Feasibility Studies of a Water Beamdump for 50 TeV FCC Proton Beam

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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-Matter interaction studies are important in relation to every powerful accelerator because:

1). **An accidental release of the beam energy. Simulations of the full impact of the FCC beam on a Cu target** [*N.A. Tahir et al., PRAB* ***19*** ***(2016) 081002***].

Static range of a single FCC proton and shower in Cu is ~1.5 m.

Full beam, 10600 proton bunches will penetrate about 350 m! "Hydrodynamic Tunneling"

2). Safe disposal of the beam after successful Operation [Beamdump].

For LHC, a C block is being used as beamdump. Beam is diluted, бx = 1.65 mm, бy = 1.4 mm. Makes an e-shaped spiral path.

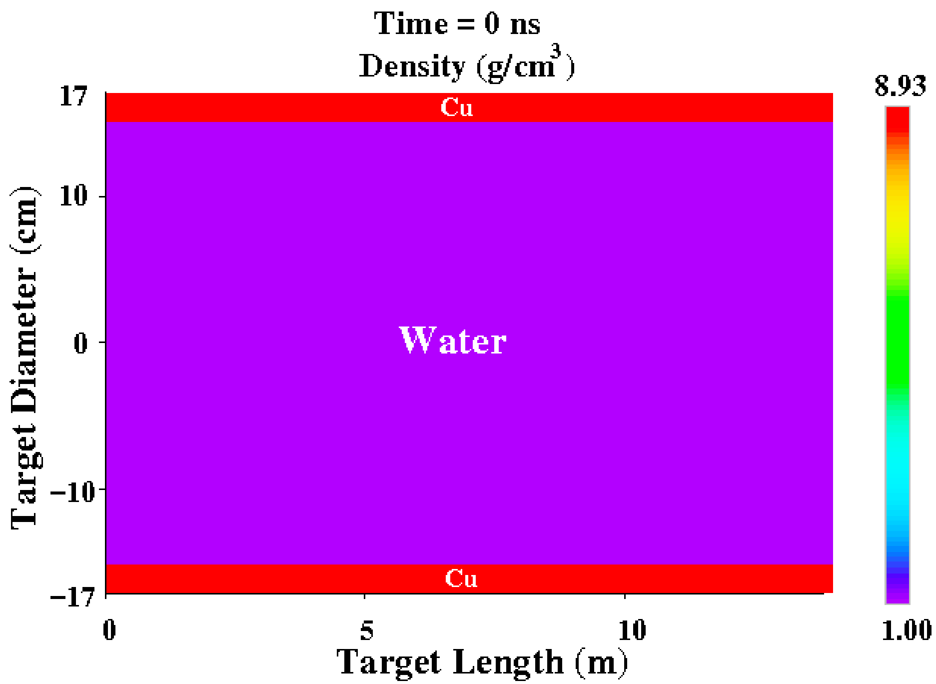
For FCC, the spiral path should be about 20 m. The experts say it is feasible, although very challenging.

It is thus natural to look for alternative concepts.

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

Simulations Strategy

The simulations are carried out using the energy deposition code FLUKA and a 2D hydrodynamic code BIG2, iteratively.
First, the FLUKA code is run to calculate the energy deposition distribution considering solid target density.
Second, This energy deposition data is used as energy input to BIG2 and thermodynamic and the hydrodynamic response of the material is simulated.
The BIG2 code is stopped when the density along the target axis is reduced by 15 % due to the outgoing radial shock wave.
The modified target density distribution is then used in FLUKA to calculate new energy deposition table that is then used in BIG2. The process is continued till the end.

Iteration step is determined by the beam parameters

FLUKA: is a fully integrated particle physics and multi-purpose Monte Carlo simulation package, capable of simulating all components of the particle cascades in matter from as low as a few MeV/u up to 10000 TeV/u.

More details about the applied models and their performance, can be found in

[*Fasso A et al 2005 FLUKA: a multi-particle transport code CERN-2005-10 , INFN/TC-05/11, SLAC-R-773*]

