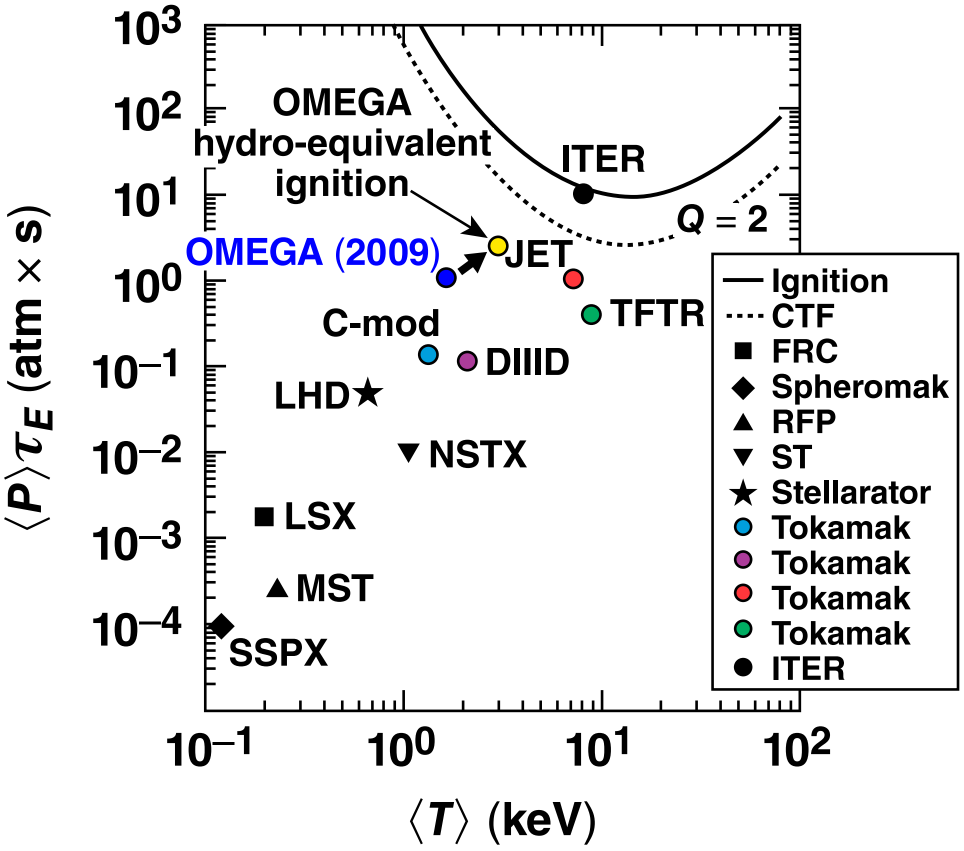
Progress in Cryogenic Target Implosions on OMEGA



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Summary

Cryogenic target implosions on OMEGA have produced areal densities of 0.3 g/cm^2

- The minimum areal density for ICF ignition is ~0.3 g/cm^2
- Cryogenic-DT implosions show good performance using a multiple-picket pulse shape that launches multiple shock waves
- The shock velocity and coalescence is measured using a cone-in-shell technique with cryogenic fuel
- The compressed areal densities are measured using new diagnostics
- An understanding of the Lawson criterion for ICF implosions has been developed

The $P_i\tau_E$ from OMEGA cryogenic implosions is comparable to that obtained on JET.

Collaborators

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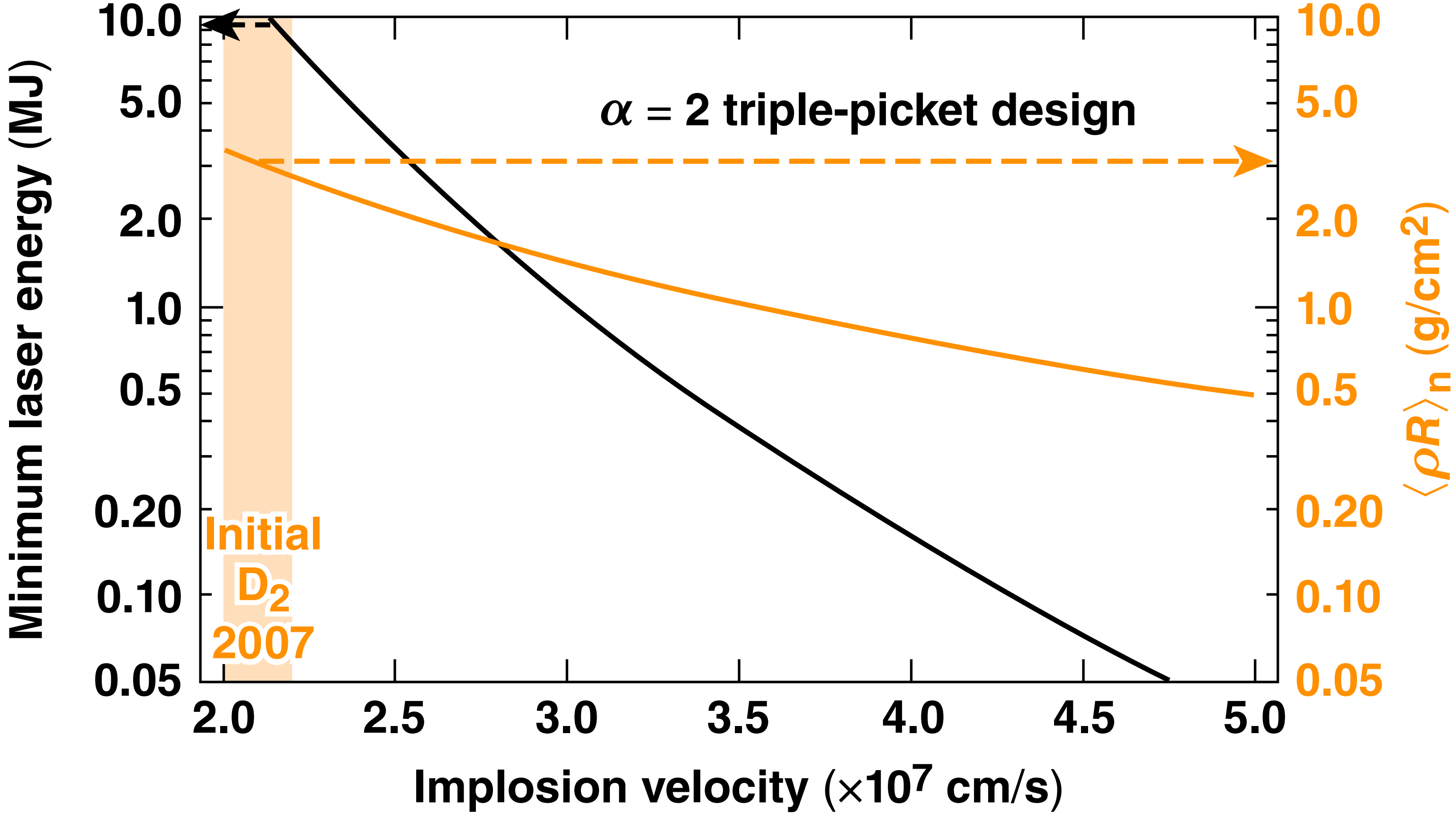
Cryogenic fuel shells driven at ~3 × 10^7 cm/s approach ignition-relevant conditions



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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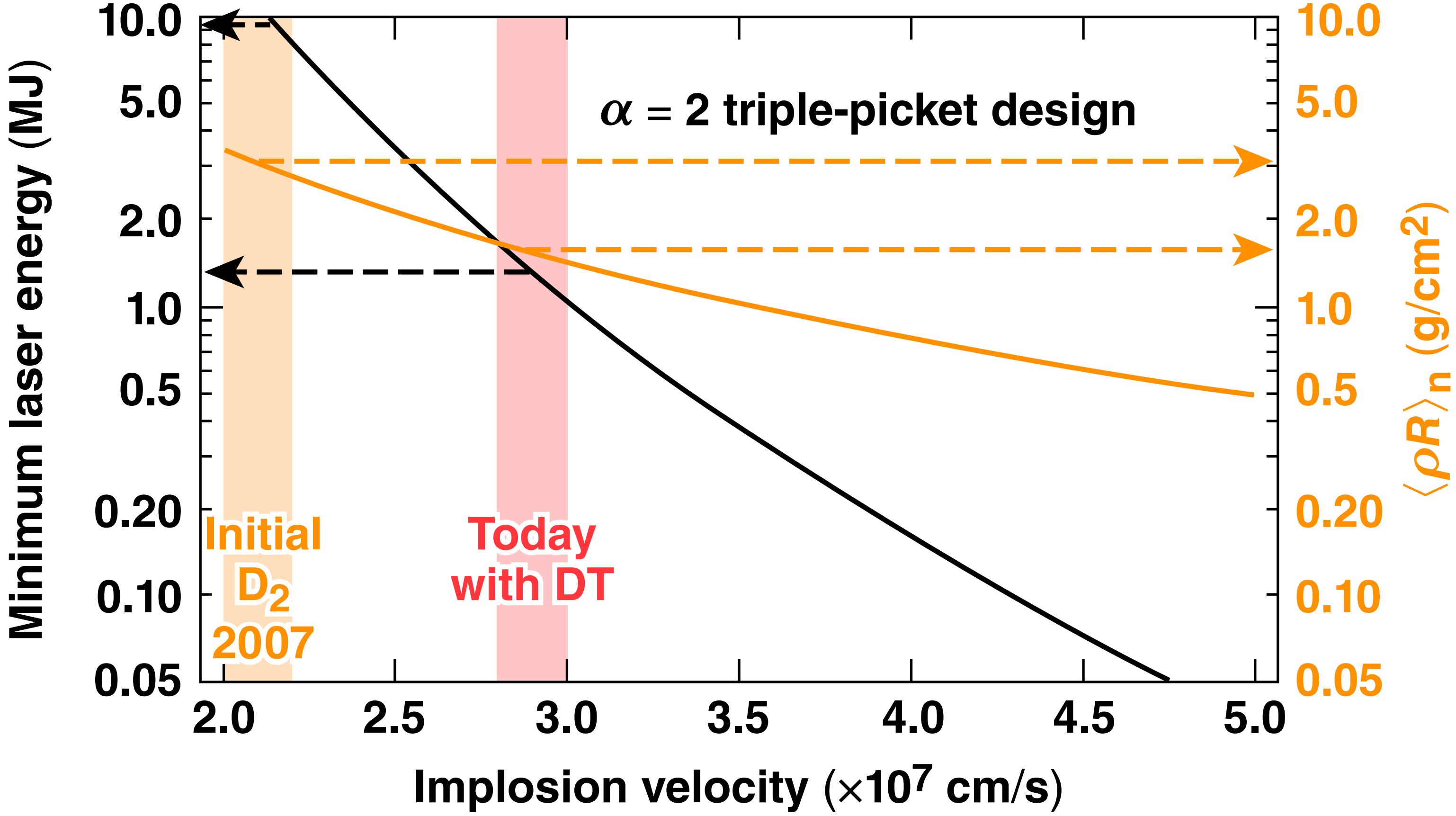

