HEDP Laboratory Astrophysics

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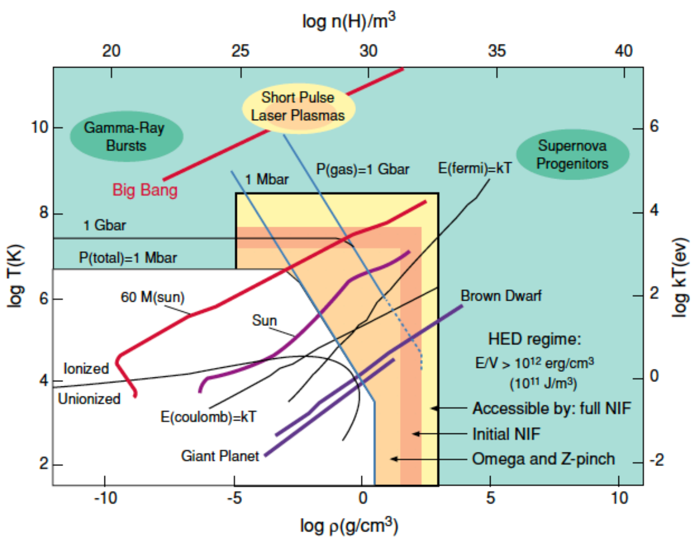
What is High-Energy-Density (HED) Plasma Physics?

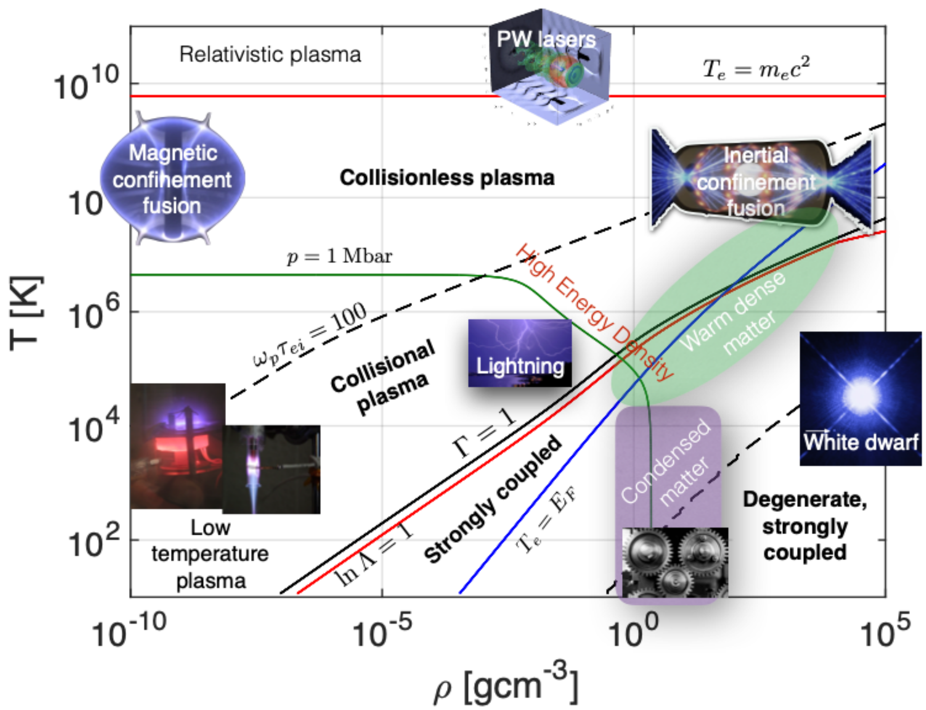
Systems with a pressure of over 1 million atmospheres (1 Mbar)
1 Mbar = 0.1 Tpascal = 10^{12} dynes/cm^2 = 10^6 atm



Frontiers in High Energy Density Physics:
The X-Games of Contemporary Science

What happens at such high pressures?
- **Materials become ionized**
- **Are generally dense plasmas**
- **Temperatures of over 100 million K**

How does this compare to other plasma?



Who studies HED plasmas and why?

National Nuclear Security Association

- **Science-based stockpile stewardship ensures a safe, secure, and effective nuclear stockpile**

Inertial Confinement Fusion Scientists and Engineers

- **Create a nuclear fusion reaction by heating and compressing a fuel target using lasers or pulsed power device**

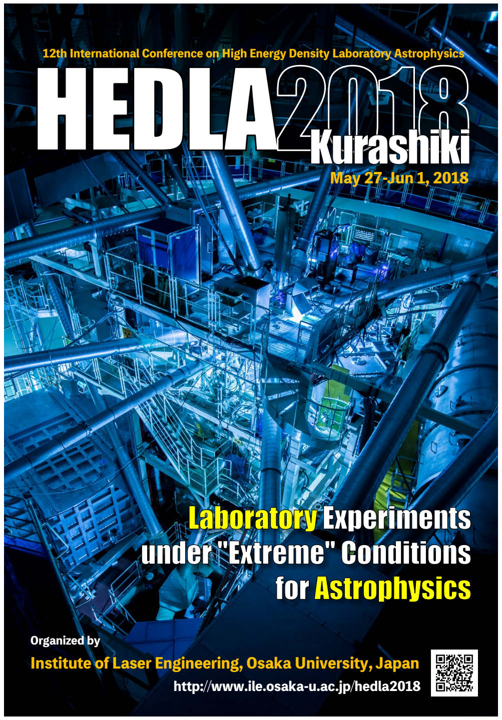
Astrophysicists

- **HEDP conditions and relevance found in SN explosions, SN remnants, accretion phenomena, reconnection, cosmic rays, and more**

It's fun!

- **Creating, observing, and modeling this extreme environment is challenging and rewarding**

HED Laboratory Astrophysics is a young, but growing field



- HEDLA started in 1996 focused on hydrodynamics
- Now includes planetary interiors, equation of state, atomic processes, radiation transport, photoionization, stellar opacity, magnetic reconnection, particle acceleration, collisionless plasmas, turbulent dynamos, nuclear astrophysics, pair plasmas…

How do I scale an astrophysical system to a laboratory experiment?*

1. Can both systems validly be described by the same equations?
2. Can the two systems have good Ryutov scaling?
3. Can the two systems have good scaling with regard to the dynamics of the process of interest?

