Staged Z-pinch Target for Fusion

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What are the Challenges?

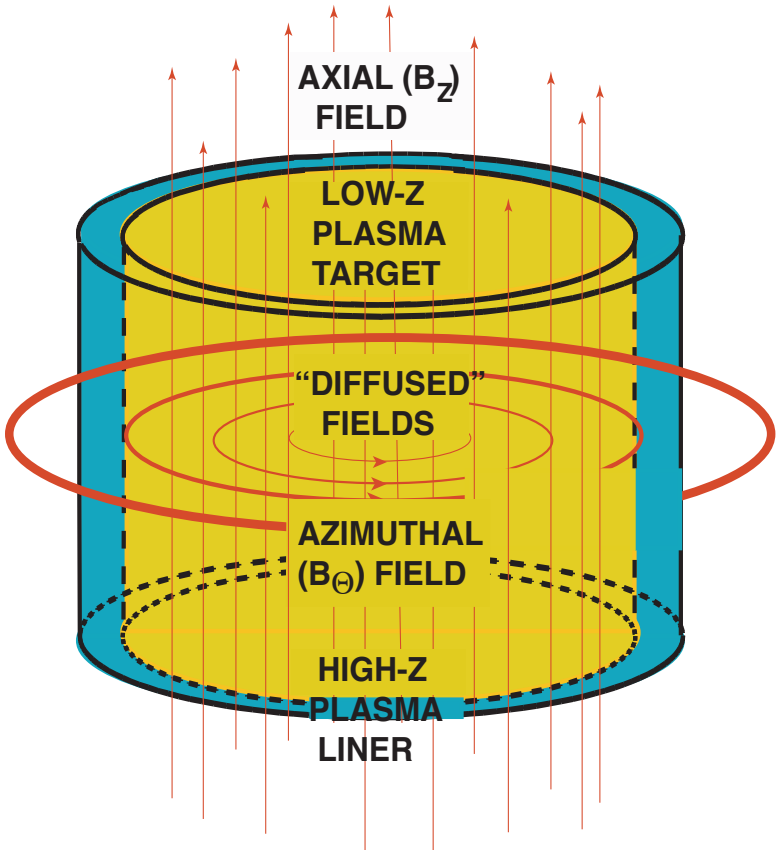
- Z-pinches today (SNL – MagLIF)
  - ρr ~ 1 x 10^{-2} gm/cm^2 = 0.01 Lawson (ICF)
  - Neutron yield ~ 10^{13}/shot (DD) = 10^{-5} $Y_{BreakEven}$
- Magneto-Rayleigh Taylor Instability

$$\gamma = \sqrt{kg - (\mathbf{kB})^2/\mu_0\rho} \simeq \sqrt{2r_0 k} \simeq (10\ \mathrm{ns})^{-1},$$

$$\text{as } \mathbf{kB} \to 0, \text{ using } r_0 = \tfrac{1}{2} g t_i^2$$

- Fusion ignition
  - Requires α particle confinement - B ~ 10's kT
- Driver size and cost per shot
  - MJ, 10 Hz drivers
  - Linear Transformer Drivers (LTDs)

Staged Z-pinch (SZP)



- High-Z liner implodes a low-Z target
- Pre-magnetized (B_z), or not
- J x B Lorentz force compression
- Magneto-sonic waves transport flux
- Stable shocks preheat the target plasma
- Magnetic fields compress as:
  - $B_{zf} = B_{z0}(r_0/r_f)^2$
  - $B_{\Theta f} = B_{\Theta 0} \ln(r_0/a_0) / \ln(r_f/a_f)$
- Magneto-inertial target compression

