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

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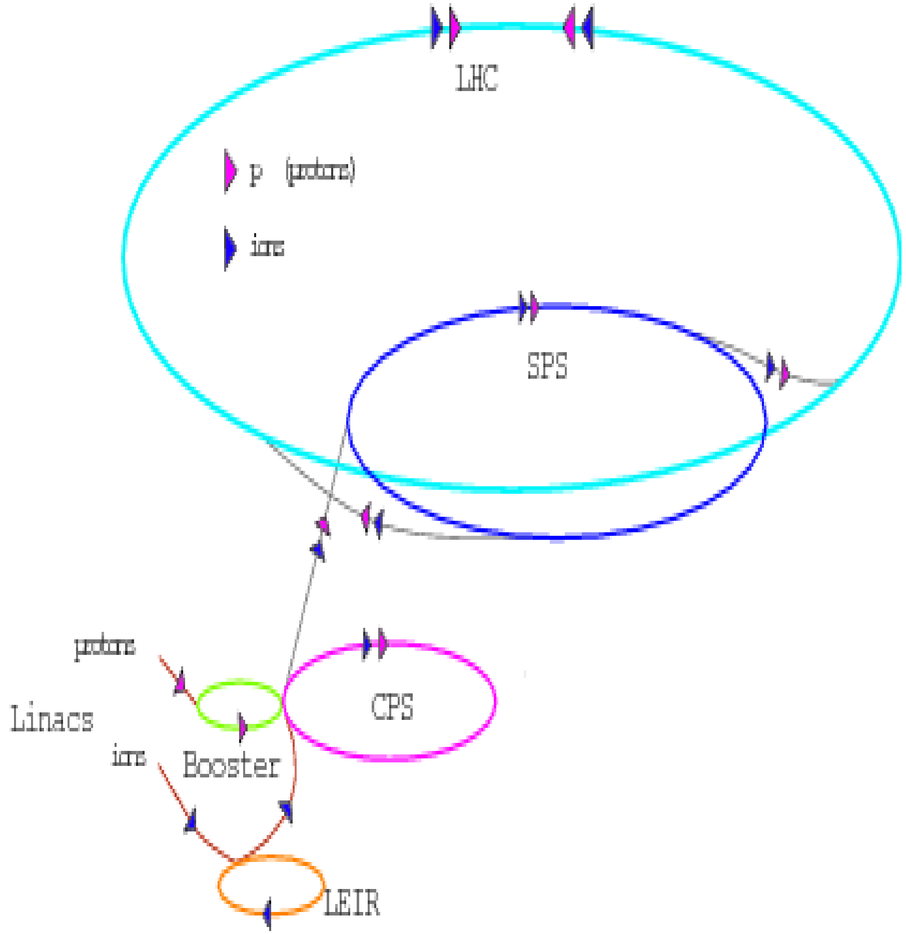
LHC Injector Complex

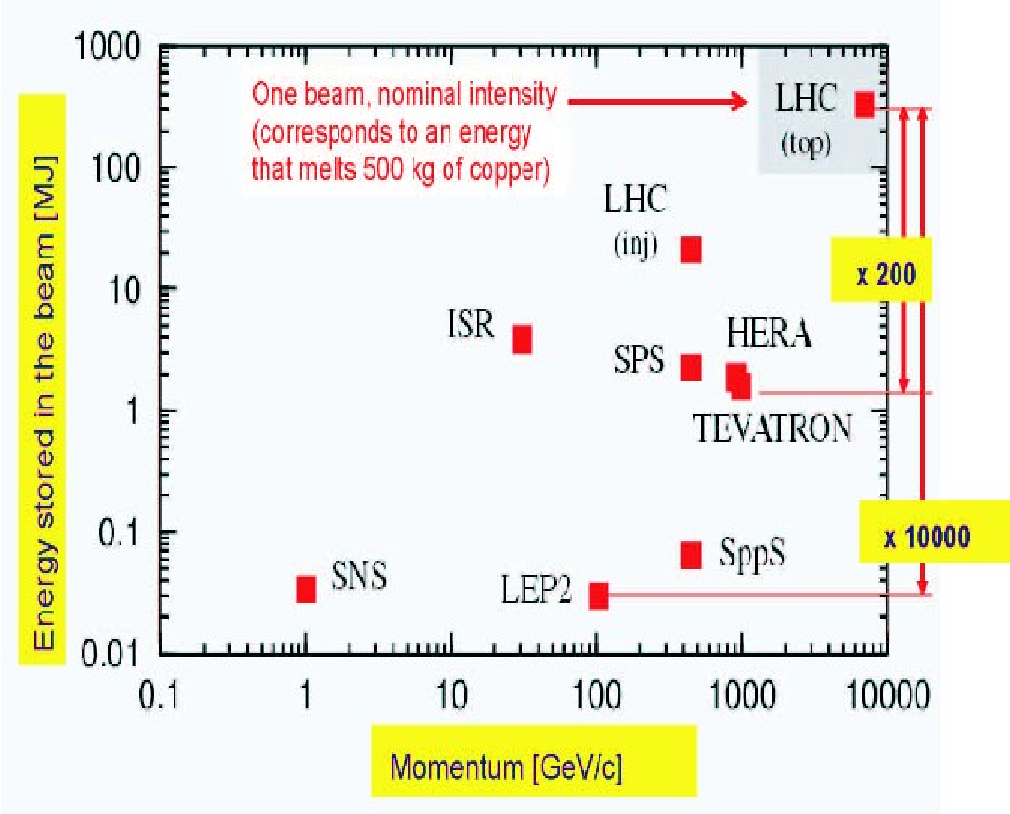
Two counter rotating beams of 7 TeV protons



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 1.15×10^{11} protons

Total number of protons is 3×10^{14}

Bunch length = 0.5 ns, Separation between bunches = 25 ns

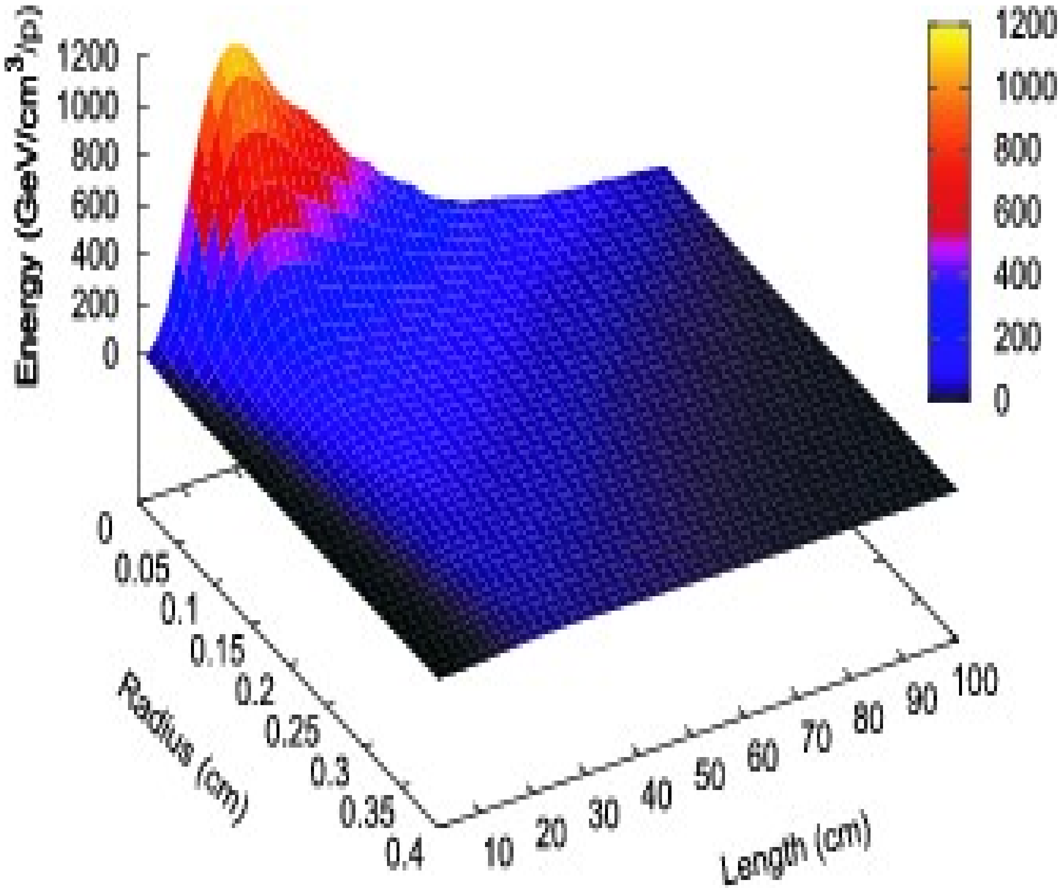
Total length of the bunch train = 89 μs

Transverse intensity distribution: Gaussian with σ = 0.2 mm

<u>First Step</u>: Energy loss of 7 TeV protons in solid copper target is calculated using the FLUKA Code

Target Geometry:

- Solid Cu Cylinder
  L = 5 m, r = 1 m
- Peak energy deposition
  1200 GeV/proton/cm^3

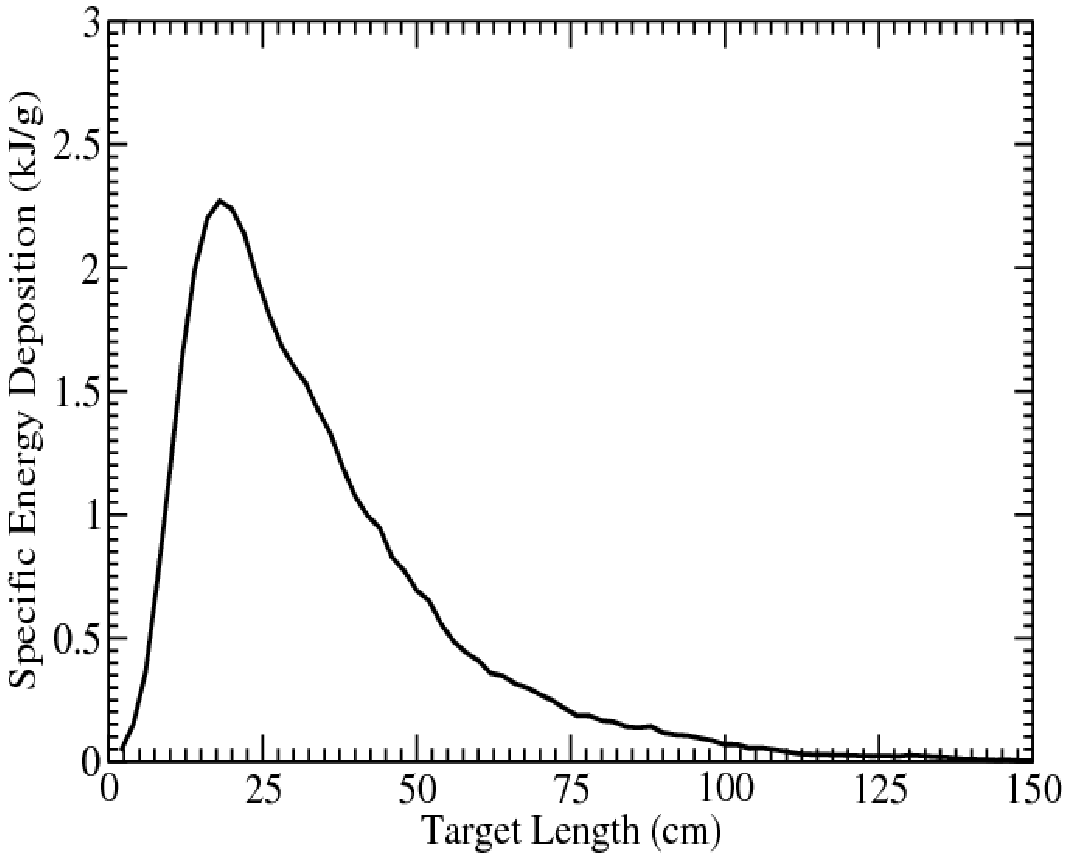


<u>Second Step:</u>

This energy loss data is converted into kJ/g and is used as input to a 2D hydrodynamic computer code, BIG2.

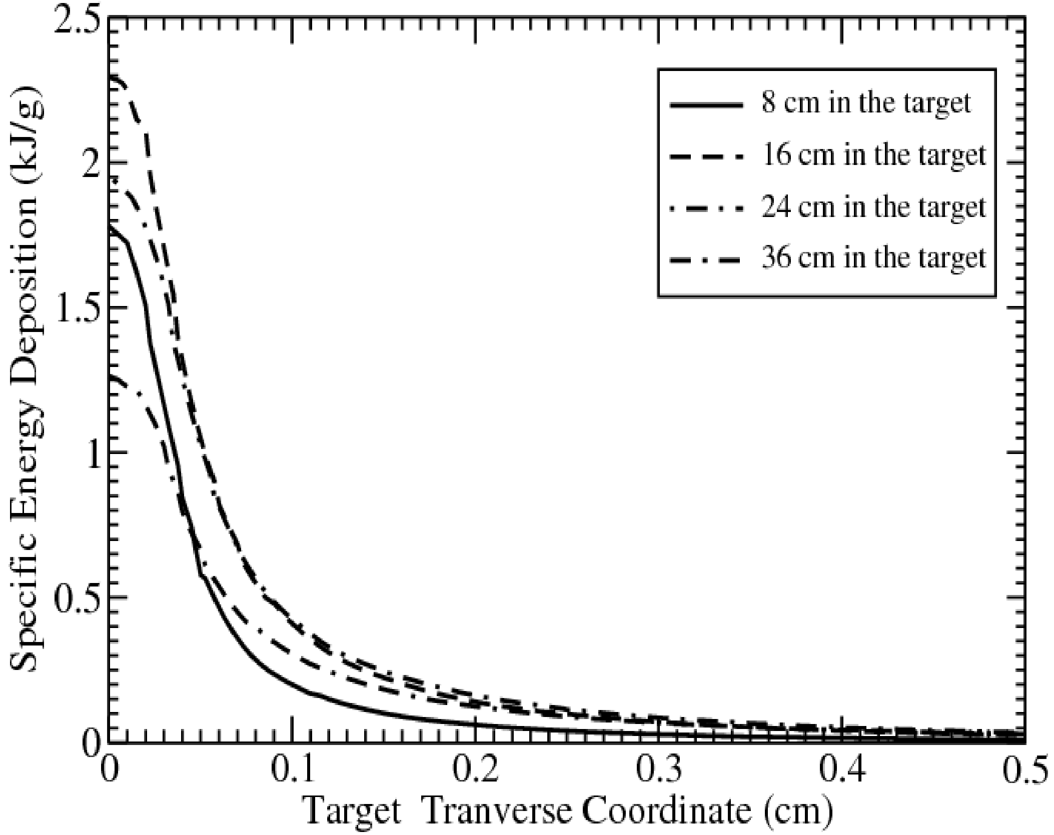
Specific Energy Deposition by a Single Bunch in Solid Copper [FLUKA Calculations]

