Measurement of self-generated spontaneous fields and their effects on ICF ion kinetic dynamics

National Ignition Facility

C. K. Li

LaB Conference, July 22-28, 2017
Moscow - St Petersburg, Russia

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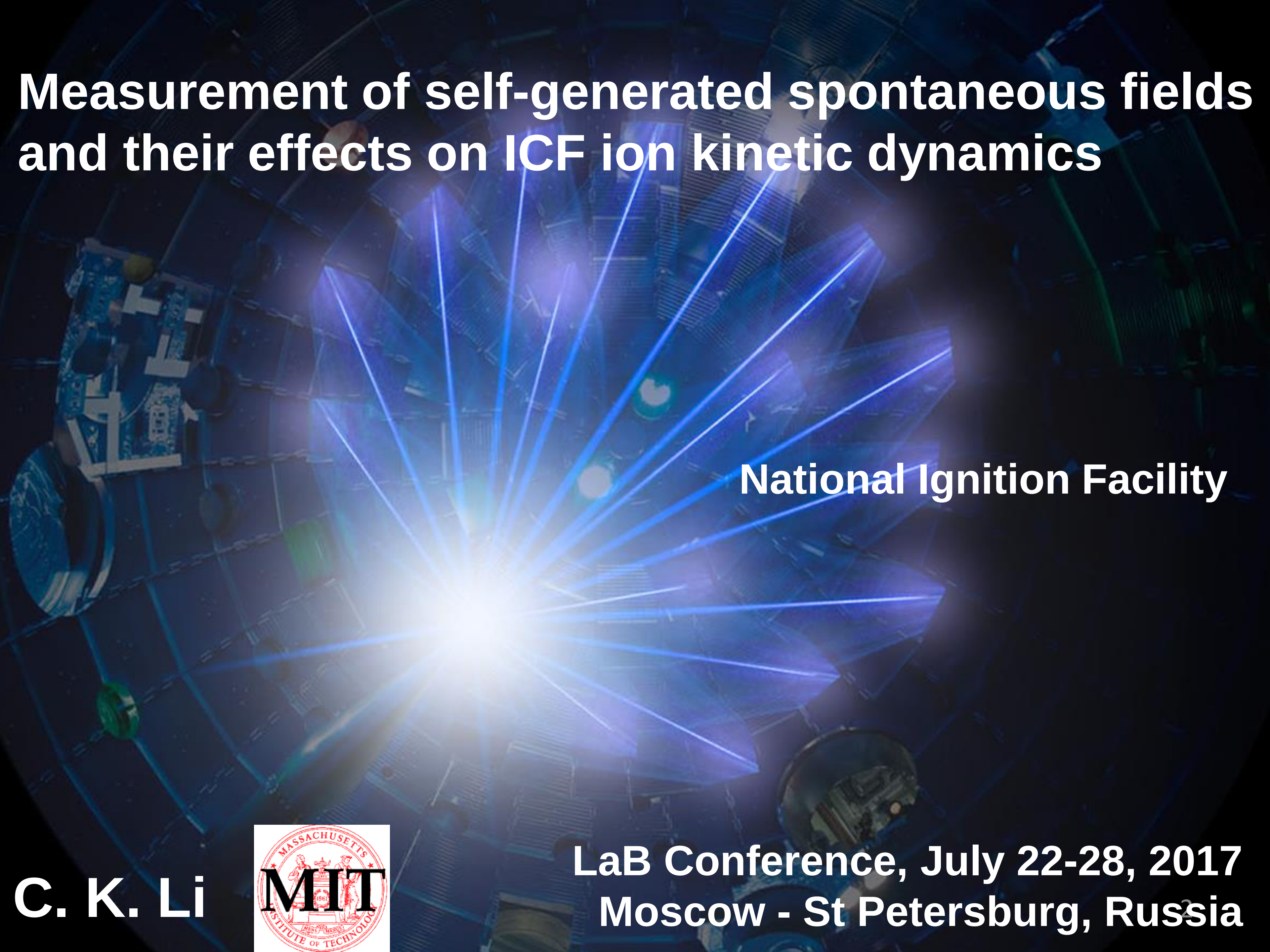

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Collaborators

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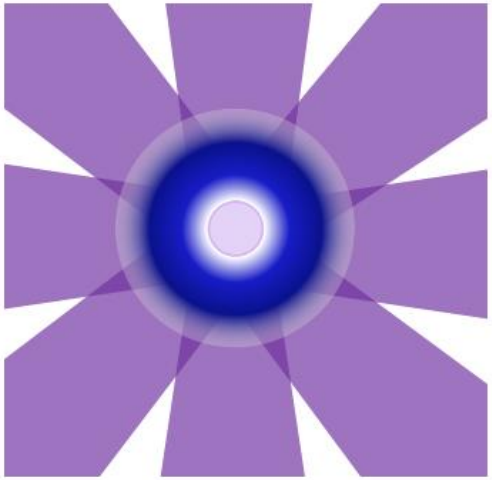
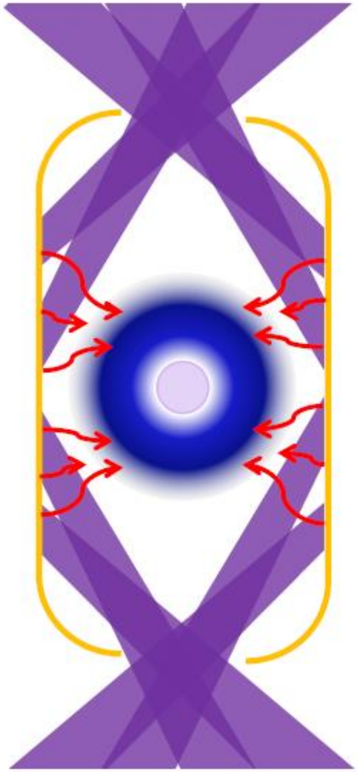
Two approaches to ICF implosions

Direct-drive (OMEGA)	Indirect-drive (NIF)

