Origin of Hydrodynamic Tunneling

By

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- **During the past two decades, significant progress has been made in the technology of particle accelerators.**

- **This has provided intense particle beams of highly energetic ions from protons up to uranium.**

- **Due to the high intensity, if the beam interacts with matter, substantial amount of specific energy is deposited in the target that leads to high pressures and phase changes. The high pressure generates shocks which lead to hydrodynamic effects.**

- **Hydrodynamic tunneling is one of the consequences of the above effects and will be explained in this talk.**

Specific power deposition:

$$P = \frac{E_s}{\tau}, \qquad \text{TW/g}$$

$$E_s = \frac{\frac{1}{\rho}\frac{dE}{dx} N}{\pi r_b^2}, \qquad \text{kJ/g}$$

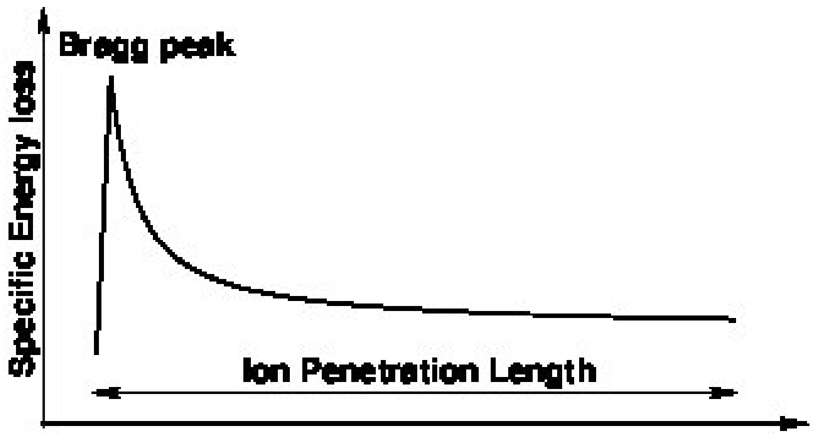
$\frac{1}{\rho}\frac{dE}{dx}$: specific energy loss due to a single ion

N : total number of particles in the beam

r_b : beam radius

To maximize P, an optimum set of parameters should be determined.

Beam-Matter Heating



Uranium Beam

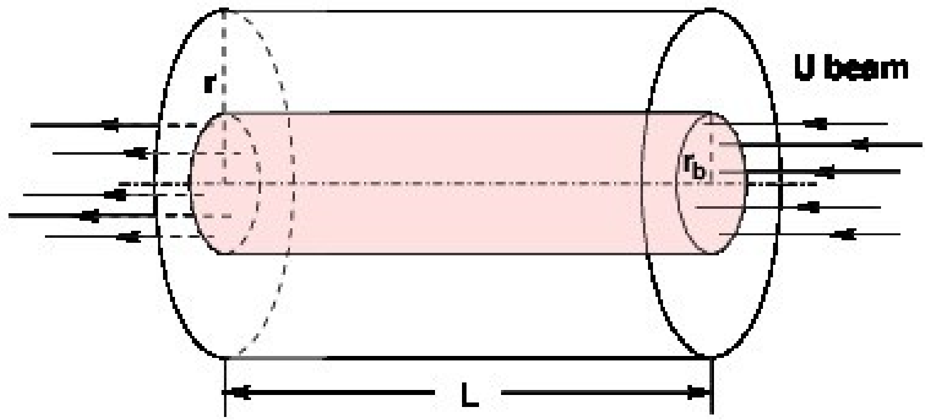
- **Particle Energy: 1 GeV/u**
- **Bunch Intensity: 10^{12} ions/bunch**

Single Bunch

- **Length: 50 ns and 1000 ns**

Five Bunches

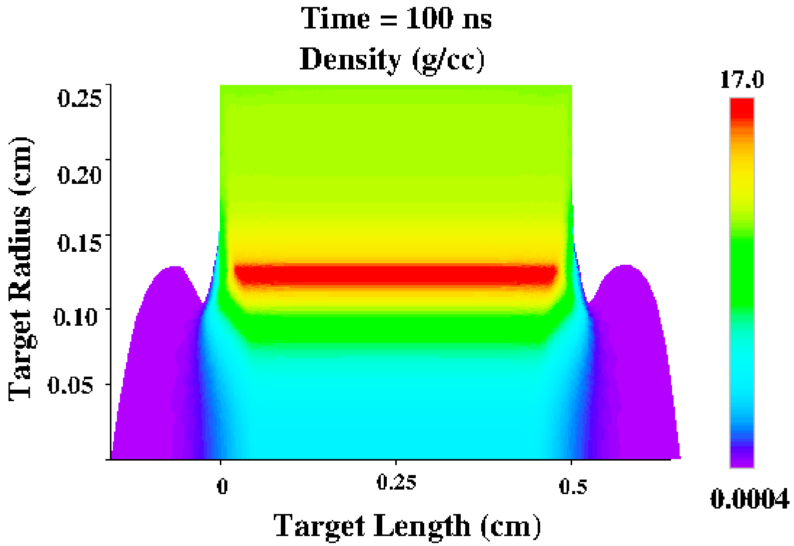
- **Bunch length : 140 ns**
- **Bunch Separation: 140 ns**

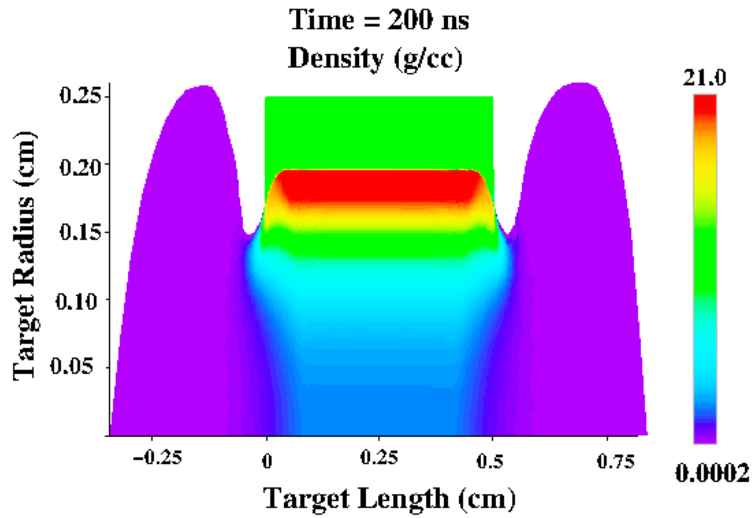


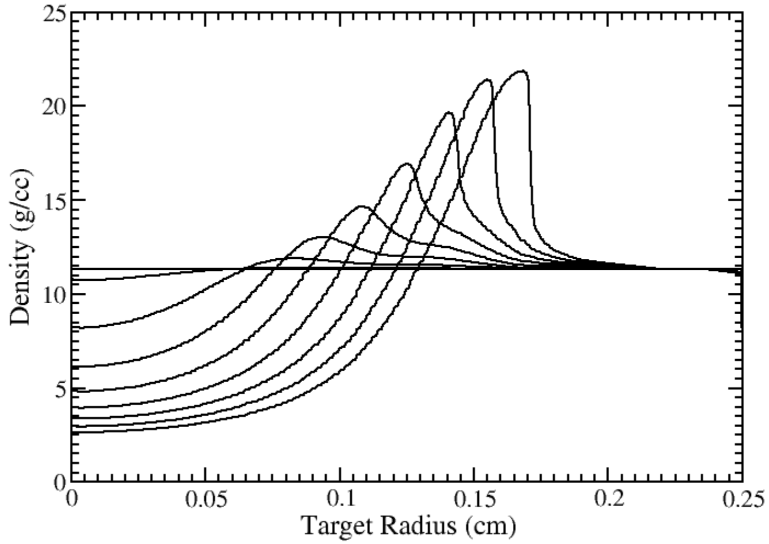
Target

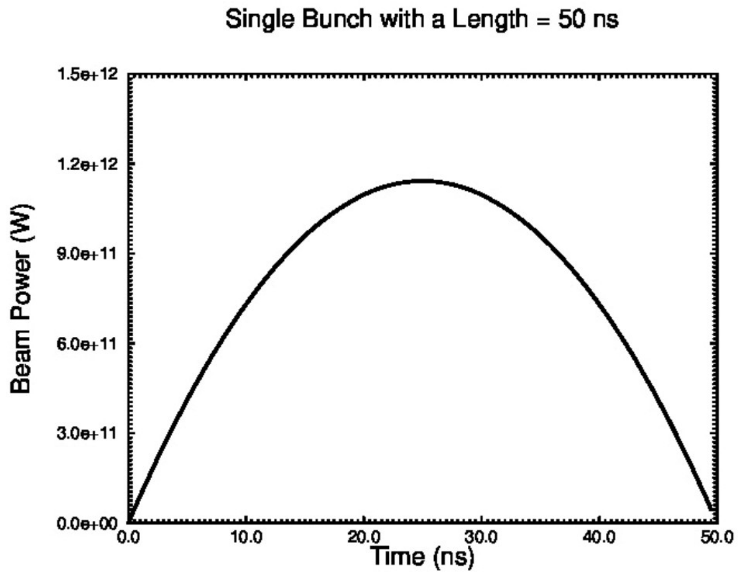
- **Lead Cylinder**
- **Length = 5 mm**
- **Radius = 2.5 mm**

