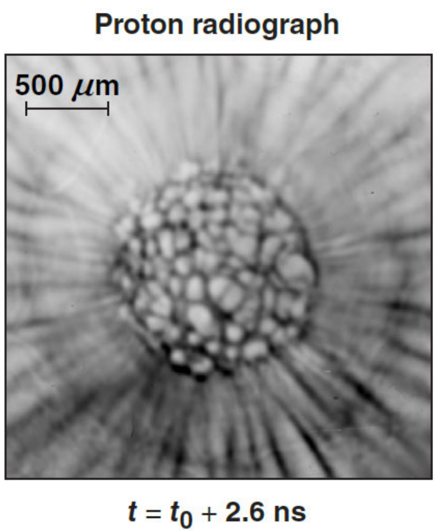
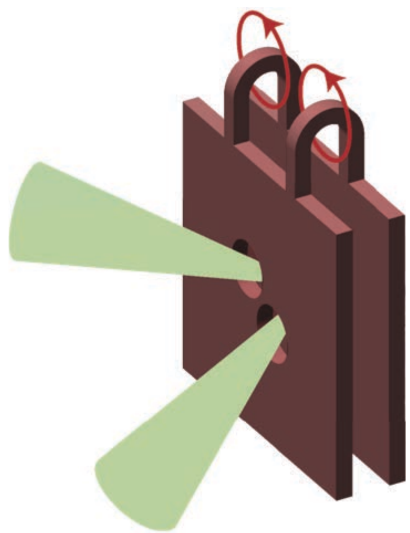
Dynamics of Magnetic Fields in Laser-Driven High-Energy-Density Plasmas for Fusion and Astrophysics

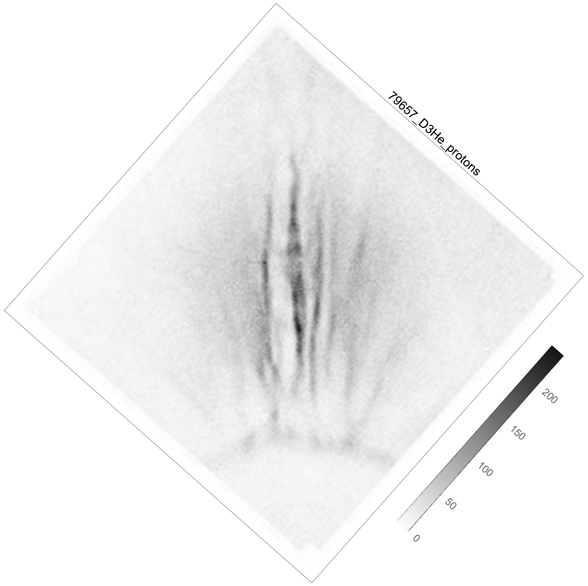
Rayleigh-Taylor Instability



Magnetic Reconnection



Magnetized Jet



Lan Gao
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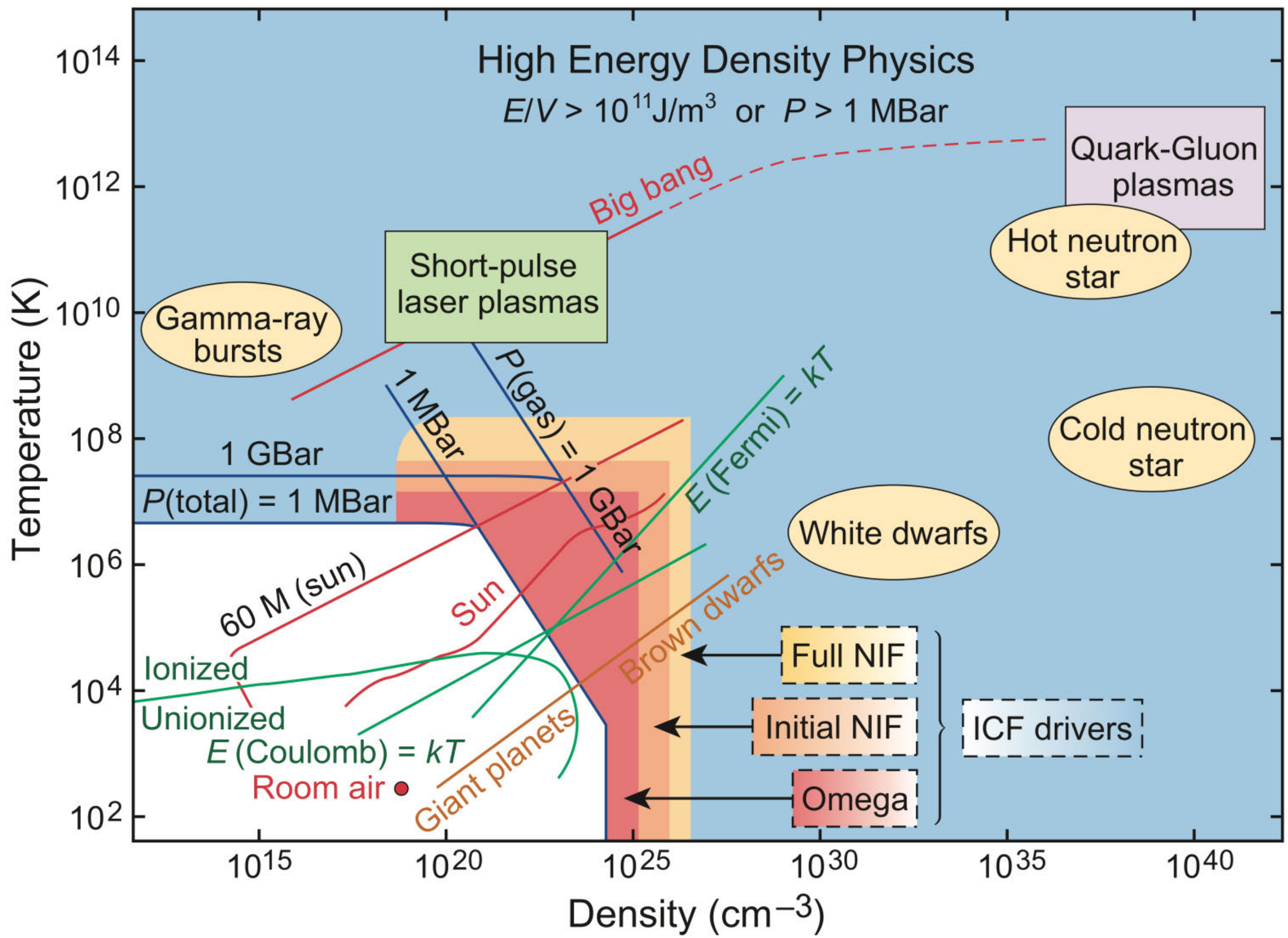
PPPL SULI program
August 3, 2017

