Introduction/Motivation

Using Proton Radiography to Measure Magnetic Fields Associated with Rayleigh-Taylor

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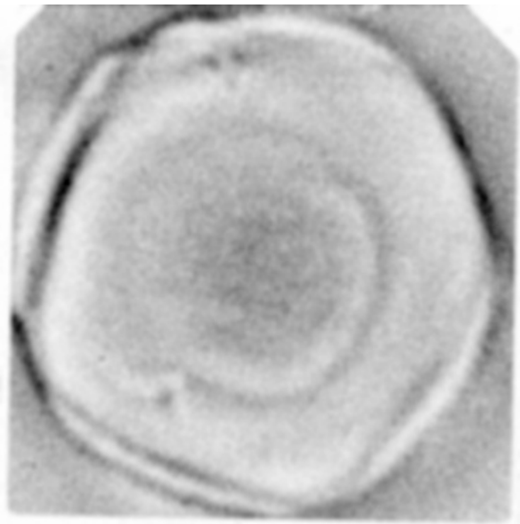

1.2 ns

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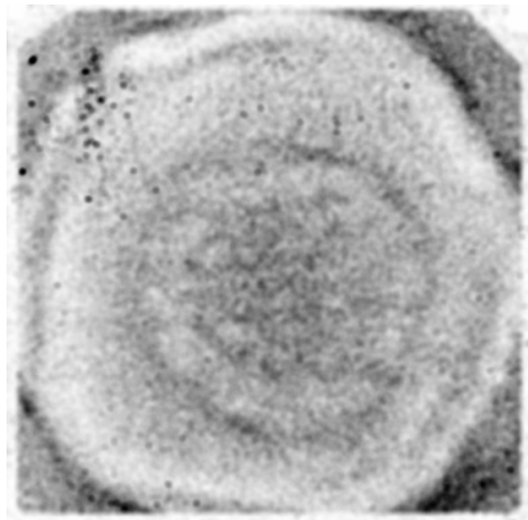

1.5 ns

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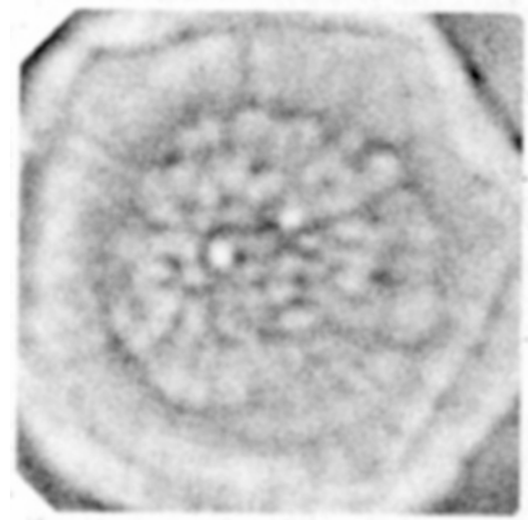

1.9 ns

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Abstract

The Rayleigh-Taylor (RT) hydrodynamic instability is a well-known and intensively studied phenomenon in the Inertial Confinement Fusion (ICF) community. The destructive nature of this instability has been a concern for shell integrity during the acceleration phase of ICF implosions, but certain modes can be stabilized through ablation and pulse shaping of the laser. These methods can stabilize the growth of RT modes, but do not preclude the formation of self-generated magnetic fields. RT induced magnetic fields on the order of mega-Gauss have been theoretically predicted and simulated, but never measured. These self-generated fields will reduce the heat flux through the hall parameter $\omega\tau$, and affect implosion dynamics. An experimental method for measuring these elusive fields using a combination of mono-energetic proton radiography and simulations is presented along with preliminary data analysis.

This work was performed in part at the LLE National Laser User's Facility (NLUF), and was supported in part by US DOE, LLNL, LLE and FSC at Univ. Rochester.

Some Important References

1. Rayleigh, London Math Soc 14, 1883
2. Taylor, Proc Royal Soc London 201, 1950
3. Mima et al, Phys Rev Lett 41 (25), 1978
4. Afanas'ev et al, Zh Eksp Teor Fiz 74, 1978
5. Evans et al, Plasma Phys. & Controlled Fusion 28 (7), 1986
6. Betti et al, Phys Rev Lett 71, 1993
7. Nishiguchi et al, Jpn J Appl Phys 41, 2002
8. Knauer et al, Phys Plasma 12, 2005

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The Rayleigh-Taylor Instability has an Impact on Plasma Dynamics

