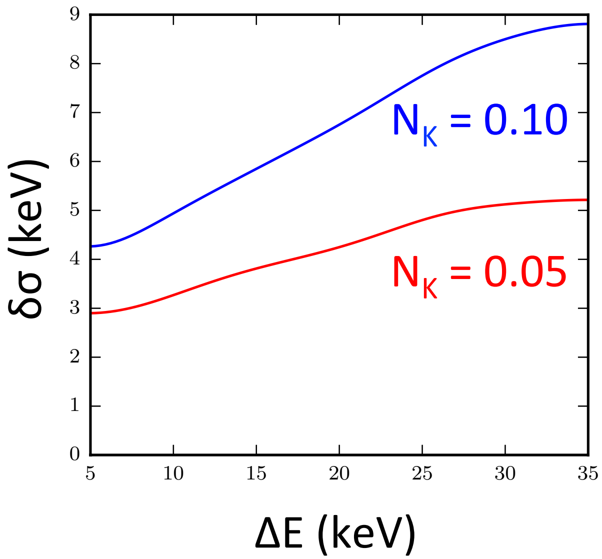
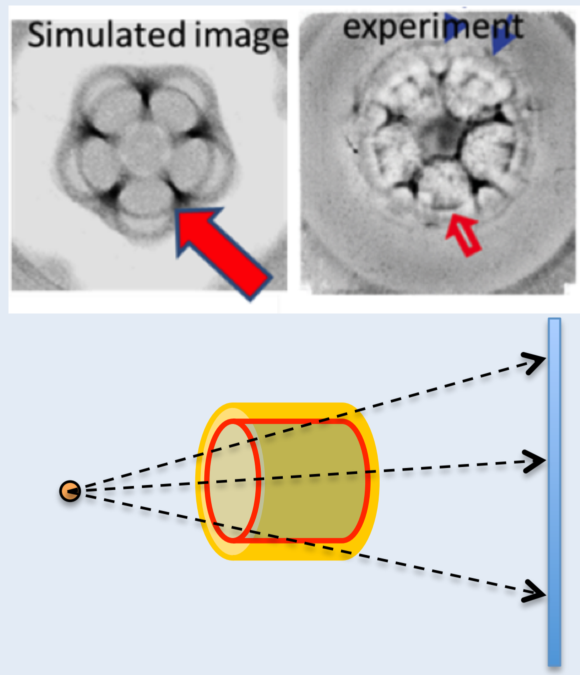
Diagnostic Signatures of Kinetic Effects in Inertial-Confinement Fusion-Relevant Plasmas

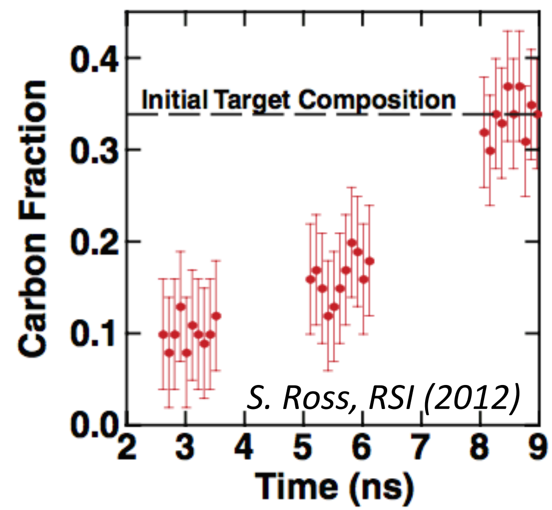
Nuclear Spectra



Proton Radiography



Thomson Scattering



Hans Rinderknecht, LLNL

ICF Diagnostics Workshop

October 7th 2015

Kinetic physics impacts the diagnostic signatures of ICF plasmas, in small but (potentially) measurable ways

- Several deviations from expected hydrodynamic behavior have been predicted and observed in ICF implosions
  - Kinetic physics – specifically, **Knudsen-layer ion loss, ion diffusion,** and **ion species thermal decoupling** – have been used to explain the observations.
- Three diagnostic signatures are modified by these kinetic effects in ways that are potentially measurable:
  - **Fusion product** spectra are narrowed and shifted by tail-ion loss
  - **Thomson scattering** is sensitive to ion concentration/diffusion
  - **Proton radiography** can detect distinctive electric field structures
- These effects are subtle, requiring *precise diagnostics* and/or *extreme experiments.*

Many Thanks to my collaborators

S. Wilks, P. Amendt, C. Bellei, L. Berzak Hopkins, O. Landen, H.-S. Park, J. Pino, H. Robey, J.R. Rygg, V. Smalyuk, **LLNL**

A.B. Zylstra, N. Hoffman, G. Kagan, K. Molvig, **LANL**

H. Sio, M.J. Rosenberg, M. Gatu Johnson, N. Sinenian,
J.A. Frenje, C.K. Li, F.H. Seguin, R.D. Petrasso, **MIT PSFC**

R. Betti, J. Delettrez, V. Yu Glebov, V. Goncharov, F.J. Marshall, D.D. Meyerhofer,
T. C. Sangster, W. Seka, C. Stoeckl, B. Yaakobi, **LLE**

T. Caillaud, O. Landoas, O. Larroche, **CEA**

A. Greenwood, A. Nikroo, J. Kilkenny **GA**

and the NIF and OMEGA Teams

Outline

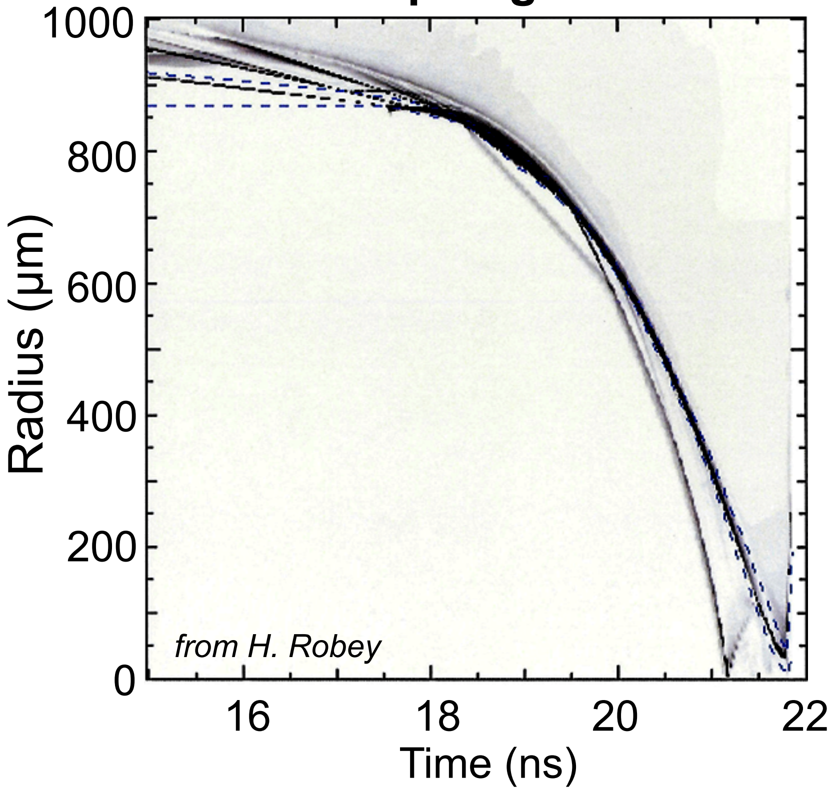
1. **Kinetic physics in Inertial Confinement Fusion**
   - **Ion distribution modification ("Tail-ion loss")**
   - **Diffusive ion species separation**
   - **Ion thermal decoupling**

2. **Impact on diagnostics**
   - **Nuclear**
   - **Thomson scattering**
   - **Proton radiography**