- 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.**



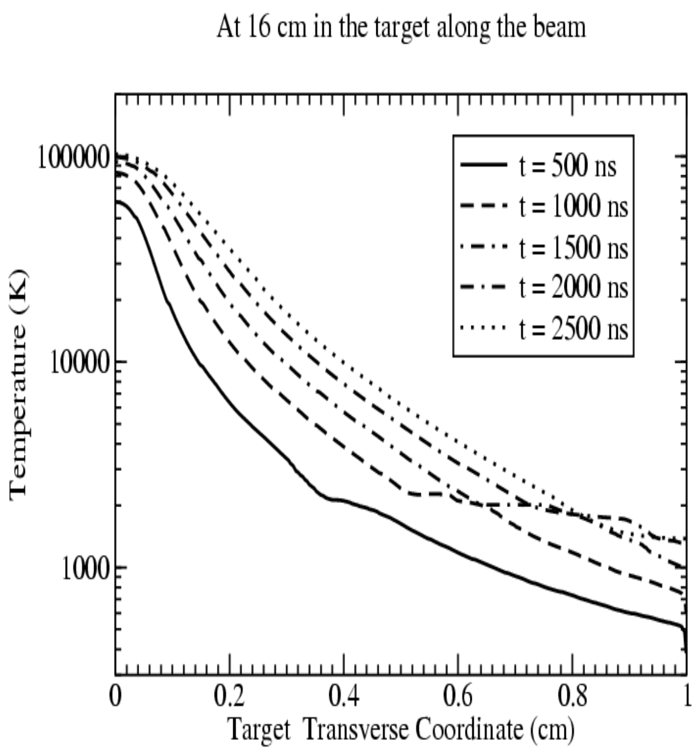
Specific Energy Deposition in Radial Direction Along the Target Axis

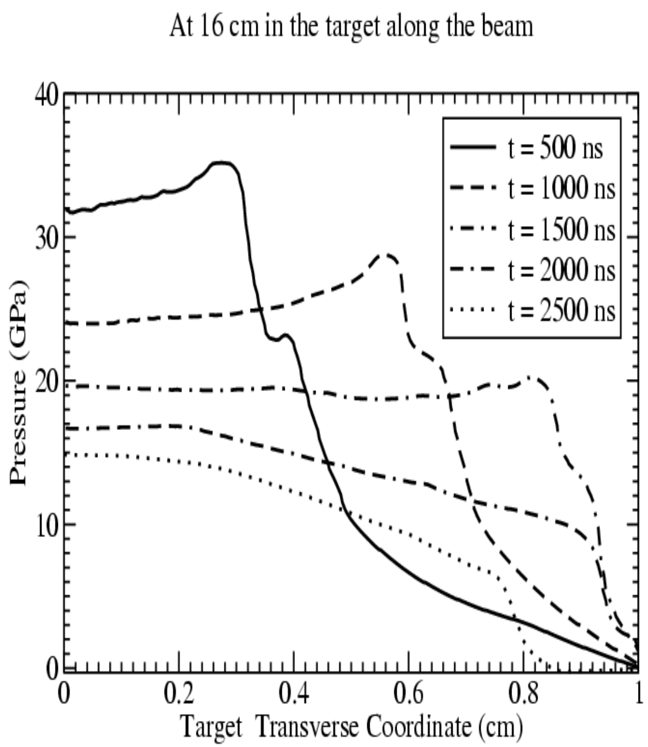
Specific energy deposition (**kJ/g**) vs radius at, L = 8 cm, **16 cm**, 24 cm and 36 cm, by a single proton bunch.

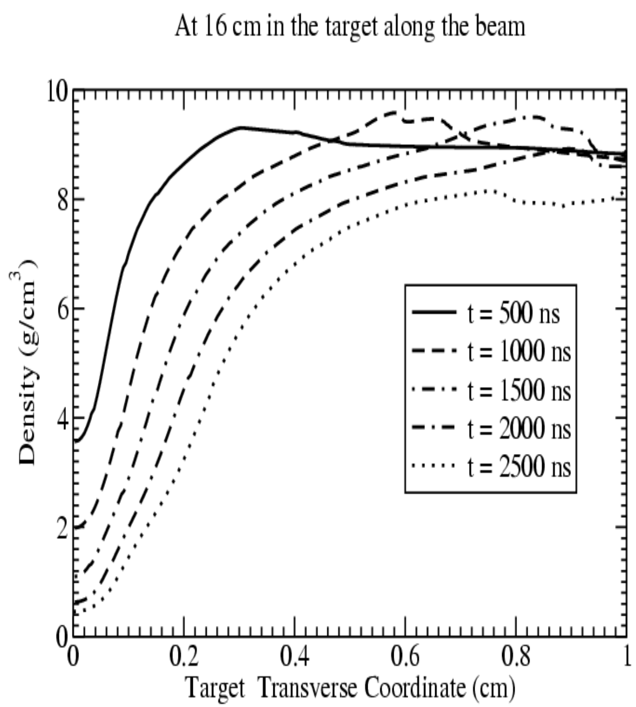


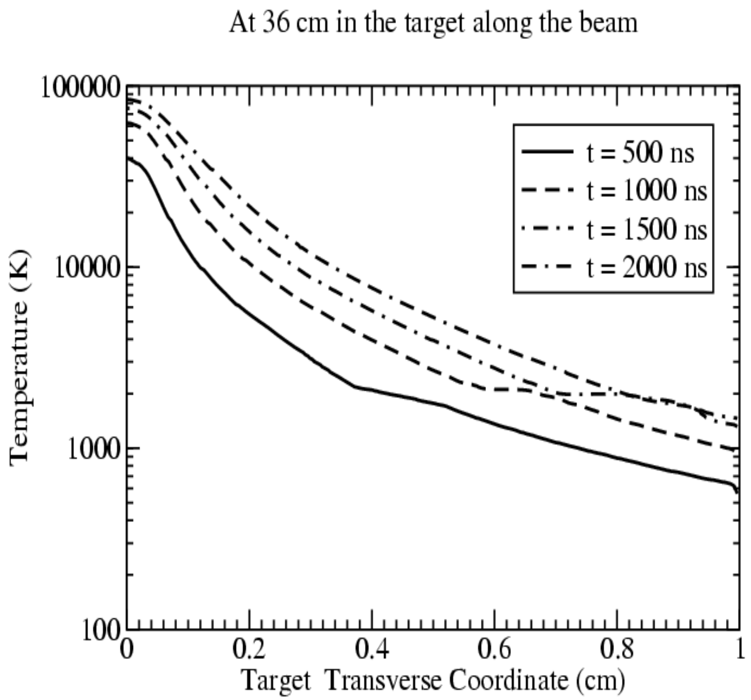
- **A solid copper cylinder facially irradiated by one LHC beam**
- **2D hydrodynamic simulations are carried out along cross section at different longitudinal positions [L = 16 cm and 36 cm]**

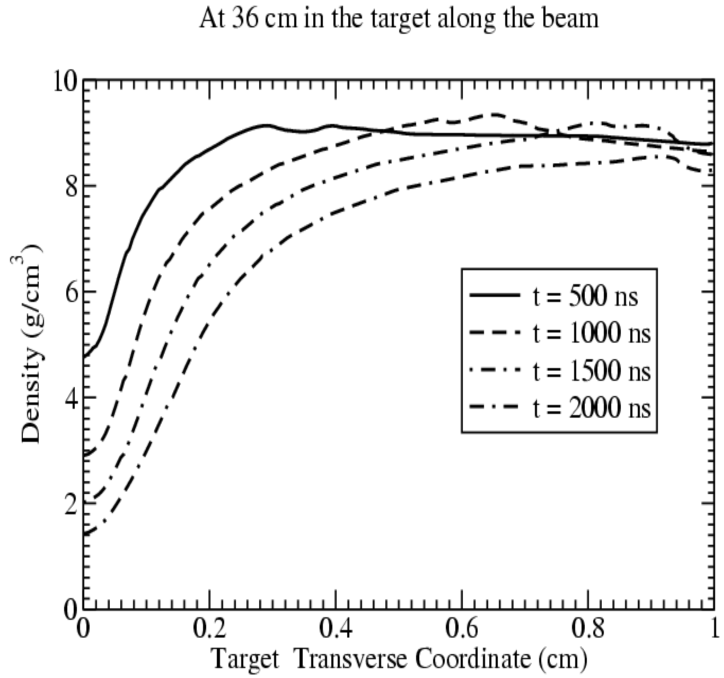
Ref.: ***N.A. Tahir, B. Goddard, V. Kain, R. Schmidt et al, J. Appl. Phys. 97 (2005) 083532.***

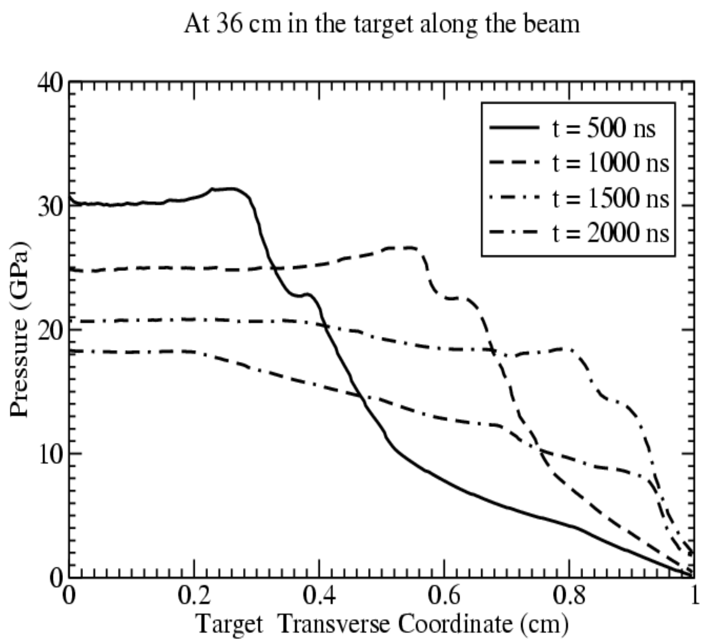




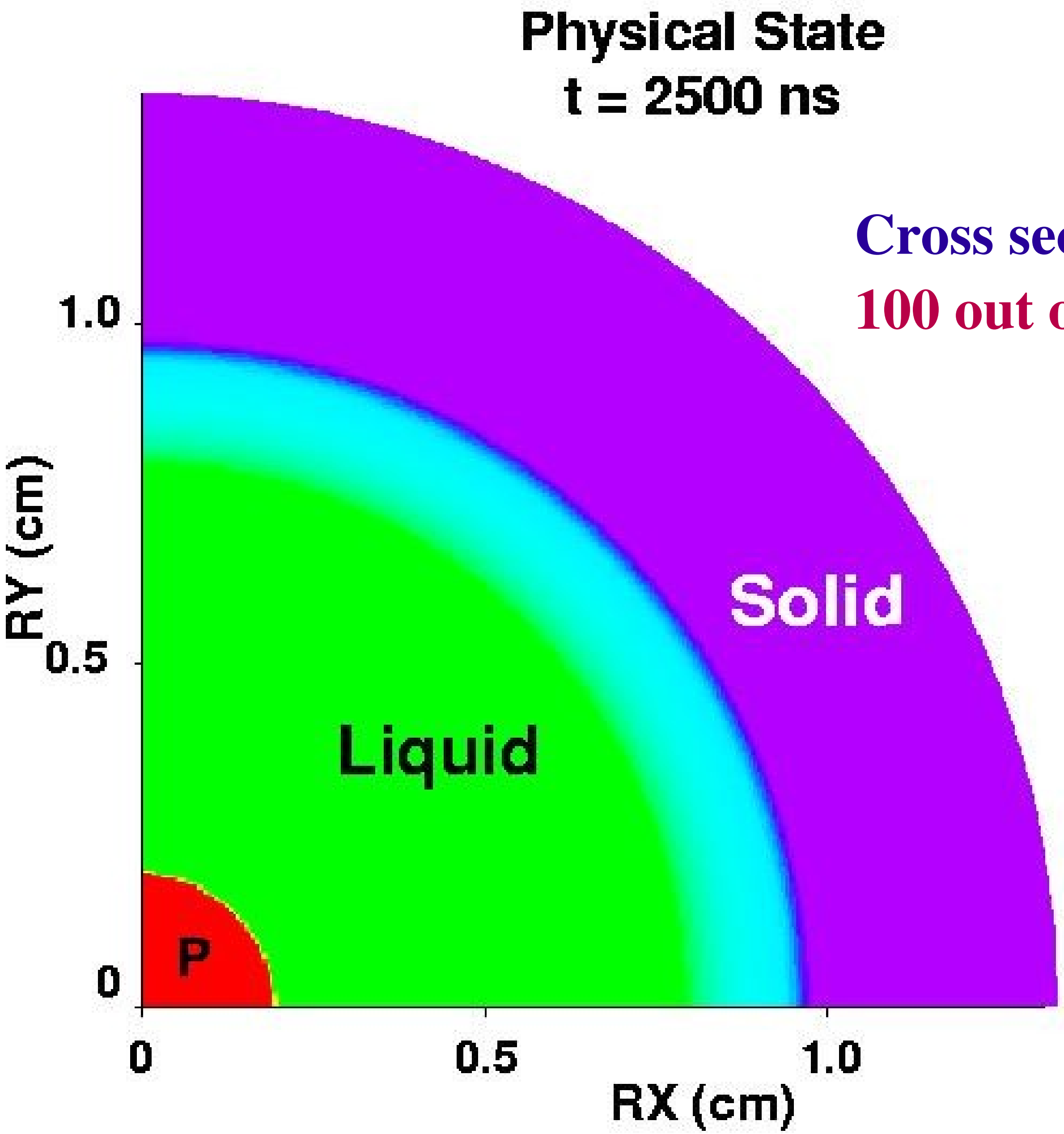








Analytic estimates based on these simulation suggested that the protons will penetrate in the target 10 – 40 m in solid copper.
This substantial range lengthening is direct consequence of proton "Tunneling Effect"



Cross section of a Cu cylinder

100 out of 2808 bunches delivere

N.A. Tahir et al., PRL 94 (2005) 135004.