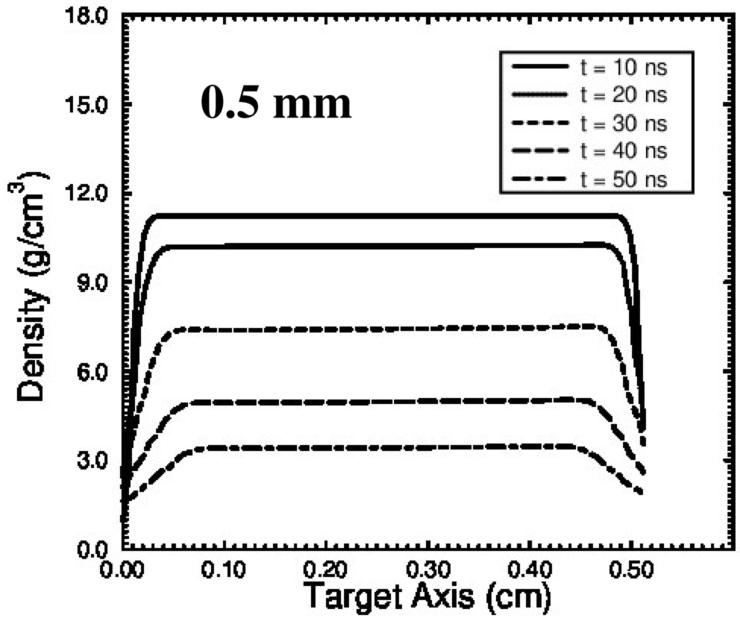
Simulations using 2D Hydrodynamic code BIG2 [*N.A. Tahir et al., PRE 63 (2001) 036407*]

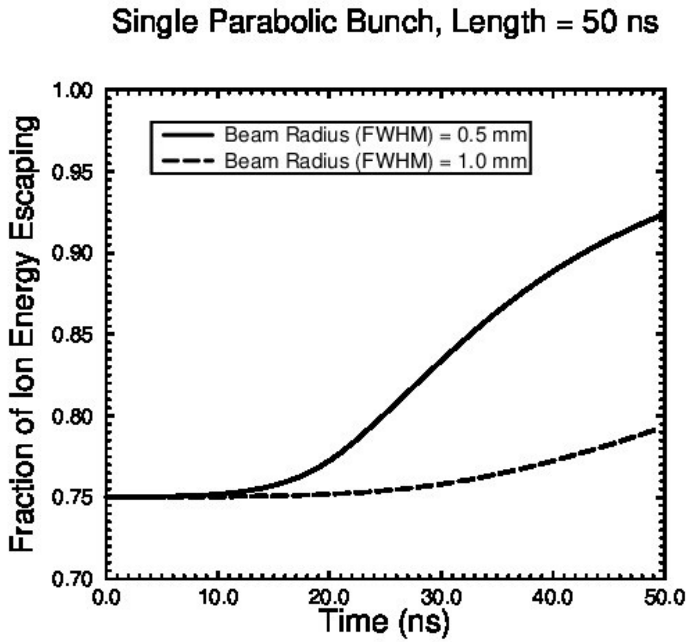

Time = 100 ns
Density (g/cc)
Target Radius (cm)
0.25
0.20
0.15
0.10
0.05
0
0.25
0.5
Target Length (cm)
17.0
0.0004

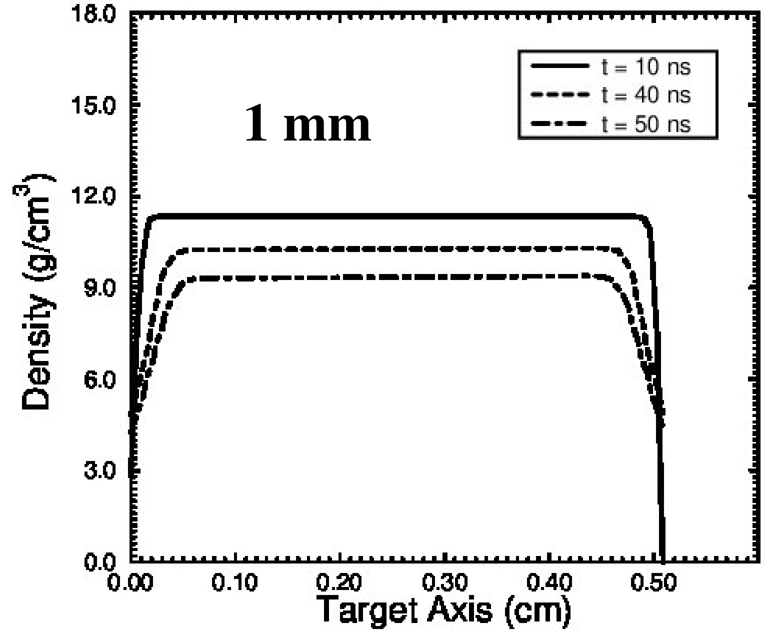

Time = 200 ns
Density (g/cc)
Target Radius (cm)
0.25
0.20
0.15
0.10
0.05
−0.25
0
0.25
0.5
0.75
Target Length (cm)
21.0
0.0002

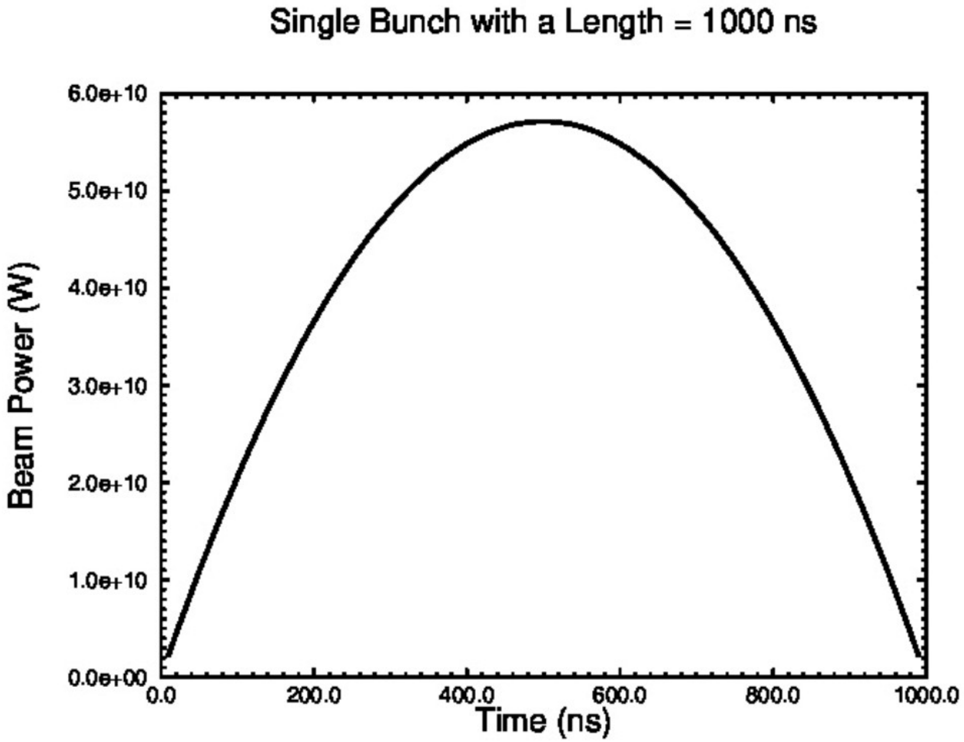

Density (g/cc)
25
20
15
10
5
0
0
0.05
0.1
0.15
0.2
0.25
Target Radius (cm)

