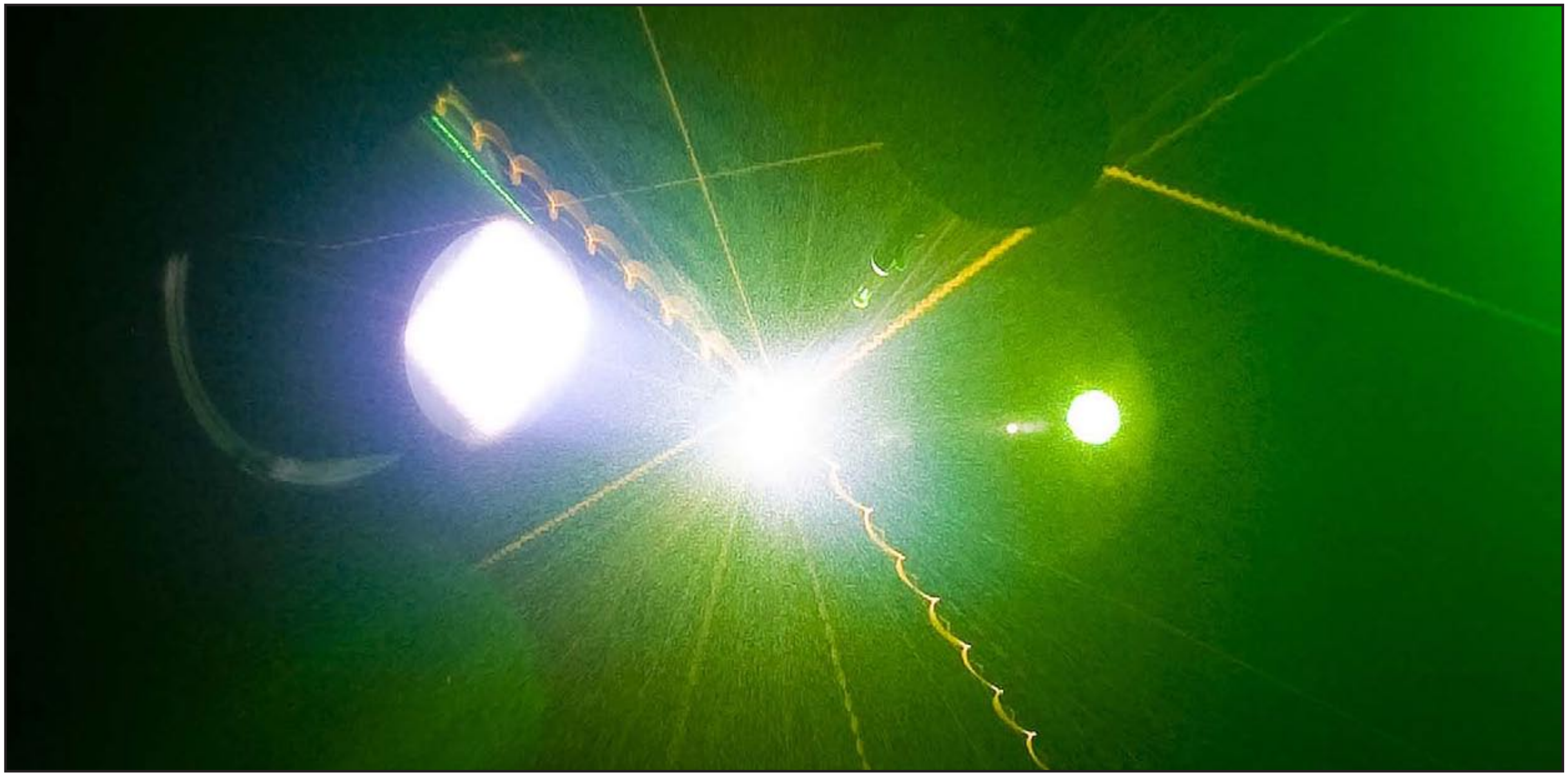
Advanced Ignition Experiments on OMEGA



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University of Rochester
Laboratory for Laser Energetics

Summary

A comprehensive scientific program to study advanced ignition concepts is being pursued at LLE

- Two advanced concepts beyond conventional "hot-spot " ignition are explored at LLE:
  - "Shock" ignition[1]
  - "Fast" ignition[2]
- Experiments with shock-ignition pulses show a 4× improvement in yield and 30% more areal density compared to conventional pulses.
- Fast-ignition-relevant experiments show favorable hydro performance of cone-in-shell targets and a ~20% conversion efficiency from short-pulse laser energy into electrons.
- OMEGA EP, a new high-energy, ultrashort-pulse laser system was completed in April 2008 and is used for advanced ignition experiments.

[1]R. Betti *et al*., Phys. Rev. Lett. 98, 155001 (2007).
[2]M. Tabak *et al*., Phys. Plasmas 1, 1626 (1994).

E17291

Collaborators

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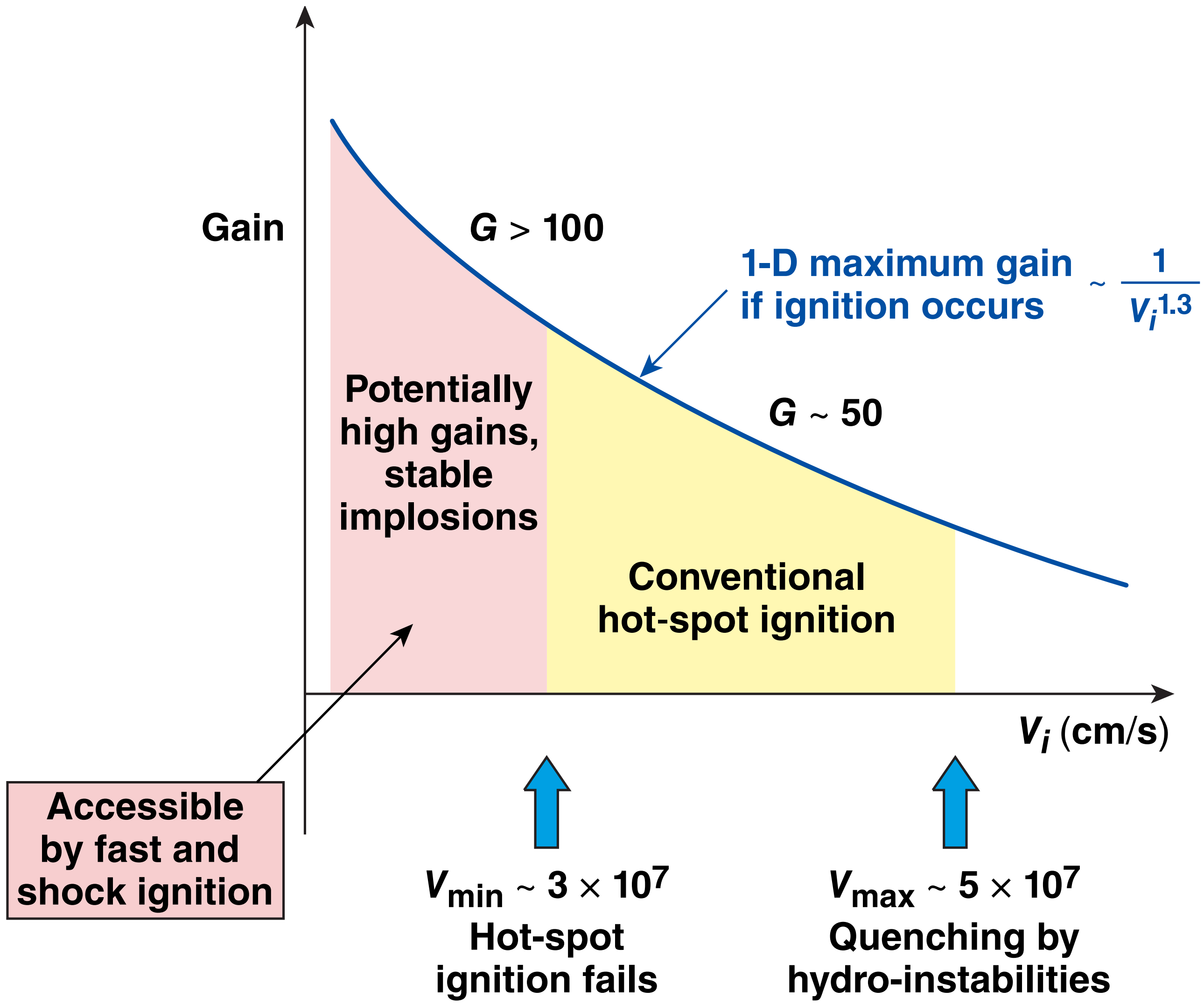
P. A. Norreys
Rutherford Appleton Laboratory

R. B. Stephens
General Atomics

Outline

- Motivation
  - "Shock" ignition uses a shock generated by the compression driver later in the implosion to reduce the energy required for ignition
  - "Fast" ignition separates the fuel assembly and heating using an ultrafast laser to heat the fuel in addition to a compression driver
- Shock-ignition experiments
- Fast-ignitor-relevant experiments
- OMEGA EP Laser System

Fast ignition and shock ignition can trigger ignition in massive (slow) targets, leading to high gains*