*Adapted from High-Energy-Density Physics:
Foundations of Inertial Fusion and Experimental astrophysics
See also Ryutov et al. ApJ., 518, 821 (1999)

1. Can both systems validly be described by the same equations?

The single fluid Euler equations describe the conversation of mass, momentum, and energy

Let’s look at a more generalized forms of the single-fluid momentum equation

Are all those terms really important? There are just so many!

Let’s look at viscosity

Let’s look at viscosity

1. Can both systems validly be described by the same equations?

The single fluid Euler equations describe the conversation of mass, momentum, and energy

$$\frac{\partial \rho}{\partial \mathrm{t}} + \nabla \cdot \mathbf{u} = \mathbf{0}$$

$$\rho \frac{\partial \boldsymbol{u}}{\partial \mathrm{t}} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla \mathrm{P}$$

$$\frac{\partial P}{\partial \mathrm{t}} + \mathbf{u} \cdot \nabla \mathrm{P} = -\gamma \mathrm{P}\, \nabla \cdot \mathbf{u}$$

If the equations remain invariant under the following transformation,

then there is direct correspondence between the two systems

2. Can the two systems have good Ryutov scaling?

3. Can the two systems have good scaling with regard to the dynamics of the process of interest?

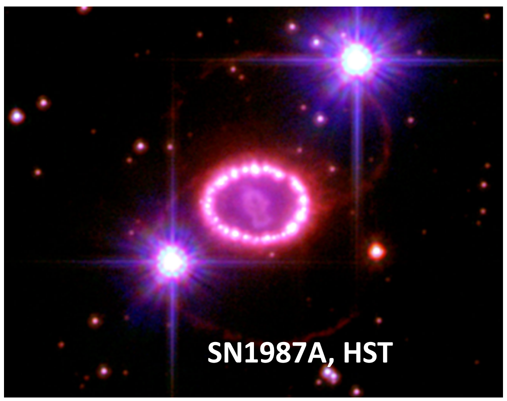
This is determined by the dimensionless numbers key to the specific astrophysical system

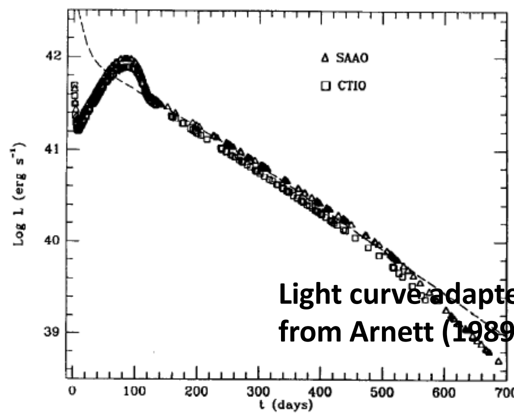
Now, an example

1. Can both systems validly be described by the same equations?
2. Can the two systems have good Ryutov scaling?
3. Can the two systems have good scaling with regard to the dynamics of the process of interest?

Scaled laboratory experiments must be motivated by a specific astrophysical process

Can hydrodynamic instabilities explain the light curve of SN1987A?





Light curve adapted from Arnett (1989)

Observations of ^{56}Co and ^{56}Ni were sooner than predicted and hydrodynamic mixing may explain the discrepancy

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The single fluid Euler equations describe the conversation of mass, momentum, and energy

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$$\frac{\partial P}{\partial \mathrm{t}} + \mathbf{u} \cdot \nabla \mathrm{P} = -\gamma \mathrm{P}\, \nabla \cdot \mathbf{u}$$

Additional terms for radiative or magnetized systems can also be included

If the equations remain invariant under the following transformation,

$$r_{\text{astro}} = a r_{\text{expt}} \qquad P_{\text{astro}} = c P_{\text{expt}}$$

$$\rho_{\text{astro}} = b \rho_{\text{expt}} \qquad t_{\text{astro}} = a \sqrt{\frac{b}{c}} t_{\text{expt}}$$

then there is direct correspondence between the two systems

For the specific example, this implies characteristic time and length scales

	SN1987A	Laboratory experiment
r	10^{11} cm	10^{2} μm
ρ	10^{-2} g/cc	1 g/cc
p	10 Mbar	1 Mbar
t	1000 s	10 ns

2. Can the two systems have good Ryutov scaling?

Spatial relations for velocity, pressure, and density must be the scaled

$$\mathbf{v}_{t=t_o} = \mathrm{v}'\mathbf{F}(r/h)$$

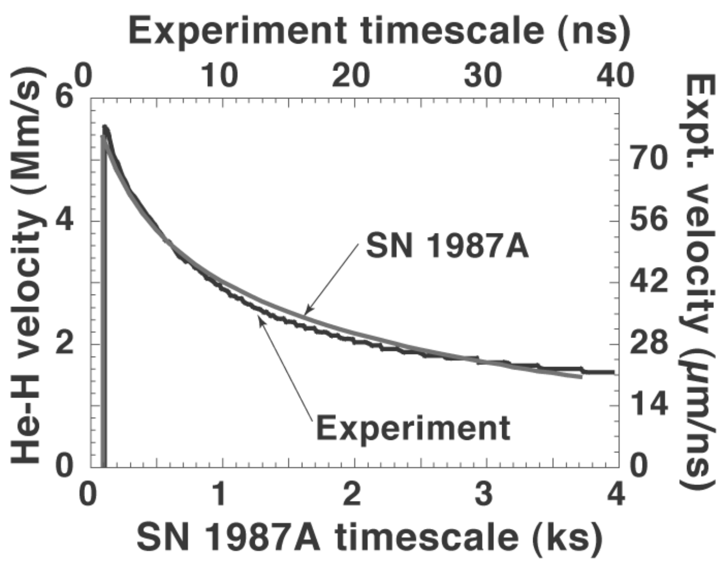
Where F(r/h), H(r/h), and G(r/h) are dimensionless functions