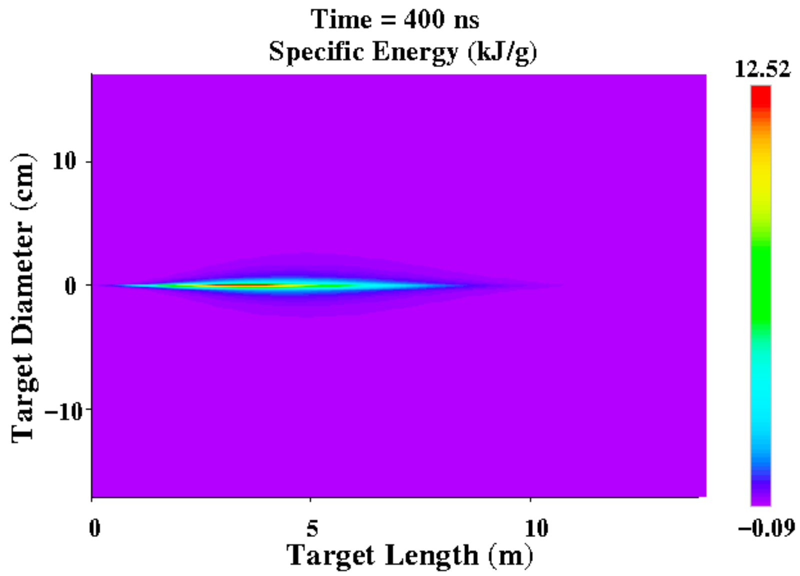
BIG2 Computer Code

Two-dimensional hydrodynamic code based on an ALE scheme, but can also be run in a fully Lagrangian as well as fully Eulerian mode.
It can handle simple and very complicated geometries and can deal with simple as well as multi-layered targets. Sophisticated, very versatile and stable mesh.
It includes heat conduction.
It includes ion beam energy deposition (SRIM for heavy ions and FLUKA for protons from LHC or SPS).
It includes elastic and plastic effects using ideal plasticity model basically Hook's law complemented with von Mises yield criterien. (important for solid targets).
Different phases of matter are treated using a sophisticated semi-empirical EOS model.

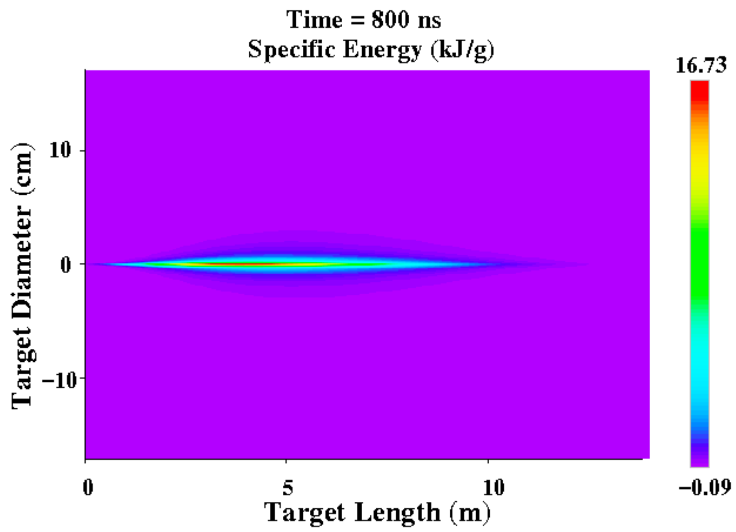
What is Hydrodynamic Tunneling?

In case of a long bunched beam, energy deposited by a certain number of bunches [few tens in case of LHC and a few in case of FCC] launches an outgoing radial shock wave that depletes the density along and around the axis.
Protons that are delivered in subsequent bunches together with their hadronic shower penetrate deeper into the target. This is called hydrodynamic tunneling of the ultra-relativistic protons
Continuation of this process leads to very substantial range lengthening of the protons and their hadronic shower.

