMS No. 1578463</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Title</strong></td>
<td>1st scenario: Scraping at low energy</td>
</tr>
<tr>
<td><strong>Particles to consider</strong></td>
<td>Protons</td>
</tr>
<tr>
<td><strong>Intensity</strong></td>
<td>$2 \times 10^{12}$ p/ring, 6% losses of the total beam (integrated over 20 ms) deposited on one jaw. Pessimistic assumption.</td>
</tr>
<tr>
<td><strong>Beam Kinetic Energy</strong></td>
<td>160 MeV</td>
</tr>
<tr>
<td><strong>Bunch length</strong></td>
<td>~650 ns</td>
</tr>
<tr>
<td><strong>Pulse period</strong></td>
<td>1.2 s</td>
</tr>
<tr>
<td><strong>Pulse time</strong></td>
<td>losses during ~20 ms (turn-by-turn; each turn spaced by 0.925/1 ms; beam during ~65% of this revolution time)</td>
</tr>
<tr>
<td><strong>How many cycles to take into account in simulations (life cycle)</strong></td>
<td>Study the steady state</td>
</tr>
<tr>
<td><strong>Beam transverse distribution</strong></td>
<td>Gaussian</td>
</tr>
<tr>
<td><strong>Beam rms horizontal size</strong></td>
<td>$1 \sigma = 9.08$ mm (Movable Mask)</td>
</tr>
<tr>
<td></td>
<td>9.60 mm (Fixed Mask)</td>
</tr>
<tr>
<td><strong>Beam rms vertical size</strong></td>
<td>$1 \sigma = 11.15$ mm (Movable Mask)</td>
</tr>
<tr>
<td></td>
<td>10.42 mm (Fixed Mask)</td>
</tr>
<tr>
<td><strong>Beam impact location</strong></td>
<td>To be determined considering 6% losses</td>
</tr>
</tbody>
</table>

12 simulation
ASSUMPTIONS

- Simplification of the geometrical model
- Symmetric condition
- Vacuum tank
- Transfer method:
  - Tank-inside $\rightarrow$ radiation
  - Tank-ambient $\rightarrow$ convection and radiation
- Emissivity:
  - Stainless steel = 0.7
  - Graphite = 0.75
- Convection: 6W/m²K (theoretical calculation for a horizontal cylinder)
- Contact:
  - Housing-graphite: frictional
  - Tank parts (screw union): bounded
  - Thermal contact computed iteratively considering thermal expansion and presfitting.
**MODEL DESCRIPTION**

- **Stainless steel 316L**
- **Graphite SGL R7550**

### Table: Material properties at 20 C

<table>
<thead>
<tr>
<th>Property</th>
<th>GR. R7550</th>
<th>Stainless Steel 316L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [Kg/m³]</td>
<td>1.80E+03</td>
<td>7.96E+03</td>
</tr>
<tr>
<td>Young’s Modulus [MPa]</td>
<td>7.19E+09</td>
<td>1.94E+11</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>1.40E-01</td>
<td>2.94E-01</td>
</tr>
<tr>
<td>Flexural strength [MPa]</td>
<td>6.00E+01</td>
<td>-</td>
</tr>
<tr>
<td>One-dir. compressive strength [MPa]</td>
<td>1.25E+02</td>
<td>-</td>
</tr>
<tr>
<td>Yield strength [MPa]</td>
<td>-</td>
<td>3.02E+02</td>
</tr>
<tr>
<td>Specific heat [J/KgC]</td>
<td>7.60E+02</td>
<td>4.85E+02</td>
</tr>
<tr>
<td>Thermal expansion Coeff. [1/C]</td>
<td>3.64E-06</td>
<td>1.71E-05</td>
</tr>
<tr>
<td>Thermal conductivity [W/m°C]</td>
<td>1.07E+02</td>
<td>1.33E+01</td>
</tr>
</tbody>
</table>

- **Material properties → Temperature dependent**
- **Model is divided in different region → finer mesh around the beam impact**
- **Indirect couple thermo-mechanical analysis**
- **First order element for thermal analysis and second order for structural**
## MODEL SET UP

### Mote Carlo simulation

![Mote Carlo simulation](image)

