High Energy Density Physics Research at FAIR: The HEDgeHOB Collaboration

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Definition:

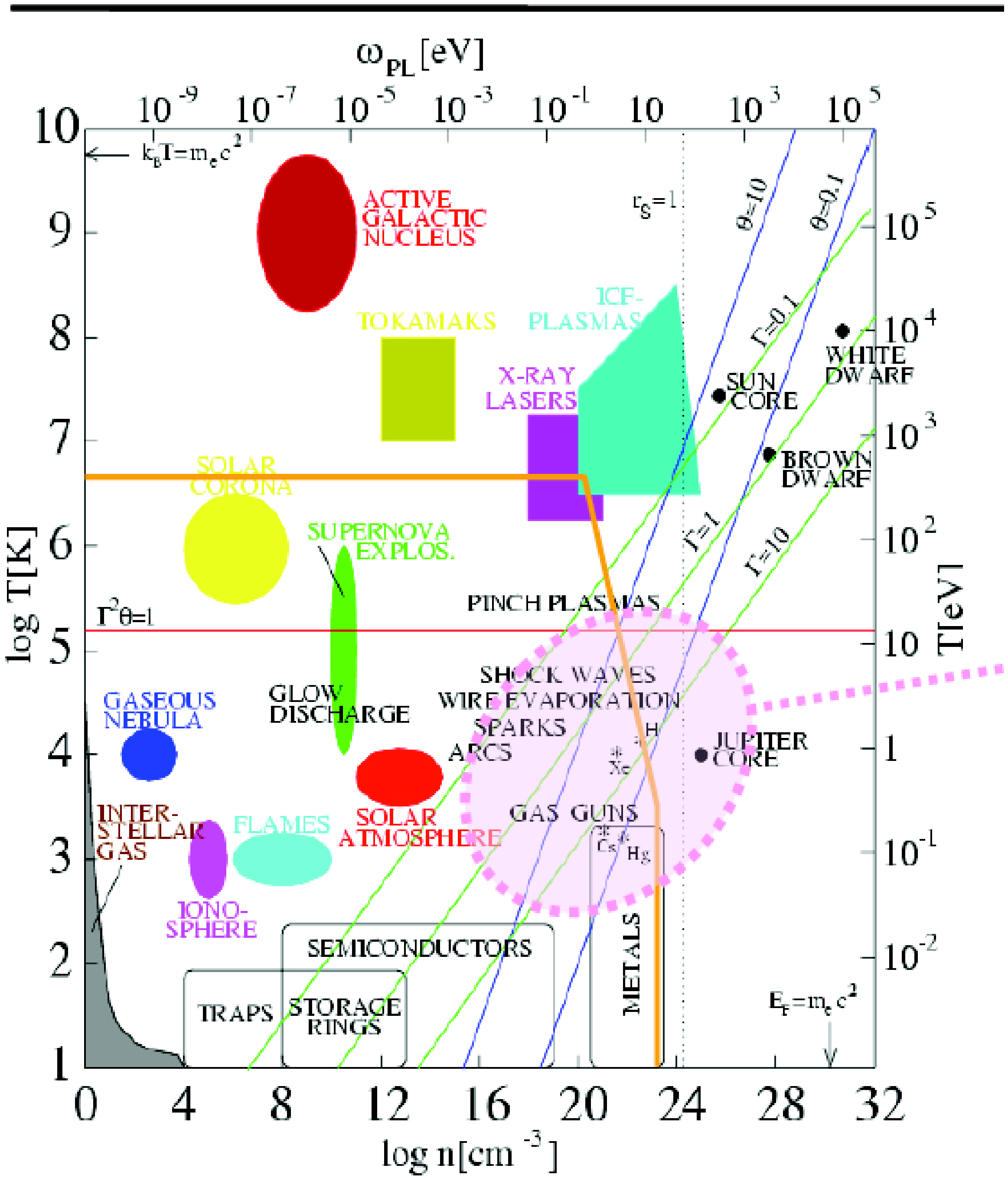
States that correspond to an energy content of 10^{11} J/m^3 or equivalently 1 Mbar pressure [HED states].

Importance:

Spans over wide areas of basic & applied physics. For example; astrophysics, planetary sciences, geophysics, inertial fusion, strongly coupled plasmas and many others.

In addition to that, HED matter has great potential for numerous lucrative industrial applications.

Region at the top and to the right of the brown line is HED matter. Region enclosed in purple circle is the WDM .



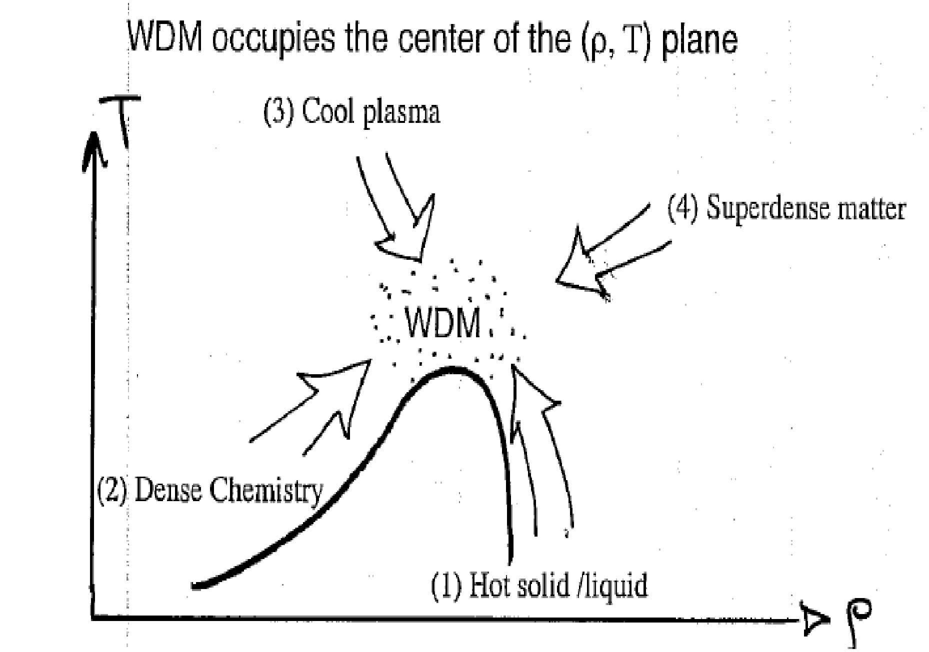
R. More

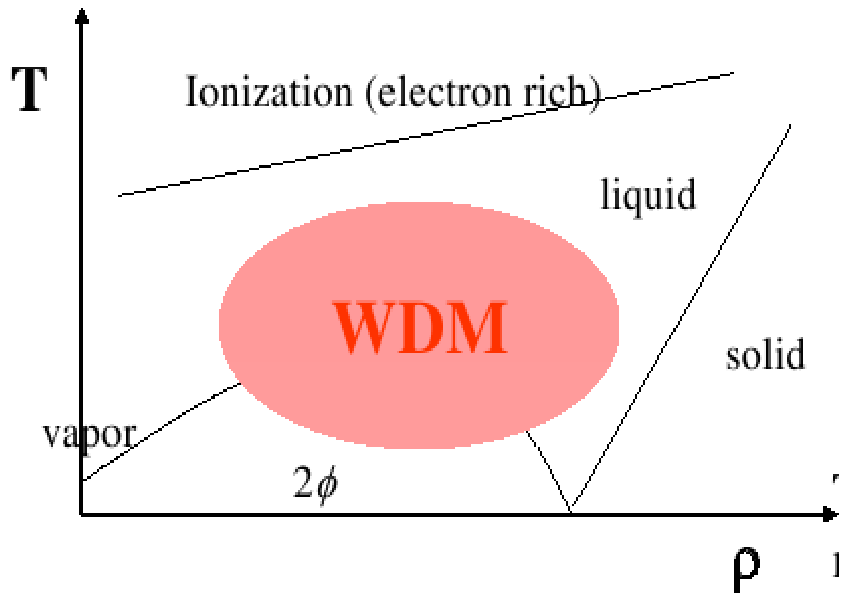
Definition: **WDM state of matter between a normal solid and an ideal plasma.**

Standard theoretical techniques break down in this region.

Experiments are badly needed to investigate physical properties of the WDM region.

WDM occurs in cores of large planets and ICF plasmas.





Intense particle beams are a novel, very efficient tool to study HEDP and WDM *[N.A. Tahir et al. PRE **60** (1999) 4715; PRE **61** (2000) 1975; PRE **62** (2000) 1224; PRE **63** (2001) 016402; PRE **63** (2001) 036407; PRB **67** (2003) 184101].*

Main Advantages of this scheme are:

- **High repetition rate, high coupling efficiency**
- **Large sample size**
- **Fairly uniform physical conditions (no sharp gradients)**
- **Precise knowledge of energy deposition in the sample**
- **Long life times**
- **Any target material can be used**

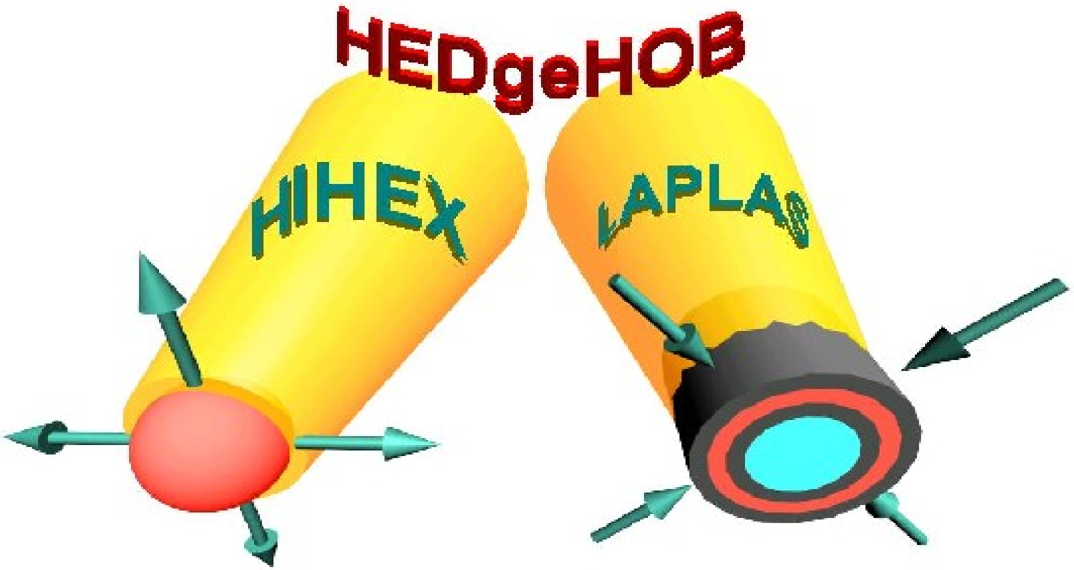
Two huge international particle accelerator projects:

FAIR in Germany and LHC in Switzerland

The new synchrotron, SIS-100 that will be built at the future **FAIR** [**F**acility for **A**ntiprotons and **I**on **R**esearch] facility, will deliver a uranium beam with three orders of magnitude higher intensity than what is currently available at the existing SIS-18 synchrotron.

SUMMARY OF PARAMETERS

	SIS-18	SIS100	
Intensity	**$4x10^9$**	**$5x10^{11}$**	[x 100]
Bunch Length	**130 ns**	**50 ns**	
Beam Energy	**0.06 kJ**	**76 kJ**	
Particle Energy	**400 MeV/u**	**0.4 – 2.7 GeV/u**	
FWHM	**1.0 mm**	**1.0 mm**	
Specific Energy Deposition in Pb	**1 kJ/g**	**150 kJ/g**	[x 150]
Specific Power Deposition in Pb	**5 GW/g**	**3 TW/g**	[x 600]



HEDgeHOB [<u>**H**</u>igh <u>**E**</u>nergy <u>**D**</u>ensity Matter <u>**Ge**</u>nerated by <u>**H**</u>eavy I<u>**o**</u>n <u>**B**</u>eams]

HIHEX [<u>**H**</u>eavy <u>**I**</u>on <u>**H**</u>eating and <u>**Ex**</u>pansion]

LAPLAS [<u>**La**</u>boratory <u>**Pla**</u>netary <u>**S**</u>cience]

Ramp Compression

Richtmyer-Meshkov Instability Growth Studies

HIHEX [Heavy Ion Heating and Expansion

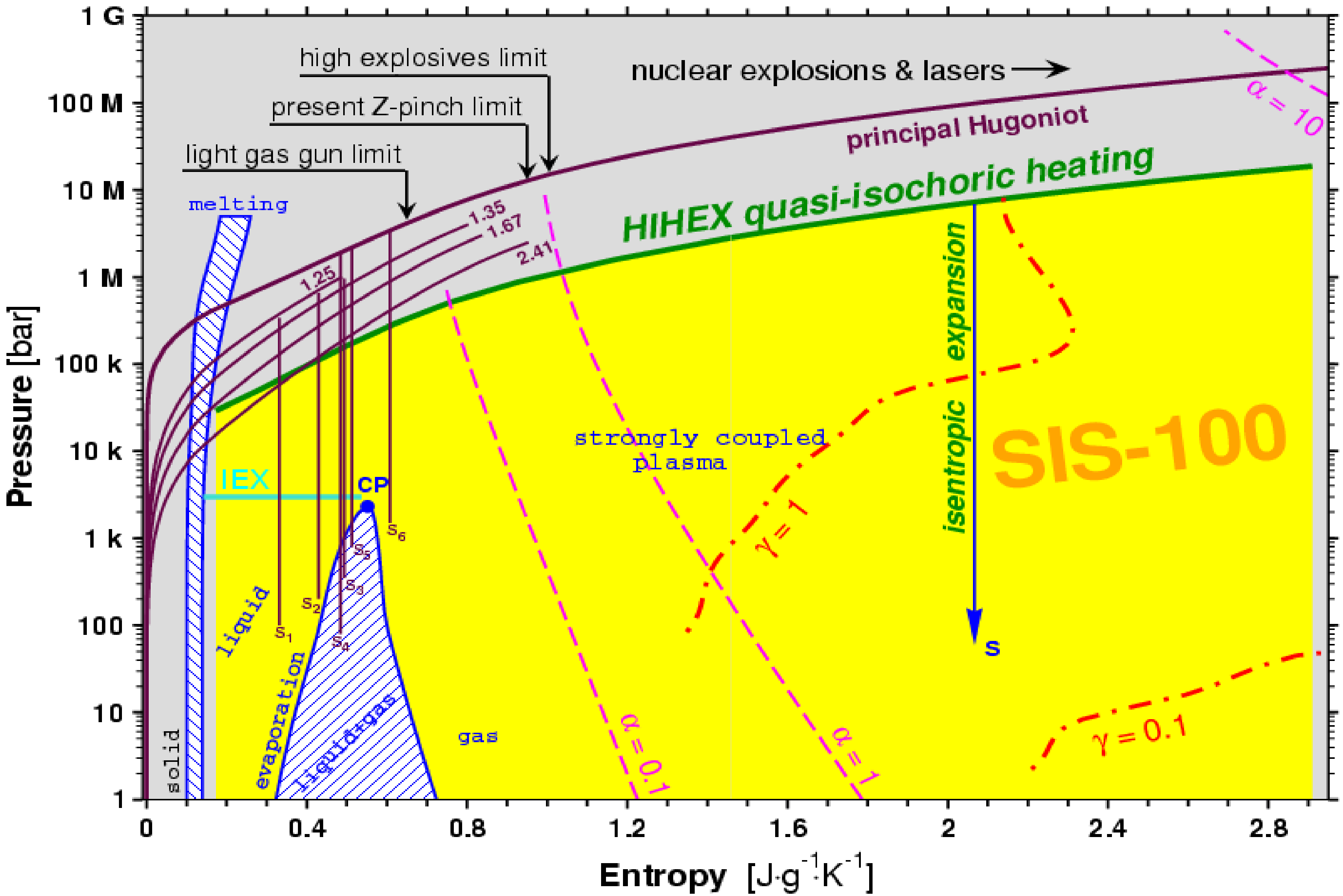
This technique involves isochoric and uniform heating of matter by an intense ion beam and the heated material is allowed to expand isentropically.

Expanded Hot Liquid
Two-Phase Liquid-Gas Region
Critical Parameters
Strongly Coupled Plasma

References:

1) D.H.H. Hoffmann et al., Phys. Plasmas 9 (2002) 3651.
2) N.A. Tahir et al., Phys. Rev. Lett. 95 (2005) 035001.

