Breakeven Fusion in A Staged Z-pinch

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ABSTRACT

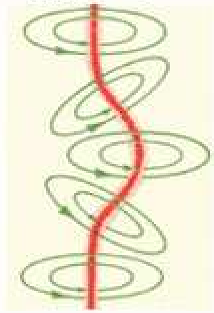
A Staged Z-pinch, configured for discharge parameters characteristic of multi-Mega joule facilities, is studied using the 2 and 1/2 D, radiation-MHD code, MACH2. In this configuration a cylindrical, xenon plasma shell implodes radially onto a coaxial, deuterium-tritium plasma target. During implosion shock fronts are formed in both plasma. The shock waves in the DT plasma preheats the plasma up to several hundred eV before adiabatic compression takes over. In the outer region of the liner plasma, a shock front forms causing Xe mass to accumulate at the outer surface of the DT region. This causes the formation of a conduction channel that the discharge current transfers into. The outer surface of Xe liner then becomes Rayleigh-Taylor (RT) unstable while the shock front that compresses the DT-target remains stable. The compression ratio of about 25 can achieve the parameters at the peak compression that can produce a thermonuclear yield from fusion neutrons more then breakeven and beyond. The interesting feature is the inner pinch remains stable even with 1% perturbation level and only become unstable when it explodes.

Outline

- Motivation from the experiments.
- 2D numerical simulation.
- Control and mitigation of RT-instability.
- Importance of high Z radiative liner.
- Shock heating and shock compression
- Possibility of breakeven in fusion energy.
- Experimental implementation.

PINCH INSTABILITIES

KINK
m = 1

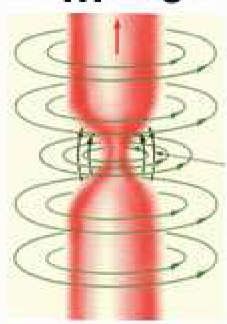


incompressible, sharp boundary:

$$\gamma = \frac{C_A}{r_o}(kr_o)\,\frac{I_m(kr_o)}{I'_m(kr_o)}\left[1 + \frac{m_2}{kr_o}\,\frac{K_m(kr_o)}{K'_m(kr_o)}\right]$$

~ (150 ns)$^{-1}$

SAUSAGE
m = 0



m = 0;

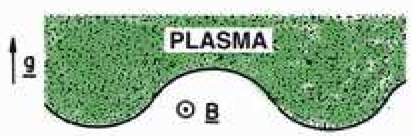
$$\gamma = \frac{C_A}{r_o}(kr_o)\,\frac{I_m(kr_o)}{I'_m(kr_o)}\ ;$$

compressible, k -> 0;

$$\gamma = \frac{C_A}{r_o}(2 - \alpha^2)^{-1/2}\,kr_o$$

~ (50 ns)$^{-1}$

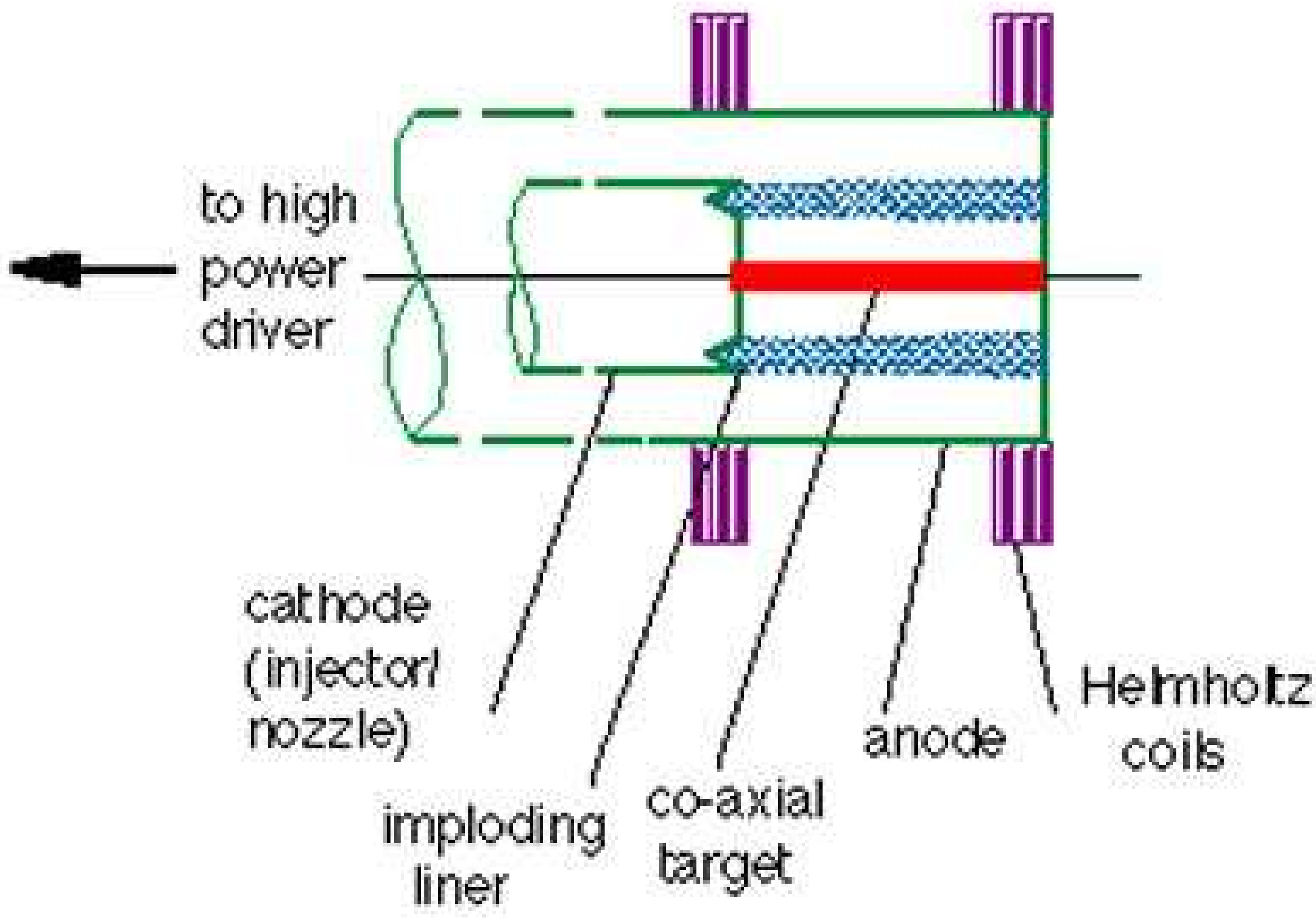
RAYLEIGH TAYLOR



$$\gamma^2 = -kg + \frac{(\bar{k}\cdot\bar{B}_o)^2}{4\pi\rho_o}$$

~ (10 ns)$^{-1}$

Staged Z-pinch



MAGNETO-INERTIAL FUSION

PINCH DYNAMICS

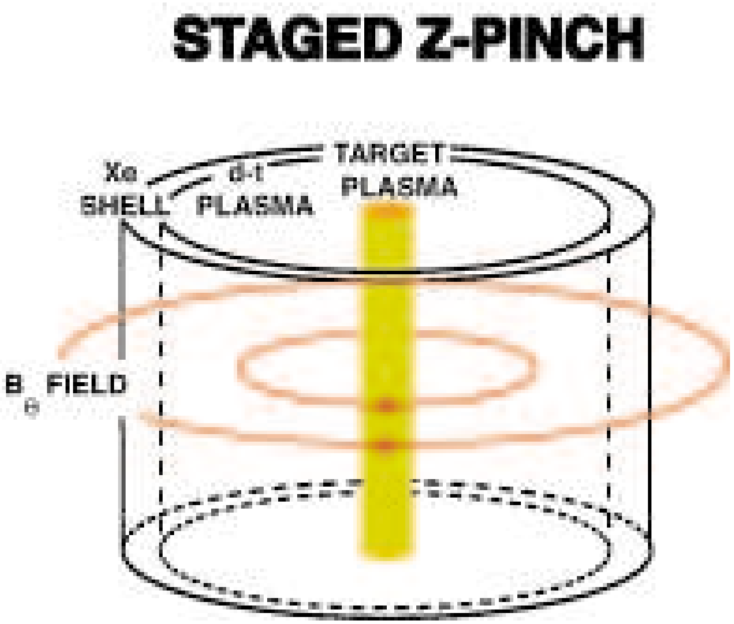
1.CURRENT DIFFUSES THROUGH HIGH Z LINER.

2 INNER LAYER OF LINER PEALS OFF DUE TO
THE DEVELOPMENT AND STAGNATION
OF SHOCK FRONT.

3.PEALED OFF LAYER COMPRESSES THE
PRE-HEATEDTARGET ALSO BY SHOCKS.

4.UNSTABLE PART OF LINER STAYS BEHIND.

5.AT PEAK COMPRESSION, CURRENT
TRANSFERS TO INNER STABLE LAYER.



BENEFITS

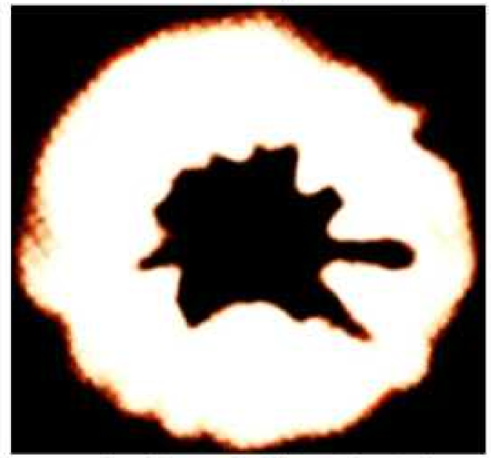
1. INERTIAL ENERGY TRANSFER TIMESCALES
2. COMPRESSION IS RT STABLE
3. BREAKEVEN FUSION IS PREDICTED