Outline

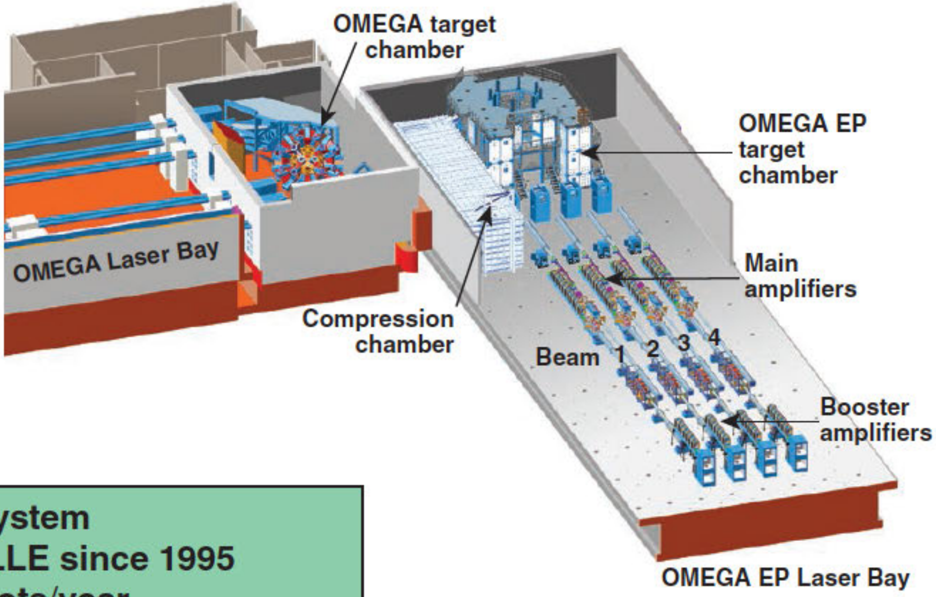
- Introduction
  - High energy density (HED) physics
  - Laser-driven HED systems
  - Rayleigh-Taylor (RT) instability
- Nonlinear RT instability experiments
  - Magnetic field generation and evolution
- Ongoing and future work relevant to astrophysics
  - Dynamo
  - Magnetic reconnection
  - Magnetized jet
- Advanced diagnostics development for HED systems
  - High-resolution x-ray spectrometer
- Summary and conclusions

High energy density (HED) physics concerns the study of matter at high densities and extreme temperatures*



* ***Frontiers in high energy density physics : The X-games of contemporary science.*** **(The National Academies Press, Washington, DC, 2003).**

Laboratory for laser energetics (LLE) at University of Rochester operates two of the world's largest lasers for HED physics research



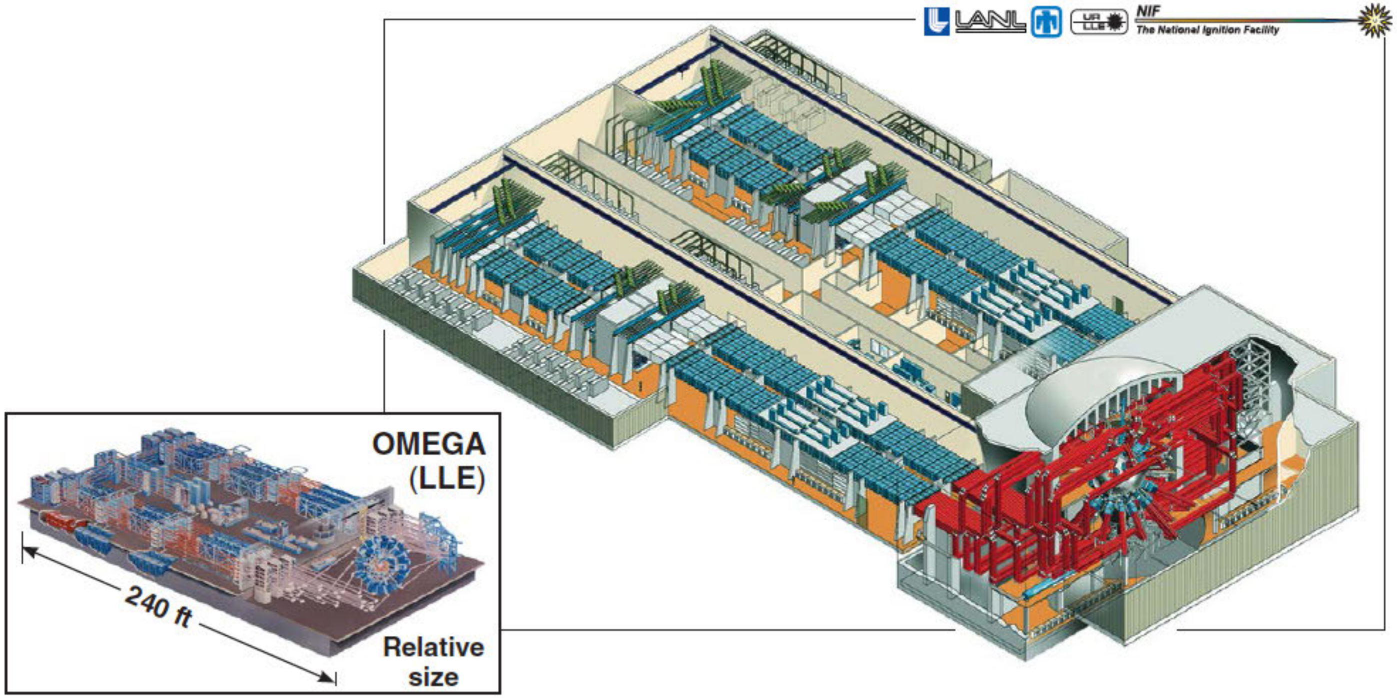
OMEGA Laser System
- Operating at LLE since 1995
- Up to 1500 shots/year
- Fully instrumented
- 60 beams
- >30-kJ UV on target
- 1% to 2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

More than half of OMEGA's shots are for external users.

OMEGA EP Laser System
- Completed 25 April 2008
- Four NIF-like beamlines; 6.5-kJ UV (10 ns)
- Two beams can be high-energy petawatt
  - 2.6-kJ IR in 10 ps
  - can propagate to the OMEGA or OMEGA EP target chamber

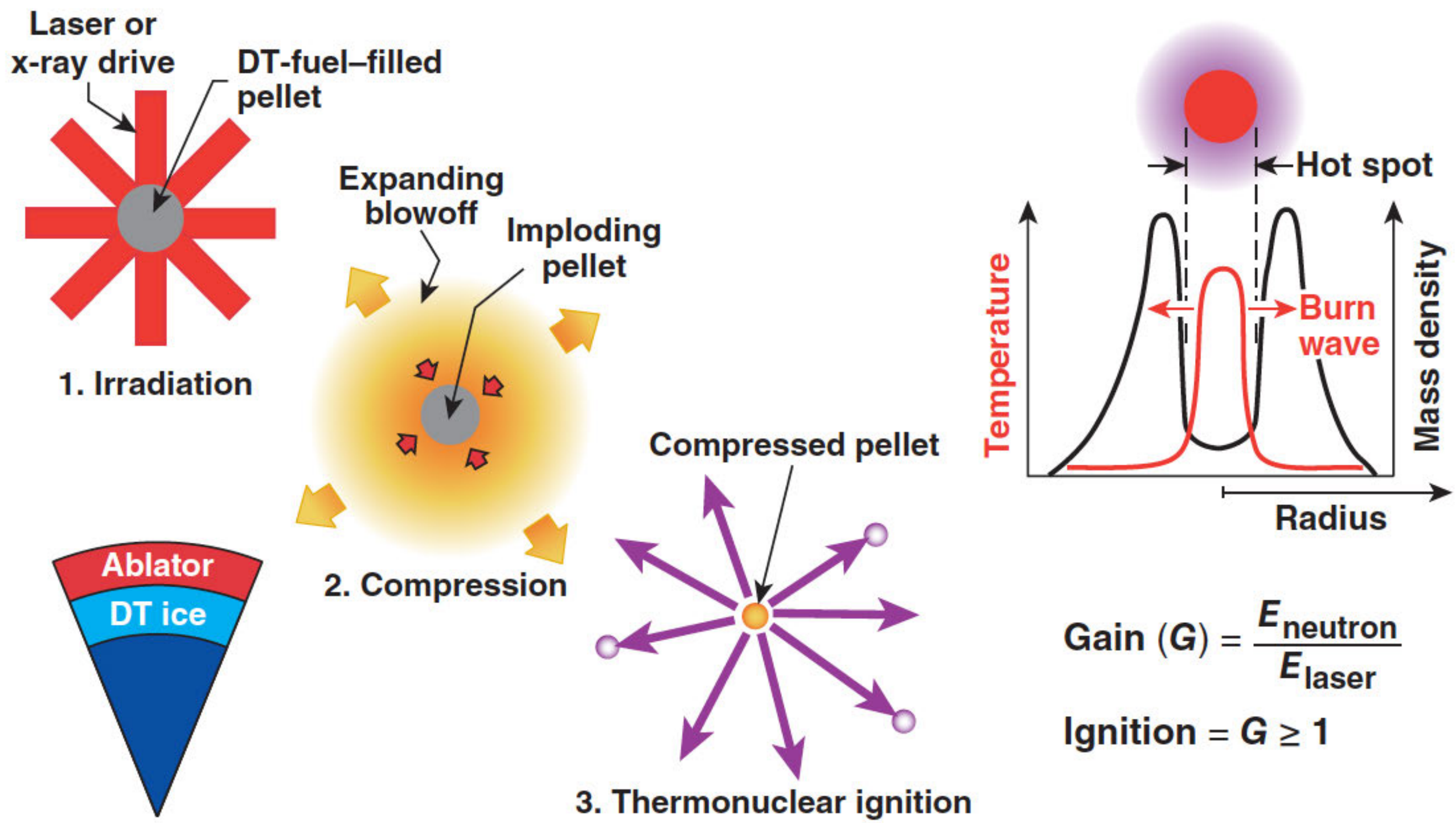
The National Ignition Facility (NIF) at LLNL aims at demonstrating fusion ignition