Physics News Update
Number 726 #3
April 7, 2005

APS News Feb. 2006

Further Advancement of the Simulations:

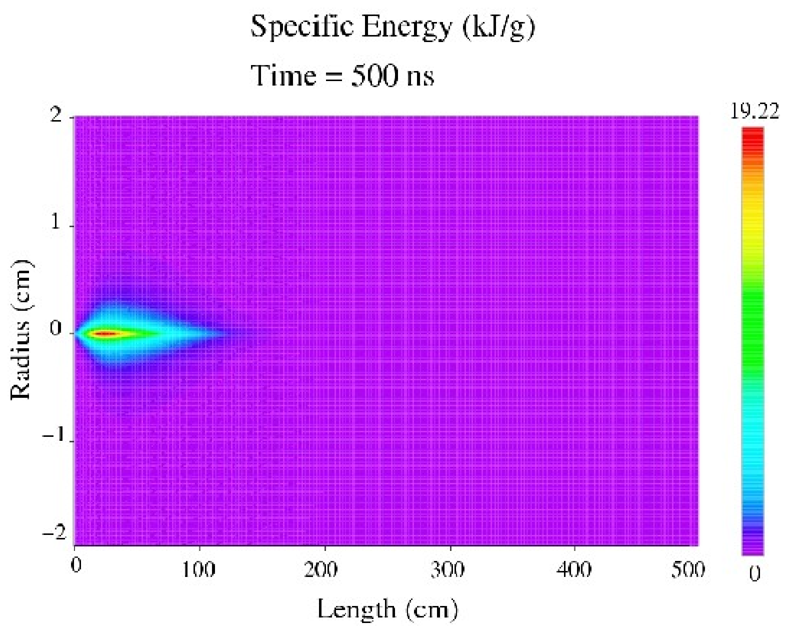
- **The target is studied in r-Z geometry.**
- **Specific energy deposition in each simulation cell at every timestep is normalized with respect to the line density along the axis.**
- **This allows for reduction of specific energy deposition in low density part of the target.**
- **This model allows for studying the proton "Tunneling Effect".**

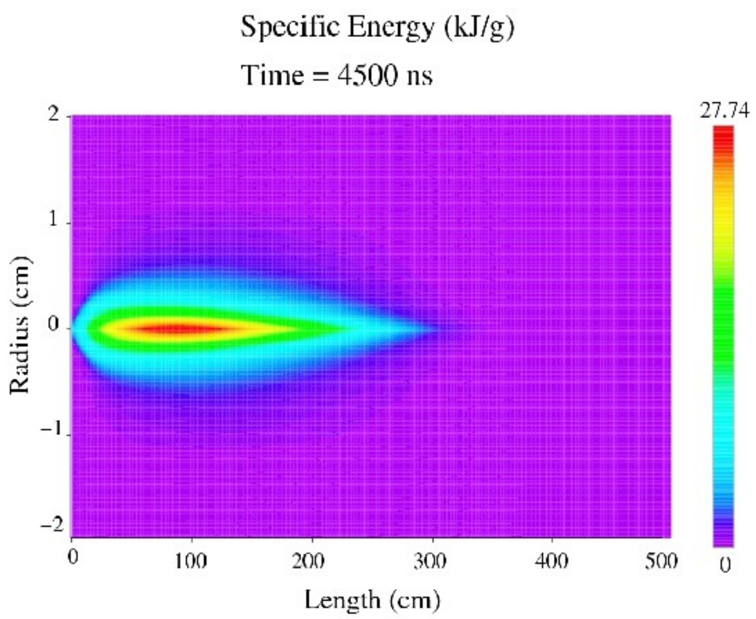
N.A. Tahir, R. Schmidt et al., Phys. Rev. E 79 (2009) 046410.