Stability of RT-instability

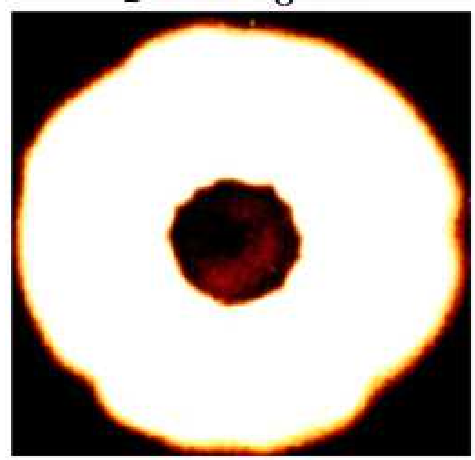
STABILIZATION OF LINEAR PINCH

End-on Kerr cell photos

Unstable pinch



Pinch stabilized with B_z and B_Θ fields

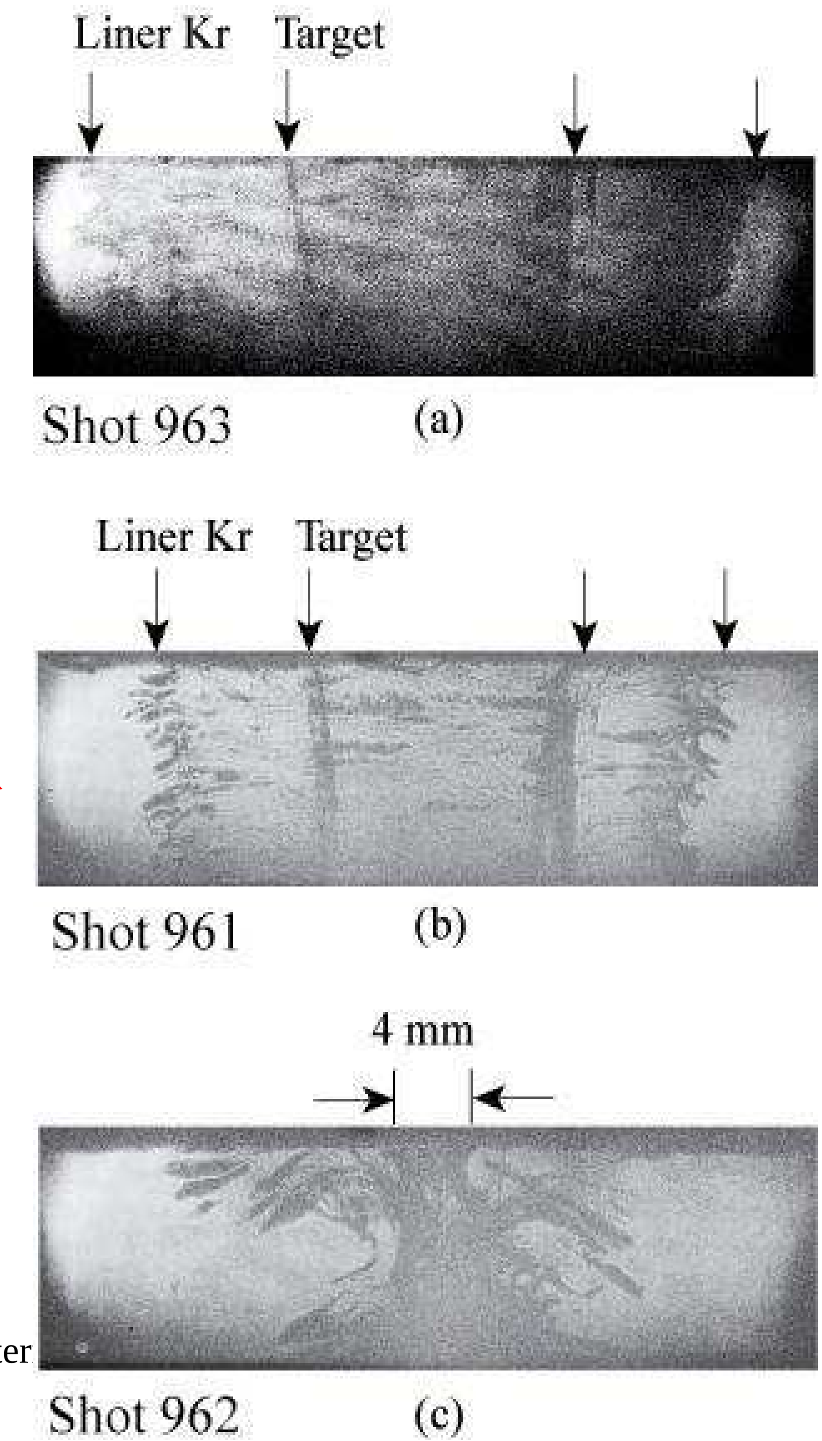


D.J.Albares, N. A. Krall and C. L. Oxley, "Rayleigh Taylor Instability in a Stabilized Linear Pinch Tube," Phys. Fluids 4, 1031(1961).

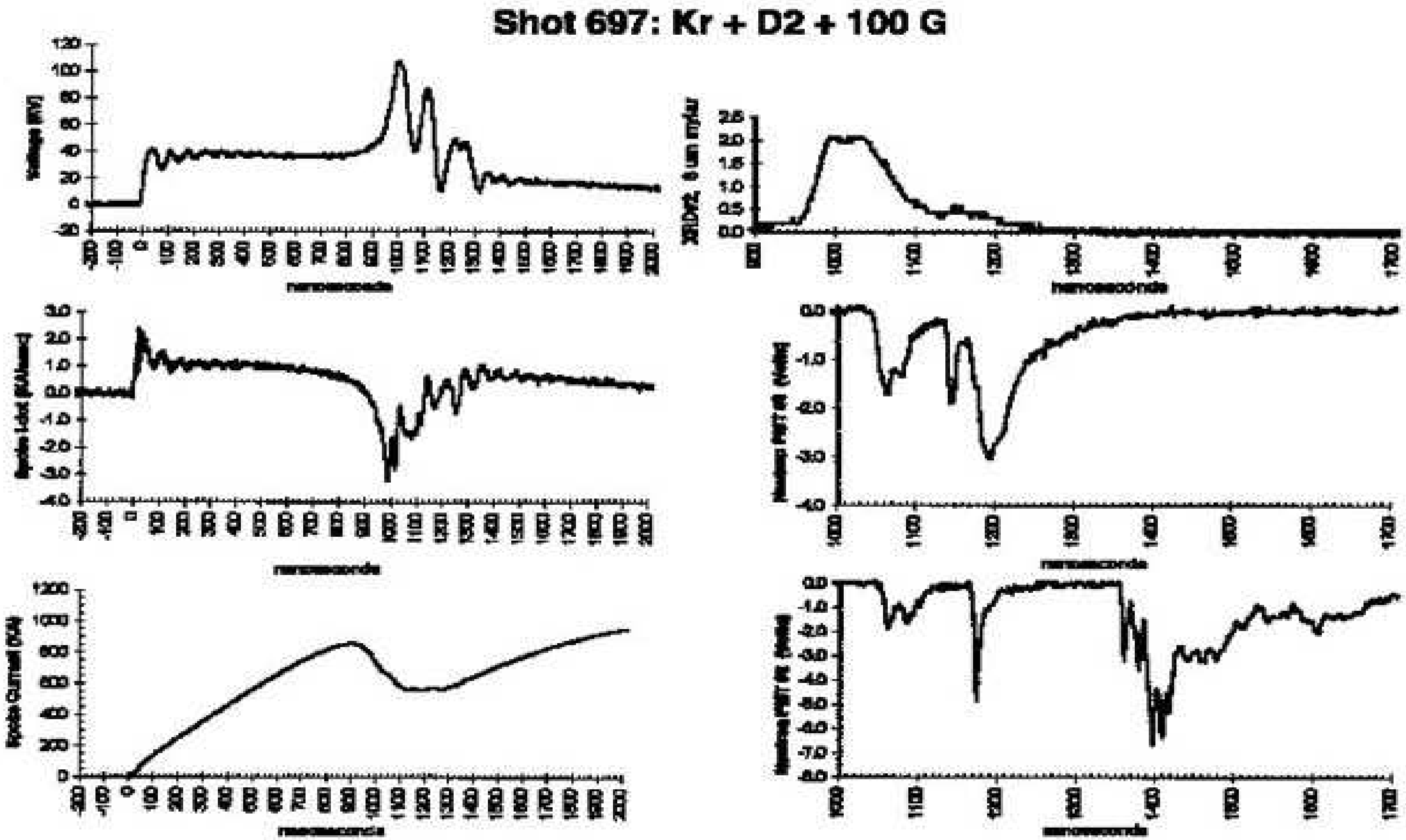
Schlieren Images of Staged Z Pinch

Before peak implosion

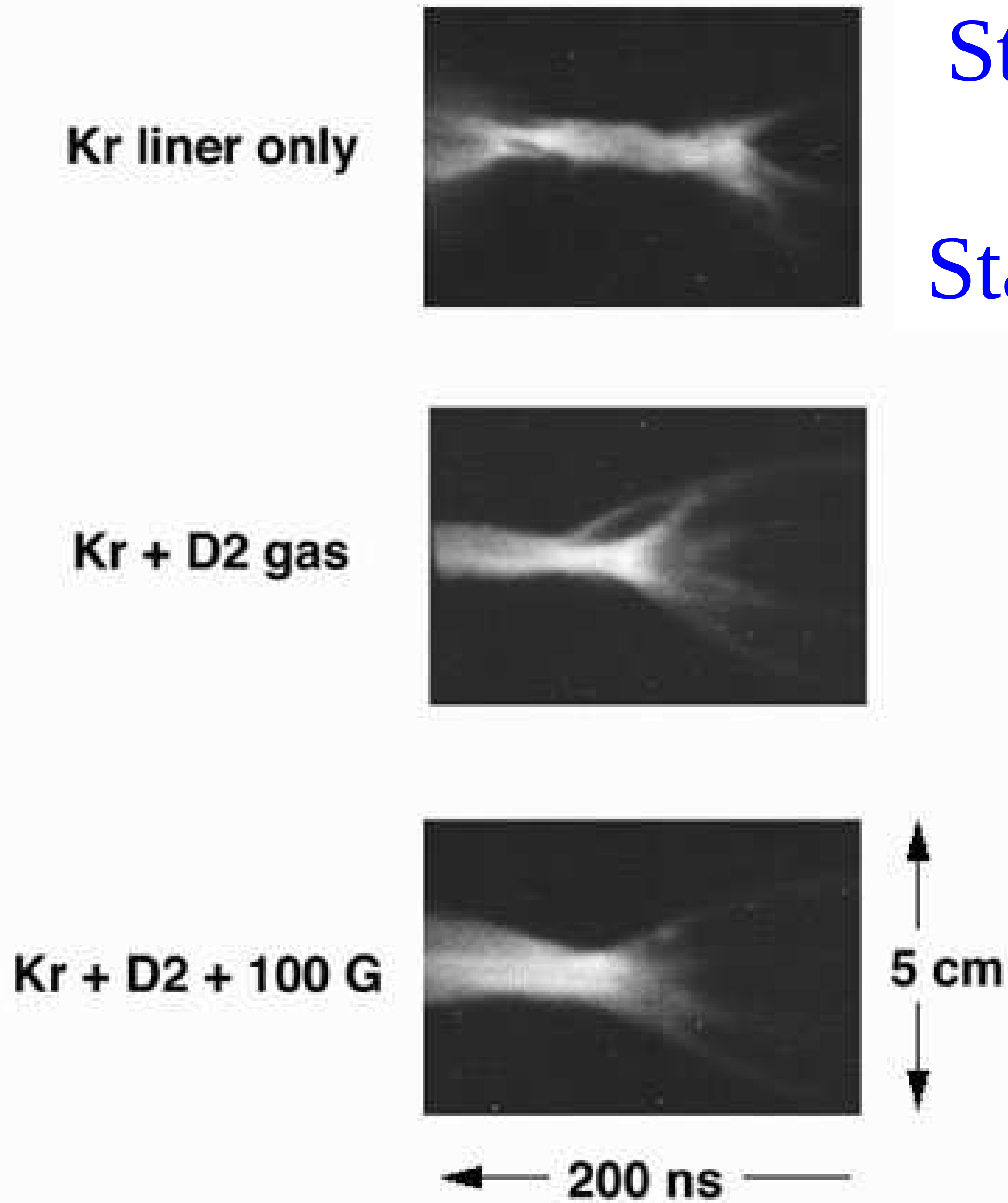
After peak implosion



Electrical Signals



Streak Images of Staged Z-pinch



Numerical Simulation

- 2&1/2 dimensional, time-dependent, single fluid, MHD simulation code.
- Used in Eulerian mode.
- External capacitor bank circuit is modeled.
- Tabular (SESAME) equations of state.
- Implicit MHD with components of **B** and **U**.
- Multi-species plasma.
- Flux-limited, single group, implicit radiation diffusion.

