Prospects of High Energy Density Matter Research at the Future Facility for Antiprotons and Ion Research (FAIR) at Darmstadt : The HEDgeHOB Collaboration

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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}	2×10^{12}	[x 500]
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**	**600 kJ/g**	[x 600]
Specific Power Deposition in Pb	**5 GW/g**	**12 TW/g**	[x 2400]

Specific power deposition:

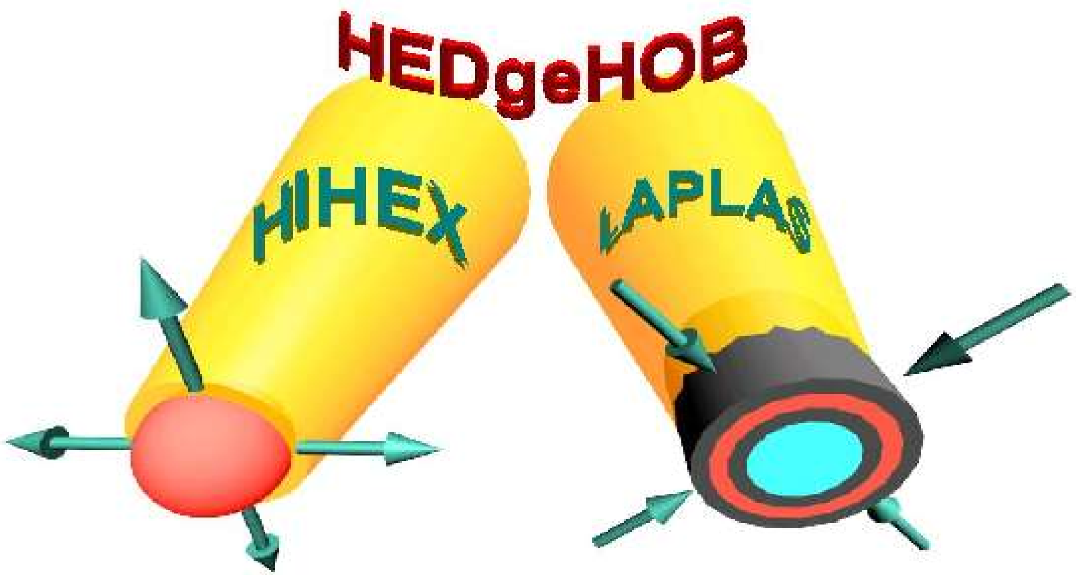
$$P = \frac{E_s}{\tau} \, , \qquad \text{TW/g}$$

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

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

N : total number of particles in the beam

r_b : beam radius



HEDgeHOB [High Energy Density Matter Generated by Heavy Ion Beams]

HIHEX [Heavy Ion Heating and Expansion]

LAPLAS [Laboratory Planetary Science]

1. HIHEX (Heavy Ion Heating and Expansion)

Isochoric heating of solid targets and then allowing isentropic expansion of the heated matter [Plane as well as Cylindrical Geometry]

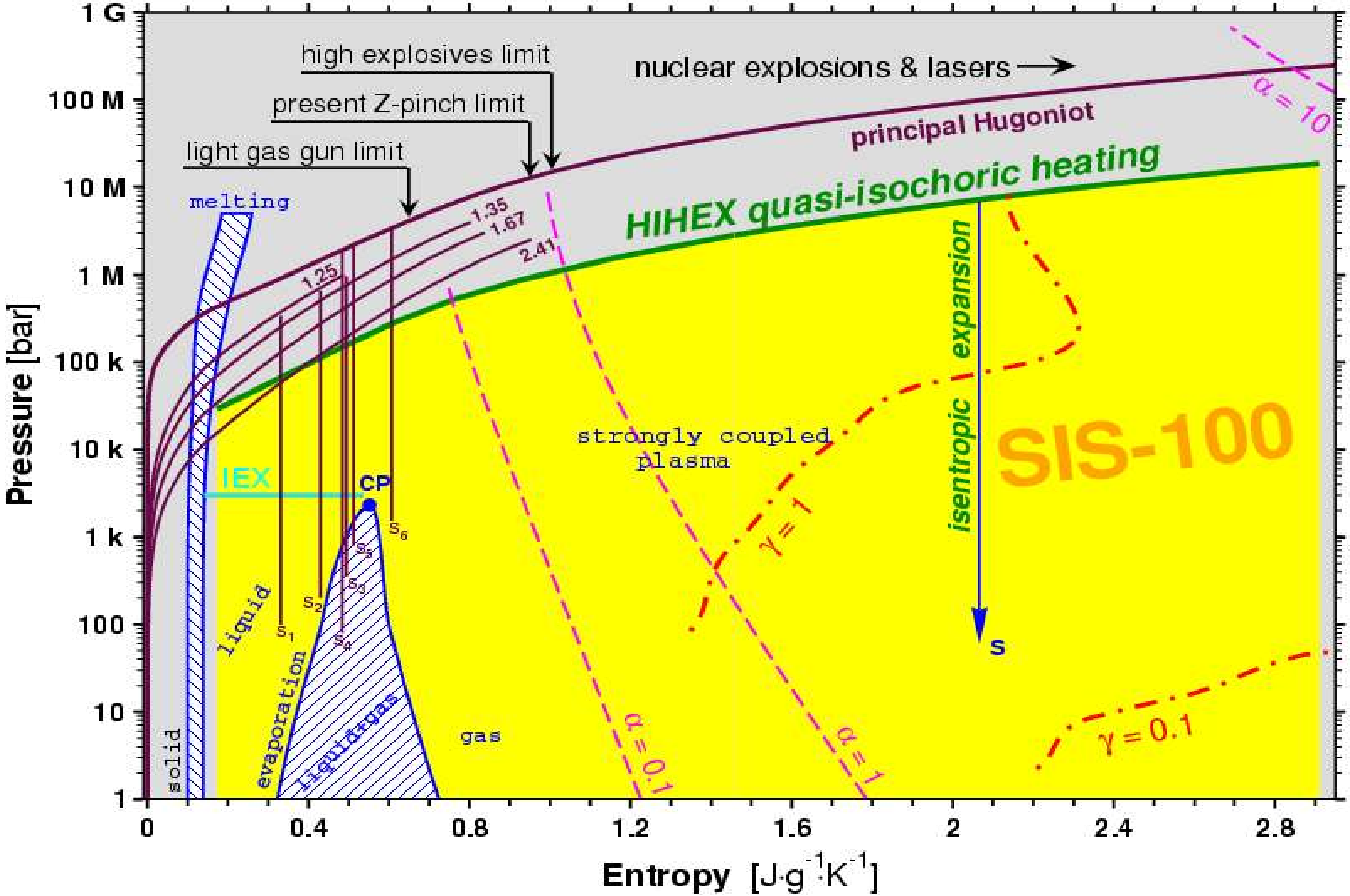
"Uniqiue Capabilities of an Intense Heavy Ion Beam as a Tool for Equation–of–State Studies", Phys. Plasmas 9 (2002) 3651.

D.H.H.Hoffmann, V.E.Fortov, I.Lomonosov, V.Mintsev, N.A.Tahir, D.Varentsov and J.Wieser

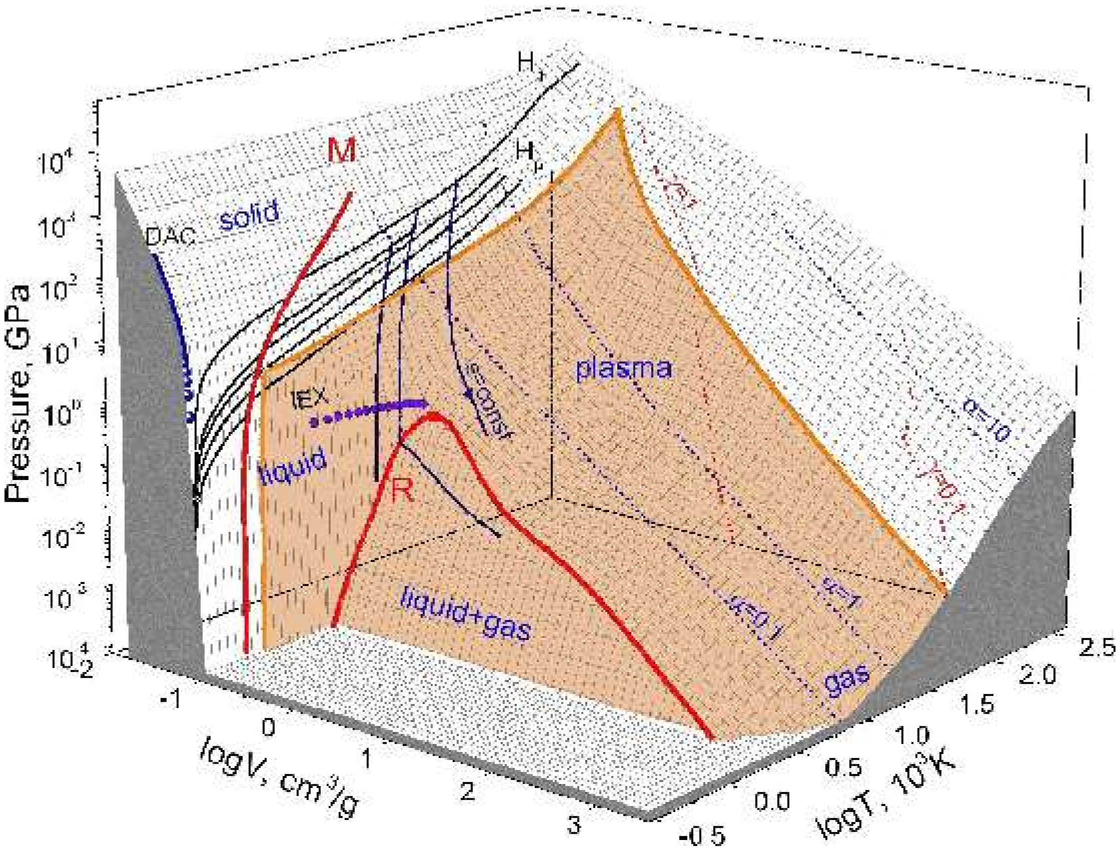
"Proposal for Study of Thermophysical Properties of HED Matter Using Current and Future Heavy Ion Accelerator Facilities at Gsi Darmstadt", Phys. Rev. Lett 96 (2005) 035001.

