The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
Energy Agency

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AUTUMN COLLEGE ON PLASMA PHYSICS

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Controlled Fusion
by a Staged Z-pinch

H.U. Rahman

GTT International Inc.
U.S.A.

Controlled Fusion by a Staged Z-pinch

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University of California, Irvine, USA

Phys. Rev Lett. **74**, 714(1995)
Phys. Of Plasmas, **58**, 367(1997)
Phys. Of Plasmas, **11**, 5595(2004)

1. GTT International Inc.
2. San Jacinto College

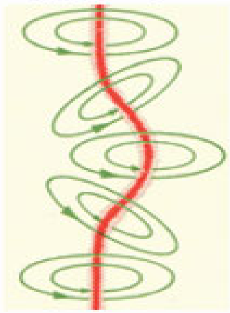
6th Symposium on Current Trends in International Fusion Research: A Review,
Washington DC 7-11 March 2005

Outline

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

PINCH INSTABILITIES

KINK
m = 1

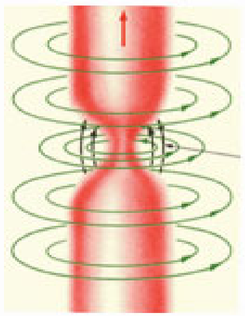


incompressible, sharp boundary:

$$\gamma = \frac{C_A (kr_o)}{r_o} \frac{I_m (kr_o)}{I'_m (kr_o)} \left[1 + \frac{m^2}{kr_o} \frac{K_m (kr_o)}{K'_m (kr_o)} \right]$$

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

SAUSAGE
m = 0



m = 0;

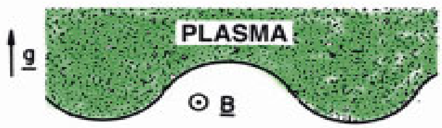
$$\gamma = \frac{C_A (kr_o)}{r_o} \frac{I_m (kr_o)}{I'_m (kr_o)} ;$$

compressible, k -> 0;

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

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

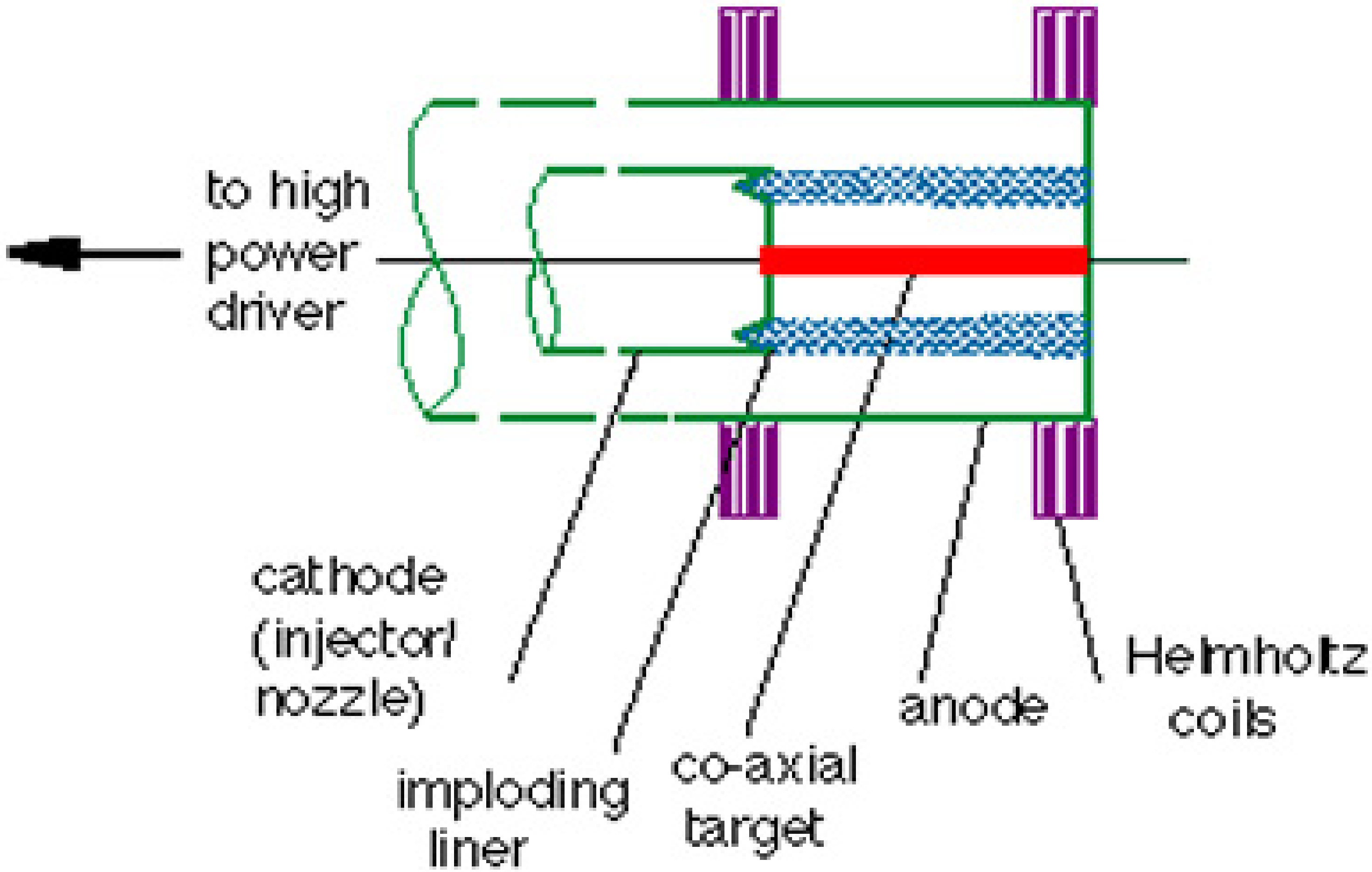
RAYLEIGH TAYLOR



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

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

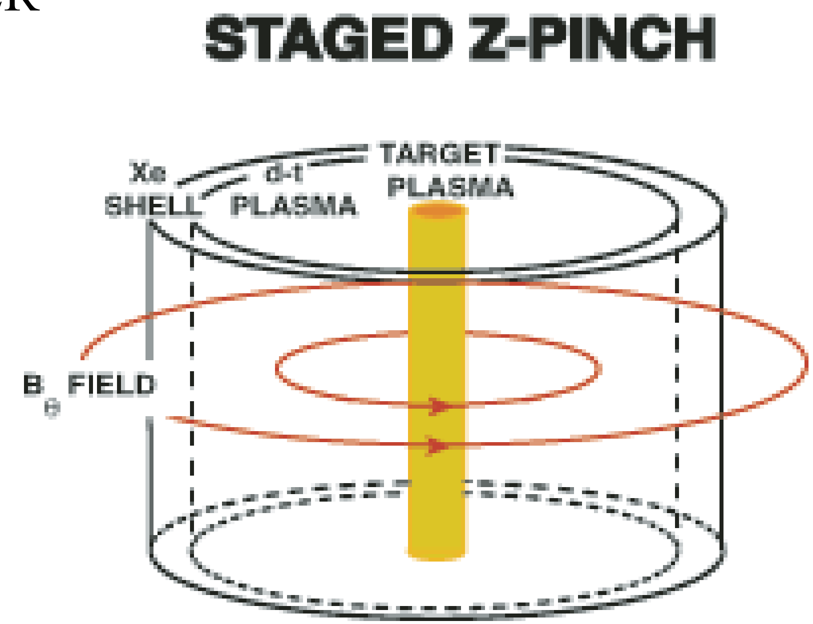
Staged Z-pinch



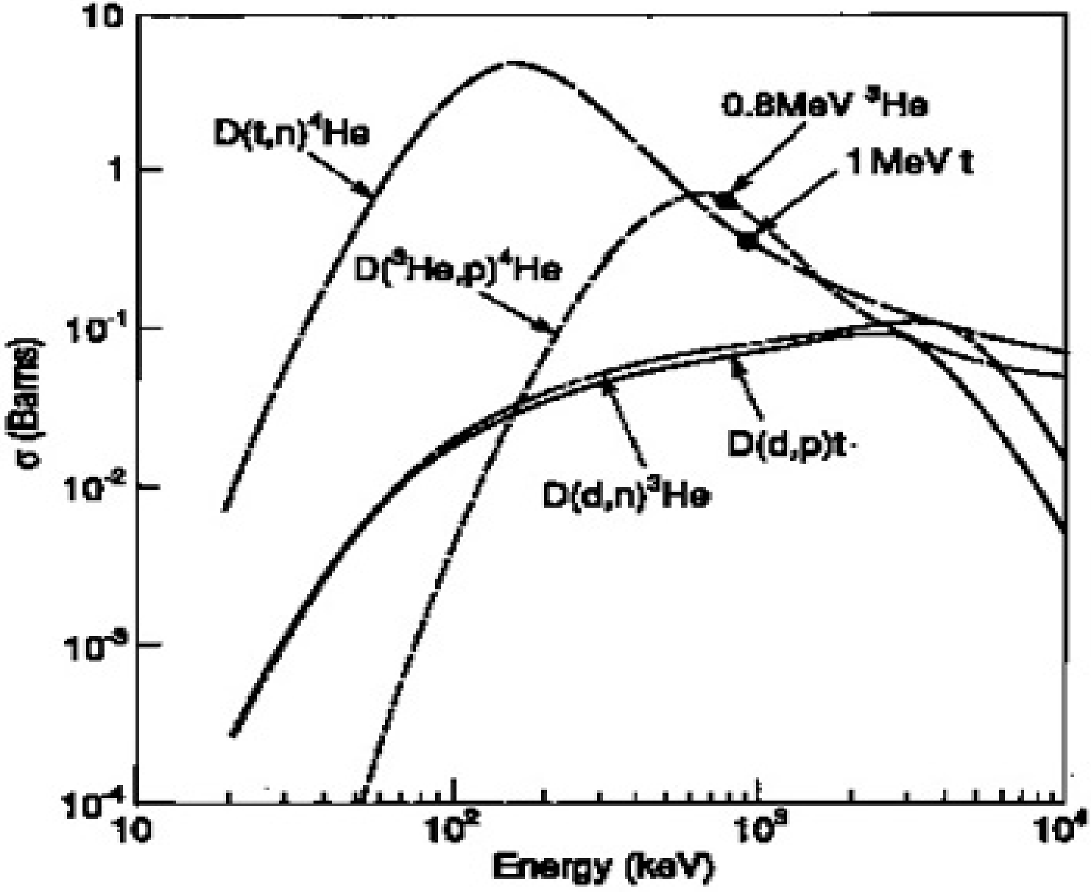
MAGNETO-INERTIAL FUSION

PINCH DYNAMICS
CURRENT DIFFUSES THROUGH HIGH Z LINER
INNER LAYER OF LINER PEALS OFF
PEALED OFF LAYER COMPRESSES TARGET
UNSTABLE PART OF LINER STAYS BEHIND
AT PEAK COMPRESSION, CURRENT
TRANSFERS TO INNER STABLE LAYER.