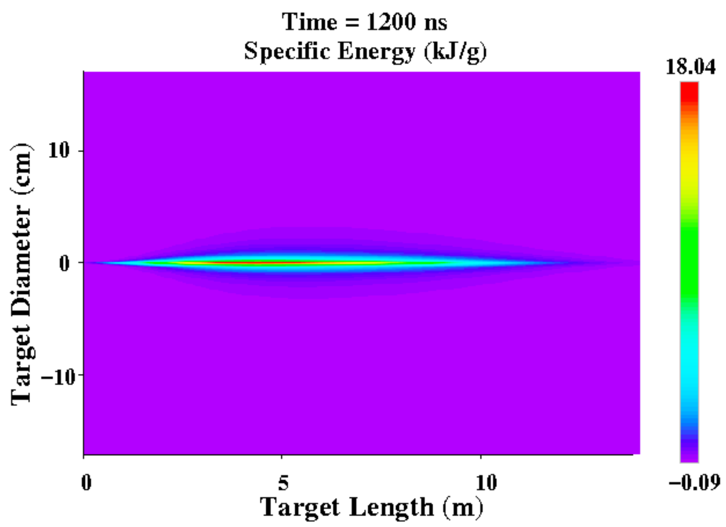
16 bunches

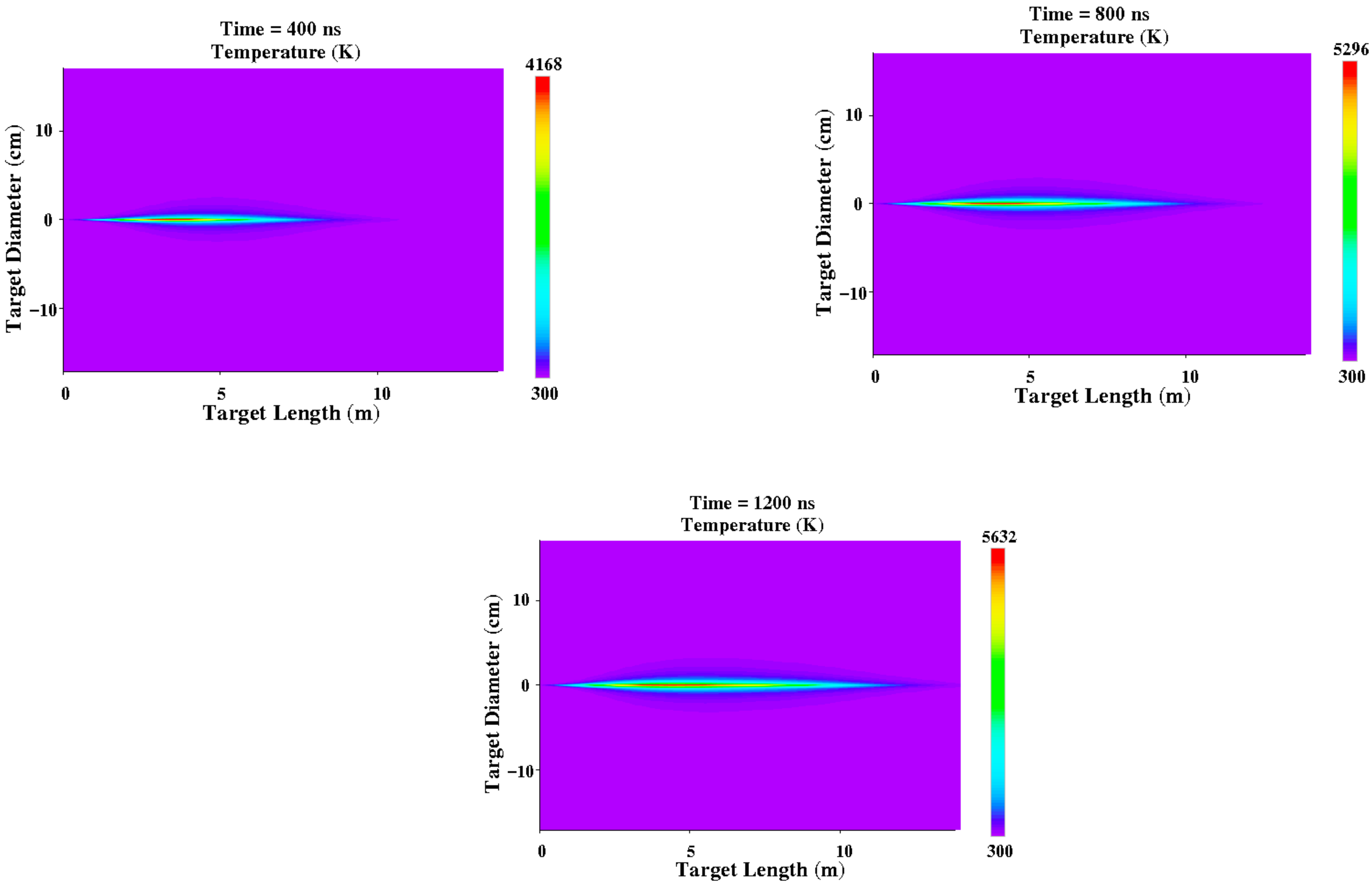


32 bunches

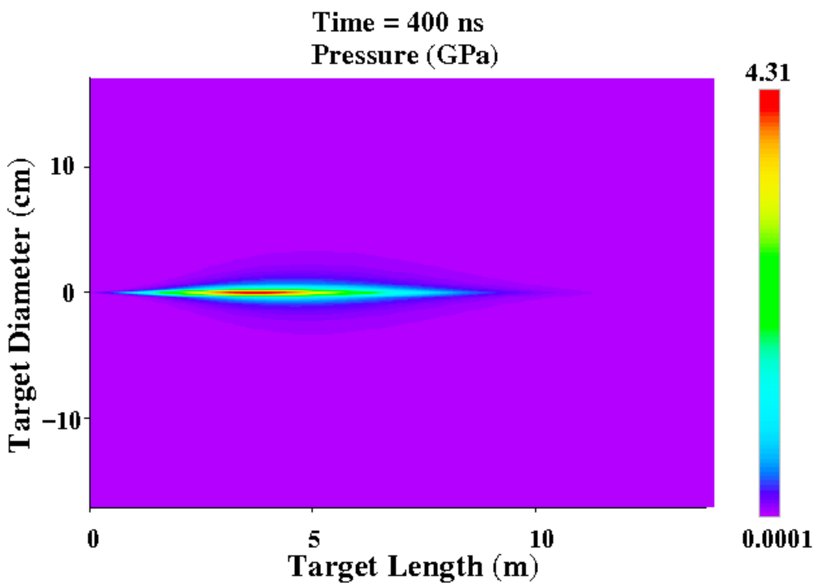


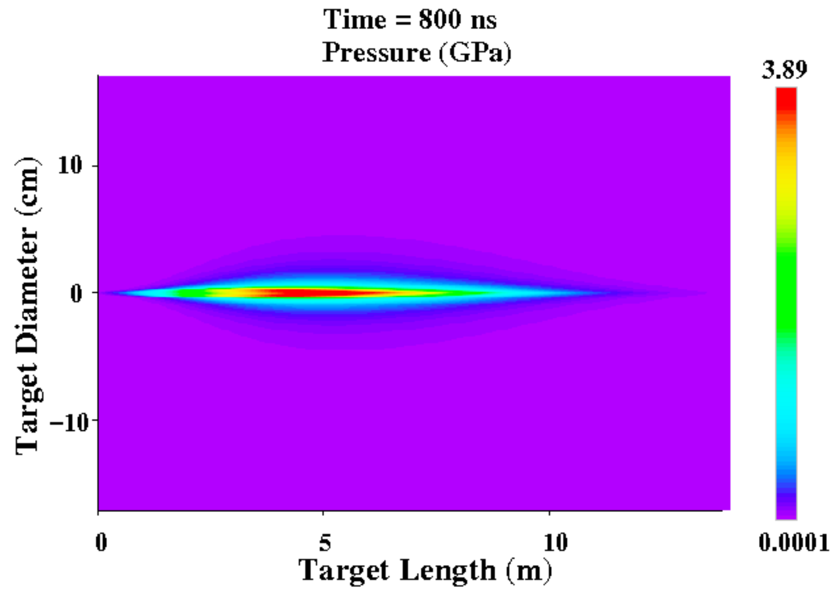
48 bunches

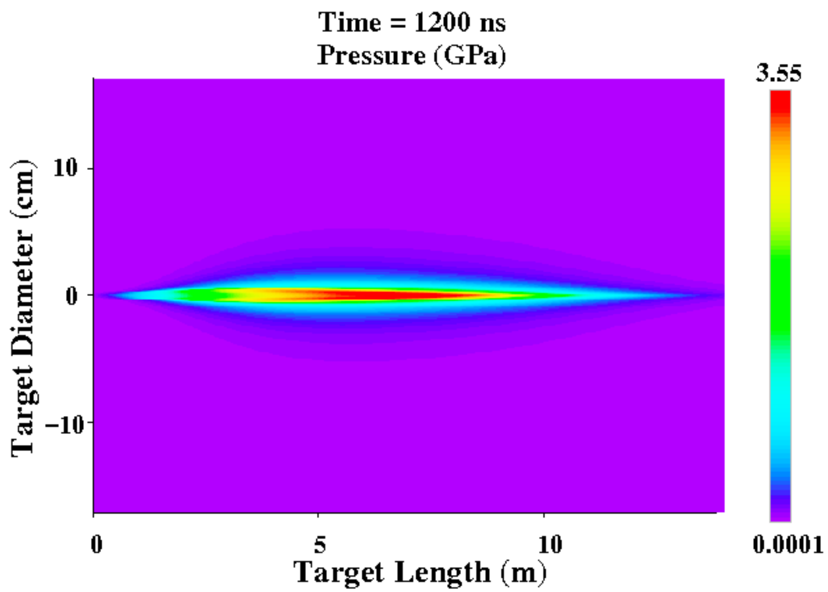


