Shock Impact of High Energy/Intensity Beams With Matter and High Energy Density Physics

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LHC Injector Complex

Two counter rotating beams of 7 TeV protons

Energy Stored in Different Machines
Each LHC beam has 362 MJ Energy
Sufficient to melt 500 kg Cu
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 ns, Separation between bunches = 25 ns

Total length of the bunch train = 89 μs

Transverse intensity distribution: Gaussian with $\sigma = 0.2$ mm
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 GeV/proton/cm³

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 in Radial Direction Along the Target Axis

Specific energy deposition (kJ/g) vs radius at, $L = 8 \text{ cm}$, $16 \text{ cm}$, $24 \text{ cm}$ and $36 \text{ cm}$, by a single proton bunch.
- A solid copper cylinder facially irradiated by one LHC beam
- 2D hydrodynamic simulations are carried out along cross section at different longitudinal positions [\( L = 16 \text{ cm and 36 cm} \)]

Analytic estimates based on these simulation suggested that the protons will penetrate in the target 10 – 40 m in solid copper. This substantial range lengthening is direct consequence of proton “Tunneling Effect”
Cross section of a Cu cylinder
100 out of 2808 bunches delivered

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Further Advancement of the Simulations:

- 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 m

r = 5 cm
Specific Energy Deposition

Saturates to 25 kJ/g
Temperature

$4 \times 10^4$ K
Pressure

30 GPa
HEDP States

Density (g/cm$^3$)
Time = 500 ns

Density (g/cm$^3$)
Time = 4500 ns

Density (g/cm$^3$)
Time = 2500 ns

Density (g/cm$^3$)
Time = 9500 ns

Physical State
Time = 9500 ns
0.35 m/μs in 89 μs penetrate 35 m
II: LHC Beam on a Carbon target

For FLUKA Calculations: $L = 5\, \text{m}$, $r = 1\, \text{m}$

For Hydrodynamic simulations:
$L = 10\, \text{m}$, $r = 2.5\, \text{cm}$

Specific Energy

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Energy (kJ/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.3</td>
</tr>
<tr>
<td>Cu</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Specific Energy Deposition

Specific Energy (kJ/g)
Time = 2000 ns

Specific Energy (kJ/g)
Time = 60000 ns

Specific Energy (kJ/g)
Time = 40000 ns

Specific Energy (kJ/g)
Time = 89000 ns

42 kJ/g
Pressure

1.17 GPa
Density (g/cm³)
Time = 20000 ns

Density (g/cm³)
Time = 60000 ns

Density (g/cm³)
Time = 40000 ns

Density (g/cm³)
Time = 89000 ns
Another Step Forward: Running FLUKA and BIG2 Iteratively

In case of carbon we run FLUKA and BIG2 using time interval of 5µs.

Solid C Cylinder
L = 10 m, r = 5 cm
Facially Irradiated by the LHC Beam
Differences are obvious in the results obtained using the analytic approximation and the iterative running approach.

After completion of C target calculations, Cu target will be considered.
Conclusions and Future Outlook

- Numerical simulations of full impact of LHC and SPS beams on solid targets have been carried out. It has been found that in both cases the target is severely damaged.
- Penetration depth of the projectile particles is much longer than predicted by a static model.
- It is interesting to note that the LHC as well as SPS can be used to Generate HED Matter [An Additional Application].
- Iterative running of the FLUKA and BIG2 code has also been carried out for LHC beam impacting on a solid carbon cylindrical target.
- Similar iterative simulations will be carried out for the LHC beam impacting of other materials like Copper and Tungsten (Collimators).
- It is also planned to carry out iterative simulations using the SPS beam in order to design HiRadMat facility experiments.

_EuCARD: Colmat: Task 9.2 Energy Deposition_