I : **LHC Beam on a Solid Copper Cylinder**

L = 5 m

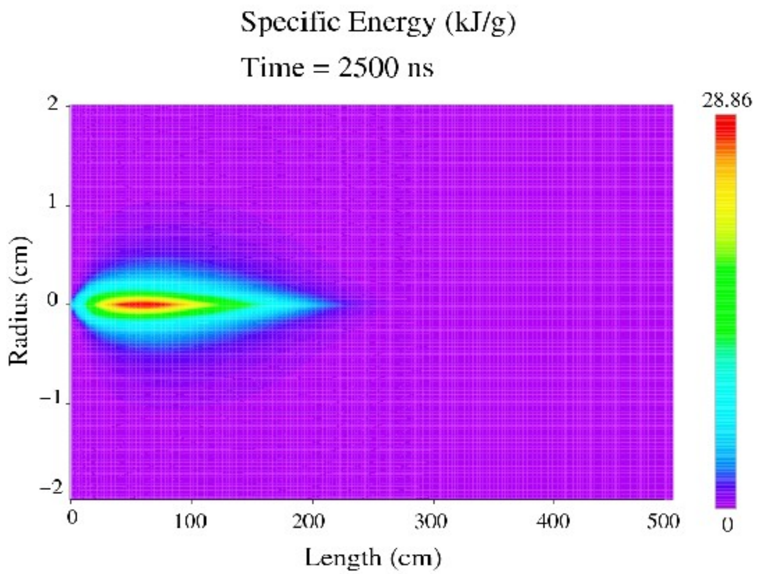
r = 5 cm

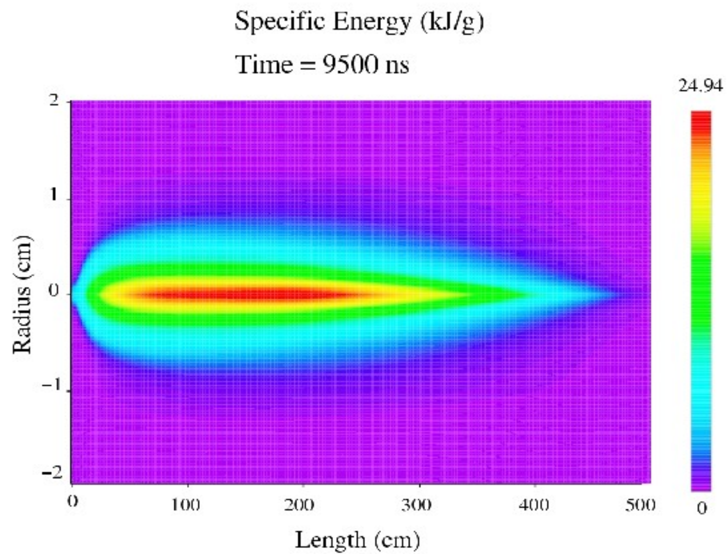




Specific Energy Deposition

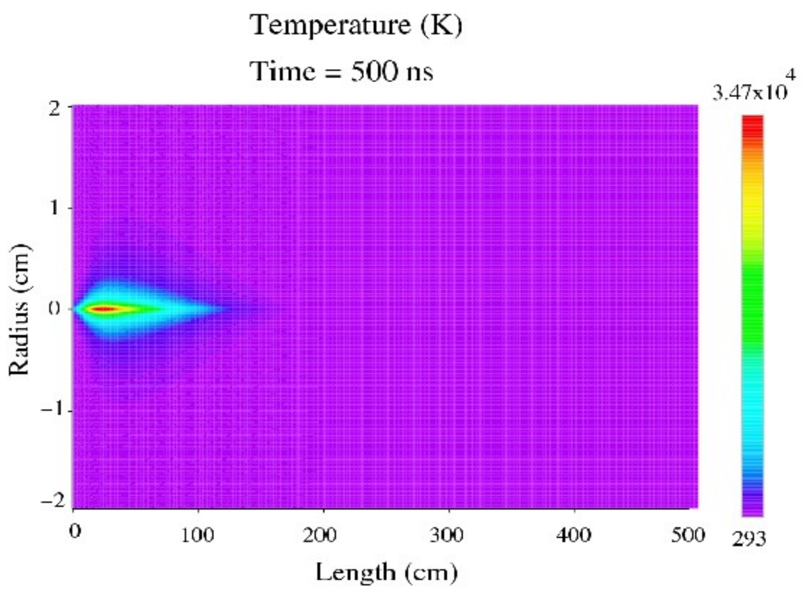
Saturates to 25 kJ/g

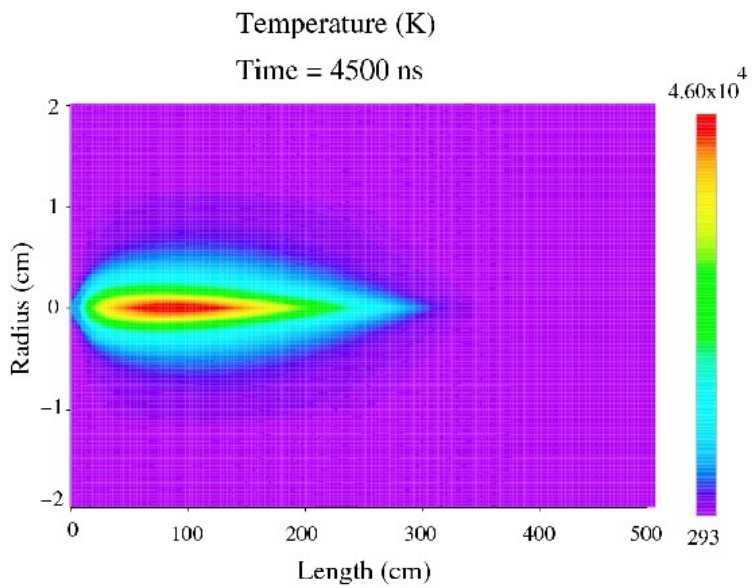


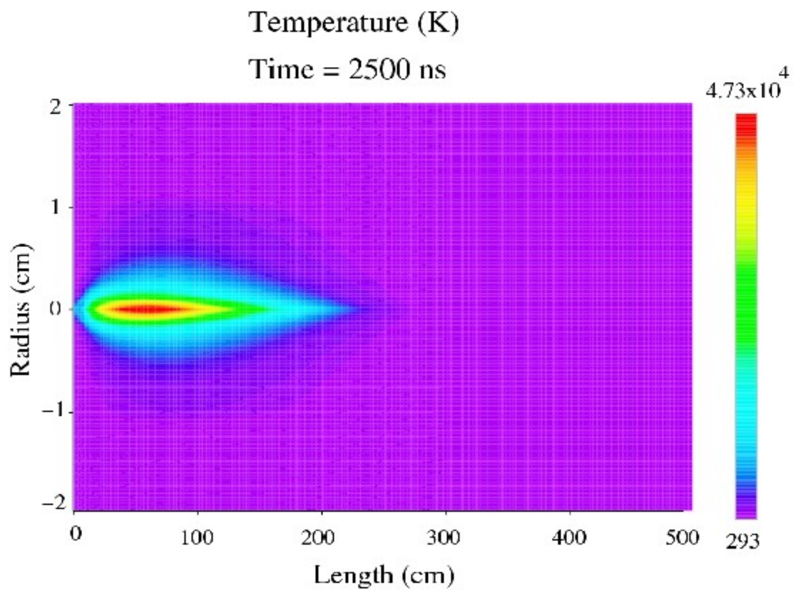


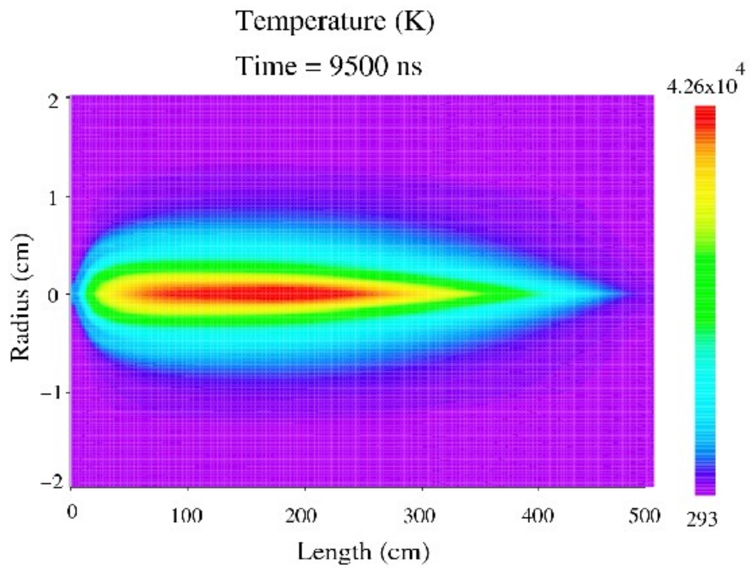
Temperature

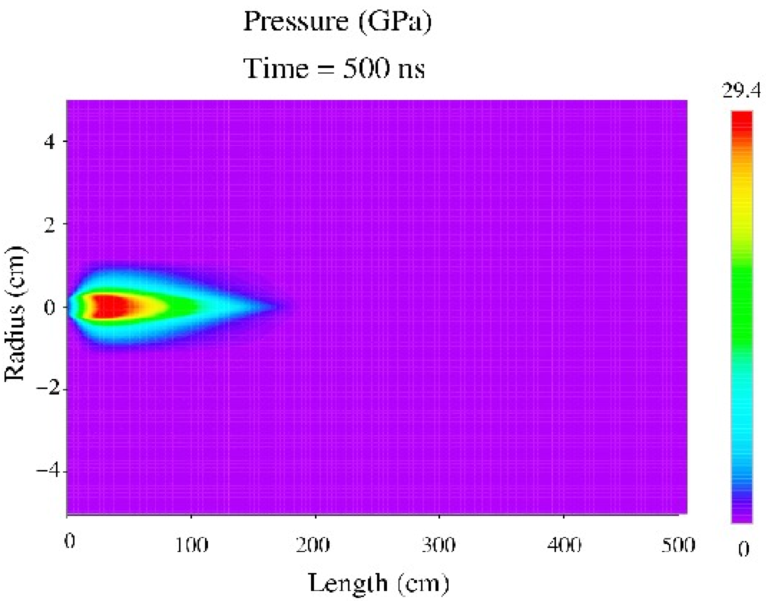
$4x10^4$ K

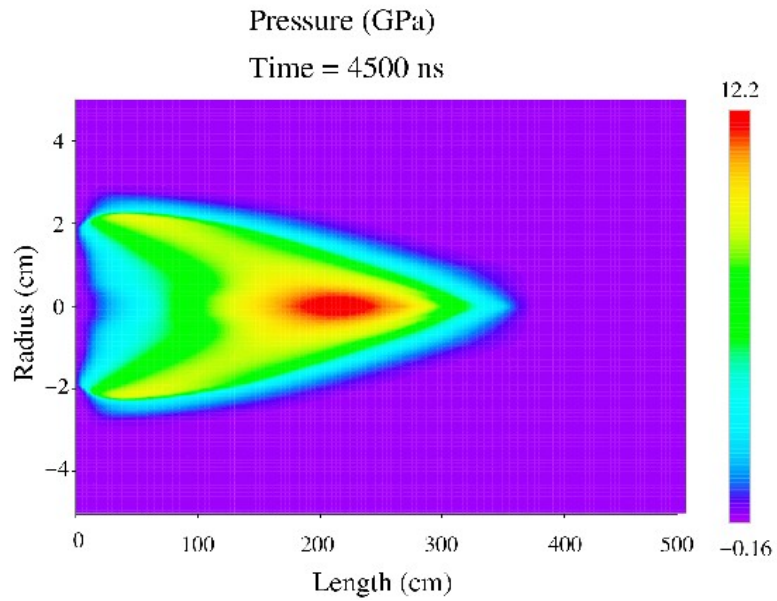






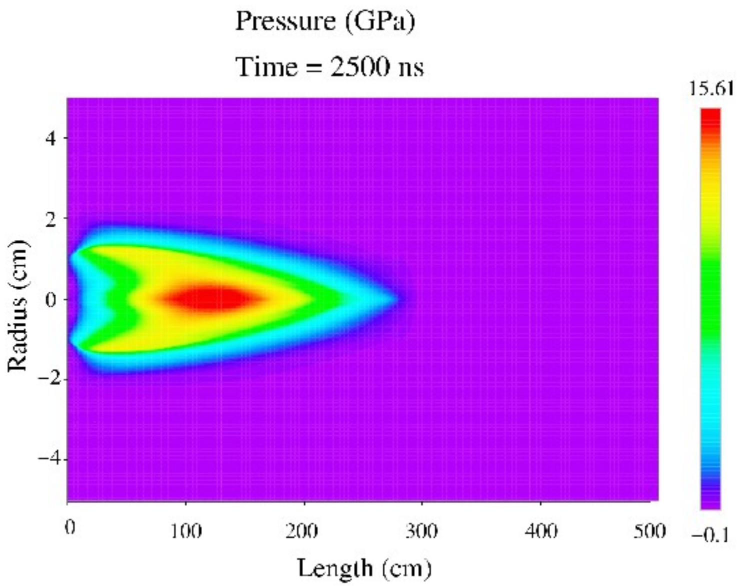


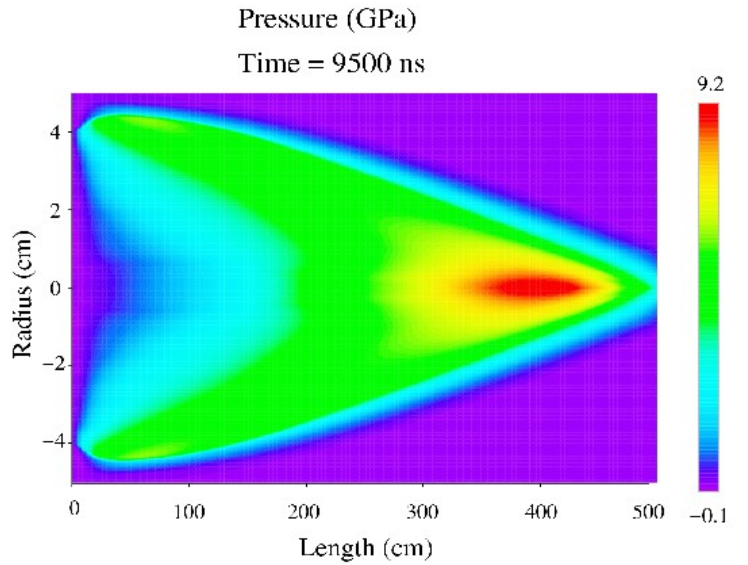




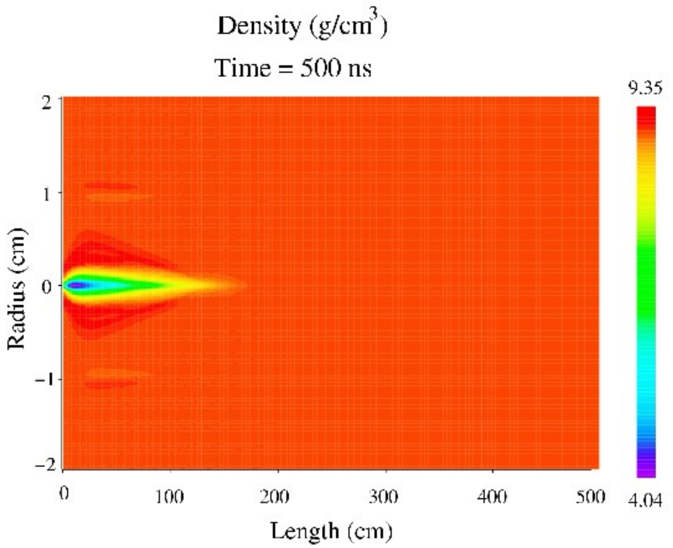
Pressure

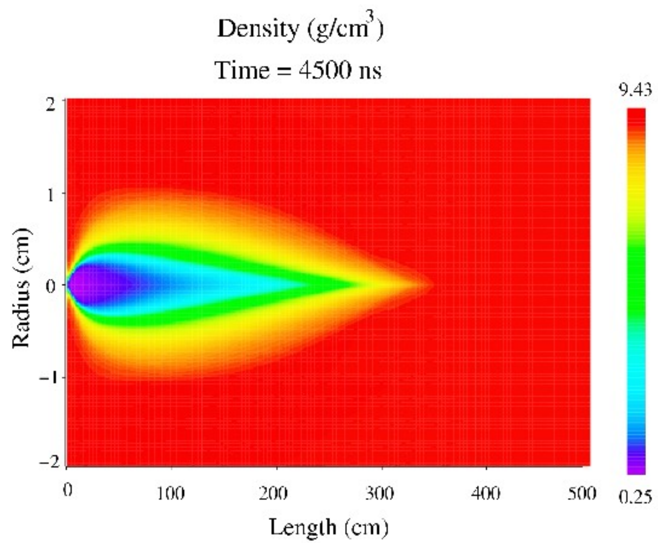
30 GPa

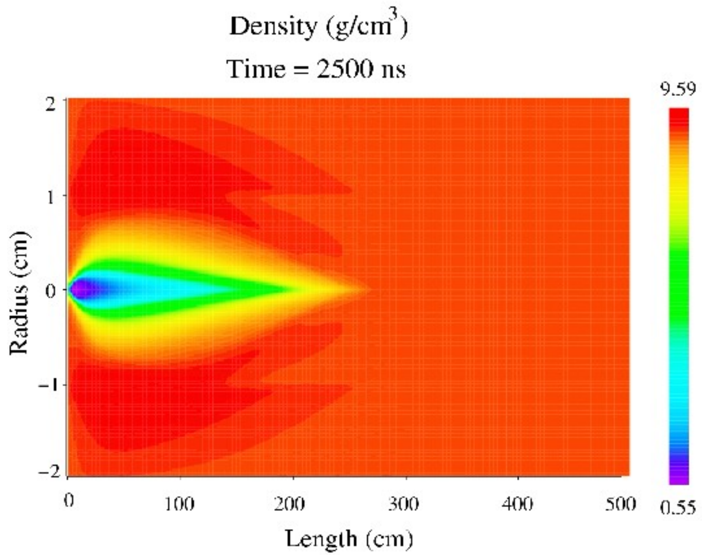


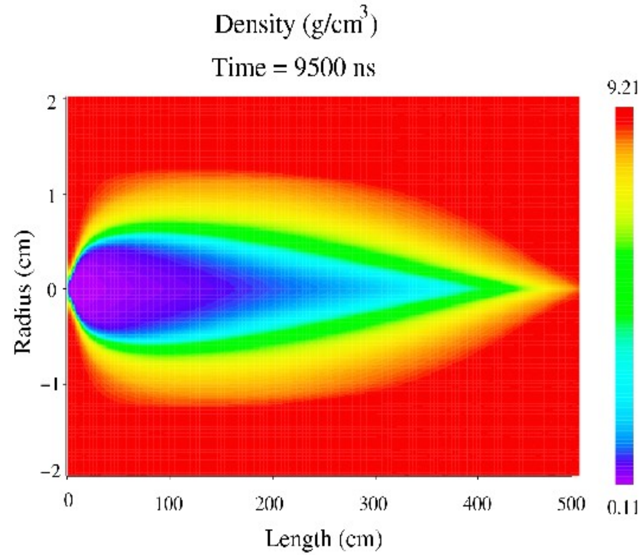


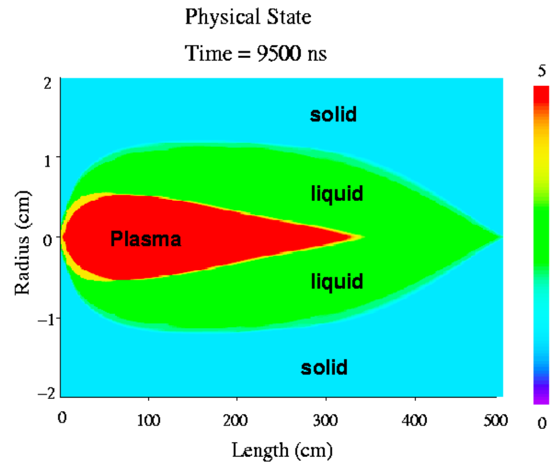