- **The NIF is a 1.8-MJ laser system (60× OMEGA's energy); NIF is a $3.5 billion facility completed in 2009**
- **The NIF is performing experiments with the goal of achieving ignition**



The achievement of ignition—a national "grand challenge"—on the NIF will change the fusion landscape.

Ablation is used to generate the extreme pressures required to compress a fusion capsule to ignition



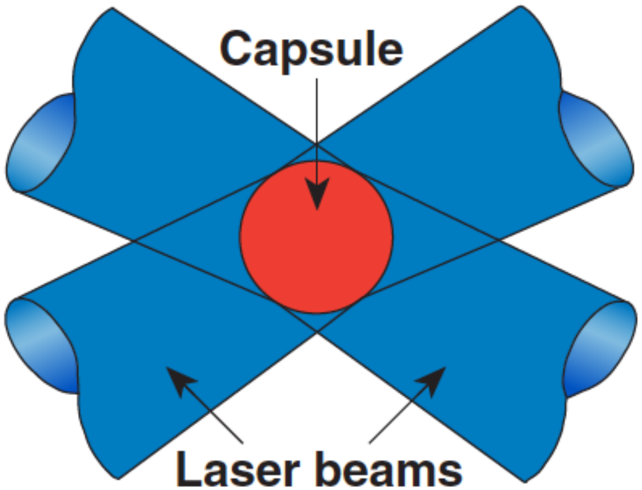
$$\text{Gain } (G) = \frac{E_{\text{neutron}}}{E_{\text{laser}}}$$

$$\text{Ignition} = G \geq 1$$

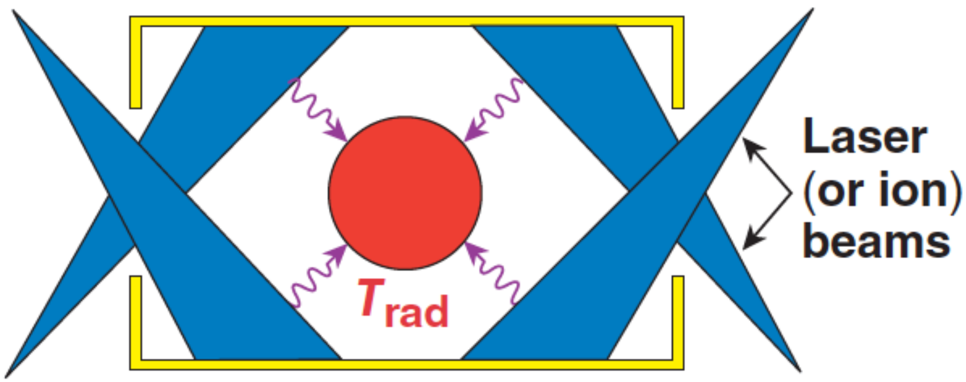
"Hot-spot" ignition requires the core temperature to be at least 5 keV and the core fuel areal density to exceed ~300 mg/cm^2.

Both direct and indirect (x-ray) drive are being used to implode the inertial confinement fusion capsules

Direct-drive target



X-ray-drive target



Hohlraum using
a cylindrical high-Z case
T_{rad} is the x-ray temperature

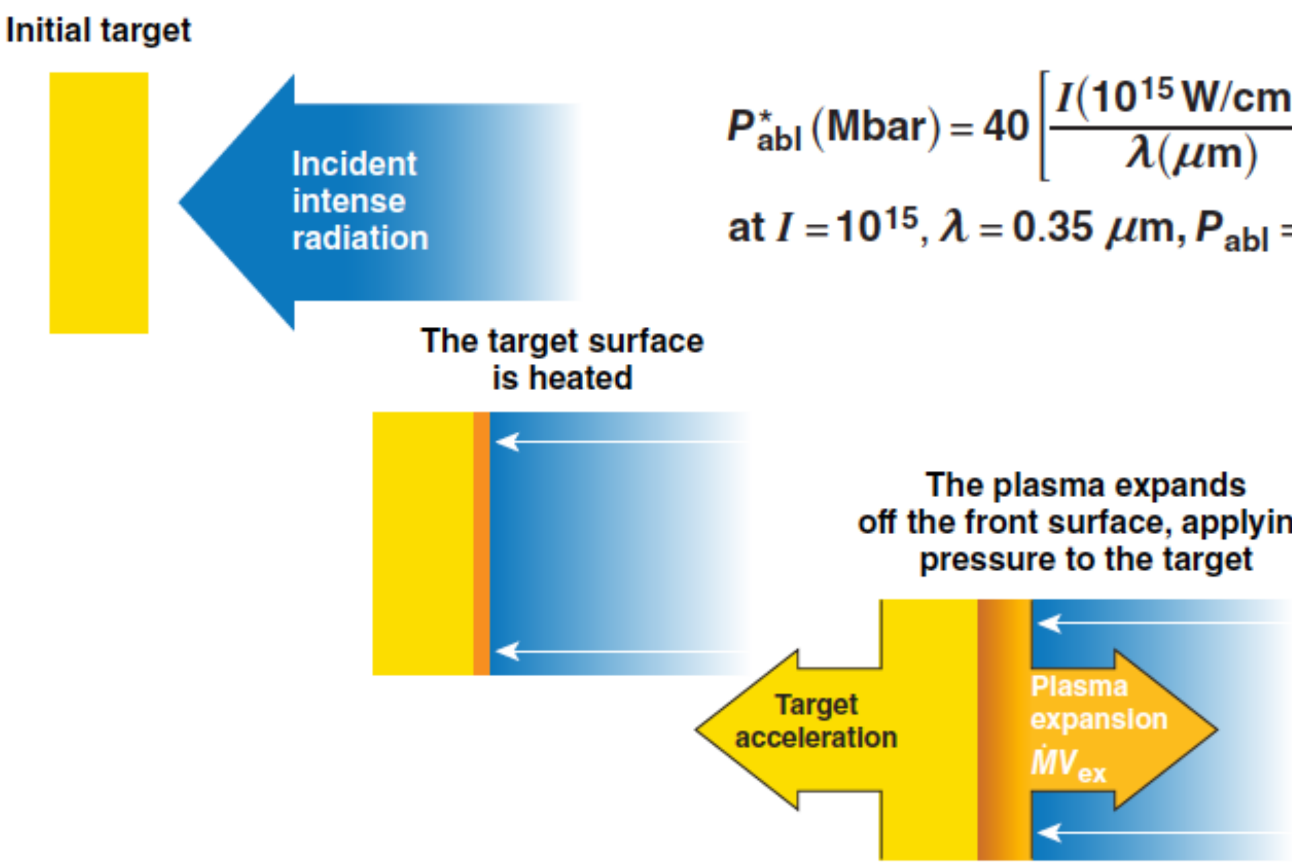
Key physics issues

- Energy coupling
- Drive uniformity
- Hydrodynamic instabilities
- Compressibility

