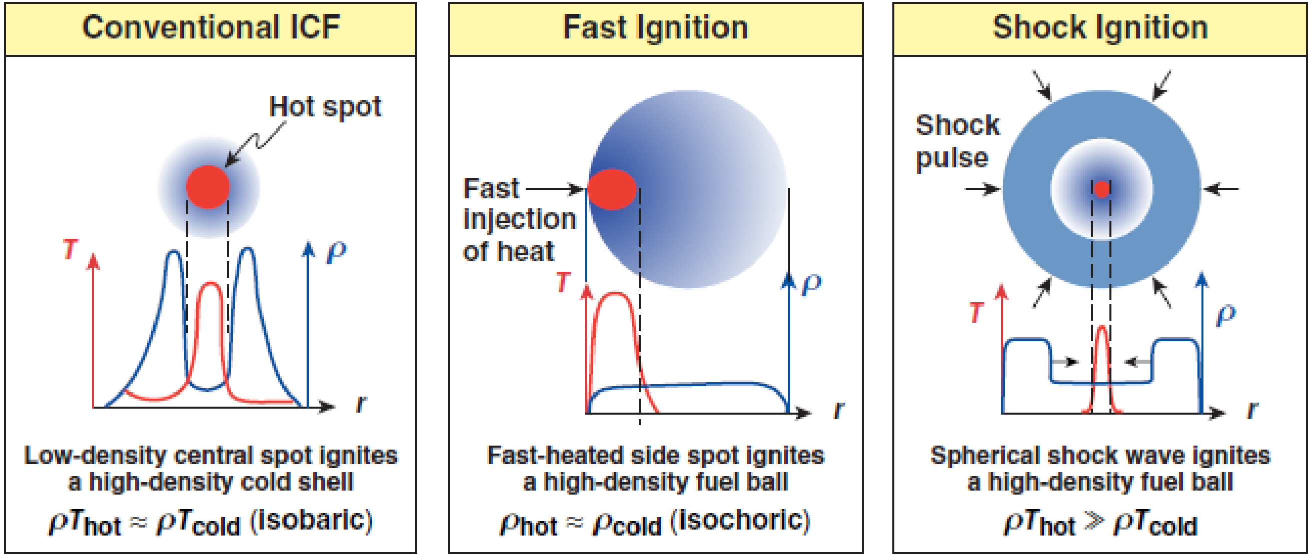
Summary: Inertial Fusion Experiments and Theory

“hot-spot” ignition

“assisted” ignition



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Fusion Energy Conference
Gandhinagar, India
22-27 Oct, 2018

Summary

Inertial Confinement Fusion (ICF) is a promising route to fusion energy but challenges remain

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- **Much of the work in ICF is related to proof-of-principle experiments to demonstrate ignition.**

- **Several different approaches to ICF are being pursued around the world; many challenges are similar**
  - **- control of nonuniformity and laser plasma interactions are the primary areas of study**

- **Several facilities around the work at various stages of development are used for ICF**
  - **- In the US: The National Ignition Facility (NIF), the OMEGA lasers, and the Z- machine**
  - **- The LMJ in France, and SGIII laser in China are being constructed for ICF.**

- **The leap from ignition to an IFE power plant requires many technological advances.**
  - **- More appropriate drivers**
  - **- Target delivery**
  - **- Reactor construction**

Acknowledgements

- The results presented in this summary is the work of many at various institutions in the US (LLNL, LANL, SNL, University of Rochester, General Atomics), France (CEA, CELIA), United Kingdom (Imperial College, AWE, Oxford), and Japan (ILE, Hamamatsu Corp.)

- Special thanks to Sylvie Jacquemot, John Kline, Ray Leeper, and Peter Norreys for inputs to this talk.

- Thanks also to other presenters in this conference for their summary inputs.

Outline

- Review of ICF
- Status and path forward
  - Hot spot ignition
  - Fast ignition – electron source and transport, target manufacture
  - Shock ignition
- IFE

Both “hot-spot” and “assisted” ICF ignition concepts are being explored globally

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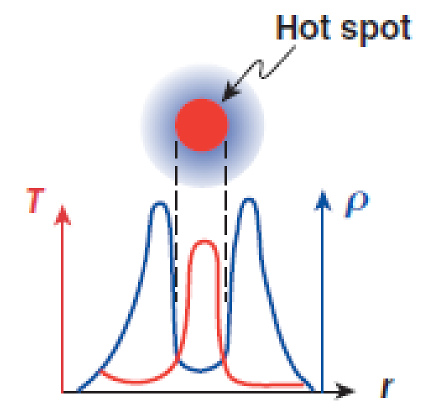
“hot-spot” ignition

Conventional ICF

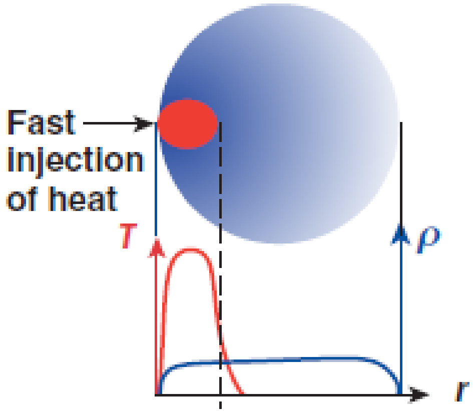


Low-density central spot ignites a high-density cold shell

$\rho T_{hot} \approx \rho T_{cold}$ (isobaric)

“assisted” ignition

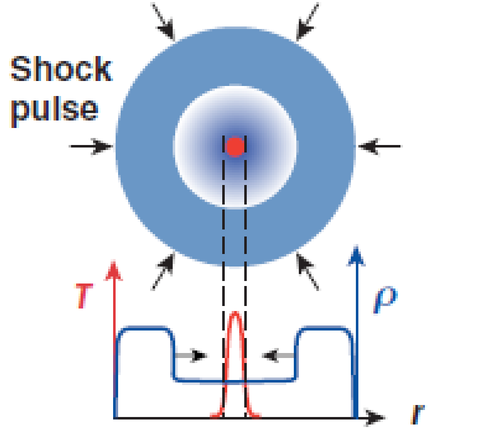
Fast Ignition



Fast-heated side spot ignites a high-density fuel ball

$\rho_{hot} \approx \rho_{cold}$ (isochoric)

