A Review of Hydrodynamic Tunneling Work

By

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Design Parameters of the LHC Beam

LHC generates two counter rotating 7 TeV proton beams

Each beam will consist of 2808 proton bunches

Each bunch will contain 1.15×10^{11} protons

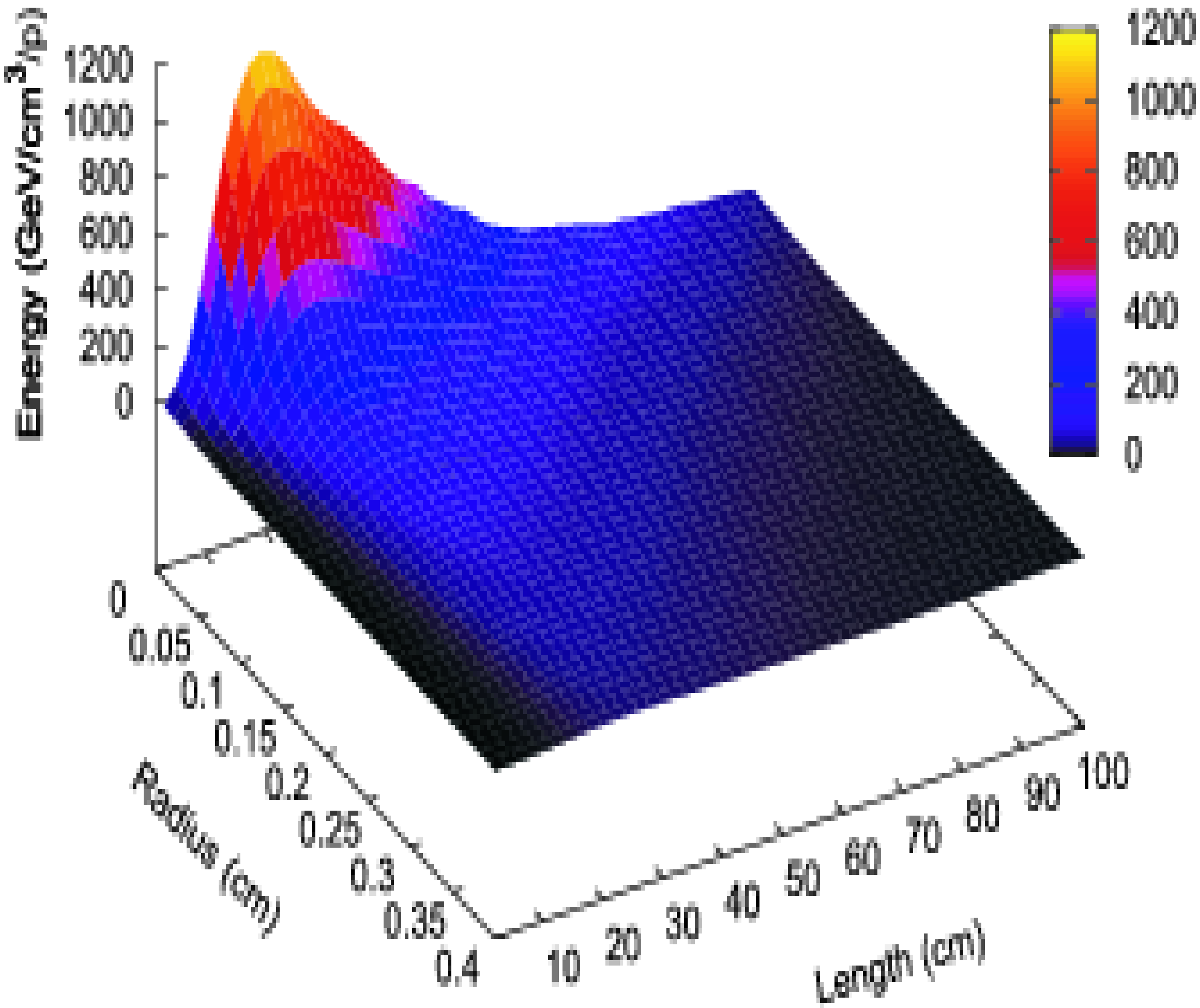
Total number of protons is 3×10^{14}

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

Total length of the bunch train = 89 μs

Transverse intensity distribution: Gaussian with $\sigma = 0.2$ mm

First Step: **Energy loss of 7 TeV protons in solid copper target is calculated using the FLUKA Code**



Target Geometry:

Solid Cu Cylinder

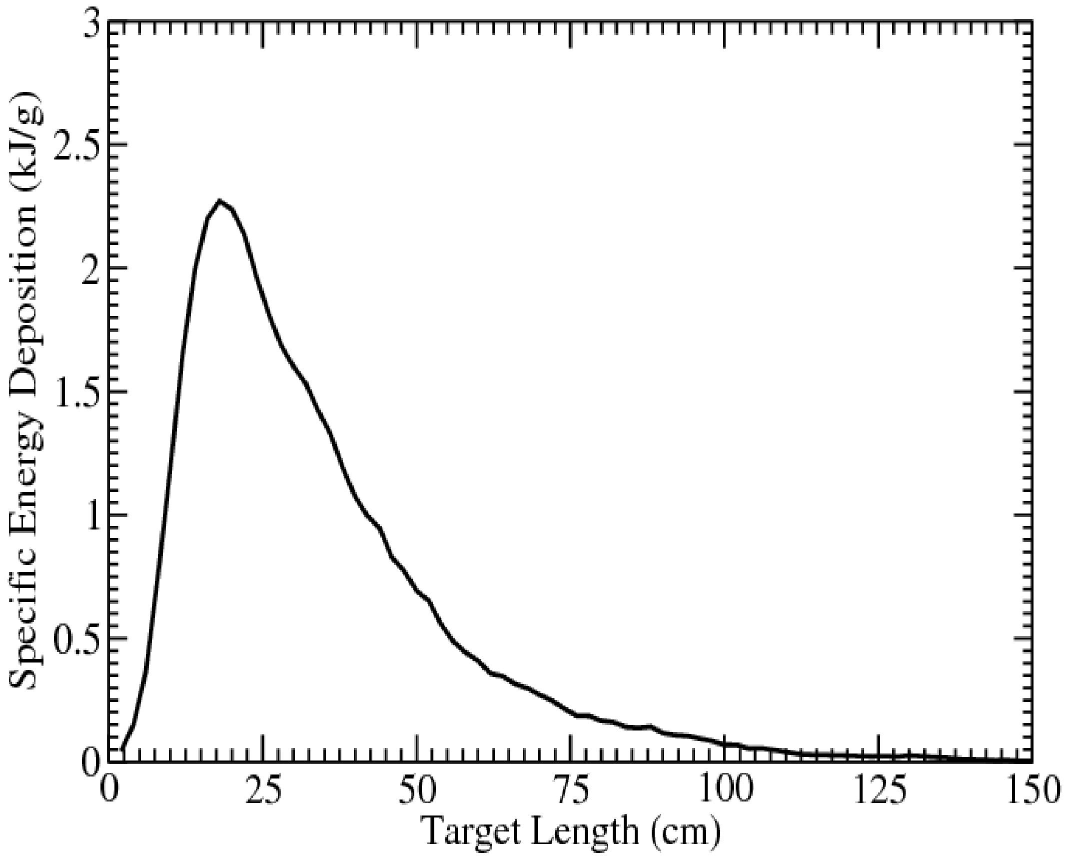
L = 5 m, r = 1 m

Peak energy deposition

1200 GeV/proton/cm^3

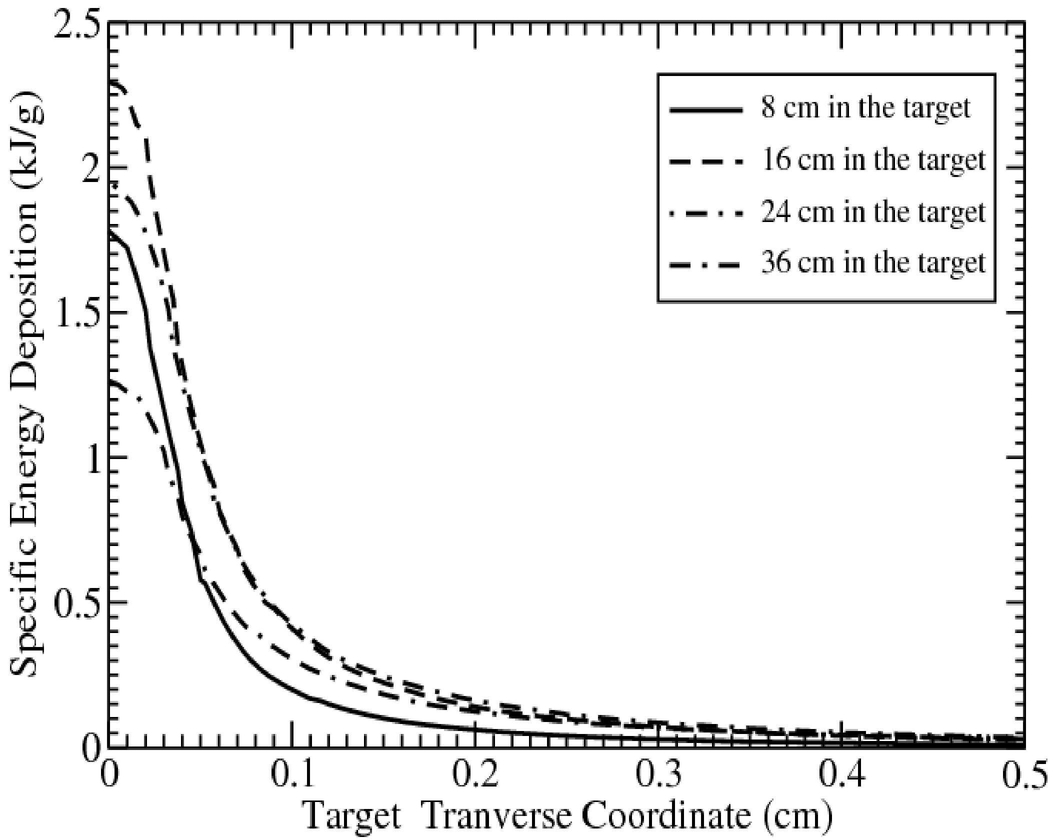
Specific Energy Deposition by a Single Bunch in Solid Copper [FLUKA Calculations]

- 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

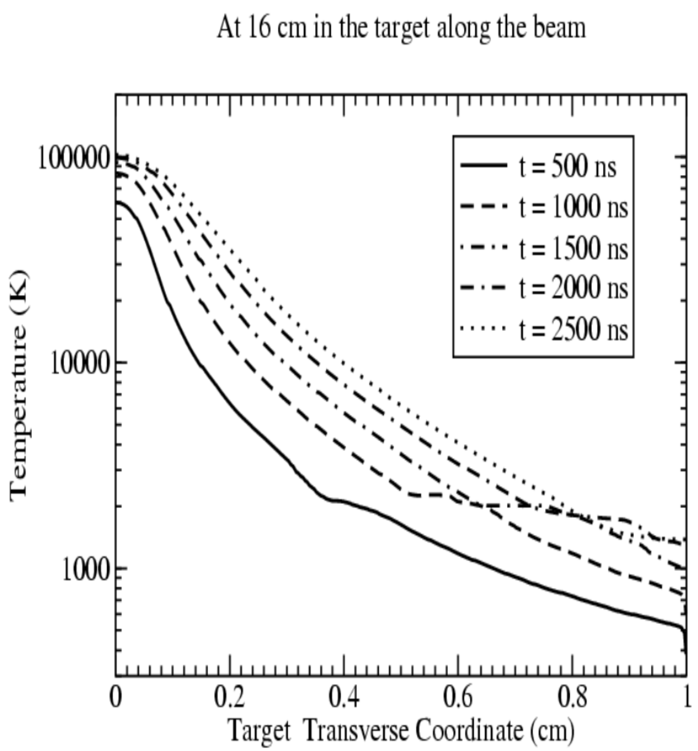
Specific energy deposition (**kJ/g**) vs radius at, L = 8 cm, **16 cm**, 24 cm and 36 cm, by a single proton bunch.

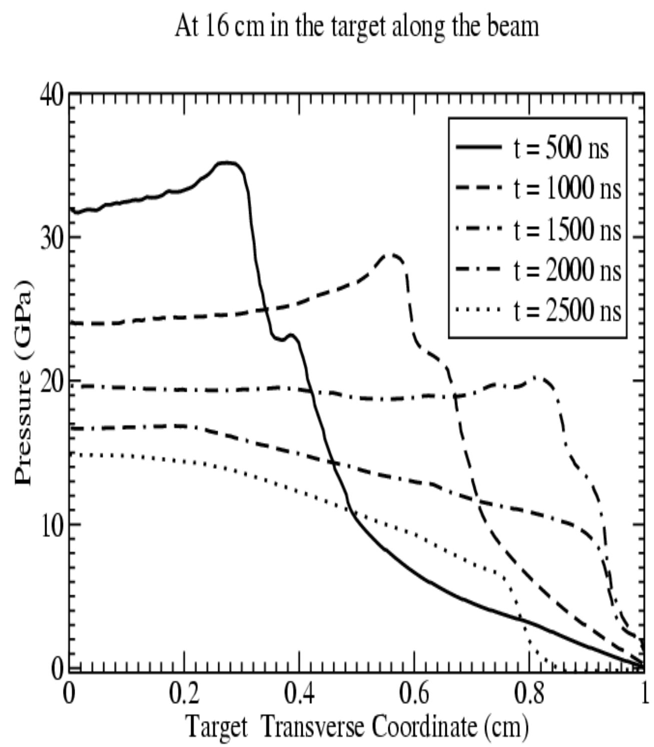


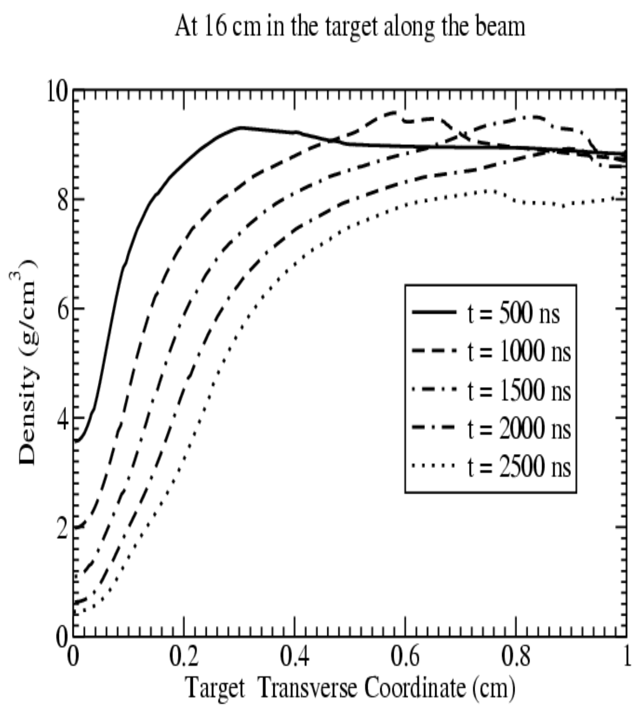
A solid copper cylinder facially irradiated by one LHC beam

2D hydrodynamic simulations are carried out along cross section at different longitudinal positions [L = 16 cm and 36 cm]

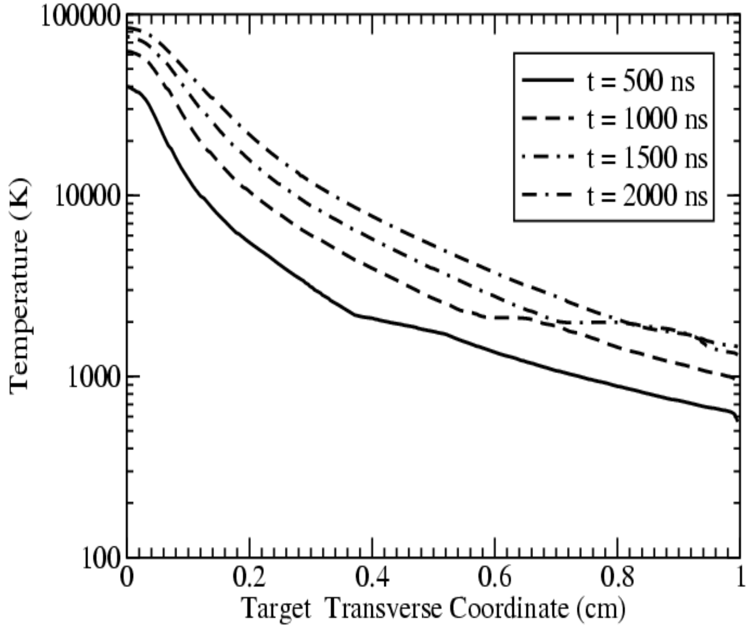
Ref.: *N.A. Tahir, B. Goddard, V. Kain, R. Schmidt et al, J. Appl. Phys. 97 (2005) 083532.*



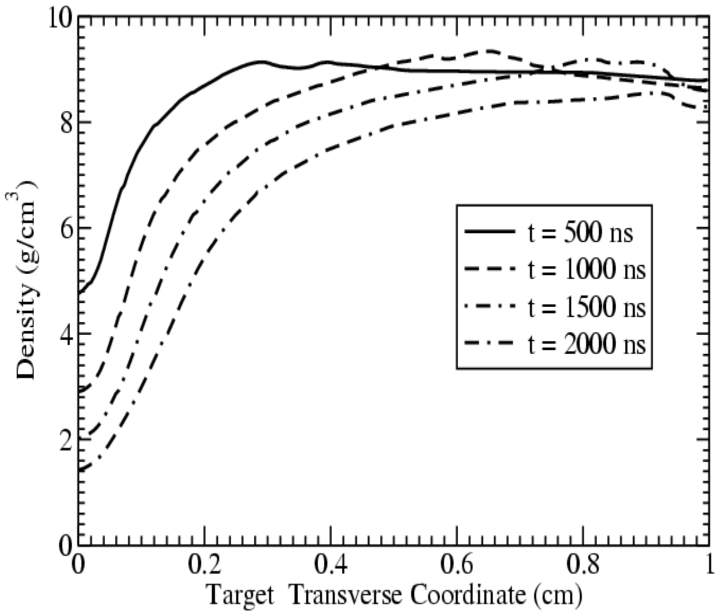




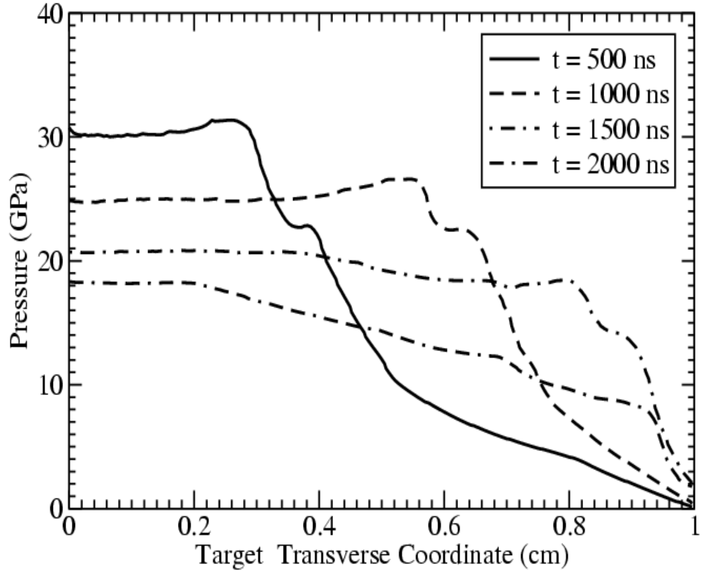
At 36 cm in the target along the beam



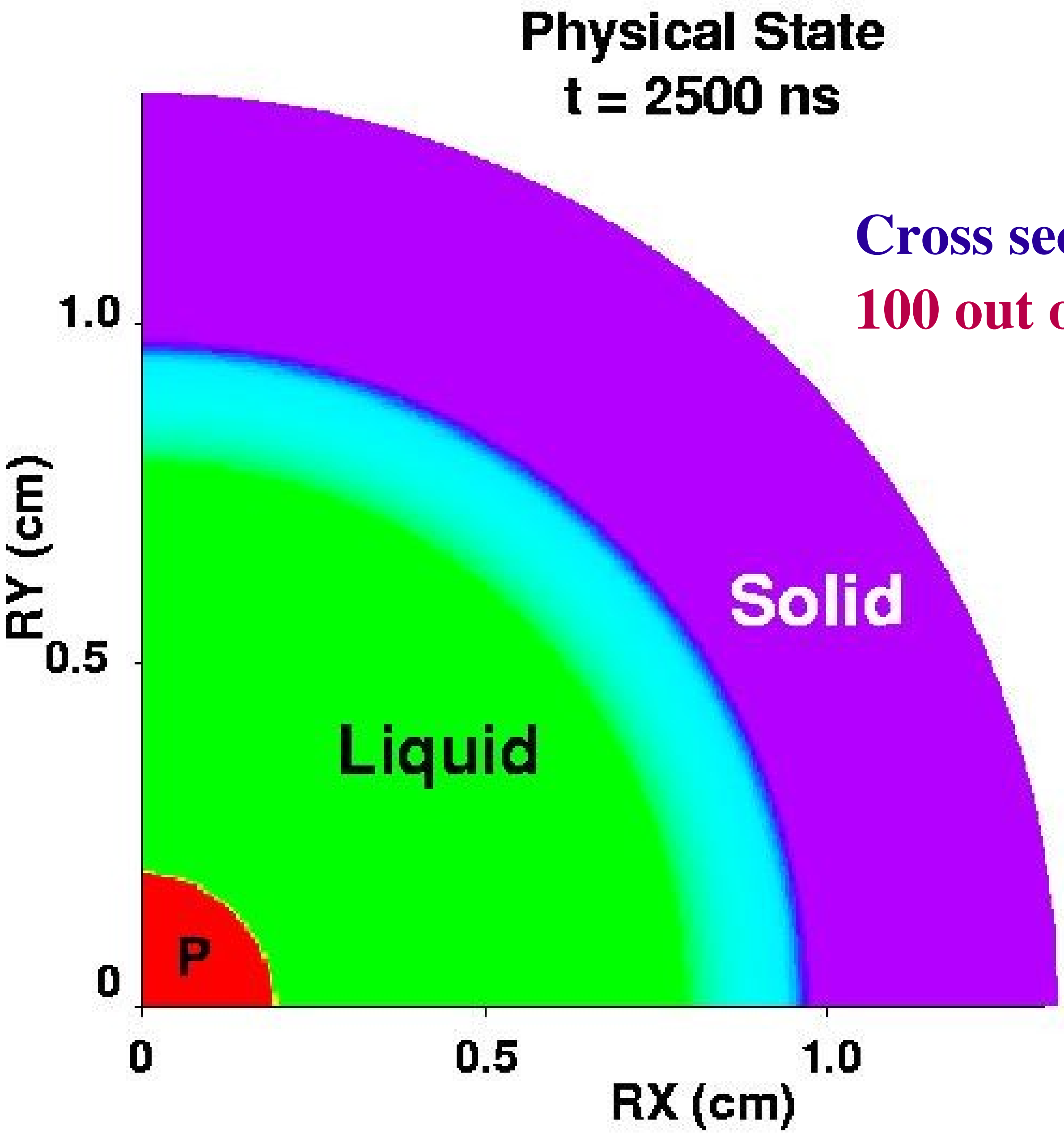
At 36 cm in the target along the beam



At 36 cm in the target along the beam



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

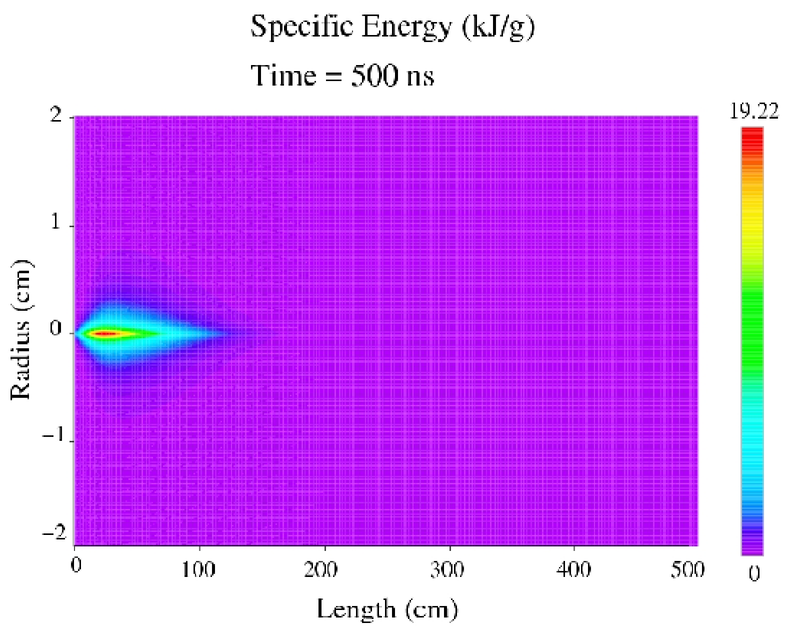
Significant extension of the previous work:

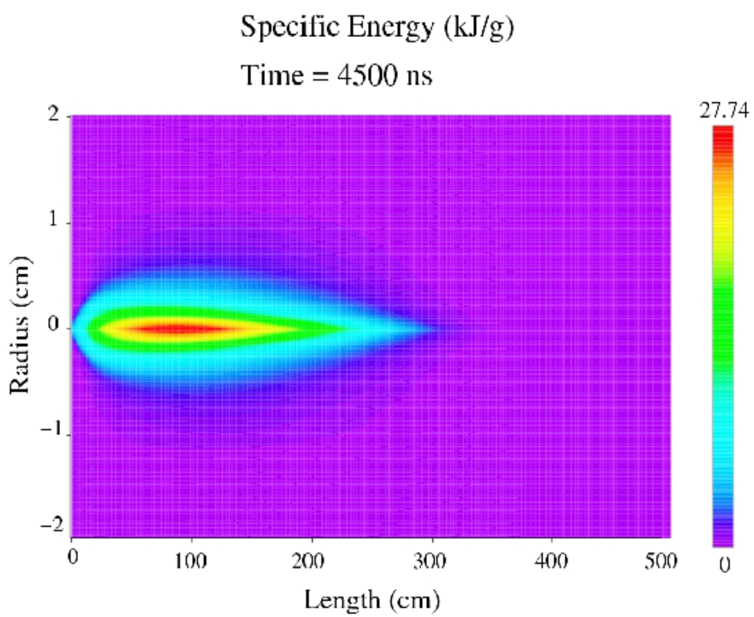
[N.A. Tahir, R. Schmidt et al., PRE 79 (2009) 046410.]

