Simulations of Damage Caused to Equipment Due to Full Impact of the LHC Beam

By

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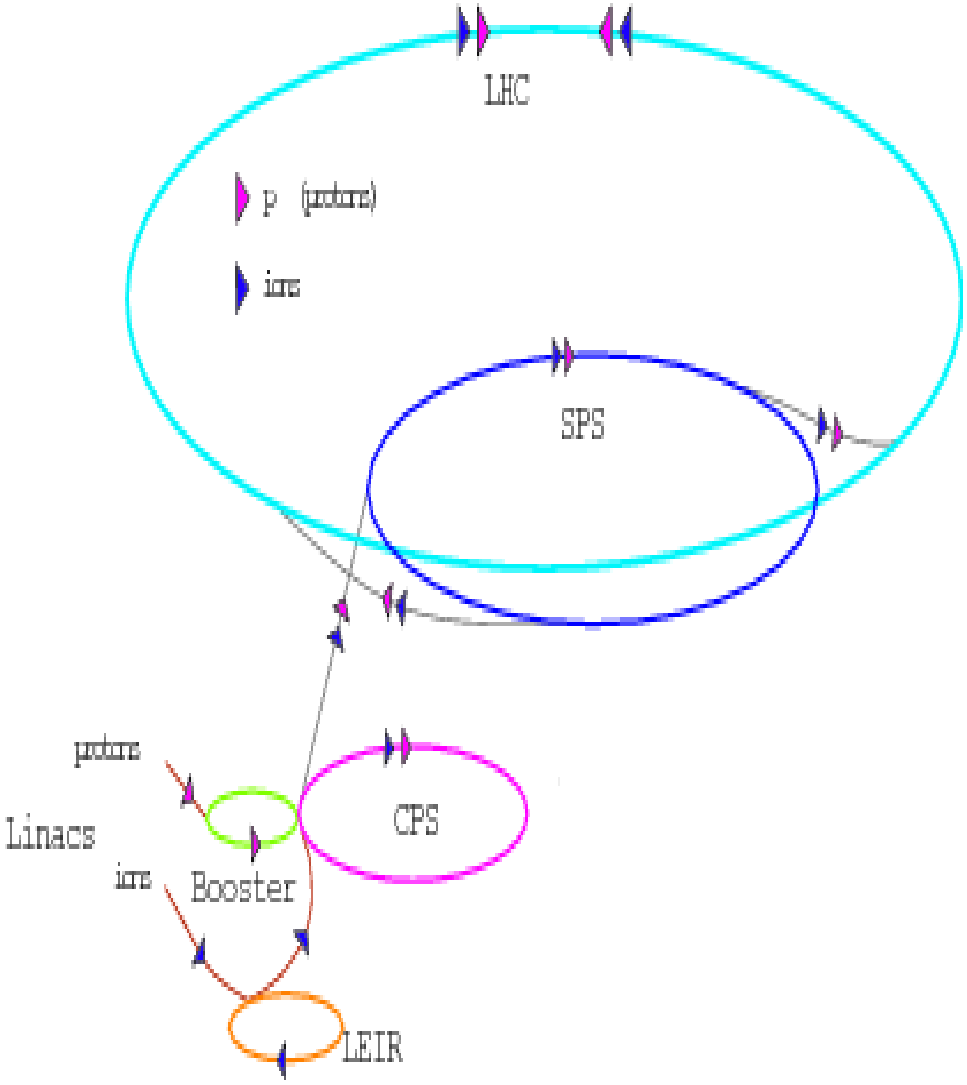
LHC Layout and Design Parameters

- Two counter rotating 7 TeV proton beams
- Each beam will contain **2808** bunches, each bunch will consist of **1.15 x 10^{11}** protons [total = **3 x 10^{14}**]
- τ = **0.5 ns**, $\Delta\tau$ = **25 ns**, total pulse length = **89 μs**
- Transverse intensity profile is Gaussian with σ = **0.2 mm**.

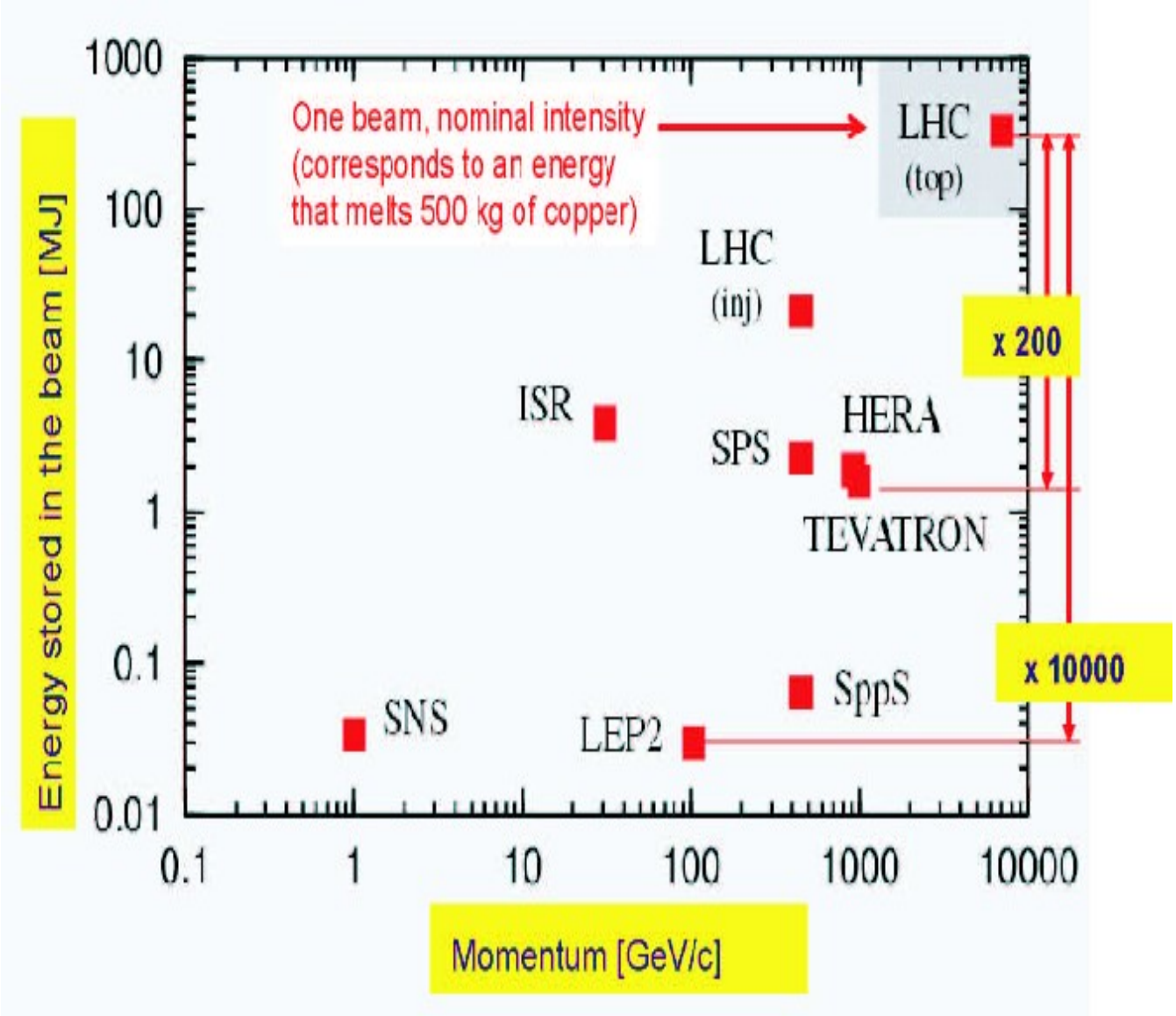


Comparison of LHC with Existing Machines

Each beam contains
362 MJ Energy

Sufficient to **melt**
500 kg or **evaporate**
60 kg of copper

Safety of operation is an extremely important issue in case of such powerful machines.



Numerical Simulations of Damage Estimation

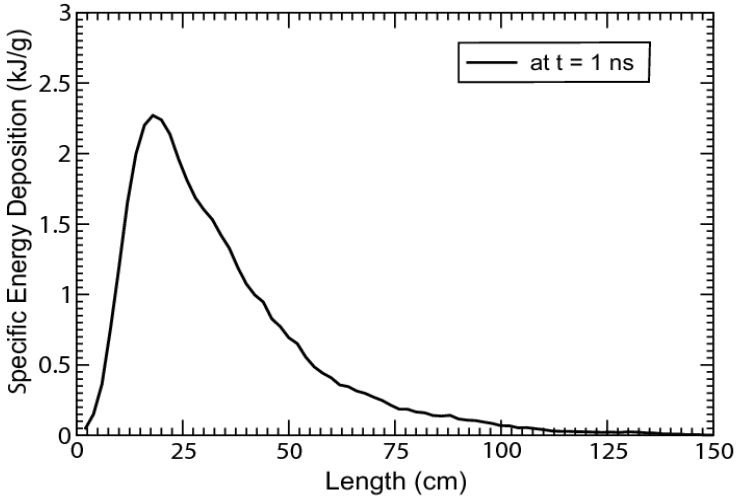
Targets made of two different materials were considered:
Copper and Graphite [1) N.A.Tahir, B.Goddard, V.Kain, R.Schmidt et al. J. Appl. Phys. 97 (2005) 083532 and 2) N.A.Tahir, C.Deutsch, V.E.Fortov, V.Gryaznov et al., Phys. Rev. Lett 95 (2005) 035001.]