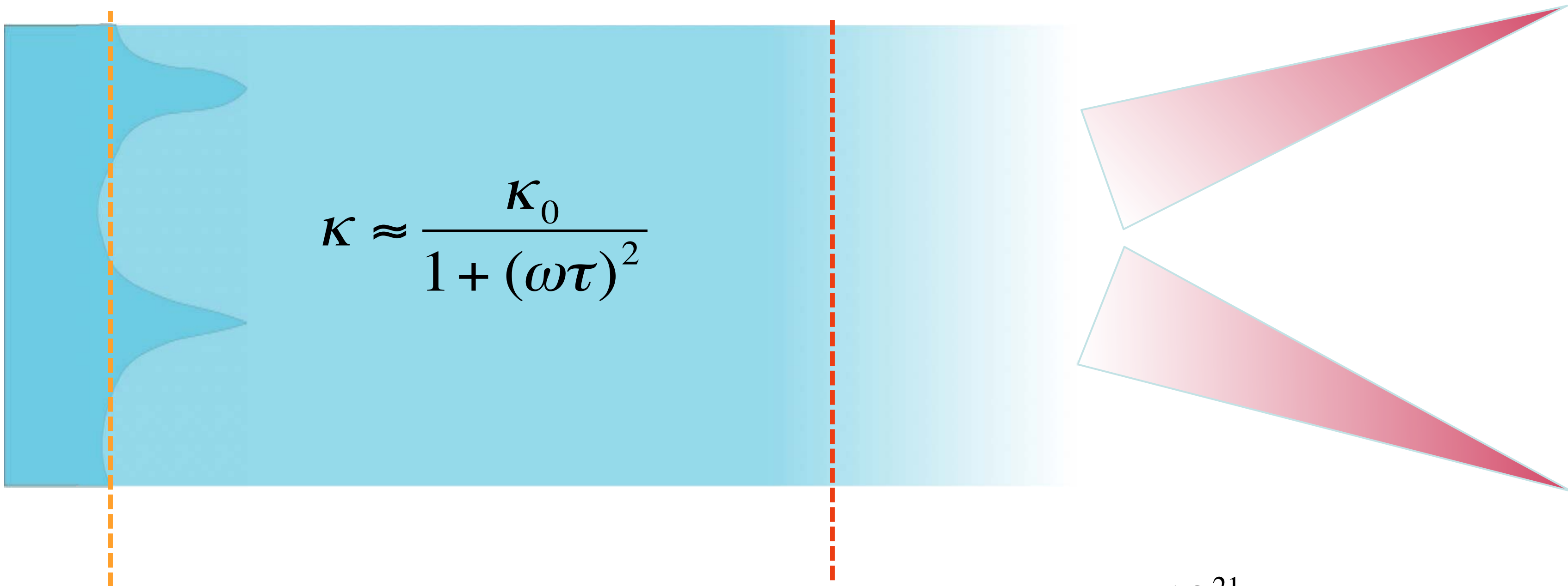
- Magnetic fields associated with the Rayleigh-Taylor instability have been theorized and simulated by many scientists [3,5,7]

- Magnetic fields generated in laser-produced plasmas can affect the thermal transport (Hall Parameter, ωτ)

$$\boxed{\kappa \approx \frac{\kappa_0}{1+(\omega\tau)^2} \qquad \omega\tau \approx \frac{200}{Z\ln\Lambda}\frac{B[MG]*T[keV]^{3/2}}{n_e[10^{21}cm^{-3}]}}$$

- Direct measurements of these fields will investigate theory and provide empirical insight to B-field generation due to RT

Thermal Transport from the Critical Surface to the Ablation Front Can be Impeded by the Presence of Magnetic Fields



Ablation Front

Critical Surface $n_{cr} = \frac{10^{21}}{\lambda[\mu m]^2}[cm^{-3}]$

- Laser energy is absorbed in the under-dense plasma through inverse bremstrahlung and near the critical surface by resonance absorption

- This energy should be deposited to the ablation surface for good coupling

- The presence of B-fields (from RT or otherwise) in the over-dense plasma can reduce the coupling

Rayleigh-Taylor Overview

The Rayleigh-Taylor Instability is Caused by the Acceleration of a Heavy Fluid into a Light Fluid

For a Classical Incompressible Neutral Fluid

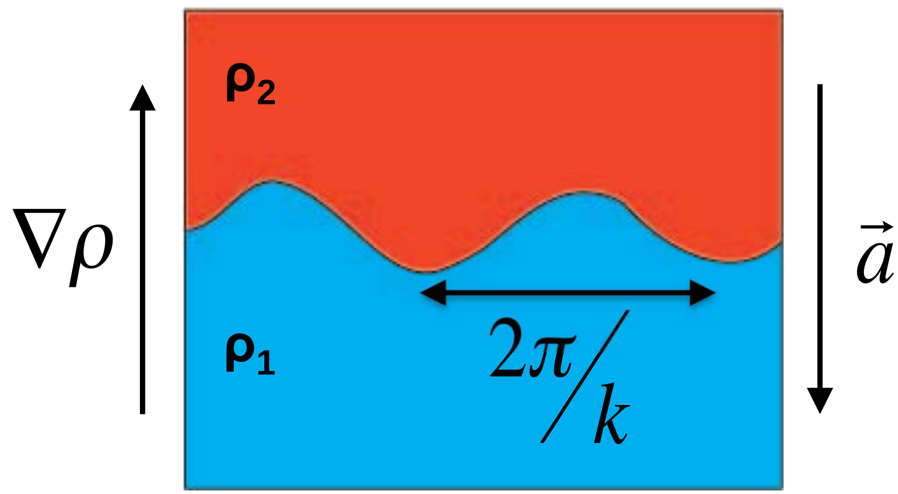
Mass Cons.: $$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u}\right) = 0$$

Mom. Cons.: $$\rho\left(\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \cdot \nabla\right)\vec{u}\right) = -\nabla p + \rho \vec{a}$$

Perturb All Quantities: $Q = Q_0 + Q_1$

Fourier Analyze: $Q_1 = \tilde{Q}_1 e^{i(\vec{k} \cdot \vec{r} - \omega t)}$

The system is unstable when the frequency is imaginary.