The target is studied in r-Z geometry using BIG2 code.
Energy deposition distribution is calculated using FLUKA considering solid copper density.
Specific energy deposition in each simulation cell at every timestep is normalized with respect to the line density along the axis.
This leads to 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

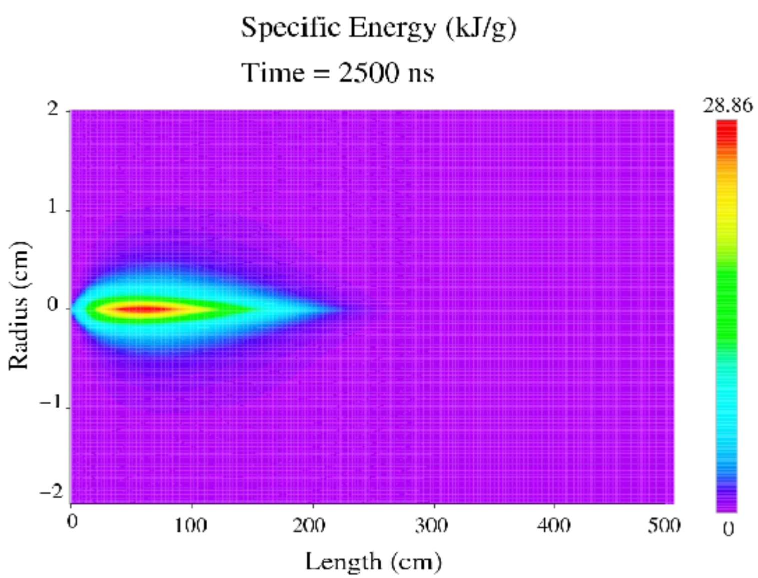
L = 5 m
r = 5 cm

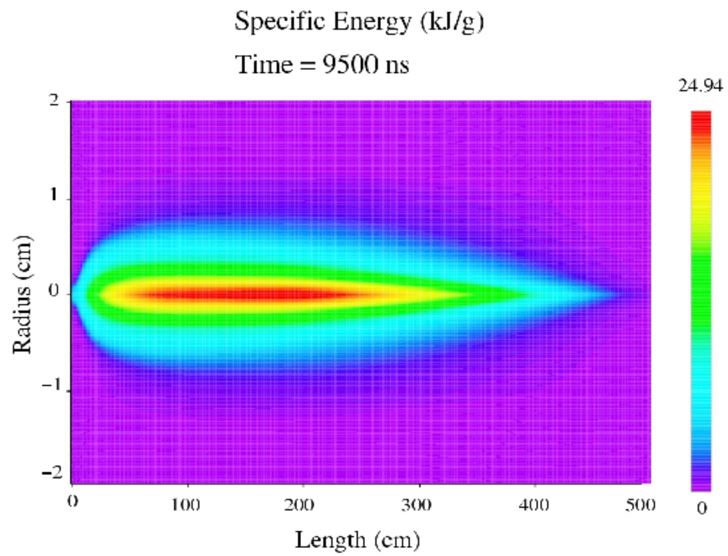


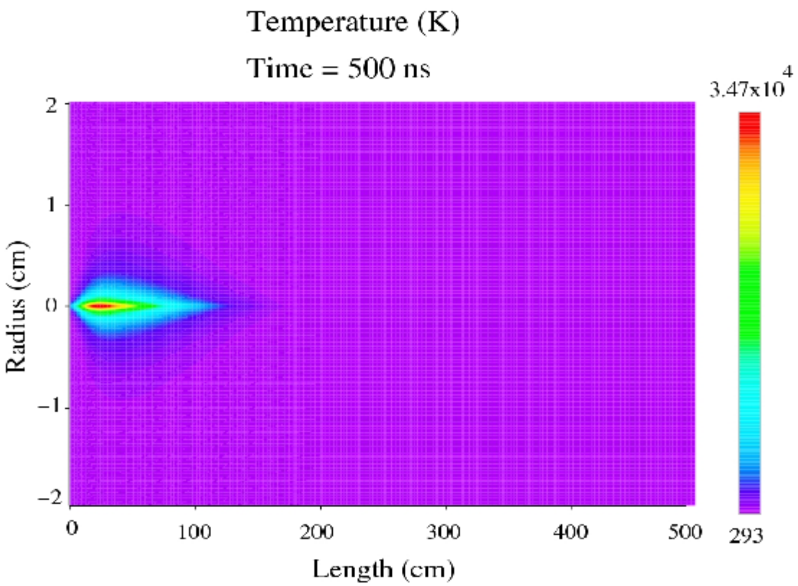


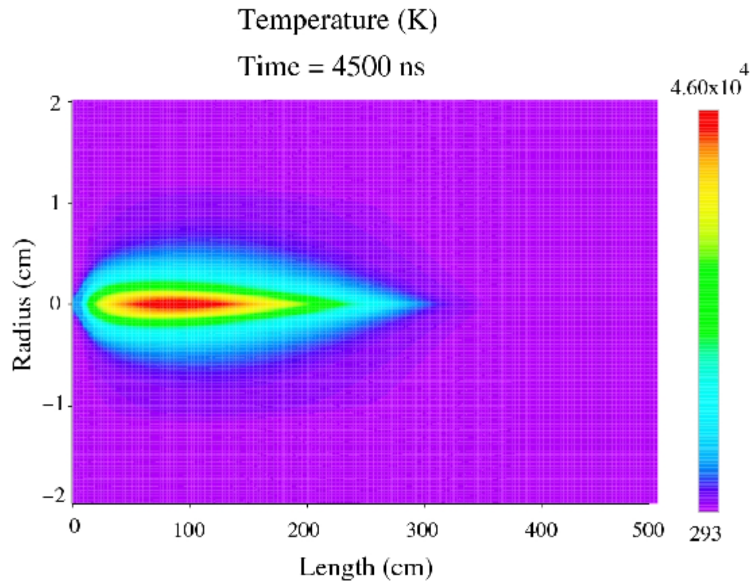
Specific Energy Deposition

Saturates to 25 kJ/g



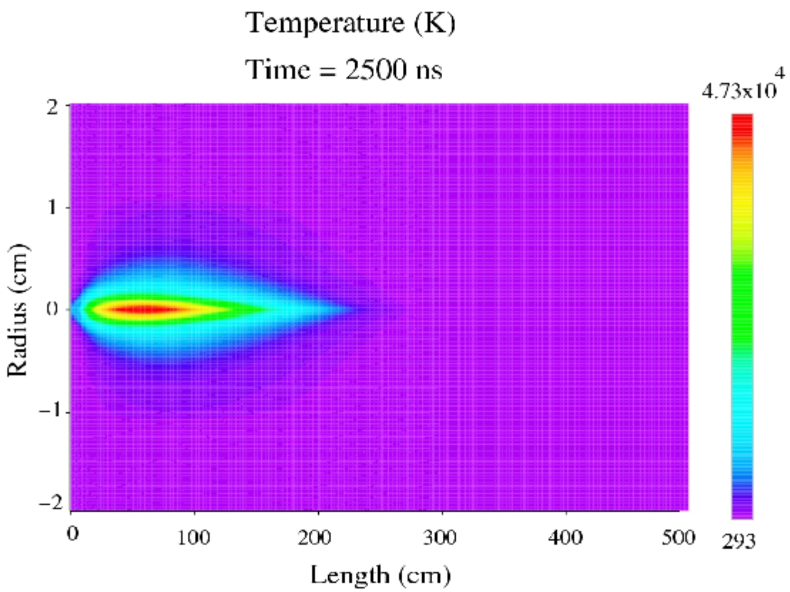


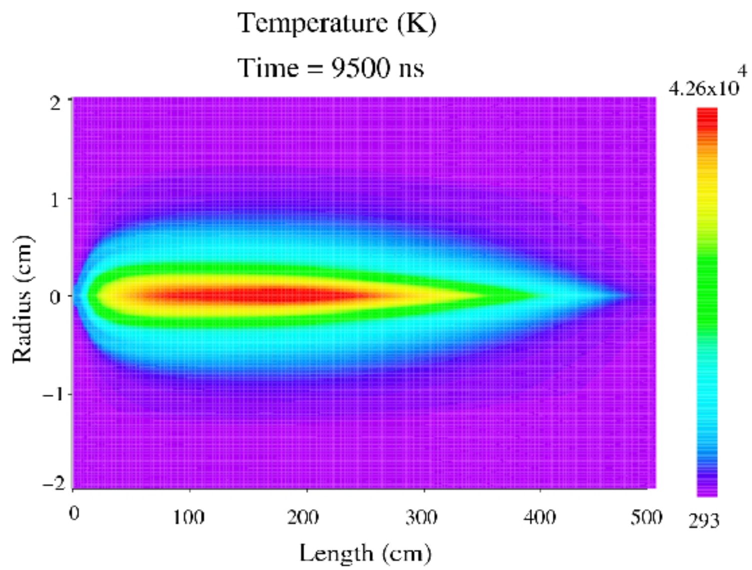


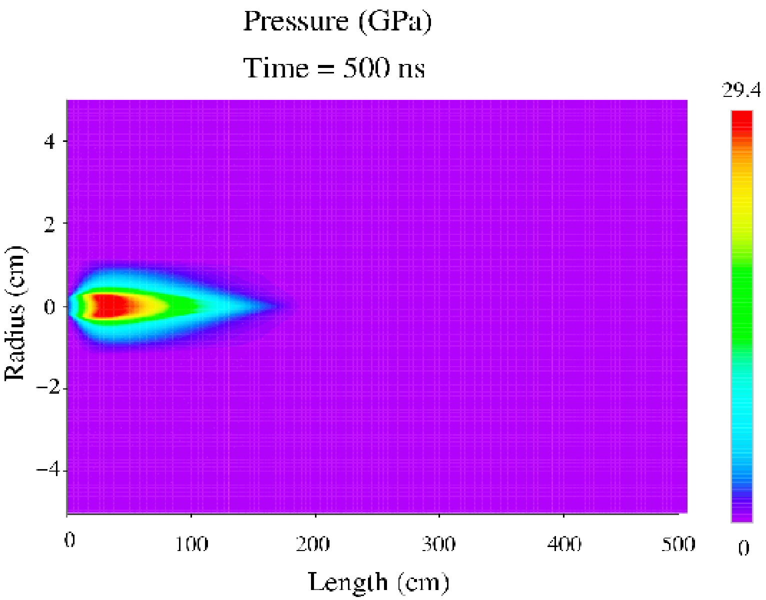


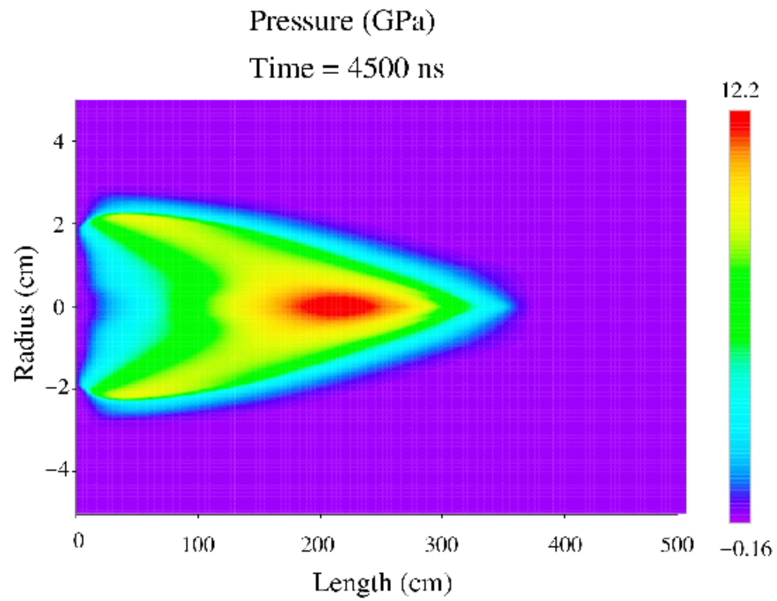
Temperature

$4x10^4$ K

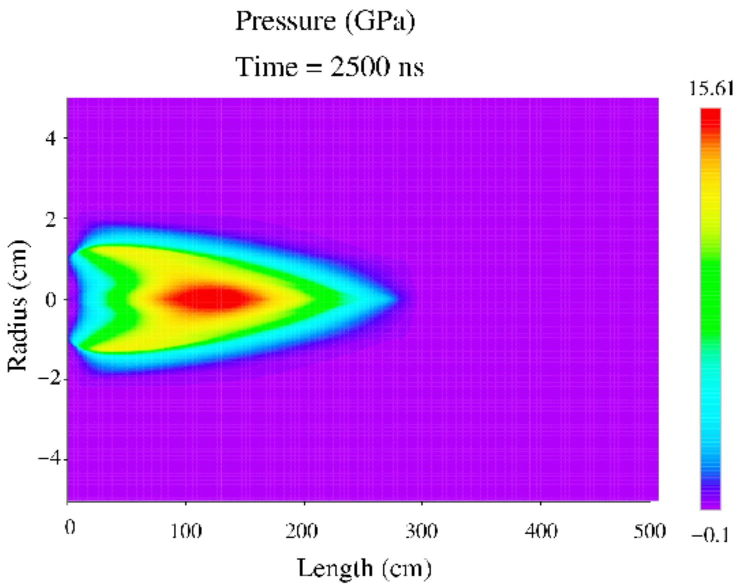




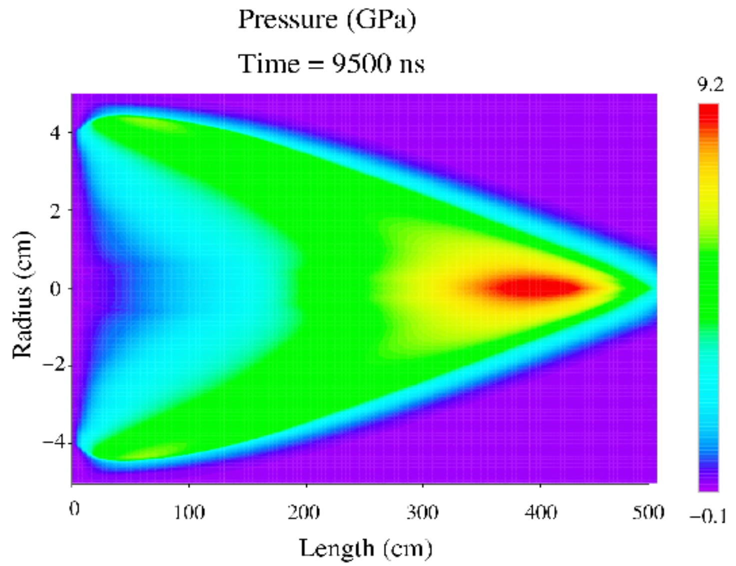




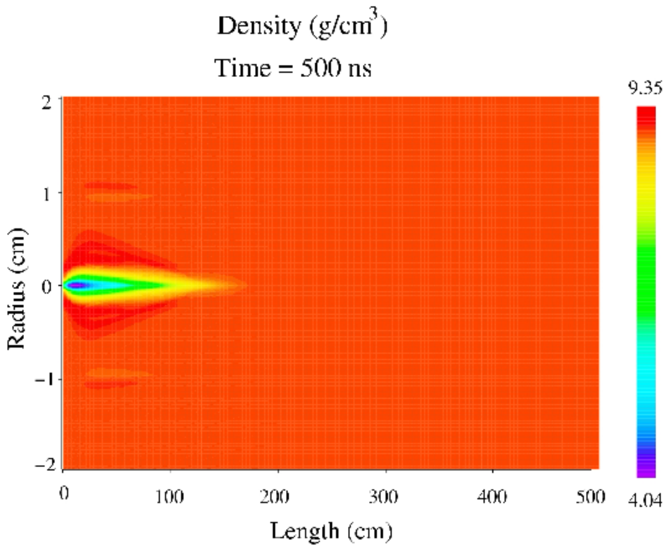
Pressure

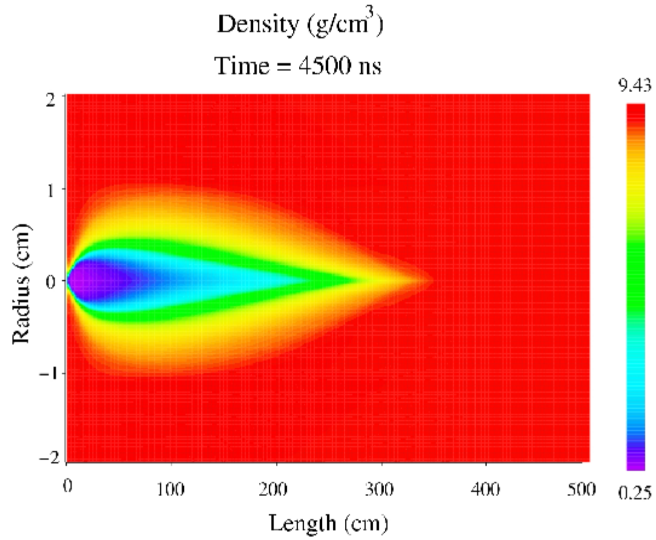


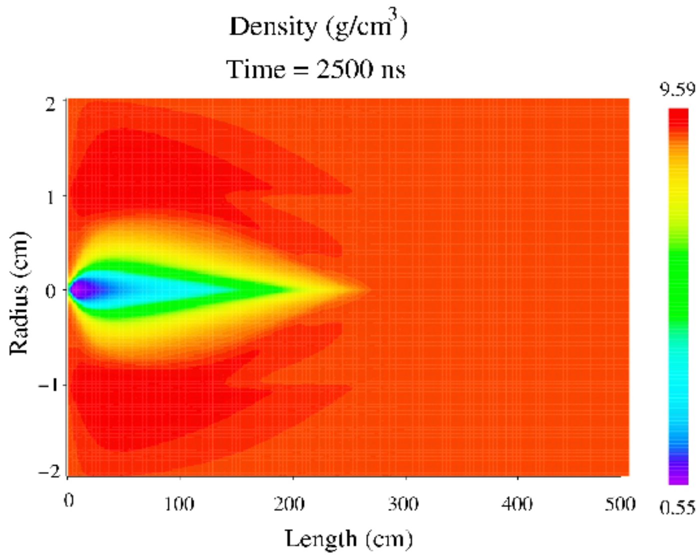
30 GPa

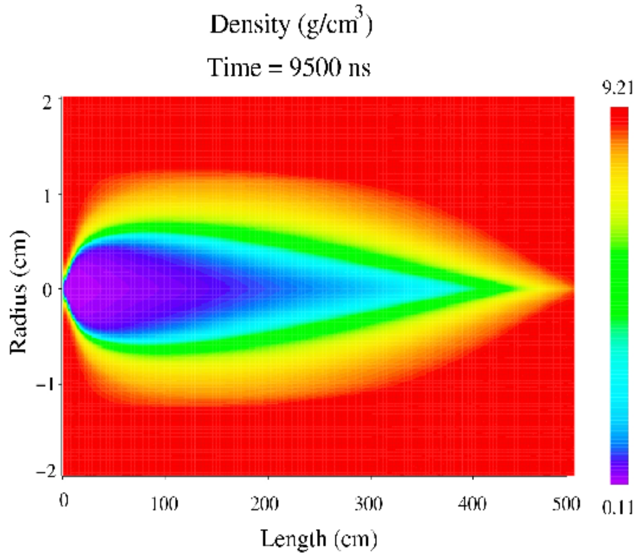


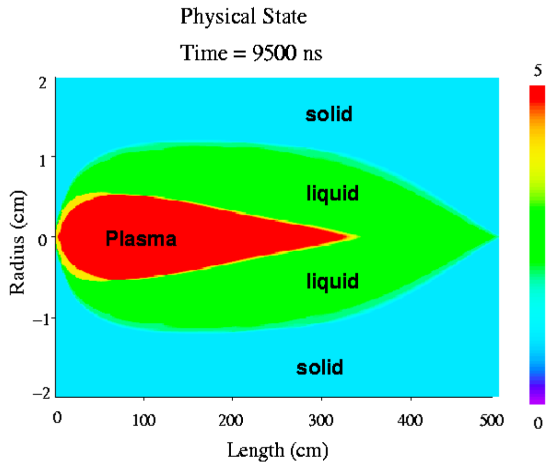
HEDP States

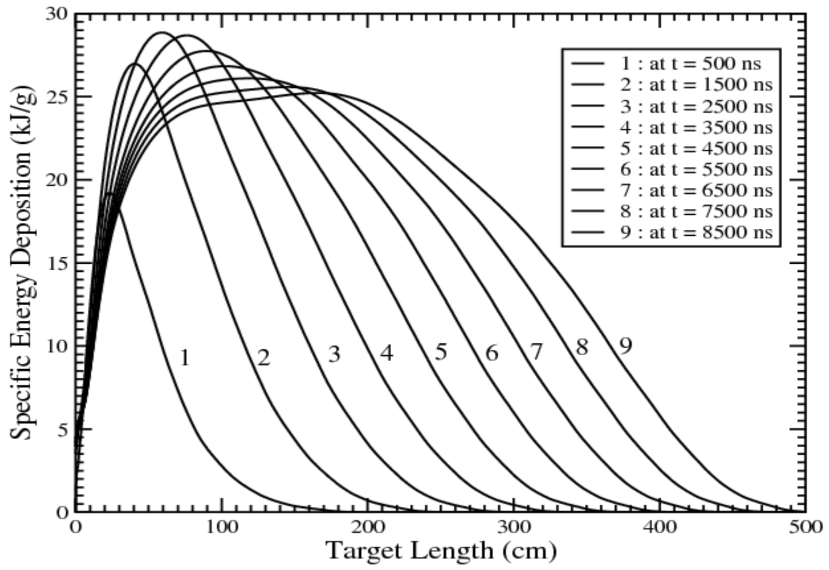

Density (g/cm^3)
Time = 500 ns
Radius (cm)
Length (cm)
9.35
4.04