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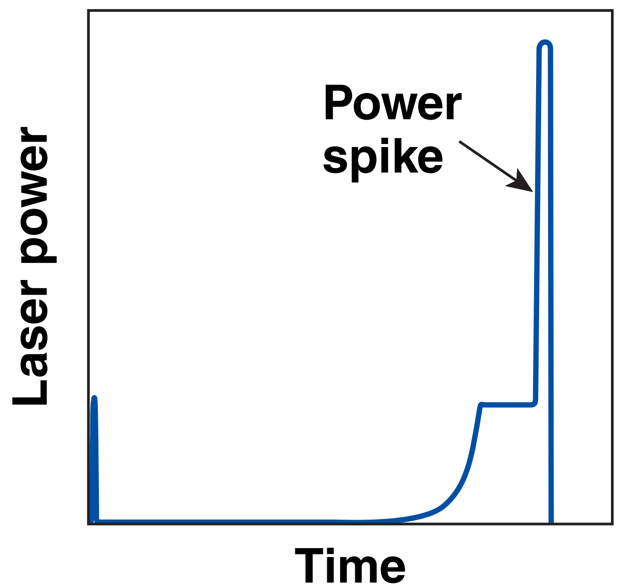
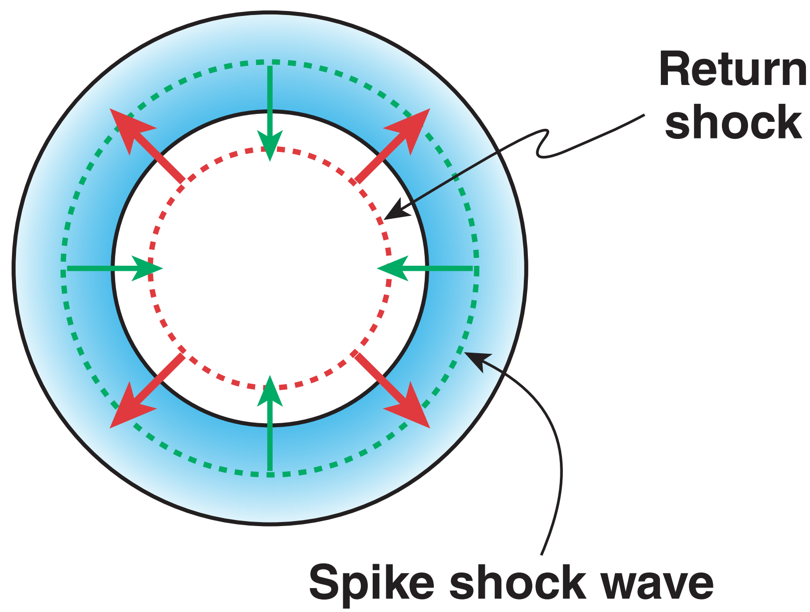
*R. L. McCrory *et al*., Phys. Plasmas 15, 055503 (2008).

A shaped laser pulse with a high-intensity spike launches a strong shock wave for ignition*





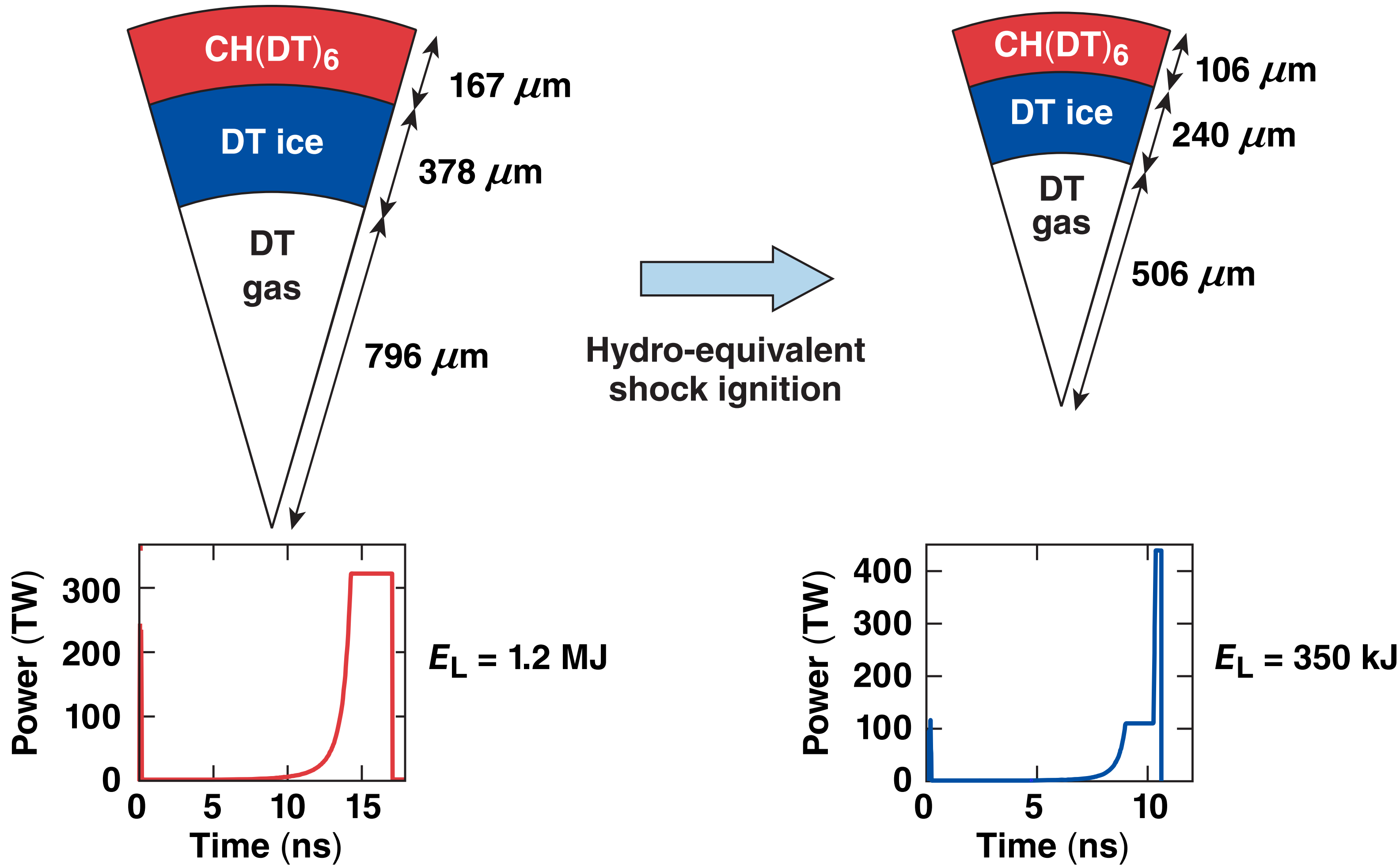
The ignitor shock wave significantly increases its strength as it propagates through the converging shell.

E16323

*R. Betti *et al*., Phys. Rev. Lett. 98, 155001 (2007).

A conventional hot-spot target requires ~3× more energy than a shock-ignition target

Low-velocity hot-spot ignition (Gain ~1) | **Shock ignition (Gain ~1)**



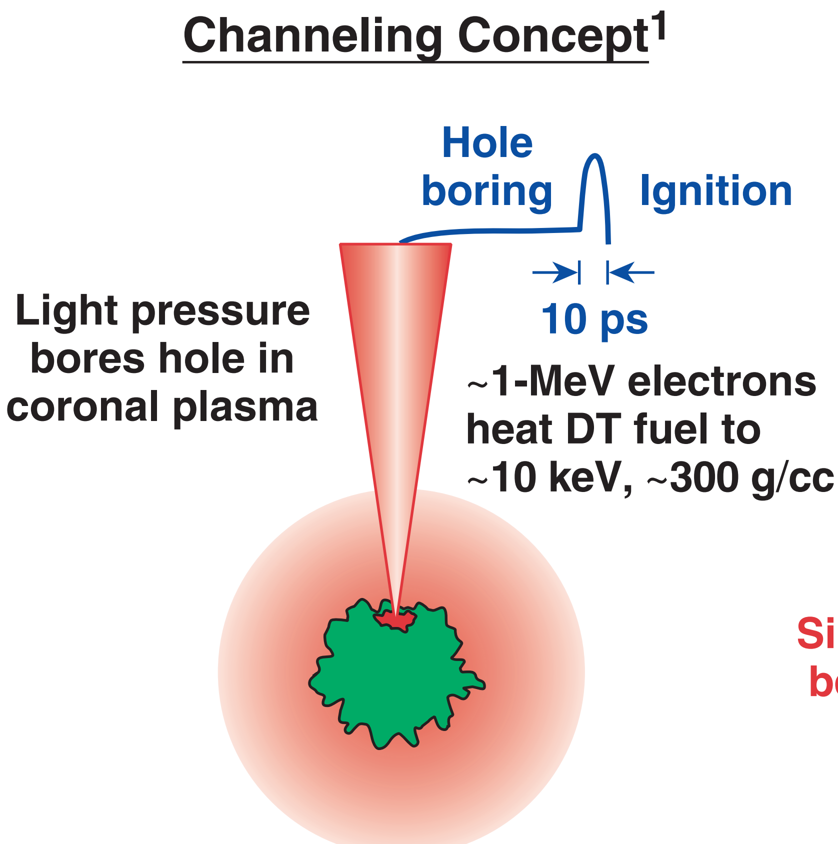
A high-velocity hot-spot design achieves a gain of 49 at 1 MJ.*

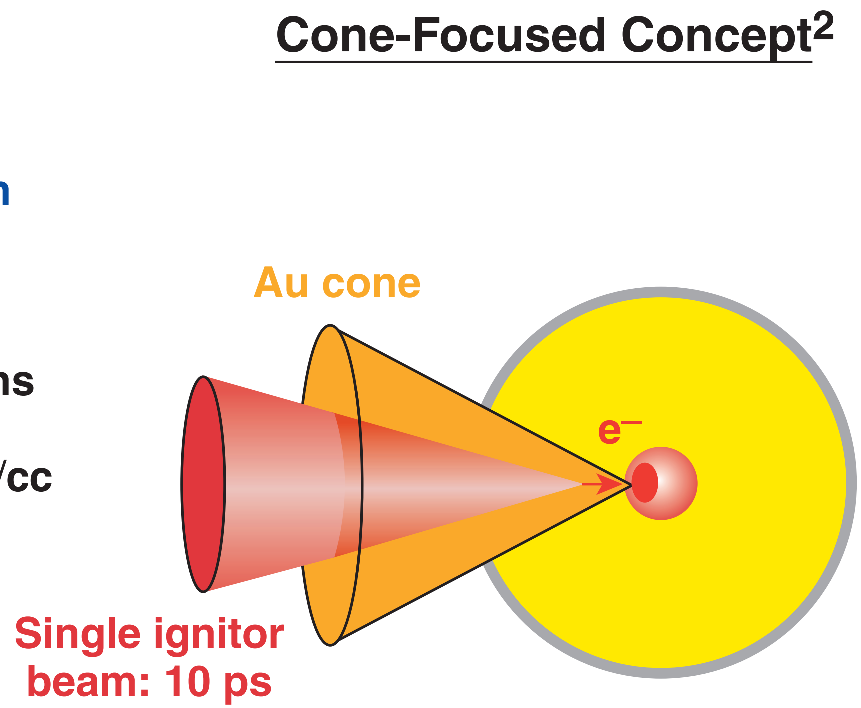
E16312a

*T. J. B. Collins, Phys. Plasmas 14, 056308 (2007).