Phase diagram of lead

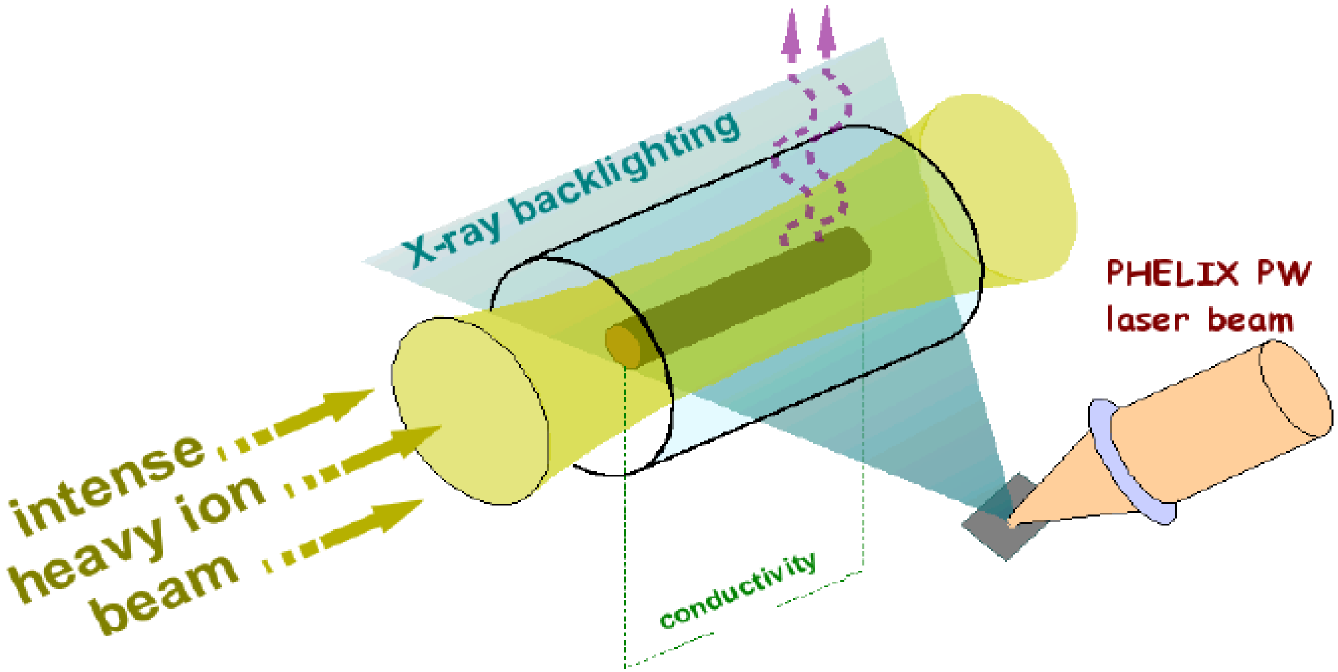


Critical Parameters of Some Metals

I.V. Lomonosov and V.E. Fortov

	T_c (K)	P_c (kbar)	ρ_c (g/cm^3)
Aluminum	6390	4.45	0.86
Copper	7800	9.00	2.28
Gold	8500	6.14	6.10
Lead	5500	2.30	3.10
Niobium	19200	11.1	1.70
Tantalum	14550	7.95	3.85
Tungsten	13500	3.10	2.17
Beryllium	8600	2.00	0.40

Cylindrical HIHEX Experiment Design Using Solid Material



Numerical Simulation Results:

Target Parameters:

Solid lead cylinder, L = 2 - 3 mm, r = 300 - 500 μm

Beam Parameters:

Uranium Beam

Particle Energy = 1 GeV/u

Beam Intensity = 10^{10} – 10^{11} ions / bunch

Bunch Length = 50 ns

Early and Intermediate Stages of FAIR

N.A. Tahir et al., Phys. Rev. Lett. **95** (2005) 035001

Simulation Results from a Typical Case

- Solid Lead Cylinder
- L = 2 mm, r = 300 μm
- N = 2.5 x10^{10}
- Bunch Length = 50 ns
- Beam spot Size (FWHM) = 2 mm

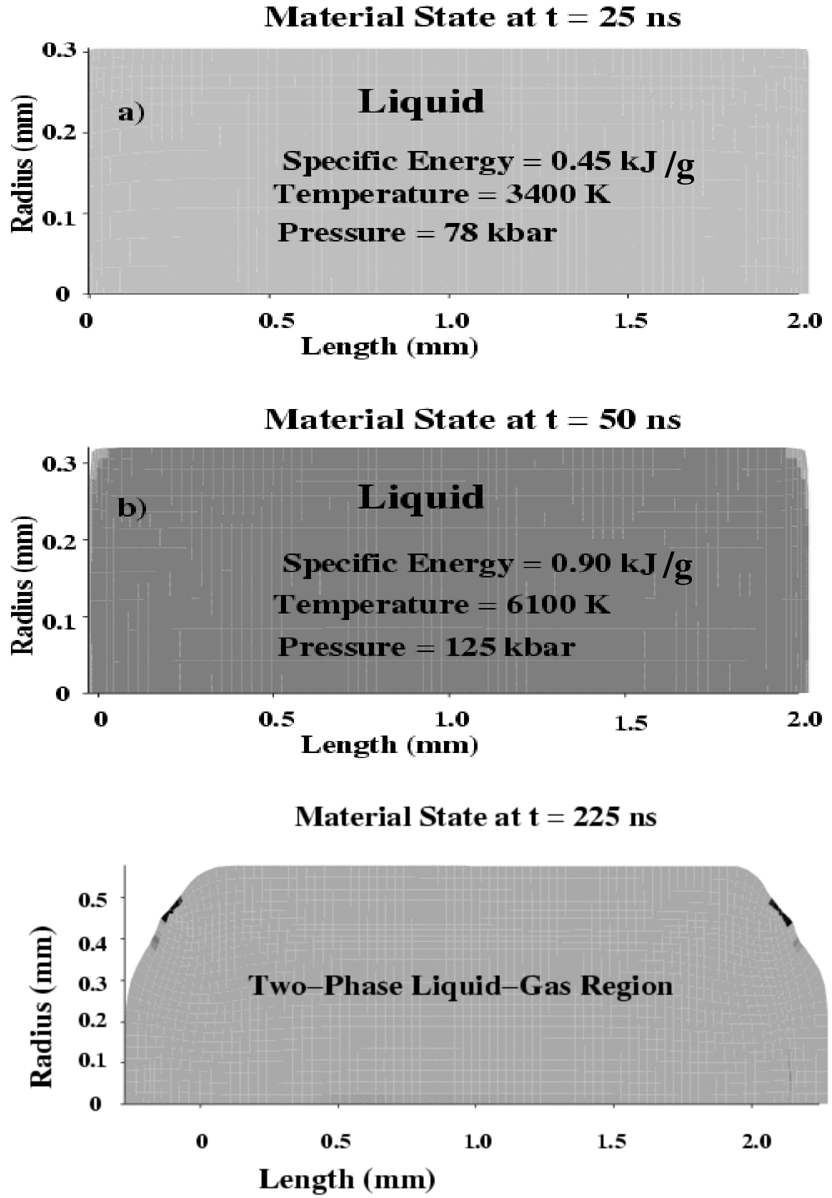


Table 1: Final Achievable Material State

Intensity	FWHM (mm)	Material State
10^{11}	1	*SCP*
	2	*SCP*
	3	*CP*
	4	*2PLG*
$7.5 \cdot 10^{10}$	1	*SCP*
	2	*G*
	3	*2PLG*
	4	*2PLG*
$5 \cdot 10^{10}$	1	*SCP*
	2	*EHL*
	3	*2PLG*
$2.5 \cdot 10^{10}$	1	*G*
	2	*2PLG*
	3	*2PLG*
10^{10}	1	*2PLG*
	2	*2PLG*

SCP : strongly coupled plasmas

CP : critical point

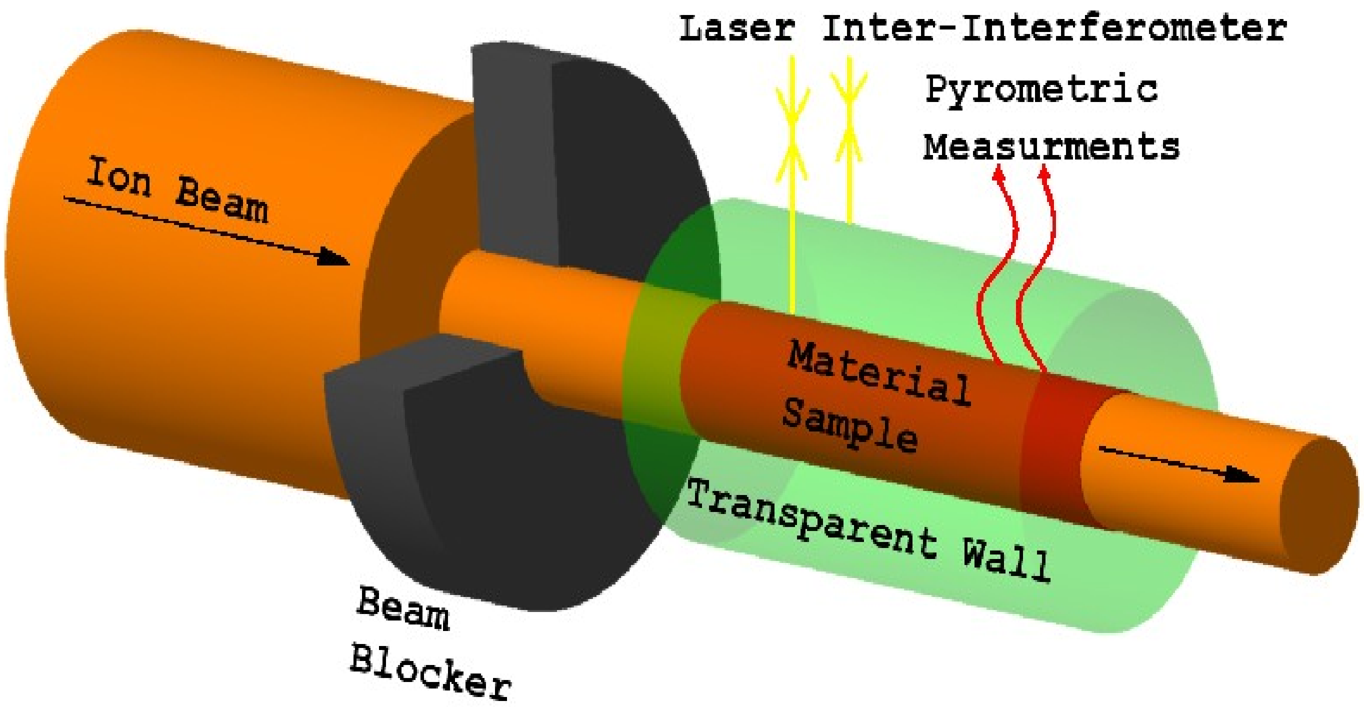
2PLG: two-phase liquid-gas

EHL : expanded hot liquid

G : Gas

HIHEX Using Porous Material

N.A. Tahir et al., High Energy Density Phys. 2 (2006) 21.



1 GeV/u uranium beam

$N = 5x10^{11}$, $\tau = 50$ ns

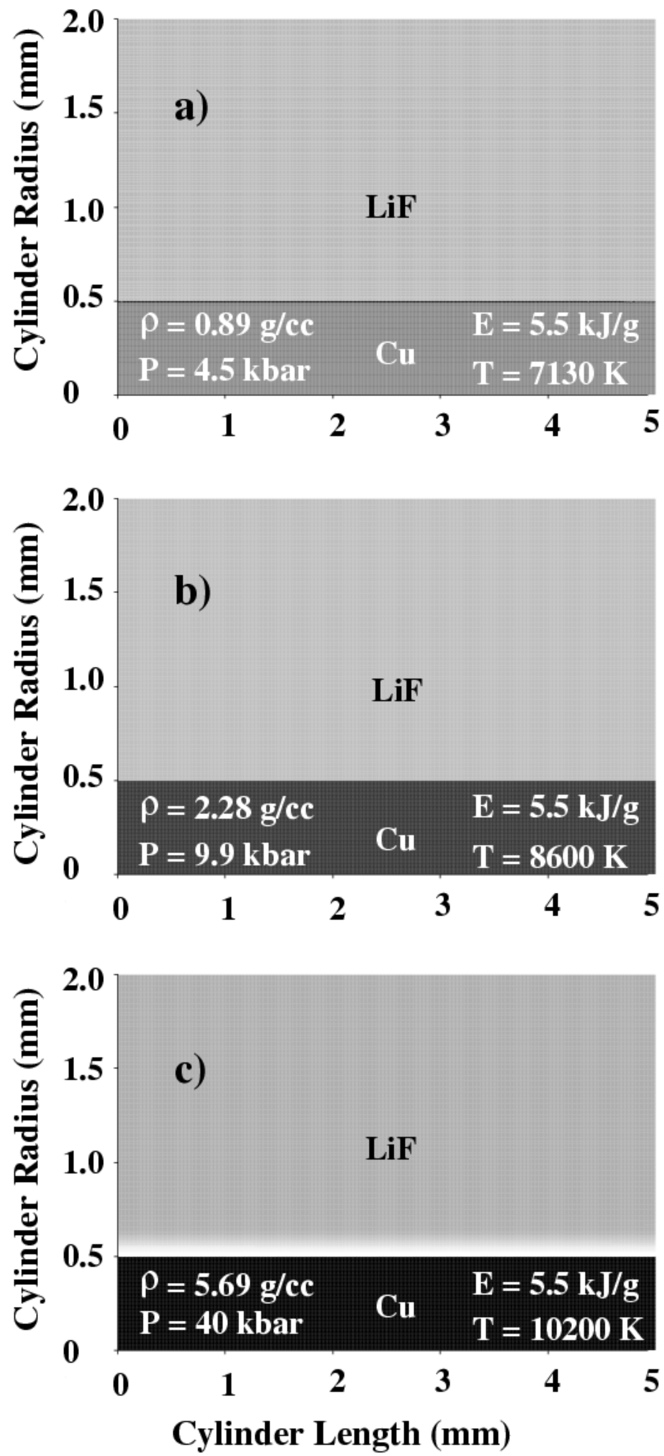
FWHM = 4 mm

$E_s = 5.5$ kJ/g

FWHM = 2 - 4 mm

$N = 10^{11} – 5x10^{11}$

$\Gamma = 5$



LAPLAS [LAboratory PLAnetary Sciences]

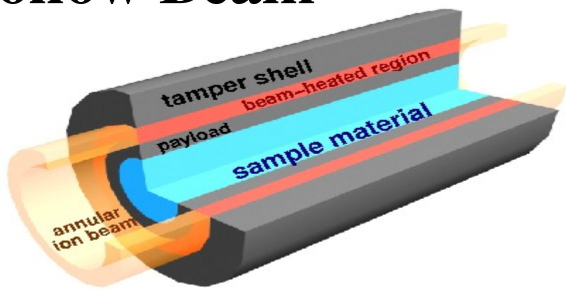
Experimental Scheme:

Low-entropy compression of a test material like H or H_2O, in a mult-layered cylindrical target [**Hydrogen Metallization , Planetary Interiors**]

N.A. Tahir et al., PRE 64 (2001) 016202; High Energy Density Phsics 2 (2006) 21;

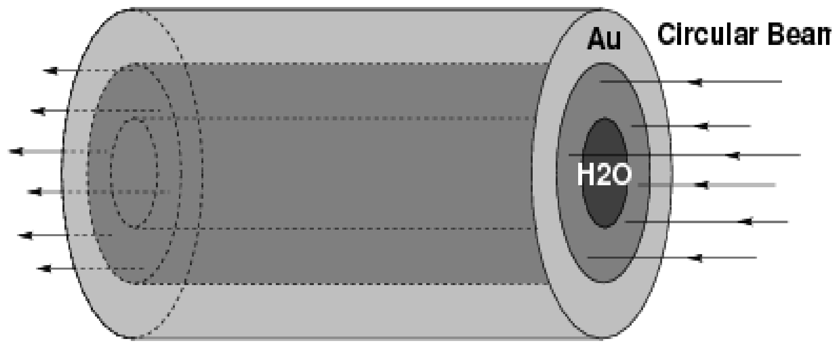
A.R. Piriz et al, PRE 66 (2002) 056403.

Hollow Beam



Au or Pb

Circular beam



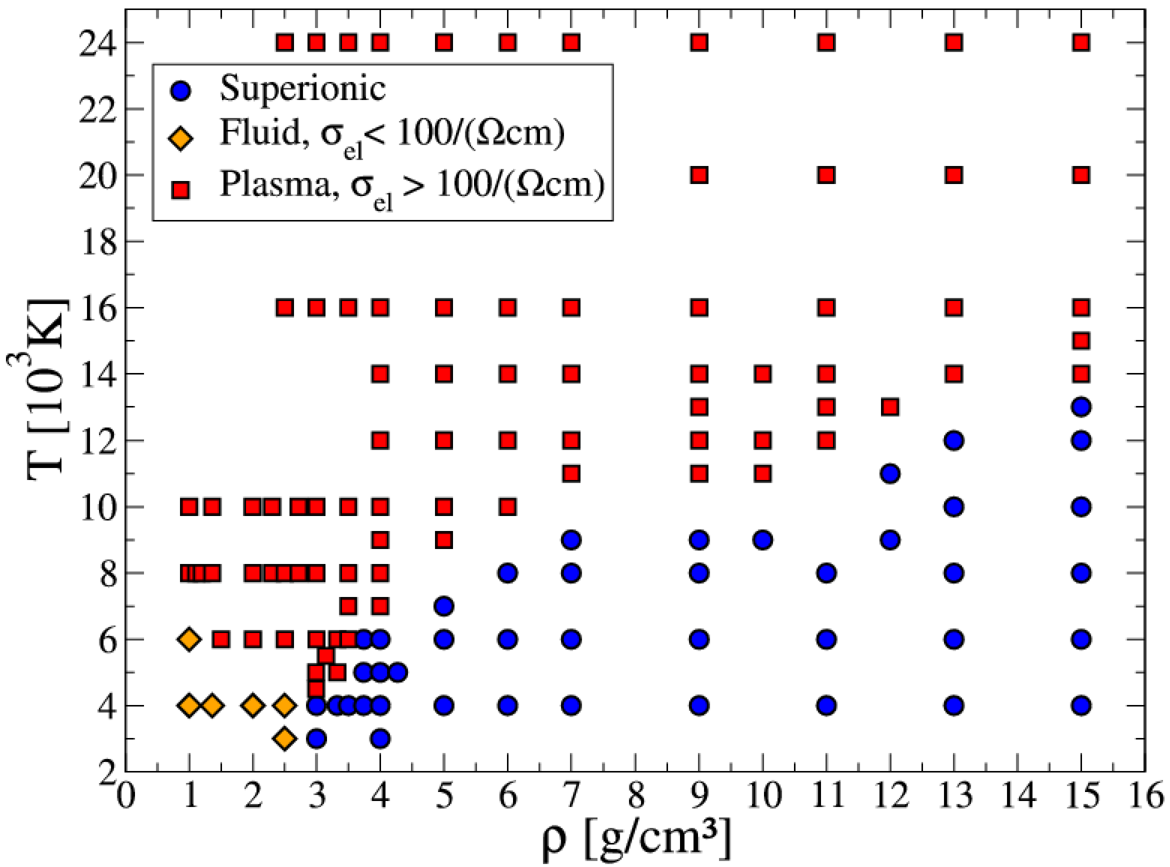
- Shock reverberates between the cylinder axis and the hydrogen-outer shell interface.
- Very high ρ (**2-3 g/cc**), ultra high P (**30 Mbar**) , low T (**of the order of 10 kK**).