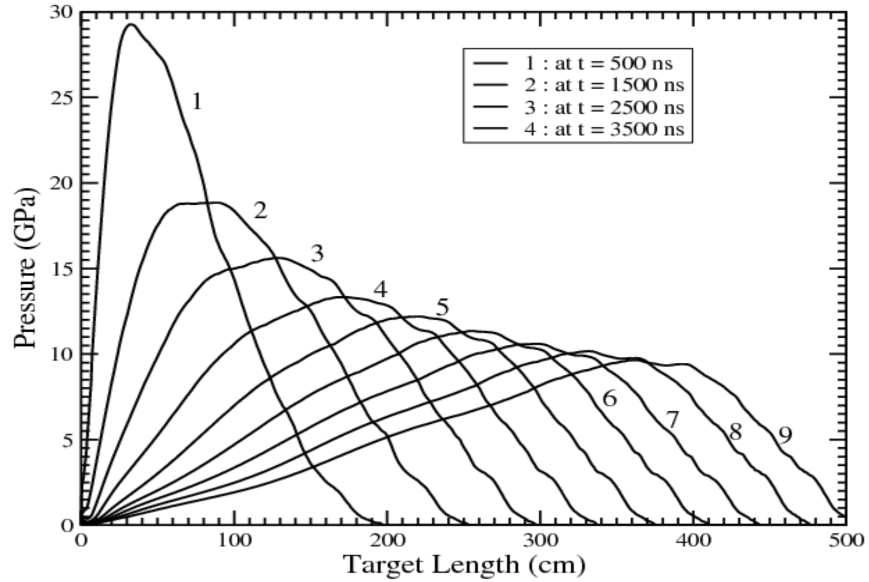

Density (g/cm^3)
Time = 4500 ns
Radius (cm)
Length (cm)
9.43
0.25


Density (g/cm^3)
Time = 2500 ns
Radius (cm)
Length (cm)
9.59
0.55

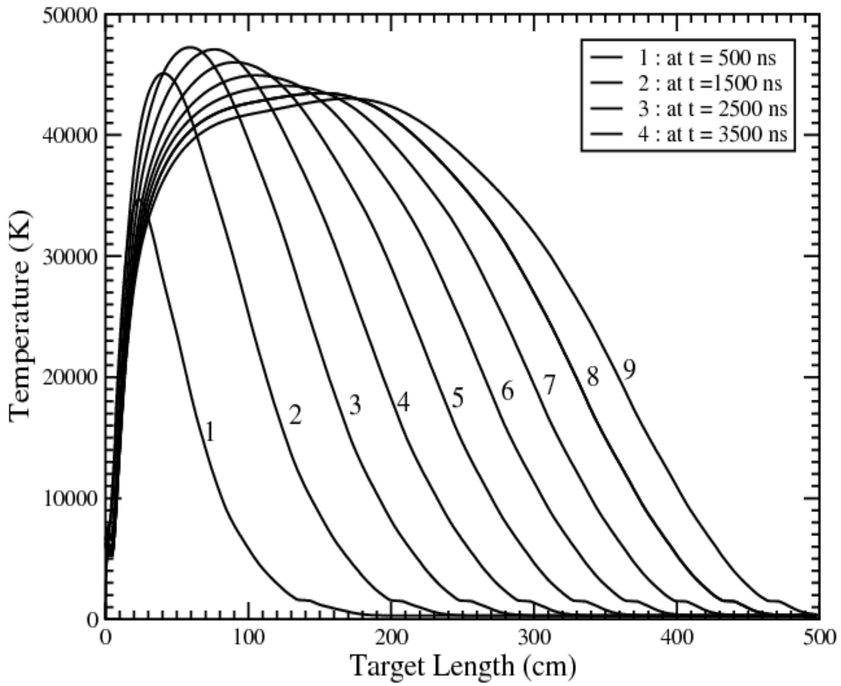

Density (g/cm^3)
Time = 9500 ns
Radius (cm)
Length (cm)
9.21
0.11

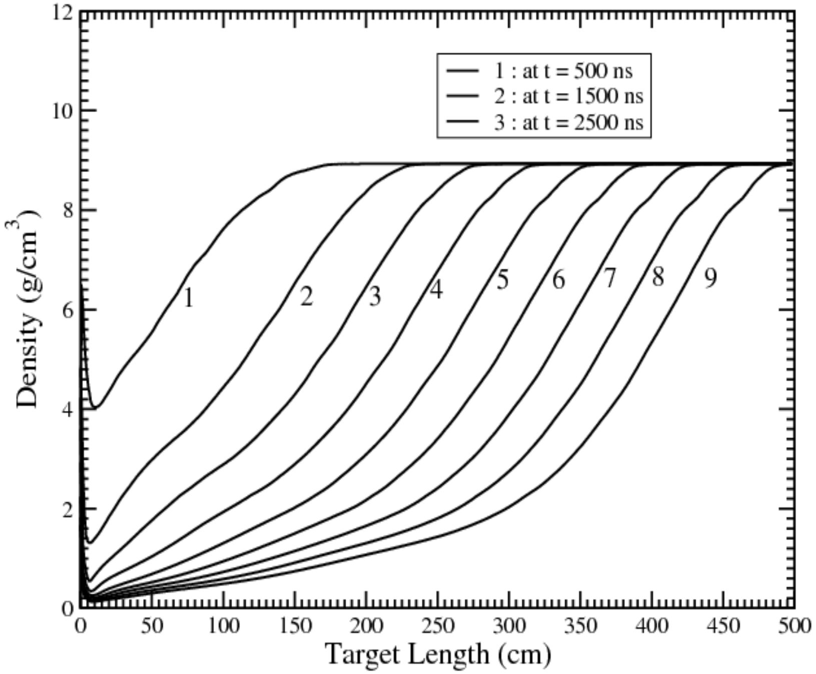

Physical State
Time = 9500 ns
solid
liquid
Plasma
liquid
solid
Radius (cm)
Length (cm)
5
0





0.35 m/μs in 89 μs penetrate 35 m





LHC Beam on Solid Carbon Cylindrical Target

[N.A. Tahir, J. Blanco Sancho et al., PRSTAB 15 (2012) 051003.]

Length = 6 m, Radius = 5 cm

Density = 2.28 g/cm^3

The FLUKA and the BIG2 codes are run iteratively

FLUKA energy loss data at solid density is used as input to BIG2 which is run for 1.5 μs.

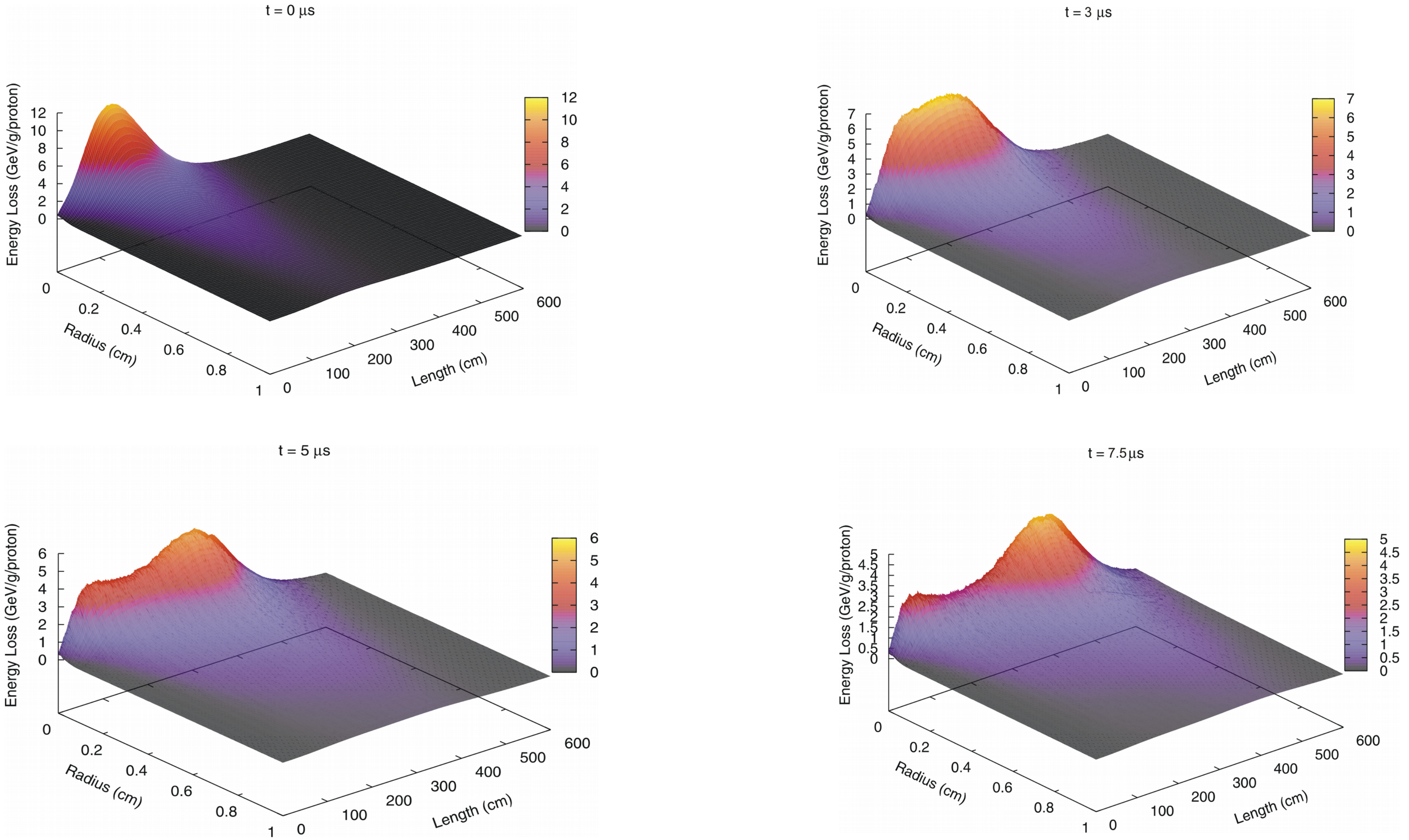
The modified density distribution is used in FLUKA to calculate energy loss corresponding to this new density distribution.

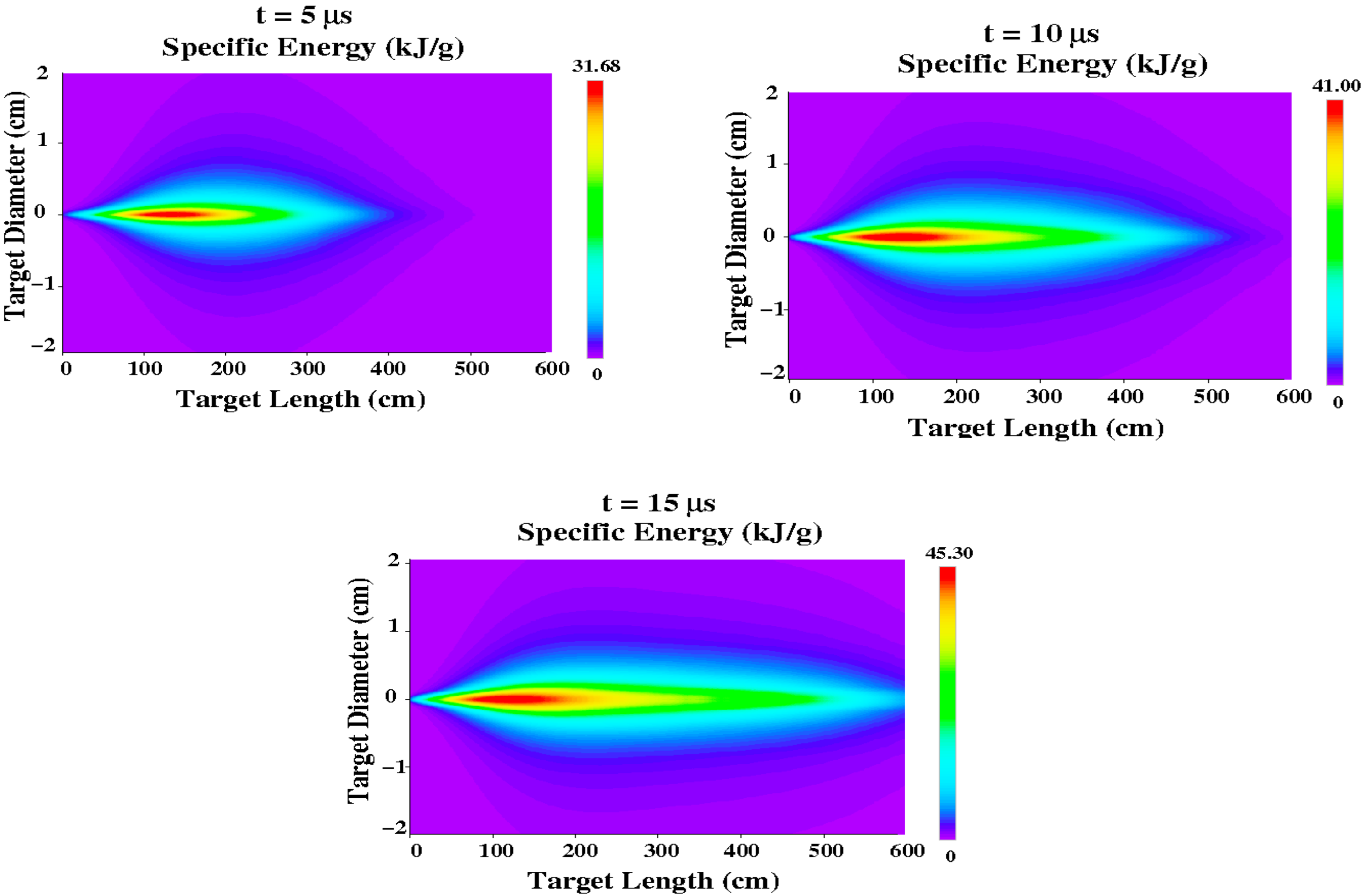
The new energy loss distribution is used in BIG2 which is run for another 1.5 μs.

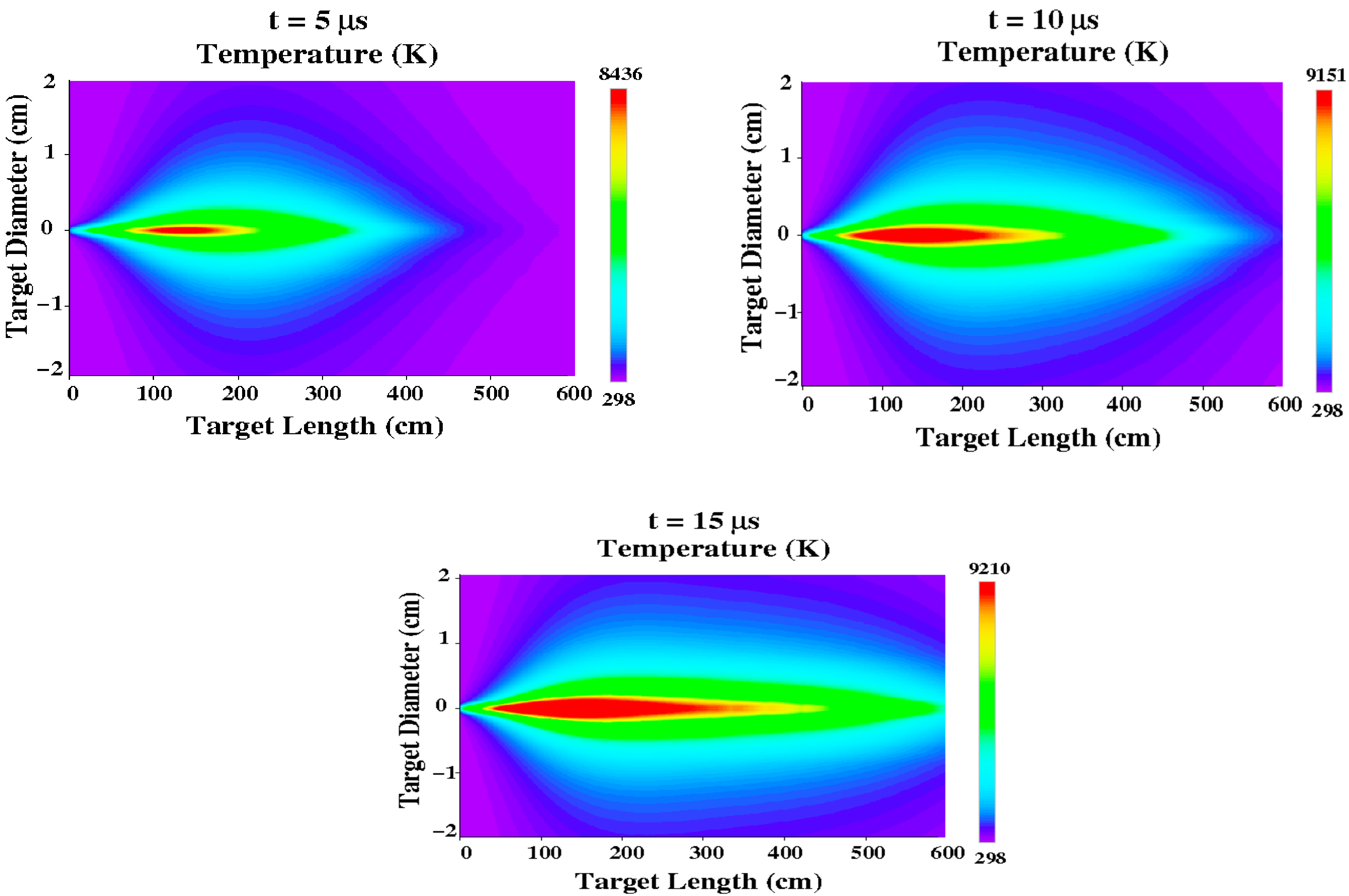
The next iteration step is 2.0 μs.

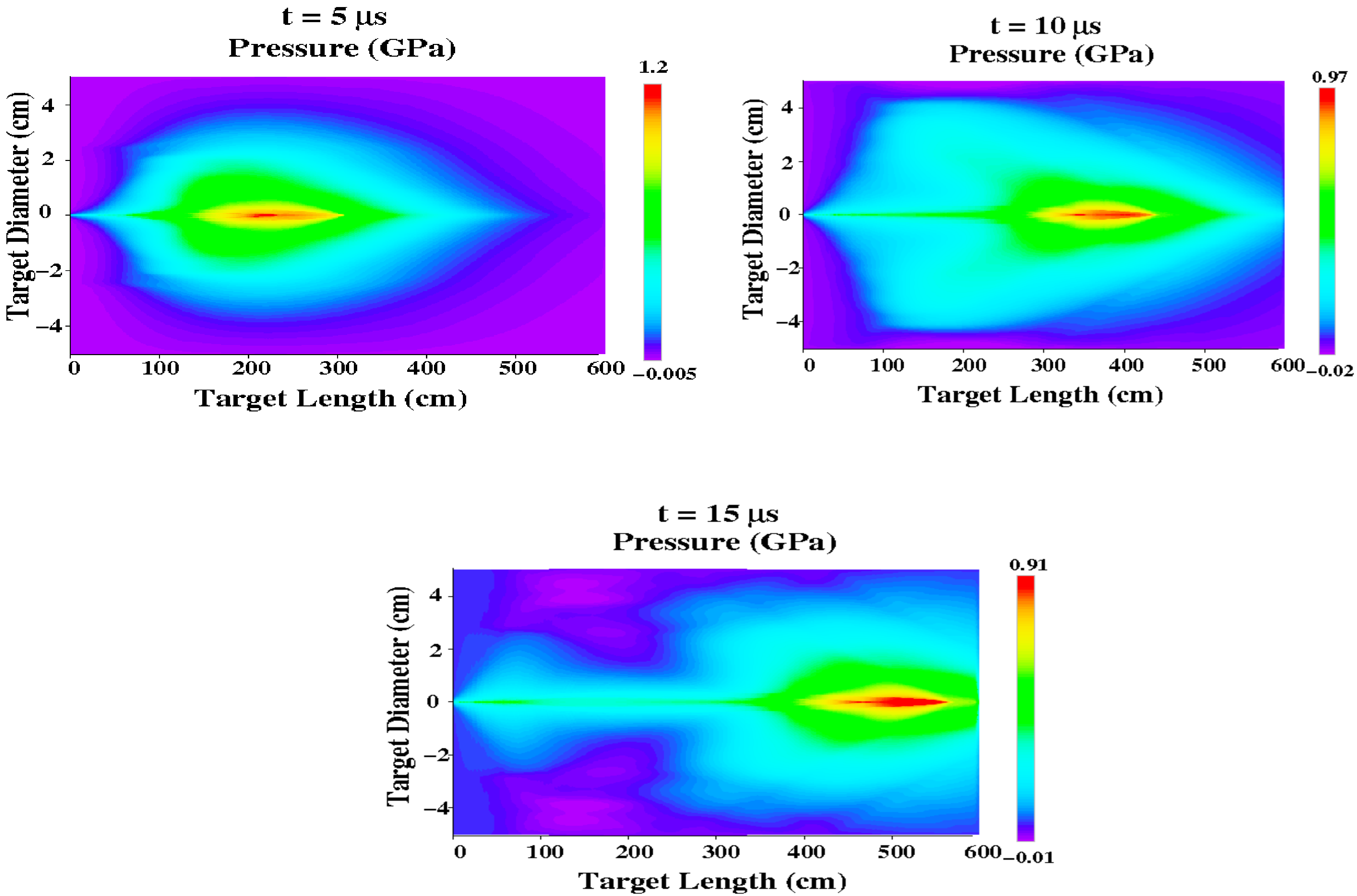
At 5 μs and after, we use an iteration step of 2.5 μs.