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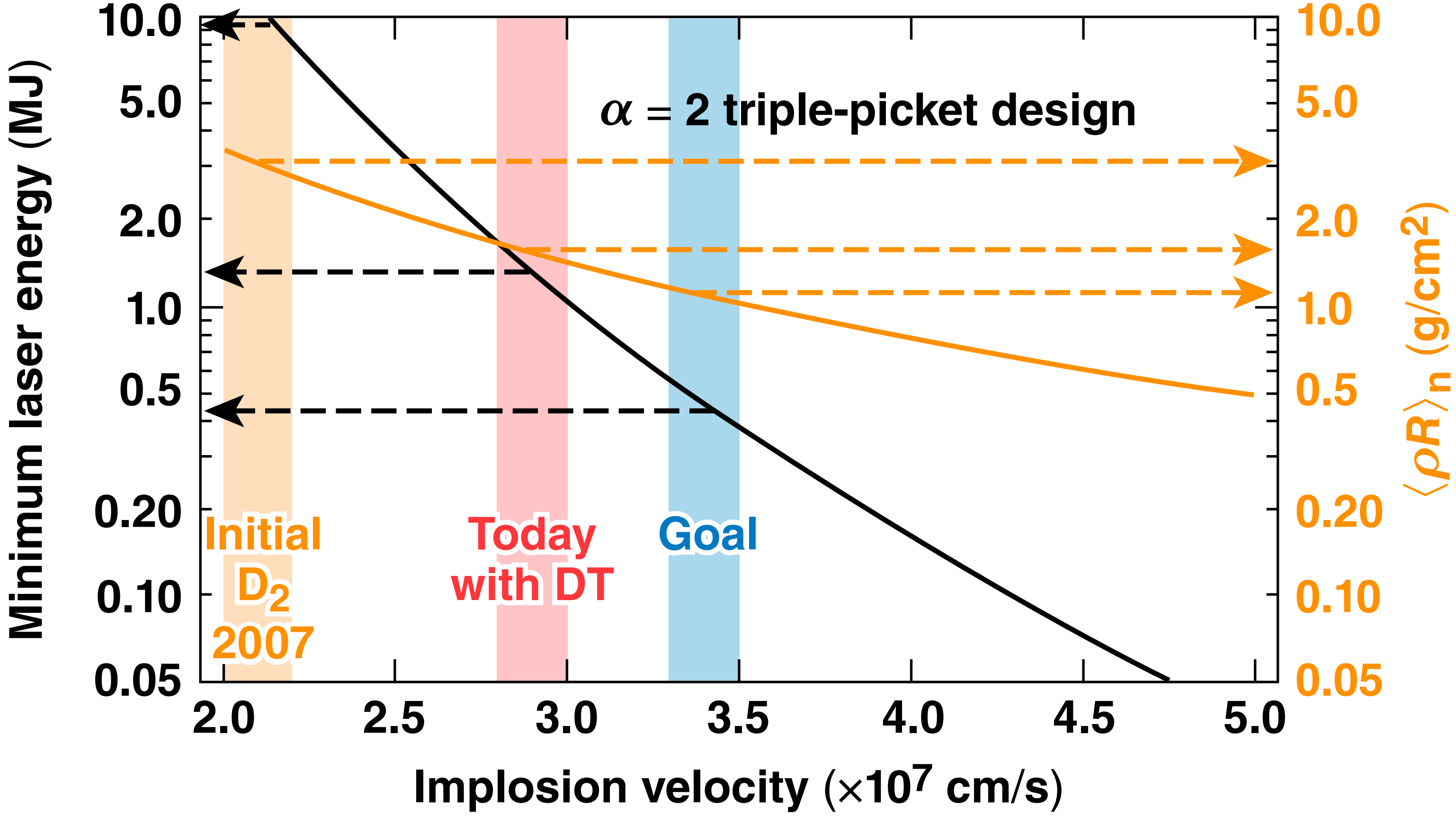
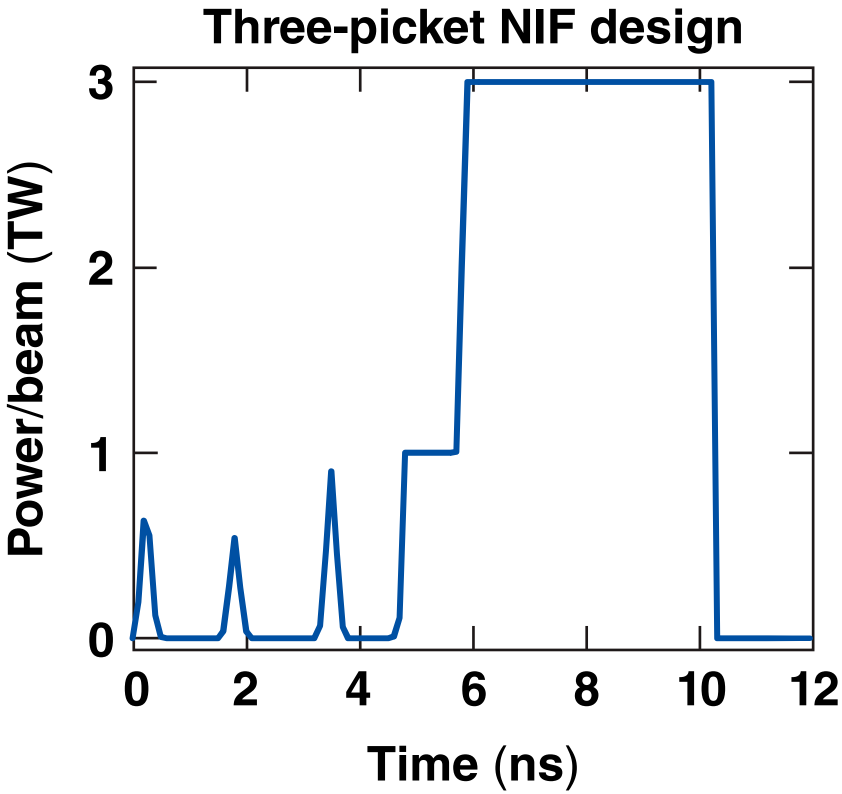


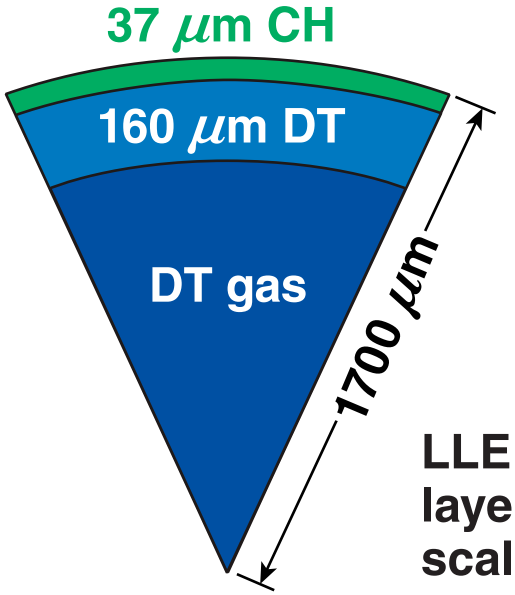
A V_{imp} ~3.5 × 10^7 cm/s is probably the OMEGA limit given intrinsic drive/ice nonuniformities.

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).

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

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





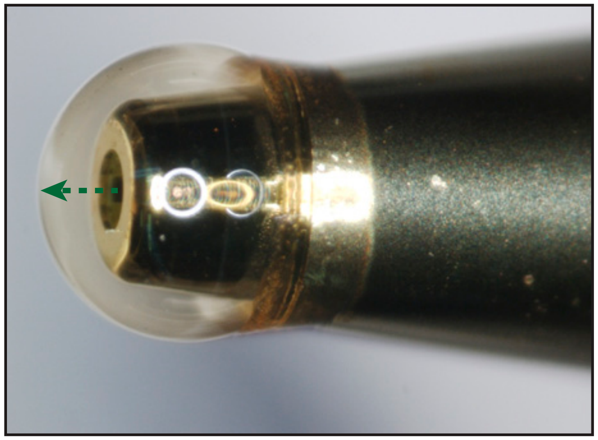
LLE has filled and layered an ignition-scale target with D_2

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

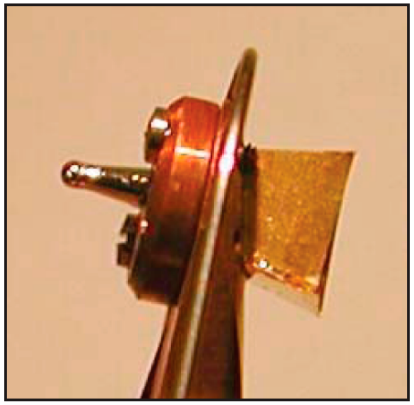
V. N. Goncharov *et al*., submitted to Physical Review Letters.