3. **Conclusions & Future Work**

Hydrodynamic codes are relied on to design and understand ICF implosions…

Simulation of Hot-spot ignition



$\lambda_{ii} \sim T_i^2/n \ln(\Lambda)$

<u>Hydrodynamic assumption</u>

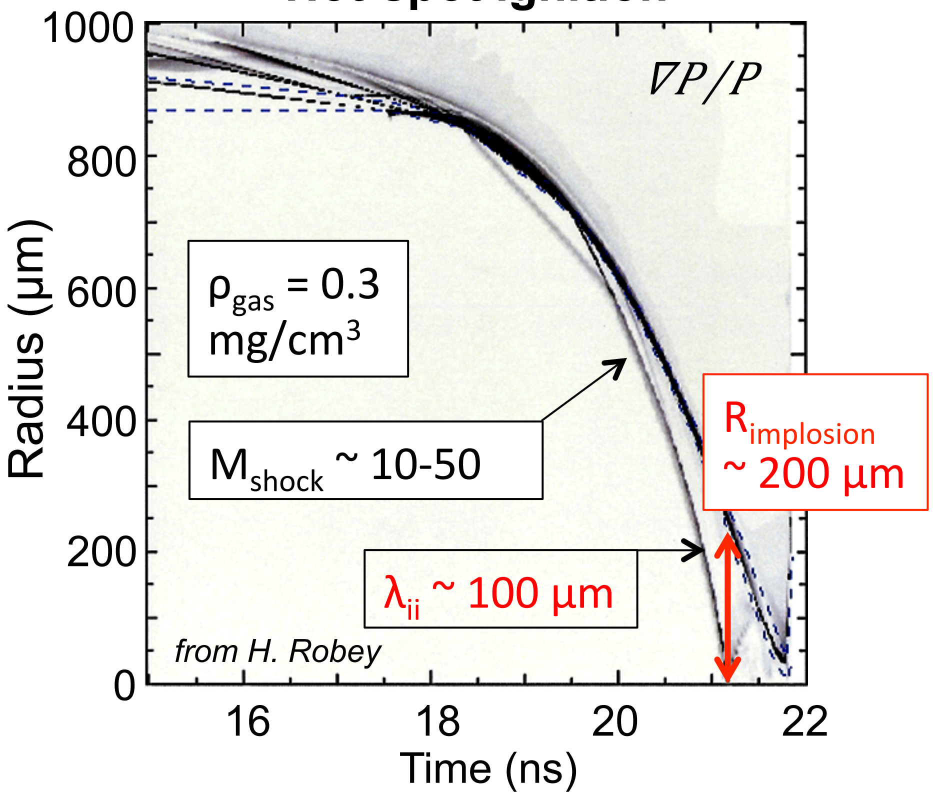
The ion mean free path λ_{ii} is short compared to the dynamical length scales:

$$\lambda_{ii} \ll \frac{P}{\nabla P} \ll \text{Radius of Implosion}$$

If true, the plasma is 'fluid-like,' and individual ion motion (*ion kinetic physics*) can be ignored…

Hydrodynamic codes are relied on to design and understand ICF implosions… but are not always valid

Simulation of Hot-spot ignition



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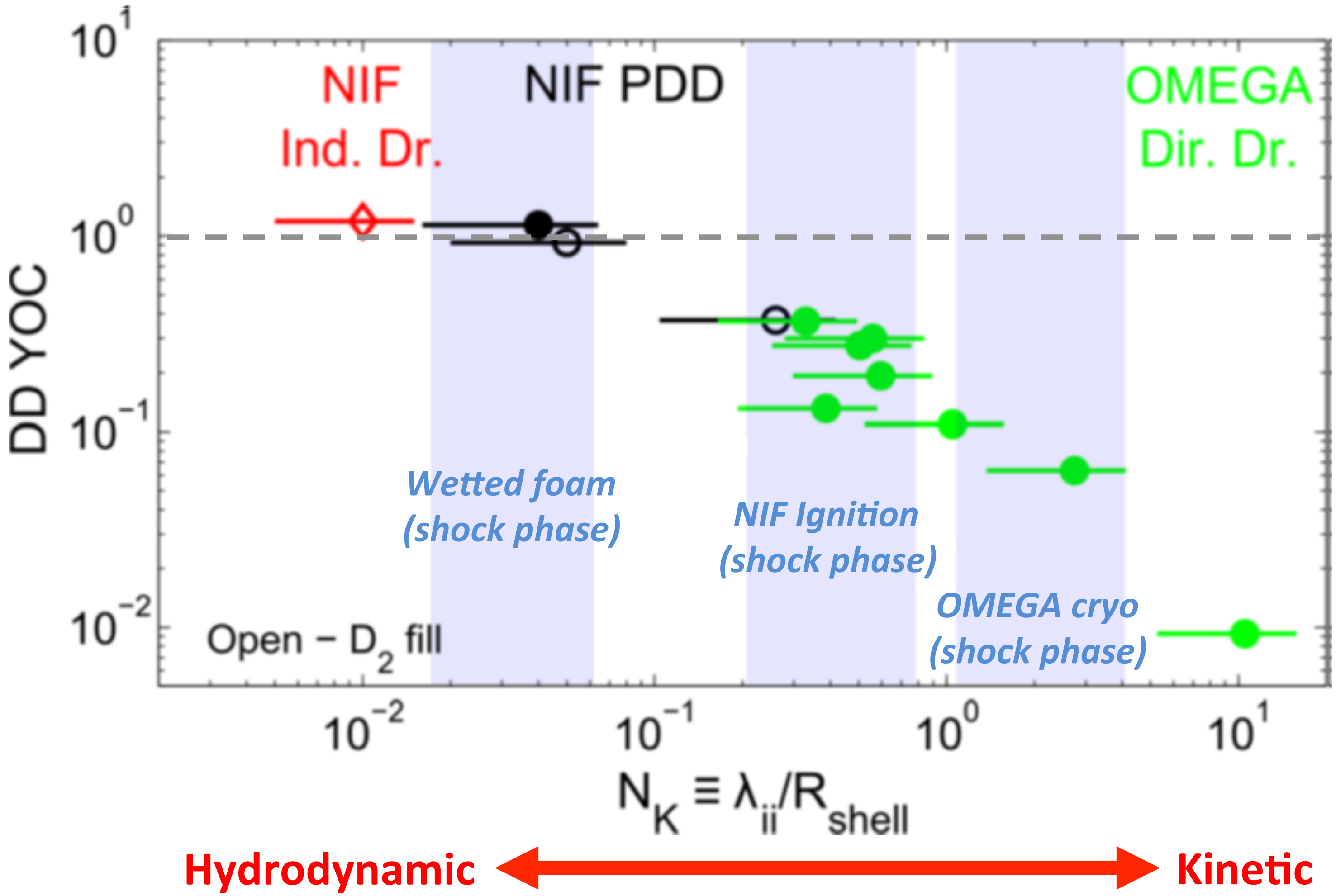
If true, the plasma is 'fluid-like,' and individual ion motion (*ion kinetic physics*) can be ignored…

… if not, *modified ion distributions* may produce unexpected behavior.