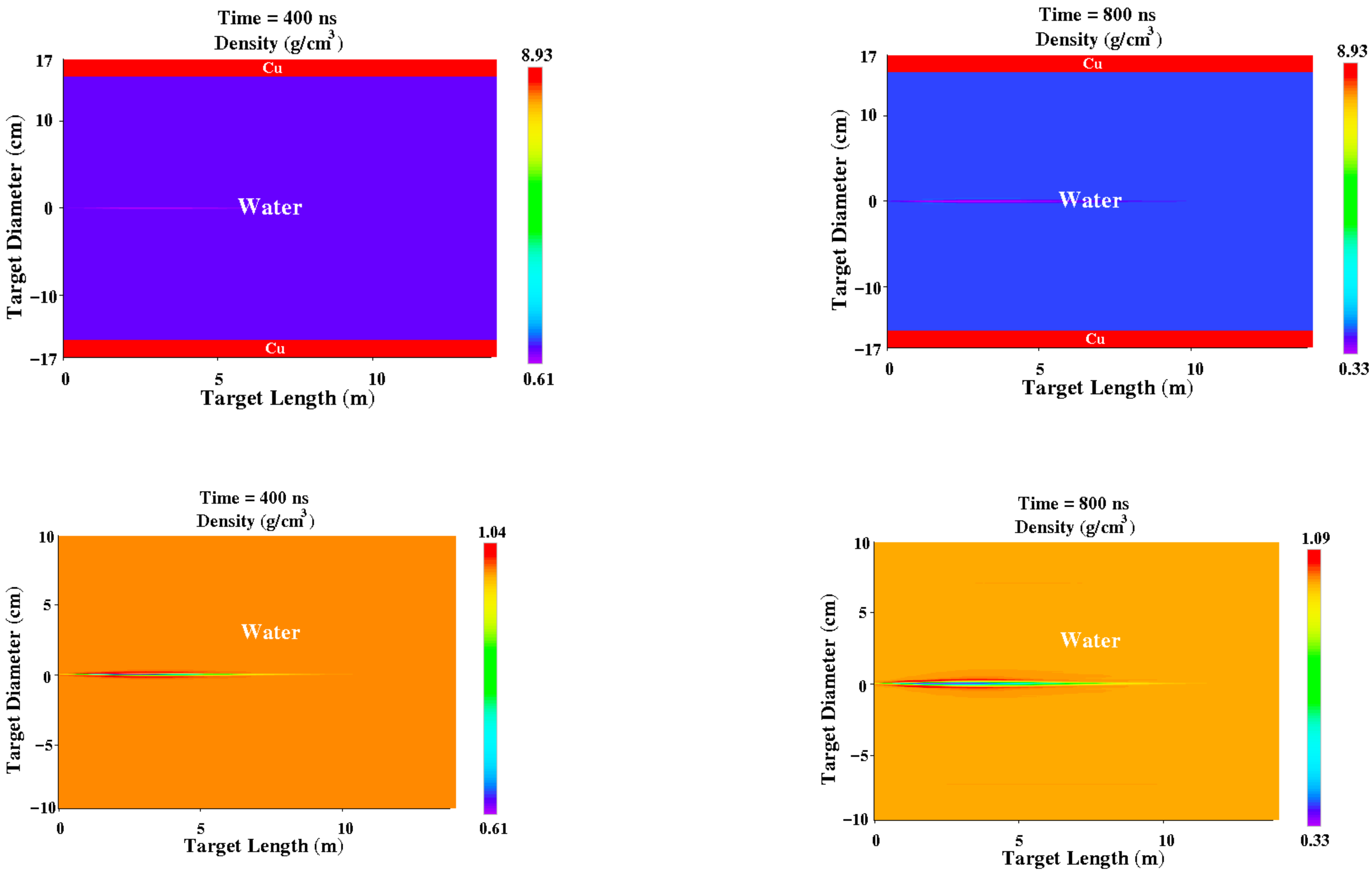


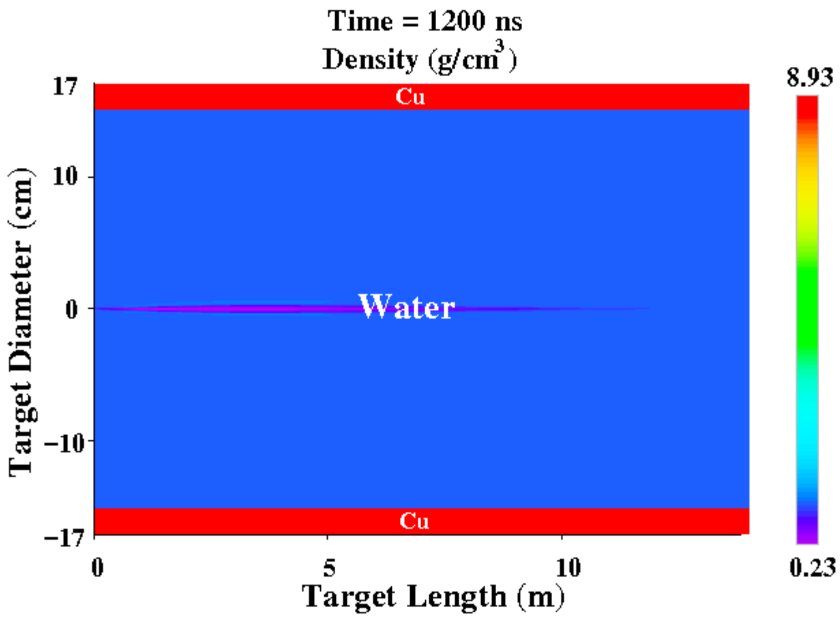
Time = 400 ns
Temperature (K)
4168
300
10
0
−10
0
5
10
Target Length (m)
Target Diameter (cm)
Time = 800 ns
Temperature (K)
5296
300
10
0
−10
0
5
10
Target Length (m)