Equation used in the simulation

MACH2

Continuity Equation:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{u})$$

Momentum Equation:

$$\rho \frac{\partial v^i}{\partial t} = -\rho v^j \nabla_j v^i + \nabla_j [-(P + Q + \frac{1}{3} u_R)\delta^{ji} + \frac{1}{\mu_0}(B^j B^i - \frac{1}{2} B^2 \delta^{ji}) + \sigma^d_{ji}]$$

Electron Specific Energy Equation:

$$\rho \frac{\partial \epsilon_e}{\partial t} = -\rho \vec{v} \cdot \nabla \epsilon_e - P_e \delta^{ji} \nabla_i v_j + \eta J^2 - \vec{J} \cdot (\frac{\nabla P_e}{e n_e}) + \nabla \cdot (\kappa_e \nabla T_e) - ac\rho \chi_{planck}(T_e^4 - T_R^4) - \rho c_{v_e} \frac{(T_e - T_i)}{\tau_{ei}}$$

Ion Specific Energy Equation:

$$\rho \frac{\partial \epsilon_i}{\partial t} = -\rho \vec{v} \cdot \nabla \epsilon_i + [-(P_i + Q)\delta^{ji} + \sigma^d_{ji}] \nabla_i v_j + \nabla \cdot (\kappa_i \nabla T_i) + \rho c_{v_e} \frac{(T_e - T_i)}{\tau_{ei}}$$

Radiation Energy Density:

$$\frac{\partial u_R}{\partial t} = -\rho \vec{v} \cdot \nabla u_R - \frac{4}{3} u_R \nabla \cdot \vec{v} + \nabla \cdot (\rho \chi_{ros} \nabla u_R) + ac\rho \chi_{planck}(T_e^4 - T_R^4)$$

Magnetic Induction:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) - \nabla \times (\eta \vec{J}) - \nabla \times (\frac{\vec{J} \times \vec{B}}{e n_e}) + \nabla \times (\frac{\nabla P_e}{e n_e})$$

Elastic Stress:

$$\frac{\partial \sigma^d_{ji}}{\partial t} = 2\mu d^d_{ji} - v^k \nabla_k \sigma^d_{ji}$$

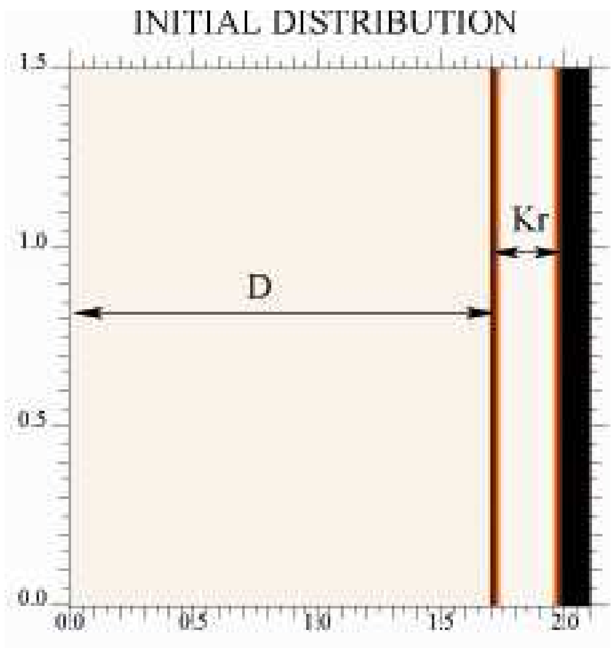
Fusion Neutron Production Rate and Energy Gain:

$$P_{DT} = 5.6 \times 10^{-13}\ n_D n_T (\sigma\nu)_{DT}$$

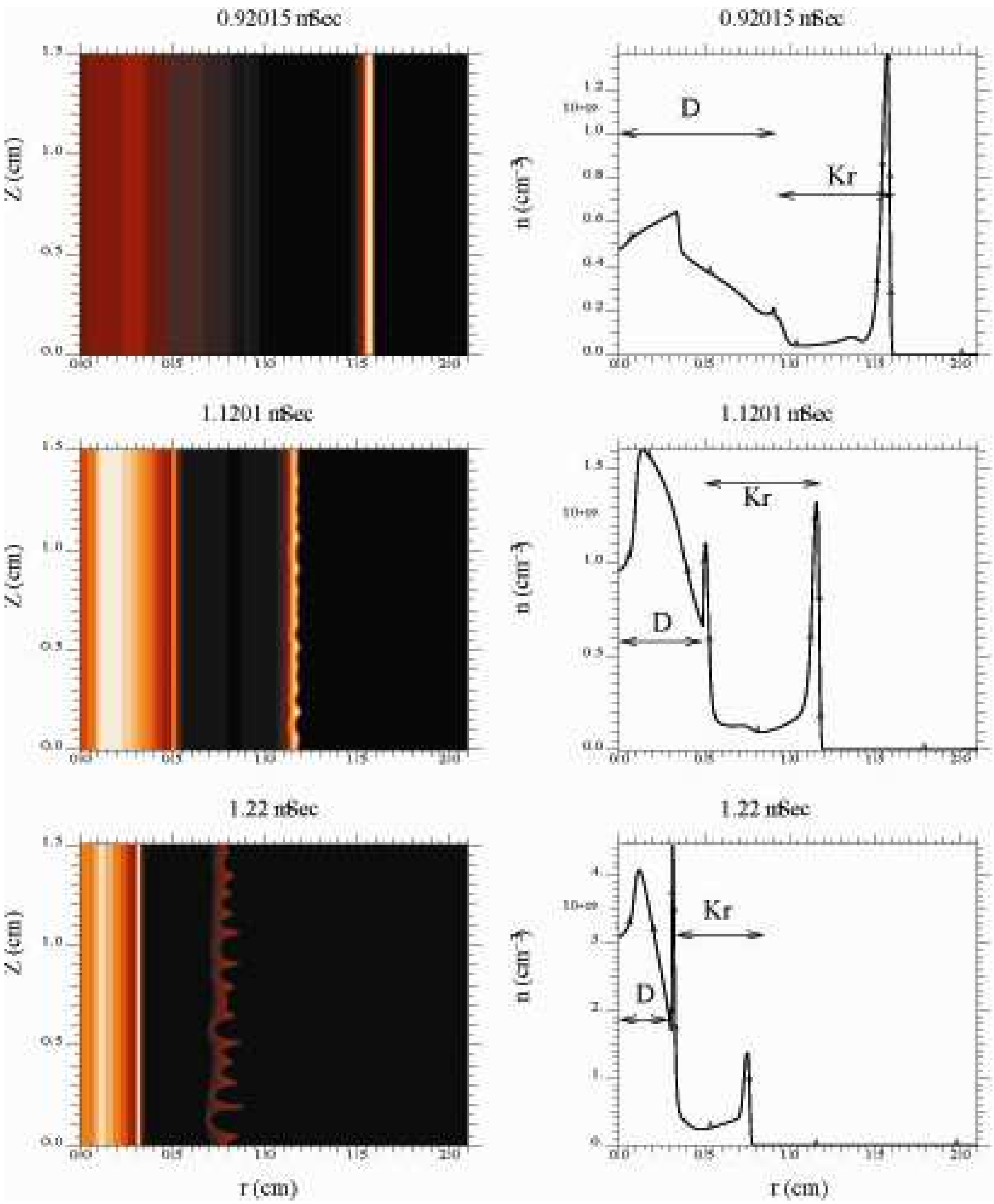
$$P_{DD} = 3.3 \times 10^{-13}\ n_D n_D (\sigma\nu)_{DD}$$

$(\sigma\nu)_{DT}$ and $(\sigma\nu)_{DD}$are determined from a table look up.

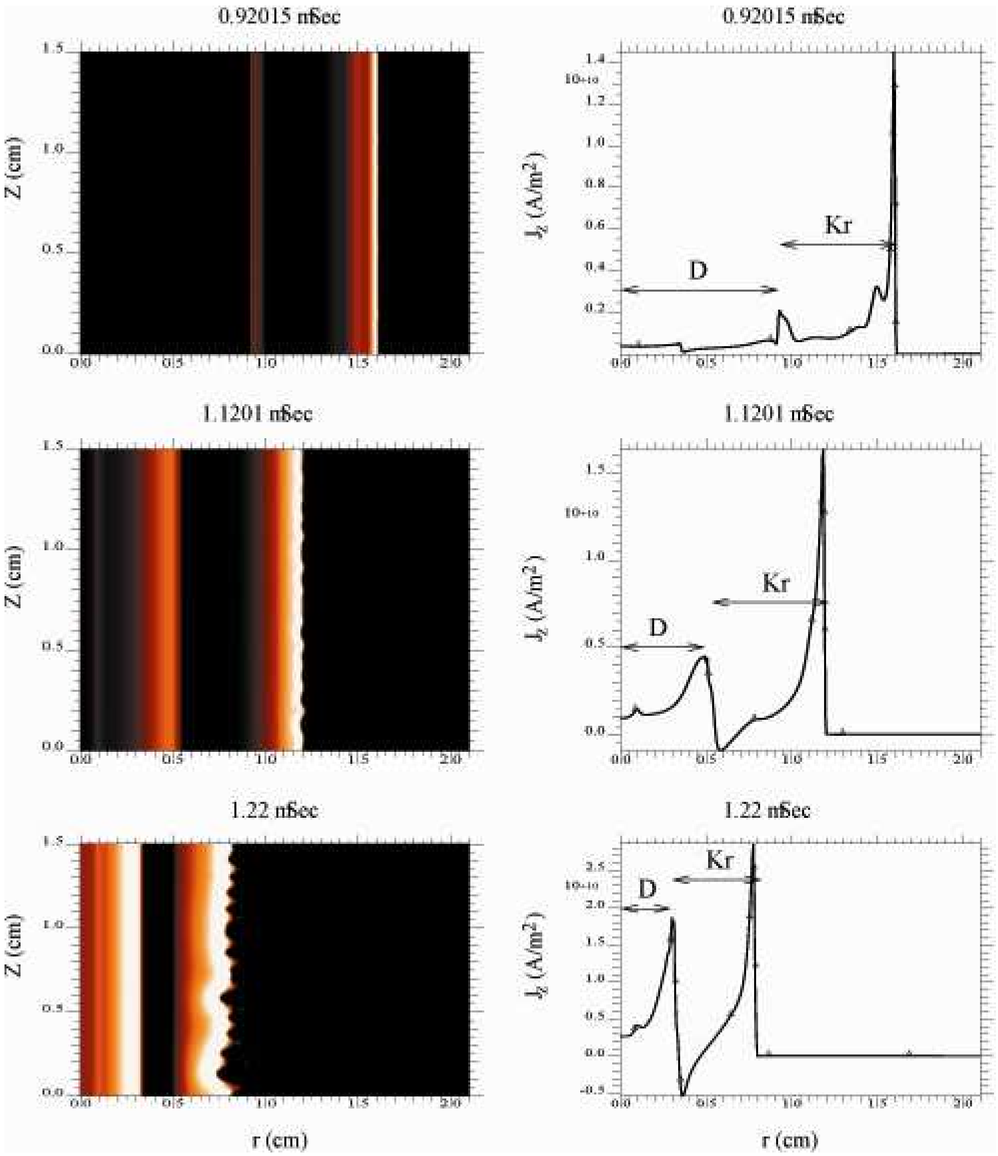
Initial configuration for UCI Pinch



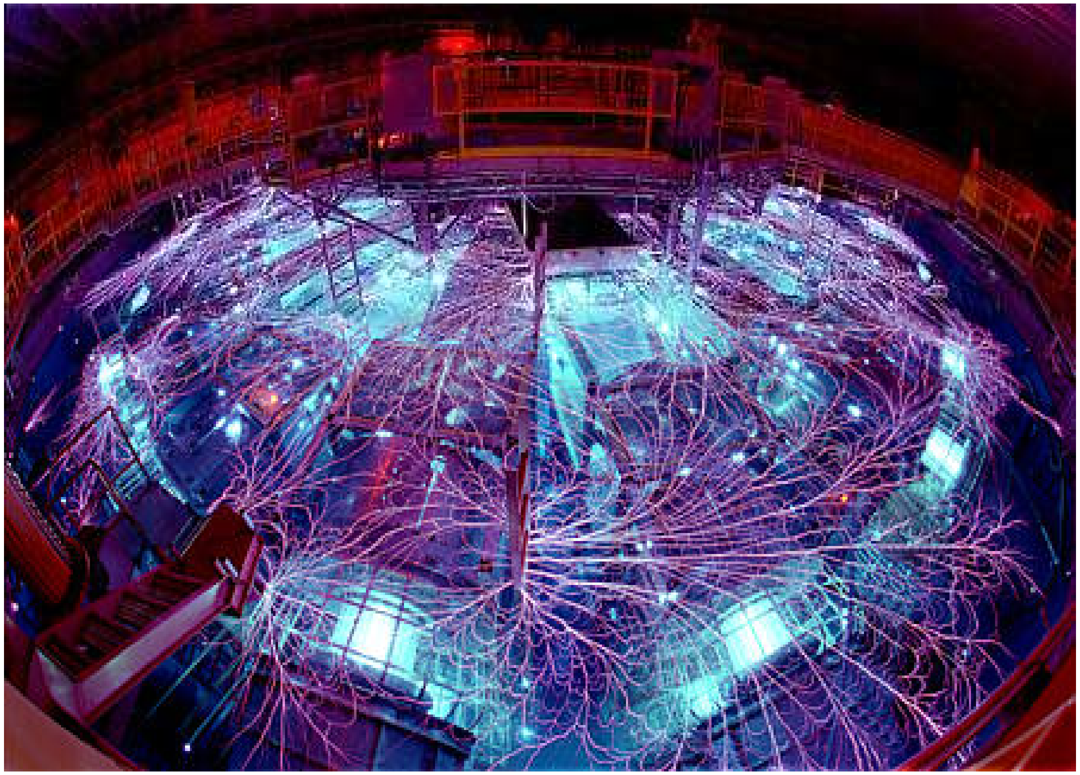
Ion density
During run-in phase



Current Density
During run in phase



Z Machine



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Initial Configuration For Mega-Joule Facility