HEDP States

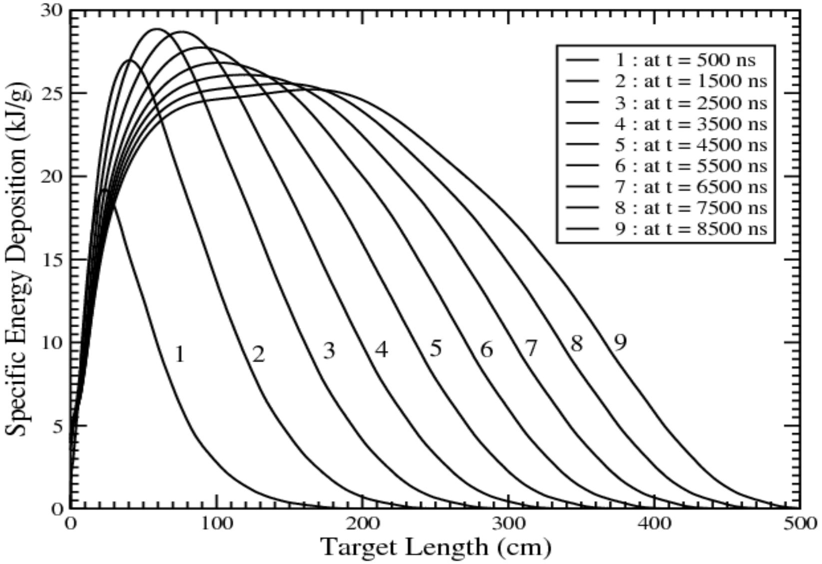

Density (g/cm3)
Time = 500 ns
Radius (cm)
Length (cm)
9.35
4.04

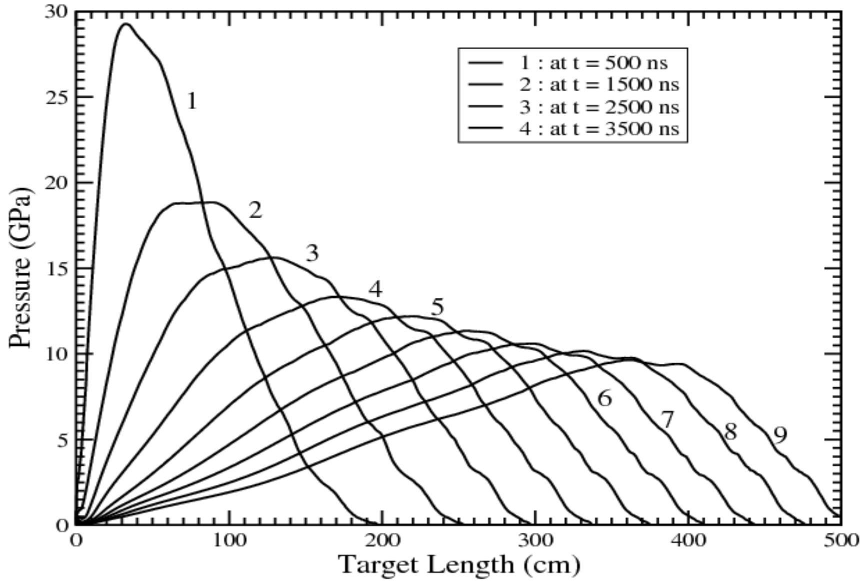

Density (g/cm3)
Time = 4500 ns
Radius (cm)
Length (cm)
9.43
0.25


Density (g/cm3)
Time = 2500 ns
Radius (cm)
Length (cm)
9.59
0.55

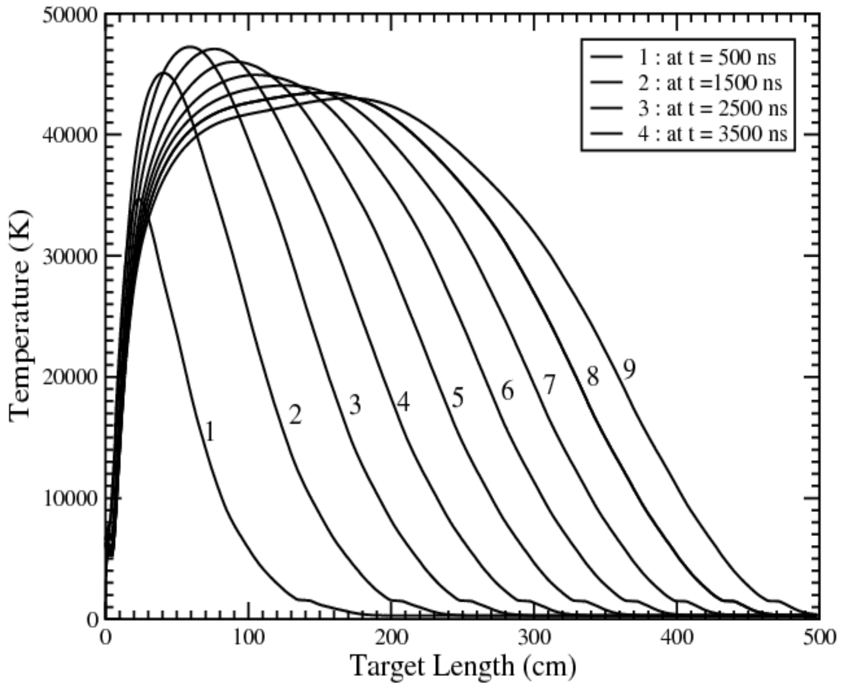

Density (g/cm3)
Time = 9500 ns
Radius (cm)
Length (cm)
9.21
0.11

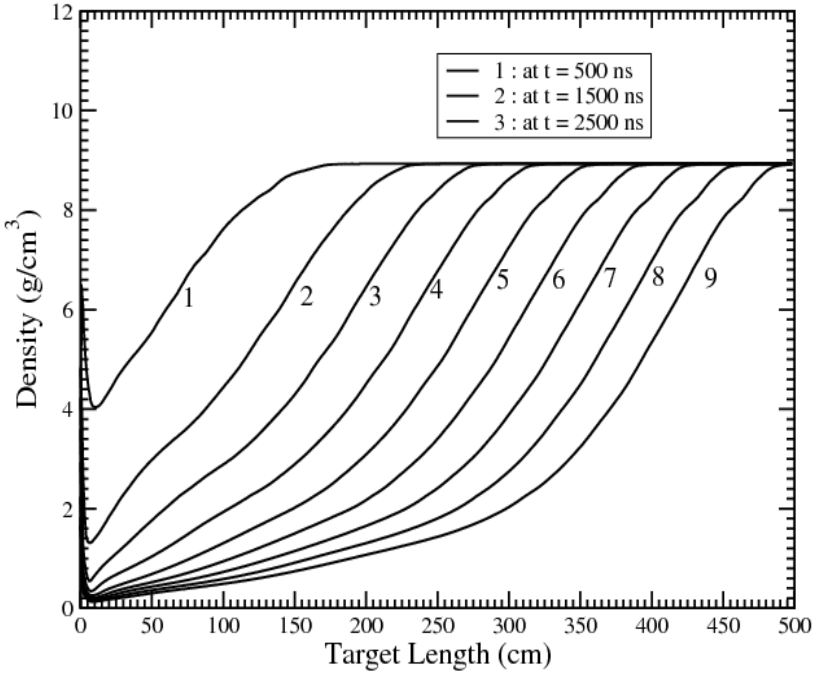

Physical State
Time = 9500 ns
solid
liquid
Plasma
liquid
solid
Radius (cm)
Length (cm)
5
0

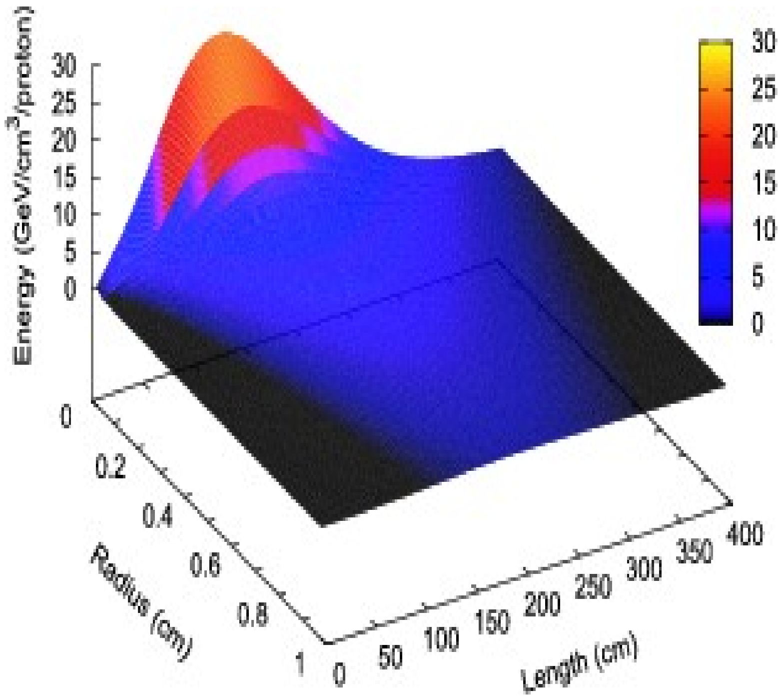




0.35 m/μs in 89 μs penetrate 35 m





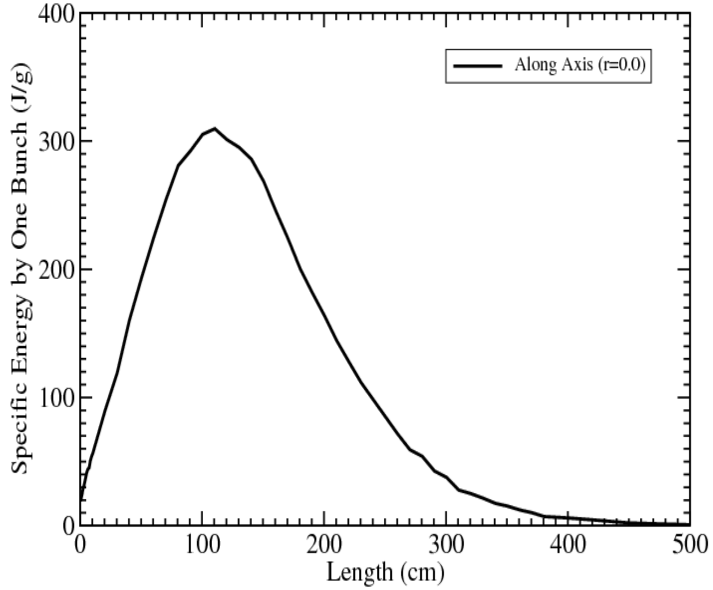


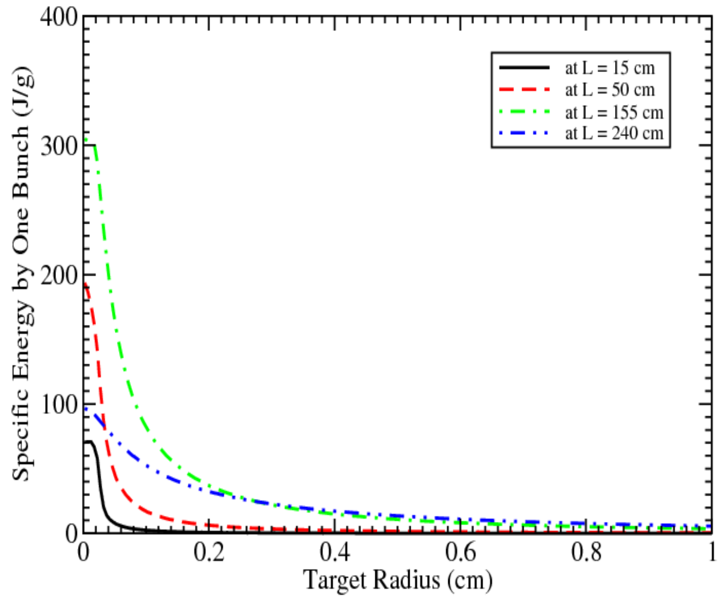
N.A. Tahir, R. Schmidt et al., Laser Part. Beams 27 (2009) 475.

