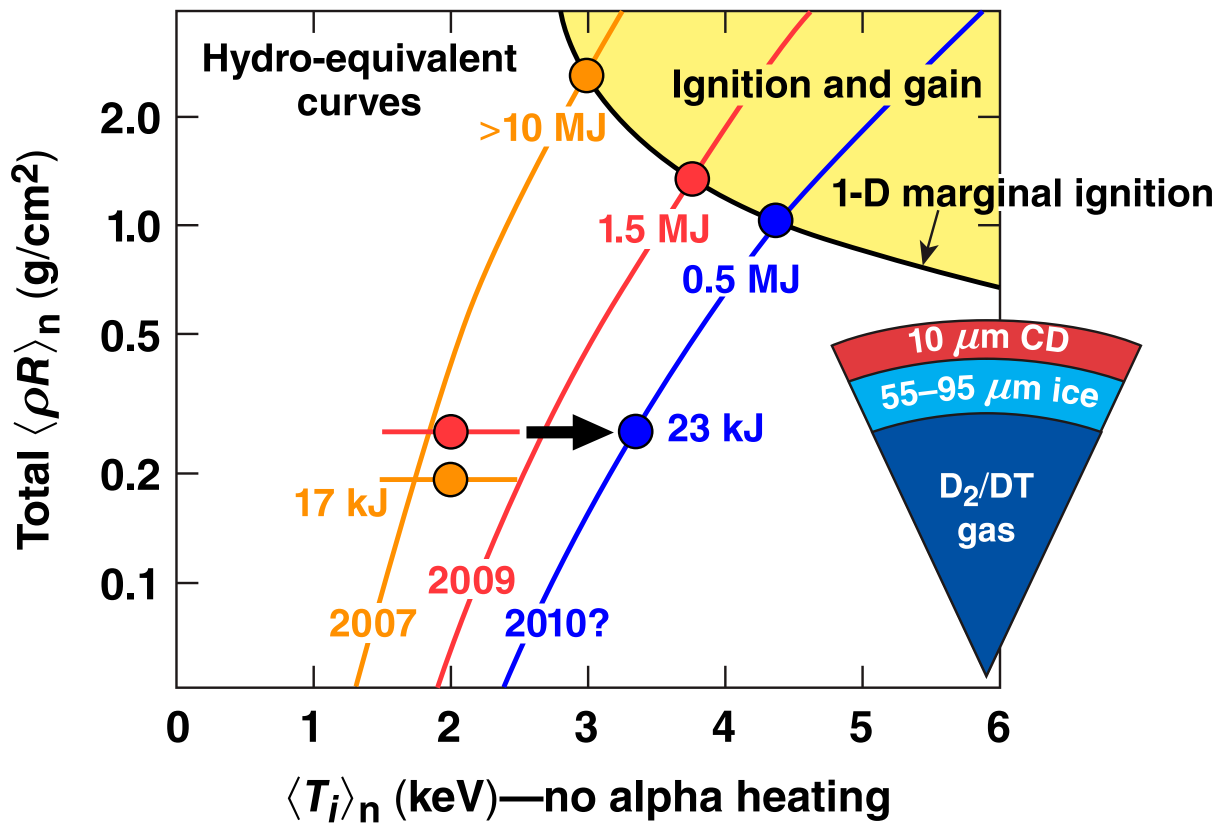
Shock-Tuned Cryogenic-DT Implosion Performance on OMEGA



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Laboratory for Laser Energetics

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American Physical Society
Division of Plasma Physics
Atlanta, GA
2–6 November 2009

Summary

Cryogenic-DT implosions on OMEGA are approaching NIF ignition hydrodynamic equivalence

- Shock velocities and coalescence are measured in cryogenic fuel using a cone-in-shell technique developed by LLE/LLNL
- Cryogenic-DT-implosion performance is optimized by tuning shock coalescence with a new multi-picket, multi-shock drive pulse
- The compressed fuel areal densities in cryogenic-DT implosions are inferred using new diagnostics
- DT areal densities of ~300 mg/cm^2 have been achieved at a drive intensity of 8×10^{14} W/cm^2 and an implosion velocity of ~3×10^7 cm/s
- Experiments planned in 2010 will increase the implosion velocity to 3.5×10^7 cm/s

Collaborators

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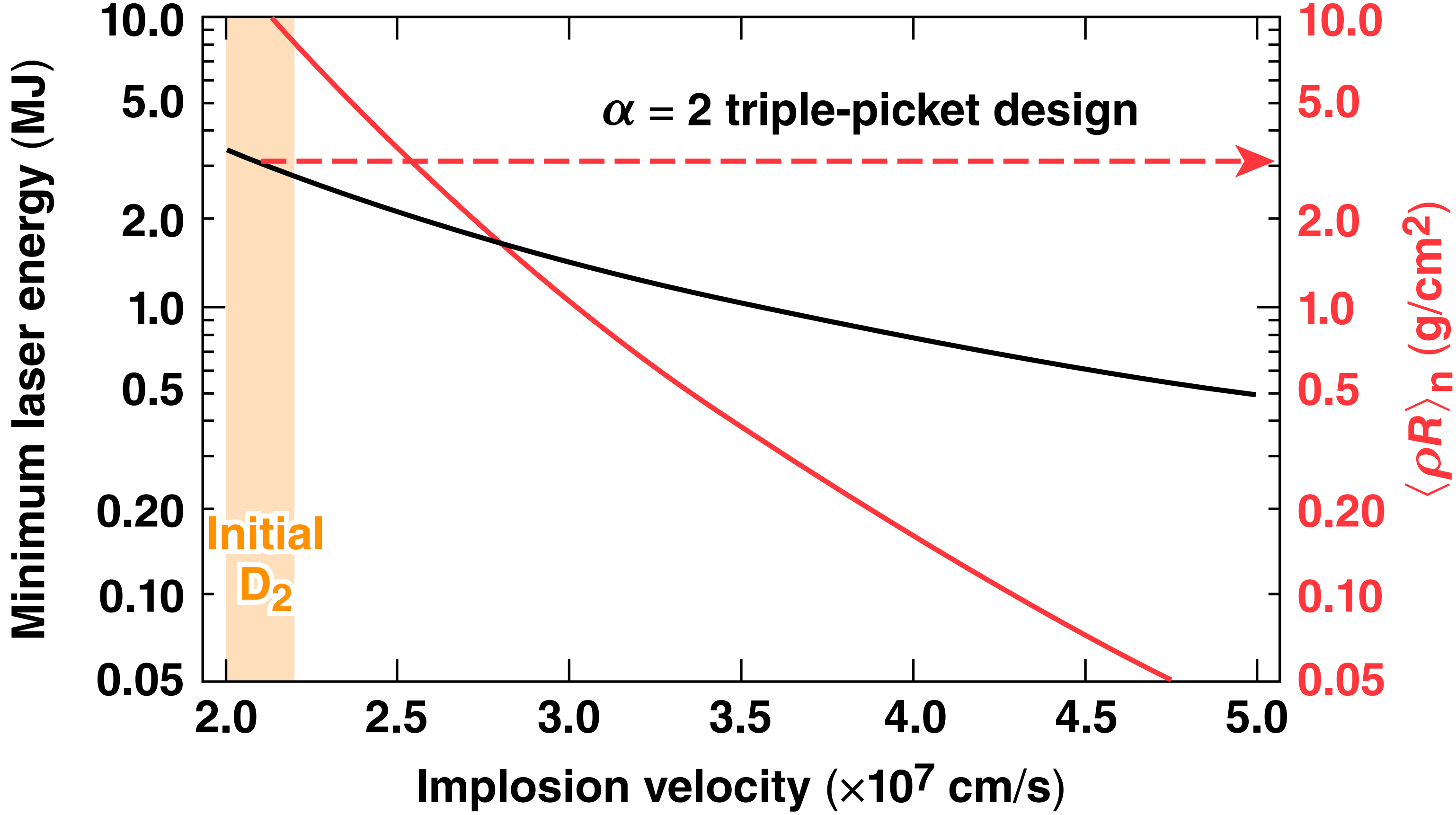
Plasma Science and Fusion Center

S. P. Padalino and K. Fletcher

SUNY Geneseo

Cryogenic fuel shells driven at ~3 × 10^7 cm/s approach ignition-relevant conditions



E18399

M.C. Hermann, M. Tabak, and J. D. Lindl, Nucl. Fusion 41, 99 (2001).
C. D. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).

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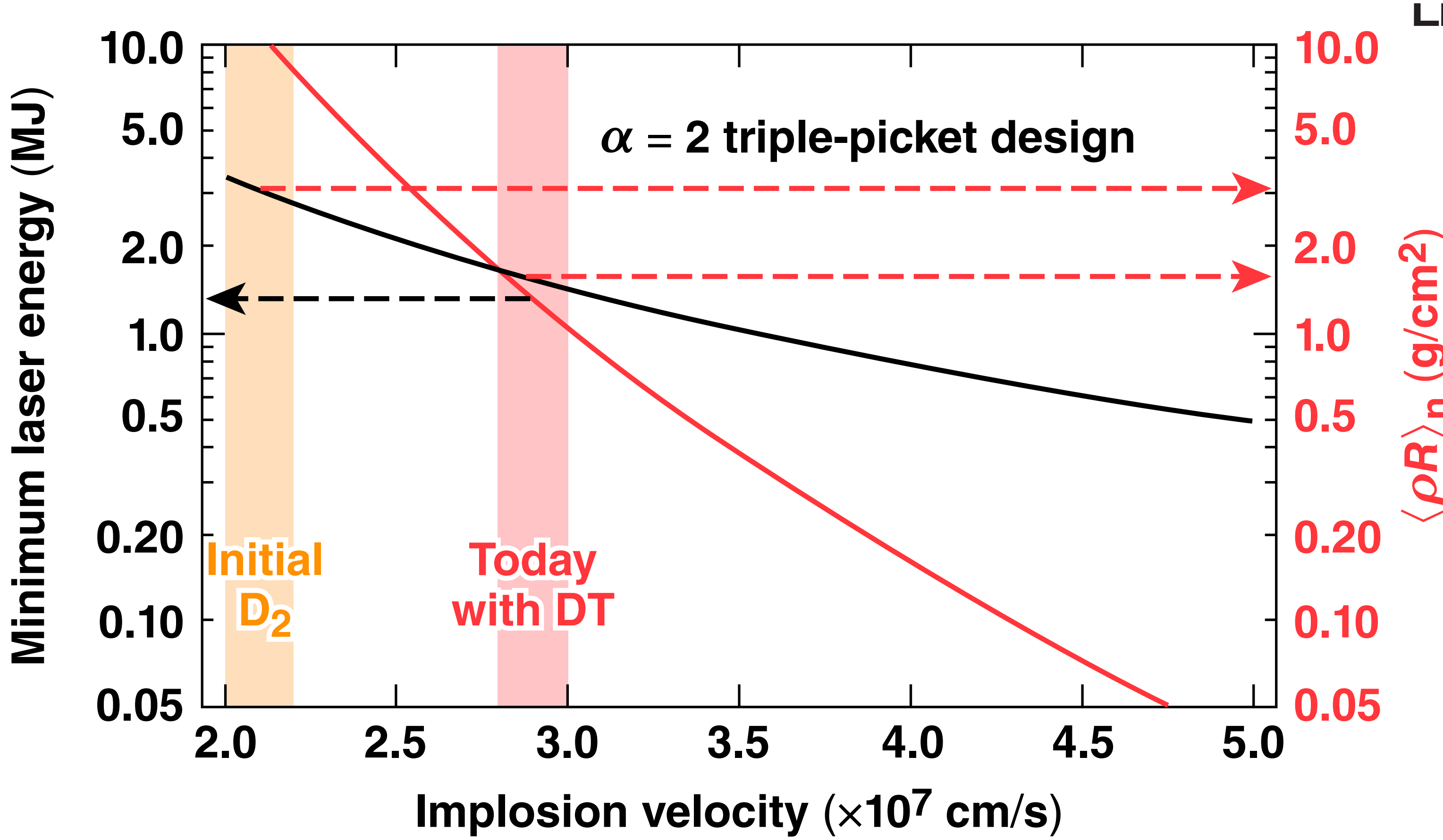
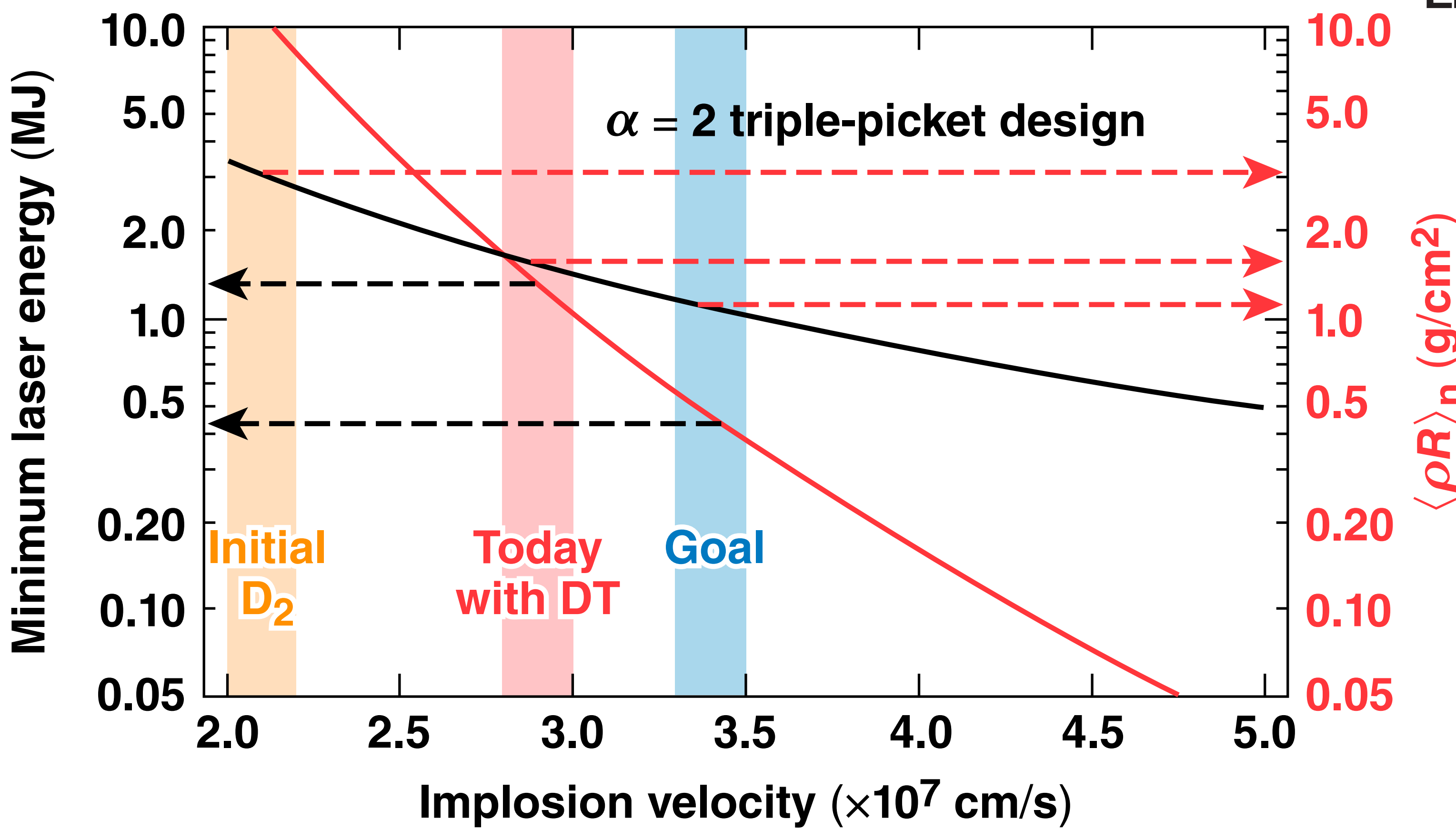