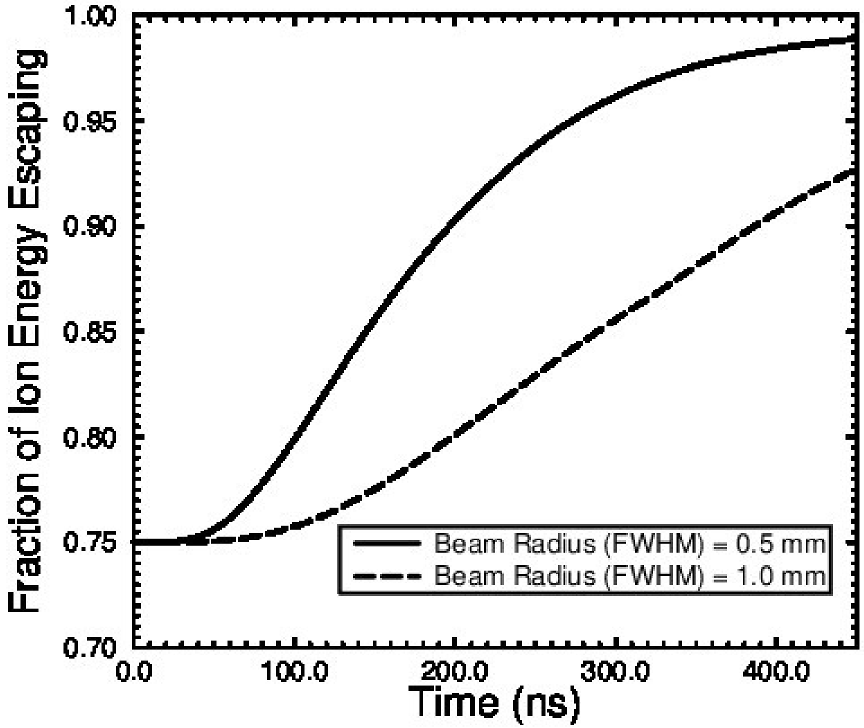

Single Bunch with a Length = 50 ns
Beam Power (W)
Time (ns)
1.5e+12
1.2e+12
9.0e+11
6.0e+11
3.0e+11
0.0e+00
0.0
10.0
20.0
30.0
40.0
50.0

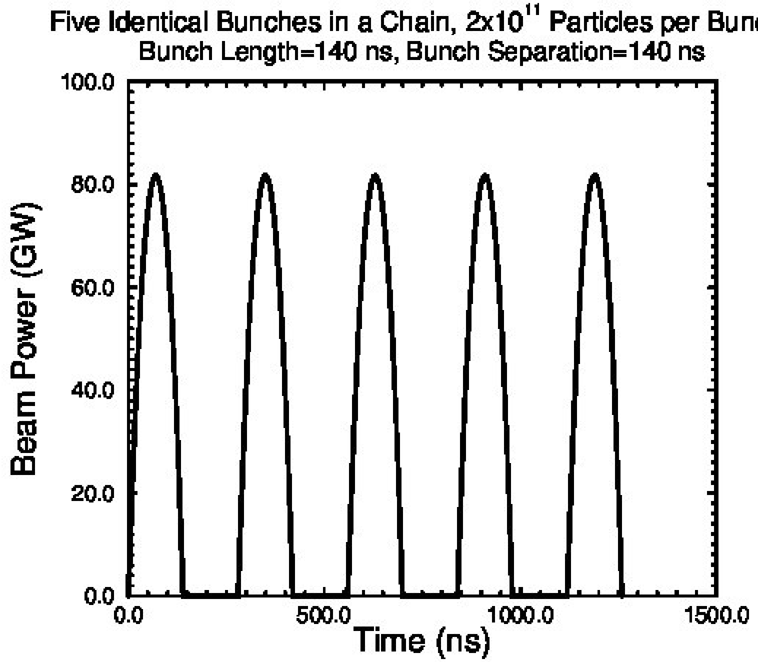

0.5 mm
t = 10 ns
t = 20 ns
t = 30 ns
t = 40 ns
t = 50 ns
Density (g/cm^3)
Target Axis (cm)
18.0
15.0
12.0
9.0
6.0
3.0
0.0
0.00
0.10
0.20
0.30
0.40
0.50

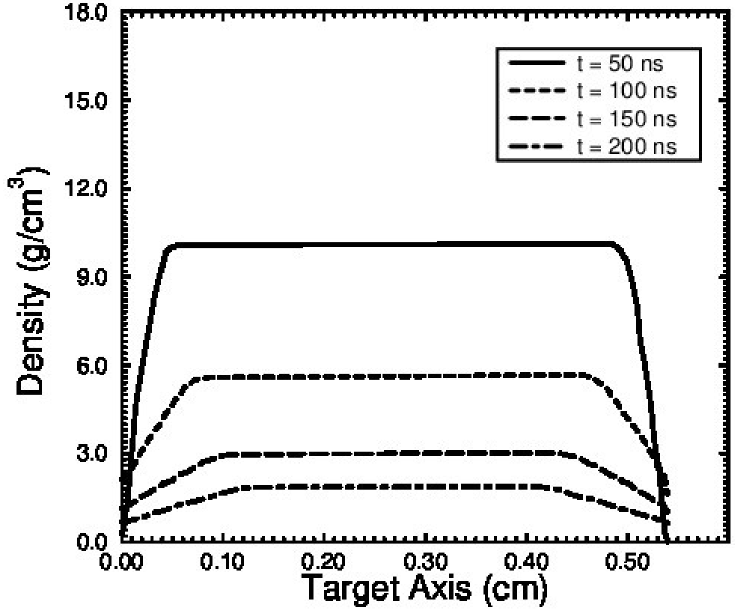

Single Parabolic Bunch, Length = 50 ns
Beam Radius (FWHM) = 0.5 mm
Beam Radius (FWHM) = 1.0 mm
Fraction of Ion Energy Escaping
Time (ns)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.0
10.0
20.0
30.0
40.0
50.0

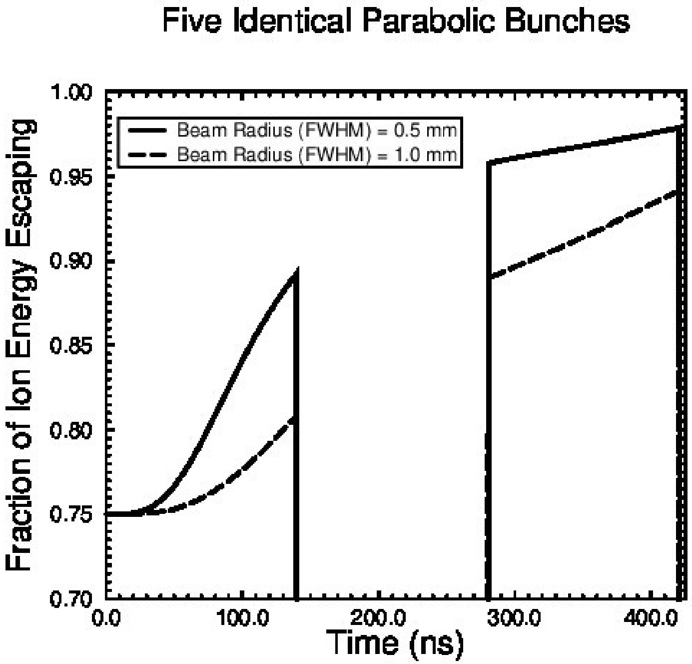

1 mm
t = 10 ns
t = 40 ns
t = 50 ns
Density (g/cm^3)
Target Axis (cm)
18.0
15.0
12.0
9.0
6.0
3.0
0.0
0.00
0.10
0.20
0.30
0.40
0.50