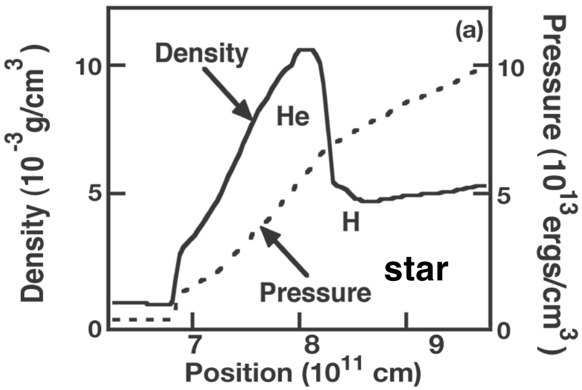
$$\rho_{t=t_o} = \rho' H(r/h)$$

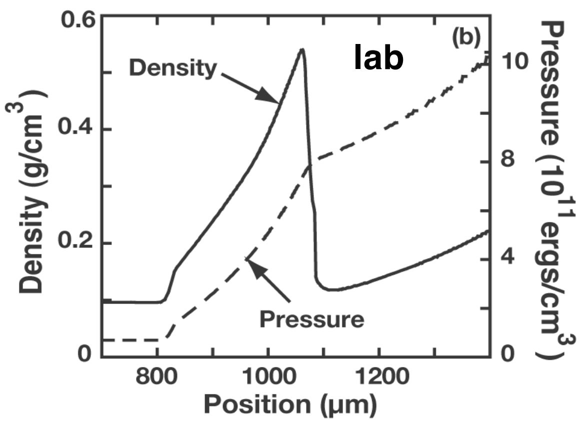
$$P_{t=t_o} = P' G(r/h)$$

This implies $Ry = v'\sqrt{\dfrac{\rho'}{P'}}$

1D Spatial profiles for SN1987A and laboratory experiment







3. Can the two systems have good scaling with regard to the dynamics of the process of interest?

This is determined by the dimensionless numbers key to the specific astrophysical system

For SN1987A this includes:

- **System must be highly collisional, $\lambda_c \ll r$**
- **Viscosity negligible, $Re \gg 1$**
- **Heat conduction negligible, $Pe \gg 1$**
- **Radiation flux negligible, $Pe_\gamma \gg 1$**

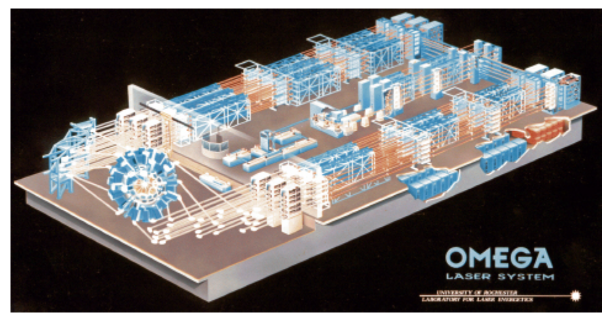
How *on Earth* do we create scaled astrophysical laboratory experiments?

- High-energy lasers
  - Omega Laser Facility, *U. of Rochester*
  - National Ignition Facility, *Lawrence Livermore Nat Lab*
  - ORION Laser Facility, *UK*
  - LMJ and LULI, *France*
  - SGII, *China*
- Pulsed Power machines
  - Z machine, *Sandia National Lab*
  - COBRA, *Cornell University*
  - MAIZE, *University of Michigan*
  - Magpie, *Imperial College*

Experiments are performed at Omega laser facility

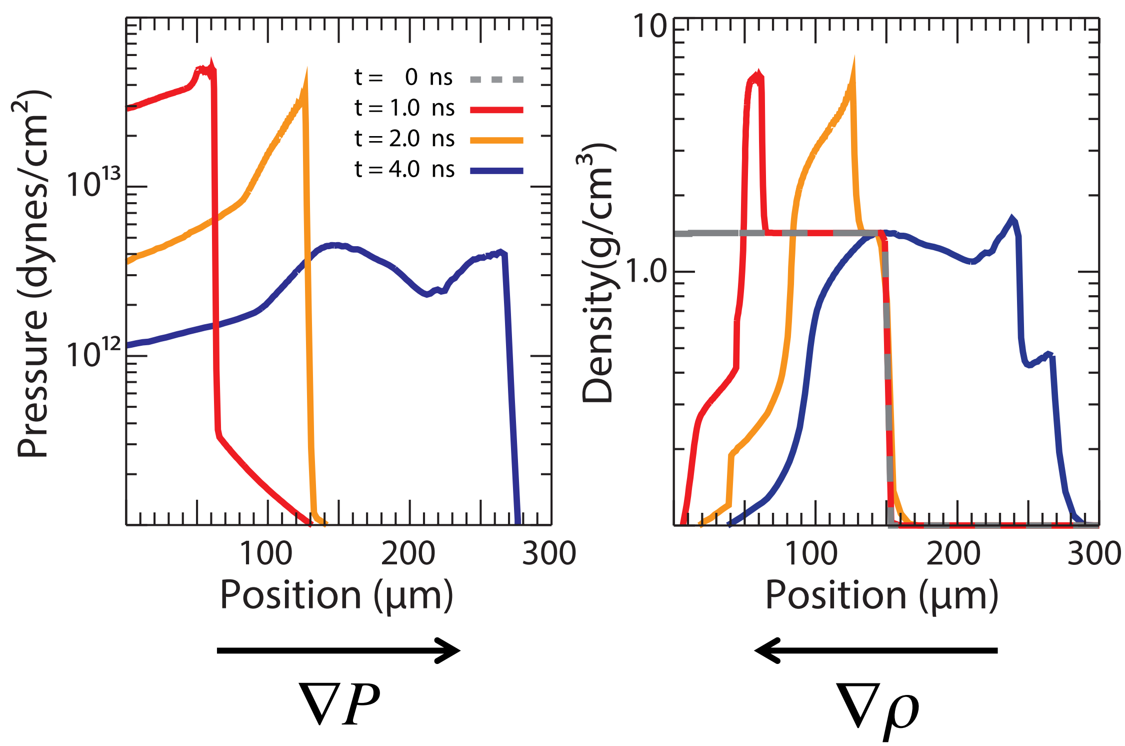
- Ten Omega Laser beams to drive shock
  - ~400 J each, ~4 kJ total energy
  - λ = .35 μm, UV light
  - 1 ns square pulse
- Produce intensity of about 10^{15} W/cm^2
- Pressure of ~40 Mbars or 40 million atmospheres