Intense lasers create HED conditions in the laboratory through ablation

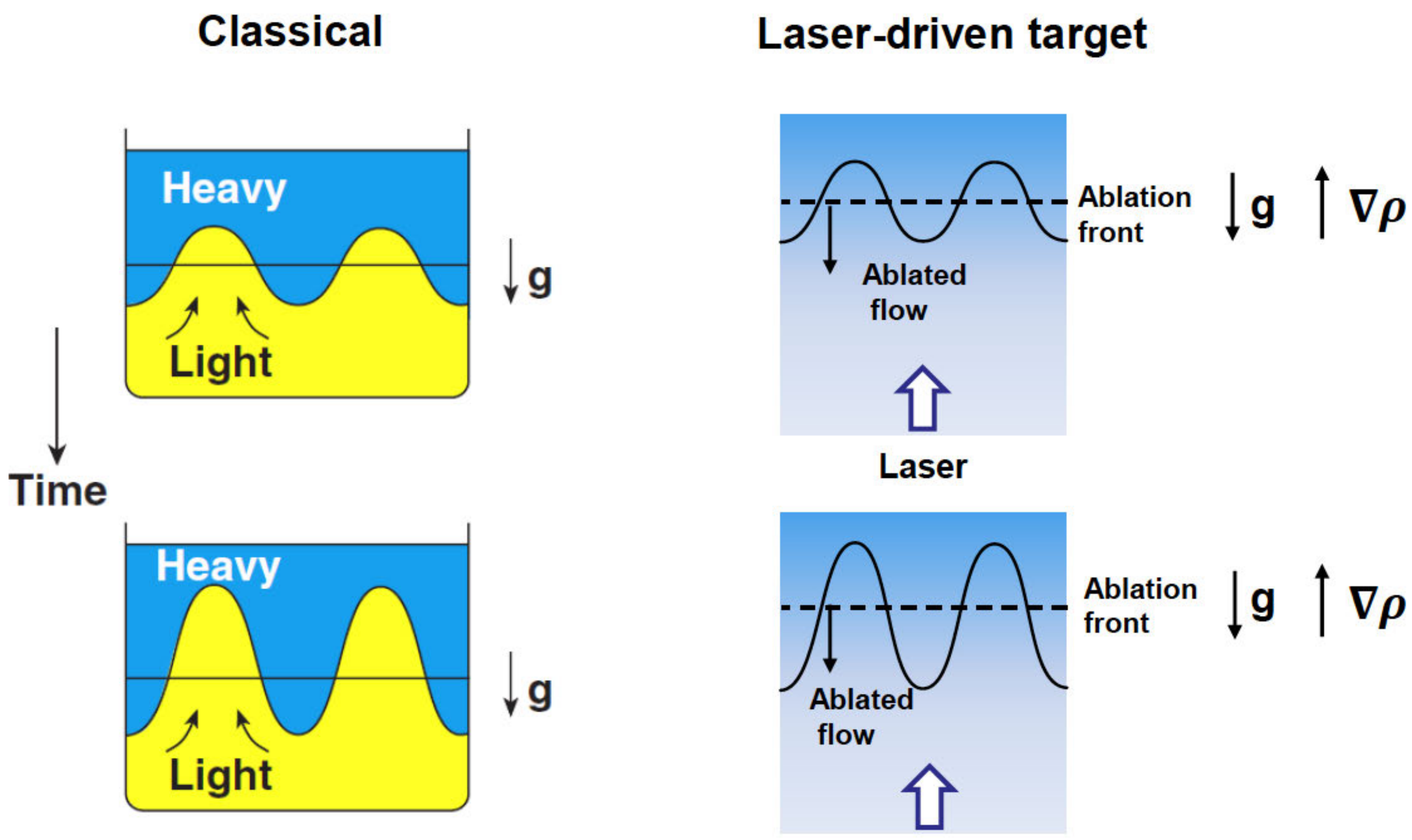
$$P^{*}_{abl}\,(\text{Mbar}) = 40\left[\frac{I(10^{15}\,\text{W/cm}^2)}{\lambda(\mu\text{m})}\right]^{2/3}$$

at $I = 10^{15}$, $\lambda = 0.35\ \mu\text{m}$, $P_{abl} = 80$ Mbar



*J. D. Lindl, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive* (Springer-Verlag, New York, 1998).

The laser-driven target is subjected to the Rayleigh-Taylor (RT) instability



The RT instability has linear and nonlinear stages*

- Linear regime (classical)**:

$$\eta = \eta_0 e^{\gamma t}$$

$$\gamma = \sqrt{AKg}, \quad A = \frac{\rho_h - \rho_l}{\rho_h + \rho_l}$$

- Linear regime (ablative)**:

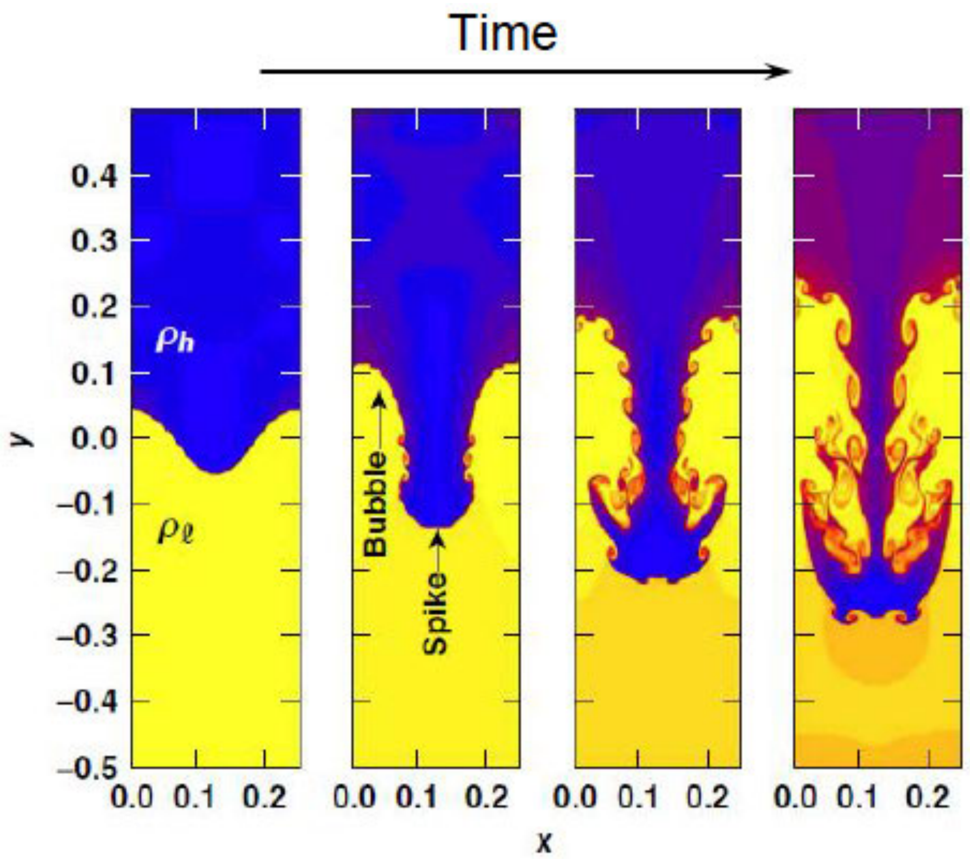
$$\gamma = \alpha\sqrt{\frac{Kg}{1+\epsilon KL}} - \beta K V_a$$

