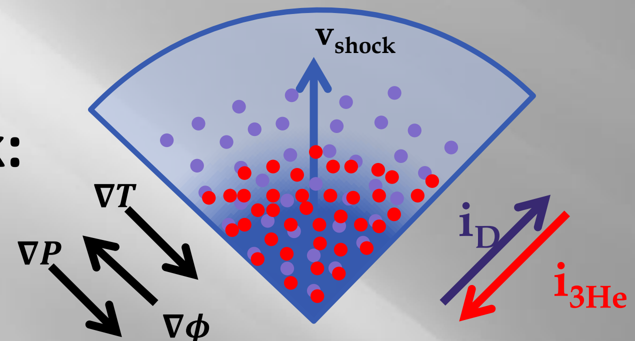
Effects of Ion Diffusion on Fusion Burn at the Shock Flash in ICF Implosions

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

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

C. K. Li

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Summary

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- ► Ratios of T^3Hed to D^3Hep reaction yields, and DDp to DTn reaction yields quantitatively illustrate the fusion yield anomaly in directly driven, exploding–pusher ICF implosions.

- ► In contrast to the case of acceleration driven isothermal atmosphere during compression burn, shock driven ion diffusions cause specie separation at shock flash.

- ► Barodiffusion and electrodiffusion are likely the dominant effects.

- ► More detailed future work will focus on quantitative study of each individual effect.

This is an ongoing experiment project

Collaborators

J. Frenje	P. Amendt	R. Betti
M. Gatu Johnson	C. Bellei	D. Meyerhofer
H. Rinderknecht	D. Casey	J. Soures
M. Rosenberg	S. Wilks	
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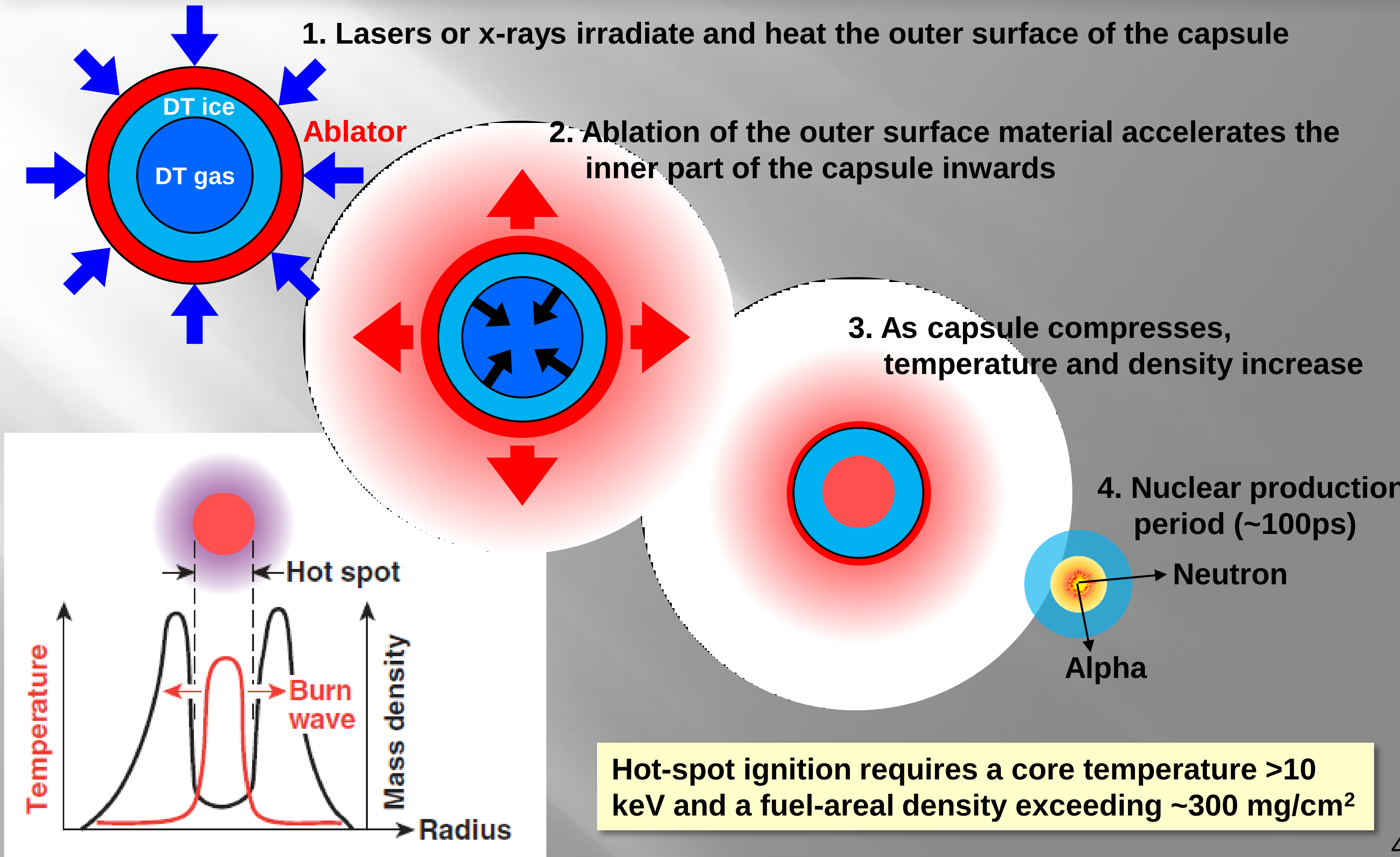
H. Sio		
A. Zylstra		
R. Petrasso		

Ablation is used to generate the extreme pressures required to compress a capsule to ignition conditions



Hot-spot ignition requires a core temperature >10 keV and a fuel-areal density exceeding ~300 mg/cm^2