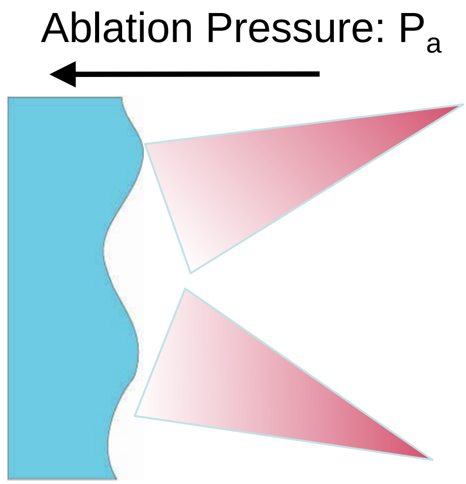


Atwood Number: $A_T = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$

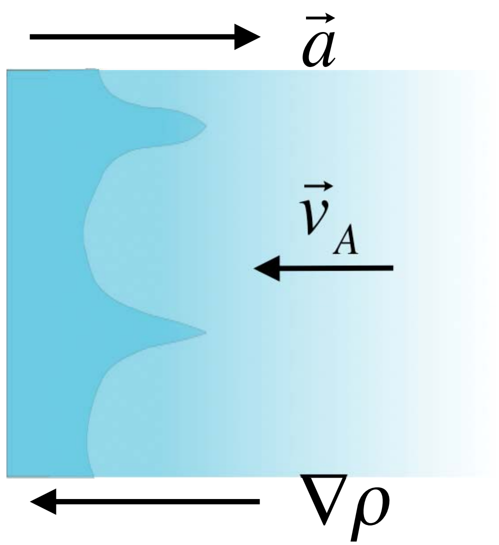
Dispersion Relation:

$$\omega = i\gamma, \gamma = \sqrt{A_T k a}$$

The Rayleigh-Taylor Instability Affects the Ablation Region in Laser-produced Plasmas



In accelerating ablation front frame



- density perturbation is continuous, not discrete

Minimum Density Scale Length: $\boxed{L_\rho = \dfrac{\rho}{\nabla\rho}}$

- density scale length has a stabilizing effect

Effective Atwood Number: $\boxed{A_T \Rightarrow A_{eff} = \dfrac{A_T}{1 + A_T k L_\rho}}$

- ablative flow stabilizes the growth rate

New Dispersion Relation [7]: $\boxed{\gamma = \sqrt{A_{eff} k a} - \beta k v_A}$

Magnetic Fields are Generated Inside of Plasmas

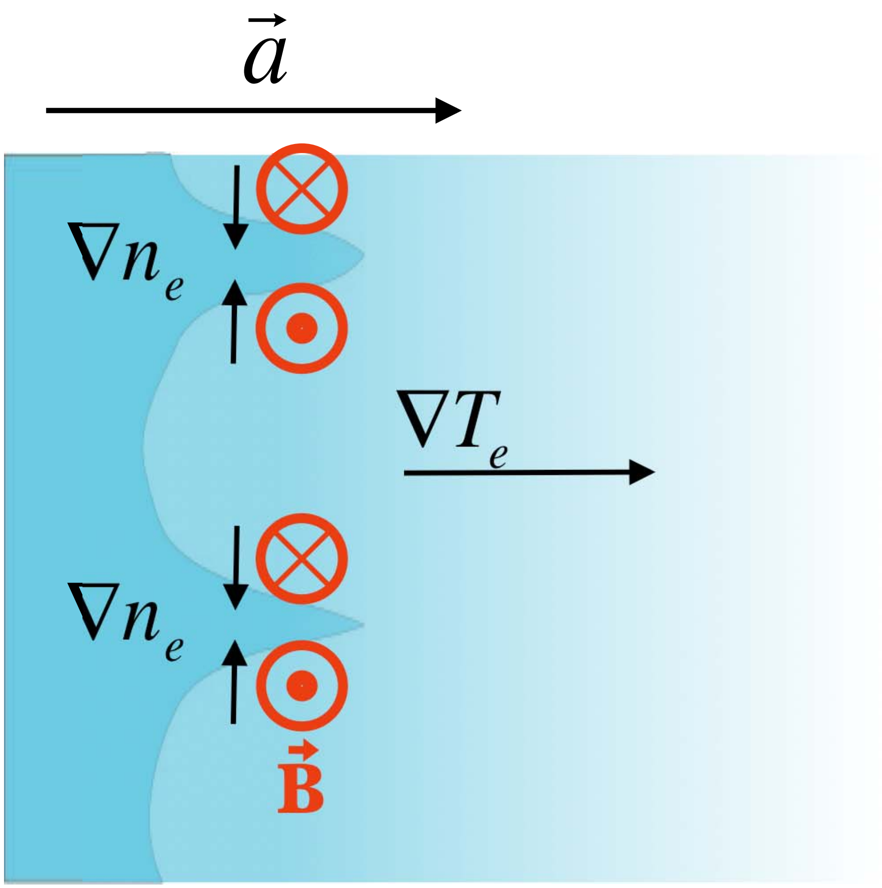
Combine the Electron Momentum Equation and Faraday's Law:

$$\underbrace{\frac{\partial}{\partial t}\left(\vec{B} - m_e \nabla \times \vec{v}_e\right)}_{\substack{\text{Conservation of} \\ \text{Generalized} \\ \text{Vorticity}}} = \underbrace{\nabla \times \left(\vec{v} \times \vec{B}\right)}_{\substack{\text{Convection} \\ \text{from Ions} \\ \text{(Dynamo)}}} + \underbrace{\nabla \times \left(\frac{\nabla p_e}{n_e e_0}\right)}_{\substack{\text{Thermo-} \\ \text{electric Field} \\ \text{Generation}}} - \underbrace{\nabla \times \frac{\left(\nabla \times \vec{B}\right) \times \vec{B}}{\mu_0 n_e e_0}}_{\substack{\text{j X B Force} \\ \text{Term}}} + \underbrace{\nabla \times \frac{\nabla \cdot \vec{P}}{n_e e_0}}_{\substack{\text{Pressure} \\ \text{Tensor} \\ \text{Term}}} - \underbrace{\nabla \times \frac{\vec{R}_T + \vec{R}_U}{n_e e_0}}_{\substack{\text{Thermal and} \\ \text{Frictional} \\ \text{Forces}}}$$

- Most terms describe B-field evolution in time and space
- Pressure Tensor is typically small relative to other terms
- Thermoelectric term typically dominates field generation

Magnetic Fields are Generated by the Rayleigh-Taylor Instability

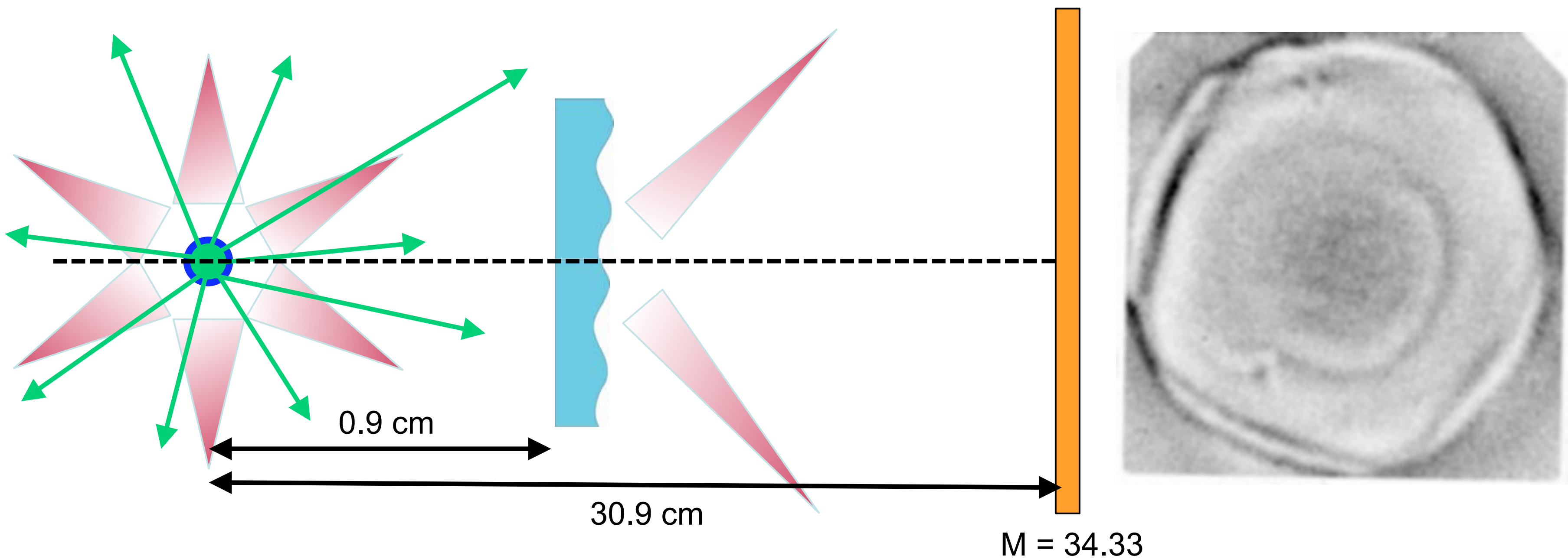
$$\frac{\partial \vec{B}}{\partial t} \approx \frac{\nabla T_e \times \nabla n_e}{n_e e_0}$$



- Thermoelectric term dominates field generation
- Modulated density creates modulated field structures
- The field is ‘π/2’ out of phase with density modulations [8]

Experiments

RT-induced Magnetic Field Experiments were Performed on October 11, 2007



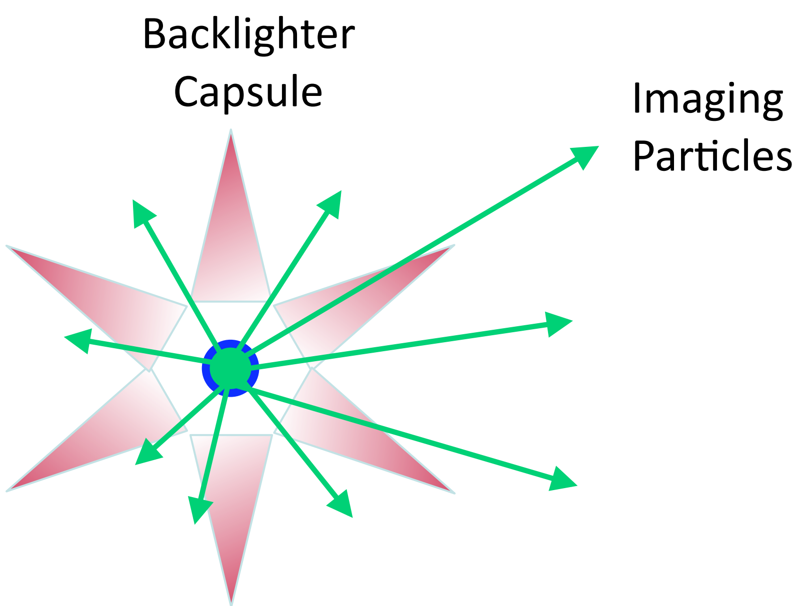
Mono-energetic quasi-isotropic proton-Backlighter