- **Load parameters**

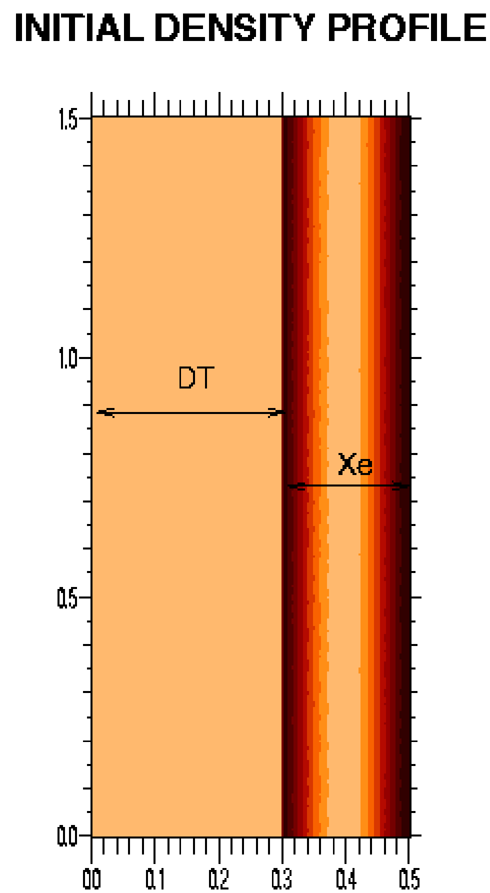
Density of Xe = 180 kg/m3
Density of DT = 3.4 kg/m3
Perturbation = 1%

- **Machine parameters**

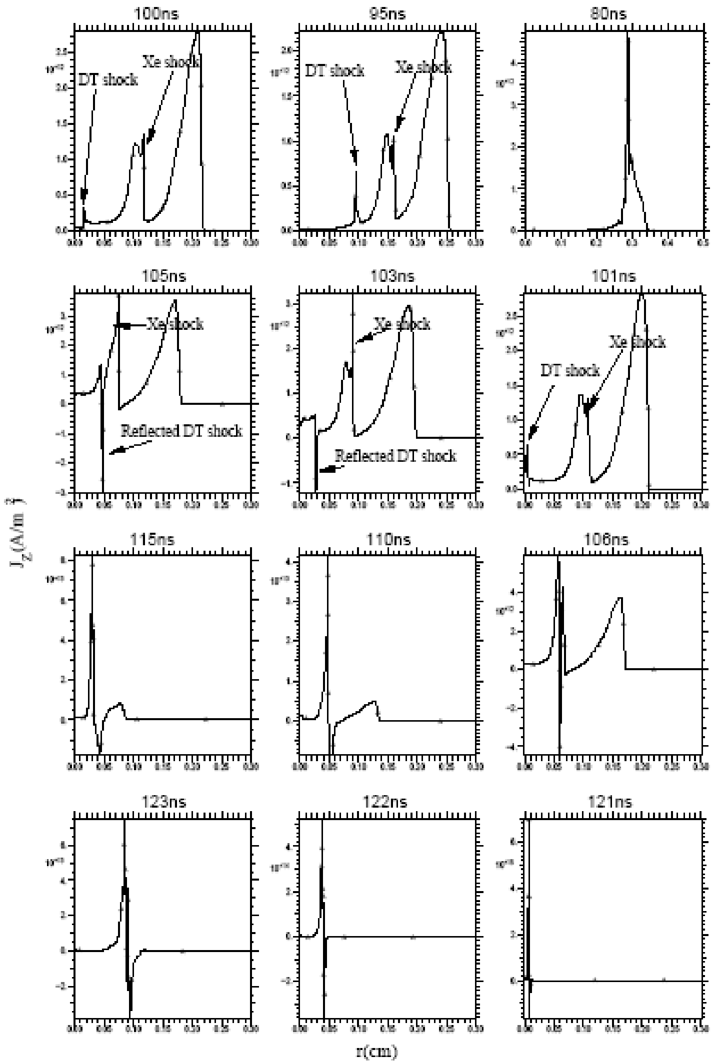
Maximum current= 18 MA
Current rise time = 90 ns
Stored Energy = 2.1 MJ