Mainline ICF simulations are made with average-ion hydrodynamic codes

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

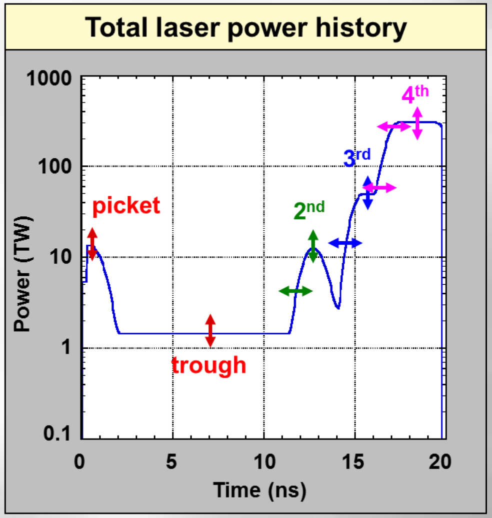
$$\rho = n_i m_i + n_e m_e$$

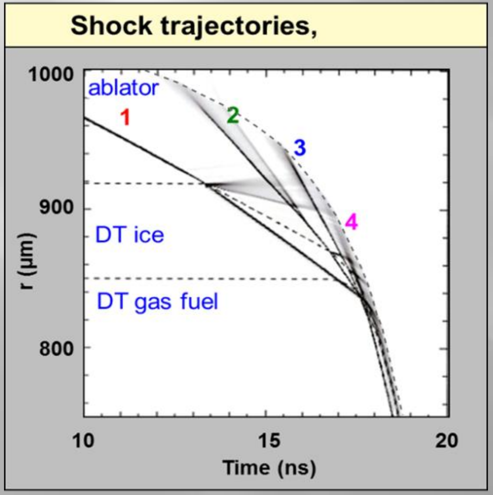
$$P = P_i + P_e$$

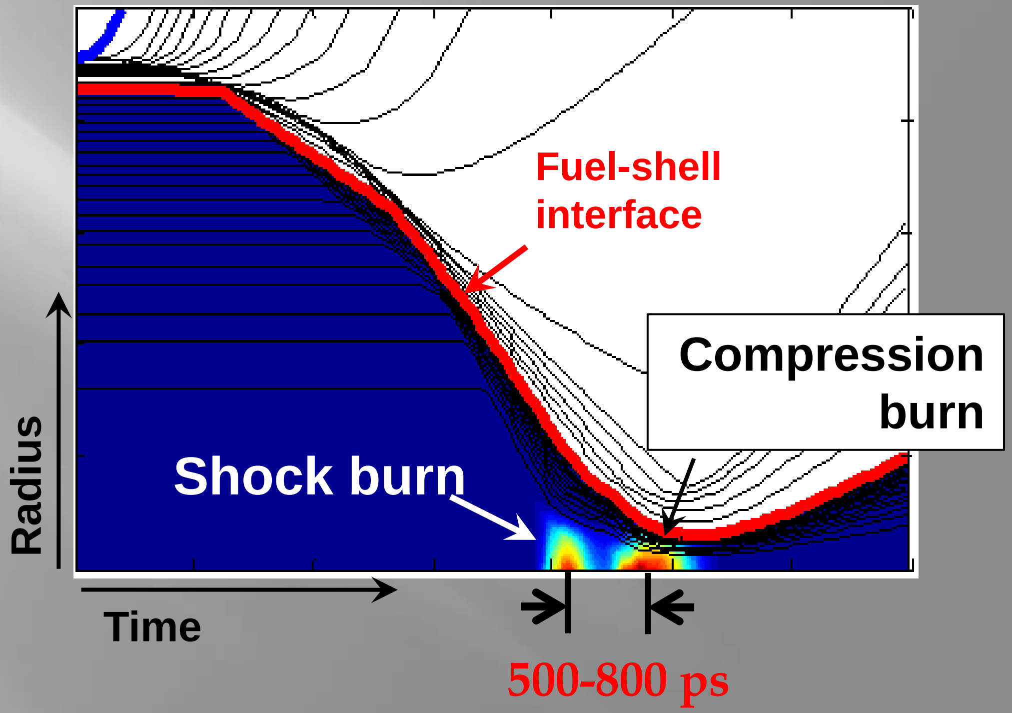
$$\mathbf{v} = \frac{1}{\rho}(n_i m_i \mathbf{v}_i + nem_e \mathbf{v}_e)$$

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

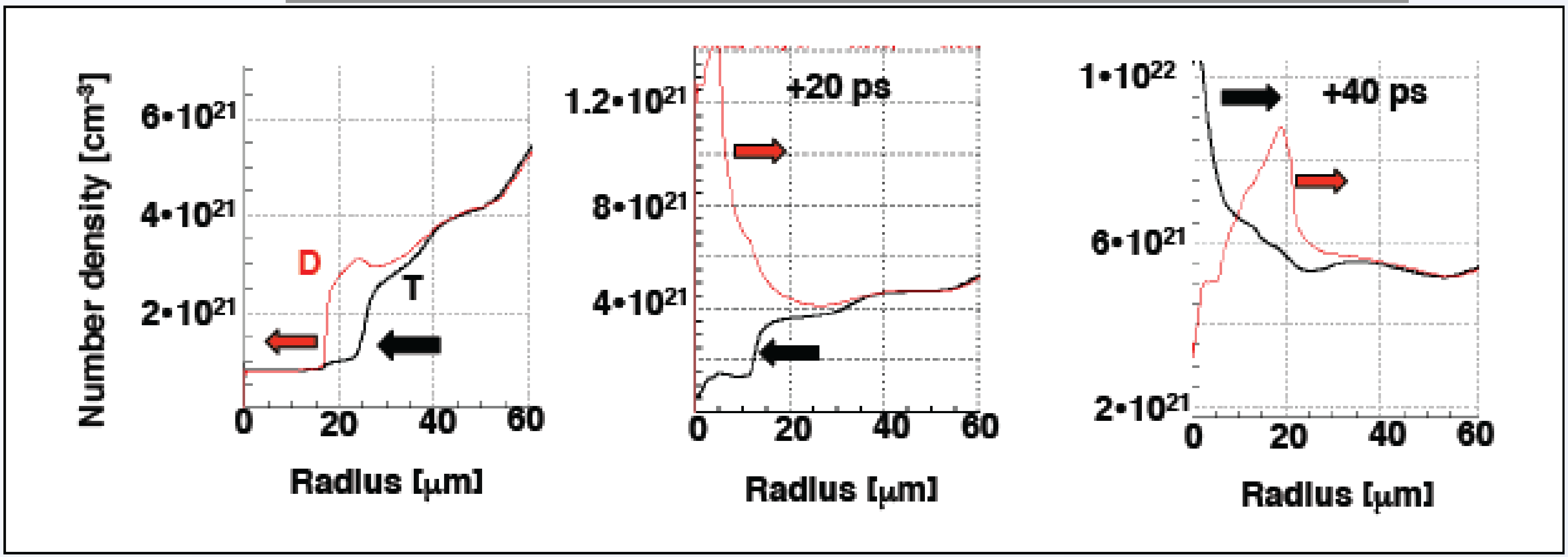
Hydro assumptions can break down during the shock-convergence phase





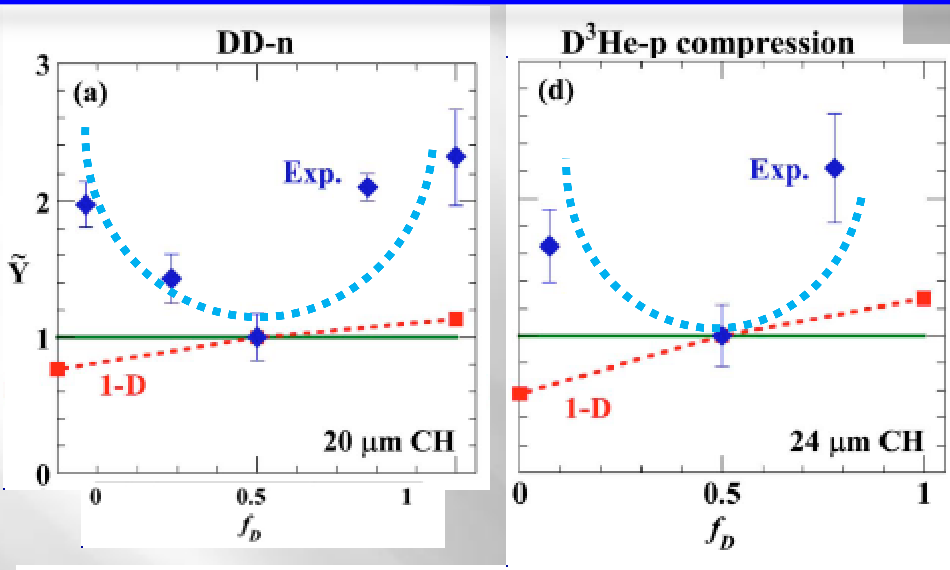


Significant fuel species separation occurs before and after shock flash in a NIF implosion, according to multi-fluid LSP simulation