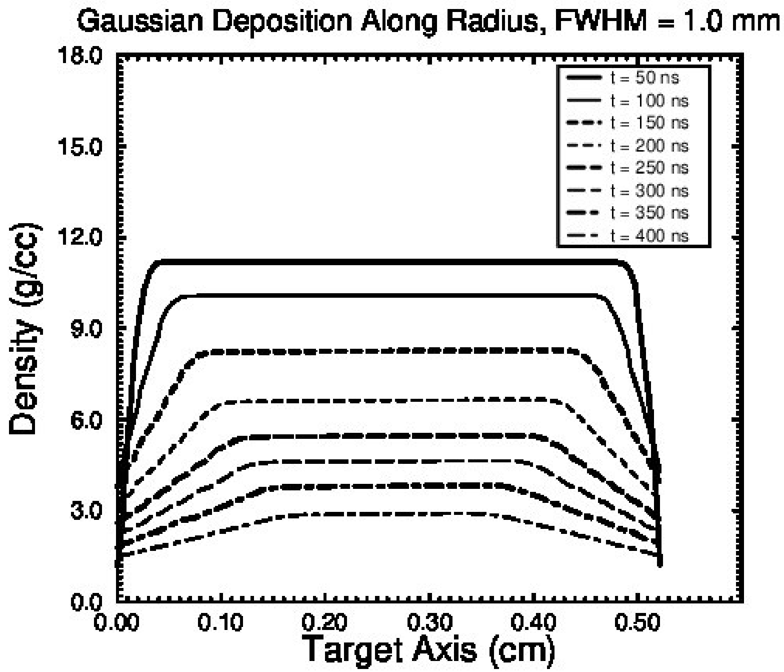

Single Bunch with a Length = 1000 ns
Beam Power (W)
Time (ns)
6.0e+10
5.0e+10
4.0e+10
3.0e+10
2.0e+10
1.0e+10
0.0e+00
0.0
200.0
400.0
600.0
800.0
1000.0


Fraction of Ion Energy Escaping
Time (ns)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.0
100.0
200.0
300.0
400.0
Beam Radius (FWHM) = 0.5 mm
Beam Radius (FWHM) = 1.0 mm


Five Identical Bunches in a Chain, 2x10^11 Particles per Bunch
Bunch Length=140 ns, Bunch Separation=140 ns
Beam Power (GW)
Time (ns)
0.0
20.0
40.0
60.0
80.0
100.0
0.0
500.0
1000.0
1500.0


t = 50 ns
t = 100 ns
t = 150 ns
t = 200 ns
Density (g/cm^3)
Target Axis (cm)
0.0
3.0
6.0
9.0
12.0
15.0
18.0
0.00
0.10
0.20
0.30
0.40
0.50


Five Identical Parabolic Bunches
Beam Radius (FWHM) = 0.5 mm
Beam Radius (FWHM) = 1.0 mm
Fraction of Ion Energy Escaping
Time (ns)
0.70
0.75
0.80
0.85
0.90
0.95
1.00
0.0
100.0
200.0
300.0
400.0


Gaussian Deposition Along Radius, FWHM = 1.0 mm
t = 50 ns
t = 100 ns
t = 150 ns
t = 200 ns
t = 250 ns
t = 300 ns
t = 350 ns
t = 400 ns
Density (g/cc)
Target Axis (cm)
0.0
3.0
6.0
9.0
12.0
15.0
18.0
0.00
0.10
0.20
0.30
0.40
0.50

Role of Hydrodynamic Tunneling in Case of SPS, LHC and FCC

Parameters	SPS	LHC	FCC
Proton Energy	450 GeV	7 TeV	50 TeV
Bunch Intensity	1.5×10^{11}	1.15×10^{11}	10^{11}
Bunches / Beam	288	2808	10600
Bunch Length	0.5	0.5 ns	0.5 ns
Bunch Separation	25/50 ns	25 ns	25 ns
Beam Duration	7.2 μs	89 μs	265 μs
Focal Spot σ	0.2 mm	0.2 mm	0.2 mm
Energy / Bunch	15.57 kJ	128.8 kJ	800 kJ
Energy / beam	3.8 MJ	362 MJ	8.5 GJ
Tunnel	6.9 km	28 km	100 km

- **An accidental release of even a small fraction of the beam energy can cause considerable damage to the equipment. This may happen by deflecting the beam with a wrong angle (towards collimators, magnets and other equipment).**
- **A very serious scenario could be the loss of the entire beam at a single point.**
- **Chances of happening of such an accident are remote.**
- **The consequences of such an accident needs to be estimated. The risk must remain acceptable. Depending on the consequences the probability for such failure has to be adequate to keep the risk acceptable.**
- **For this purpose we carried out numerical simulations of the full impact of the LHC beam and the FCC beam with solid targets.**

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

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.

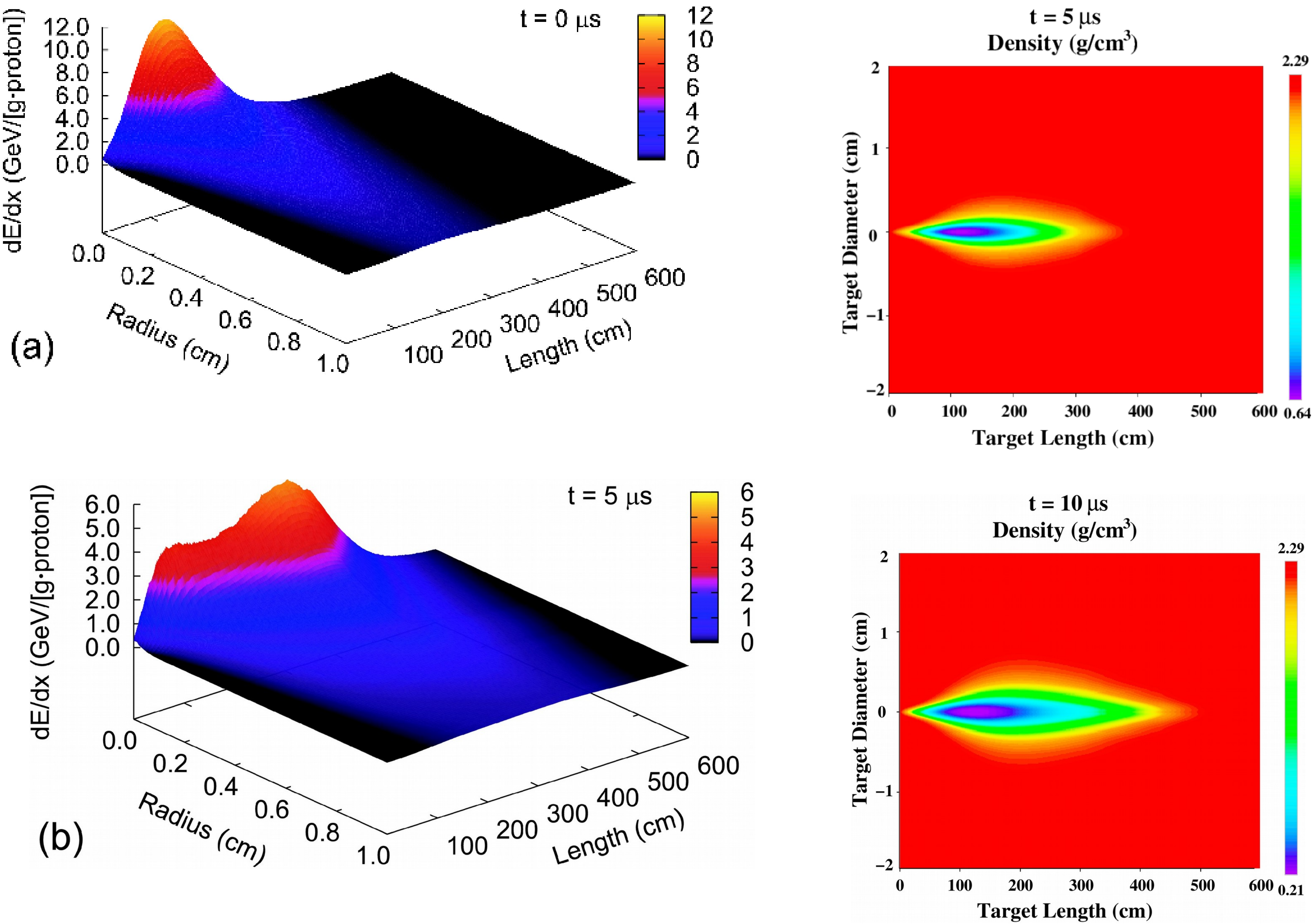
Continuation of this process leads to <u>very substantial range lengthening</u> of the protons and their shower.