Iteratively Calculated Energy Loss Using FLUKA [σ = 0.5mm]

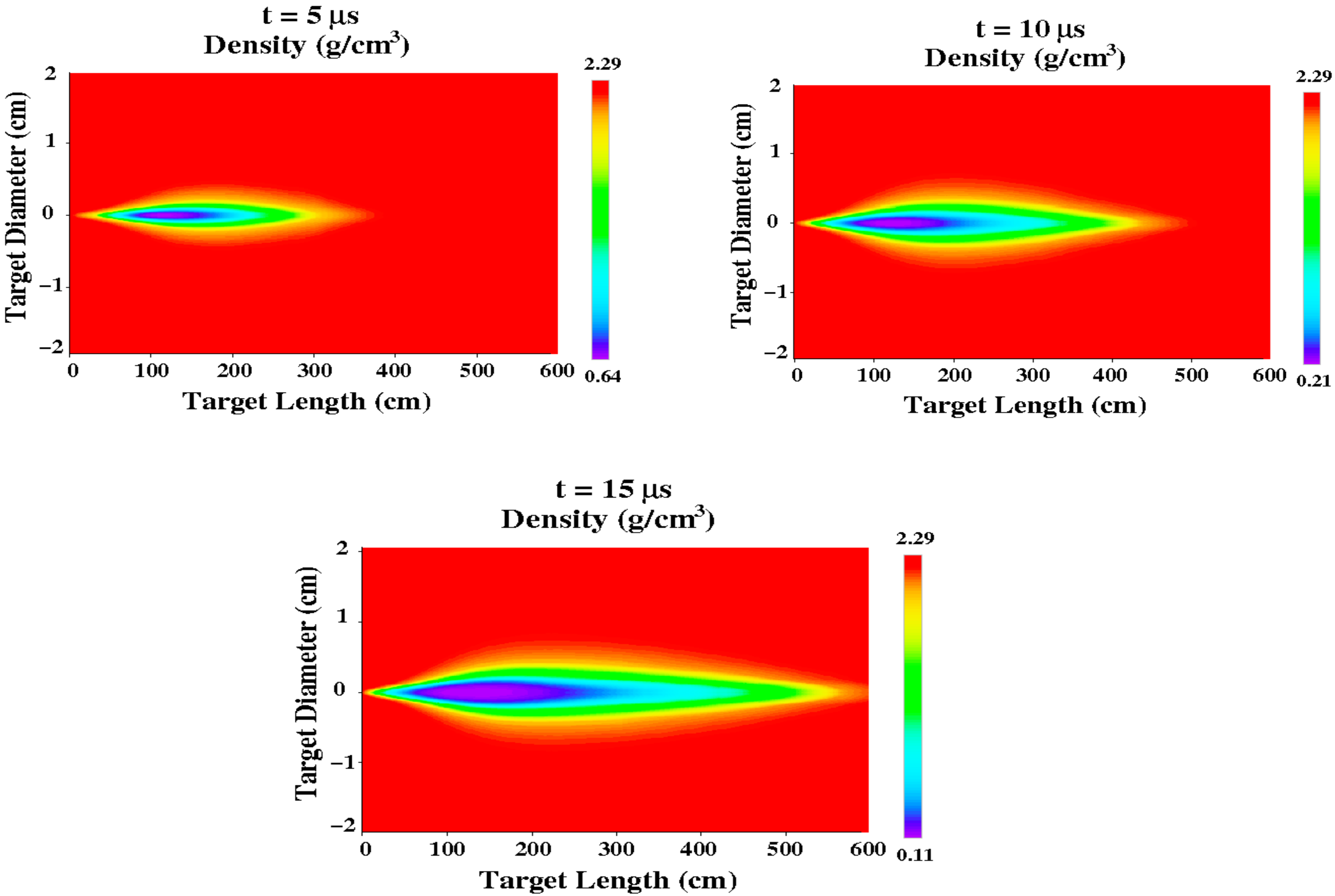


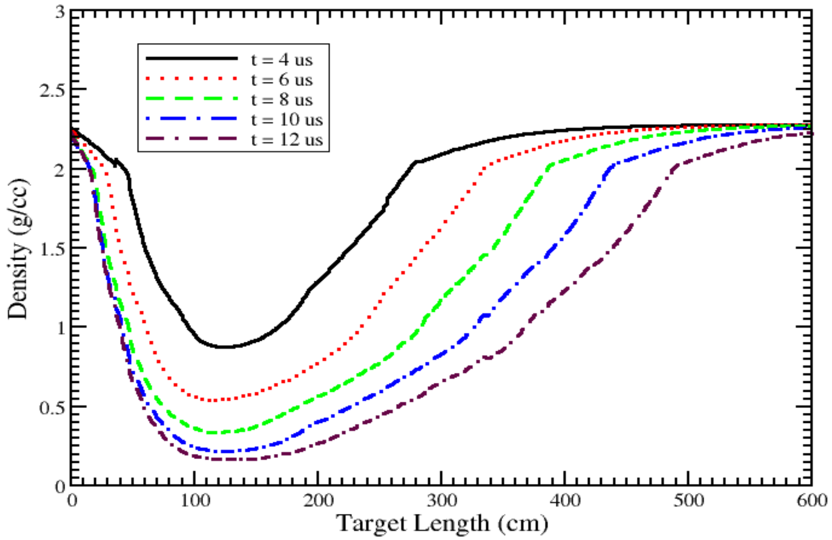

t = 5 μs
Specific Energy (kJ/g)
31.68
0
Target Diameter (cm)
2
1
0
−1
−2
0
100
200
300
400
500
600
Target Length (cm)
t = 10 μs
Specific Energy (kJ/g)
41.00
0
Target Diameter (cm)
Target Length (cm)
t = 15 μs
Specific Energy (kJ/g)
45.30
0
Target Diameter (cm)
Target Length (cm)

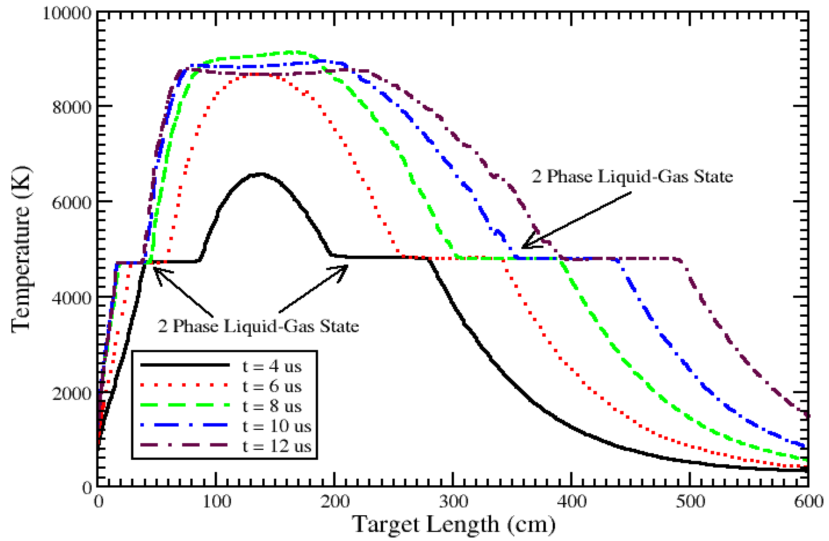

t = 5 μs
Temperature (K)
8436
298
Target Diameter (cm)
Target Length (cm)
t = 10 μs
Temperature (K)
9151
298
Target Diameter (cm)
Target Length (cm)
t = 15 μs
Temperature (K)
9210
298
Target Diameter (cm)
Target Length (cm)



t = 5 μs
Pressure (GPa)
1.2
−0.005
Target Diameter (cm)
Target Length (cm)
t = 10 μs
Pressure (GPa)
0.97
−0.02
Target Diameter (cm)
Target Length (cm)
t = 15 μs
Pressure (GPa)
0.91
−0.01
Target Diameter (cm)
Target Length (cm)


t = 5 μs
Density (g/cm3)
2.29
0.64
2
1
0
−1
−2
0
100
200
300
400
500
600
Target Diameter (cm)
Target Length (cm)
t = 10 μs
Density (g/cm3)
2.29
0.21
2
1
0
−1
−2
0
100
200
300
400
500
600
Target Diameter (cm)
Target Length (cm)
t = 15 μs
Density (g/cm3)
2.29
0.11
2
1
0
−1
−2
0
100
200
300
400
500
600
Target Diameter (cm)
Target Length (cm)



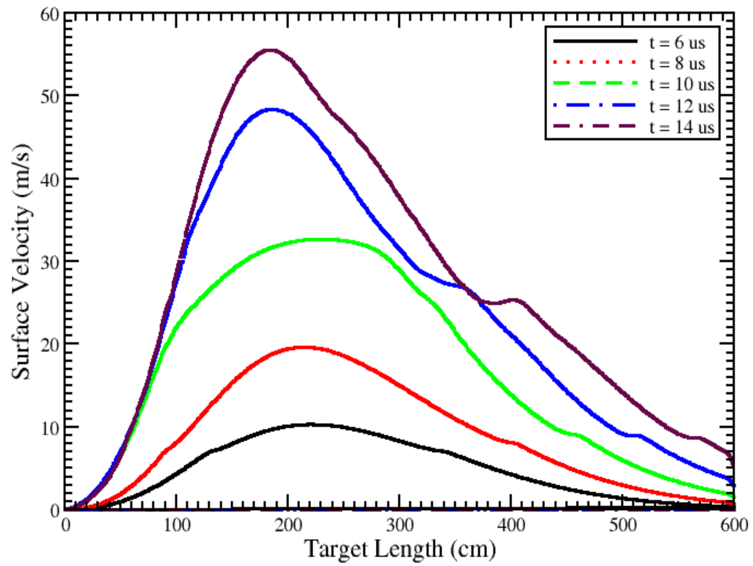


At t = 6 μs, the beam heated region is about 4 m.

The depletion front moves with a constant speed of 0.25 m / μs.

Distance penetrated in 83 μs = 0.25 x 83 μs = 20.75 m.

Total penetration in 89 μs = 4.0 m + 20.75 m = 25 m !!



Ref: R. Schmidt, J. Blanco Sancho, F. Burkart, D. Grenier, D. Wollmann, N.A. Tahir, A. Shutov and A.R. Piriz, Phys. Plasmas 21 (2014) 080701.

Super Proton Synchrotron Beam Parameter

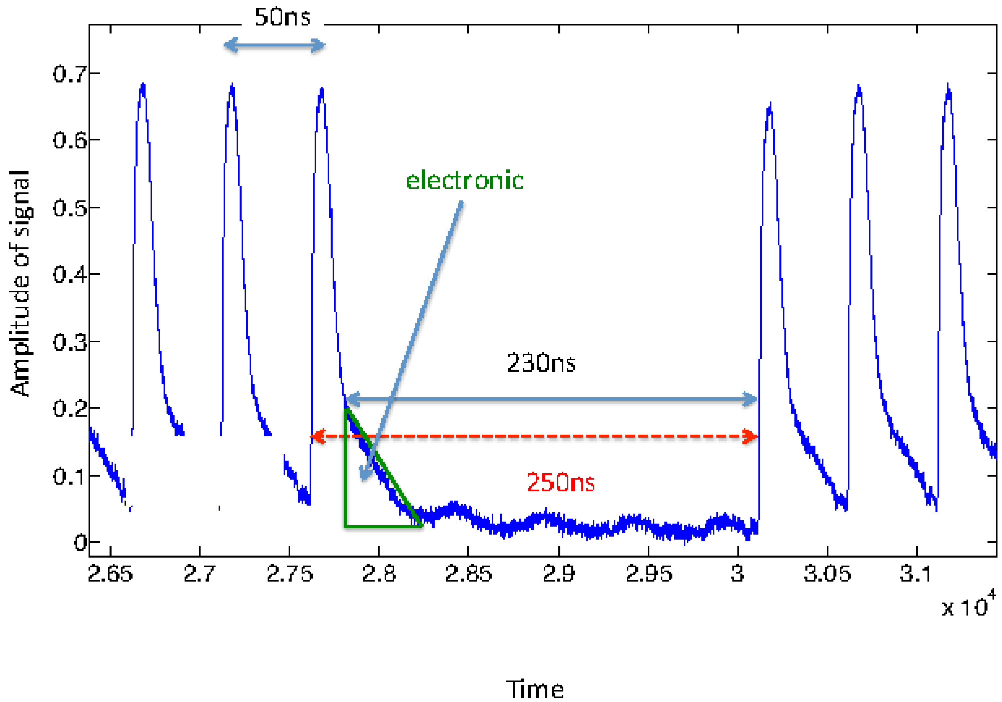
440 GeV protons

Bunch length : 0.5 ns

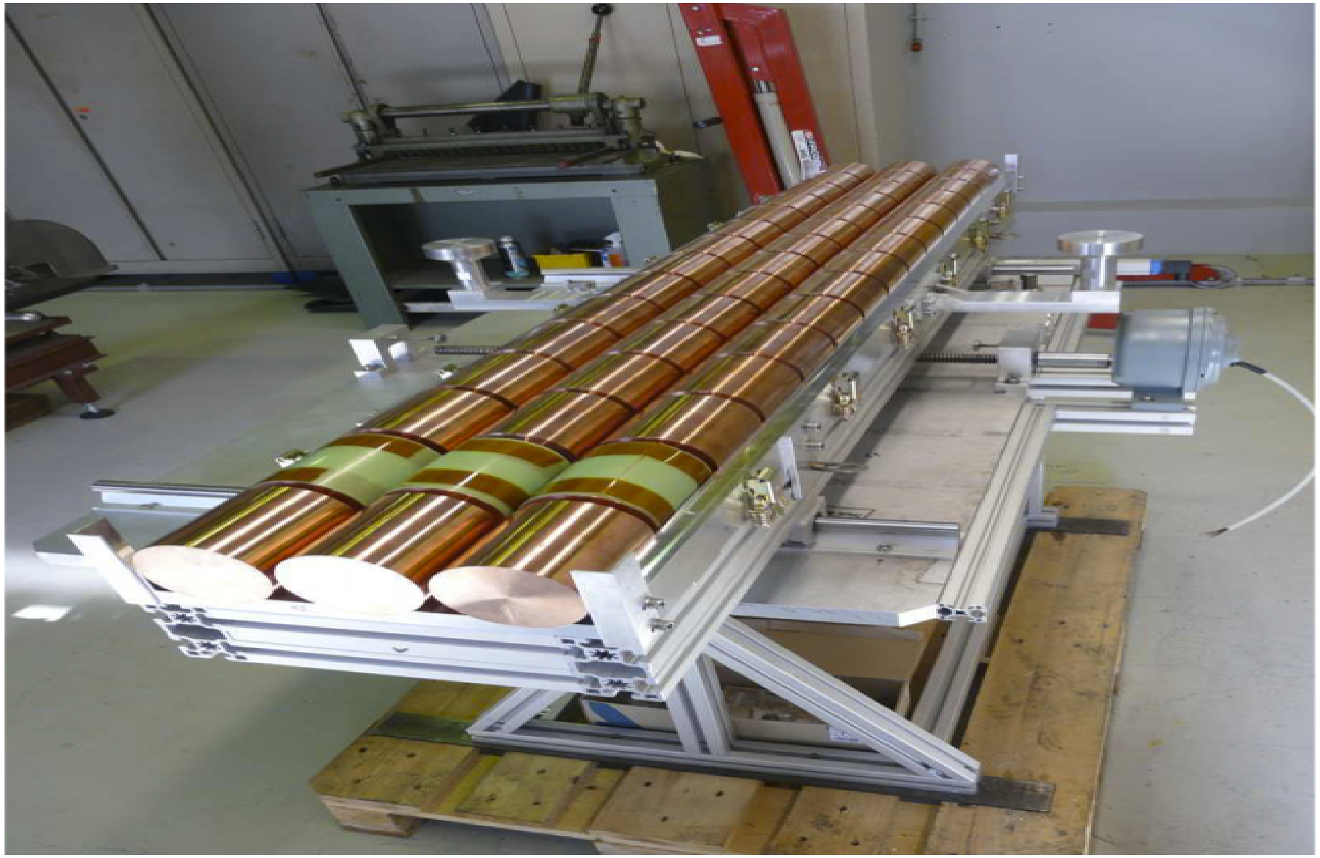
Bunch Separation: 50 ns

Bunch Intensity : 1.5×10^{11}

σ : 0.2 mm



Packets of 36 Bunches and Gap of 250 ns

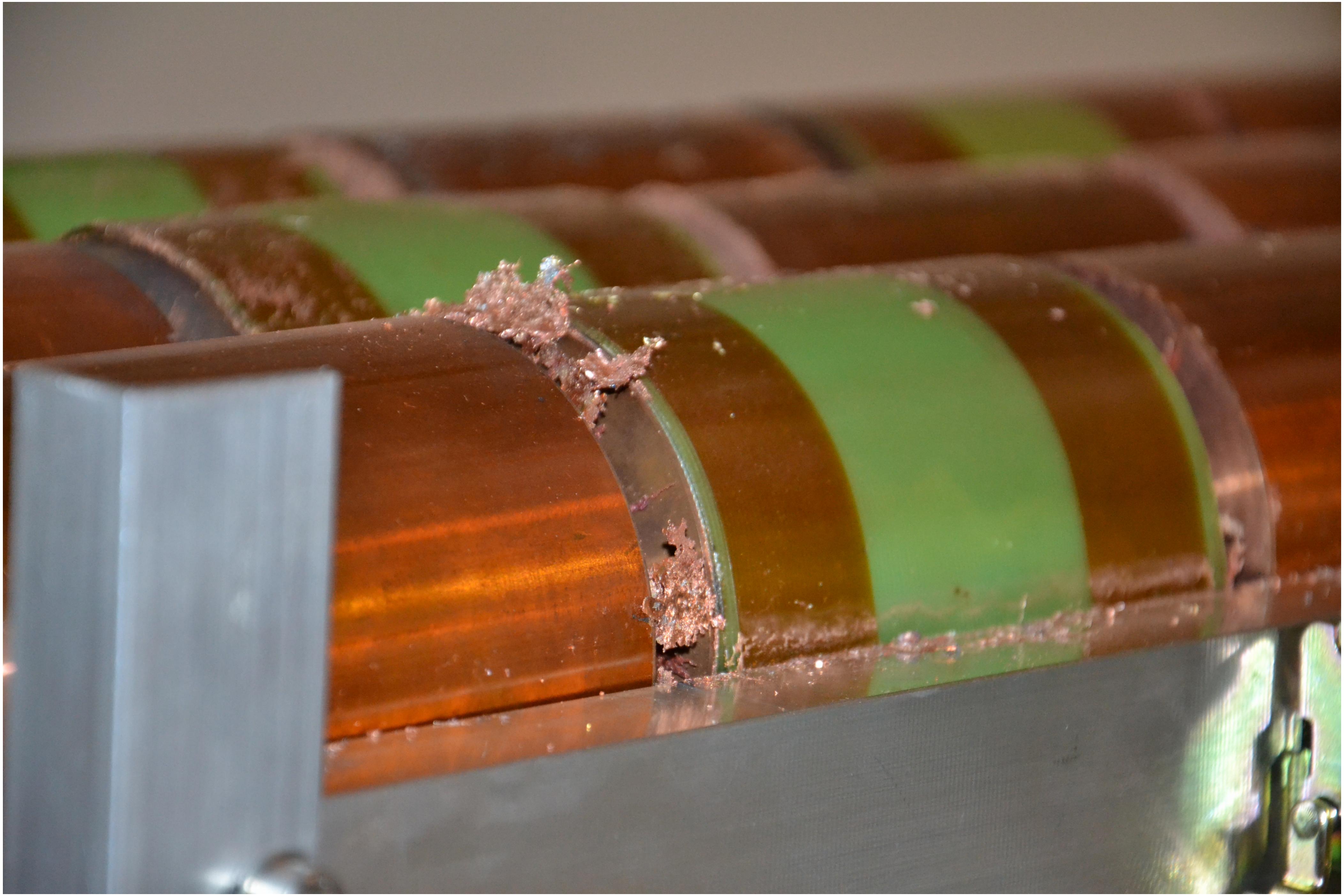


Three sets of targets
Each comprises of 15 solid Cu cylinders L = 10 cm, r = 4 cm.
Gap of 1 cm between between neighboring cylinders
Al cover on on the top
Al caps around first & last cylinder
to avoid contamination