The two viable fast-ignition concepts share fundamental issues: hot-electron production and transport to the core

UR LLE

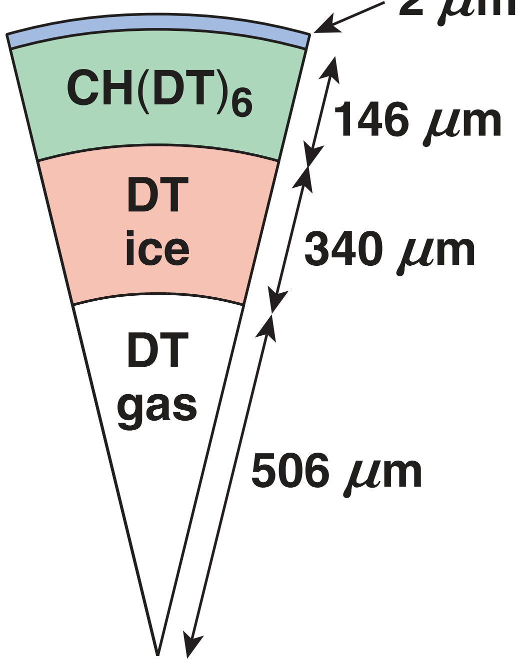




[1] M. Tabak *et al*., Phys. Plasmas 1, 1626 (1999).
[2] P. A. Norreys, Phys. Plasmas 7, 3721 (2000).

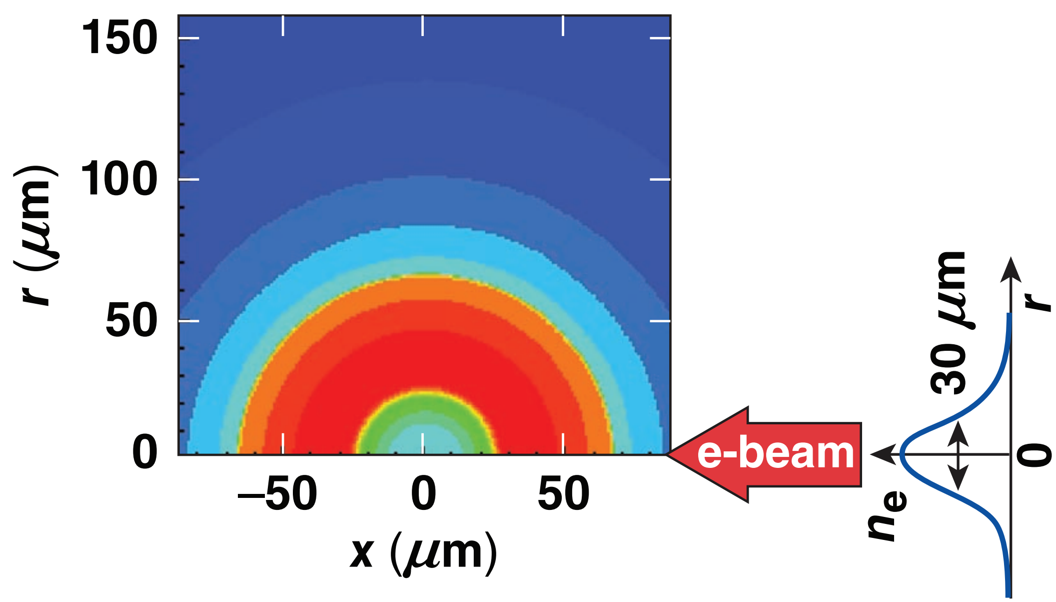
E11710d

In integrated simulations an optimized target[1,2] ignites with a gain = 100 when heated with 43 kJ of electrons



Gaussian, relativistic-Maxwellian e-beam

FWHM	30 μm
Duration τ	10 ps
T_e	2 MeV
Divergence half-angle	20°
Distance to the target	125 μm

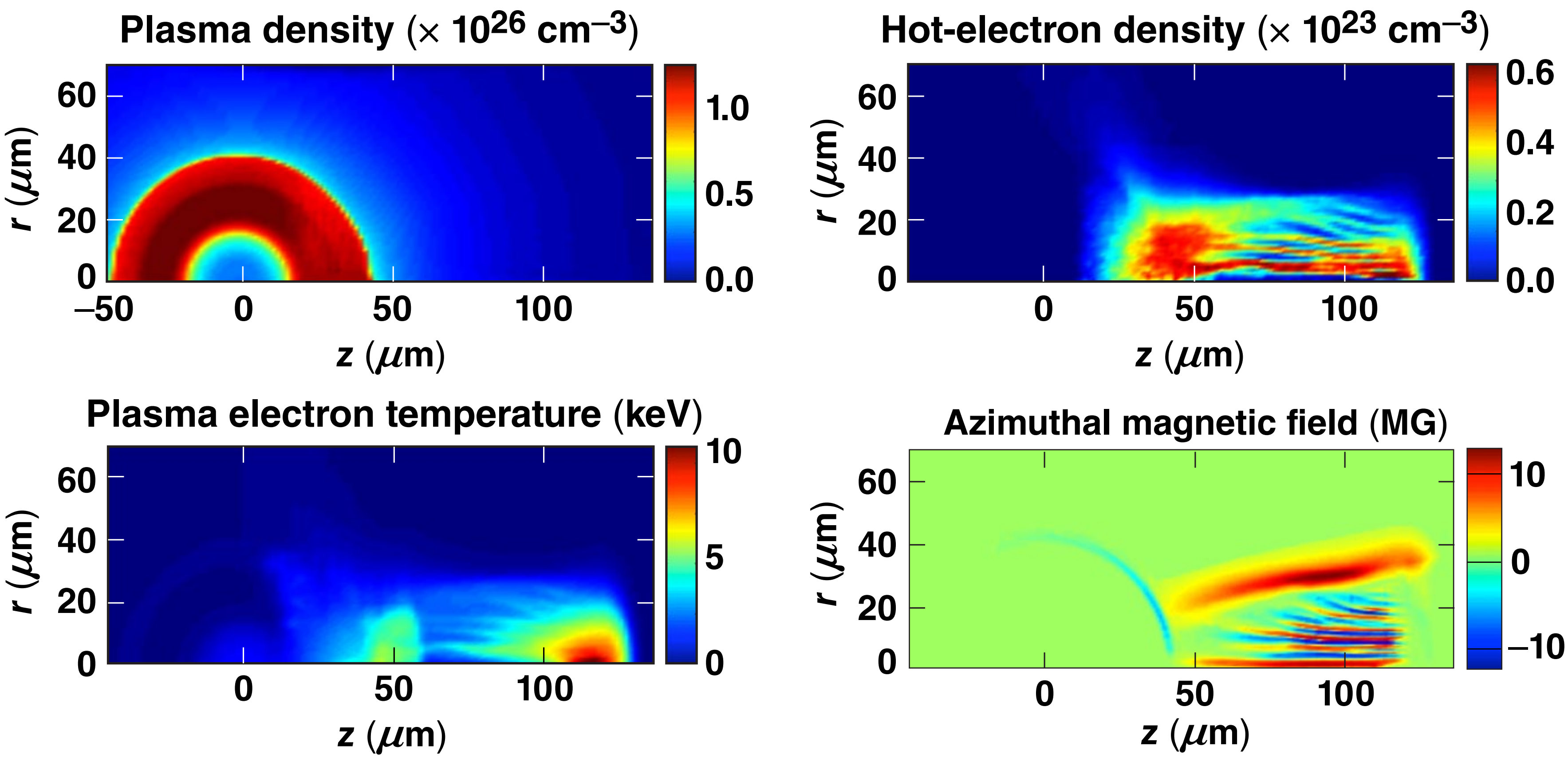


[1]R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005).
[2]A. A. Solodov (YI1.00002).

TC7792d

The self-generated magnetic field collimates the electron beam[1,2]

Snapshots at t = 8 ps after the beginning of the e-beam



Total e-beam energy = 43 kJ, angular divergence = 20°

[1] L. Gremillet *et al*., Phys. Plasmas 9, 941 (2002).
[2] J. J. Honrubia and J. Meyer-ter-Vehn, Nucl. Fusion 46, L25 (2006).