Simulations Strategy

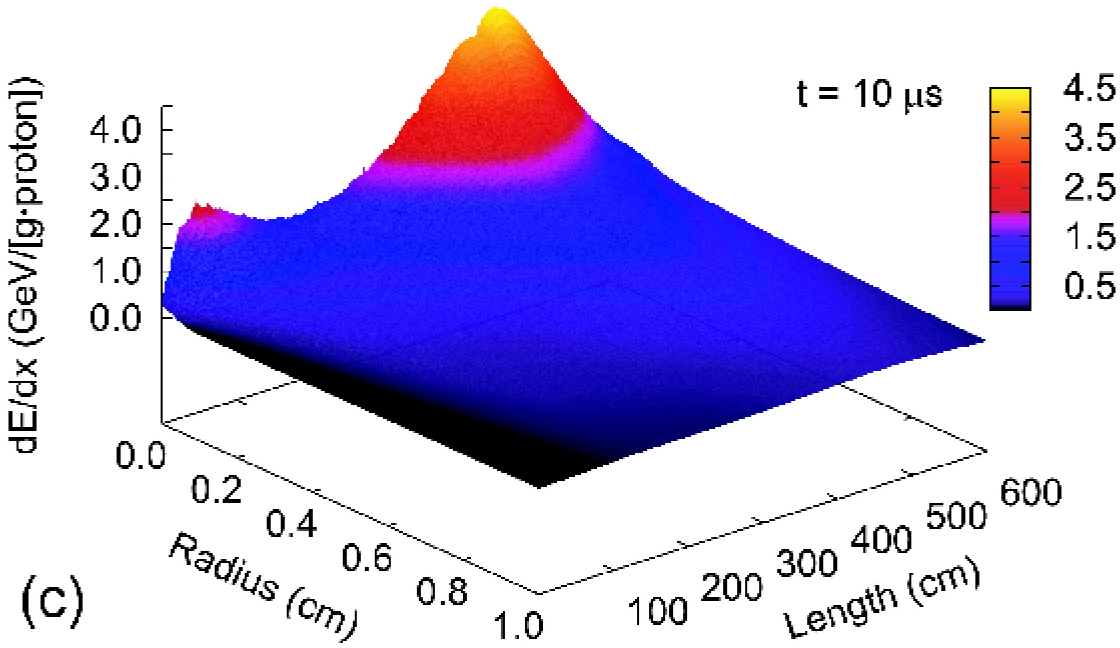
The simulations are carried out using the energy deposition code FLUKA and a 2D hydrodynamic code BIG2, iteratively.

- **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.**

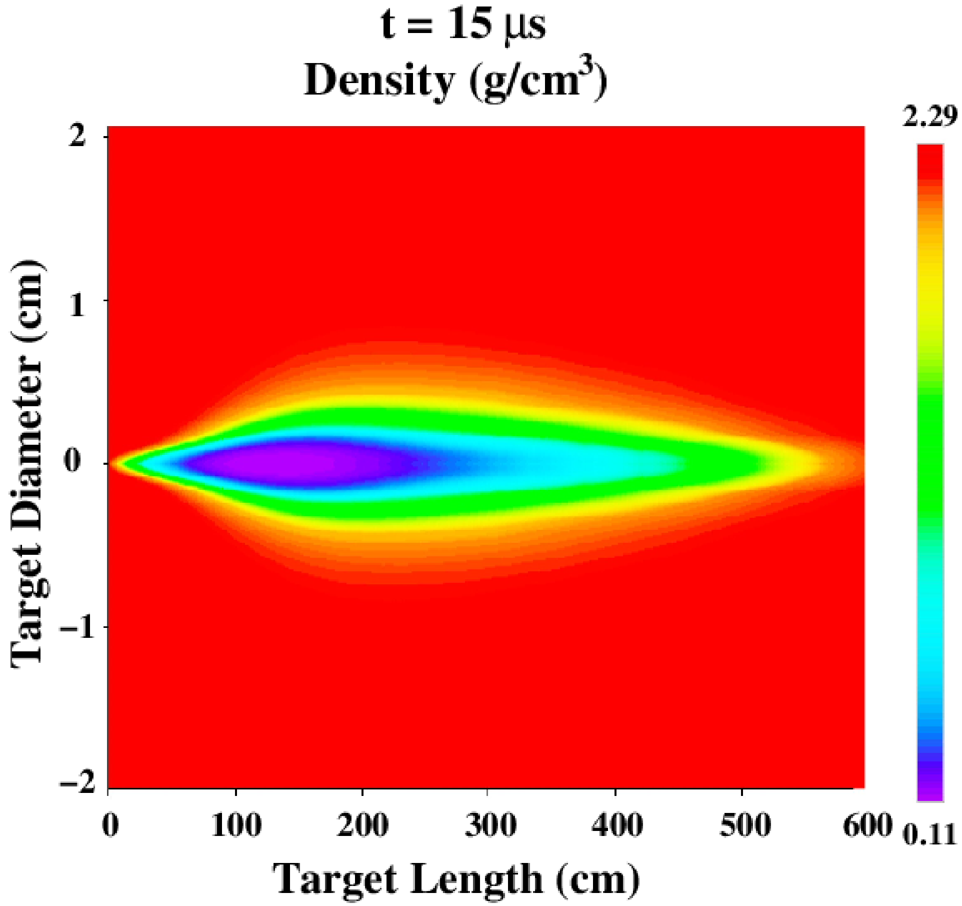
Iteration step is determined by the beam parameters