N.A.Tahir et al

Phase diagram of lead



Phase Diagram of Lead in P-V-T Space

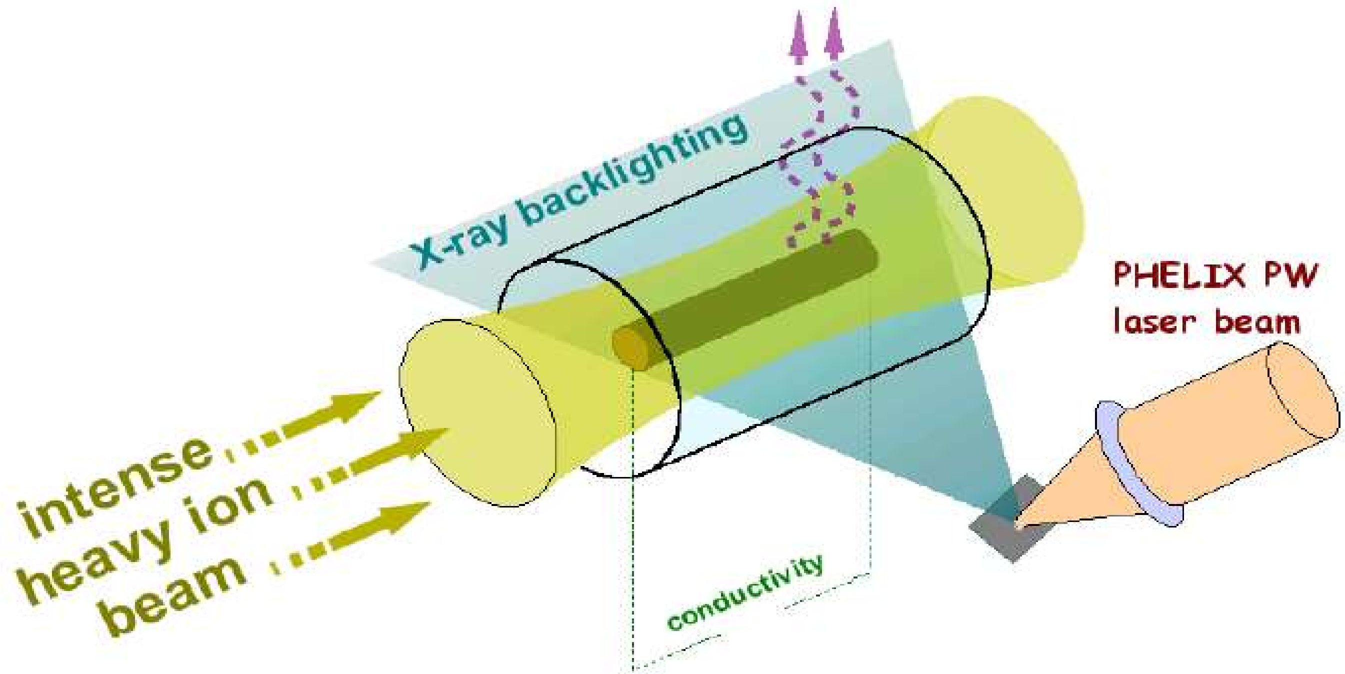


Critical Parameters of Some Metals

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

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

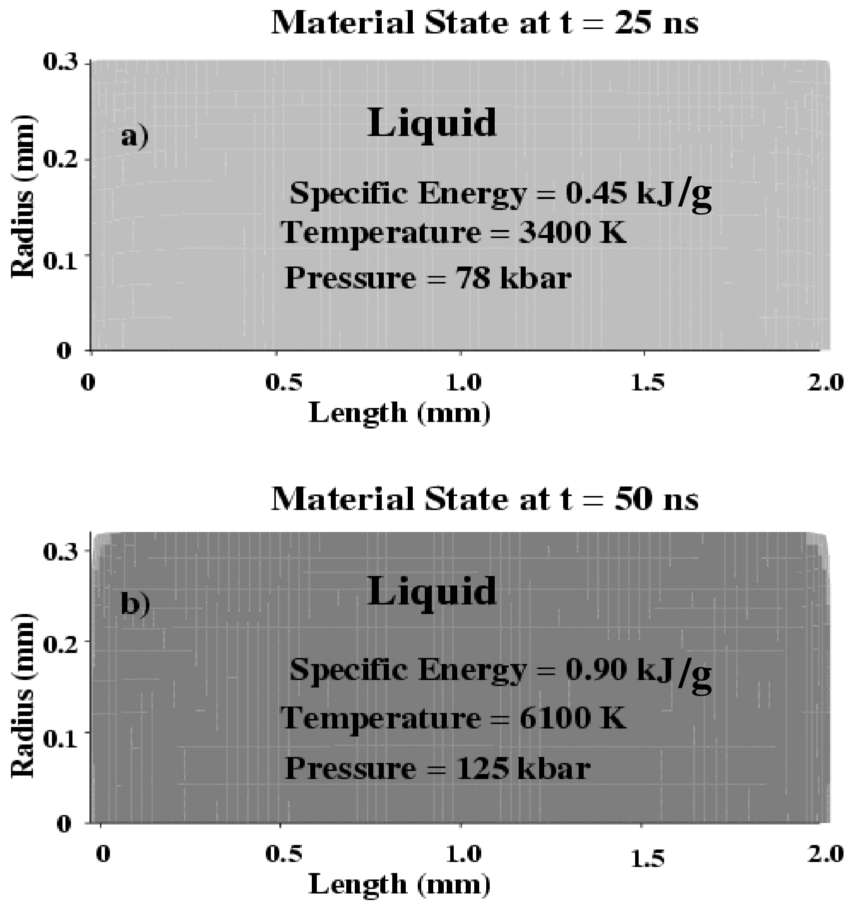
Bunch Length = 50 ns

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



Material State During Expansion

The heated material is allowed to expand and after 225 ns the temperature, pressure and the density decrease substantially and the material enters two-phase liquid-gas region

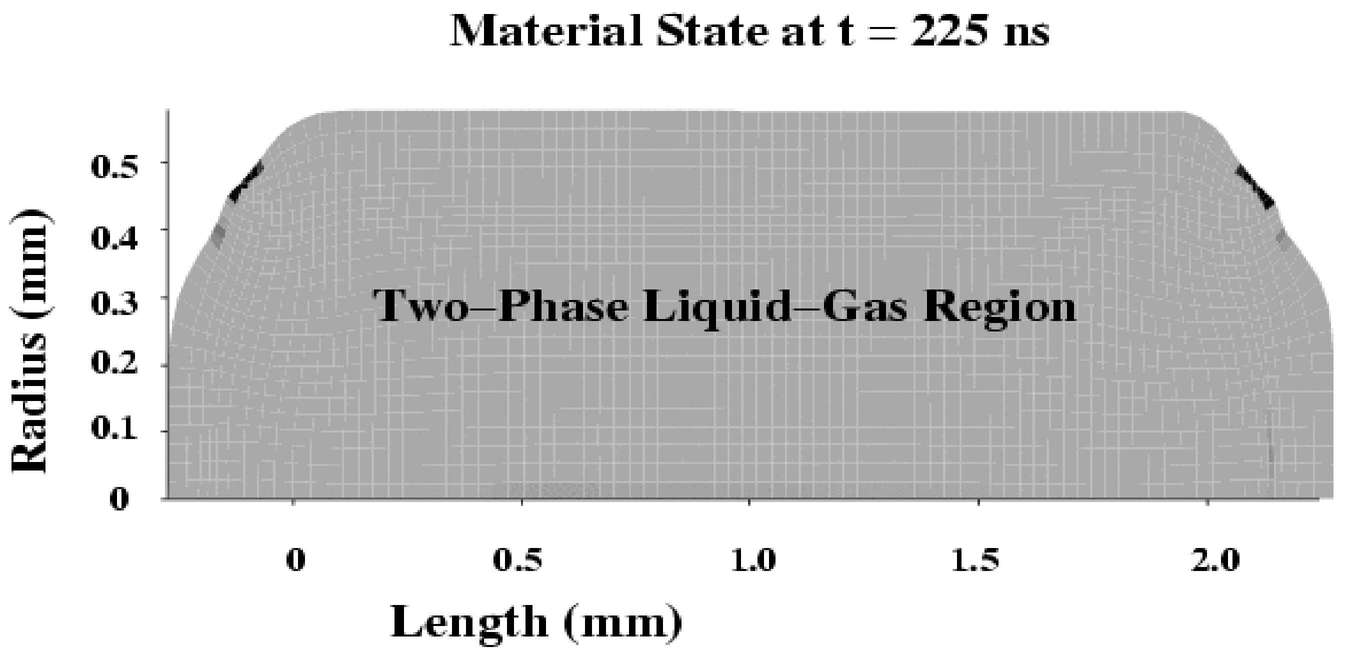
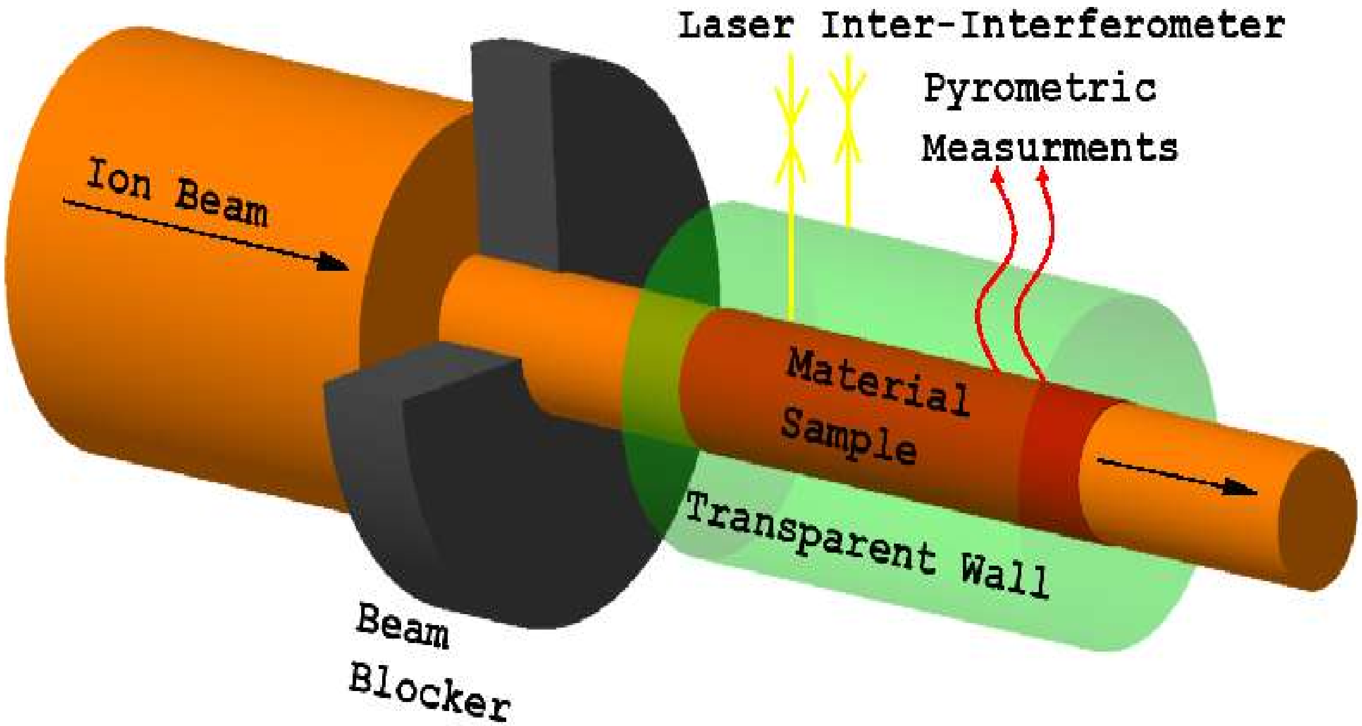