BENEFITS
INERTIAL ENERGY TRANSFER TIMESCALES
COMPRESSION IS RT STABLE
BREAKEVEN FUSION IS PREDICTED



Fusion Cross Sections



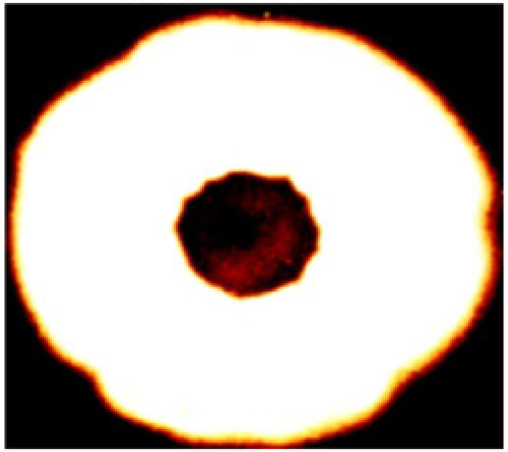
Stability of RT-instability

STABILIZATION OF LINEAR PINCH

End-on Kerr cell photos

Unstable pinch

Pinch stabilized with B_z and B_Θ fields

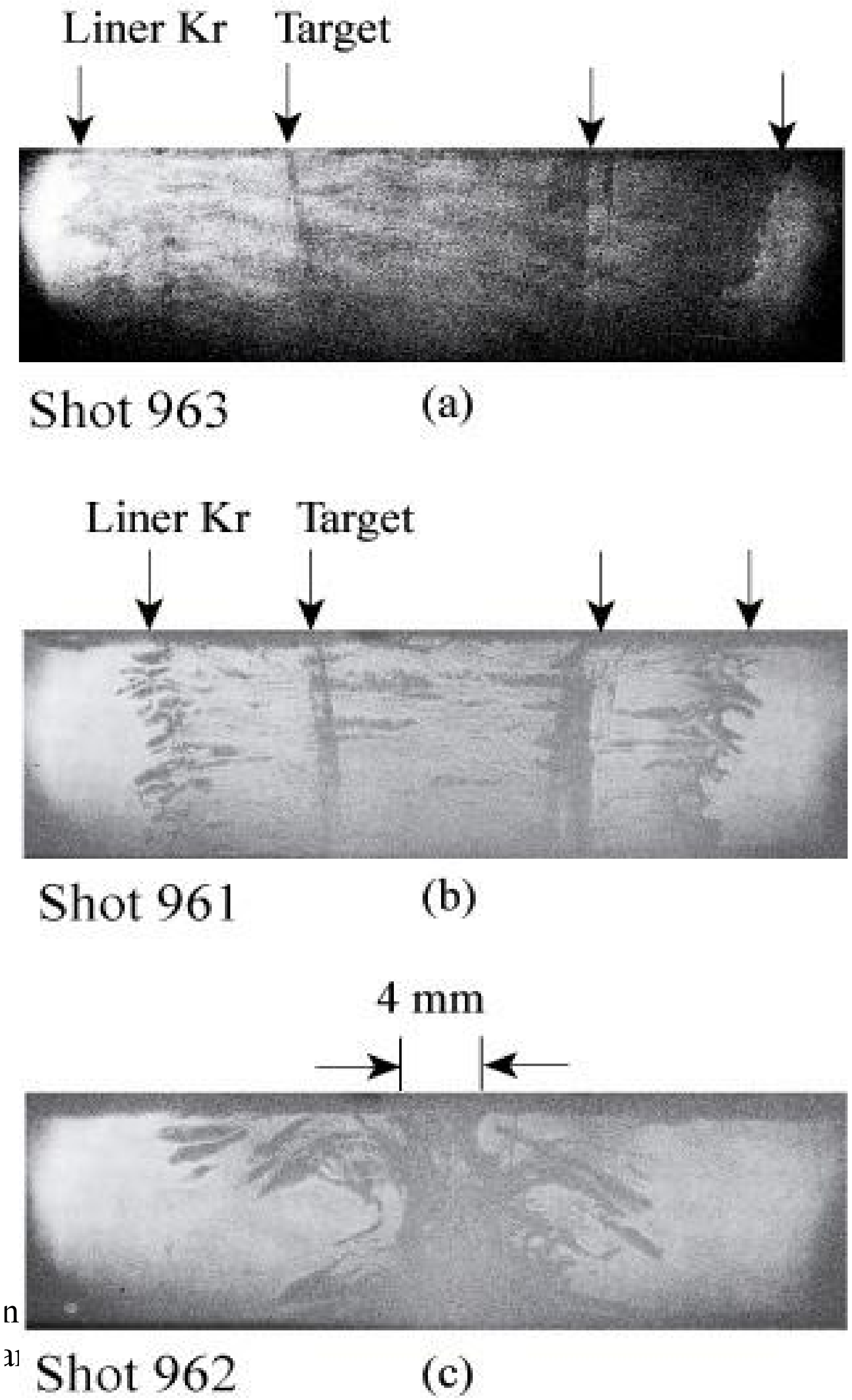


D.J.Albares, N. A. Krall and C. L. Oxley, "Rayleigh Taylor Instability in a Stabilized Linear Pinch Tube," Phys. Fluids 4, 1031(1961).

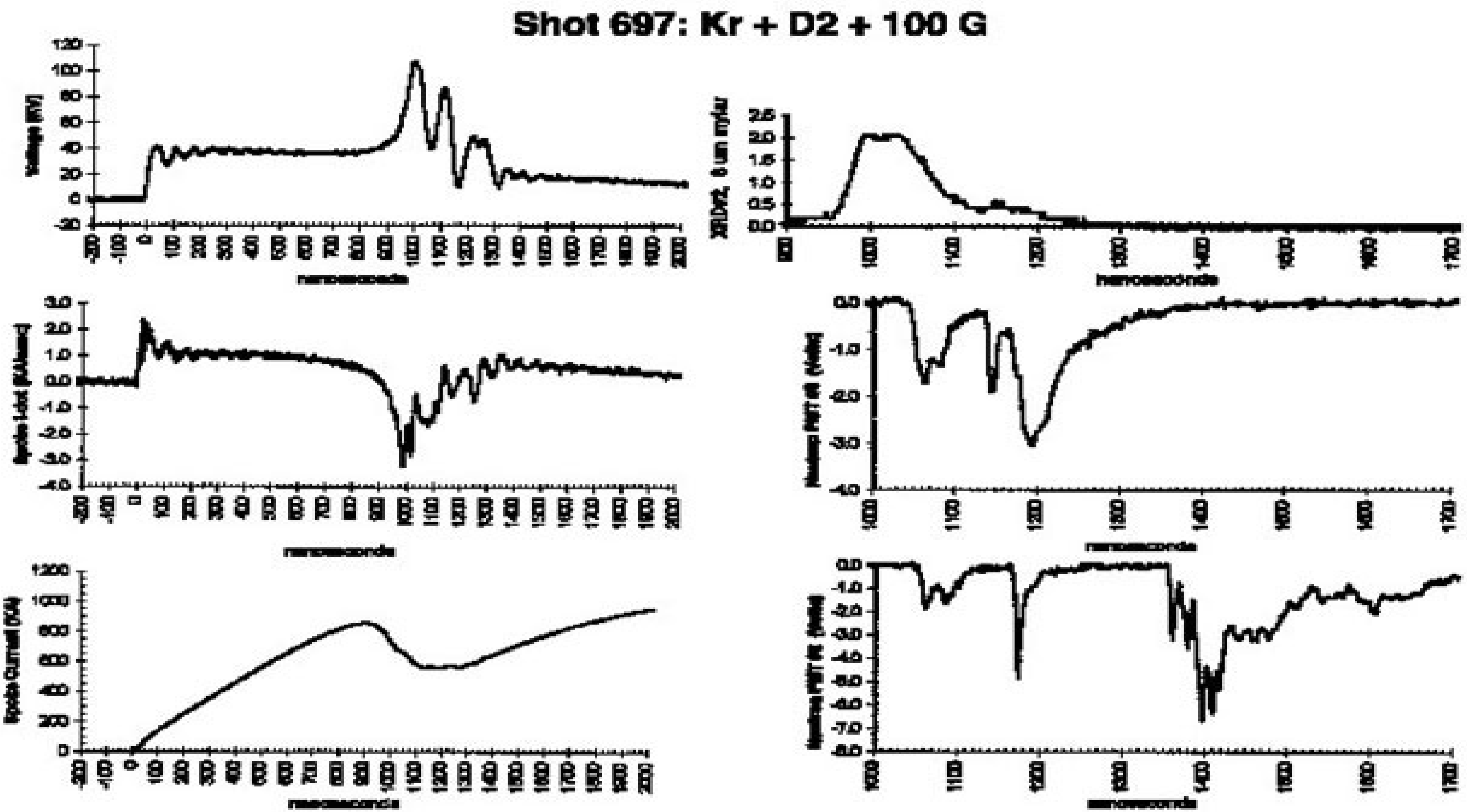
Schlieren Images of Staged Z Pinch

Before peak implosion

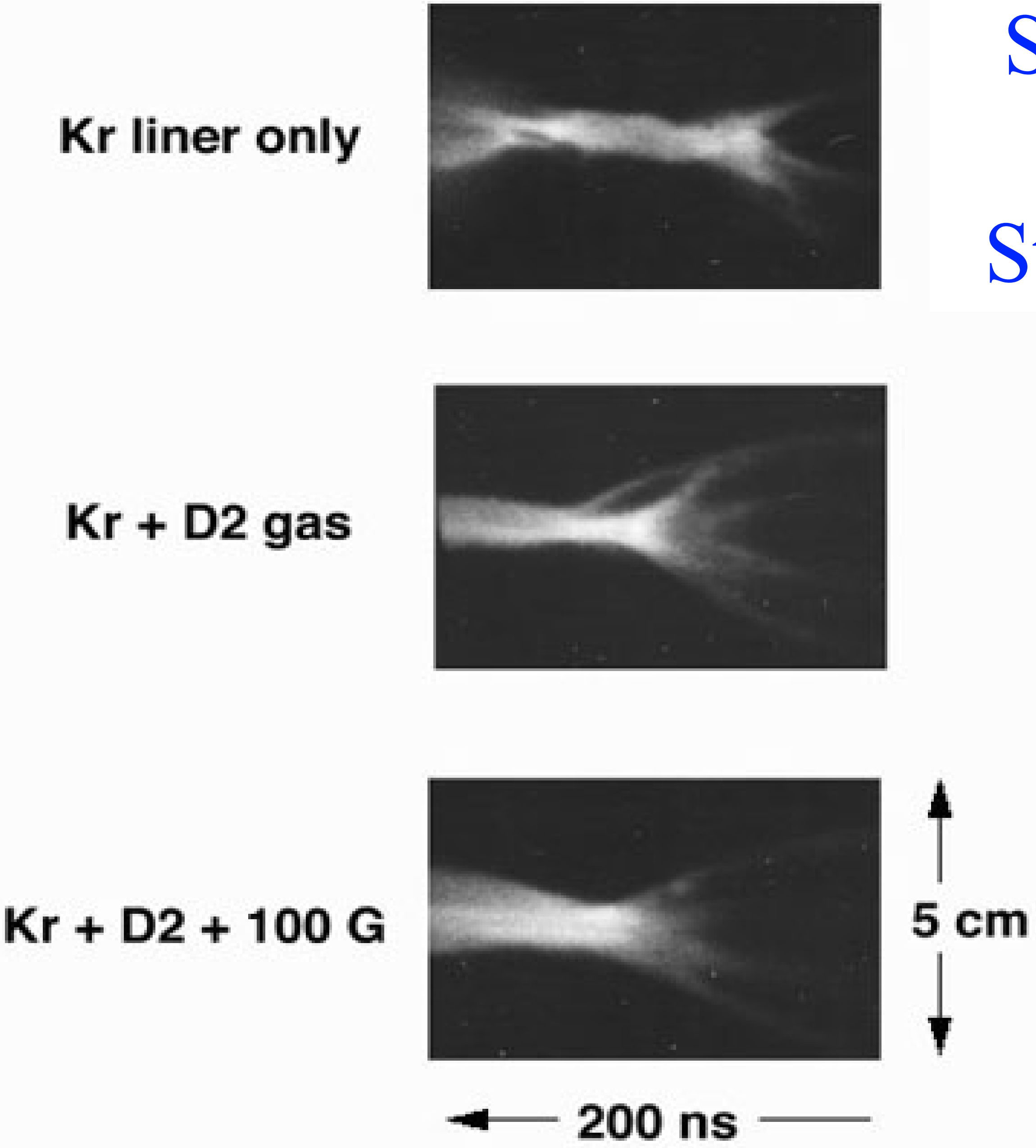
After peak implosion



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:

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

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

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

Elastic Stress:

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

Fusion Neutron Production Rate and Energy Gain:

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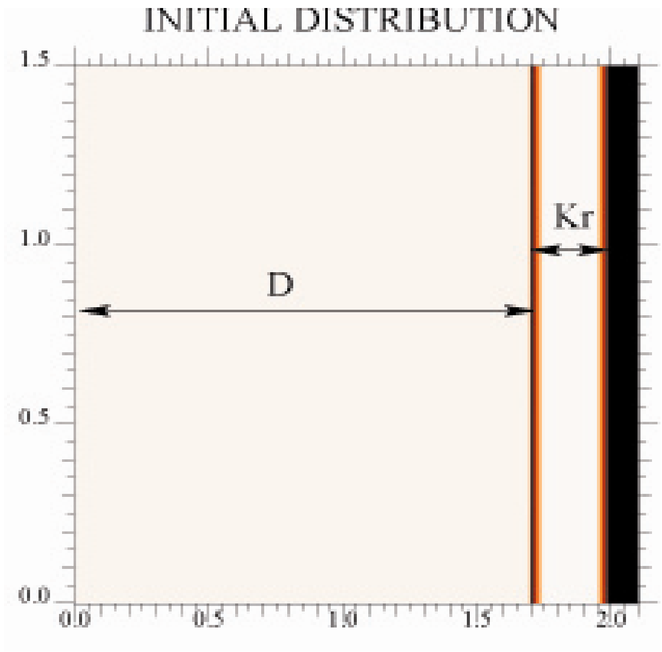
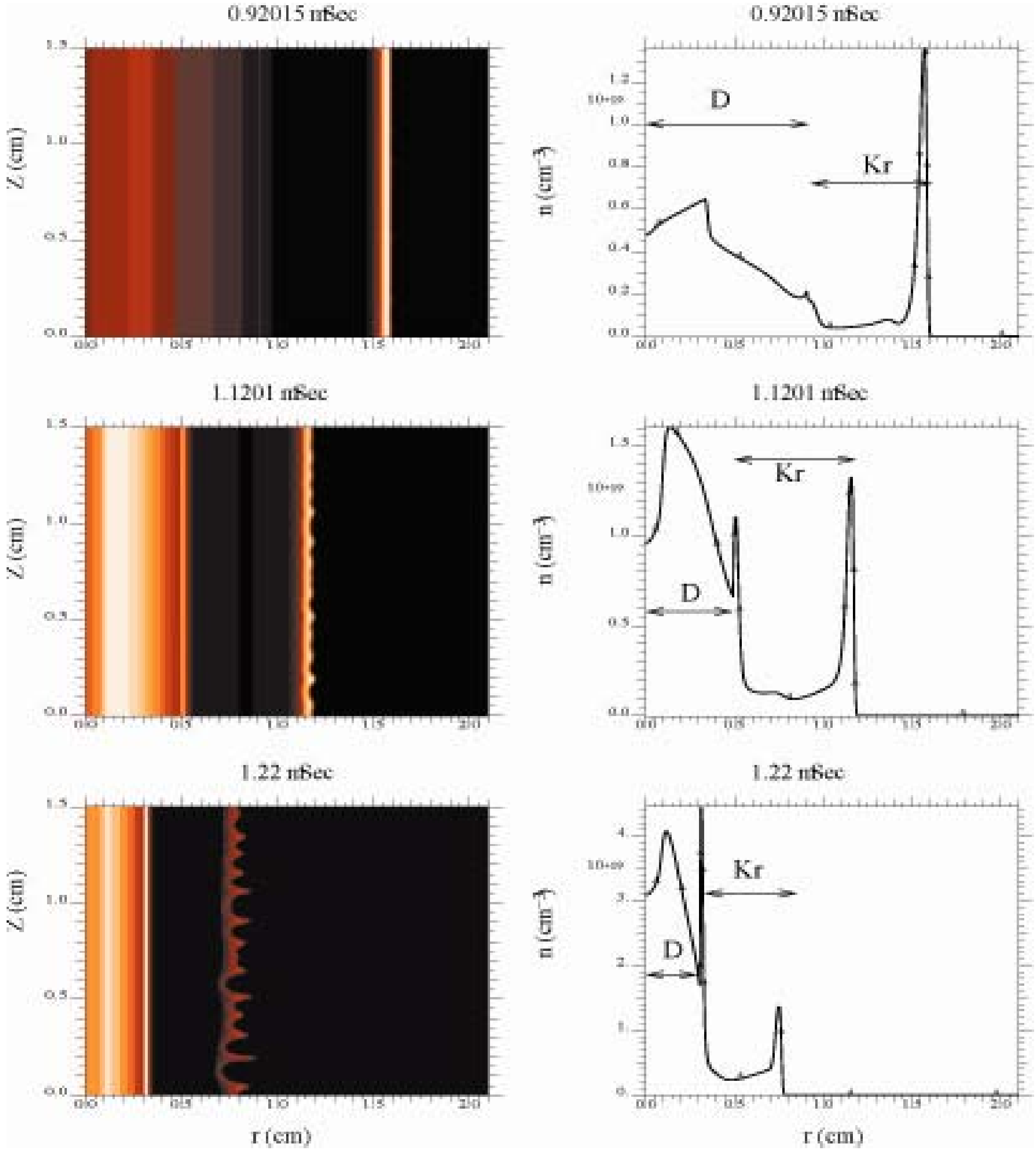
$(\bar{\sigma \nu})_{DT}$ **and** $(\bar{\sigma \nu})_{DD}$**are determined from a table look up.**

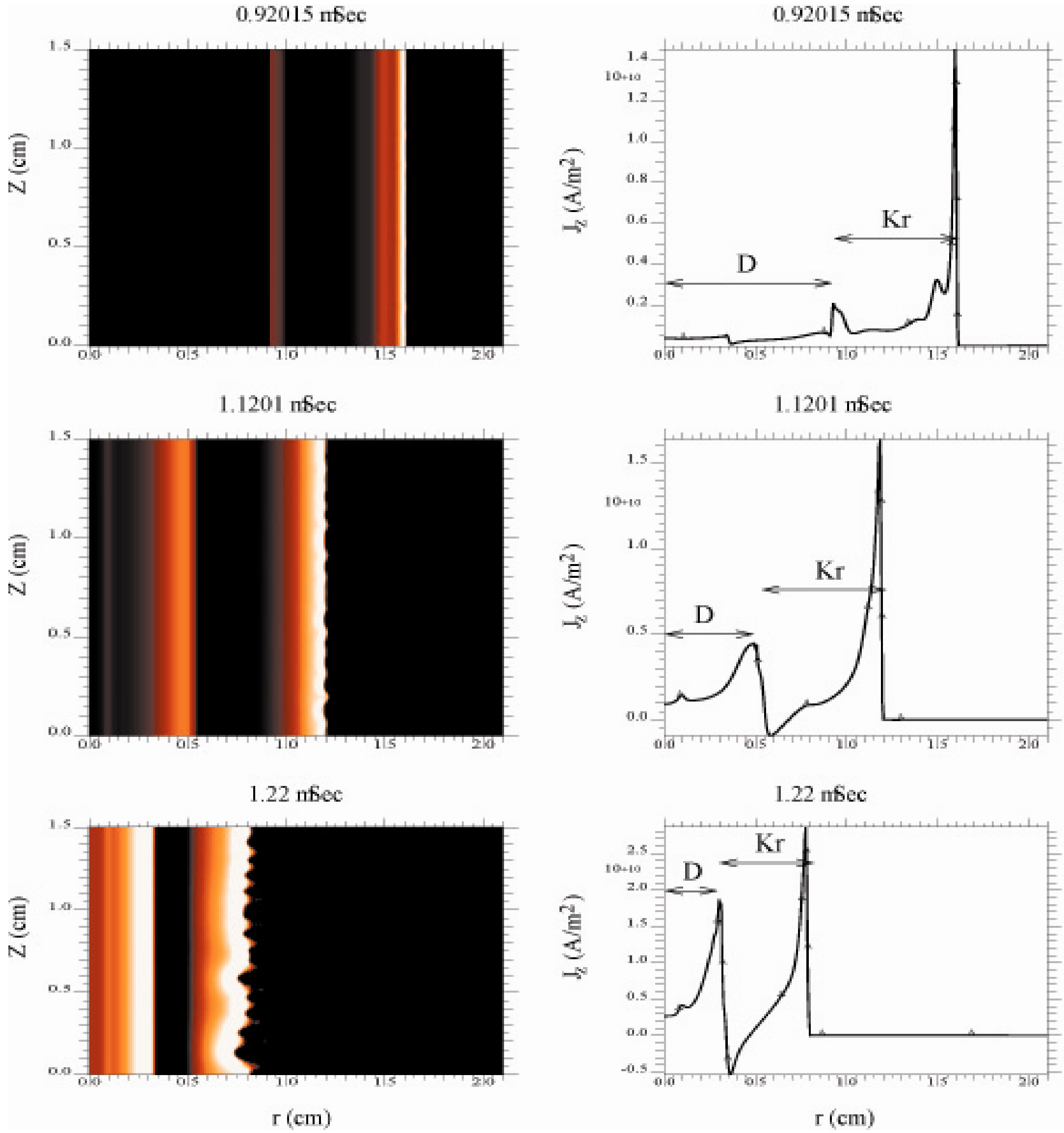
Initial configuration for UCI Pinch



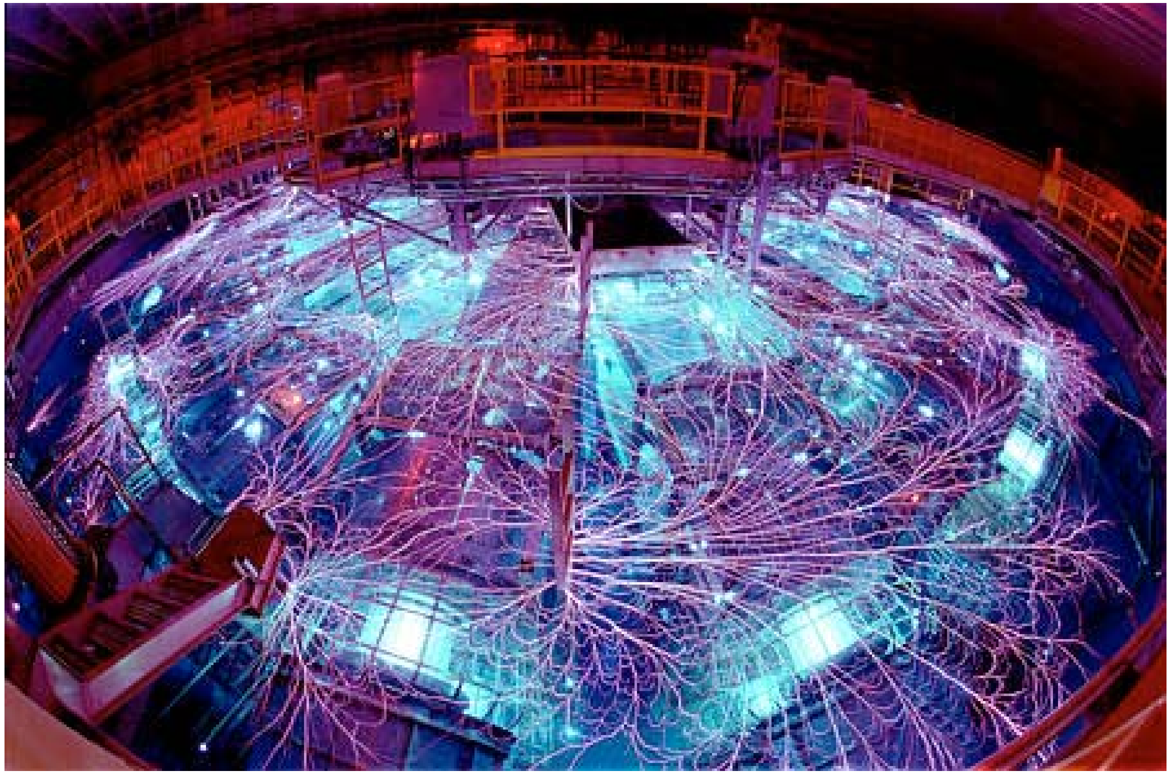
Ion density
During run-in phase



Current Density During run in phase



Z Machine



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Initial Configuration For Z-Facility