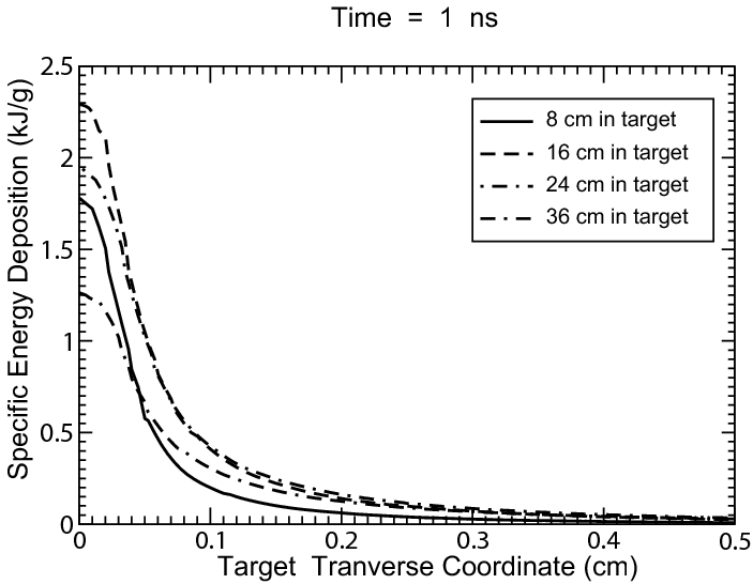
STEP I : To calculate the energy deposited by protons and the secondary particles (Shower) in the target material using FLUKA code.

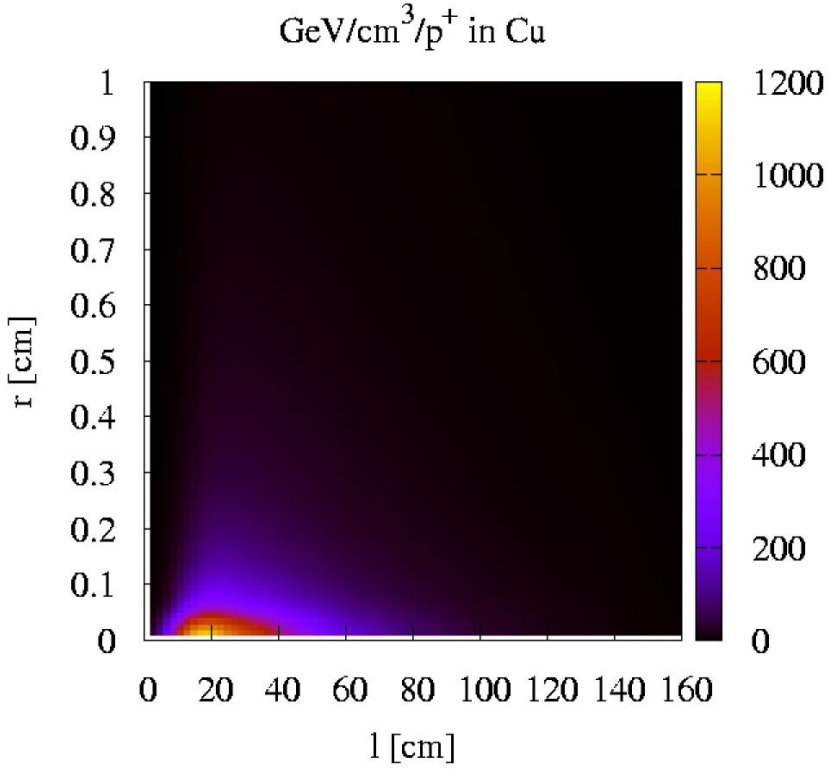
STEP II: To couple this energy deposition data in a 2D hydrodynamic code BIG2 to study the thermodynamic and hydrodynamic response of the material due to beam heating.
Target physical conditions in BIG2 are evaluated using a semi-empirical EOS model that allows for phase transitions.

FLUKA Calculations:

Solid **Cu** cylinder: **L = 5 m, r = 1 m**







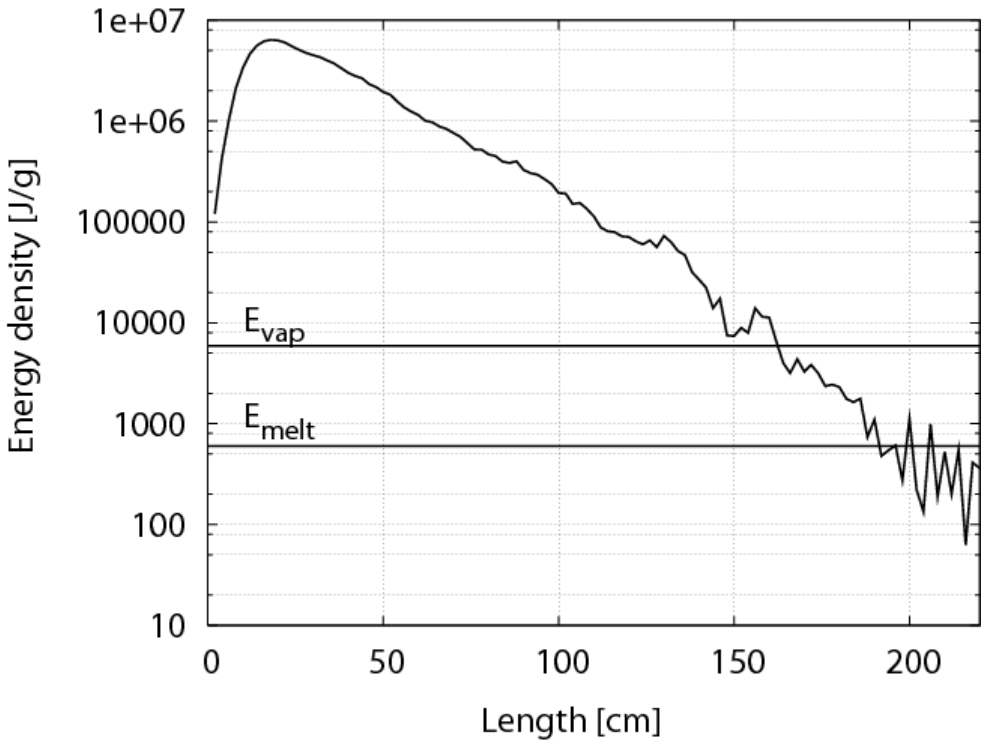
Inelastic nuclear scattering length of copper at 7 TeV protons is 15 cm

Peak deposition occurs at L = 16 cm

At 1.5 m deposition is 1250 times less

Static Estimations of Beam Penetration

- If **Melting** is taken as damage limit, penetration depth is about **2 m.**
- If **Evaporation** is taken to be the damage limit, penetration depth is **350 m.** Evaporation energy for Cu is **5.93 kJ/g**. [0.7 kJ/g is average energy deposited /bunch]



8 bunches will evaporate **1 m** long cylinder with radius = beam radius.

Hydrodynamic Simulations [Dynamic Estimation]