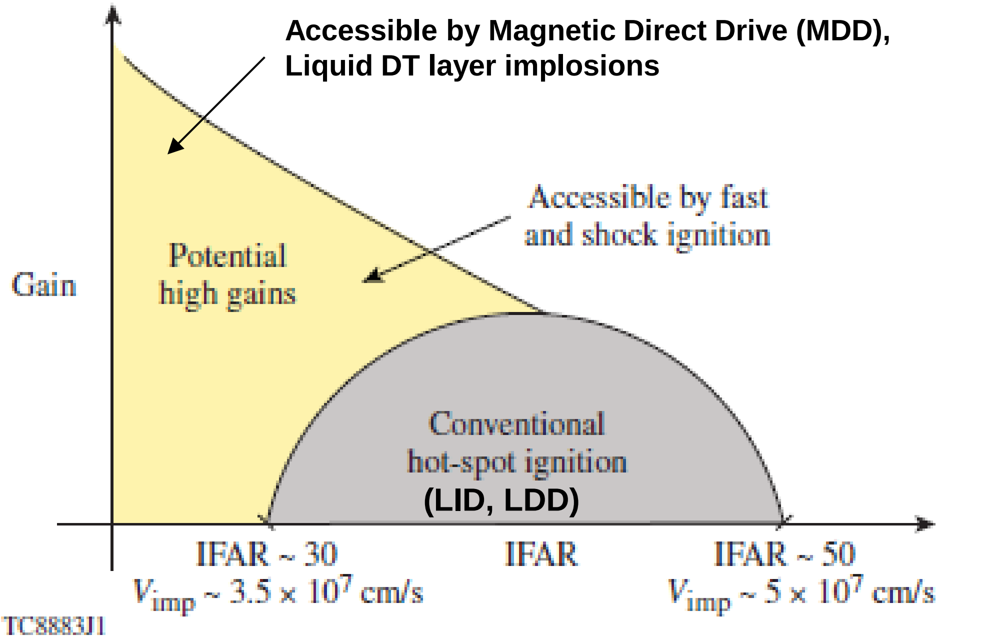
Shock Ignition



Spherical shock wave ignites a high-density fuel ball

$\rho T_{hot} \gg \rho T_{cold}$

These approaches have greatly expanded the parameter space for ignition

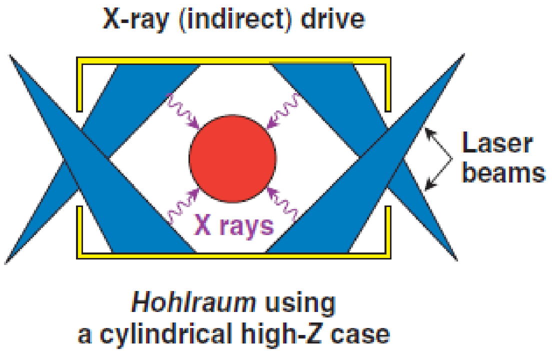


In-Flight Aspect Ratio
IFAR=R/ΔR

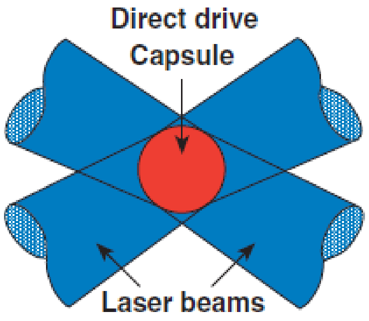
Increasingly unstable

The three hotspot ICF approaches use different methods of setting up the drive

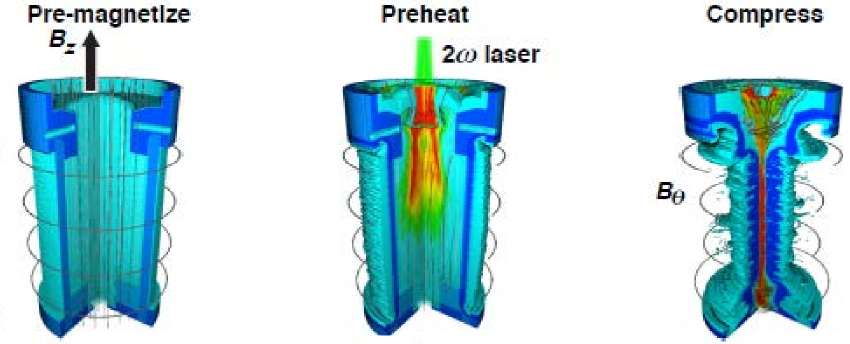
Laser Indirect Drive[1]



Laser Direct Drive[2]

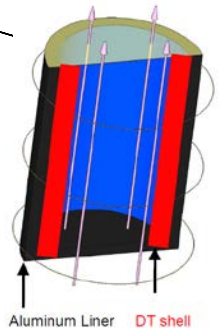


Magnetic Direct Drive[3]