II: <u>LHC Beam on a Carbon target</u>

For FLUKA Calculations: L = 5 m,
r = 1 m

For Hydrodynamic simulations:
L = 10 m, r = 2.5 cm

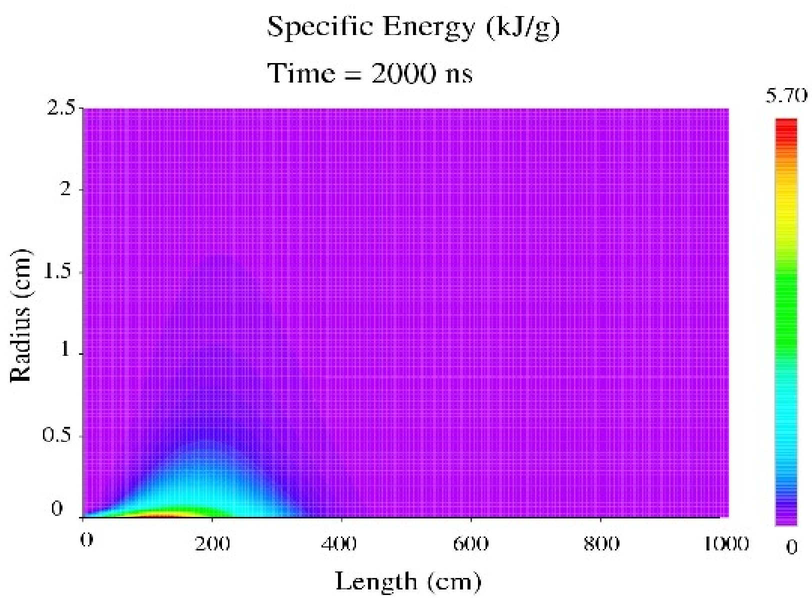


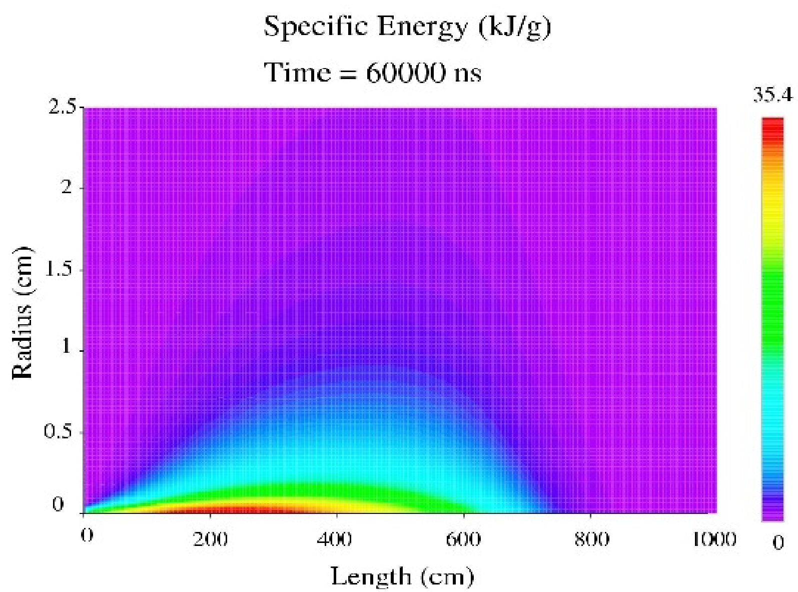


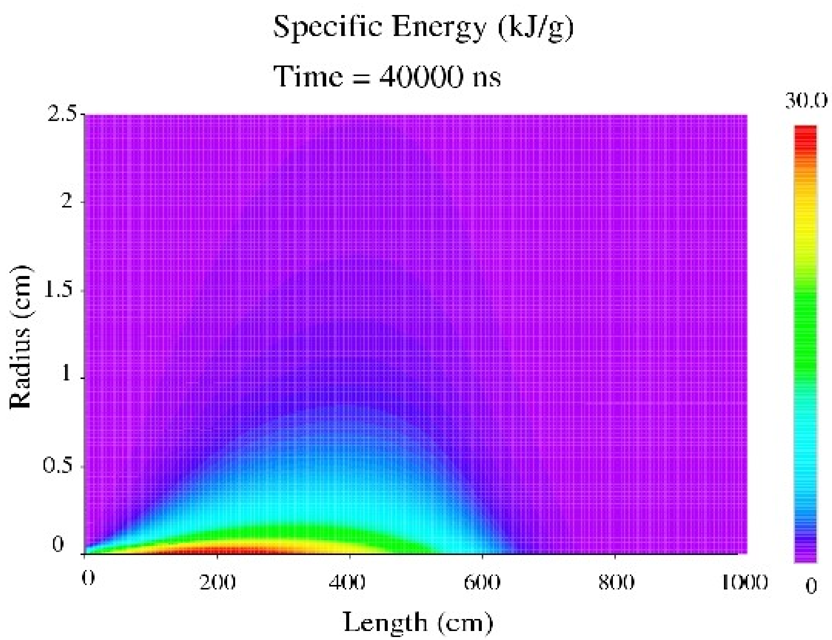
<u>Specific Energy</u>

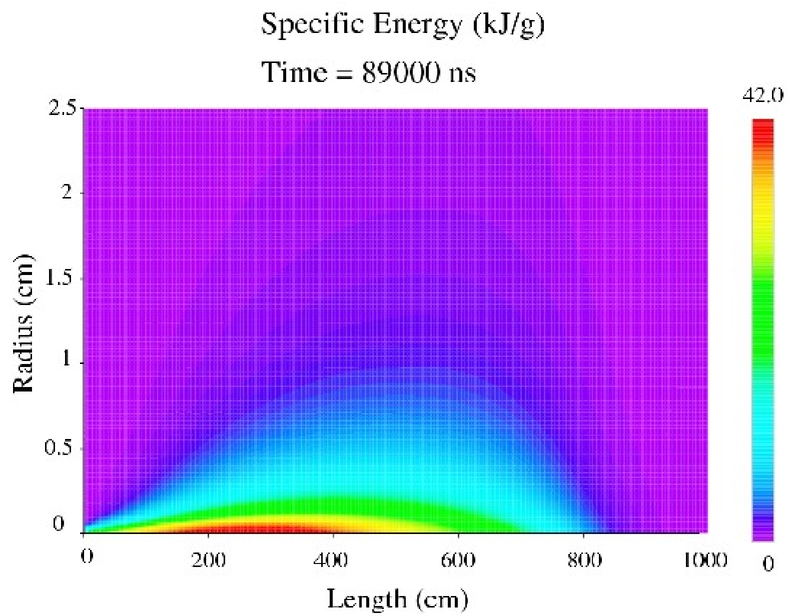
C	**Cu**
0.3 kJ/g	**2.3 kJ/g**

Specific Energy Deposition

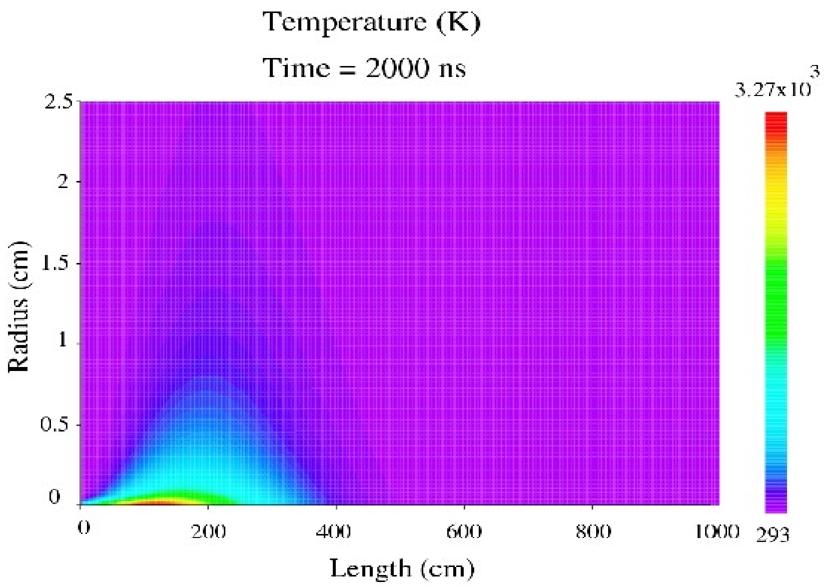


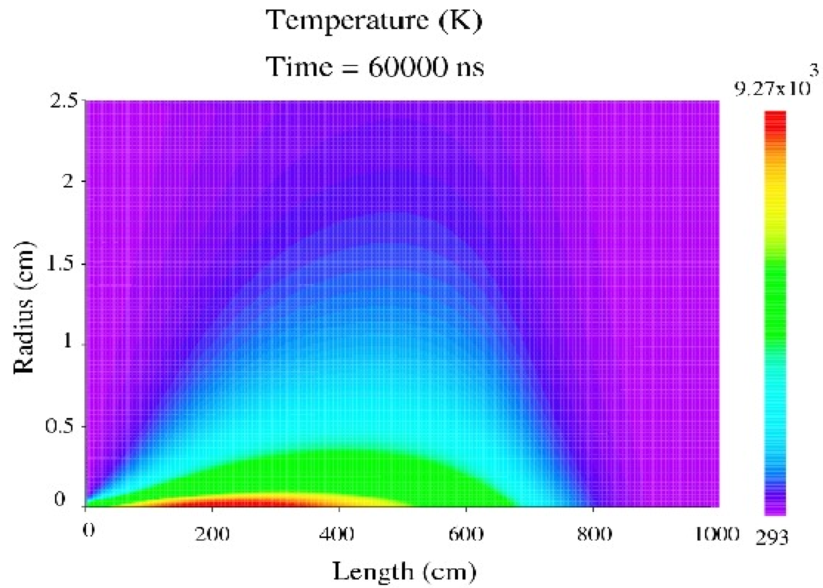




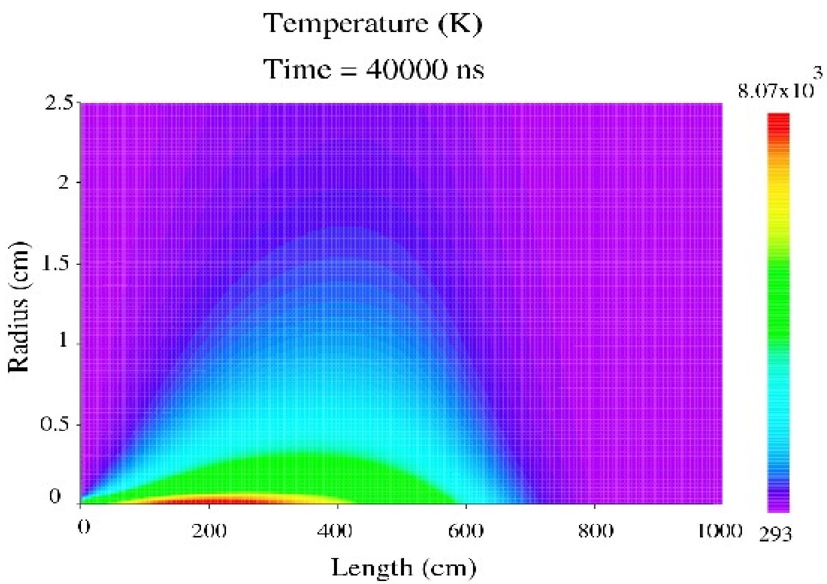


42 kJ/g

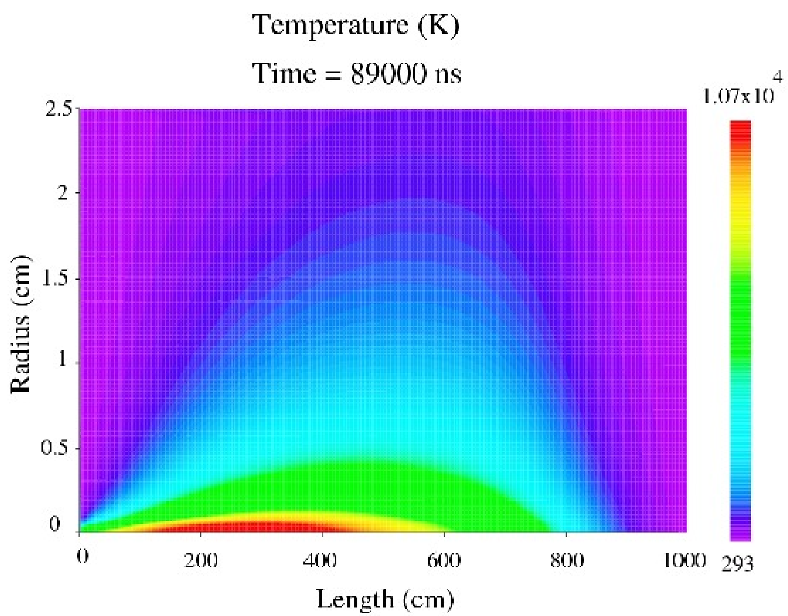




Temperature

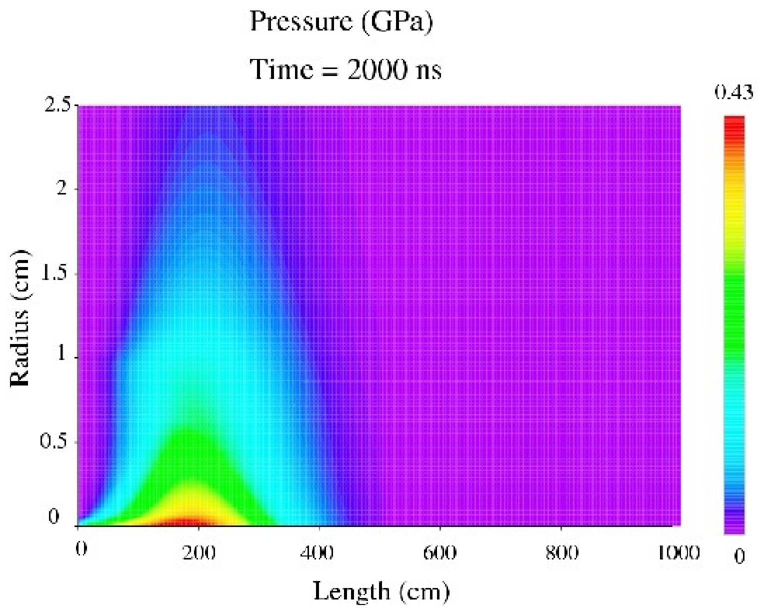


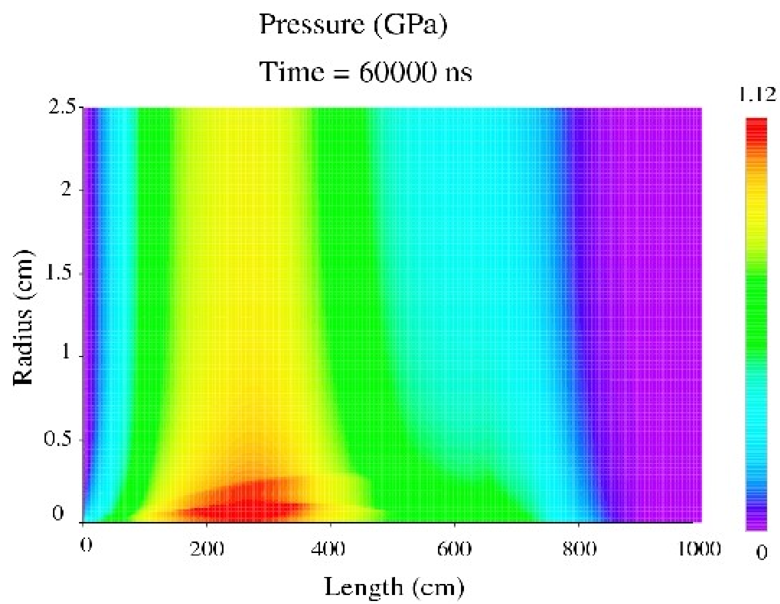
10^4 K

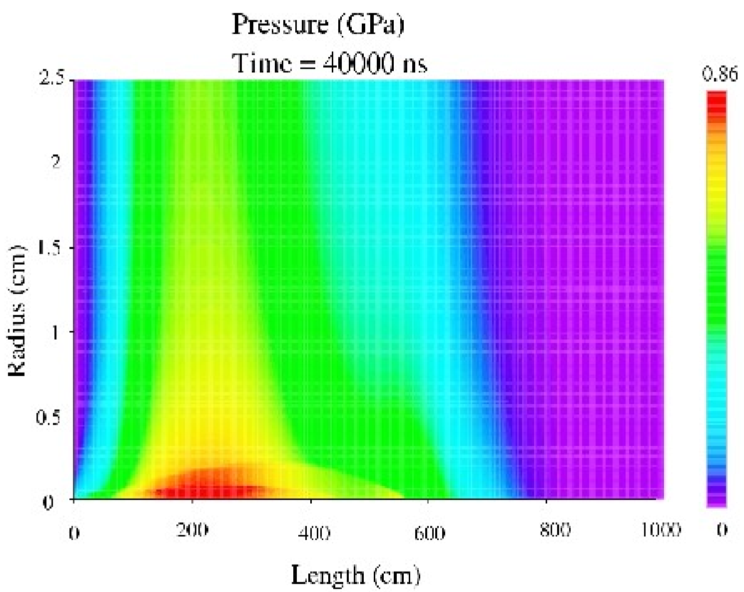


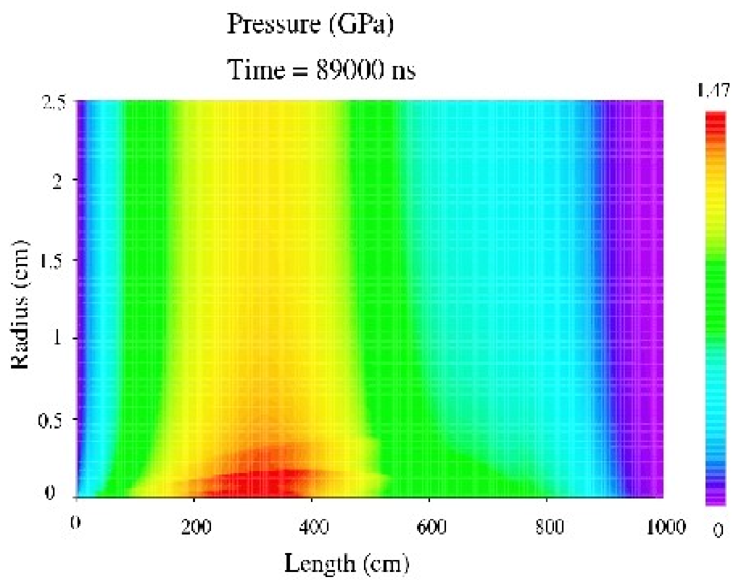
Pressure

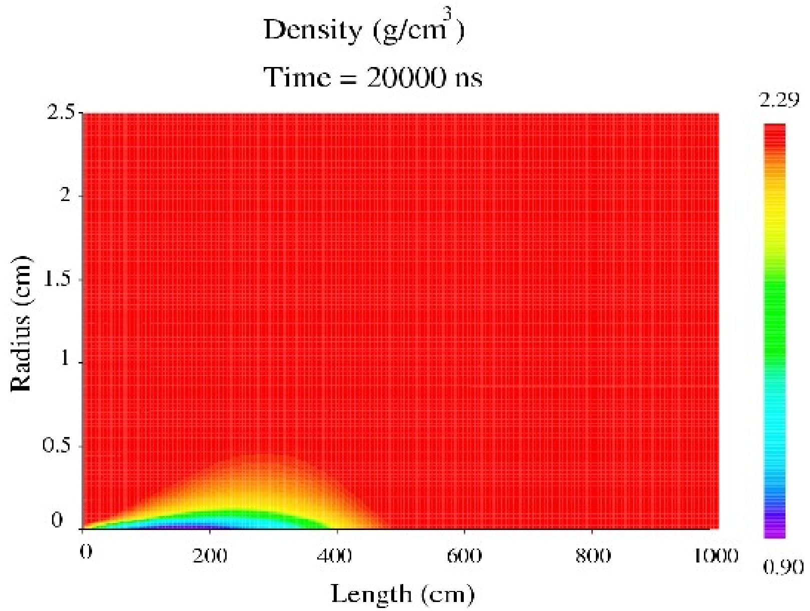
1.17 GPa

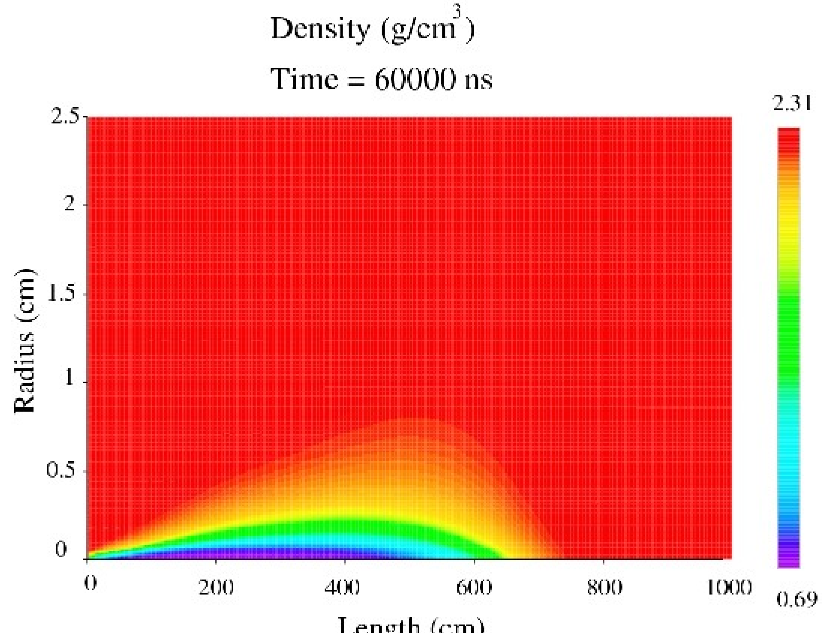




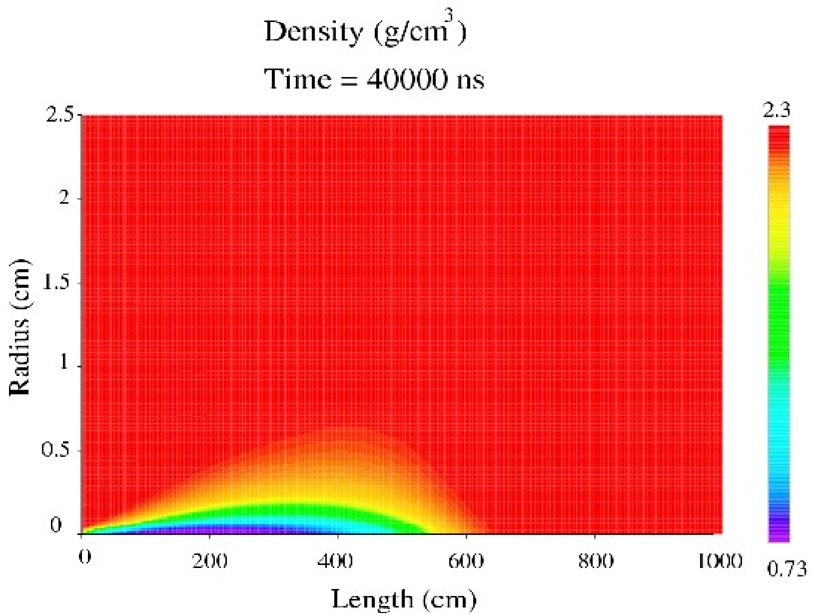