1. **First target is irradiated with 144 bunches with beam σ = 2 mm.**

2. **Second target is irradiated with 108 bunches with beam σ = 0.2 mm.**

3. **Third target is irradiated with 144 bunches with beam σ = 0.2 mm.**



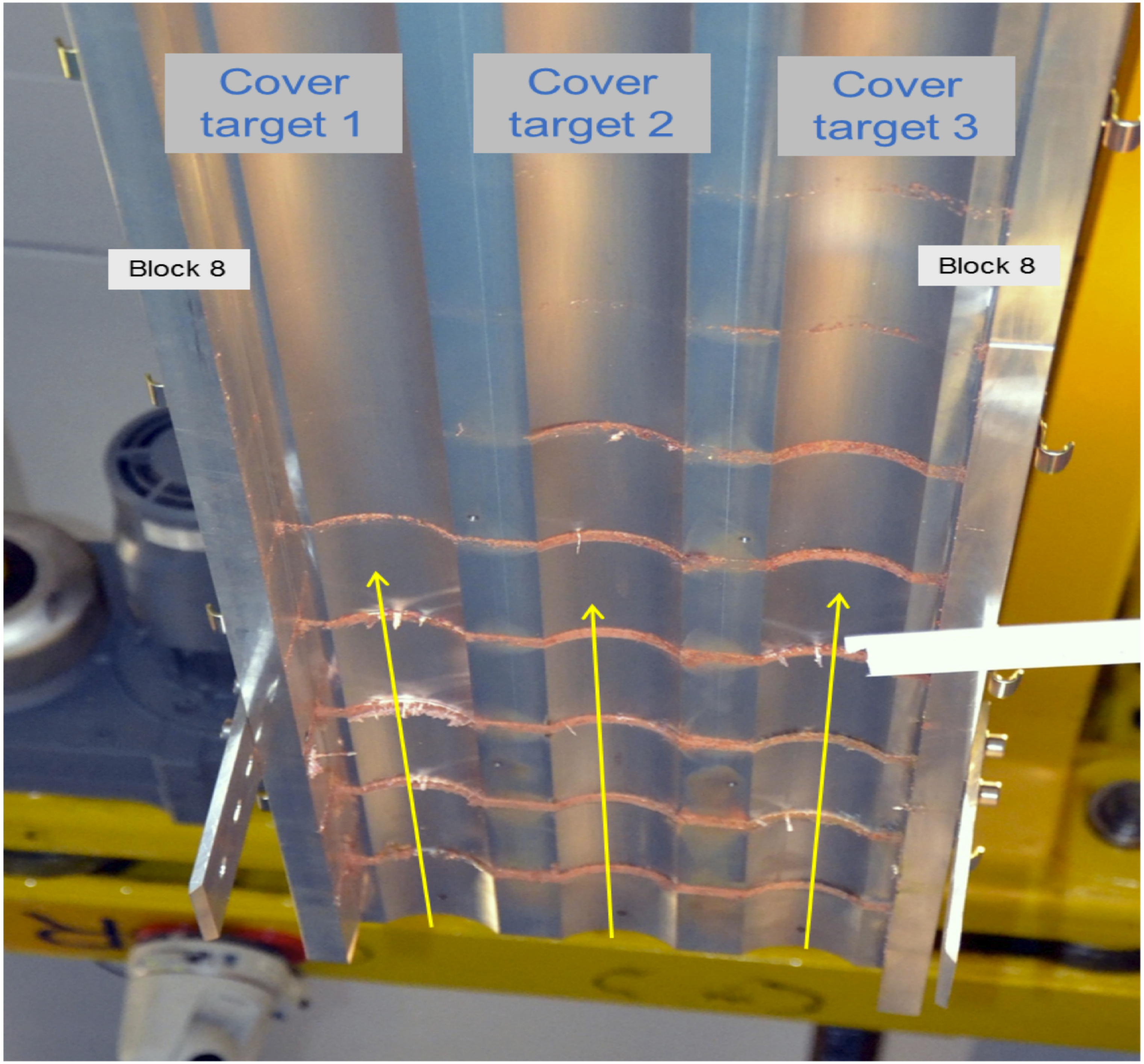

Cover target 1
Cover target 2
Cover target 3
Block 8
Block 8

Table 1: Beam Parameters

Expt	$N_{bunches}$	σ (mm)	E_b(MJ)
1	144	2.0	1.52
2	108	0.2	1.14
3	144	0.2	1.52

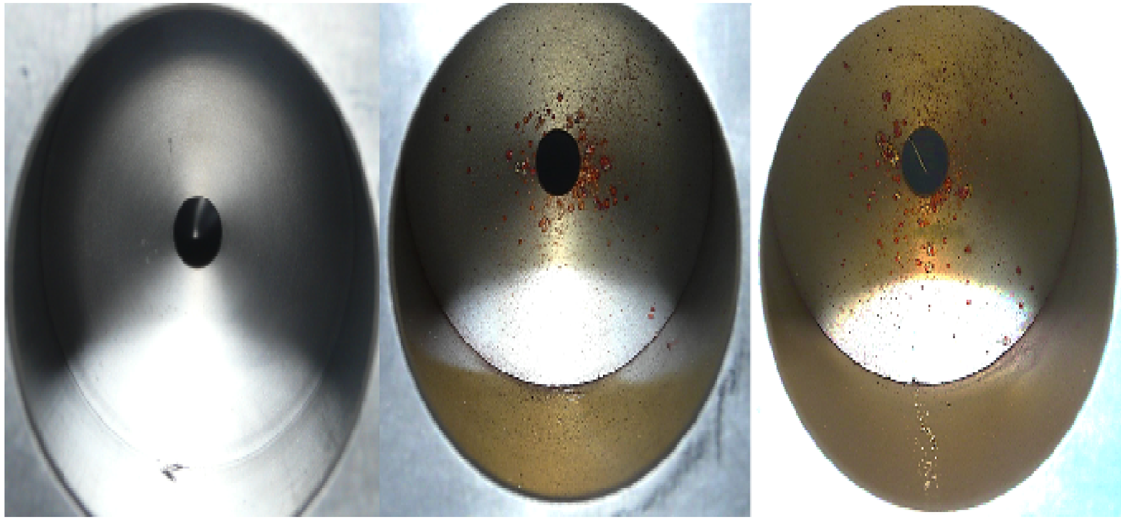
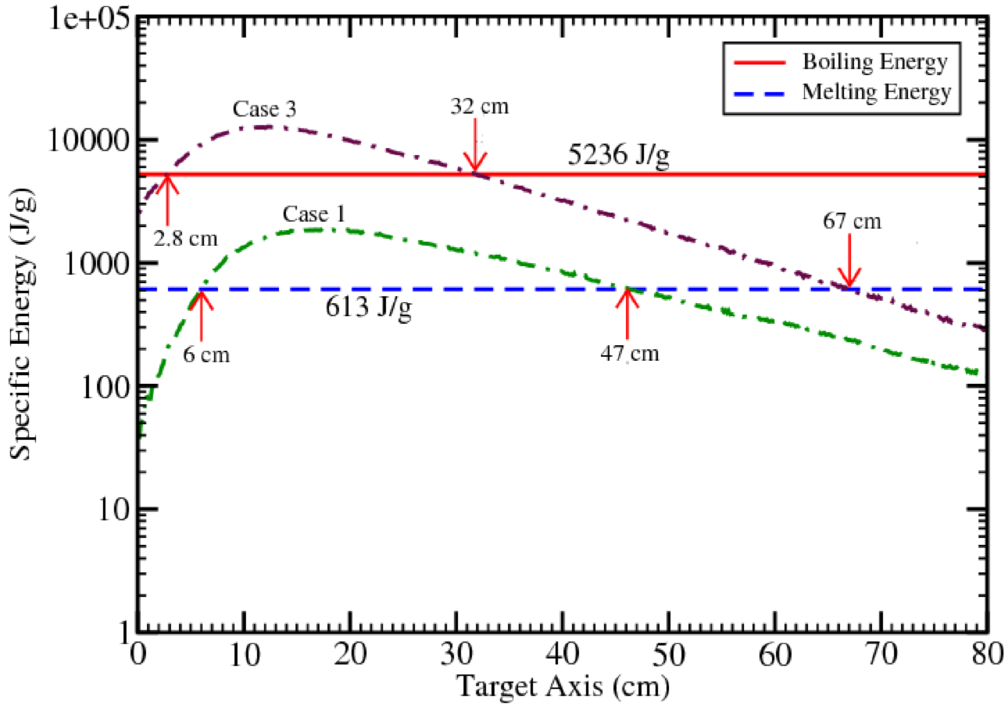


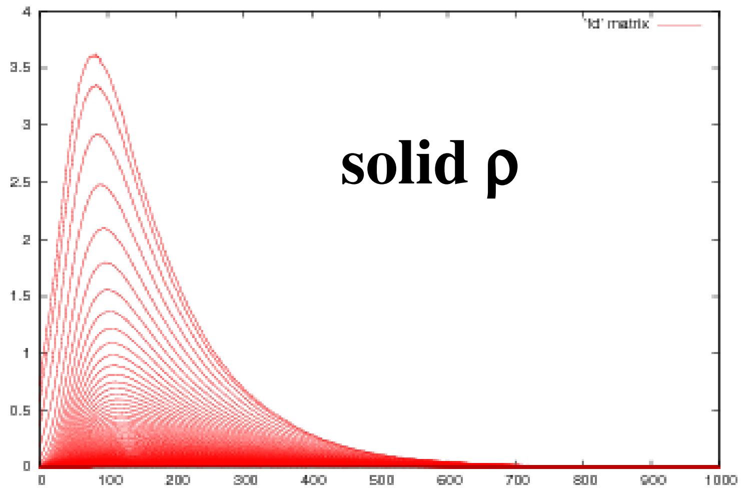
Table 2: Summary of Results

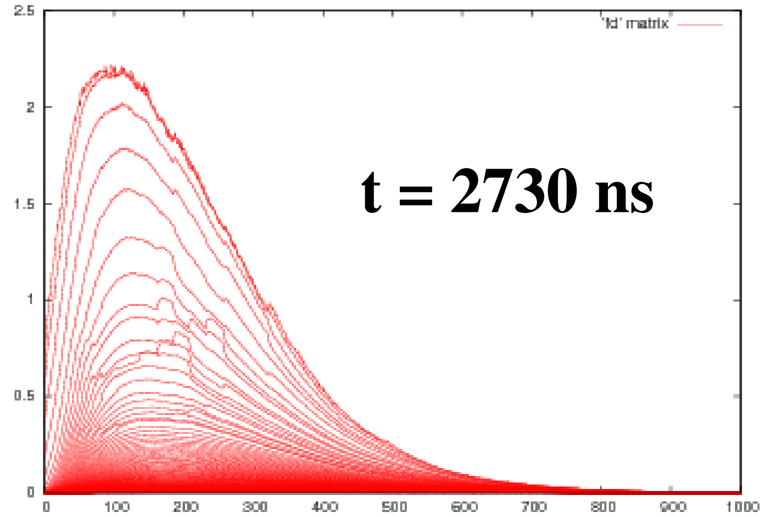
Expt	Static Simulations (cm)	Measured (cm)	Δ (cm)
1	47	55 ± 5	8± 5
2	64	75 ± 5	11± 5
3	67	85 ± 5	18± 5

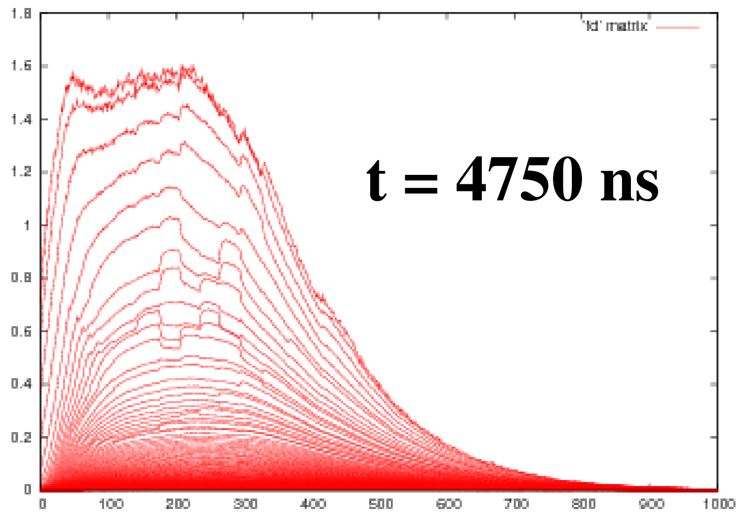


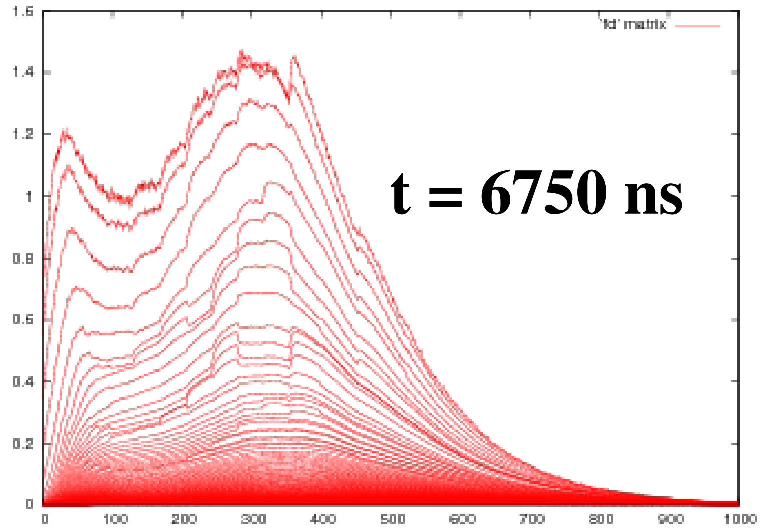
Simulations have been carried out to understand the experimental measurements

