Extreme States of Matter Induced by Intense Particle Beams : The FAIR / HEDgeHOB Collaboration

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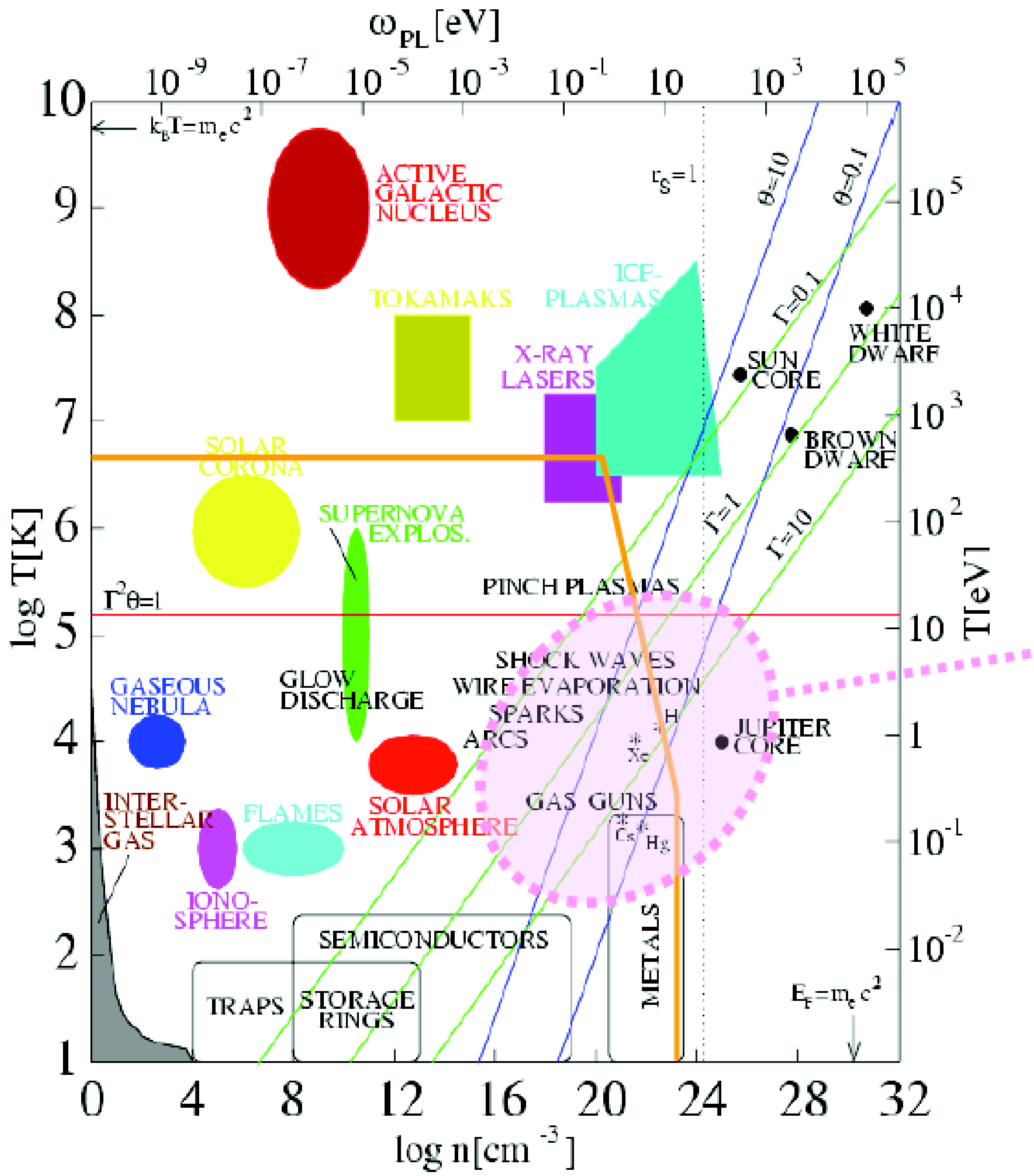
Definition:

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.



1. Static Techniques

Compression in a *DAC*

Time Scale [hours to days]

2. Dynamic Techniques

Time Scale [ps - μs]

(a) Shock Compression

High Power Lasers

Gas Guns

High Power Explosives

Magnetic Devices

(b) Isochoric Heating

Intense Particle Beams

"Accelerator" or

"Laser Generated"

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 Ion Beams are:

- High repetition rate, high coupling efficiency
- Large sample size [mm^3 - cm^3]
- Fairly uniform physical conditions (no sharp gradients)
- Precise knowledge of energy deposition in the sample
- Long life times
- Any target material can be used
- Unrivaled flexibility (Generate HED matter by isochoric heating as well as by shock compression)

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	4×10^{9}	5×10^{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]

ISOCHORIC HEATING TECHNIQUE

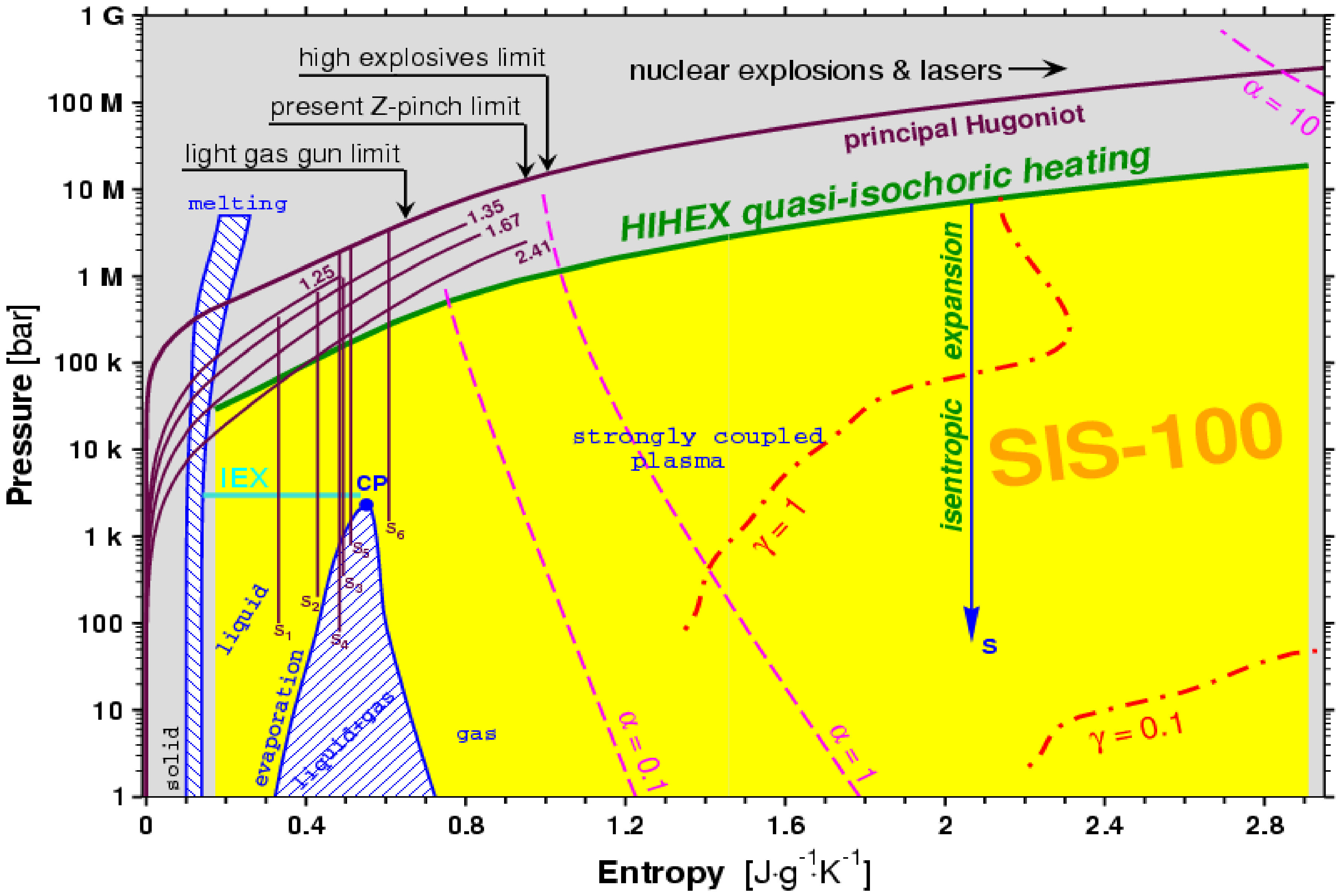
1. HIHEX [Heavy Ion Heating and Expansion

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

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

Phase diagram of lead

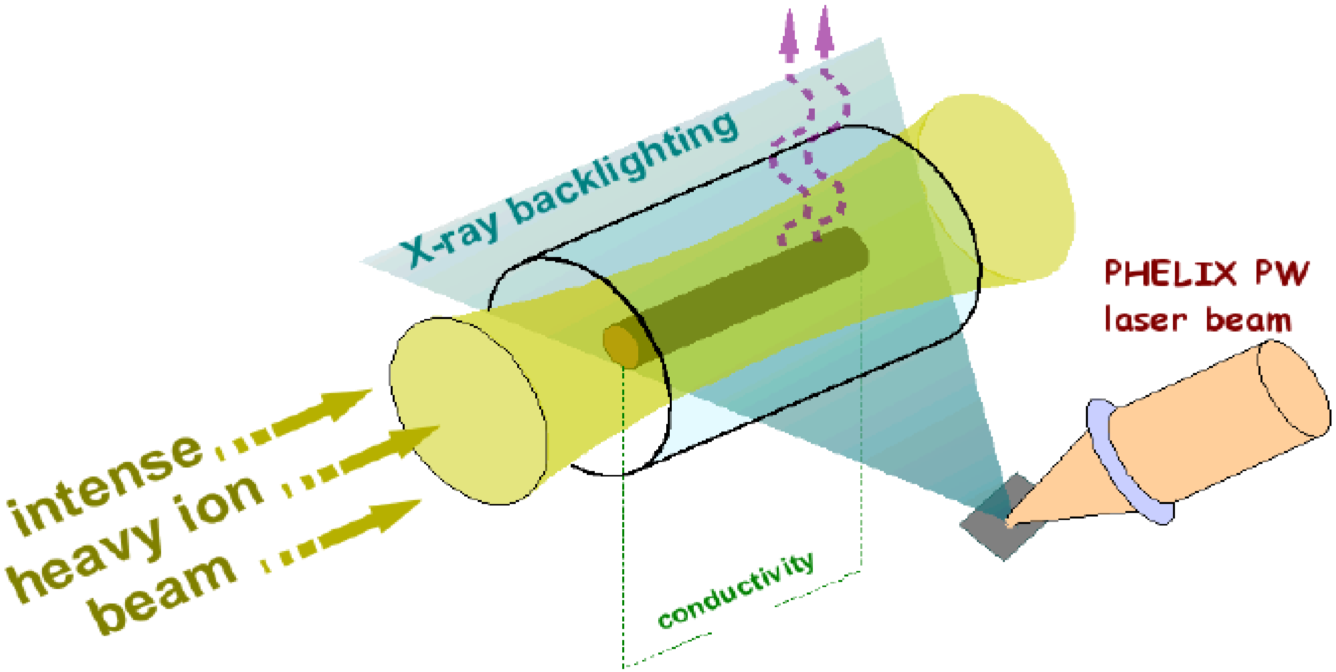


Critical Parameters of Some Metals

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

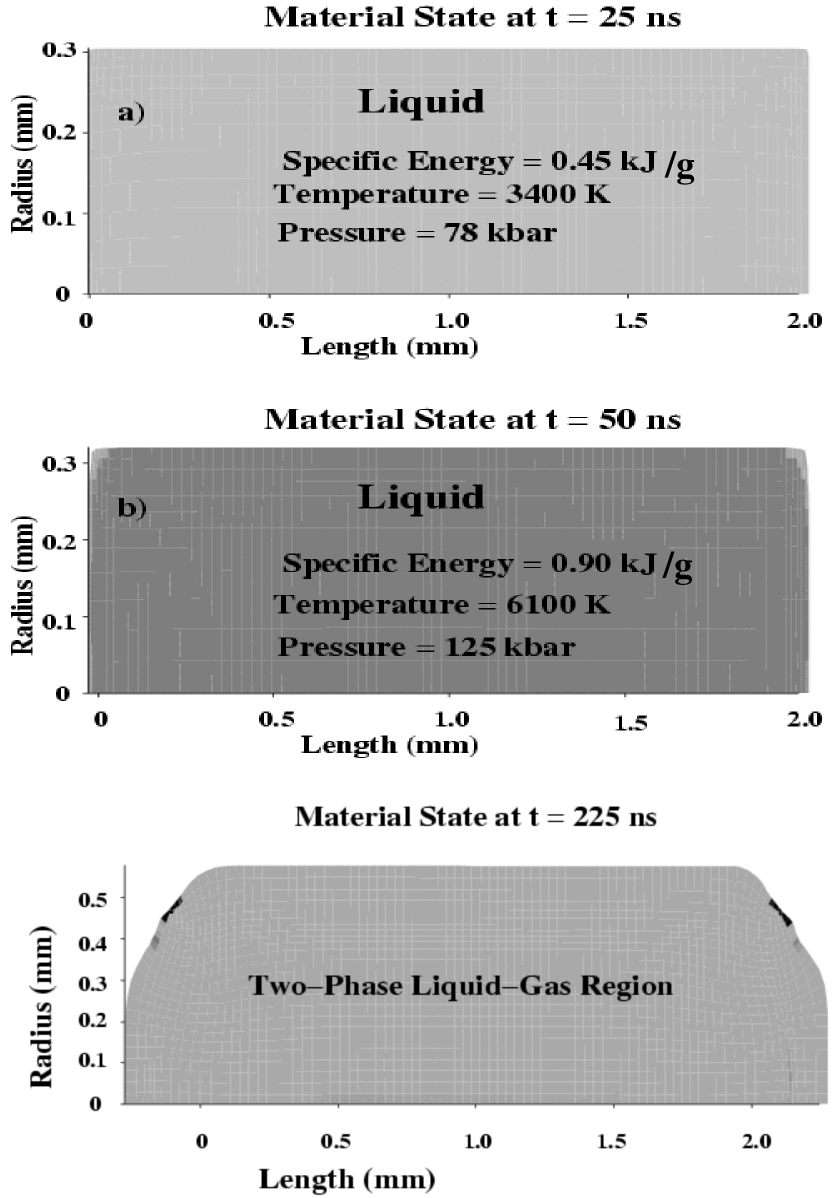


Table 1: Final Achievable Material State

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

2. LAPLAS [LAboratory PLAnetary Sciences]

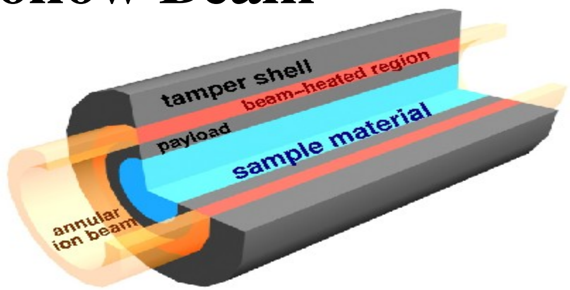
Experimental Scheme:

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;

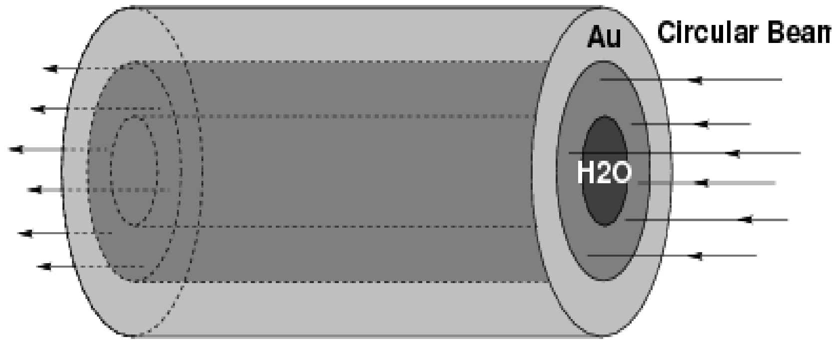
A.R. Piriz et al, PRE 66 (2002) 056403.

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**

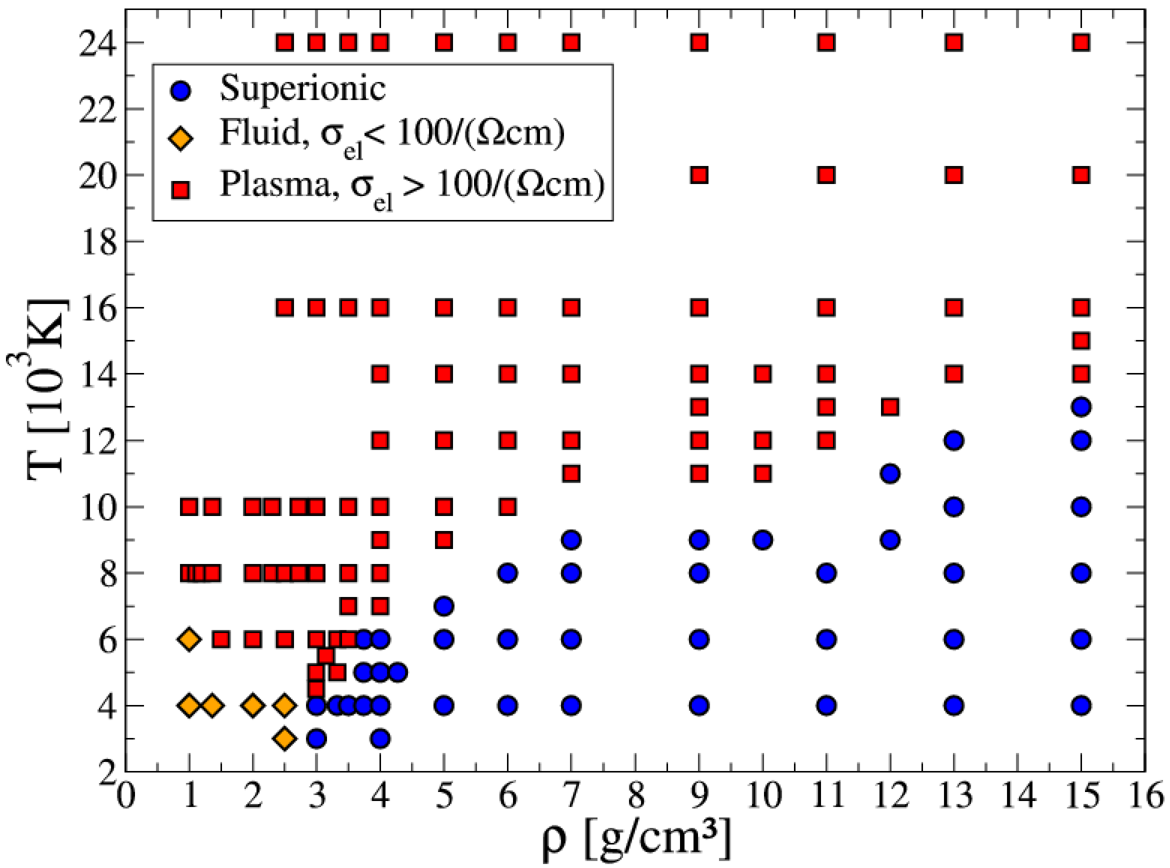
  ρ = 1.2 g/cc, P = 11 Mbar,

  T = 5 ev

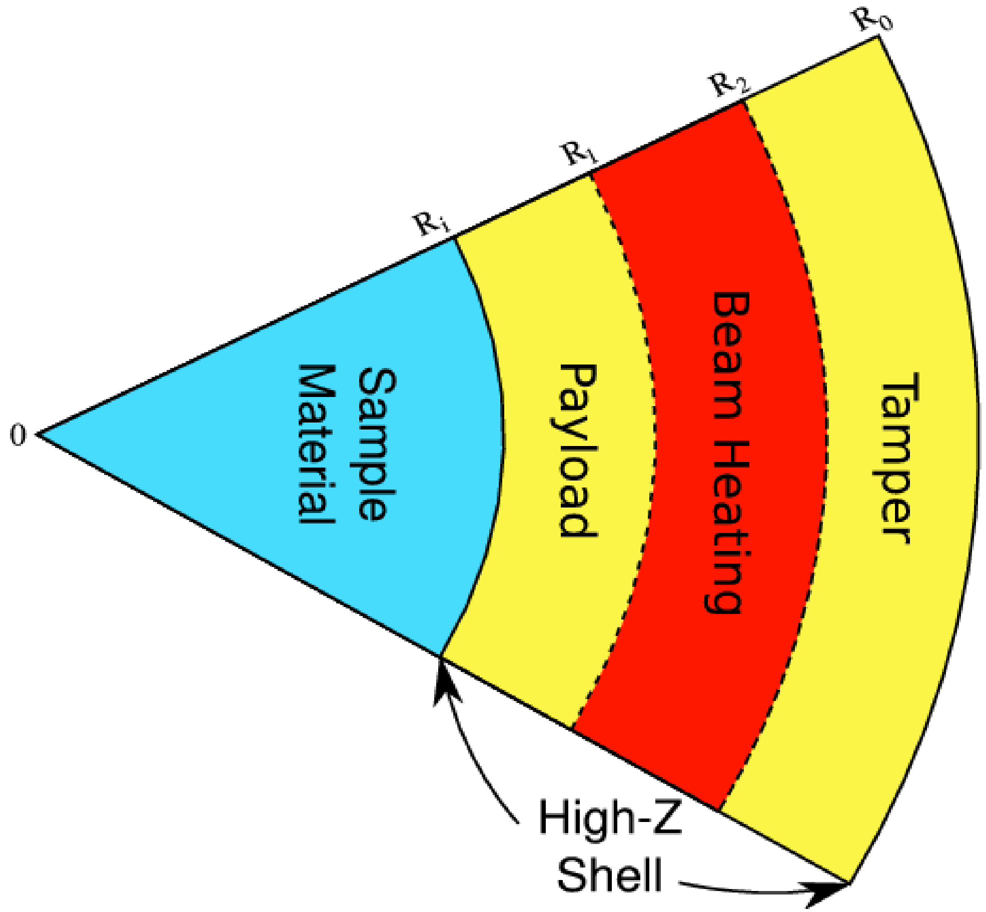
Phase Diagram of Water [QMD Simulations]

Mattsson & Desjarlais, PRL 97 (2006) 017801

M. French et al., PRB 79 (2009) 054107



N.A. Tahir et al, New J. Phys. 12 (2010) 073022.