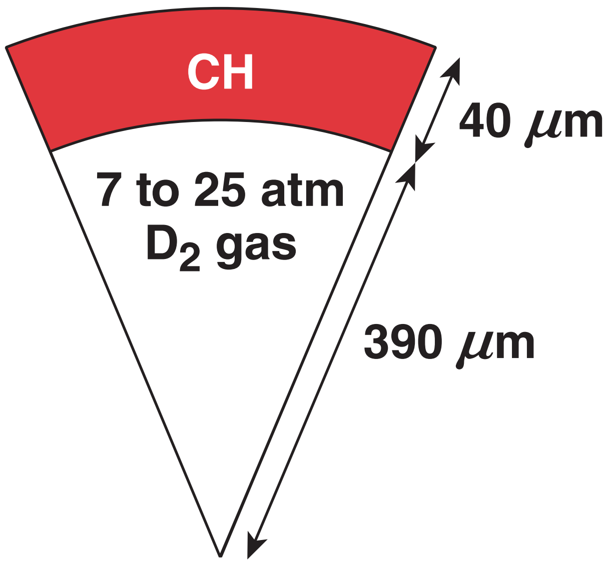
TC7793e

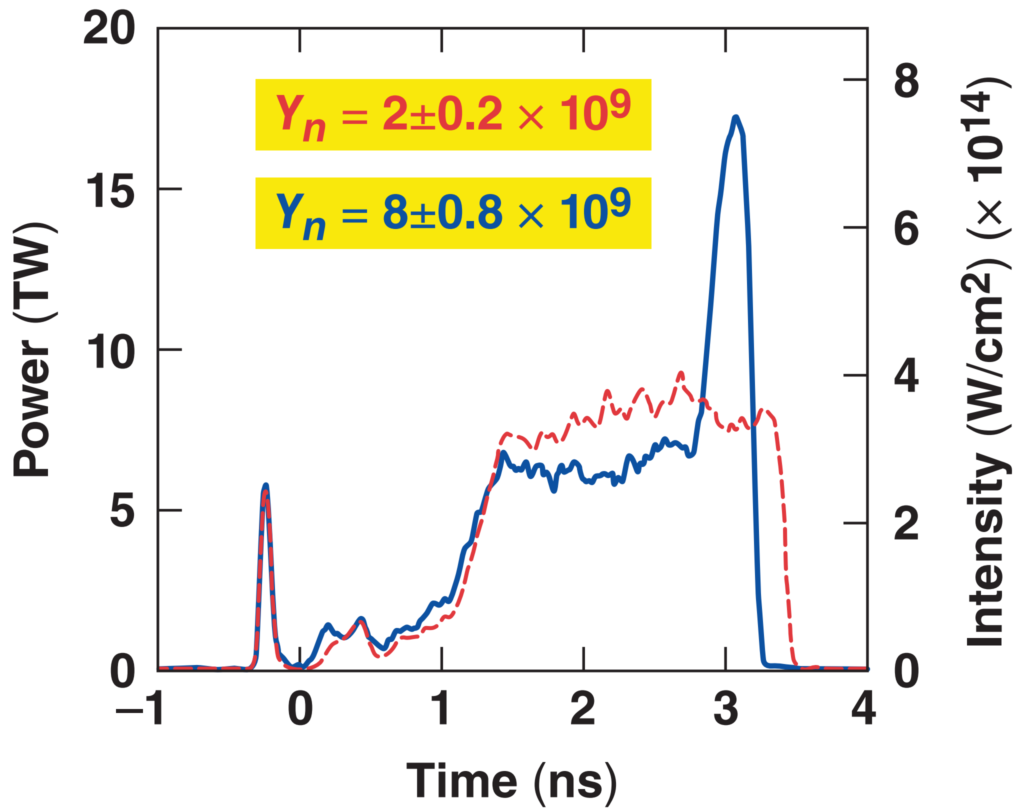
Outline

- Motivation
- Shock-ignition experiments
  - CH shells have been used on OMEGA to test the performance of shock-ignition pulse shapes
  - timing of the shocks is critical to optimize the performance of the implosion
  - with optimized shock timing the neutron yields improve by up to a factor of 4, the areal density by up to 30%
- Fast-ignitor-relevant experiments
- OMEGA EP Laser System

CH shells have been imploded on OMEGA to test the performance of shock-ignition pulse shapes

E_L = 19 kJ, α = 1.3,
V_i = 1.7 × 10^7 cm/s, SSD off





The neutron yield increases considerably when a shock is launched at the end of the pulse.

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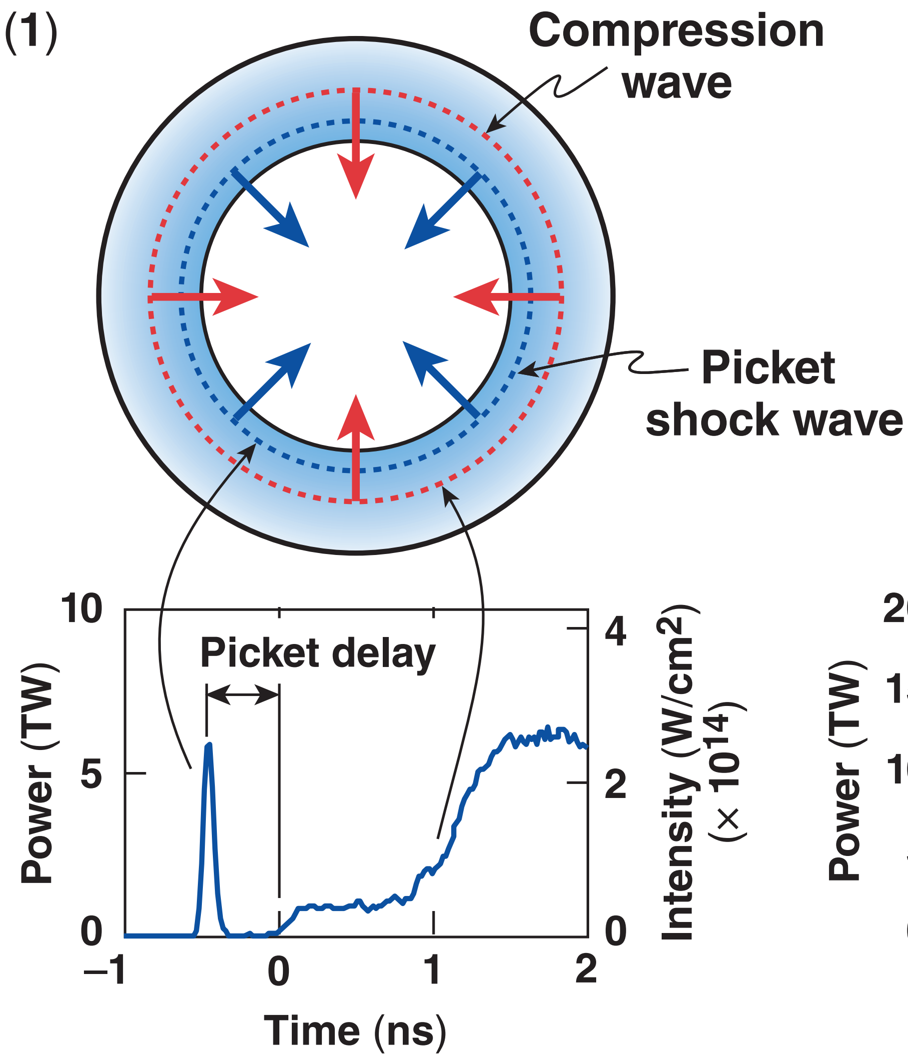
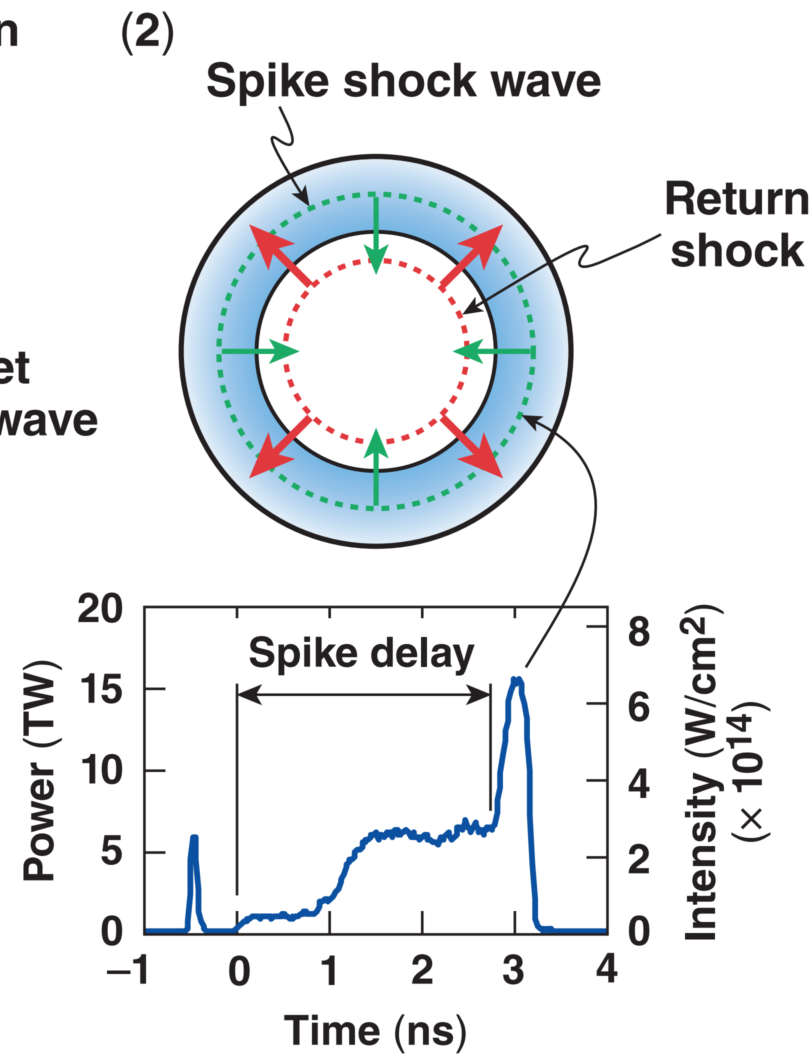
The correct timing of the shock waves is crucial for optimized implosion performance*