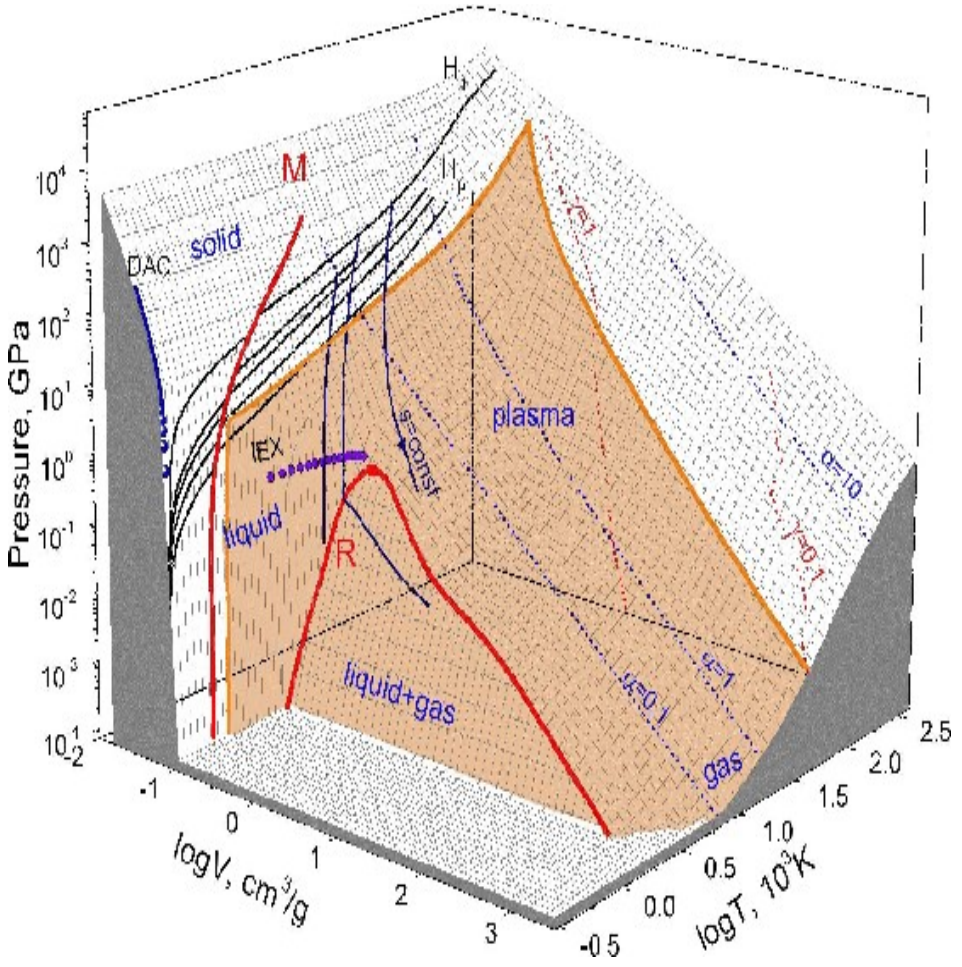
BIG2 Code:

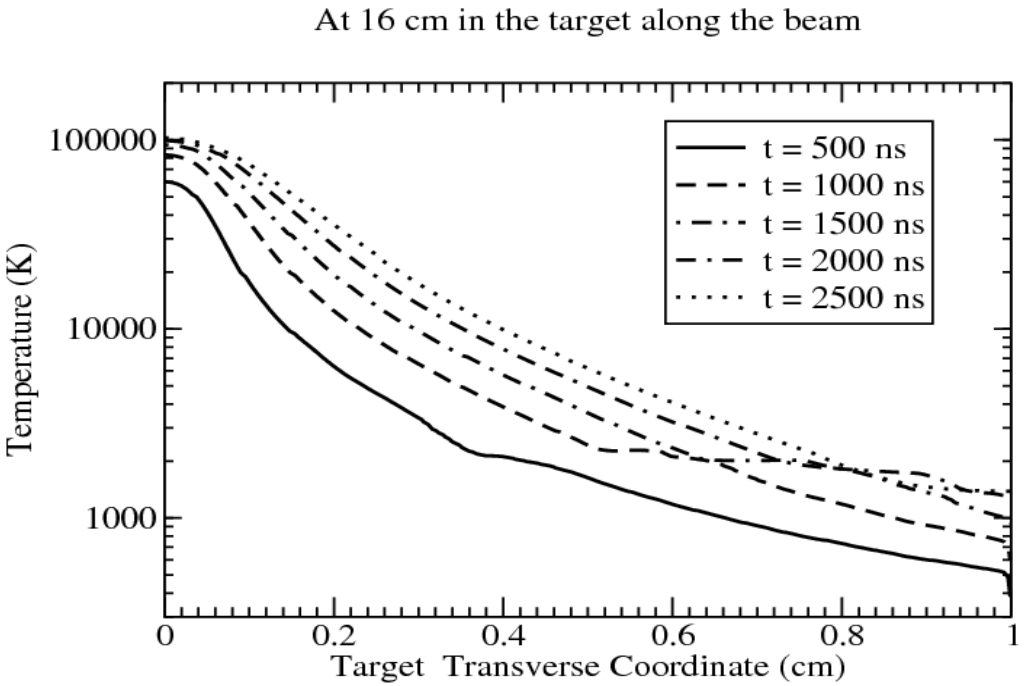
2D Hydrodynamics

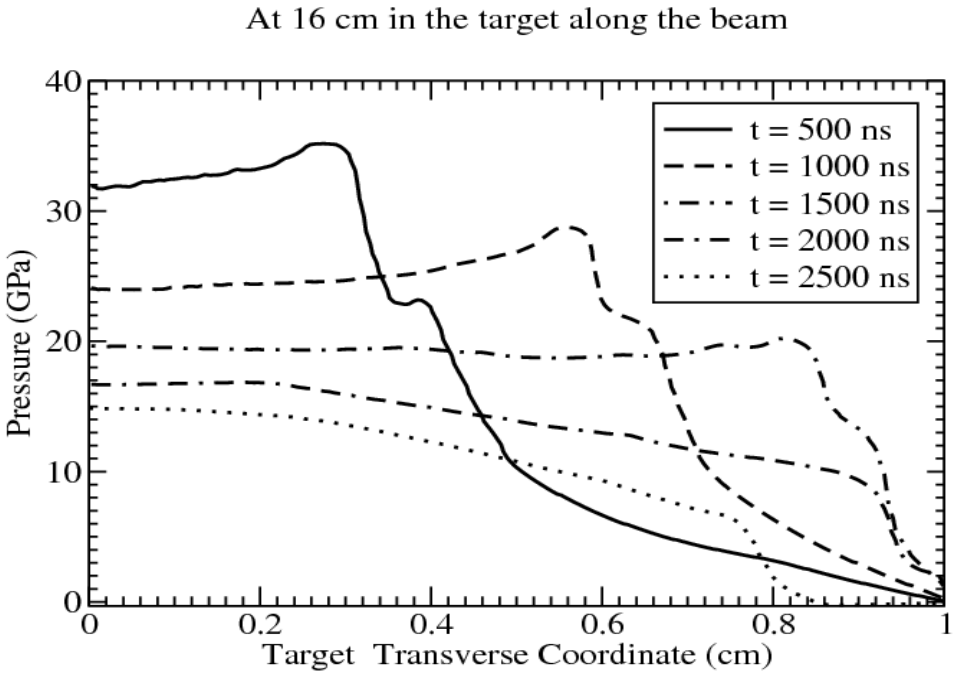
Godunov Type Scheme

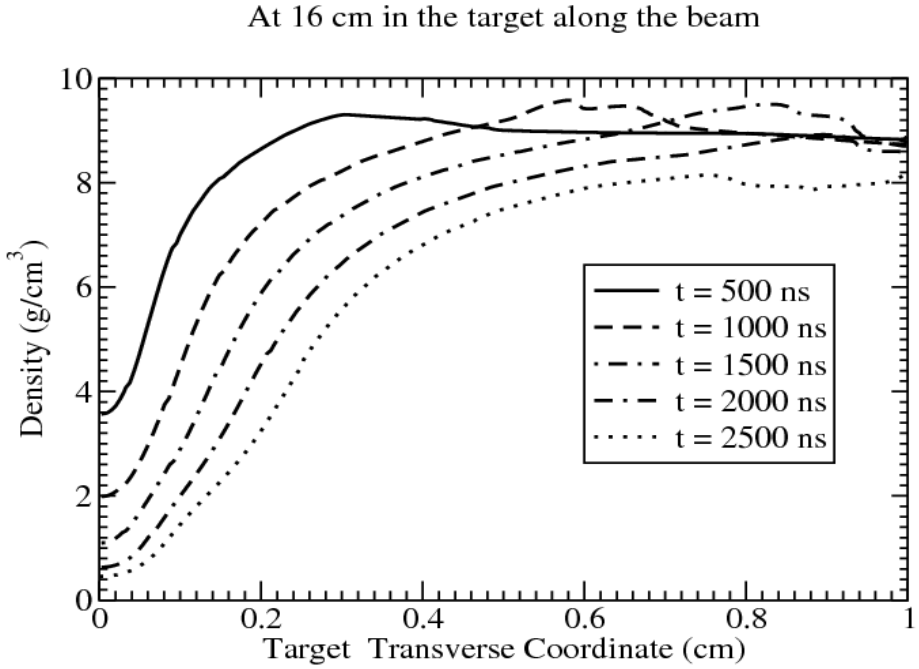
Allows for Heat Conduction

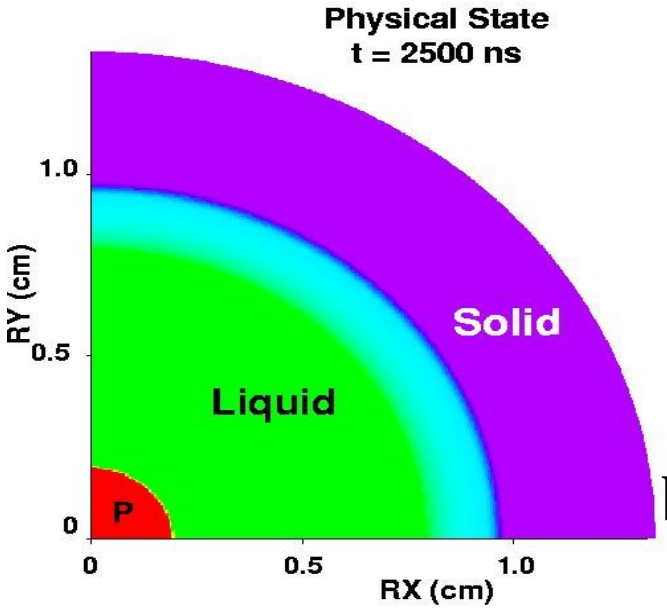
Includes Equation-of-State Data from a semi-empirical Model that treats all material phases including phase transitions [Bushman & Fortov Sov. Tech. Rev. B Therm. Phys. 1, 219 (1987)]