Hollow Beam

1.5 GeV/u U ions

τ = 50 ns

Sample : Water

Outer Shell: W & Nb

R_i = 0.2 mm

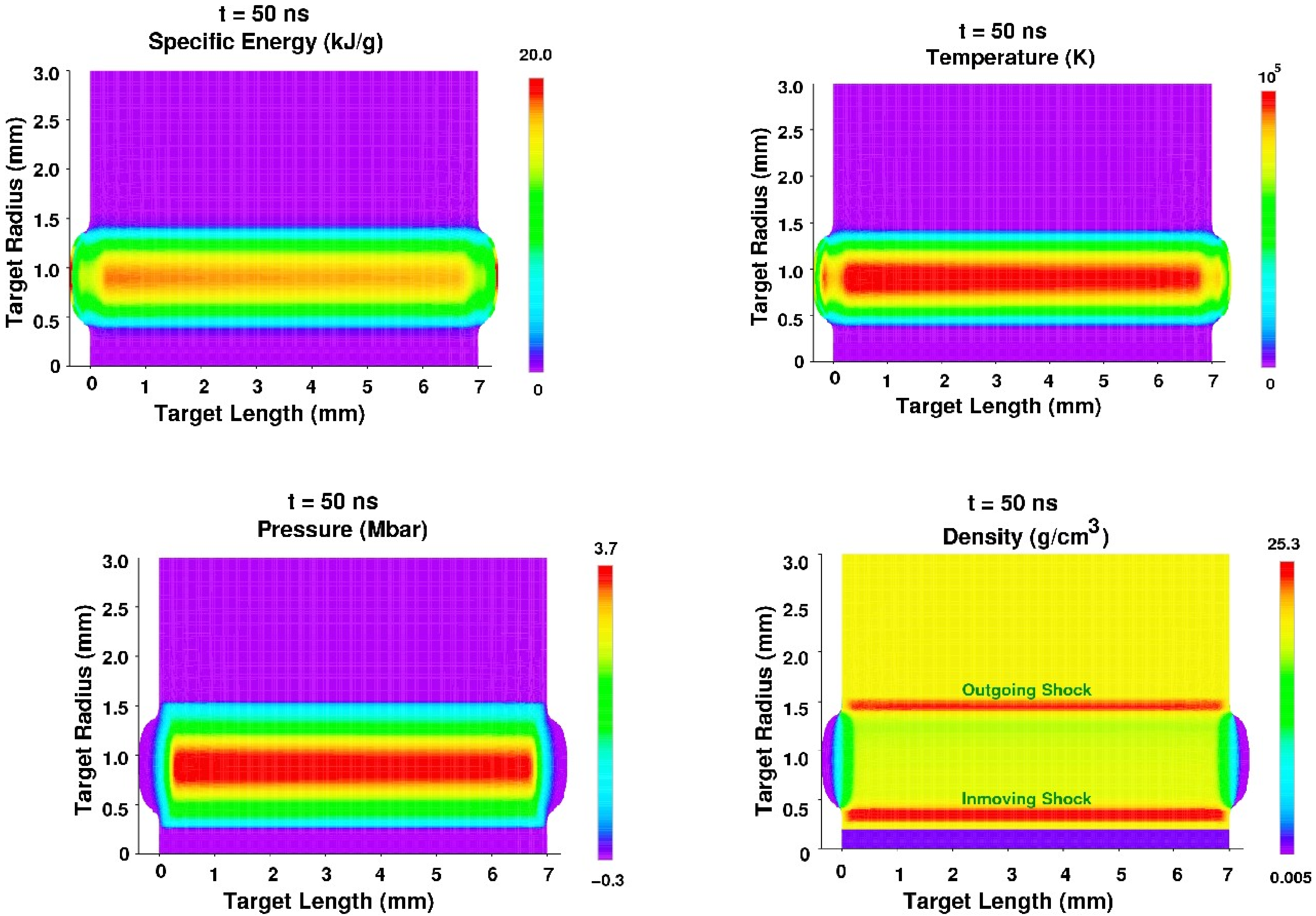
R_1 = 0.4 mm

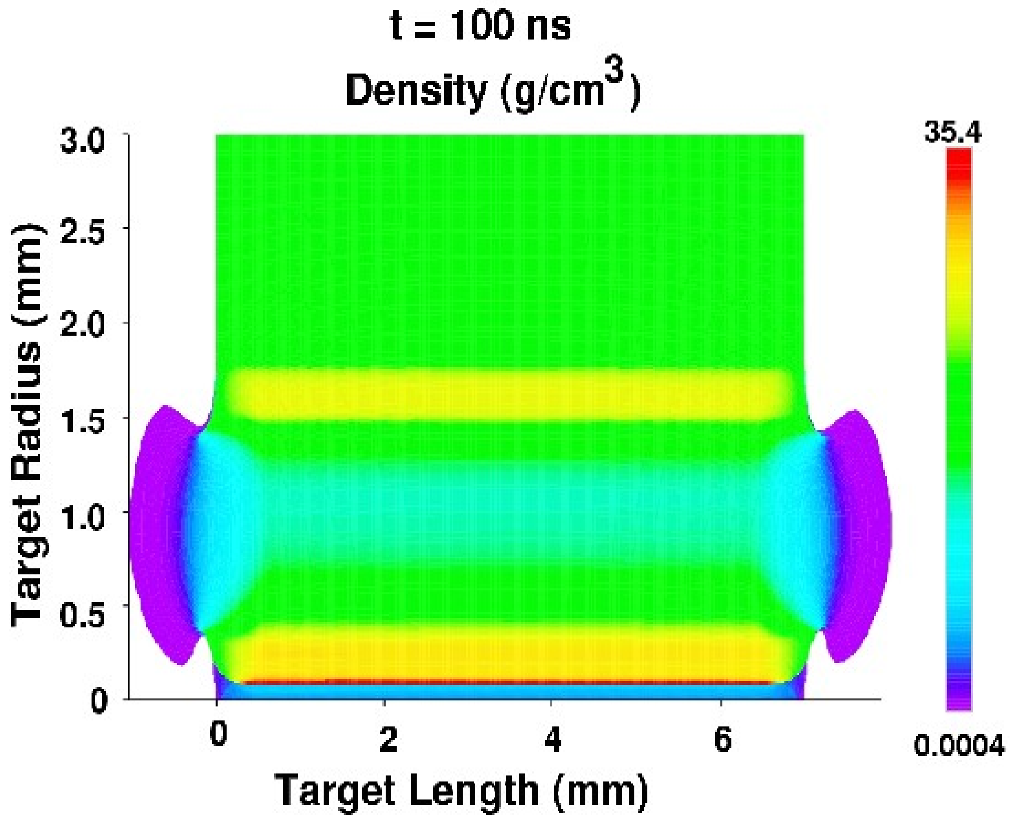
R_2 = 1.4 mm

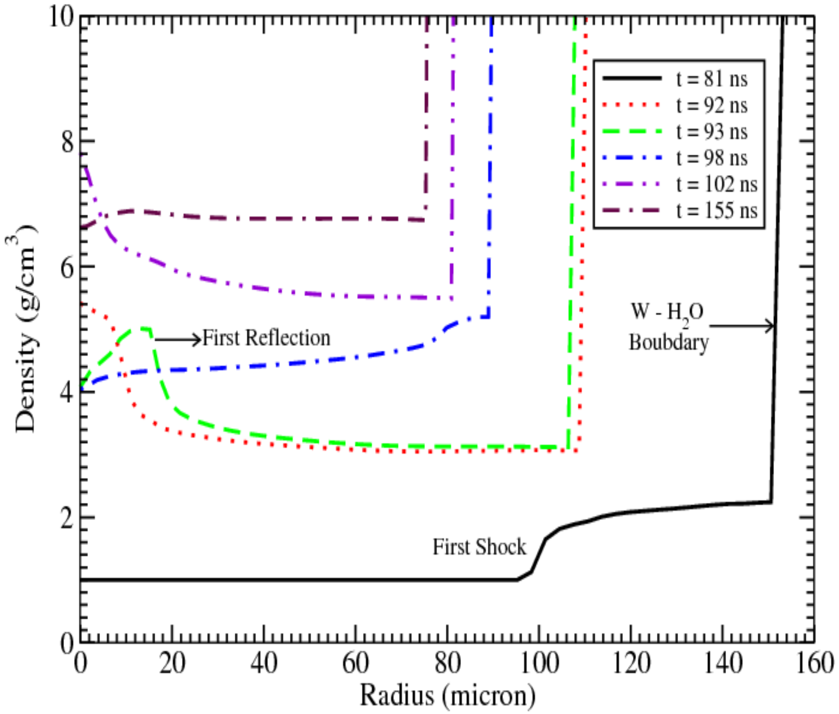
R_o = 3.0 mm

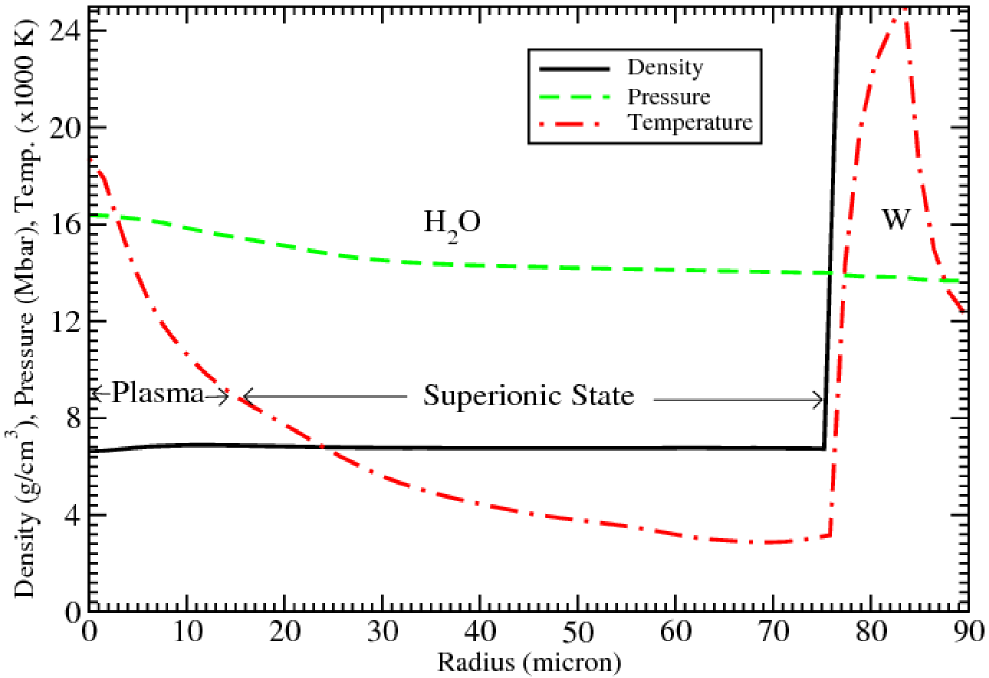
L = 7.0 mm

N.A. Tahir et al., New J. Phys. 12 (2010) 073022



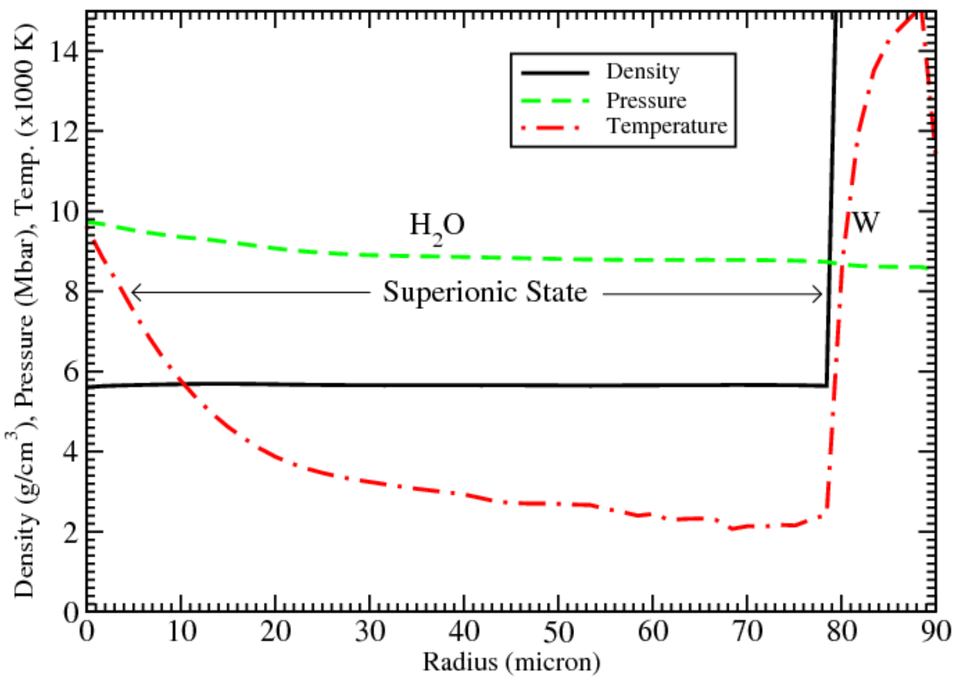

t = 100 ns
Density (g/cm3)
35.4
0.0004
Target Radius (mm)
3.0
2.5
2.0
1.5
1.0
0.5
0
0
2
4
6
Target Length (mm)

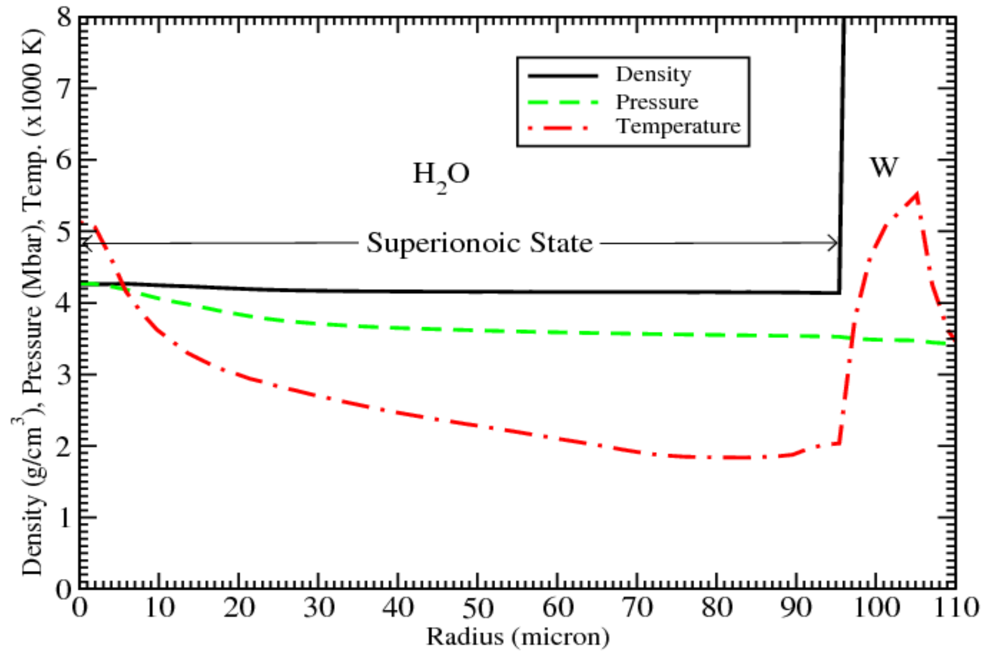

t = 81 ns
t = 92 ns
t = 93 ns
t = 98 ns
t = 102 ns
t = 155 ns
First Reflection
W - H2O Boubdary
First Shock
Density (g/cm3)
Radius (micron)
10
8
6
4
2
0
0
20
40
60
80
100
120
140
160