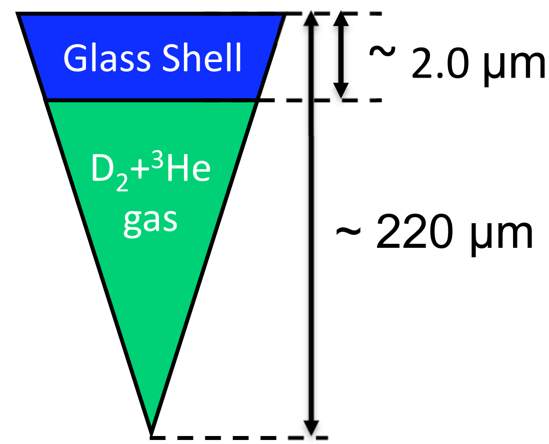
2-ns square pulse drives a seeded 20-μm CH foil*

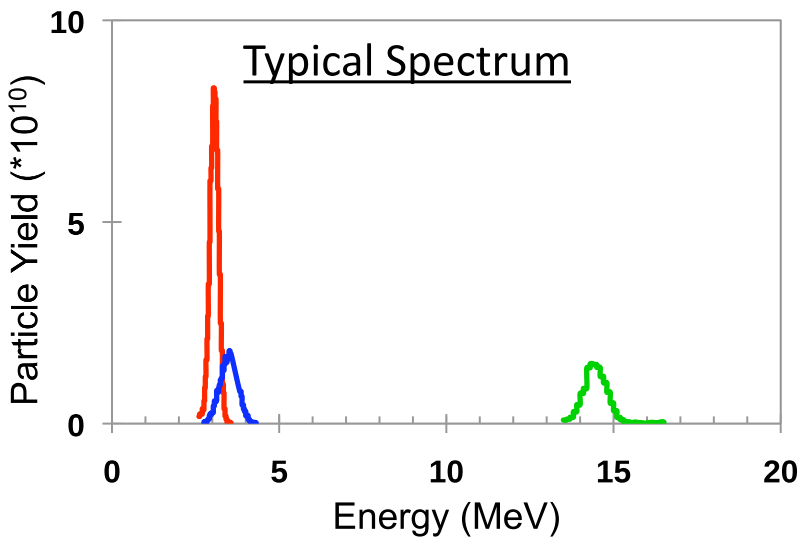
100 cm^2 CR39 detector array records 15-MeV proton tracks

* Linear modulations of λ ~120 μm, initial amplitude a_0 ~0.5 μm, on-target-energy ~3300 J (12 SSD-beams, 2-ns, I ~3.3*10^{14} W/cm^2)

Mono-Energetic Protons Produced by an Exploding Pusher were Used to Radiograph the Seeded Foils