Hydro simulations fail to describe nuclear yields produced in ignition shock-phase relevant plasmas

NIF, Ω

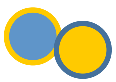
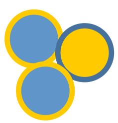


"Hydrodynamic Performance"

M. Rosenberg, POP **21**, 122712 (2014)

Hydrodynamic codes are relied on to design and understand ICF implosions, but only model one ion species

Experiment

Species (%)		Mass	Charge
D (50%)		**2 amu**	**+1 e**
T (50%)		**3 amu**	**+1 e**

Hydrodynamic Simulation (“Single-ion fluid”)

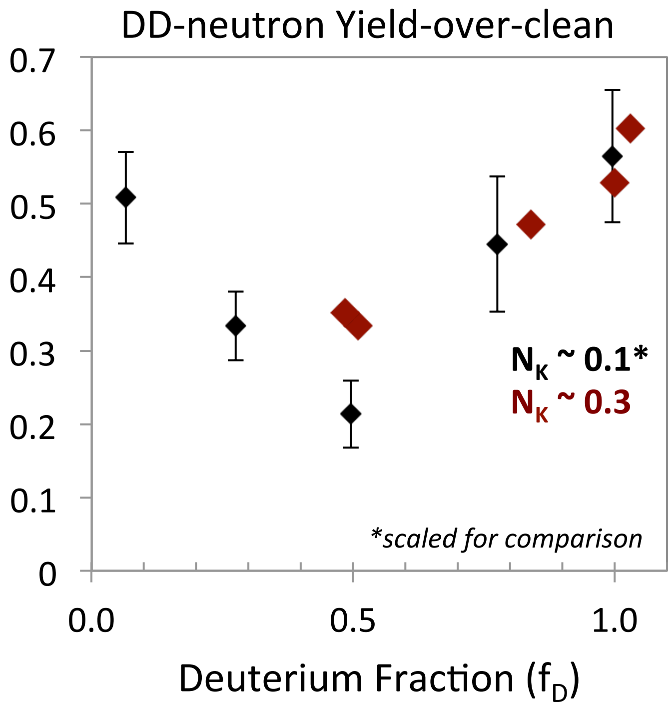
Species	Mass	Charge
“DT”	**2.5 amu**	**+1 e**

***Multiple-ion kinetic physics* may produce unexpected behavior:**

- **Diffusive change to ion concentration (~ λ_{ii})**
- **Decoupling of ion temperatures (~ τ_{ii})**

Several multi-species related "anomalies" have been observed in both low- and high-N_K implosions

Low – Moderate N_K:



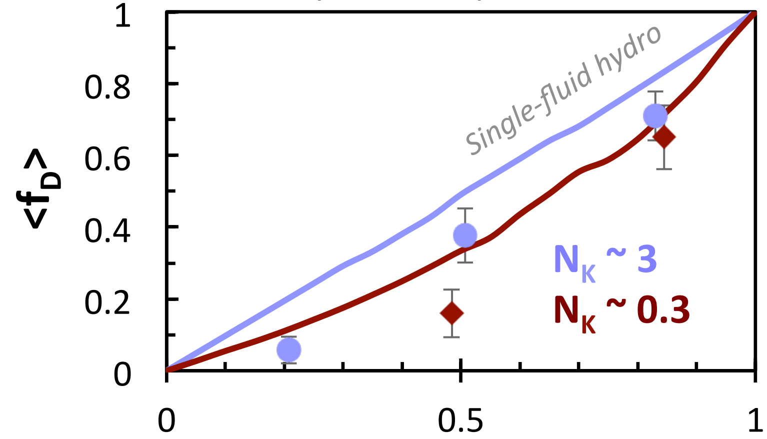
J. R. Rygg, et al. POP **13**, 052702 (2006)

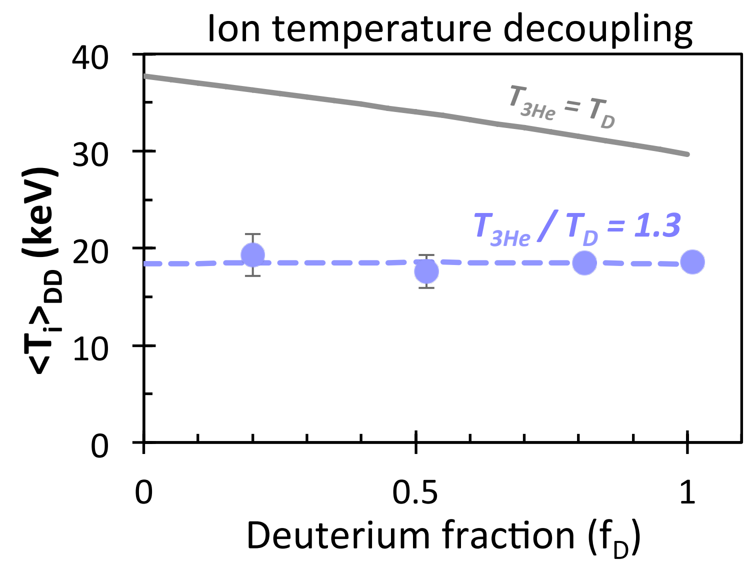
See Also:

H. W. Herrmann, et al. POP **16**, 056312 (2009)

D. T. Casey, et al. PRL **108**, 075002 (2012)

Moderate – High N_k:





H. G. Rinderknecht, et al., PRL 2015

How do these kinetic effects – ion distribution function, and multi-species diffusion and thermal decoupling – impact diagnostic signatures?

NIF

Diagnostic systems sensitive to ions:

- fusion diagnostics (nuclear) *This talk*
- Thomson scattering (optical)
- Proton radiography (nuclear)
- *Opacity imaging (x-ray)*
- *Spectral imaging (x-ray)*
- *Compton scattering (gamma)*
- *…*

Note that, by their very nature, kinetic physics effects occur on the scale of collision time (τ_{ii}) and/or the mean free path (λ_{ii}).

We need either very **sensitive diagnostics** or very **extreme experiments.**

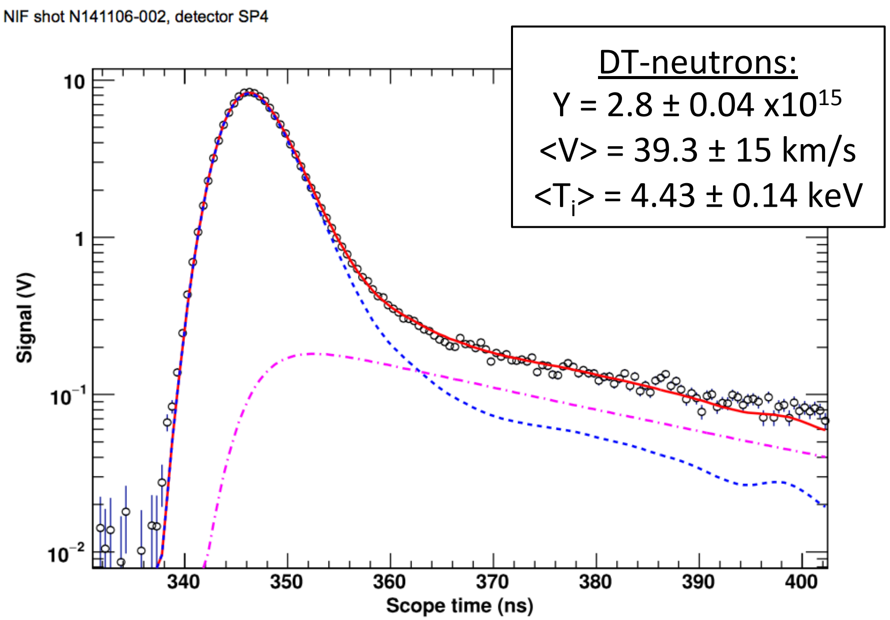
Outline

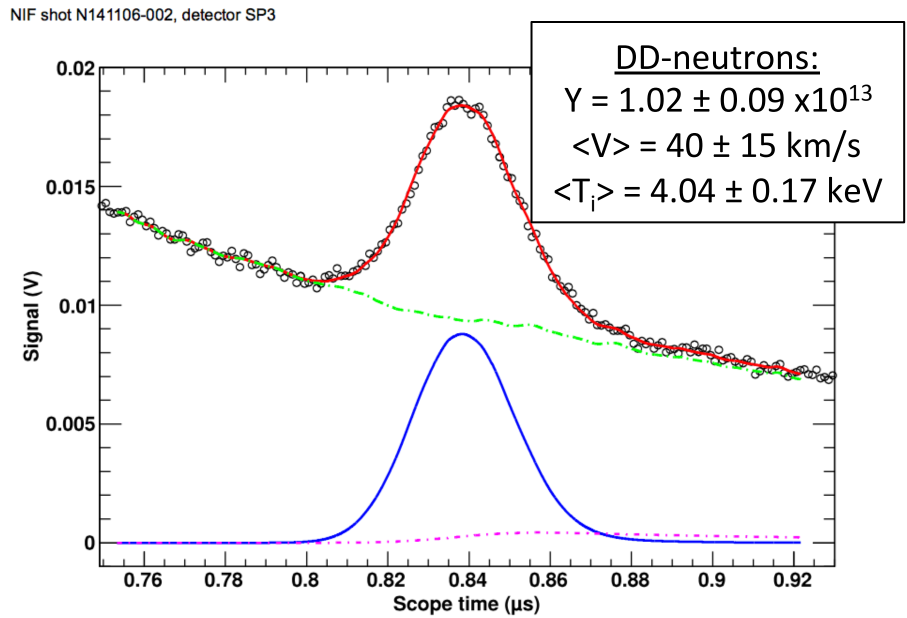
1. Kinetic physics in Inertial Confinement Fusion
   – Ion distribution modification ("Tail-ion loss")
   – Diffusive ion species separation
   – Ion thermal decoupling