τ = 50 ns, R_1 = 0.4 mm, R_2 = 1.2 mm

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

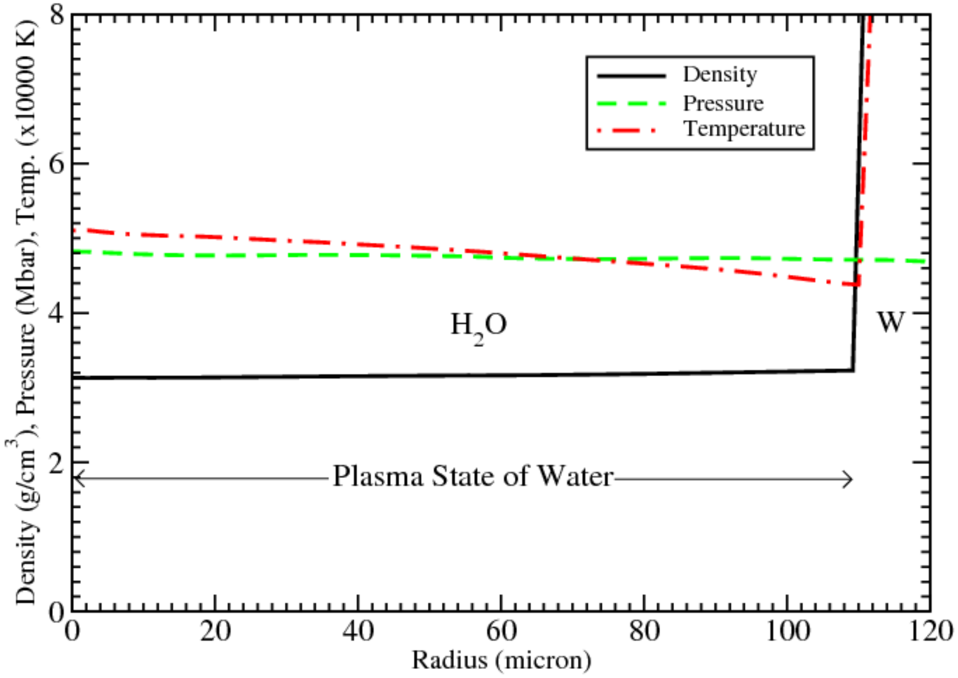


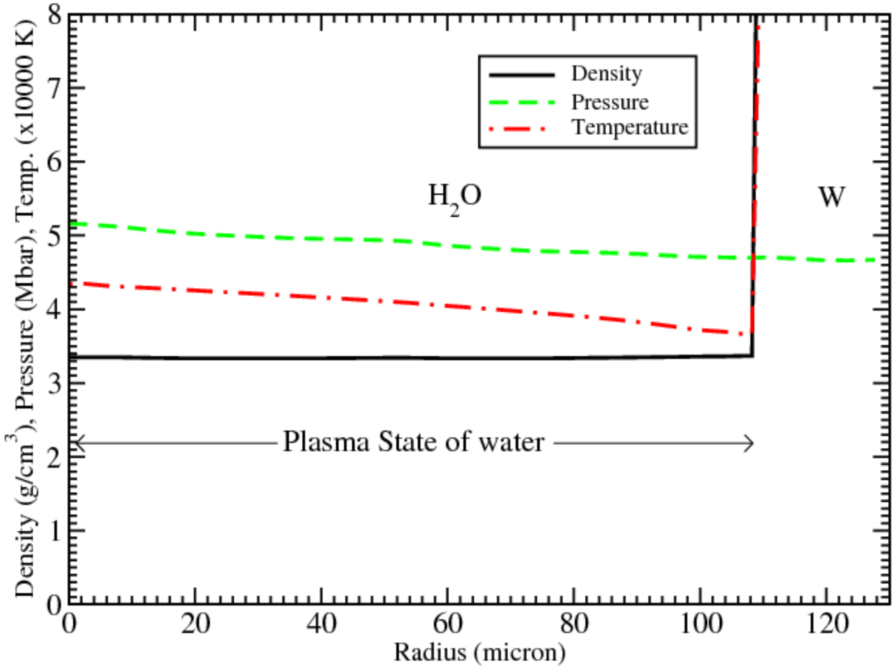


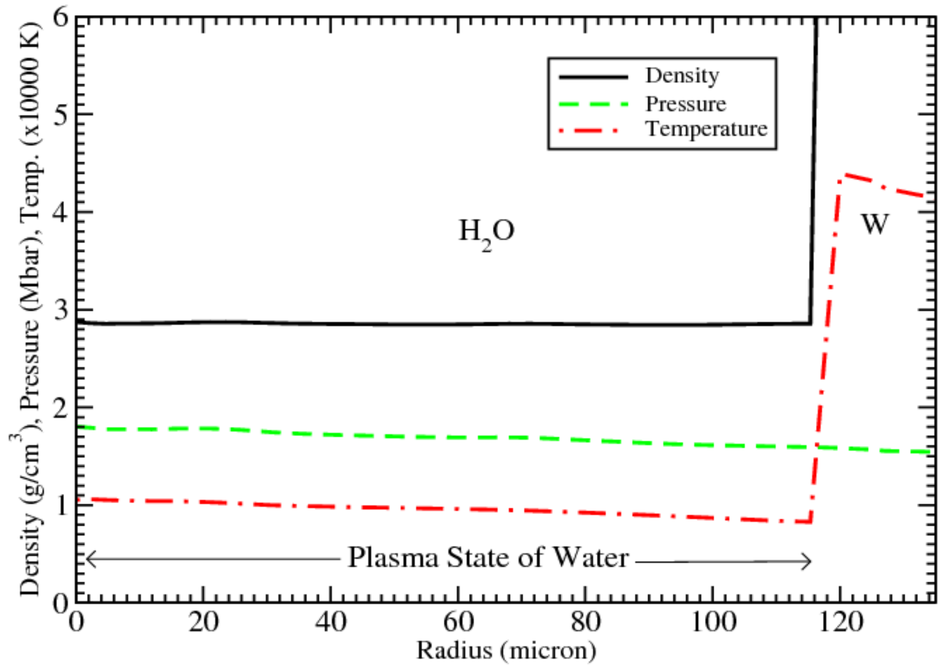
Circular Beam

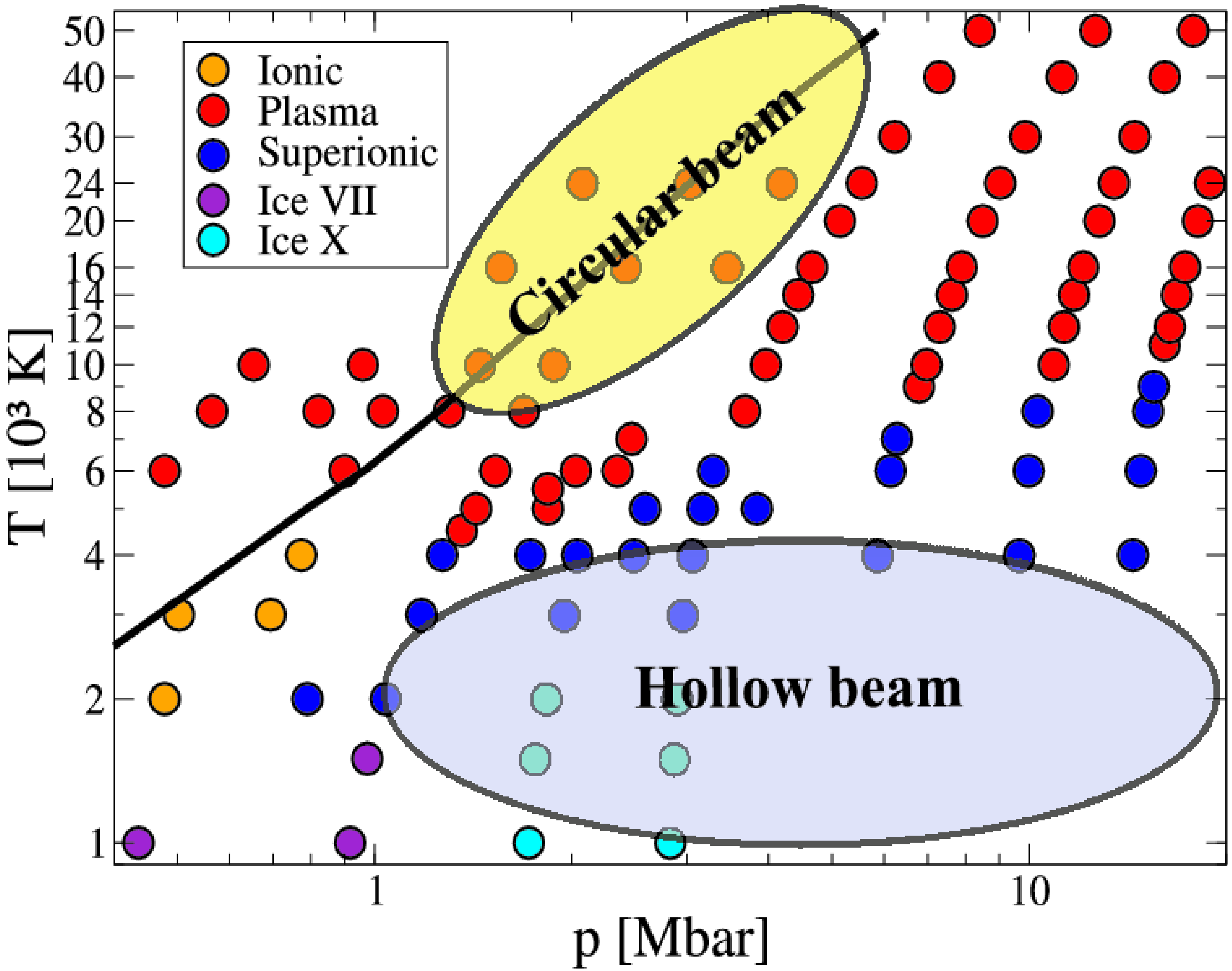
FWHM = 1.5 mm

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

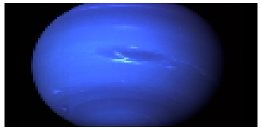
IOP Press Release

N.A. Tahir et al., New J. Phys. 12 (2010) 073022.

Pounding particles to create Neptune's water in the lab

22 July 2010

We know 'icy' Neptune is partially comprised of water molecules but until now we have had little means to test how water behaves in the extreme conditions that Neptune presents.



This is about to change as an international group of physicists draw up plans to use the new Facility for Antiprotons and Ion Research (FAIR) in Germany, which will be ready in 2015, to expose water molecules to heavy ion beams and thereby generate the same level of pressure on the water molecules that they experience within the very inhospitable core of Neptune.

The new plans being published in *New Journal of Physics* (co-owned by the Institute of Physics and German Physical Society) today, Thursday 22 July, explain how using high energy uranium beams in the future German facility is going to enable researchers to create conditions that push water molecules into a 'superionic' state and thereby observe water in conditions never before replicated.

The predicted 'superionic' state is an exotic hybrid phase of water composed of an oxygen lattice and a hydrogen liquid which under ambient conditions form stable H2O molecules in an ice lattice or in a liquid.

A total of 15 European, Russian and Chinese researchers from GSI Helmholzzentrun für Schwerionenforschung, Universität Rostock, Universidad de Castilla-La Mancha, Universite Paris-Sud, the Russian Academy of Sciences, and the Chinese Academy of Science explain how the use of the new heavy ion beams can simulate pressures up to several million times greater than anything on the surface of the Earth.

The researchers suggest that research into this 'superionic' state could be of paramount importance for the understanding of the magnetic field of Neptune and Uranus, which are very different from that of the Earth's.

The researchers cite the past decade's progress in the technology of strongly bunched, well focused, high quality intense heavy ion beams as the enabling force for this experiment - such beams will be made available when construction of FAIR is complete.

The heavy ion beams, which will be generated by the new particle accelerator at FAIR, will have advantages over other methods of exposing particles to high pressure, such as high explosives, gas guns, lasers, or pulsed power, because they will be able to apply a more uniform and more targeted pressure on the water molecules.

The researchers write, "The FAIR accelerator facilities will provide very powerful high quality heavy ion beams with unprecedented intensities. Extensive theoretical work on beam matter heating over the past decade has shown that the ion beams that will be generated at FAIR will be a very unique and very efficient tool to study High Energy Density Particles in those regions of the parameter space that are not so easy to access with the traditional method."

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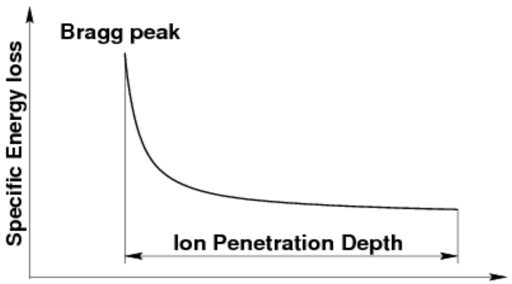
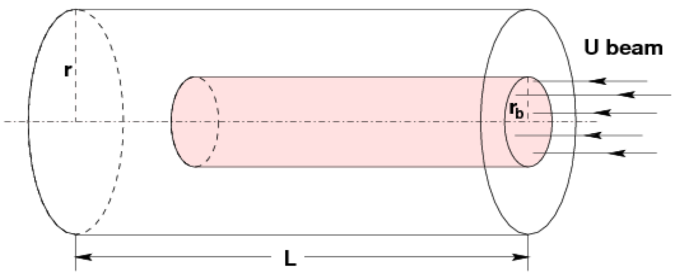
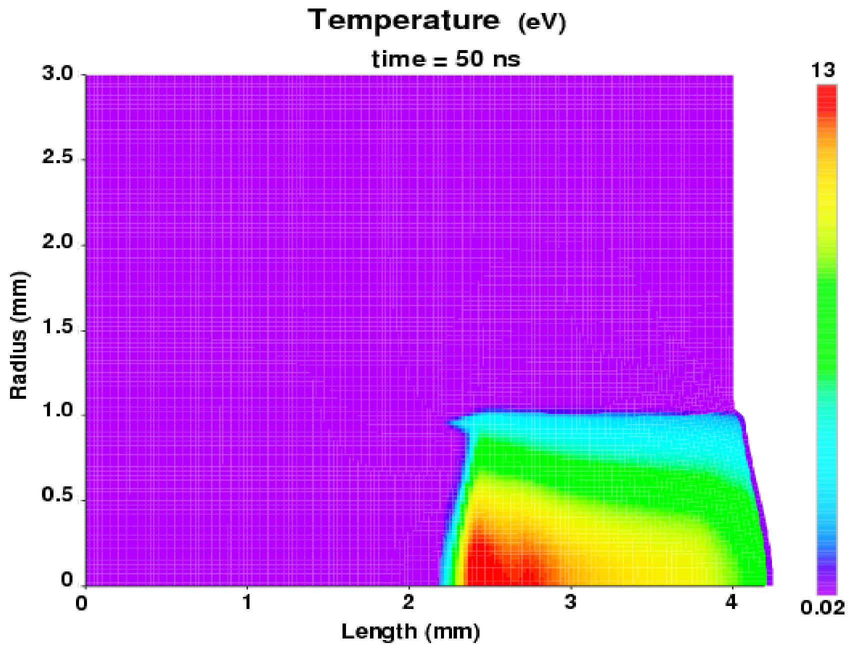
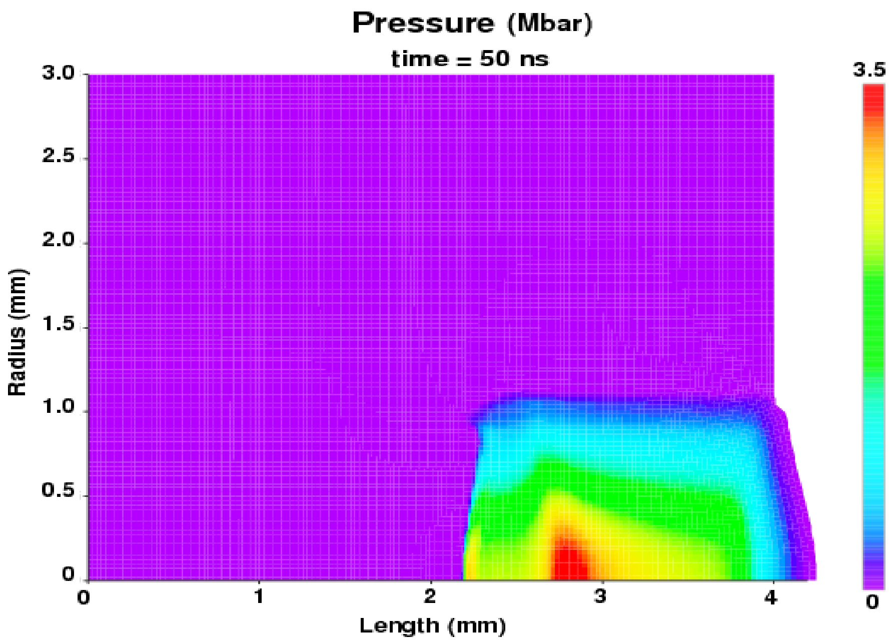
N.A. Tahir et al., PRE 61 (2000) 1975