E18399a

M.C. Hermann, M. Tabak, and J. D. Lindl, Nucl. Fusion 41, 99 (2001).
C. D. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).

Cryogenic fuel shells driven at ~3 × 10^7 cm/s approach ignition-relevant conditions



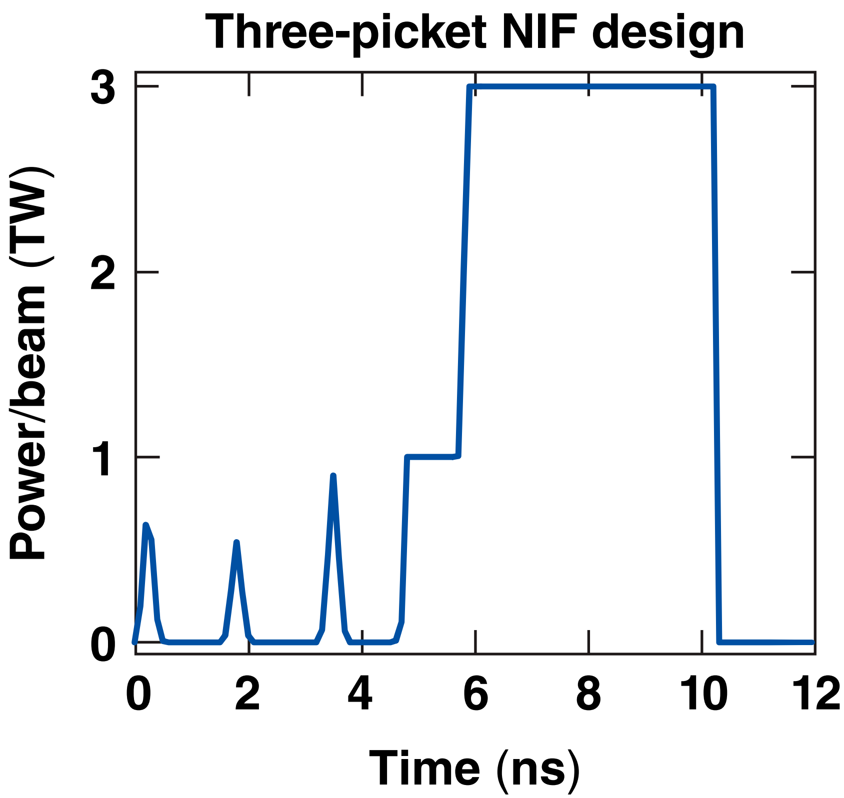
A V_{imp} ~3.5 × 10^7 cm/s is probably the OMEGA limit given intrinsic drive/ice nonuniformities.

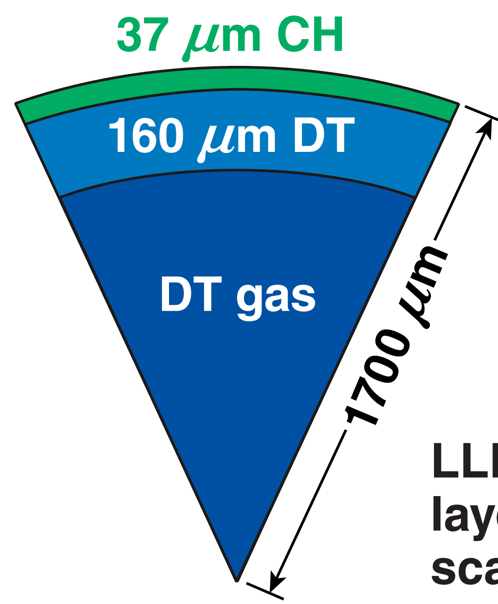
M.C. Hermann, M. Tabak, and J. D. Lindl, Nucl. Fusion 41, 99 (2001).
C. D. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).

E18399b

The new ignition design uses a multi-picket, multi-shock drive instead of the continuous low-intensity foot

Gain$_{1\text{-}D}$ = 48





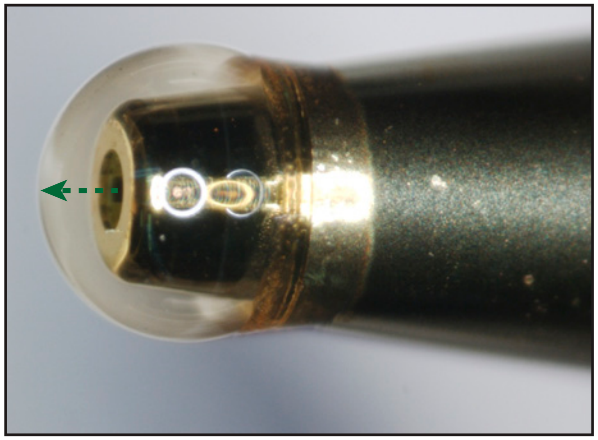
LLE has filled and layered an ignition-scale target with D_2

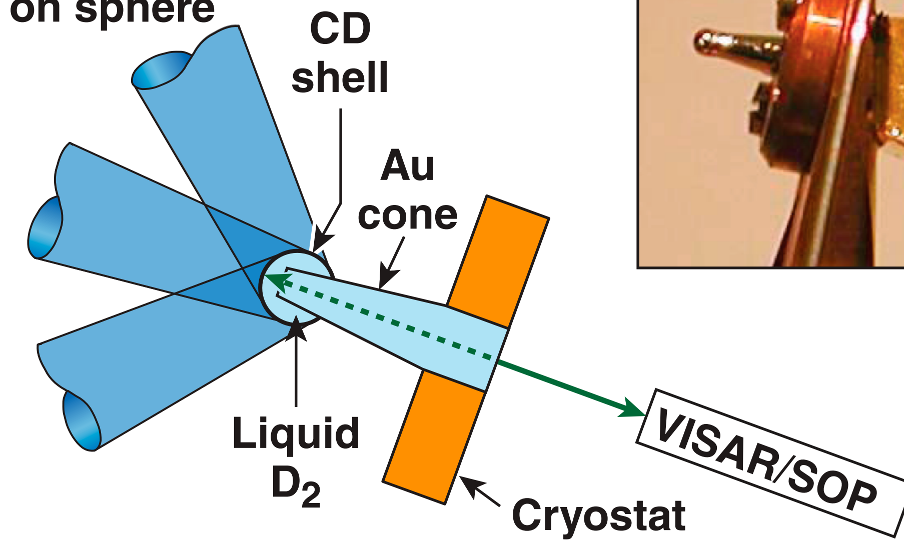
The multiple picket design is more stable, energetically more favorable for IR to UV conversion, and is easier to tune for shock coalescence.

See V. N. Goncharov (UO5.00002).

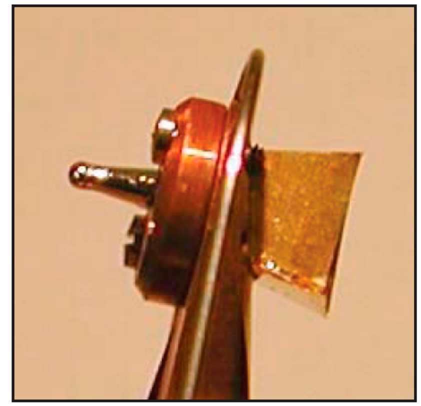
Validation of the design adiabat requires measurements of the shock velocity and coalescence

Capsule/cone detail





Full target

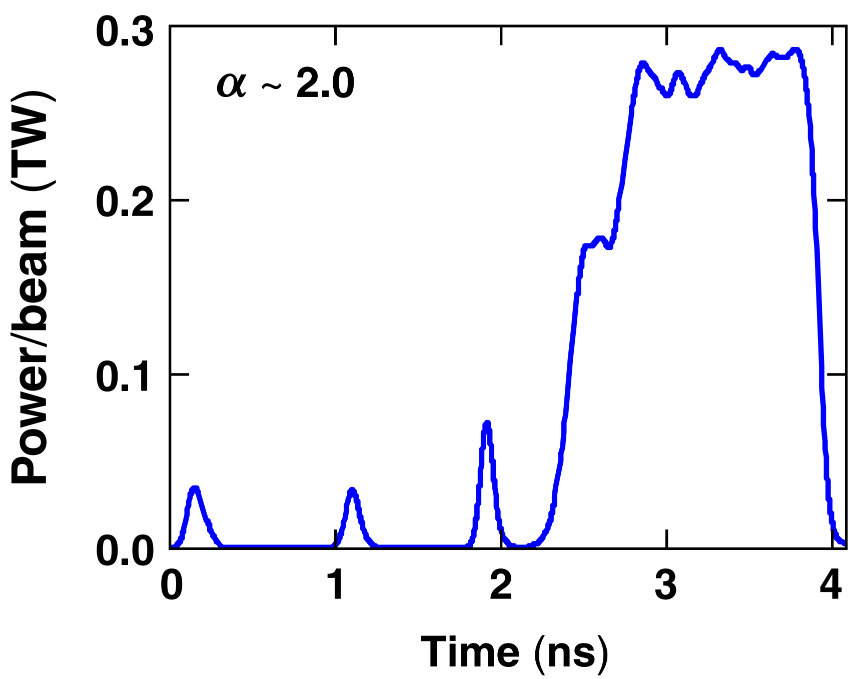


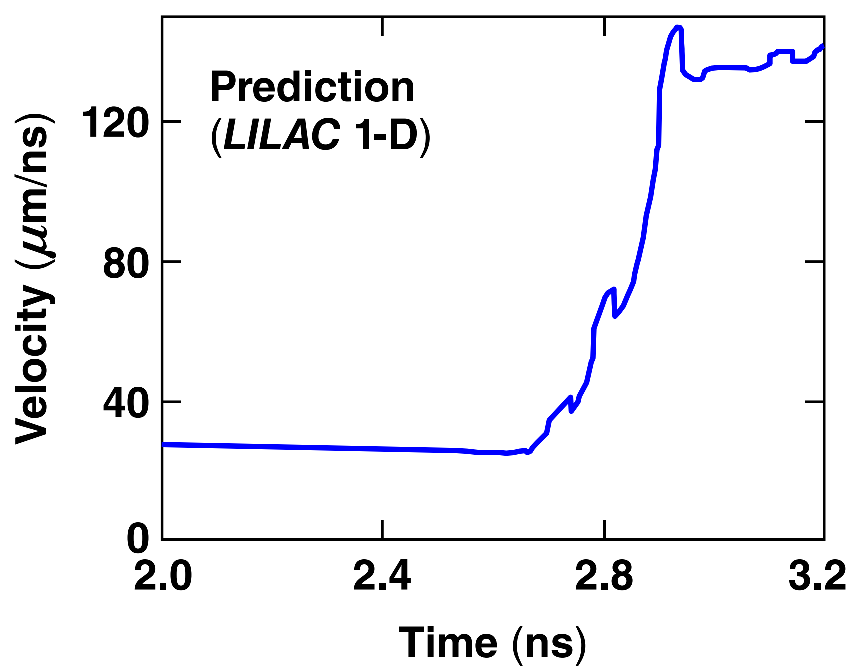
The technique was initially developed for shock-tuning ignition capsules on the NIF.