Load parameters

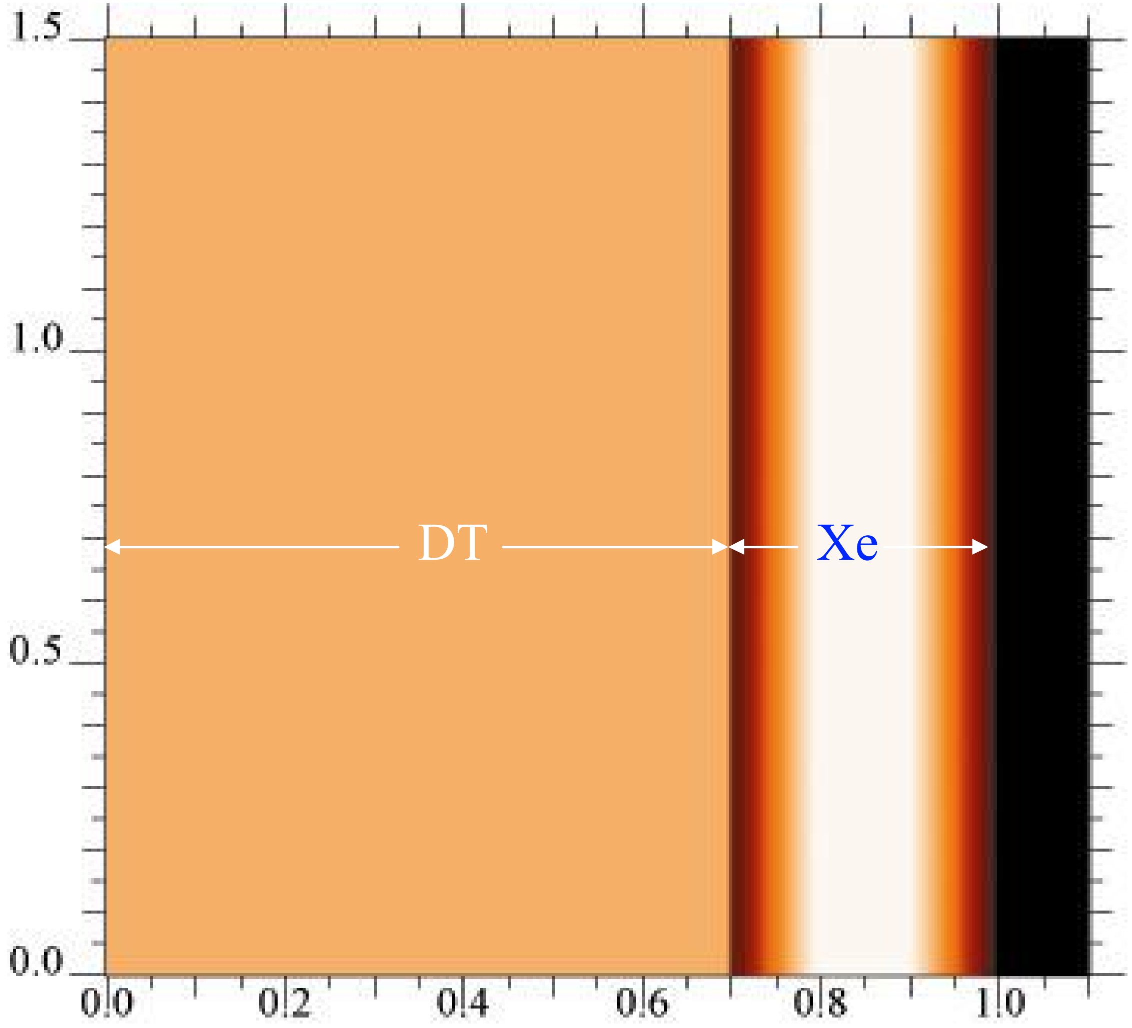
Density of Xe = 43 kg/m^3
Density of DT = 0.2 kg/m^3
Perturbation = 0.1%

Z-parameters

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

GRID

352x128

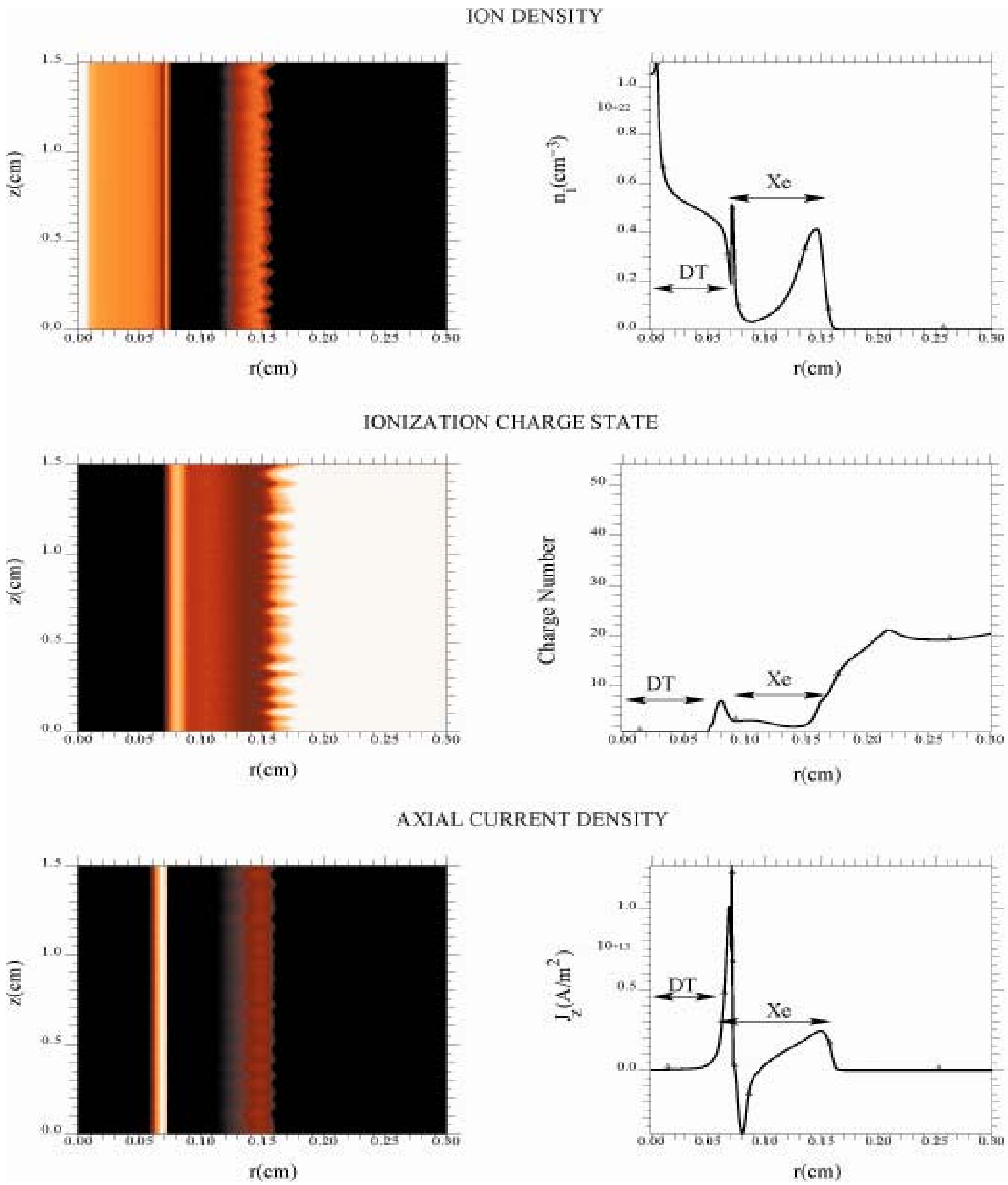


Dynamics of pinch
During run-in Phase

Density

Ionization Charge state

Axial current density



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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