2. Impact on diagnostics
   – Nuclear spectra
   – Thomson scattering
   – Proton radiography

3. Conclusions & Future Work

Spectra of fusion products contain substantial information about the fusing plasma





State of the art:
- DT-n and DD-n spectra are measured with ~%-level accuracy
- 0^{th}—2^{nd} moments interpreted as [Yield, flow velocity, $\langle T_i \rangle$]

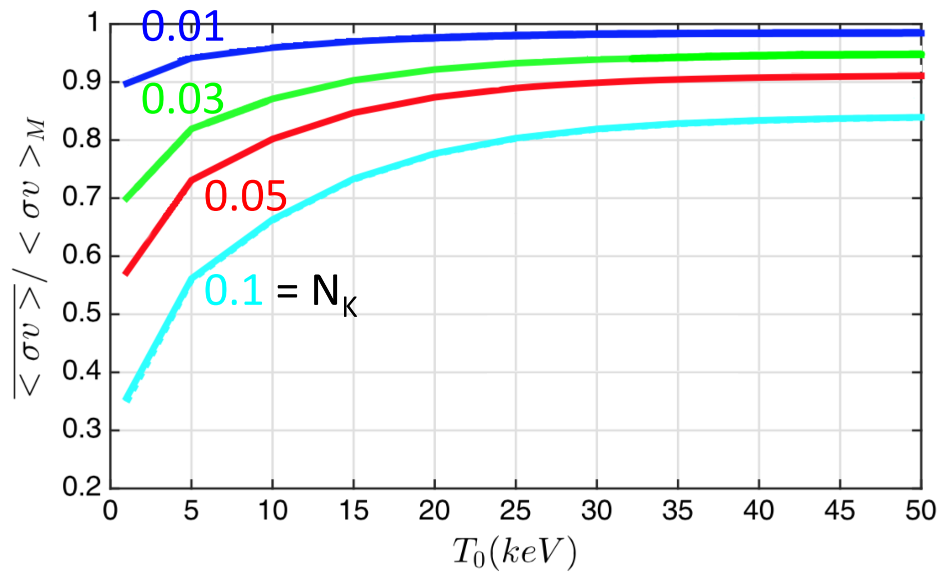
Near Future:
- Measure 3^{rd} & 4^{th} moments → T_i variance, flow/T_i correlation, …
- Improve precision (~ 0.1%), linearity, dynamic range

For more on nTOF spectral measurement & improvements, see Gary Grim's talk.

Brysk, Plasma Physics 1973
Ballabio, et al., NF 1998 (incl. relativistic)
Murphy, POP 2014 (turbulent kinetic energy)

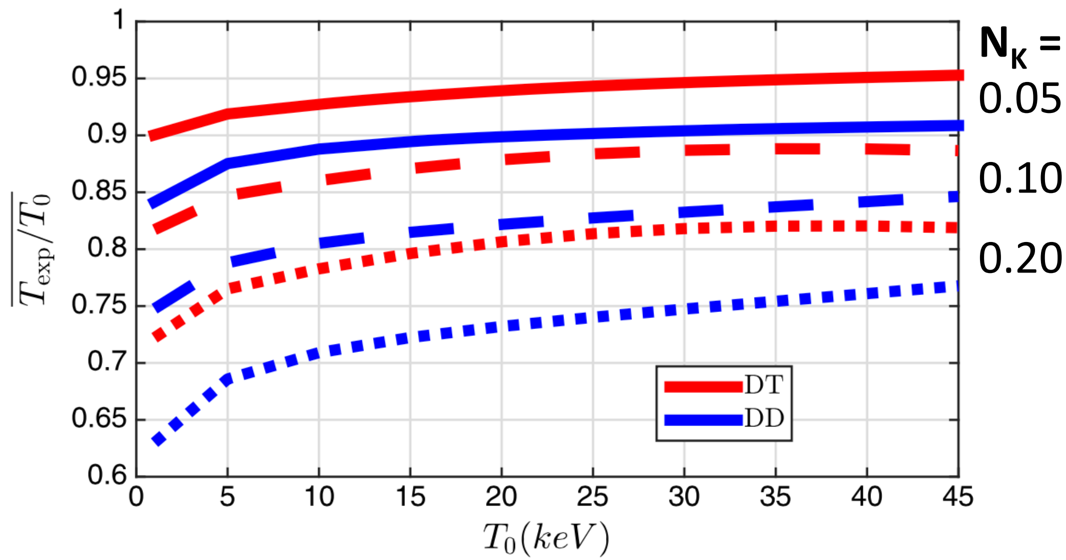
Both the fusion reactivity and the width of the fusion product spectra are reduced by tail ion loss

Fusion reactivity:



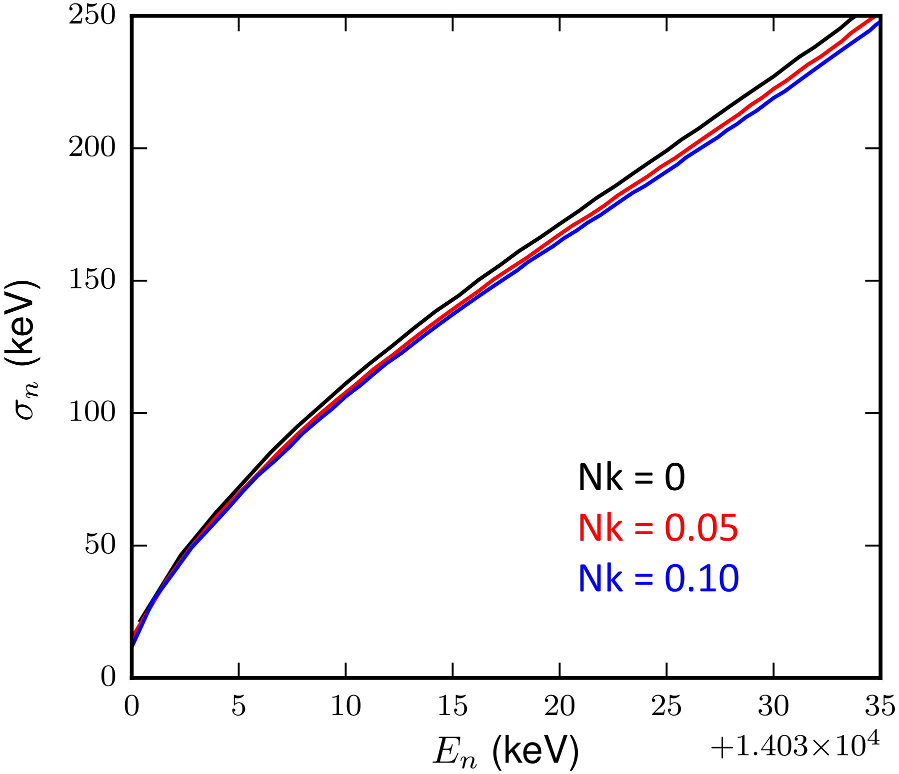
Inferred T_i from spectra:
<Ti> ~ (FWHM)^2