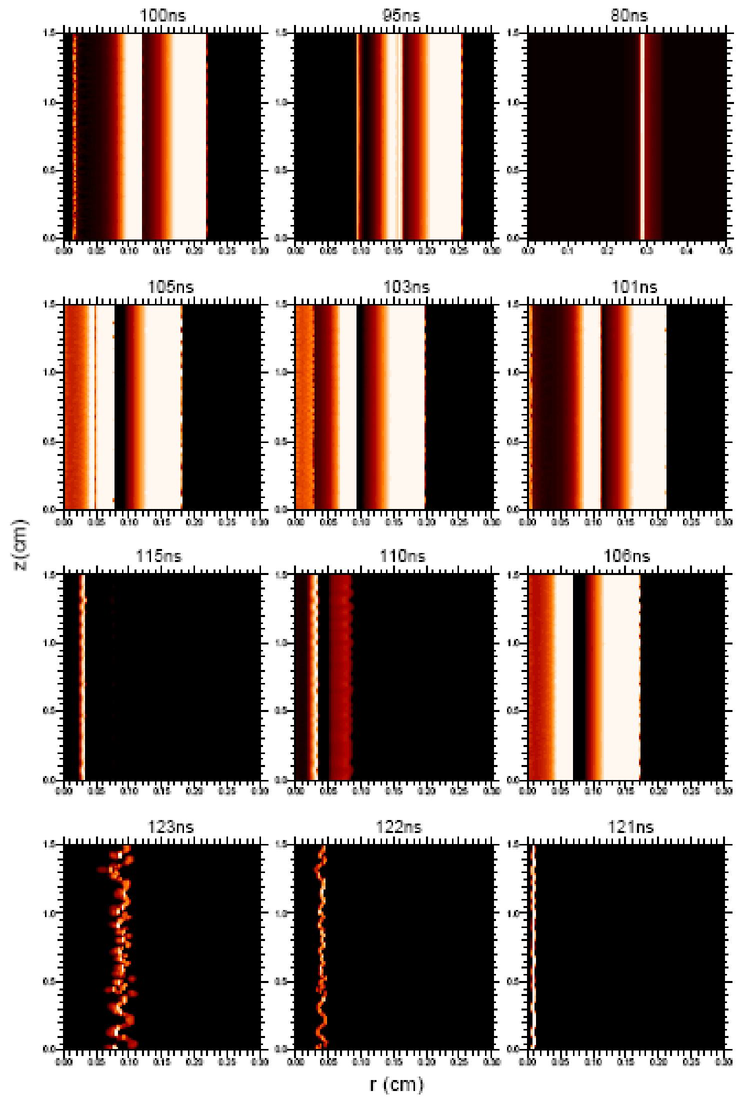
- **GRID**

160x120 Adaptive mesh

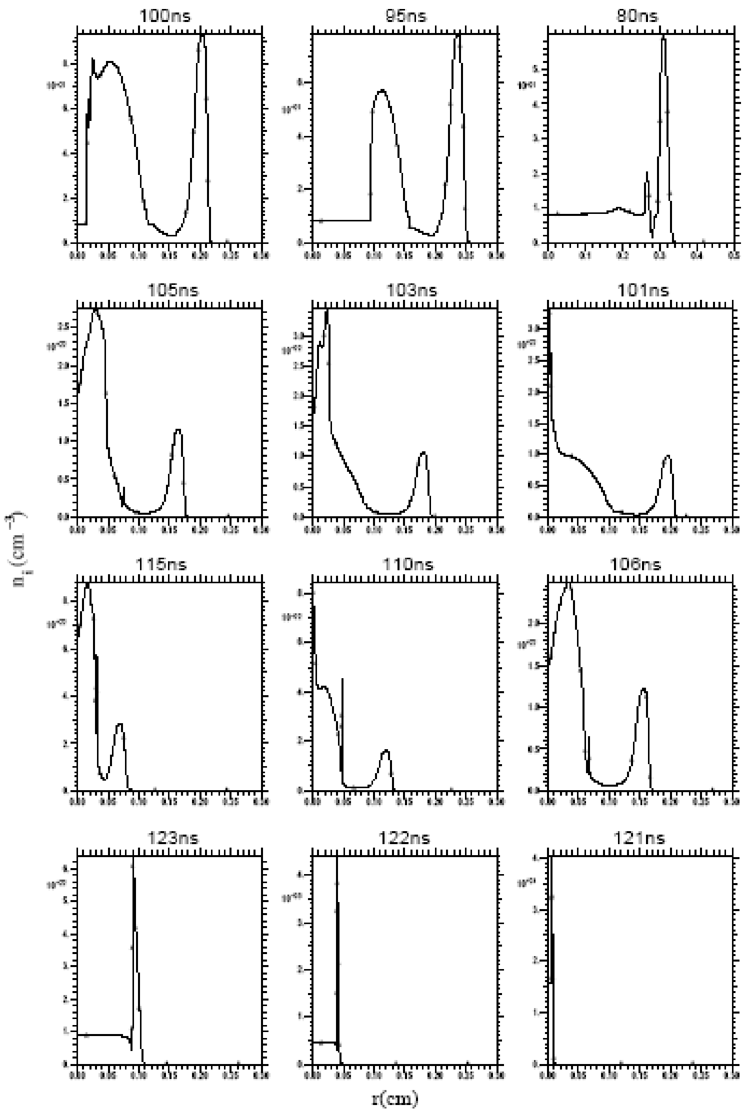


Axial Current Density

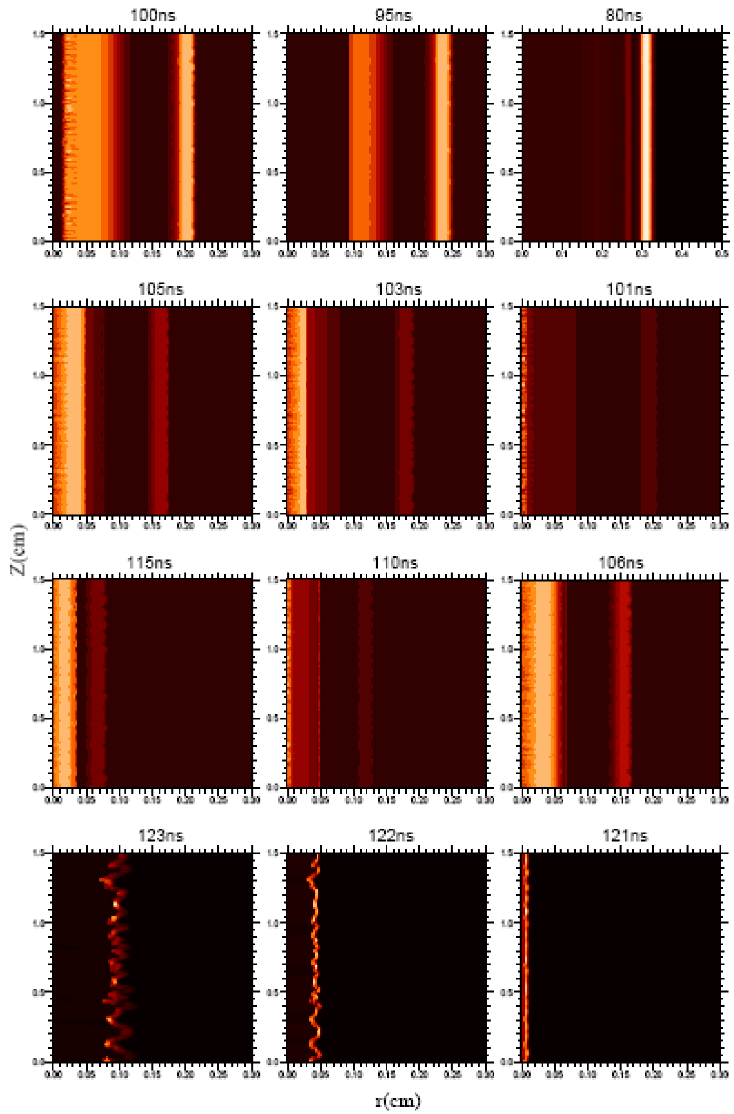




Ion Density

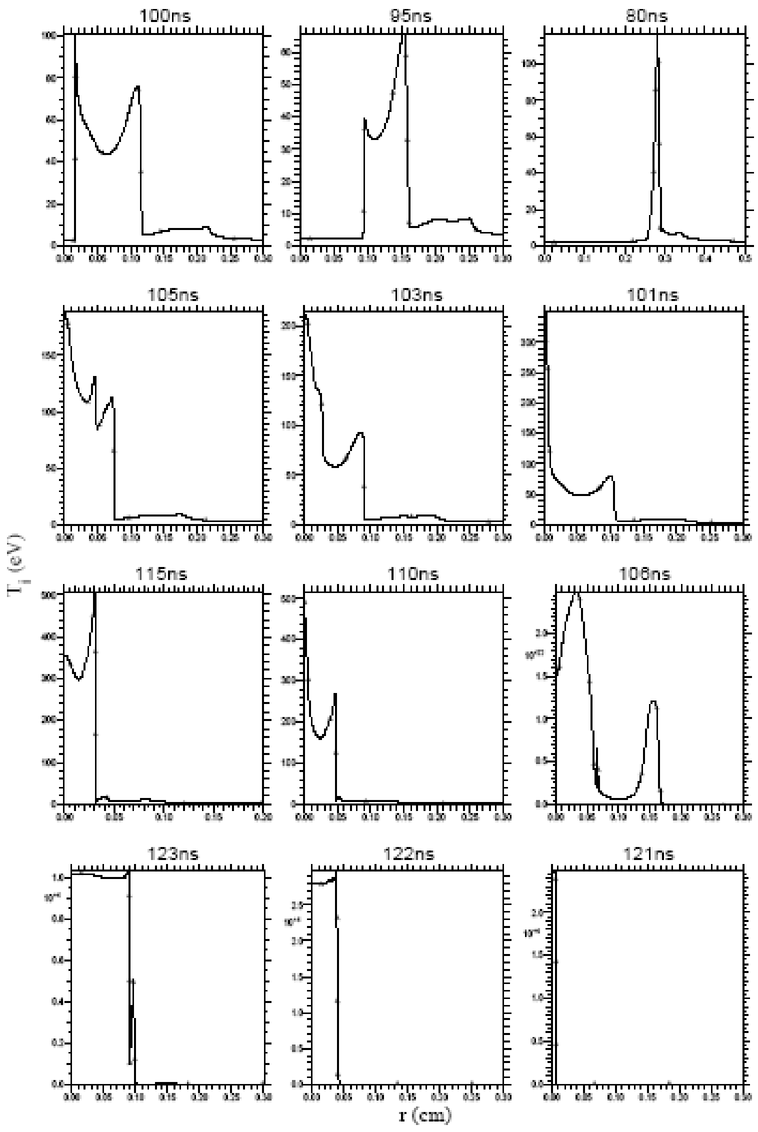


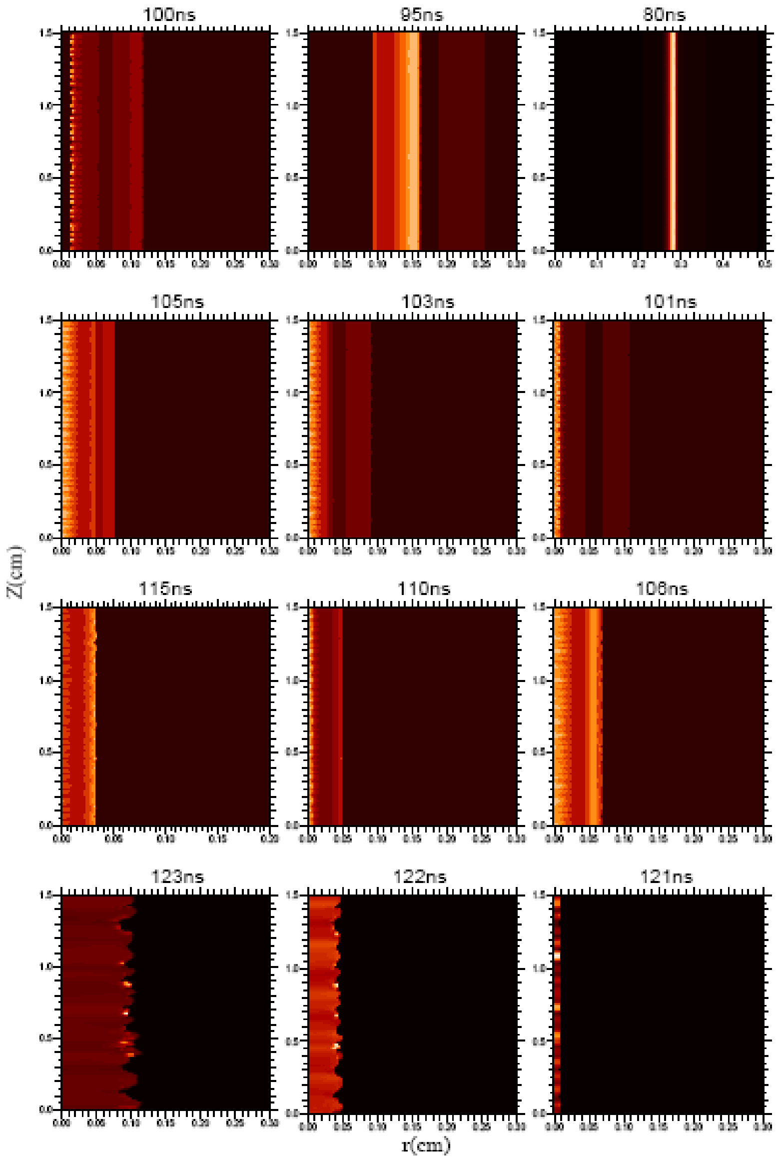
100ns
95ns
80ns
105ns
103ns
101ns
115ns
110ns
106ns
123ns
122ns
121ns
n_i (cm^{-3})
r(cm)



100ns
95ns
80ns
105ns
103ns
101ns
115ns
110ns
106ns
123ns
122ns
121ns
Z(cm)
r(cm)

Ion Temperature





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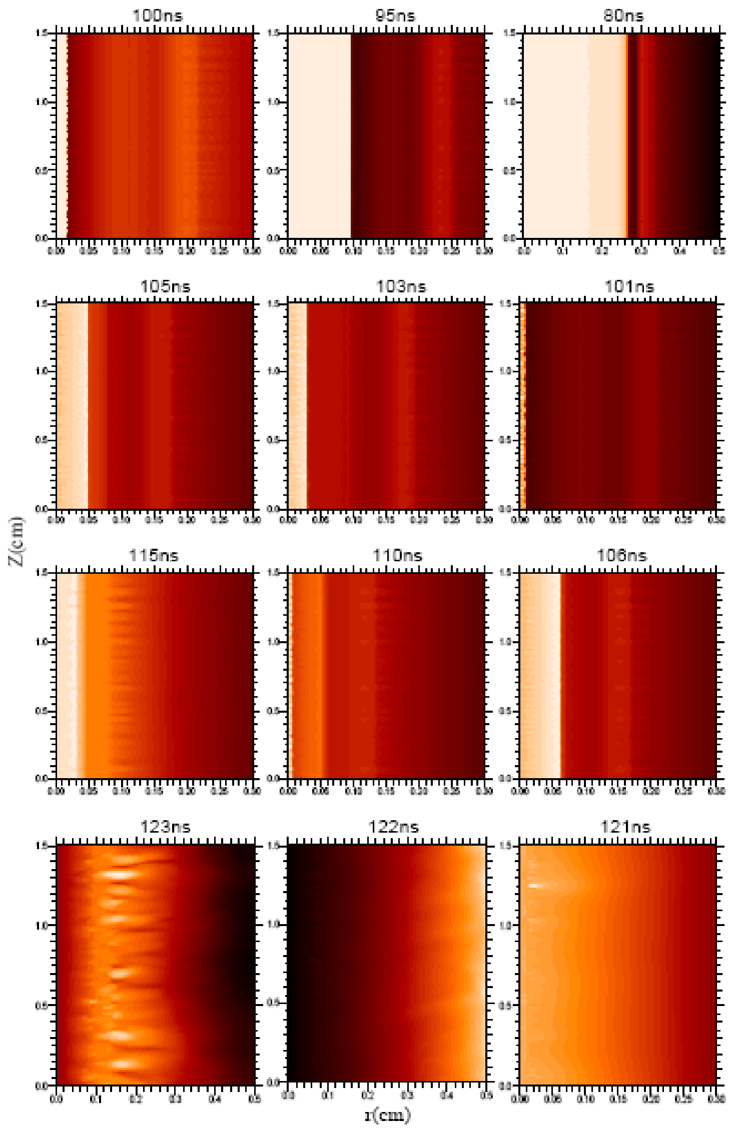
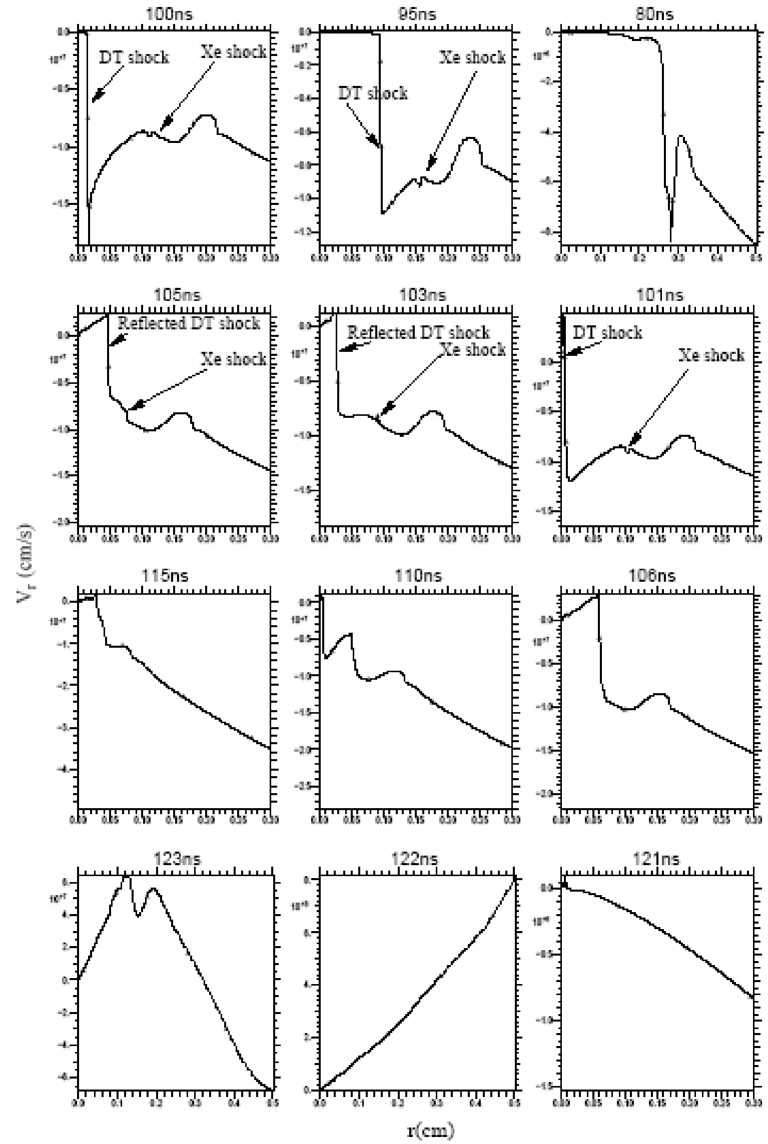
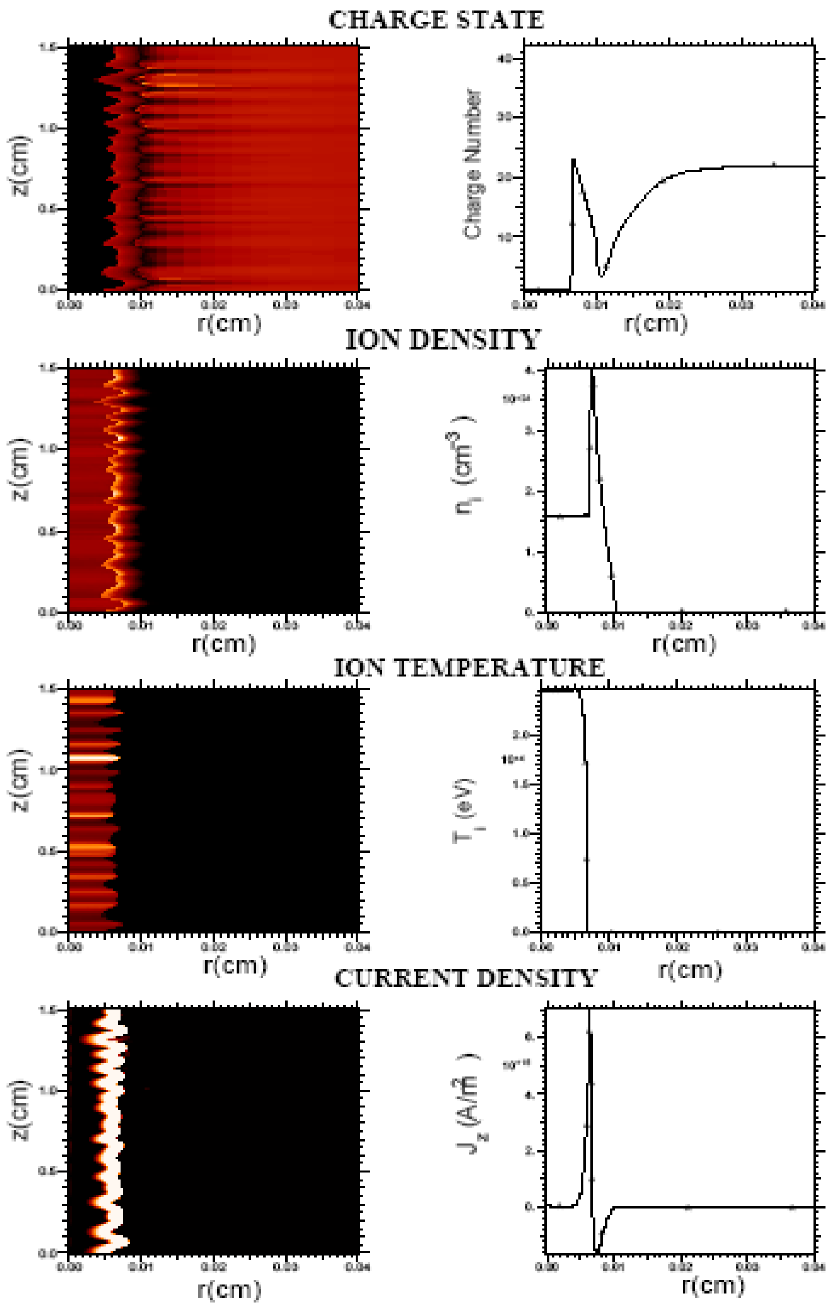
Radial Velocity