FLUKA and BIG2 are run iteratively using an iteration period of 700 ns

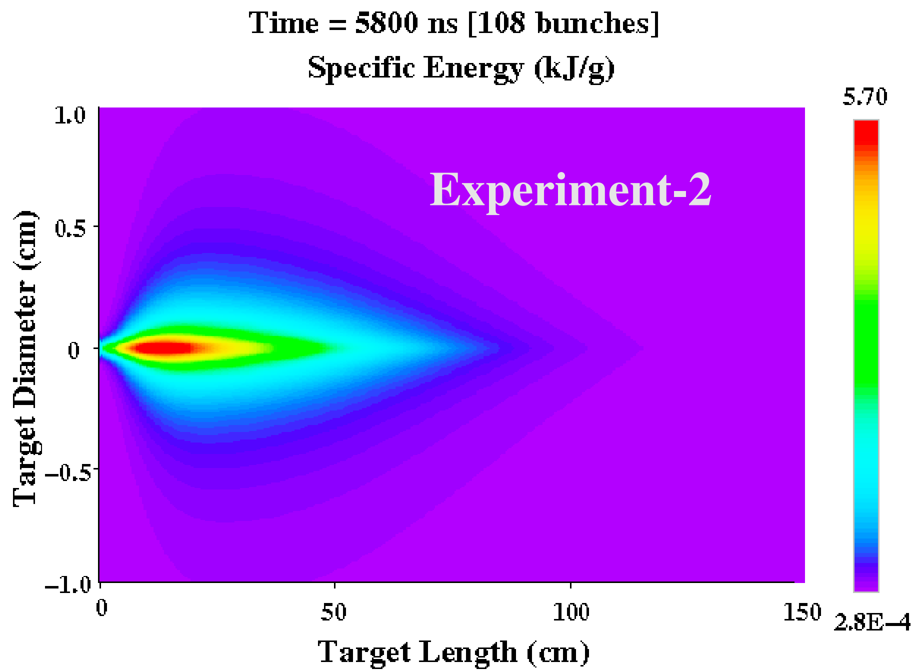


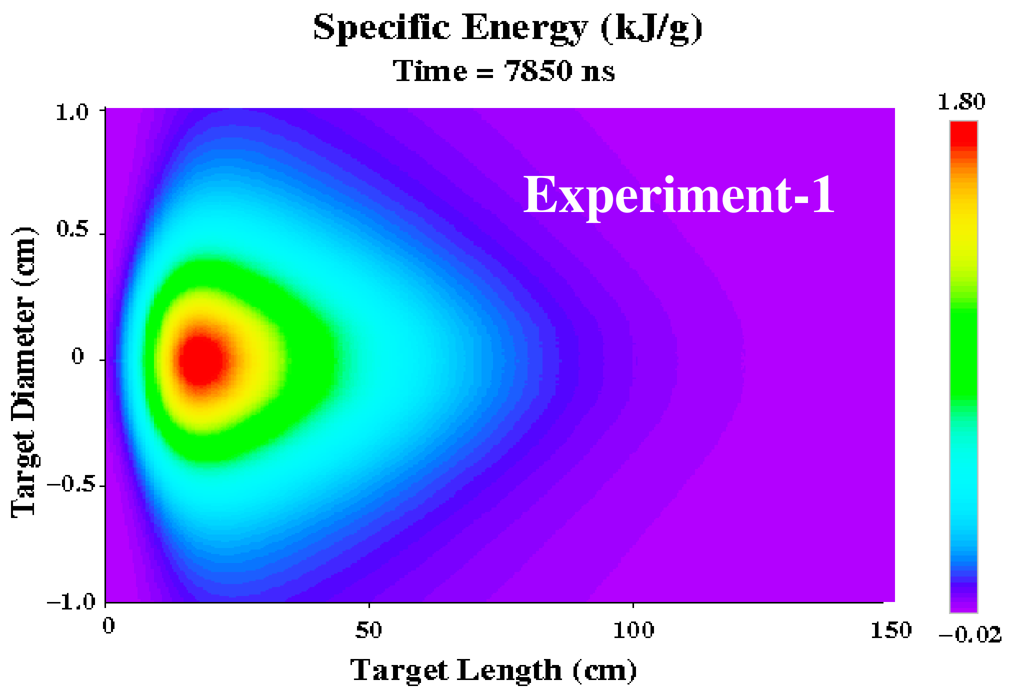


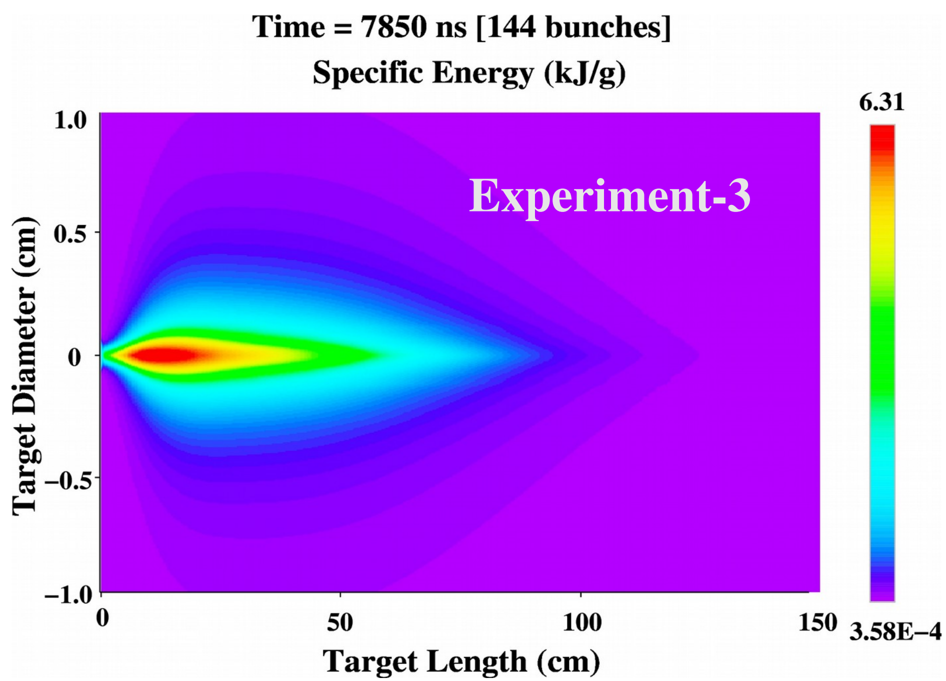




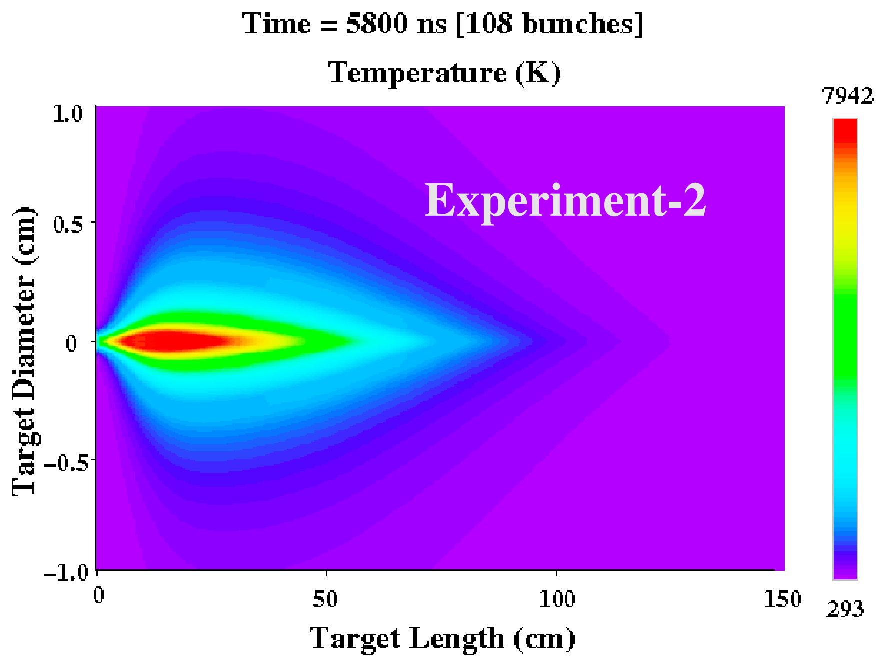
Specific Energy Deposition

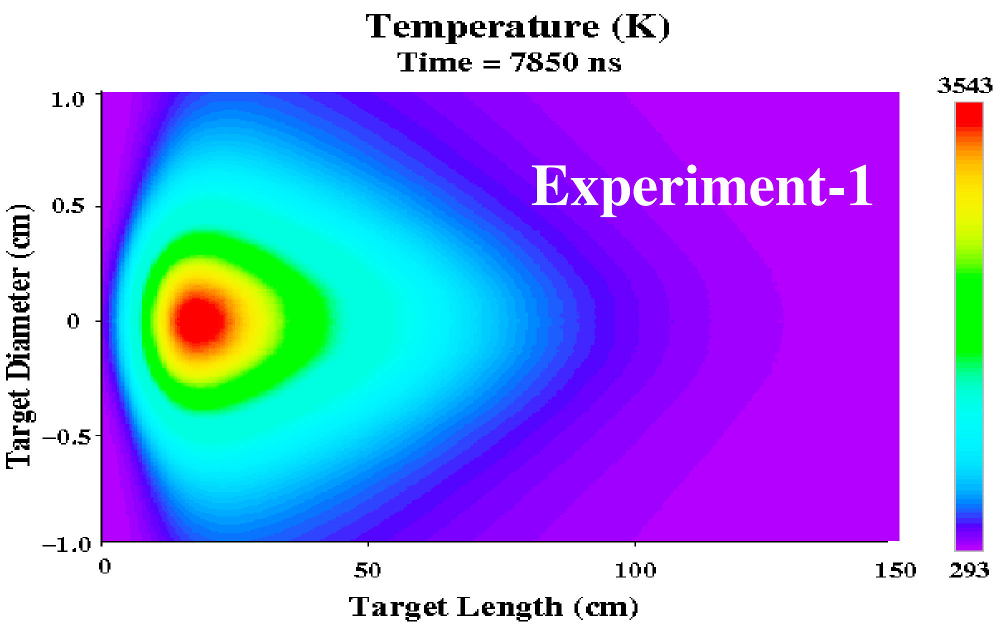


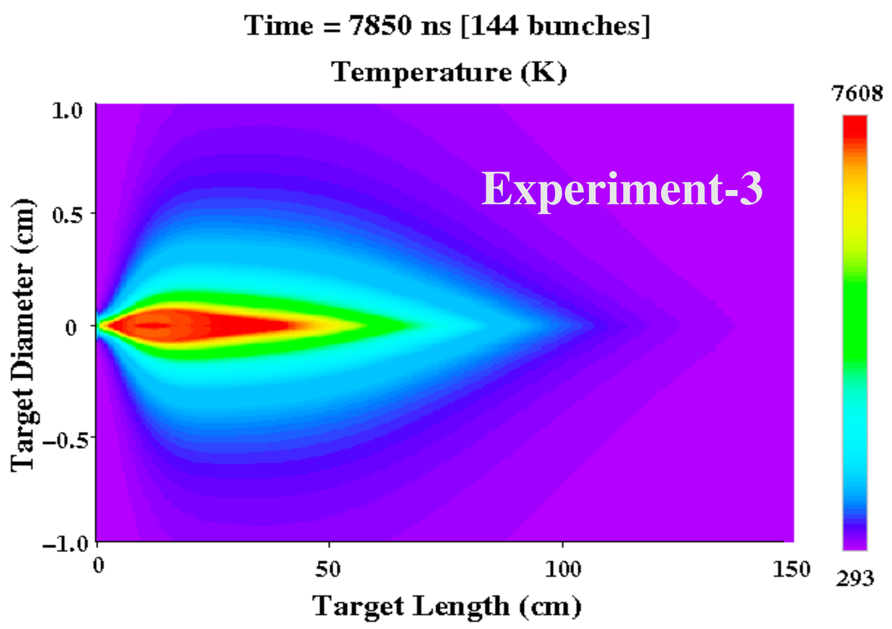




Temperature

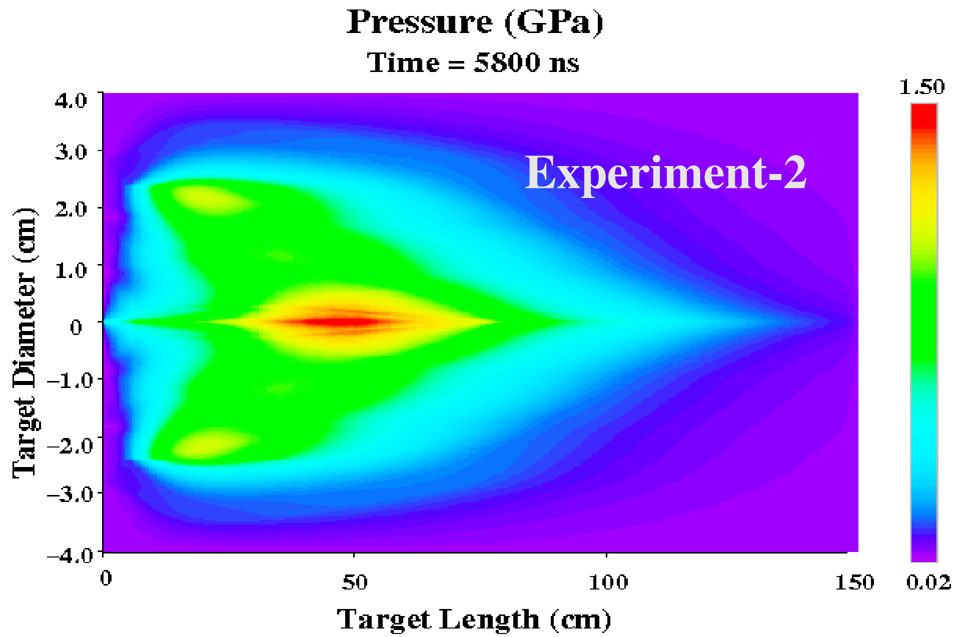


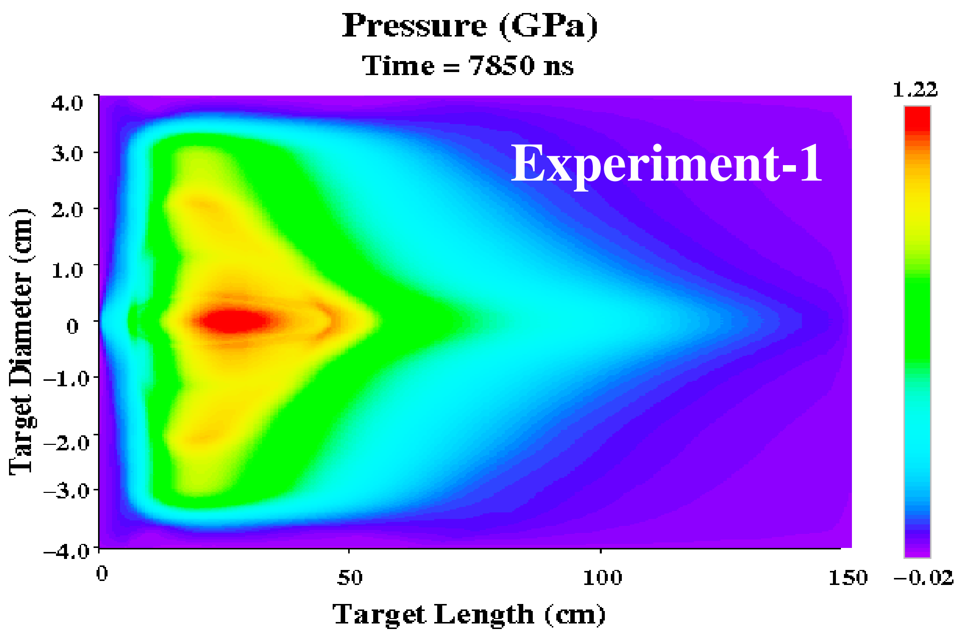




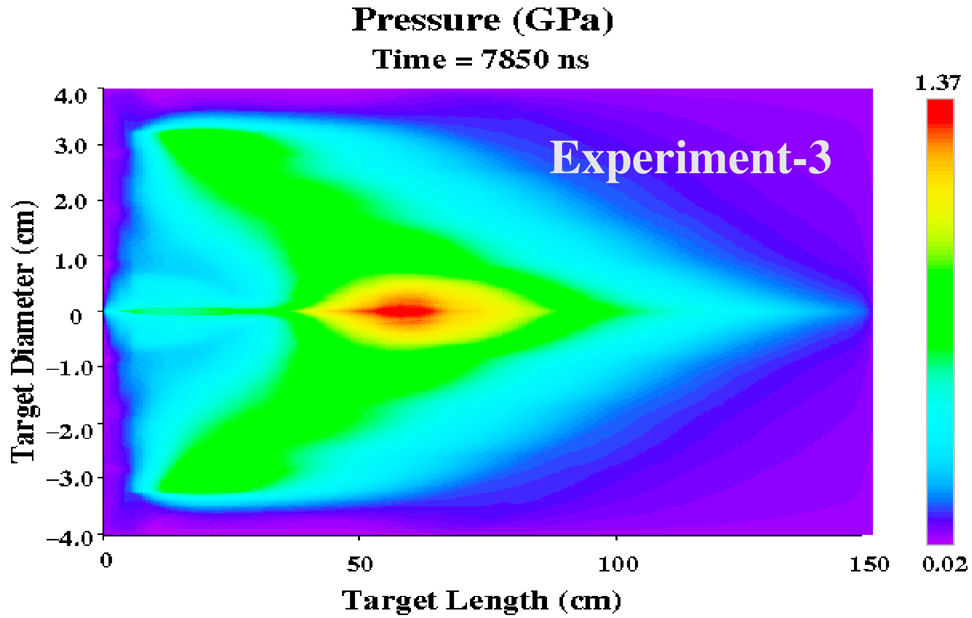
Pressure

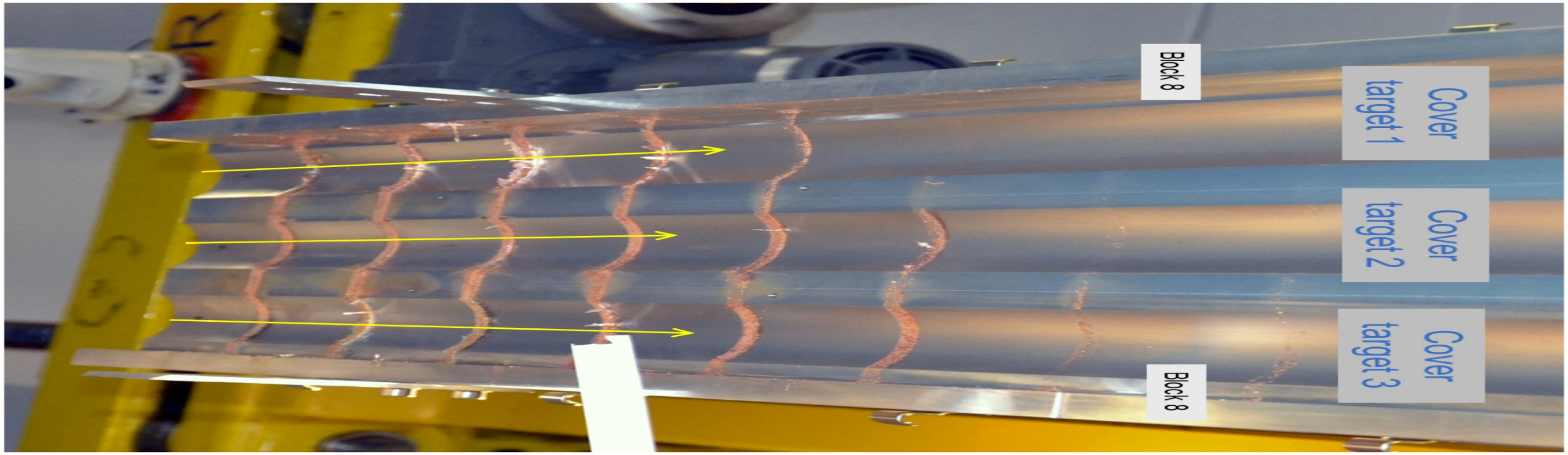
Time = 5800 ns [108 bunches]

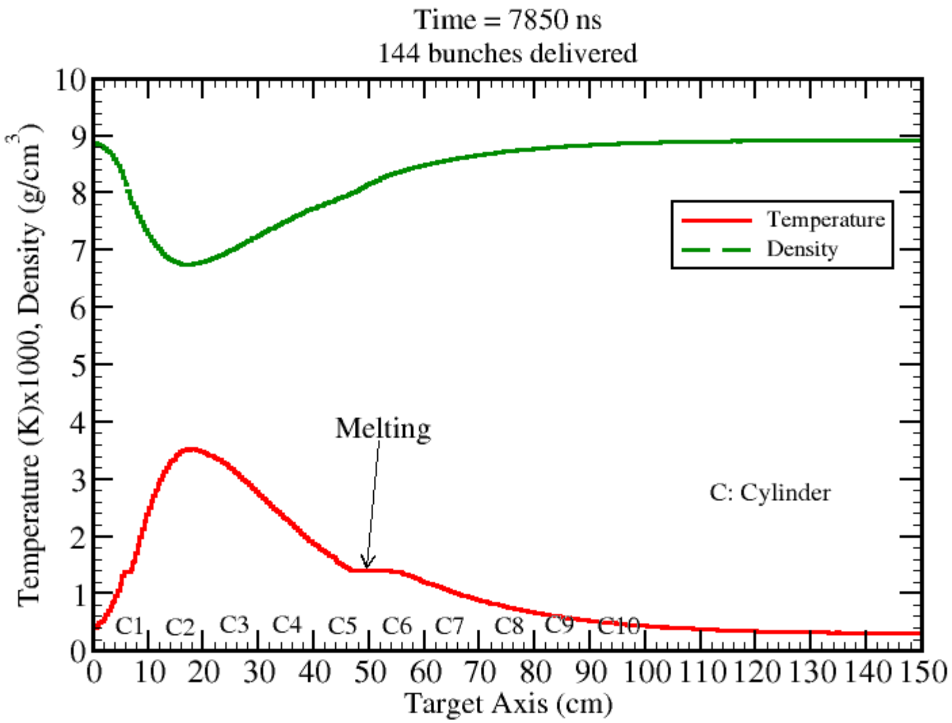


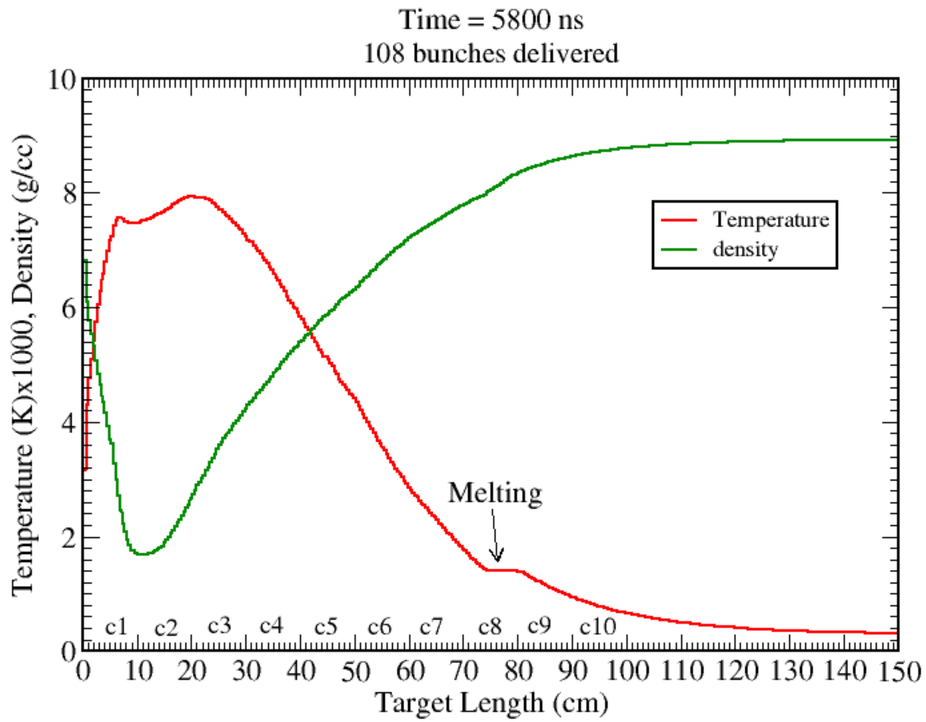


Time = 7850 ns [144 bunches]




Block 8
Cover target 1
Cover target 2
Cover target 3
Block 8


Time = 7850 ns
144 bunches delivered
Temperature
Density
Melting
C: Cylinder
C1 C2 C3 C4 C5 C6 C7 C8 C9 C10
Temperature (K)x1000, Density (g/cm³)
Target Axis (cm)


Time = 5800 ns
108 bunches delivered
Temperature
density
Melting
c1 c2 c3 c4 c5 c6 c7 c8 c9 c10
Temperature (K)x1000, Density (g/cc)
Target Length (cm)

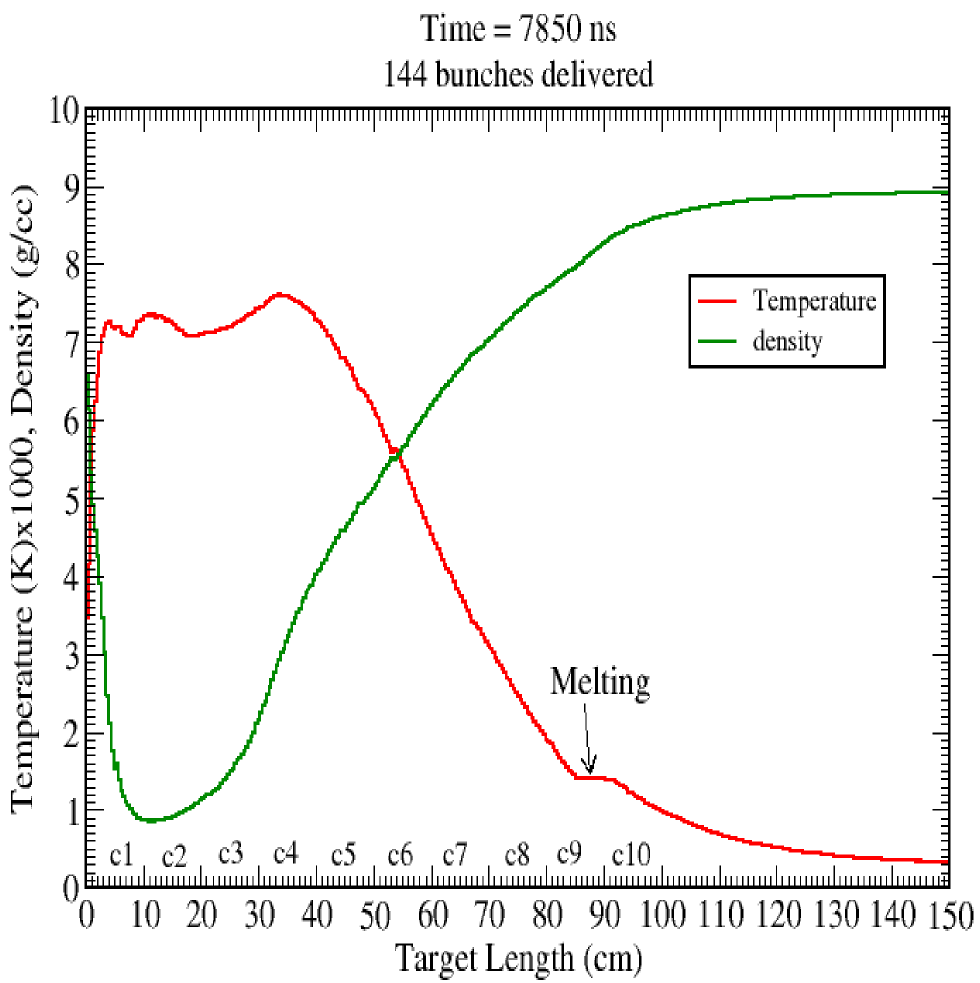
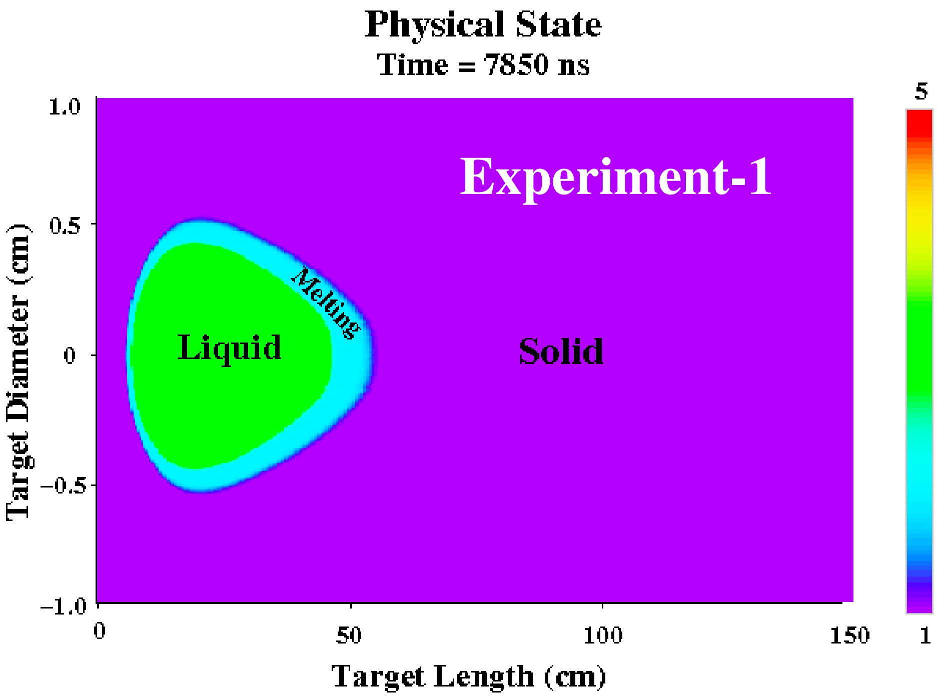
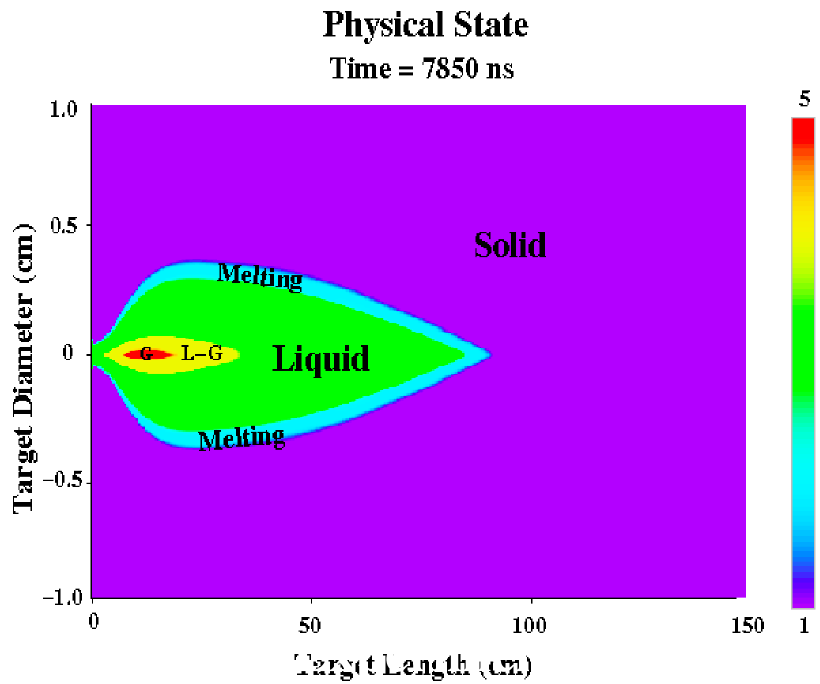


Table 3: Comparison

Expt.	Measured (cm)	Hydro Siml. (cm)
1	55±5	55
2	75±5	75
3	85±5	85

Generation of Warm Dense Matter





1. N.A. Tahir, F. Burkart, R. Schmidt et al., PRE 90 (2014) 063112.

2. N.A. Tahir, F. Burkart, R. Schmidt et al., HEDP 21 (2016) 27.

Finally the targets were declared safe for physical handling and the cylinders were dissected in order to determine the penetration length of the protons and their hadronic shower more precisely.