Inside the Omega target chamber



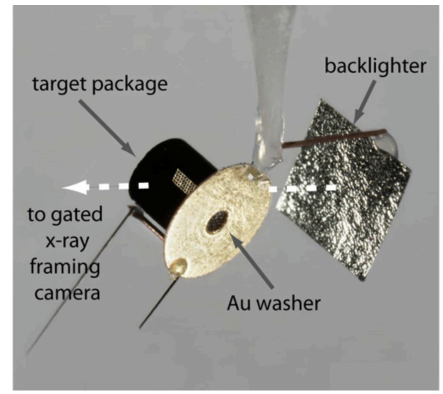
The Omega Laser System

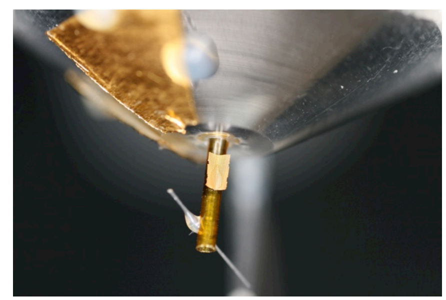
We create a RT unstable interface under HED conditions



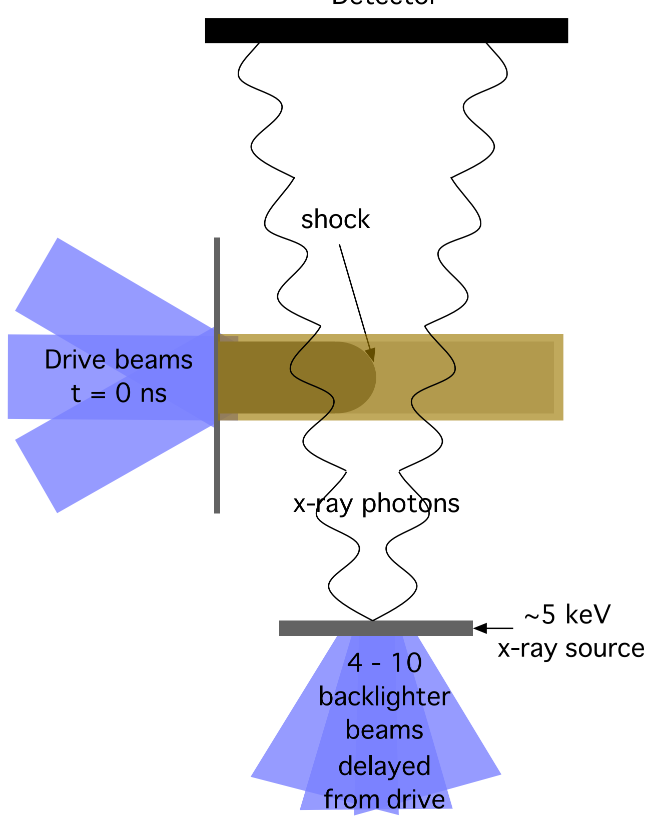
Key components of target for Rayleigh-Taylor experiment

- **150 µm plastic (1.41 g/cc)**
  - **Tracer strip material: $C_{500}H_{457}Br_{43}$ (1.42 g/cc)**
  - **Entire surface machined with seed perturbation**
- **2-3 mm carbon foam (50 - 400 mg/cc)**

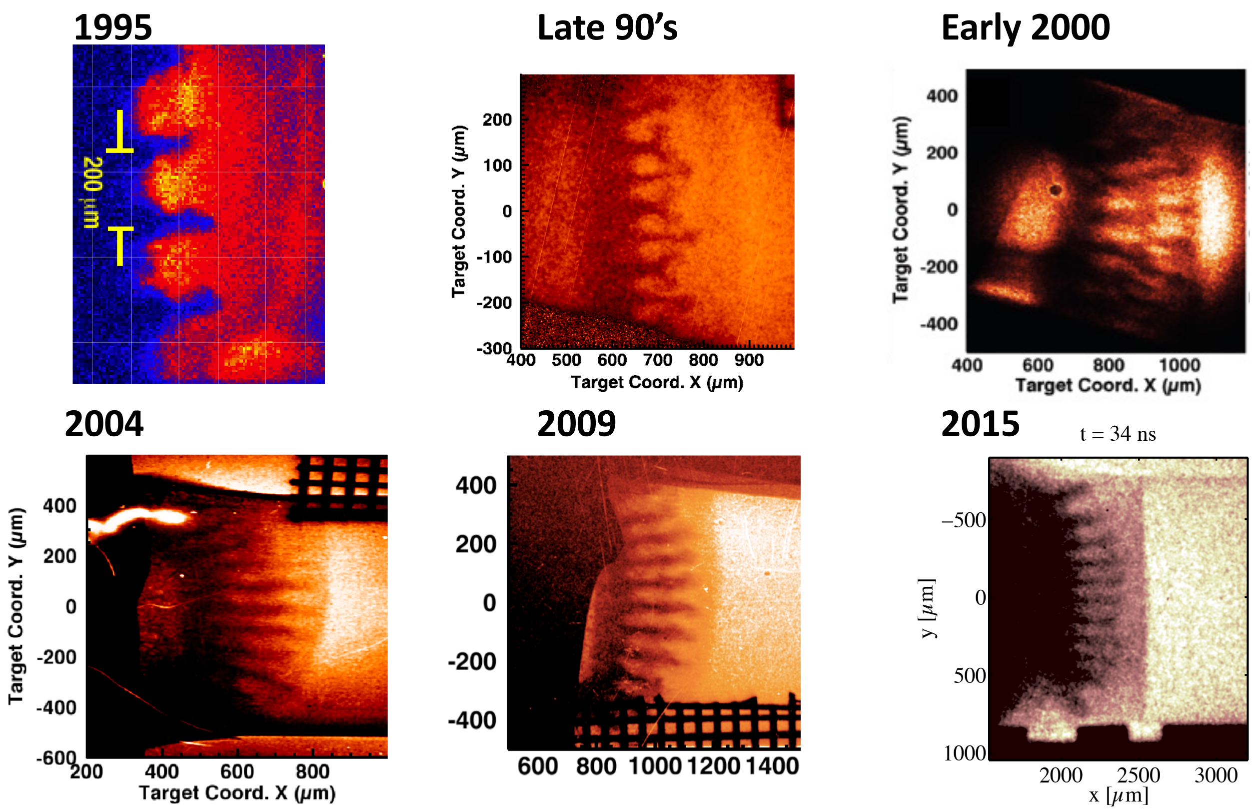




We use x-ray radiography to image the instability of the evolution



HED RT experiments have been performed on many laser facilities over the past 2 decades