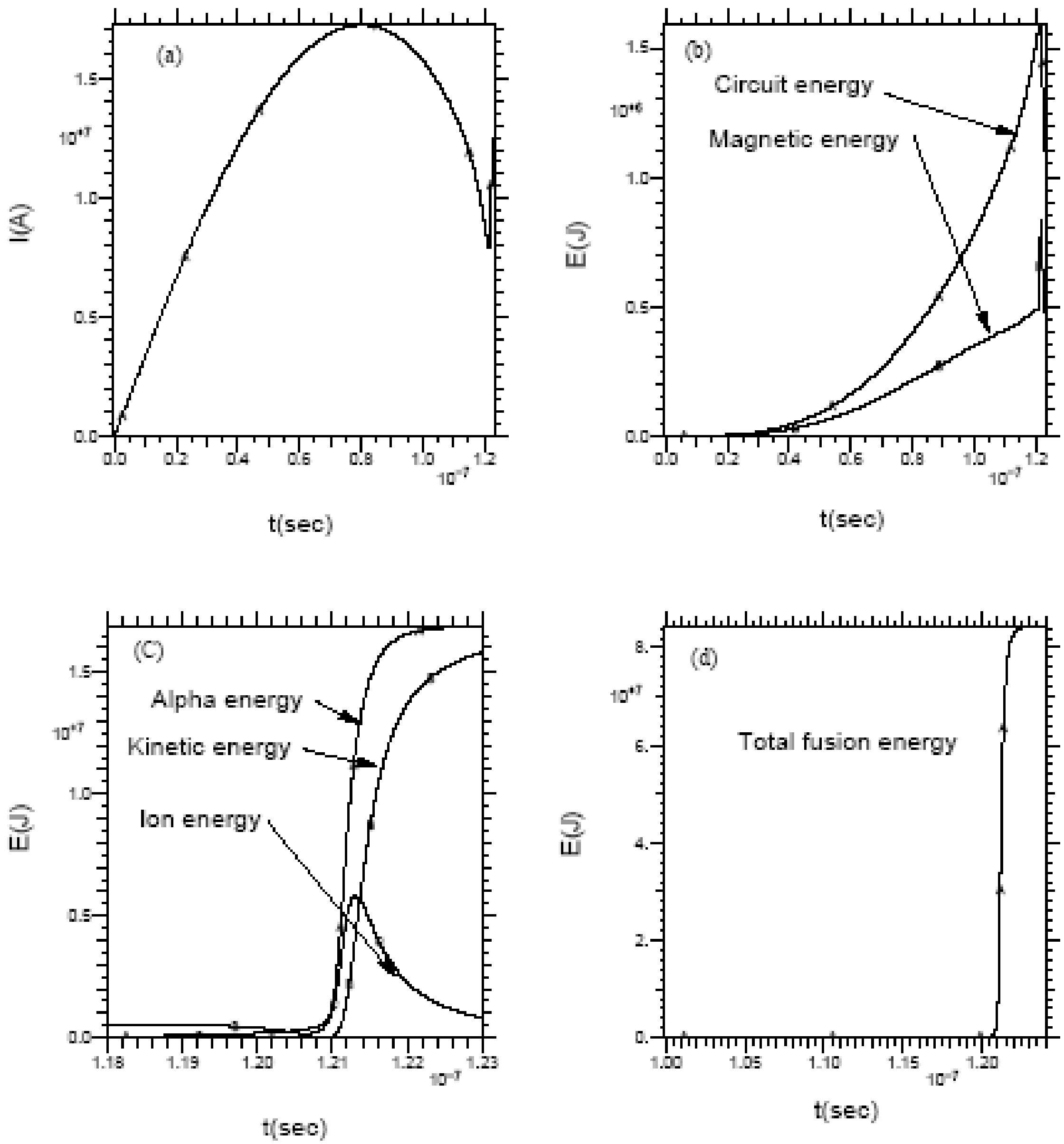




Peak Parameters



Global parameters



Rayleigh-Taylor Instability

$$\xi = \xi_0 e^{\gamma t}$$

$$\gamma = \sqrt{gk}$$

$$R = \frac{1}{2} g t^2$$

$$\xi = \xi_0 e^{\sqrt{2Rk}}$$

ξ_0	Initial perturbations
R	Pinch radius
k	Wave number
g	Pinch Acceleration

Growth of perturbations depend upon the radius of the pinch

Energy coupling

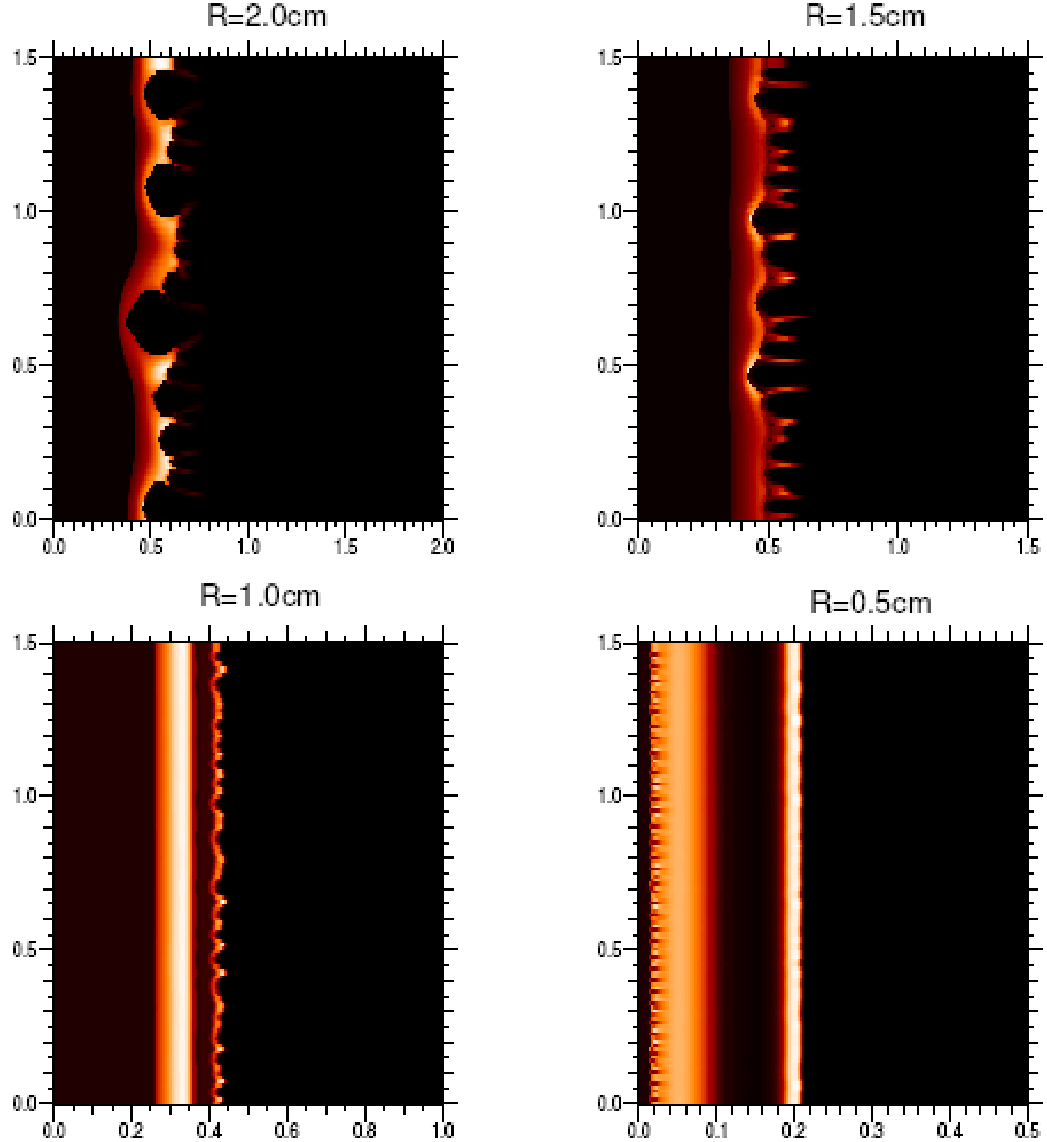
$$W = \int_{R_0}^{R} \frac{B_\theta^2}{8\pi} \bullet 2\pi R \bullet h dR \qquad B_\theta = \frac{2I}{cR}$$

$$= h\left(\frac{I}{c}\right)^2 \ln\left(\frac{R_0}{R}\right)$$

Final energy of the pinch depends weakly on the compression ratio!