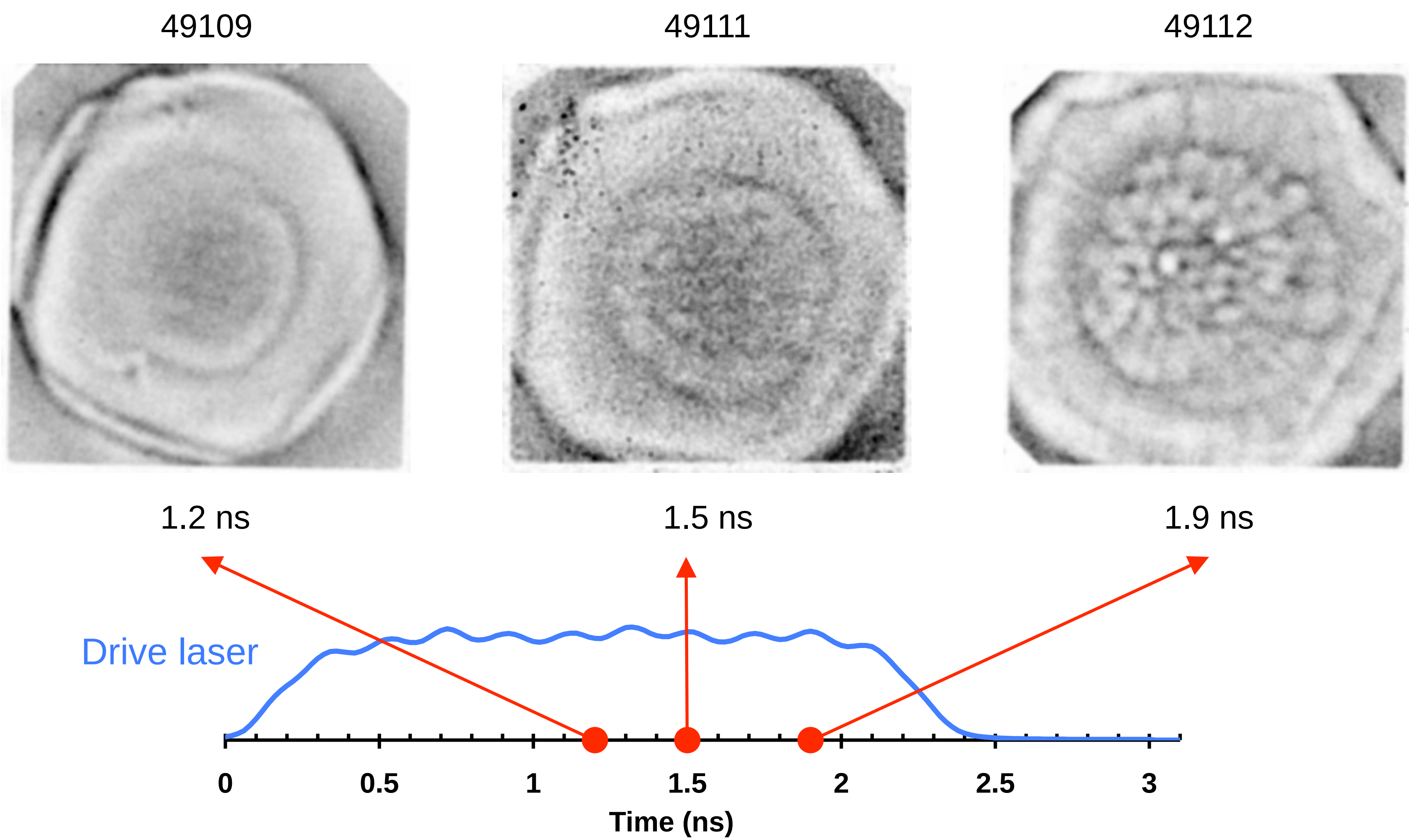


Laser drive ~ 10 kJ in a 1-ns square pulse
T_i ~ 10 keV

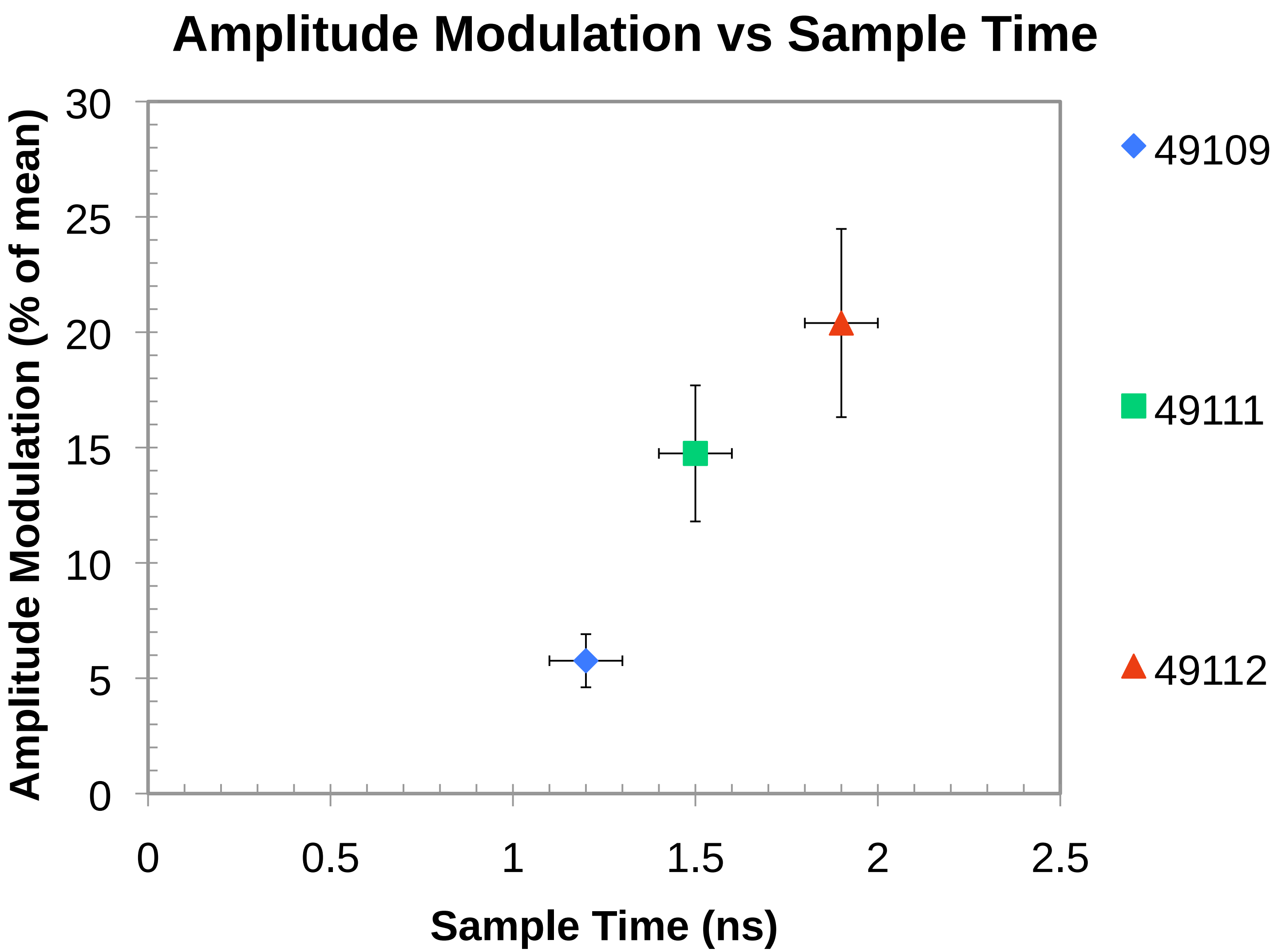
D + D → T (1 MeV) + **p** (3 MeV, Y~ 1×10^9)
D + ^{3}He → α (3.6 MeV) + **p** (15 MeV ,Y~ 1×10^8)