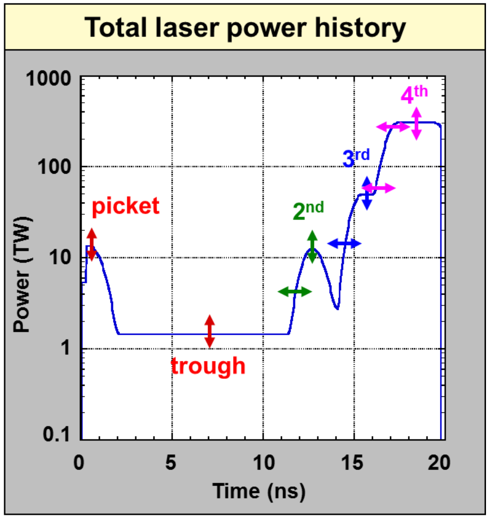
Laser directly irradiates capsule

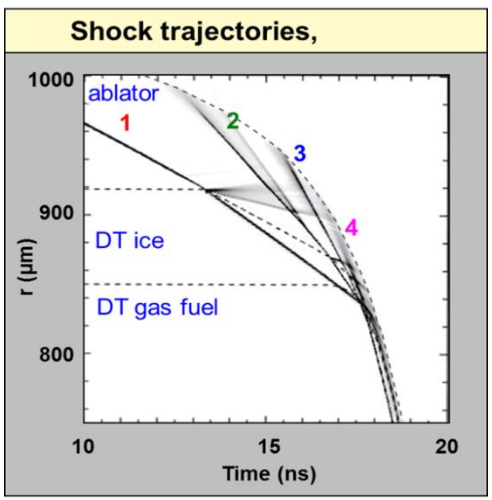


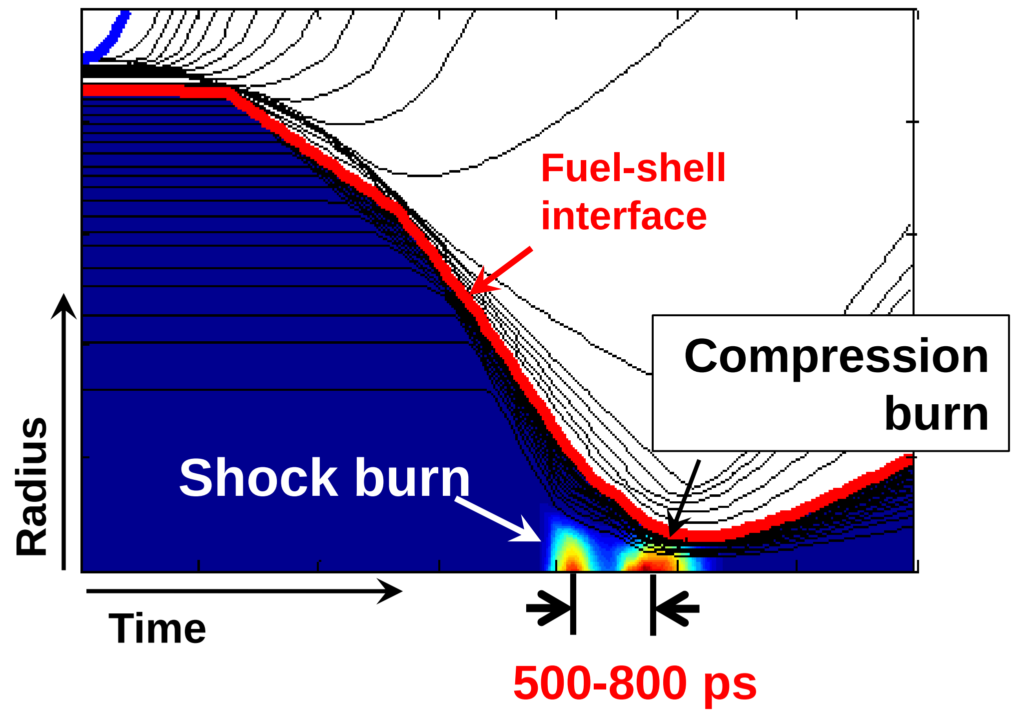


Laser produces x-rays inside a hohlraum, which irradiate the capsule

ICF implosions result in two phases of nuclear burn: shock burn and compression burn







Hydro assumptions can break down during the shock-convergence phase

Mainline ICF simulations are made with average-ion hydrodynamic approximation

Single-fluid model

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

$$\rho\left(\frac{\partial v}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{v} = \nabla\mathbf{J}\times\mathbf{B} - \nabla P + \frac{\rho}{m}\mathbf{F}$$

$$\frac{m}{ne^2}\frac{\partial \mathbf{J}}{\partial t} = \mathbf{E} + \mathbf{v}\times\mathbf{B} - \frac{1}{en}\mathbf{J}\times\mathbf{B} + \frac{1}{en}\nabla P_e - \eta\mathbf{J}$$

Averaged quantities over all species

$$\rho = \Sigma n_i m_i + n_e m_e$$

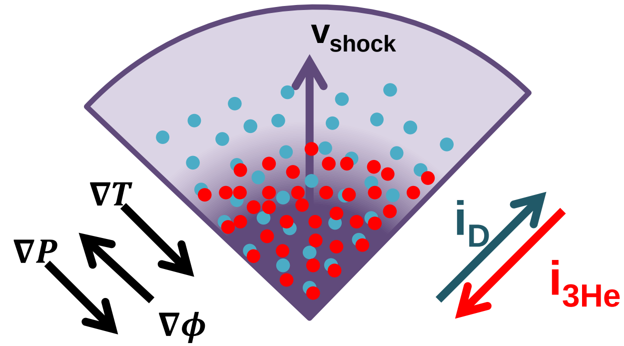
$$P = P_i + P_e$$

$$\mathbf{v} = \frac{1}{\rho}(n_i m_i \mathbf{v}_i + nem_e \mathbf{v}_e)$$

$$\mathbf{J} = en(\mathbf{v}_i - \mathbf{v}_e)$$

Strong gradients in pressure, electric potential or temperature can cause species separation

Rebound Shock:



Gradients cause differential mass flux

Mass flux $$i_D = -\rho D\left(\frac{d\alpha}{dx} + k_p \frac{d\ln P}{dx} + k_E \frac{e\nabla\Phi}{k_B T} + k_T \nabla \ln T\right) = -i_{3He},$$

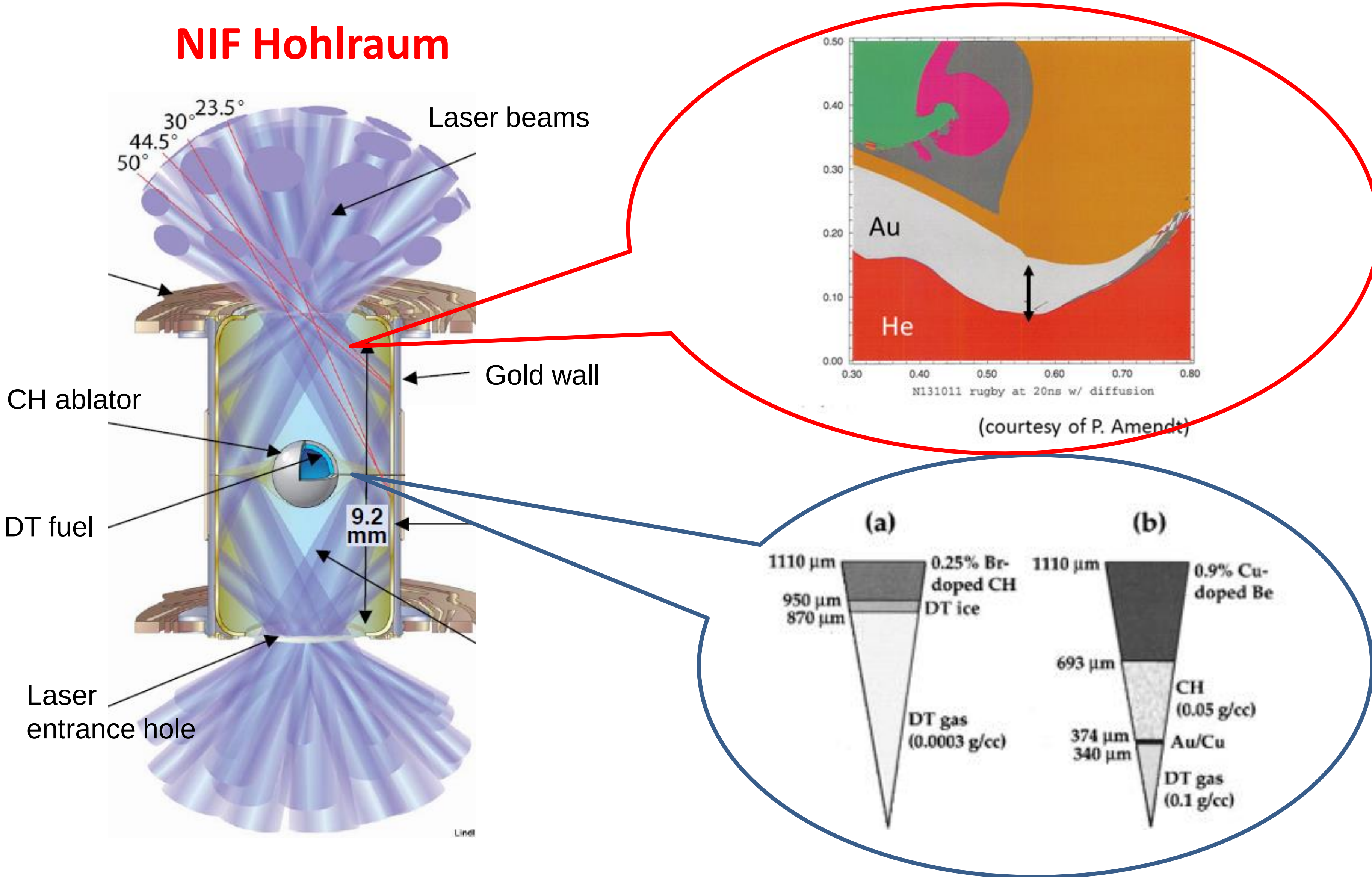
Classical diffusion | **Baro-diffusion** | **Electro-diffusion** | **Thermo-diffusion**

$$\alpha = \rho_D/\rho_{tot} \sim f_D$$

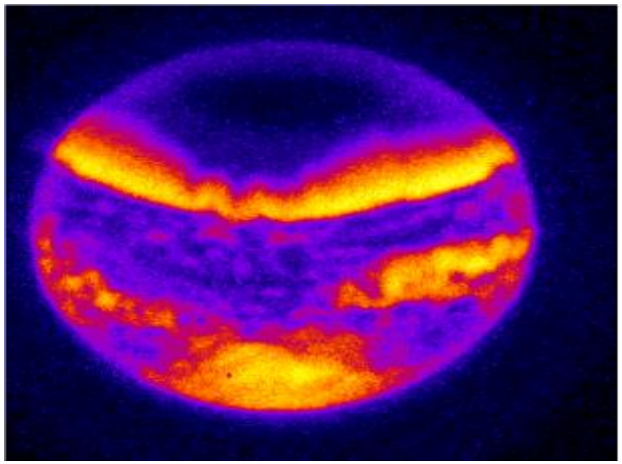
These effects will impact DT as well as D^3He.