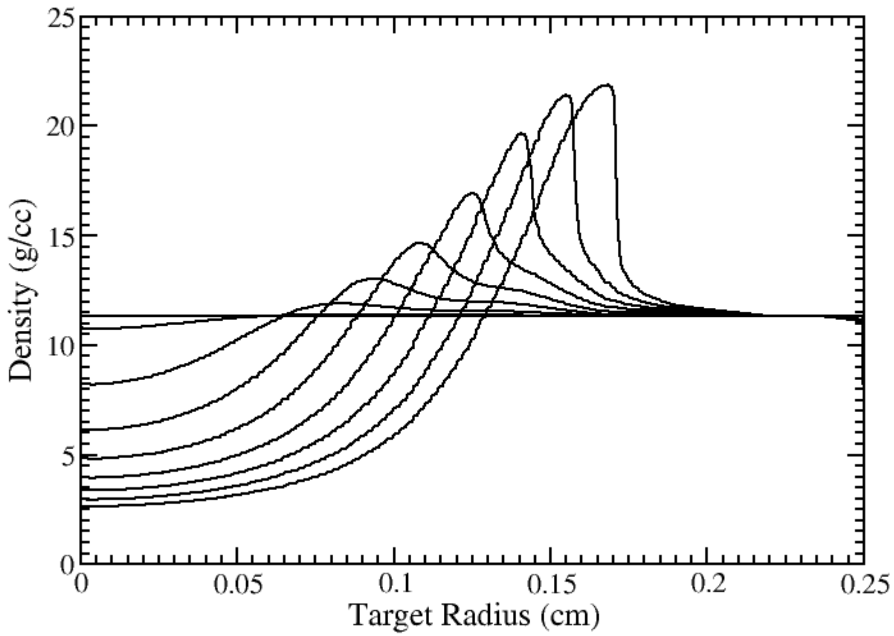


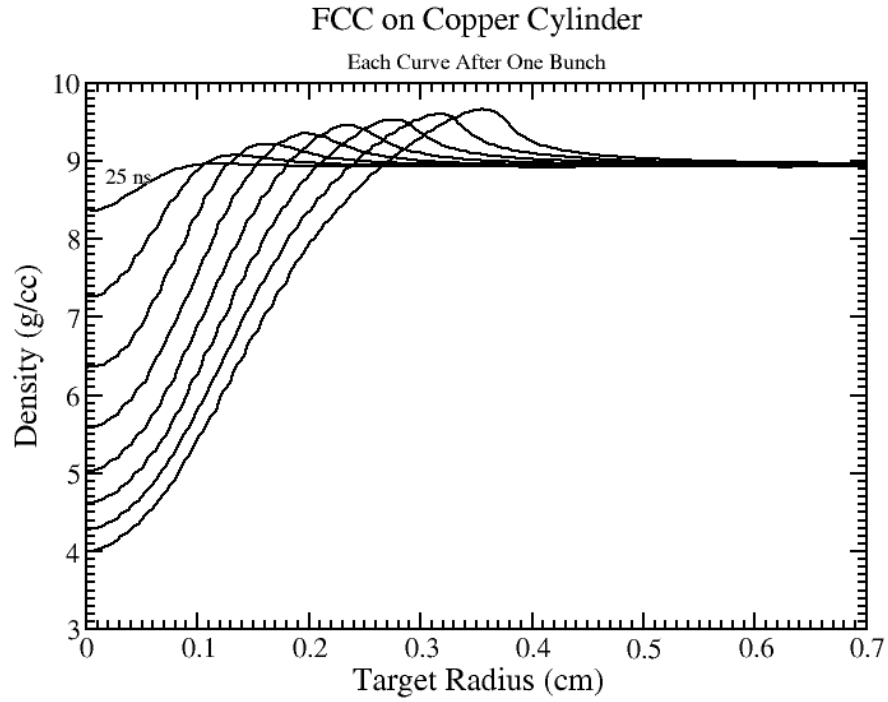
t = 0 μs
dE/dx (GeV/[g·proton])
12.0
10.0
8.0
6.0
4.0
2.0
0.0
12
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
Radius (cm)
100
200
300
400
500
600
Length (cm)
(a)
t = 5 μs
Density (g/cm³)
2.29
0.64
Target Diameter (cm)
2
1
0
−1
−2
0
100
200
300
400
500
600
Target Length (cm)
t = 5 μs
dE/dx (GeV/[g·proton])
6.0
5.0
4.0
3.0
2.0
1.0
0.0
6
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
Radius (cm)
100
200
300
400
500
600
Length (cm)
(b)
t = 10 μs
Density (g/cm³)
2.29
0.21
Target Diameter (cm)
2
1
0
−1
−2
0
100
200
300
400
500
600
Target Length (cm)

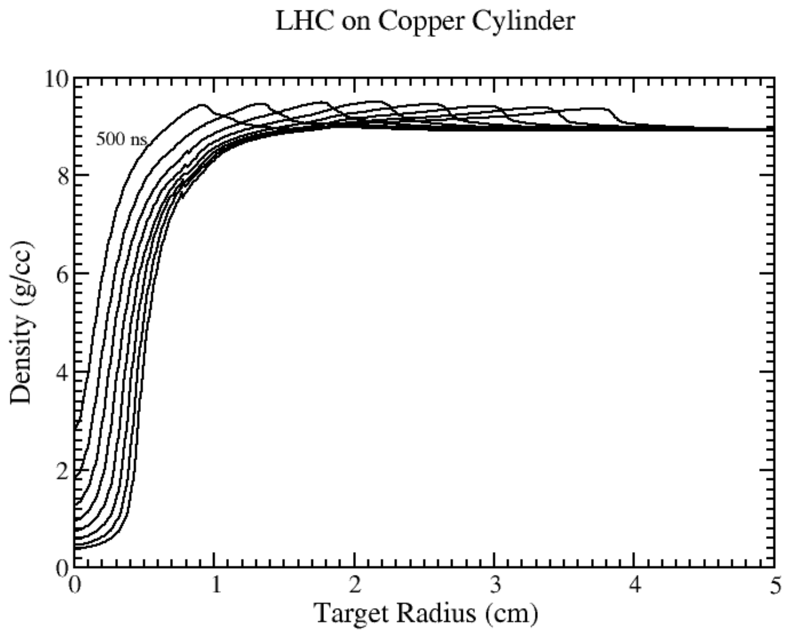

t = 10 μs
4.5
3.5
2.5
1.5
0.5
dE/dx (GeV/[g·proton])
4.0
3.0
2.0
1.0
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Radius (cm)
100
200
300
400
500
600
Length (cm)

(c)


t = 15 μs
Density (g/cm^3)
2.29
0.11
Target Diameter (cm)
2
1
0
−1
−2
0
100
200
300
400
500
600
Target Length (cm)


Density (g/cc)
Target Radius (cm)
0
5
10
15
20
25
0
0.05
0.1
0.15
0.2
0.25


FCC on Copper Cylinder
Each Curve After One Bunch
25 ns
Density (g/cc)
Target Radius (cm)
3
4
5
6
7
8
9
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


LHC on Copper Cylinder
500 ns
Density (g/cc)
Target Radius (cm)
0
2
4
6
8
10
0
1
2
3
4
5

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

- **BIG2 is a 2D hydrodynamic computer code based on a Godunov type numerical scheme.**
- **It can work in Eulerian as well as Lagrangian algorithm.**
- **It can handle simple and complicated geometries and can deal with single as well as multi-layered targets.**
- **It uses sophisticated, very versatile and stable mesh.**
- **It includes thermal conduction.**
- **It includes ion energy deposition [uses SRIM for heavy ion energy deposition and FLUKA for SPS, LHC and FCC protons].**

- **It treats elastic plastic effects using Prandtl-Reuss model, which means Hooks law complemented with von Mises yield criterion:**

$$M = [3(б^2_{xx}+2б^2_{xy}+б^2_{yy})/2Y^2_0]$$

If M < 1, elastic regime, Otherwise the material is plastified.

б represents components of the stress tensor Y_0 is yield strength.

- **Different phases of the target material are treated using a semi-empirical EOS model [*I.V. Lomonosov LPB 25 (2007)567*]. This package includes treatment for solid, melting, liquid, 2-phase liquid-gas and gaseous states. In addition to that, it includes data of all the experimental measurements made for a given material. *Effects of first ionization level are included by combining it with a plasma chemical model.***

Hydrodynamic Simulations

1. Lagrangian algorithm

Coordinate system moves with the fluid (velocity "v")

Advantages

Well defined material interfaces

Free boundary conditions applicable

High degree of compression with high resolution can be studied

Disadvantages

Strong distortions of the computational mesh

2. Eulerian algorithm

Coordinate system is fixed (velocity "zero")