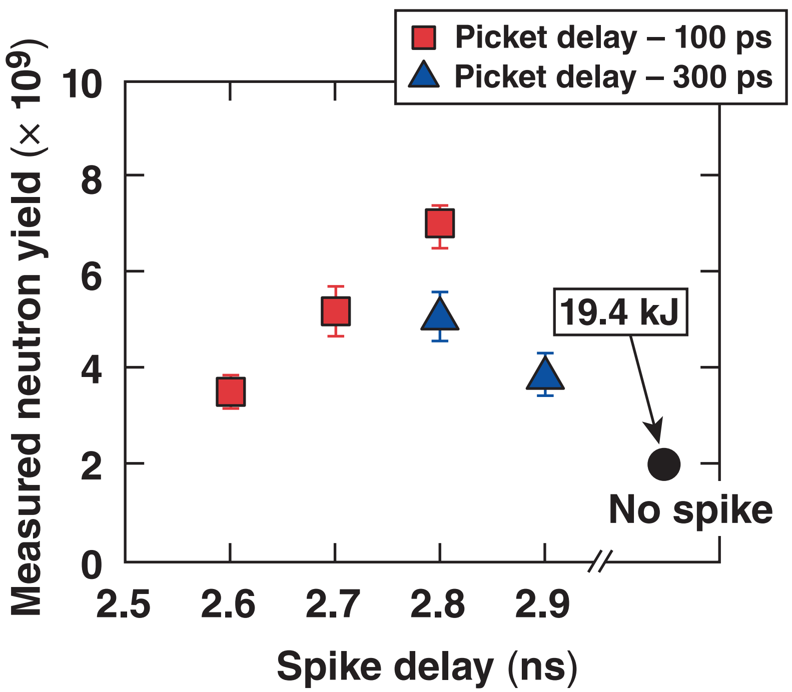


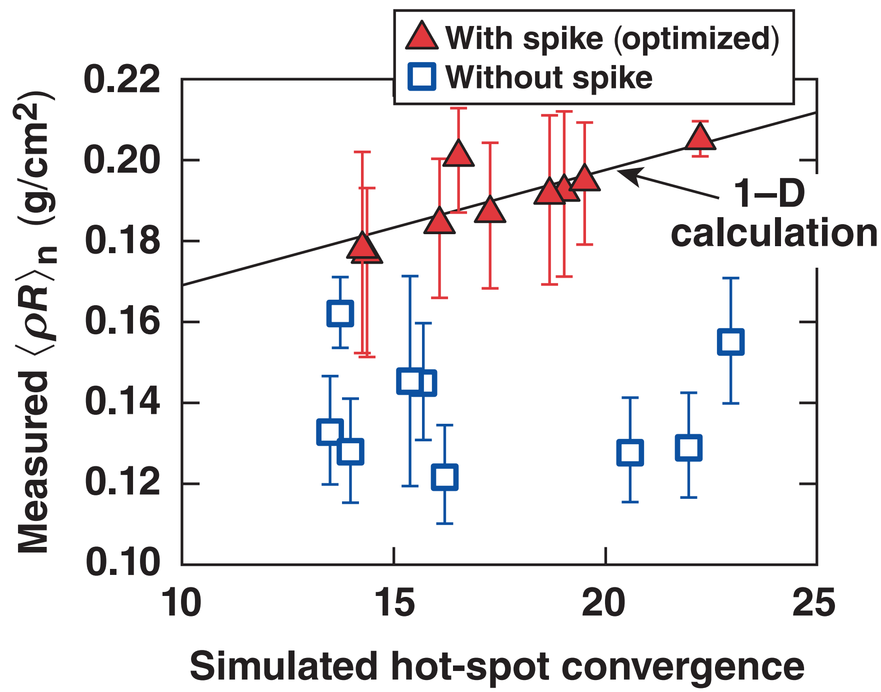


E16130a

*W. Theobald, Phys. Plasmas 15, 056306 (2008).

The picket and spike timing has a significant effect on the measured neutron yield and areal density ⟨ρR⟩





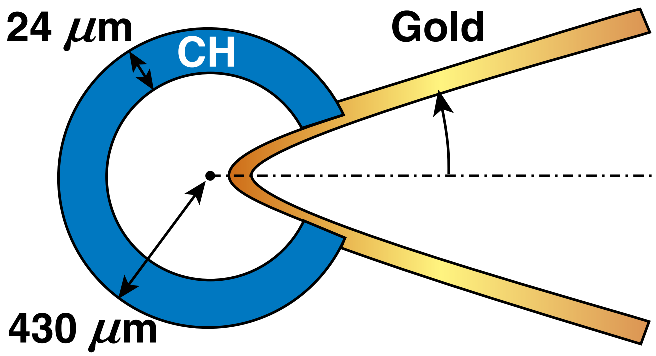
The shock-ignition implosions show an improved performance with respect to areal density and neutron yields.

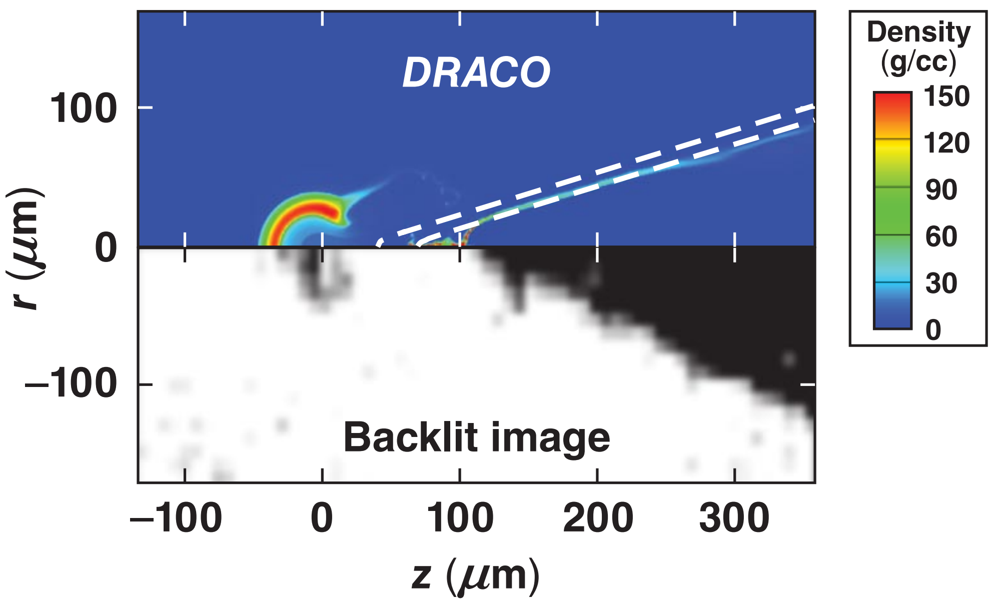
E17294

Outline

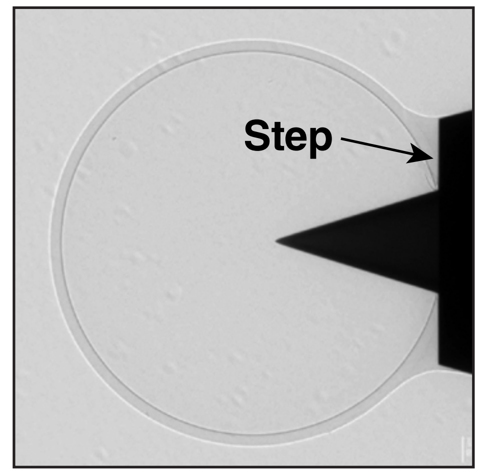
- Motivation
- Shock-ignition experiments
- Fast-ignitor-relevant experiments
  - fuel-assembly experiments with cone in shell targets show good performance and no early filling of the cone with plasma
  - a conversion efficiency from laser energy into hot electrons of ~20% was inferred using two independent experimental methods
- OMEGA EP Laser System

Cone-in-shell fuel-assembly experiments were performed on OMEGA*





Radiograph of target



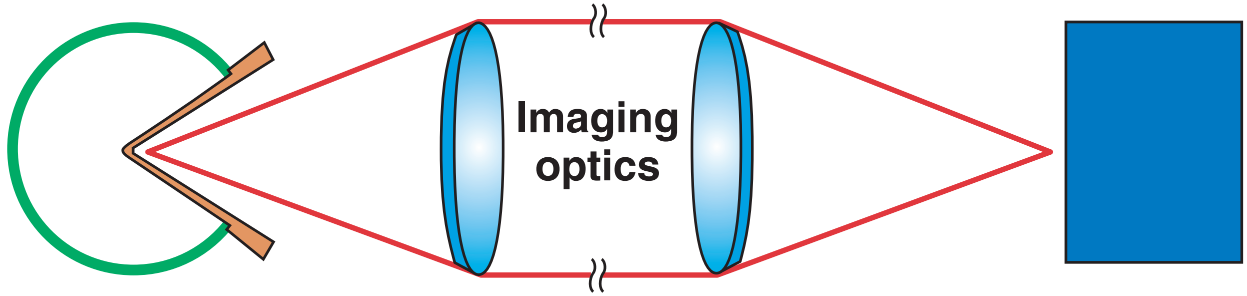
The measured areal density was >60% of the 1-D prediction for a full sphere.