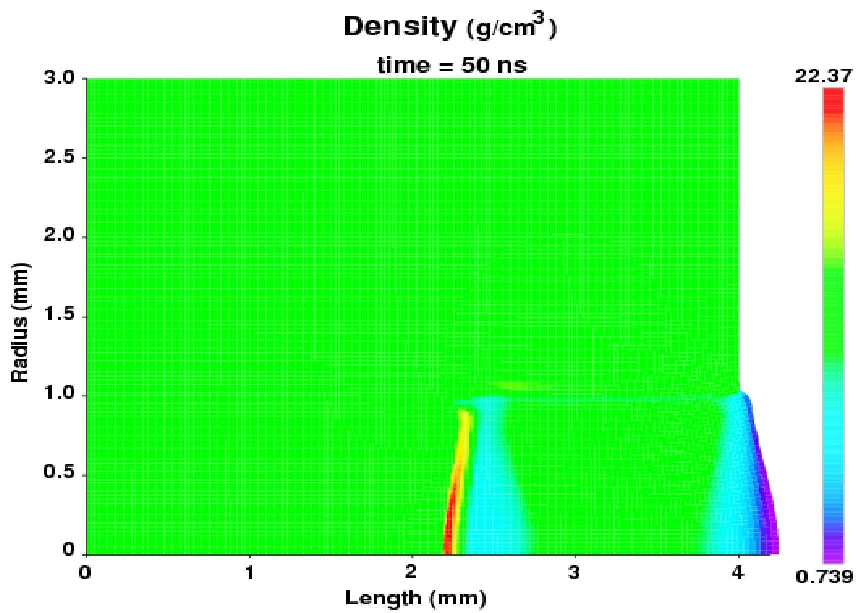


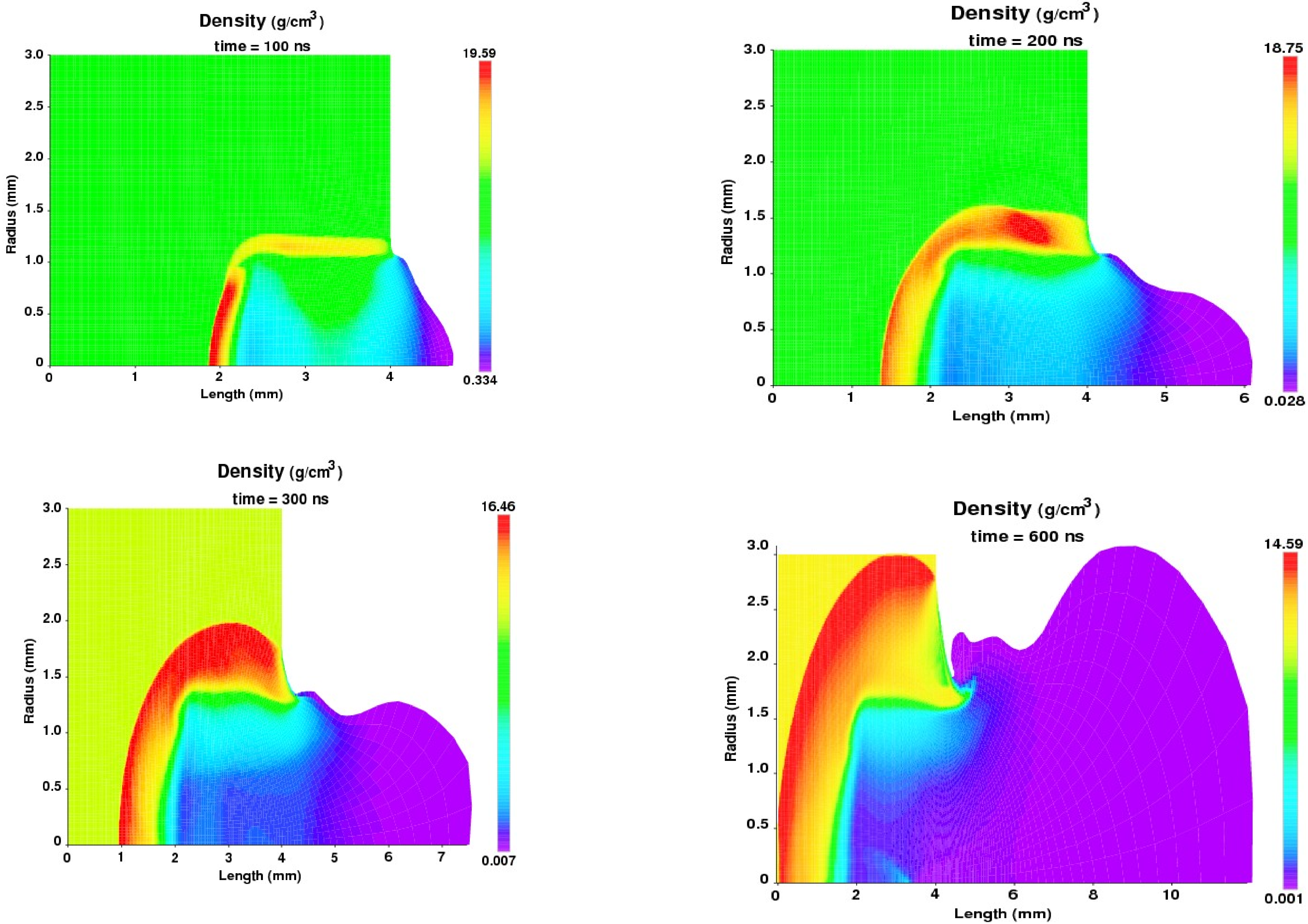


200 MeV/u U Ions
N = 2x10^{11}
τ = 50 ns
FWHM = 1 mm
Lead Cylinder
L = 4 mm
r = 3 mm








Density (g/cm3)
time = 100 ns
Radius (mm)
Length (mm)
19.59
0.334
Density (g/cm3)
time = 200 ns
Radius (mm)
Length (mm)
18.75
0.028
Density (g/cm3)
time = 300 ns
Radius (mm)
Length (mm)
16.46
0.007
Density (g/cm3)
time = 600 ns
Radius (mm)
Length (mm)
14.59
0.001

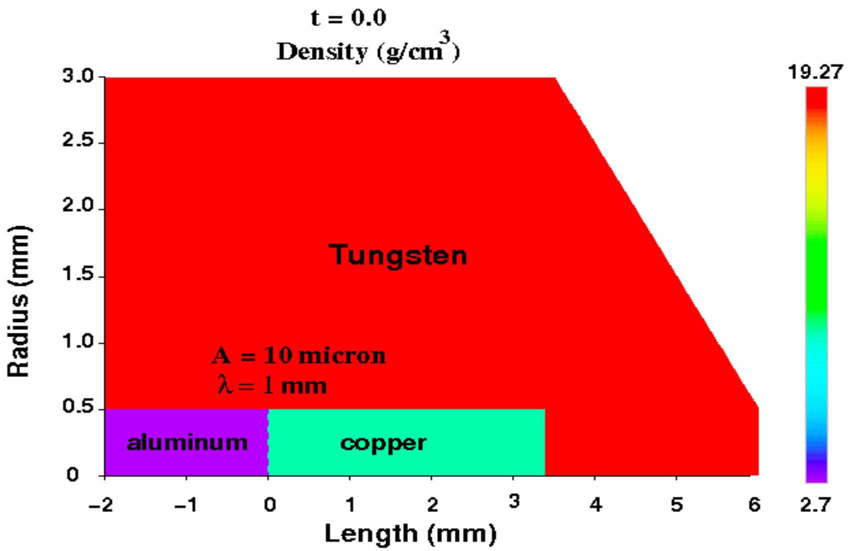
Ion Beam Generated Plane Shock Waves Using a Mach Type Reflection Scheme

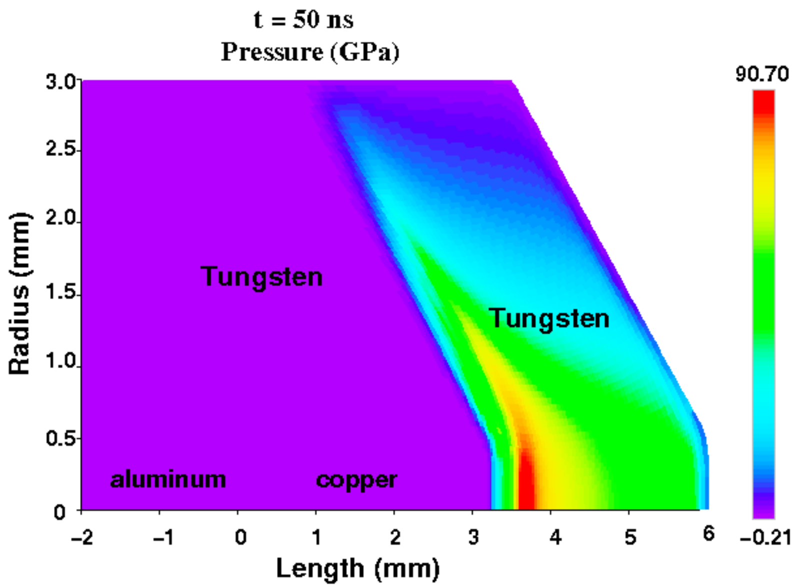
N.A. Tahir et al., Phys. Plasmas 18 (2011) 032704.