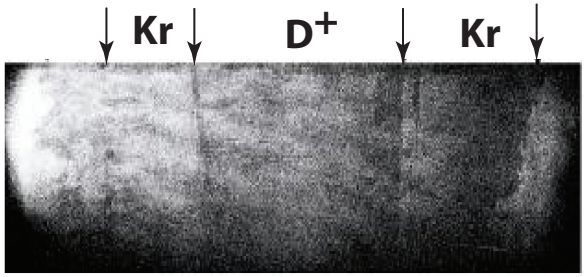
1. H. U. Rahman, F. J. Wessel, and N. Rostoker, Physical Review Letters 74, 714 (1995).
2. H. U. Rahman, F. J. Wessel, P. Ney, R. Presura, et. al., Physics of Plasmas 19, 122701:1–13(2012).
3. F. J. Wessel, H. U. Rahman, R. Presura, and P. Ney, IEEE Trans.Plasma Science 43(8), 2463(2015).

SZP Tested at UCI - 1 MA, 1.2 μs, 10^{-2} T, 50 kJ MACH2 Code Benchmarked

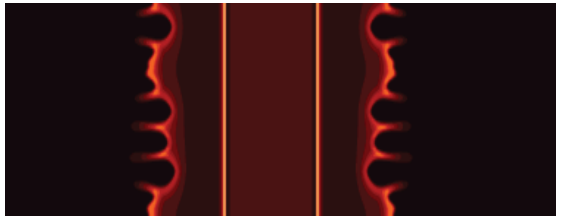
5ns N_2 laser Schlieren

MACH2 SIMULATION

1.10 μs

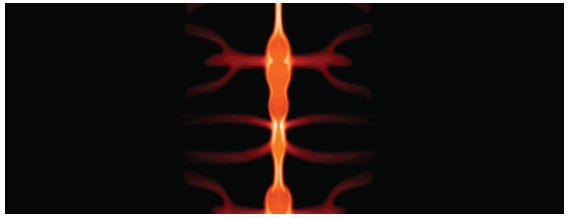


SHOT 963

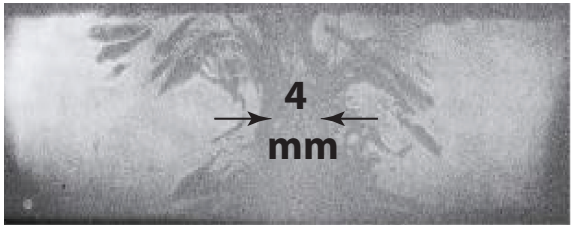


1.20 μs

SHOT 961



1.30 μs



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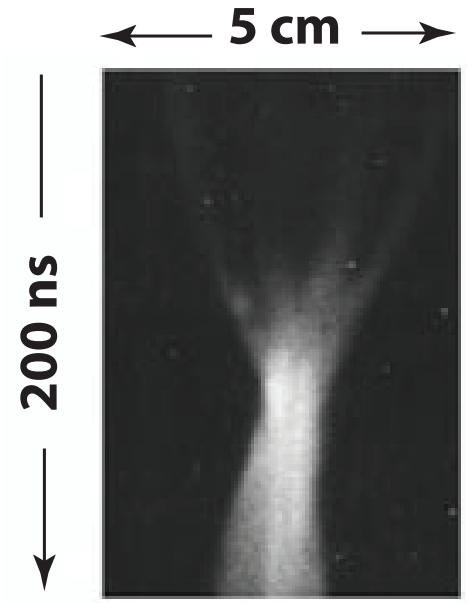