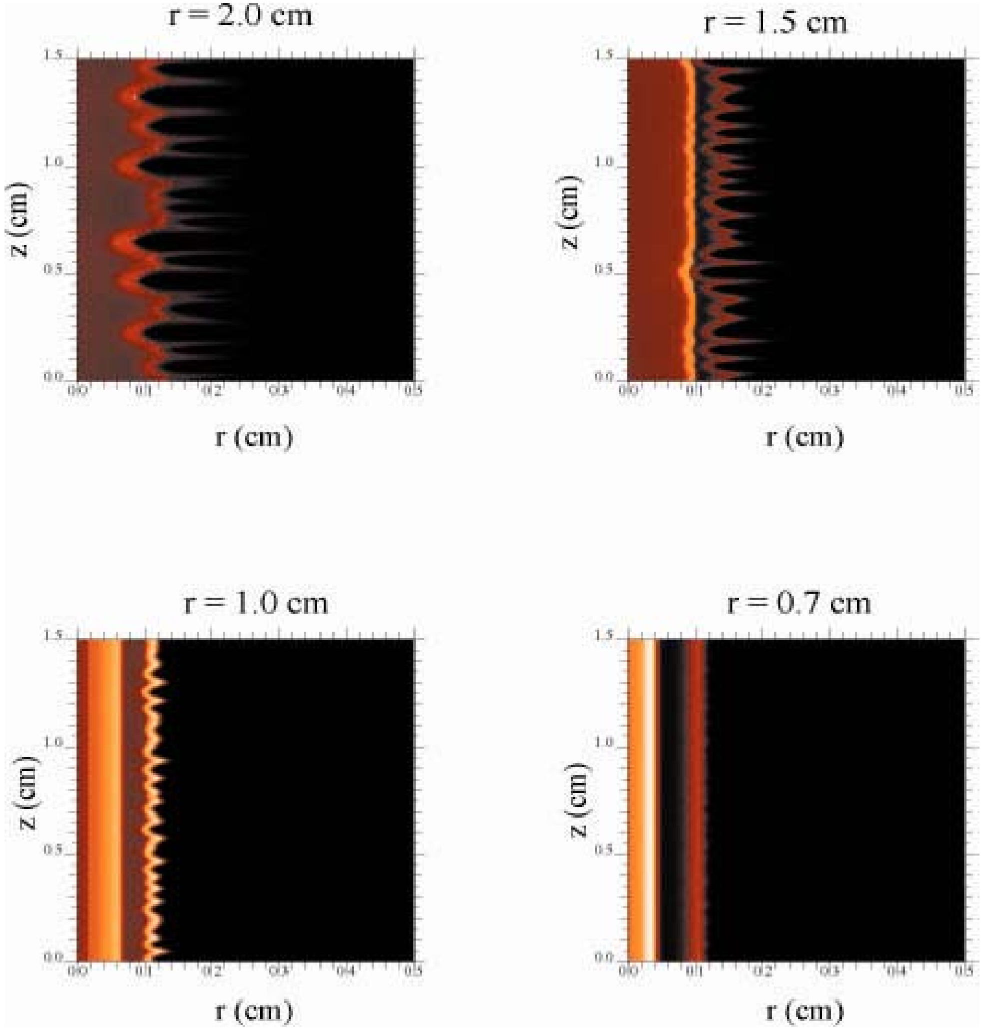
Energy coupling

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

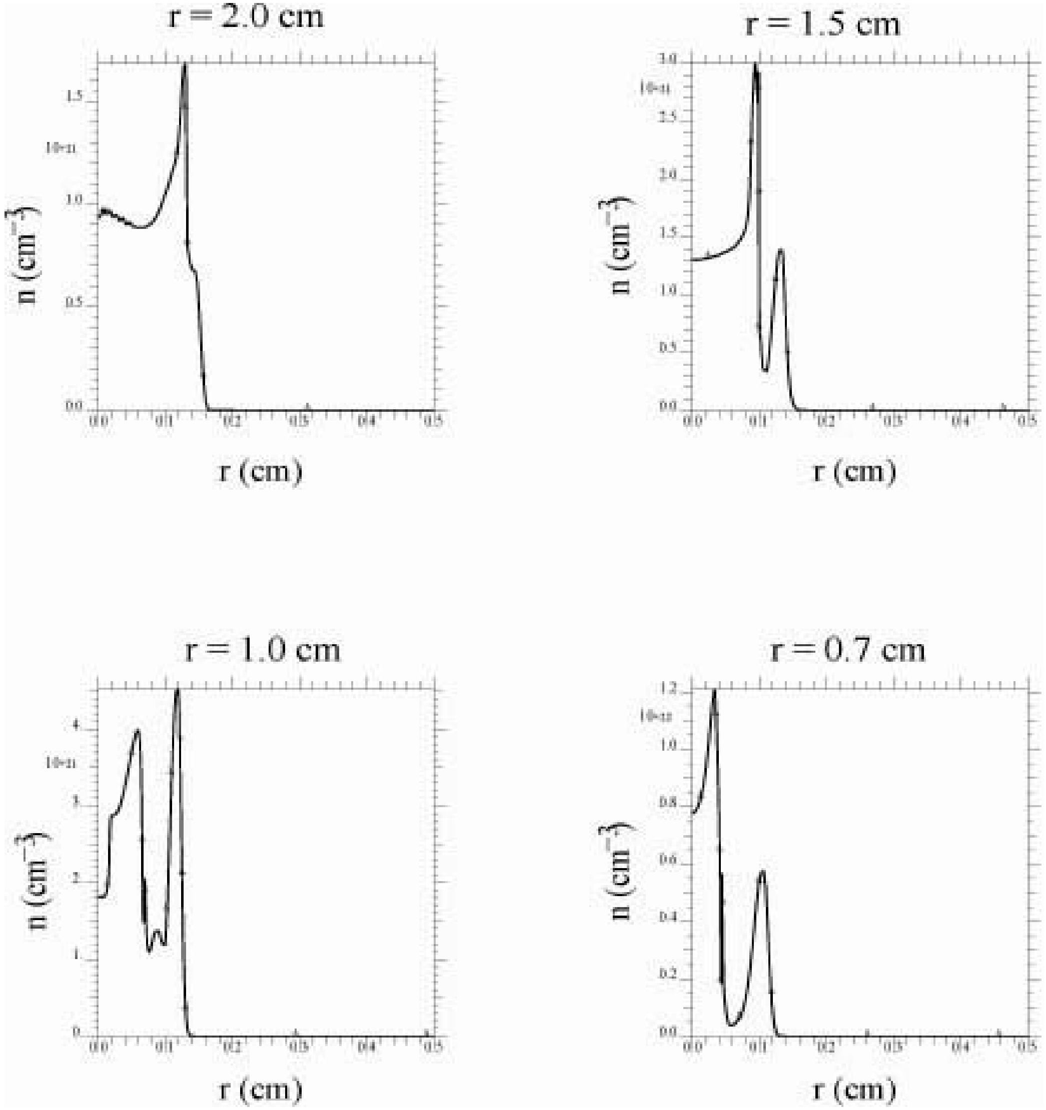
$$= h\left(\frac{I}{c}\right)^2 \ln\left(\frac{R_0}{R}\right)$$

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

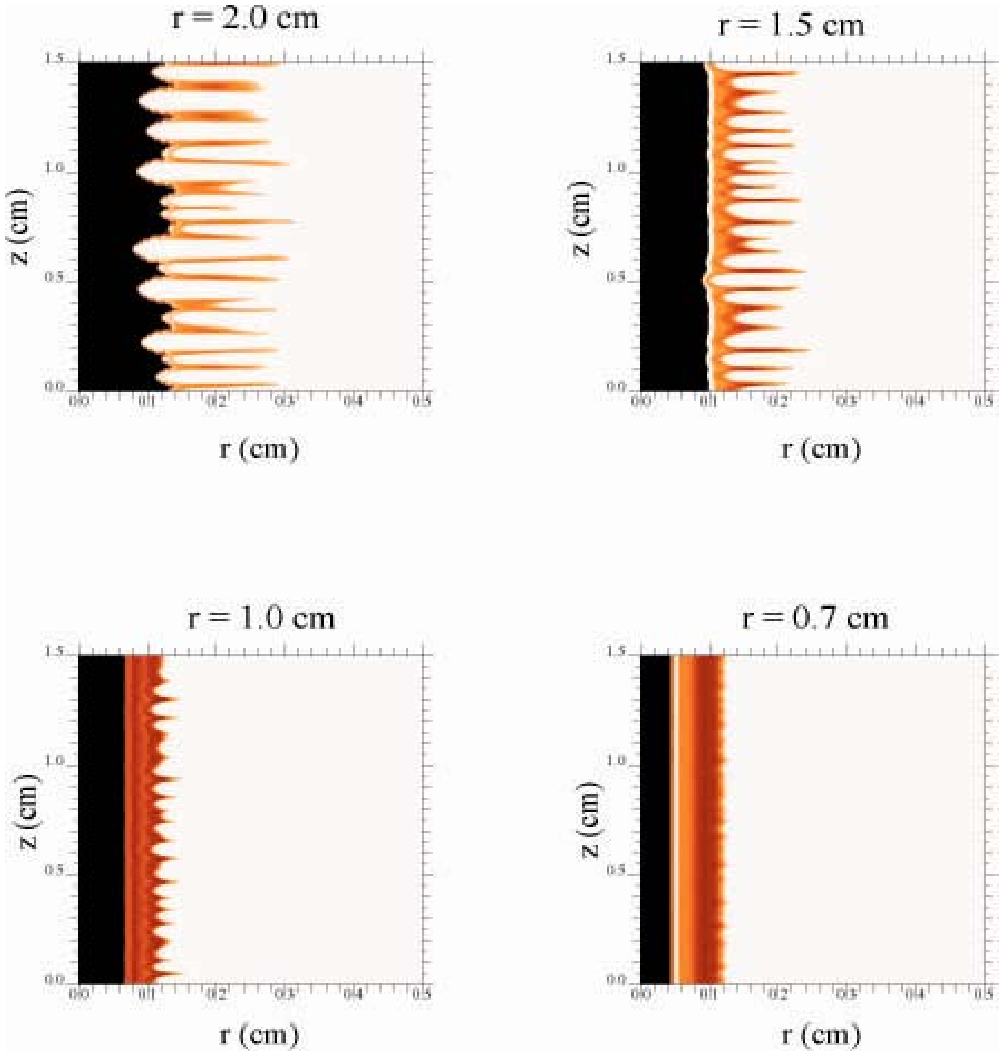
ION DENSITY (Four initial radii)