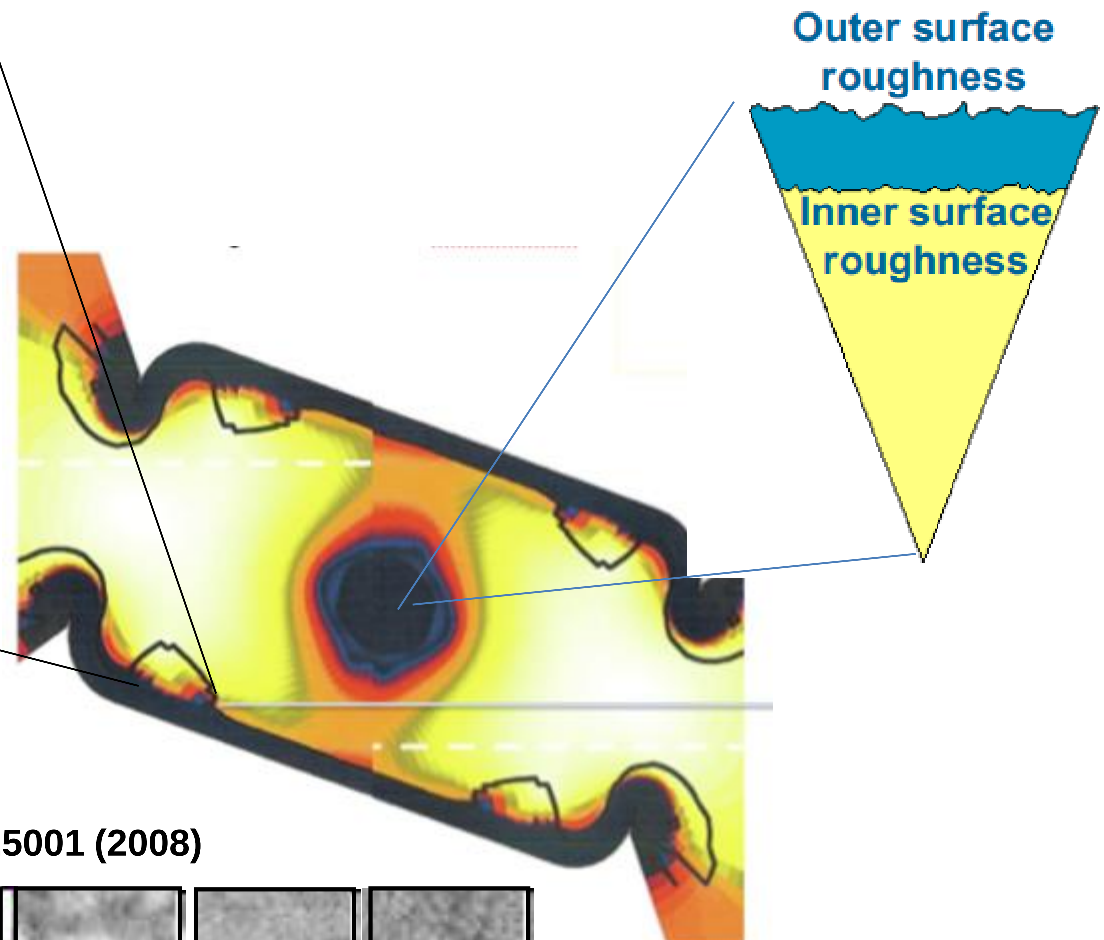
P. Amendt, et al. PRL 109, 075002 (2012)

Interfaces are present in hohlraum and capsule of a typical indirect-drive ICF target



Interfaces are hydrodynamically unstable during laser-plasma interactions and ICF implosions, and are affected by fields





C. K. Li *et al*, Phys. Rev. Letts. 100, 225001 (2008)

Time-gated, monoenergetic proton radiography offers unique measurements of self-generated E+B fields, providing insight into ion kinetic dynamics

Imploded capsules:

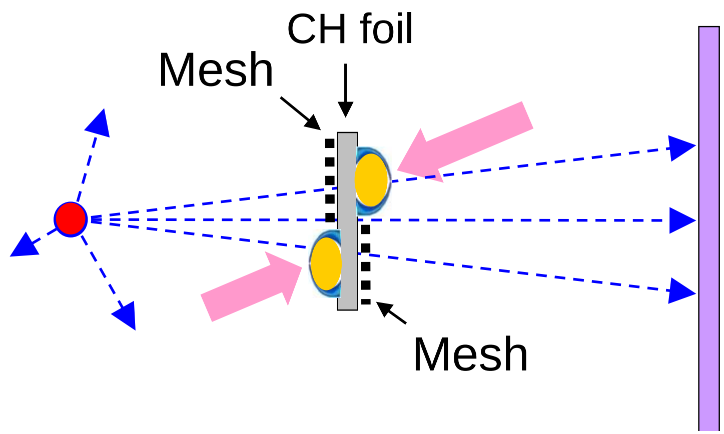
- Expansion of corona plasma → current filaments → B fields
- Converging shock front → radial E fields
- ………....

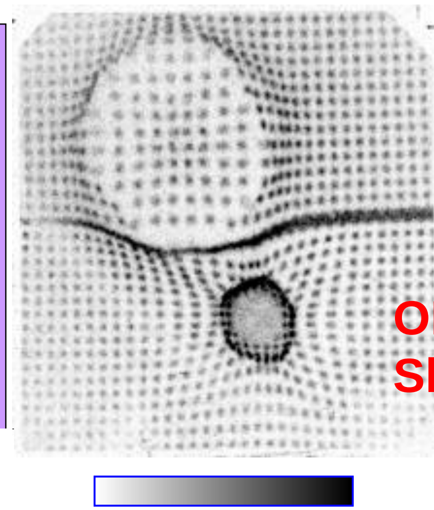
Laser-driven hohlraums

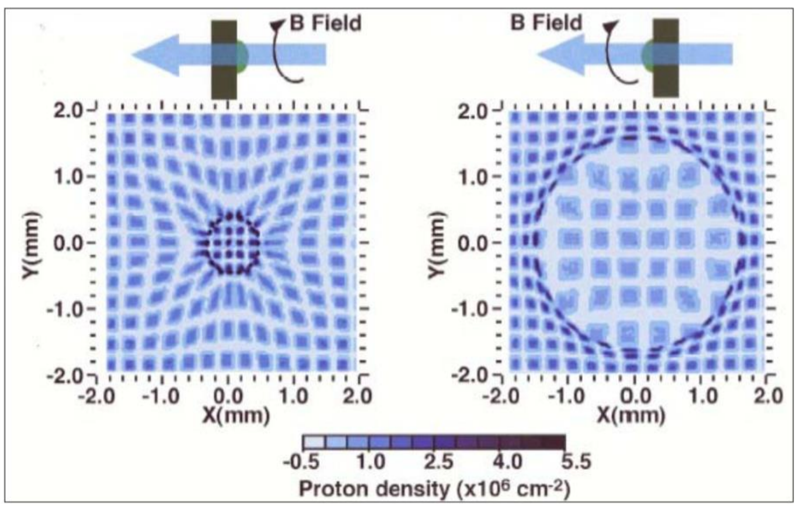
- Charge sheath formed by Ponderomotive force → E fields
- ∇P at hohlraum wall → E fields
- Diffusive mix at interfaces → ambipolar E fields
- $\nabla n \times \nabla T$ around laser spots → B fields
- Hydro unstable interfaces → RT induced B fields
- …………....