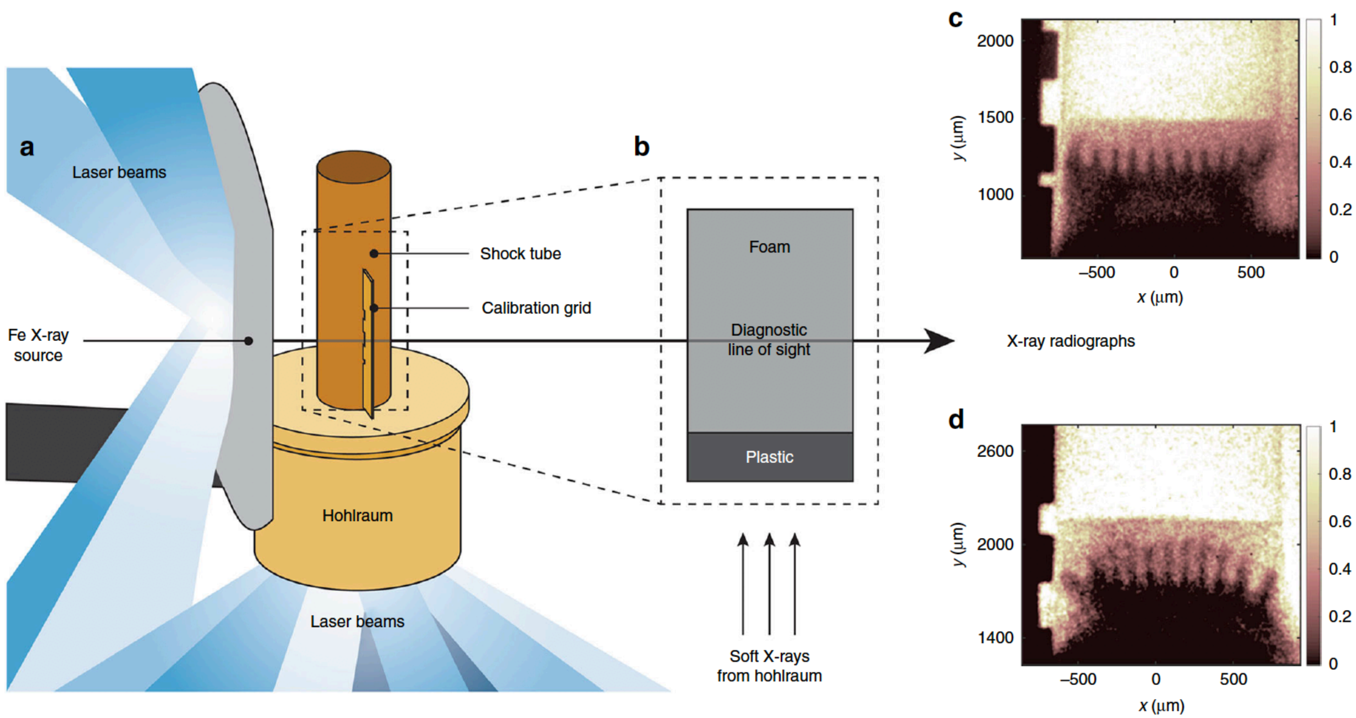
nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-03548-7 OPEN

How high energy fluxes may affect Rayleigh–Taylor instability growth in young supernova remnants

C.C. Kuranz[1], H.-S. Park[2], C.M. Huntington[2], A.R. Miles[2], B.A. Remington[2], T. Plewa[3], M.R. Trantham[1], H.F. Robey[2], D. Shvarts[4,5], A. Shimony[4,5], K. Raman[2], S. MacLaren[2], W.C. Wan[1,6], F.W. Doss[6], J. Kline[6], K.A. Flippo[6], G. Malamud[1,5], T.A. Handy[1], S. Prisbrey[2], C.M. Krauland[7], S.R. Klein[1], E.C. Harding[8], R. Wallace[2], M. J. Grosskopf[9], D.C. Marion[1], D. Kalantar[2], E. Giraldez[7] & R.P. Drake[1]



a
Laser beams
Fe X-ray
source
Shock tube
Calibration grid
Hohlraum
Laser beams
b
Foam
Diagnostic
line of sight
Plastic
Soft X-rays
from hohlraum
X-ray radiographs
c
d
y (µm)
x (µm)

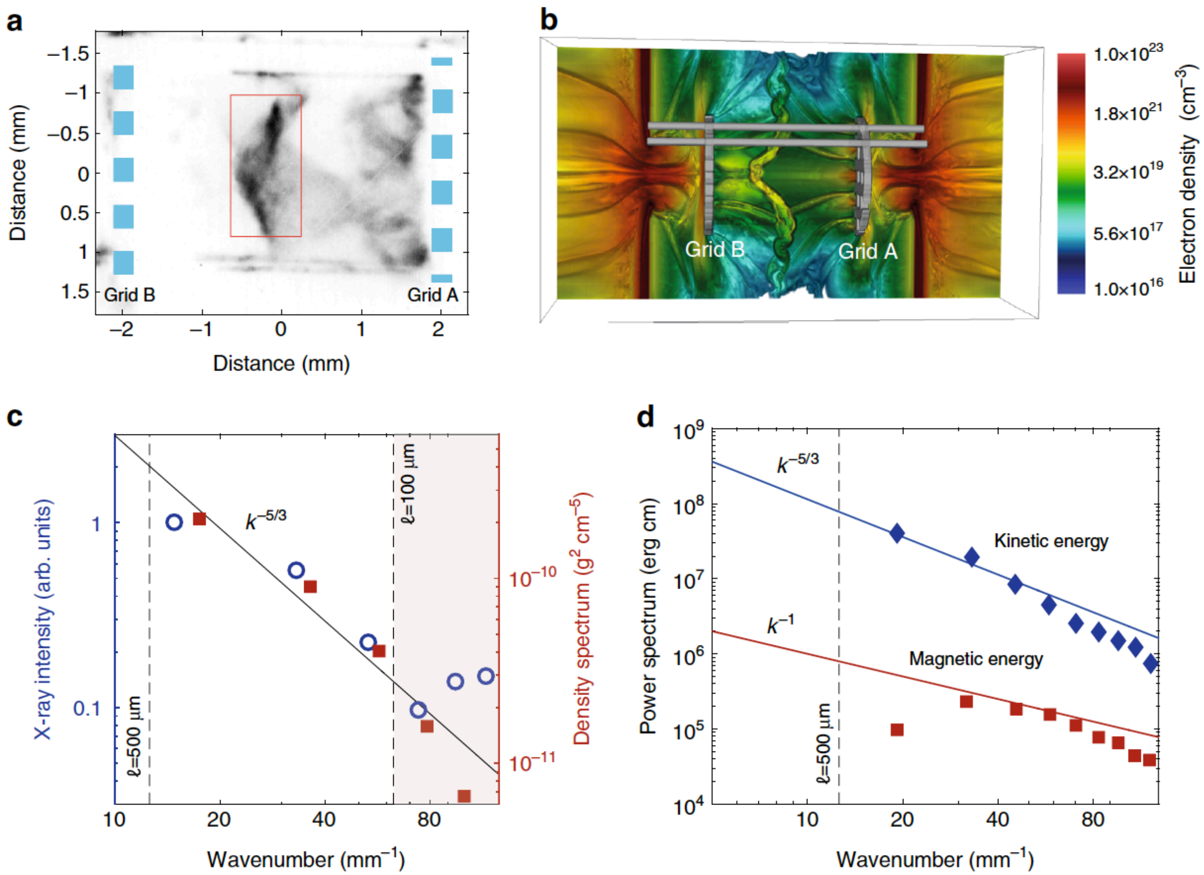
nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-02953-2 OPEN