C. Bellei et al, Phys. Plasmas 20, 012701 (2013)

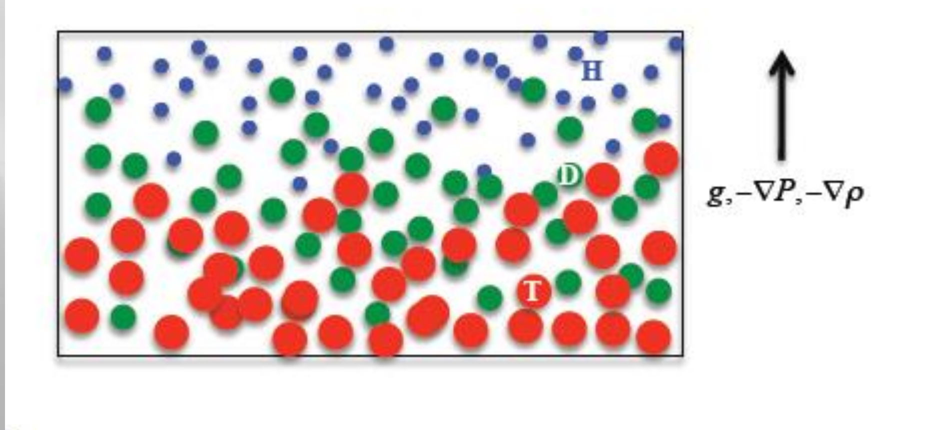
The observed ICF fusion yield anomaly has been related to the imbalance of fuel species densities in the burn region



For the hydrodynamic equivalent mixtures, the scaled yields are

$$\tilde{Y}_n = Y_n \frac{(3 - f_D)^2}{f_D^2}$$

$$\tilde{Y}_p = Y_p \frac{(3 - f_D)^2}{f_D(1 - f_D)}$$

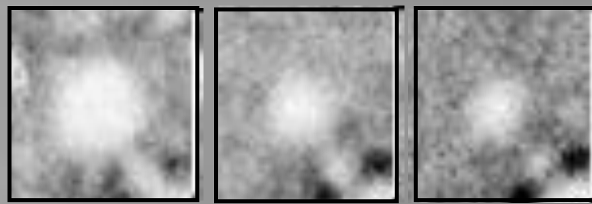


The effects of ion diffusion have been proposed to cause separation of fuel species, leading to this imbalance

J R. Rygg *et al.*, Phys. Plasmas (2008)

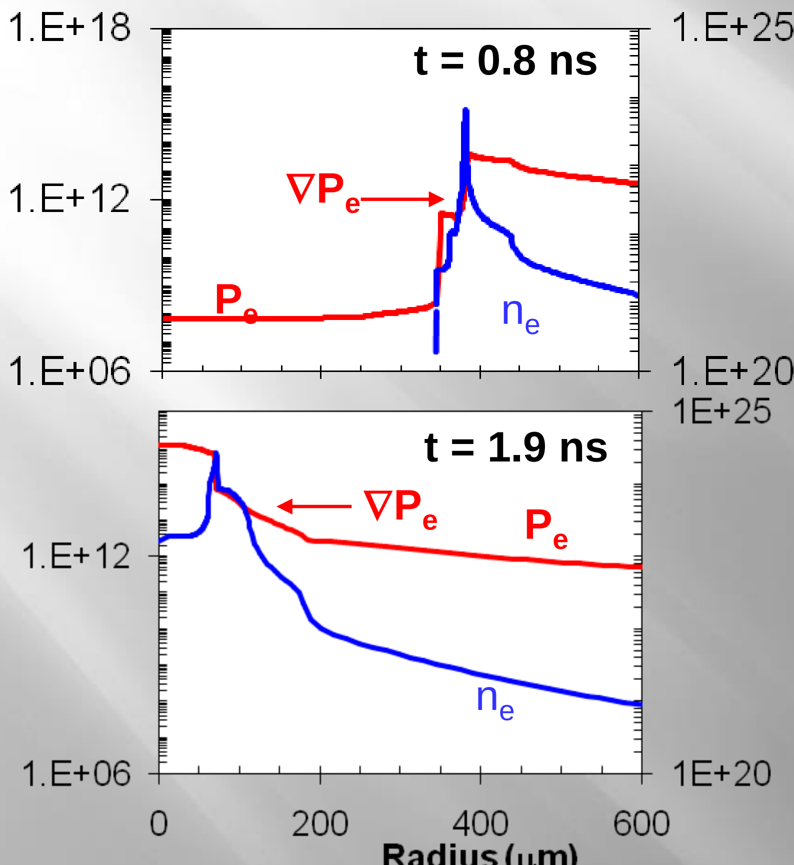
P. A. Amendt *et al.*, Phys. Rev. Lett. <u>109</u> 225001 (2010)

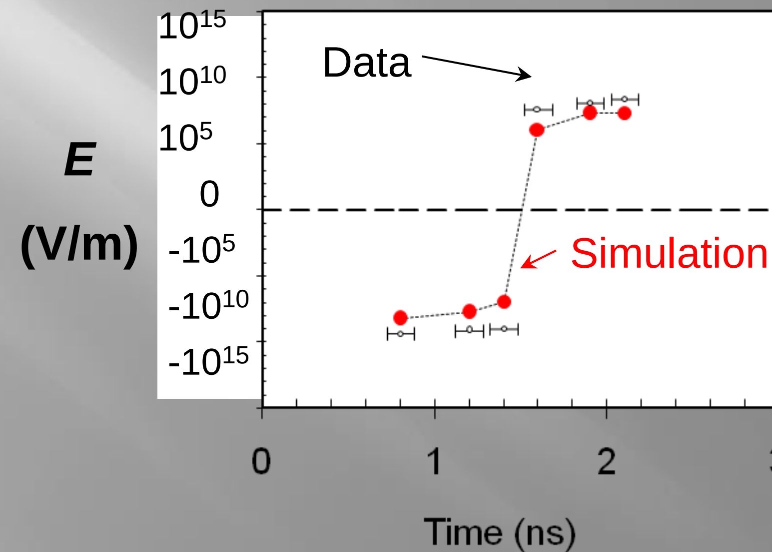
Observation of self-generated radial electric fields in an imploded capsule has been made