See T. R. Boehly (UO5.00001), M. A. Barrios (JI2.00002), T. R. Boehly *et al.*, Phys. Plasmas 16, 056302 (2009).

E16636g

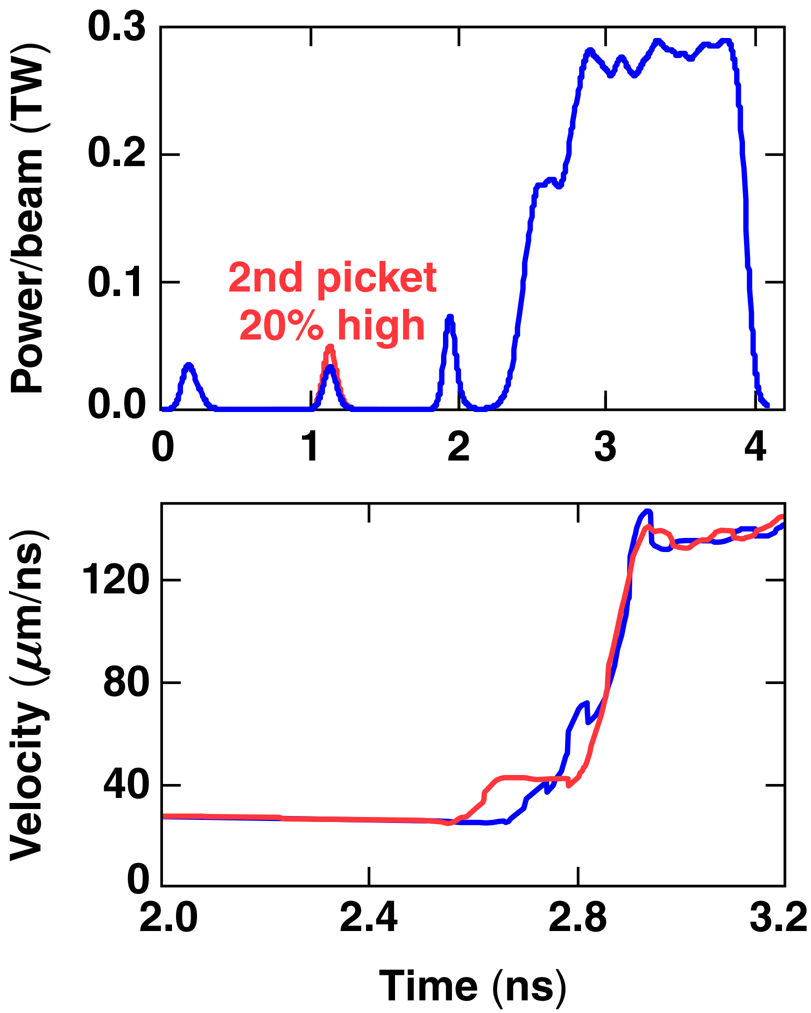
The shocks coalesce almost simultaneously at the inner surface of the fuel for an optimized drive pulse





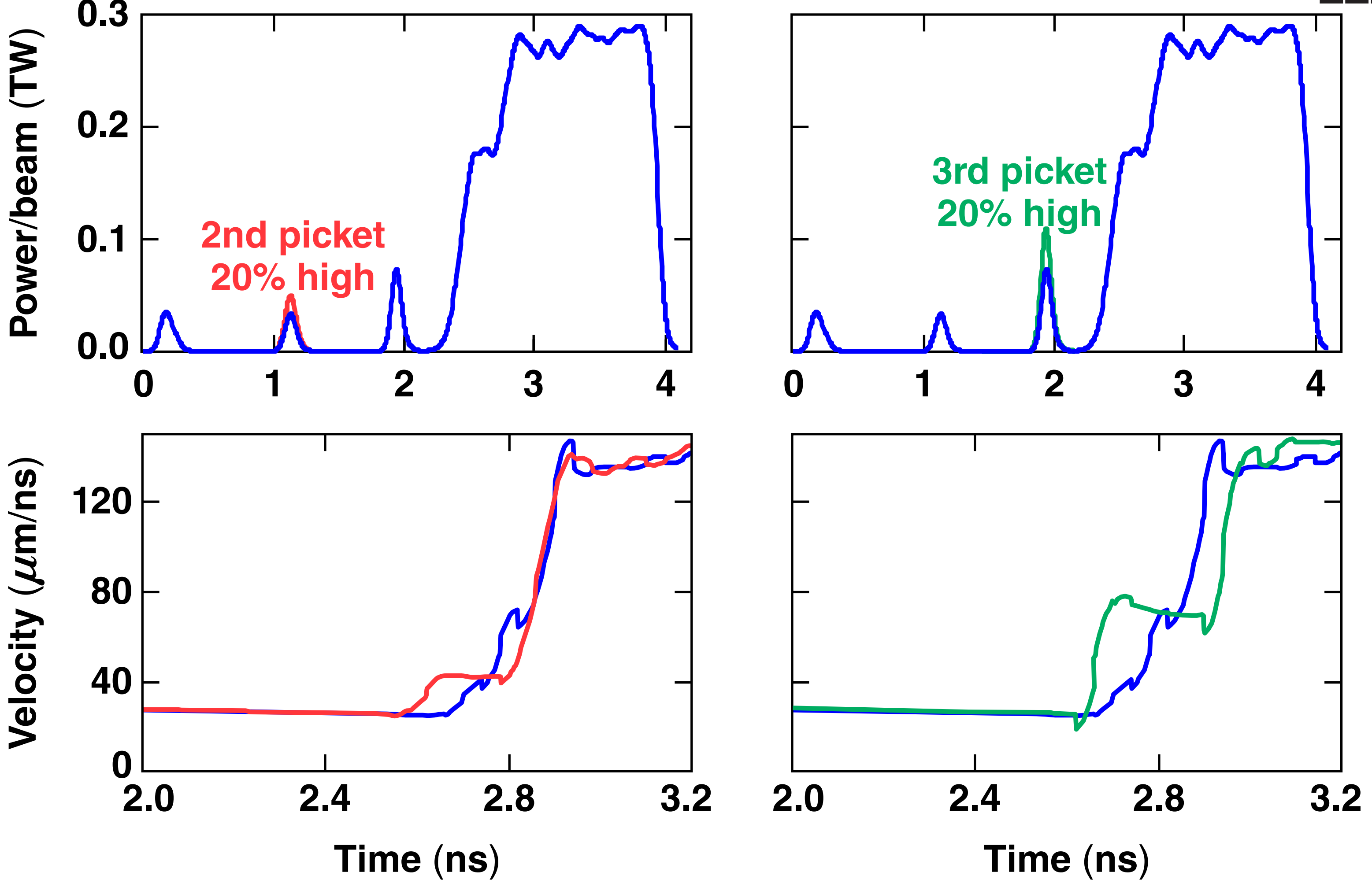
E18401

Using the cone-in-shell technique, it is possible to determine which picket is not properly tuned



E18402

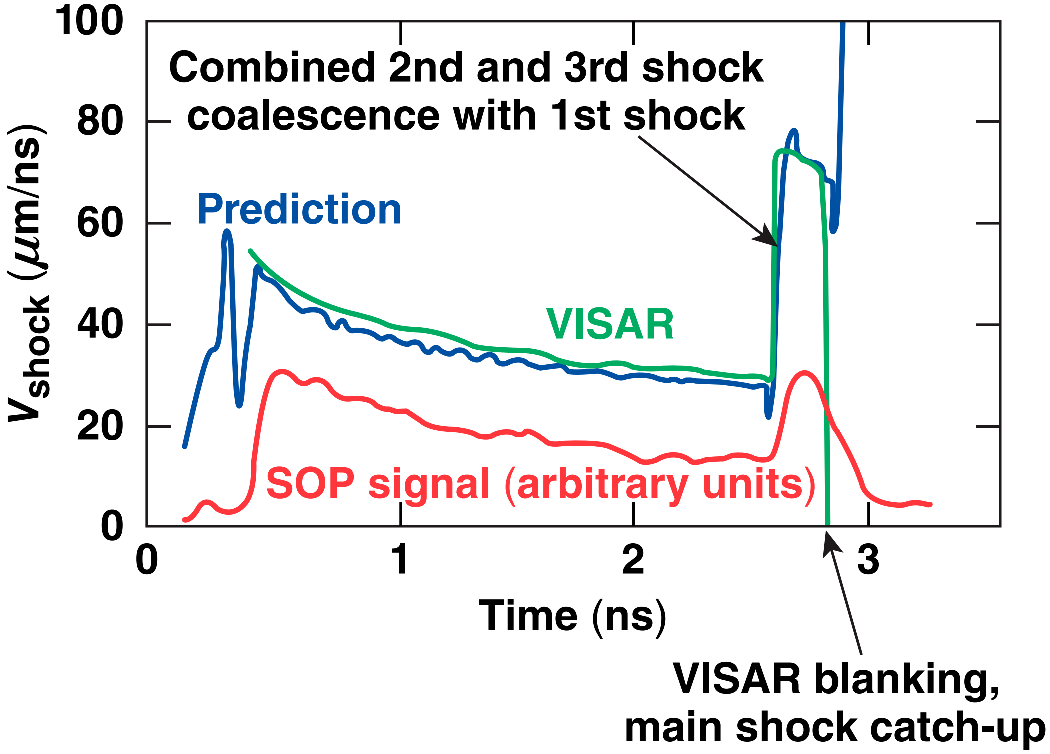
Using the cone-in-shell technique, it is possible to determine which picket is not properly tuned

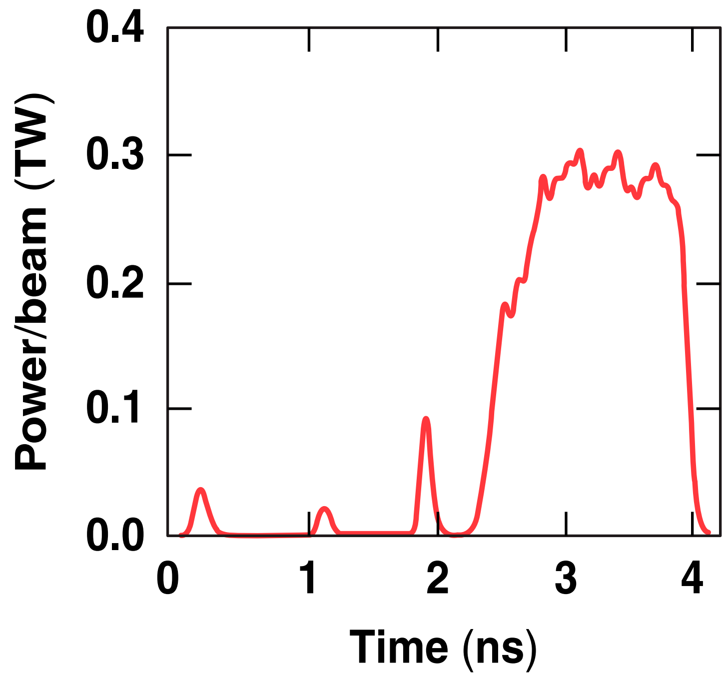


Shock coalescence can be measured more accurately using ASBO and SOP than the 100 ps requirement.