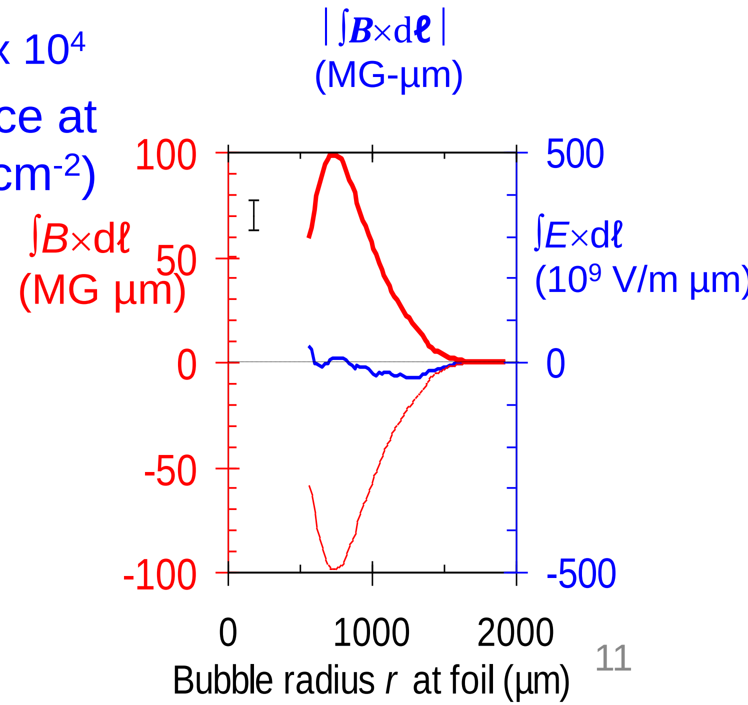
Coupled with ion-kinetic processes, self-generated fields have important effects on aspects of ICF kinetic dynamics

E & B were separated and mapped by imaging two plasma bubbles, identical except for the sign of B





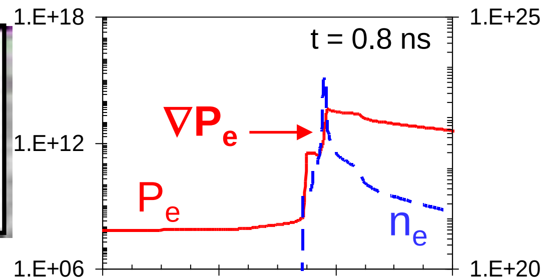


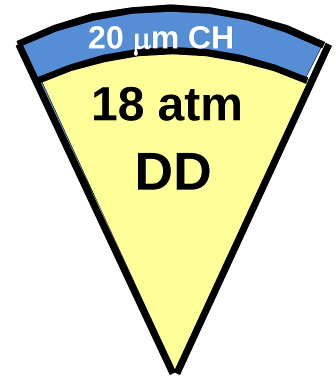


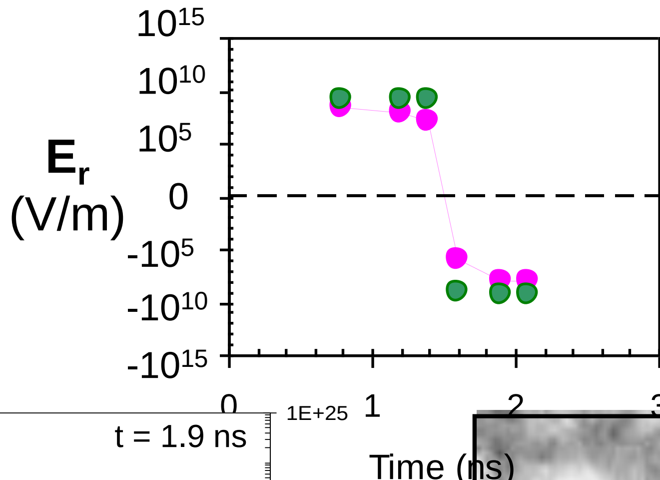
Face-on radiography → B fields
Side-on radiography → E fields

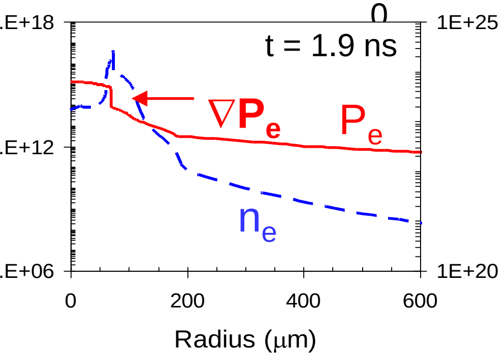
R. D. Petrasso *et al* PRL (2009)

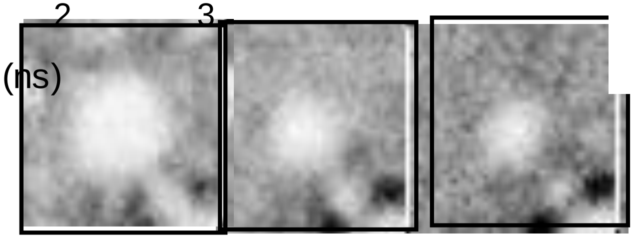
Proton fluence focusing and its reversal indicate the direction change of self-generated radial E fields associated with moving shock front

