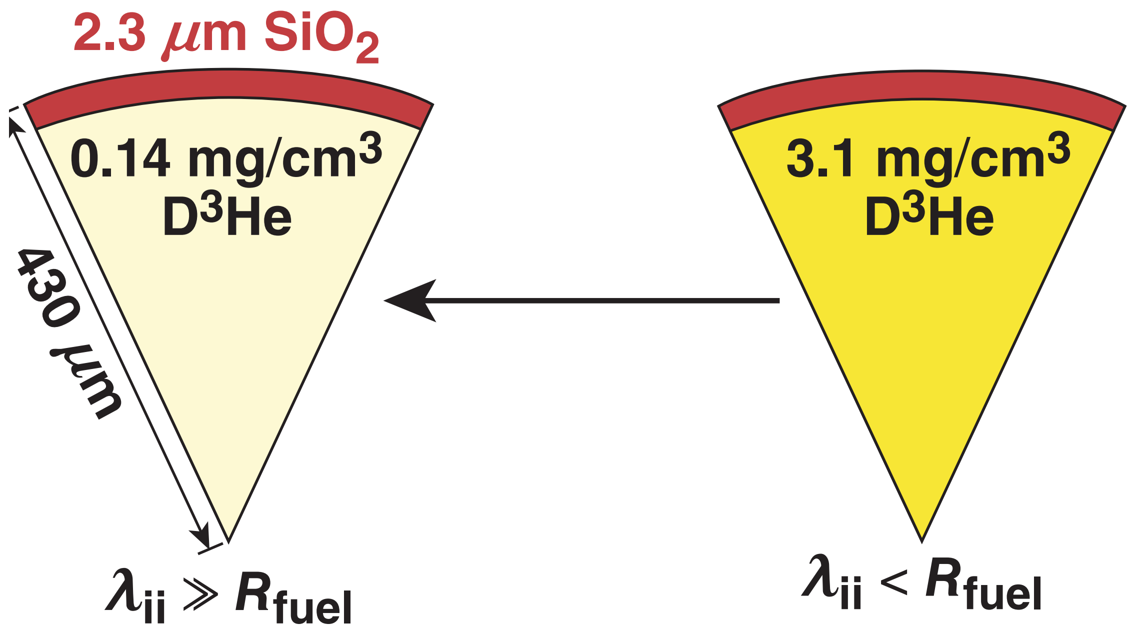
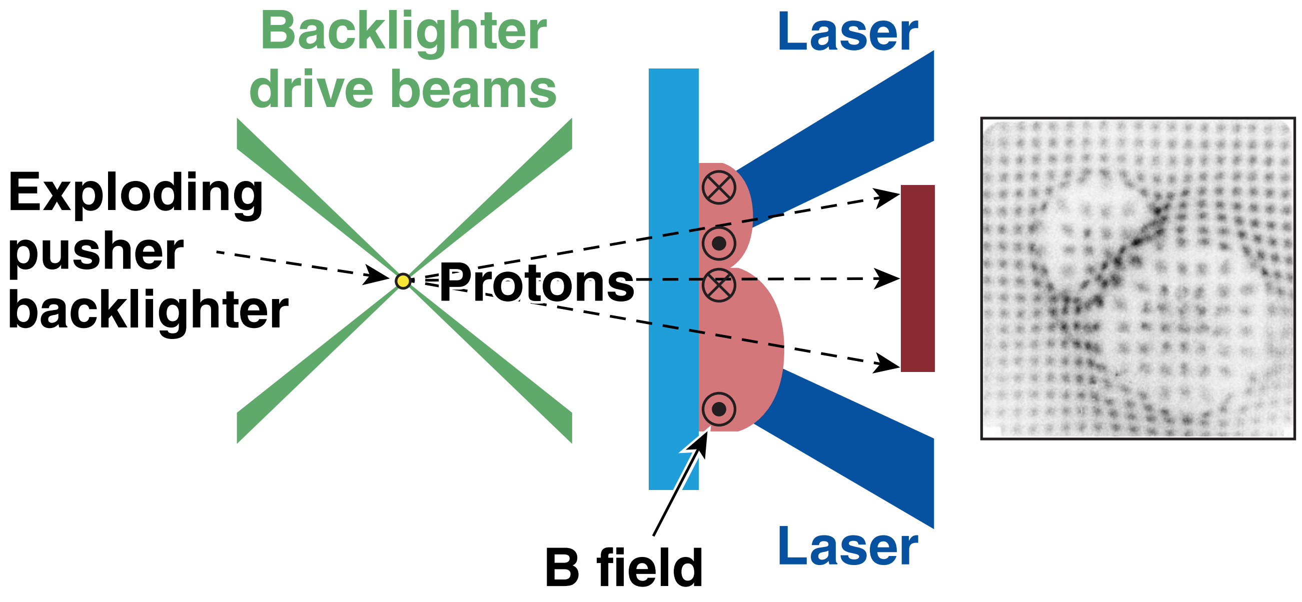
Demonstration of Ion Kinetic Effects in Inertial Confinement Fusion Implosions and Investigation of Magnetic Reconnection Using Laser-Produced Plasmas

Ion kinetic effects in ICF implosions



Proton radiography of (asymmetric) magnetic reconnection



M. J. Rosenberg
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Summary

Inertial confinement fusion (ICF) laser facilities [OMEGA and the National Ignition Facility (NIF)] have been used to probe a variety of physics phenomena in high-energy-density plasmas

- Shock-driven ICF implosions have
  - demonstrated ion kinetic effects
  - been used to probe strongly driven magnetic reconnection

- A strong trend of decreasing yield-over-clean (YOC) with an increasing Knudsen number ($N_K = \lambda_{ii}/R_{fuel}$) for $N_K > 0.1$ is observed and attributed to ion diffusion and the preferential escape of high-energy ions

- The magnetic reconnection rate in laser-produced, strongly driven plasmas is dictated by the flow velocity and is insensitive to initial asymmetries

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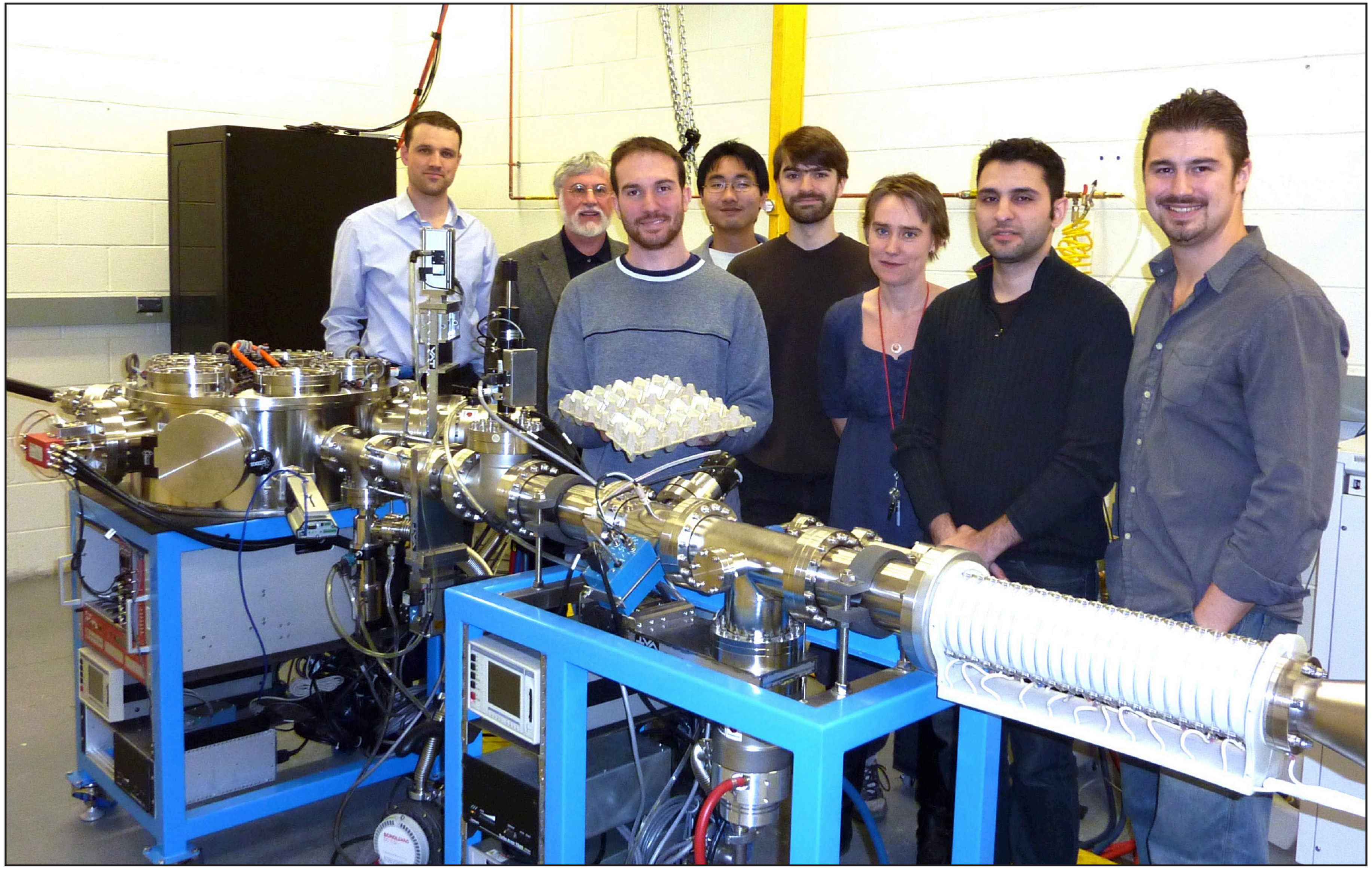
*Ph.D. thesis advisor

The MIT High-Energy-Density (HED) Accelerator is both a valuable hands-on training ground and an essential facility for developing diagnostics



E25731

Outline

- Ion kinetic effects during the shock-convergence phase of ICF implosions
- Asymmetric magnetic reconnection in strongly driven, laser-produced plasmas

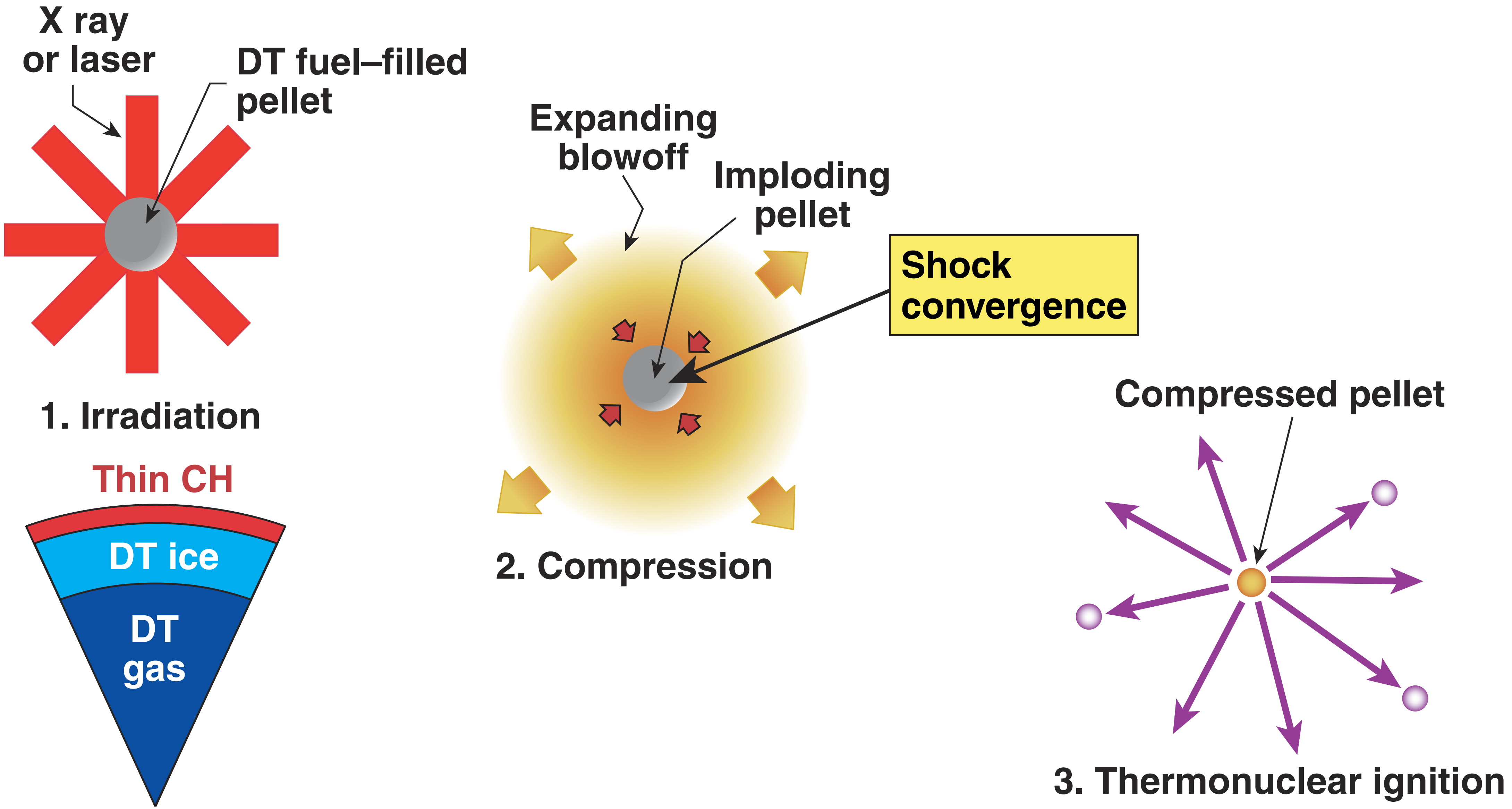
Outline

- **Ion kinetic effects during the shock-convergence phase of ICF implosions**

- Asymmetric magnetic reconnection in strongly driven, laser-produced plasmas

Ion Kinetic Effects Motivation

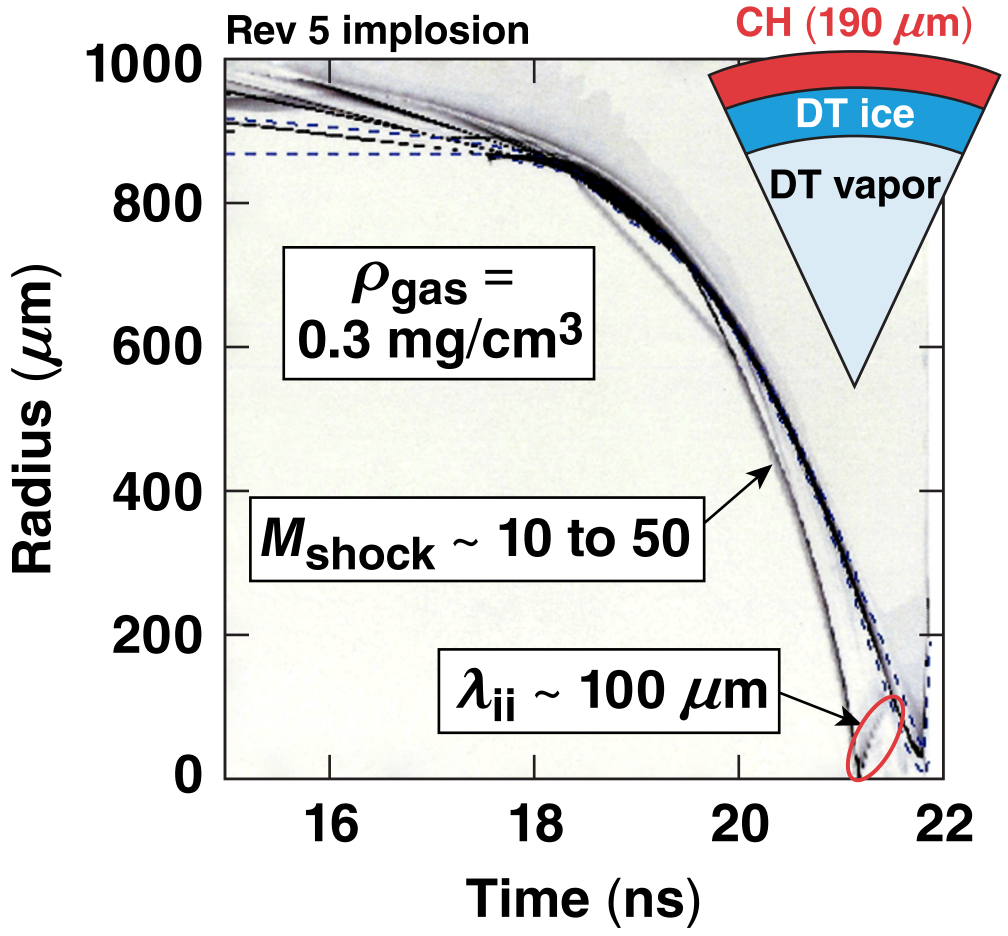
In hot-spot ICF, strong shocks set the initial fuel conditions prior to main compression and burn