E18402a

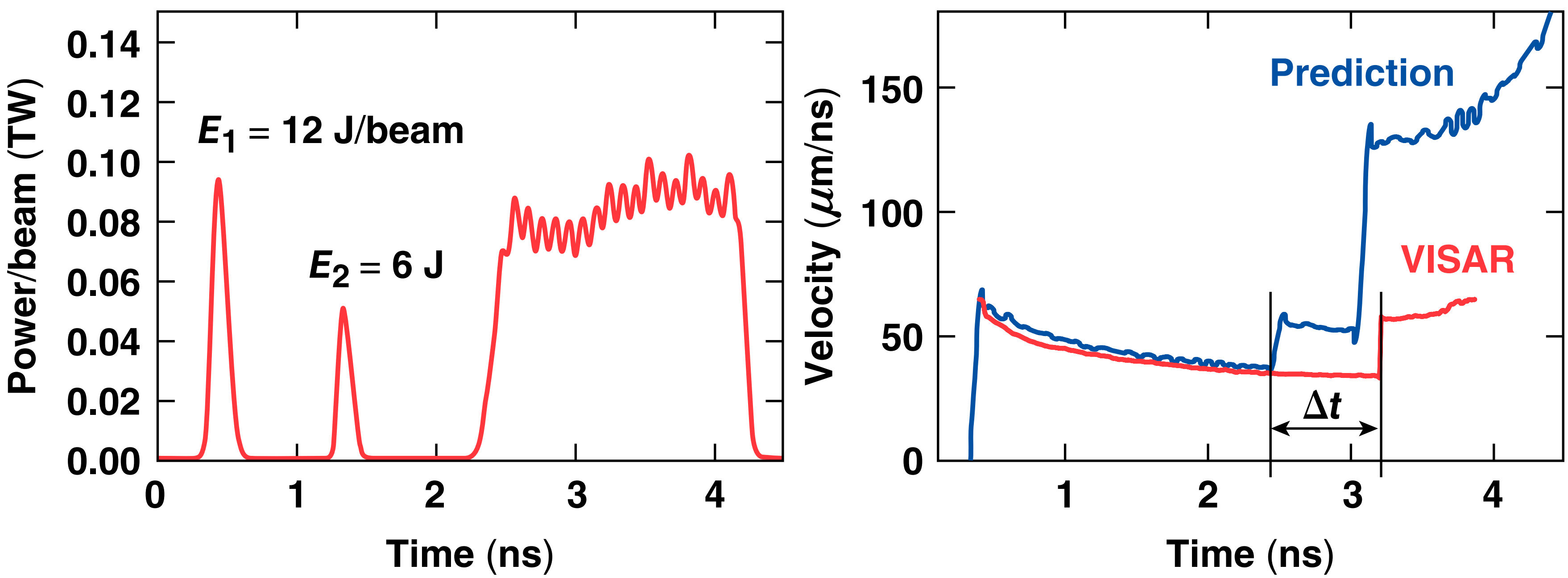
This last case was demonstrated in a recent cone-in-shell experiment





TC8705a

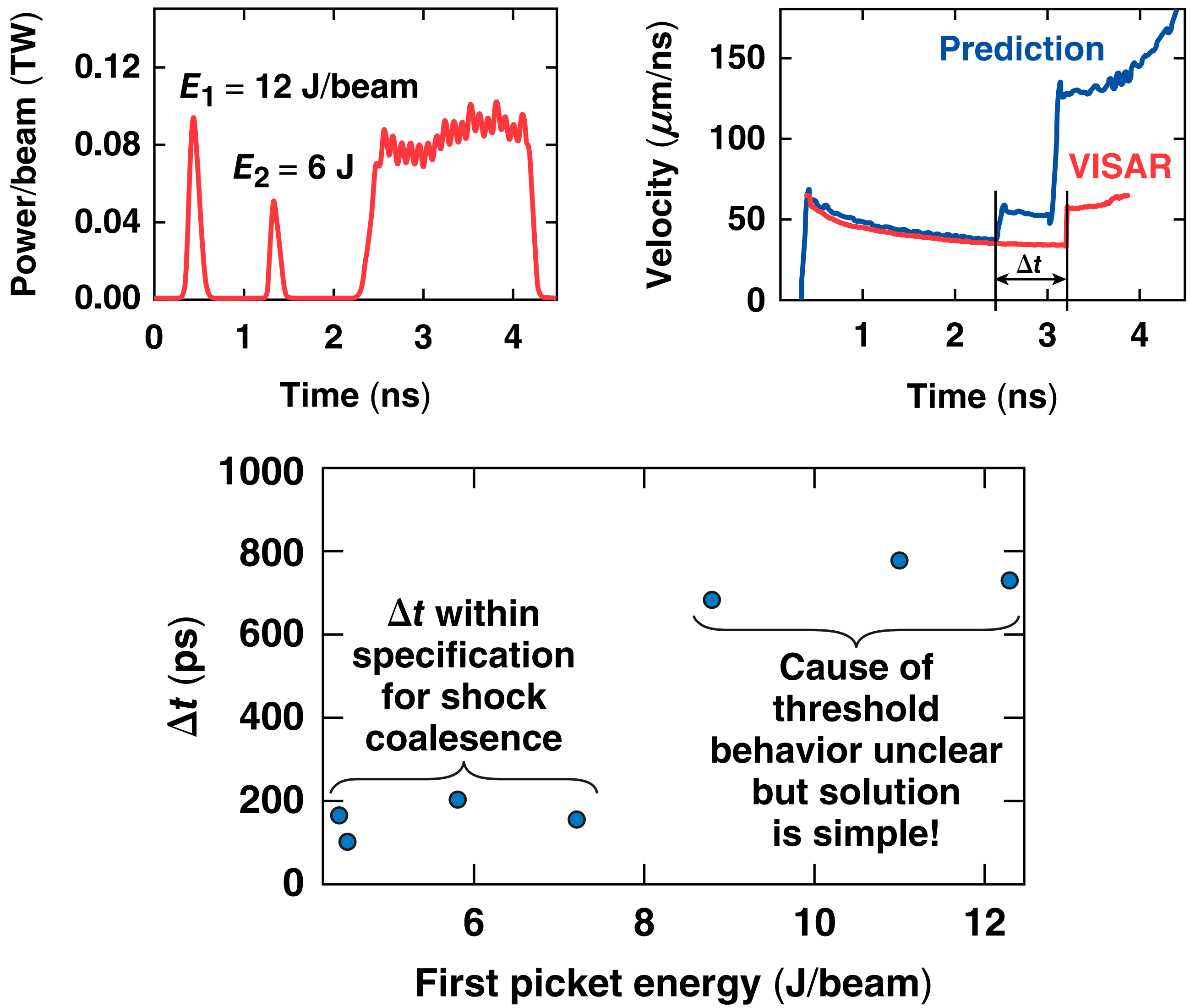
Shock velocity measurements set the requirements for the picket energies



The delay in shock coalescence appears to be correlated with the energy of the first picket.

TC8430d

The first picket energy is typically 6 J/beam



TC8432c

A "Lawson's criterion" in terms of burn-averaged ρR and T_i shows the requirements for ignition

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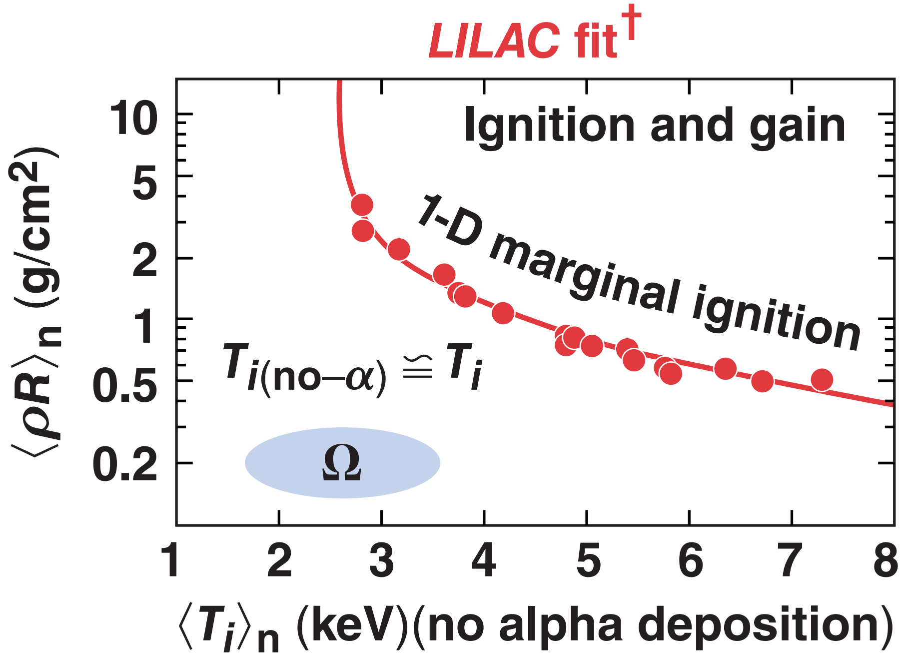
$$\langle \rho R \rangle_n > 1.3 \left(\frac{4}{\langle T_i \rangle_n (\text{keV})} \right)^{2.4} (\text{g/cm}^2)$$



Both T_i and ρR can be measured experimentally.

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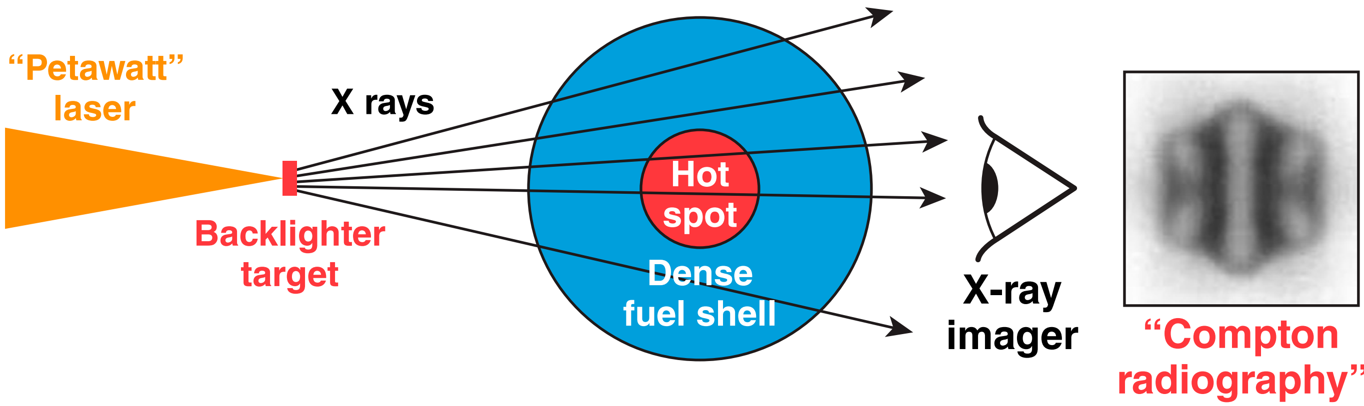
* C. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).
** M. C. Herrmann, M. Tabak, and J. D. Lindl, Nucl. Fusion 41, 99 (2001).
† R. L. McCrory *et al.*, Phys. Plasmas 15, 055503 (2008). See R. Betti (PT3.00001).