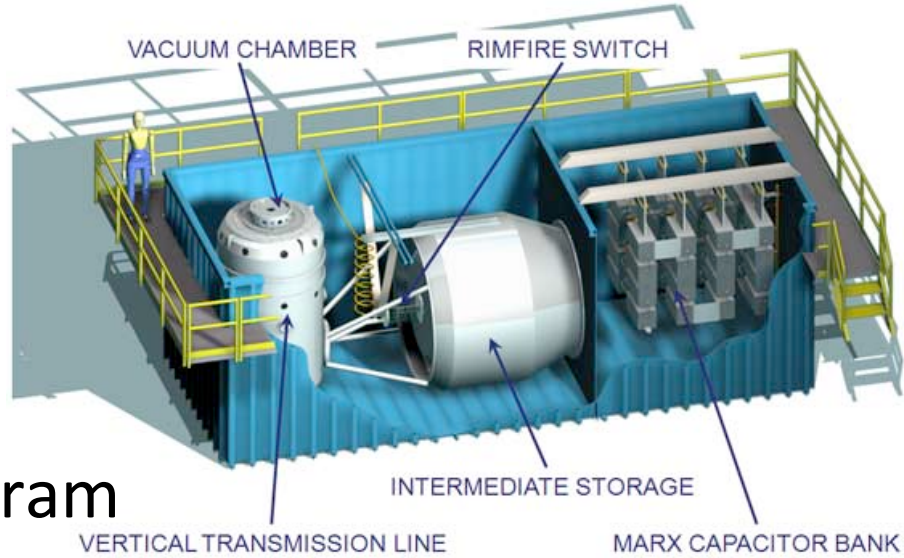
Optical streak

- Stable Shock Implosion
- $n_i = 3 \times 10^{21}\ cm^{-3}$
- $T_i = 0.8$ keV
- $Y_{expt} \sim 0.5 \times 10^{10}$/shot
- $Y_{sim} \sim 0.2 \times 10^{10}$/shot

H. U. Rahman, P. Ney, A. Van Drie, N. Rostoker, F. J. Wessel, , et. al., Physics of Plasmas 11:5595(2004).

3 Year Project Plan

- University Nevada, Reno
  - 12 mo. – reproduce past SZP results
  - 24 mo. – Composite Mass Injector (CMI)
  - 36 mo. - high yield demo with G ~ 0.1 (DT scaled)
- Technology 2 Market
- Potential Enhancements
  - SNL Z Facility Science Program
  - Small Scale Machine (LTD)