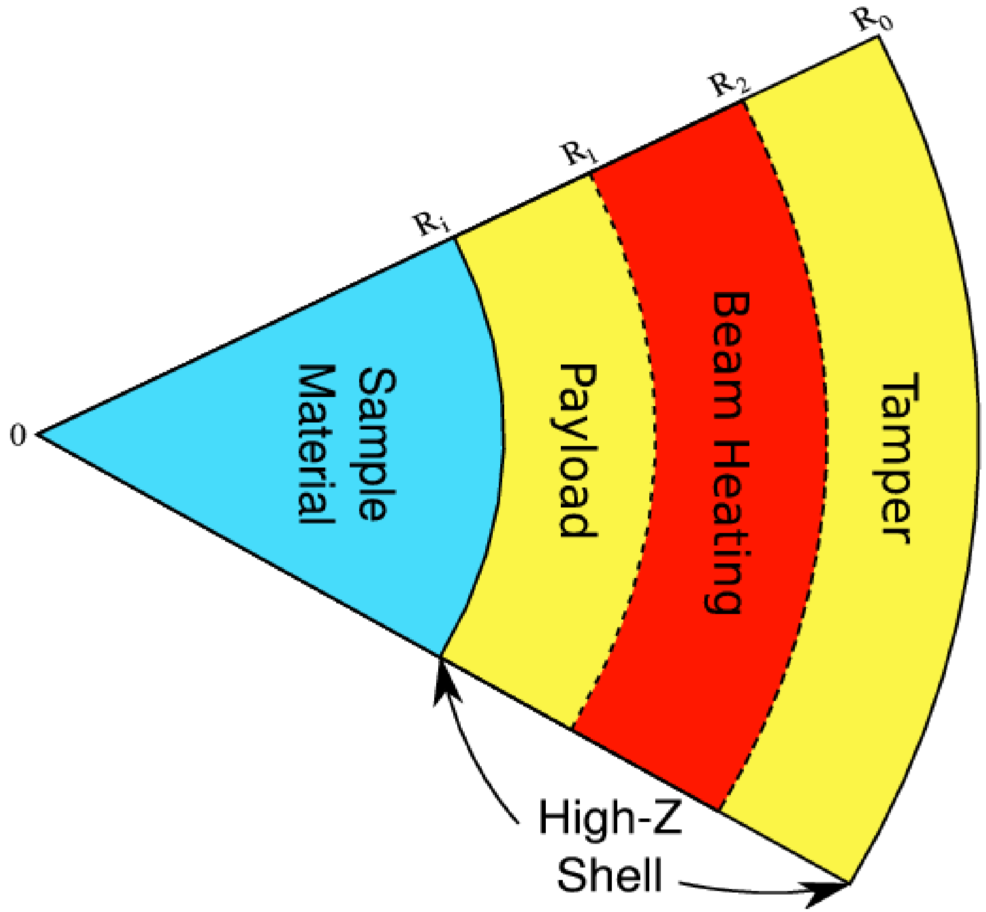
- **Very high densities, high pressure, higher temperature**
  ρ = 1.2 g/cc, P = 11 Mbar, T = 5 ev

Phase Diagram of Water [QMD Simulations]

Mattsson & Desjarlais, PRL 97 (2006) 017801

M. French et al., PRB <u>79</u> (2009) 054107





Hollow Beam

1.5 GeV/u U ions

τ = 50 ns

Sample : Water

Outer Shell: W & Nb

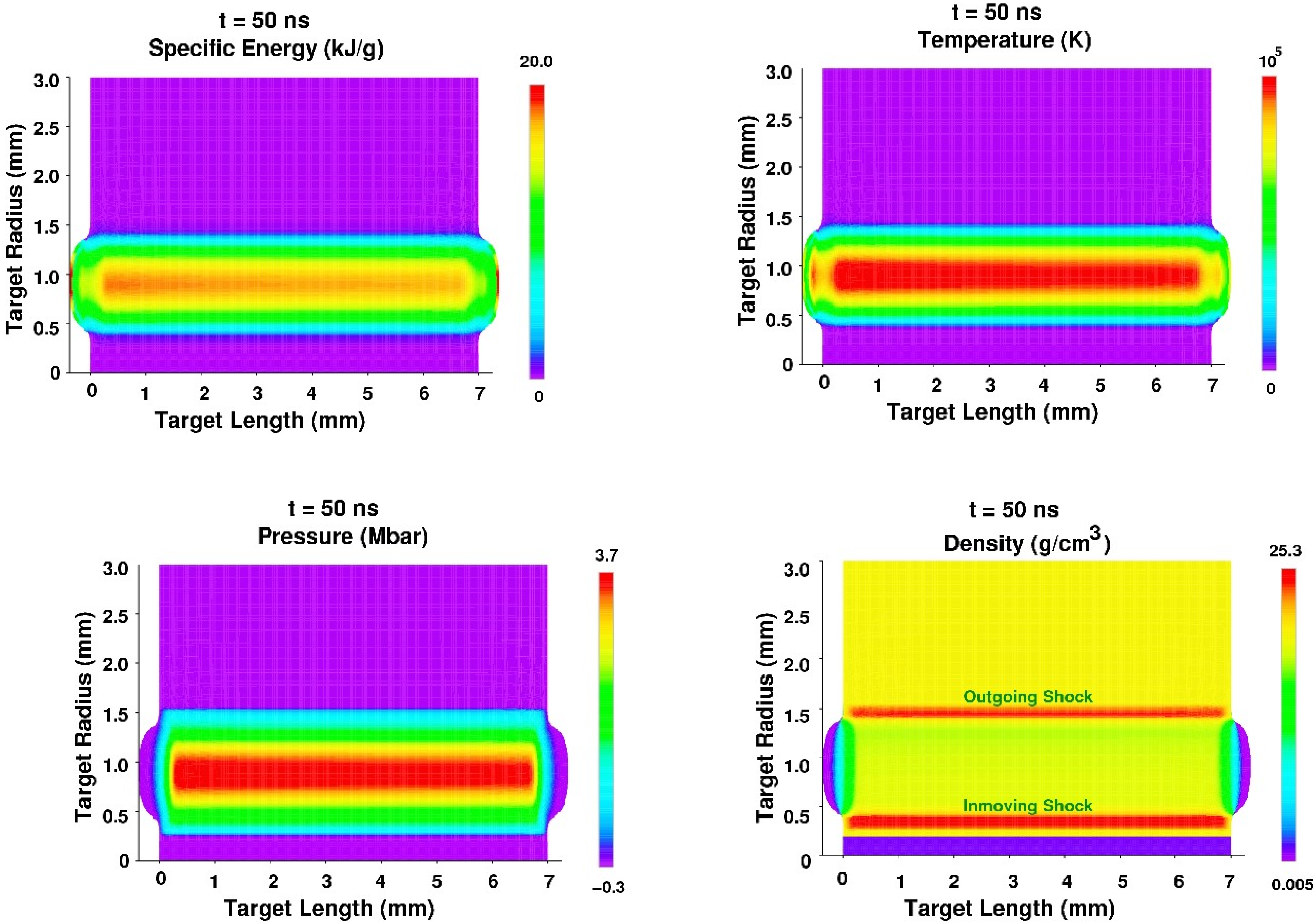
R_i = 0.2 mm

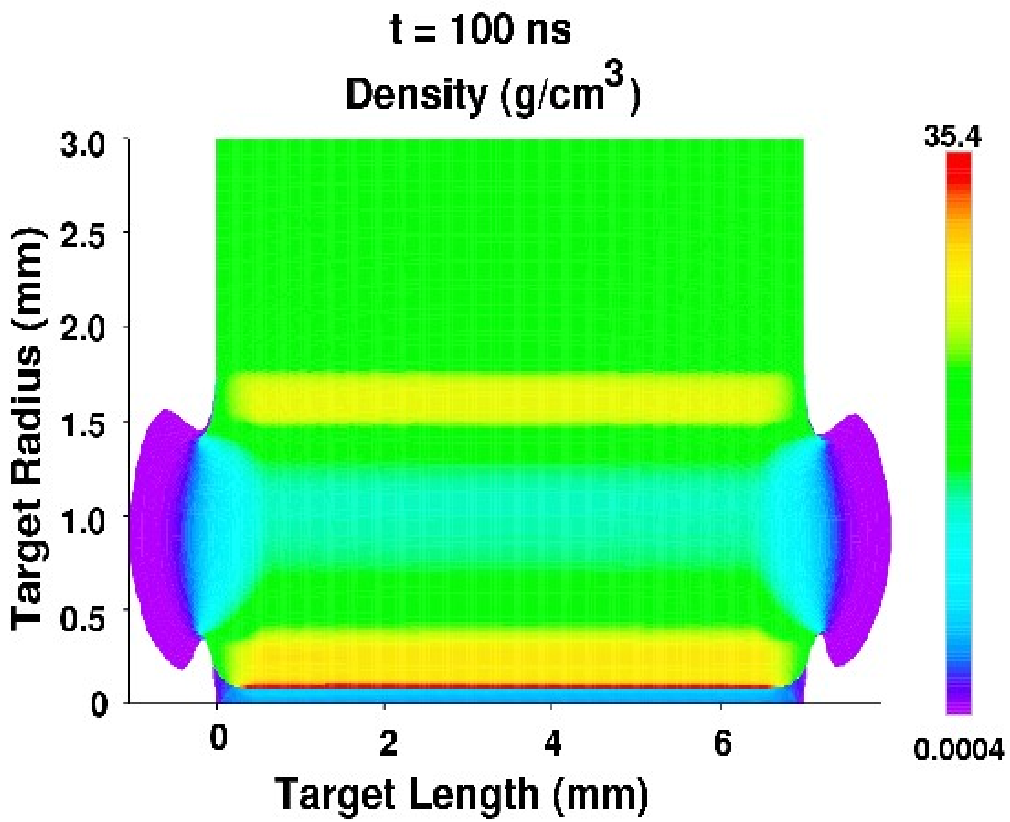
R_1 = 0.4 mm

R_2 = 1.4 mm

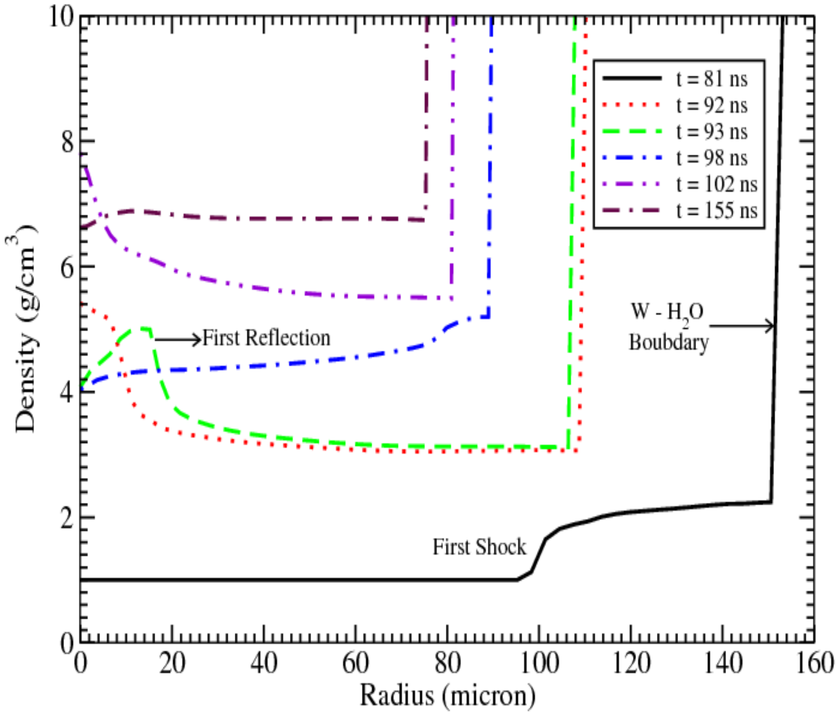
R_o = 3.0 mm

L = 7.0 mm

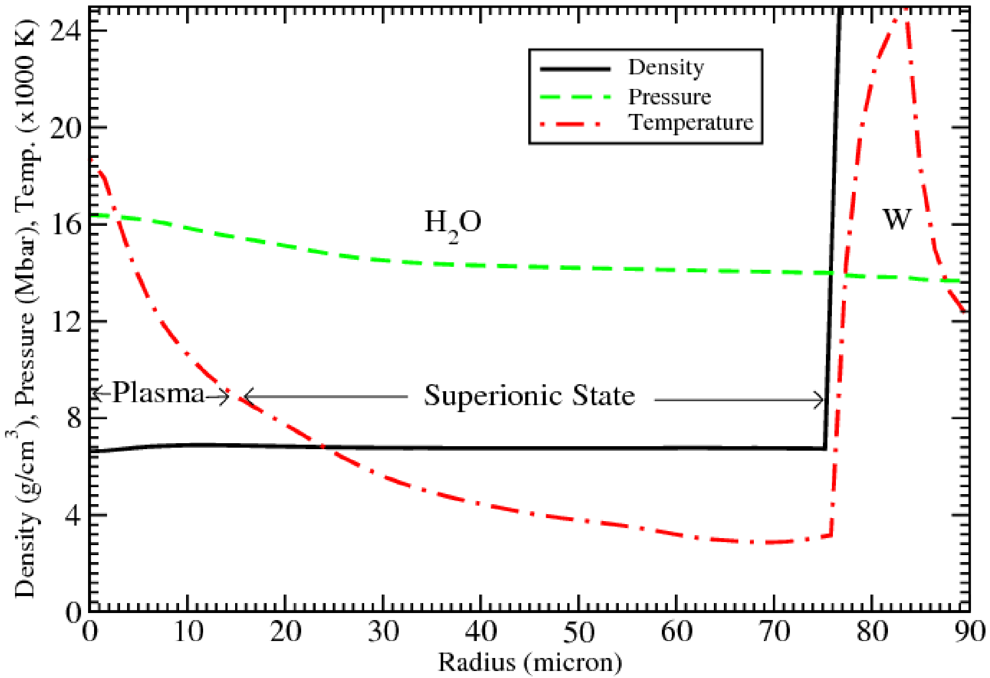

t = 50 ns
Specific Energy (kJ/g)
Target Radius (mm)
Target Length (mm)
20.0
0
t = 50 ns
Temperature (K)
Target Radius (mm)
Target Length (mm)
10^5
0
t = 50 ns
Pressure (Mbar)
Target Radius (mm)
Target Length (mm)
3.7
−0.3
t = 50 ns
Density (g/cm^3)
Outgoing Shock
Inmoving Shock
Target Radius (mm)
Target Length (mm)
25.3
0.005



t = 100 ns
Density (g/cm3)
3.0
2.5
2.0
1.5
1.0
0.5
0
Target Radius (mm)
0
2
4
6
Target Length (mm)
35.4
0.0004

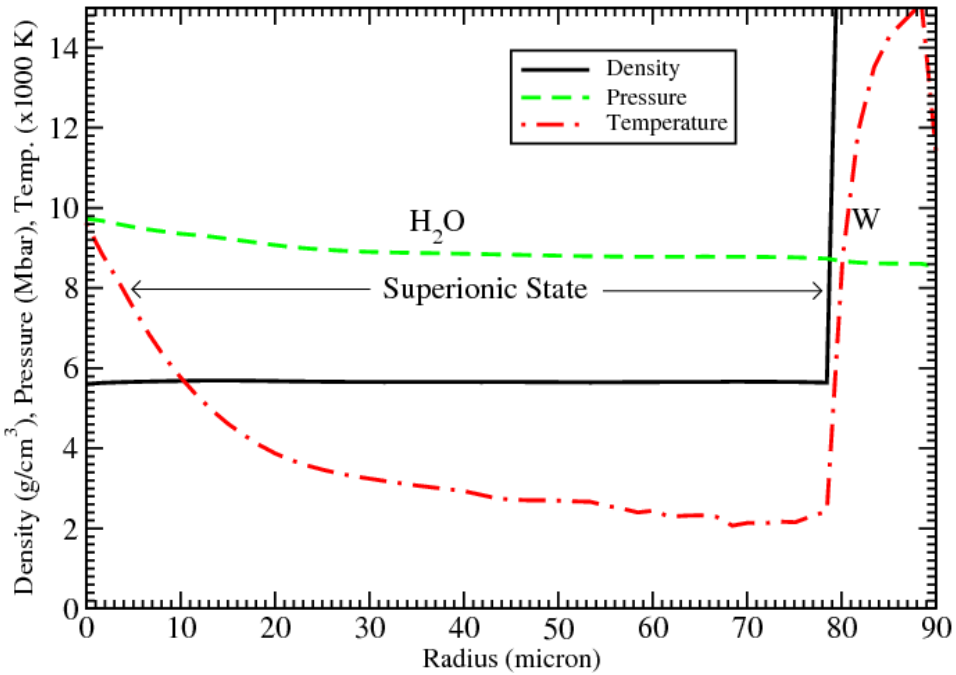


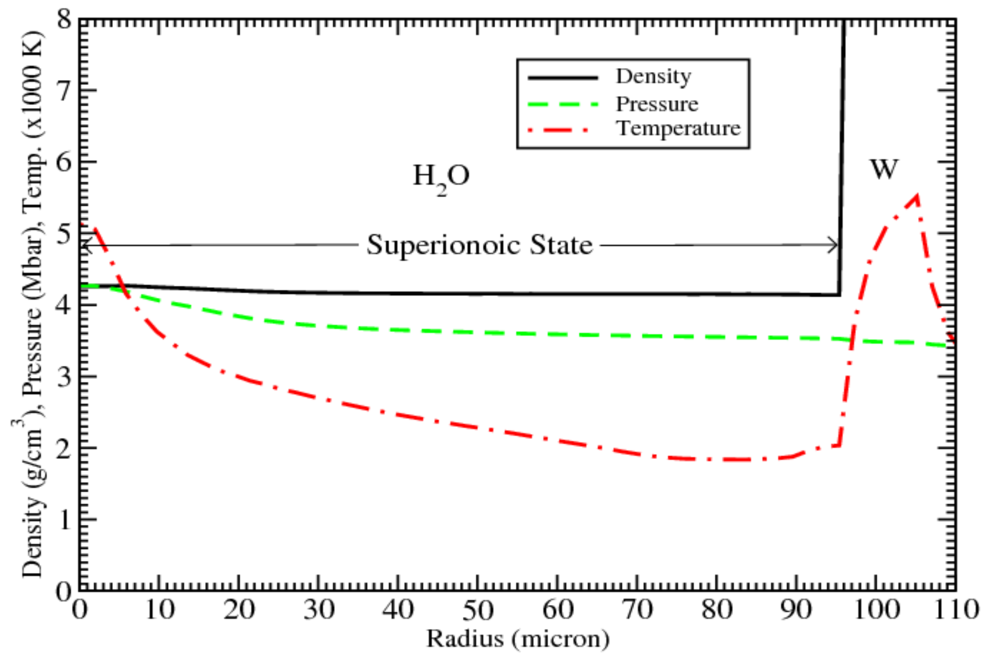
t = 81 ns
t = 92 ns
t = 93 ns
t = 98 ns
t = 102 ns
t = 155 ns
First Reflection
W - H2O
Boubdary
First Shock
Density (g/cm3)
Radius (micron)
0
2
4
6
8
10
0
20
40
60
80
100
120
140
160