- Nonlinear regime***: $\eta \geq 0.1\lambda$

Slower growth

Bubbles and spikes

Bubble competition and merger

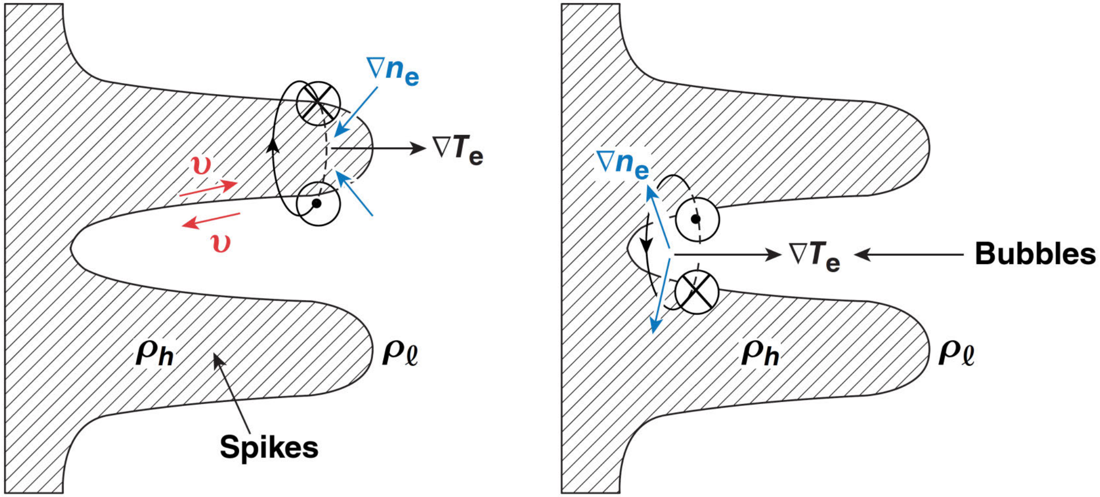


*Shengtai Li and Hui Li. "Parallel AMR Code for Compressible MHD or HD Equations". Los Alamos National Laboratory (2006).

**J. D. Kilkenny et al., Phys. Plasmas 1, 1379 (1994).

*** R. Betti and J. Sanz, Phy. Rev. Lett. 97, 205002 (2006).

Magnetic fields are generated by the Biermann battery mechanism



- **Biermann battery:**

$$\mathbf{E} = -\frac{\nabla P_e}{e n_e}$$

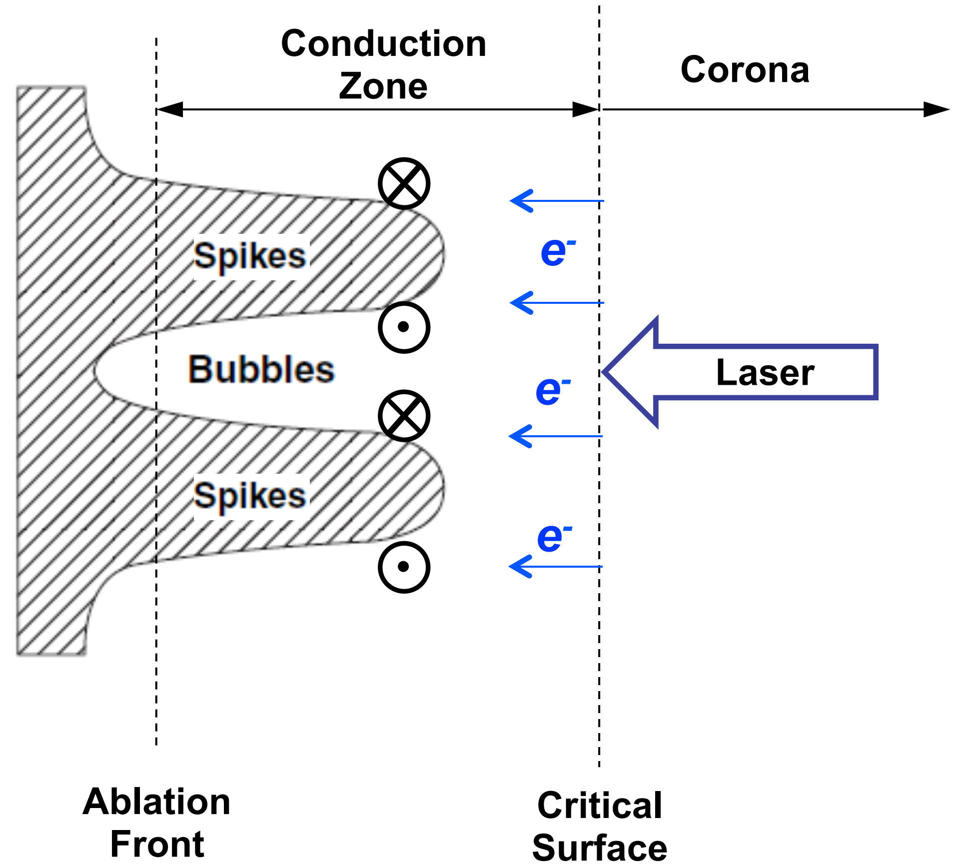
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \sim -\frac{\nabla n_e \times \nabla T_e}{e n_e}$$

Azimuthal magnetic fields are generated by $\nabla n_e \times \nabla T_e$.

*K. Mima *et al.*, Phys. Rev. Lett., 41, 1715 (1978);
R. G. Evans, Plasma Phys. Control. Fusion., 28, 1021 (1986);
B. Srinivasan *et al.*, Phys. Rev. Lett., 108, 165002 (2012).
M. Manuel et al., Phys. Rev. Lett., 108, 255006 (2012).