Less sensitive to short wavelength laser speckle than LDD

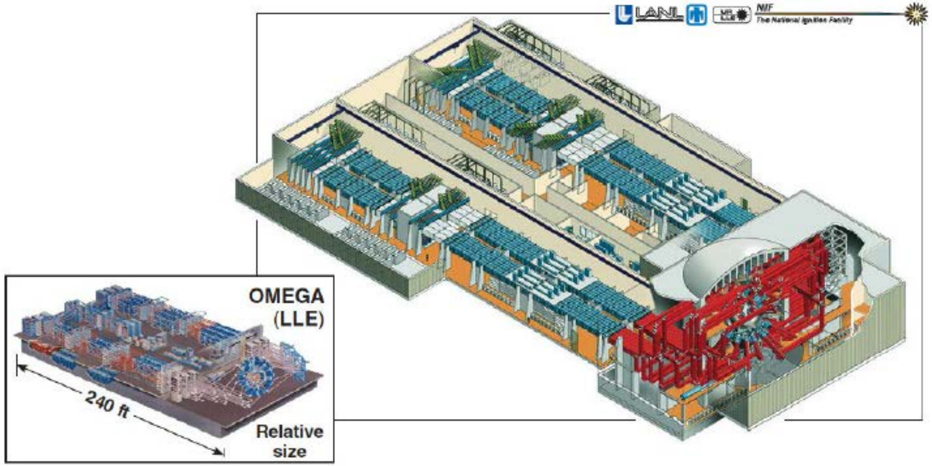
Couples x3-4 more energy into the capsule than LID

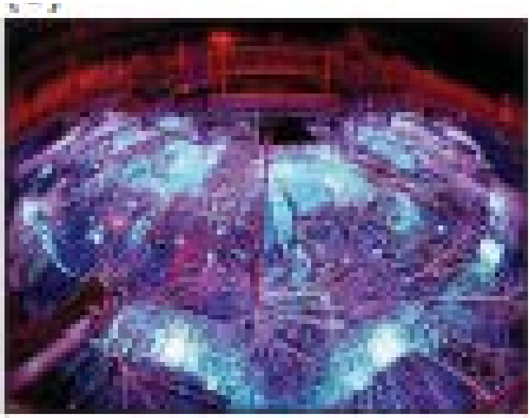


Relaxed convergence and implosion velocity requirements

[1] Lindl et al., Phys. Plasmas 11, 39 (2004); [2] Nuckolls et al., Nature 239, 139 (1972); [3] Slutz et al., Phys. Plasmas 056303 (2010).

Several facilities in the U.S are used for these different approaches



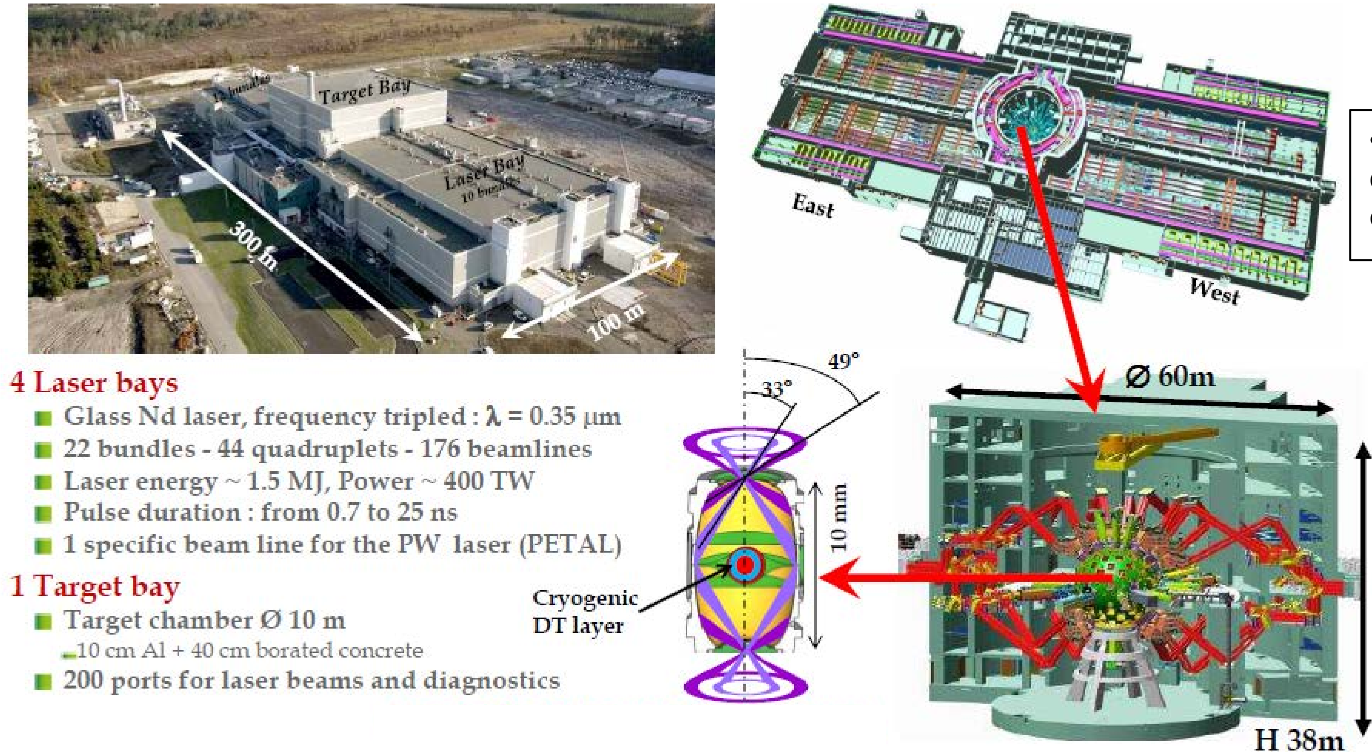


OMEGA: TW laser, 30 kJ UV
λ = 0.351 nm
60 beams
Shot cycle: ~1/hour
OMEGA EP: PW laser
4 beams in short
or long pulse mode

NIF: TW laser, ~1.9 MJ
λ = 0.351 nm
192 beams arranged near the pole
Shot cycle: ~1/day

Z: 20 MA
Shot cycle: ~1/day

Upcoming facilities such as that in France (LMJ)[1] will accelerate progress in ICF