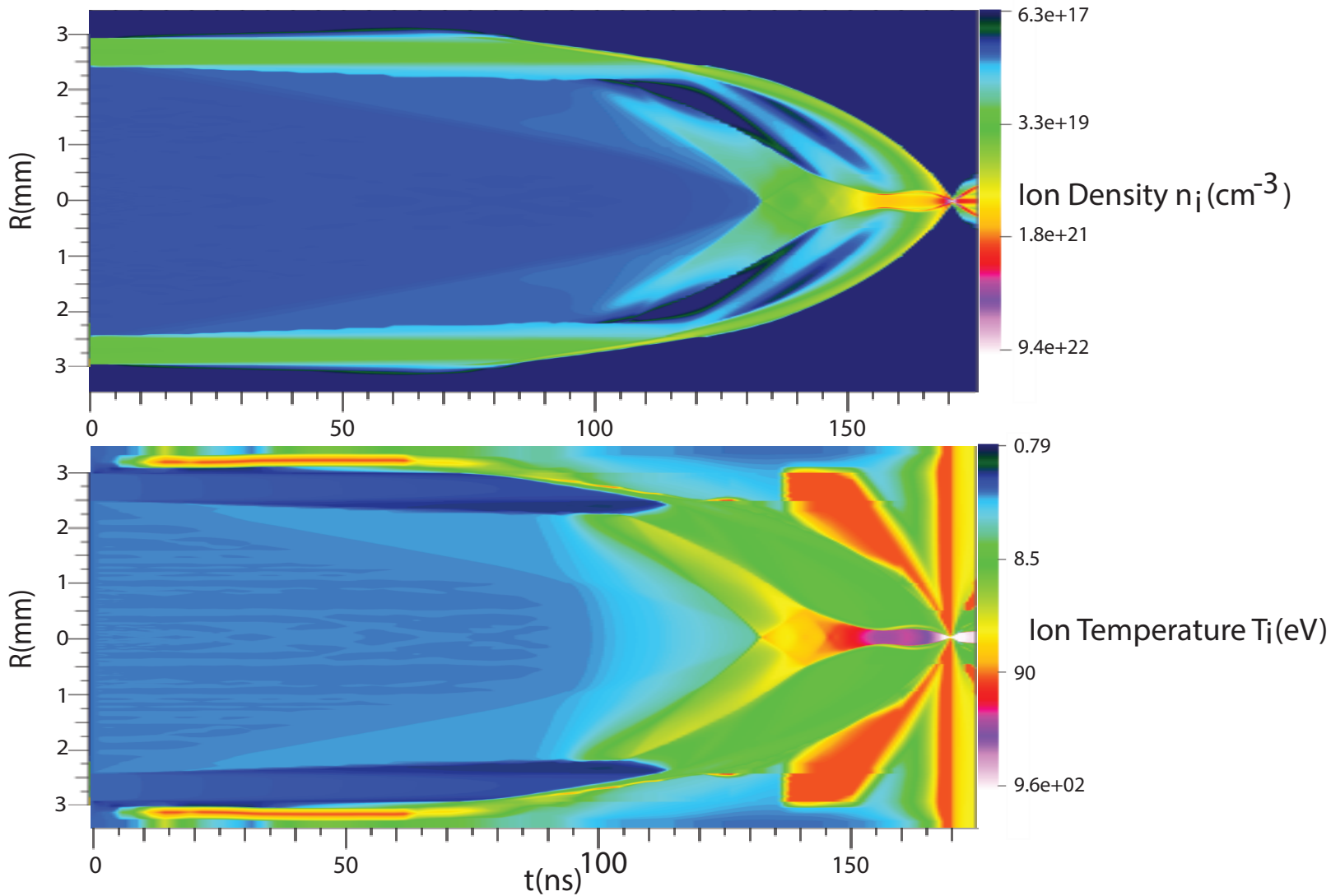


Zebra Facility
1 MA, 0.1 μs
< 10^{-2} T, 200 kJ

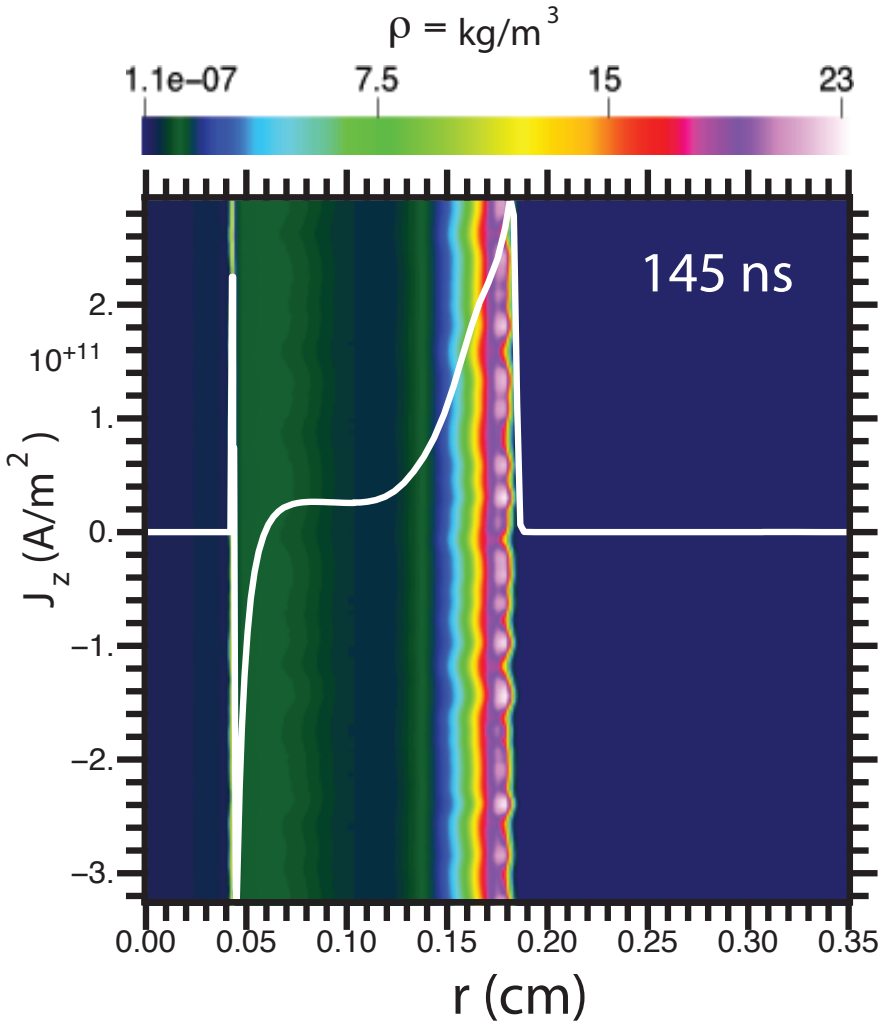
Simulations for University of Nevada, Reno, Zebra: Xe - > DT, 1 MA, 200 kJ, 0.1 μs, < 10^{-2} T B_z