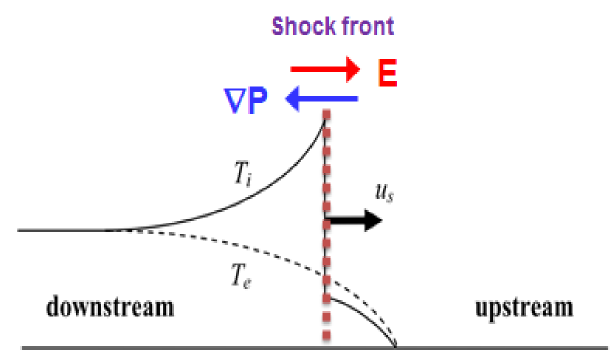








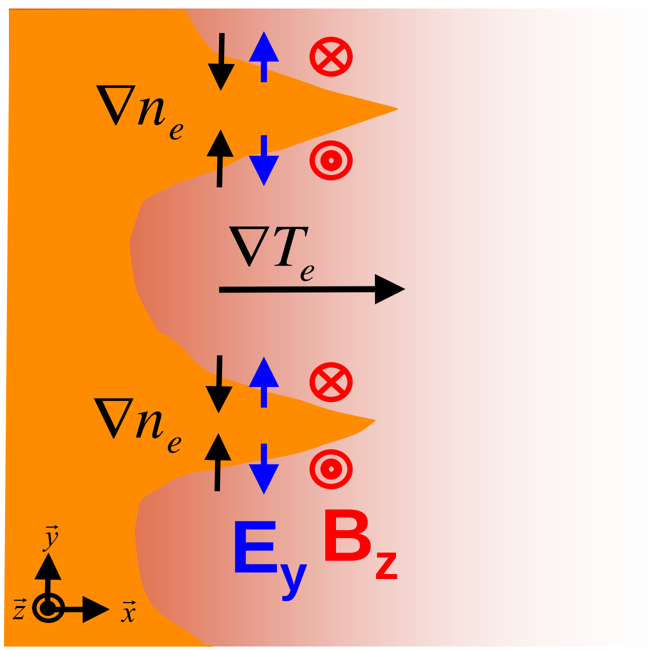


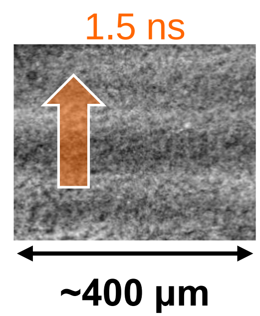


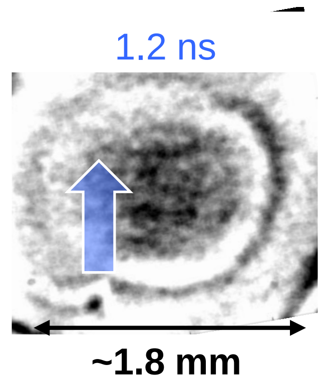
- Modify the structure of shock front
- Enhance diffusion and species separation
- …………

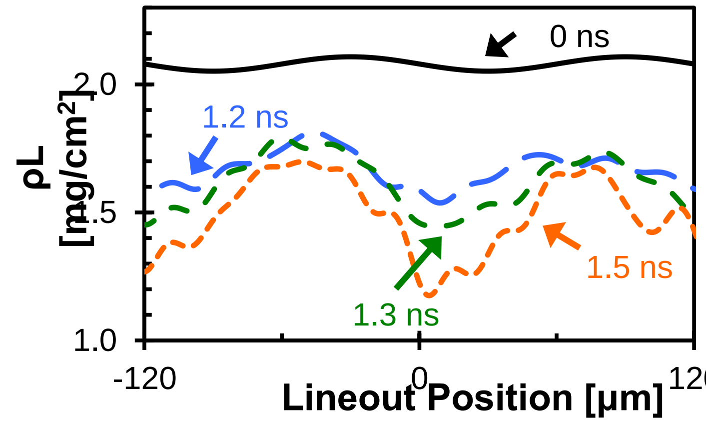
C. K. Li *et al* PRL (2008)
P. A. Amendt *et al* PRL (2010)

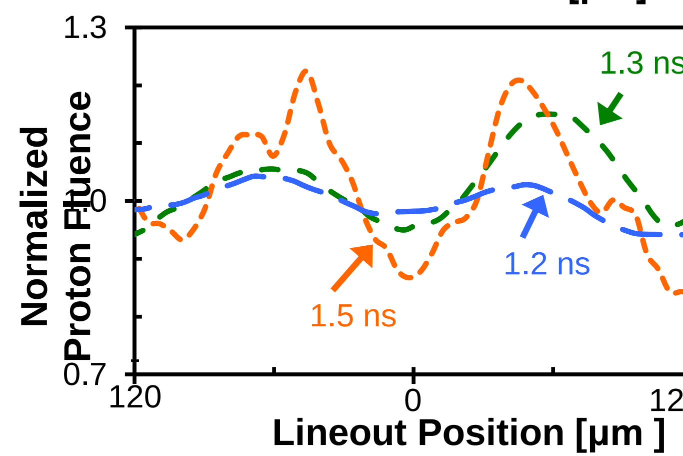
Proton radiography indicates the generation of B fields by Rayleigh-Taylor instabilities