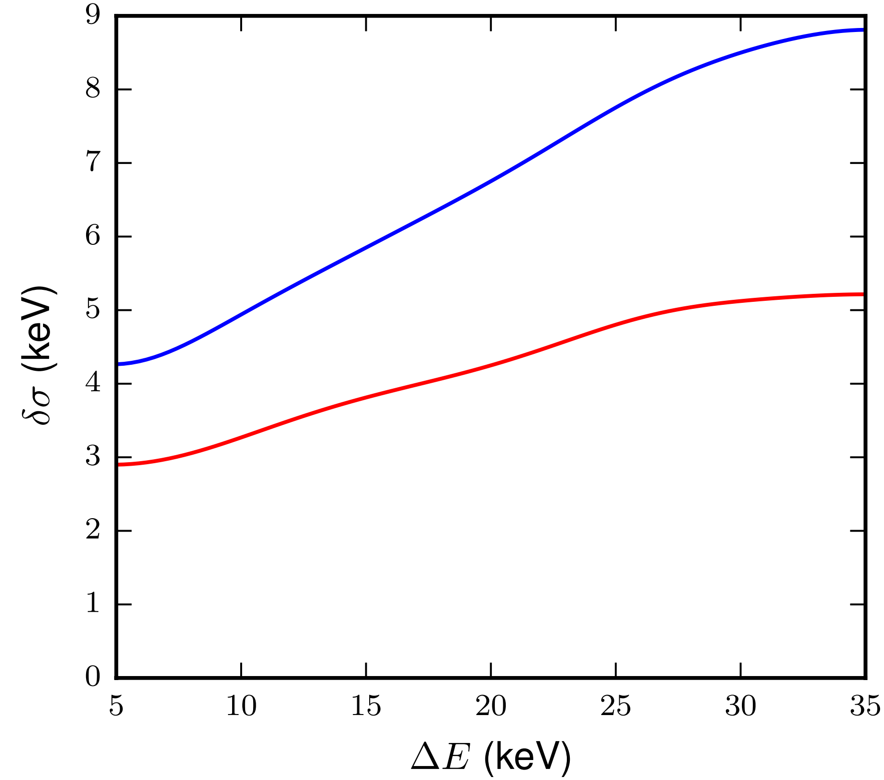
For a given spectrum, this introduces a degeneracy between Ti and N_K



Kagan, et al., PRL 2015

Degeneracy between <Ti> and Knudsen number can be broken with sensitive (~keV) spectral measurements





Simulations of the DT-neutron spectrum produced using a modified ion distribution function[1] show the moments vary with N_K.

[1]Molvig, et al., PRL 2012

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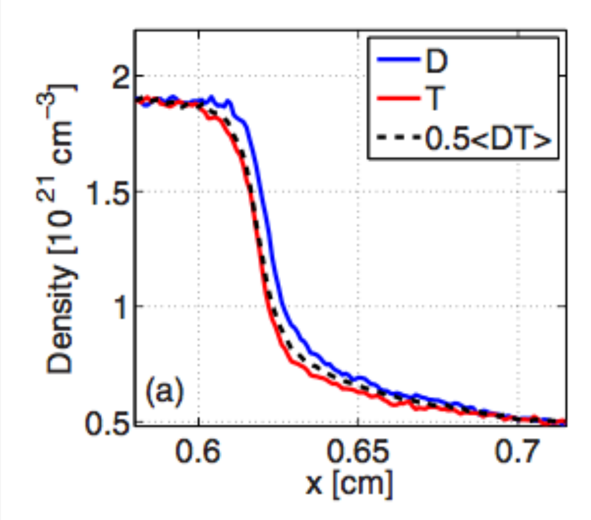
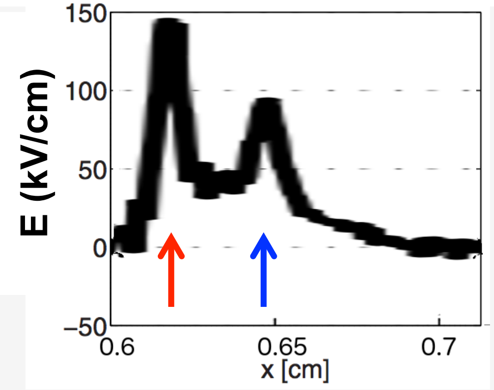
Kinetic simulations show distinctive E-field structures are associated with multi-species shocks and diffusion layers

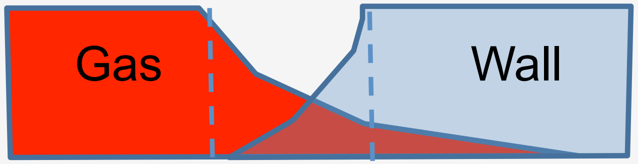
a) Shock front in multi-species plasma

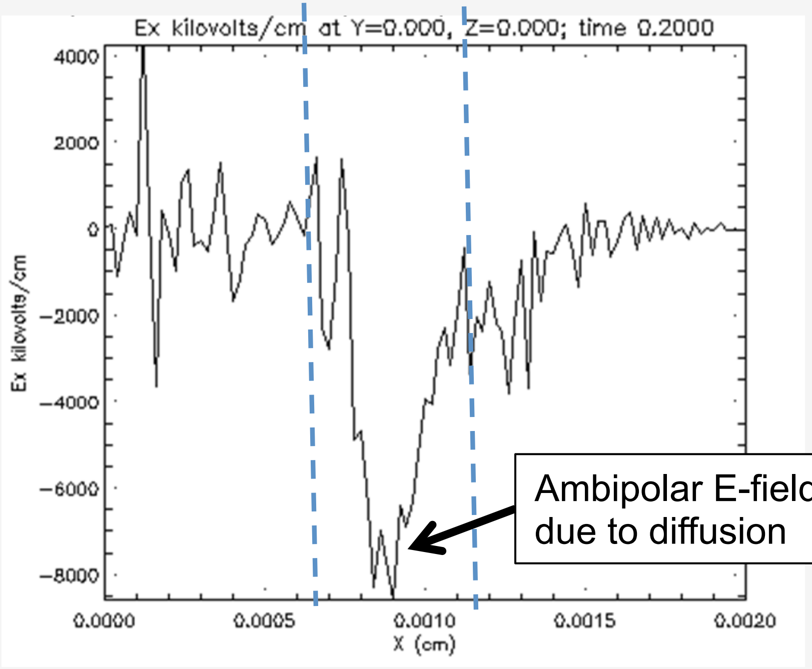
C. Bellei and P. Amendt, PRE **90**, 013101 (2014)





b) Hohlraum gas/wall interface (S. Wilks)