1.6 ns 1.9 ns 2.1ns

LILAC simulations by J. Delettrez





0.8 ns 1.2 ns 1.4 ns

C. K. Li *et al.*, PRL 100 225001 (2008)

Recent work by Amendt *et al* delineates the effects of ion diffusion in plasmas of imploded capsule

Classical diffusion	Barotropic diffusion	Electro diffusion	Thermal diffusion

Mass diffusivity flux

$$i_1 = -\rho D\left(k_\alpha \ln P + k_p \frac{d\ln P}{dx} - k_E \frac{eE}{k_B T} + k_T \frac{d\ln T}{dx} \right)$$

Classical diffusion coefficient

$$k_\alpha = -\alpha(1-\alpha)\left[\left(1-\frac{m_1}{m_2}\right)\left(1+\frac{Z_2 T_e}{T}\right)-\frac{\Delta Z T_e}{T}\right] f\left(\alpha, Z_1, Z_2, m_1/m_2, T_e/T\right)$$

Barodiffusion coefficient k_p :

$$k_p = \alpha(1-\alpha)(Z_2 - Z_1)\left(\frac{\alpha\frac{1+Z_1}{m_1}+(1-\alpha)\frac{1+Z_2}{m_2}}{\alpha\frac{Z_1(1+Z_1)}{m_1}+(1-\alpha)\frac{Z_1(1+Z_2)}{m_2}}\right)$$

Electrodiffusion coefficient k_E :

$$k_E = \alpha(1-\alpha)\left[\left(\frac{Z_1}{m_1}-\frac{Z_2}{m_2}\right)\left(m_1\alpha + m_2(1-\alpha)\right)\right]$$

Thermaldiffusion coefficient

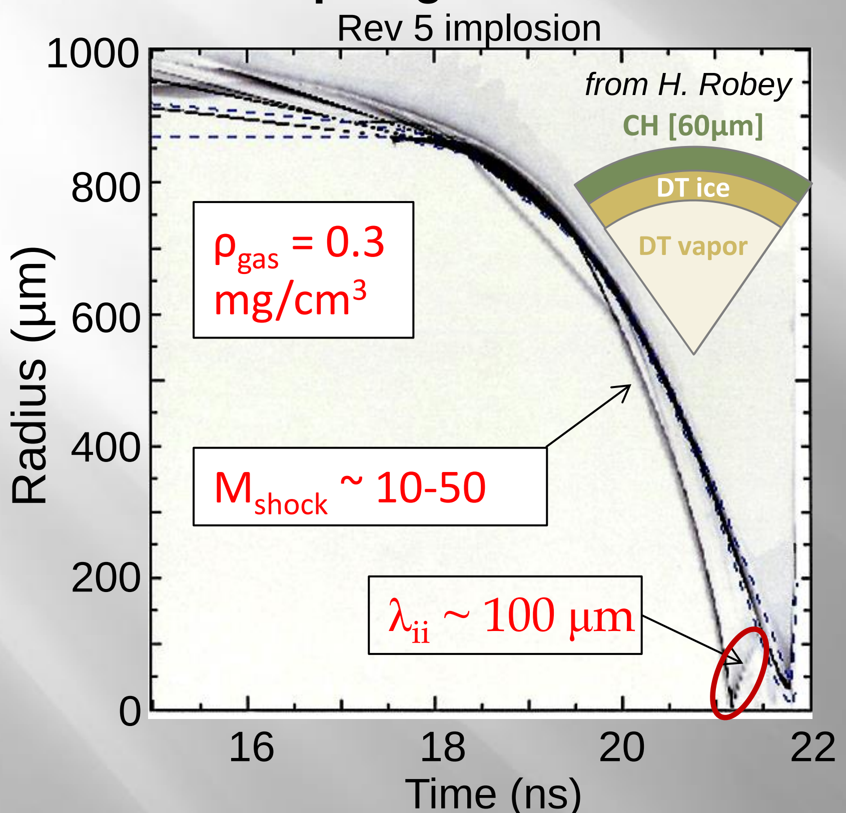
$$k_T = \frac{k_p + k_\alpha + k_E\left[1-\frac{k_\alpha \Delta Z}{\left[\alpha Z_1 m_1/m_2+(1-\alpha)Z_2\right]\left[\alpha(1+Z_1)+(1-\alpha)(1+Z_2)m_1/m_2\right]}\right]}{\frac{\Delta Z m_1 k_\alpha}{m_2\left(1+\bar{Z}\right)\left[\alpha+(1+\alpha)m_1/m_2\right]}+\frac{\gamma+1}{\gamma}}$$

P. A. Amendt *et al*., PRL. <u>109</u> 225001 (2010)

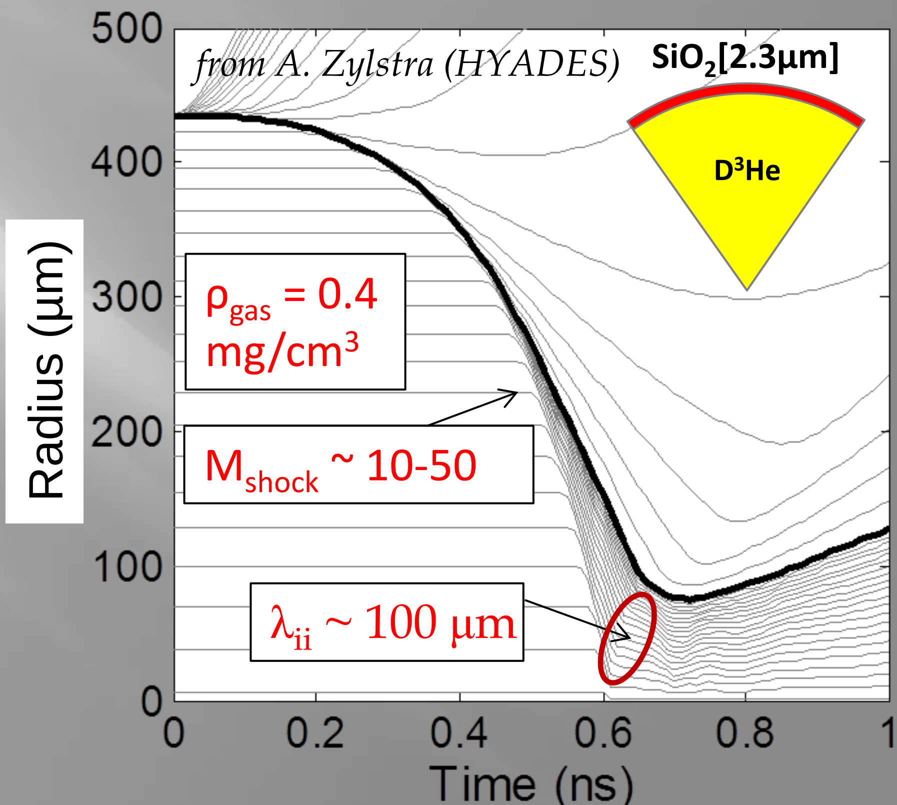
PRL, accepted (2012)