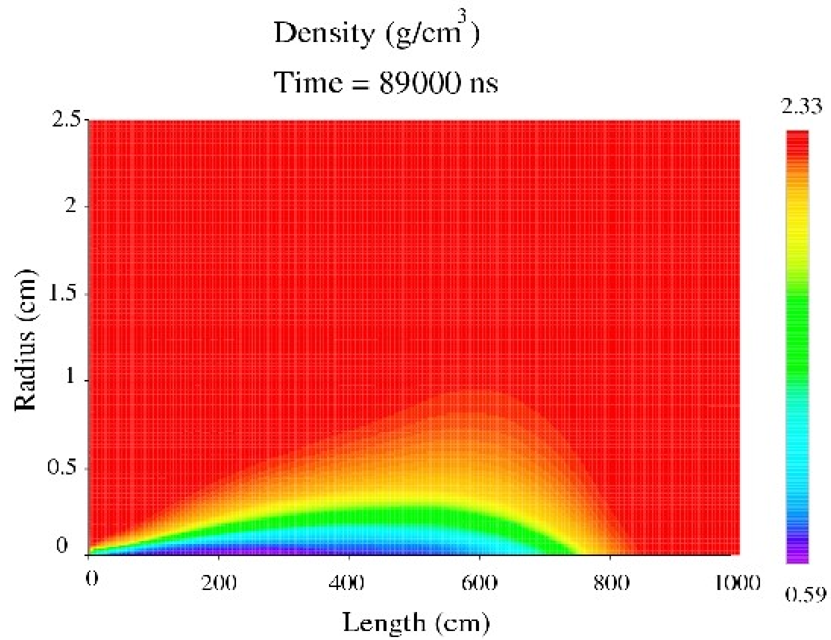


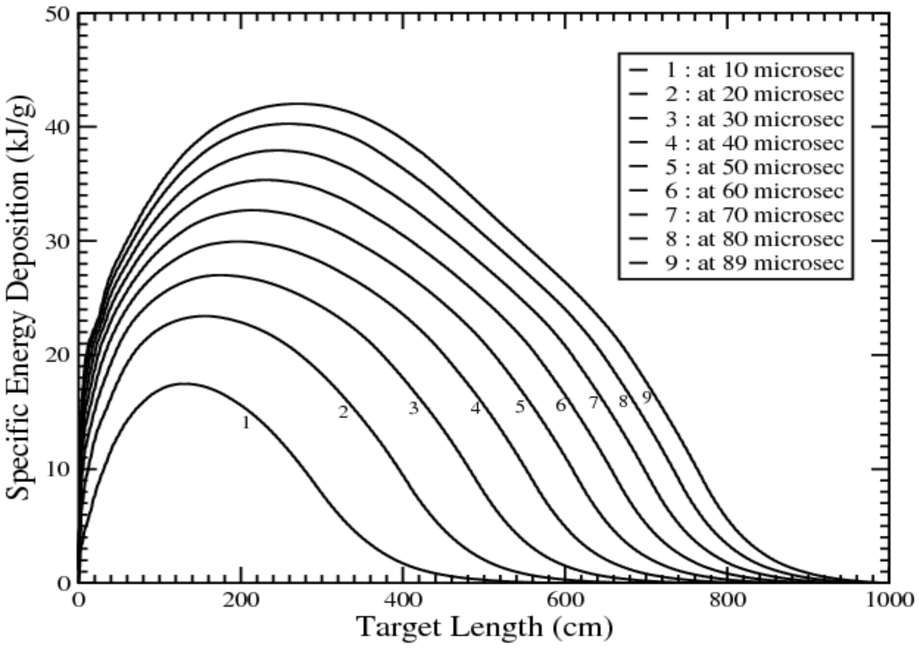

Density (g/cm3)
Time = 20000 ns
Radius (cm)
Length (cm)
2.29
0.90

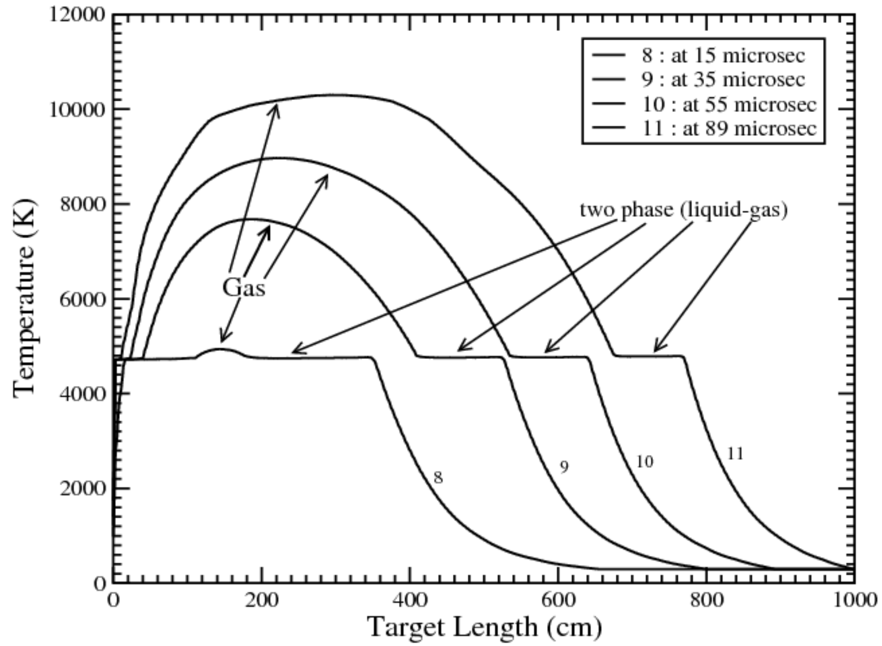

Density (g/cm3)
Time = 60000 ns
Radius (cm)
Length (cm)
2.31
0.69

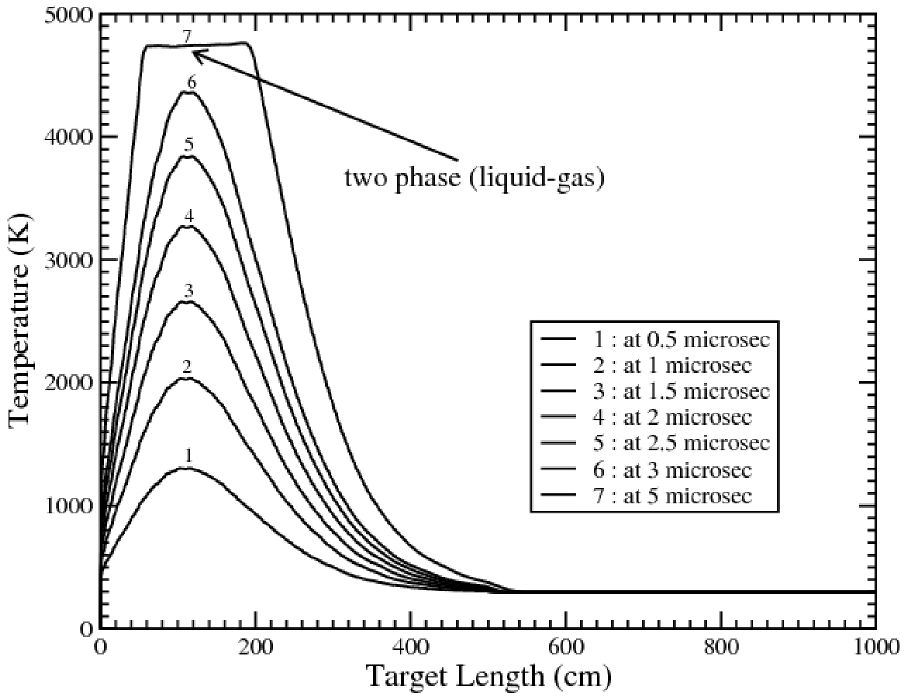
Density

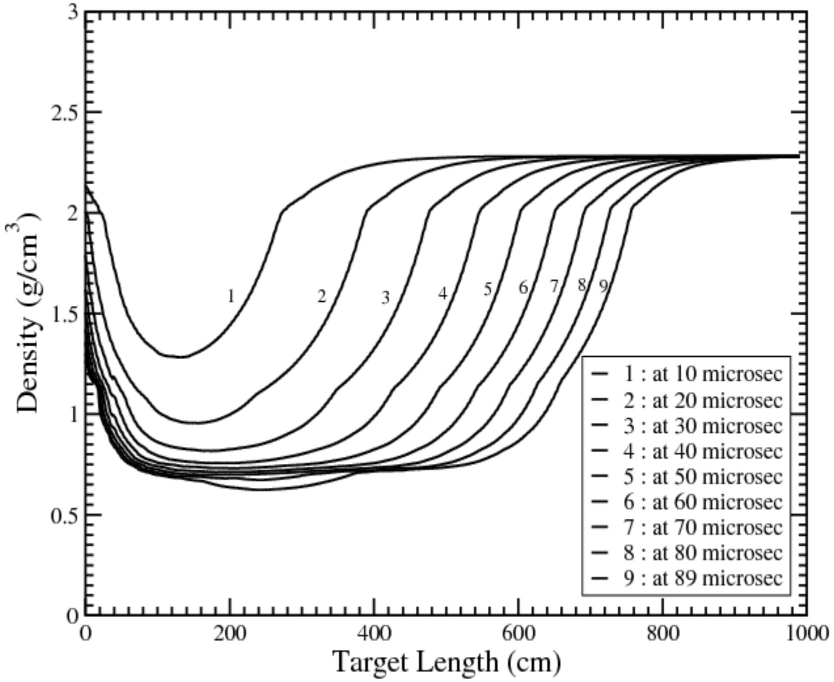

Density (g/cm3)
Time = 40000 ns
Radius (cm)
Length (cm)
2.3
0.73


Density (g/cm3)
Time = 89000 ns
Radius (cm)
Length (cm)
2.33
0.59


Specific Energy Deposition (kJ/g)
Target Length (cm)
1 : at 10 microsec
2 : at 20 microsec
3 : at 30 microsec
4 : at 40 microsec
5 : at 50 microsec
6 : at 60 microsec
7 : at 70 microsec
8 : at 80 microsec
9 : at 89 microsec

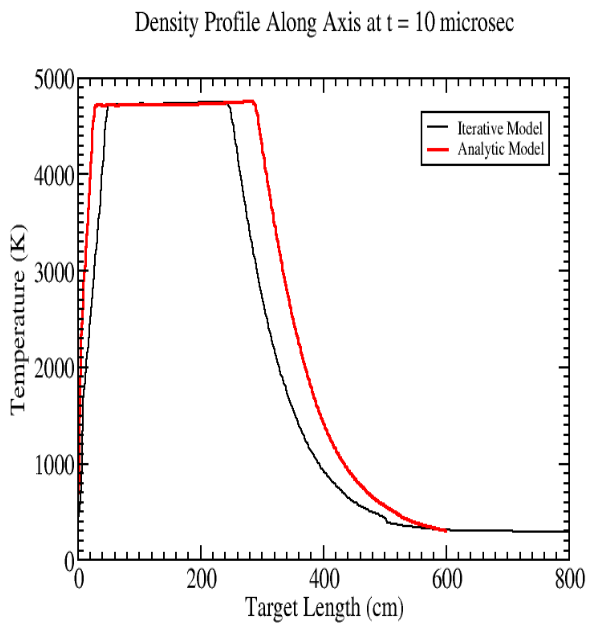

Temperature (K)
Target Length (cm)
8 : at 15 microsec
9 : at 35 microsec
10 : at 55 microsec
11 : at 89 microsec
Gas
two phase (liquid-gas)