Target Diameter (cm)
Time = 1200 ns
Temperature (K)
5632
300
10
0
−10
0
5
10
Target Length (m)
Target Diameter (cm)

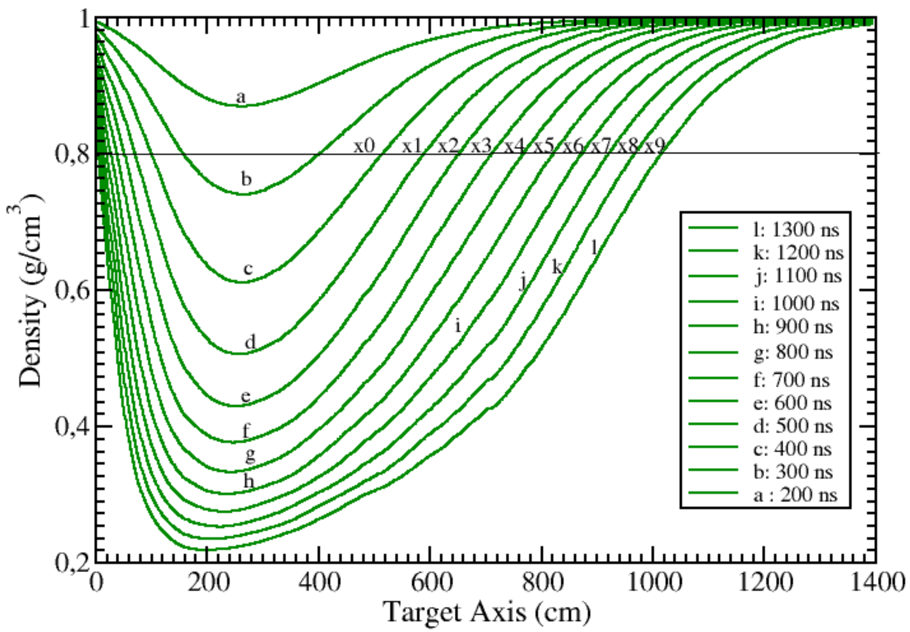

Time = 400 ns
Pressure (GPa)
4.31
0.0001
Target Diameter (cm)
10
0
−10
0
5
10
Target Length (m)