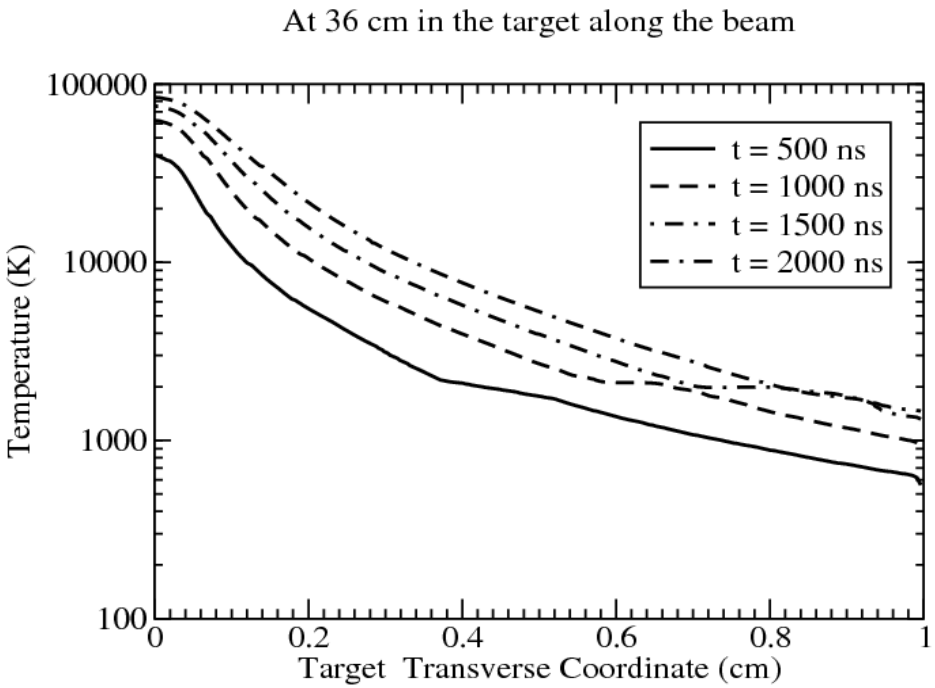


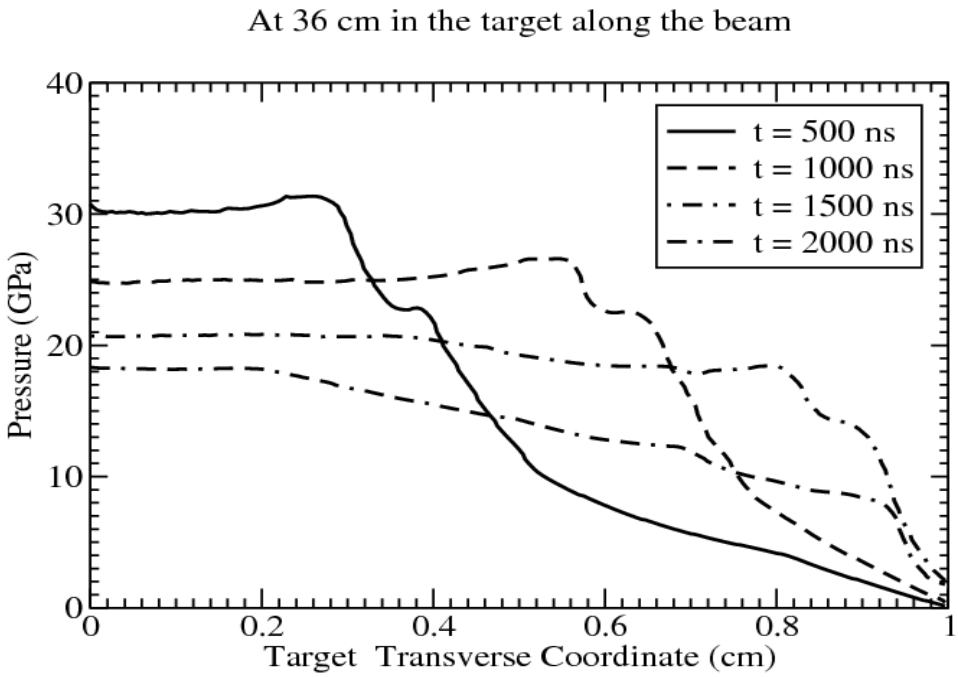
100

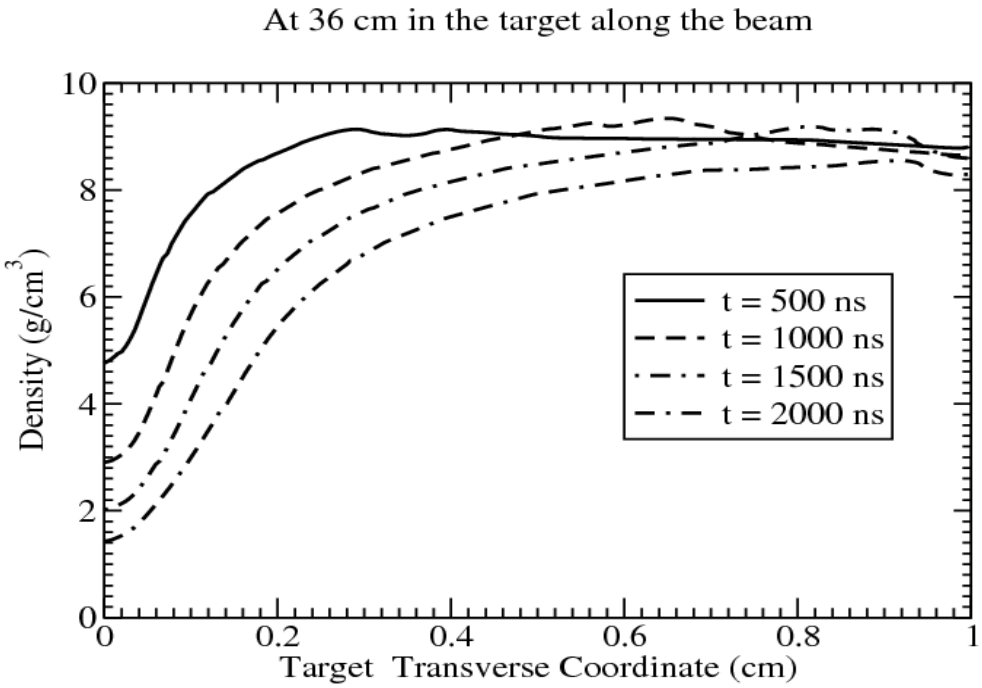
out of

2808

bunches


At 36 cm in the target along the beam
Temperature (K)
100000
10000
1000
100
0
0.2
0.4
0.6
0.8
1
Target Transverse Coordinate (cm)
t = 500 ns
t = 1000 ns
t = 1500 ns
t = 2000 ns


At 36 cm in the target along the beam
Pressure (GPa)
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1
Target Transverse Coordinate (cm)
t = 500 ns
t = 1000 ns
t = 1500 ns
t = 2000 ns


At 36 cm in the target along the beam
Density (g/cm3)
10
8
6
4
2
0
0
0.2
0.4
0.6
0.8
1
Target Transverse Coordinate (cm)
t = 500 ns
t = 1000 ns
t = 1500 ns
t = 2000 ns

Due to reduction in density at the target center, protons delivered in subsequent bunches will tunnel further and further, thereby increasing the particle range substantially. This effect has been observed in heavy ion heated targets [N.A. Tahir et al, Phys. Rev. E 63 (2001) 036401-1-8].

To have a precise calculation of the penetration depth, one needs a 3D code (work in progress), nevertheless combining the 2D simulation results with analytic considerations one may estimate the material destruction to a good approximation.

About 80 bunches make approximately 1 m length of Cu target transparent. This means that the penetration depth will be approximately 35 m.