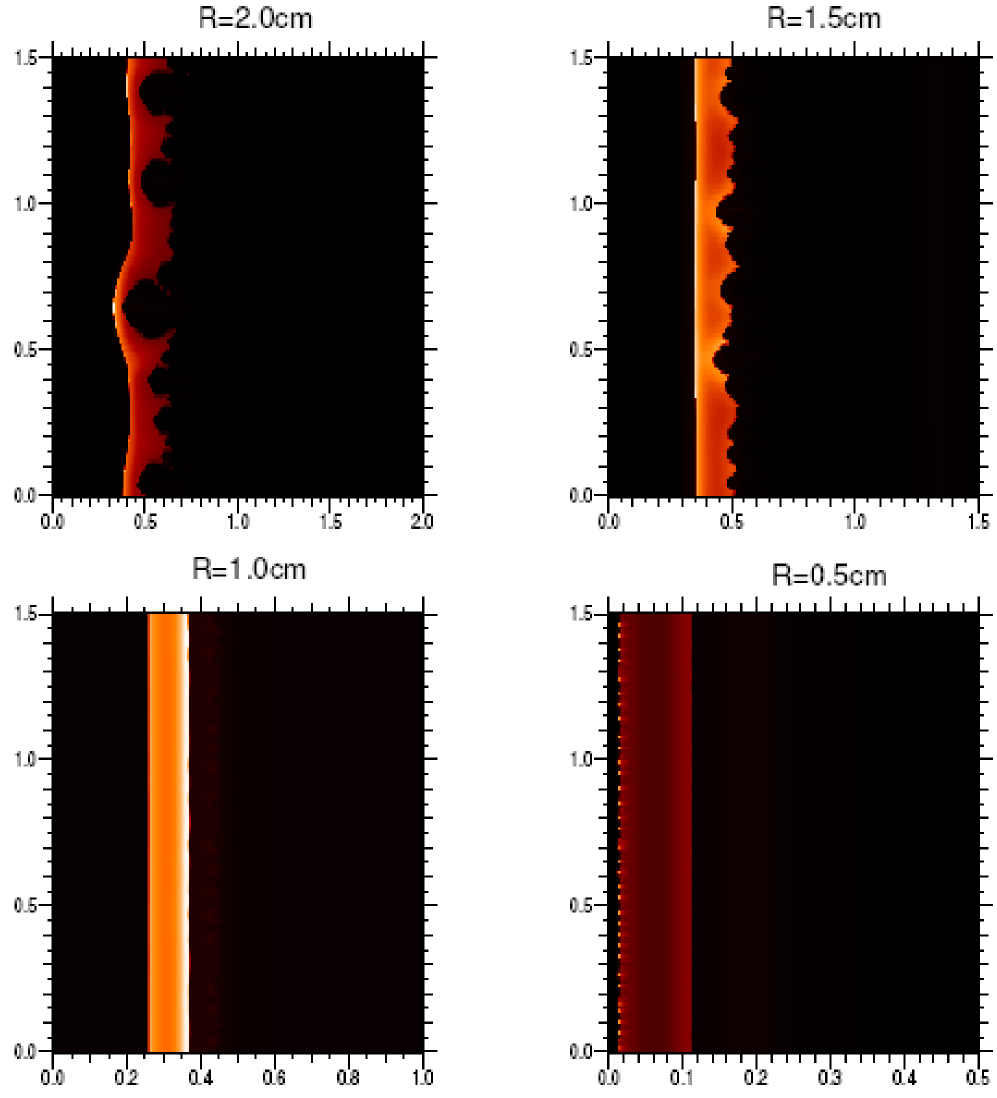
ION DENSITY AT 100ns

(for 4 initial radii)



ION TEMPERATURE AT 100ns

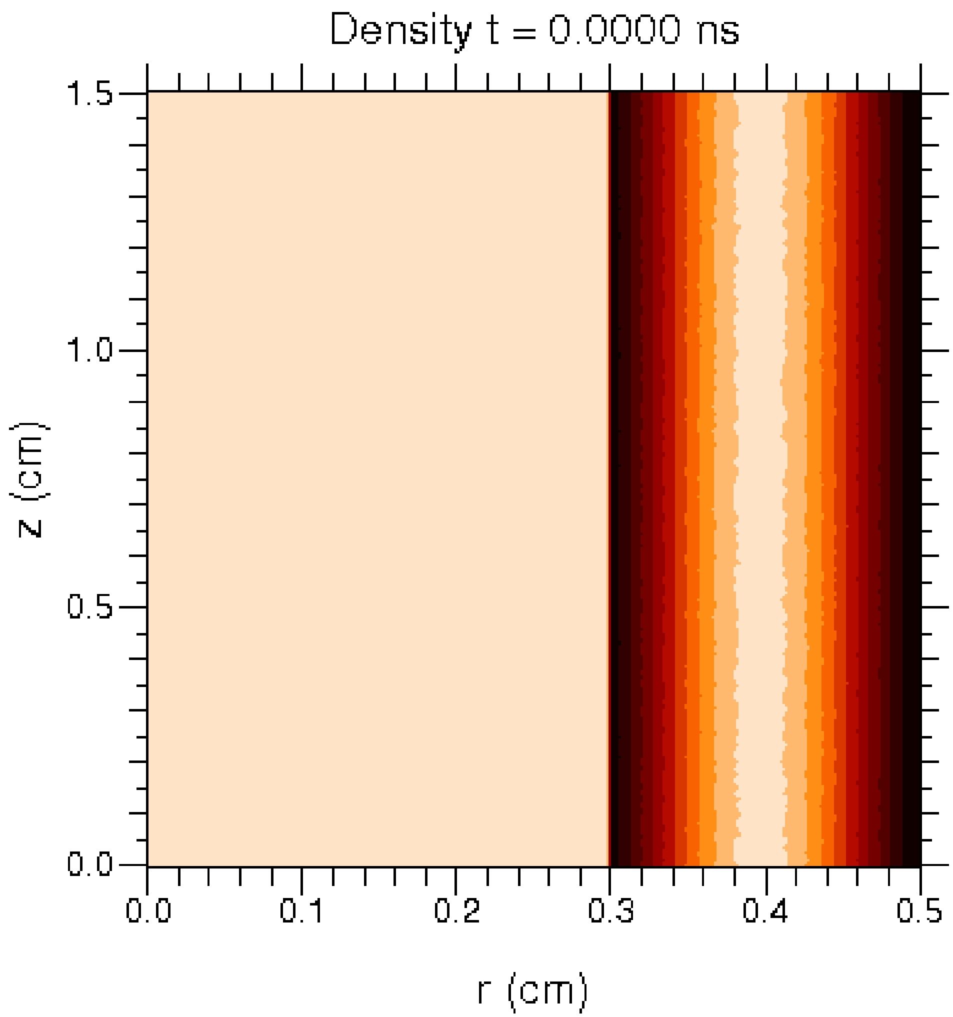
(for 4 initial radii)



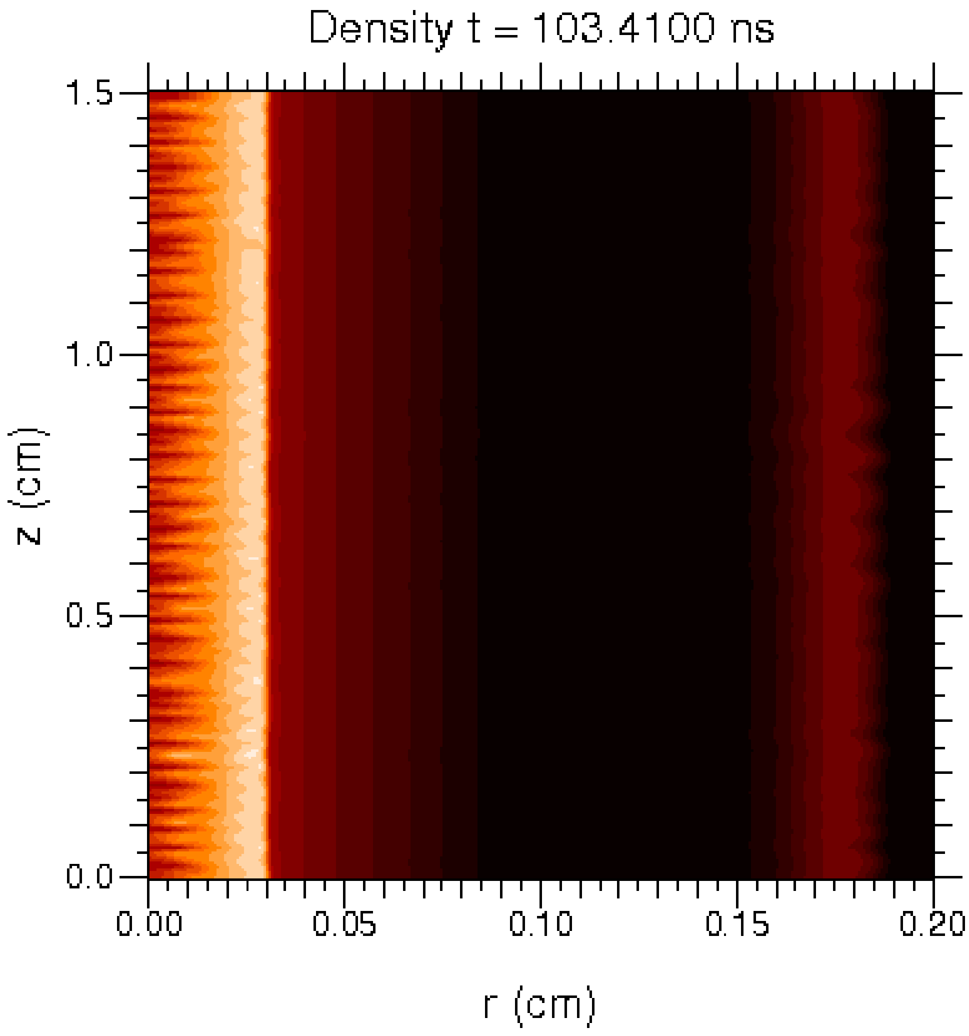
Large Energy Production

- Xe liner plasma and DT target plasma is used.
- Both the masses of the liner and the target are optimized
- Optimized parameters of similar to Z-facility are used
- Initial radius of 0.5cm is used
- Compression ratio of less then 25 is needed.
- Perturbation level of 1% is used
- **80 MJ of Energy is produced with a stored energy of 2 MJ.**
- Real breakeven is possible with existing technology.