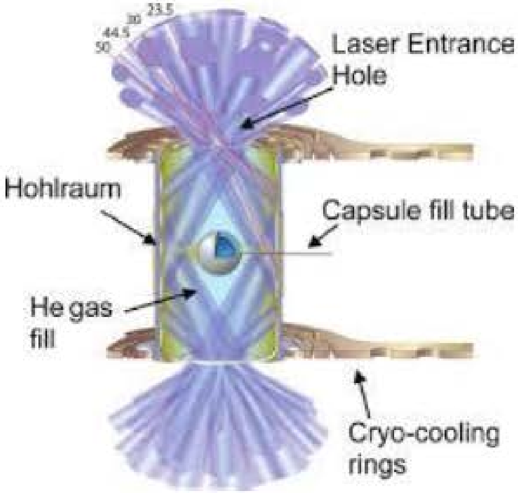
- Initial fusion experiments with 6 bundles or 12 quads will begin in 2019

- Similar facilities in China (SG III) and Russia are being constructed

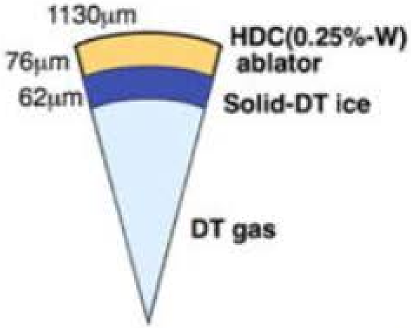
[1] S. Jacquemot, private communication (2018)

Indirect drive experiments[1] have been performed at the largest energy scales (~1.9 MJ) on the NIF

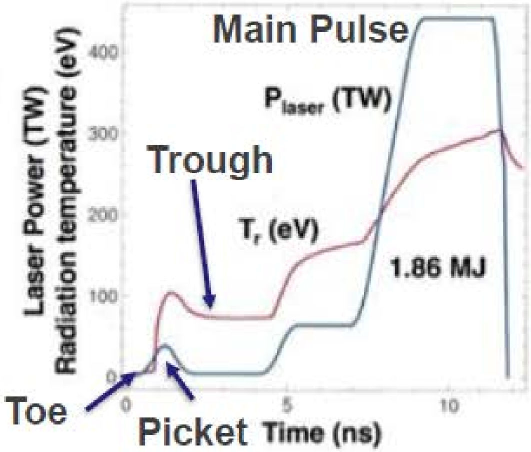
Hohlraum Target



Capsule



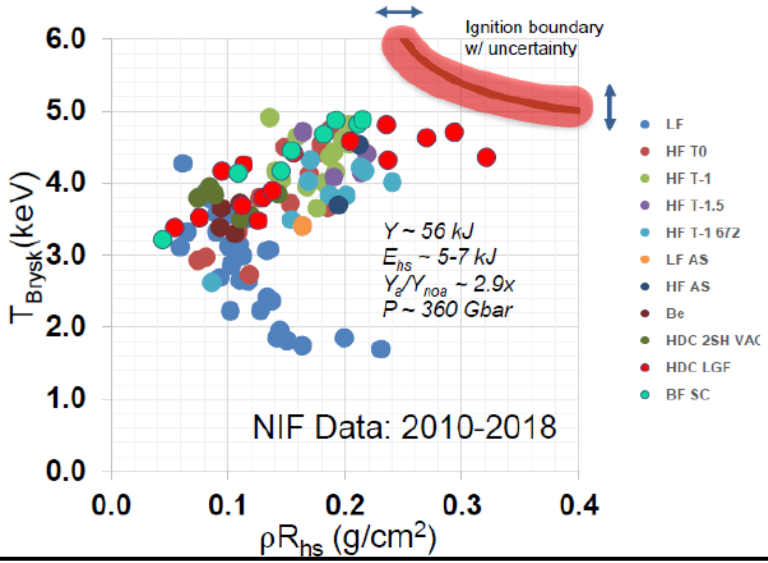
Laser Pulse

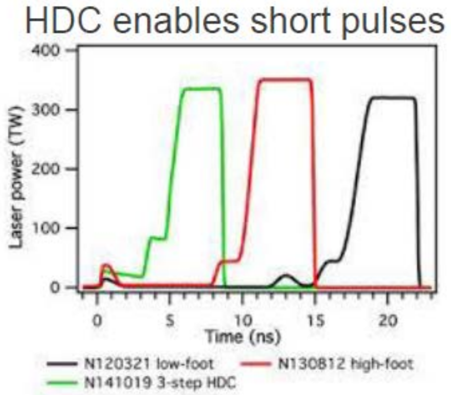


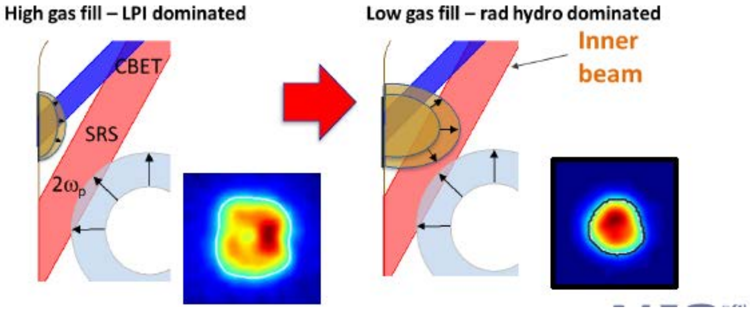
- Many variations in ablator materials[2], hohlraum case-capsule size ratio[3], adiabat have been investigated

[1] Kline et al., Wed IFE/1; [2] Divol et al., Phys. Plasmas 24, 056309 (2017); [3] Callahan et al., Phys. Plasmas 26, 056305 (2018)

LID has benefitted from reducing Laser Plasma Interactions in the hohlraum though challenges remain in symmetry control





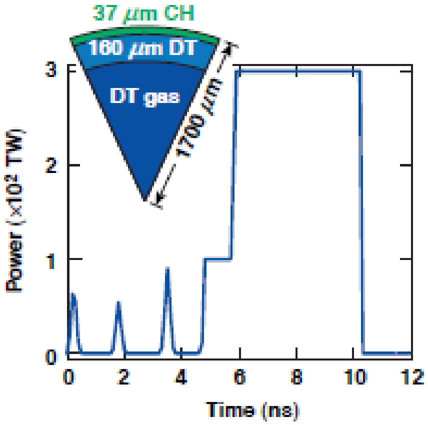


- Future work includes
  - quantifying beam power imbalance
  - quantifying feature (defects, tent, fill-tube) driven mix
  - Modifying hohlraum shapes[1]
  - Increased laser energy

[1] Robey et al., Phys. Plasmas 25, 012711 (2018).