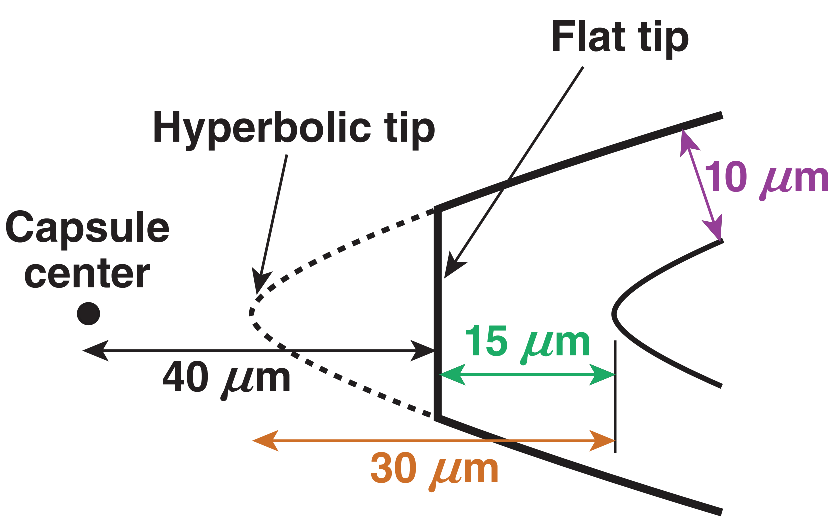
TC7487b

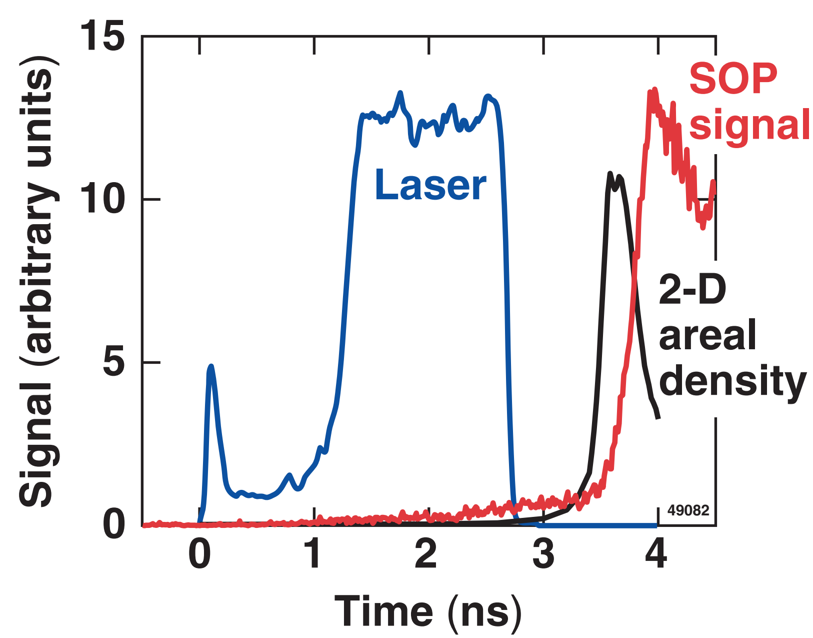
*C. Stoeckl, Phys. Plasmas 14, 112702 (2007).

Shock breakout is close to peak compression in the low-adiabat experiments with a 15-μm-thick cone tip

Streaked Optical Pyrometer (SOP)*





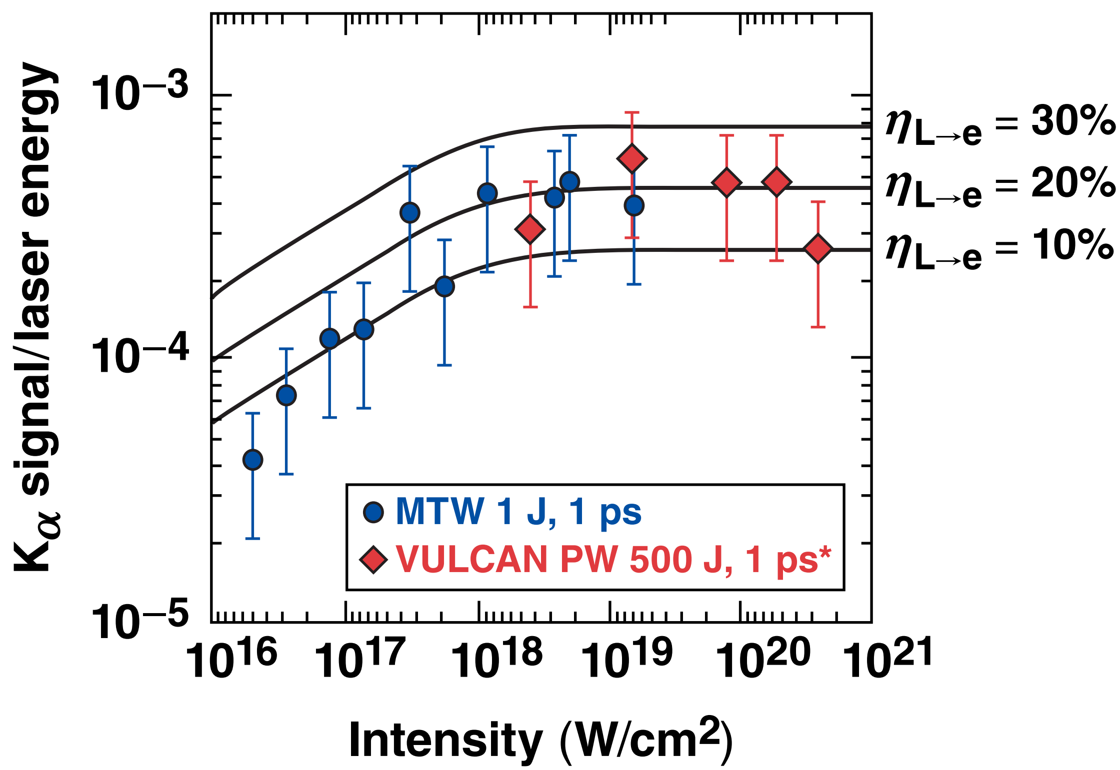


E17295

*J. A. Oertel, Rev. Sci. Inst. 70, 803 (1999).

A conversion efficiency of $\eta_{L \to e}$ = 20% into energetic electrons can be inferred from K_α yields

- K_α production is insensitive to fast-electron energy spectrum and range for $I > 10^{18}$ W/cm^2
- Cu targets: $500 \times 500 \times 20\ \mu m^3$

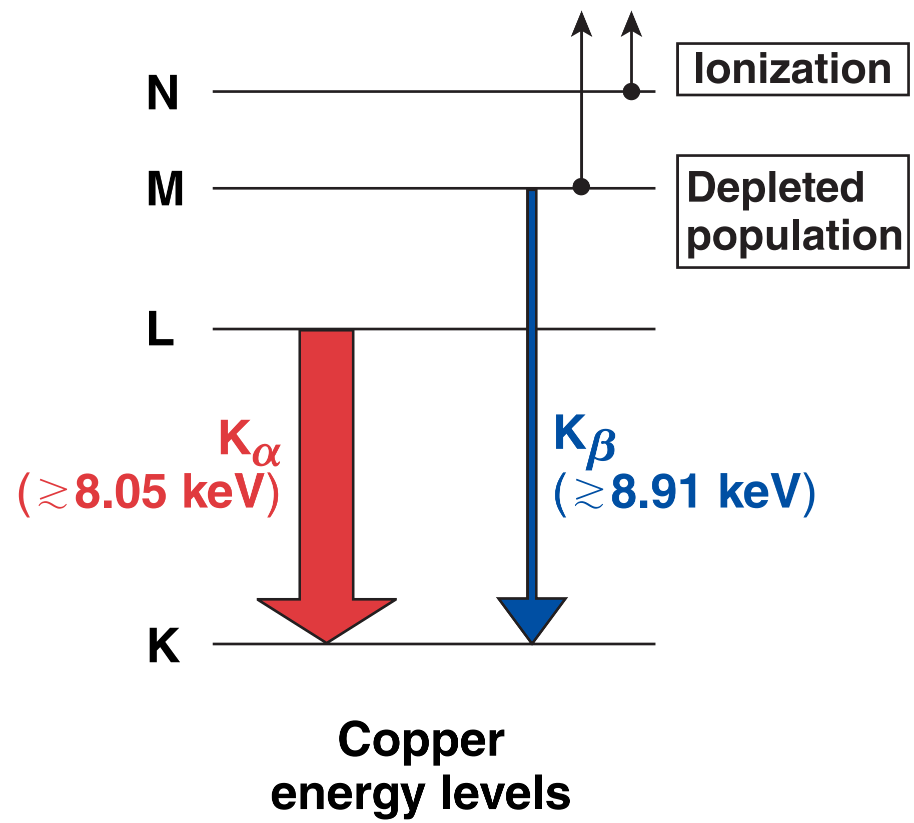


E16150b

*W. Theobald *et al.*, Phys. Plasmas 13, 043102 (2006).

Target bulk heating affects L→K and M→K electron transitions[1,2]

- Inelastic electron–electron collisions heat the target.
- Collisional ionization with thermal background plasma occurs.
- $T_e > 100$ eV causes significant M-shell depletion.
- Target heating is inferred from K_β/K_α.



[1] J. Myatt *et al.*, Phys. Plasmas 14, 056301 (2007).
[2] G. Gregori *et al.*, Contrib. Plasma Phys. 45, 284 (2005).