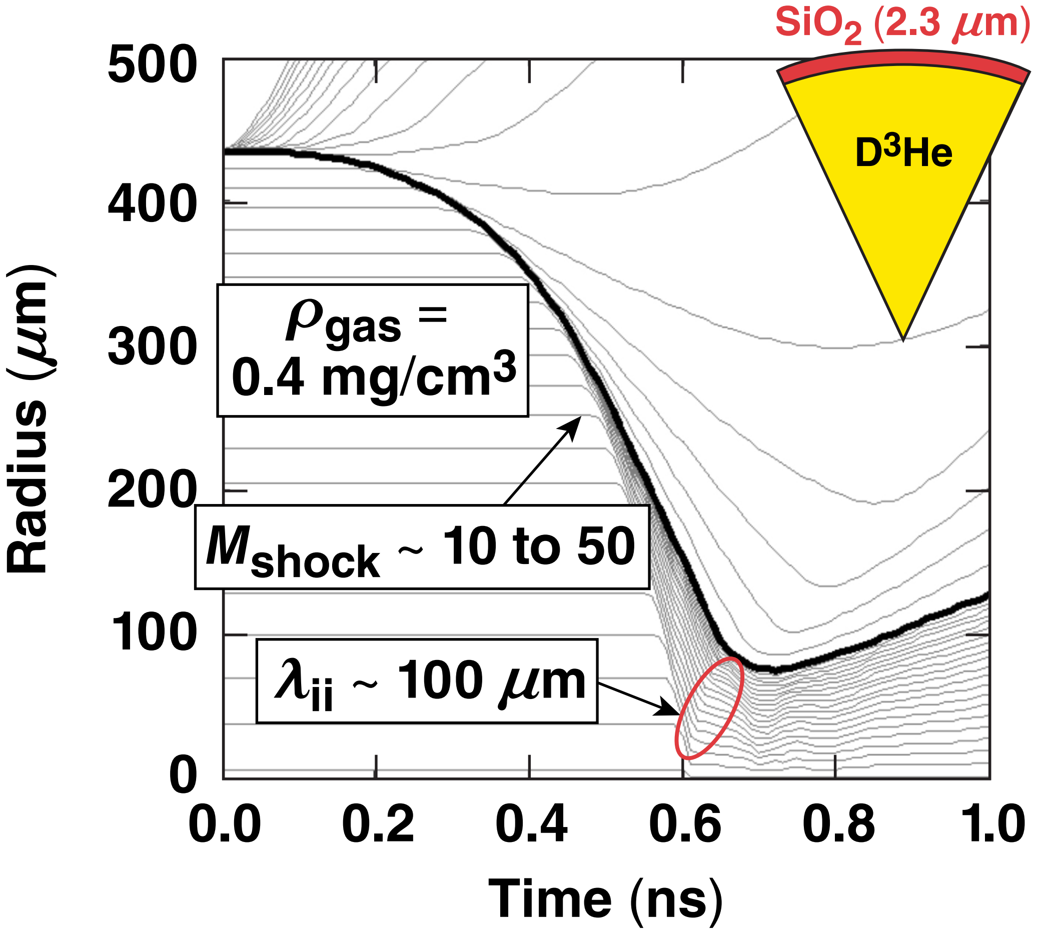
Shock convergence

Shock-driven “exploding pushers” generate kinetic conditions similar to the shock-convergence phase of hot-spot–ignition implosions

NIF hot-spot–ignition simulation*



OMEGA expoding-pusher simulation**



These implosions are a simple test bed for exploring ion kinetic effects independent of the complicated physics at compression (e.g., hydrodynamic instabilities).

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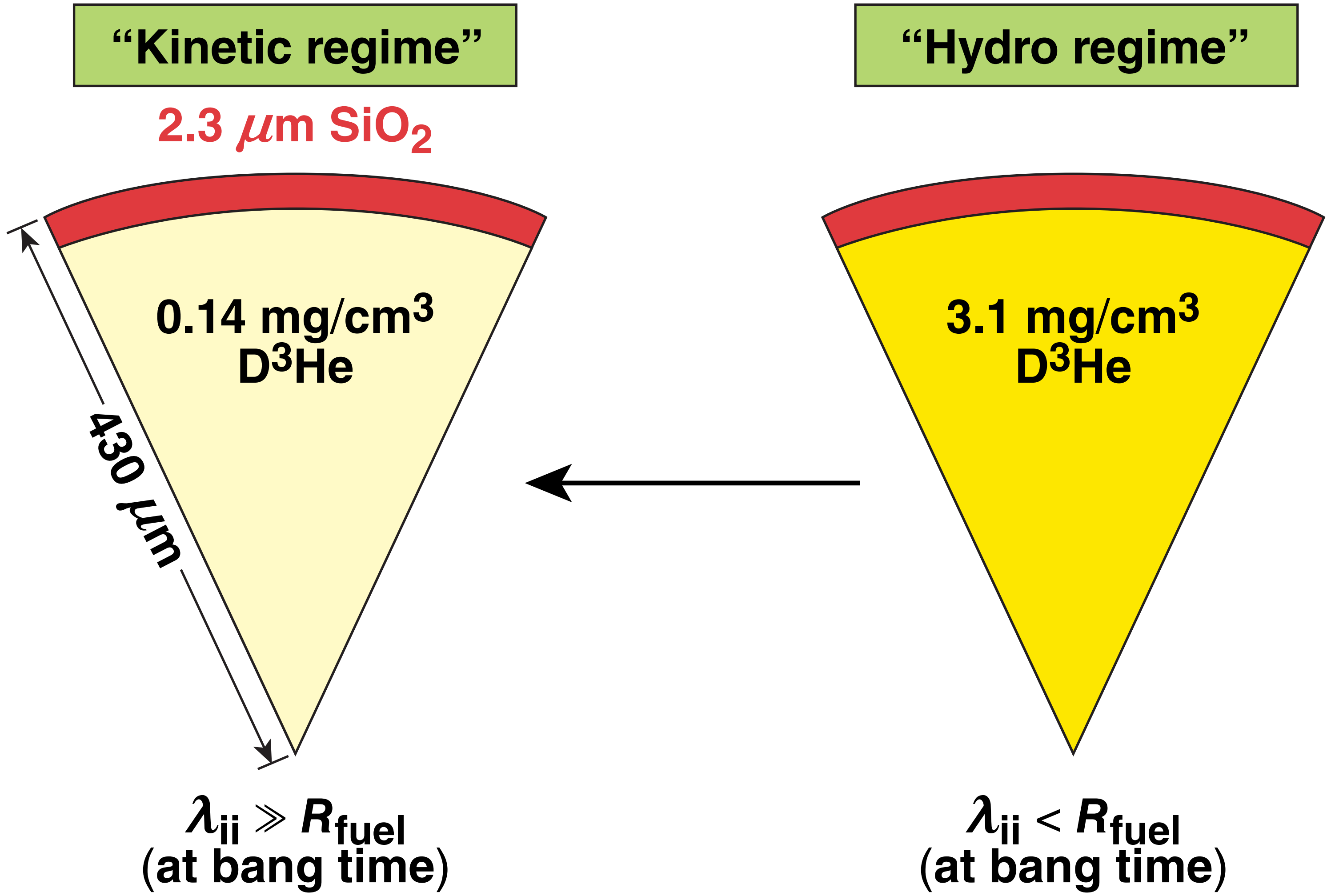
* H. Robey

** A. Zylstra (*HYADES*)

A fuel-density scan in D^3He-filled exploding pushers on the 60-beam OMEGA laser was used to isolate and study ion kinetic effects

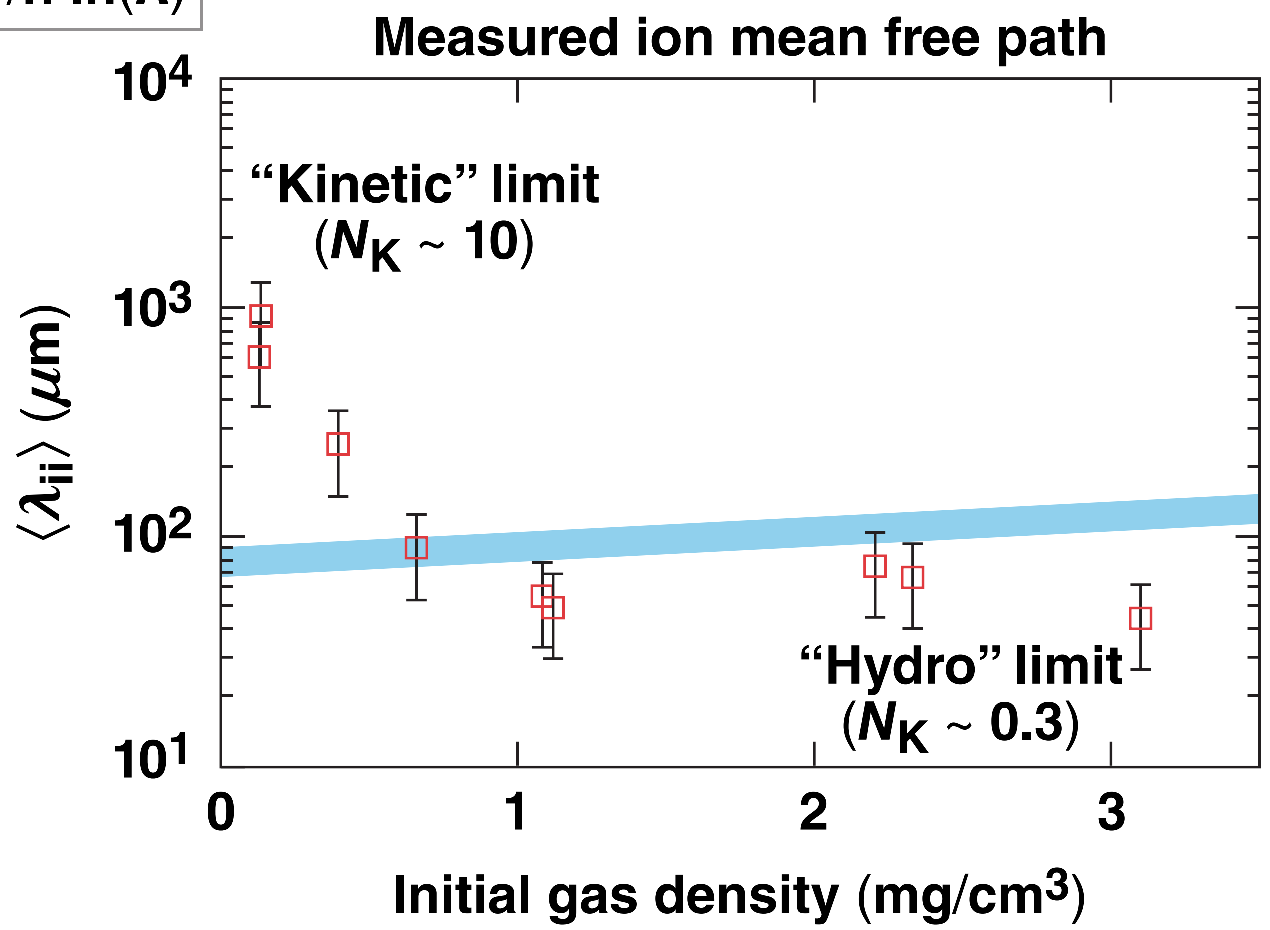


These experiments attempt to identify the conditions under which hydrodynamic models break down.

M. J. Rosenberg *et al.*, Phys. Rev. Lett. 112, 185001 (2014).

As ρ_{gas} is decreased, λ_{ii} increases from ~50 μm to ~1000 μm and $N_K = \lambda_{ii}/R_{fuel}$ increases from ~0.3 to 10

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



Approximate fuel radius at bang time

Implosions spanned the “strongly kinetic” to “hydrodynamic-like” regimes.

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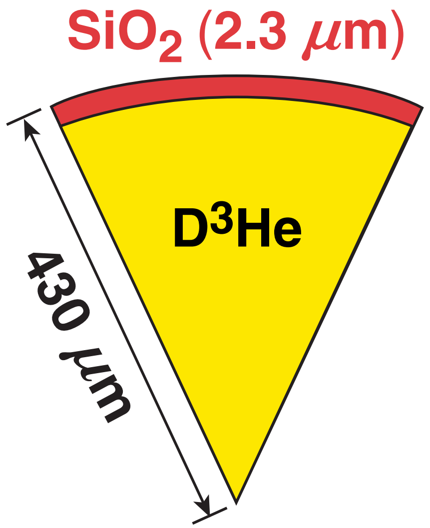
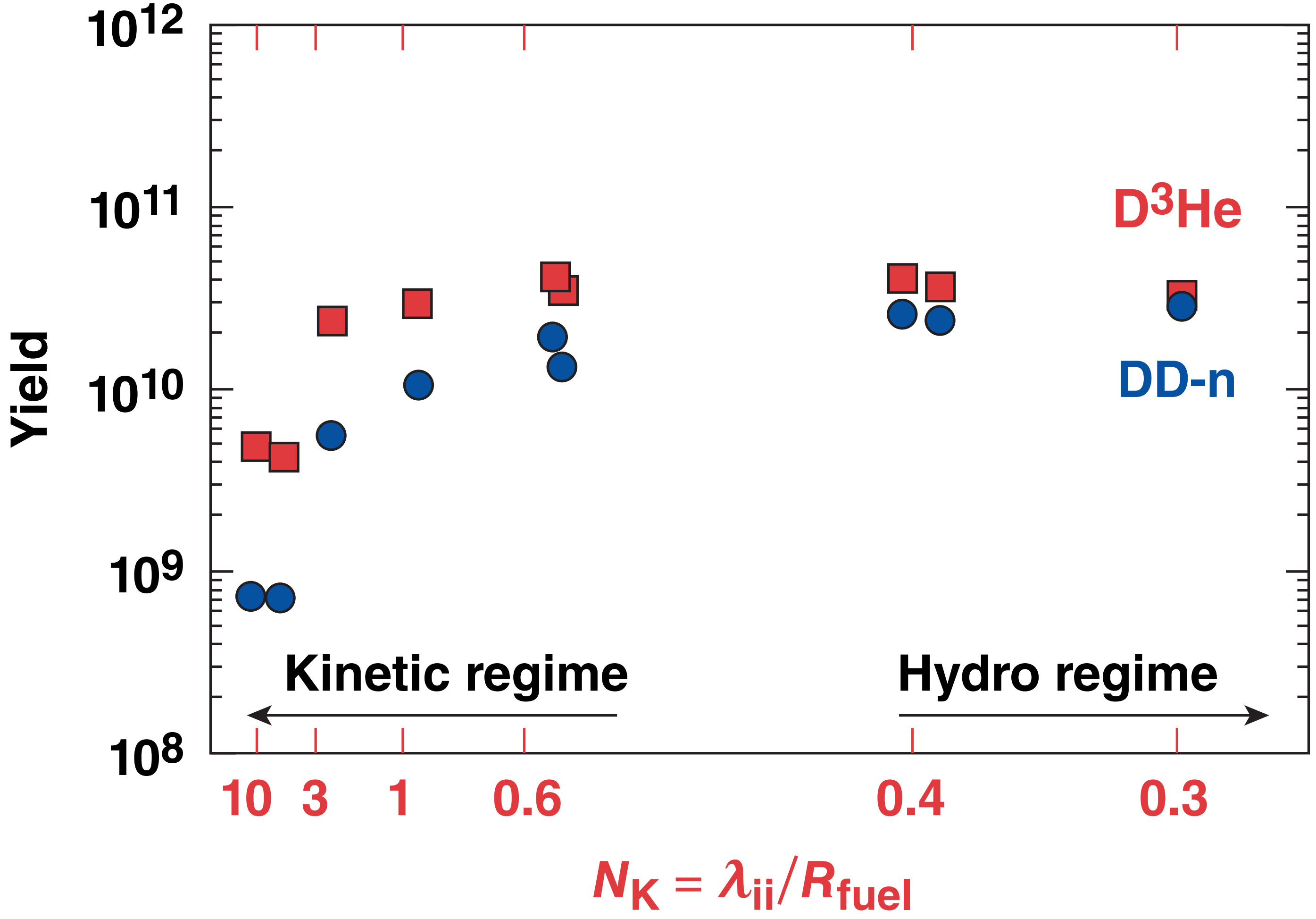
Measured DD and D^3He yields drop off sharply in the high-N_K/kinetic limit