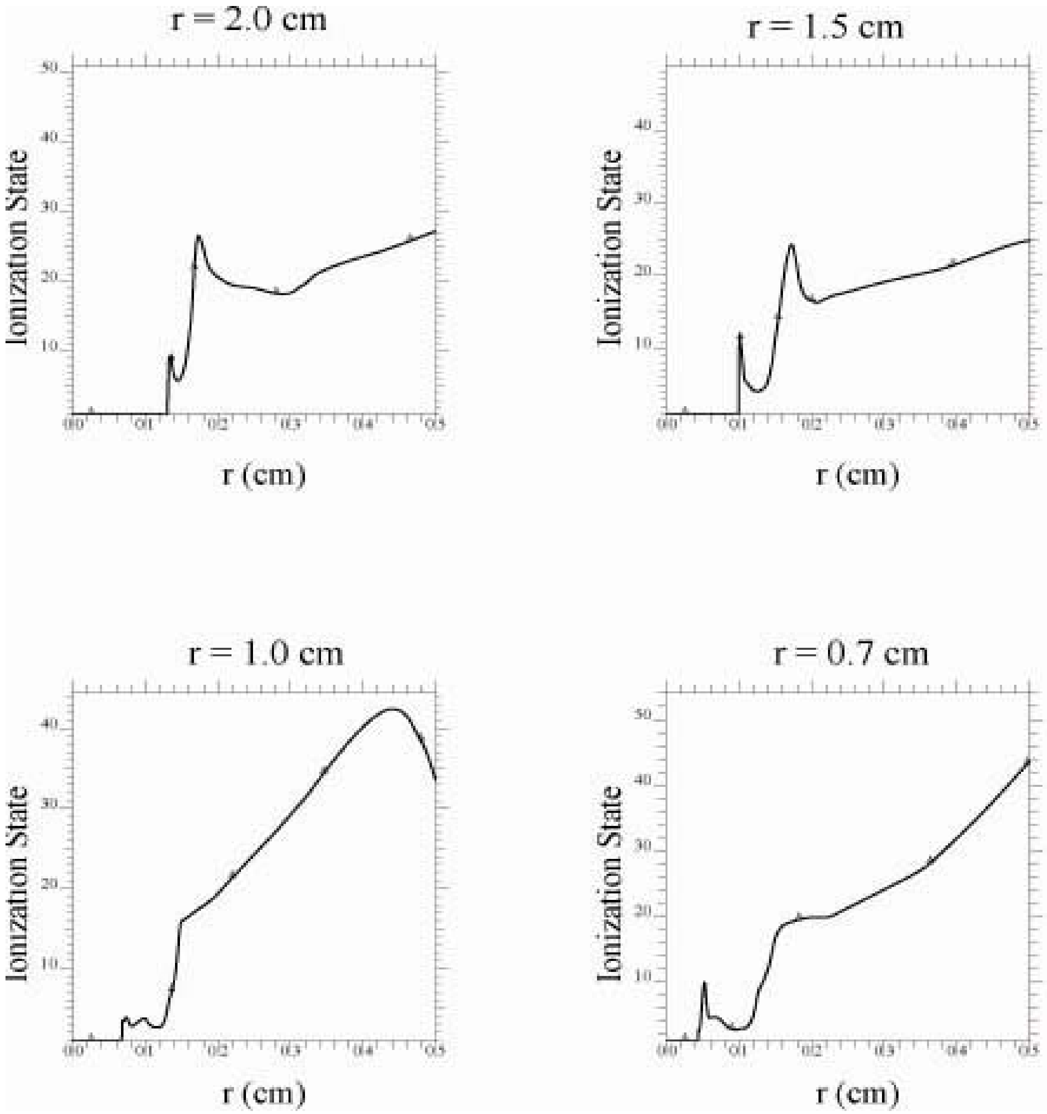
Ion density profiles



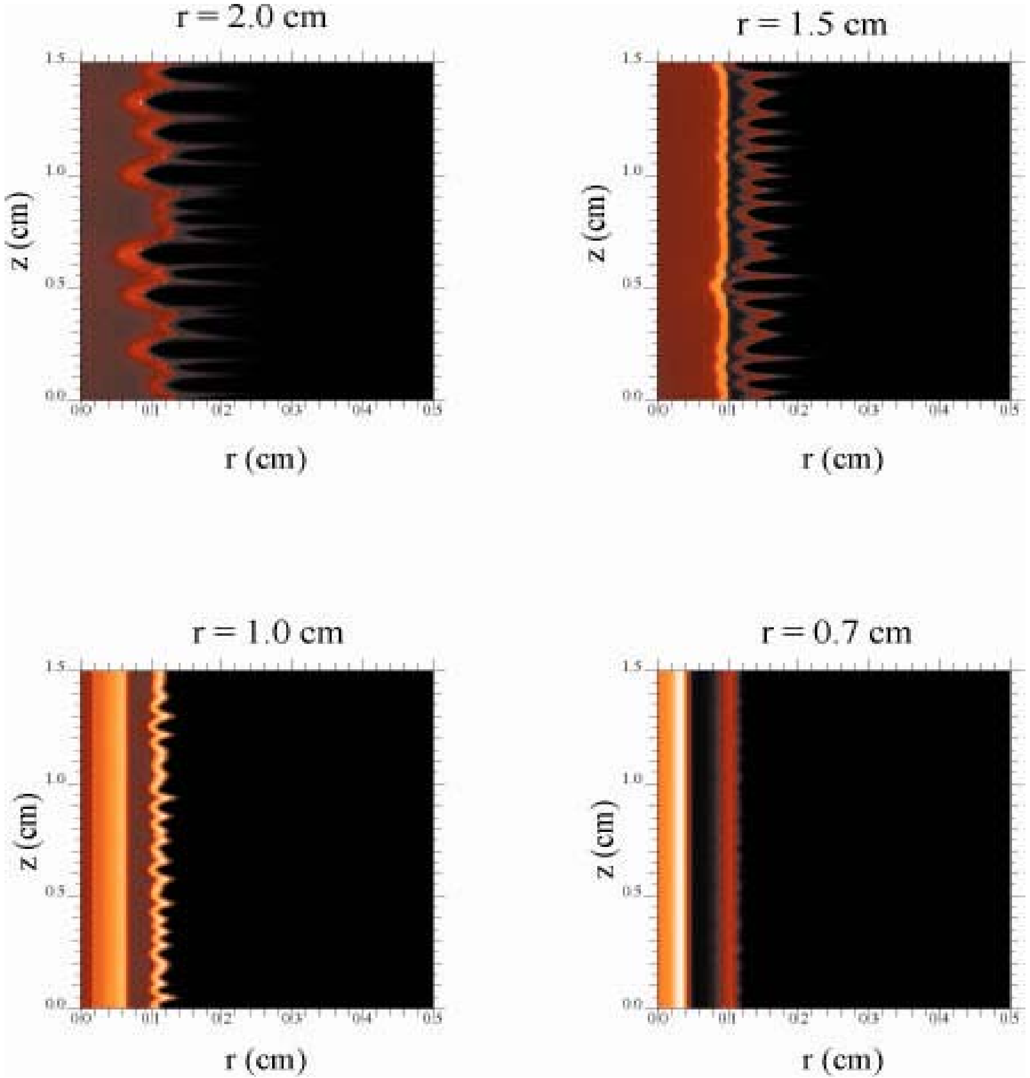
Ionization charge state (four initial radii)



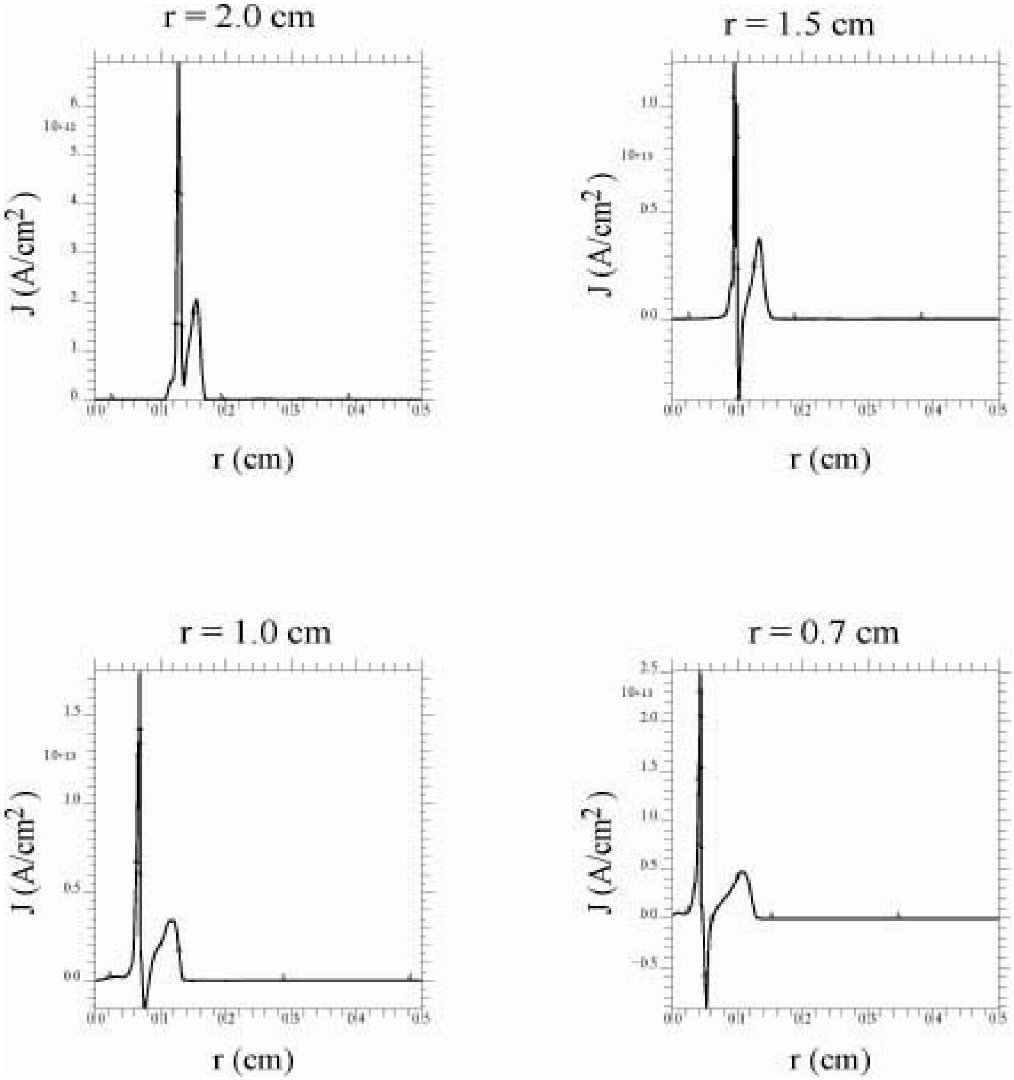
Profiles of charge state



Axial current (four initial radii)