### Ansys

![Ansys](image)

### Transfer data data

![Fig: Check line of maximum energy deposition](image)

---

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Energy (J/pulse)</th>
<th>Error (%)</th>
<th>Energy (J/pulse)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario 1 - H</strong></td>
<td>Movable</td>
<td>30.51</td>
<td>5.96</td>
<td>30.325725</td>
</tr>
<tr>
<td><strong>Scenario 1 - H</strong></td>
<td>Movable</td>
<td>30.51</td>
<td>5.96</td>
<td>30.325725</td>
</tr>
<tr>
<td><strong>Scenario 1 - H</strong></td>
<td>Fixed</td>
<td>0.50</td>
<td>0.10</td>
<td>30.82</td>
</tr>
<tr>
<td><strong>Scenario 1 - H</strong></td>
<td>Fixed</td>
<td>0.50</td>
<td>0.10</td>
<td>30.82</td>
</tr>
<tr>
<td><strong>Scenario 1 - V</strong></td>
<td>Movable</td>
<td>30.49</td>
<td>5.95</td>
<td>30.346777</td>
</tr>
<tr>
<td><strong>Scenario 1 - V</strong></td>
<td>Movable</td>
<td>30.49</td>
<td>5.95</td>
<td>30.346777</td>
</tr>
<tr>
<td><strong>Scenario 1 - V</strong></td>
<td>Fixed</td>
<td>0.40</td>
<td>0.08</td>
<td>30.39</td>
</tr>
<tr>
<td><strong>Scenario 1 - V</strong></td>
<td>Fixed</td>
<td>0.40</td>
<td>0.08</td>
<td>30.39</td>
</tr>
<tr>
<td><strong>Scenario 2 - H</strong></td>
<td>Movable</td>
<td>239.72</td>
<td>3.75</td>
<td>239.02652</td>
</tr>
<tr>
<td><strong>Scenario 2 - H</strong></td>
<td>Movable</td>
<td>239.72</td>
<td>3.75</td>
<td>239.02652</td>
</tr>
<tr>
<td><strong>Scenario 2 - H</strong></td>
<td>Fixed</td>
<td>131.09</td>
<td>2.05</td>
<td>228.65</td>
</tr>
<tr>
<td><strong>Scenario 2 - H</strong></td>
<td>Fixed</td>
<td>131.09</td>
<td>2.05</td>
<td>228.65</td>
</tr>
<tr>
<td><strong>Scenario 2 - V</strong></td>
<td>Movable</td>
<td>242.11</td>
<td>3.78</td>
<td>241.98775</td>
</tr>
<tr>
<td><strong>Scenario 2 - V</strong></td>
<td>Movable</td>
<td>242.11</td>
<td>3.78</td>
<td>241.98775</td>
</tr>
<tr>
<td><strong>Scenario 2 - V</strong></td>
<td>Fixed</td>
<td>136.21</td>
<td>2.13</td>
<td>235.20</td>
</tr>
<tr>
<td><strong>Scenario 2 - V</strong></td>
<td>Fixed</td>
<td>136.21</td>
<td>2.13</td>
<td>235.20</td>
</tr>
<tr>
<td><strong>Scenario 3 - H</strong></td>
<td>Movable</td>
<td>12.50</td>
<td>15.42</td>
<td>12.45</td>
</tr>
<tr>
<td><strong>Scenario 3 - H</strong></td>
<td>Movable</td>
<td>12.50</td>
<td>15.42</td>
<td>12.45</td>
</tr>
<tr>
<td><strong>Scenario 3 - H</strong></td>
<td>Fixed</td>
<td>0.26</td>
<td>0.32</td>
<td>12.60</td>
</tr>
<tr>
<td><strong>Scenario 3 - H</strong></td>
<td>Fixed</td>
<td>0.26</td>
<td>0.32</td>
<td>12.60</td>
</tr>
<tr>
<td><strong>Scenario 3 - V</strong></td>
<td>Movable</td>
<td>12.47</td>
<td>15.38</td>
<td>12.455252</td>
</tr>
<tr>
<td><strong>Scenario 3 - V</strong></td>
<td>Movable</td>
<td>12.47</td>
<td>15.38</td>
<td>12.455252</td>
</tr>
<tr>
<td><strong>Scenario 3 - V</strong></td>
<td>Fixed</td>
<td>0.24</td>
<td>0.29</td>
<td>12.53</td>
</tr>
<tr>
<td><strong>Scenario 3 - V</strong></td>
<td>Fixed</td>
<td>0.24</td>
<td>0.29</td>
<td>12.53</td>
</tr>
</tbody>
</table>