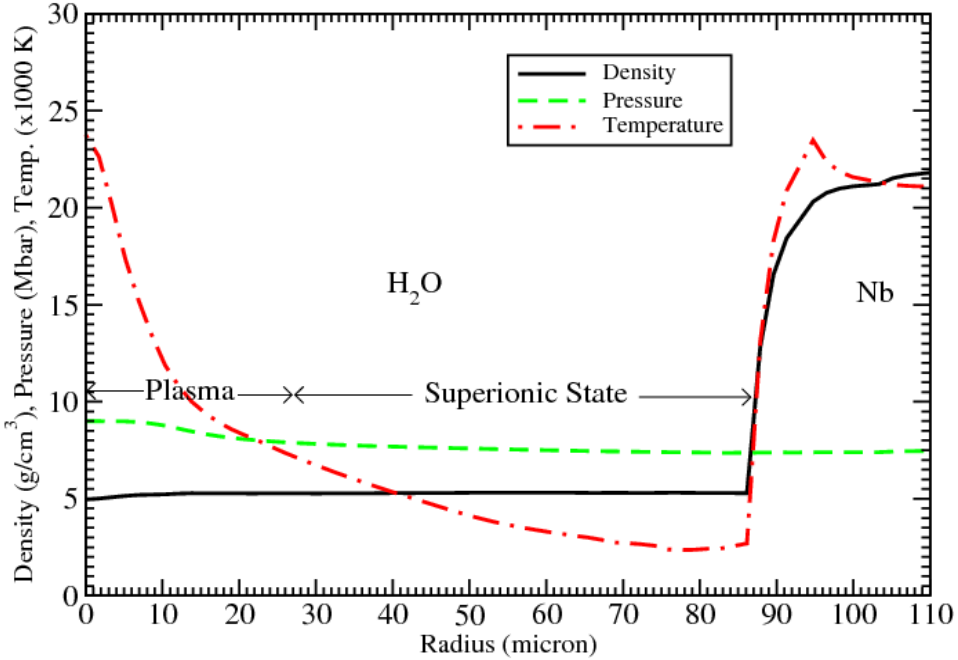


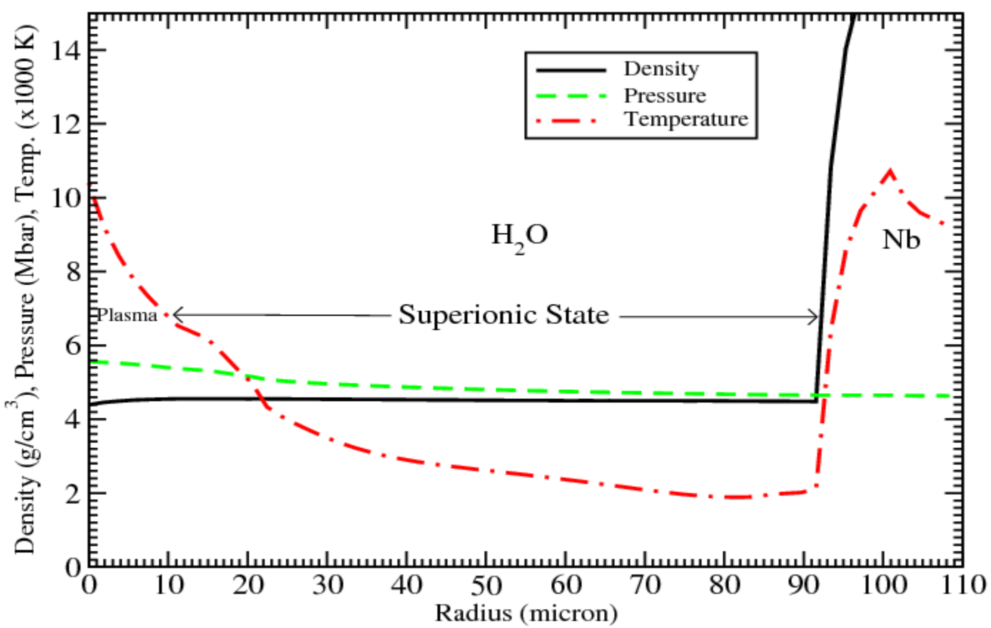
τ = 50 ns, R_1 = 0.4 mm, R_2 = 1.2 mm

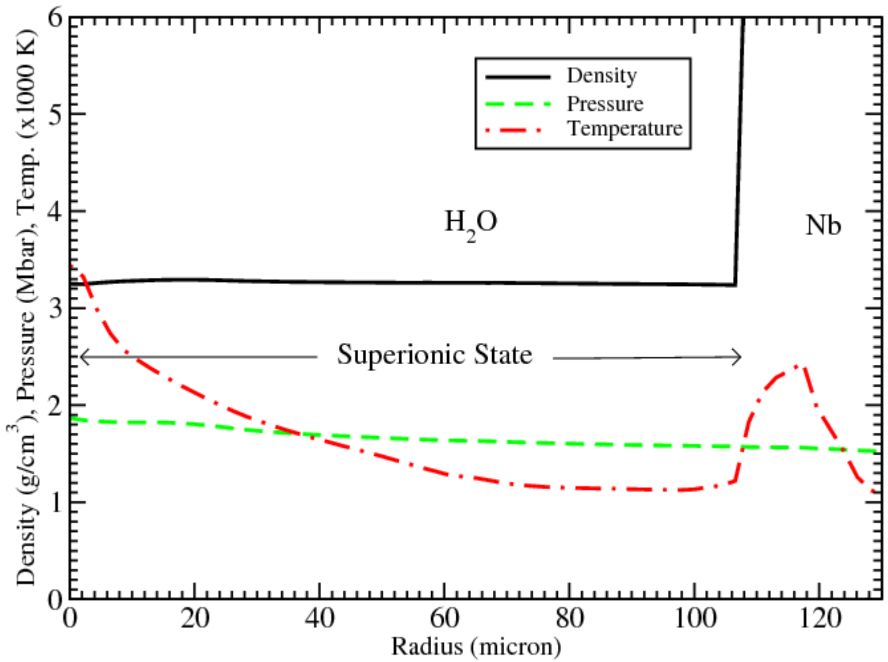
N = $5x10^{11}$, $3x10^{11}$ and 10^{11}

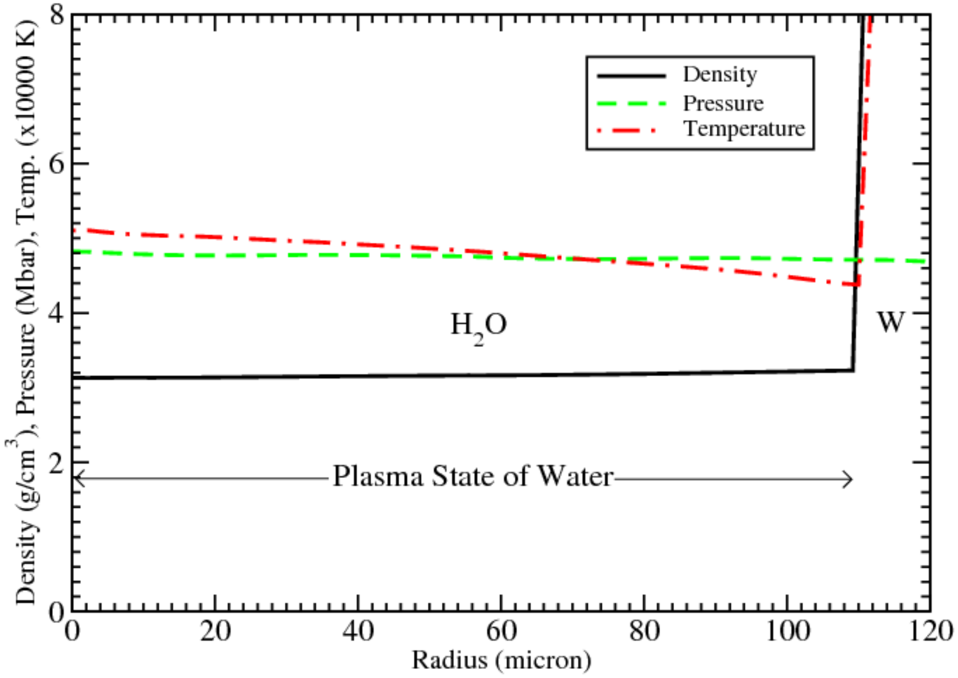





Density
Pressure
Temperature
H_2O
Nb
Plasma
Superionic State
Density (g/cm^3), Pressure (Mbar), Temp. (x1000 K)
Radius (micron)
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
80
90
100
110


Density
Pressure
Temperature
H_2O
Nb
Plasma
Superionic State
Density (g/cm^3), Pressure (Mbar), Temp. (x1000 K)
Radius (micron)
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
70
80
90
100
110

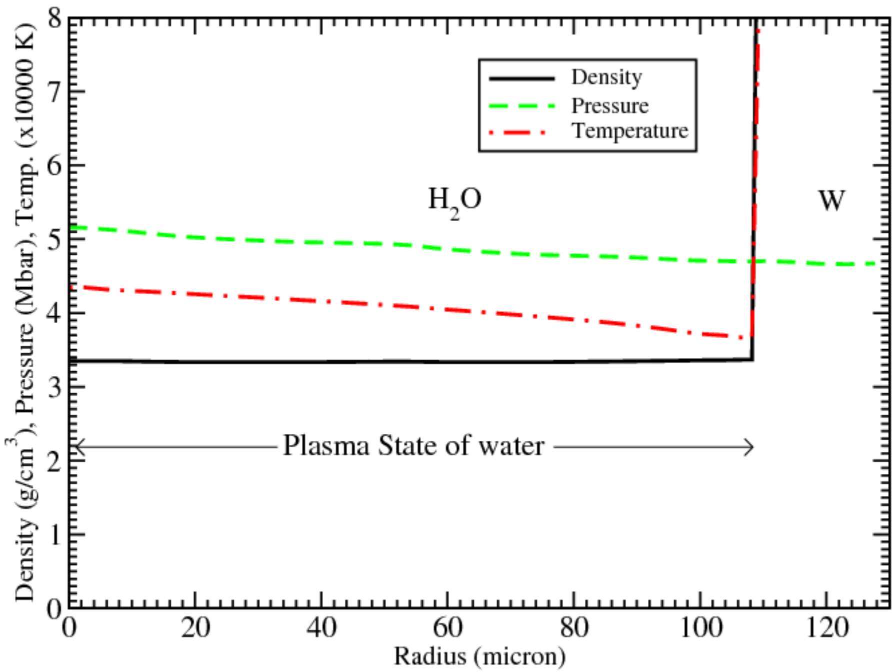

Density
Pressure
Temperature
H_2O
Nb
Superionic State
Density (g/cm^3), Pressure (Mbar), Temp. (x1000 K)
Radius (micron)
0
1
2
3
4
5
6
0
20
40
60
80
100
120

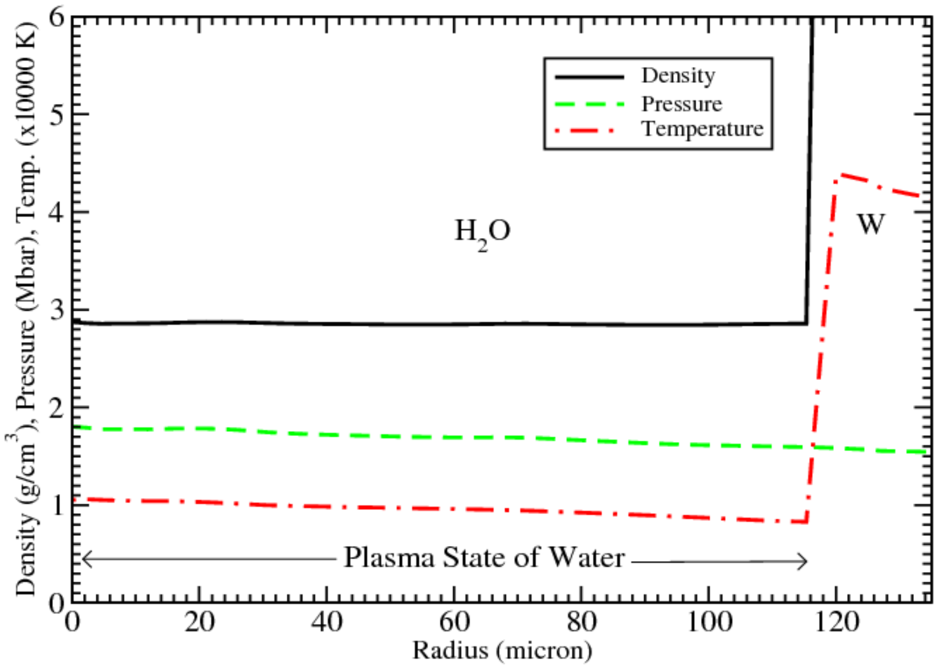


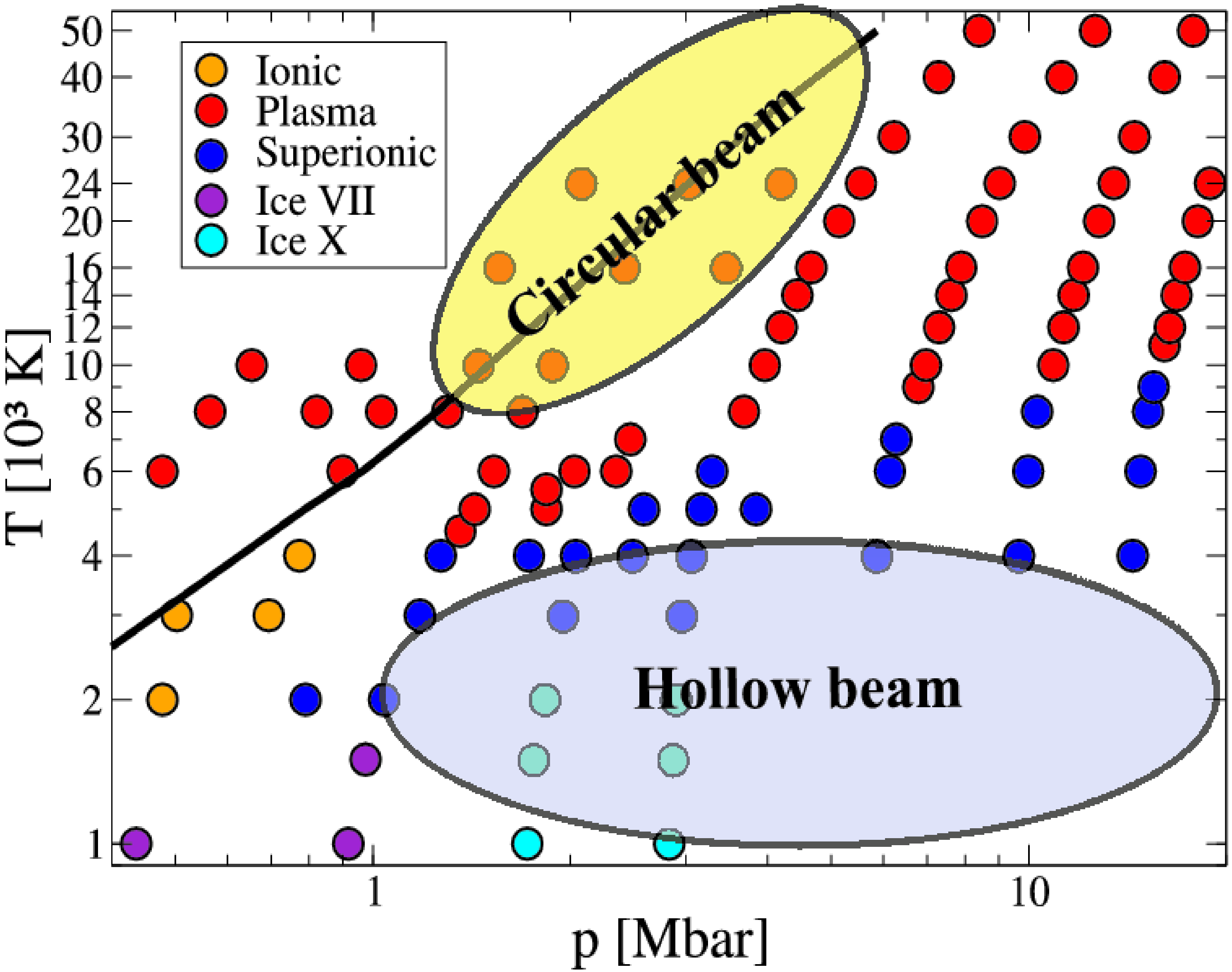
Circular Beam

FWHM = 1.5 mm

N = 5×10^{11}, 3×10^{11}, 10^{11}





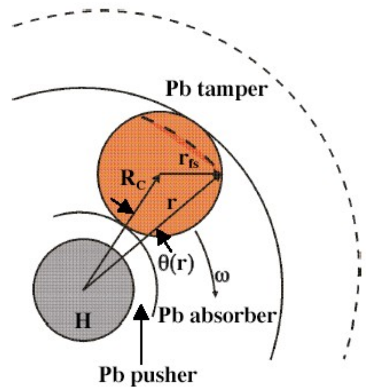


Ionic
Plasma
Superionic
Ice VII
Ice X
Circular beam
Hollow beam
T [10³ K]
p [Mbar]
50
40
30
24
20
16
14
12
10
8
6
4
2
1
1
10

High Frequency Rotating Ion Beam

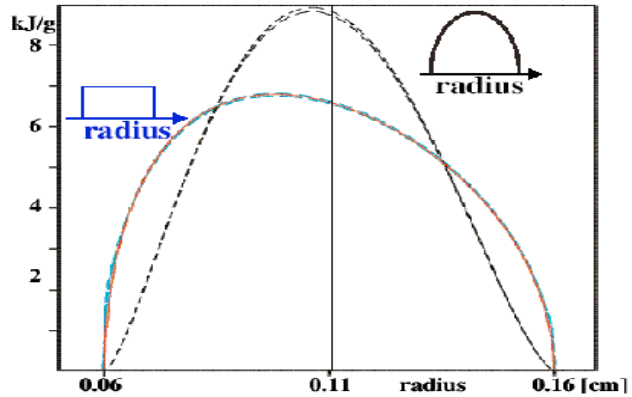
A.R. Piriz et al, Plasma Phys. Controlled Fusion 45 (2003) 1733.

- Analysis of symmetry level achieved by a rotating ion beam.
- Analytic model and numerical simulations
- Spatial power profile: rectangular as well as Parabolic
- Temporal power profile: rectangular as well as Parabolic



Power Constant in Time

- Circular shape of the focal spot introduces radial distribution in the energy deposition.
- For both cases, the relative pressure asymmetry:
  $\Delta P/P \sim 1/N$
- **$N = \omega \tau$ where $\omega = 2\pi\nu$**
- For τ **= 50 ns,** one would require an ω **= 2 GHz to** achieve **1 %** asymmetry.