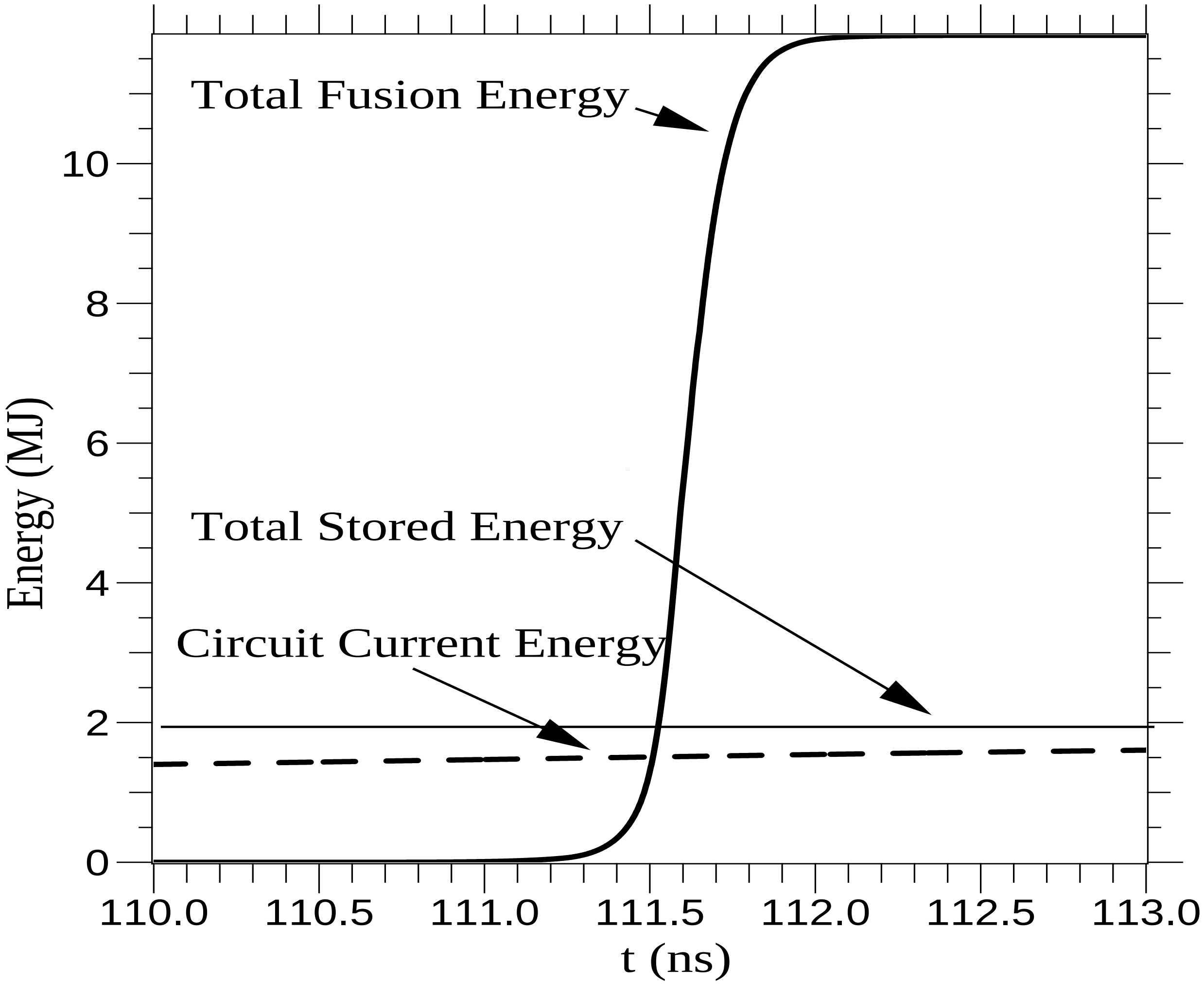
Profiles of axial currents



Large Energy Production

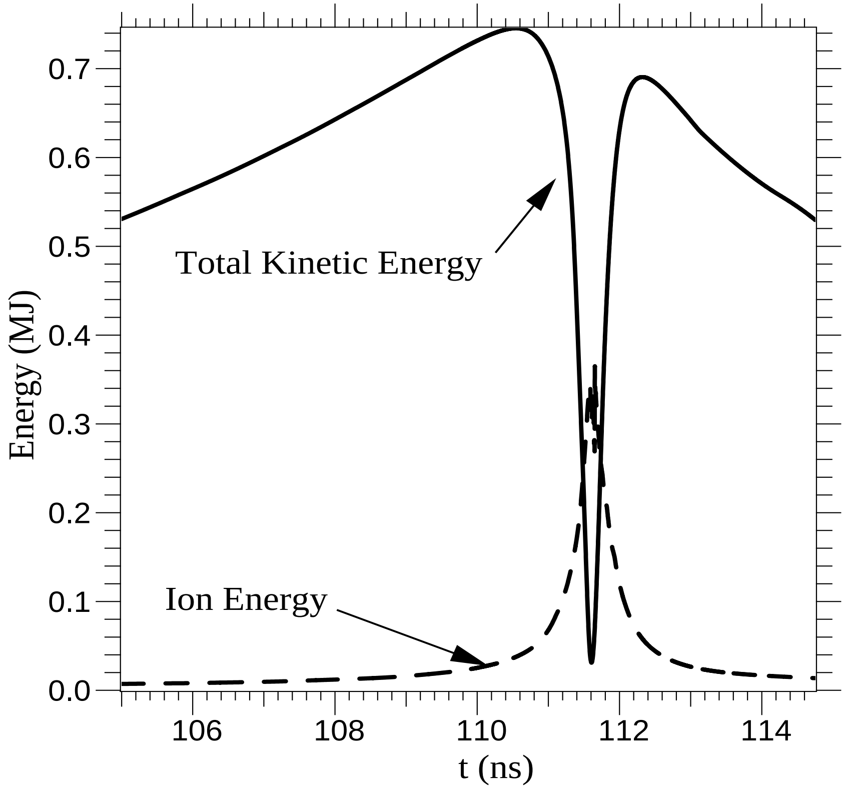
- Xe liner is used
- Both the masses of the liner and the target are optimized
- Optimized parameters of the Z-facility are used
- Initial radius of 0.7cm is used
- Perturbation level of 0.1% is used
- 12 MJ of Energy is produced with a stored energy of 2 MJ.
- Real breakeven is possible with existing technology

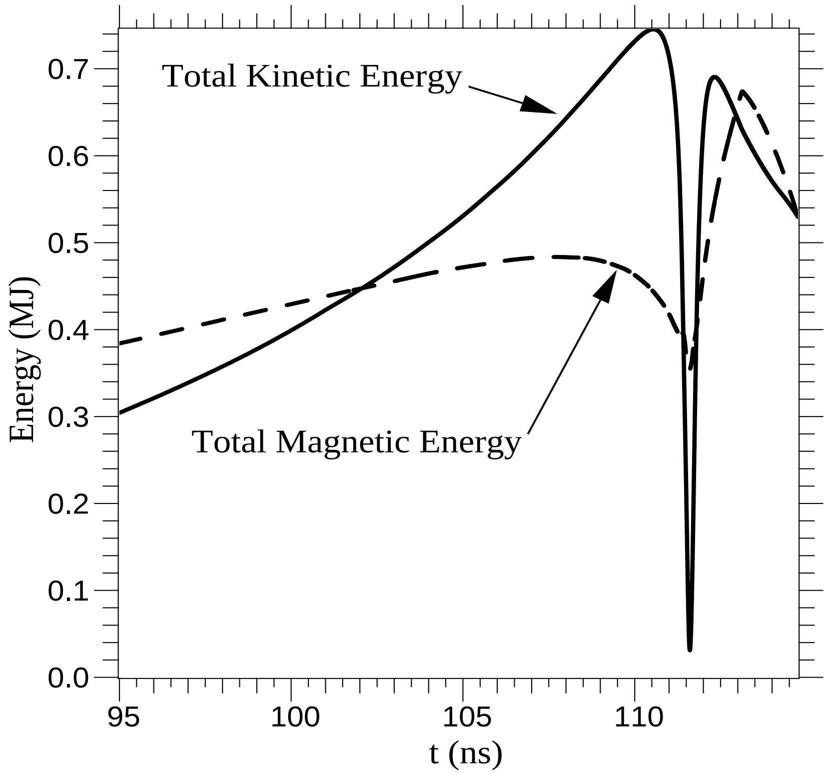
Breakeven



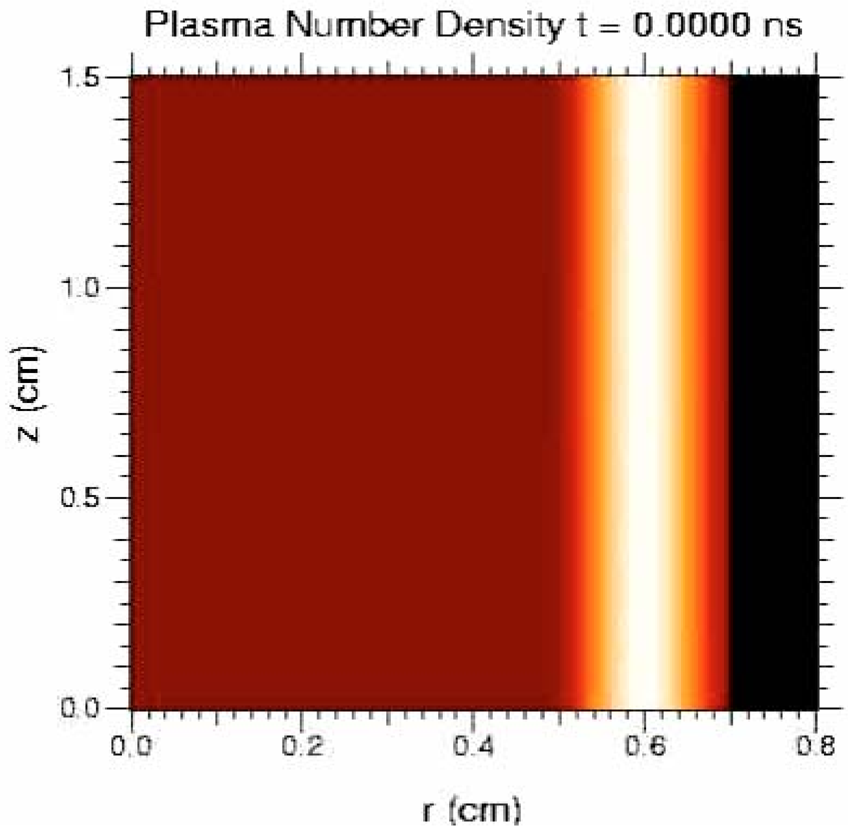
Total Fusion Energy
Total Stored Energy
Circuit Current Energy
Energy (MJ)
0
2
4
6
8
10
110.0
110.5
111.0
111.5
112.0
112.5
113.0
t (ns)

Energies

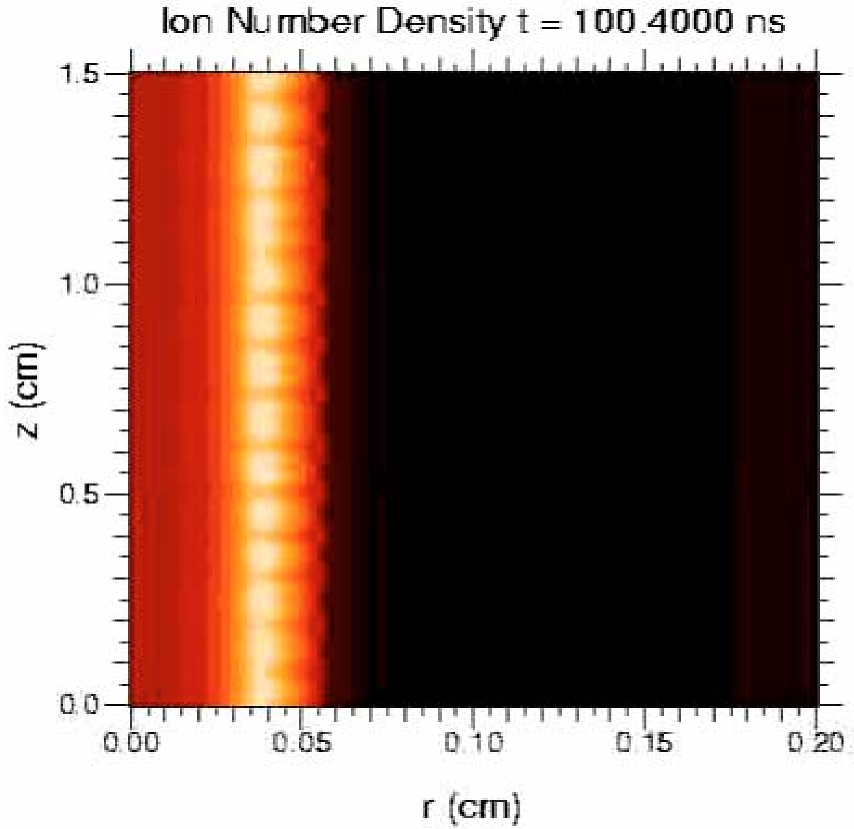

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Energy (MJ)
Total Kinetic Energy
Ion Energy
106
108
110
112
114
t (ns)


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Energy (MJ)
Total Kinetic Energy
Total Magnetic Energy
95
100
105
110
t (ns)

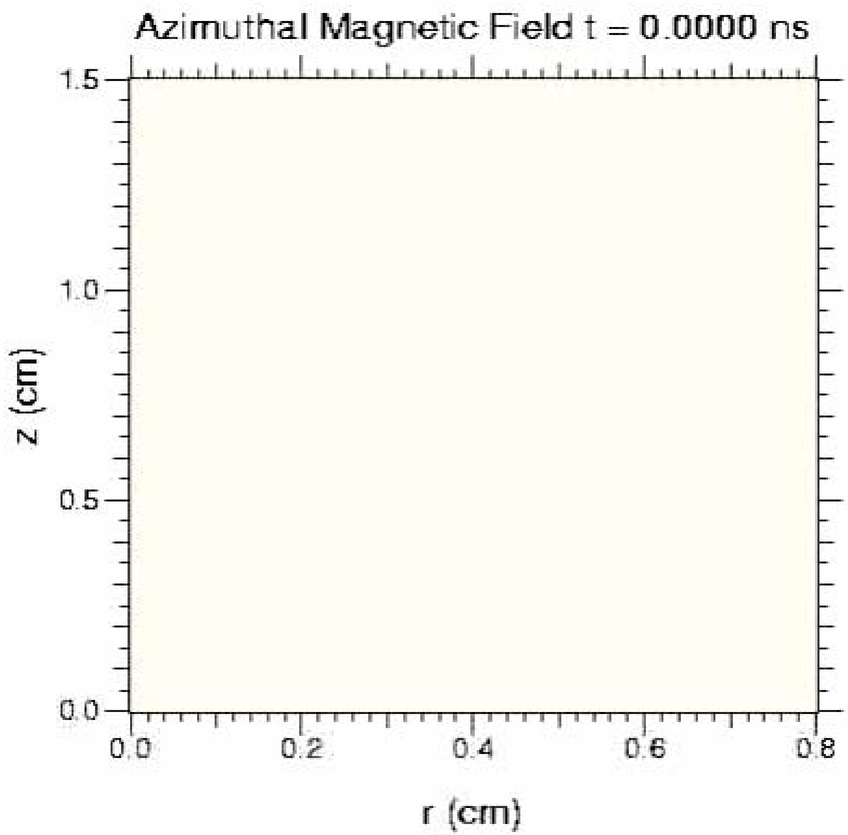
Ion Density (full run)