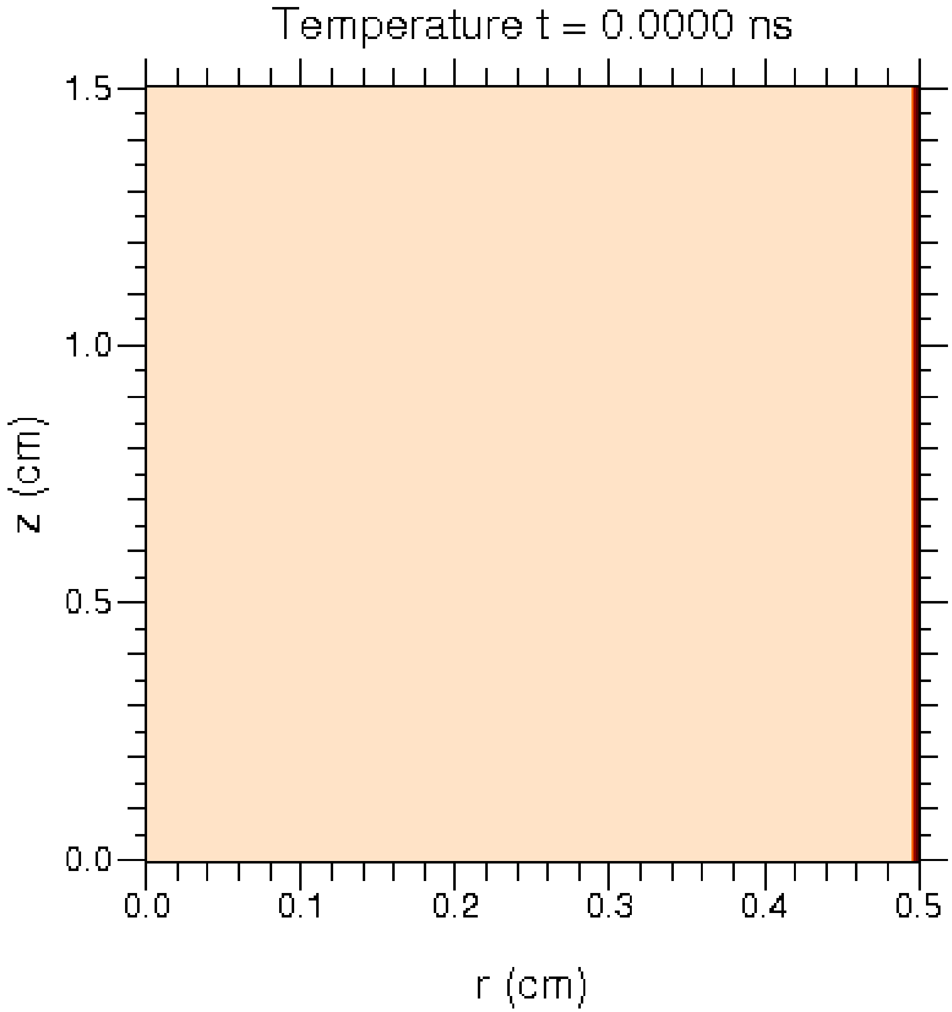
Ion Density (full run)



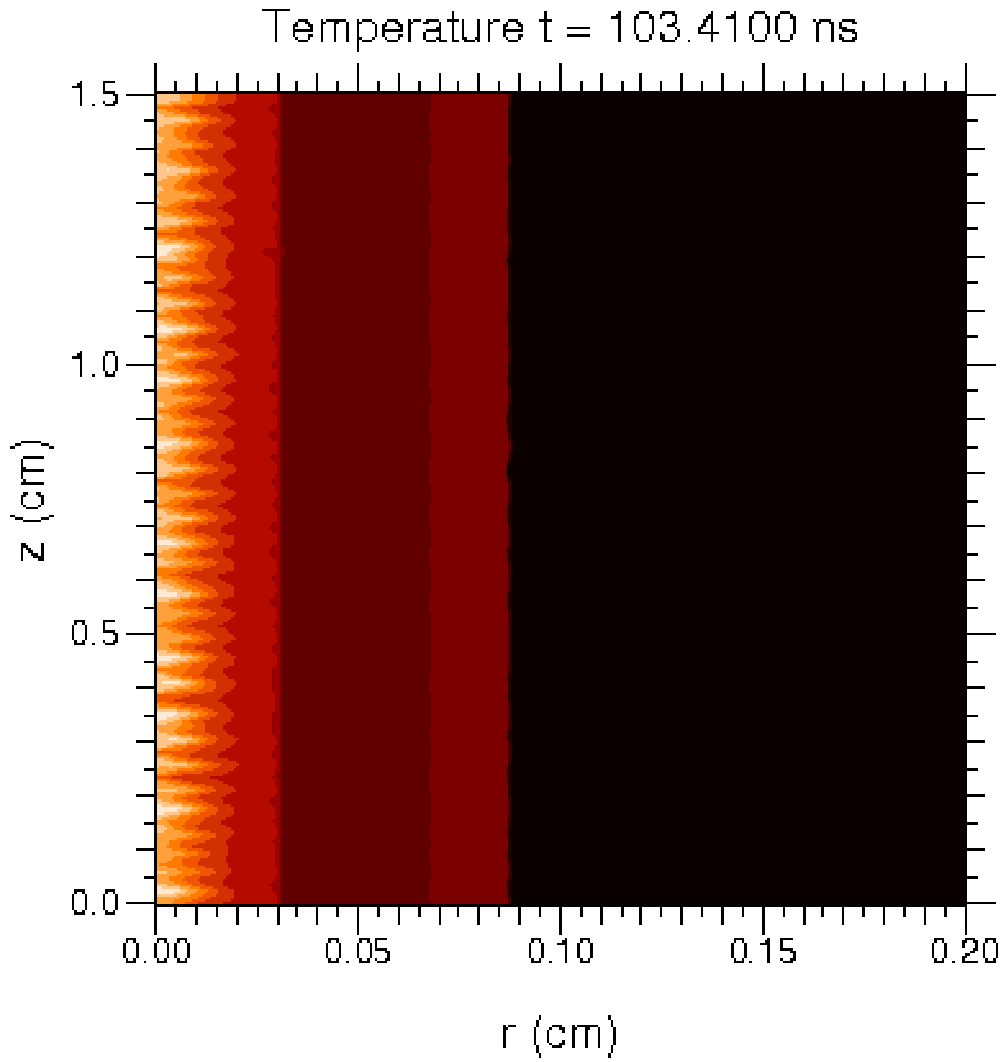
Ion Density (near the peak)



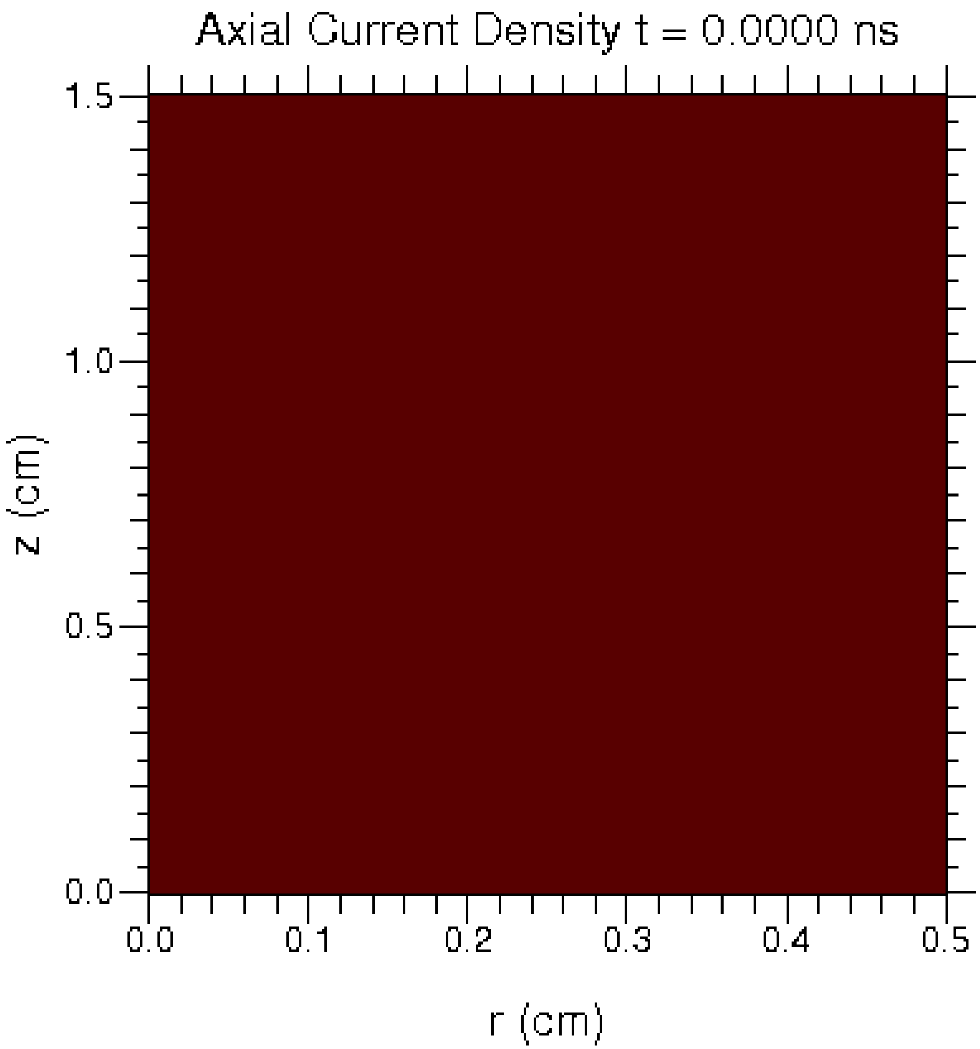
Ion Temperature (Full run)



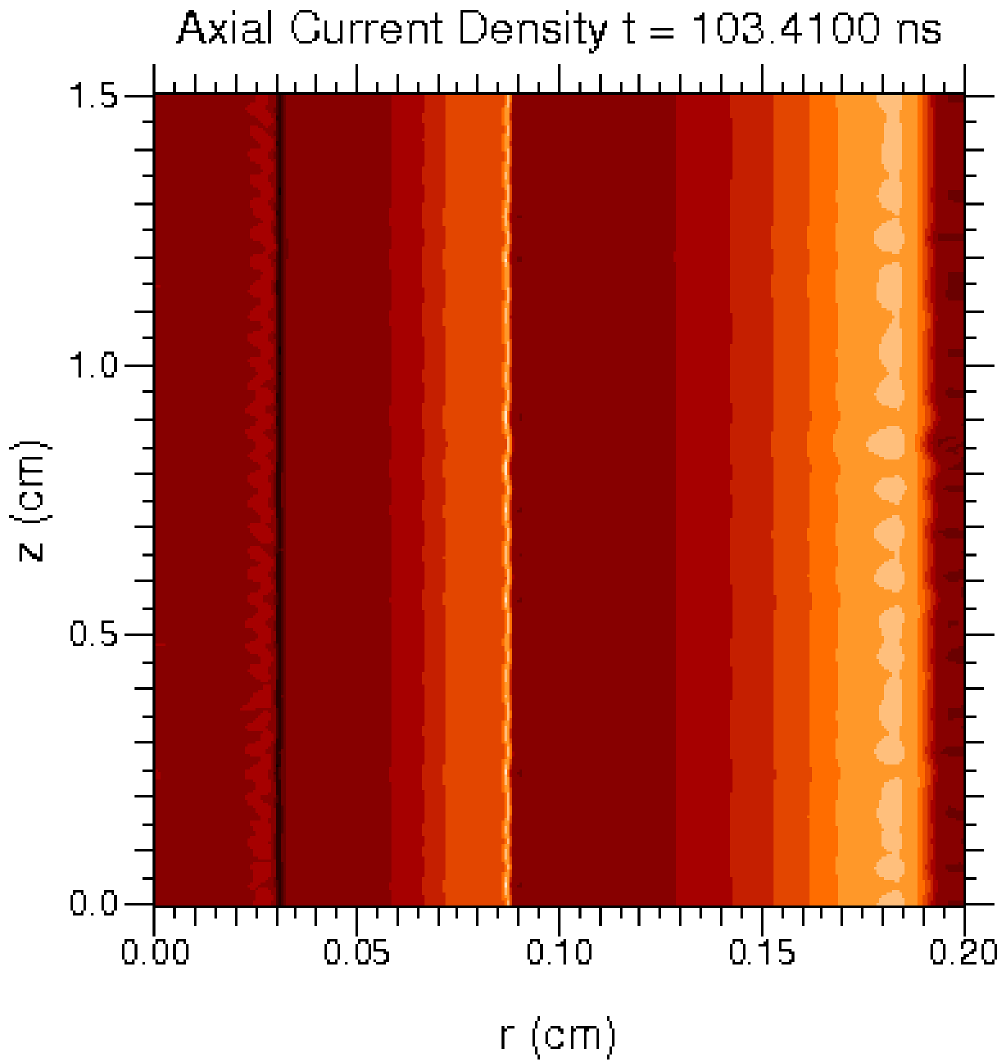
Ion Temperature (near the peak)



Axial current (full run)



Axial current (near peak)



Conclusions

- R-T instability can be controlled.
- Shock compression and heating is identified
- Pinch current is amplified.
- Current rise time is reduced.
- Breakeven fusion (i.e., nuclear energy larger than stored energy) is possible.
- Reactor design is not yet considered.