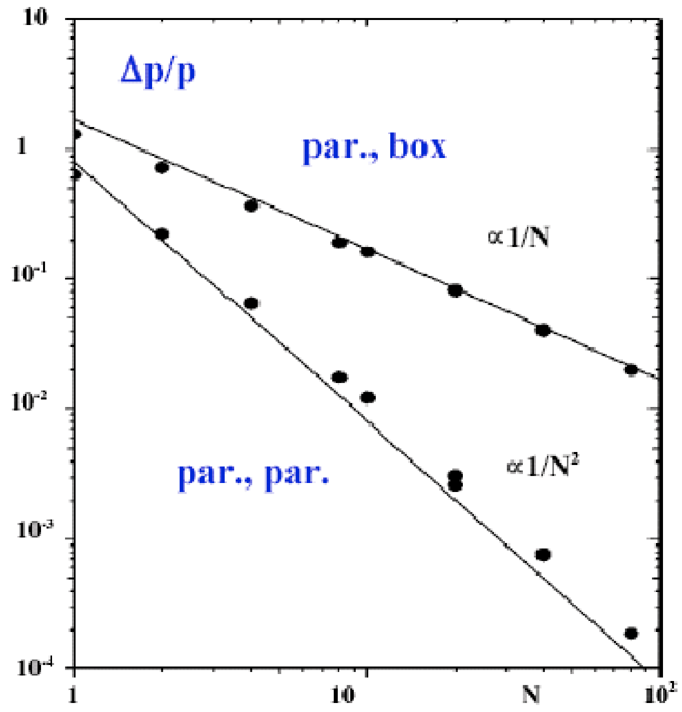
<u>**For achieving 1 % asymmetry**</u>

1. **With uniform temporal profile one needs N = 100.**

   For τ = 50 ns one need ω = 2 GHz

2. **With parabolic temporal profile one needs N = 10.**

   For τ = 50 ns one need ω = 0.2 GHz



Conceptual Design for Ramp Compression Experiment Using Intense Heavy Ion Beams to Study Material Properties

First Results

In collaboration with A. Ng

FAIR Beam

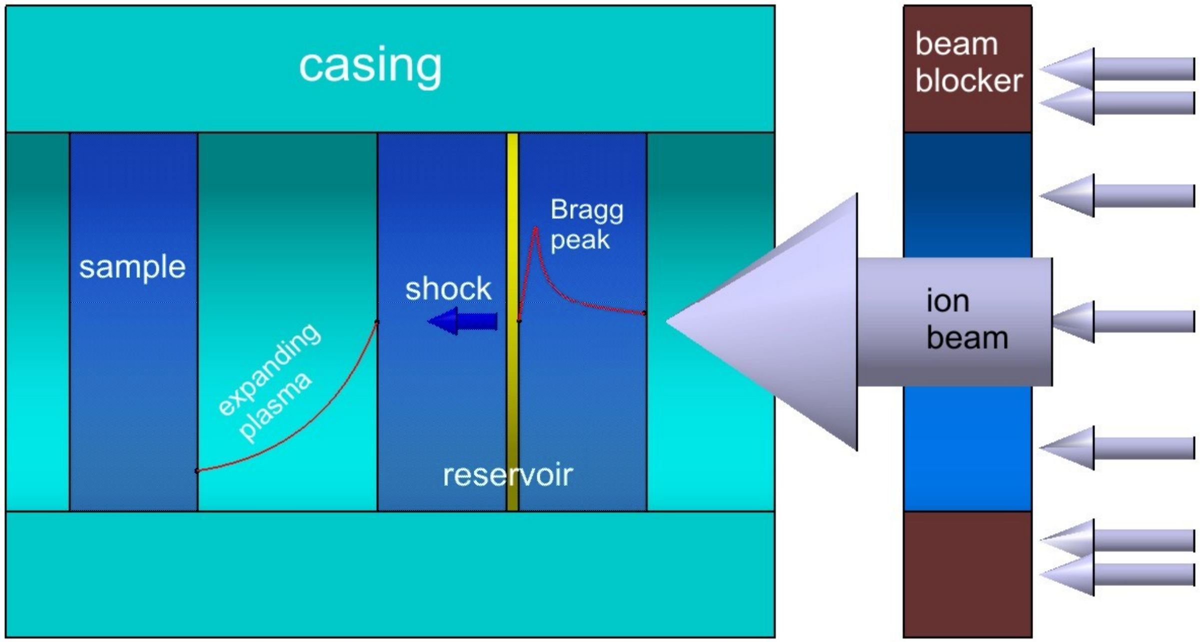
Pb Reservoir

Al Sample

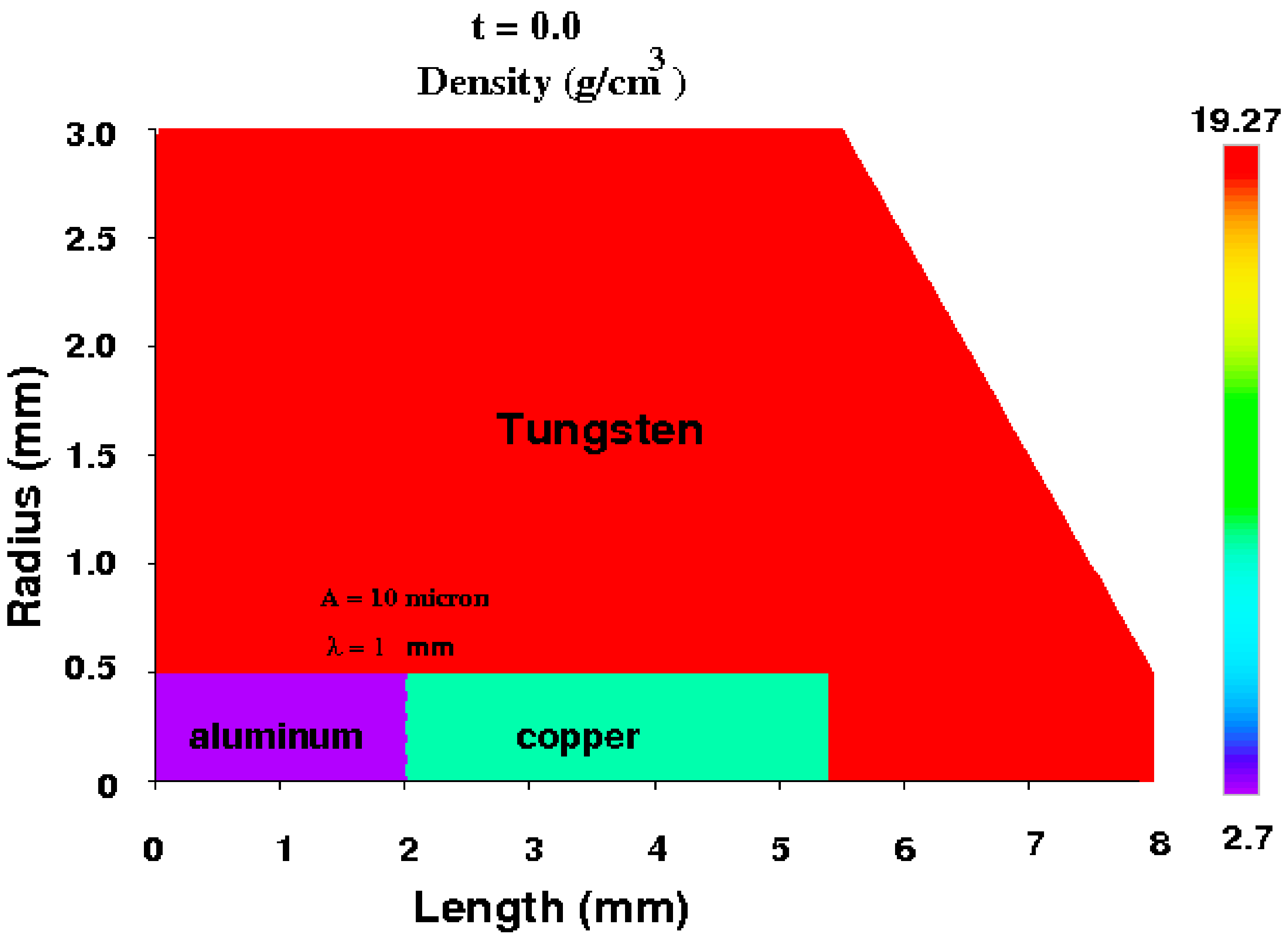
70 % compression

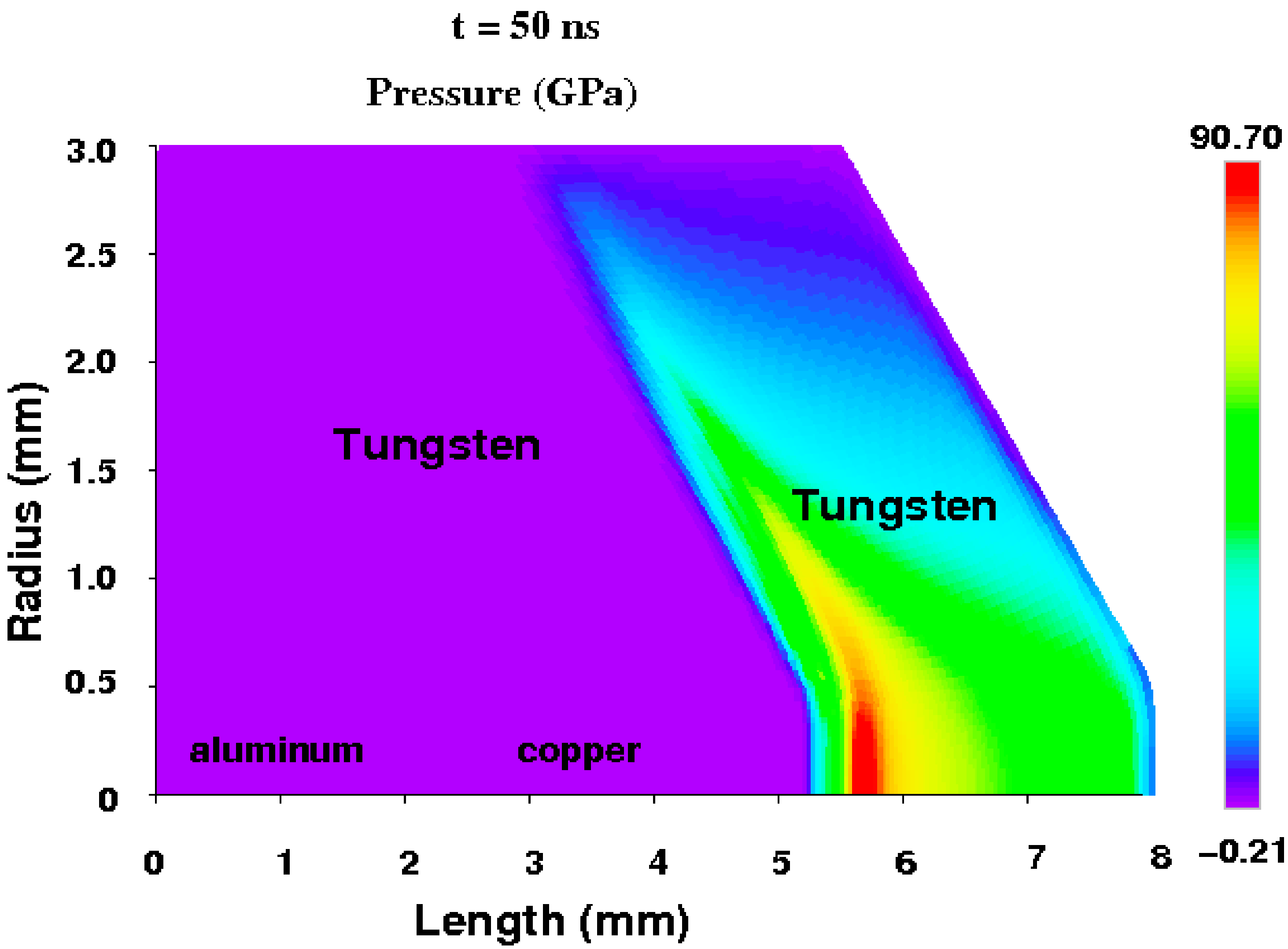
T about 900 K

P of the order of Mbar



Richtmyer-Meshkov Instability Studies

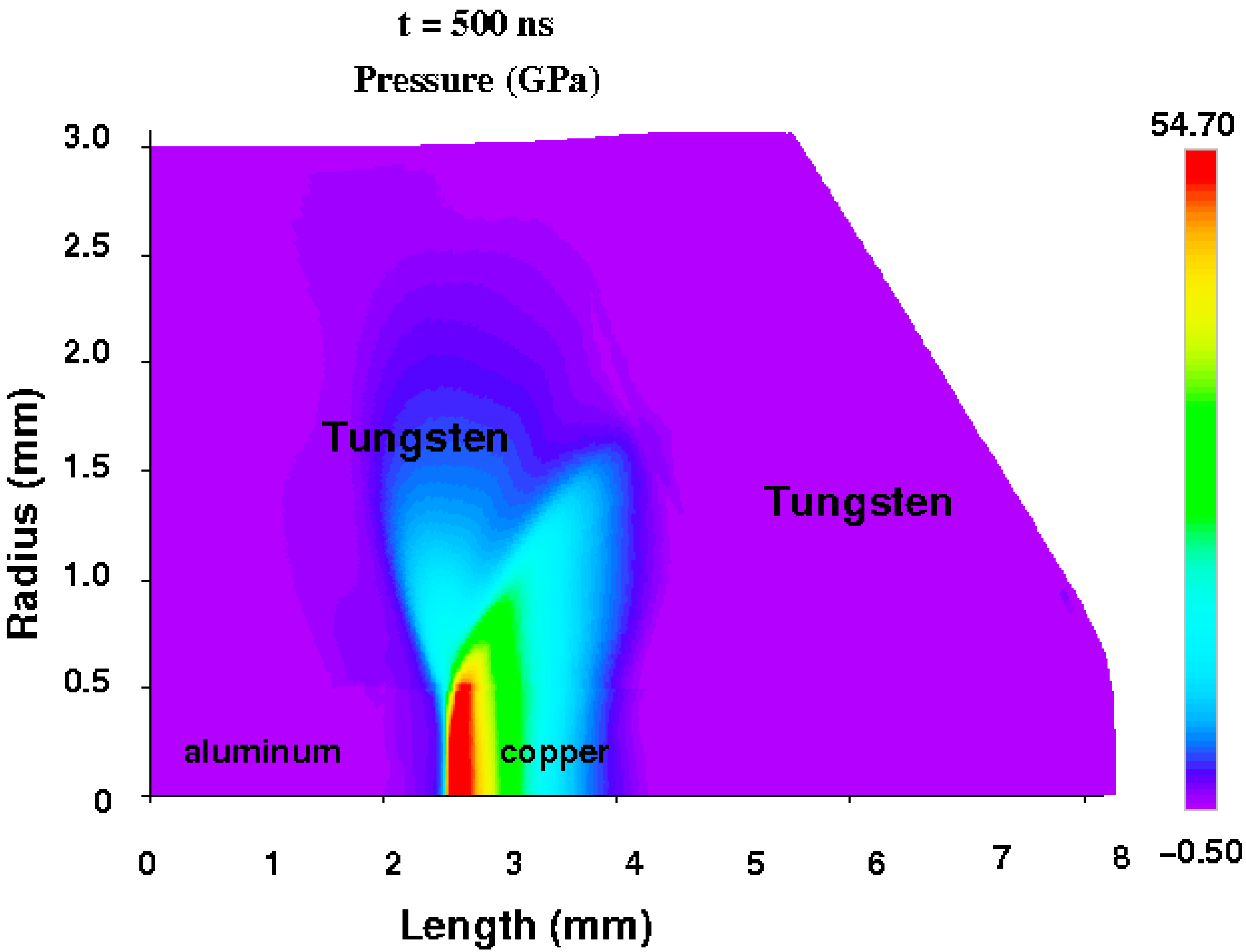




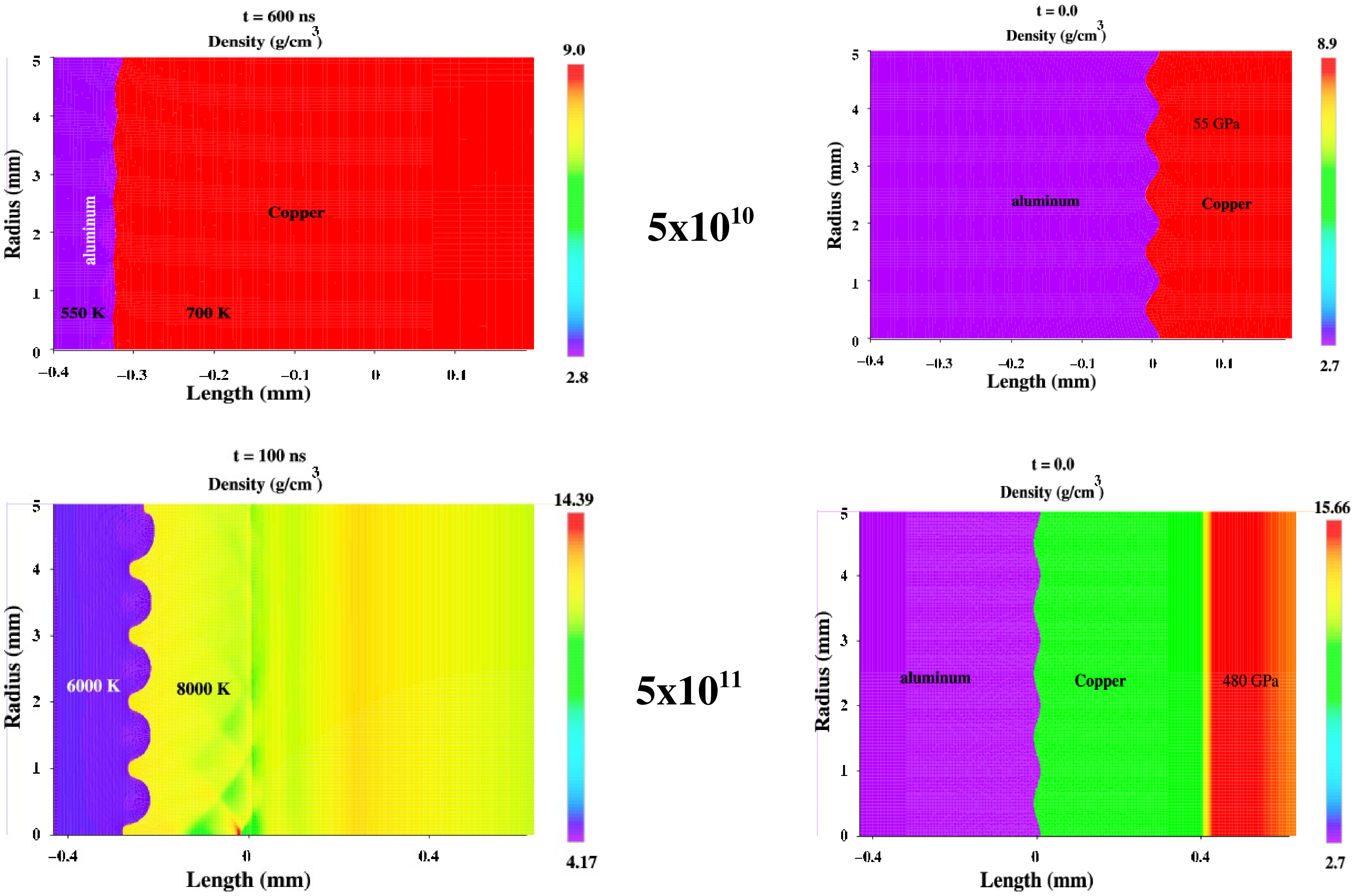
N = 5×10^{10}

1 GeV/u U

FWHM = 3 mm



t = 500 ns
Pressure (GPa)
3.0
2.5
2.0
1.5
1.0
0.5
0
Radius (mm)
Tungsten
Tungsten
aluminum
copper
0
1
2
3
4
5
6
7
8
Length (mm)
54.70
–0.50


t = 600 ns
Density (g/cm³)
9.0
2.8
Radius (mm)
Length (mm)
aluminum
Copper
550 K
700 K
5x10^10
t = 0.0
Density (g/cm³)
8.9
2.7
aluminum
Copper
55 GPa
t = 100 ns
Density (g/cm³)
14.39
4.17
6000 K
8000 K
5x10^11
t = 0.0
Density (g/cm³)
15.66
2.7
aluminum
Copper
480 GPa