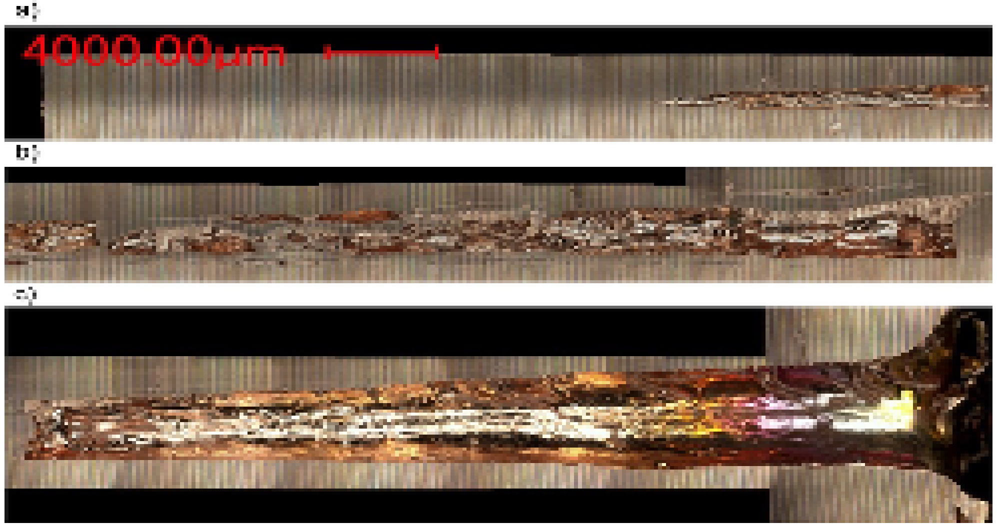
An overview of this work is presented in this talk while the details are reported in:

Ref.: ***F. Burkart, R. Schmidt, V.Raginel, D. Wollmann, N.A. Tahir, A. Shutov and A.R. Piriz, J. Appl. Phys. 118 (2015) 055902.***

Experiment-3

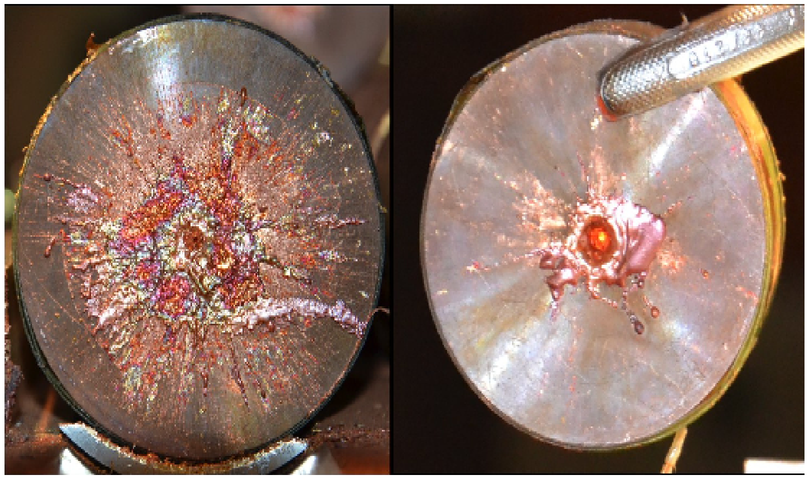
Front Face (left)   Rear Face (right)

Cylinder 1



Cylinder 3

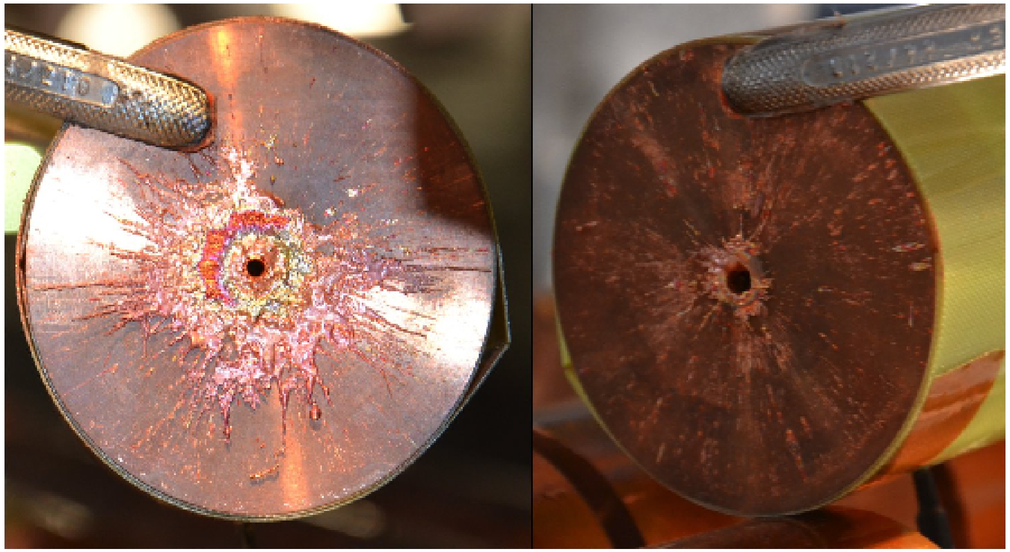
Cylinder 2



Cylinder 4

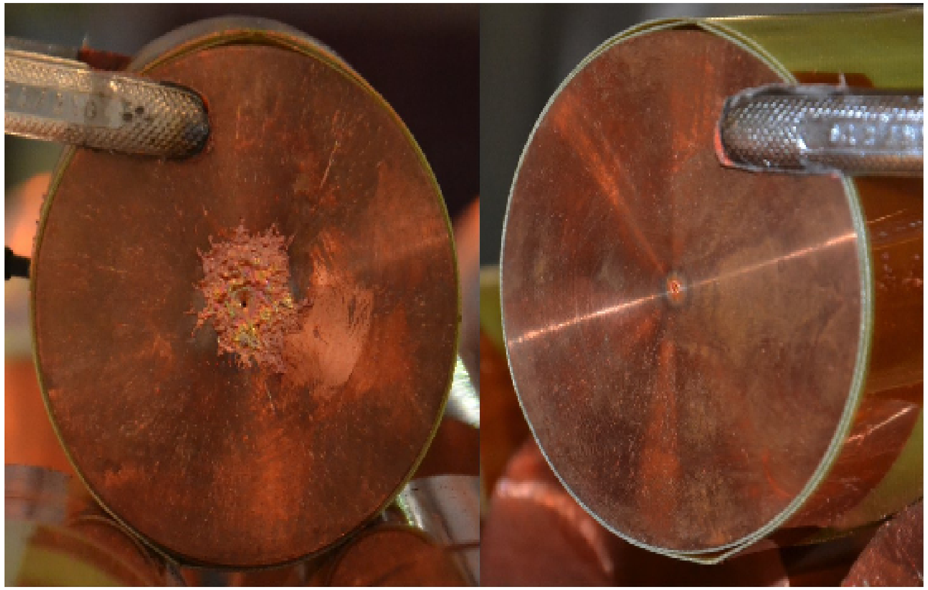
Cylinder 5

Cylinder 6



Cylinder 7

Cylinder 8



Cylinder 9

Improved Results

Experiment	Hydro Simulations (cm)	Improved Measurements (cm)	Δ (cm)
1	56.0	58.0	2.0
2	80.0	79.5	0.5
3	90.0	85.0	5.0

FCC Beam on Solid Copper Cylinder

Length = 5 m **Radius = 2 cm**

FLUKA and BIG2 used iteratively to simulate the beam-target heating.

Initially an iteration step of 25 ns was used and only after 300 ns, the step could be increased to 100 ns.

The work took about 15 months.

Energy Comparison for FCC

Parameters	**LHC**	**FCC**
Proton Energy	**7 TeV**	**50 TeV**
Bunch Intensity	**1.15×10^{11}**	**10^{11}**
Bunches / Beam	**2808**	**10600**
Bunch Length	**0.5 ns**	**0.5 ns**
Bunch Separation	**25 ns**	**25 ns**
Beam Duration	**89 μs**	**265 μs**
Focal Spot σ	**0.2 mm**	**0.2 mm**
Energy / Bunch	**128.8 kJ**	**800 kJ**
Energy / beam	**362 MJ**	**8.5 GJ**
Tunnel	**28 km**	**100 km**

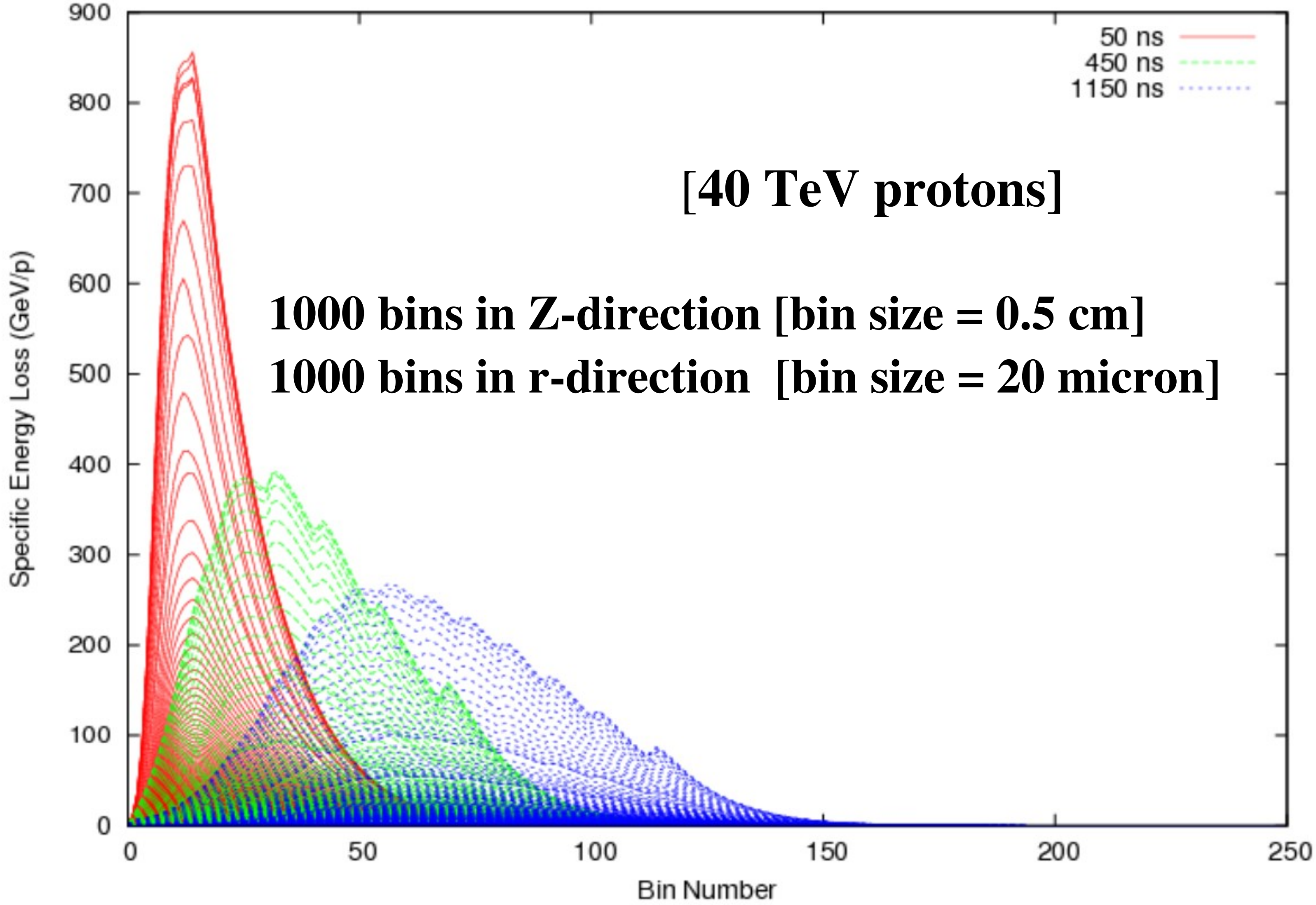
Equivalent to: A 380 (560 t) at speed of 850 km/h

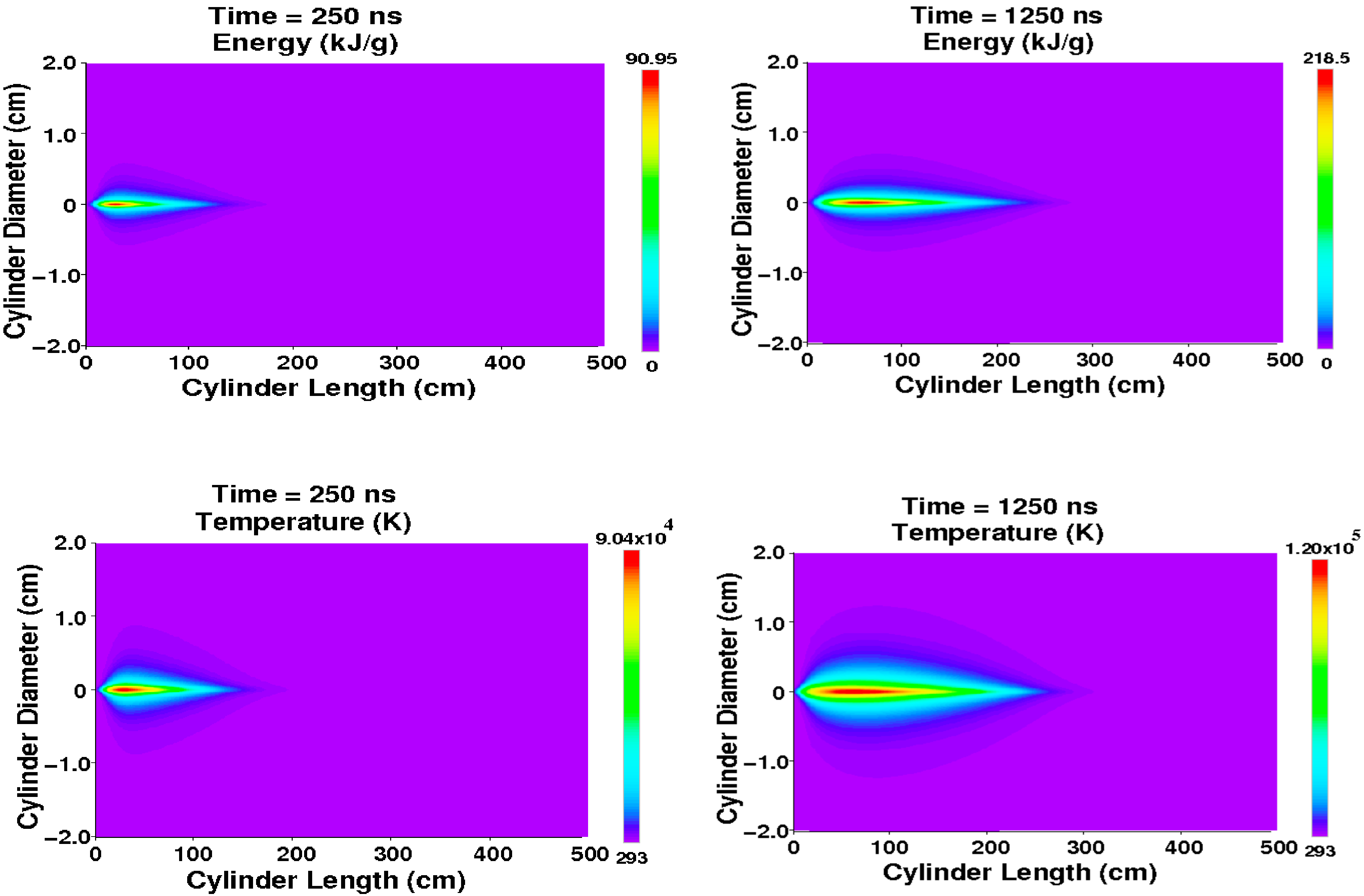
Beam-Target Coupling Parameters

[Solid Density]

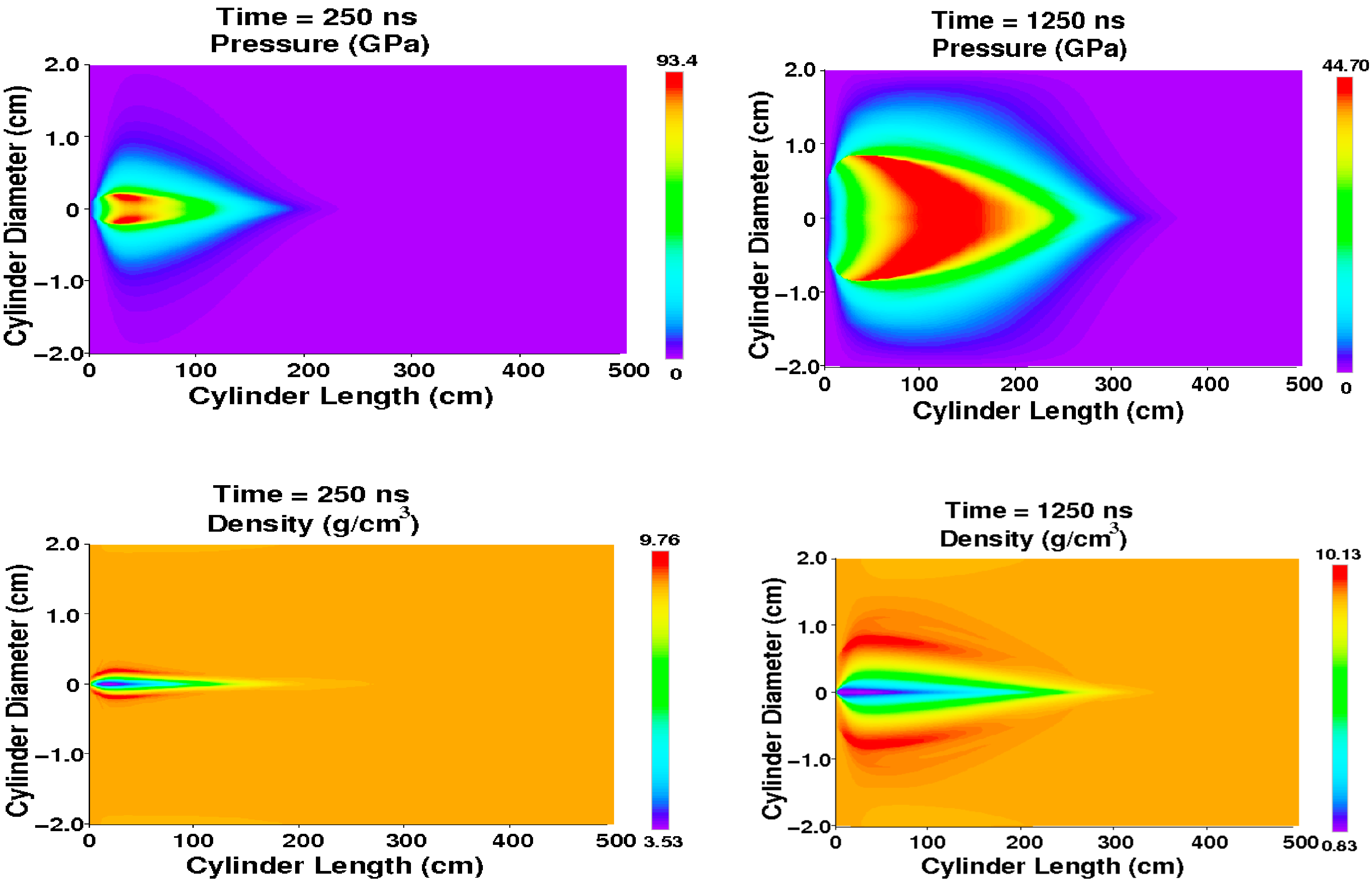
	Energy (TeV)	E_p(GeV/g/p) [FLUKA]	I_{bunch}	E_S(kJ/g) [BIG2]	T(K)
SPS	0.44	3.6	1.50×10^{11}	0.08	515
LHC	7	134	1.15×10^{11}	2.4	5019
FCC	40	920	10^{11}	14.4	27440

Solid Density Value: 920 GeV/g/p

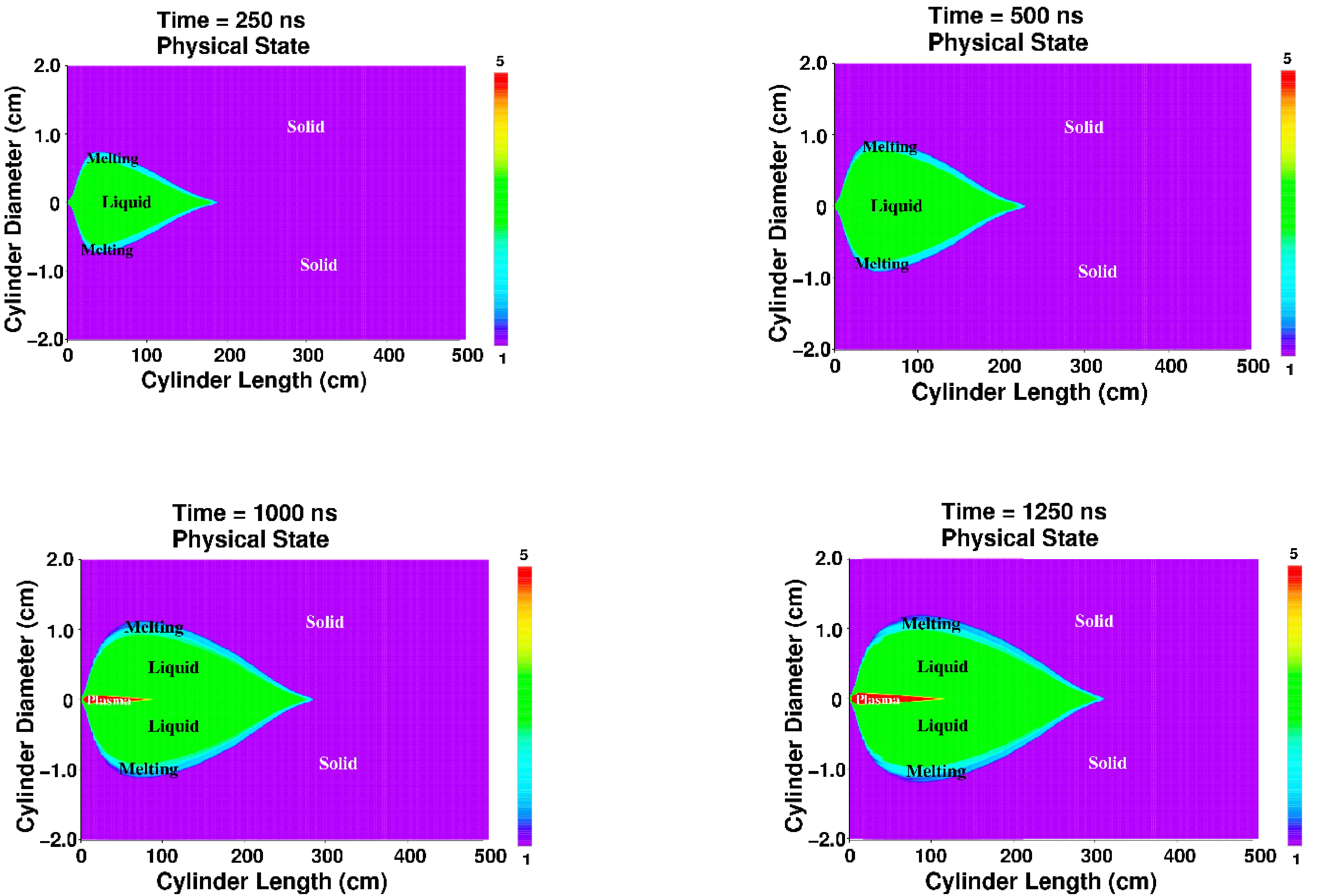




Time = 250 ns
Energy (kJ/g)
90.95
0
Cylinder Diameter (cm)
2.0
1.0
0
−1.0
−2.0
0
100
200
300
400
500
Cylinder Length (cm)
Time = 1250 ns
Energy (kJ/g)
218.5
0
Cylinder Diameter (cm)
2.0
1.0
0
−1.0
−2.0
0
100
200
300
400
500
Cylinder Length (cm)
Time = 250 ns
Temperature (K)
9.04x10^4
293
Cylinder Diameter (cm)
2.0
1.0
0
−1.0
−2.0
0
100
200
300
400
500
Cylinder Length (cm)
Time = 1250 ns
Temperature (K)
1.20x10^5
293
Cylinder Diameter (cm)
2.0
1.0
0
−1.0
−2.0
0
100
200
300
400
500
Cylinder Length (cm)