Table 1: Final Achievable Material State

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	$2PLG$

HIHEX Using Porous Material



1 GeV/u uranium beam

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

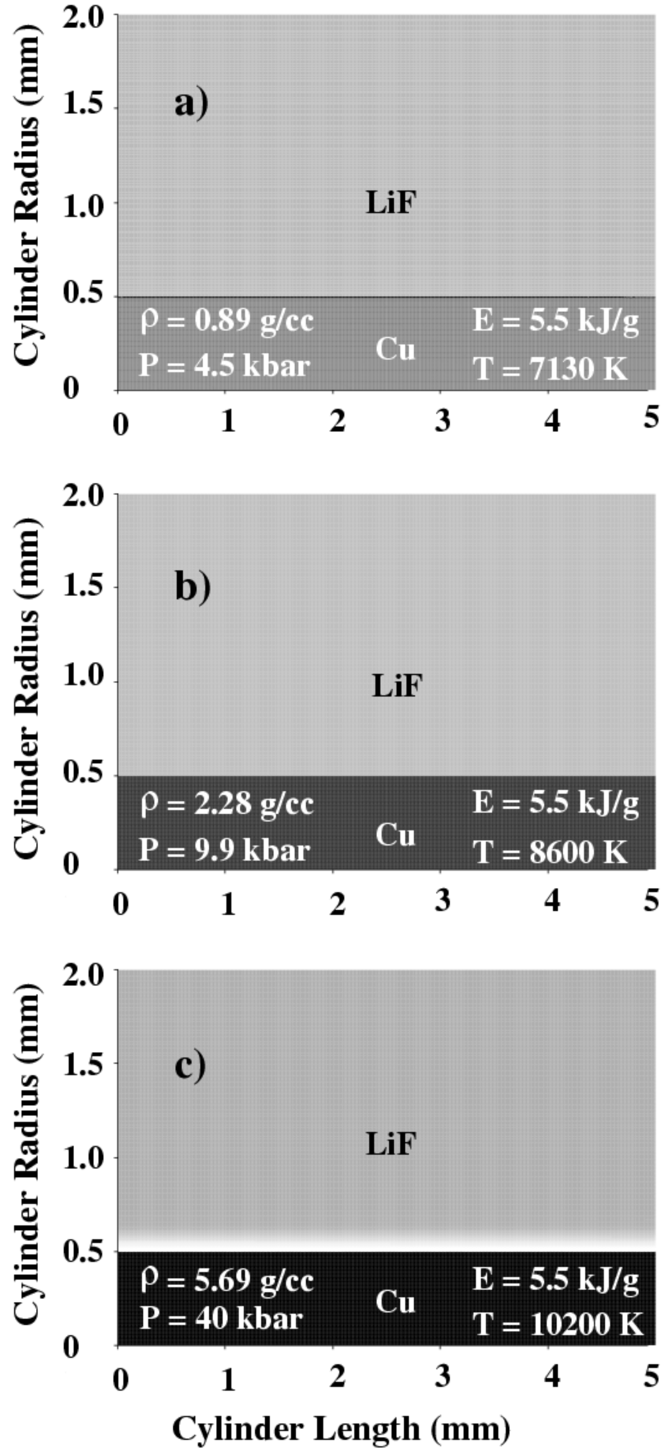
FWHM = 4 mm

E_s = 5.5 kJ/g

FWHM = 2 - 4 mm

$N = 10^{11} - 10^{12}$

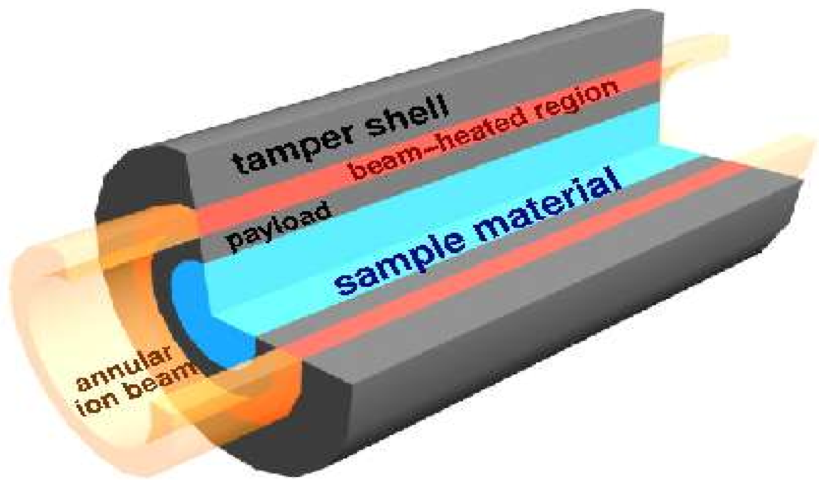
$\Gamma = 5$

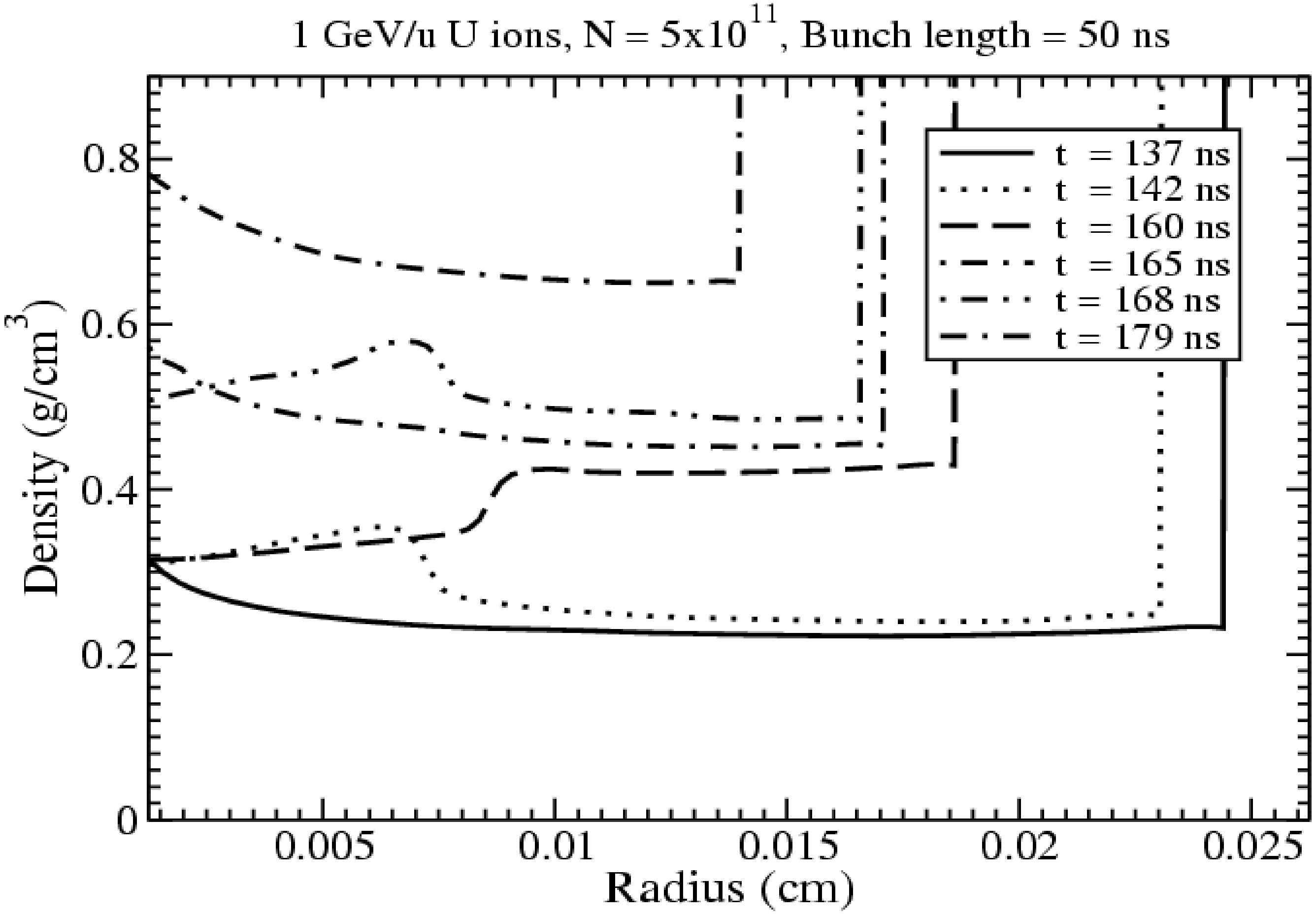


Low-Entropy Compression for:

1. LAboratory PLAnetary Sciences (LAPLAS)
2. Hydrogen Metallization

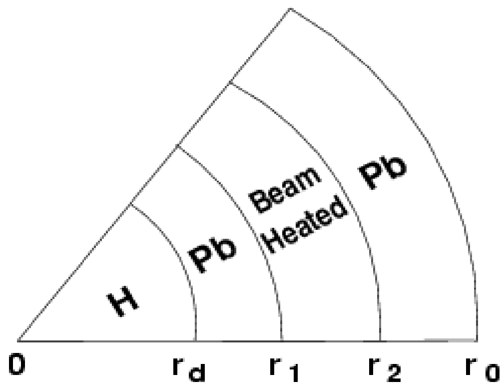
Multiple Shock Reflection Technique is Employed to Achieve these Conditions in the Sample Material

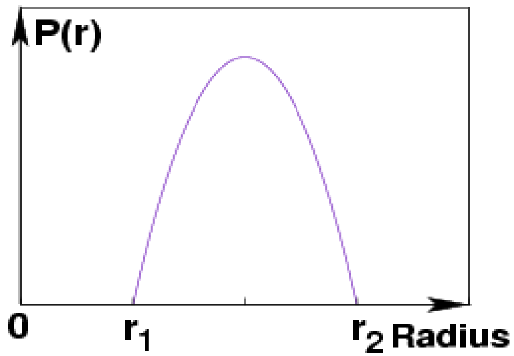



1 GeV/u U ions, N = 5x10^11, Bunch length = 50 ns
Density (g/cm^3)
Radius (cm)
0
0.2
0.4
0.6
0.8
0.005
0.01
0.015
0.02
0.025
t = 137 ns
t = 142 ns
t = 160 ns
t = 165 ns
t = 168 ns
t = 179 ns

Crossectional View of the Target

[N.A.Tahir et al., Phys. Rev. E 63 (2001) 016402]





Target Parameters	Beam Parameters
r_d = 0.4 mm	2.7 GeV/u Uranium
r_1 = 0.6 mm	N =0.2 – 1.5 x 10^{12}
r_2 = 2.1 mm	τ = 20 ns
r_0 = 3.5 mm	E_b = 21 – 155 kJ
L = 1.0 cm	R_{ion} = 5.9 cm

Summary of Results

ρ = 1 –2 g/cm^3

P = 2 – 10 Mbar

T = 0.2 – 0.6 eV

2. LAPLAS (Laboratory Planetary Science)

Low entropy compression of a sample material for example hydrogen, in a multi–layered cylindrical target driven by an intense heavy ion beam with an annular focal spot.

a) 2D Hydrodynamic Simulations:

N.A.Tahir, D.H.H.Hoffmann et al., PRE 63 (2001) 016402.

b) Analytic Modelling of the Implosion:

A.R.Piriz, R.F.Portugues, N.A.Tahir and D.H.H.Hoffmann, PRE 66 (2002) 056403.

c) Generation of Annular Focal Spot:

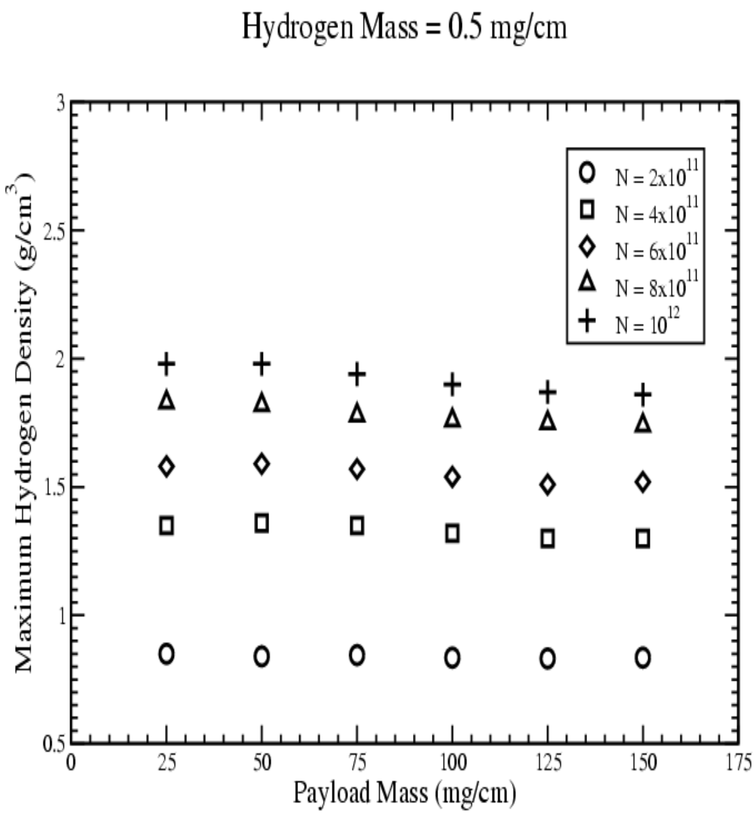
A.R.Piriz, M.Temporal, J.J. Lopez Cela, N.A.Tahir, D.H.H. Hoffmann Plasma Phys. Controlled Fusion 45 (2003) 1733.

d) Hydrodynamic Stability of the Implosion:

Rayleigh-Taylor and Richtmeyer-Meshkov Instabilities

N.A. Tahir et al., J. Phys. A: Math. Gen. 36 (2003) 6129

- **Maximum hydrogen density vs payload mass for different beam intensities, keeping the specific energy deposition constant.**
- **Results insensitive to large variation in payload mass.**

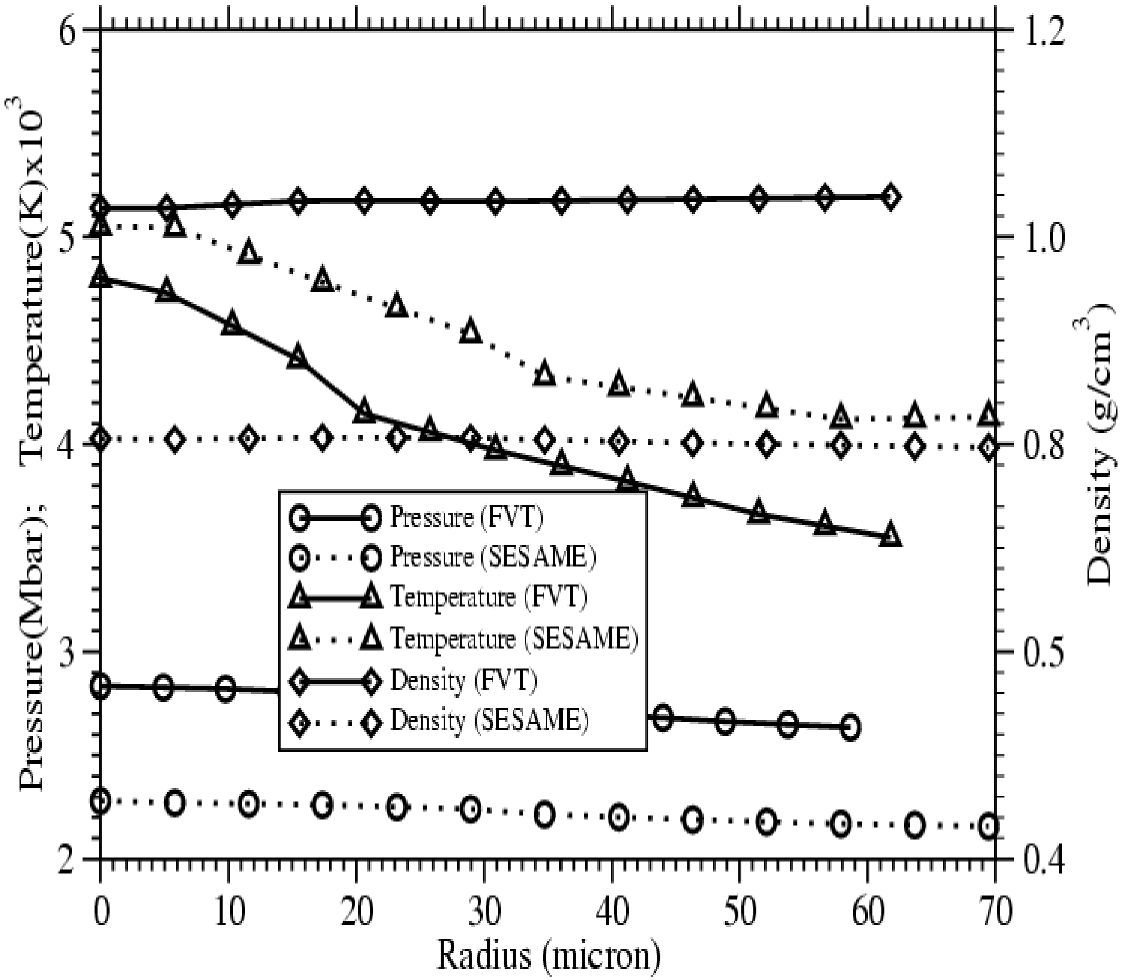


N.A. Tahir et al., Phys. Rev. B 67 (2003) 184101.