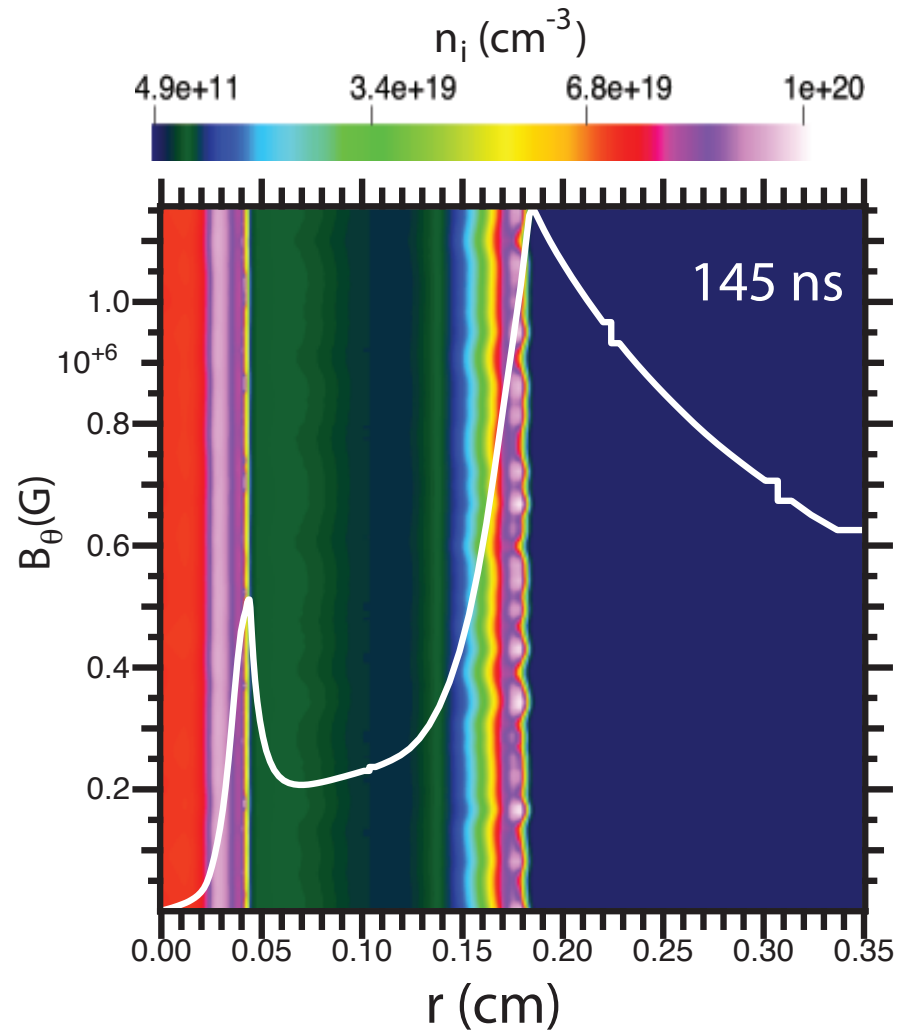
Liner & Target Radii, r_{L0}, r_{T0} [cm]	0.3, 0.25
Liner &Target Densities, ρ_L, $\rho_T \times 10^{-3}$ [kg/m^3],	6, 1
Peak Current & Implosion Time, I_z [MA], τ_i [ns]	1.1, 170
Minimum Radius & Dwell Time, R_f [mm], τ_d [ns]	0.02, 0.8
Density & Temperature, $\hat{n}_i$ [10^{22} cm^{-3}], $\hat{T}_i$[keV]	11.2, 10
Peak Azimuthal Magnetic Field, $\hat{B}_\theta$ [MG]	136
Peak Kinetic- & Ion-Thermal Energies $\hat{E}_k, \hat{E}_i$ [kJ]	3.4, 1.7
Fusion Energy, $(E_f = E_n + E_\alpha)$ [kJ]	1.287
Energy Gain, G $= E_f/E_i$	0.9
Neutron Yield, Y [10^{15} neutrons/shot]	1.7