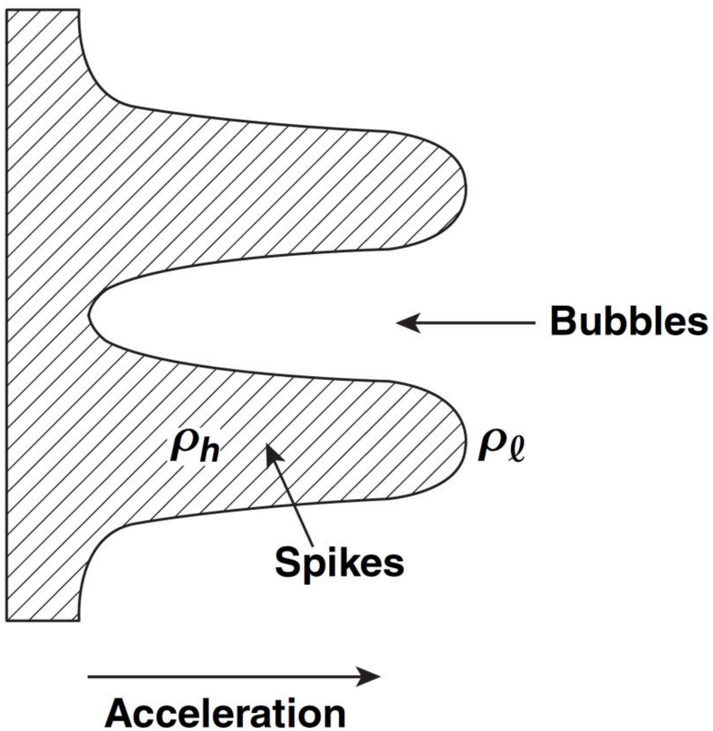
A strong magnetic field may modify the heat transport

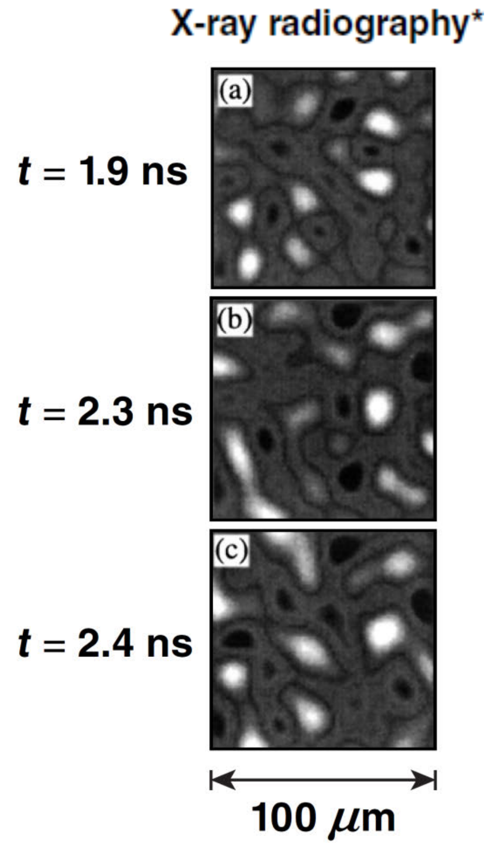
- Hall parameter $\chi \equiv \omega_{ce}\tau_{ei}$
- $\kappa_{\perp} \approx \kappa_{\parallel}/\chi^2$ for large $\chi \gg 1$
- The heat flux is reduced
- Plasma dynamic is altered



*S. Braginskii, Review of Plasma Physics (1965).

The growth rate for RT instability in laser-driven targets has been inferred with x-ray radiography





X-ray photons are sensitive to density modulations.

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*V. A. Smalyuk *et al.,* Phys. Rev. Lett., 81, 5342 (1998)

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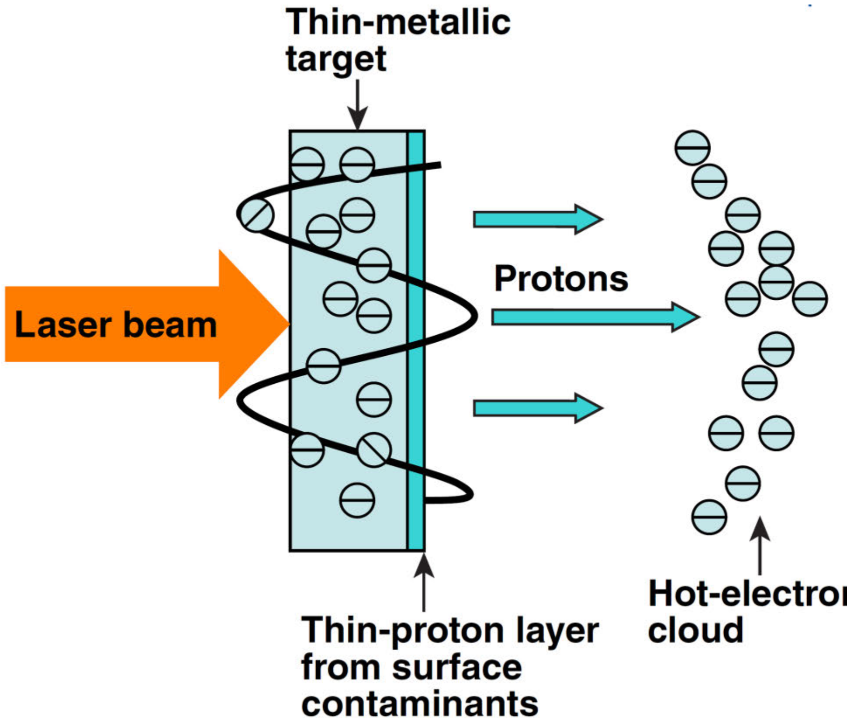
Target Normal Sheath Acceleration (TNSA)* generates MeV proton beams in intense (>10^{18} W/cm^2) laser-solid interactions

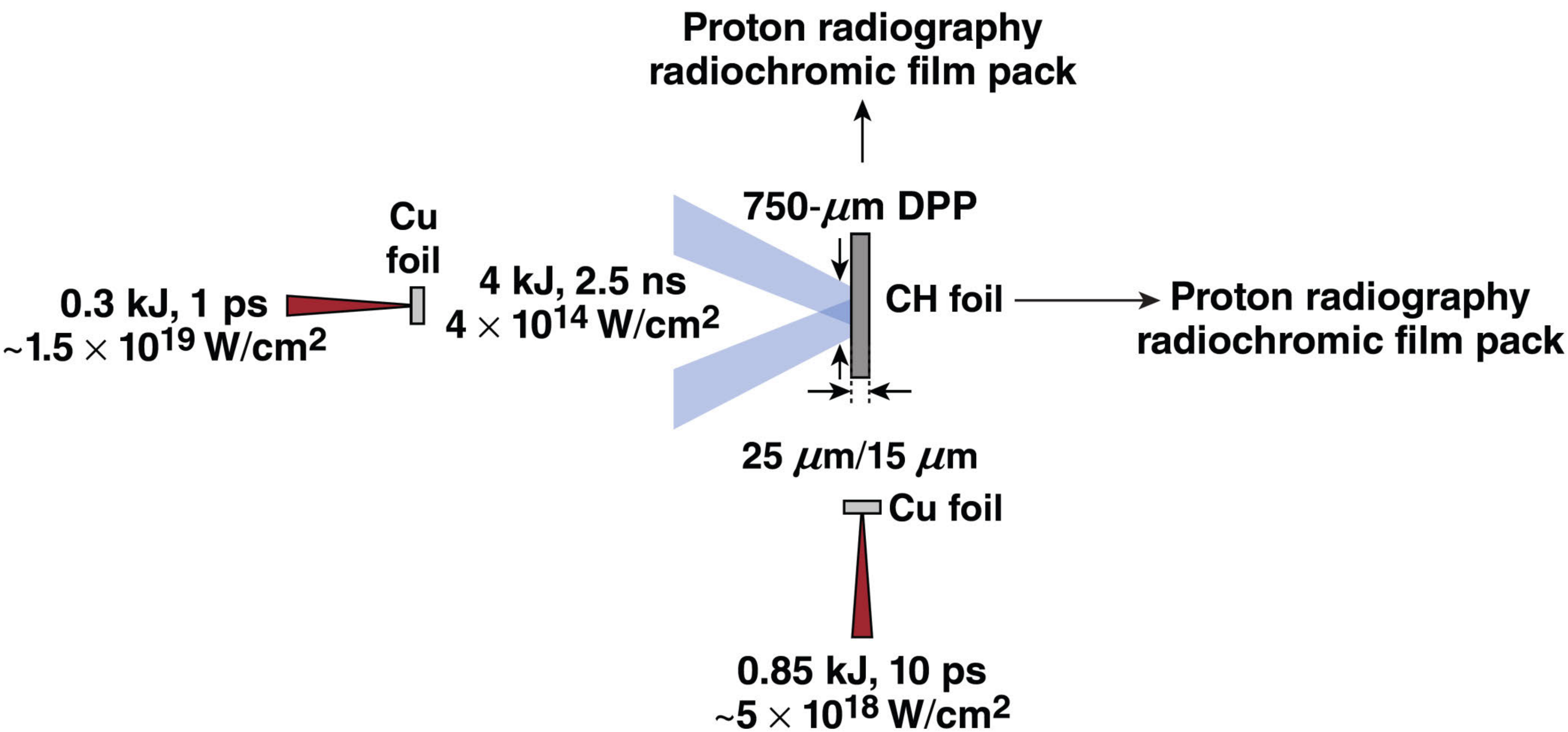
- Hot electrons escape from the rear side of the target
- An electrostatic field is built up, with a field gradient of the order of MeV/μm
- Protons are accelerated to tens of MeV