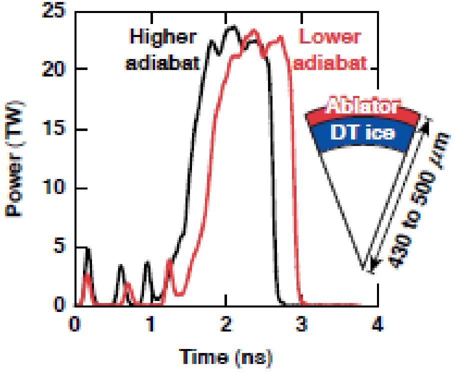
Laser Direct Drive experiments[1] on OMEGA are scaled from ignition designs

1.5-MJ, spherically symmetric direct-drive design



- V_{imp} = 3.8 to 4 × 10^7 cm/s
  Adiabat α = 1.6 to 3
  $IFAR_{2/3}$ = 20 to 25
  CR = 20 to 23

26- to 29-kJ OMEGA cryogenic design



- V_{imp} and IFAR are controlled by varying the ablator (7.5 to 12 μm) and fuel thickness (40 to 66 μm)

Adiabat
$\alpha = P/P_{Fermi}$

IFAR = shell radius/ shell thickness

*IFAR: in-flight aspect ratio
**CR: convergence ratio

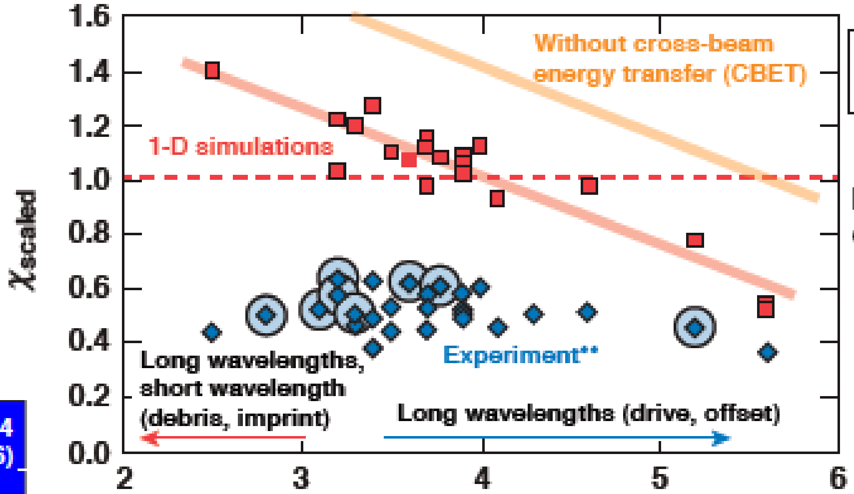
TC12314l

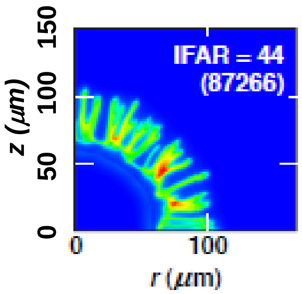
[1] P. B. Radha et al., Mon IFE/OVP

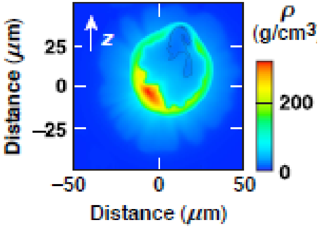
Laser Direct Drive experiments performed on OMEGA are likely dominated by nonuniformity growth

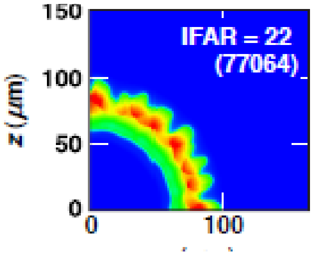
Generalized Lawson criterion*

$$\chi_{\text{scaled}} = P\tau/P\tau_{\text{ign}} = (\rho R_{\text{no}\,\alpha})^{0.61} \left(0.12\, Y^{16}_{\text{no}\,\alpha}/M^{\text{stag}}_{\text{DT}}\right)^{0.34} \left(E^{\text{NIF}}_{\text{laser}}/E^{\text{OMEGA}}_{\text{laser}}\right)^{0.35}$$









- A large engineering effort on OMEGA is devoted to improving Uniformity
- 3D code development Including detailed physics models is in progress

* R. Betti *et al.*, Phys. Rev. Lett. 114, 255003 (2015); A. Bose *et al.*, Phys. Rev. Lett. E 94, 011201(R) (2016).
** S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016).