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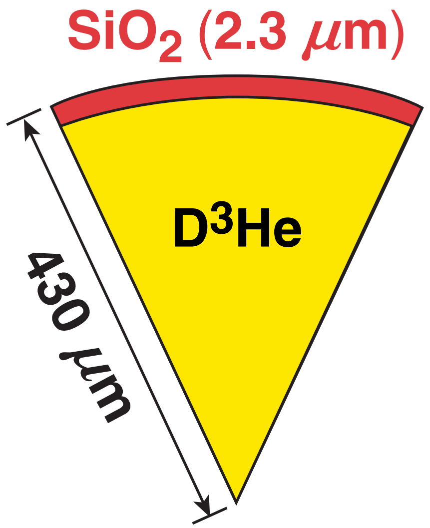
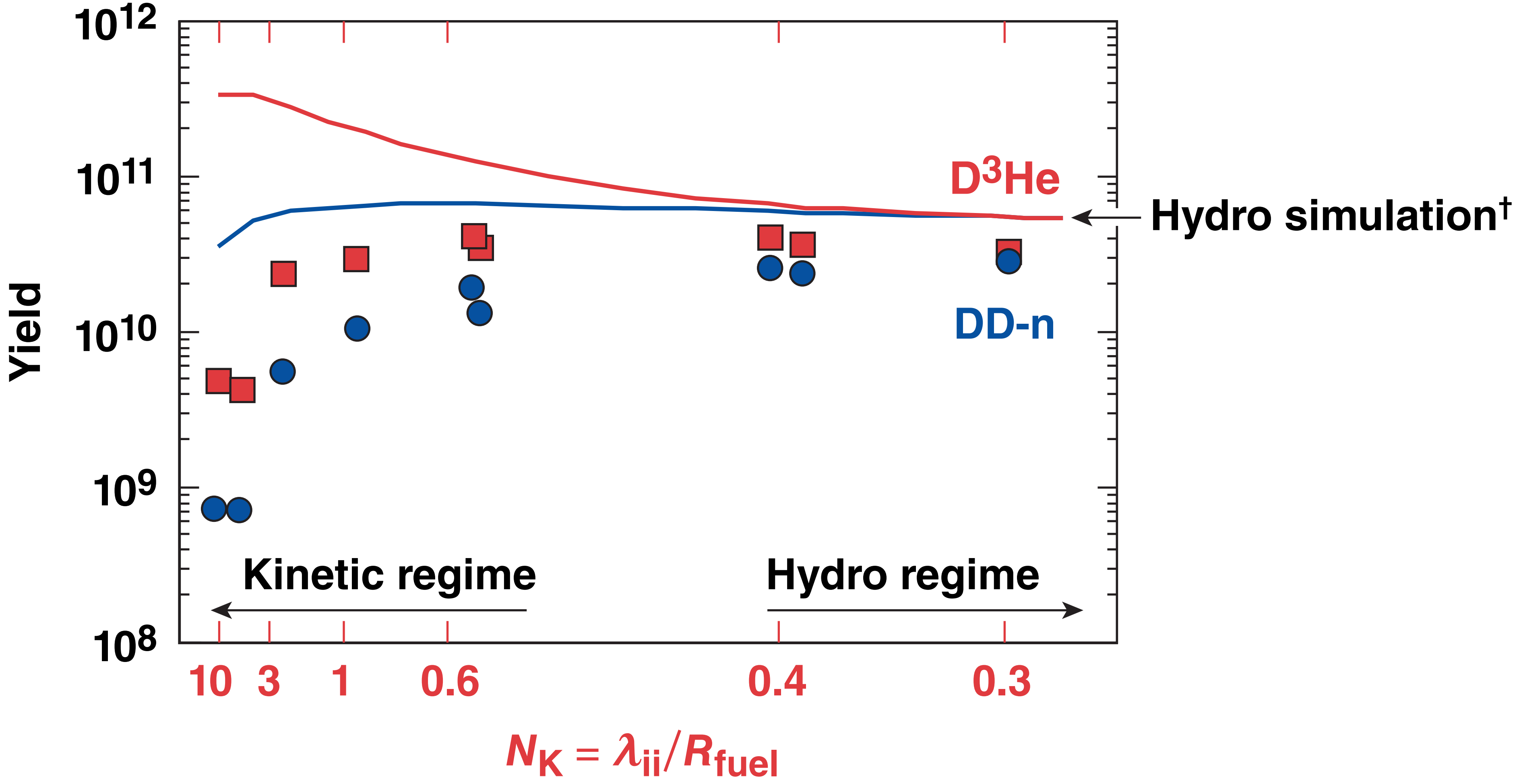
Hydrodynamic simulations increasingly deviate from the data in the kinetic regime





All hydro simulations (*DUED*, *LILAC*, *HYADES*, etc.) show these yield trends.

E24401e

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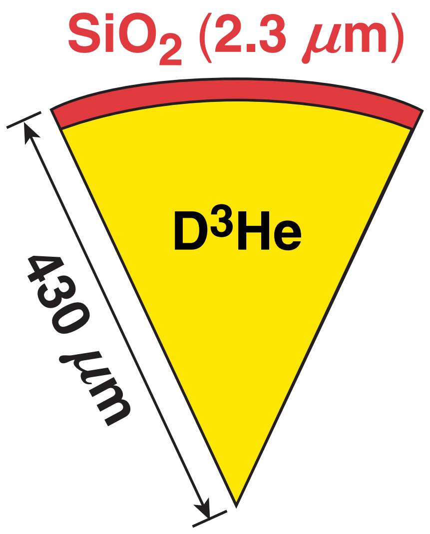
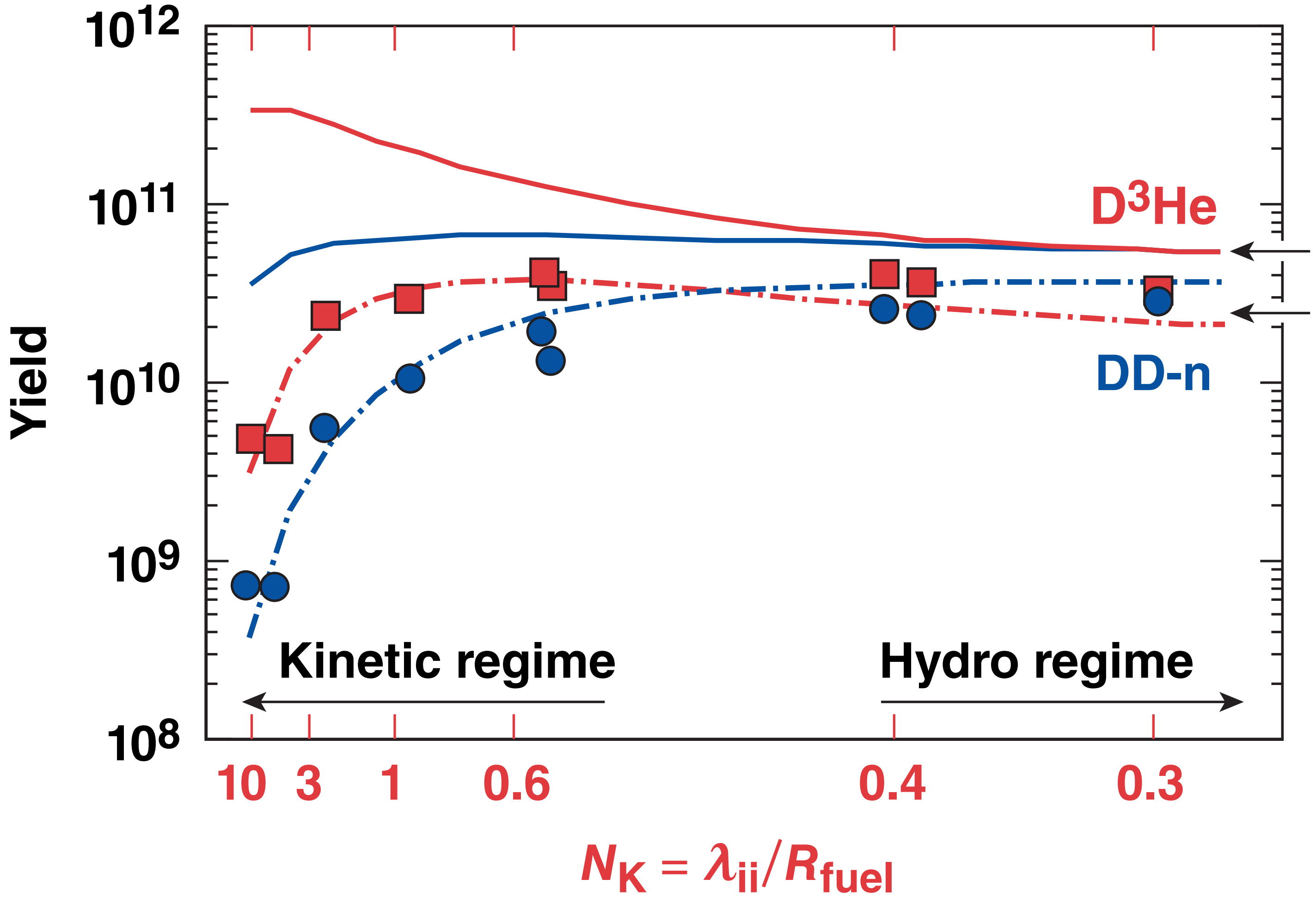
† Simulations by N. M. Hoffman, LANL

Including "reduced ion kinetic"* models in a hydro simulation brings modeled yields into better agreement with the experiment





Hydro simulation[†]

Best fit to data using reduced ion kinetic models,[†] with multipliers on
(1) ion diffusion
(2) tail ion loss
(3) ion thermal conduction

Reduction of fusion reactivity caused by non-Maxwellian tail ion loss** and ion diffusion are inferred to be significant.

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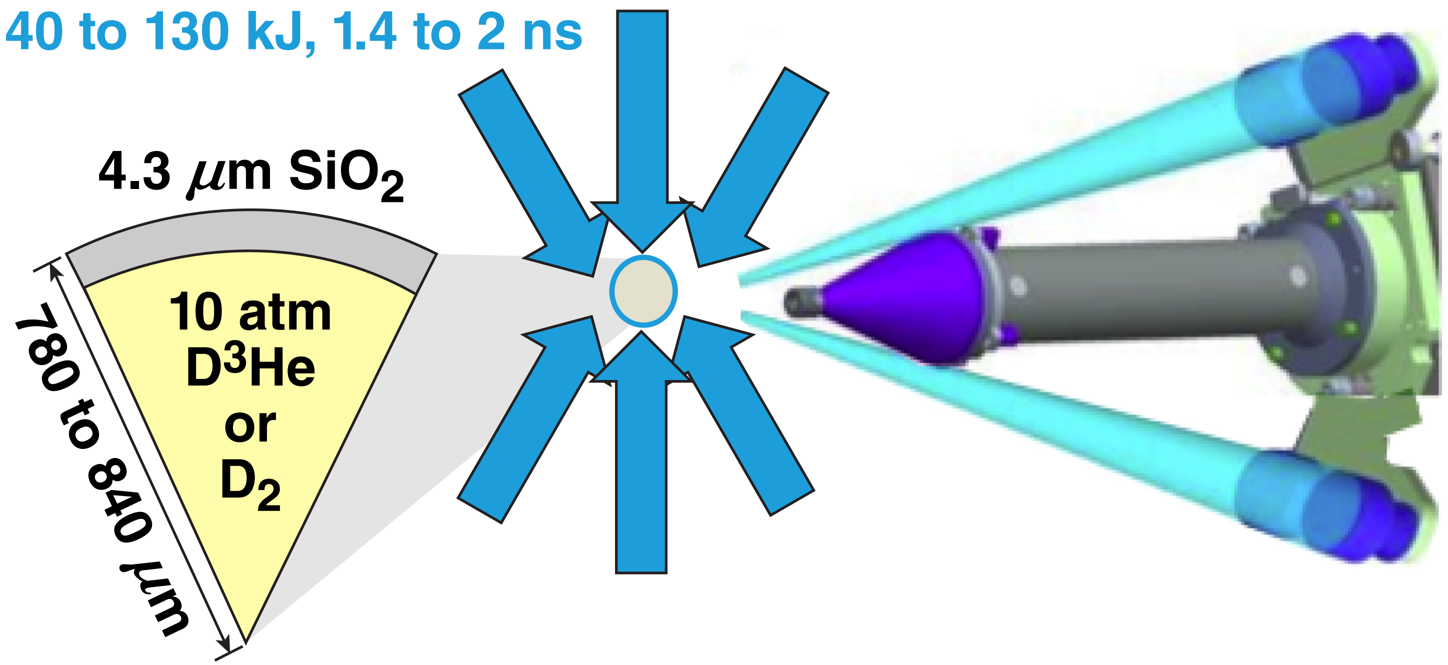
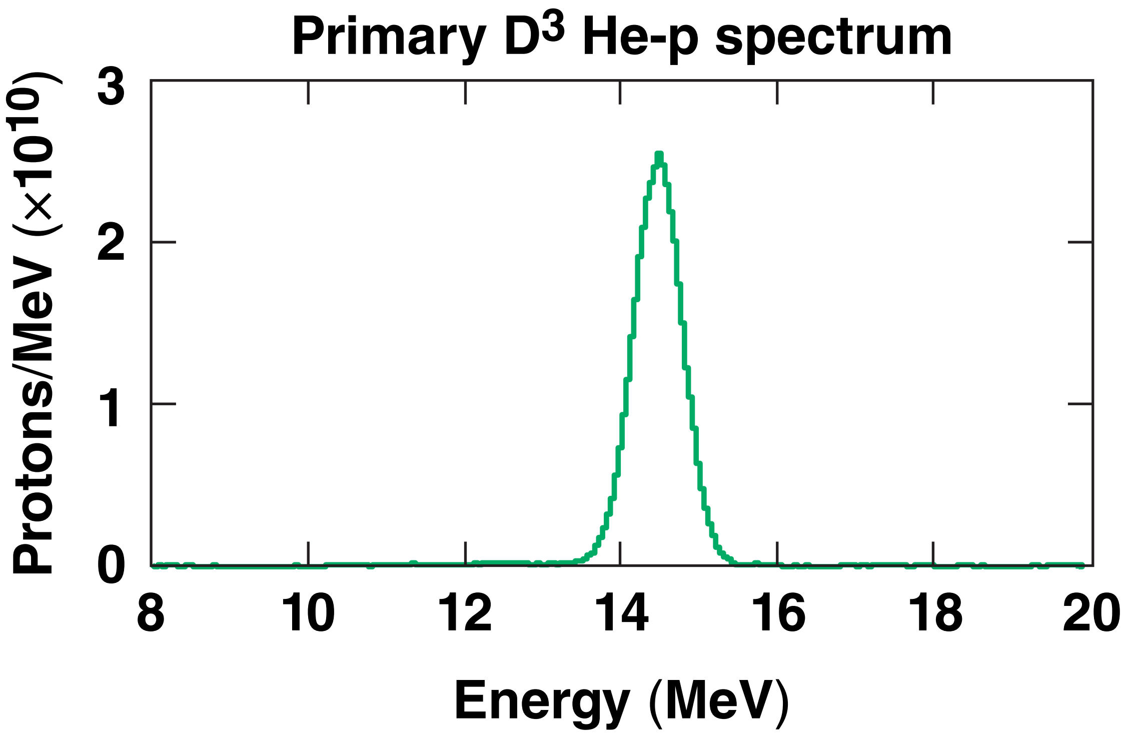
*N. M. Hoffman *et al*., Phys. Plasmas 22, 052707 (2015).
**K. Molvig *et al*., Phys. Rev. Lett. 109, 95001 (2012);
B. J. Albright *et al*., Phys. Plasmas 20, 122705 (2013).
†Simulations by N. M. Hoffman, LANL

Direct-drive exploding pushers on the NIF were also studied to investigate ion kinetic effects





NIF exploding pushers provide access to the low-N_K regime in shock-driven implosions.