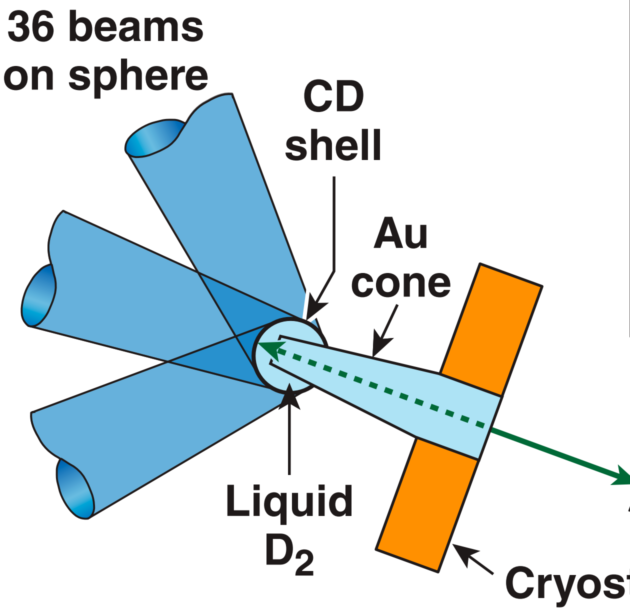
Validation of the design adiabat requires measurements of the shock velocity and coalescence

Capsule/cone detail



Full target

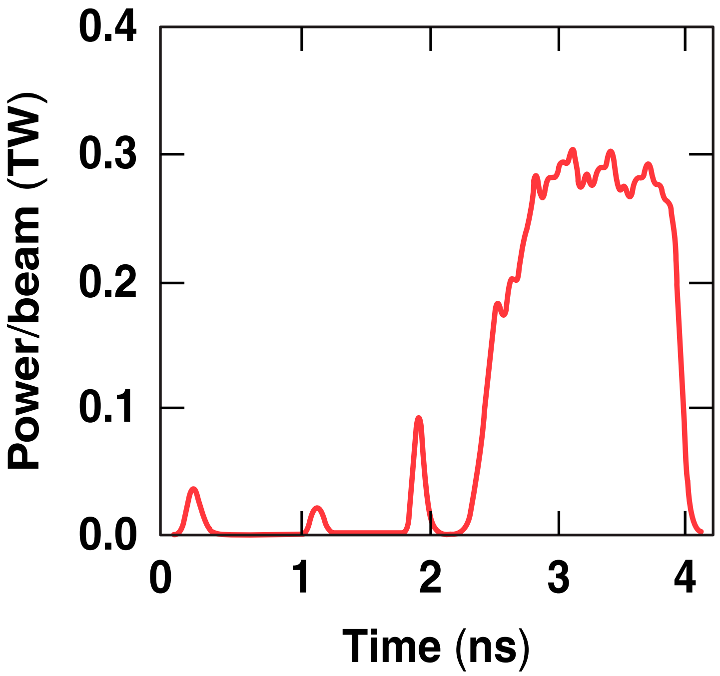


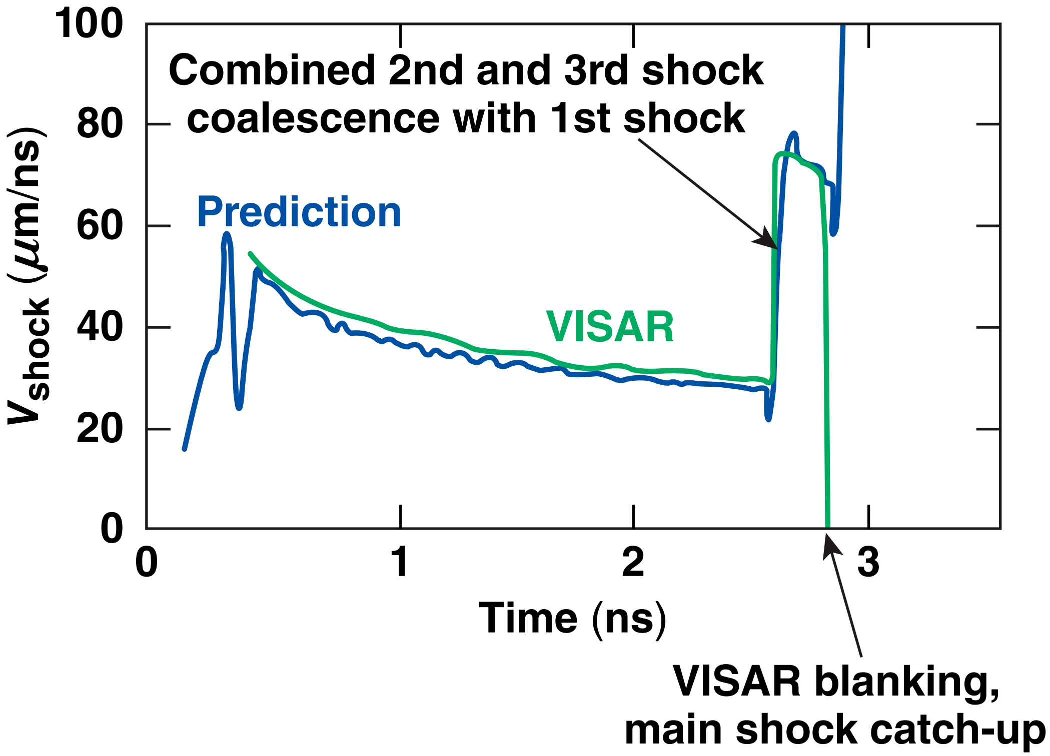


The technique was initially developed for shock-tuning ignition capsules on the NIF.

T. R. Boehly *et al.*, Phys. Plasmas 16, 056302 (2009).

Good shock timing is observed with multiple-picket pulse shapes





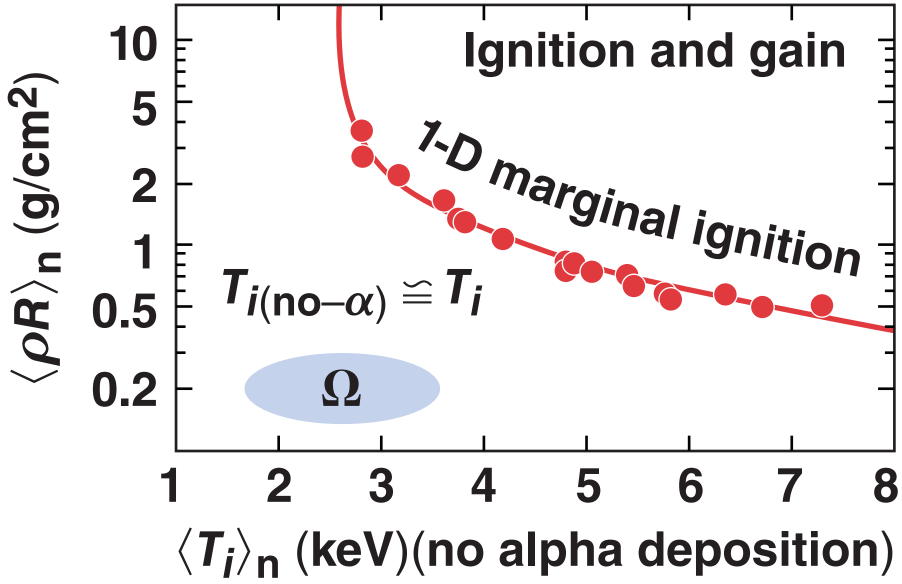
Combined 2nd and 3rd shock coalescence with 1st shock

VISAR blanking, main shock catch-up

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

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

LILAC fit[†]



Both T_i and ρR can be measured experimentally!

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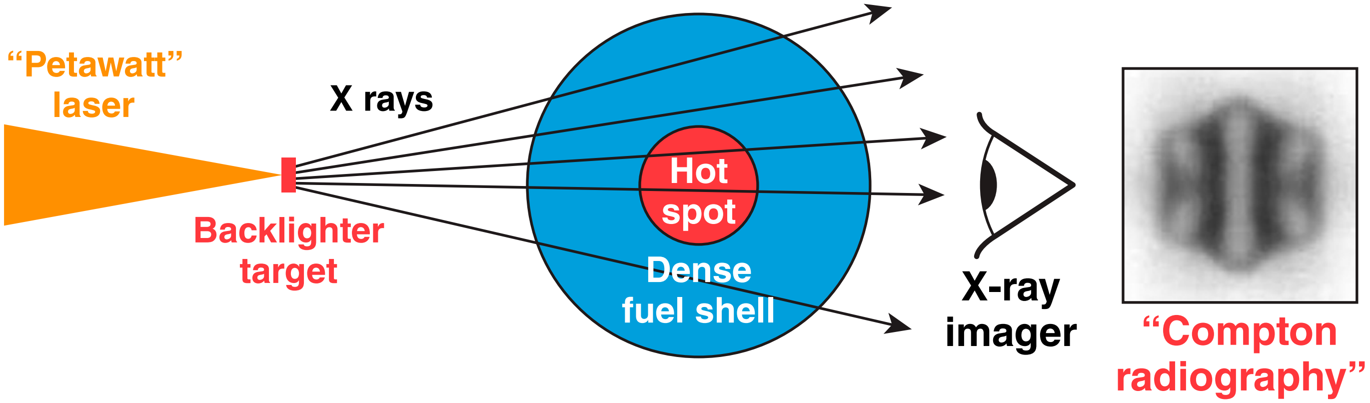
* C. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).