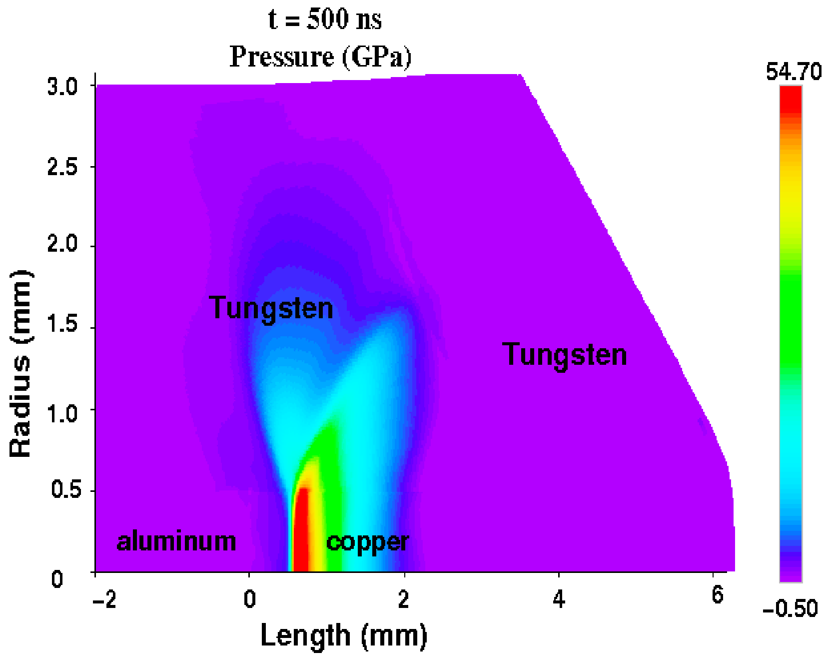
U ions 400 MeV/u

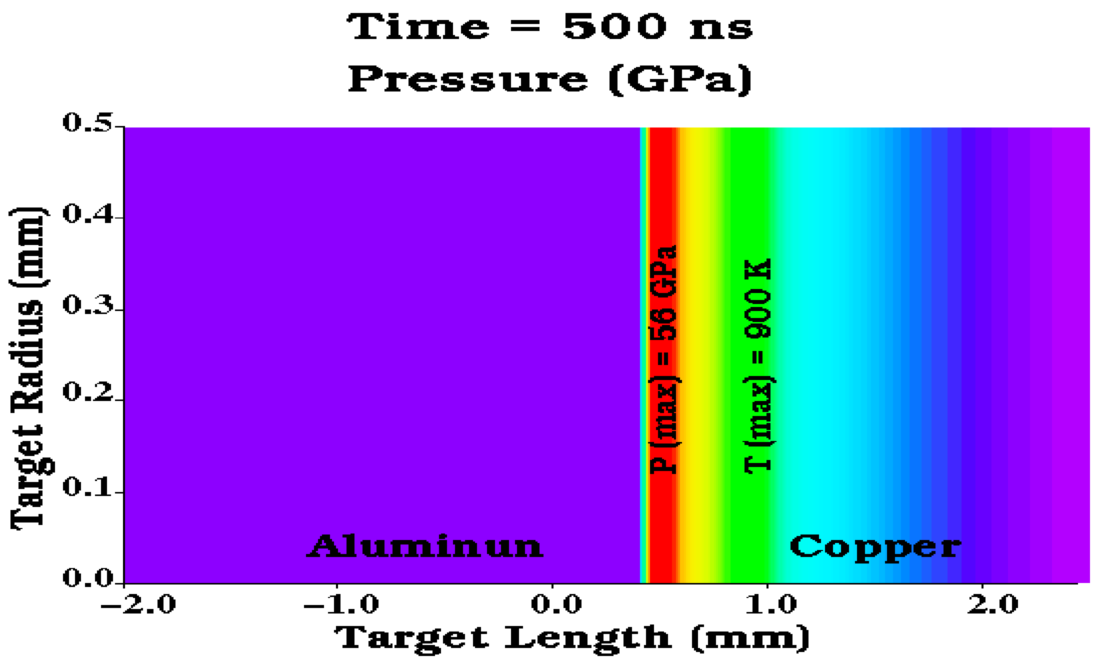
N = $5x10^{10}$

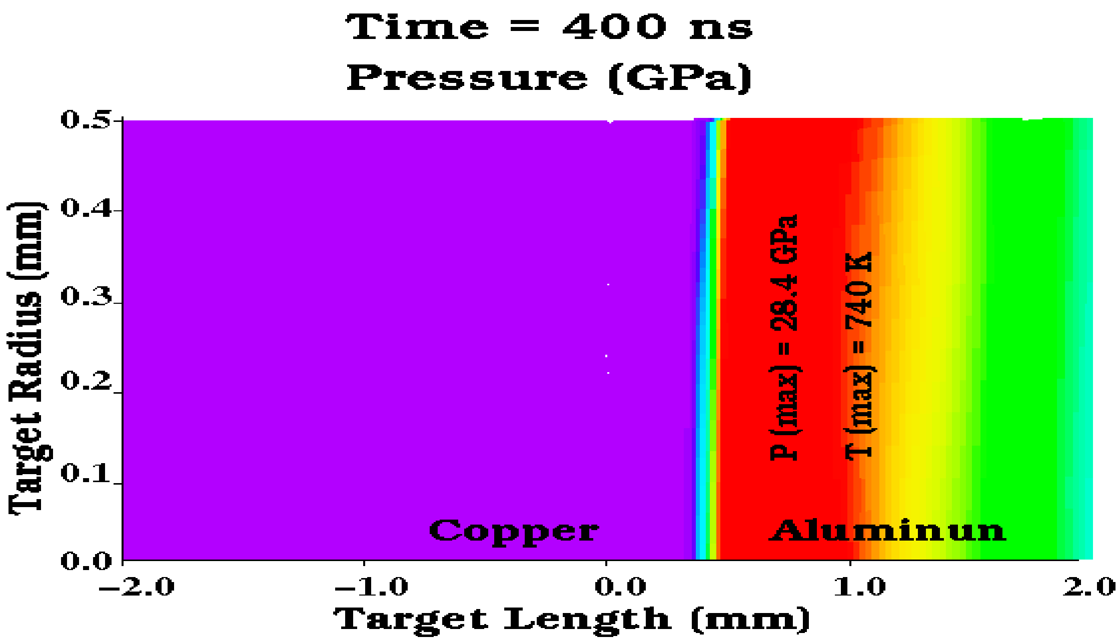
FWHM = 2 mm





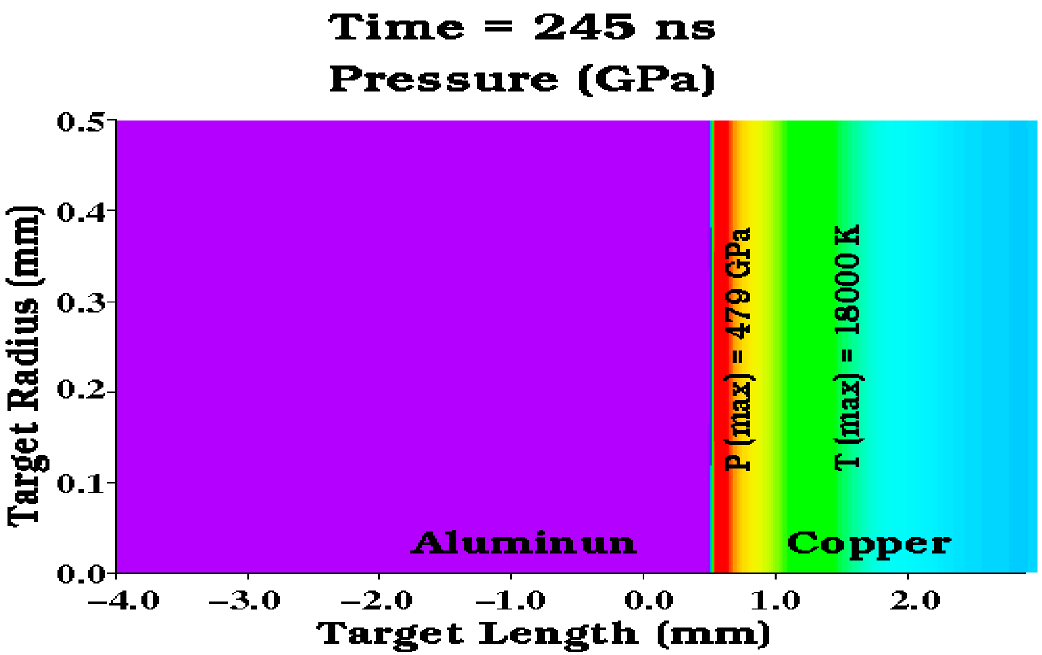


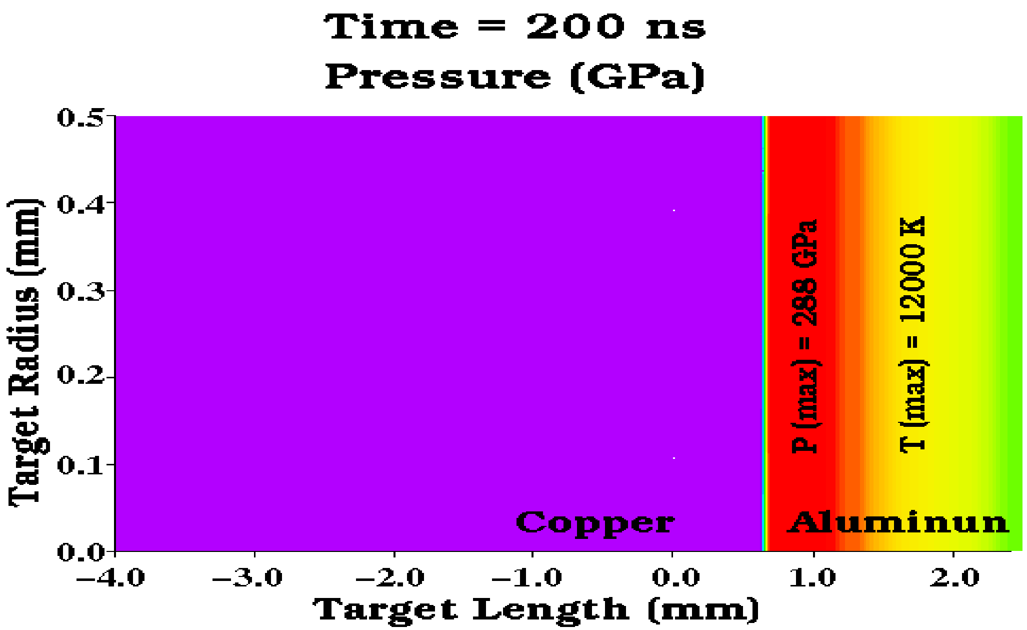




$N = 5 \times 10^{10}$

- **Material remains solid**
- **Material properties important!!**





<u>Fluid Case</u>

U ions 400 MeV/u

N = 5 x 10^{11}

FWHM = 2 mm

3. Proposed Experiment to Study Richtmyer-Meshkov Instability Growth:

Fluids [5×10^{11}] as well as solids [5×10^{10}]

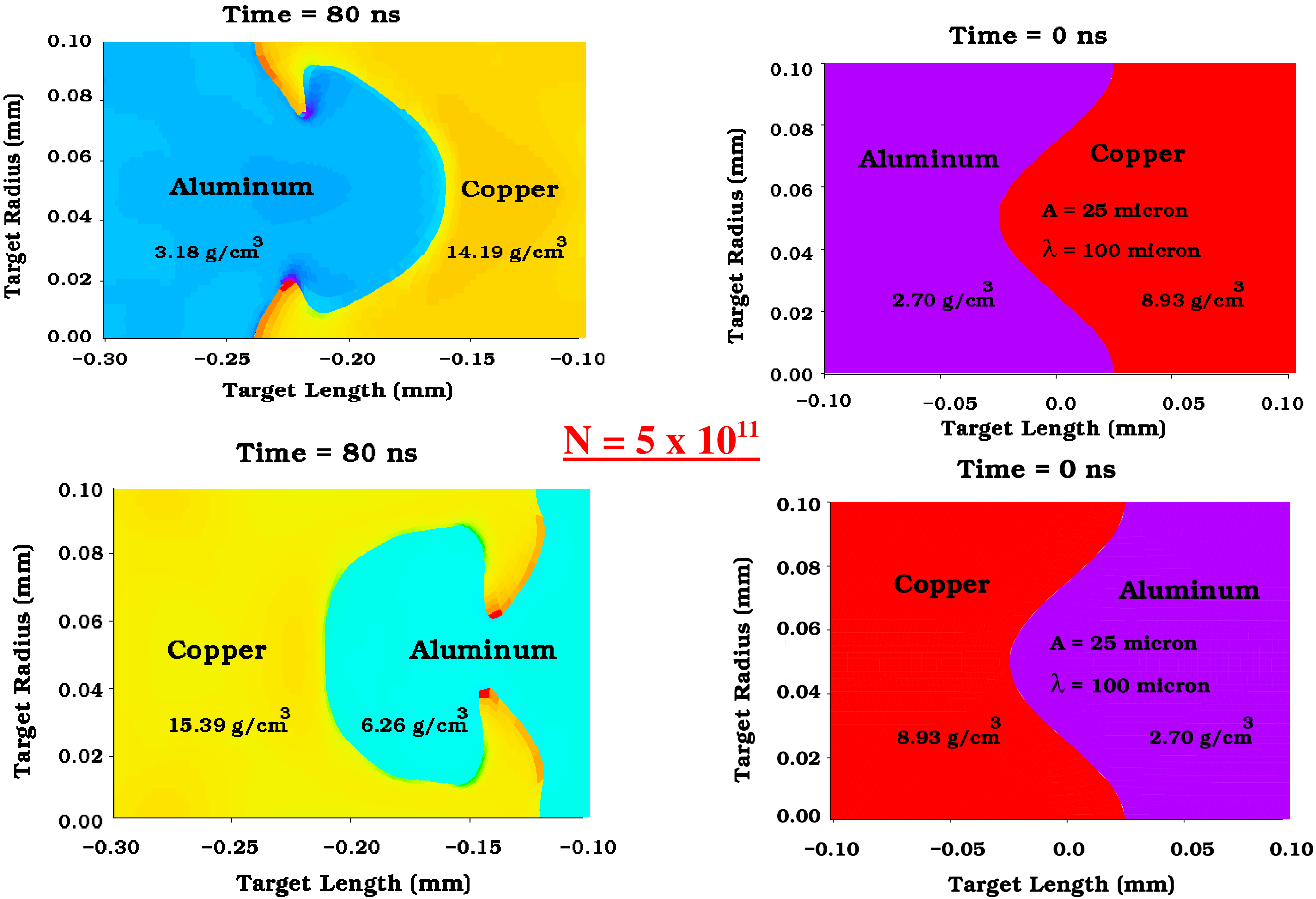
Linear as well as non-linear regime

We Consider perturbation with

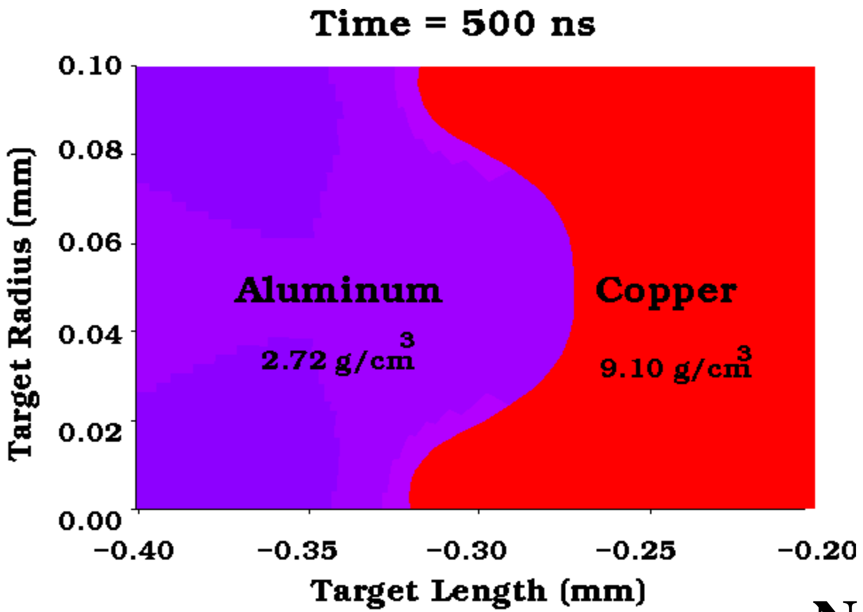
$\lambda = 100\ \mu m$; $k = 6.29 \times 10^{2}\ cm^{-1}$

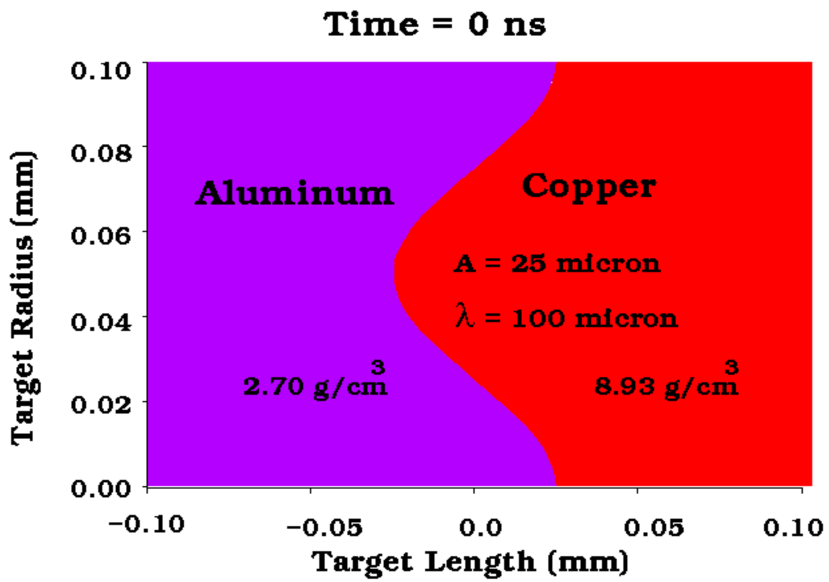
$A = 25\ \mu m$ and $1\ \mu m$

$kA = 1.57$ and 0.0629



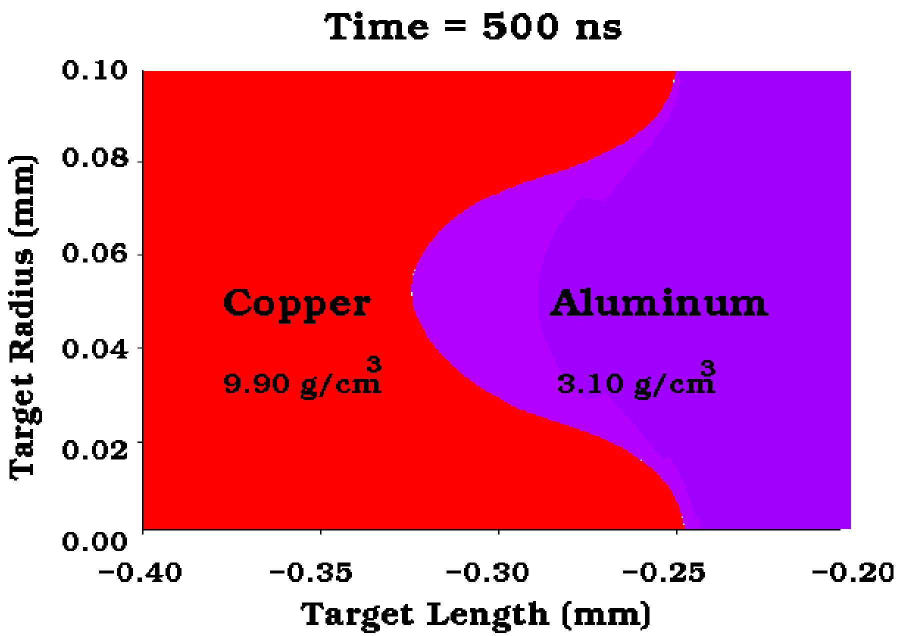
Time = 80 ns
Aluminum
Copper
3.18 g/cm3
14.19 g/cm3
Target Radius (mm)
Target Length (mm)
Time = 0 ns
Aluminum
Copper
A = 25 micron
λ = 100 micron
2.70 g/cm3
8.93 g/cm3
Target Radius (mm)
Target Length (mm)
N = 5 x 10^11
Time = 80 ns
Copper
Aluminum
15.39 g/cm3
6.26 g/cm3
Target Radius (mm)
Target Length (mm)
Time = 0 ns
Copper
Aluminum
A = 25 micron
λ = 100 micron
8.93 g/cm3
2.70 g/cm3
Target Radius (mm)
Target Length (mm)