* Courtesy of Jose Antonio Briz Monago

---

*16/01/2018*  
**J. Maestre and I. Lamas– EN-STI**
CONTACT: Thermal resistance

Fig: Contact pressure computed at working temperature

- The contact pressure is lost at 95°C approx.
- Low interference is used to compute the TCC

Thermal contact coefficient

<table>
<thead>
<tr>
<th>Thermal Conductivity</th>
<th>SS316L</th>
<th>R7550</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst case 63°C</td>
<td>1.31E+01</td>
<td>1.03E+02</td>
</tr>
</tbody>
</table>

Contact pressure

- Contact Conductance $h$: $3.76E+03$ W/(m²*K)
- Effective roughness $\sigma$: $3.97126E-06$ m
- Young's Modulus for coupling $E$: $7.38E+09$ N/m²
- Absolute asperity slope $m_a$: $0.15746574 \times 2.08E-01$ rad
- Poisson’s Ratio $\nu$: $0.14$
- Absolute roughness $R_a$: $1.60E-06$ m
- Young's Modulus $E$: $7.38E+09$ N/m²
- Effective mean absolute asperity slope $m_{\text{eff}}$: $0.260934332$ rad
- Effective roughness $\sigma_{\text{eff}}$: $3.97126E-06$ m
- Young's Modulus for coupling $E_{\text{coupling}}$: $7.38E+09$ N/m²
- Contact Conductance $h_{\text{contact}}$: $4.93E+03$ W/(m²*K)
- Contact pressure $p$: $3.76E+03$ W/(m²*K)
- Harmonic mean thermal conductivity $k_s$: $2.33E+01$ W/(m*K)
- Effective mean absolute asperity slope $m_{\text{eff}}$: $0.260934332$ rad
- Effective mean absolute roughness $\sigma_{\text{eff}}$: $3.97126E-06$ m
- Young's Modulus for coupling $E_{\text{coupling}}$: $7.38E+09$ N/m²
- Contact Conductance $h_{\text{contact}}$: $4.93E+03$ W/(m²*K)
- Contact pressure $p$: $1.85E+06$ N/m²
- Harmonic mean thermal conductivity $k_s$: $2.33E+01$ W/(m*K)
- Effective mean absolute asperity slope $m_{\text{eff}}$: $0.260934332$ rad
- Effective mean absolute roughness $\sigma_{\text{eff}}$: $3.97126E-06$ m
- Young's Modulus for coupling $E_{\text{coupling}}$: $7.38E+09$ N/m²
- Contact Conductance $h_{\text{contact}}$: $4.93E+03$ W/(m²*K)

Details contact

- Frictional: coeff. frict = 0.1
CONTACT: Structural integrity

High interference

Christensen failure criterion for brittle materials

\[
C1 \quad \frac{1}{T} \left[ \frac{1}{C} \left( \sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 \right) + \frac{1}{2C} \left( \sigma_{11} - \sigma_{22} \right)^2 + \frac{1}{2C} \left( \sigma_{22} - \sigma_{33} \right)^2 + \frac{1}{2C} \left( \sigma_{33} - \sigma_{11} \right)^2 \right] + \frac{3}{2C} \left( \sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2 \right) \leq 1
\]

\[
C2 \quad \sigma_1 \leq T \quad \text{if} \quad T \leq \frac{C}{2}
\]

Where C and T are the failure stress in uniaxial and compression (absolute value). C = 125 MPa; T = 40 MPa

The worst scenario corresponds with the high interference.
Eq. stress in graphite and housing is lower than max limit
CONTACT: Deformation