Laser-driven protons are ultra bright, extremely collimated, and have high peak energy (58 MeV) and short burst duration (picosecond scale).

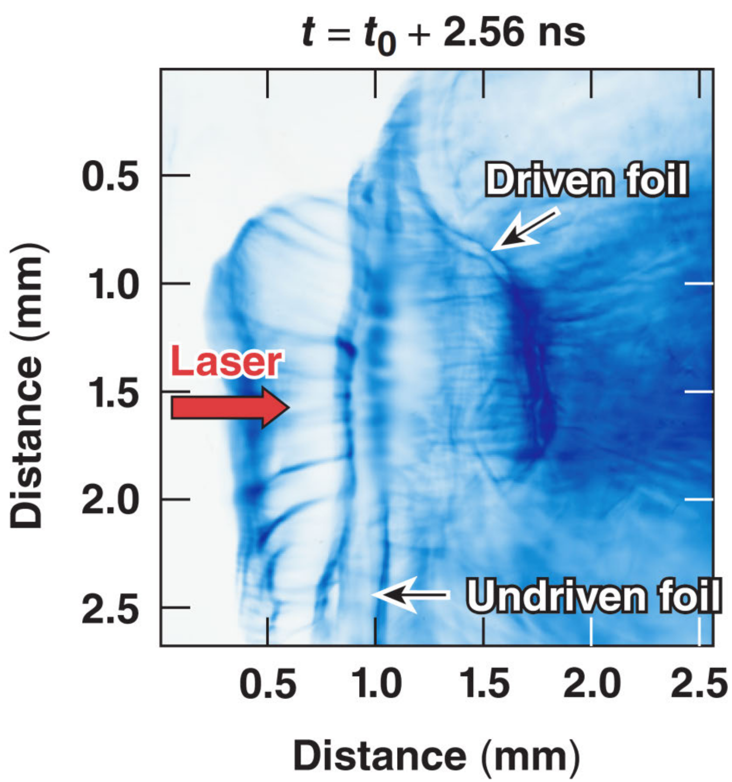
*S. C. Wilks *et al.*, Phys. Plasma 8, 542 (2001)

Magnetic-field generation has been studied in side-on and face-on geometries using the acceleration of planar plastic targets



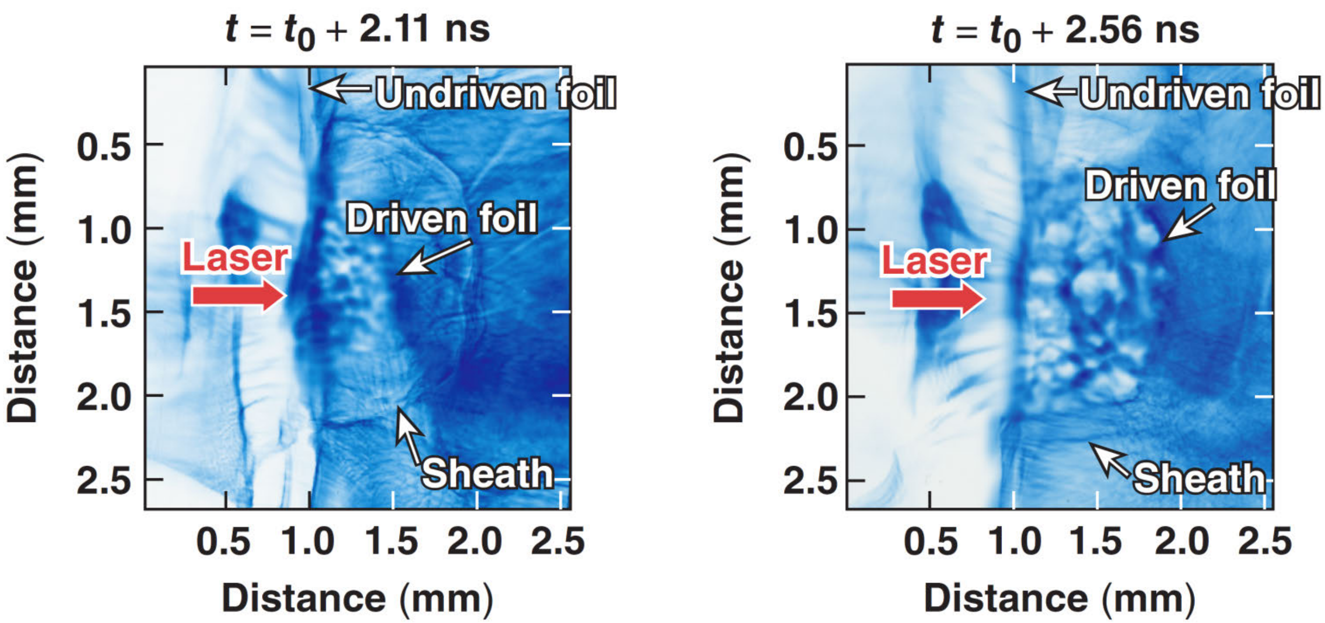
Side-on geometry

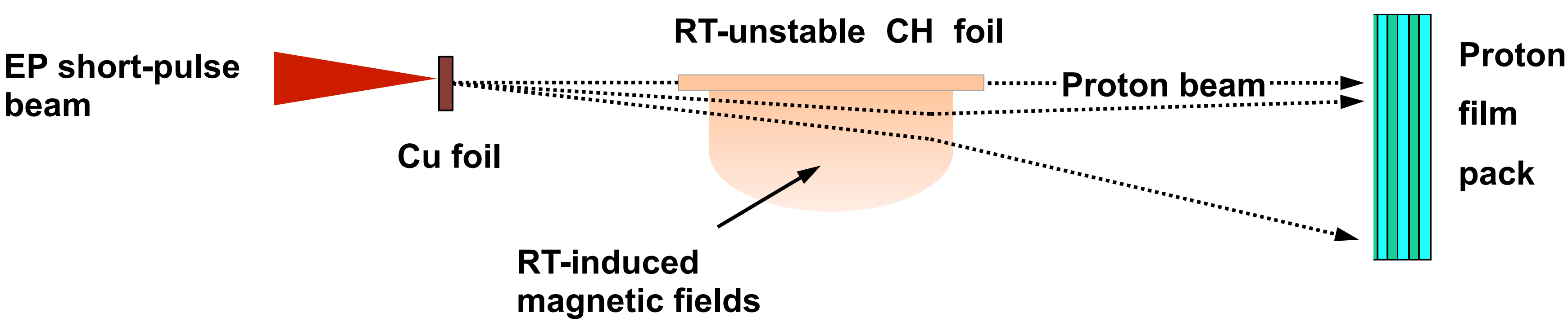
25-μm-thick CH targets were unbroken by instability formation