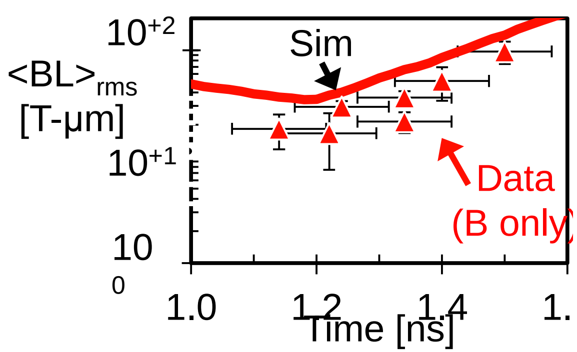


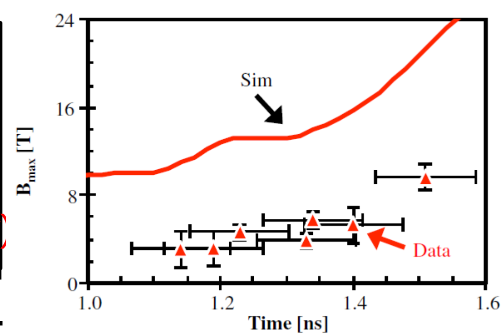






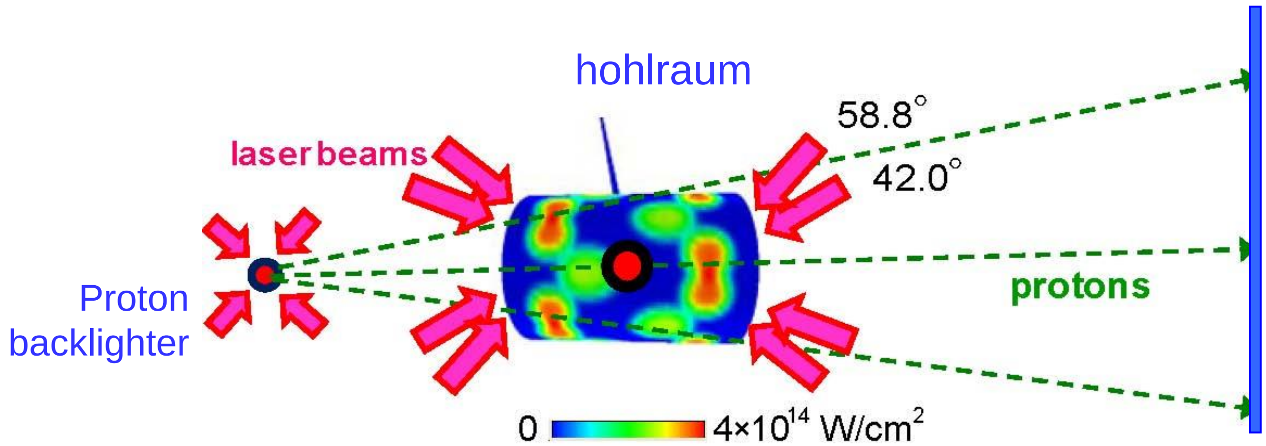


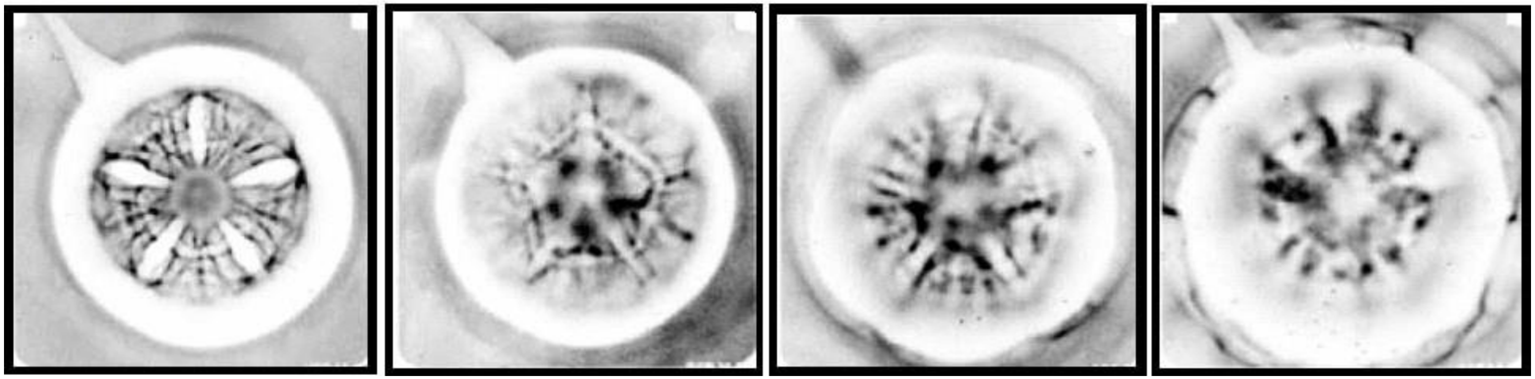




M. J-E Manuel *et al* PRL (2012)

Time resolved proton radiographs of indirect-drive ICF implosions at OMEGA illustrate fields and flows in hohlraums





0.5 ns | 1 ns | 1.5 ns | 1.8 ns

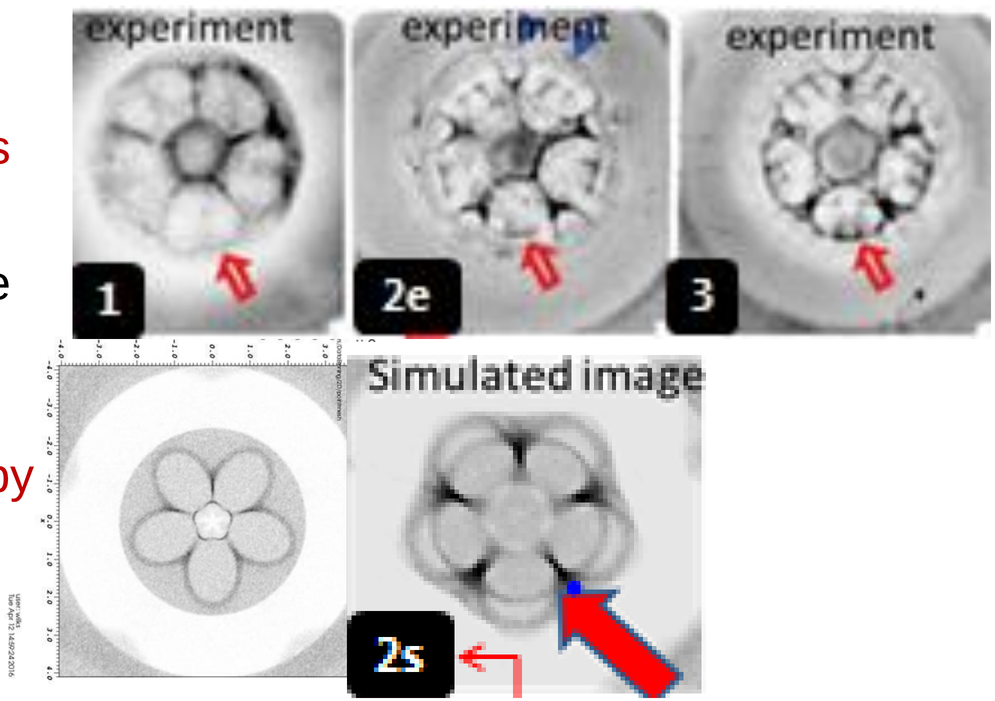
Fields are generally not included in hydro simulations