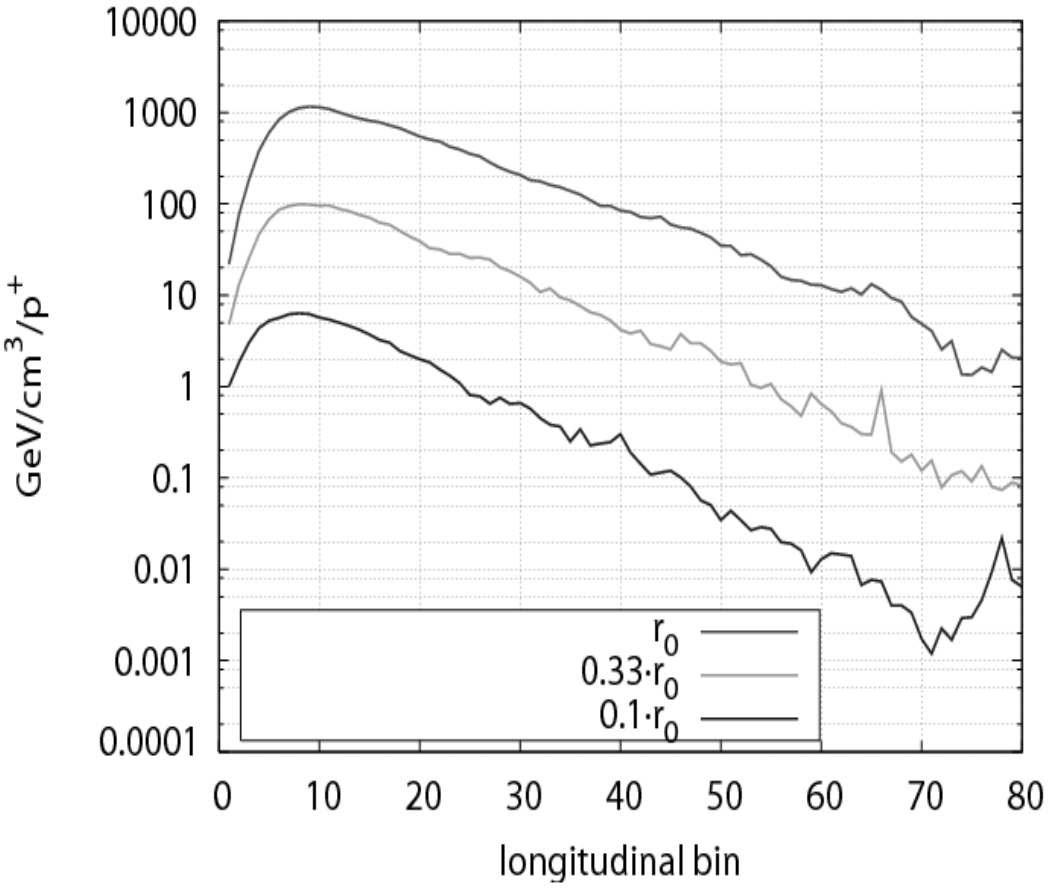
Proton Energy Loss at Different Material Density

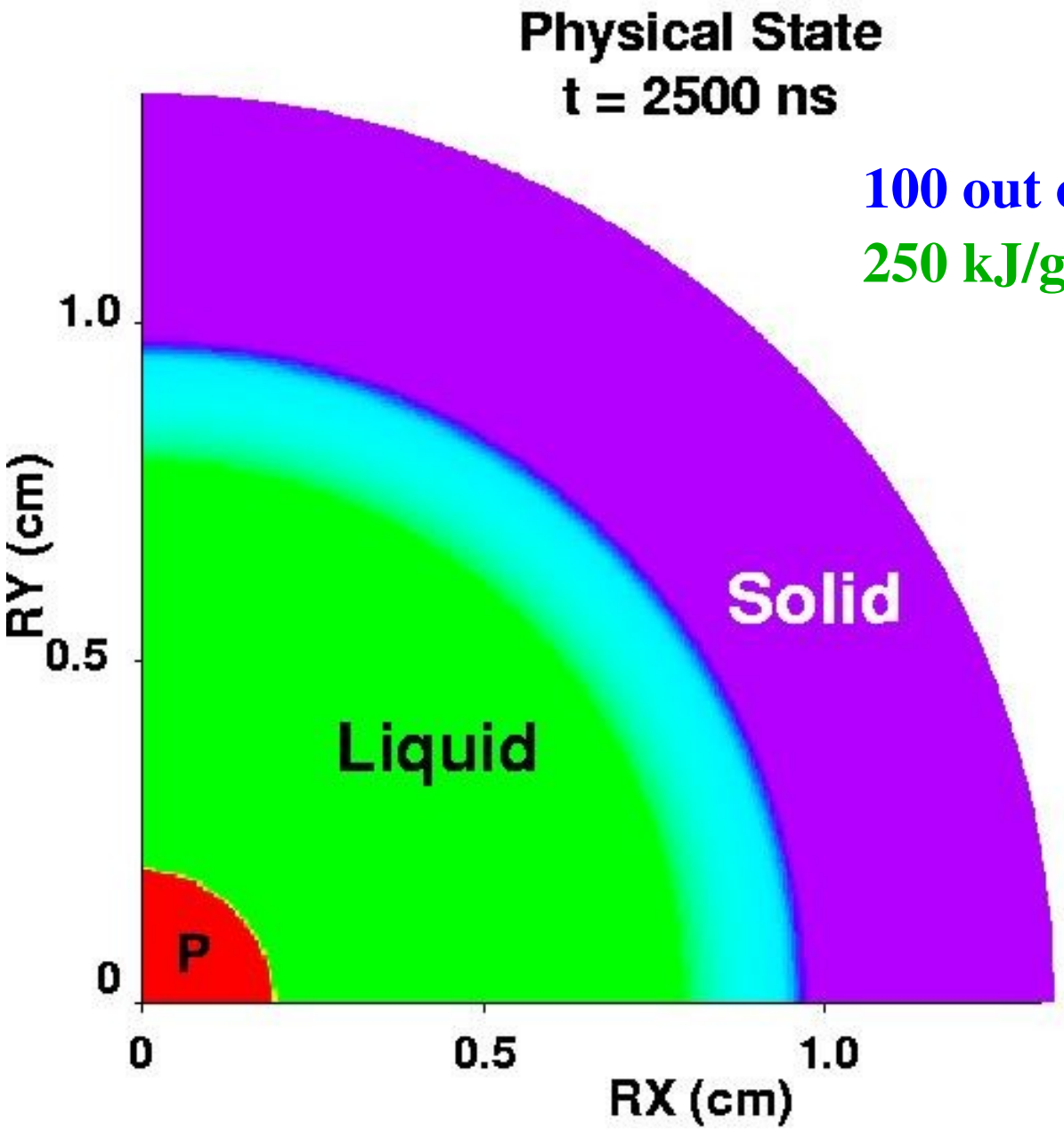
FLUKA calculates dE/dV at constant target density. This is not valid!

Changing density will change dE/dV (L).

This will influence the hydro-dynamic motion.

One needs to do full 3D simulations to have a complete estimate of the penetration depth.





100 out of 2808 bunches delivered

250 kJ/g [Comparable to FAIR]

HED Physics

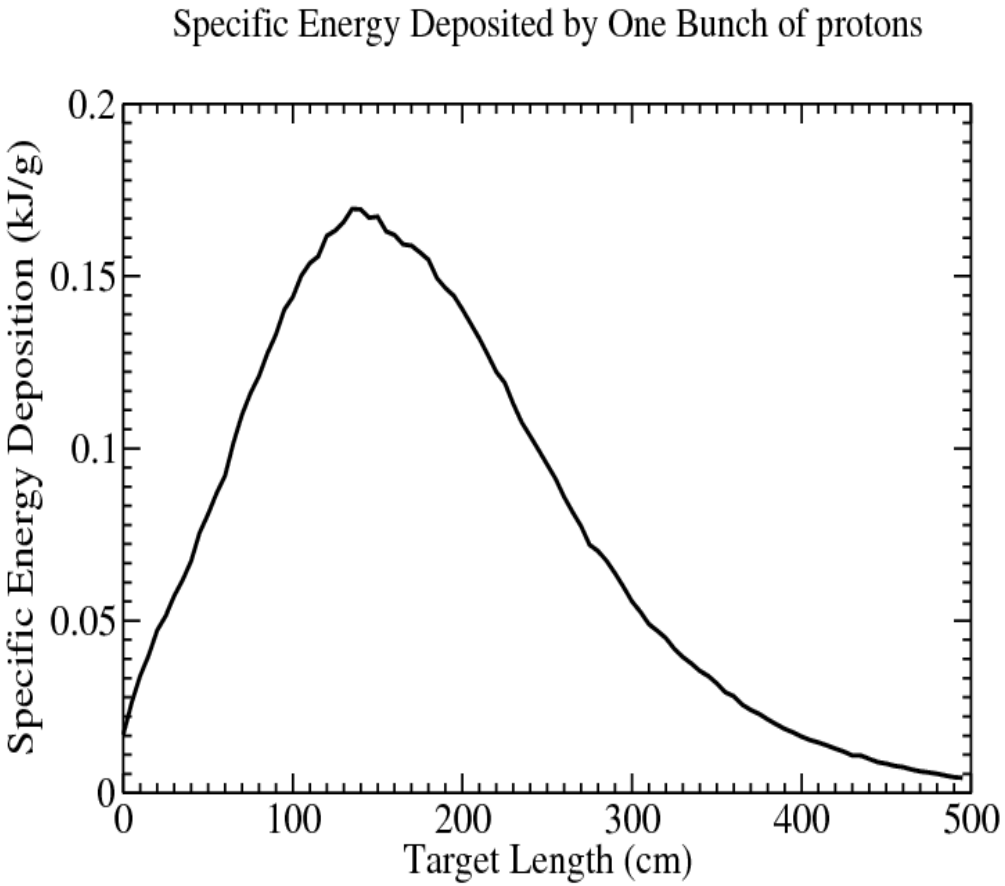
N.A. Tahir et al., PRL 94 (2005) 135004.