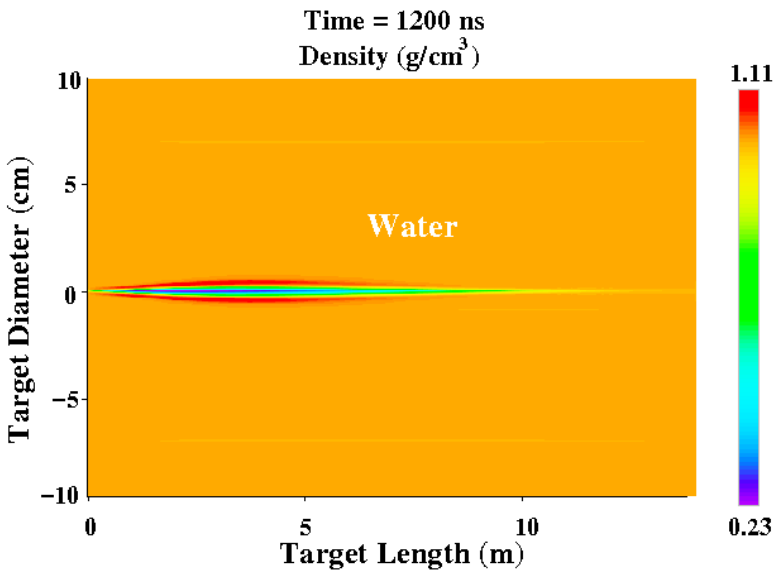

Time = 800 ns
Pressure (GPa)
3.89
0.0001
Target Diameter (cm)
10
0
−10
0
5
10
Target Length (m)


Time = 1200 ns
Pressure (GPa)
3.55
0.0001
Target Diameter (cm)
10
0
−10
0
5
10
Target Length (m)