Challenges to ignition remain in mitigating the effects of Laser Plasma Interactions which do not scale to larger facilities

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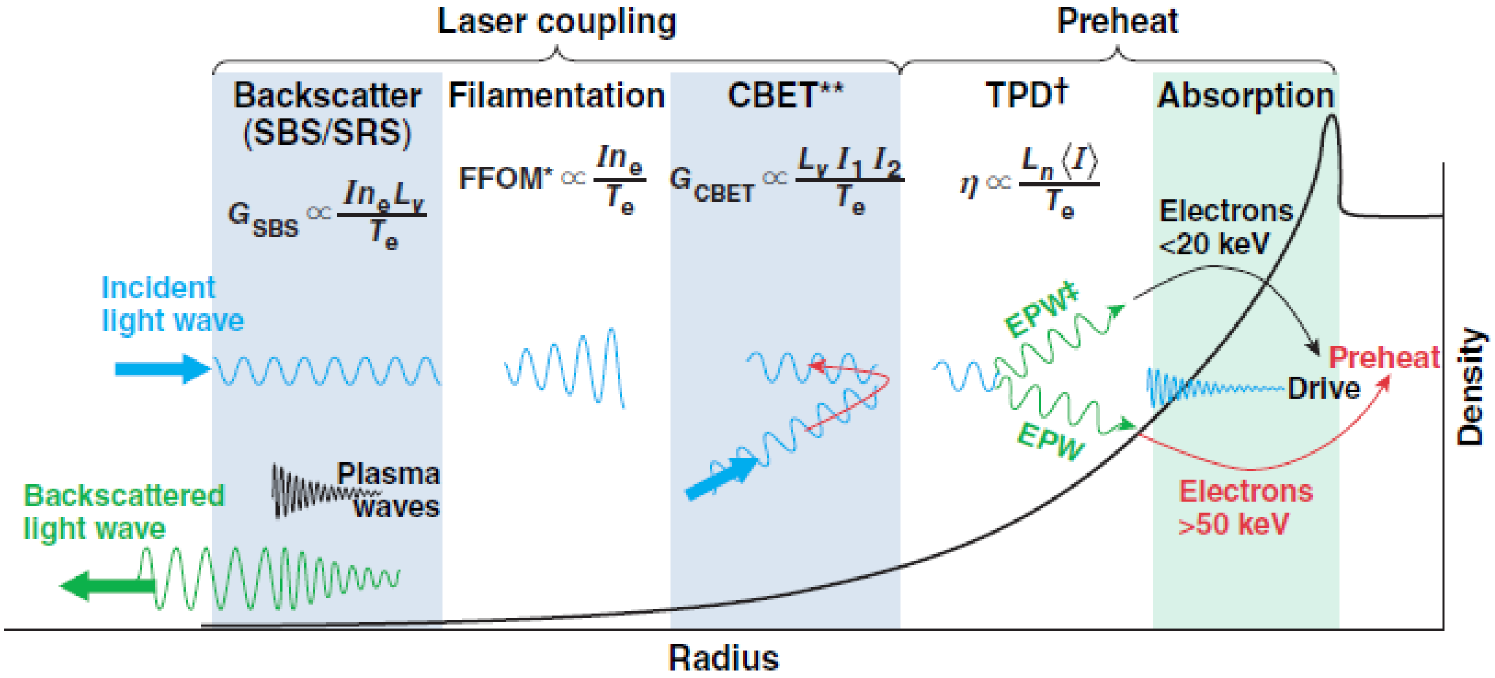

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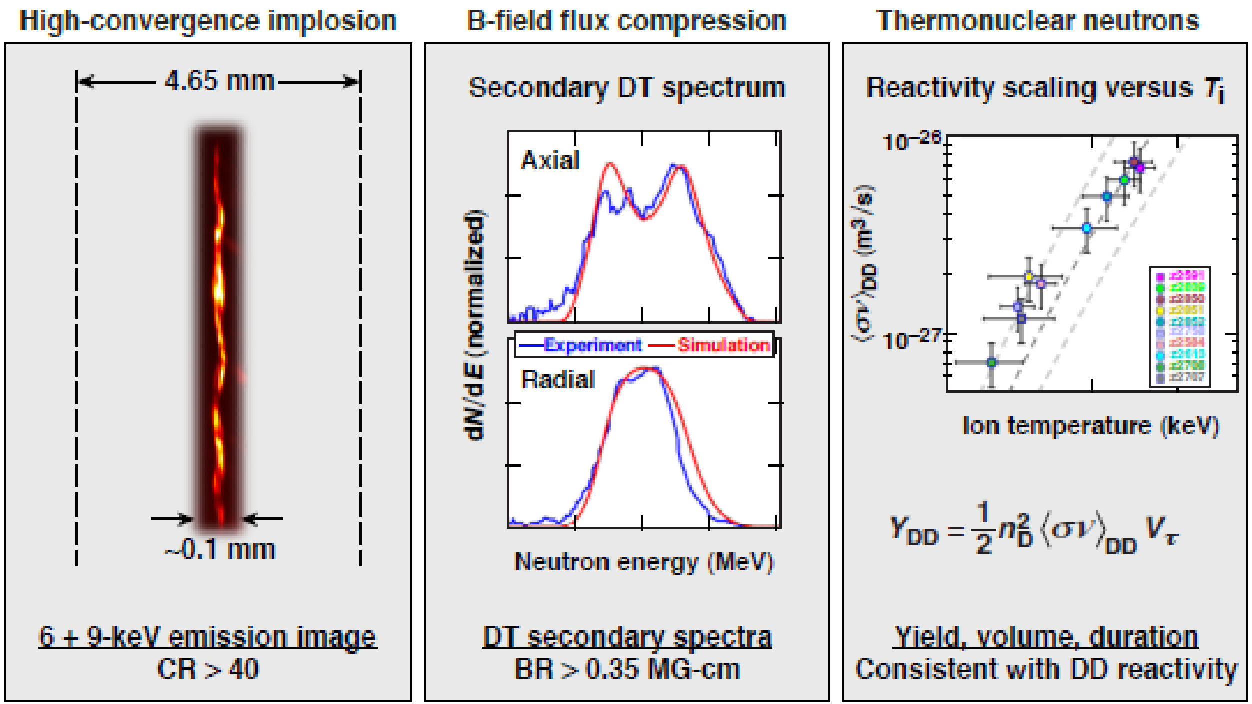
Magnetic Direct Drive shows promise of high yields though similar challenges of nonuniformity and mitigating laser plasma interactions persist