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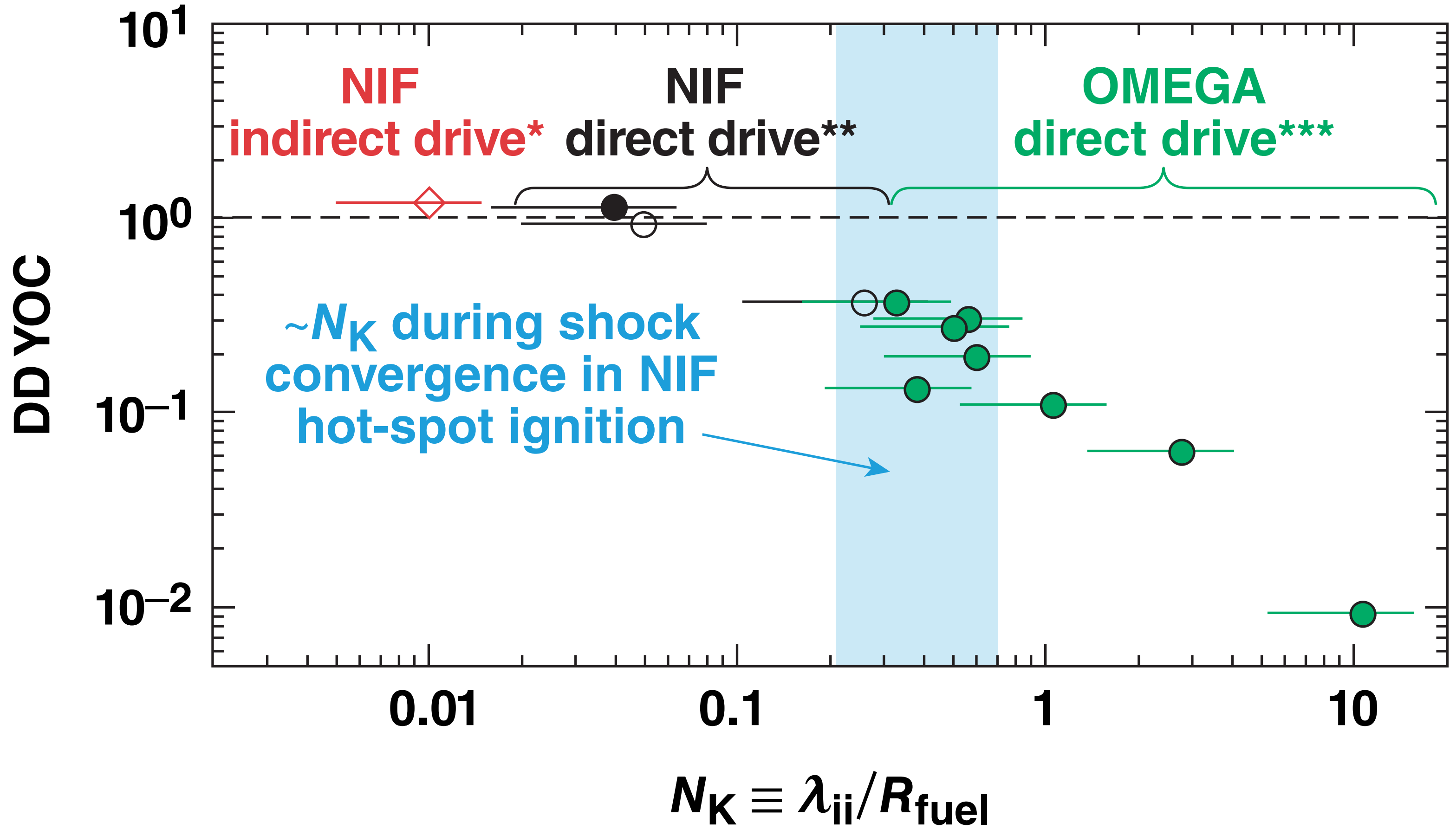
*M. J. Rosenberg *et al*., Phys. Plasmas 21, 122712 (2014).

Exploding pushers on the NIF and OMEGA show a unified trend of decreasing DD YOC with increasing N_K



Shock-convergence phase of hot-spot–ignition implosions is in a regime where kinetic effects start to become prevalent.

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* Compared to *HYDRA*, S. Le Pape *et al*., Phys. Rev. Lett. 112, 225002 (2014).

** Compared to *DRACO*, M. J. Rosenberg *et al*., Phys. Plasmas 21, 122712 (2014).

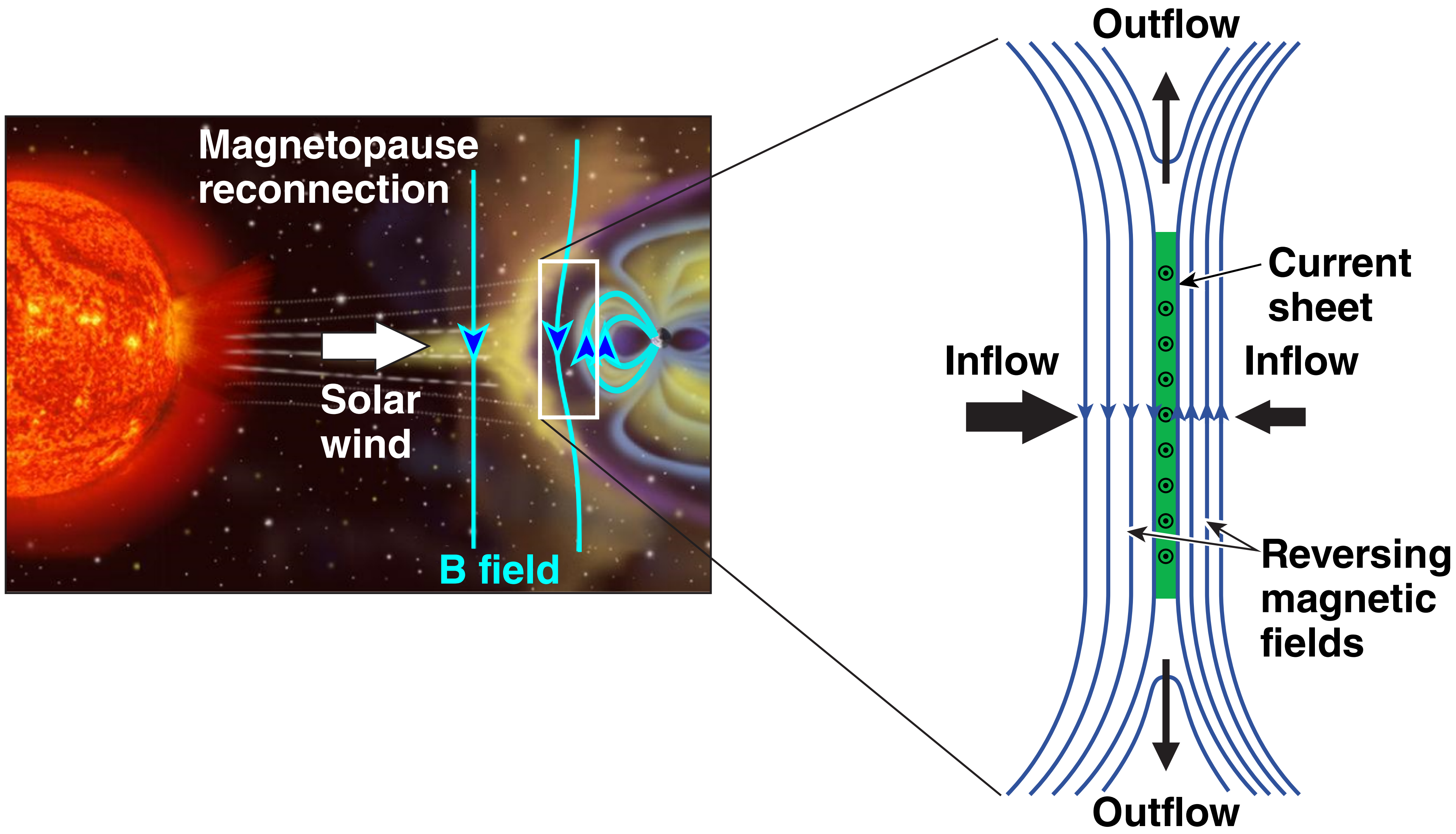
*** Compared to *DUED*, M. J. Rosenberg *et al*., Phys. Rev. Lett. 112, 185001 (2014).

E24406b

Outline

- Ion kinetic effects during the shock-convergence phase of ICF implosions
- **Asymmetric magnetic reconnection in strongly driven, laser-produced plasmas**

(Asymmetric) magnetic reconnection is a ubiquitous phenomenon in both astrophysical and laboratory plasmas, where antiparallel magnetic fields merge and annihilate



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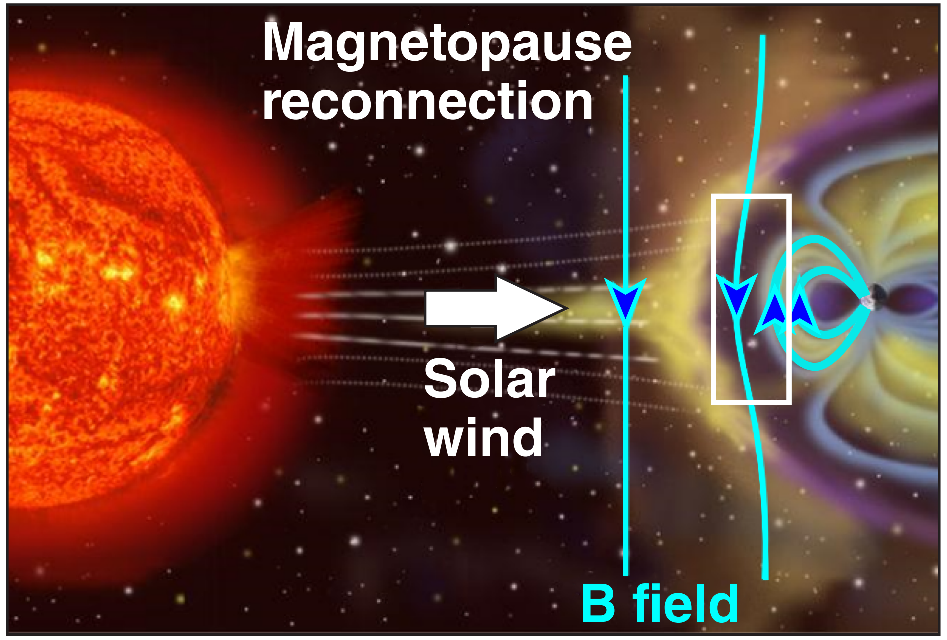
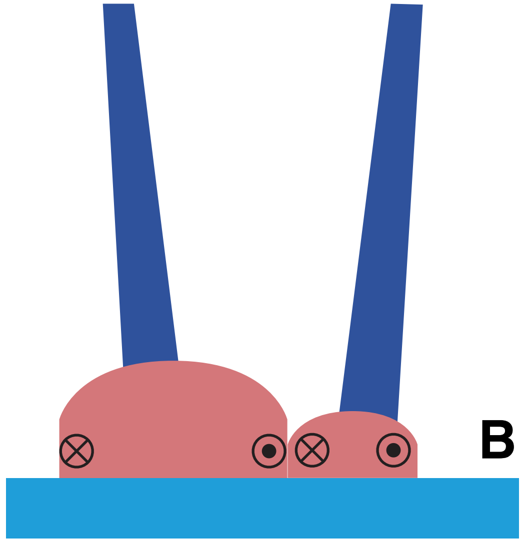


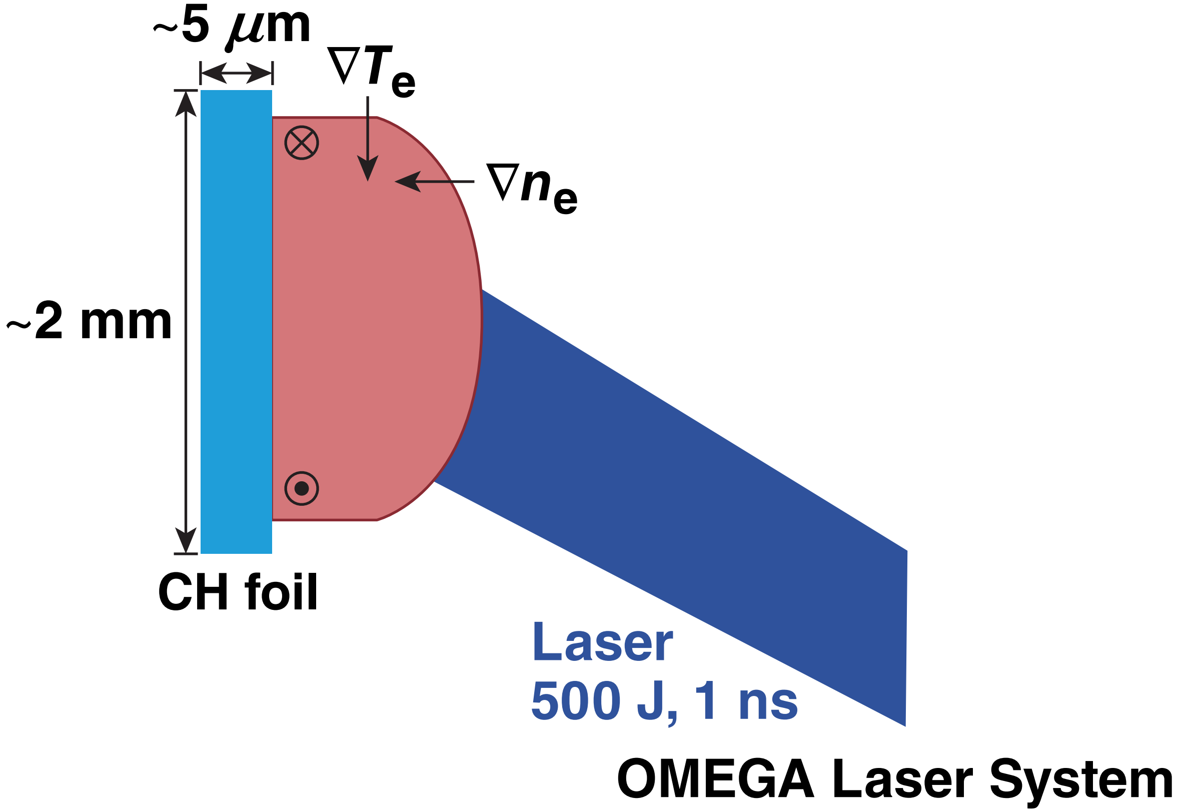
(Asymmetric, $\beta \geq 1$, strongly driven reconnection)

Laser-produced plasmas
(Asymmetric, $\beta \geq 1$, strongly driven reconnection)



Magnetic fields are generated in laser–foil interactions

$$\partial \mathbf{B}/\partial t \propto \nabla T_e \times \nabla n_e{}^*$$



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*J. A. Stamper *et al.*, Phys. Rev. Lett. 26, 1012 (1971).