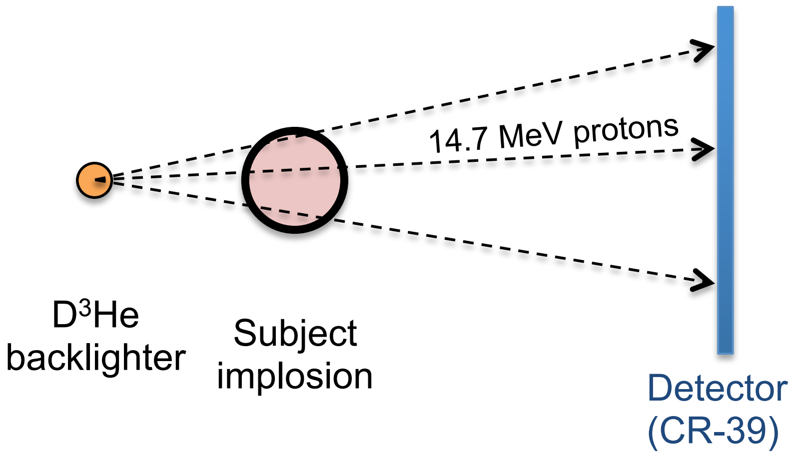


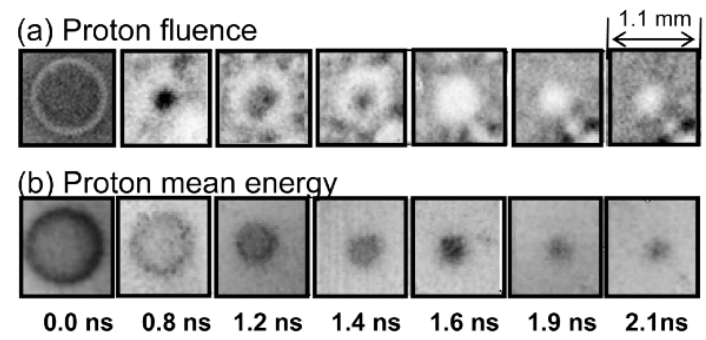


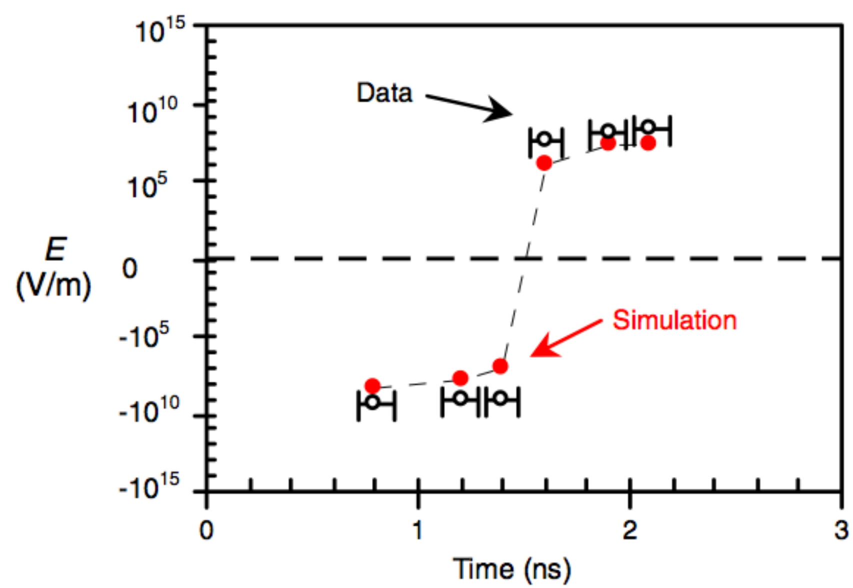
~0.8 GV/m E fields at the interface

Shock- and interface-localized electric fields may be diagnosed using charged particles

Proton radiography using monoenergetic fusion protons is well developed[1-3].







Diagnostic is currently limited to moderate areal-density plasmas: 14.7 MeV proton has a range ~ 100 mg/cm^2

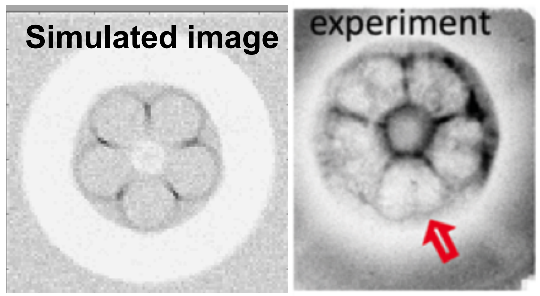
[1] C.K. Li, et al., PRL **100**, 225001 (2008)
[2] J.R. Rygg, et al., Science **319,** 1223 (2008)
[3] C.K. Li, et al., Science **327**, 1231 (2010)

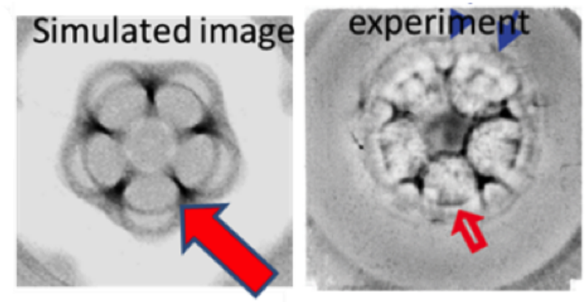
In gas-filled hohlraums, E-fields generated by pressure-gradient and diffusion are observed

Early time:

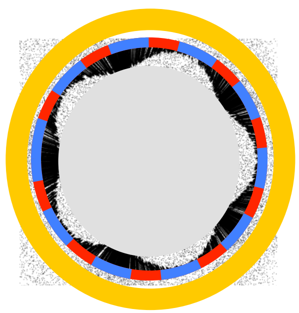
Later:

Proton fluence

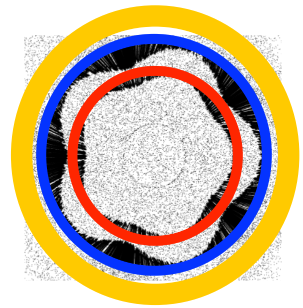




on axis view of simulated E:



Hohlraum wall



diffusive & ∇P-generated E-field in same position

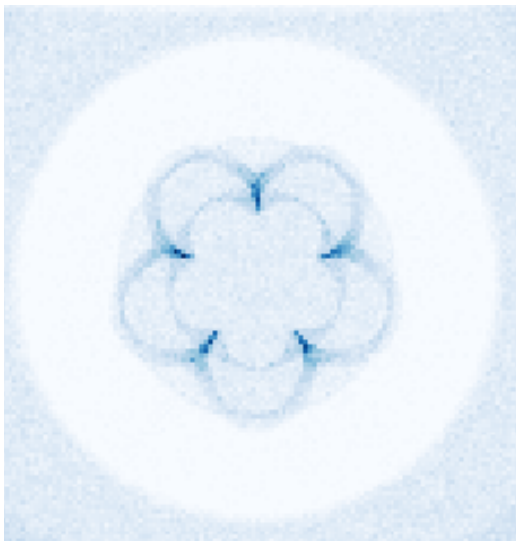
diffusive field moves inward faster than ∇P

Simulations with both E-fields included accurately capture these features.

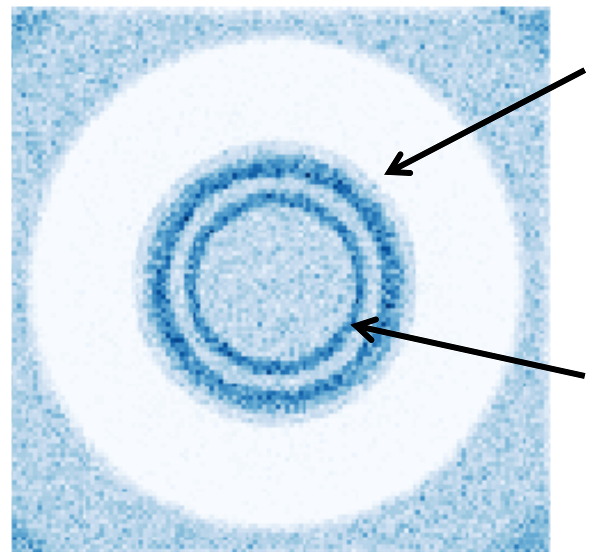
C.K. Li, MIT; S. Wilks, LLNL

Proton radiographs provide quantitative information for studies of E-fields at shocks and interfaces

Simulated image



Simulated image with improved symmetry



Images can be made cleaner by more uniform beam pointing.

Prospects for NIF:

1. **D³He-proton backlighter** is in development (Rygg, Li, Zylstra, …), shots in Dec.
2. **TNSA using ARC** could provide higher energy protons, higher resolution (lower uniformity; how to quantitatively analyze the broadband source?)