Uranium beam

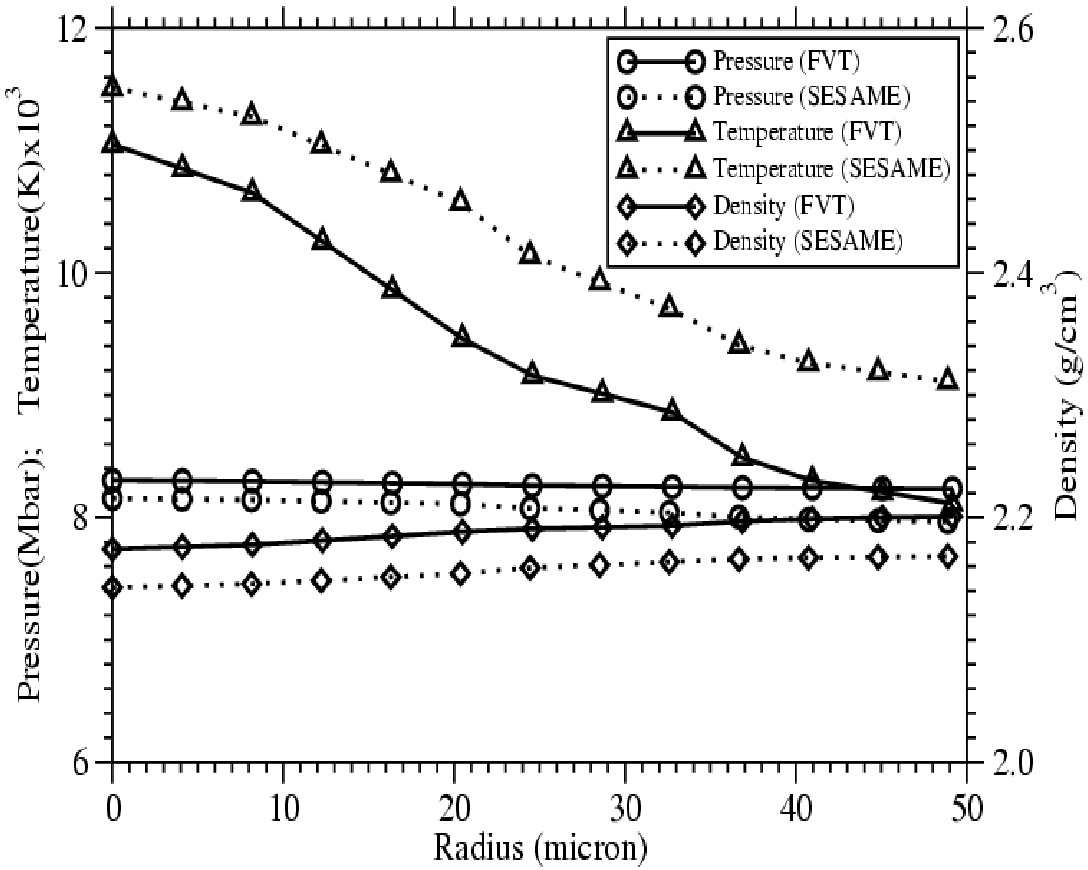
Intensity, N = 10^{11} ions per bunch

Bunch length, τ = 50 ns



Beam intensity
N = 4.10^{11}
ions per bunch

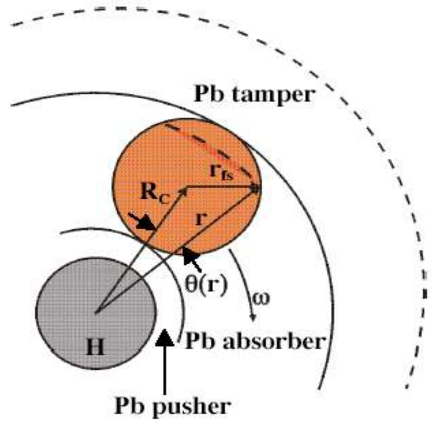
Difference is minimized as the beam intensity increases



High Frequency Rotating Ion Beam

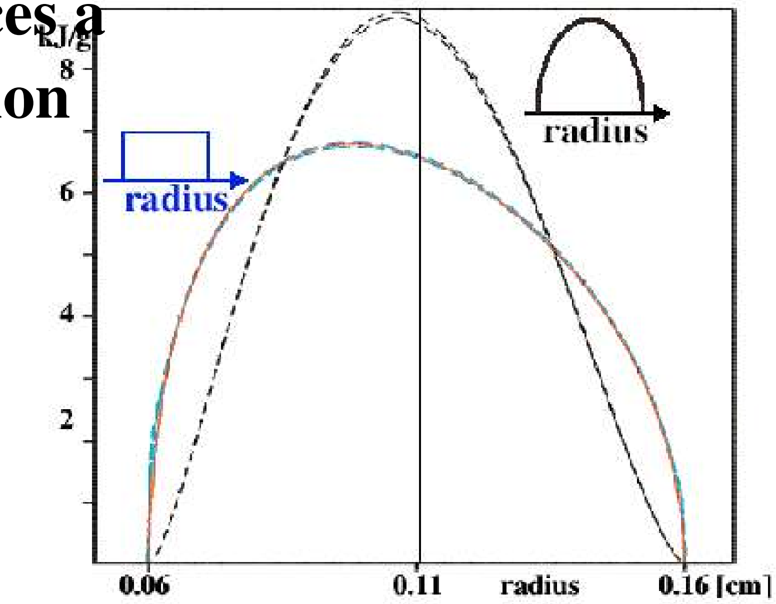
[A.R. Piriz, M. Temporal, J.J. Lopez Cela, N.A. Tahir, D.H.H. Hoffmann, Plasma Phys. Controlled Fusion 45 (2003) 1733.]

- Analysis of symmetry level achieved by a rotating beam
- Analytic model and numerical simulations
- Spatial power profile, uniform as well as Gaussian
- Temporal power profile, uniform as well as Gaussian



Power Constant in Time

Circular shape of the focal spot introduces a radial distribution in the energy deposition



For both cases the relative pressure asymmetry:

$$\frac{\Delta P}{P} \propto \frac{1}{N}$$

where N = ω τ

ω = 2πν and τ is the bunch length

For τ = 50 ns one needs ω = 2 GHz in order to achieve 1 % asymmetry

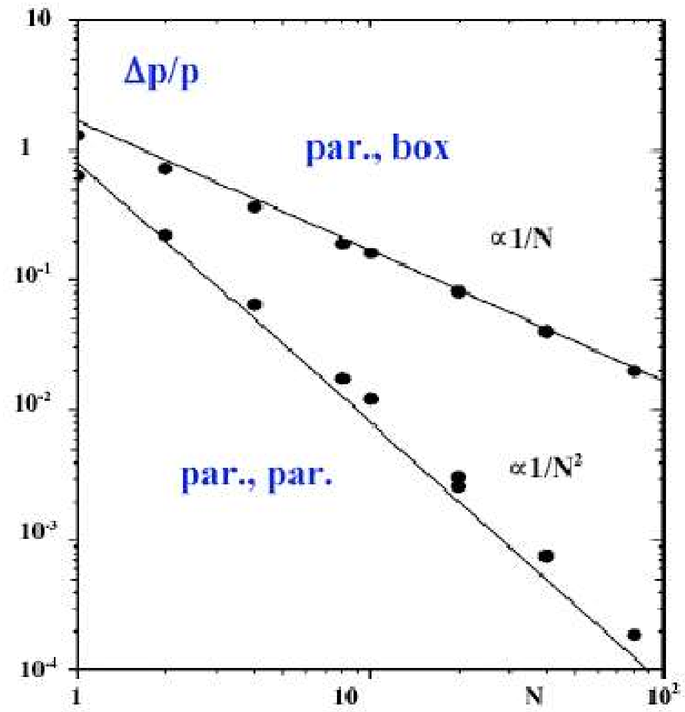
<u>For achieving 1 % asymmetry</u>

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

For τ = 50 ns one need ω = 2 GHz

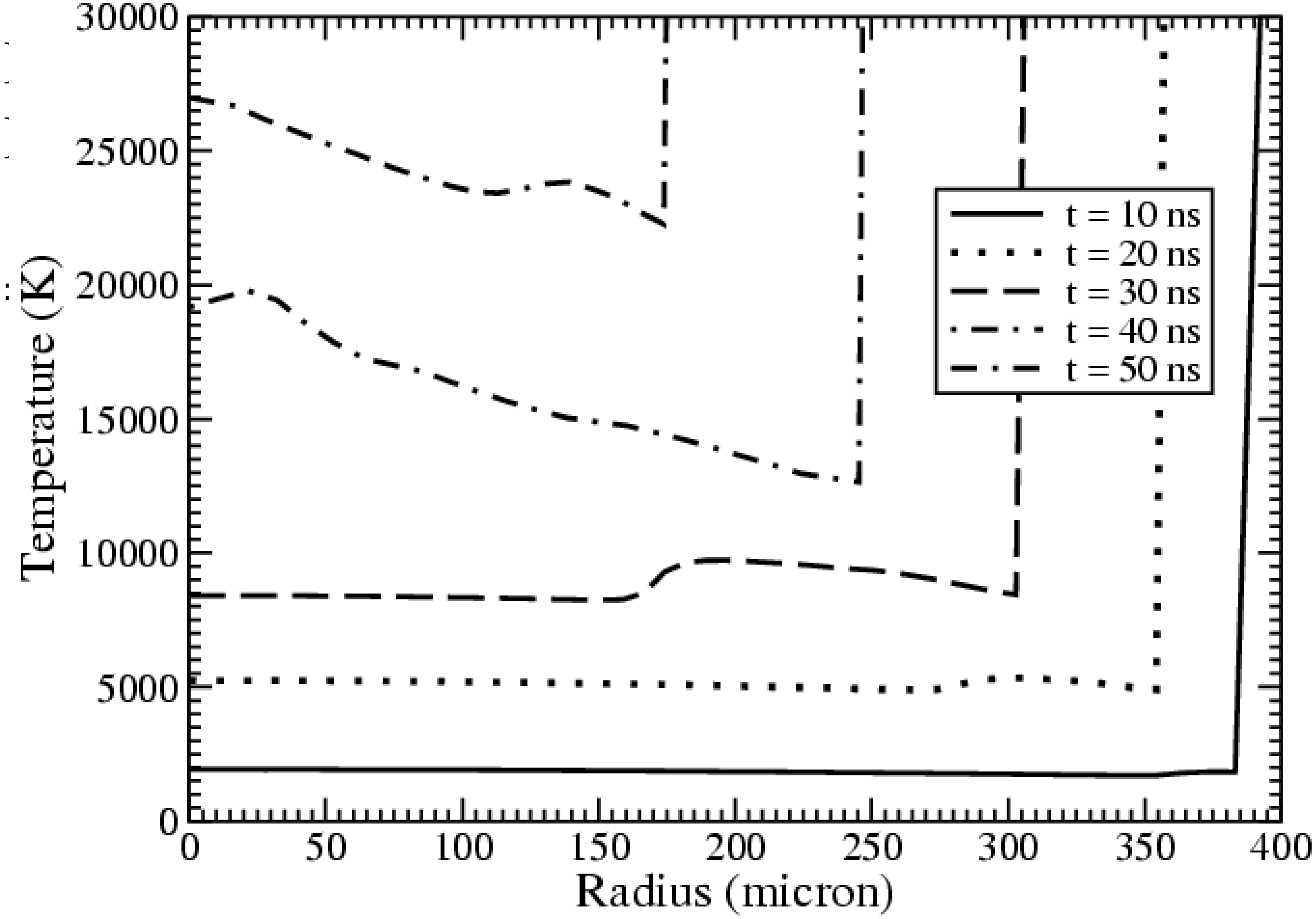
2. With parabolic temporal profile one needs N = 10.