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

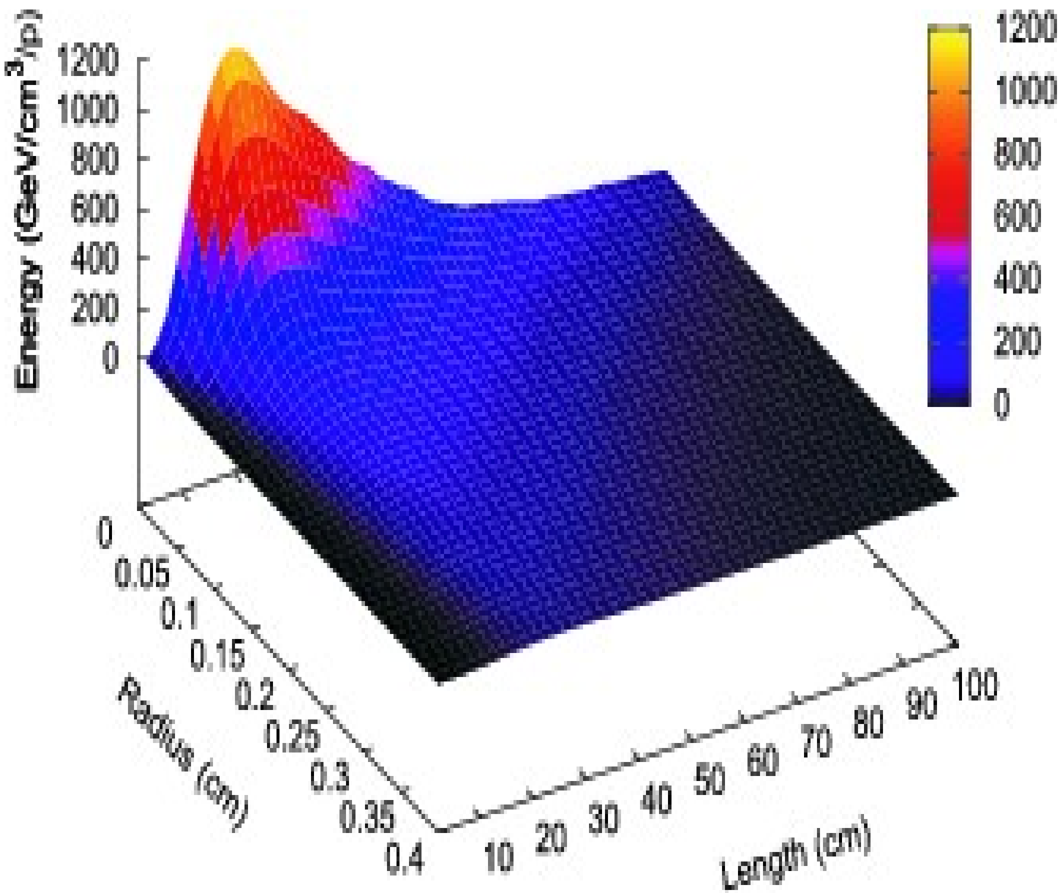
Total length of the bunch train = 89 μs

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

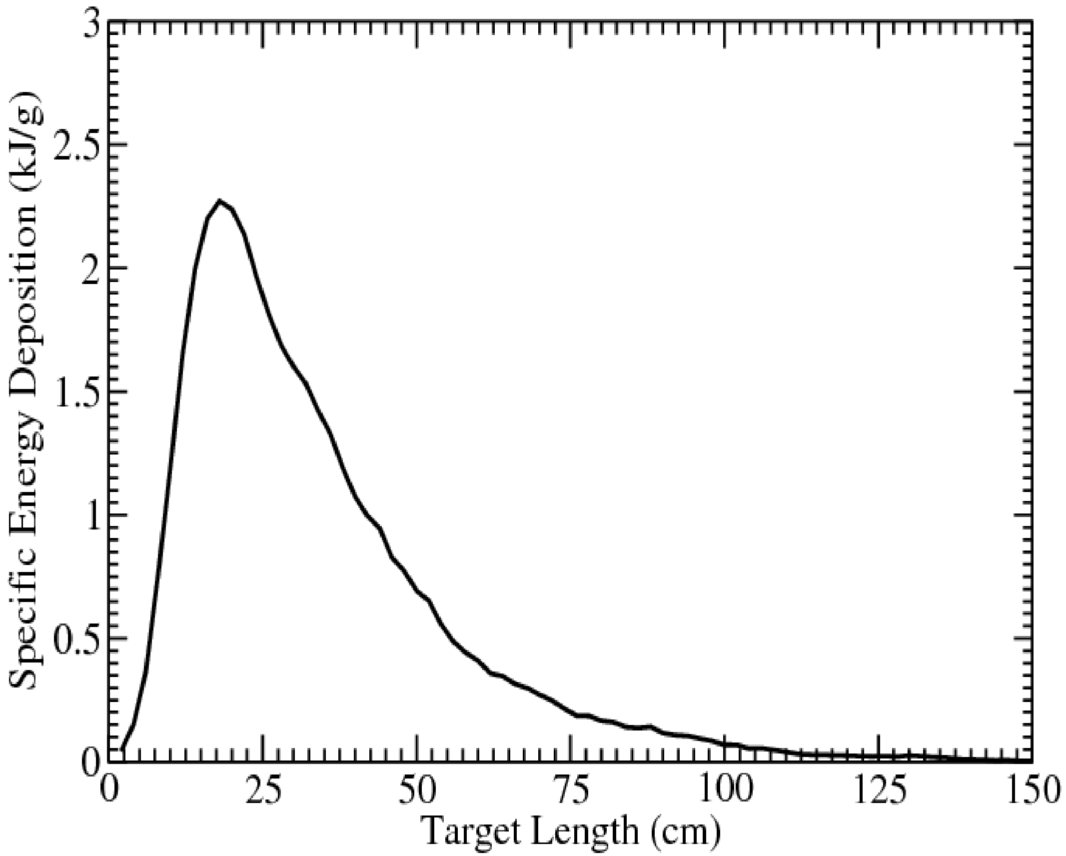


<u>Second Step:</u>

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

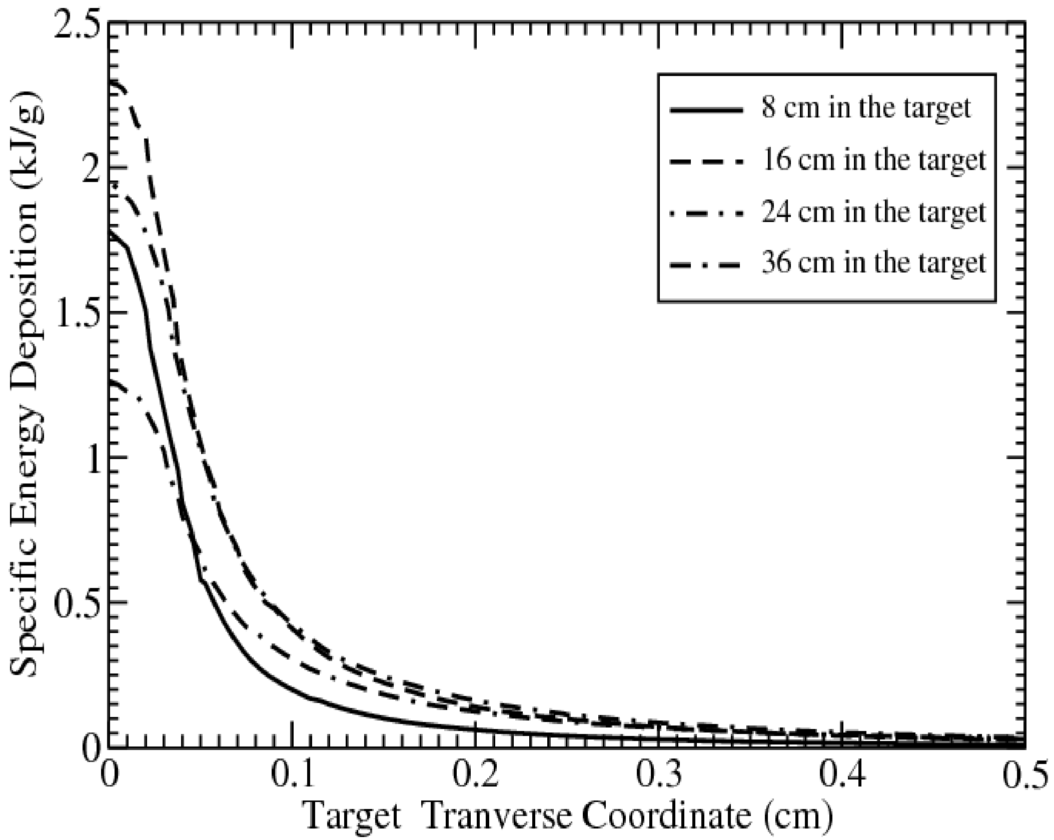
Specific Energy Deposition by a Single Bunch in Solid Copper [FLUKA Calculations]

- 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.



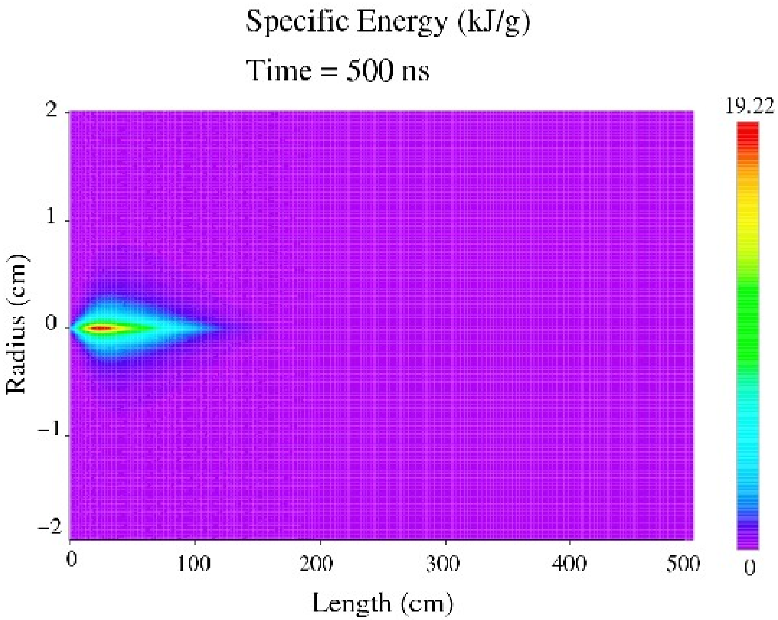
Target Parameters

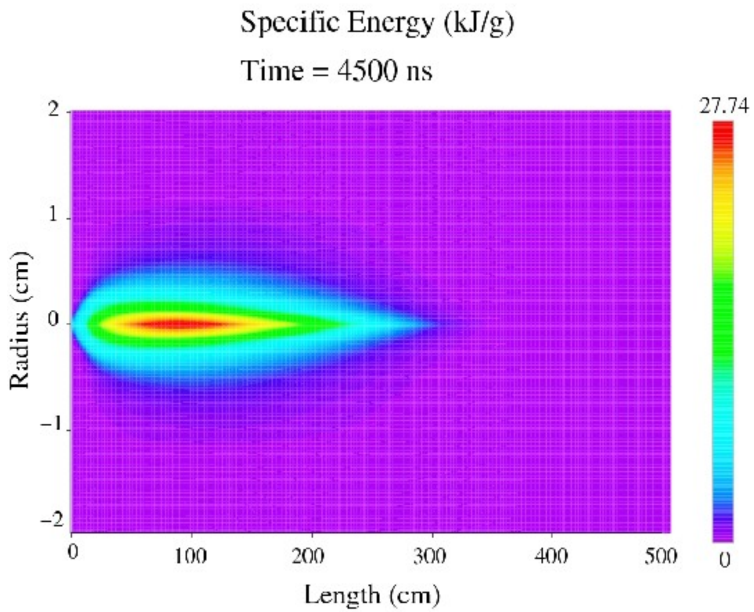
[N.A. Tahir et al., J. Appl. Phys. 97 (2005) 135004; PRL 94 (2005) 083532; Phys. News Update No: 726#3, APS News February 2006, PRE 79 (2009) 046410, Laser Part. beams 27 (2009) 475.]

Solid copper target facially irradiated by the LHC beam

L = 5 m, r = 5 cm

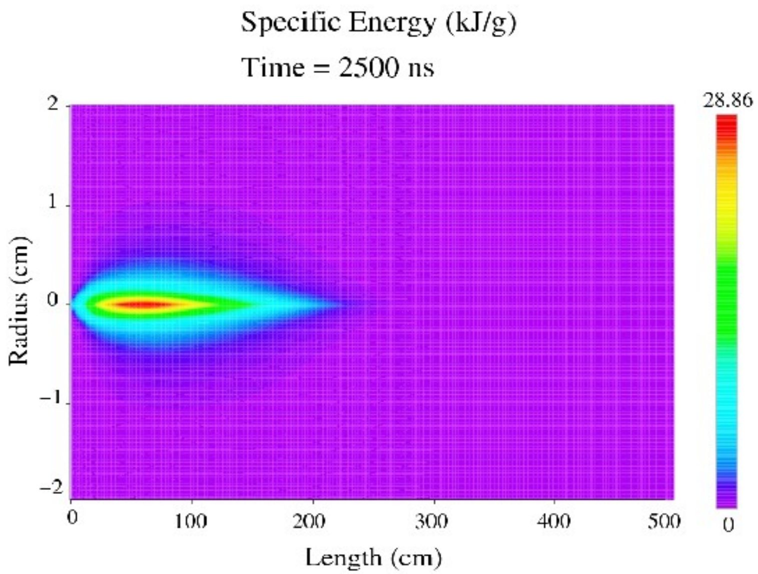
- **The target is studied in r-Z geometry**
- **Specific energy deposition in each simulation cell at every timestep is normalized with respect to the line density along the axis.**
- **This allows for reduction of specific energy deposition in low density part of the target.**
- **This model allows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