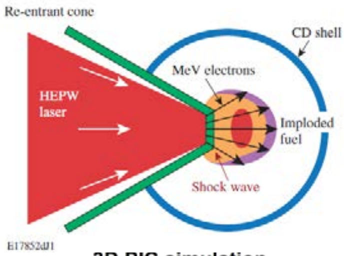


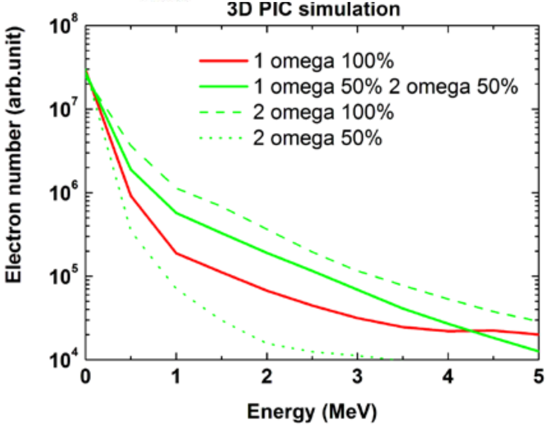
- An enhanced Z, with larger current, higher B-field, and tritium is planned.
- The goal is to demonstrate a yield of ~100 kJ

M. R. Gomez *et al.*, Phys. Rev. Lett. 113, 155003 (2014);
P. F. Schmit *et al.*, Phys. Rev. Lett. 113, 155004 (2014);
K. D. Hahn *et al.*, Rev. Sci. Instrum. 85, 043507 (2014).

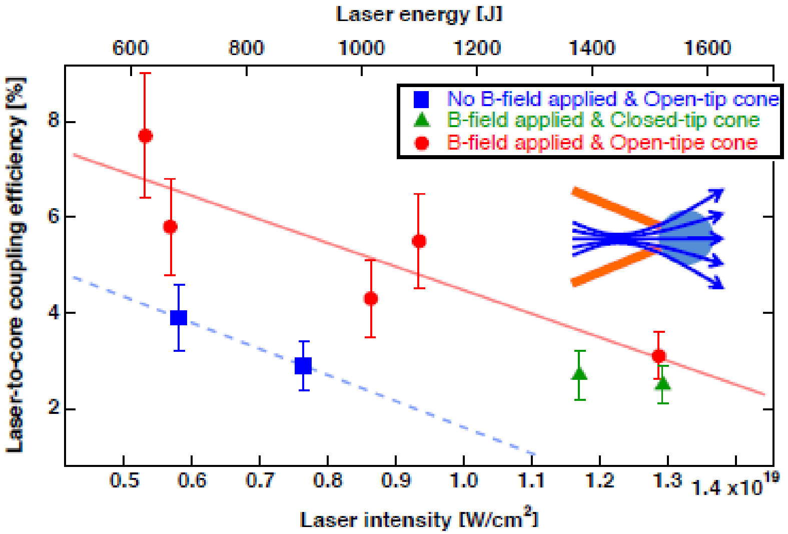
Fast ignition benefits from improved flux of fast-electrons and more effective transport using magnetic fields

Two color laser can increase the electron intensity, and reduce electron divergence[1]

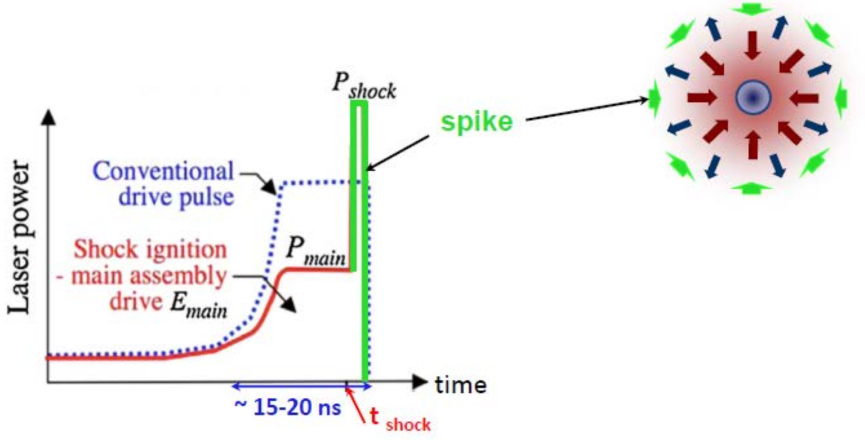




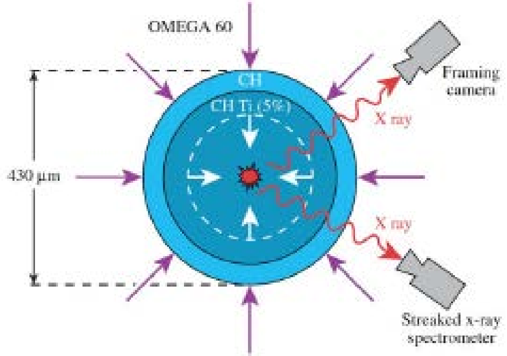
Imposed magnetic fields can be used to guide fast-electron transport[2]