Exploding pushers generate conditions similar to the shock convergence phase of hot-spot ignition implosions

NIF hot-spot ignition simulation



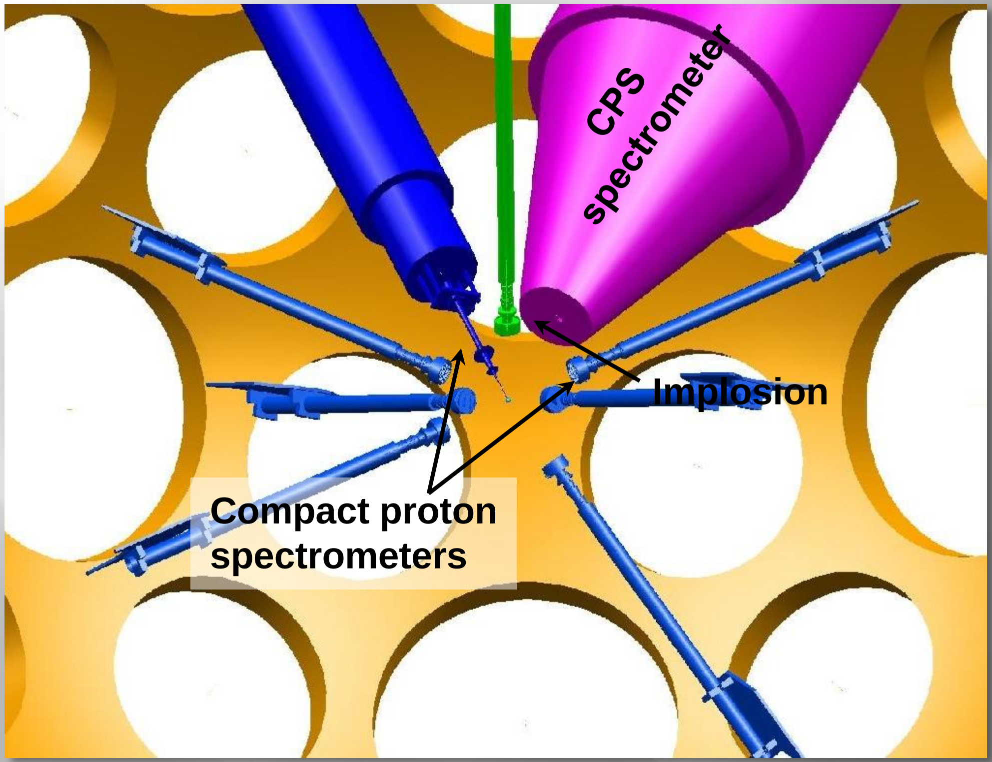
OMEGA exploding pusher simulation



Shock phase characterized by high temperature, moderate density, large λ_{ii}, kinetic effects

A comprehensive set of diagnostics was used to measure implosion conditions and assess performance of hydro models

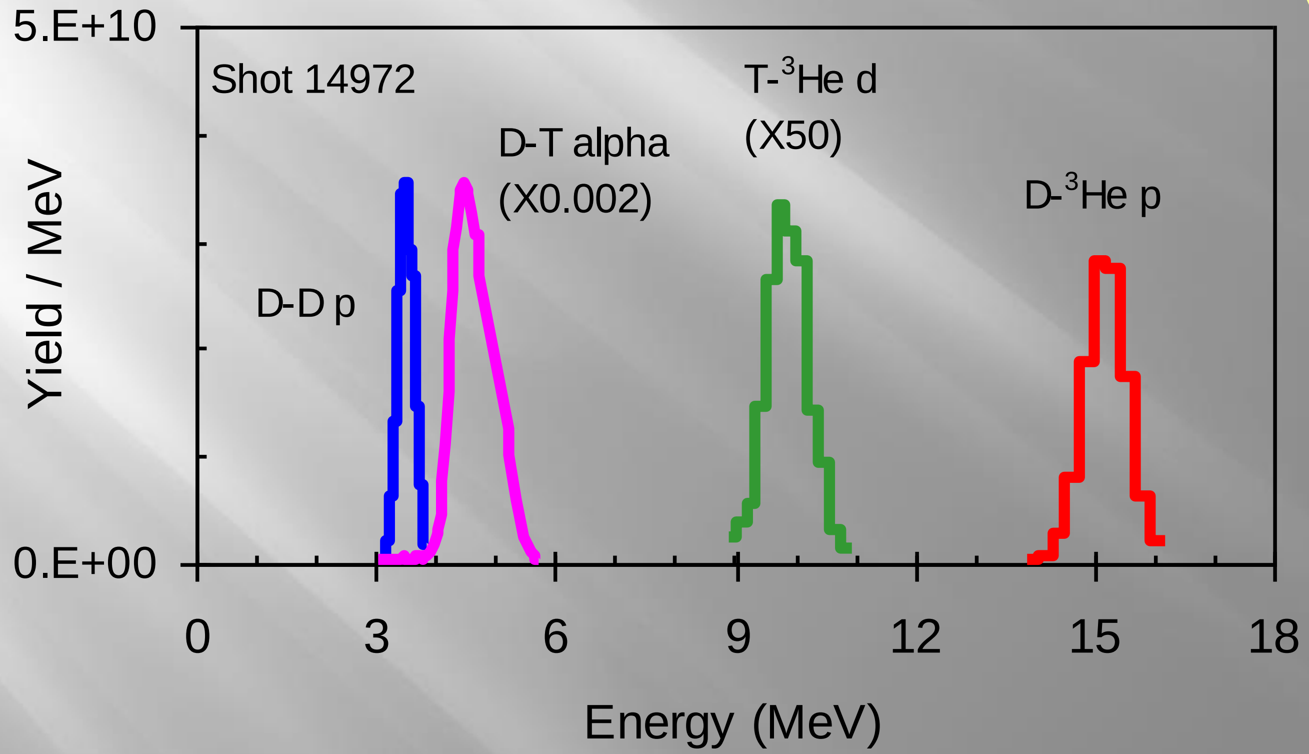
OMEGA target chamber
(only a few of the many diagnostics)

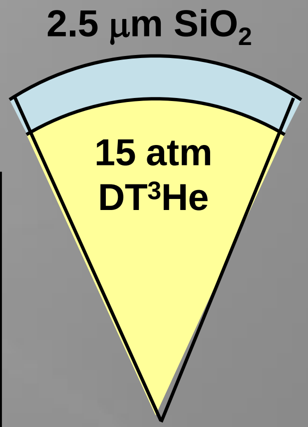


Key measurements:

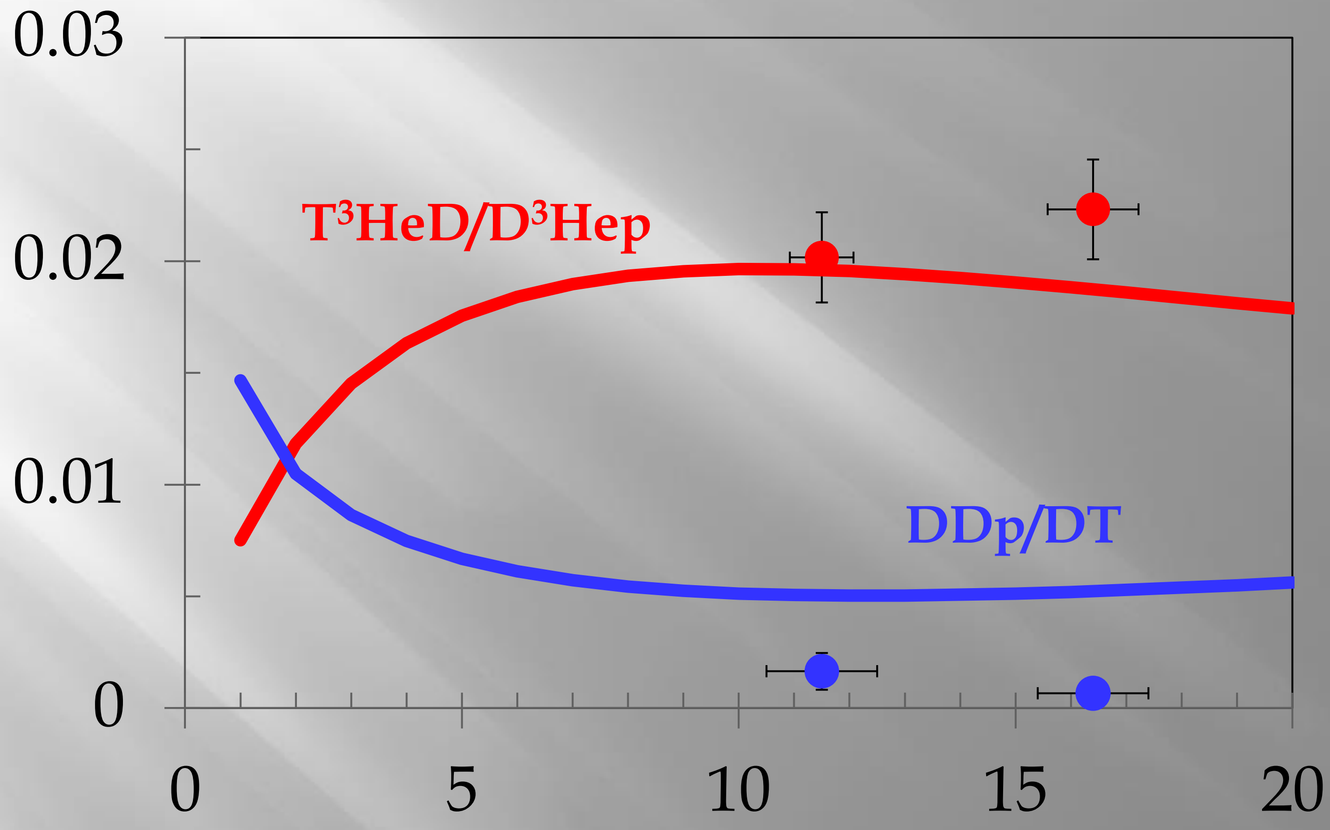
- DD and D^3He yields
- Burn-averaged T_i
- DD and D^3He burn histories
- DD and D^3He burn profiles
- Fuel ρR (ion density)
- X-ray self-emission images (R)
- Scattered light

The first spectra of 4 nuclear reactions are simultaneously measured from a single capsule implosion that filled with DT³He gas