** M. C. Herrmann, M. Tabak, and J. D. Lindl, Nucl. Fusion 41, 99 (2001).

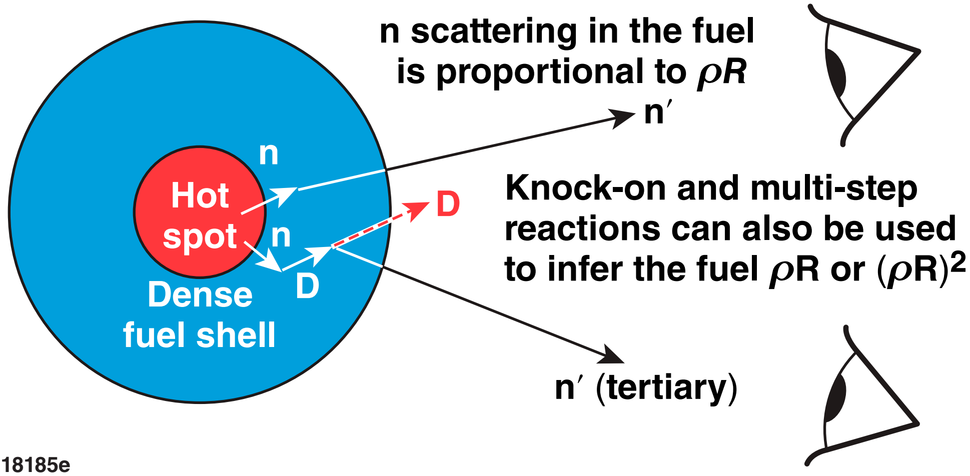
[†] R. L. McCrory *et al.*, Phys. Plasmas 15, 055503 (2008).

There are 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



n scattering in the fuel is proportional to ρR

Knock-on and multi-step reactions can also be used to infer the fuel ρR or $(\rho R)^2$

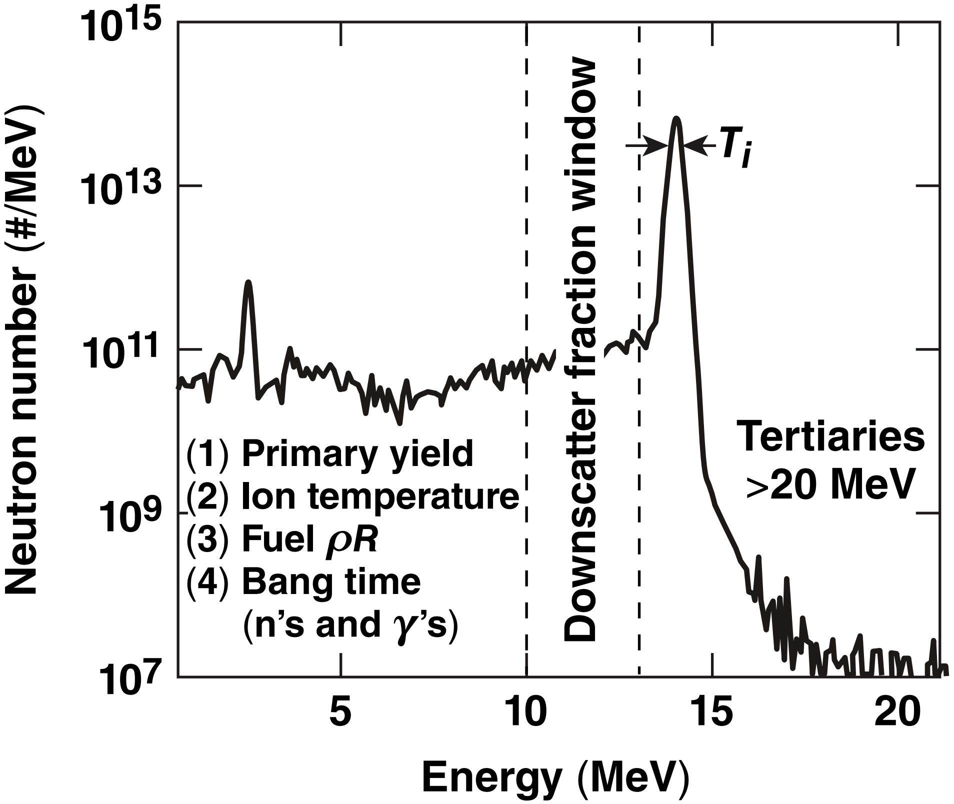
(1) nTOF spectroscopy

(2) Magnetic recoil spectroscopy

(3) CPS for KO-D (low ρR)

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

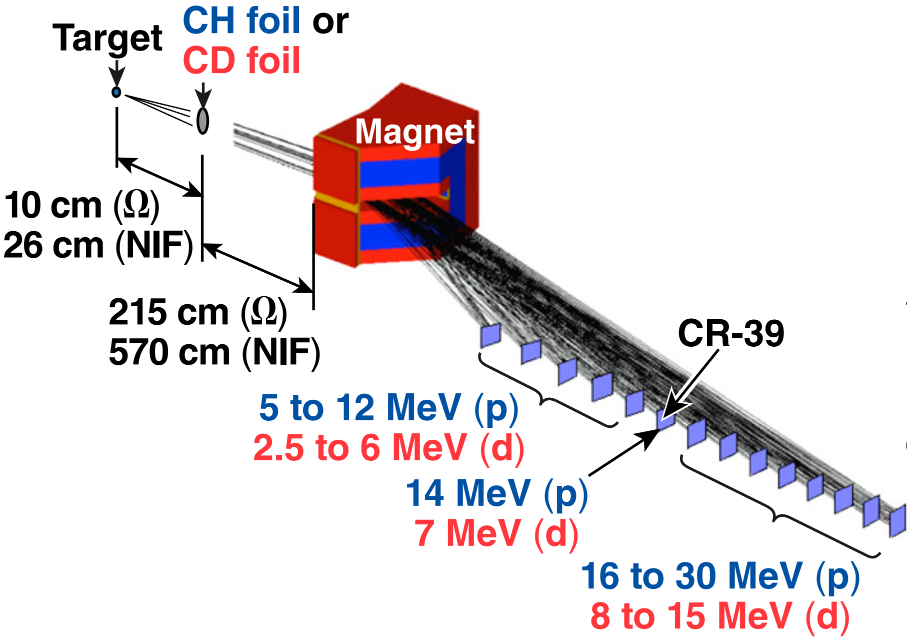
Much of the target performance can be inferred from the emitted neutron spectrum

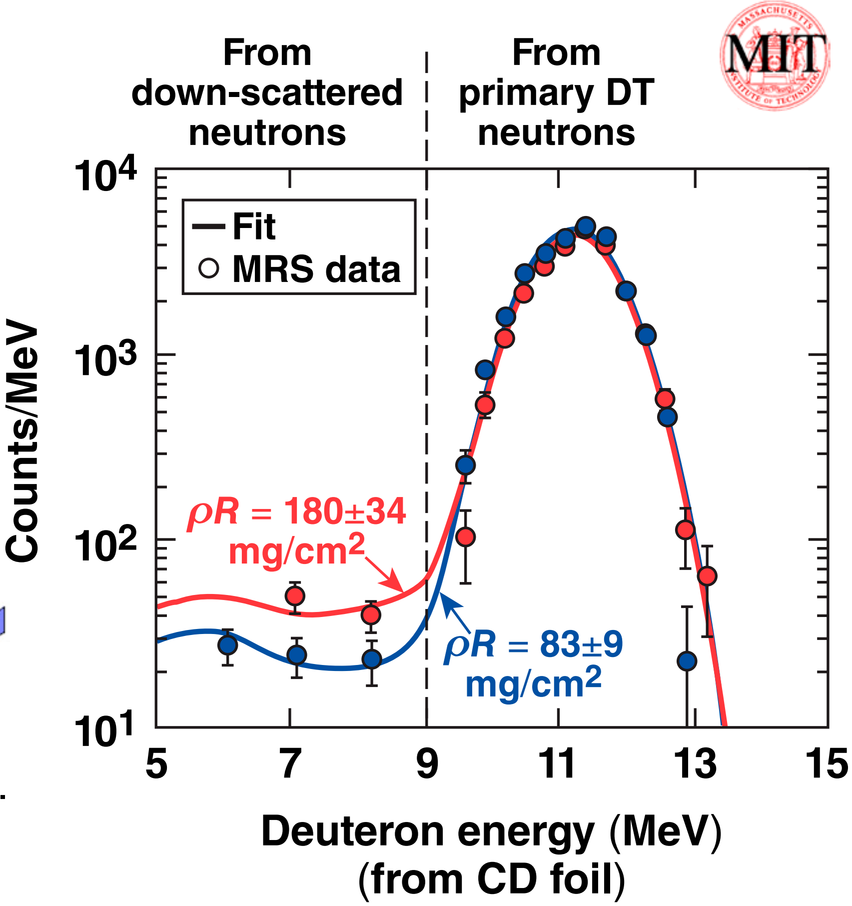


Issues:

- 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

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



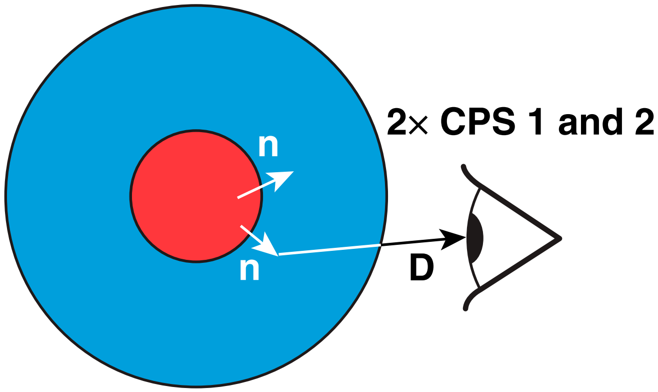


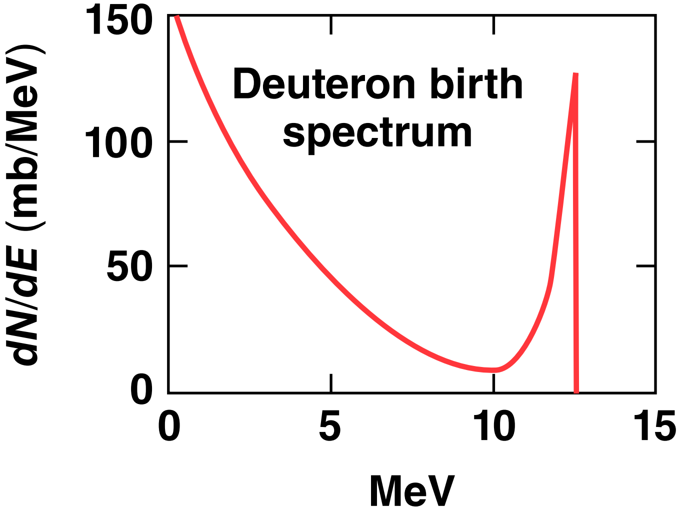
J. A. Frenje *et al*., NIF MRS System Design Review (April 2006).

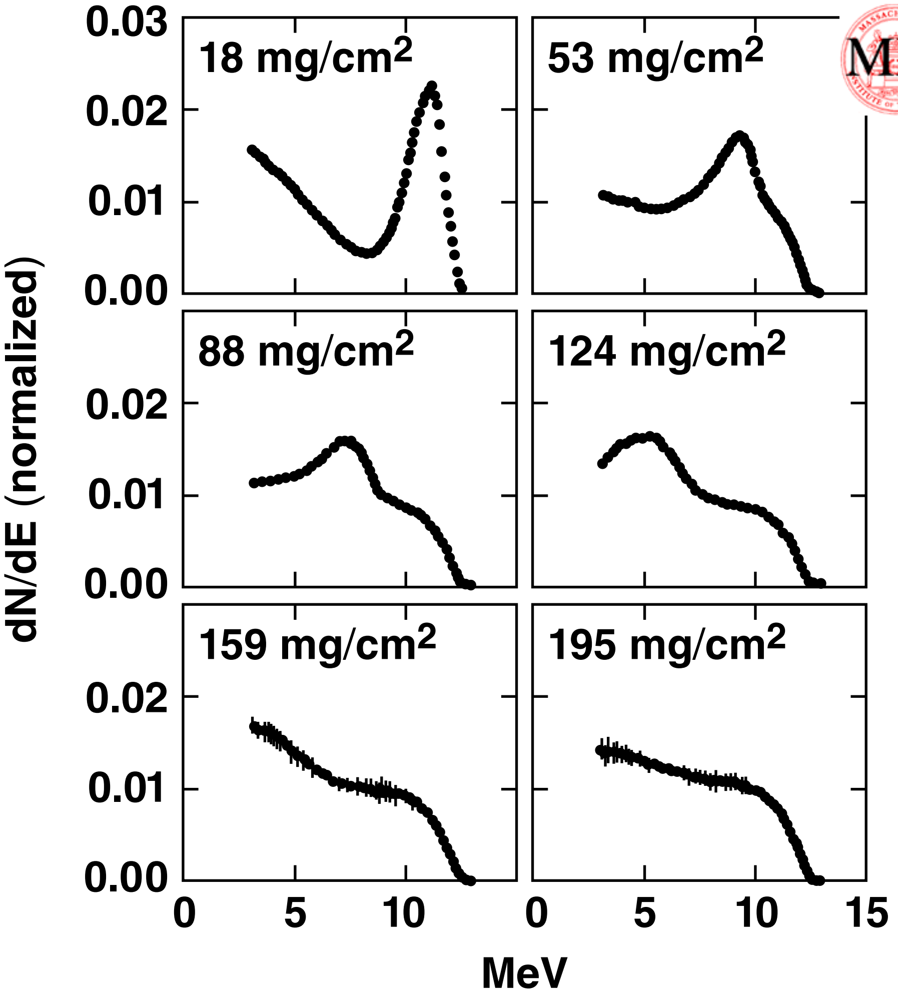
J. A. Frenje *et al*., to be published in Rev. Sci. Instrum. (2008).

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

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







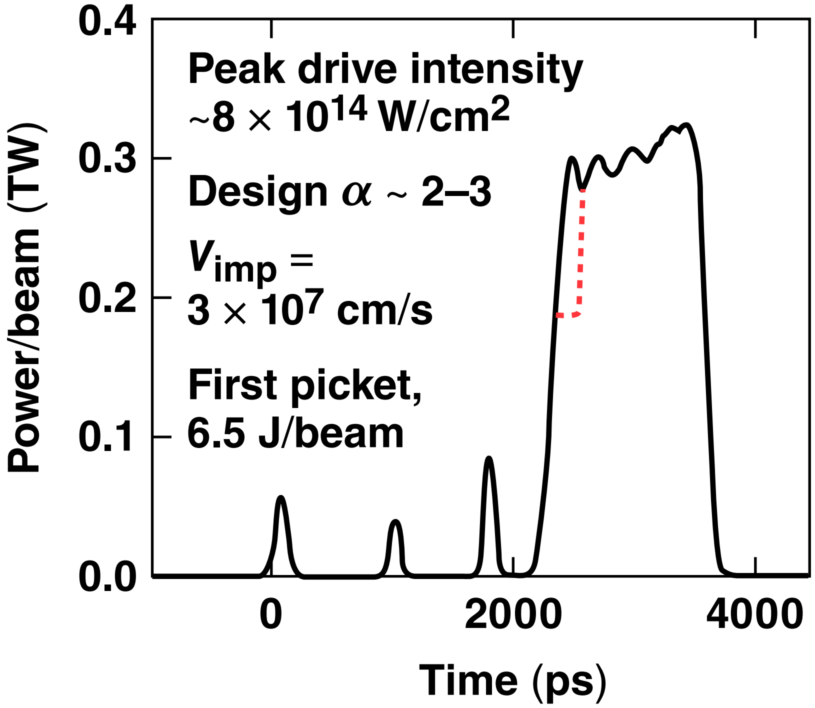
The shape of the KO-D spectrum does not change for ρR > 180 mg/cm^2.

E18403b

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

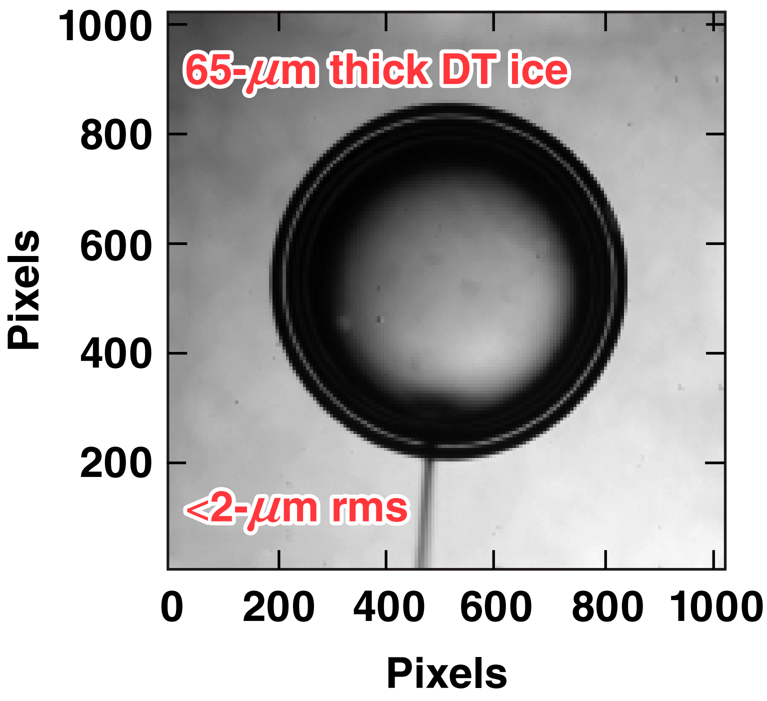
Multiple-picket pulse shapes are being used to drive cryogenic-DT implosions on OMEGA