E16143b

A comparison of K_β/K_α to *LSP* calculations gives $\eta_{L\rightarrow e} \approx 20\%$ consistent with the K_α-yield measurements*

FSC

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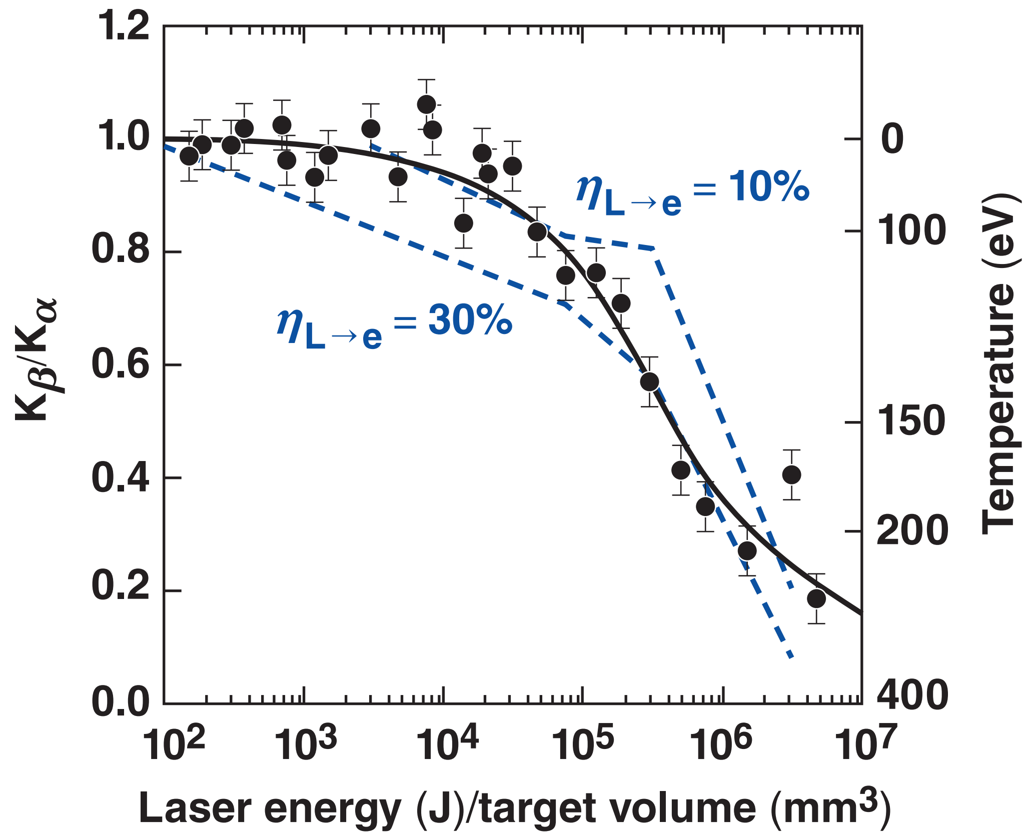
- **Provides a self-consistency check on $\eta_{L\rightarrow e}$**
- **Confirms that the dominant physics in the simple refluxing K_α-production model are correctly accounted for.**



Solid density targets are heated to temperatures greater than 200 eV with 5 J of laser energy.

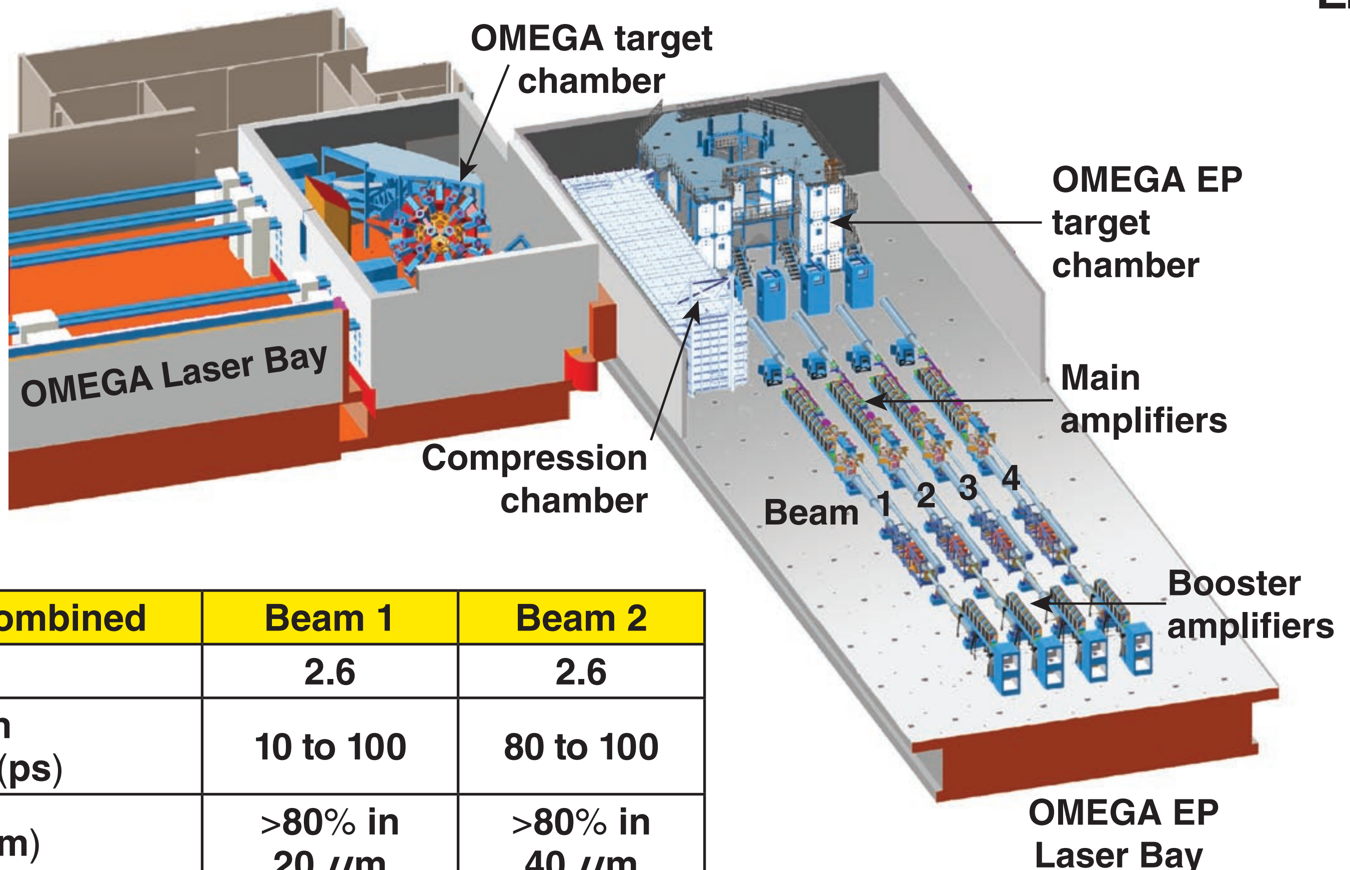
E16314b

*P. M. Nilson *et al.*, Phys. Plasmas 15, 056308 (2008).

Outline

- Motivation
- Shock-ignition experiments
- Fast-ignitor-relevant experiments
- **OMEGA EP Laser System**
  - OMEGA EP can provide up to 2.6 kJ in 10 ps and 2.6 kJ in 100 ps into the OMEGA target chamber for integrated FI experiments
  - Simulations of integrated FI experiments using OMEGA EP have shown core heating of up to 1 keV
  - LLE has the infrastructure in place to field cryogenic cone-in-shell targets

Short-pulse OMEGA EP beams can be directed either to OMEGA or to the new OMEGA EP target chamber

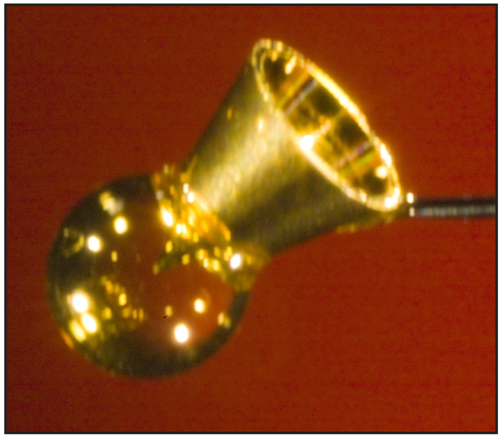


Short pulse combined	Beam 1	Beam 2
IR energy (kJ)	2.6	2.6
Pulse duration at full energy (ps)	10 to 100	80 to 100
Focusing (diam)	>80% in 20 μm	>80% in 40 μm
Intensity (W/cm^2)	3×10^{20}	2×10^{18}

In October 2008 OMEGA EP delivered 1.3 kJ in 10 ps to a target.

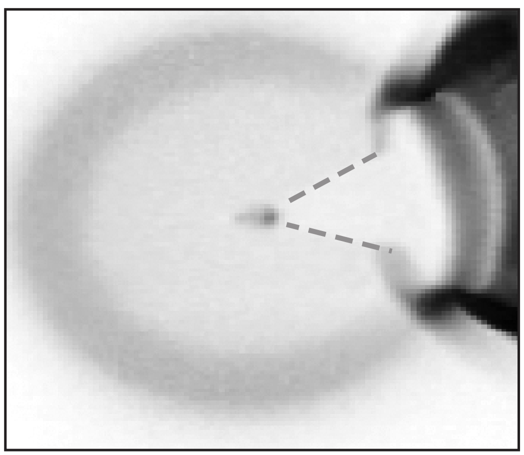
G6957u

Integrated FI experiments with cone-in-shell targets have started on OMEGA

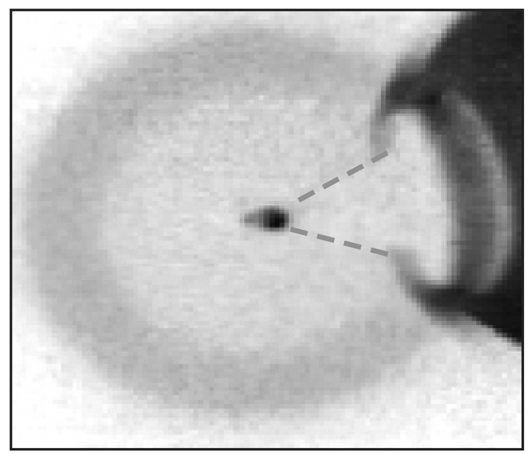


CD shell	~870-μm diam
Driver energy	~18 kJ
Short pulse	~1.3 kJ
Pulse duration	~10 ps
Focus	~40-μm diam

No short pulse



With short pulse



- **The hard x-rays produced by the short-pulse interaction saturate the current neutron detectors.**