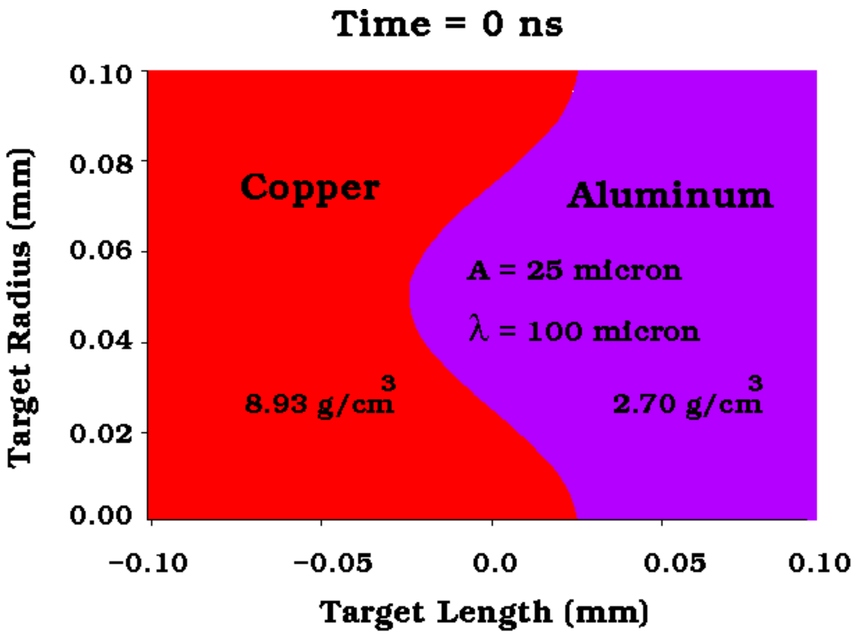




N = 5 x 10^{10} / bunch

Material Properties Included

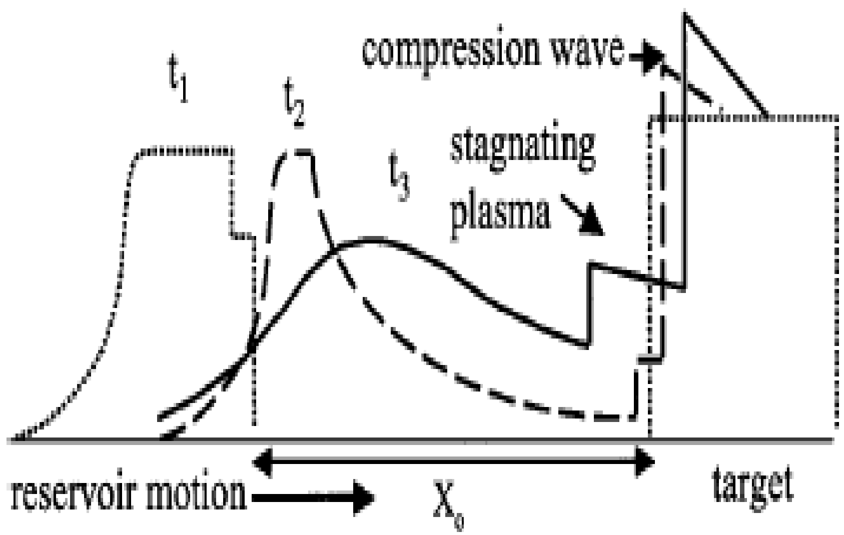




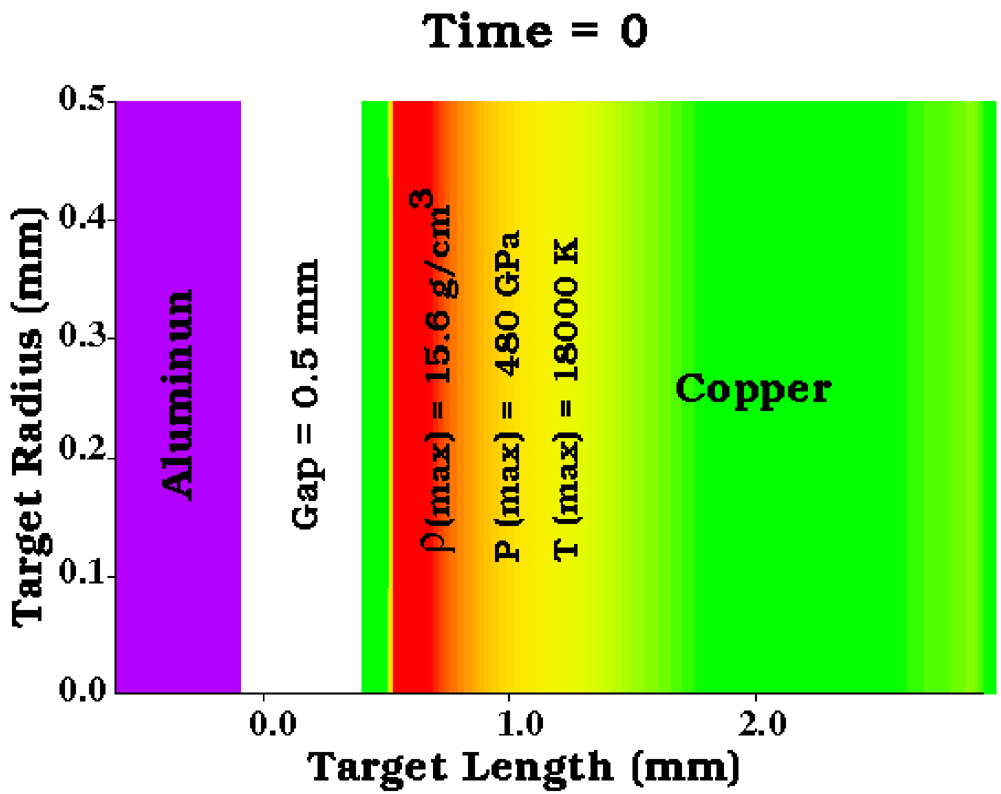
4. Ramp Type Compression of Solid Samples [In Collaboration with Andrew Ng]

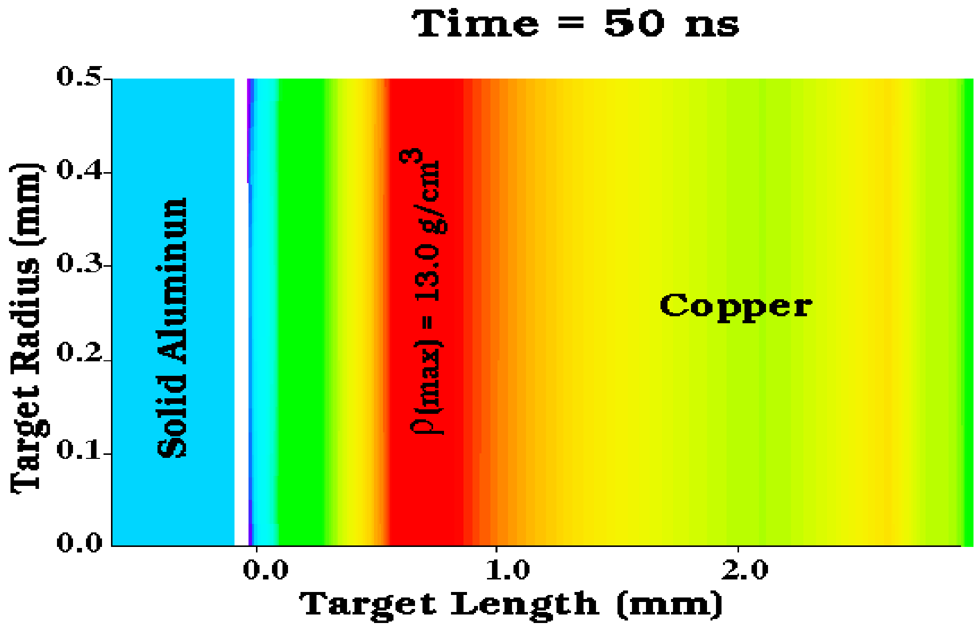
Laser-Driven Scheme

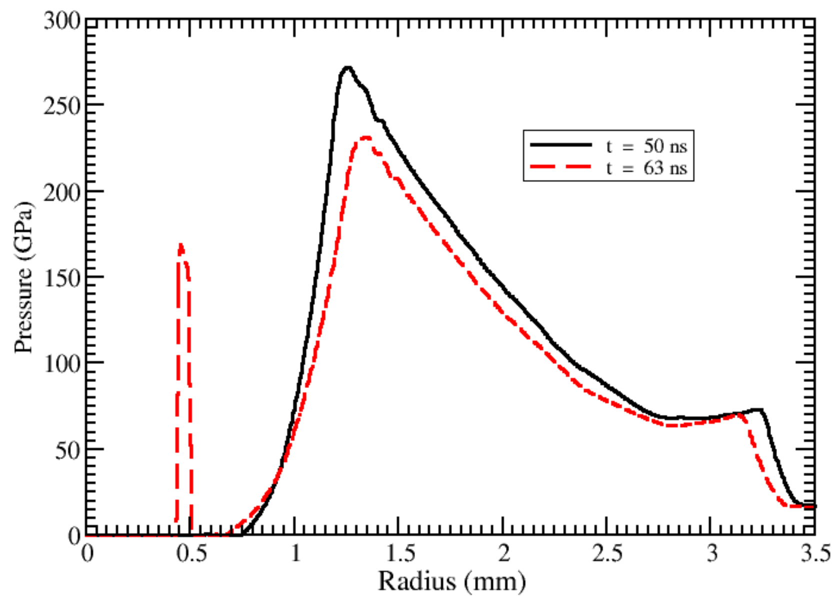
J. Edwards et al., PRL 92 (2004) 075002.

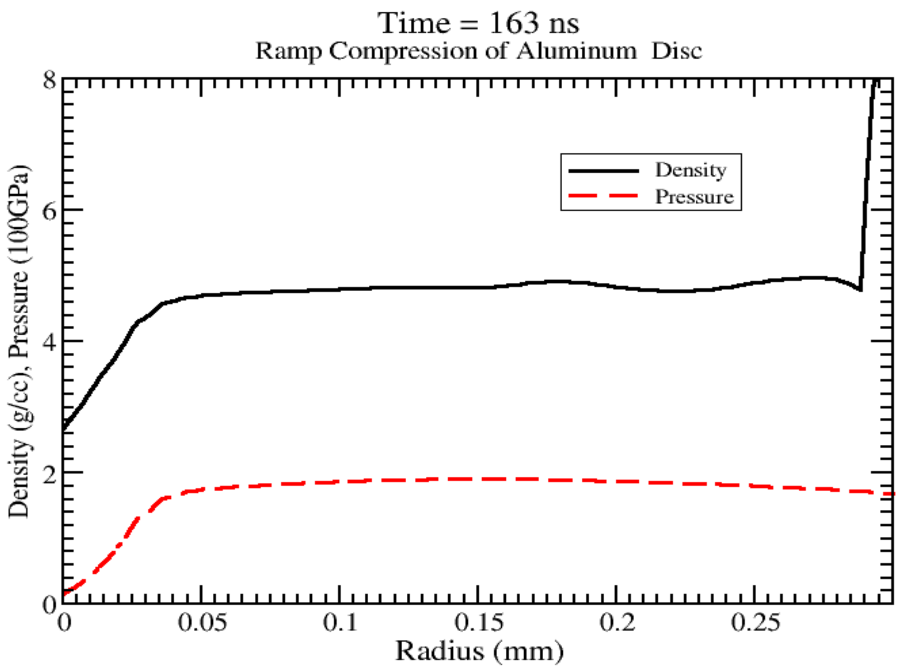


Ion Beam-Driven Scheme









Optimization Required

- **Gap ??**
- **Thickness of Sample??**
- **Reservoir Pressure??**
- **Initial Position of Shock??**

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.