Current drive pulse used to implode cryogenic-DT targets



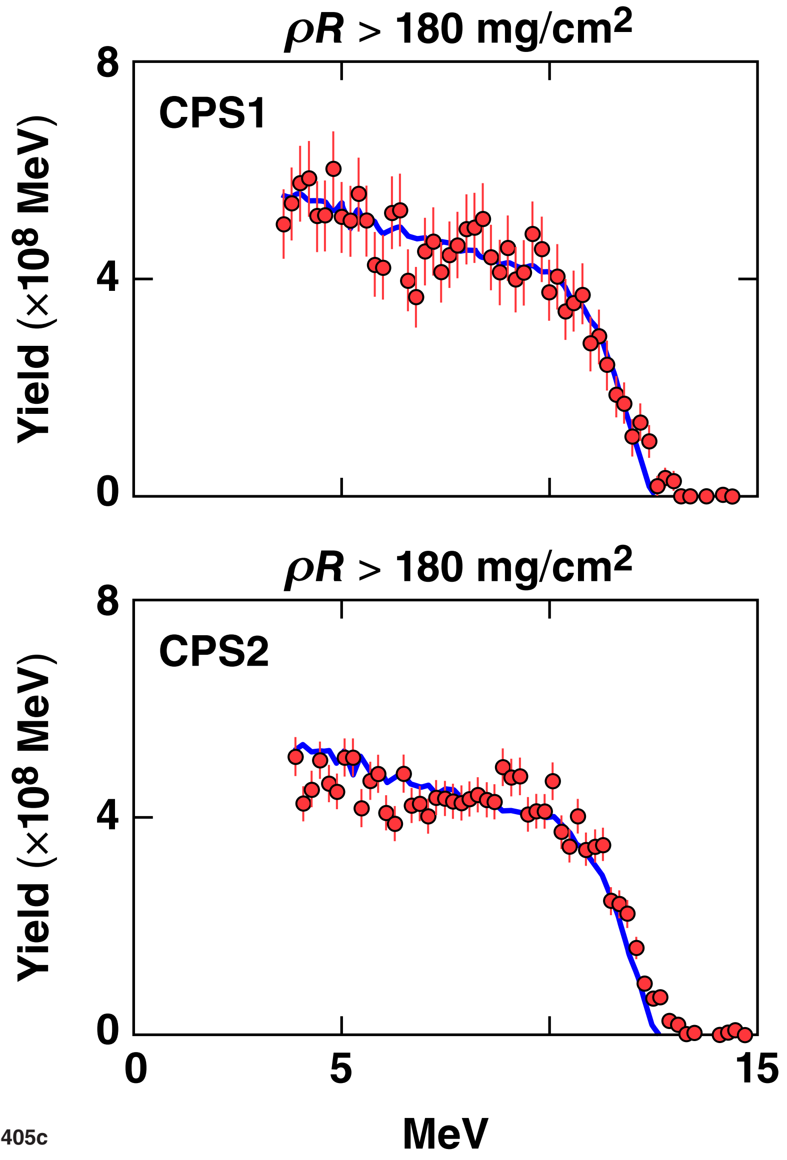
Picket energies and relative timing are adjusted to optimize the shock coalescence

Shadowgraph of a stalk-mounted cryogenic-DT capsule

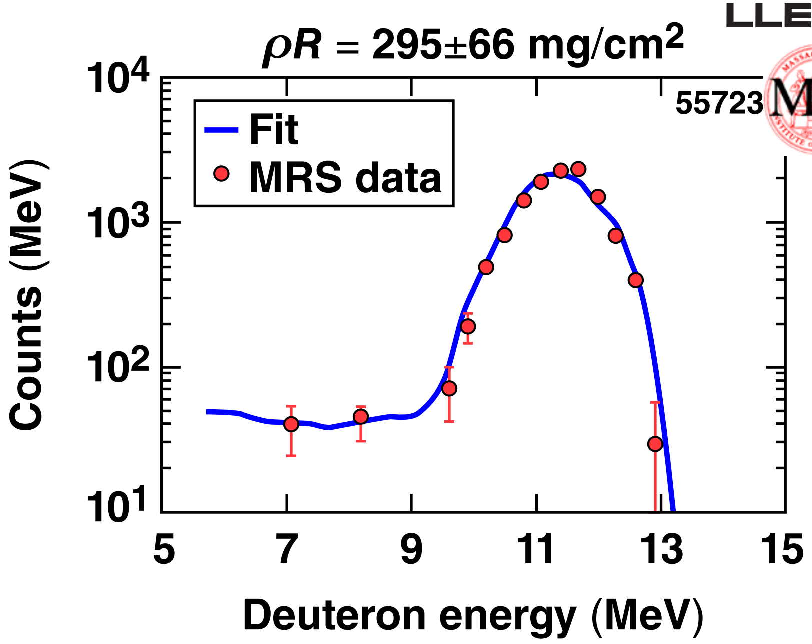


Target vibration at T_0 is significantly reduced with stalk-mounted targets

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


$\rho R > 180$ mg/cm^2

$\rho R > 180$ mg/cm^2

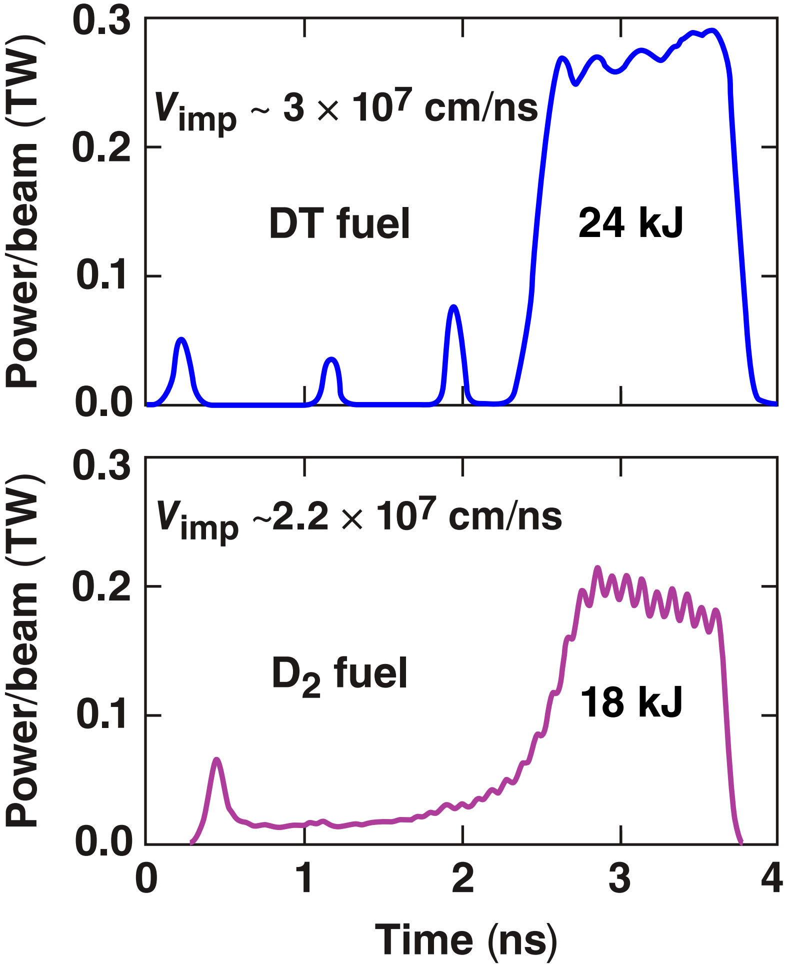

$\rho R = 295 \pm 66$ mg/cm^2

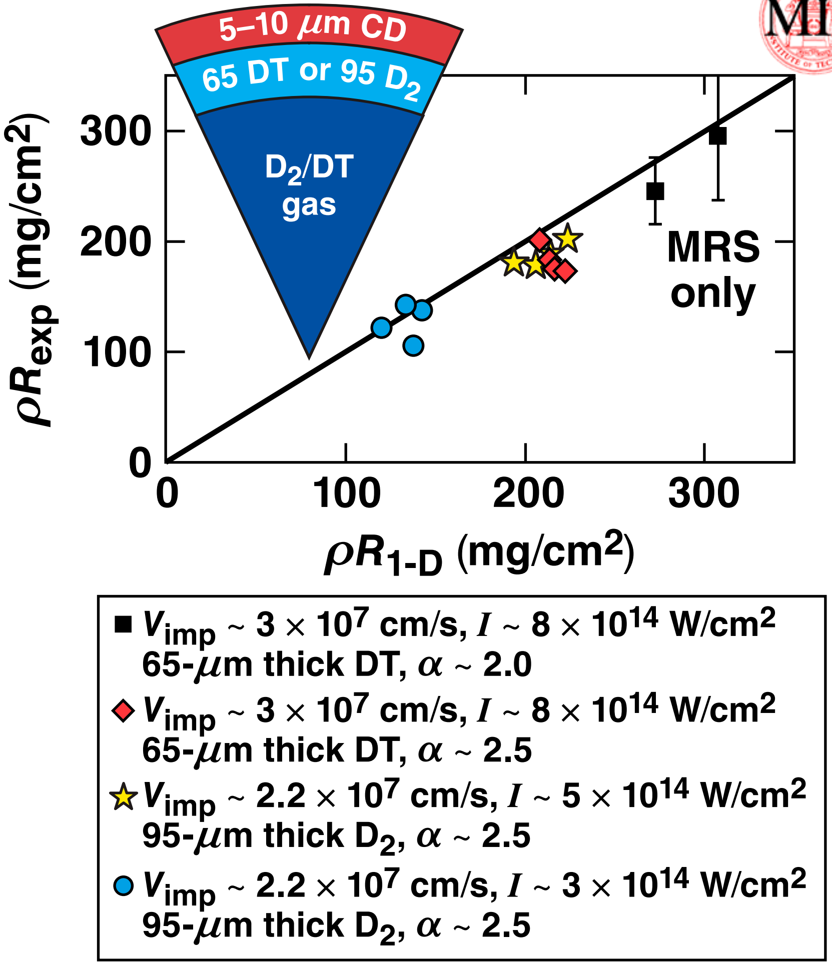
The error bar is dominated by the hit statistics.