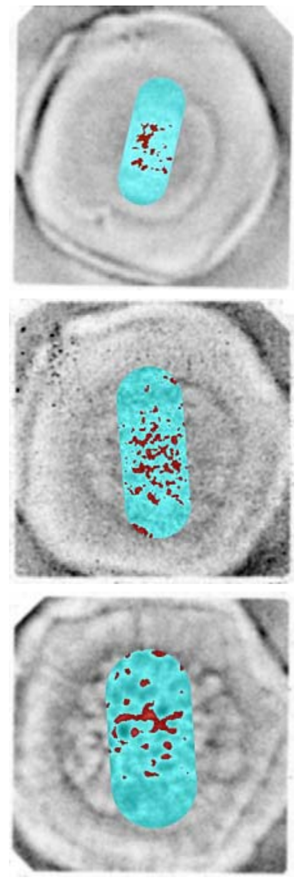
Burn duration ~ 120 ps
Burn region size (FWHM) ~ 45 μm

15-MeV Proton Radiographs were Taken at Three Times Relative to the RT-foil Laser Pulse



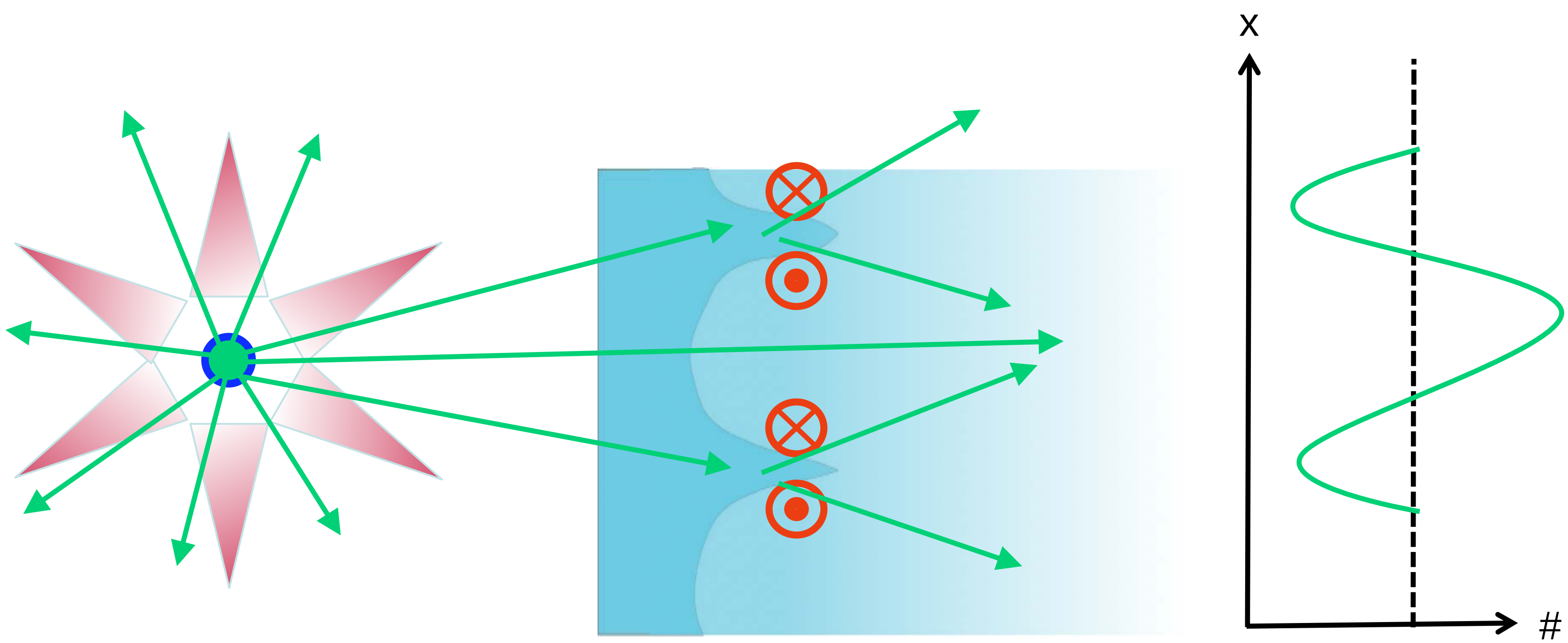
Preliminary Analysis Demonstrates an Increase in Modulation Amplitude Over the Sampled Times