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







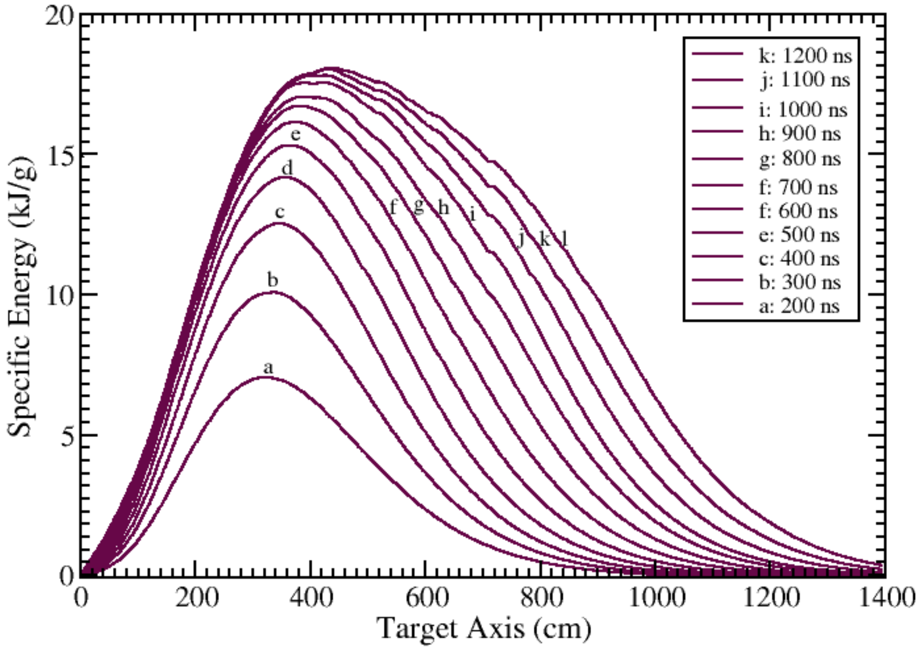
x4 = 56.7 cm, x5 = 53.1 cm, x6 =49.8 cm

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

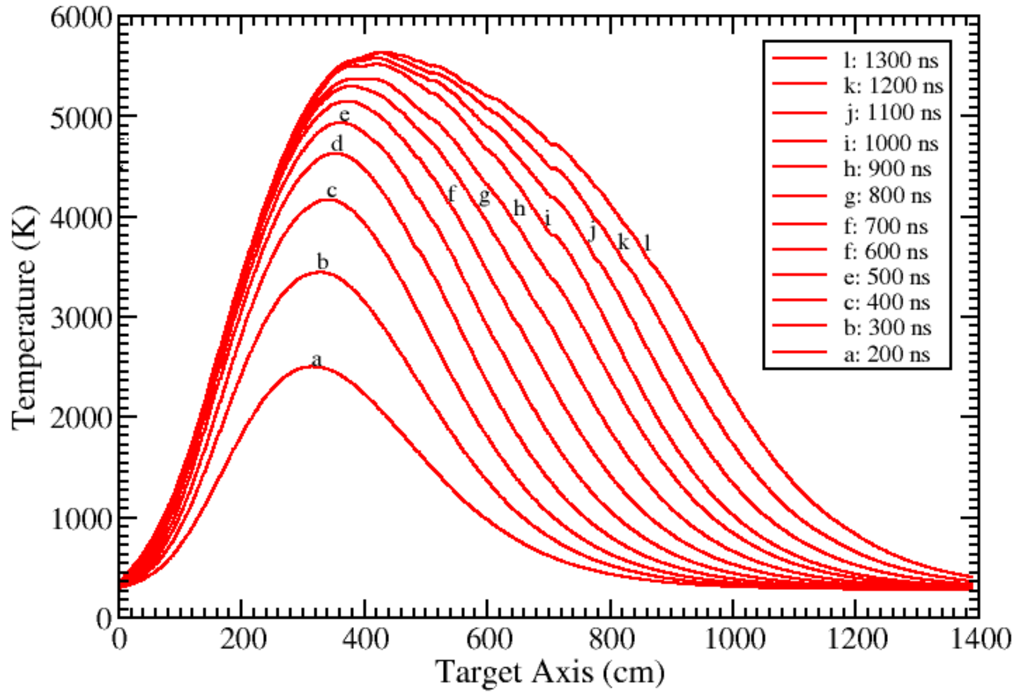
av. speed = 4.8×10^{6} m/s.

beam duration = 265×10^{-6} s

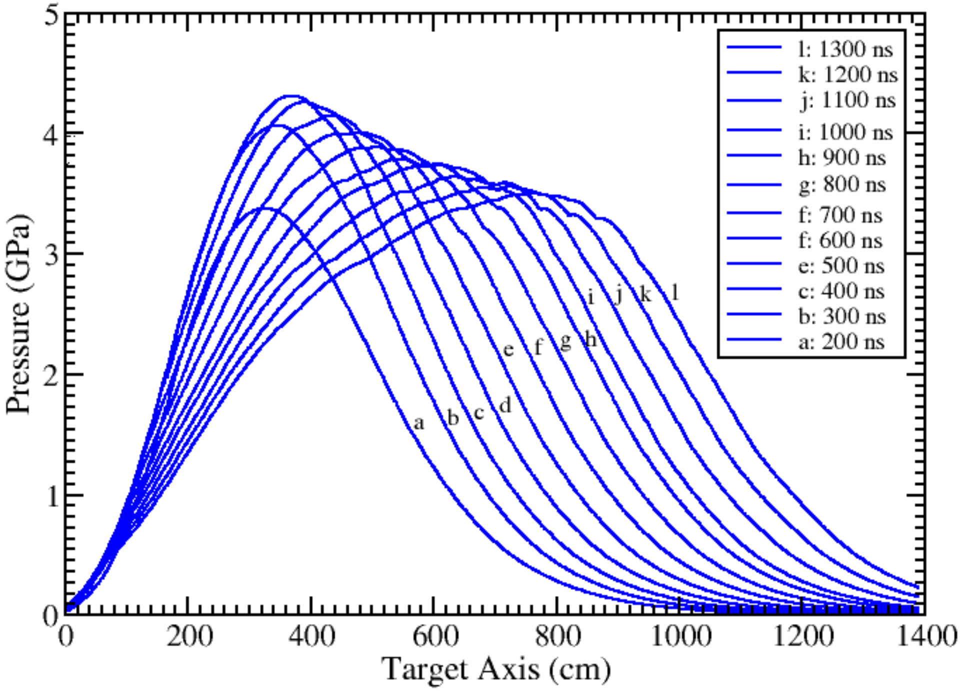
distance traveled ~ 1.3 km



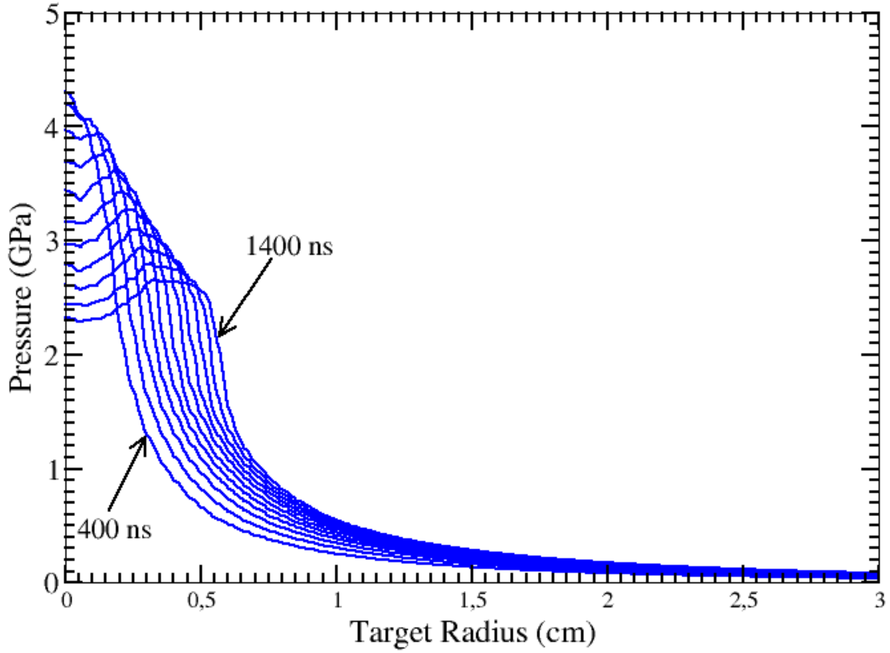
Specific Energy (kJ/g)
Target Axis (cm)
k: 1200 ns
j: 1100 ns
i: 1000 ns
h: 900 ns
g: 800 ns
f: 700 ns
f: 600 ns
e: 500 ns
c: 400 ns
b: 300 ns
a: 200 ns