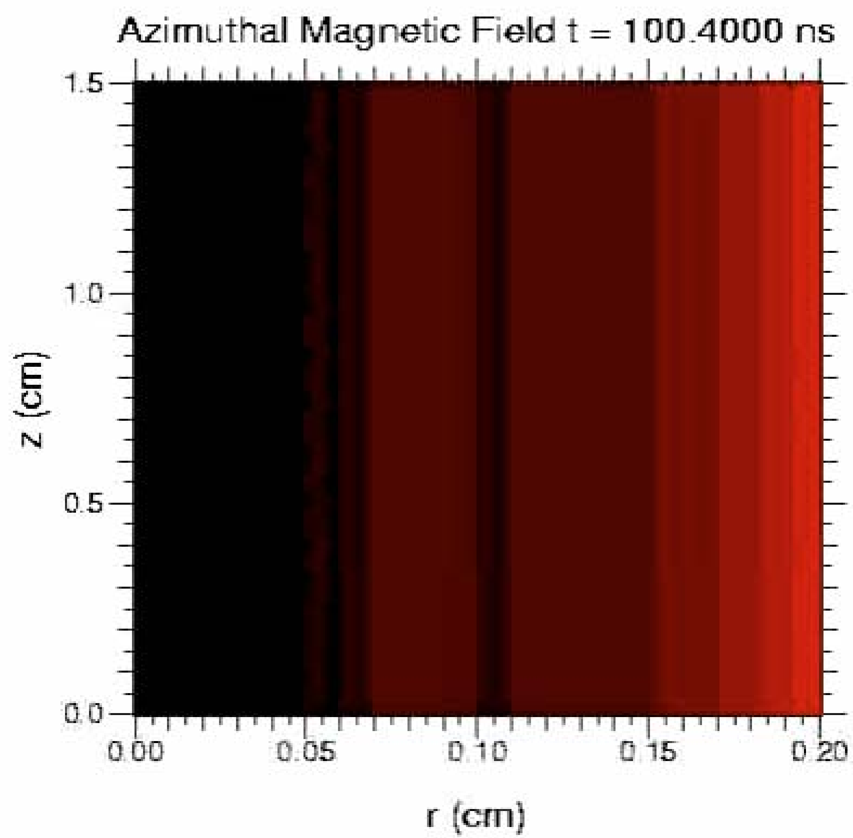
Ion Density (near peak)



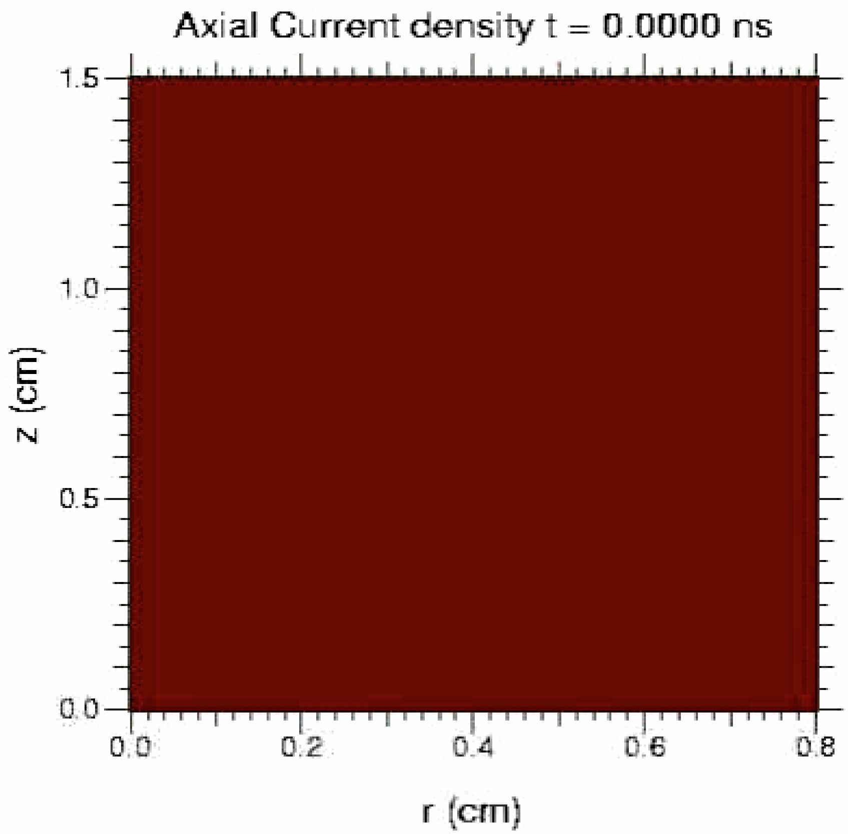
Magnetic Field (Full run)



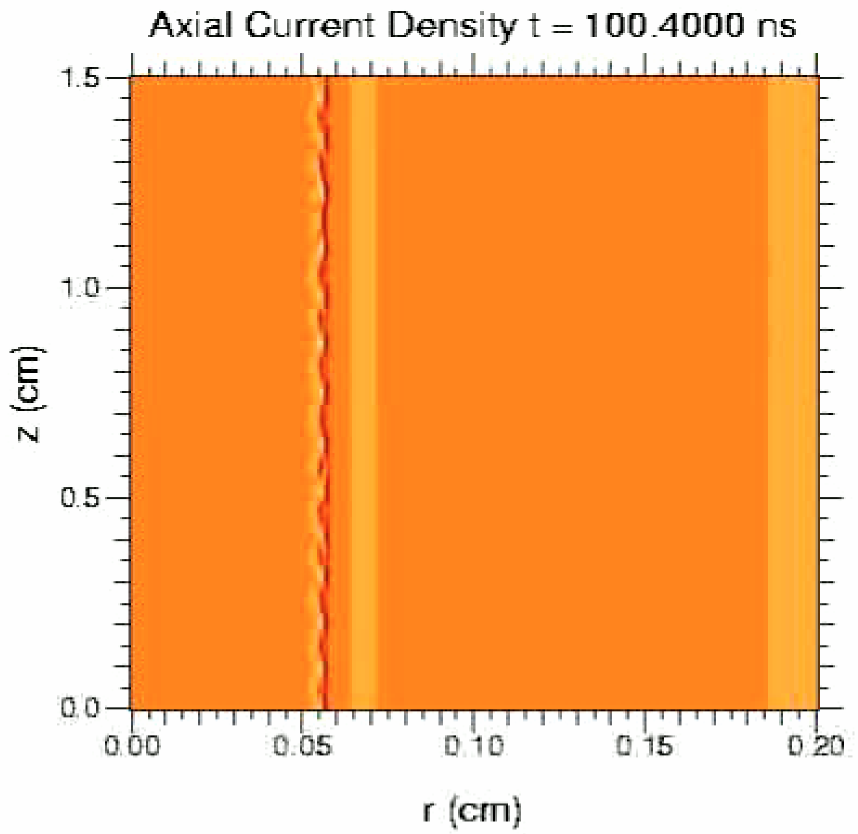
Magnetic field (near peak)



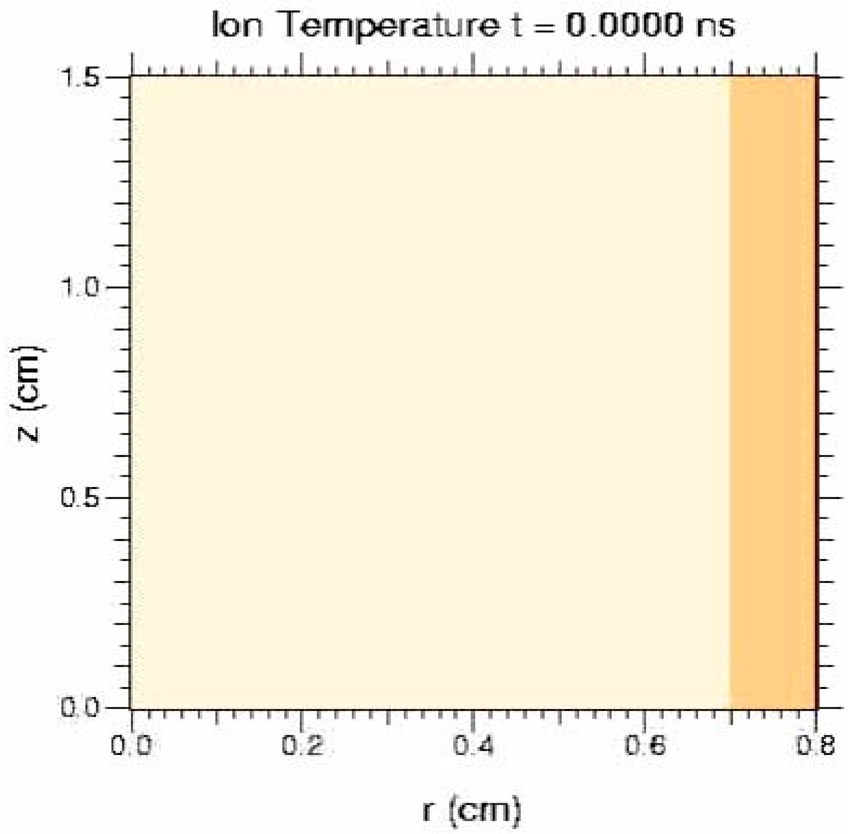
Axial current (full run)



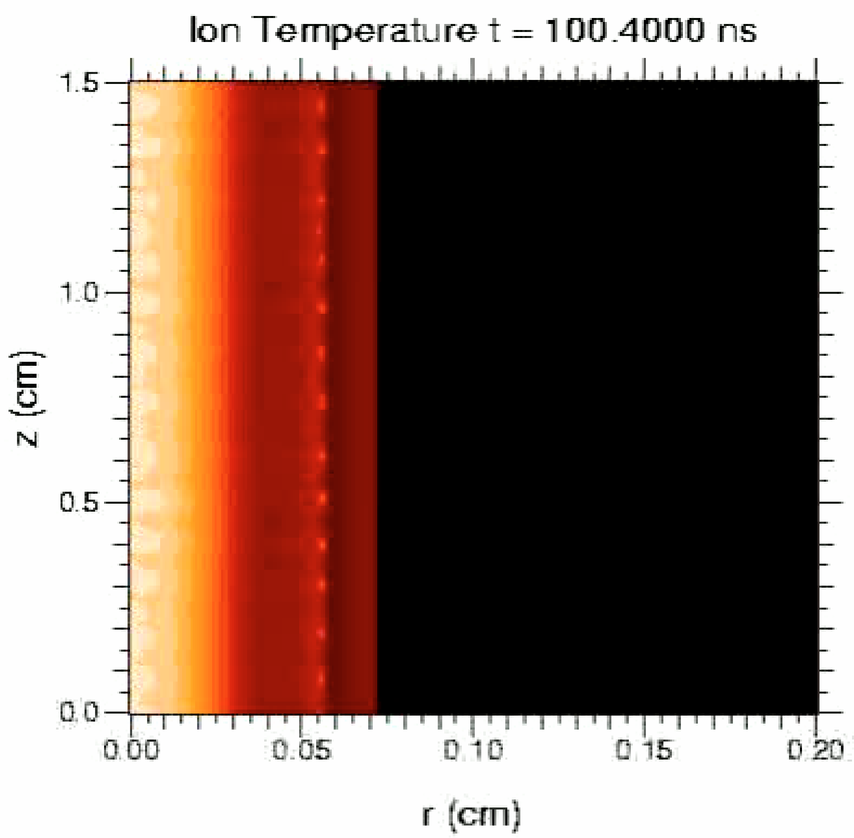
Axial current (near peak)



Plasma ion temperature (full run)



Plasma ion temperature (Near peak)



Conclusions

- R-T instability can be controlled.
- 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.