Future Work

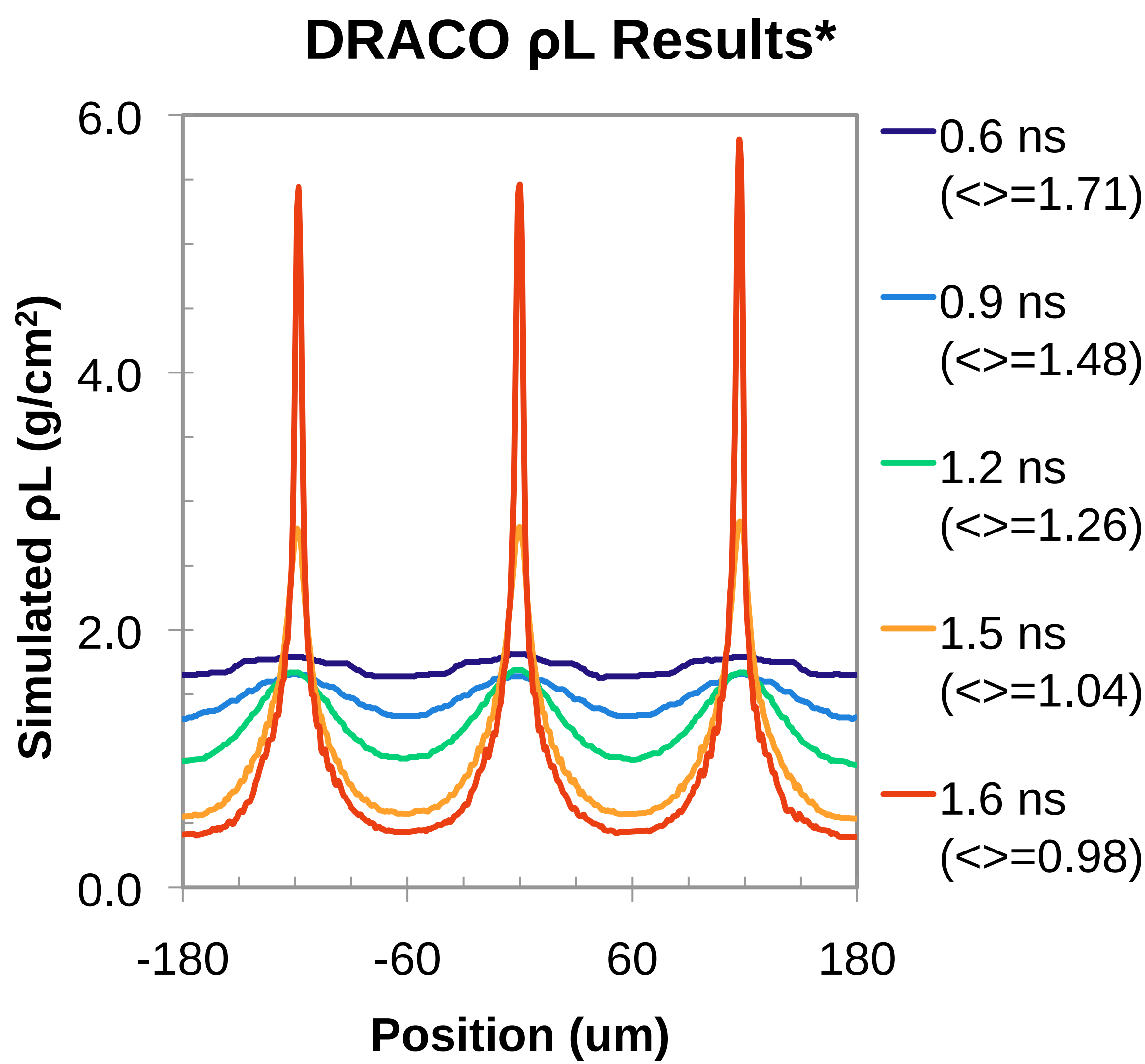
The Proton Radiographs are Used to Measure Deflections due to Both Coulomb-Scattering and Field Effects



- A semi-uniform flux of 15-MeV protons impinge the RT subject
- Protons that traverse spikes will be Coulomb-scattered the most
- The B-field deflects protons to enhance the amplitude modulations

Simulations Will be Used to Separate Deflections due to Scattering and to Magnetic Fields

1. DRACO will simulate density profiles
2. B-fields will be modeled and simulated in Geant4
3. Geant4 will simulate proton trajectories through matter and fields
4. The simulated radiographs will be compared to data
5. Different density profiles and B-field models will be used to best match the data



* ρL calculated from Suxing's DRACO simulations of 11-06-2007

Future Work

- A Geant4 simulation has been benchmarked for simple proton radiography experiments, and must be upgraded to properly implement complex structures

- Compare different radiography simulations using various density and field distributions with the current data of linear RT experiments

- Analyze and compare the ‘eggcrate’ RT experiments with simulations, in which 3D modulations were manufactured in an ‘eggcrate’ pattern

- Quantitatively determine the measured value of B-fields associated with RT

Summary

- Thermoelectric currents from non-collinear density and temperature gradients associated with RT, generate B-fields in laser-produced plasmas

- B-fields generated in laser-produced plasmas can affect the thermal transport from the critical density to the ablation surface

- A method for measuring B-fields associated with RT has been presented using a combination of proton radiography and simulations