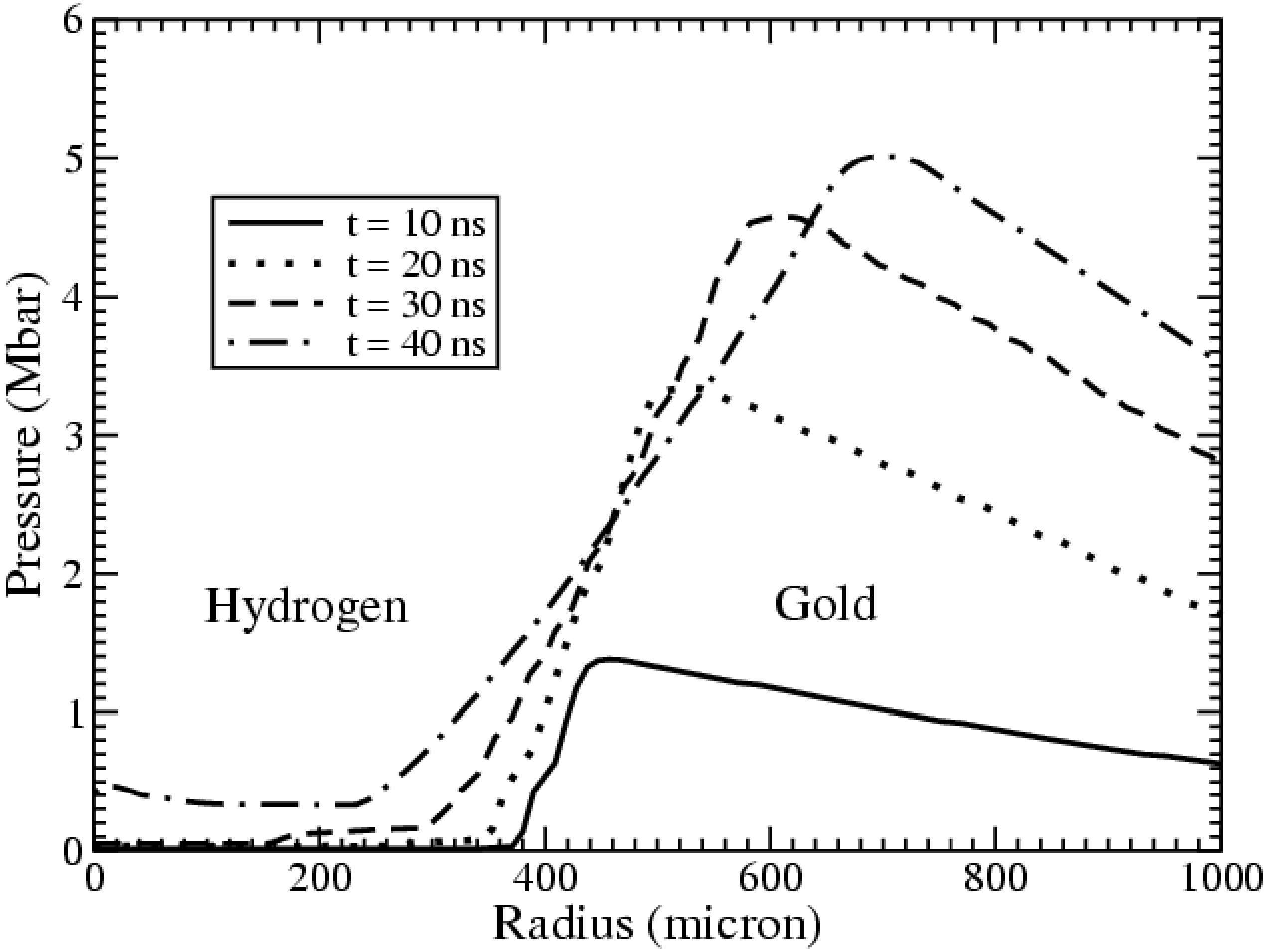
For τ = 50 ns one need ω = 0.2 GHz



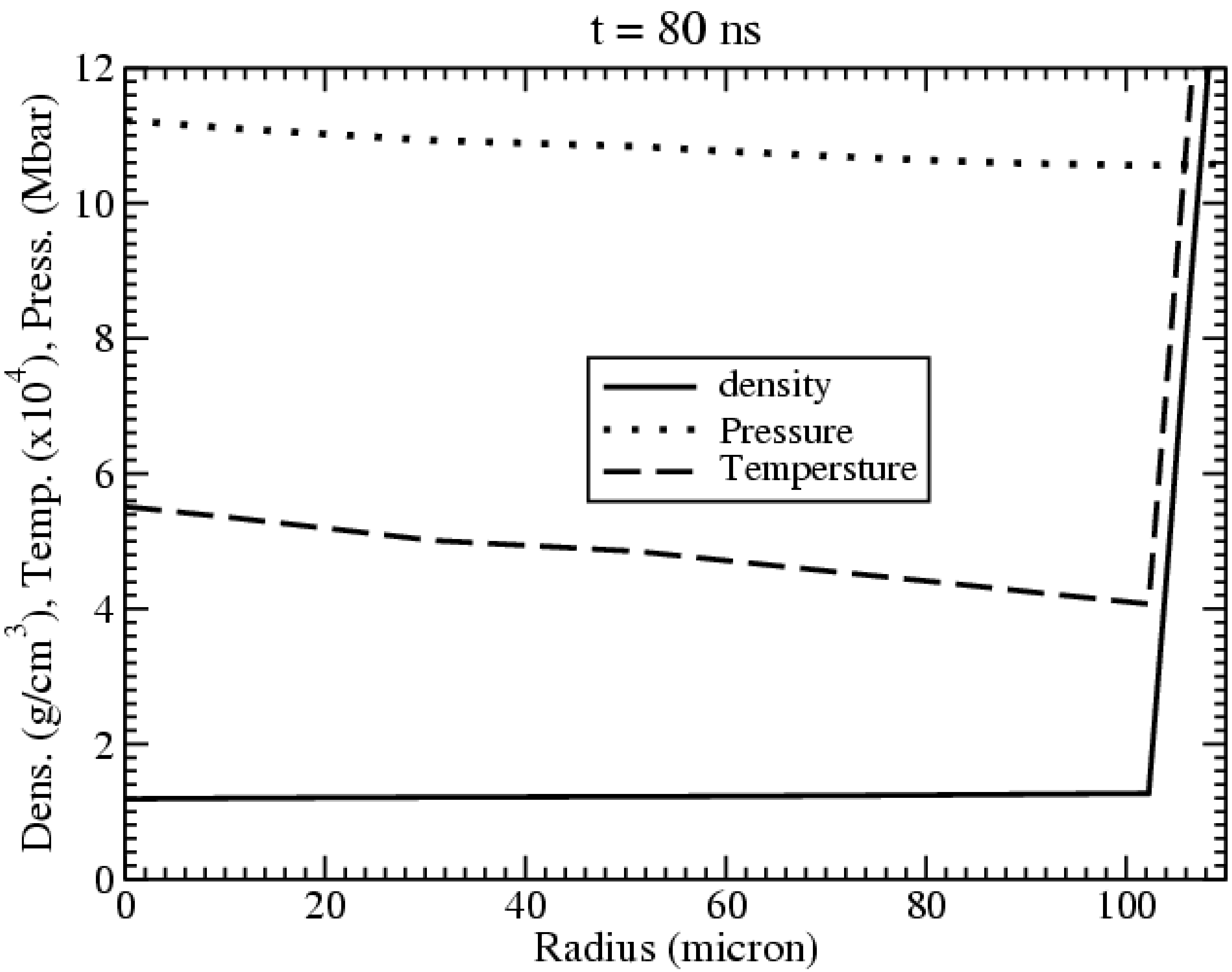
$N = 10^{12}$ uranuim ions, 2 GeV/u, τ = 50 ns, FWHM = 1.5 mm