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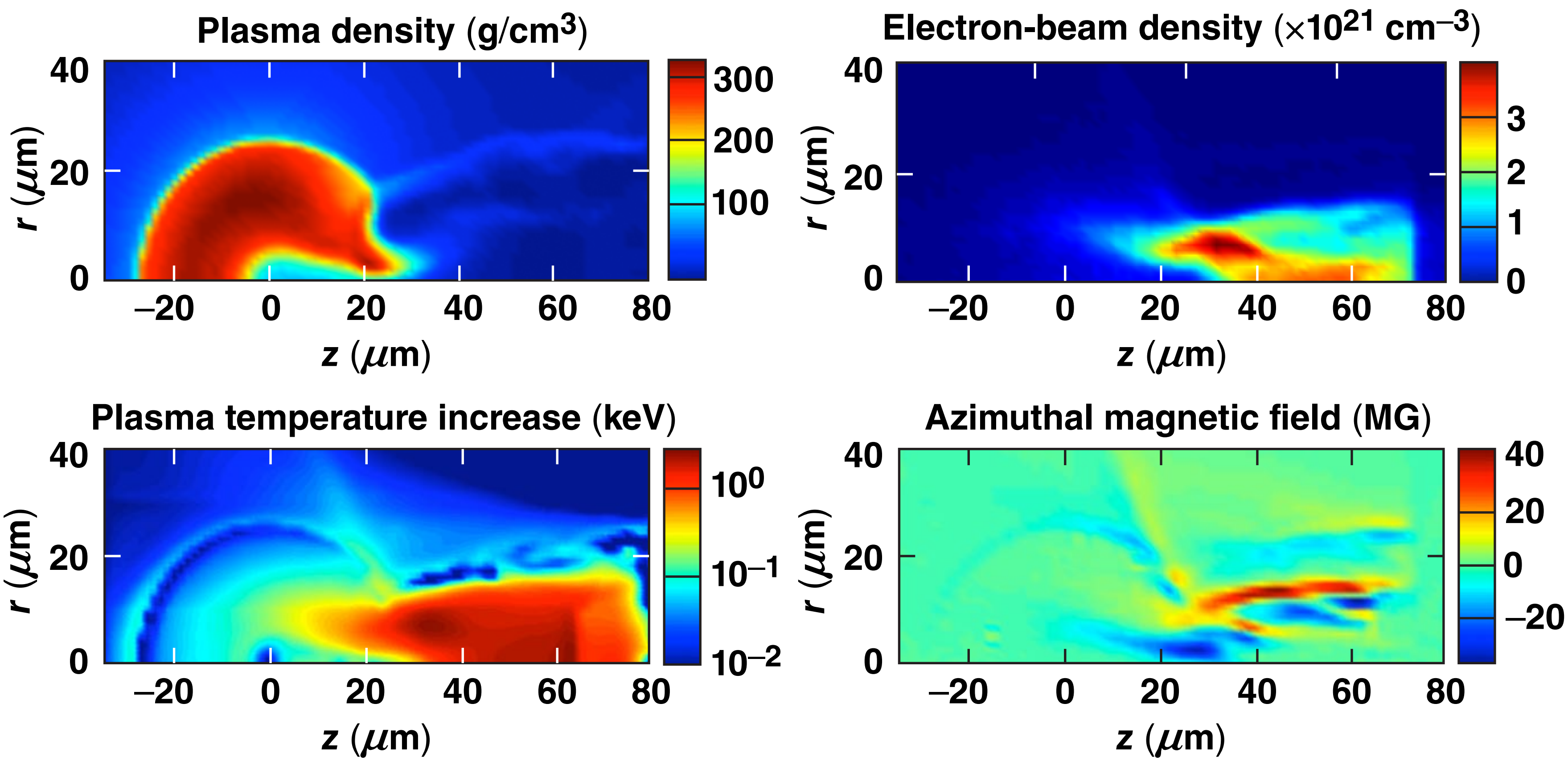
With 2.6 kJ of short-pulse energy the hot electrons are predicted to heat up the core by up to 1 keV*

Snapshots at $t = 6$ ps after the beginning of the e-beam



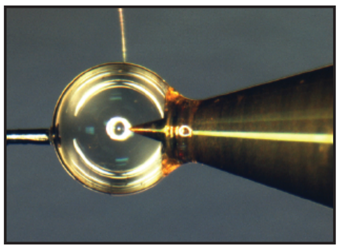
With hot electrons the neutron yield increases from 1.6×10^9 to 5×10^9.

E16811b

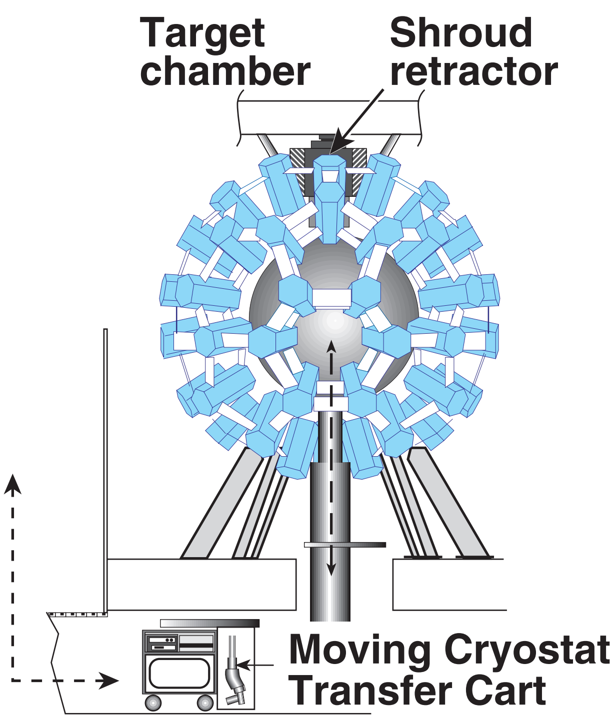
*A. A. Solodov (YI1.00002).

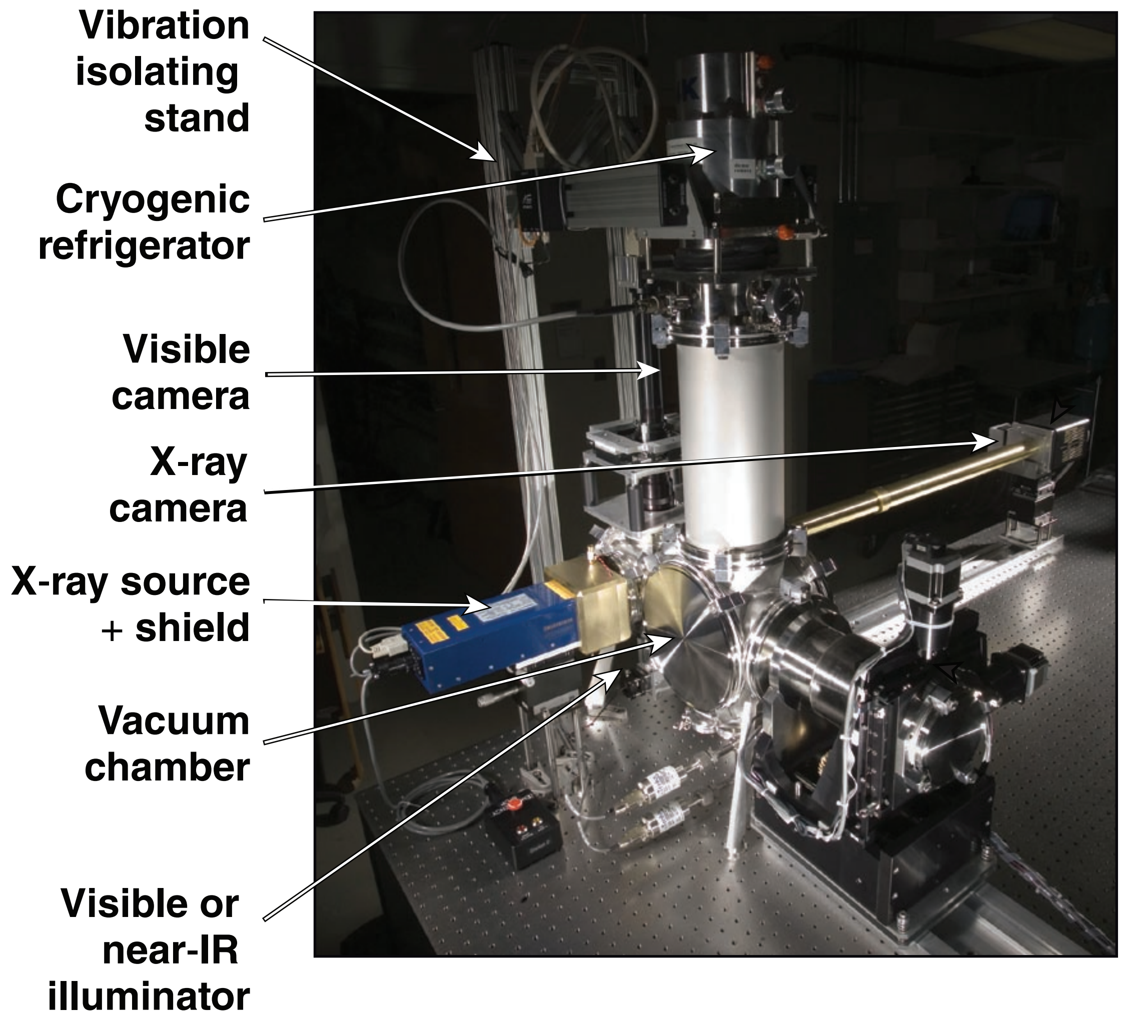
LLE has the infrastructure to field cryogenic DT-filled fast-ignitor targets

FSC UR LLE



Fill-tube-based FI cone-in-shell target





The cryogenic layering test stand

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Summary/Conclusions

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UR LLE

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[1] R. Betti et al., Phys. Rev. Lett. 98, 155001 (2007).
[2] M. Tabak et al., Phys. Plasmas 1, 1626 (1994).

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