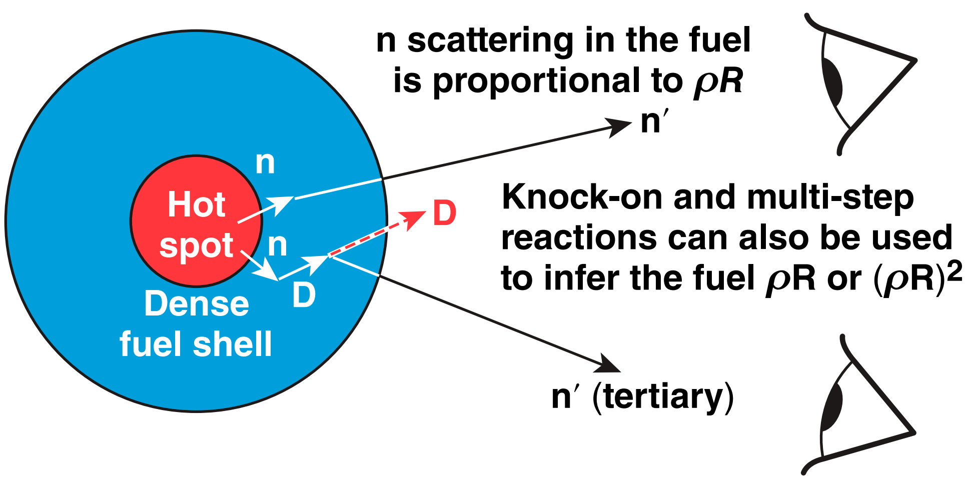
I1770c

There are a few options available to measure the fuel areal density in DT implosions

1. *Externally* backlight (point-projection) the core and compressed shell using a high-energy petawatt-class laser



2. *Internally* backlight the compressed shell using the fusion neutrons



(1) nTOF spectroscopy*

(2) Magnetic recoil spectroscopy**

(3) CPS for KO-D (low ρR)

(4) ^{12}C activation—$(\rho R)^2$ at OMEGA

* See V. Yu. Glebov (TO7.00006)

** See J. A. Frenje (NI2.00004).

E18185b

Much of the target performance can be inferred from the emitted neutron spectrum

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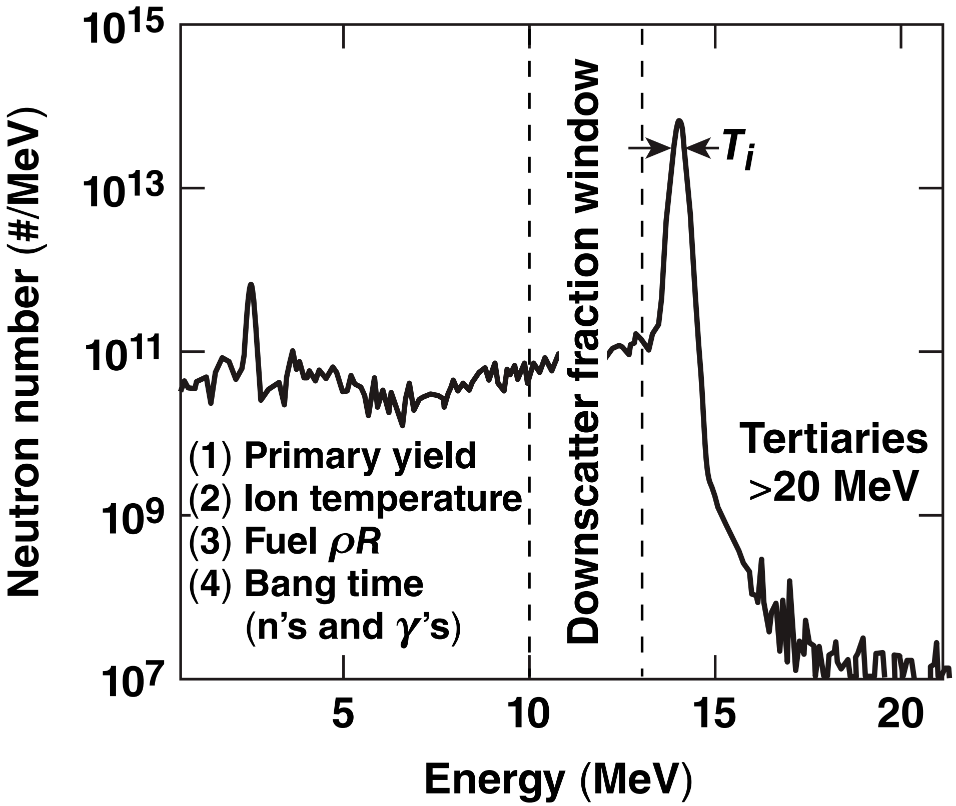


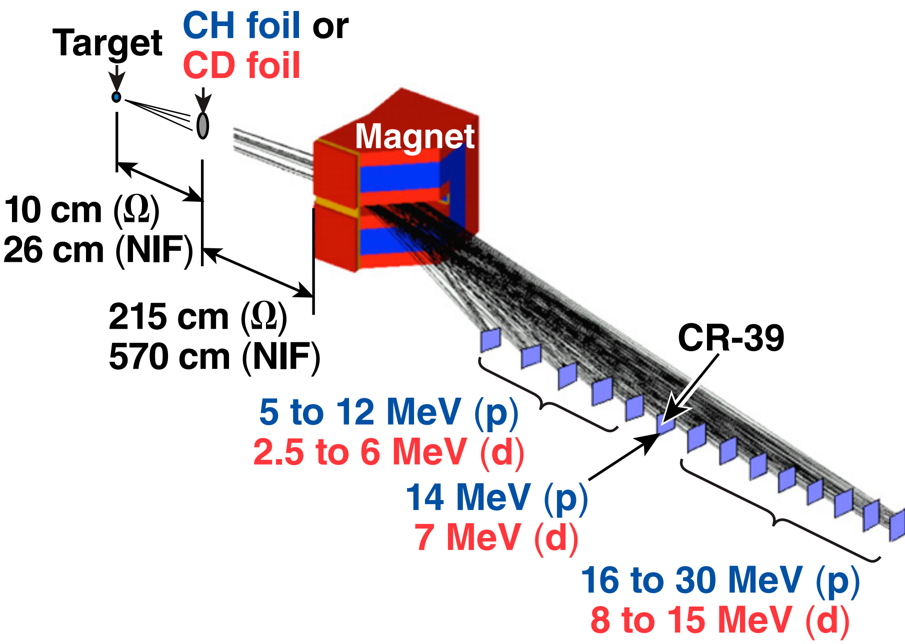
Issues:

- T+T fusion neutrons restrict the down-scatter "window" to 10 to 13 MeV
- Tertiary neutron measurements require higher primary yields
- Cross section uncertainties*
  - (n,D), (n,T), (T+T)
- Energy-dependent detector sensitivities

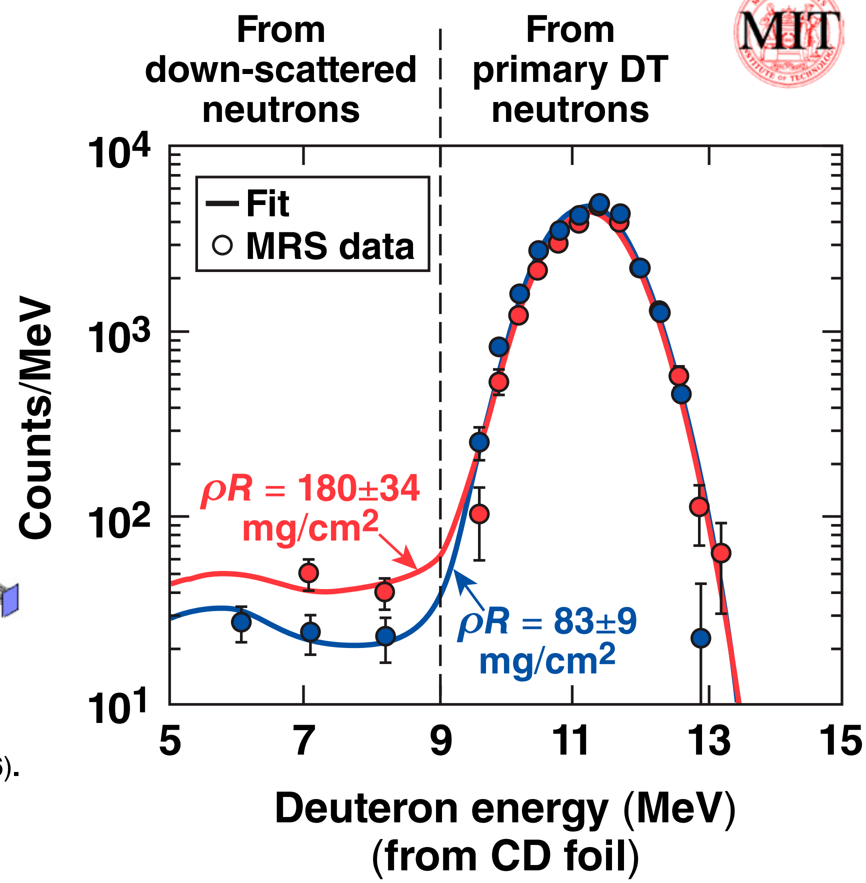
E18217a

*See J. A. Frenje (NI2.00004)

A magnetic recoil spectrometer (MRS) is used to infer the areal density in OMEGA cryogenic-DT implosions



J. A. Frenje *et al.*, NIF MRS System Design Review (April 2006).
J. A. Frenje *et al.*, to be published in Rev. Sci. Instrum. (2008).

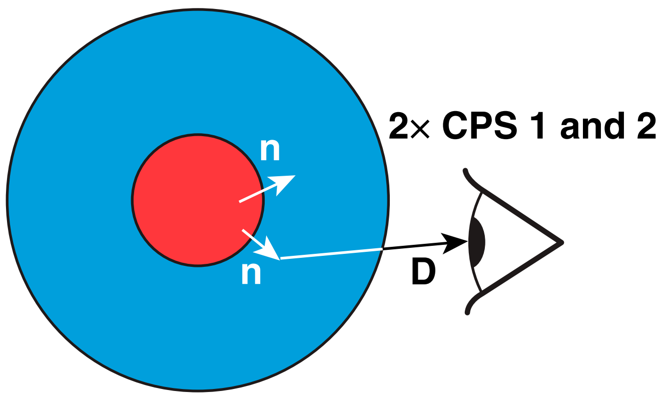


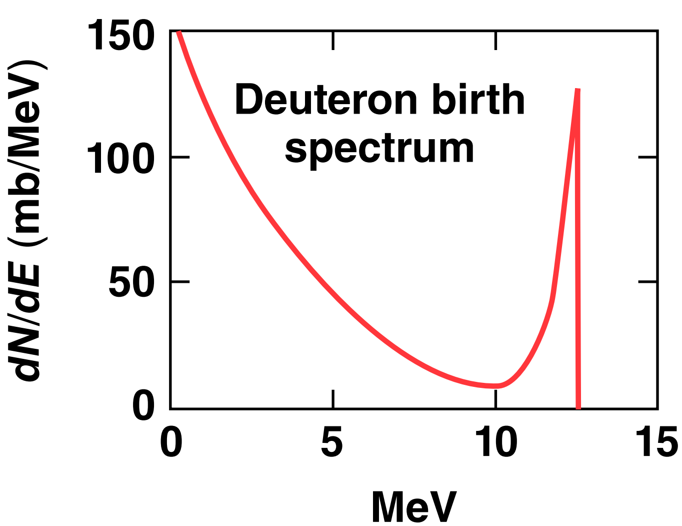
The MRS has been used on ~17 cryogenic DT implosions and measured areal densities from <100 mg/cm^2 to ~300 mg/cm^2.

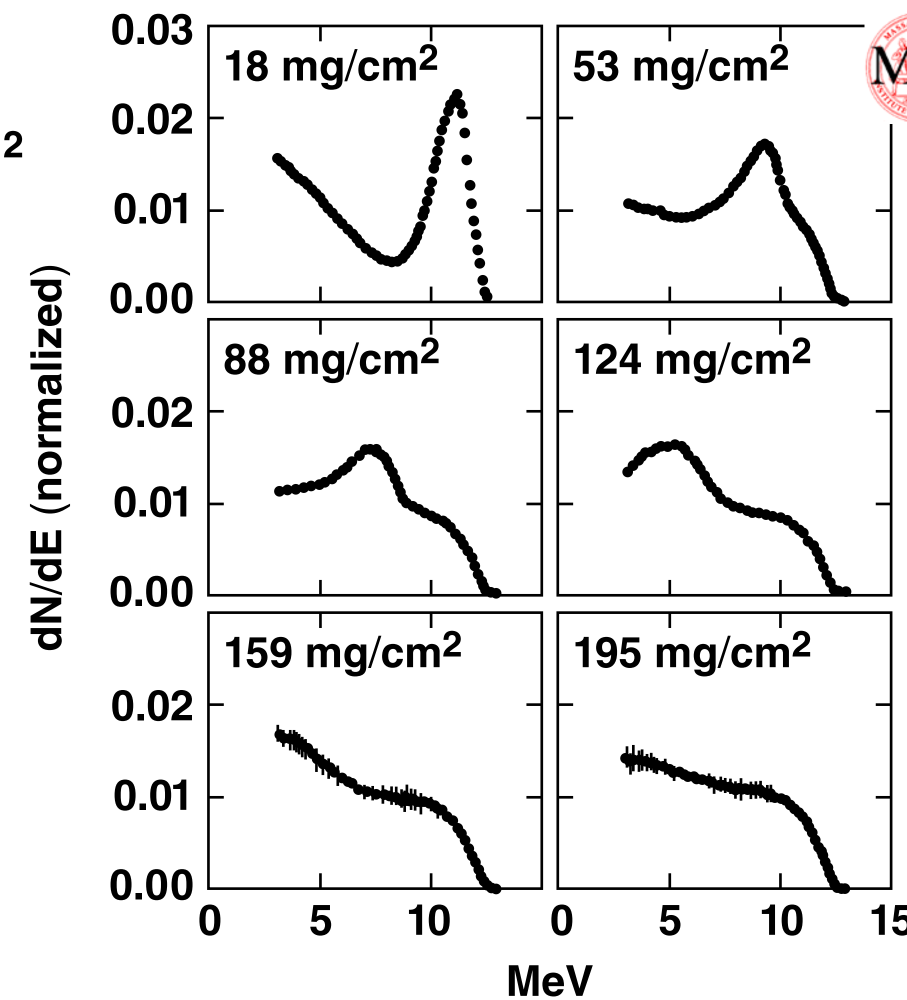
E18155c

See J. A. Frenje (NI2.00004).