Laboratory evidence of dynamo amplification of magnetic fields in a turbulent plasma

P. Tzeferacos[1,2], A. Rigby[1], A. F. A. Bott[1], A.R. Bell[1], R. Bingham[3,4], A. Casner[5], F. Cattaneo[2], E.M. Churazov[6,7], J. Emig[8], F. Fiuza[9], C.B. Forest[10], J. Foster[11], C. Graziani[2], J. Katz[12], M. Koenig[13], C.-K. Li[14], J. Meinecke[1], R. Petrasso[14], H.-S. Park[8], B.A. Remington[8], J.S. Ross[8], D. Ryu[15], D. Ryutov[8], T.G. White[1], B. Reville[16], F. Miniati[17], A.A. Schekochihin[1], D.Q. Lamb[2], D.H. Froula[12] & G. Gregori[1,2]

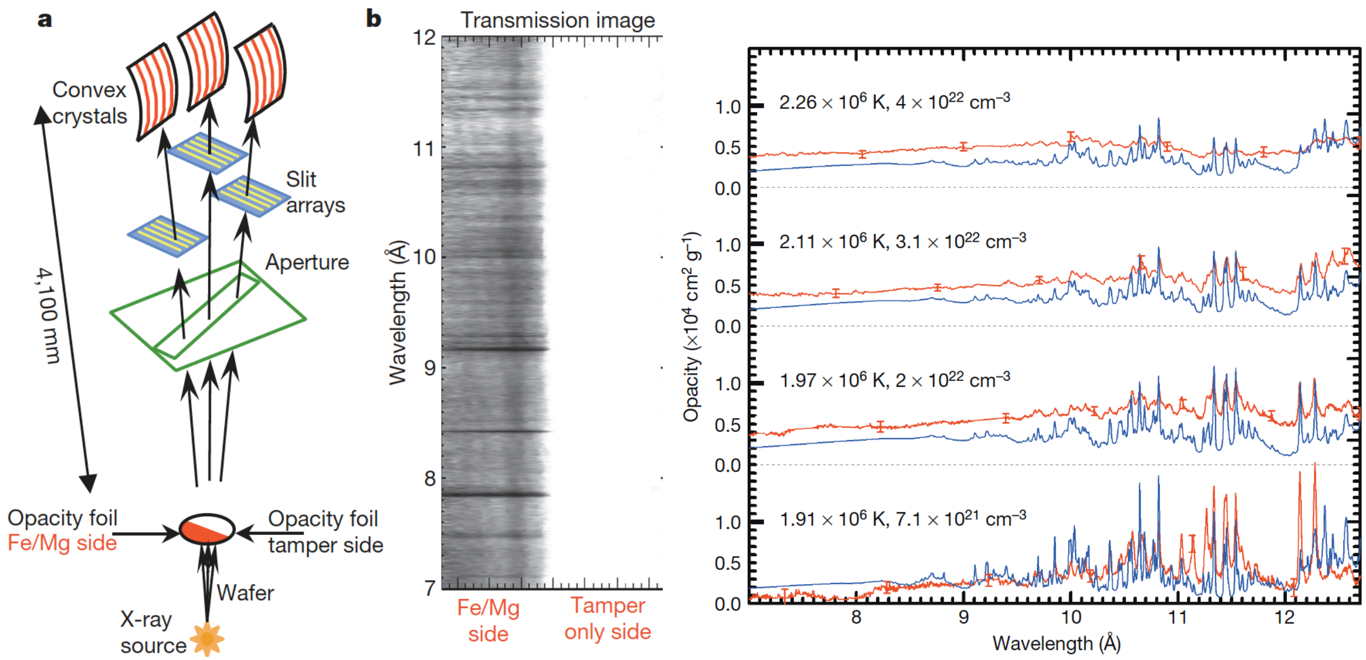

a
Distance (mm)
Distance (mm)
Grid B
Grid A
b
Grid B
Grid A
1.0x10^23
1.8x10^21
3.2x10^19
5.6x10^17
1.0x10^16
Electron density (cm^-3)
c
X-ray intensity (arb. units)
Density spectrum (g^2 cm^-5)
k^-5/3
ℓ=500 μm
ℓ=100 μm
Wavenumber (mm^-1)
d
Power spectrum (erg cm)
k^-5/3
k^-1
Kinetic energy
Magnetic energy
ℓ=500 μm
Wavenumber (mm^-1)

LETTER

doi:10.1038/nature14048

A higher-than-predicted measurement of iron opacity at solar interior temperatures

J. E. Bailey[1], T. Nagayama[1], G. P. Loisel[1], G. A. Rochau[1], C. Blancard[2], J. Colgan[3], Ph. Cosse[2], G. Faussurier[2], C. J. Fontes[3], F. Gilleron[2], I. Golovkin[4], S. B. Hansen[1], C. A. Iglesias[5], D. P. Kilcrease[3], J. J. MacFarlane[4], R. C. Mancini[6], S. N. Nahar[7], C. Orban[7], J.-C. Pain[2], A. K. Pradhan[7], M. Sherrill[3] & B. G. Wilson[5]



a
Convex crystals
Slit arrays
Aperture
4,100 mm
Opacity foil Fe/Mg side
Opacity foil tamper side
Wafer
X-ray source
b
Transmission image
Wavelength (Å)
Fe/Mg side
Tamper only side
2.26 × 10^6 K, 4 × 10^22 cm^-3
2.11 × 10^6 K, 3.1 × 10^22 cm^-3
1.97 × 10^6 K, 2 × 10^22 cm^-3
1.91 × 10^6 K, 7.1 × 10^21 cm^-3
Opacity (×10^4 cm^2 g^-1)
Wavelength (Å)