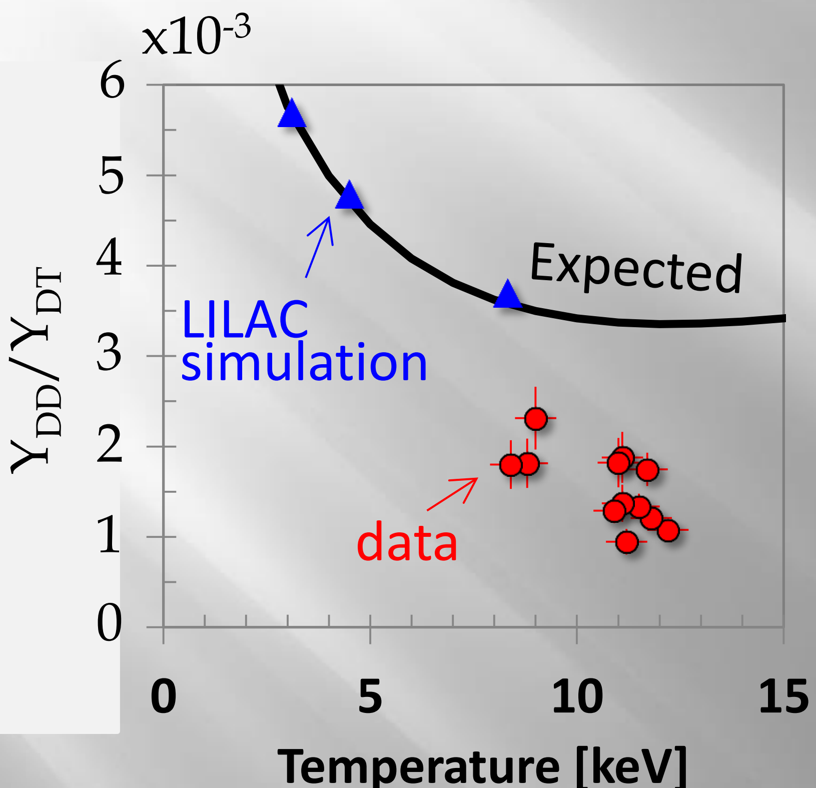


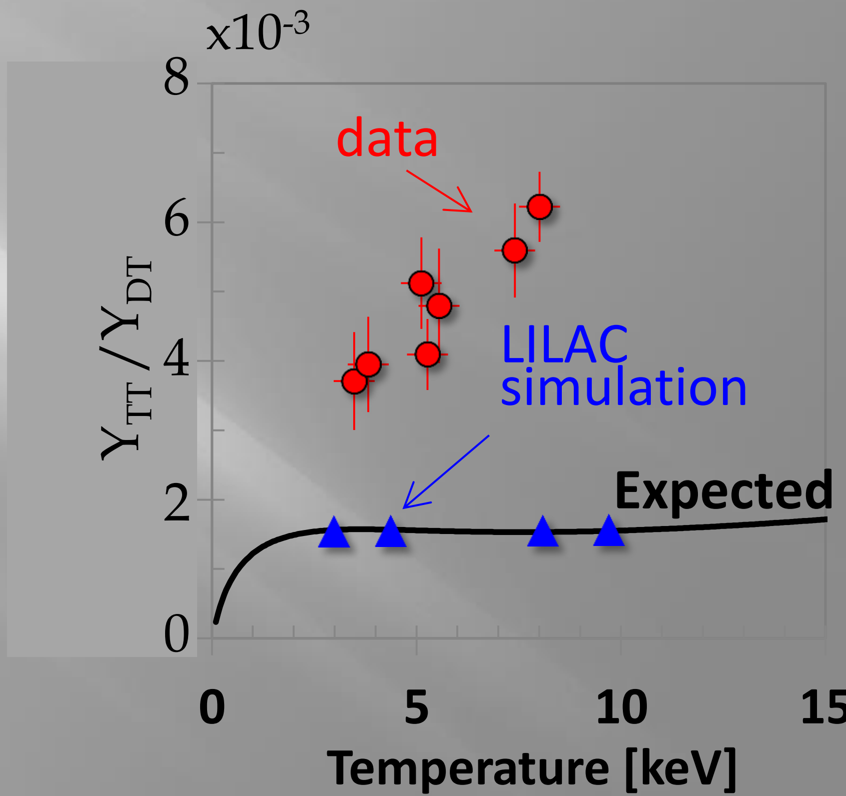


The Y_{T3HeD}/Y_{DHep} and Y_{DDn}/Y_{DT} yield ratios are deviated from the predictions, qualitatively indicating the fuel stratification



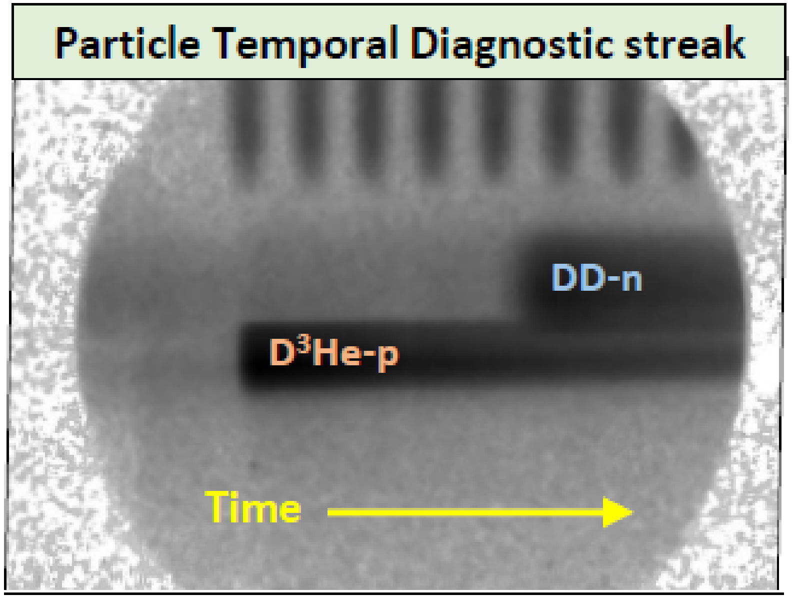
While DD yields relative to the DT yield are lower than expected, TT reaction yields are higher than expected (assuming a constant density ratio f_t/f_d)

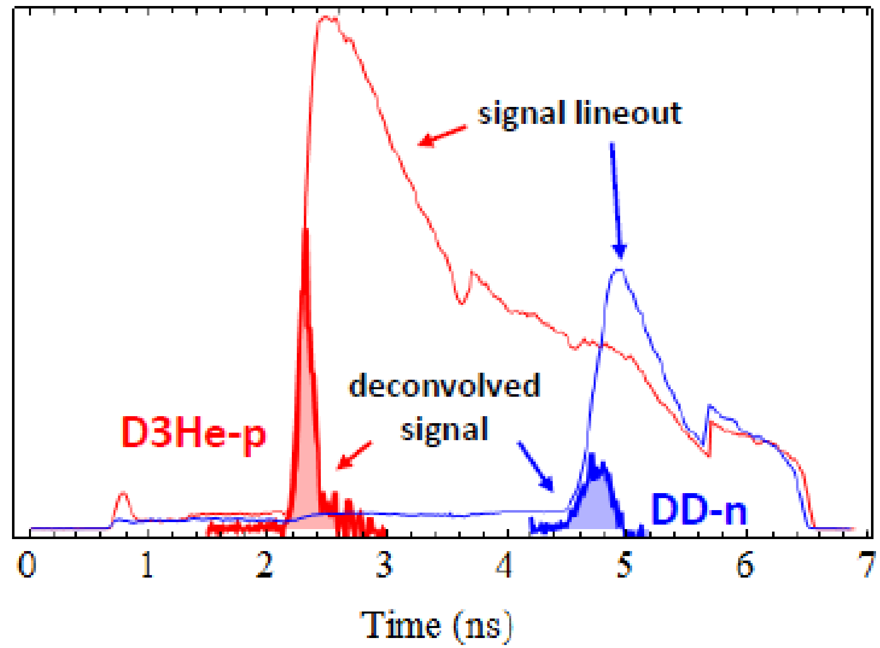




D. T. Casey et al, Phys. Rev. Lett. 108, 075002 (2012).

Measurement of D3He-p and DD-n burn history on a single diagnostic has been developed at OMEGA