The knock-on deuteron spectrum can be used to infer *ρR* using the two charged particle spectrometers (CPS's)





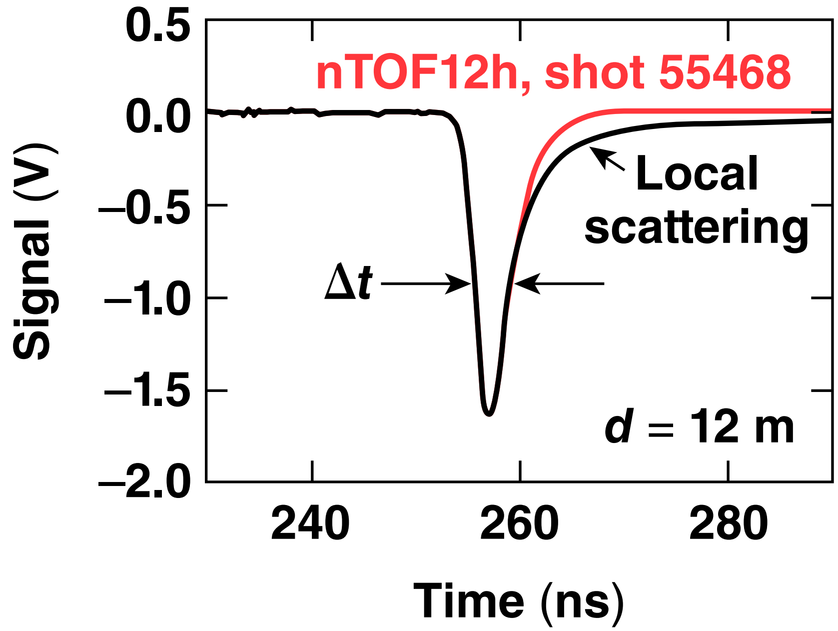


The shape of the KO-D spectrum no longer changes for *ρR* > 180 mg/cm^2.

E18403

J. A. Frenje *et al*., Phys. Plasmas 16, 042704 (2009).

Ion temperatures have been measured using the same technique for nearly three decades



$$T_i \propto \left(\frac{\Delta t}{d}\right)^2$$

A number of issues must be addressed to minimize the uncertainty:

(1) **Local neutron scattering in x-ray shielding**

(2) **Impulse-response function of the detector, cables, and digitizer**

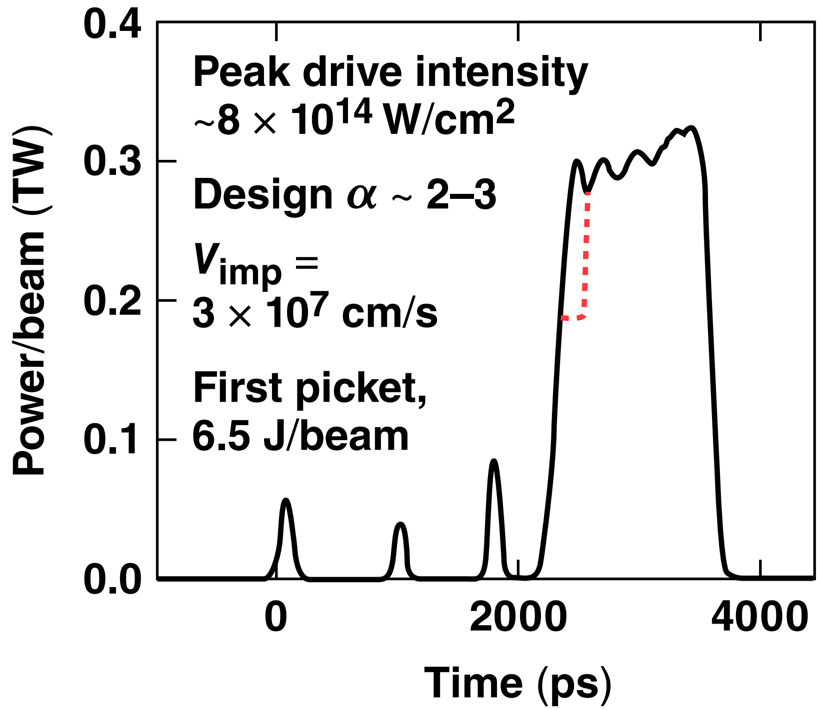
(3) **Scope and shot noise that vary shot-to-shot**

Ultimately, hot-spot quenching due to mix may limit T_i at OMEGA.

*H. Brysk, Plasma Phys. 15, 611 (1973).

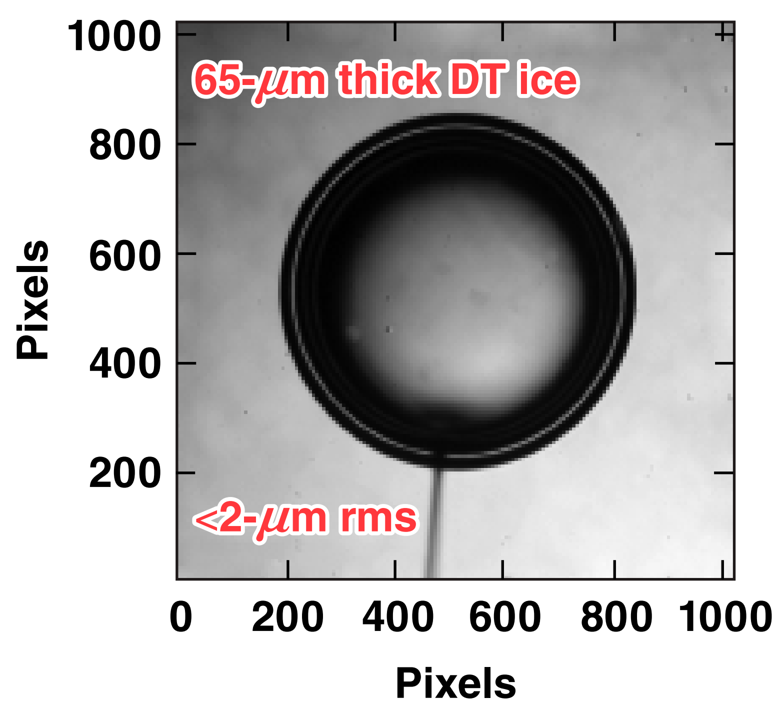
Multiple-picket pulse shapes are being used to drive cryogenic-DT implosions on OMEGA

Current drive pulse used to implode cryogenic-DT targets



Picket energies and relative timing are adjusted to optimize the shock coalescence

Shadowgraph of a stalk-mounted cryogenic-DT capsule

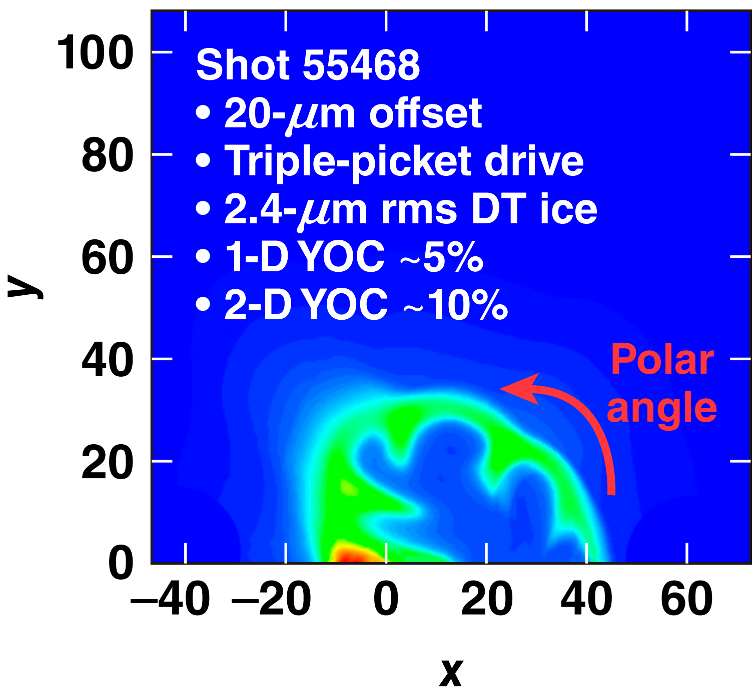


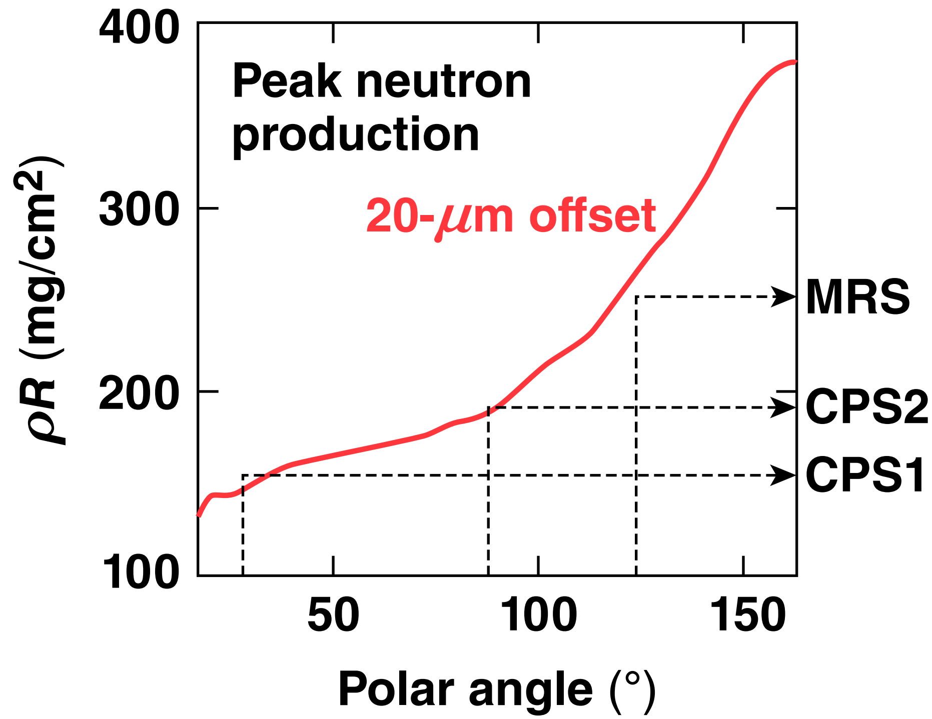
Target vibration at T_0 is significantly reduced with stalk-mounted targets

I1902

The ρR variation caused by target offsets in 2-D *DRACO* simulations is consistent with measurements

Measurement	Experimental (mg/cm^2)	*DRACO* 2-D (mg/cm^2)	Fraction of 2-D ρR measured
MRS	~220	~250	~90%
CPS2	>180	~190	~100%
CPS1	~170	~160	~100%





E18407

The ρR variation caused by target offsets in 2-D *DRACO* simulations is consistent with measurements

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MRS	~220	~250	~90%
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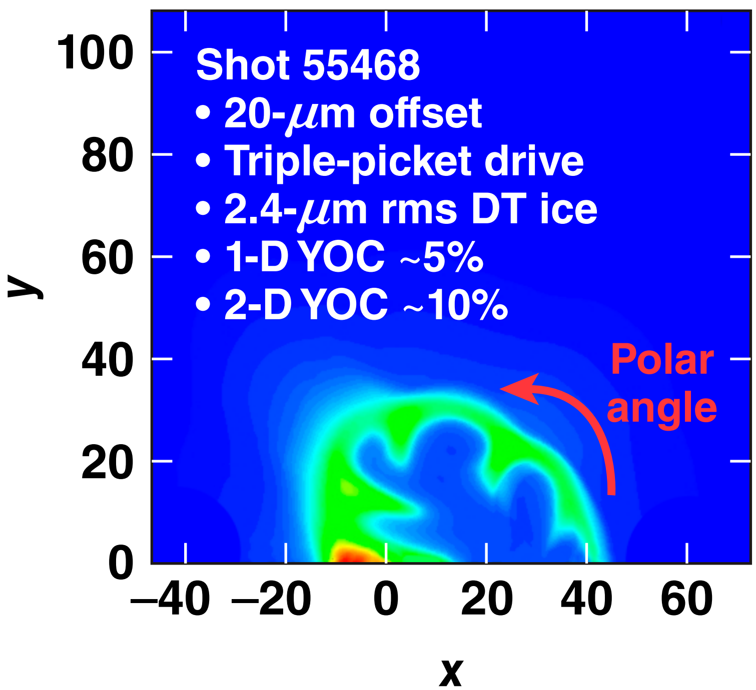