Temperature (K)
Target Length (cm)
two phase (liquid-gas)
1 : at 0.5 microsec
2 : at 1 microsec
3 : at 1.5 microsec
4 : at 2 microsec
5 : at 2.5 microsec
6 : at 3 microsec
7 : at 5 microsec

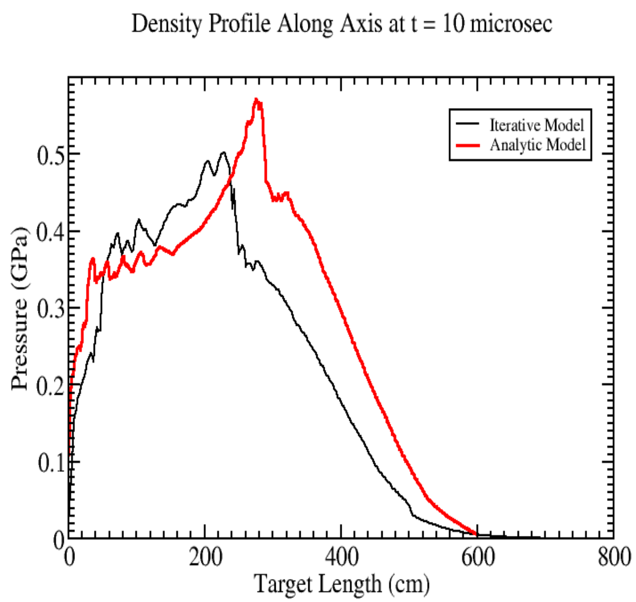

Density (g/cm^3)
Target Length (cm)
1 : at 10 microsec
2 : at 20 microsec
3 : at 30 microsec
4 : at 40 microsec
5 : at 50 microsec
6 : at 60 microsec
7 : at 70 microsec
8 : at 80 microsec
9 : at 89 microsec

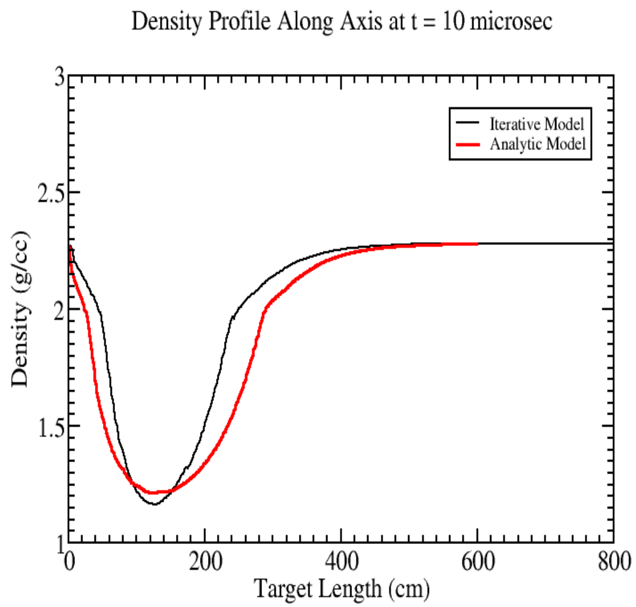
Another Step Forward: Running FLUKA and BIG2 Iteratively

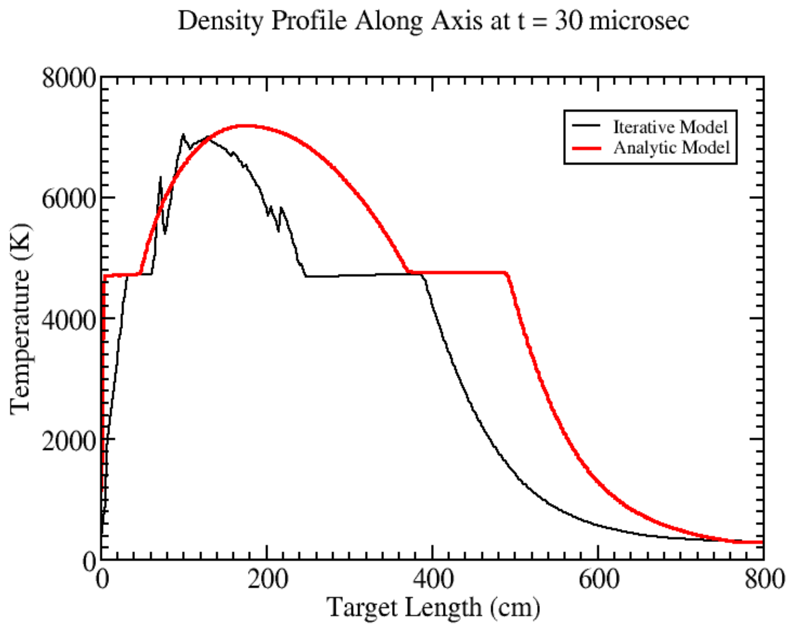
In case of carbon we run FLUKA and BIG2 using time interval of 5μs.

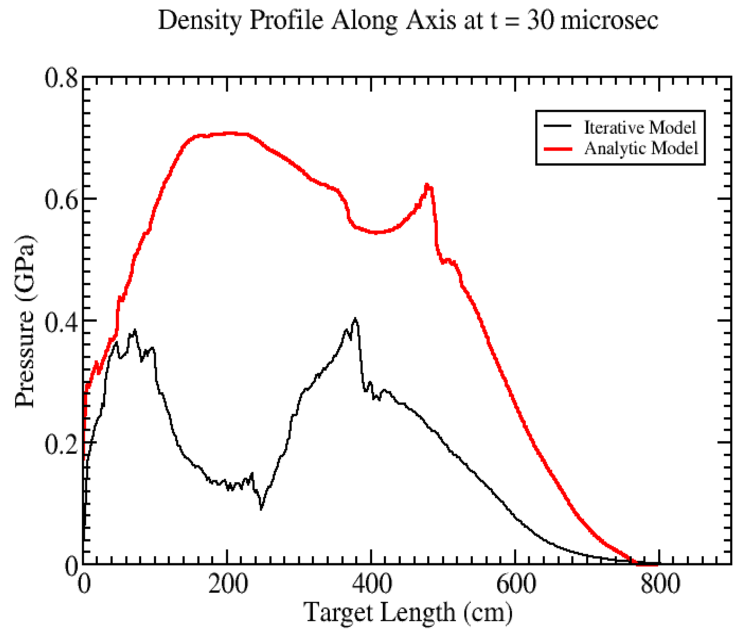


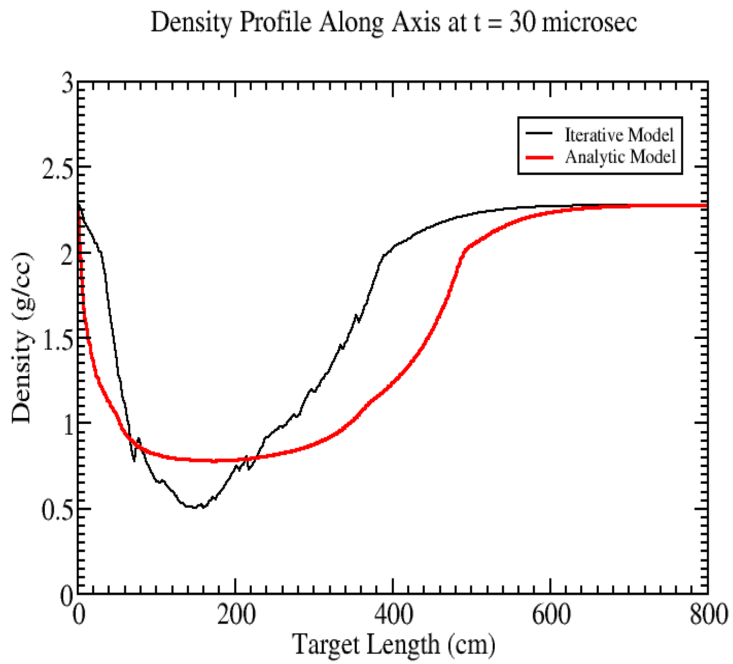
Solid C Cylinder
L = 10 m, r = 5 cm
Facially Irradiated
by the LHC Beam

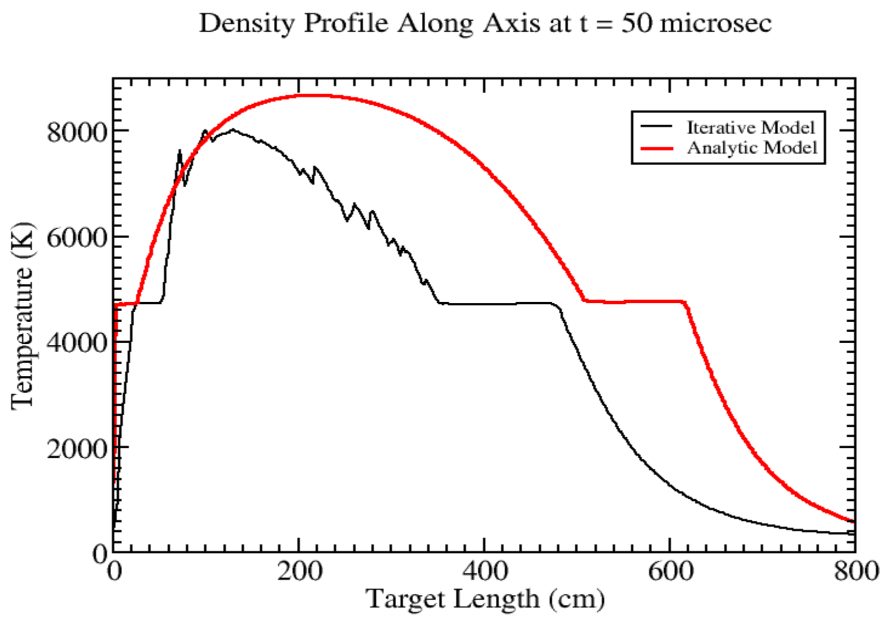


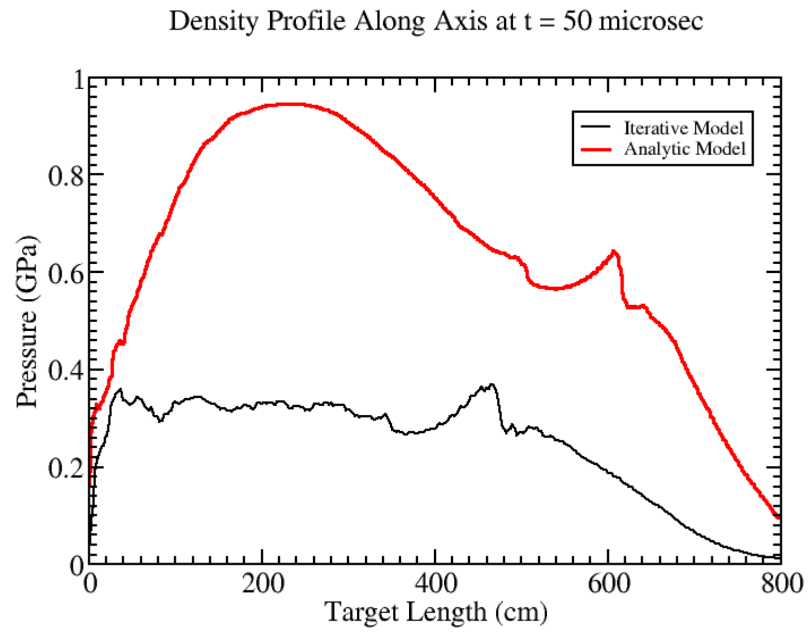


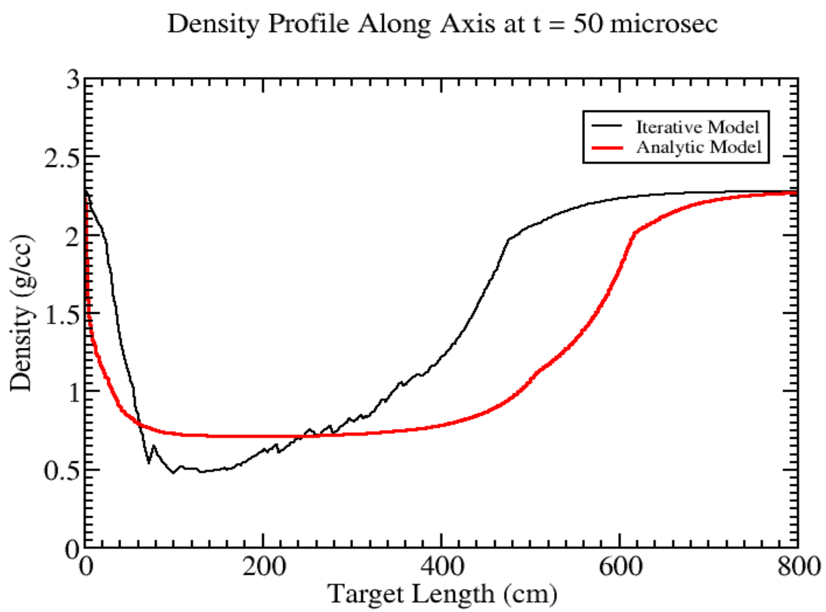

Density Profile Along Axis at t = 30 microsec
Temperature (K)
Target Length (cm)
Iterative Model
Analytic Model
0
2000
4000
6000
8000
200
400
600
800


Density Profile Along Axis at t = 30 microsec
Pressure (GPa)
Target Length (cm)
Iterative Model
Analytic Model
0
0.2
0.4
0.6
0.8
200
400
600
800


Density Profile Along Axis at t = 30 microsec
Density (g/cc)
Target Length (cm)
Iterative Model
Analytic Model
0
0.5
1
1.5
2
2.5
3
200
400
600
800







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 ipacting 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