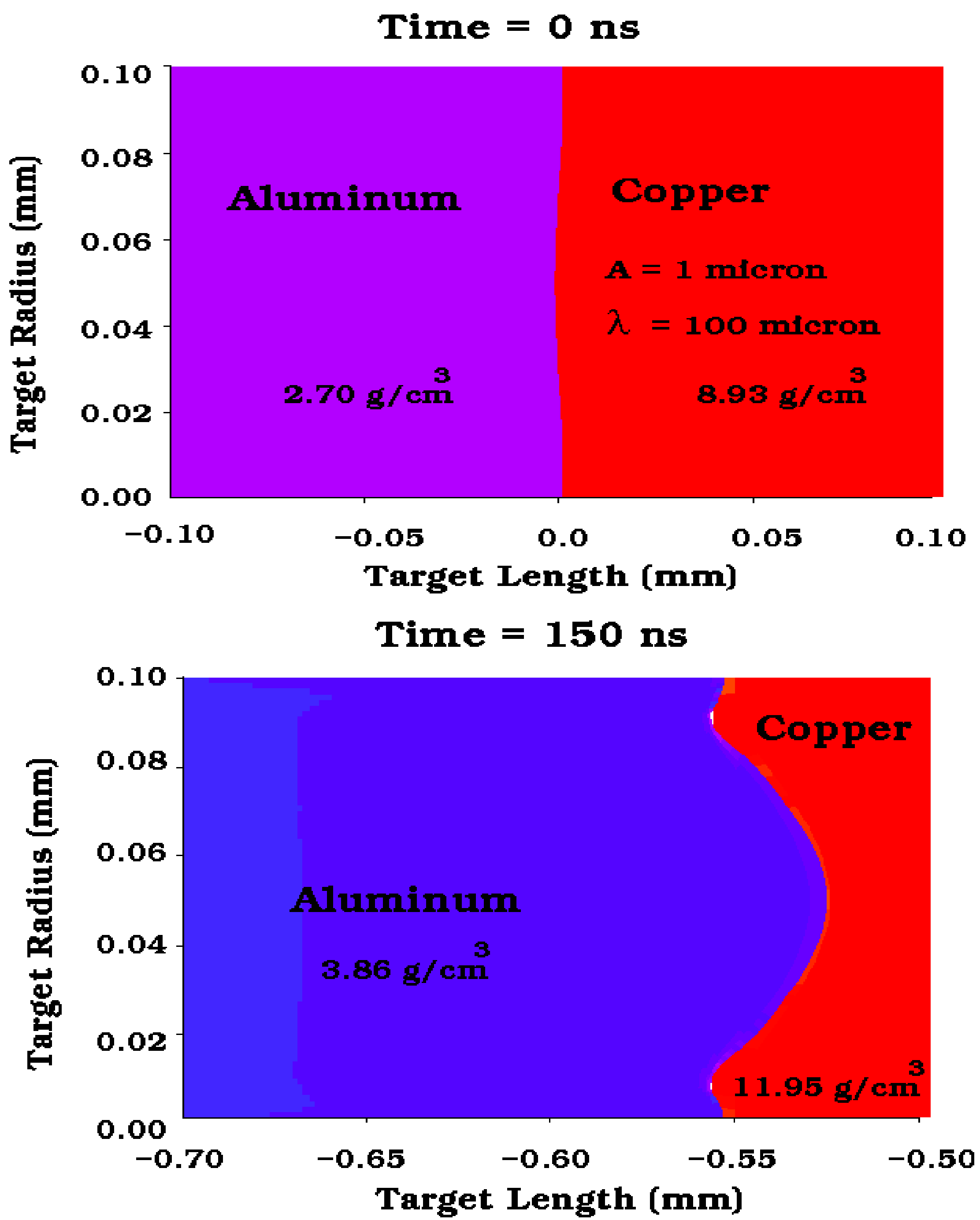
A). **HIHEX [Heavy Ion Heating and Expansion]**
One can use solid as well as porous targets; all interesting physical state, EHL, 2PLG, CP, SCP can be accessed using the beam at the FAIR facility.

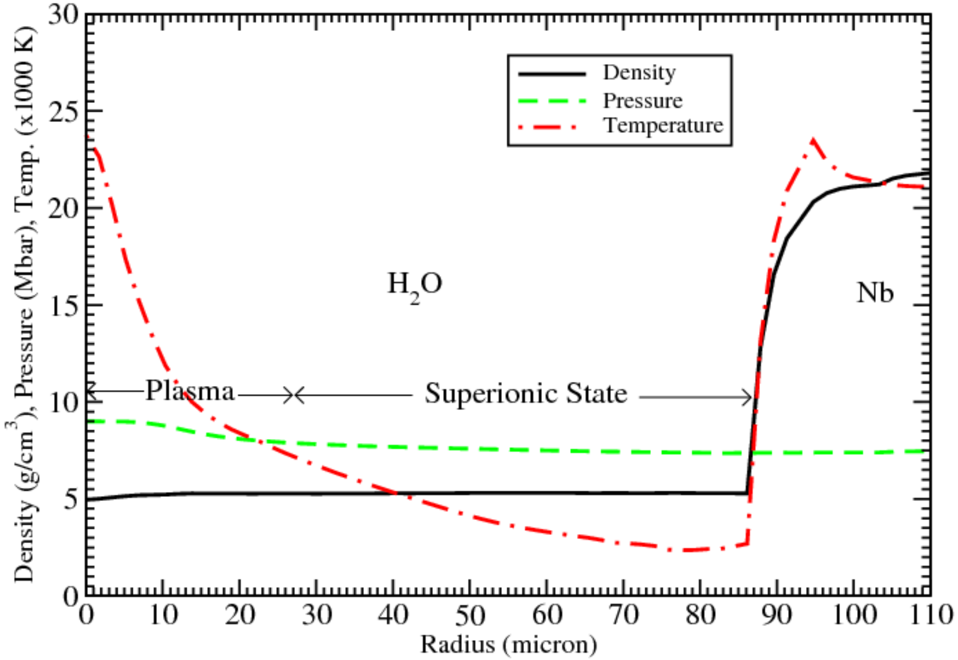
B). **LAPLAS [LAboratory PLAnetary Sciences]**
The scheme is robust, insensitive to large variations in beam and target parameters, hydrodynamically stable (**Rayleigh-Taylor** and Richtmeyer-Meshkov).

C) . **Richtmyer-Meshkov Instability Growth Studies**

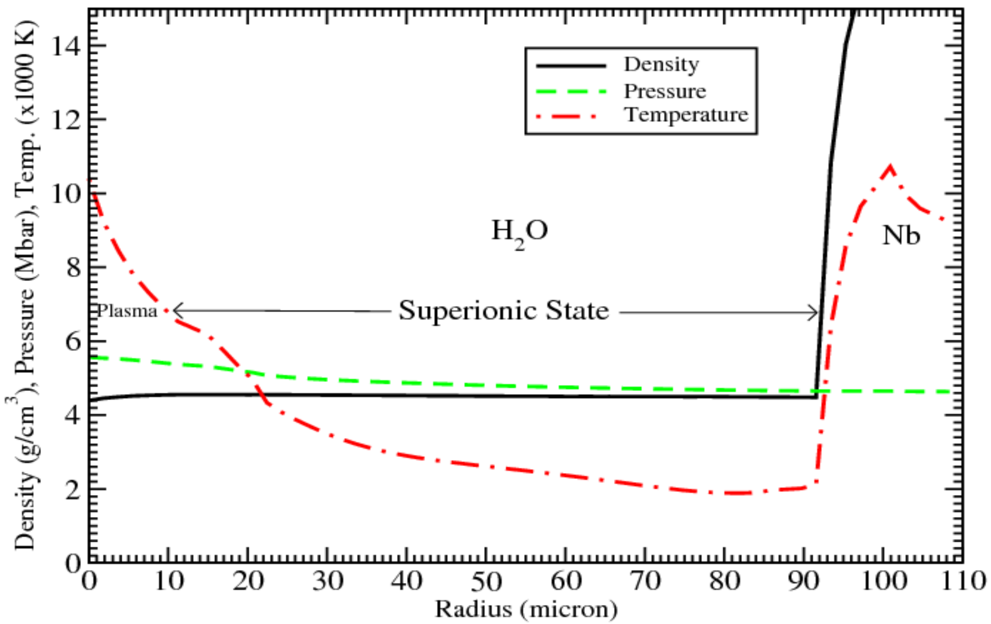
D). **Ramp Compression**: Studies of Material properties under dynamic conditions

“ Work is in progress to investigate more experiment designs”

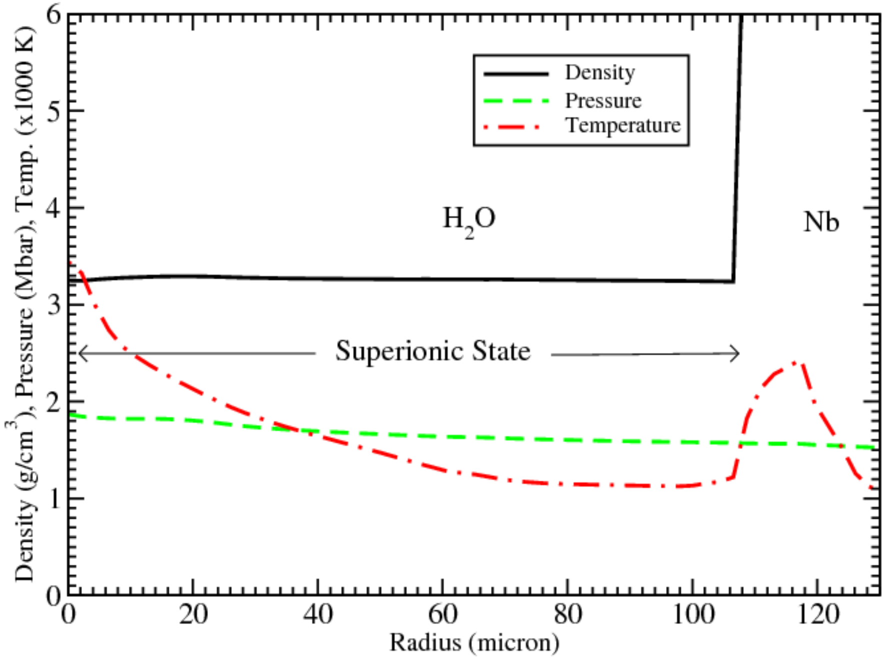

Time = 0 ns
Aluminum
Copper
A = 1 micron
λ = 100 micron
2.70 g/cm3
8.93 g/cm3
Target Radius (mm)
Target Length (mm)
0.00
0.02
0.04
0.06
0.08
0.10
−0.10
−0.05
0.0
0.05
0.10
Time = 150 ns
Aluminum
Copper
3.86 g/cm3
11.95 g/cm3
Target Radius (mm)
Target Length (mm)
0.00
0.02
0.04
0.06
0.08
0.10
−0.70
−0.65
−0.60
−0.55
−0.50



Density
Pressure
Temperature
H2O
Nb
Plasma
Superionic State
Density (g/cm3), Pressure (Mbar), Temp. (x1000 K)
Radius (micron)



Density
Pressure
Temperature
H2O
Nb
Plasma
Superionic State
Density (g/cm3), Pressure (Mbar), Temp. (x1000 K)
Radius (micron)



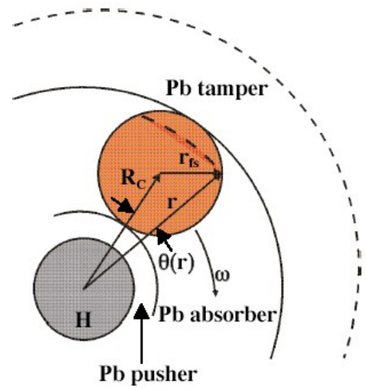
Density
Pressure
Temperature
H2O
Nb
Superionic State
Density (g/cm3), Pressure (Mbar), Temp. (x1000 K)
Radius (micron)

High Frequency Rotating Ion Beam

1) A.R. Piriz et al., PRE 67 (2003) 01750

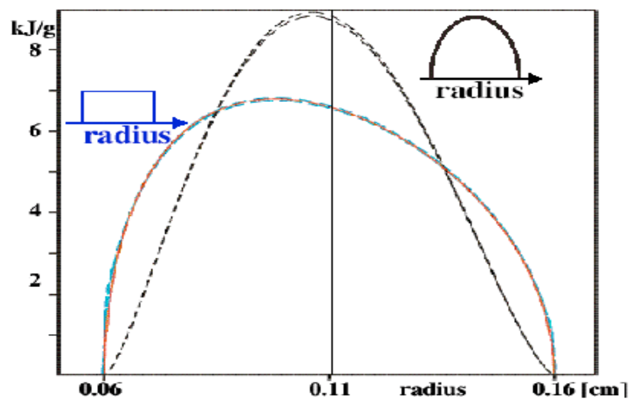
2) A.R. Piriz et al, Plasma Phys. Controlled Fusion 45 (2003) 1733

- 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

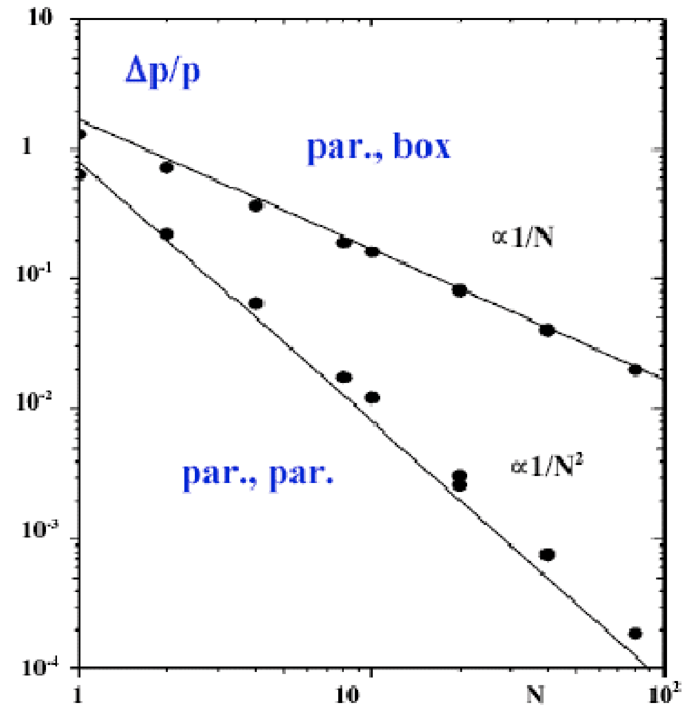


Power Constant in Time

- 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