High interference

Fig: Total deformation at ambient temperature

Fig: Total deformation at working temperature
CONTACT: Deformation

Fig : Total deformation at ambient temperature of a transversal cut of the graphite

Fig : Total deformation at working temperature of a transversal cut of the graphite

Fig : Total deformation at working temperature

→ High deformation in the graphite. (0.20 mm approx.)
→ Lost of planimetry on internal faces of the graphite.
→ The deformation depend on the temperature and contact interference
To reduce the thermal deformation and fluctuations
- Check different material for the housings:
  - Stainless steel 316L
  - Ti6-Al4-V (low thermal expansion coeff.)
- Check different configuration of the graphite block
  - Quadrilateral apertures
  - Octagonal apertures (better distribution of stress)

Measurement of the highest deformation at working and ambient temperature for the high and low interference case.
SCENARIO 1: Thermal

- Simulation at the steady state
- The primary particles are stopped in the movable mask.
- Working temperature is 62°C approx. This temp. is lightly lower in the case of horizontal case due to extension mask.
SCENARIO 1: Thermal

→ Simulation at the steady state
→ The primary particles are stopped in the fixed mask.
→ Working temperature is 59 C approx.
SCENARIO 1: Thermal

→ The surface treatment of the stainless steel is critical to decrease the temperature of the masks.

→ Thermal transient analysis considering a average power per cycle. As a representative behavior, only Sc1 with movable mask on is simulated

→ Working temperature is reached after more than 10 h

Fig : Temperature of the movable mask, for the Sc. 1 V considering a emissivity of 0.28, this is, without any thermo-surface treatments

Fig : Maximum temperature in the movable for different values of the emissivity of the stainless steel
SCENARIO 2: Thermal

→ Transient simulations
→ The primary particles go through the both mask
→ High gradient of temperature in the movable mask
SCENARIO 2: Thermal

→ Transient simulations
→ The primary particles go through the fixed mask
→ The temperature reaches 30 C after 10 pulses similar as the movable mask in
SCENARIO 3: thermal

Simulation at the steady state
The primary particles are stopped in the movable mask.
Working temperature is 39 C approx.
SCENARIO 3: Thermal

→ Simulation at the steady state
→ The primary particles are stopped in the fixed mask.
→ Working temperature is 37 C approx.
SCENARIO 1: Mechanical

Fig: Eq. Von-Mises Stress of the housing considering Movable mask in

Fig: Evaluation of failure criterion considering Movable mask in

→ Steady analysis is simulated.
→ Initial presfitting is take into account, being the maximum interference case, between the mask and housing, the worst scenario
→ The horizontal scenario is more critical structurally
→ Stress of the housing is lower than the yield limit (safety factor greater than 2)
→ Graphite are evaluated as a brittle material and have a safety factor greater than 3.
SCENARIO 2: Mechanical

Assumptions:
- Pessimistic scenario with the movable mask out
- Presfitting guarantee the contact between the graphite and the housing.
- No damping is considered in the material
- Simulation are carried out during the first cycle where the highest thermal gradient appear.

Velocity of P Waves
\[ v_p = \sqrt{\frac{K + \frac{4}{3} \mu}{\rho}} = \sqrt{\frac{\lambda + 2\mu}{\rho}} \approx 2050 \text{ m/s} \]
CONCLUSION

• Scenario 1 is the most adverse from the thermal point of view, reaching a max temperature of 62 C, on a limited region;
• This temperature is reached after more than 10h of operation;
• In scenario 2, high gradients of temperature are observed which can produce high level of thermal stresses. Wave stress propagation must be considered.
• In scenario 1 and 3 the primary protons are stopped by the first mask they encounter.
• A good thermal contact is extremely important in order to evacuate the heat from the mask. This contact is lost at 95 C approx. for the more pessimistic case.
• The presfitting produce deformations in the graphite that modify the planimetry of the windows apertures.
• Structural analysis have been carried out for the scenario 1, that is the most exigent. The horizontal case is more critical than the vertical. Even so, the safety factor is higher than 2 for the housing and than 3 for the graphite.
• A dynamic studio have been simulated for the scenario 2 during the first cycle. The simulations show a relatively low stress level produced by the stress waves.