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



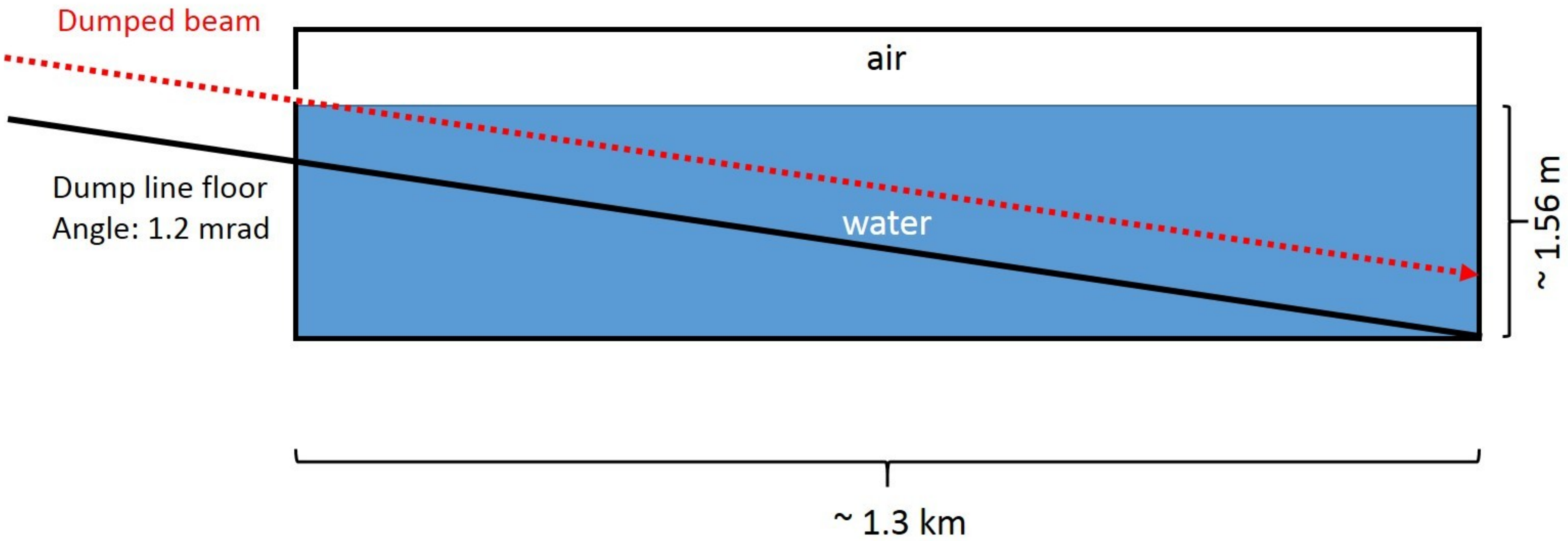
Pressure (GPa)
Target Axis (cm)
l: 1300 ns
k: 1200 ns
j: 1100 ns
i: 1000 ns
h: 900 ns
g: 800 ns
f: 700 ns
f: 600 ns
e: 500 ns
c: 400 ns
b: 300 ns
a: 200 ns



Pressure (GPa)
Target Radius (cm)
1400 ns
400 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:

More work needs to be done to investigate this interesting possibility.

Recent Publications

1. N.A. Tahir, J. Blanco, A. Shutov, R. Schmidt and A.R. Piriz, *PRSTAB* 15 (2012) 051003.
2. N.A. Tahir, J. Blanco, R. Schmidt, A. Shutov and A.R. Piriz, *High Energy Density Physics* 9 (2013) 269.
3. N.A. Tahir, F. Burkart, A. Shutov, R. Schmidt, D. Wollmann and A.R. Piriz, *Phys. Rev. E* 90 (2014) 063112.
4. R. Schmidt, J. Blanco, F. Burkart, D. Grenier, D. Wollmann, N.A. Tahir, A. Shutov and A.R. Piriz, *Phys. Plasmas* 21 (2014) 080701.
5. F. Burkart, R. Schmidt, V. Raginel, D. Wollmann, N.A. Tahir, A. Shutov and A.R. Piriz, *J. Appl. Phys.* 118 (2015) 055902.
6. N.A. Tahir, F. Burkart, R. Schmidt, A. Shutov, D. Wollmann and A.R. Piriz, *High Energy Density Physics* 21 (2016) 27.
7. N.A. Tahir, F. Burkart, R. Schmidt, D. Wollmann, A. Shutov and A.R. Piriz, *PRAB* 19 (2016) 081002.