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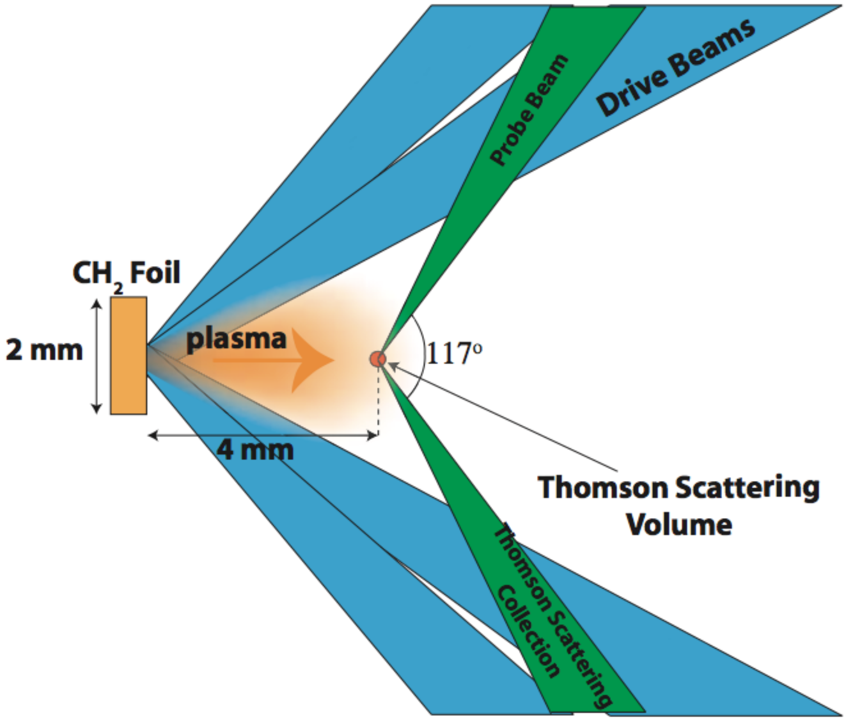
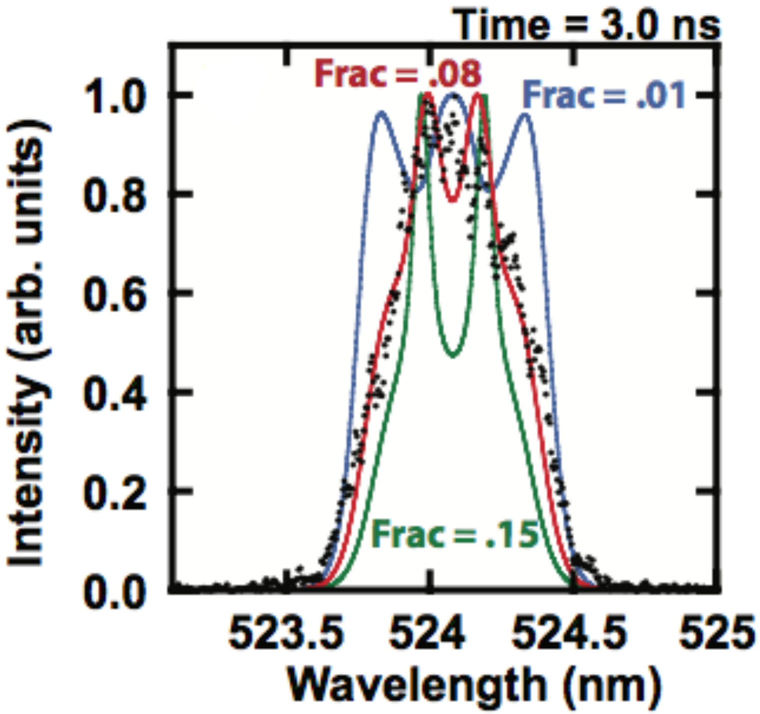
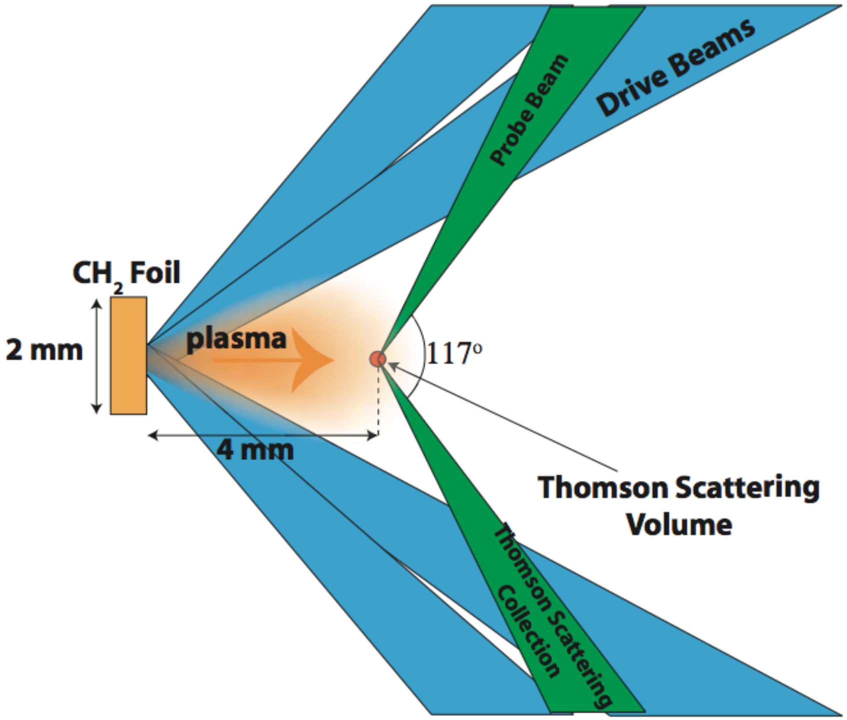
Thomson scattering ion feature is sensitive to ion concentration in a plasma

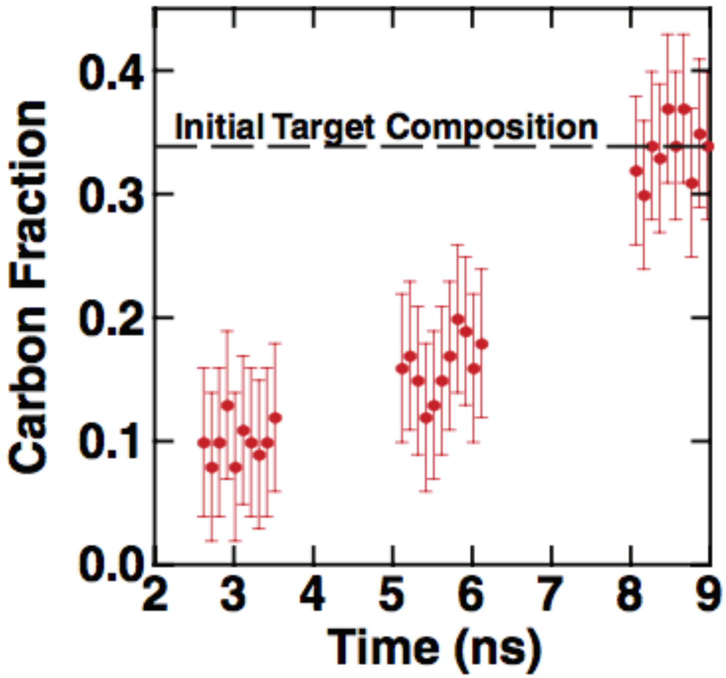




*S. Ross, RSI **83**, 10E323 (2012)*

Thomson scattering ion feature is sensitive to ion concentration in a plasma, which can vary over time



