Application of LHC and SPS (HiRadMat) to Study High Energy Density States in Matter

By

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Design Parameters of the LHC Beam

LHC will provide two counter rotating 7 TeV proton beams

Each beam will consist of \(2808\) proton bunches

Each bunch will contain \(1.15 \times 10^{11}\) protons

Total number of protons is \(3 \times 10^{14}\)

Bunch length = \(0.5\) \(\text{ns}\), Separation between bunches = \(25\) \(\text{ns}\)

Total length of the bunch train = \(89\) \(\mu\text{s}\)

Transverse intensity distribution: Gaussian with \(\sigma = 0.2\) \(\text{mm}\)

\(362\) \(\text{MJ}\) energy / beam sufficient to melt 500 kg copper
**First Step:** Energy loss of 7 TeV protons in solid copper target is calculated using the FLUKA Code

**Target Geometry:**
- **Solid Cu Cylinder**
  \[ L = 5 \text{ m}, \ r = 1 \text{ m} \]
- **Peak energy deposition**
  \[ 1200 \text{ GeV/proton/cm}^3 \]

**Second Step:**
This energy loss data is converted into kJ/g and is used as input to a 2D hydrodynamic computer code, BIG2.
Specific Energy Deposition by a Single Bunch in Solid Copper [FLUKA Calculations]

- Specific energy (kJ/g) deposited by one bunch of protons along L at r = 0.
- Maximum deposition of about 2.3 kJ/g occurs at L ~ 16 cm.
Specific energy deposition (kJ/g) vs radius at, L = 8 cm, 16 cm, 24 cm and 36 cm, by a single proton bunch.
• The target is studied in r-Z geometry.
• Specific energy deposition in each simulation cell at every timestep is normalized with respect to the line density along the axis.
• This allows for reduction of specific energy deposition in low density part of the target.
• This model allows for studying the proton “Tunneling Effect”.

I: LHC Beam on a Solid Copper Cylinder

\[ L = 5 \text{ m} \]

\[ r = 5 \text{ cm} \]
Specific Energy Deposition

Specific Energy (kJ/g)
Time = 500 ns

Specific Energy (kJ/g)
Time = 2500 ns

Specific Energy (kJ/g)
Time = 4500 ns

Specific Energy (kJ/g)
Time = 9500 ns

Saturates to 25 kJ/g
Temperature

$4 \times 10^4 \text{ K}$
Pressure

30 GPa
Penetration depth = 35 m
II: SPS Beam on a Tungsten Target (HiRadMat Facility)

- SPS Beam accelerates protons to 450 GeV
- 288 bunches in the beam
- Each bunch contains $1.15 \times 10^{11}$ protons
- Total number of protons is about $3 \times 10^{13}$
- Bunch length = 0.5 ns, Separation between bunches = 25 ns
- Total length of the bunch train ~ 7 μs
- Transverse intensity distribution: Gaussian with $\sigma = 0.088$ mm, 0.28 mm and 0.88 mm

Solid tungsten cylindrical target facially irradiated
$\sigma = 0.088 \text{ mm}$

FLUKA Energy Loss Calculations [GeV/cc/p]

$\sigma = 0.28 \text{ mm}$

$\sigma = 0.88 \text{ mm}$
FLUKA Calculations of Energy Loss
Specific Energy Deposition per Bunch

Solid tungsten cylinder $L = 2 \text{ m}, r = 5 \text{ cm}$
Facially irradiated by the SPS beam
Specific Energy Deposition (7.2 μs)

<table>
<thead>
<tr>
<th>σ (mm)</th>
<th>$E_s$ (kJ/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.088</td>
<td>7.4</td>
</tr>
<tr>
<td>0.280</td>
<td>6.75</td>
</tr>
<tr>
<td>0.880</td>
<td>5.83</td>
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</tbody>
</table>
### Temperature (7.2 μs)

<table>
<thead>
<tr>
<th>σ (mm)</th>
<th>T (10⁴ K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.088</td>
<td>4.0</td>
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<tr>
<td>0.280</td>
<td>3.7</td>
</tr>
<tr>
<td>0.880</td>
<td>2.6</td>
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</tbody>
</table>
Minimum Density (7.2 µs)

<table>
<thead>
<tr>
<th>σ (mm)</th>
<th>ρ (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.088</td>
<td>0.61</td>
</tr>
<tr>
<td>0.280</td>
<td>1.09</td>
</tr>
<tr>
<td>0.880</td>
<td>3.24</td>
</tr>
</tbody>
</table>
Profiles at $t = 7.2 \mu$s
Conclusions

- Numerical simulations of full impact of LHC and SPS beams on solid targets have been carried out.

- It is seen that in both cases the target is severely damaged.

- Penetration depth of the projectile particles is much longer than predicted by a static model.

- An additional application of the LHC as well as SPS can be to study HED physics.

- Fully integrated simulations with FLUKA coupled to BIG2 are required.