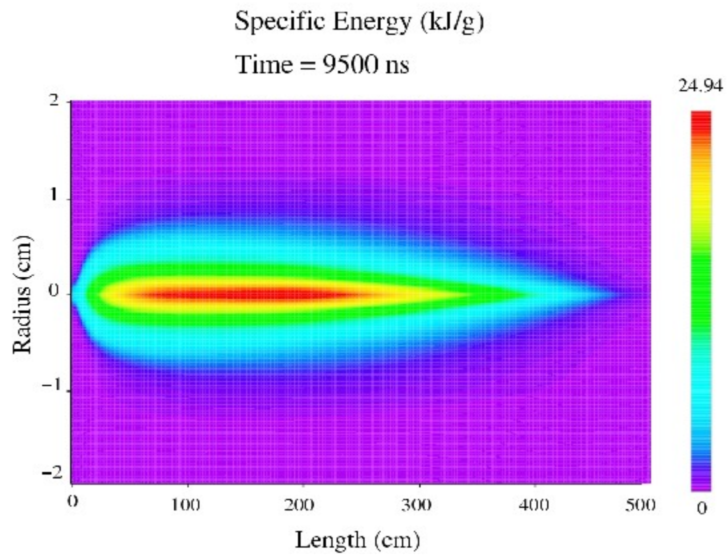


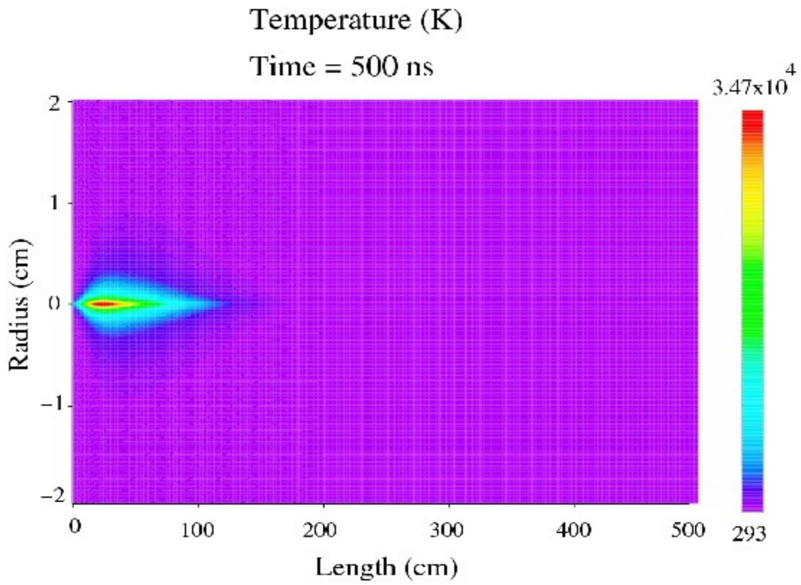


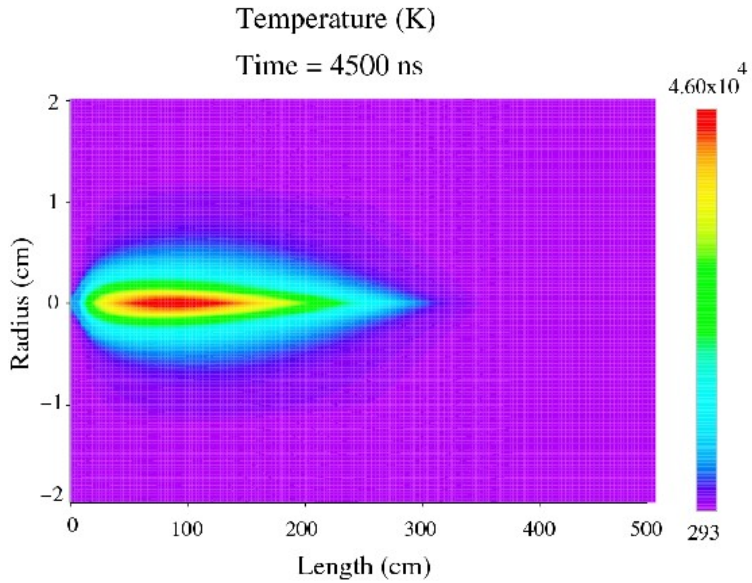
Specific Energy Deposition

Saturates to 25 kJ/g

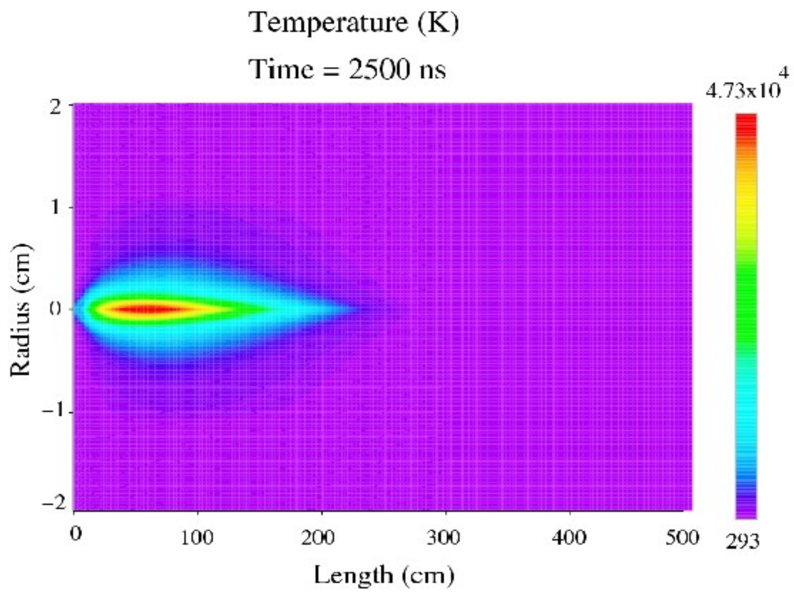




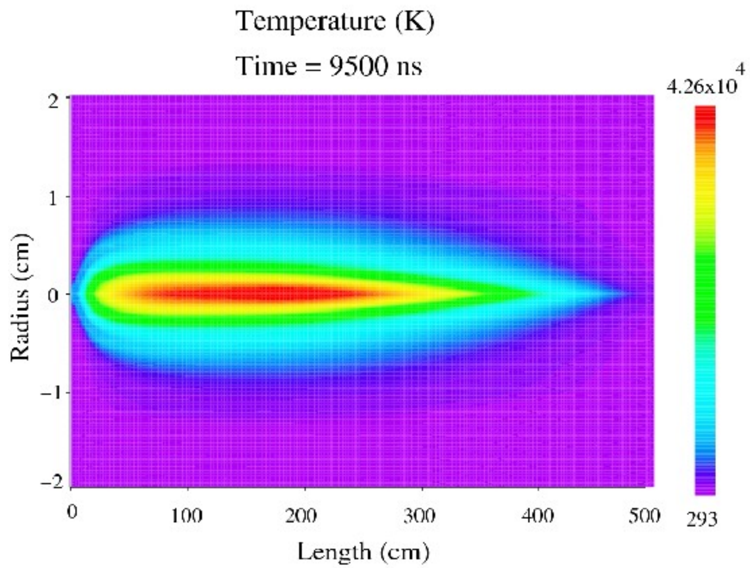




Temperature

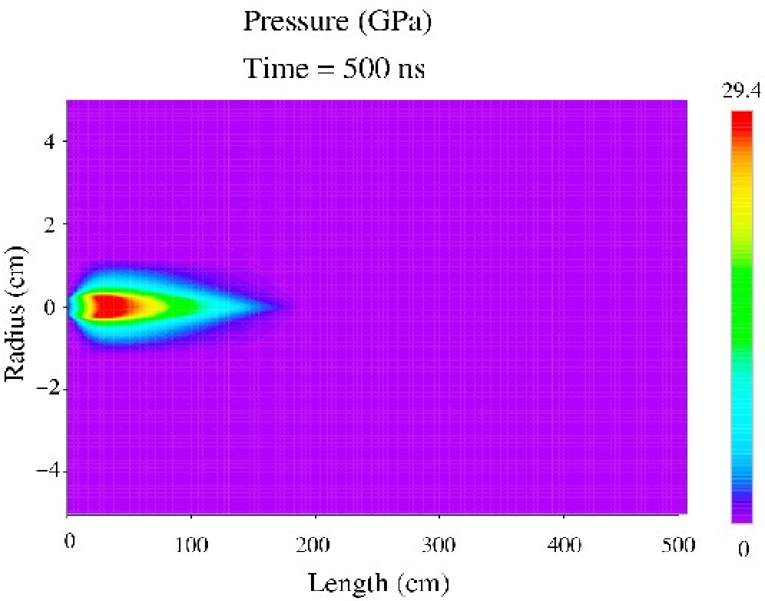


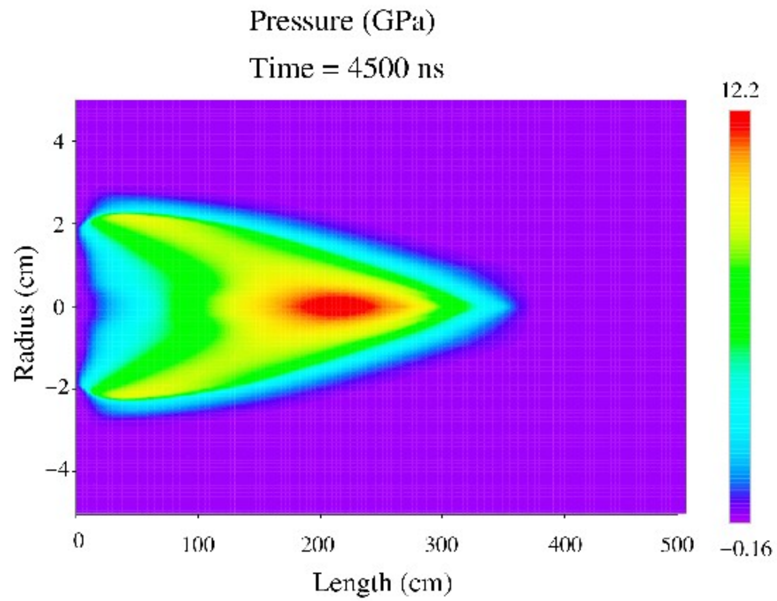
$4x10^4$ K

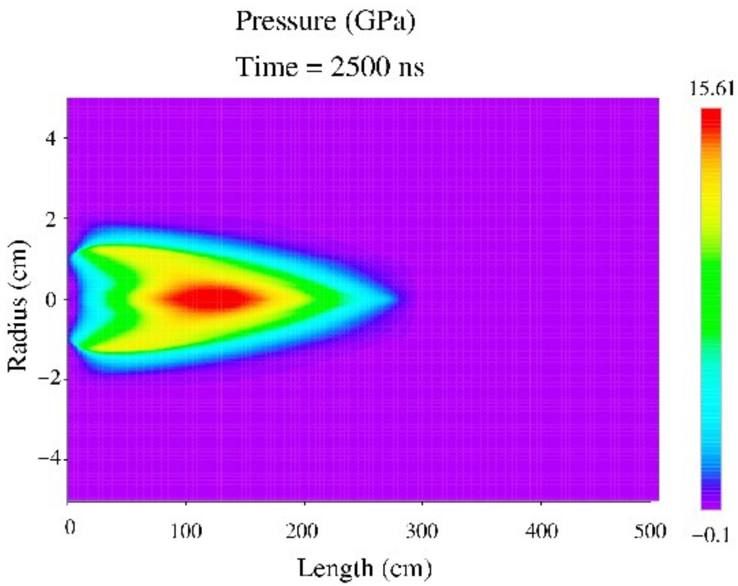


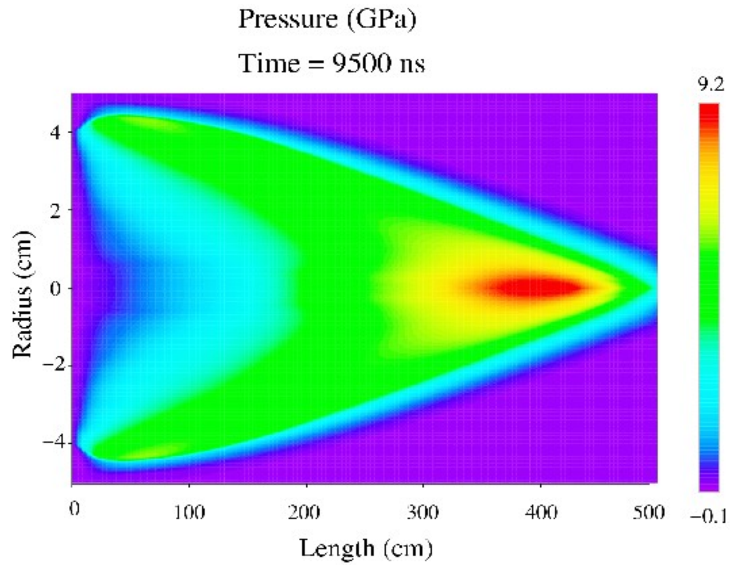
Pressure

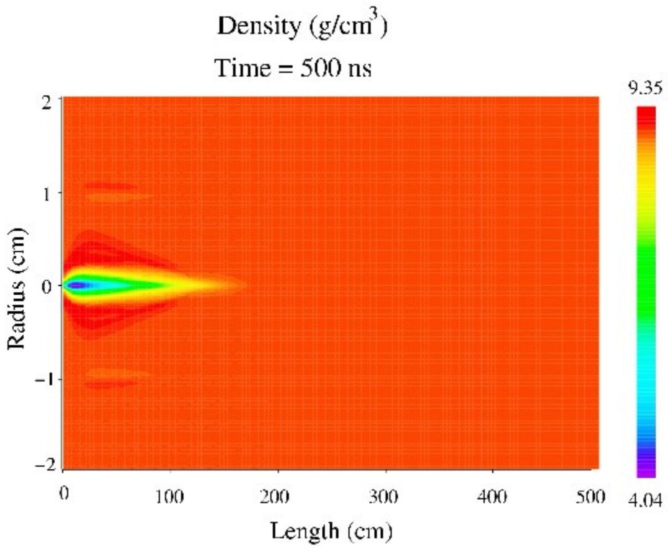
30 GPa

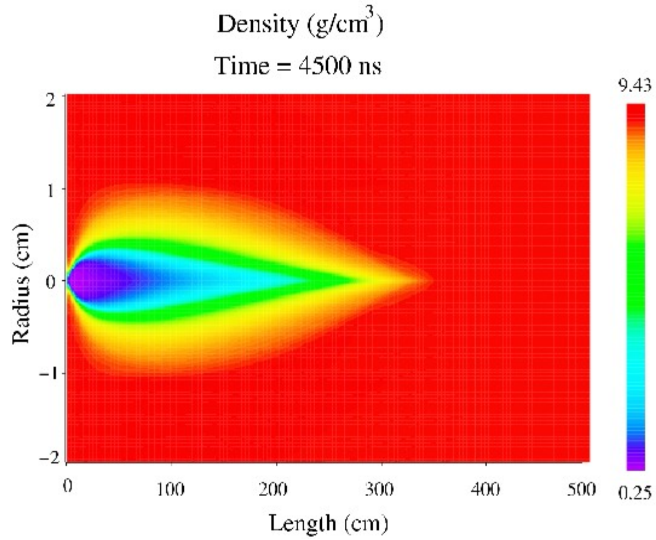




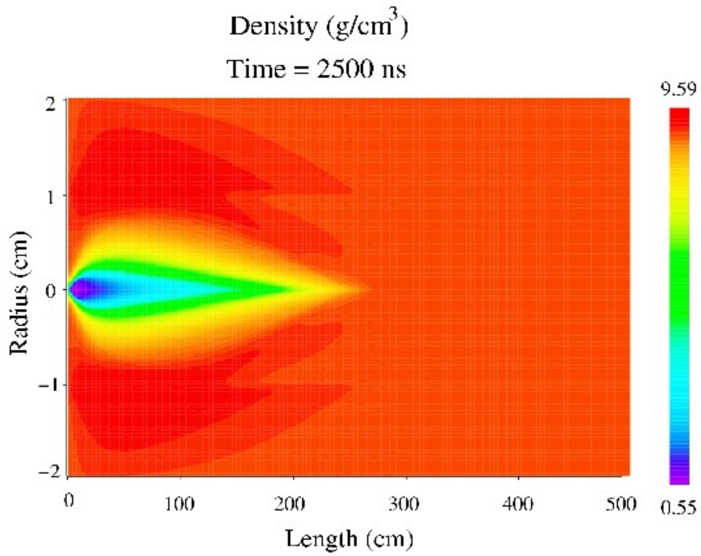


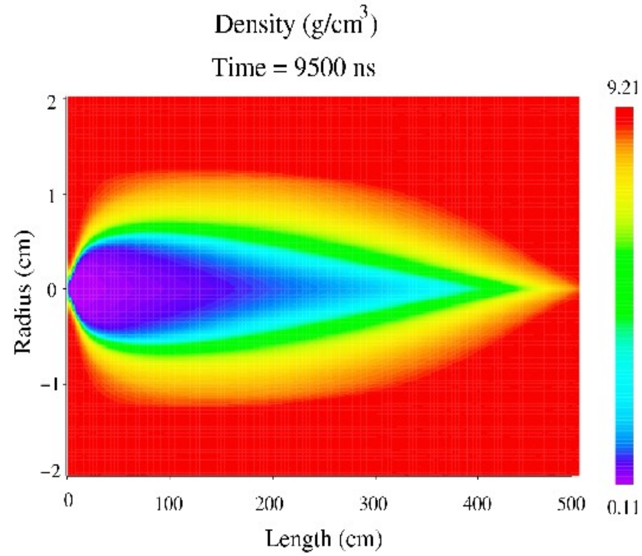


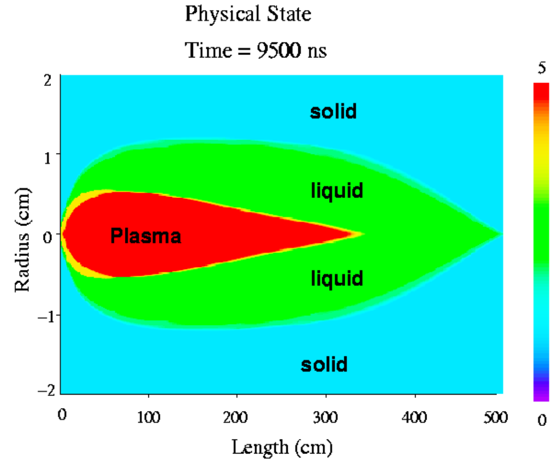

Density (g/cm3)
Time = 500 ns
9.35
4.04
Radius (cm)
Length (cm)

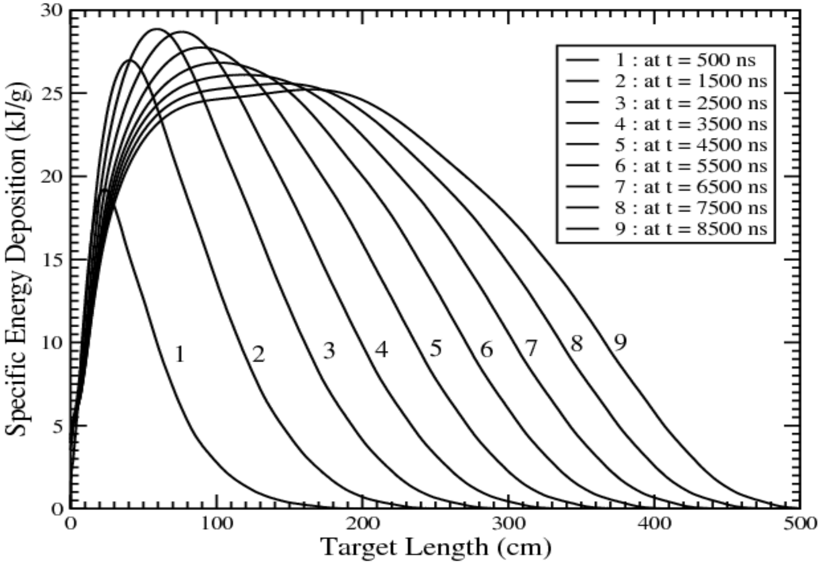

Density (g/cm3)
Time = 4500 ns
9.43
0.25
Radius (cm)
Length (cm)

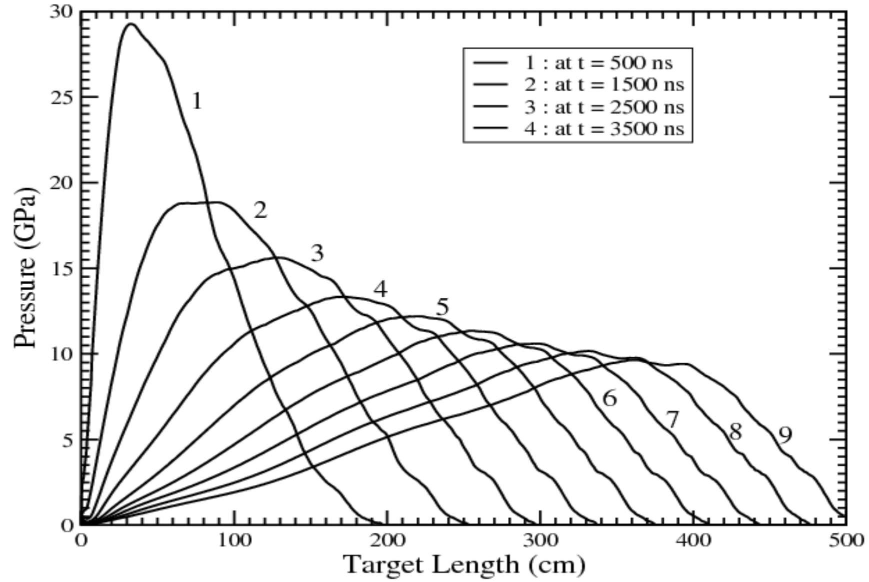
HEDP States


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

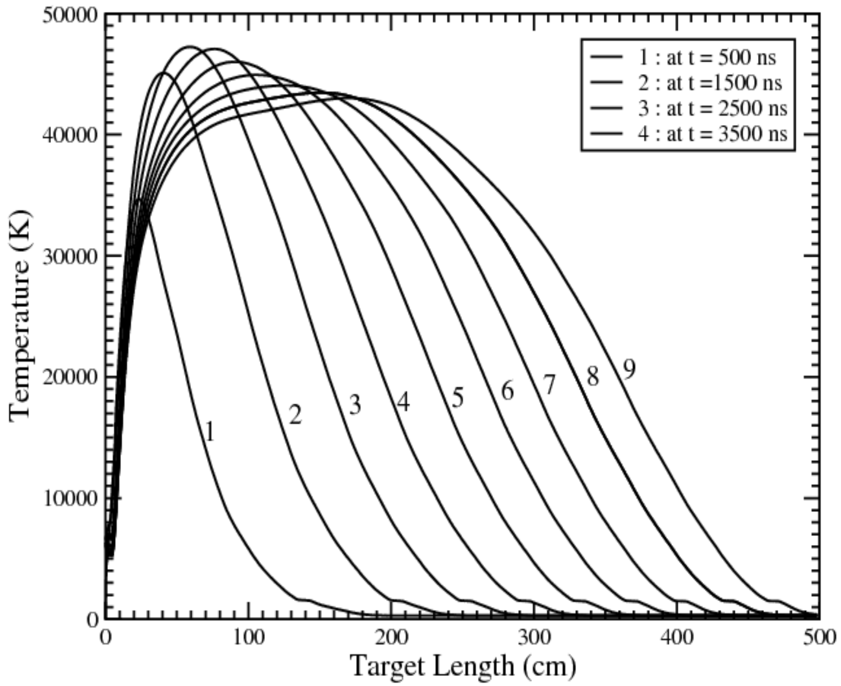

Density (g/cm3)
Time = 9500 ns
9.21
0.11
Radius (cm)
Length (cm)

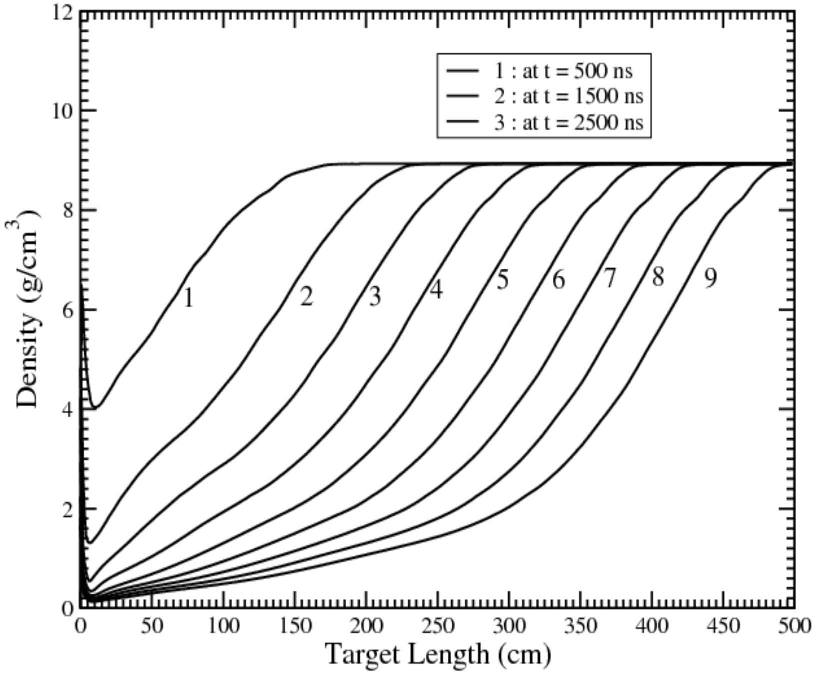

Physical State
Time = 9500 ns
solid
liquid
Plasma
liquid
solid
5
0
Radius (cm)
Length (cm)





0.35 m/μs in 89 μs penetrate 35 m





CONCLUSIONS:

1. An intense heavy ion beam is a very efficient tool to induce HED states in matter; large sample size, week gradients, long life times.