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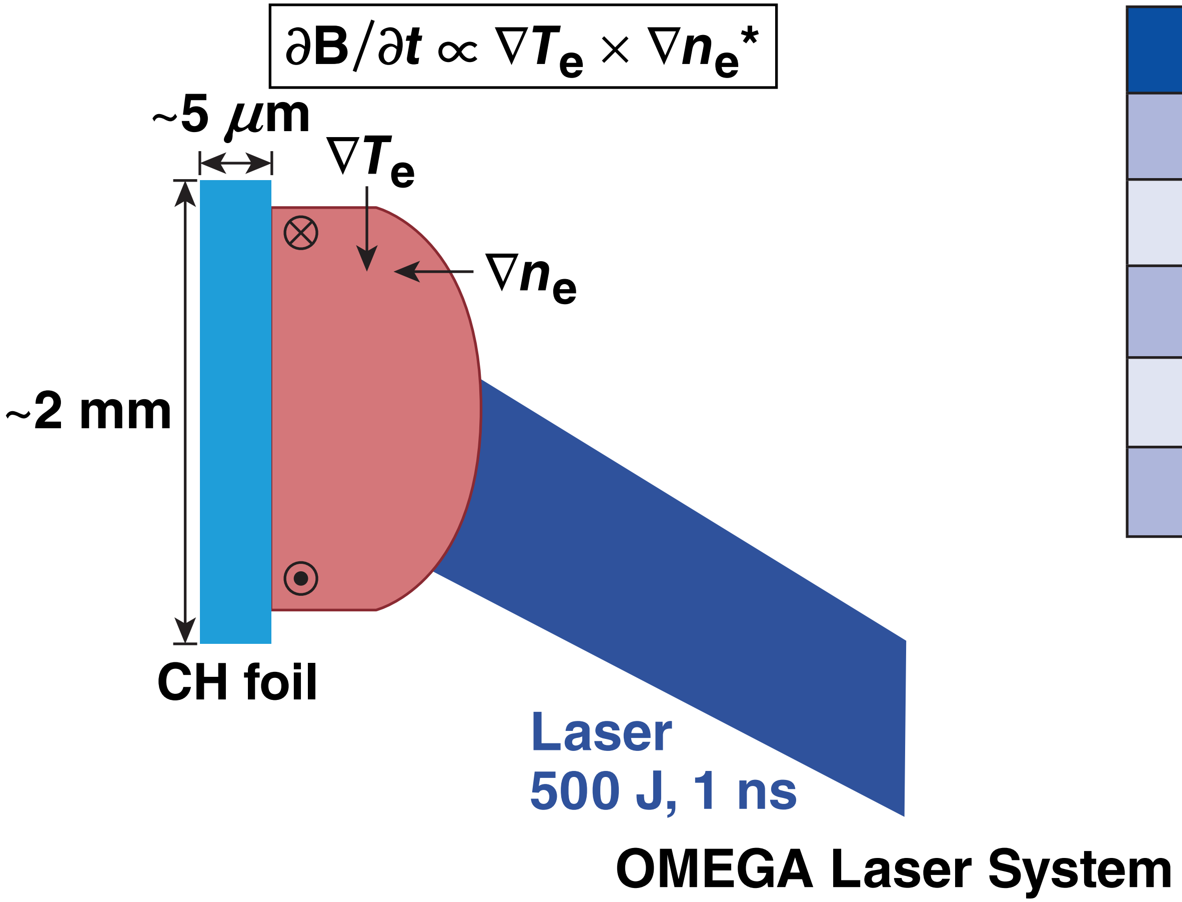

Parameter	Value at perimeter
Magnetic field	~0.5 MG
Electron density	~10^{20} cm^{-3}
Plasma beta (β)	~10
Flow velocity (V_b)	~500 μm/ns
Alfvén speed (V_A)	~100 μm/ns

$V_b/V_A > 1$ indicates a strongly driven reconnection.

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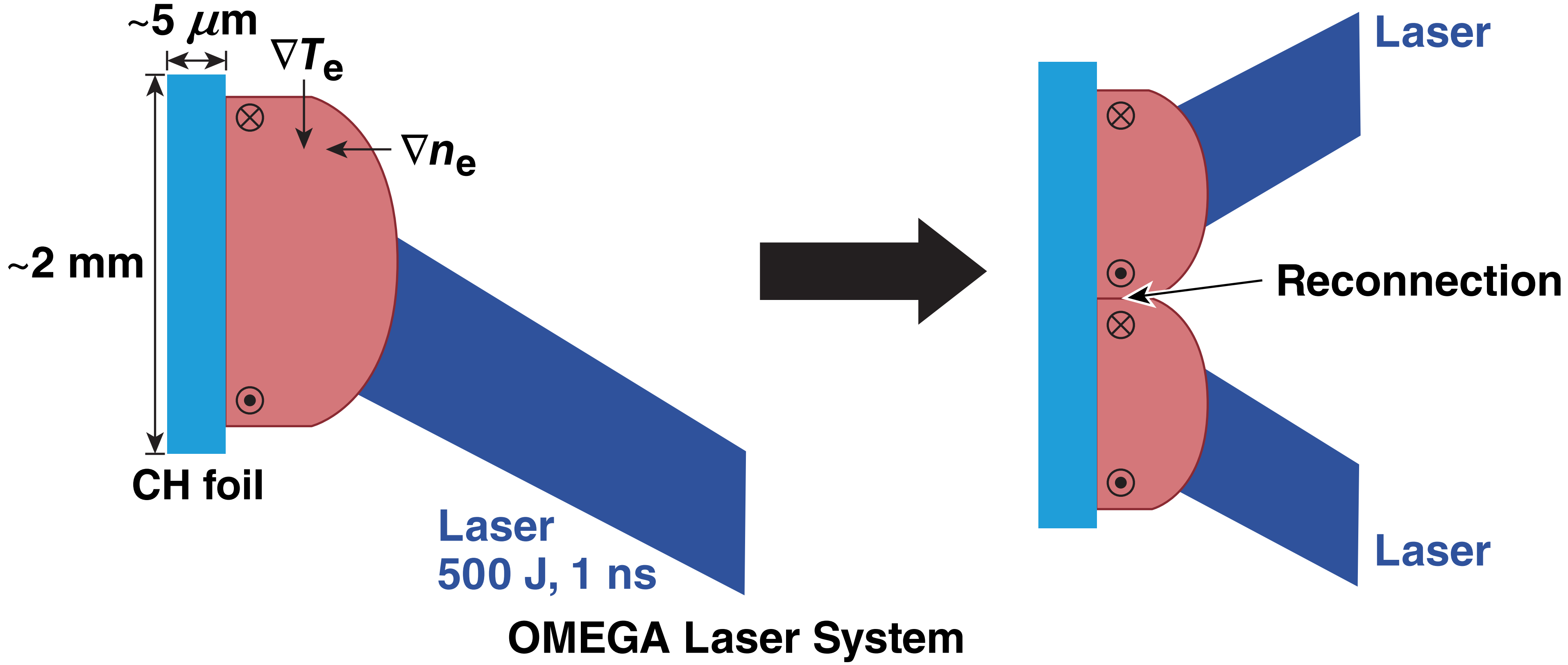
*J. A. Stamper *et al.*, Phys. Rev. Lett. 26, 1012 (1971).

Magnetic fields are generated in laser–foil interactions and magnetized plasma bubble pairs can be driven to reconnect

$\partial B/\partial t \propto \nabla T_e \times \nabla n_e$*



This class of experiments is an established platform for high-β, strongly driven reconnection, and is distinct from most reconnection experiments (tenuous plasmas, $\beta \ll 1$, quasi-steady state).**

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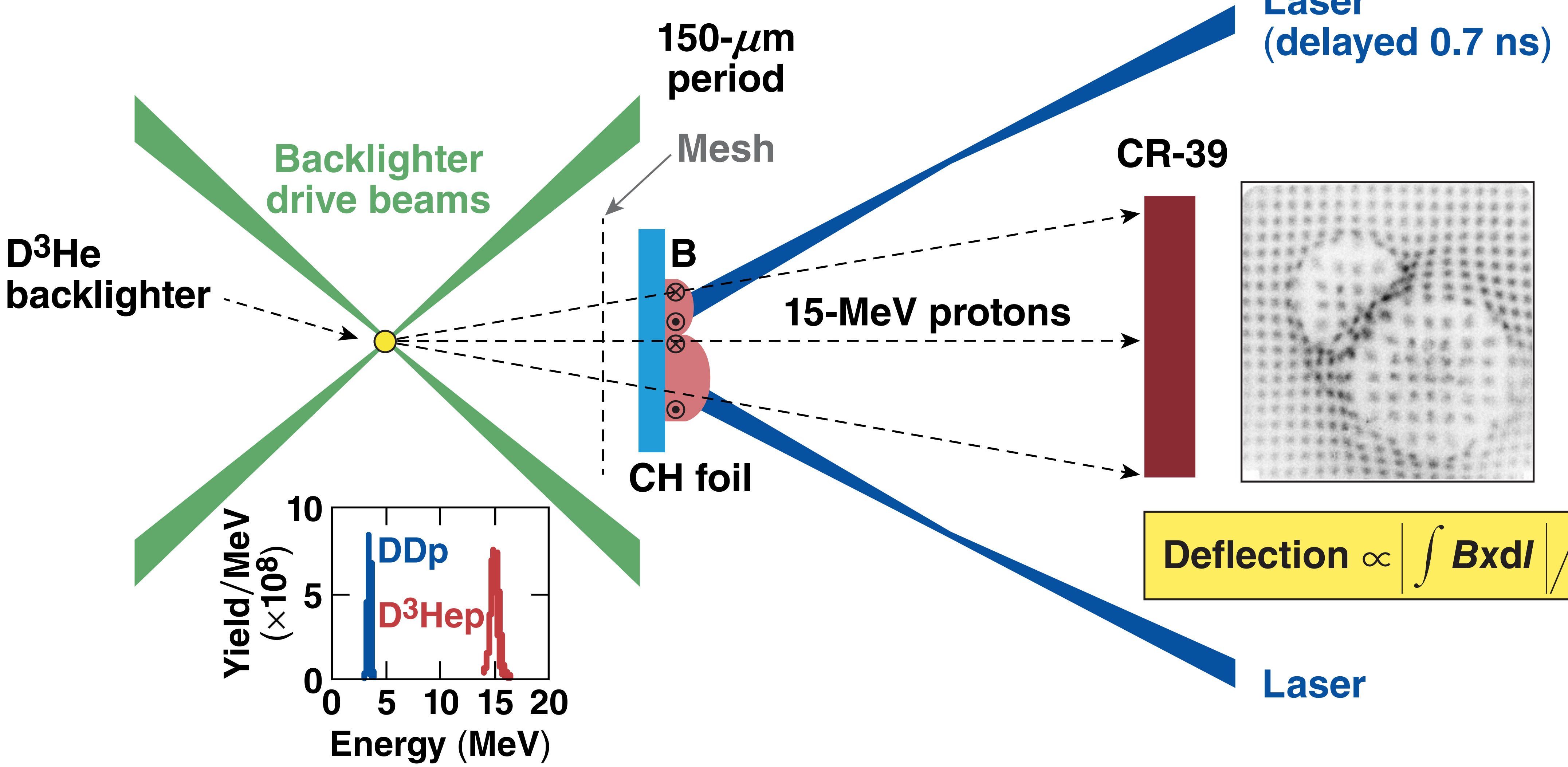
*J. A. Stamper *et al*., Phys. Rev. Lett. 26, 1012 (1971).

**P. M. Nilson *et al*., Phys. Rev. Lett. 97, 255001 (2006); C. K. Li *et al*., Phys. Rev. Lett. 99, 055001 (2007); and J. Zhong *et al*., Nat. Phys. 6, 984 (2010).

Monoenergetic proton radiography has been used on OMEGA to study magnetic-field evolution in strongly driven asymmetric reconnection experiments



Deflection $\propto \left| \int B \times dl \right| / v_p$

Images have been analyzed to infer quantitative maps of $\left| \int B \times dl \right|$ from proton beamlet deflection.