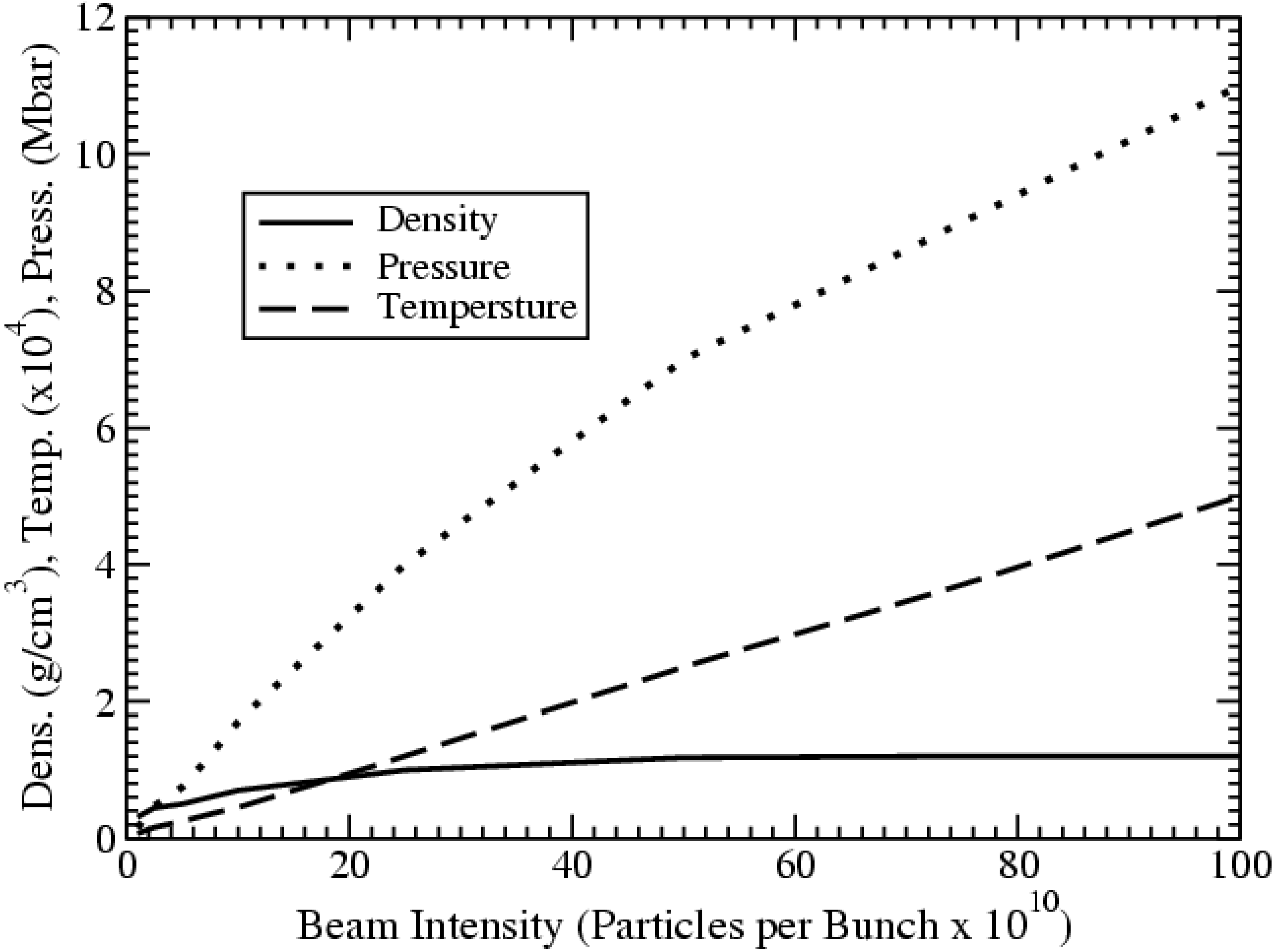
L = 1 cm, r_h = 0.4 mm, r_g = 3 mm





t = 10 ns
t = 20 ns
t = 30 ns
t = 40 ns
Hydrogen
Gold
Pressure (Mbar)
Radius (micron)
0
1
2
3
4
5
6
0
200
400
600
800
1000


t = 80 ns
Dens. (g/cm3), Temp. (x10^4), Press. (Mbar)
Radius (micron)
density
Pressure
Tempersture
0
2
4
6
8
10
12
0
20
40
60
80
100



Density
Pressure
TemAperature
Dens. (g/cm^3), Temp. (x10^4), Press. (Mbar)
Beam Intensity (Particles per Bunch x 10^{10})
0
2
4
6
8
10
12
0
20
40
60
80
100

Hydrodynamic Stability of the Target

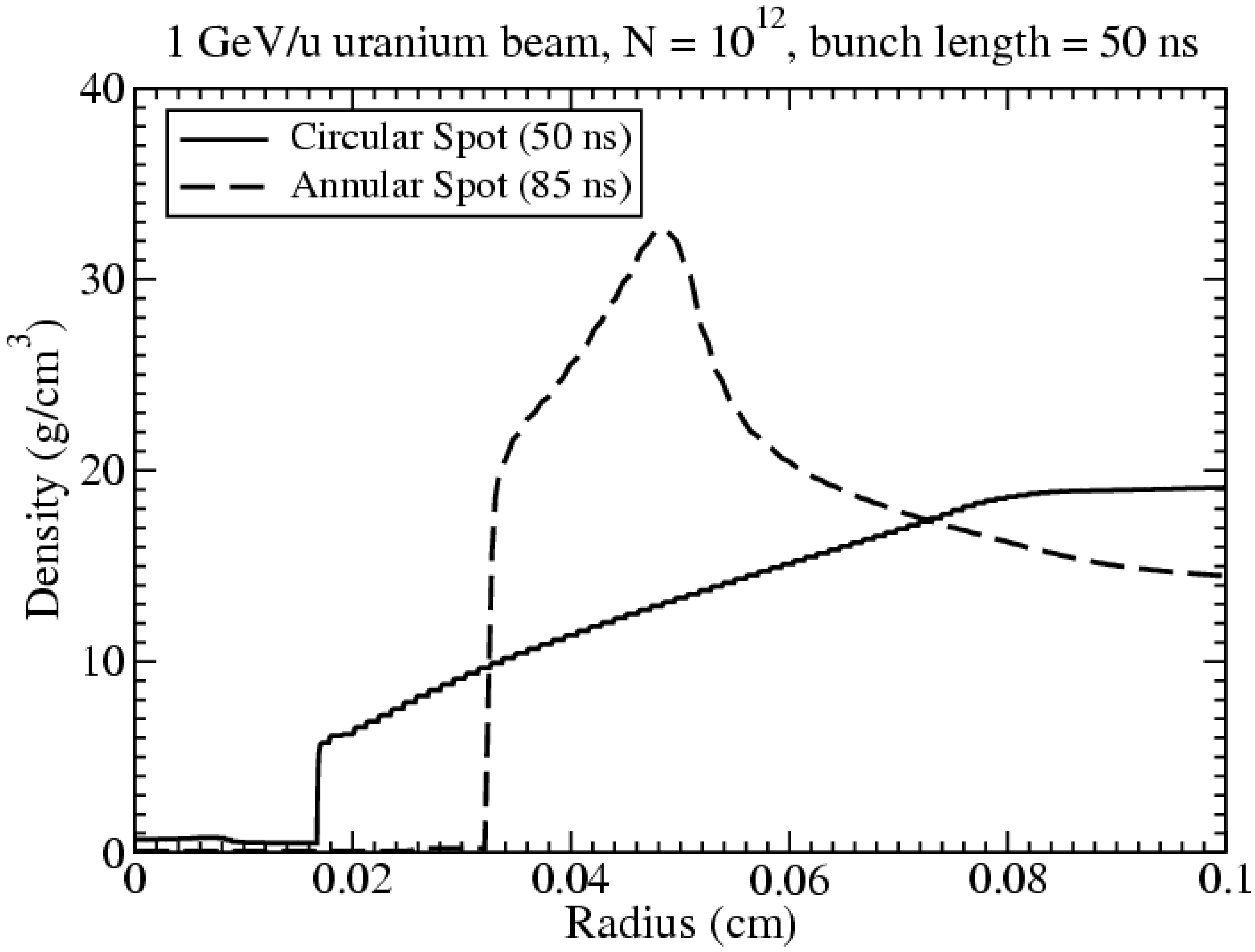
1. Rayleigh-Taylor (R-T) instability can occur in the pusher (payload) region. Different situation in two cases.

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

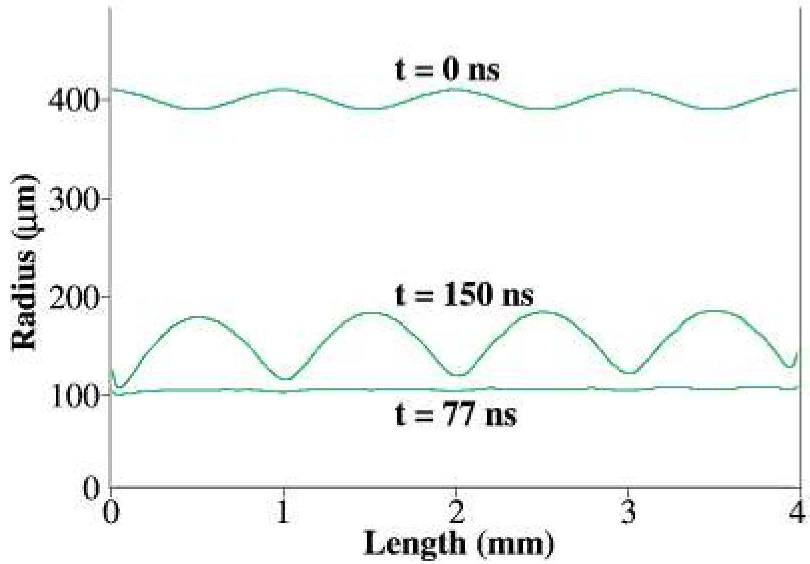
$$\gamma = 2\,x10^{7}\,sec^{-1}$$
$$\Delta t = 5\,x10^{-8}\,sec$$

e-folding = 1



1. Perturbation along length

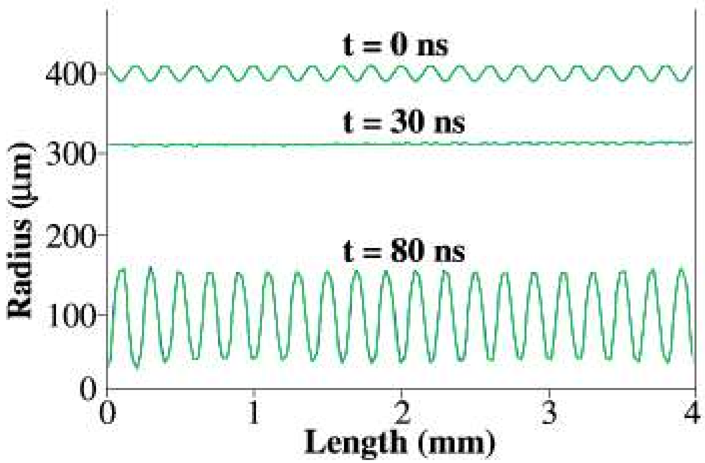
L = 0.4 cm, $k = 62.8\ cm^{-1}$, $A = 10\ \mu m$, $k \cdot A = 6.28 \times 10^{-2}$