Mass density
$\rho \sim 250$ g/cm^3

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

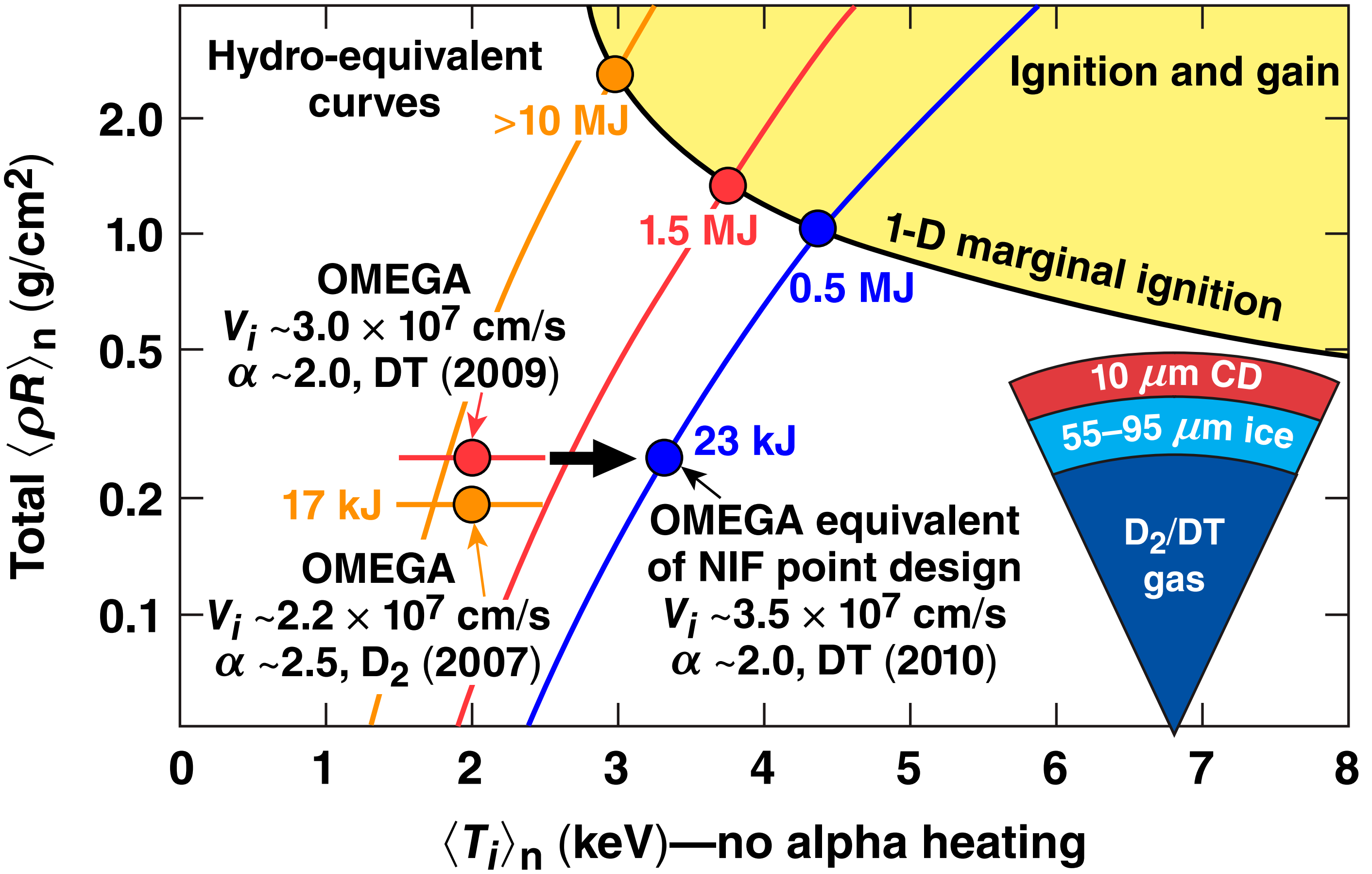
Measured areal densities are consistent with 1-D performance at velocities up to 3 × 10^7 cm/s





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

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



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

"Classic" work on ICF ignition has focused on static models of the hot spot and has neglected the dense shell

- Lawson criterion applied to the hot spot

  $nT_i\tau_E > 3 \times 10^{15}\ \mathrm{cm^{-3}\ keV\ s}$ ⇒ n, τ cannot be measured

- Static models of the ignition condition use the hot-spot areal density and ion temperature

  $\rho R_{\text{hot spot}} \approx 0.3\ \mathrm{g/cm^2}$ $\quad T_i \approx 5$ to 10 keV

  $\rho R_{\text{hot spot}}$ cannot be measured

- J. D. Lawson, Proc. Phys. Soc. London B70, 6 (1957).
- S. Yu. Gus'kov *et al*., Nucl. Fusion 16, 957 (1976).
- S. Atzeni and A. Caruso, Phys. Lett. A 85, 345 (1981).
- S. Atzeni and A. Caruso, Nuovo Cimento B 80, 71 (1984).
- R. Kishony *et al*., Phys. Plasmas 4, 1385 (1997).
- J. D. Lindl, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive* (Springer-Verlag, New York, 1998).
- S. Atzeni and J. Meyer-ter-Vehn, *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter*, International Series of Monographs on Physics (Clarendon Press, Oxford, 2004).

R. Betti *et al*., presented at the 51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, GA, 2–6 November 2009 (Paper PT3.00001).

Ion temperatures, areal densities, and neutron yields are the fuel assembly parameters that can be measured with existing diagnostics

- Neutron yields and neutron rates are measured with scintillators

N_{neutron} $\quad \frac{dN_{\text{neutron}}}{dt}$

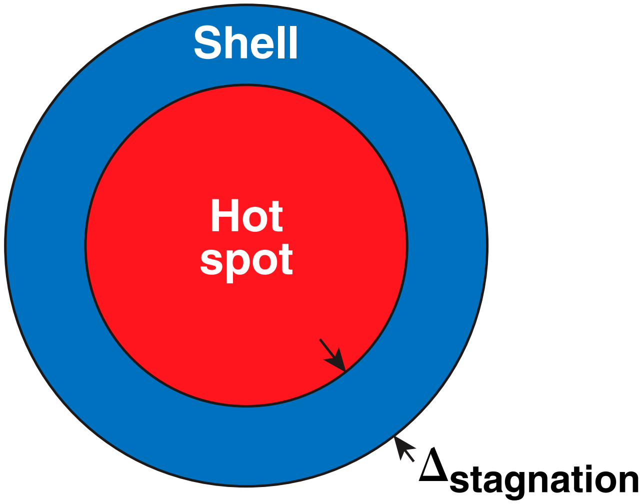
- Ion temperature (neutron averaged) is measured with the neutron time-of-flight detectors

$\langle T_i \rangle_{\text{neutron}}$

- Total areal density (neutron averaged) is measured with magnetic recoil spectrometer measuring the downscattered neutron fraction.

$$\langle \rho R \rangle_{\text{neutron}} \equiv \left\langle \int_0^\infty \rho dr \right\rangle_{\text{neutron}}$$

Total $\rho R \approx$ shell $(\rho\Delta)_{\text{stagnation}}$



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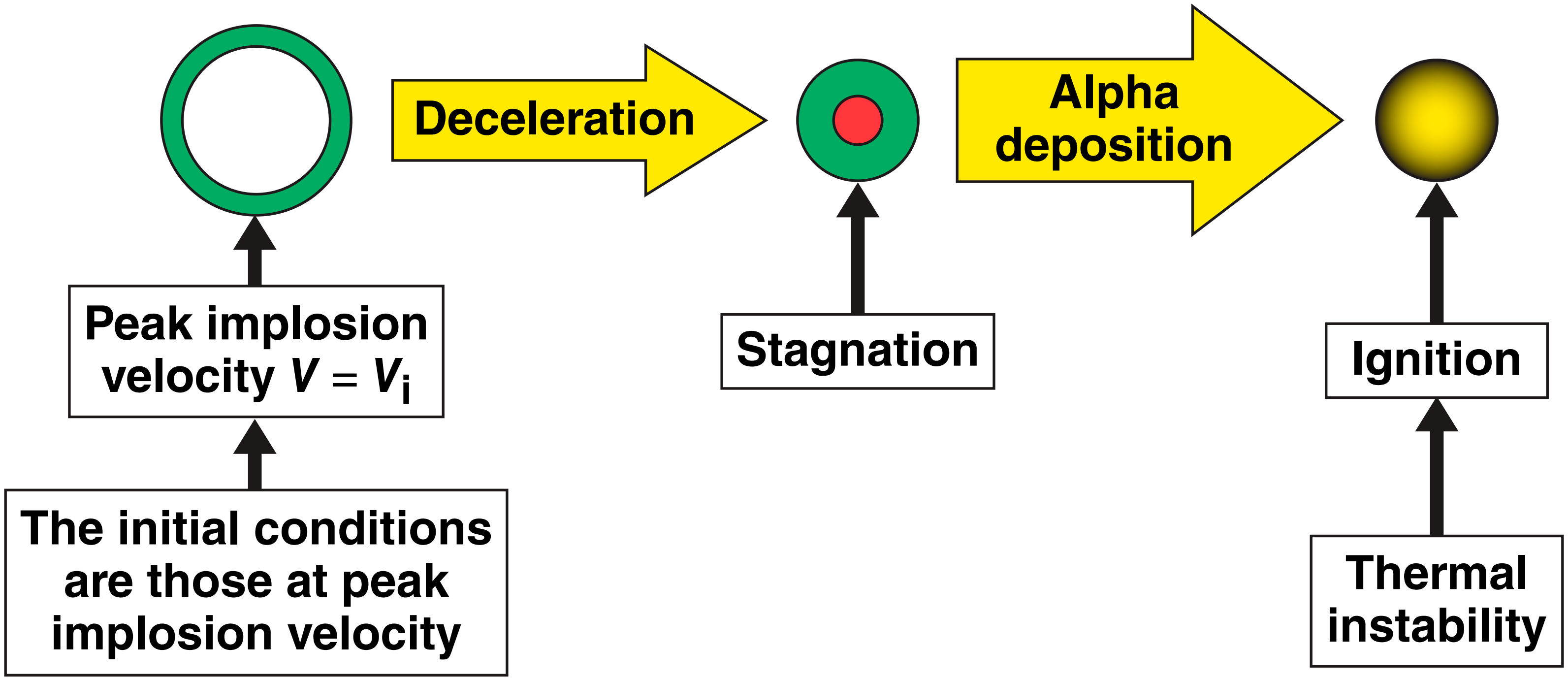
A dynamic model of ignition relates the hot-spot stagnation properties to those of the shell