Phys. News Update: April 7, 2005, No: 726#3

APS News 7 Feb. 2006

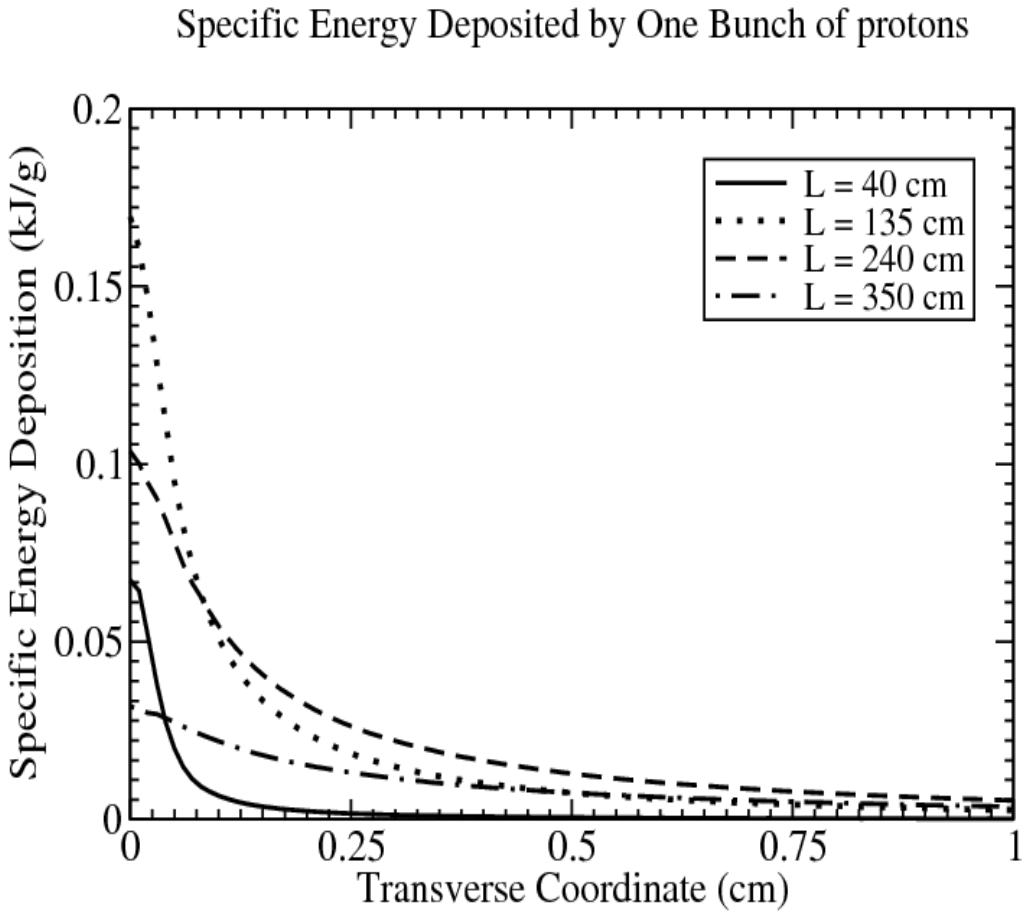
Specific Energy Deposition by a Single Bunch in Solid Carbon [FLUKA Calculations]

- Specific energy (**kJ/g**) deposited by one bunch of protons along L at r = 0.
- Maximum deposition of about **0.17 kJ/g** occurs at **L = 135 cm.**



Specific Energy Deposition in Radial Direction Along the Target Axis

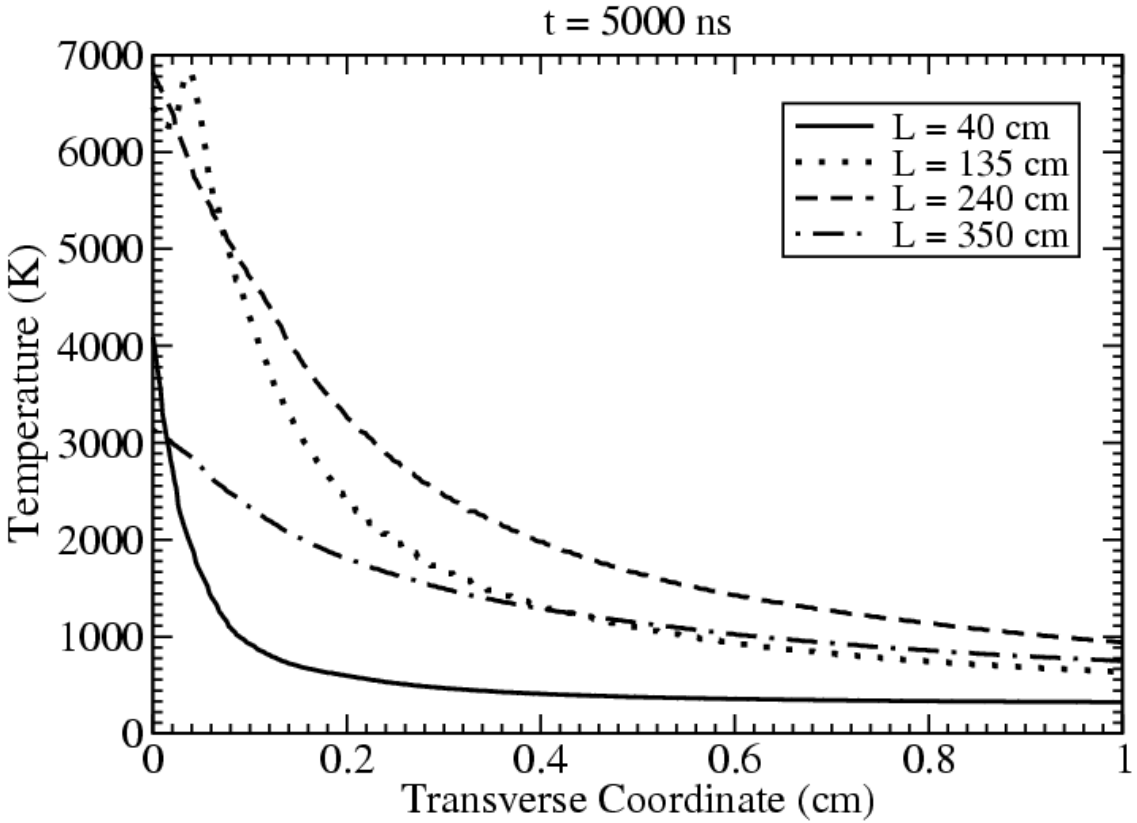
- Specific energy deposition (**kJ/g**) vs radius at, L = 40 cm, **135 cm**, 240 cm and 350 cm by a single bunch.