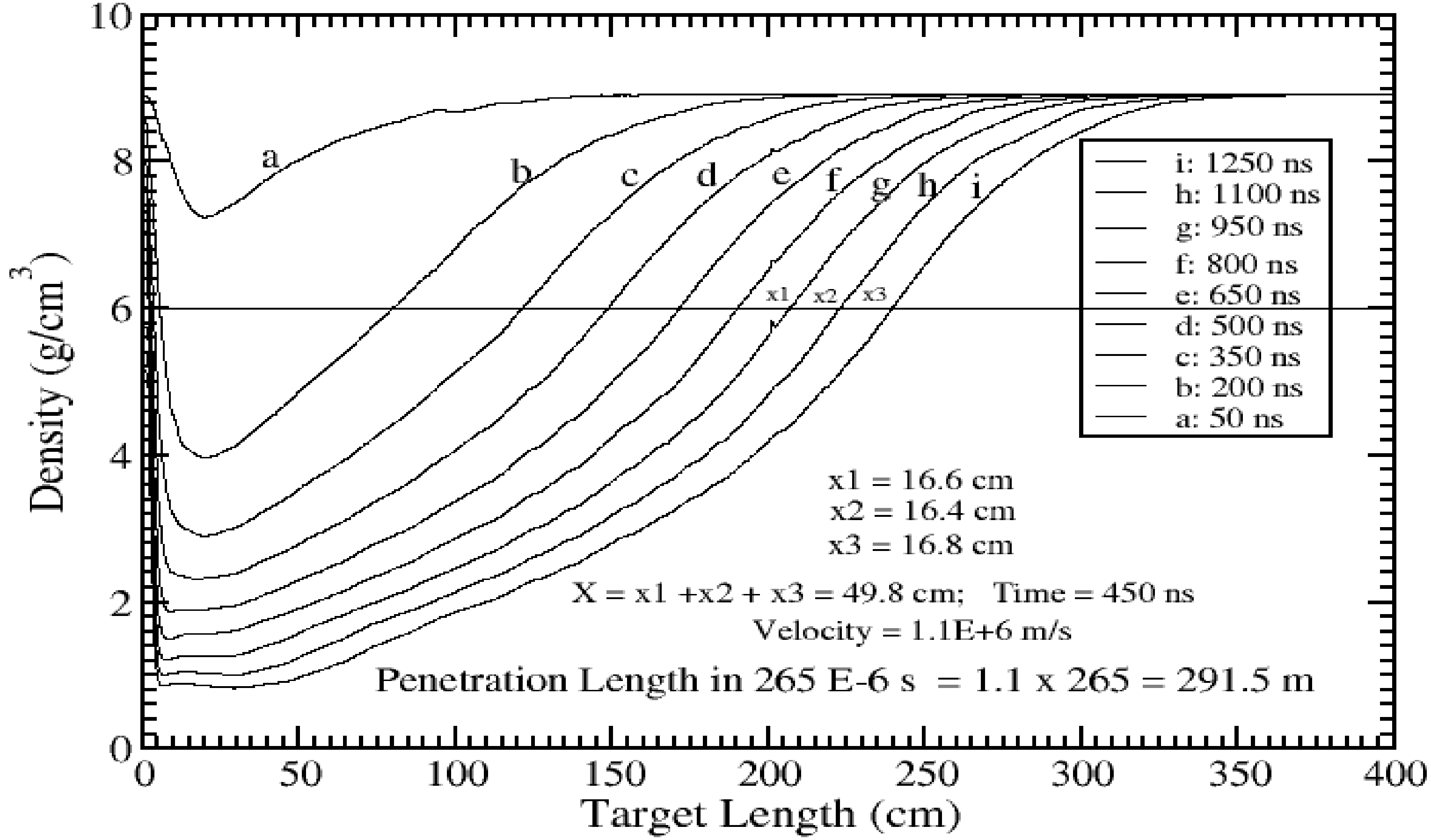
Time = 250 ns
Pressure (GPa)
93.4
0
Time = 1250 ns
Pressure (GPa)
44.70
0
Time = 250 ns
Density (g/cm³)
9.76
3.53
Time = 1250 ns
Density (g/cm³)
10.13
0.83
Cylinder Diameter (cm)
2.0
1.0
0
−1.0
−2.0
Cylinder Length (cm)
0
100
200
300
400
500


Time = 250 ns
Physical State
Time = 500 ns
Physical State
Time = 1000 ns
Physical State
Time = 1250 ns
Physical State
Cylinder Diameter (cm)
Cylinder Length (cm)
Solid
Melting
Liquid
Plasma
2.0
1.0
0
−1.0
−2.0
0
100
200
300
400
500
5
1

Calculation of Penetration Distance

N.A. Tahir, F. Burkart, R. Schmidt et al., PRAB 19 (2016)

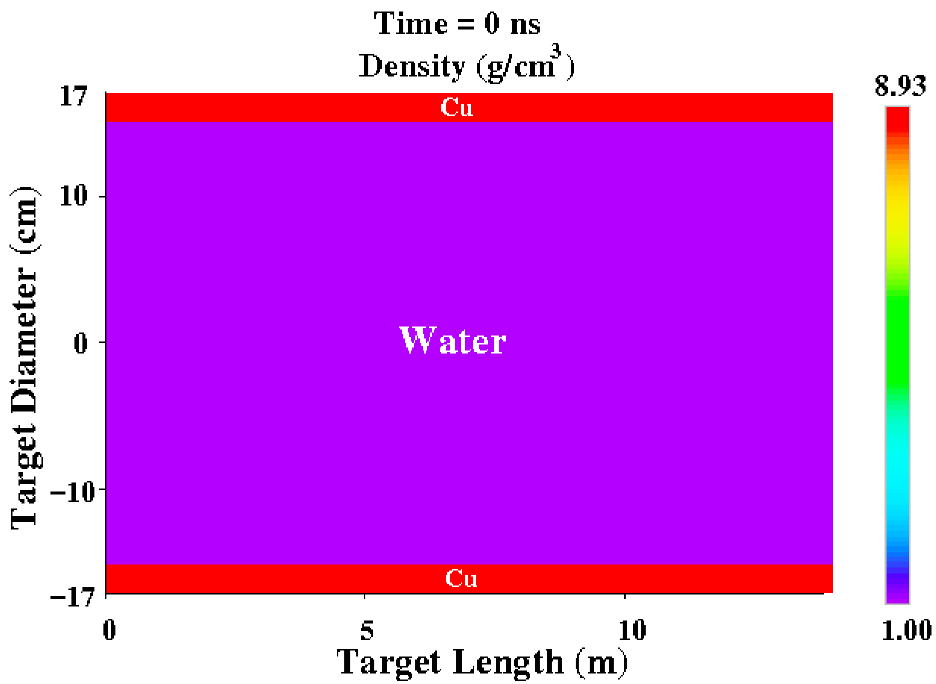
19   (2016) 08102 and Phys. Plasmas 24 (2017) 072712.



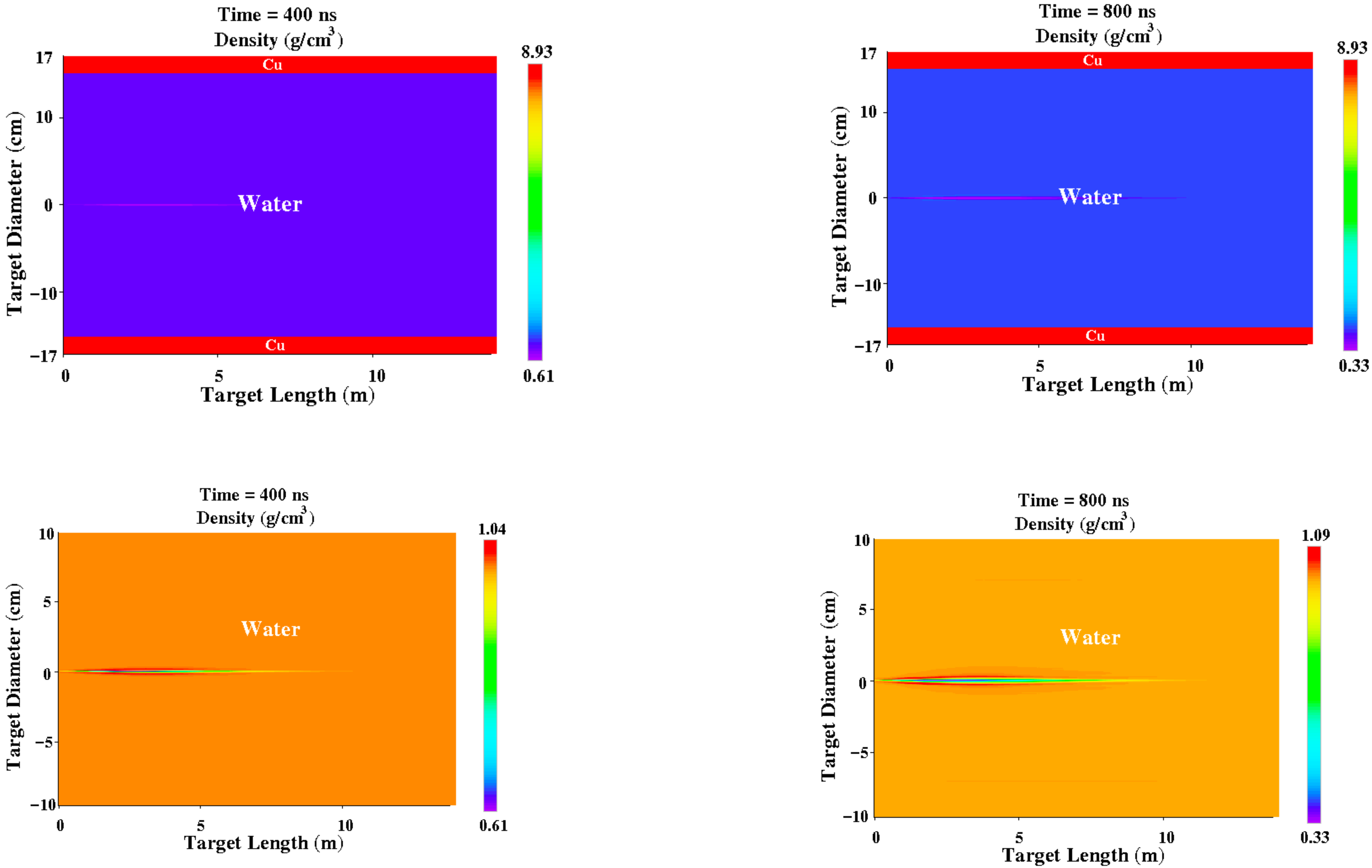
Water as beamdump material?

Feasibility study using numerical simulations!

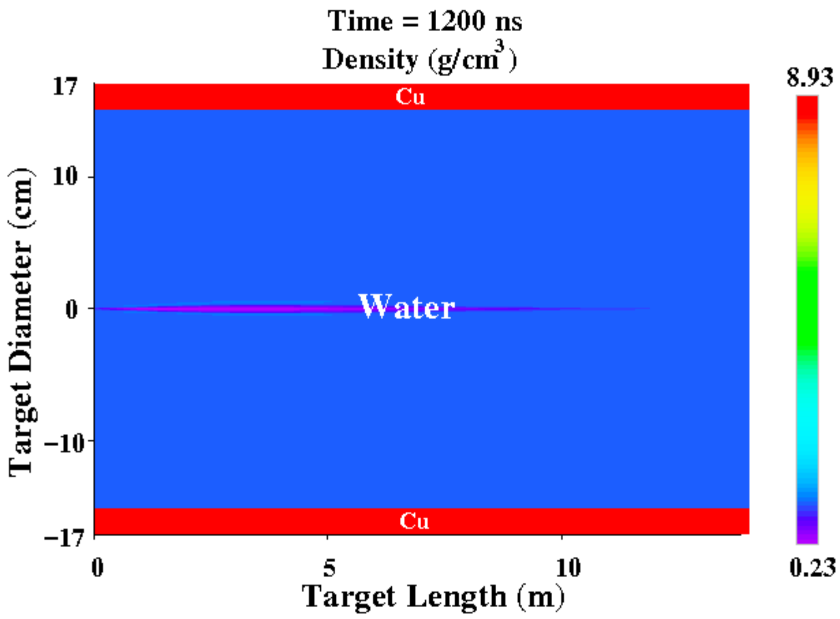
- A copper tube
- Inner radius =15 cm
- Outer radius = 17 cm
- Length = 14 m
- Filled with normal water

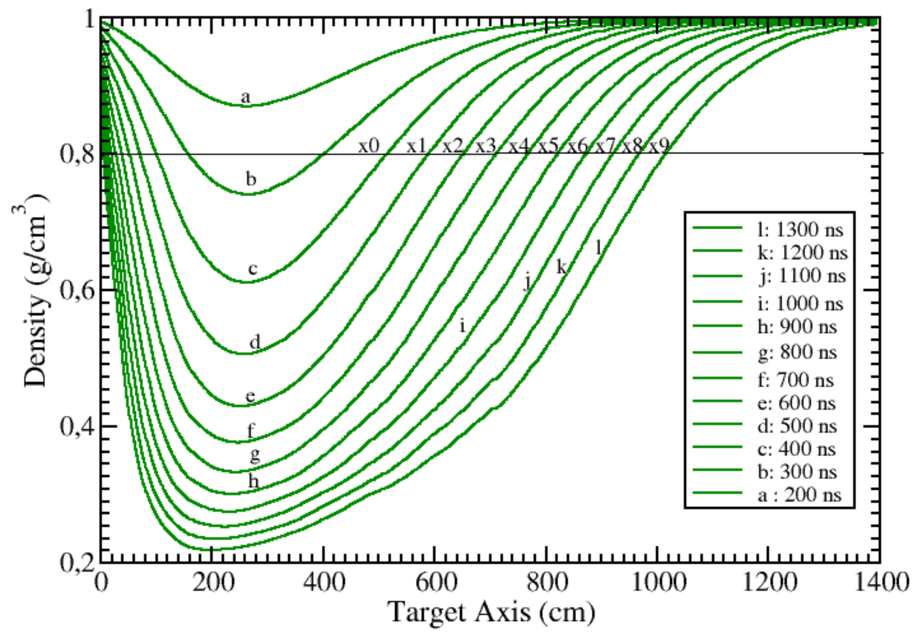


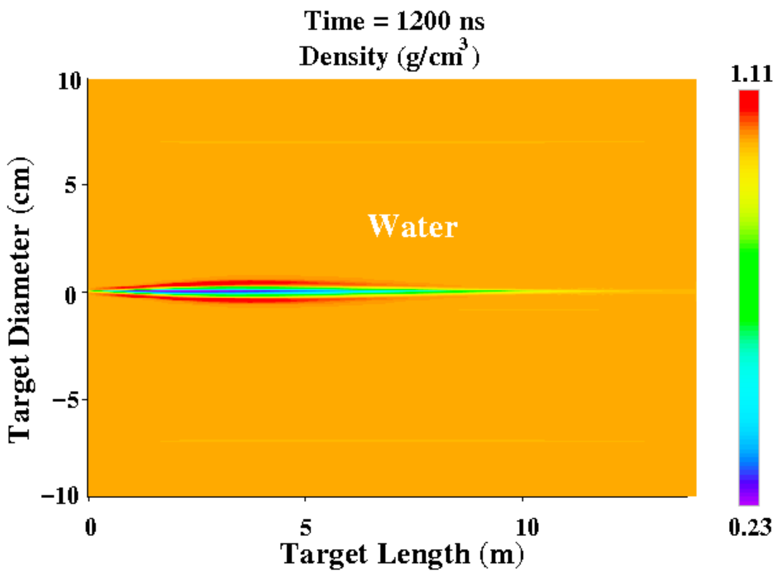
FCC beam focal spot size, б = 0.4 mm



Time = 400 ns
Density (g/cm³)
Cu
Water
Cu
Target Diameter (cm)
Target Length (m)
8.93
0.61
Time = 800 ns
Density (g/cm³)
Cu
Water
Cu
Target Diameter (cm)
Target Length (m)
8.93
0.33
Time = 400 ns
Density (g/cm³)
Water
Target Diameter (cm)
Target Length (m)
1.04
0.61
Time = 800 ns
Density (g/cm³)
Water
Target Diameter (cm)
Target Length (m)
1.09
0.33







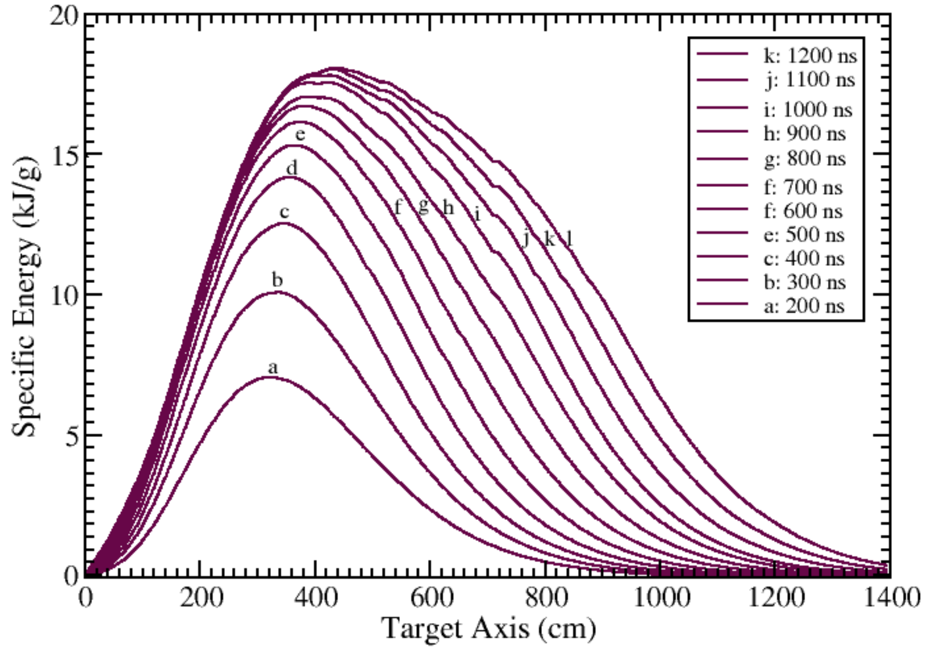
x4 = 56.7 cm, x5 = 53.1 cm, x6 =49.8 cm

x7 = 47.9 cm, x8 = 48.2 cm, x9 = 48 cm.

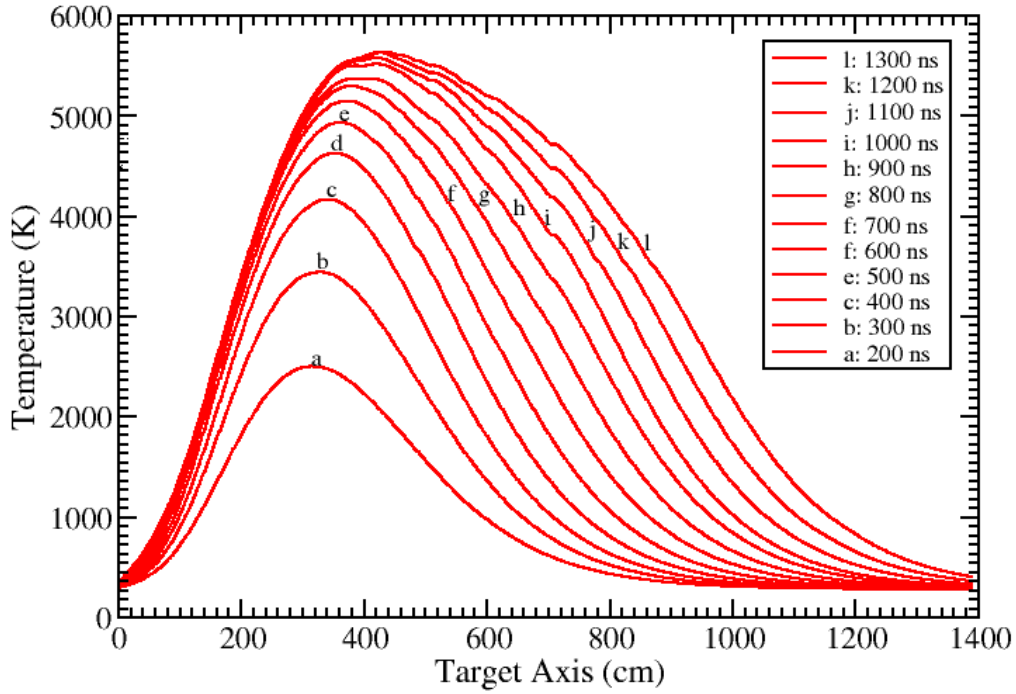
av. speed = 4.8×10^6 m/s.

beam duration = 265×10^{-6} s

distance traveled ~ 1.3 km



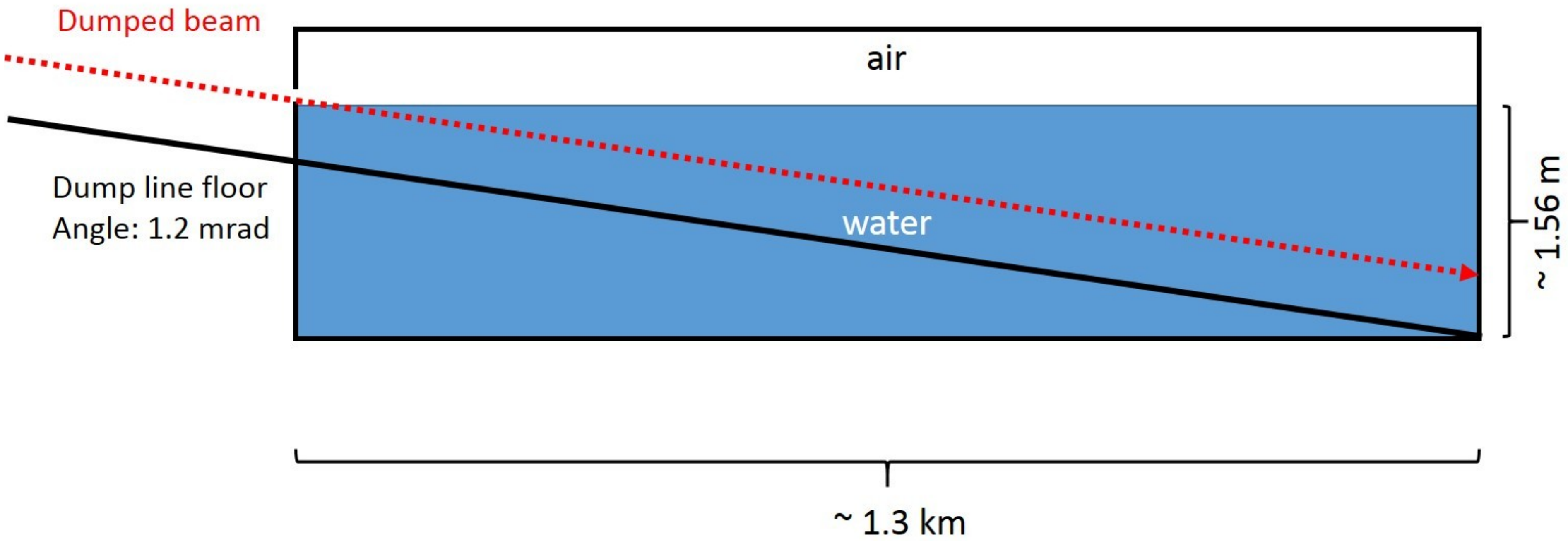
Specific Energy (kJ/g)
Target Axis (cm)
k: 1200 ns
j: 1100 ns
i: 1000 ns
h: 900 ns
g: 800 ns
f: 700 ns
f: 600 ns
e: 500 ns
c: 400 ns
b: 300 ns
a: 200 ns



Temperature (K)
Target Axis (cm)
l: 1300 ns
k: 1200 ns
j: 1100 ns
i: 1000 ns
h: 900 ns
g: 800 ns
f: 700 ns
f: 600 ns
e: 500 ns
c: 400 ns
b: 300 ns
a: 200 ns

Technical Design Proposal

Windowless



- **The beamdump is located at 2.3 km from the kicker magnets.**
- **At the point of the beambump, the beam focal spot size is expected to be бx = 3 mm and бy = 1.3 mm**
- **In our calculations we use б = 0.4 mm.**
- **Factor 10 larger focal spot size!**
- **Specific energy deposition will also reduce.**
- **With additional quadrupole in the FCC dump line one can achieve б = 9 mm. Specific energy**
- **deposition will reduce by a factor 20.**
- **Can one use a ‘WINDOW’ at the entrance of the beamdump?**

Due to the lower specific energy deposition in Case of diluted focal spot, the length of the water pipe can be significantly reduced. Instead of 1.3 km, it could be 500 – 700 m!

Conclusions

The work shows that hydrodynamic tunneling is a reality, which can have important implication on the machine protection design and the beamdump design.

It is therefore important to consider this effect in beam-matter interaction related problems in case of powerful accelerators.