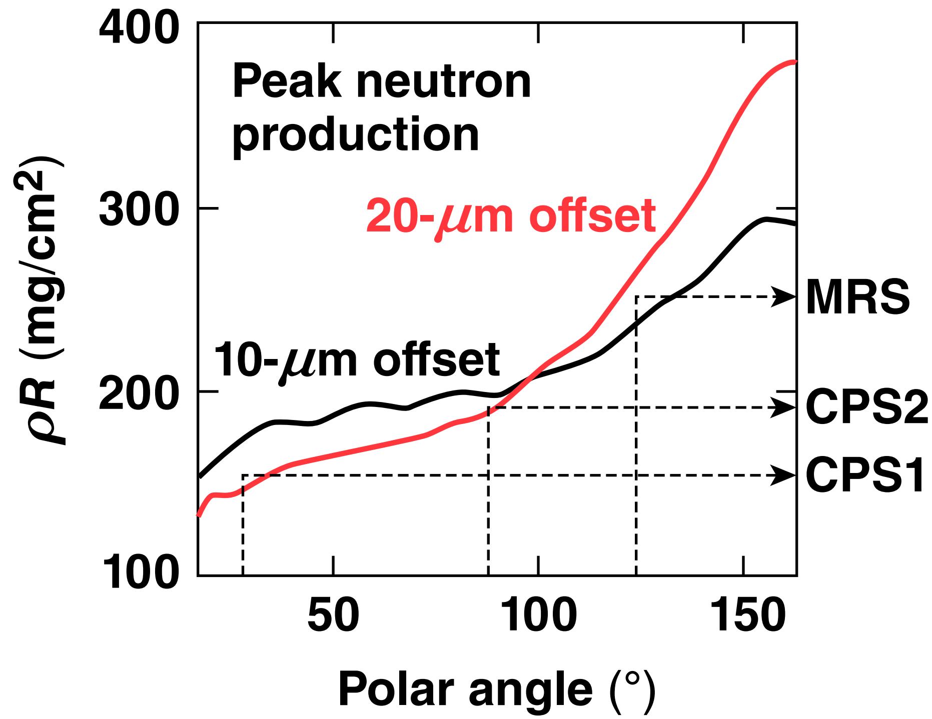

The goal for target alignment is to be within 10-μm of TCC.

E18407a

A recent multiple-picket cryogenic-DT implosion produced an areal density of ~180 mg/cm^2

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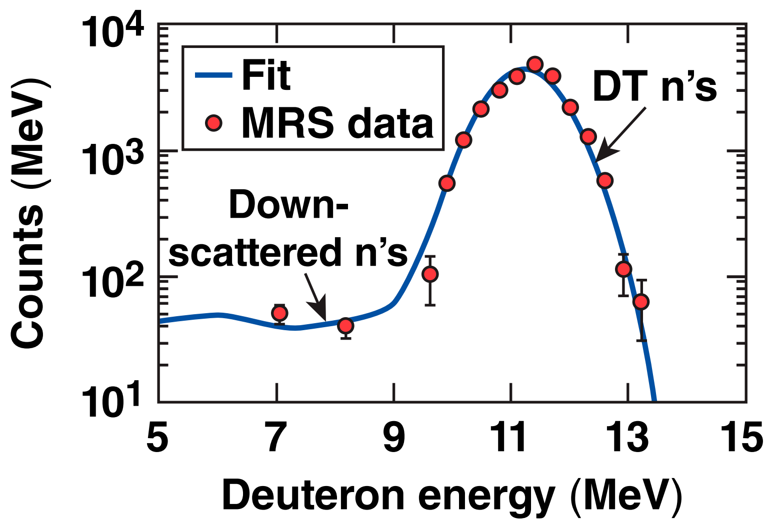
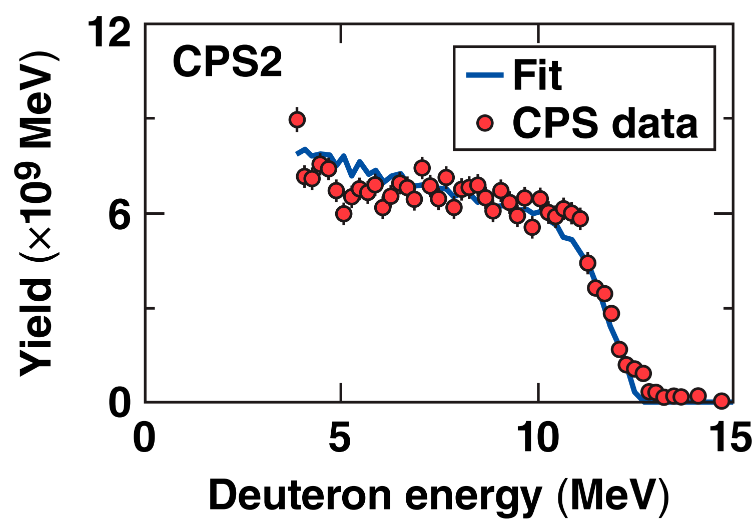
The MRS is used to infer areal density in cryogenic-DT implosions



The MRS down-scatter fraction (#n′/#n) is used to infer a fuel $\langle \rho R \rangle_n$ of 180±35 mg/cm^2

The shape of the knock-on deuterium spectrum is used to infer the fuel areal density*

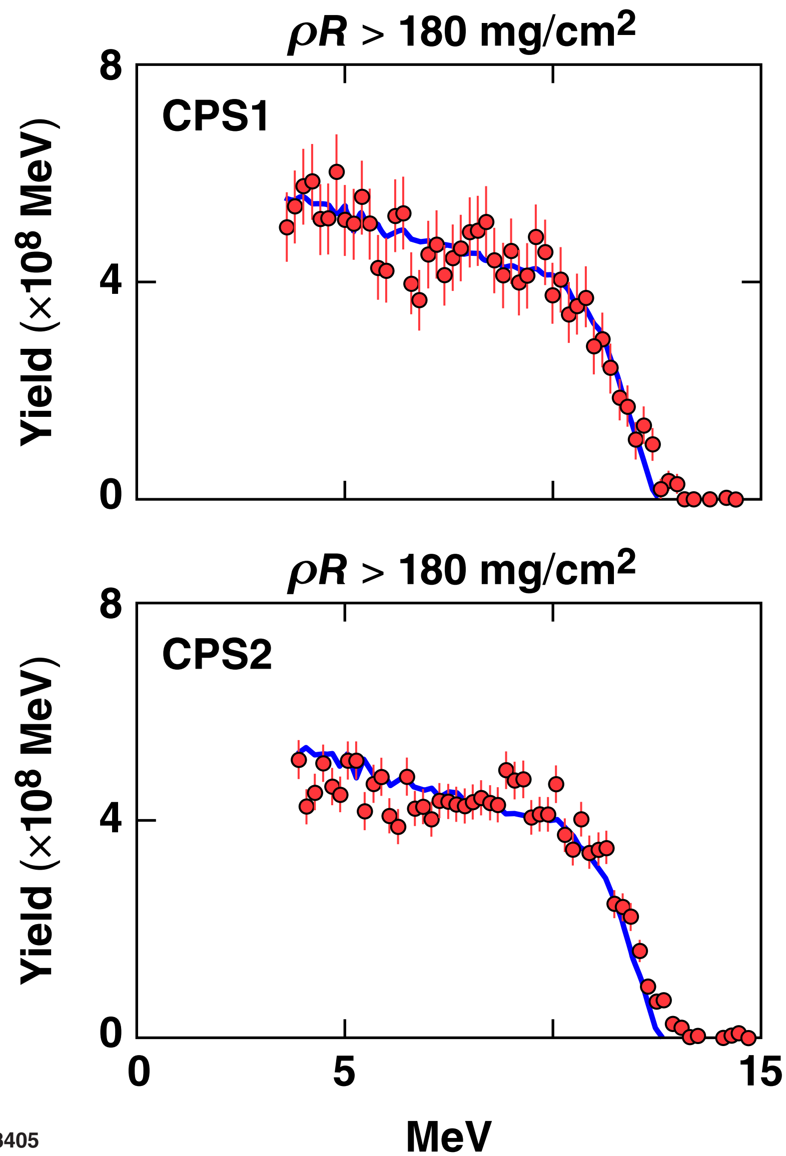


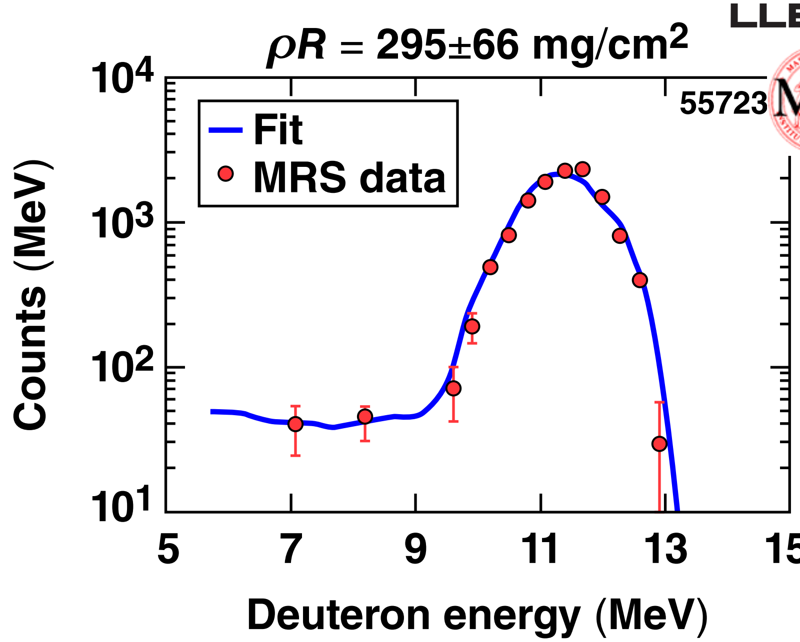
The spectrum is fully saturated indicating a $\langle \rho R \rangle_n \gtrsim$ 180 mg/cm^2

The ion temperature is 2.2 keV with a neutron yield of 3.4 × 10^{12} (YOC = 5.8%)

I1903a

The most recent multiple-picket cryogenic DT implosion produced an areal density of nearly 300 mg/cm^2





55723

The error bar is dominated by the hit statistics.

E18405

Two-body T-T neutron peak removed in the modeling.