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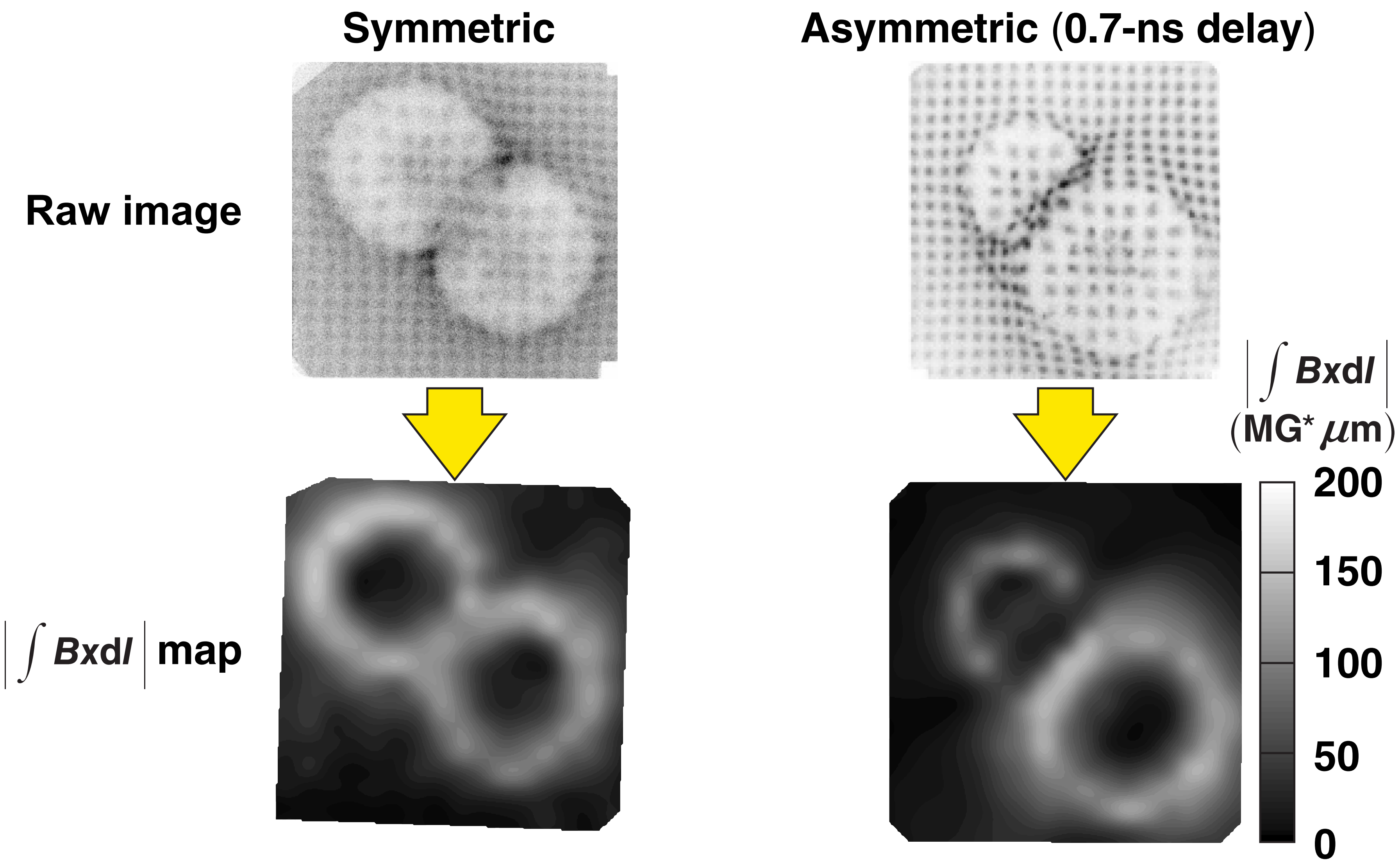
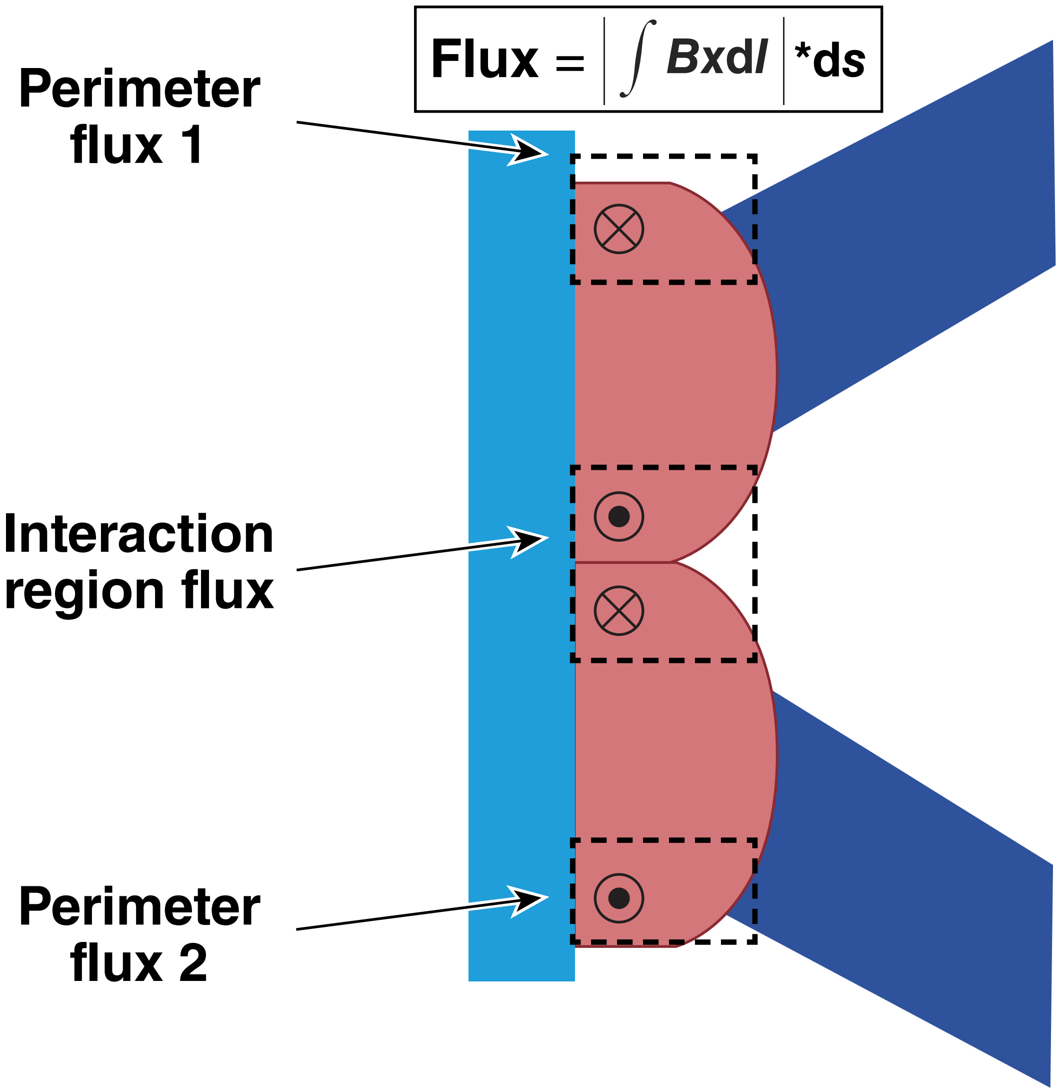
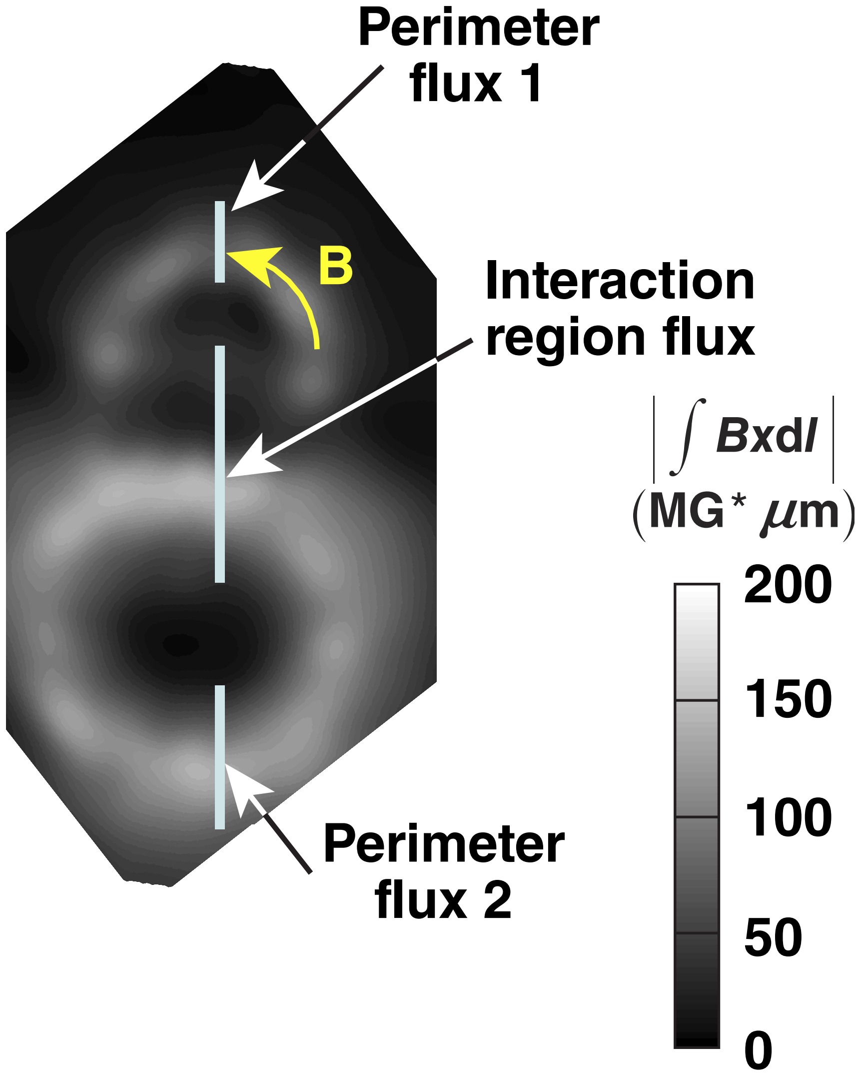
Maps of path-integrated magnetic-field strength show the deformation and annihilation of magnetic-field structures



Magnetic flux is measured at the perimeter of each bubble and in the interaction region and compared to infer the annihilated flux



$$\text{Flux} = \left|\int Bxdl\right| {}^{*}ds$$



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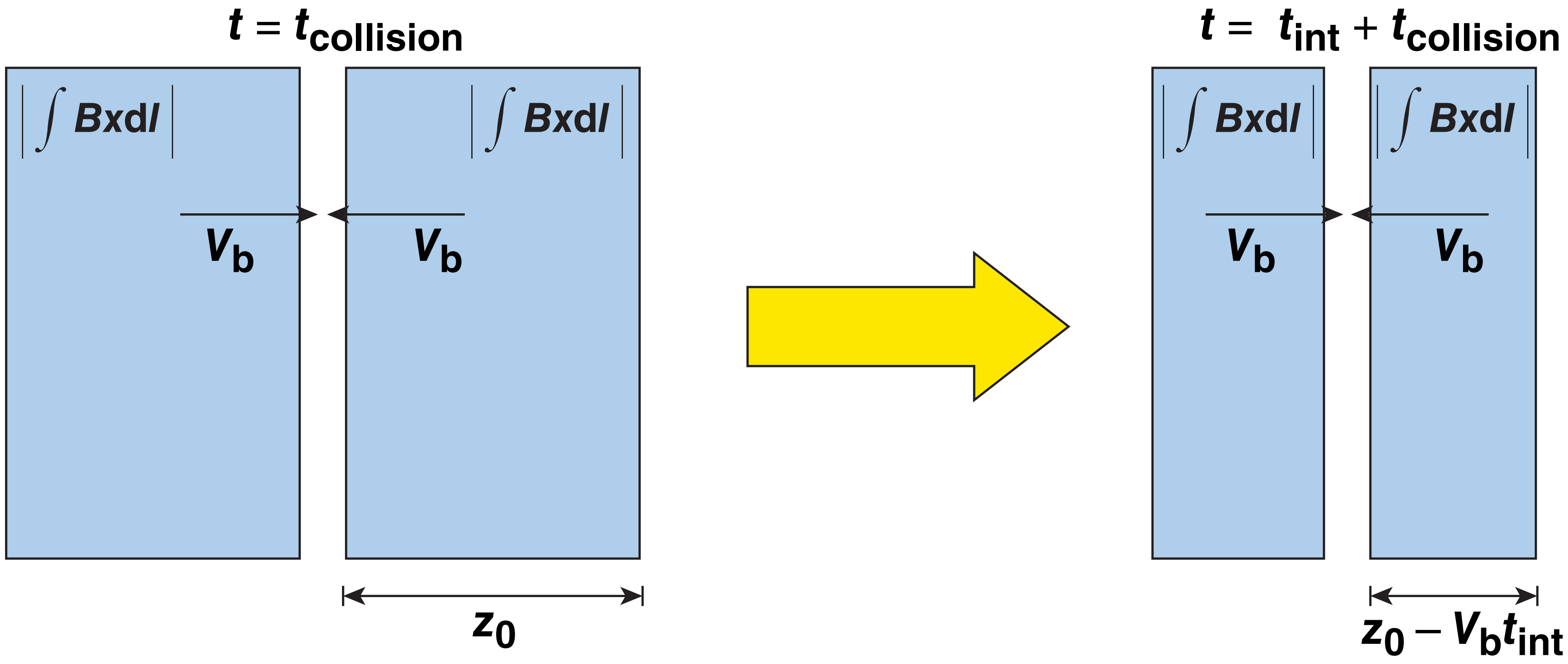
A simple, flow-based model posits that flux is annihilated at the rate that magnetic fields advect into the reconnection region



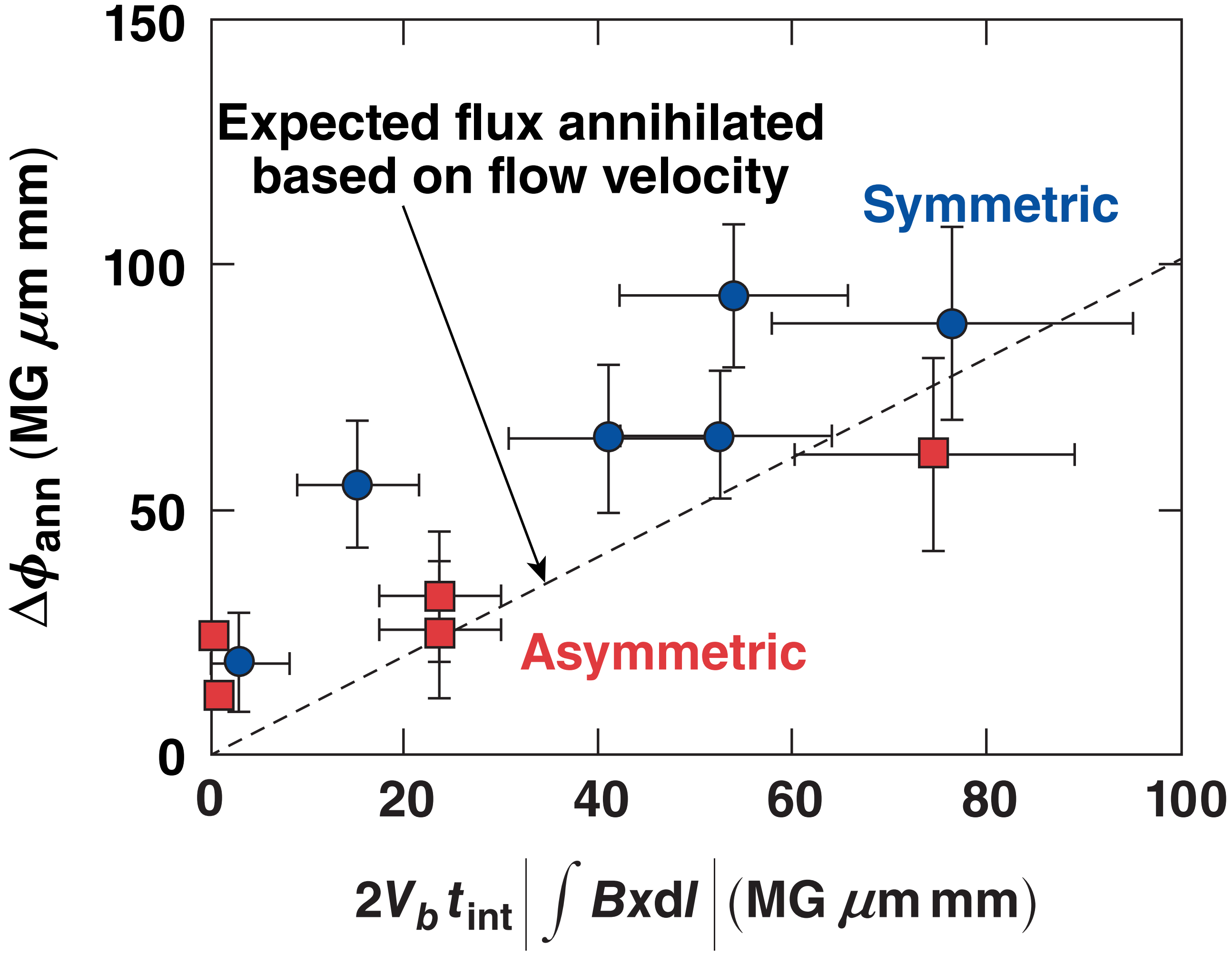
Total flux $= 2\left|\int Bxdl\right| z_0$

Total flux $= 2\left|\int Bxdl\right|\left(z_0 - v_b t_{\text{int}}\right)$

Total amount of flux annihilated based on flow velocity is: $2V_b t_{\text{int}}\left|\int Bxdl\right|$.