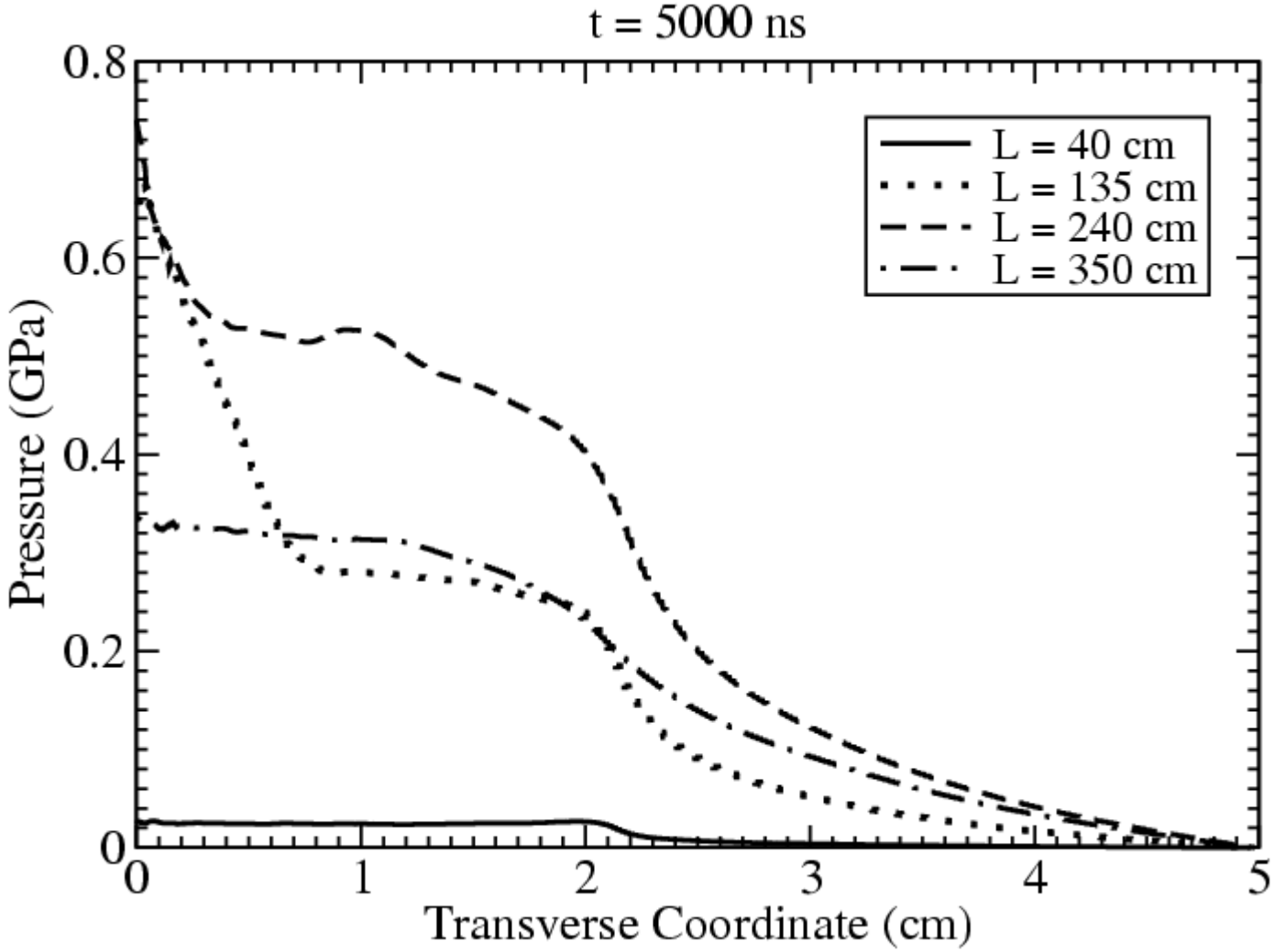


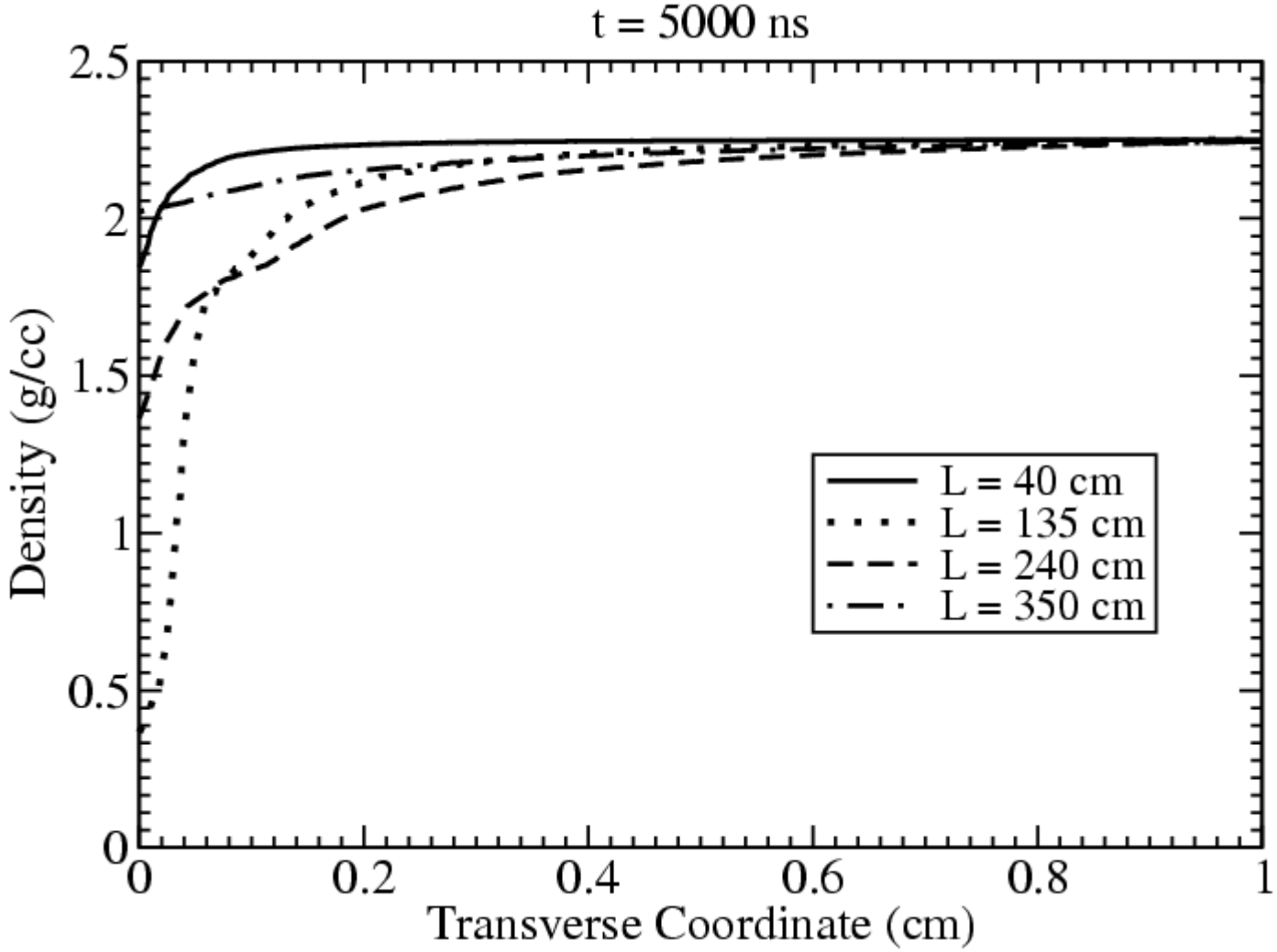
Temperature vs Radius at different Longitudinal Positions

250 out of 2808 bunches have been delivered

Sublimation Temperature = 3295 K




t = 5000 ns
0.8
0.6
0.4
0.2
0
Pressure (GPa)
0
1
2
3
4
5
Transverse Coordinate (cm)
L = 40 cm
L = 135 cm
L = 240 cm
L = 350 cm


t = 5000 ns
Density (g/cc)
Transverse Coordinate (cm)
0
0.5
1
1.5
2
2.5
0
0.2
0.4
0.6
0.8
1
L = 40 cm
L = 135 cm
L = 240 cm
L = 350 cm

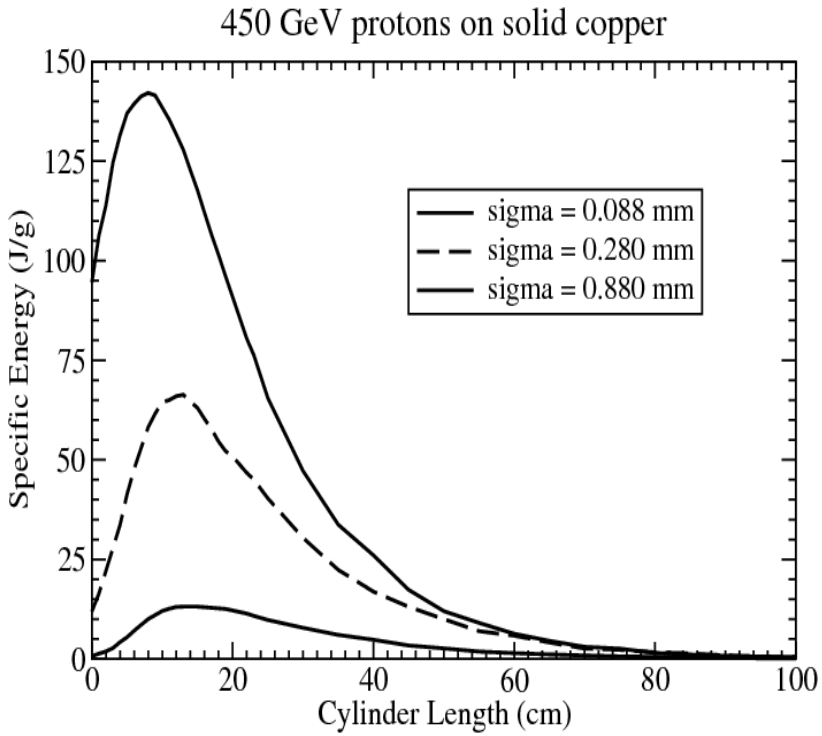
Simulations of Targets Irradiated with SPS Beam