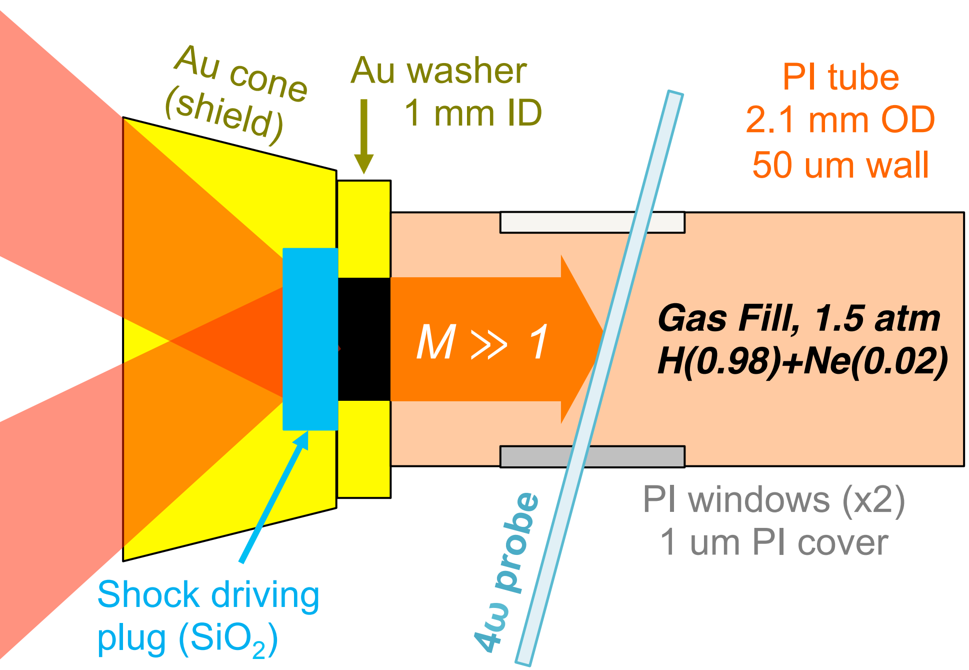


2ω, 4ω (n_C = 0.4, 1.6 x10^{22} cm^{-3}) is working at OMEGA
5ω (n_C = 2.5 x10^{22} cm^{-3}) is under development for NIF

*S. Ross, RSI **83**, 10E323 (2012)*

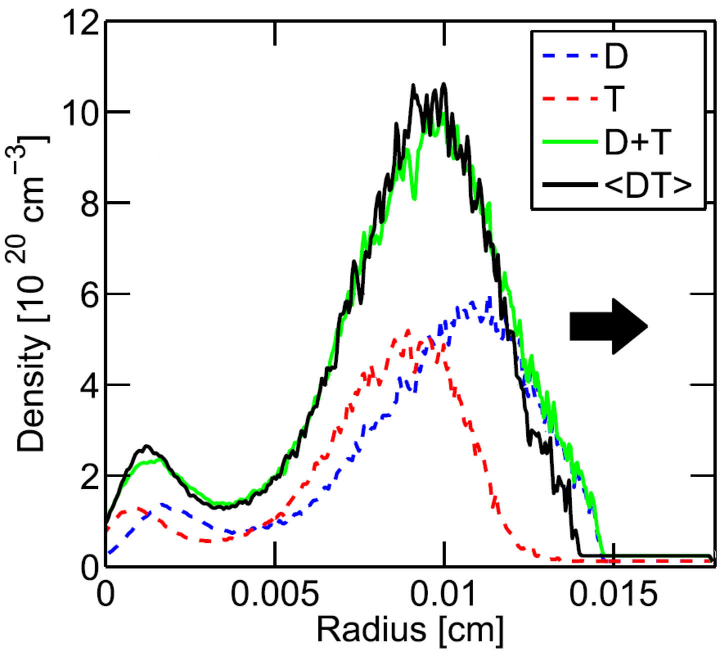
OMEGA shots in January will study shock structure in kinetic multi-species plasmas

Planar shock target*



**similar to OMEGAJet-14A*

Simulated multi-species shock separation**



***Adapted from Bellei, et al. POP (2014)*

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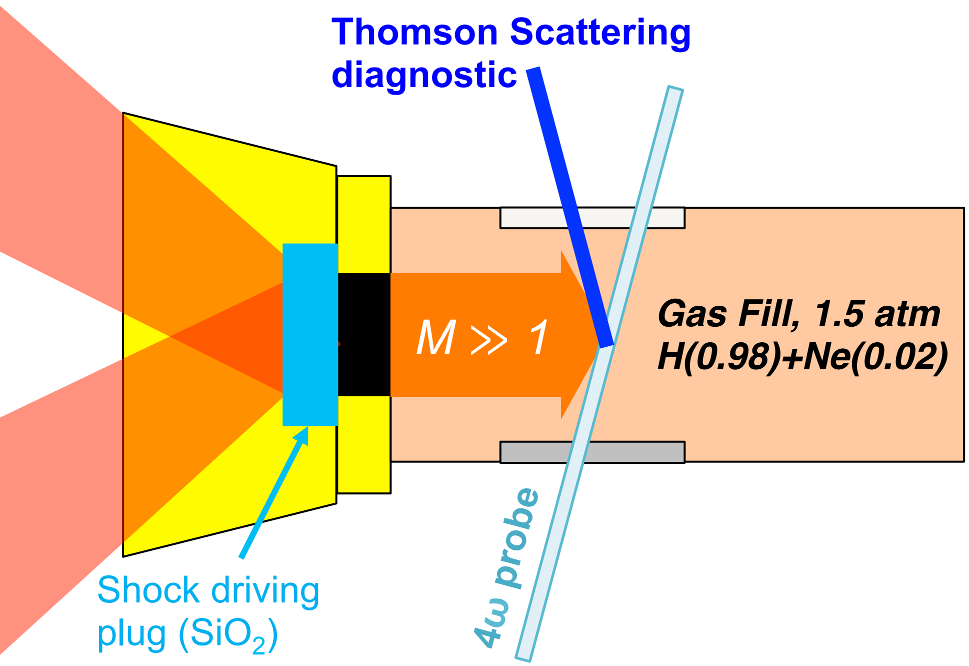
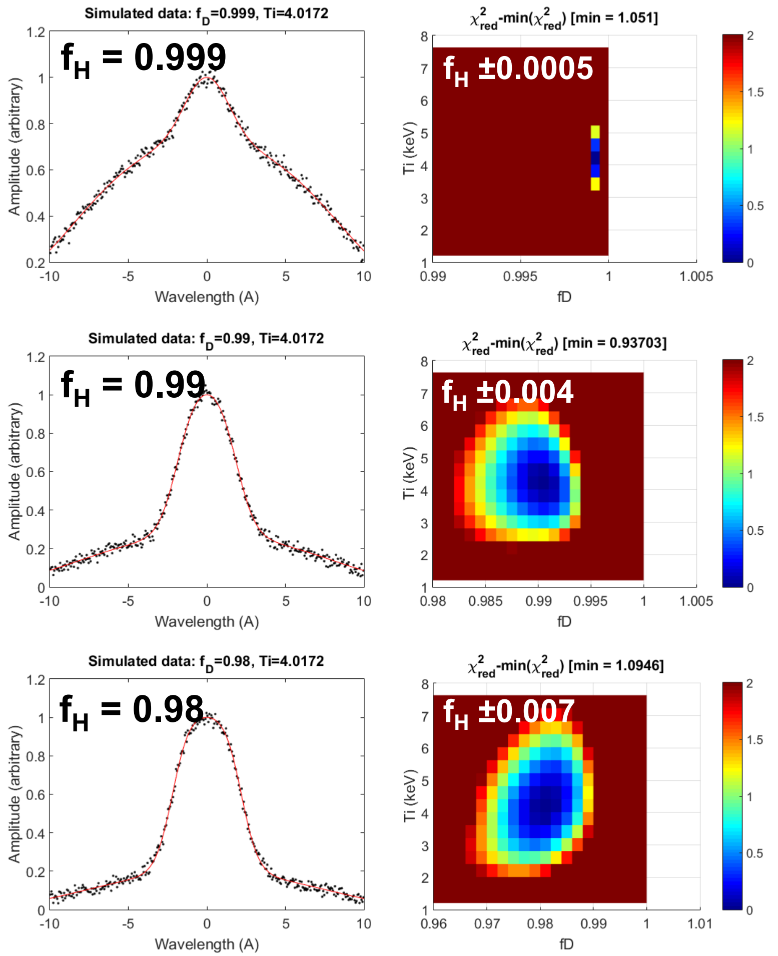


*similar to OMEGAJet-14A

Simulated Thomson Scattering data



OMEGA shot time has been allocated in FY16 for Thomson scattering and proton backlighting of this shock experiment

NIF

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