C. K. Li *et al*., Science (2010)

Recent simulations reproduce OMEGA experiments, indicating kinetic effects at Au/gas interfaces

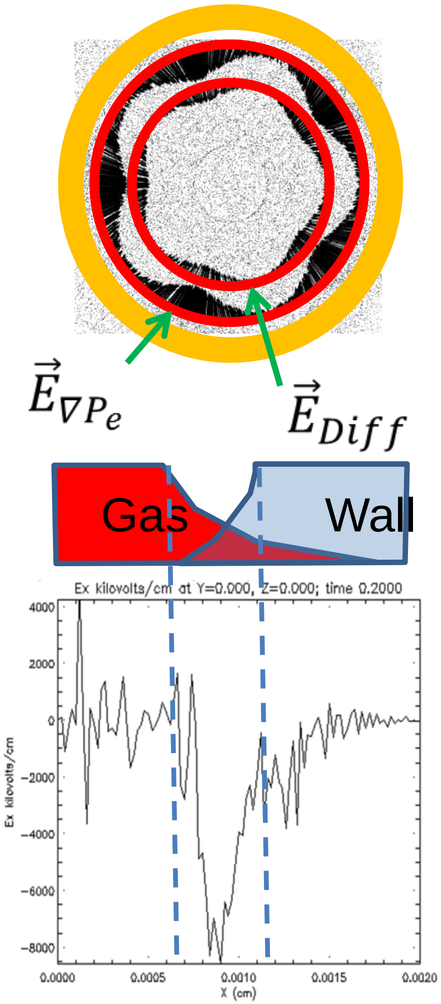
OMEGA experiments

0.4 atm Neopentane



Simulation by S. Wilks

On axis view of $\vec{E}$



- **1** At early times, diffusion-related field and wall ∇P_e fields are in same spot.
- **2e** As time proceeds, diffusion field moves inward faster than overdense wall.
- **2s** Simulations with both E-fields included can capture these features.
- **3** Once laser is off, diffusive field dominates.

- Modify the structure of interface
- Enhance diffusion, species separation

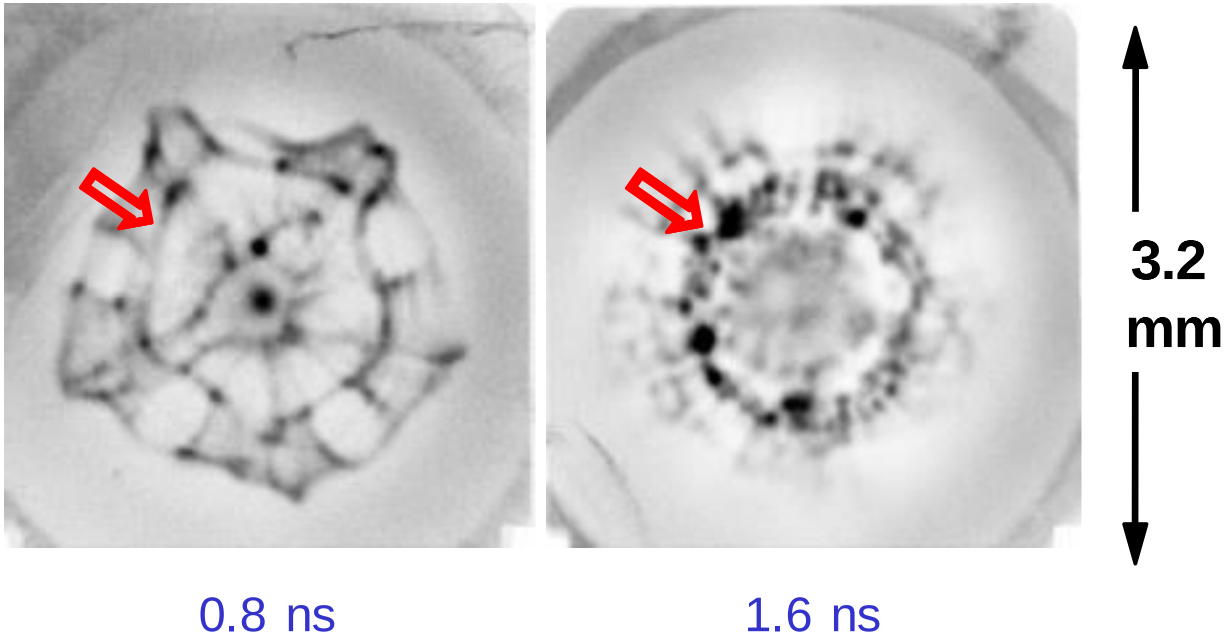
Interpenetration occurs due to the classical Rayleigh-Taylor instability as the lighter, decelerating ionized fill gas pushes against the heavier, expanding gold wall blow-off

Rayleigh-Taylor growth

$$\gamma_{RT} = \sqrt{2\pi A_t a k}$$

@ Au-Gas interface

$$A_t = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \approx 0.54$$



The consequence is a reduced benefit of the gas fill because the enhanced interpenetration (or mixing) between the Au blow-off and the gas plasma leads to high-Z material stagnating earlier in the hohlraum interior

C. K. Li *et al*, PRL (2012)

Summary

Peak values are E ~ 10^9 V m^{-1} and B ~ 10^6 gauss in different ICF implosion scenario

- ICF capsule implosions
- Laser-irradiated hohlraums
- Quantitative measurements of the effects of such fields on ICF implosions are difficult ongoing undertaking