E25643

Flux is annihilated at the flow-based rate in both symmetric and asymmetric experiments



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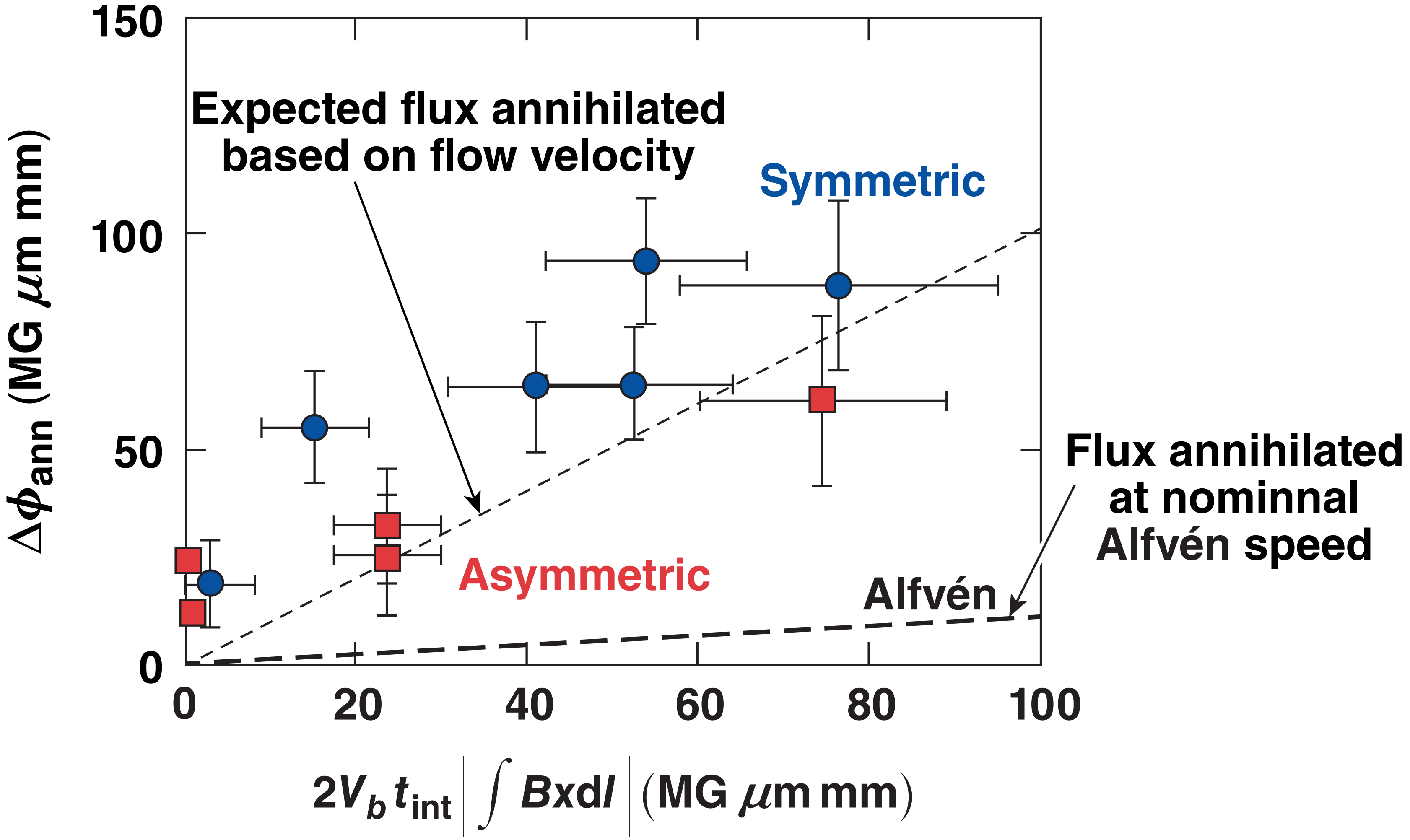
The reconnection rate in this strongly driven system is much faster than the nominal Alfvén speed



In this strongly driven system, regardless of asymmetries, reconnection occurs at a super-Alfvénic rate dictated by flow velocity as a result of flux pileup.*

E25646

M. J. Rosenberg *et al*., Nat. Commun. 6, 6190 (2015).

*W. Fox, A. Bhattacharjee, and K. Germaschewski, Phys. Rev. Lett. 106, 215003 (2011).

Summary/Conclusions

Inertial confinement fusion (ICF) laser facilities [OMEGA and the National Ignition Facility (NIF)] have been used to probe a variety of physics phenomena in high-energy-density plasmas

- Shock-driven ICF implosions have
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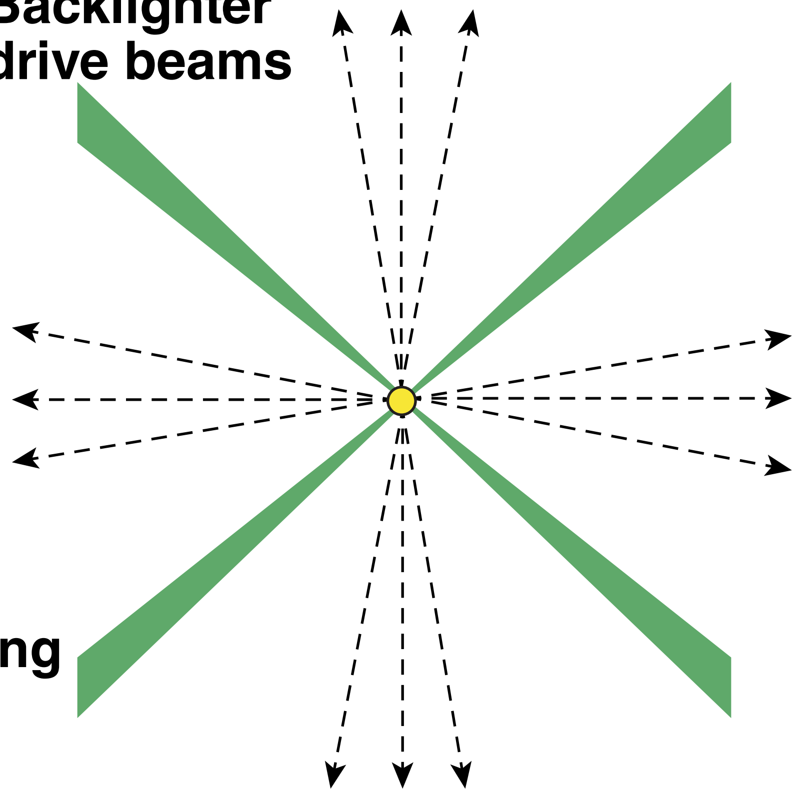
- A strong trend of decreasing yield-over-clean (YOC) with an increasing Knudsen number ($N_K = \lambda_{ii}/R_{fuel}$) for $N_K > 0.1$ is observed and attributed to ion diffusion and the preferential escape of high-energy ions

- The magnetic reconnection rate in laser-produced, strongly driven plasmas is dictated by the flow velocity and is insensitive to initial asymmetries

Large laser facilities are an excellent platform for fundamental and programmatic science, and an outstanding training ground for the next generation of high-energy-density scientists.

Appendix

On OMEGA, D^3He exploding pushers have provided an isotropic source of monoenergetic protons for backlighting laser-plasma experiments

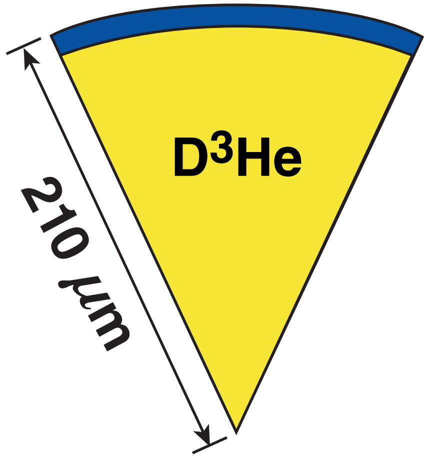


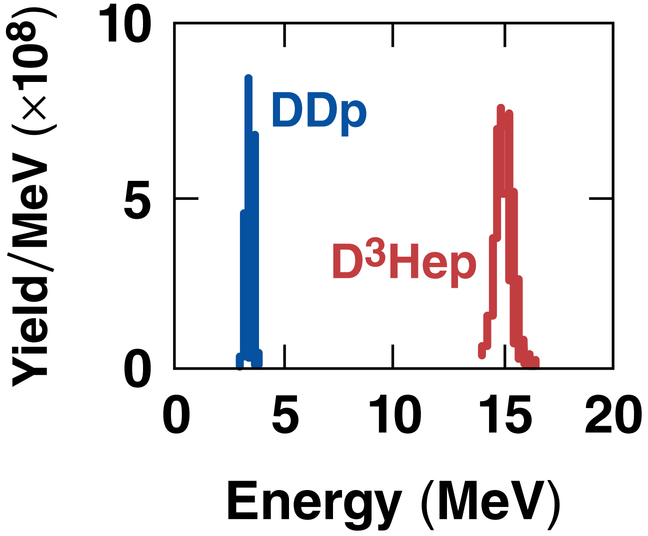
(12 kJ total, 1 ns)
~20 to 30 beams

Backlighter drive beams

D^3He exploding pusher

~50-μm source size,
~100-ps source duration





C. K. Li *et al*., Rev. Sci. Instrum. 77, 10E725 (2006).
M. J.-E. Manuel *et al*., Rev. Sci. Instrum. 83, 063506 (2012).

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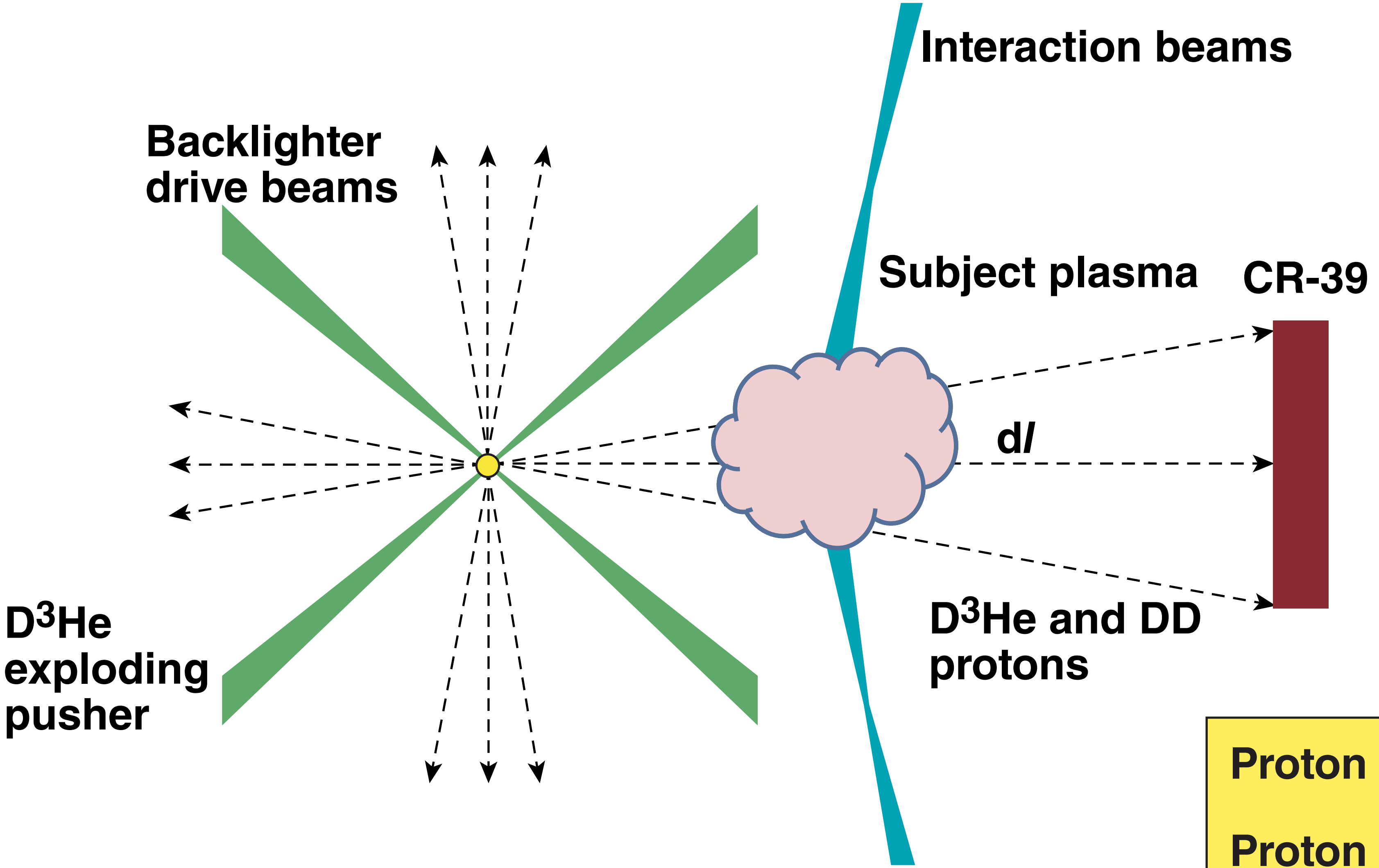
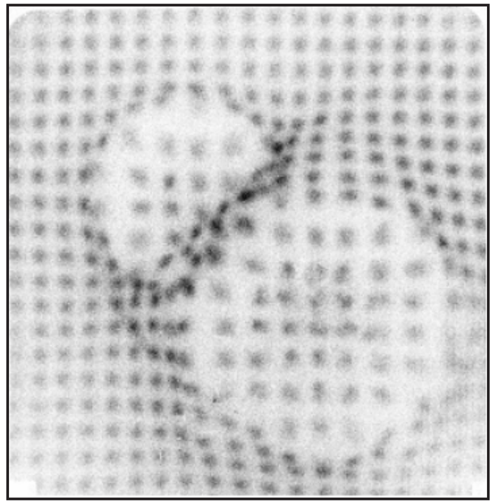
This backlighting technique provides quantitative information and images of electric and magnetic fields in HED plasma experiments



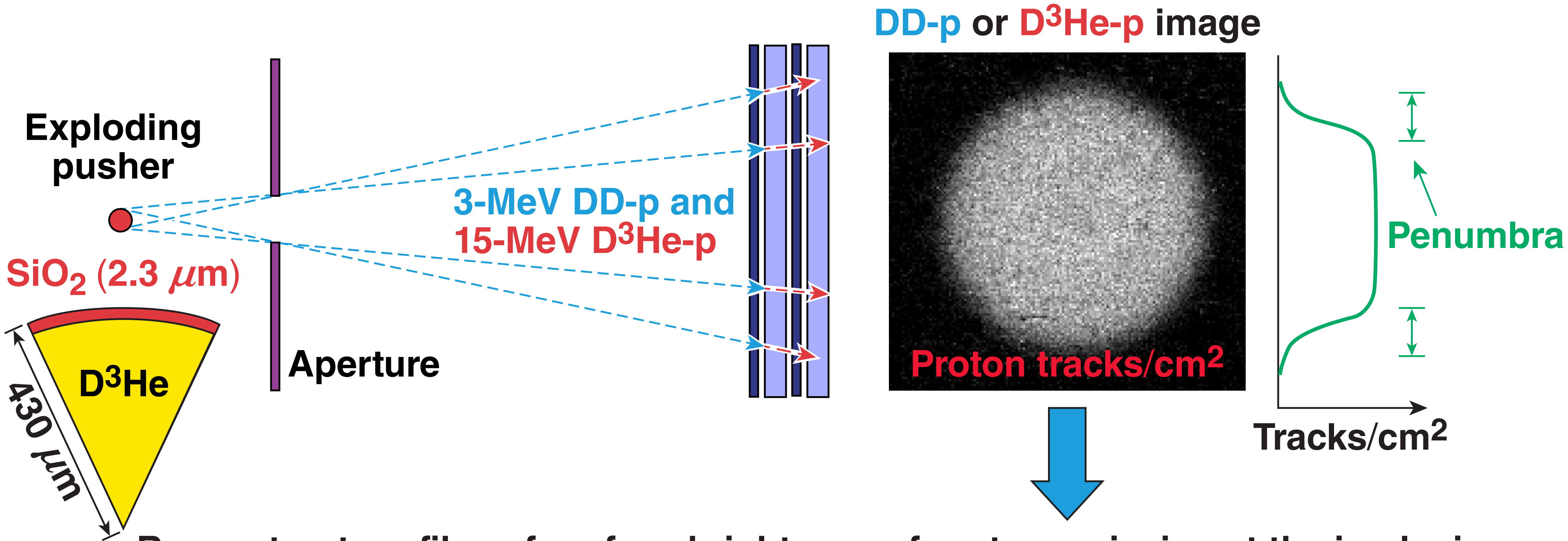
15-MeV (D^3He) p image



Proton deflection $\propto \left| \int B x dl \right| \Big/ v_p$

Proton deflection $\propto \left| \int E_{\parallel} {}^{*} dl \right| \Big/ E_p$

To better understand ion kinetic effects, penumbral imaging of DD and D^{3}He reactions was used to infer burn profiles



Reconstruct profiles of surface brightness of proton emission at the implosion

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M. J. Rosenberg *et al*., Phys. Plasmas 22, 062702 (2015).
Penumbral imaging technique:
F. H. Séguin *et al*., Rev. Sci. Instrum. 75, 3520 (2004);
F. H. Séguin *et al*., Phys. Plasmas 13, 082704 (2006).