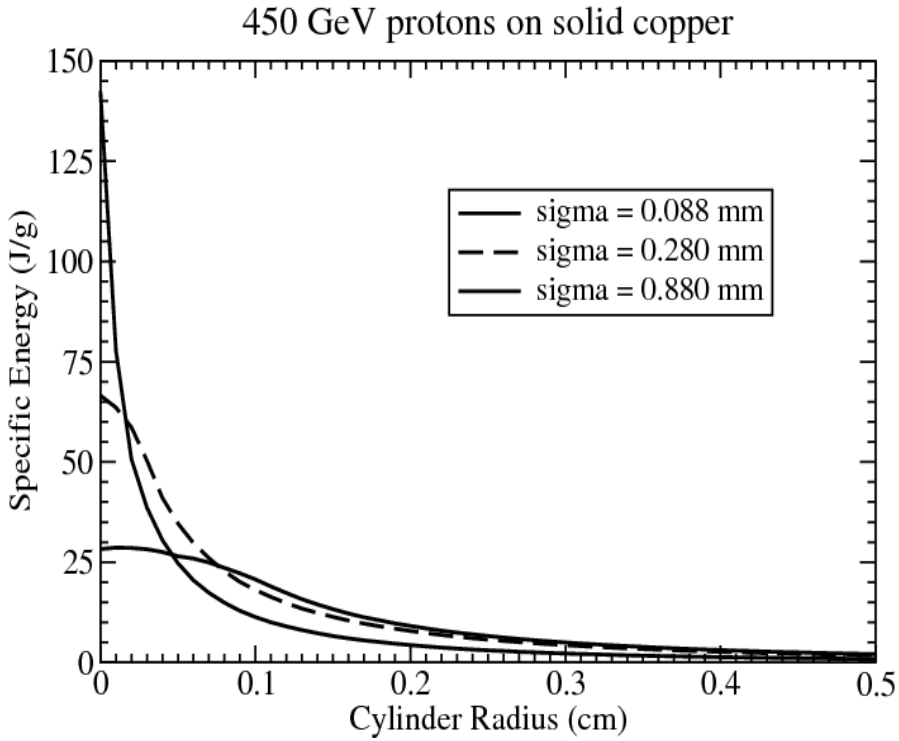
Proton Energy = 450 GeV

Bunched Beam with 288 bunches

Bunch Length = 0.5 ns, Separation = 25 ns

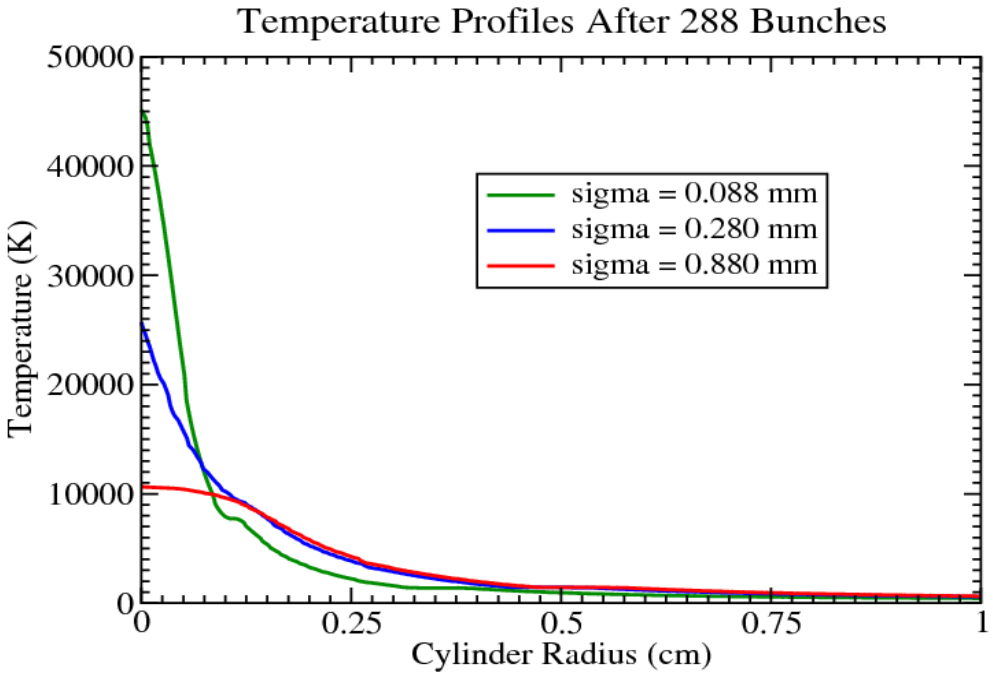
Transverse Part. Distribution Gaussian [σ = 0.088 mm, 0.28 mm & 0.88 mm]

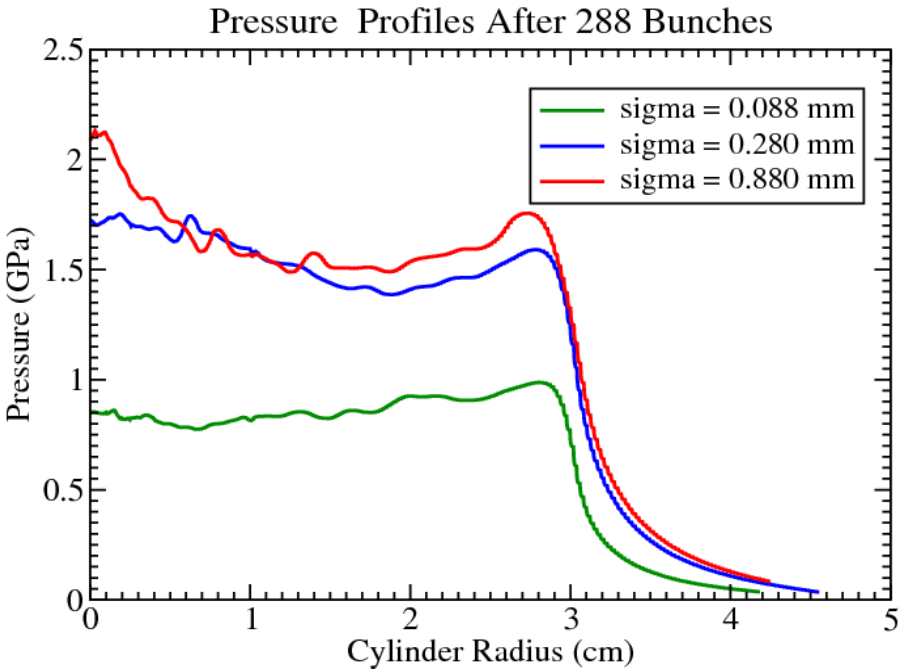


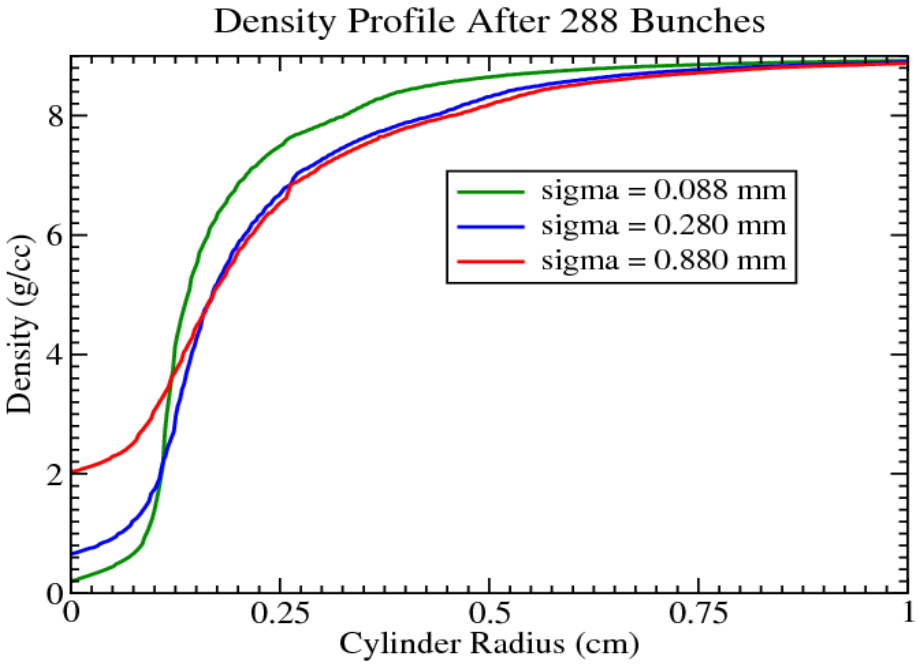


Copper Cylinder Irradiated by SPS Beam

2D Simulation Results With BIG2 code using the FLUKA Energy Deposition Data







Summary and Future Work

	LHC	SPS
Energy	7 TeV	450 GeV
No. of Bunches	2808	288
Total Intensity	$3x10^{14}$	$3x10^{13}$
Pulse Duration	89 μs	7.34 μs

Targets of W, Cu and C have been used

Currently the calculations have been done in tewo steps :

1. **The energy deposition by protons (including that by the secondary particles) is first calculated by FLUKA assuming solid density**
2. **This data is then coupled to the 2D hydrodynamic code, BIG2 and calculations are done**

The final goal is to carry out full 3D simulations including the the modification in energy loss due to reduction in target density.

WORK IS IN PROGRESS!

Analytic Estimation of Penetration Depth