Measured areal densities are consistent with 1-D performance at velocities up to 3×10^7 cm/s

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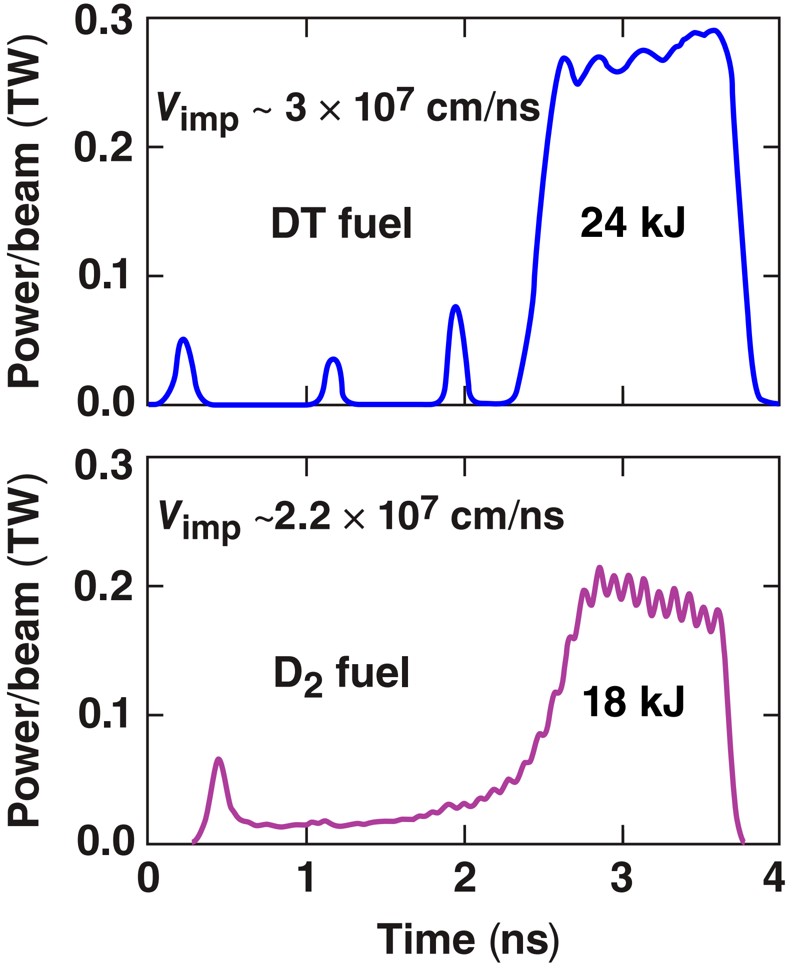
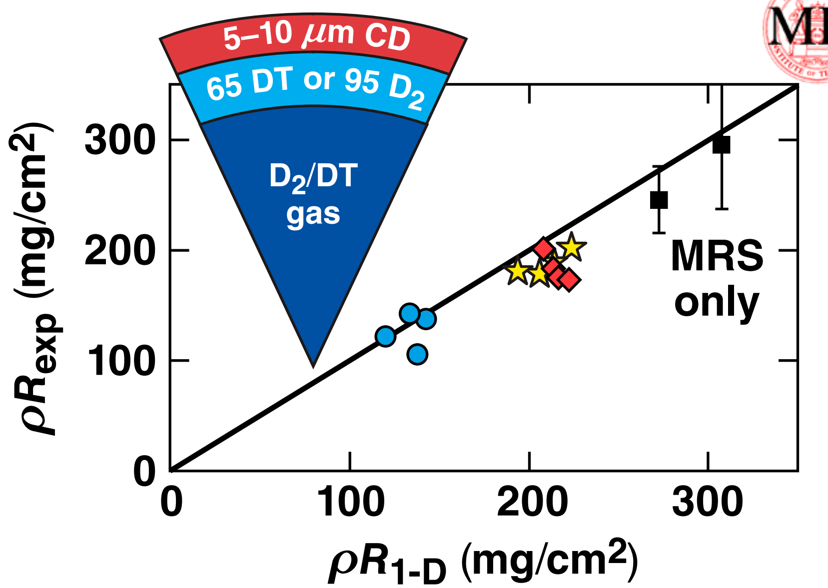


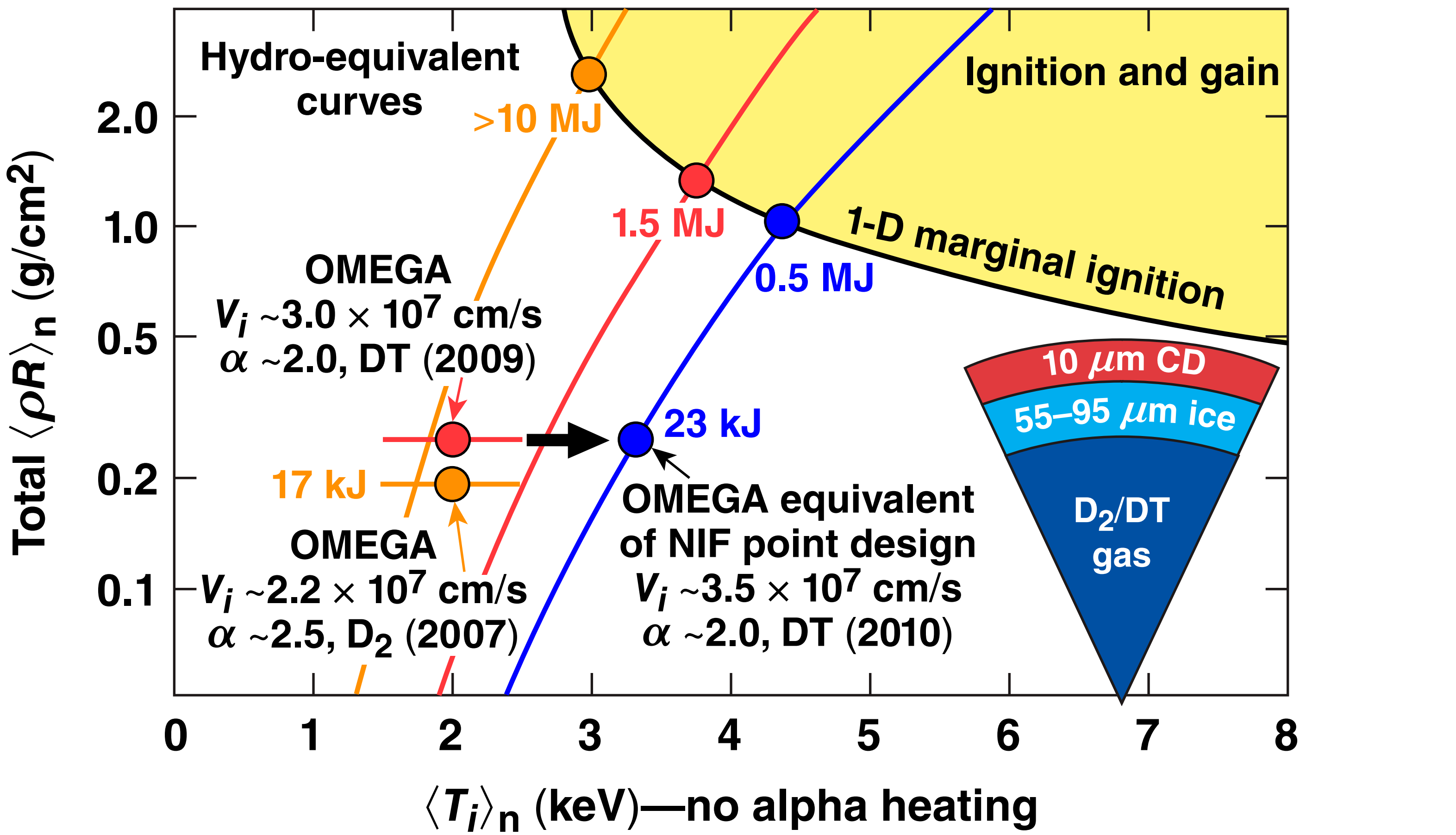


- ■ V_{imp} ~ 3×10^7 cm/s, I ~ 8×10^{14} W/cm^2 65-μm thick DT, α ~ 2.0
- ◆ V_{imp} ~ 3×10^7 cm/s, I ~ 8×10^{14} W/cm^2 65-μm thick DT, α ~ 2.5
- ☆ V_{imp} ~ 2.2×10^7 cm/s, I ~ 5×10^{14} W/cm^2 95-μm thick D_2, α ~ 2.5
- ● V_{imp} ~ 2.2×10^7 cm/s, I ~ 3×10^{14} W/cm^2 95-μm thick D_2, α ~ 2.5

1-D areal densities have been achieved for drive intensities from $<3 \times 10^{14}$ up to 8×10^{14} W/cm^2.

E18406

Raising the implosion velocity is the final step in demonstrating hydro equivalence



E18409

R. L. McCrory *et al.*, Phys. Plasmas 15, 055503 (2008).

Summary/Conclusions

Cryogenic-DT implosions on OMEGA are approaching NIF ignition hydrodynamic equivalence

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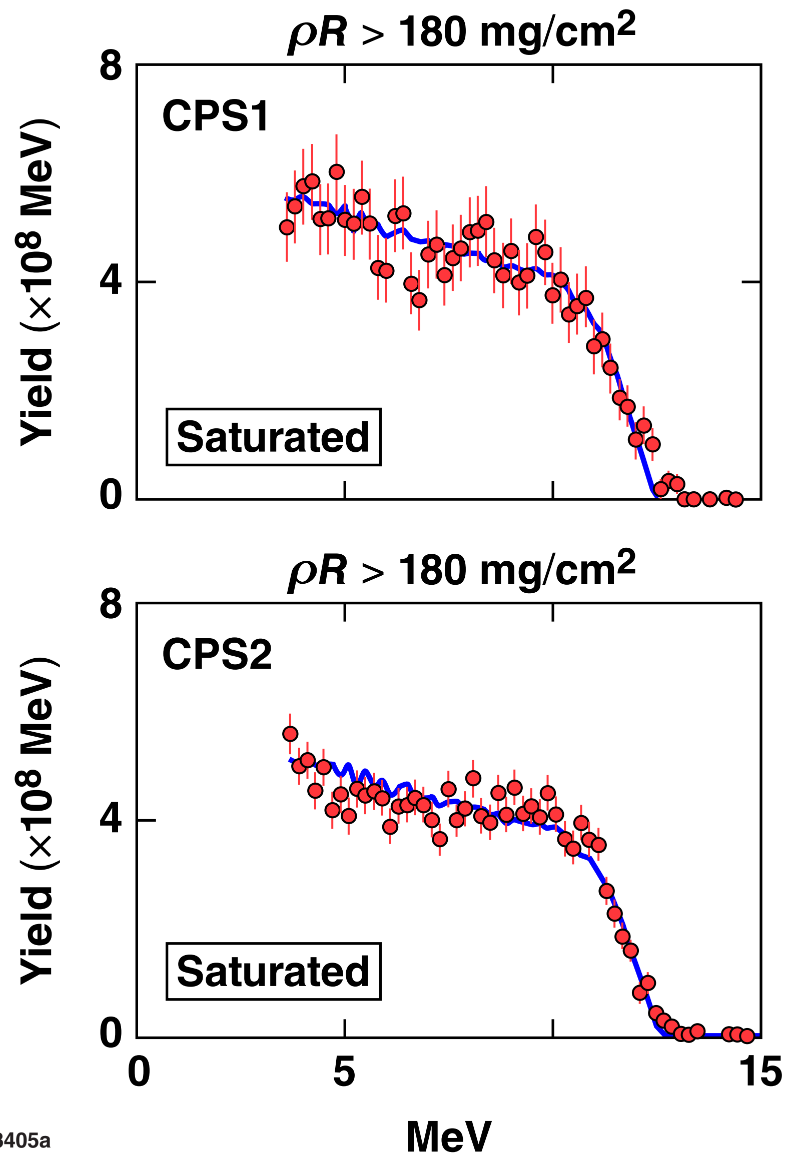
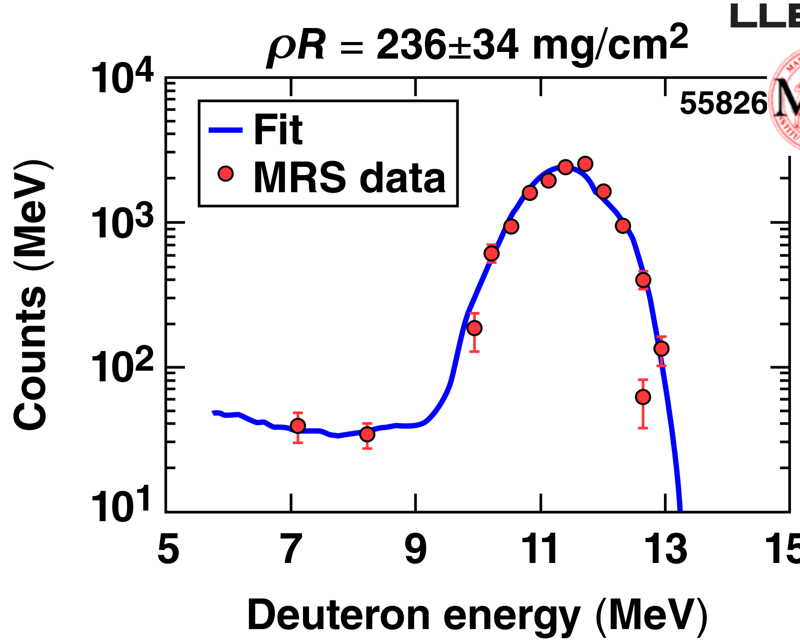
- Shock velocities and coalescence are measured in cryogenic fuel using a cone-in-shell technique developed by LLE/LLNL
- Cryogenic-DT-implosion performance is optimized by tuning shock coalescence with a new multi-picket, multi-shock drive pulse
- The compressed fuel areal densities in cryogenic-DT implosions are inferred using new diagnostics
- DT areal densities of ~300 mg/cm^2 have been achieved at a drive intensity of 8×10^{14} W/cm^2 and an implosion velocity of ~3×10^7 cm/s
- Experiments planned in 2010 will increase the implosion velocity to 3.5×10^7 cm/s

The most recent multiple-picket cryogenic DT implosion produced an areal density of nearly 300 mg/cm^2





55826

The error bar is dominated by the hit statistics.

E18405a

Two-body T-T neutron peak removed in the modeling.