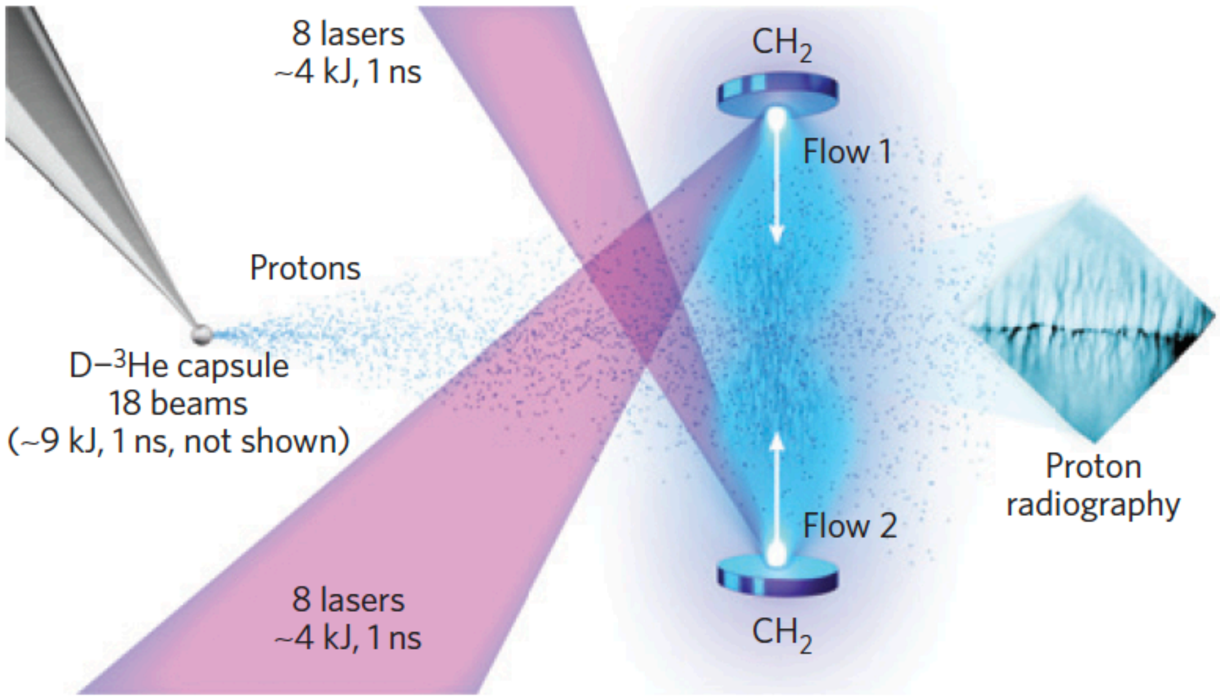
nature physics

LETTERS

PUBLISHED ONLINE: 19 JANUARY 2015 | DOI: 10.1038/NPHYS3178

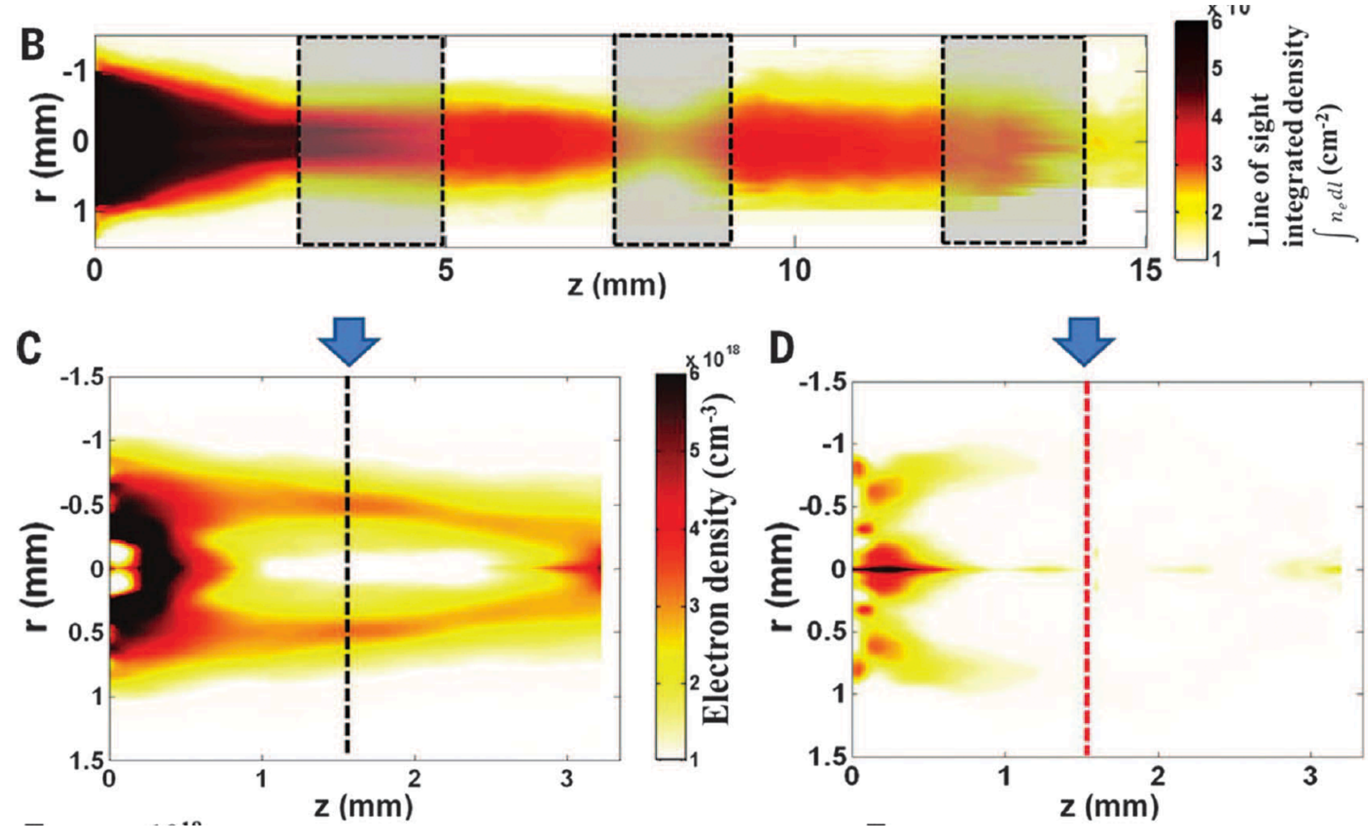
Observation of magnetic field generation via the Weibel instability in interpenetrating plasma flows