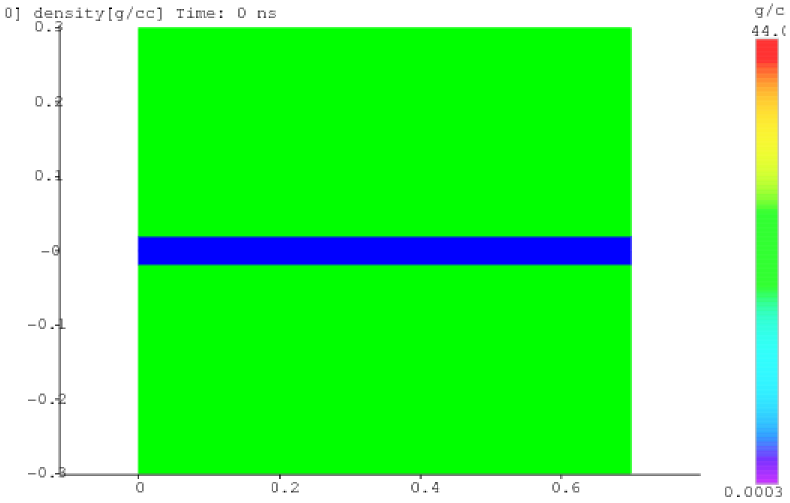
Advantages

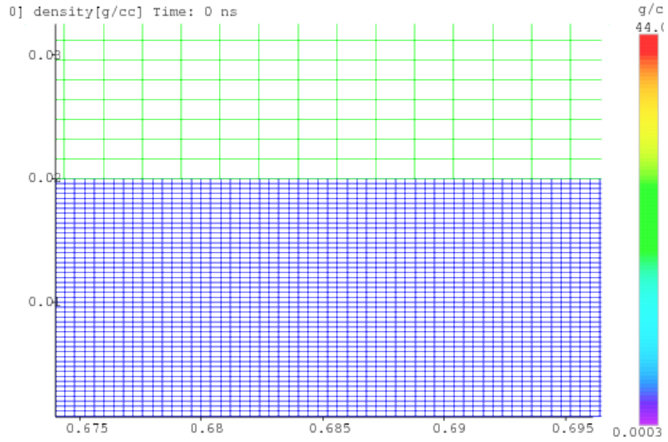
No mesh distortion

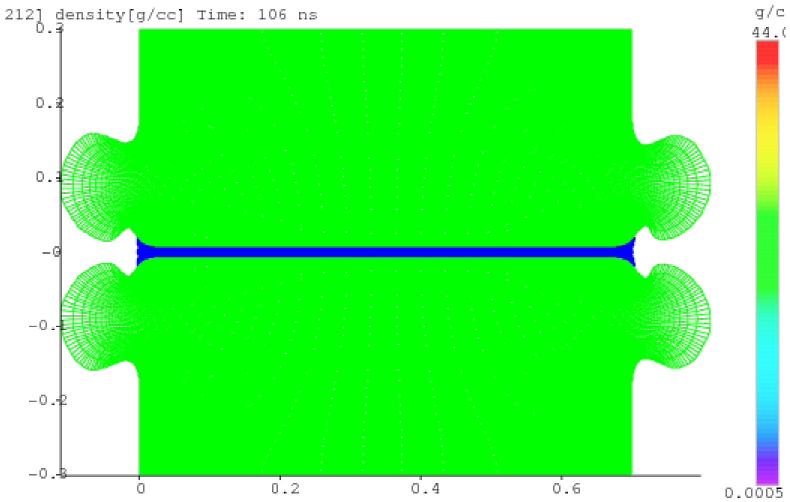
Disadvantages

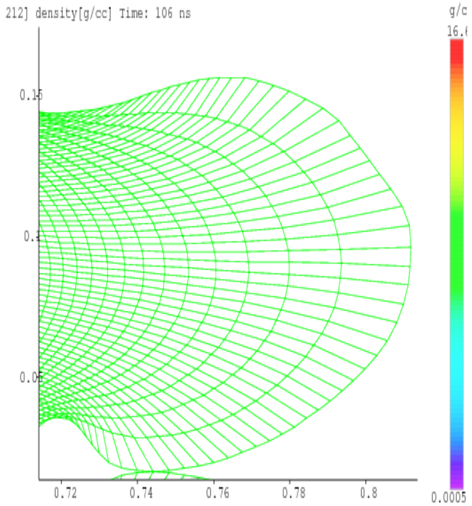
Material interfaces lose their sharp definitions, special treatment at interfaces, complicated, inaccuracies.

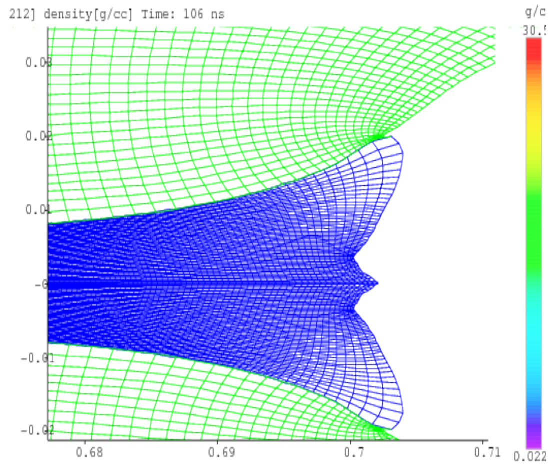
Local regions of fine resolution difficult to achieve