Shock ignition[1] experiments[2] are planned for LMJ and the NIF



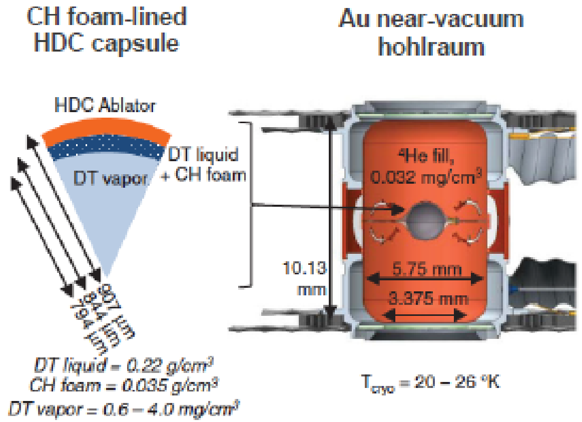
Schematic of shock-strength experiment

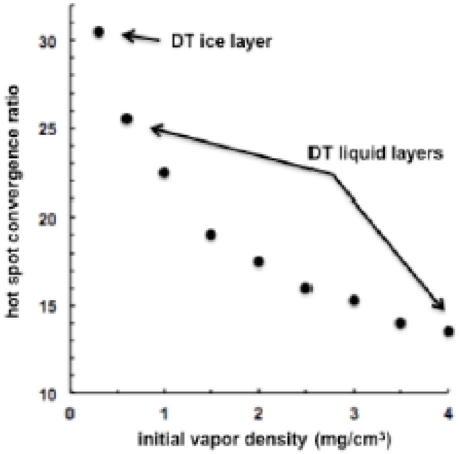


- OMEGA experiments[2] have demonstrated improved yield (x4) compared to a no spike pulse shape with the same compression
- Experiments indicate the presence of the shock from the spike[3] (~300 Mbar peak ablation pressure).
- What is the role of hot electrons from SRS and other plasma instabilities on ignition relevant larger density scale-lengths? NIF experiments[4] (LLE, AWE, Rutherford) have begun. LMJ experiments[5] (CEA, CELIA, ILE, LLE etc.) are planned to study the shock strength and role of laser plasma interactions.

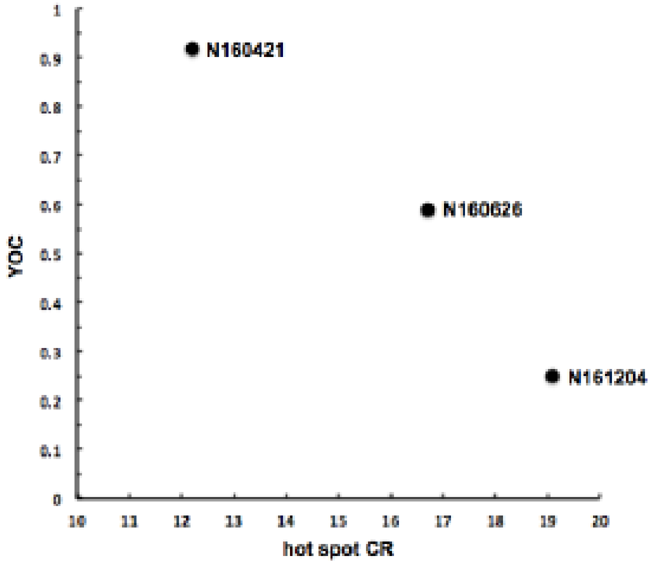
[1] Betti et al., Phys. Rev. Lett. 98, 155001 (2007); [2] Theobald et al., Phys. Plasmas 15, 055503 (2008);
[3] Nora et al., Phys. Rev. Lett. 114 (2015); [4] Theobald et al; [5] Baton et al.

Liquid DT in a foam layer[1] relaxes the constraints on hot spot formation by using the shock to directly heat the high-density vapor





Results from NIF shots[2] show promise at low CR



- This target concept[4] can be applied to LDD, shock ignition, and fast ignition[5]

[1] Olsen and Leeper, Phys. Plasmas 20, 092705 (2013); [2] Olsen and Leeper, Phys. Rev. Lett. 117, 245001 (2016);
[3] Zylstra et al., Phys. Plasmas 25, 056304 (2018); [4] Walters et al., Fusion Sci. Technol. 73, 305 (2018);

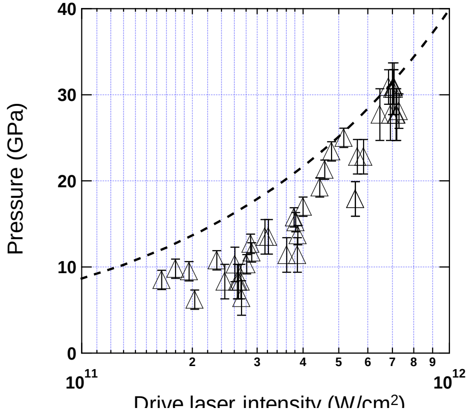
The leap to IFE requires technological/scientific advances beyond ignition

Driver development

- Heavy ion beams
- Diode pumped lasers[1]

\- 0.5 Hz, ~50 J, (1.6-7.7)x10^{11} W/cm^2
\- reqd: ~10 Hz, few MJ, ~10^{15} W/cm^2

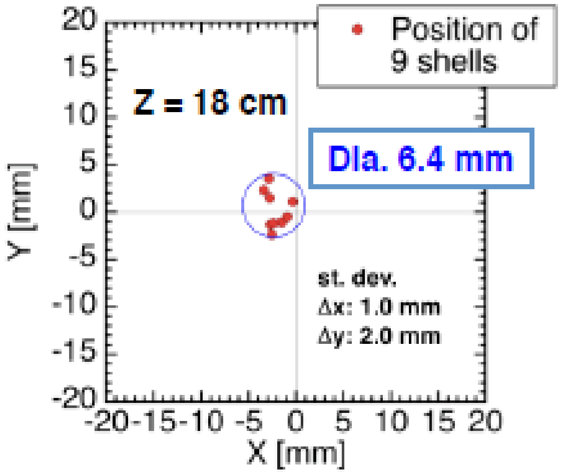
Inferred shock pressures



Target injection

- 0.5 Hz injection of shells tested[2]

Distributions of shells



Reactor design

- Design of first wall to withstand neutron, x-ray and gamma flux[3]

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[1] Watari et al., Hamamatsu Corp. Wed IFE-P4; [2] Mori et al., Hamamatsu Wed IFE-P4; [3] Perlado et al., Madrid, Wed IFE/1-4

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- The leap from ignition to an IFE power plant requires many technological advances.
  - More appropriate drivers
  - Target delivery
  - Reactor construction

With new facilities coming online, interesting IFE-related physics will emerge over the next decade.