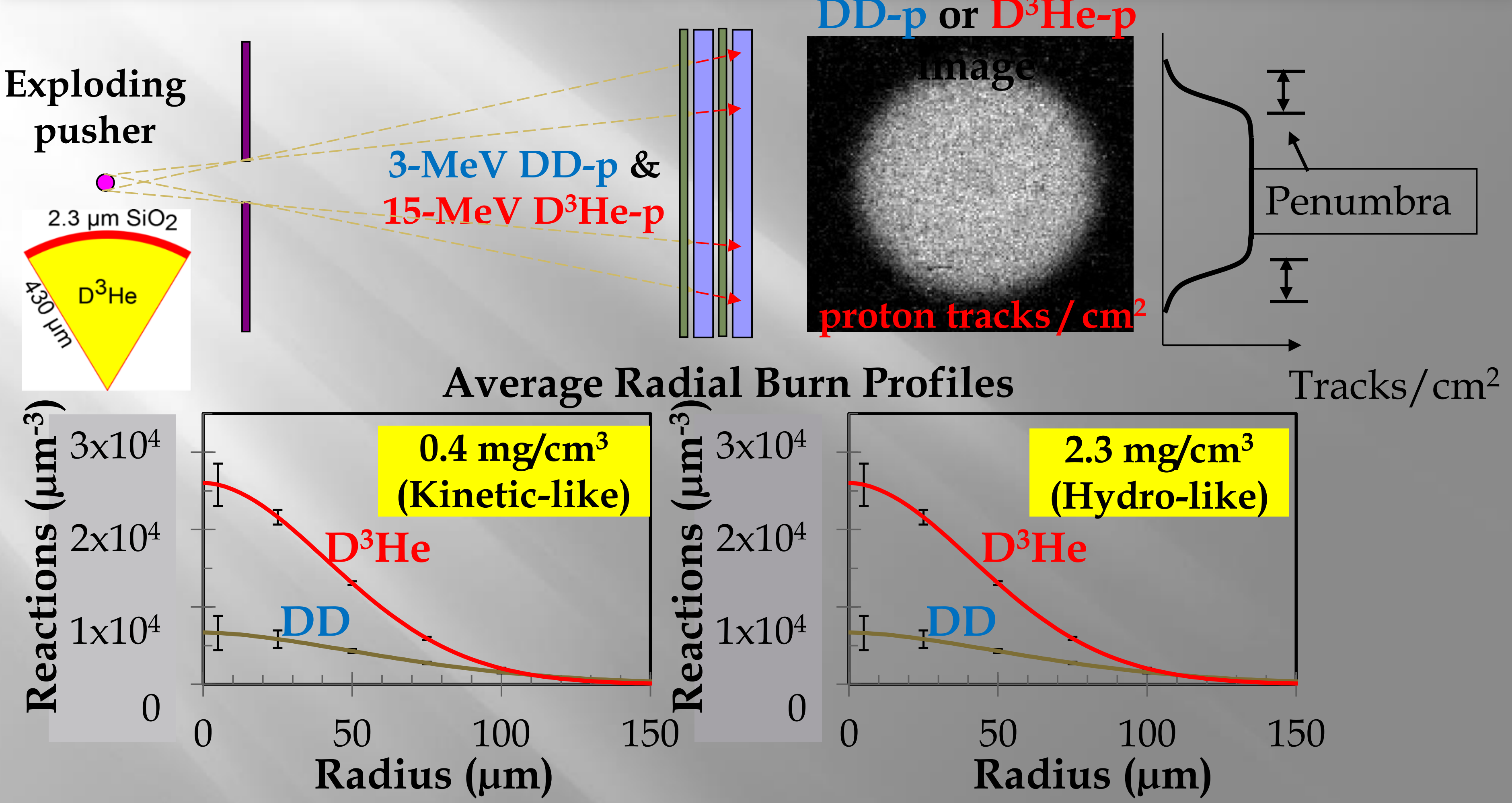


This diagnostic will explore detailed effects of kinetic and multi-ion physics on fusion burn.

Current relative accuracy: ± 20 ps
Goal relative accuracy: ± 10 ps

Hong Sio *et al*., to be submitted (2014)

Penumbral imaging of the fusion burn was used to infer burn profiles across the hydrodynamic and kinetic regimes

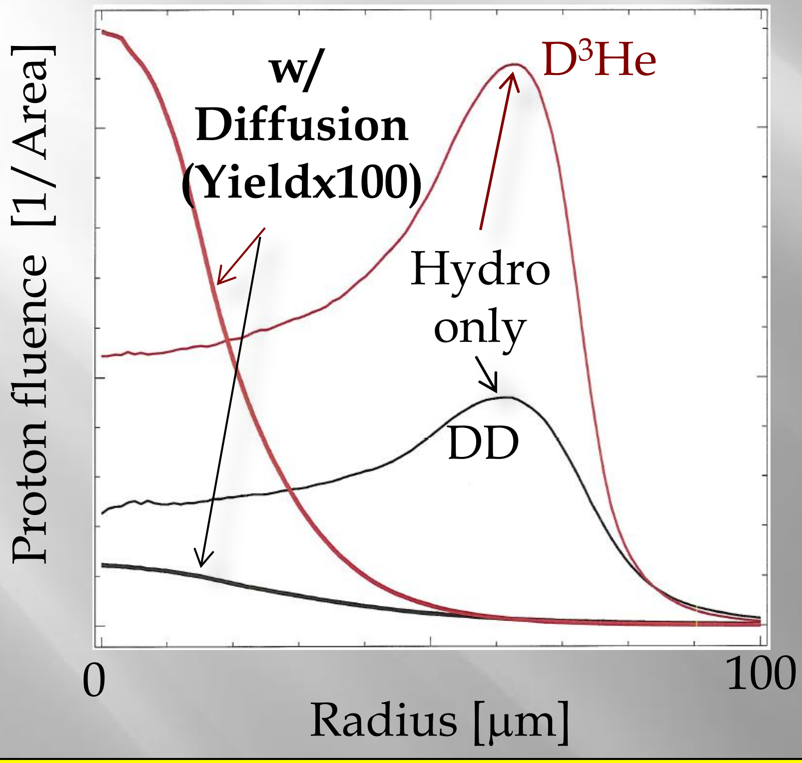


Séguin *et al*., RSI (2004), PoP (2006)

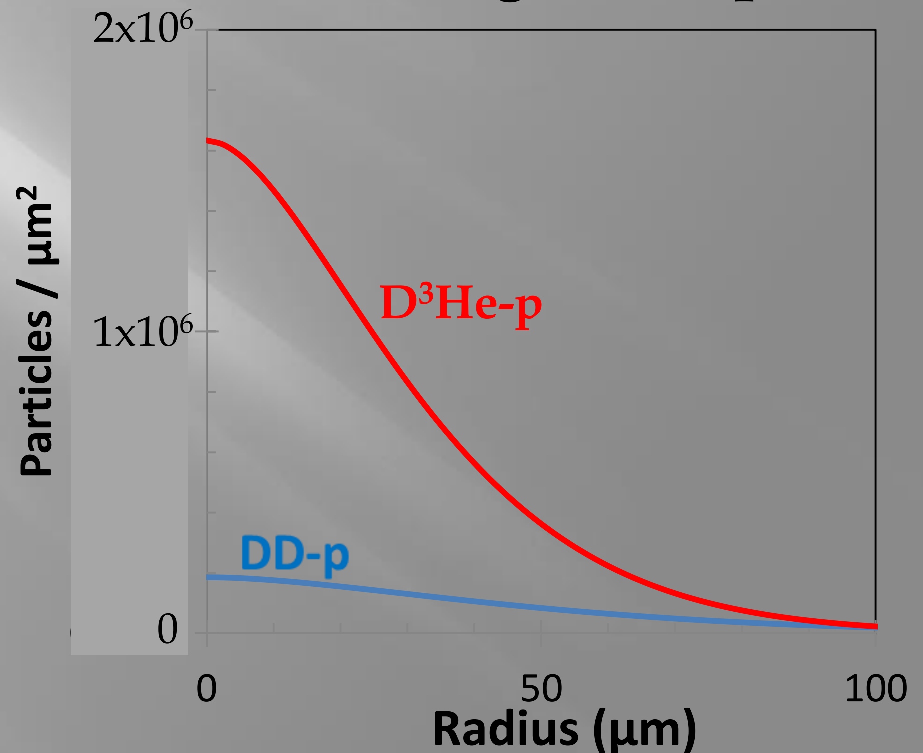
Measured burn profiles are centrally-peaked, in stark contrast to the pure-hydro model but in agreement with a diffusion model

0.4 mg/cm³ (kinetic regime)

Simulated brightness profiles



Measured brightness profiles



These results further demonstrate that ion diffusion is substantial in the long-λ_{ii} implosi

Simulations by P. Amendt, LLNL

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