2. Construction of the future FAIR facility at Darmstadt will enable one to carry out novel and unique experiments in this filed.

3. Theoretical studies (simulations + analytic modeling) has shown that an intense heavy ion beam can be employed using four very different schemes to study HED physics.

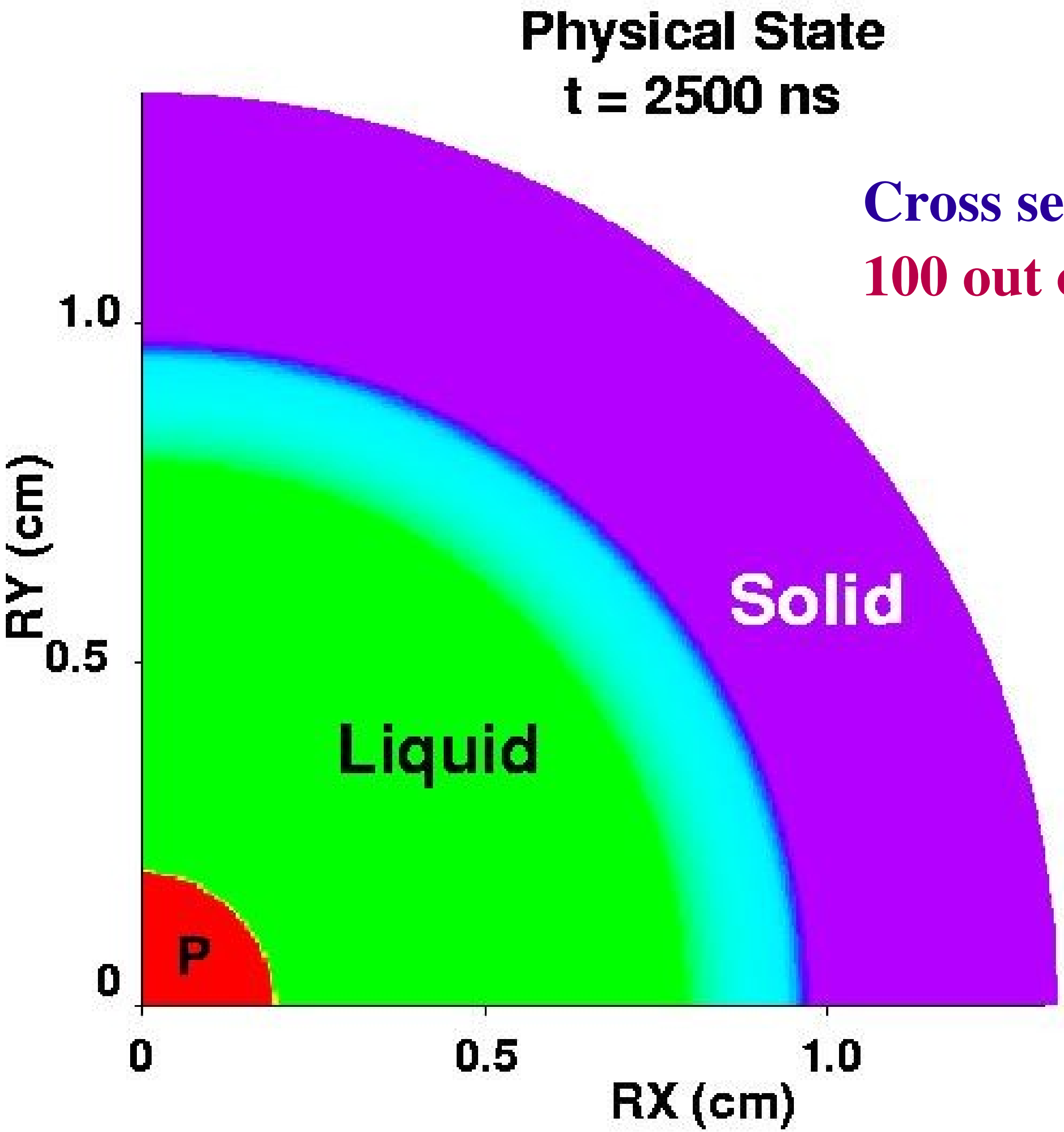
   A). HIHEX [Heavy Ion Heating and Expansion]
   One can use solid as well as porous targets; all interesting physical state, EHL, 2PLG, CP, SCP can be accessed using the beam at the FAIR facility.

   B). LAPLAS [LAboratory PLAnetary Sciences]
   The scheme is robust, insensitive to large variations in beam and target parameters, hydrodynamically stable (**Rayleigh-Taylor** and Richtmeyer-Meshkov).

   C). Ramp Compression: Studies of Material properties under dynamic conditions

   D) . Richtmyer-Meshkov Instability Growth Studies

4. The Large Hadron Collider may be used as a tool to study WDM [**Additional, very important application of the LHC**]



Cross section of a Cu cylinder

100 out of 2808 bunches delivered

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

Physics news Update
April 7, 2005
No: 726#3

APS News, February 7, 2006

B. Analytic Modeling

1.Simulations of the LAPLAS scheme were followed by development of an analytic model to analyze the implosion dynamics of the target. **[A.R. Piriz et al., Phys. Rev. E 66 (2002) 056403].**

If

the **hydrogen mass** << **the payload mass**

and

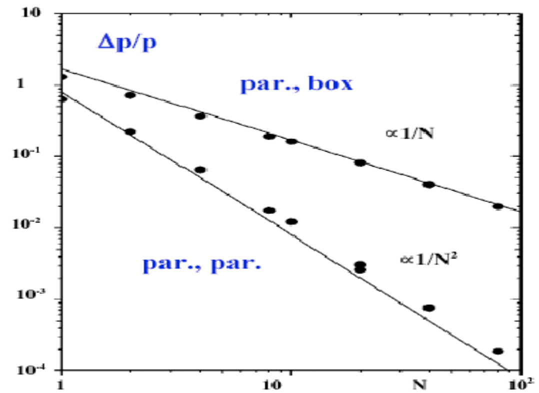
the payload mass << **the absorber mass**

The compression results are very insensitive to large variations in the beam and target parameters. The scheme is therefore very robust which is a very important result for the experimentalists.

2.Generation of an annular focal spot using an RF-Wobbler. Symmetry issues?

Relative Pressure for Rectangular and Parabolic Temporal Profiles

- With rectangular power temporal profile, one needs **N = 100** to achieve **1 %** asymmetry. This means for τ = 50 ns, ω = 2 GHz will be required.
- With a parabolic temporal power profile, one would require **N = 10** so that for τ = 50 ns, ω = 0.2 GHz would be sufficient to achieve **1 %** asymmetry in the driving pressure.



Hydrodynamic Stability of the Target

A.R. Piriz et al, PRE 72 (2005) 056313

N.A. Tahir et al, Phys. High Energy Density 2 (2006) 21

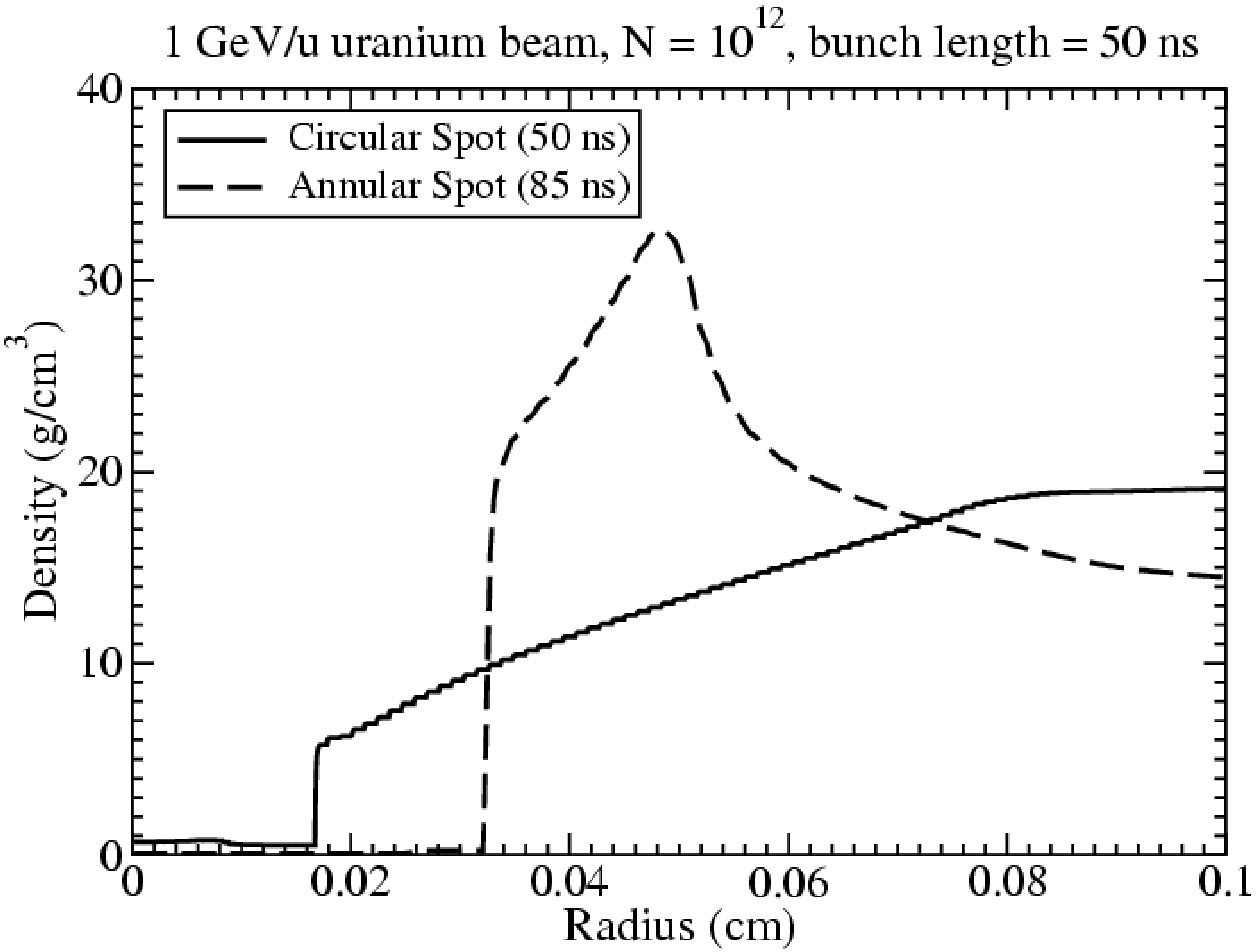
1. Rayleigh-Taylor (R-T) instability can occur in the pusher (payload) region. Different situation in two cases.

2. Richtmeyer-Meshkov (R-M) instability can occur if the Au-H interface is corrugated.

We have investigated these problems in case of LAPLAS targets

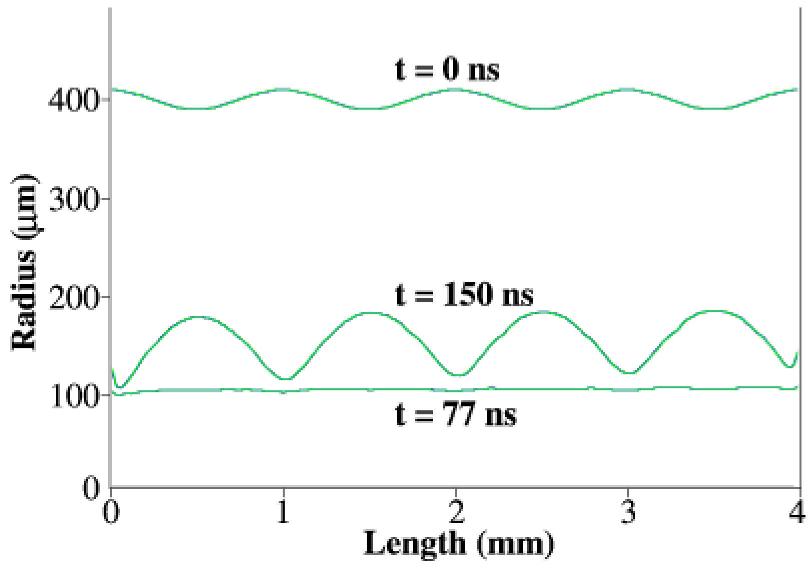
$$\gamma = 2\text{x}10^{7}\, sec^{-1}$$
$$\Delta t = 5\text{x}10^{-8} sec$$

e-folding = 1



1. Perturbation along length

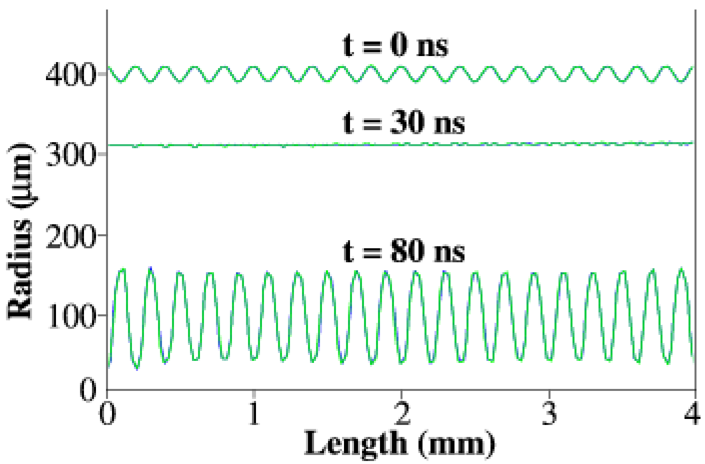
L = 0.4 cm, $k = 62.8\ cm^{-1}$, A = 10 μm, $k \cdot A = 6.28 \times 10^{-2}$



Phase inversion is helpful

With smaller amplitudes the stability situation is very good

$k = 3.14 \cdot 10^2\ cm^{-1}$, $A = 10\ \mu m$, $k \cdot A = 0.314$



For larger k, phase inversion occurs faster

For smaller amplitudes the stability situation is very good

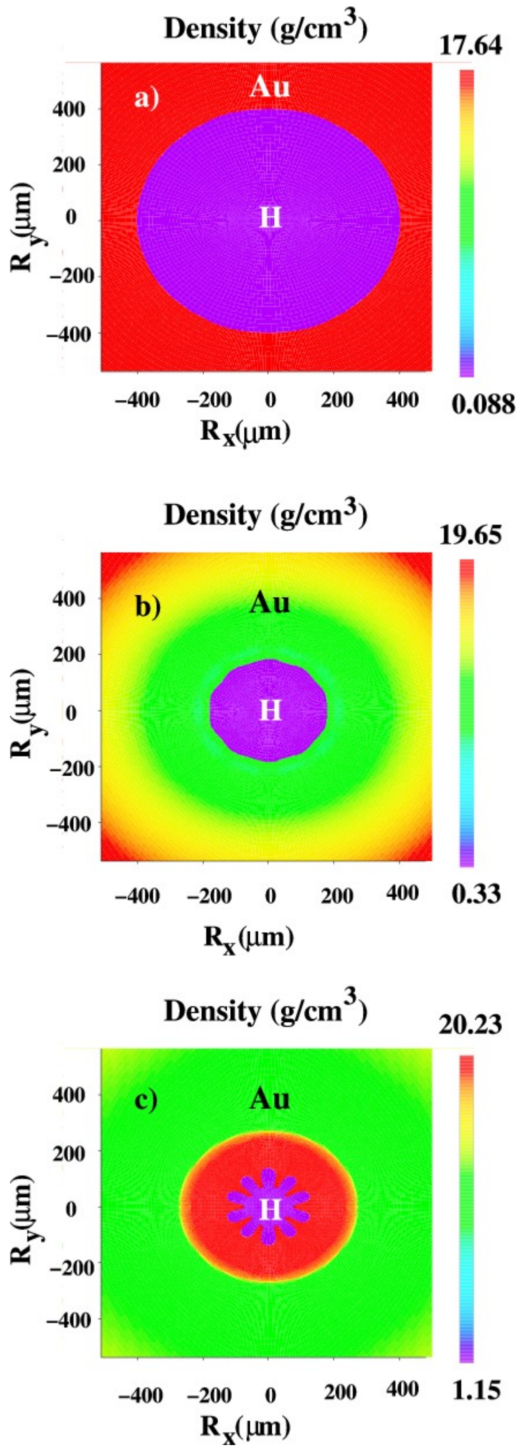
2. Perturbation along circumference

r = 0.4 mm and we consider 10 wavelengths.

$k = 2.5 \cdot 10^2\ cm^{-1}$

$A = 1\ \mu m$

$k \cdot A = 2.5 \cdot 10^{-2}$



For:
Smaller wavenumbers
smaller amplitudes
Stability is good