Simulations for UNR, Zebra
1 MA, 200 kJ, 0.1 μs, < 10^{-2} T B_z

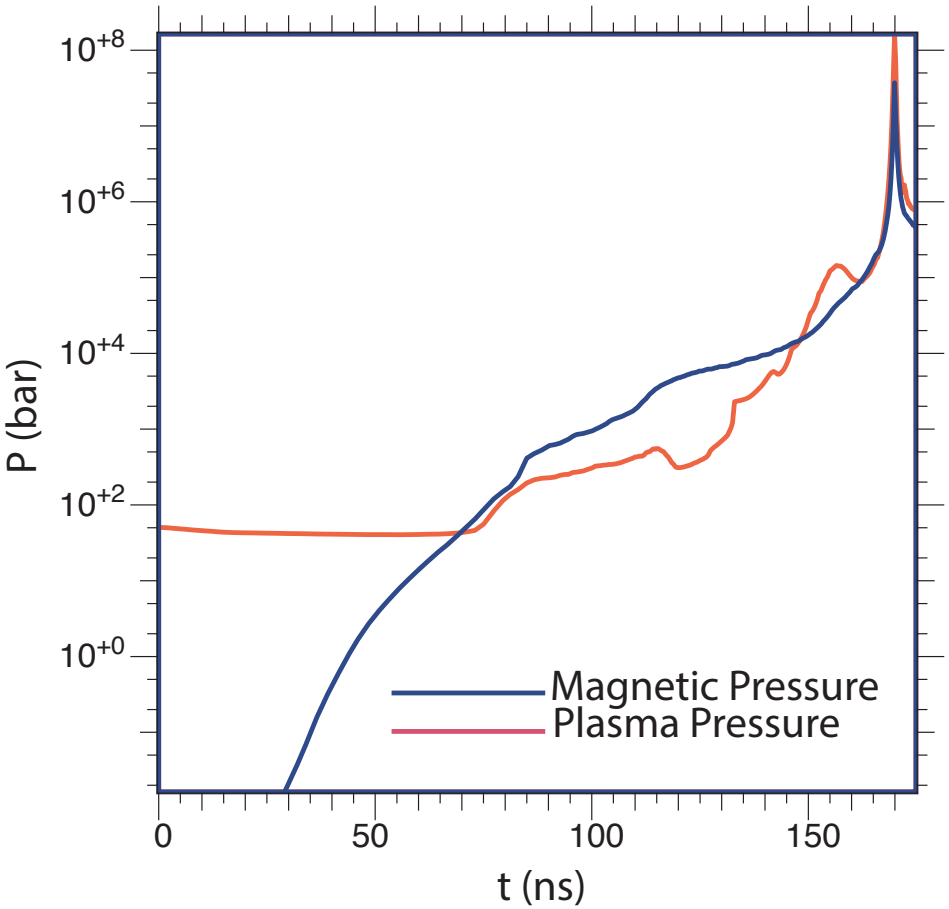


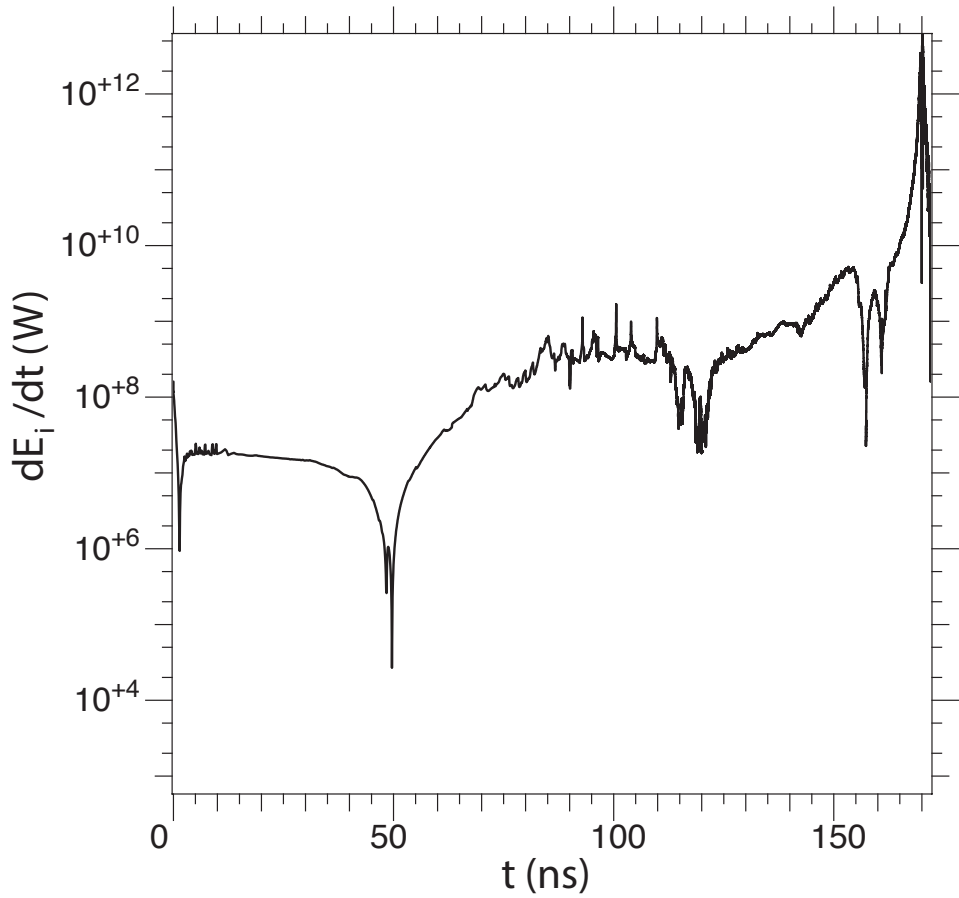
Simulations for UNR, Zebra
ρ_i & n_i with J_z & B_θ





University of Nevada, Reno
Zebra – Pressures & B_θ





Summary

- The SZP is low-risk
  - Established basis - experiments, theory, computations
  - Stable, magneto-sonic shock front

- The SZP is high payoff
  - Shock-wave pre-heat of the target
  - Magnetic-field compression to 10's kT
  - High-target convergence ratios
  - Fusion ignition