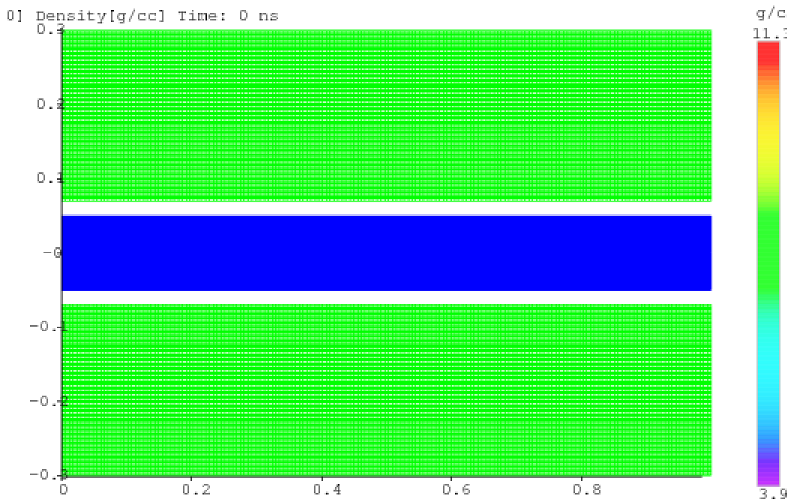

0] density[g/cc] Time: 0 ns
g/c
44.(
0.0003
0
0.2
0.4
0.6

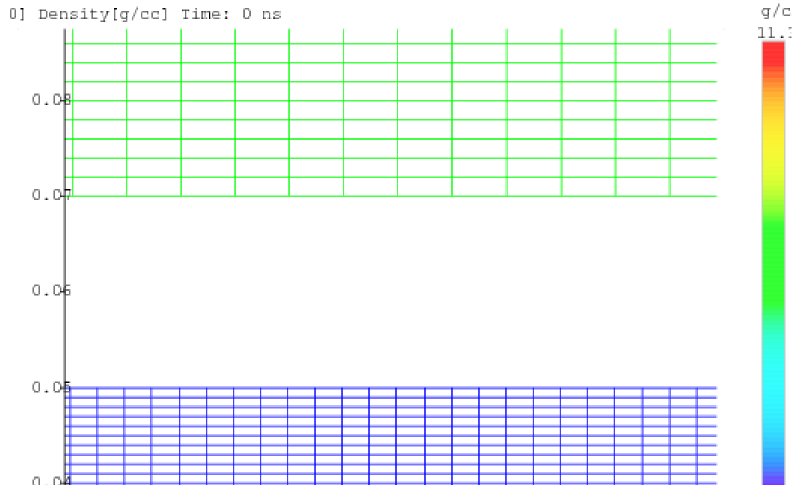

0] density[g/cc] Time: 0 ns
g/c
44.(
0.0003
0.675
0.68
0.685
0.69
0.695

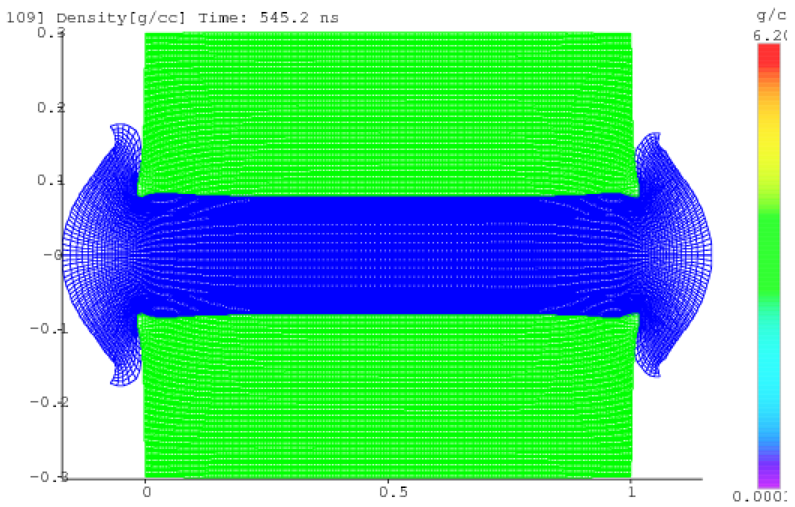

212] density[g/cc] Time: 106 ns
g/c
44.(
0.0005
0
0.2
0.4
0.6

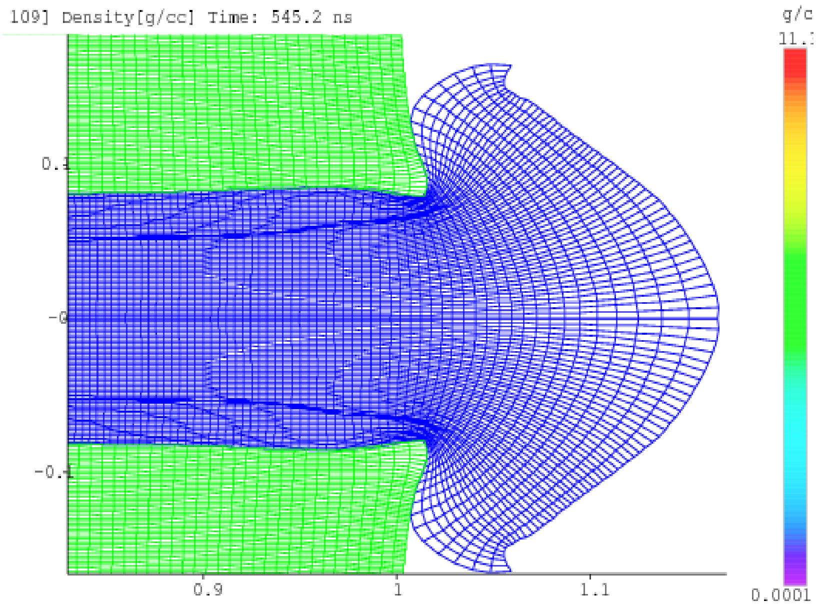

212] density[g/cc] Time: 106 ns
g/c
16.(
0.0005
0.72
0.74
0.76
0.78
0.8

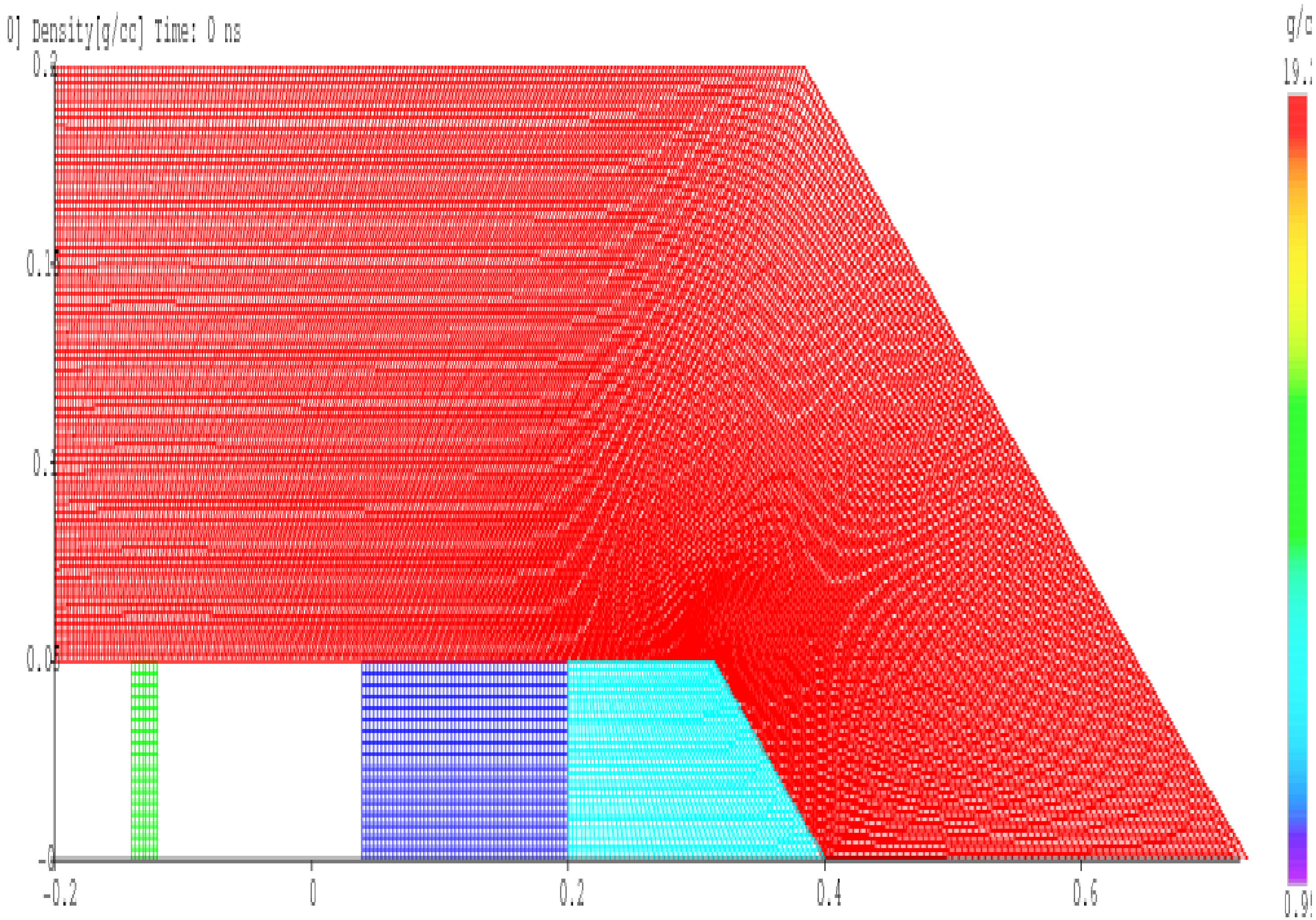

212] density[g/cc] Time: 106 ns
g/c
0.022
0.68
0.69
0.7
0.71


0] Density[g/cc] Time: 0 ns
g/c
11.1
3.9
0
0.2
0.4
0.6
0.8


0] Density[g/cc] Time: 0 ns
g/c
0.08
0.07
0.06
0.05


109] Density[g/cc] Time: 545.2 ns
g/c
0
0.5
1


109] Density[g/cc] Time: 545.2 ns
g/c
0.0001
0.9
1
1.1


0] Density[g/cc] Time: 0 ns
0.2
0.15
0.1
0.05
-0
-0.2
0
0.2
0.4
0.6
g/c
19.
0.9

Historical View of Hydrodynamic Tunneling

Simulations were done in the 80's to study the impact of the 20 TeV Superconducting Super Collider (SSC) proton beam with a carbon beam dump.

Energy deposition code MARS and hydrodynamic code, MESA (2D and 3D) were used for this purpose.

Beam duration = 290 μs

σ = 2 mm

Two fluences considered: 4×10^{17} and 10^{19} protons/s

First case: wave speed: 7 cm/s, penetration length = 20 m

Second case: wave speed: 70 cm/s, penetration length = 200 m

Beam dump length = 8 m

1. Impact of LHC 7 TeV proton beam with

1. Copper cylinder: L = 5 m; r = 5 cm; б = 0.2 mm;
   Beam duration = 89 μs.
   Solid density energy deposition data normalized with line density in each simulation cell at every time step.
   Penetration distance = 35 m.
2. Carbon cylinder: L = 6 m; r = 5 cm; б = 0.4 mm;
   FLUKA and BIG2 iteratively.
   Penetration distance = 25 m.

2. Design of Experiment at HiRadMat Facility

450 GeV SPS proton beam with Cu cylinder

FLUKA and BIG2 used iteratively

L = 1.5 m; r = 5 cm

288 proton bunches, bunch length = 0.5 mm

Bunch separation 25 ns.

Beam duration 7.2 µs.

б = 0.1, 0.2 and 0.5 mm

Penetration distance longer for shorter б.

It was concluded that 150 cm long Cu cylinder

Should be sufficient to stop the beam.

3. Interpretation of Experiments

440 GeV proton beam

Bunch length = 0.5 ns, Bunch separation = 50 ns,

Beam Duration = 7.2 μs.

Focal spot б = 2 mm, 144 bunches.

б = 0.2 mm, 108 bunches and 144 bunches.

15 solid copper cylinders, each 10 cm long having a radius = 4 cm with 1 cm gap in between.

For simplicity we used a single cylinder 150 cm long.

FLUKA and BIG2 used iteratively. Simulation results agreed with the experimental measurements within a few per cent.

4. Impact of FCC 40 TeV Proton Beam on Copper Target

40 TeV protons
10600 bunches, bunch length = 0.5 ns,
bunch separation = 25 ns, б = 0.2 mm.
Impact on a solid Cu cylinder
Length = 5 m, radius = 2 cm
FLUKA and BIG2 used iteratively.
Penetration distance about 310 m!
For 50 TeV it could be around 350 m.

5. Impact of FCC 50 TeV Proton Beam on Water Target

50 TeV protons

10600 bunches, bunch length = 0.5 ns,

bunch separation = 25 ns, б = 0.4 mm.

Impact on water cylinder

Length = 15 m, radius = 15 cm

FLUKA and BIG2 used iteratively.

Penetration distance about 1.3 km.

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7. R. Schmidt, J. Blanco Sancho, F. Burkart et al., Phys. Plasmas 21 (2014) 080701.
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14. **N.A. Tahir, R. Schmidt, M. Brugger et al., Phys. Plasmas 16 (2009) 082703.**
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