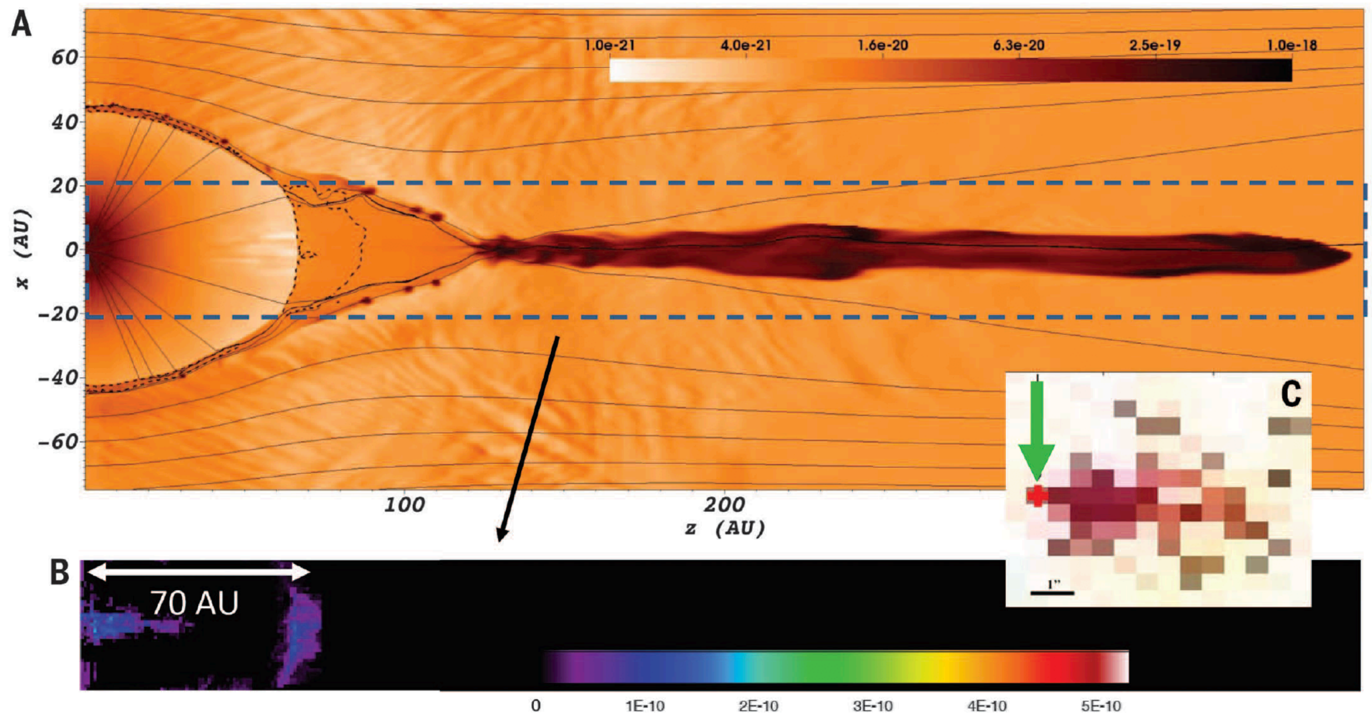
C. M. Huntington[1]*, F. Fiuza[1], J. S. Ross[1], A. B. Zylstra[2], R. P. Drake[3], D. H. Froula[4], G. Gregori[5], N. L. Kugland[6], C. C. Kuranz[3], M. C. Levy[1], C. K. Li[2], J. Meinecke[5], T. Morita[7], R. Petrasso[2], C. Plechaty[1], B. A. Remington[1], D. D. Ryutov[1], Y. Sakawa[7], A. Spitkovsky[8], H. Takabe[7] and H.-S. Park[1]


8 lasers
~4 kJ, 1 ns
CH_2
Flow 1
Protons
$D-^3He$ capsule
18 beams
(~9 kJ, 1 ns, not shown)
Proton
radiography
Flow 2
8 lasers
~4 kJ, 1 ns
CH_2

Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field

B. Albertazzi *et al.*
Science **346**, 325 (2014);
DOI: 10.1126/science.1259694


B
r (mm)
z (mm)
Line of sight integrated density $\int n_e dl$ (cm^{-2})
C
r (mm)
z (mm)
Electron density (cm^{-3})
x 10^{18}
D
r (mm)
z (mm)



A
60
40
20
0
-20
-40
-60
x (AU)
100
200
z (AU)
1.0e-21
4.0e-21
1.6e-20
6.3e-20
2.5e-19
1.0e-18
C
1"
B
70 AU
0
1E-10
2E-10
3E-10
4E-10
5E-10

Additional HEDLA Work

"Two-dimensional blast-wave-driven Rayleigh Taylor instability: Experiment and Simulation," Kuranz et al. *Astrophysical Journal*, 2009

"Laboratory evidence of dynamo amplification of magnetic fields in a turbulent plasma," P. Tzeferacos et al. *Nature Communications* 2018

"A higher-than-predicted measurement of iron opacity at solar interior temperatures," J. Bailey et al. *Nature Letters,* 2015

"How high energy fluxes may affect Rayleigh-Taylor instability growth in young supernova remnants, " Kuranz et al. *Nature Communications,* 2018

"Observation of magnetic field generation via the Weibel instability in interpenetrating plasma flows," Huntington et al., *Nature Physics,* 2015

"Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field," *Science*, 2014

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We have Low Temperature plasmas, plasma and laser accelerators, plasma propulsion, high-energy-density plasmas, space and astrophysical plasmas, plasma transport, high power microwaves, pulsed power experiments, laser experiments, modeling and simulation, biomedical applications, plasma and laser diagnostics, environmental and energy applications