Phase inversion is helpful

With smaller amplitudes the stability situation is very good

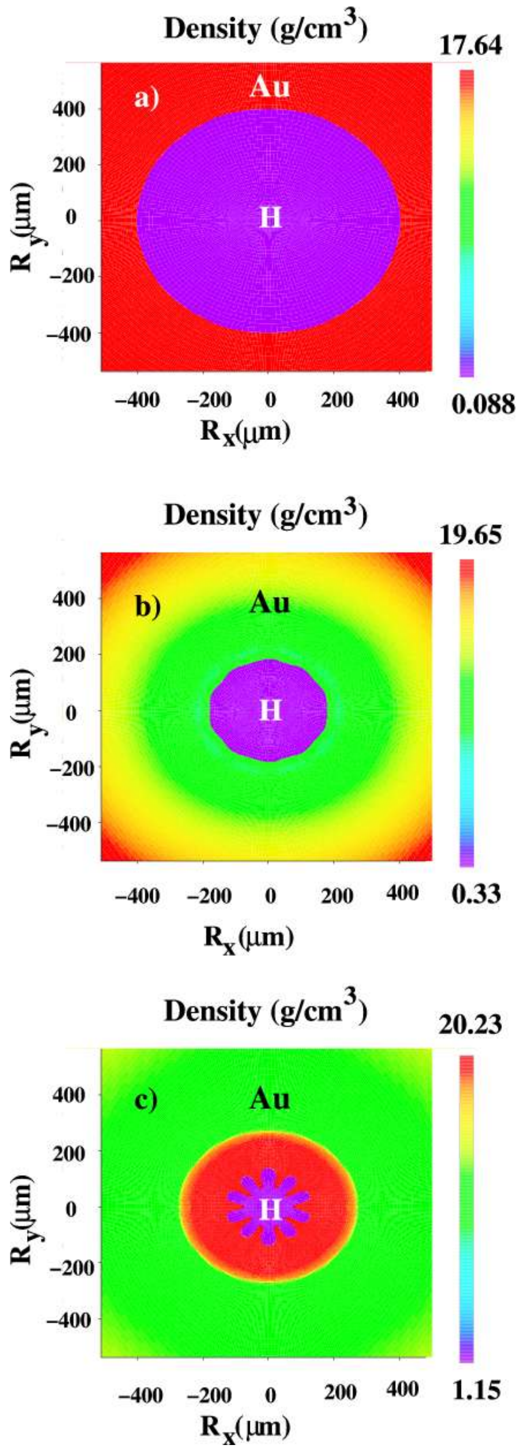
$k = 3.14 \cdot 10^2\ cm^{-1}$, $A = 10\ \mu m$, $k \cdot A = 0.314$



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.

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

$A = 1\ \mu\mathrm{m}$

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

For:

Smaller wavenumbers

smaller amplitudes

Stability is good

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 two 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).

Role of the CERN Large Hadron Collider (LHC) to Study HED Matter

LHC will provide two counter rotating 7 TeV proton beams

Each beam will consist of 2028 proton bunches

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

Total number of protons is 3×10^{14}

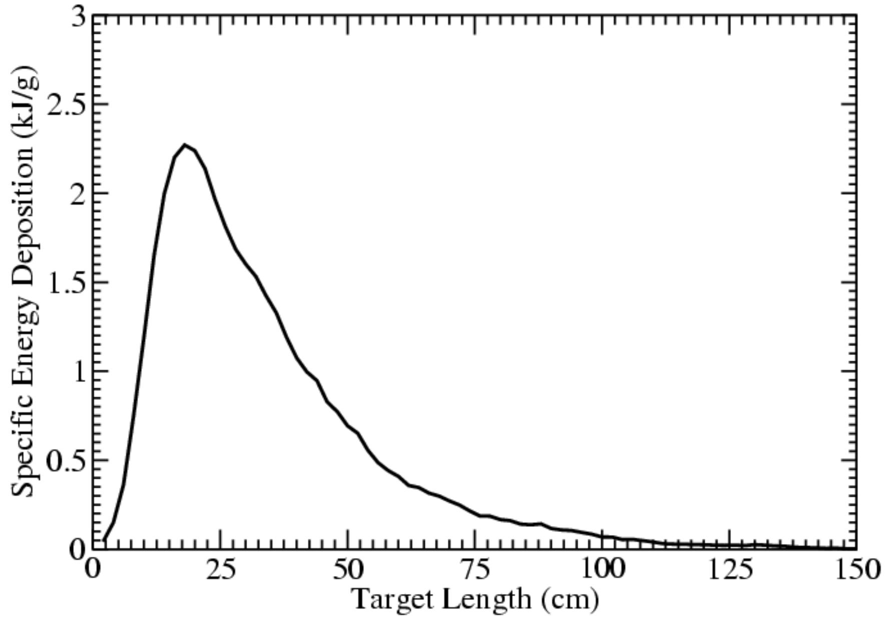
Bunch length = 0.5 ns, Separation between bunches = 25 ns

Total length of the bunch train = 89 μs

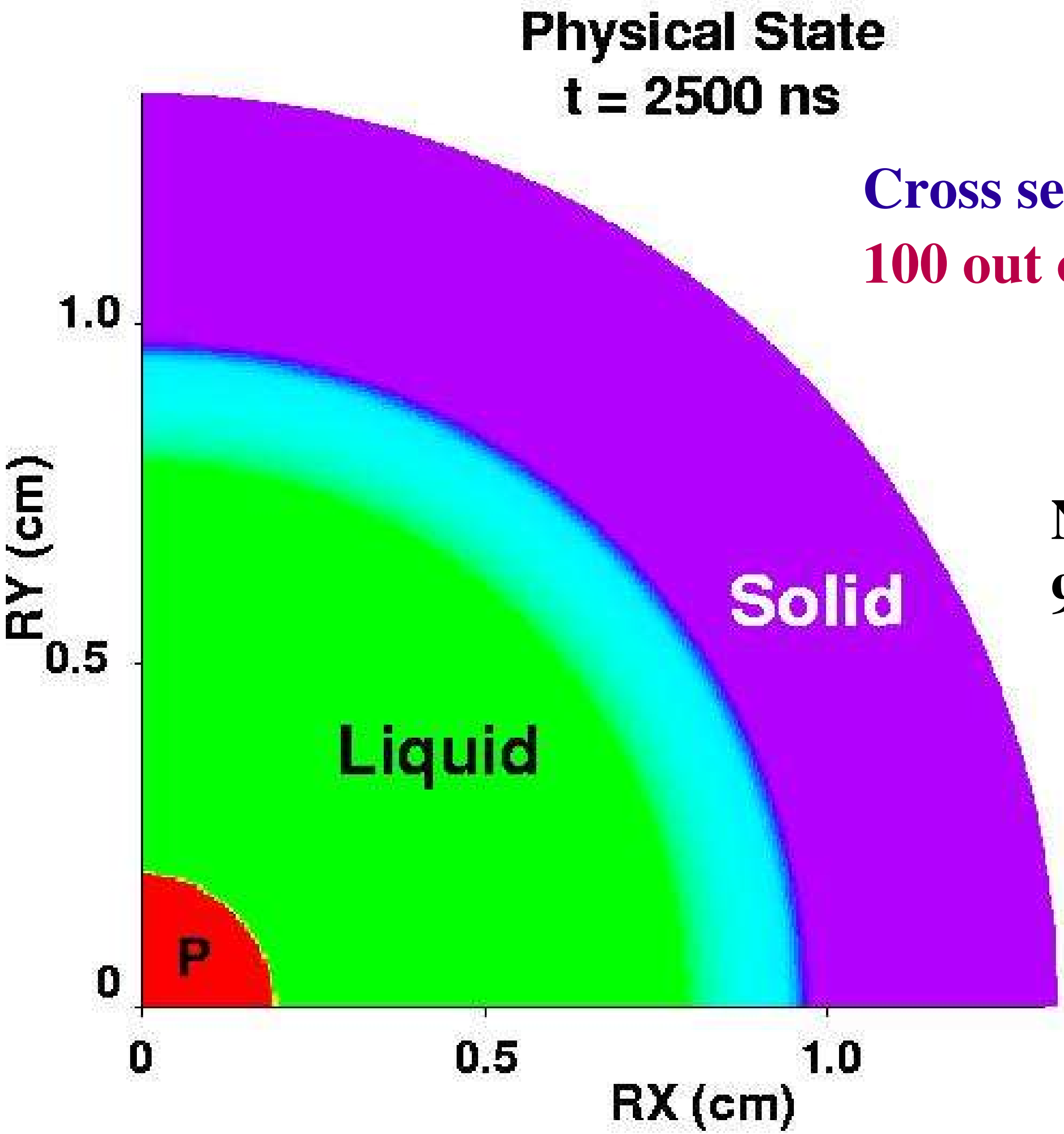
Transverse intensity distribution: Gaussian with $\sigma = 0.2$ mm

Energy deposition by LHC protons using the FLUKA code

Energy deposited by a single bunch along axis at r = 0



- FLUKA is a well established particle interaction and transport Monte Carlo code.
- Capable of simulating all components of the particle cascades in matter up to TeV energies.



Cross section of a Cu cylinder

100 out of 2028 bunches delivered

250 kJ/g

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