Dynamic model of hot-spot formation and ignition



Deceleration

Alpha deposition

Peak implosion velocity $V = V_i$

The initial conditions are those at peak implosion velocity

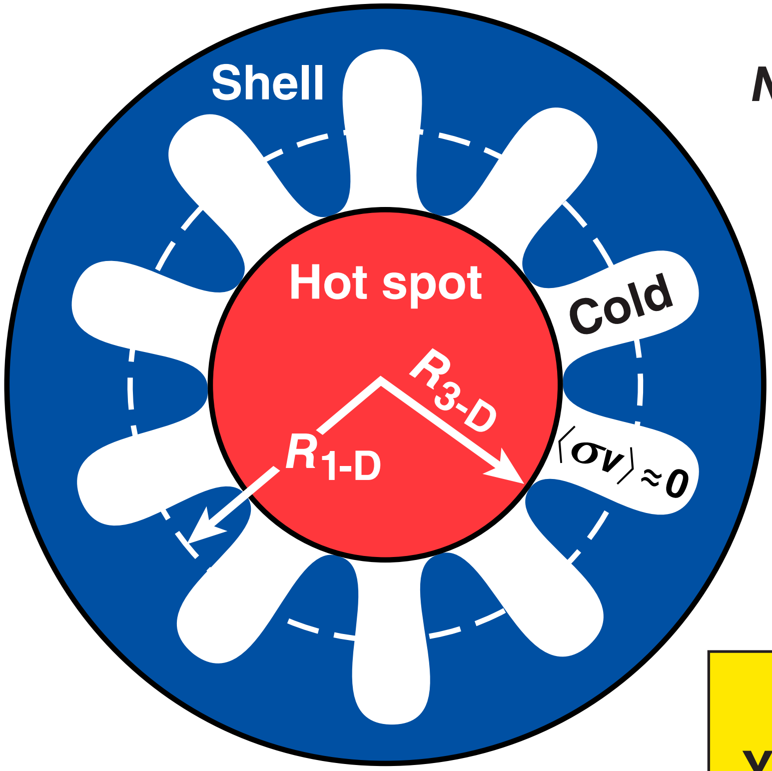
Stagnation

Ignition

Thermal instability

- R. Betti *et al*., Phys. Plasmas 8, 5257 (2001).
- R. Betti *et al*., Phys. Plasmas 9, 2277 (2002).
- J. Sanz *et al*., Phys. Plasmas 12, 112702 (2005).
- Y. Saillard, Nucl. Fusion 46, 1017 (2006).
- J. Garnier and C. Cherfils-Clérouin, Phys. Plasmas 15, 102702 (2008).
- C. D. Zhou and R. Betti, Phys. Plasmas 15, 102707 (2008).
- R. Betti *et al*., presented at the 51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, GA, 2–6 November 2009 (Paper PT3.00001).

The 3-D fusion yield is reduced by the Rayleigh–Taylor instability that cools down parts of the hot spot



$$V_{3\text{-D}} \sim R^3_{3\text{-D}} < V_{1\text{-D}} \sim R^3_{1\text{-D}}$$

$$N^{3\text{-D}}_{\text{neutron}} \sim n_i^2 \langle\sigma v\rangle V_{3\text{-D}}\, \tau_{\text{burn}} \sim N^{1\text{-D}}_{\text{neutron}} \frac{V_{3\text{-D}}}{V_{1\text{-D}}}$$

- The yield-over-clean YOC = 3-D fusion yield; 1-D yield is approximately equal to the ratio unmixed volume/1-D volume

Can be measured

$$\text{YOC} \equiv \frac{N^{3\text{-D}}_{\text{neutron}}}{N^{1\text{-D}}_{\text{neutron}}} \approx \frac{V_{3\text{-D}}}{V_{1\text{-D}}}$$

YOC without α-deposition $\text{YOC}^{\text{no-}\alpha}$

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*R. Kishony and D. Shvarts, Phys. Plasmas 8, 4925 (2001).
R. Betti *et al*., presented at the 51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, GA, 2–6 November 2009 (Paper PT3.00001).

The OMEGA (DT) campaign aims to achieve a hydro-equivalent demonstration of ignition

- **Where does OMEGA currently stand?**

  $\langle \rho R \rangle_n \approx 0.2\ \mathrm{g/cm^2}$ $\langle T_i \rangle_n \approx 2.1\ \mathrm{keV}$ YOC ≈ 10%

  Igniton parameter $\chi = 0.008$ $\Rightarrow$ $\boxed{\chi \equiv \rho R \left(\frac{T}{4.7}\right)^2 \mathrm{YOC}^{0.7}}$

- **A scale 1:60 (25 kJ:1.5 MJ) hydro-equivalent demonstration of ignition on OMEGA requires**

  $\langle \rho R \rangle_n \approx 0.3\ \mathrm{g/cm^2}$ $\langle T_i \rangle_n \approx 3.4\ \mathrm{keV}$ YOC ≈ 15%

  Ignition parameter $\chi = 0.04$

R. Betti *et al*., presented at the 51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, GA, 2–6 November 2009 (Paper PT3.00001).

An effective $P\tau_E$ for ICF can be constructed using the ignition model and compared with $P\tau_E$ in MCF

- Use $\langle \sigma v \rangle \sim C_\alpha T^3$ consistent with the analytic model

$$(P\tau_E)_{\mathrm{ICF}} \approx 98 \frac{\chi^{3/4}}{\langle T \rangle_n (\mathrm{keV})} \mathrm{atm} \times s$$

- OMEGA: $\chi \approx 0.008, T \approx 2.1\ \mathrm{keV} \Rightarrow P\tau_E \approx 1.2\ \mathrm{atm} \times s$
- JET: $P\tau_E \sim 1.2\ \mathrm{atm} \times \mathrm{s}$*

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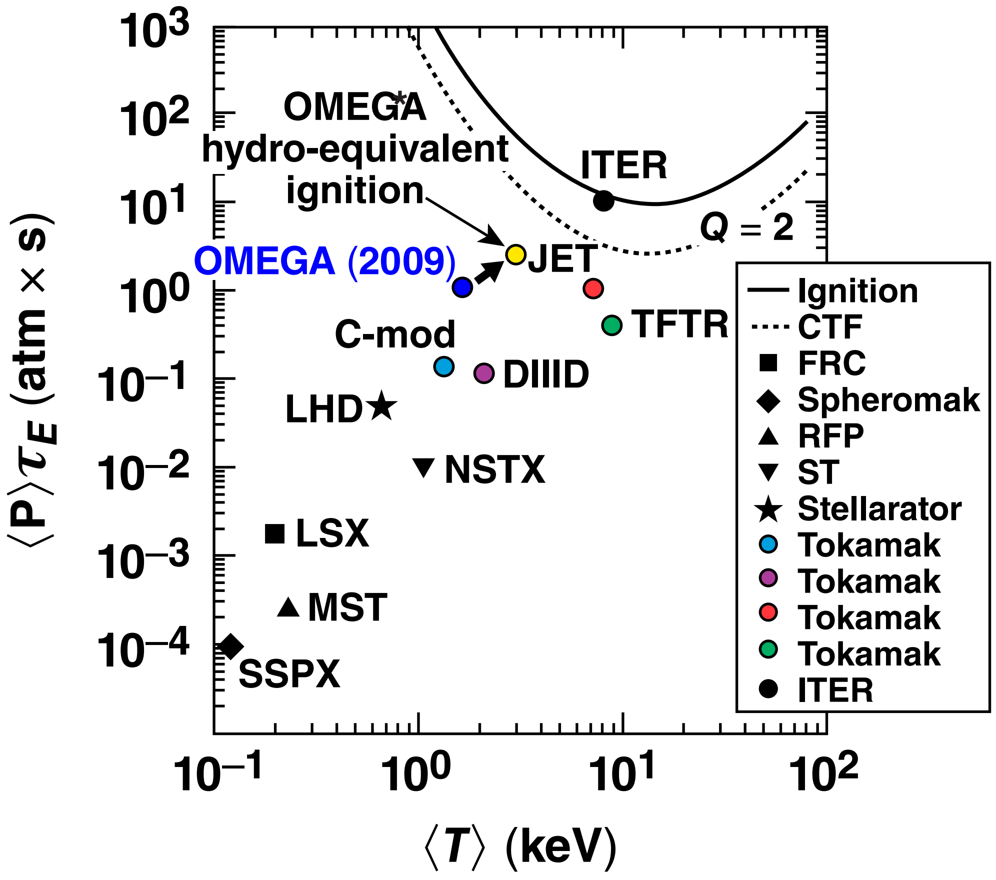
* "Review of Burning Plasma Physics," FESAC Report DOE/SC-0041 (September 2001).

R. Betti *et al.*, presented at the 51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, GA, 2–6 November 2009 (Paper PT3.00001).

The Lawson plots show the current performance and the future directions for OMEGA



OMEGA hydro-equivalent ignition:**
$\chi \approx 0.04$, $\langle T \rangle \approx 3.4$ keV, $p\tau_E \approx 2.6$ atm × s

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*Figure courtesy of J. P. Freidberg (MIT)

**Assuming the YOC prediction is correct

Summary/Conclusions

Cryogenic target implosions on OMEGA have produced areal densities of 0.3 g/cm^2

- The minimum areal density for ICF ignition is ~0.3 g/cm^2
- Cryogenic-DT implosions show good performance using a multiple-picket pulse shape that launches multiple shock waves
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