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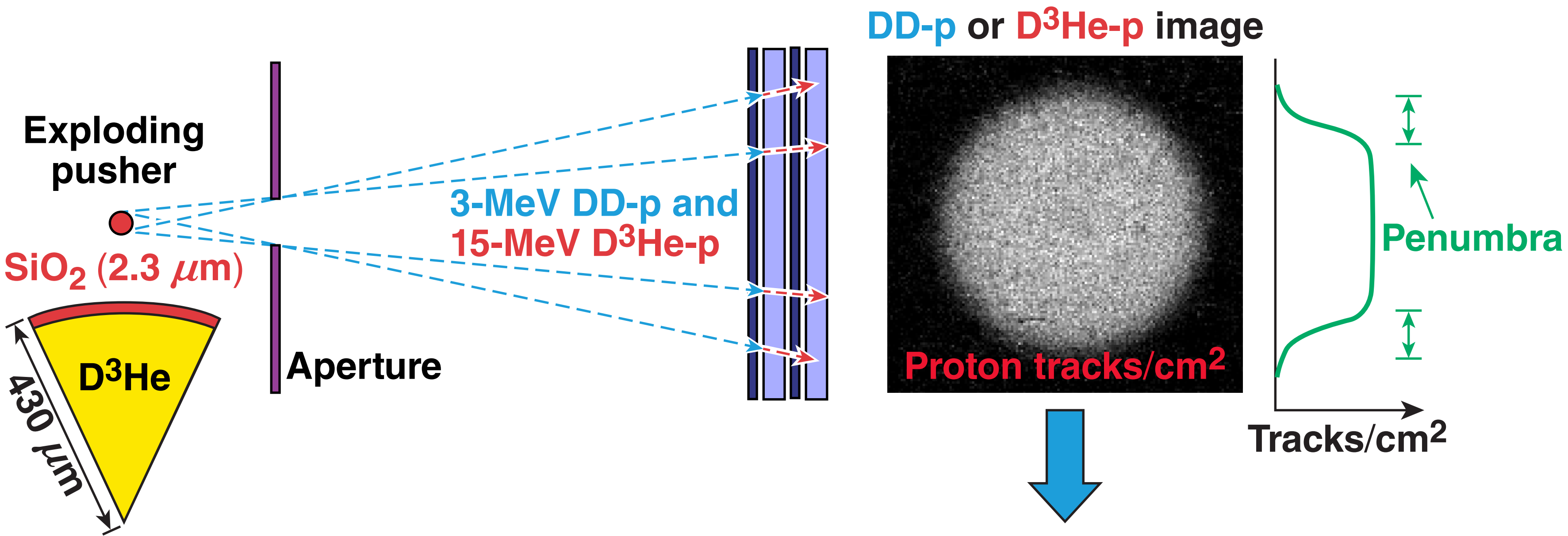
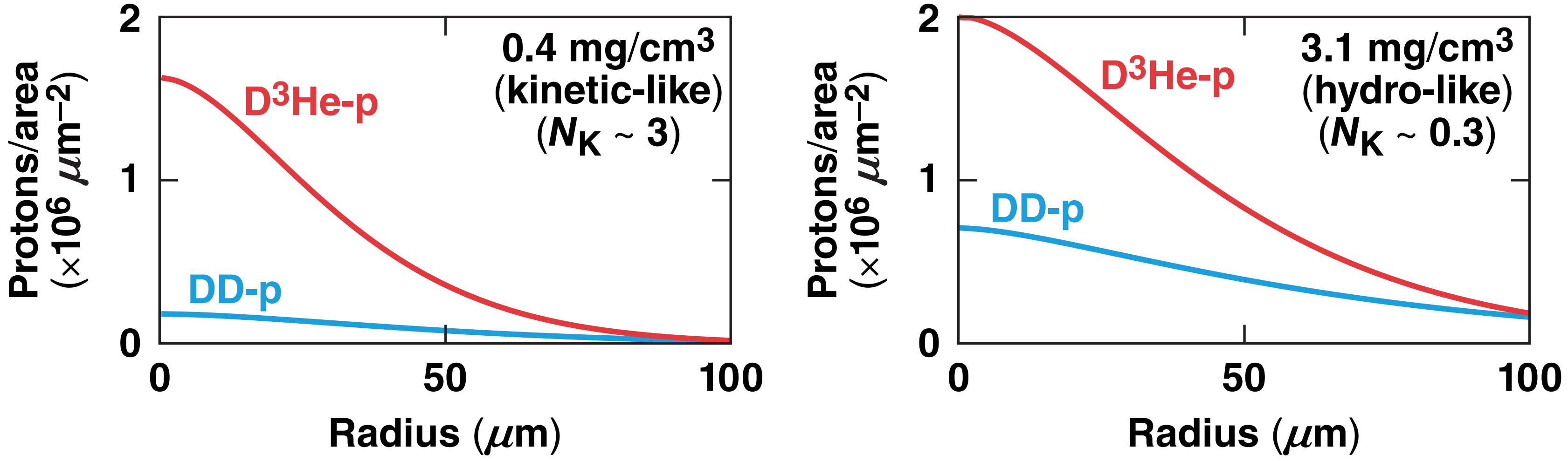
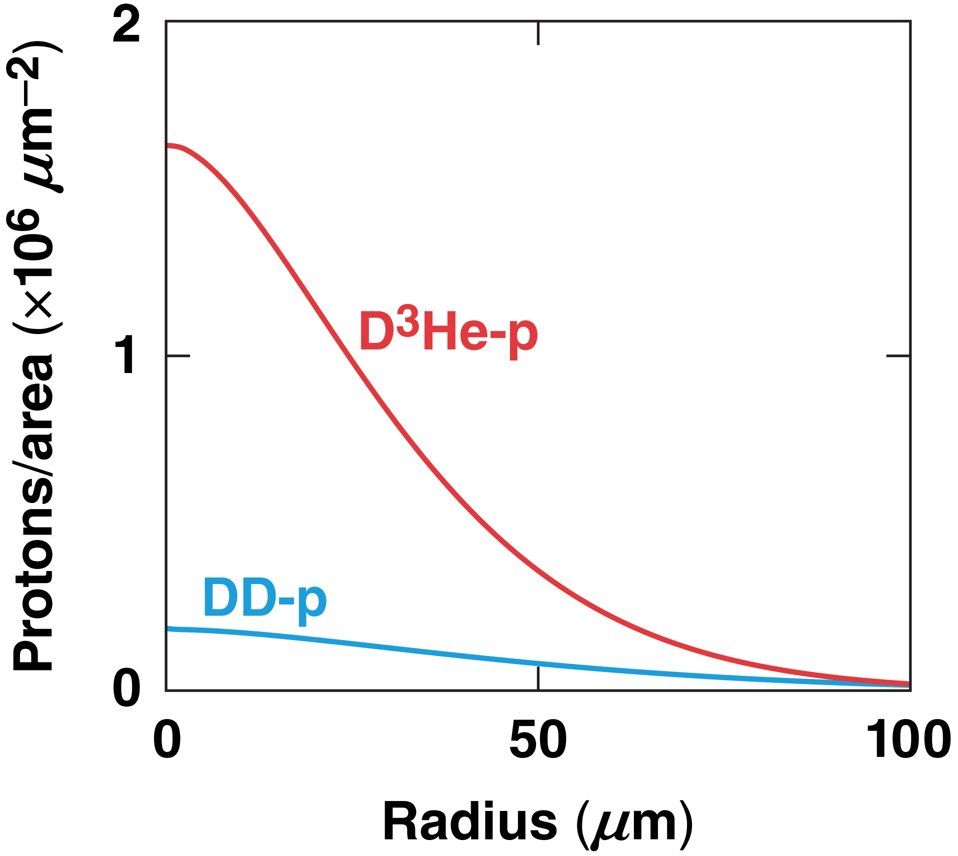


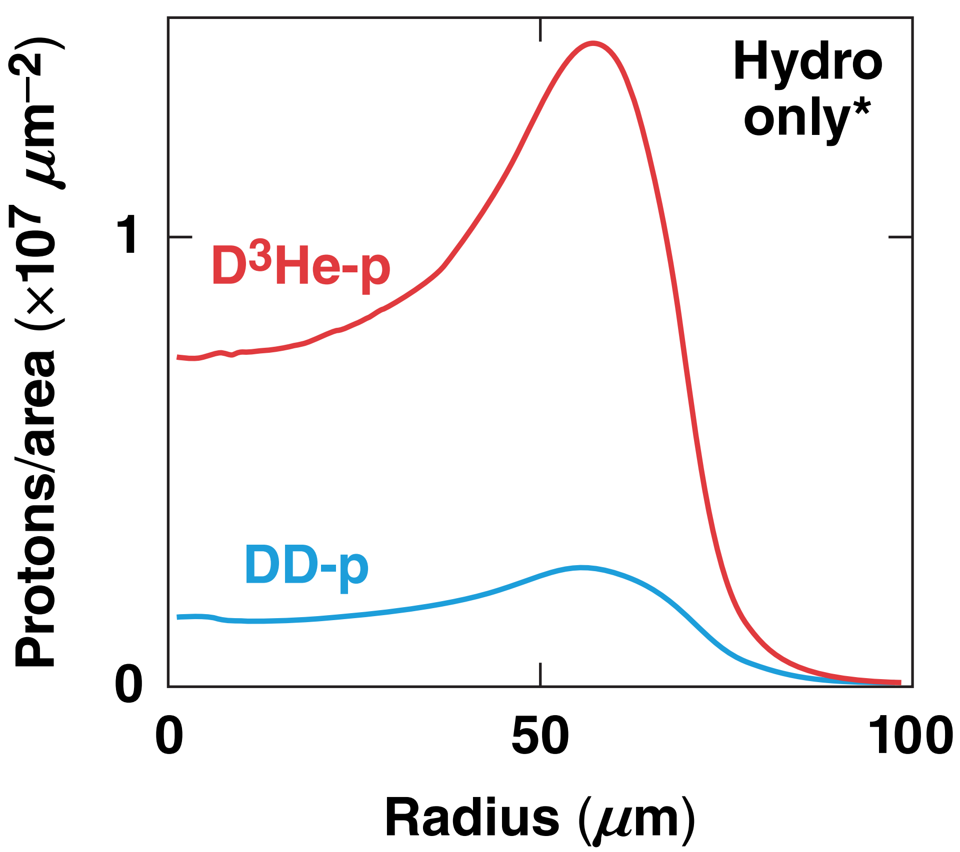
Surface-brightness profiles of proton emission (forward fit to data)



In the "kinetic" regime, measured spatial burn profiles are centrally peaked, in stark contrast to a pure-hydro model

0.4 mg/cm^3 (kinetic regime, N_K ~ 3)


Measured surface-brightness profiles


Simulated surface-brightness profiles

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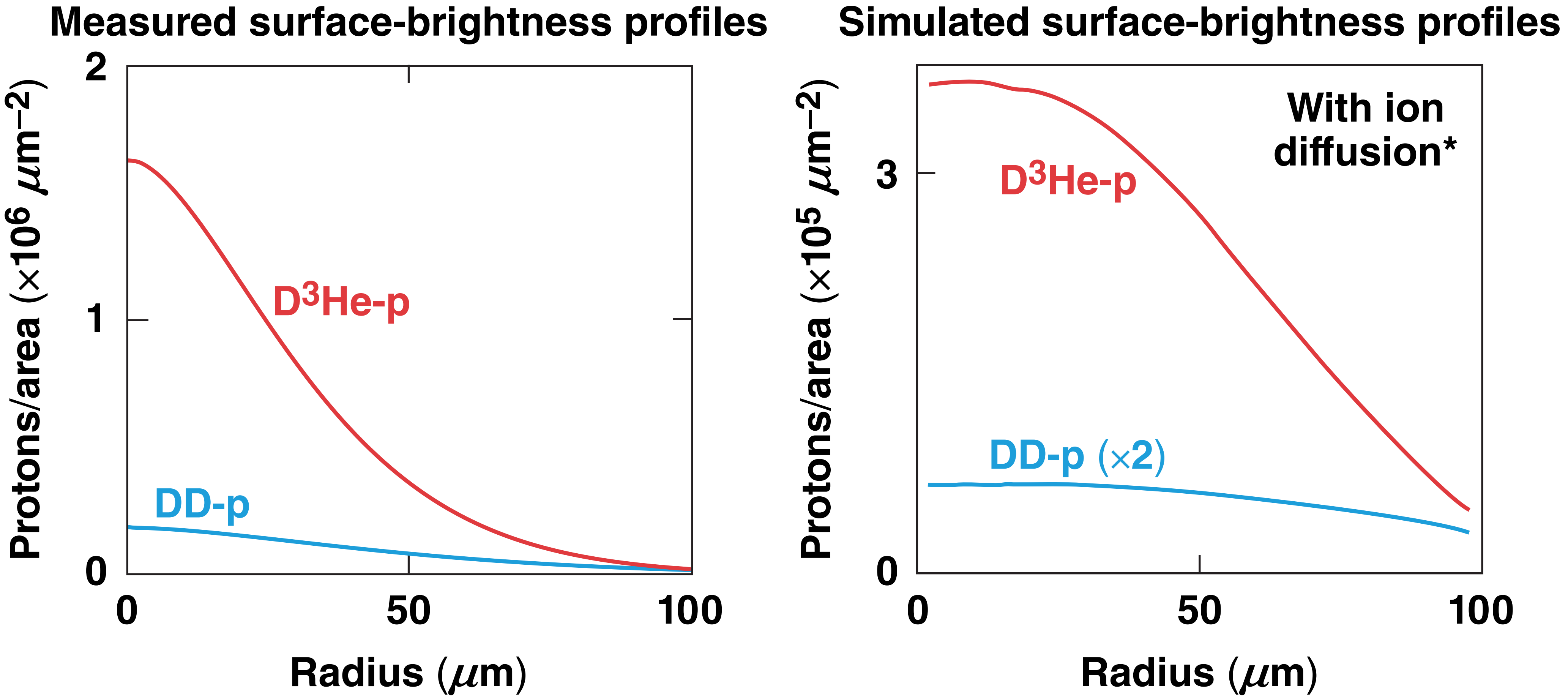
*Simulations by P. Amendt, LLNL

Inclusion of ion diffusion recovers the centrally peaked burn profiles observed experimentally

0.4 mg/cm^3 (kinetic regime, N_K ~ 3)



Ion diffusion causes significant escape of fuel ions and penetration of shell ions into the fuel.

E24404a

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*R. W. Schunk, Rev. Geophys. Space Phys. 15, 429 (1977); Simulations by P. Amendt, LLNL