Proton energy: 13 MeV

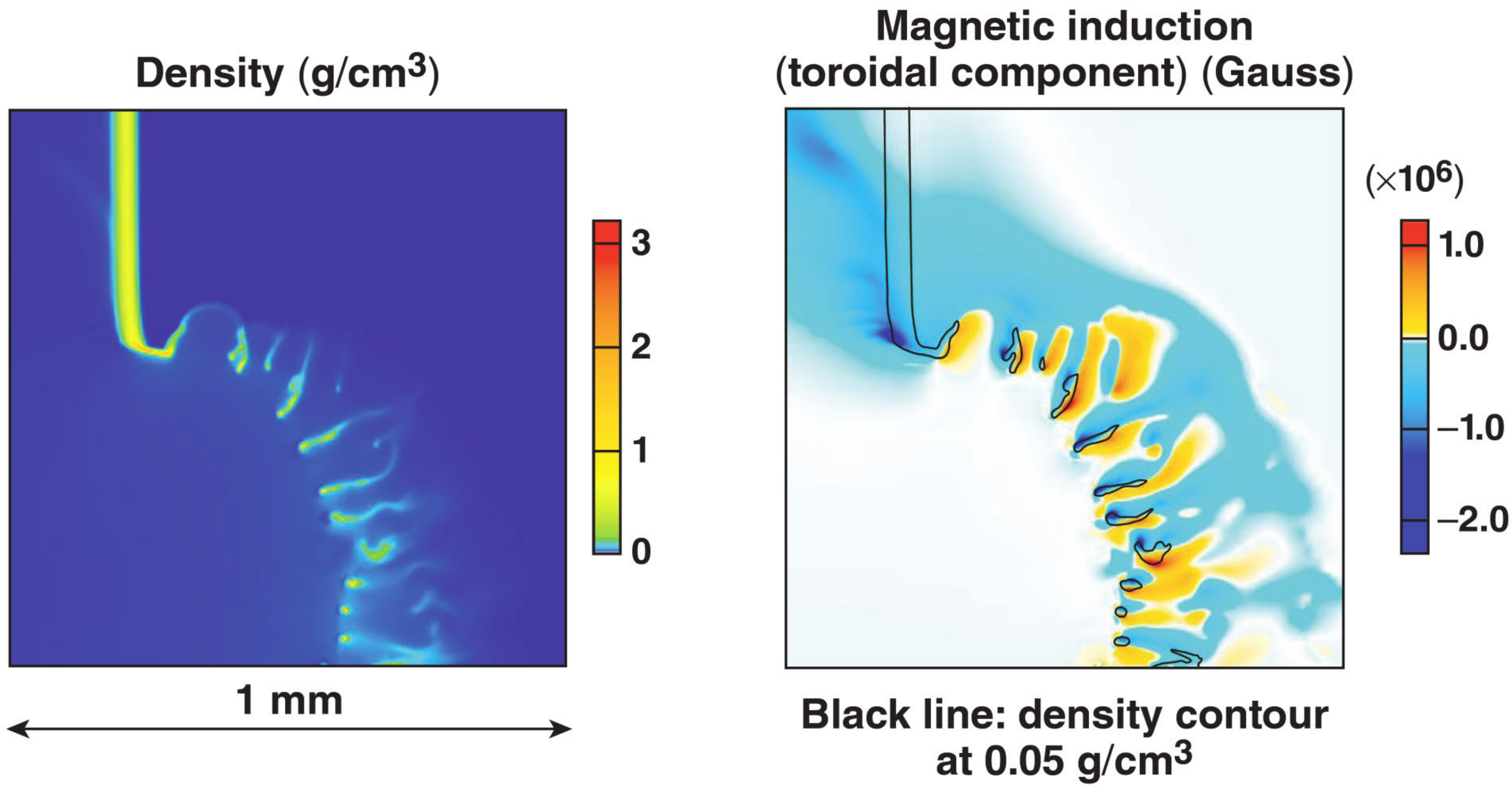
Proton radiography of 15-μm-thick foils reveals magnetic field generation and its evolution*





*L. Gao *et al.*, Phys. Rev. Lett. 109, 115001 (2012).

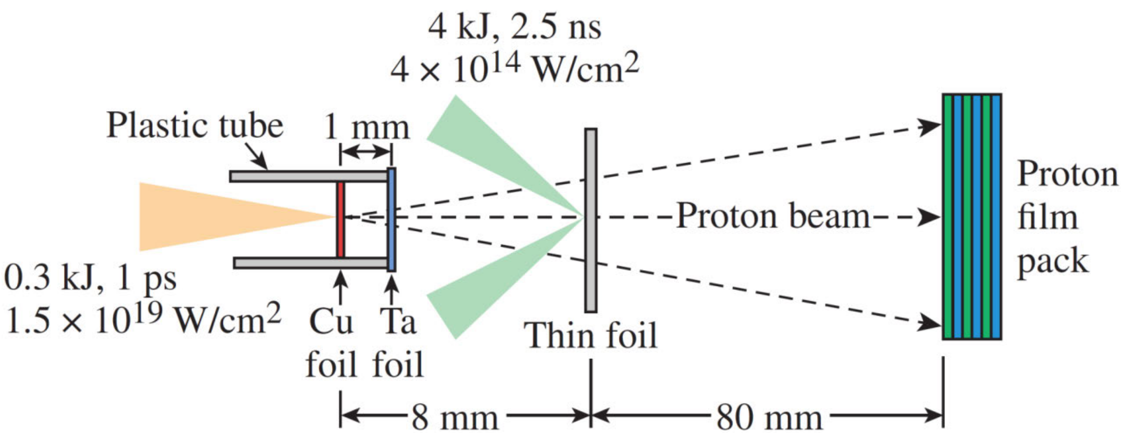
MG-level magnetic fields are predicted in a broken 15-μm-thick CH foil using 2-D magnetohydrodynamic (MHD) *DRACO** simulation



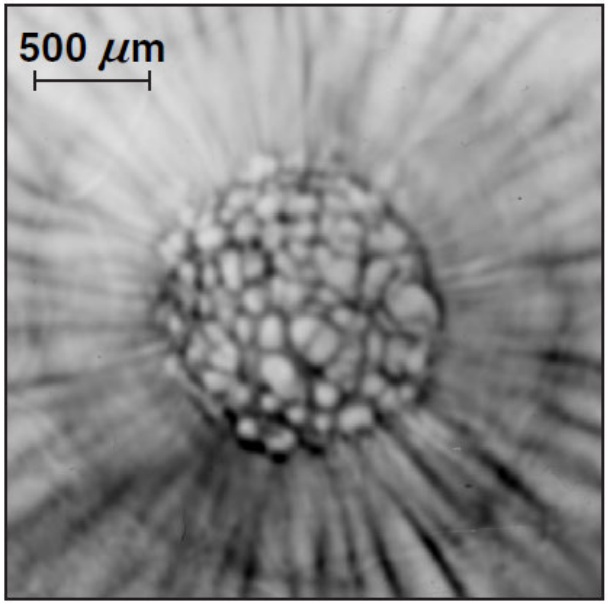
$t = t_0 + 2.1$ ns

*D. Keller *et al*., Bull. Am. Phys. Soc. 44, 37 (1999);
P. B. Radha *et al*., Phys. Plasmas 12, 032702 (2005).

Face-on probing reveals magnetic field generation by the RT instability

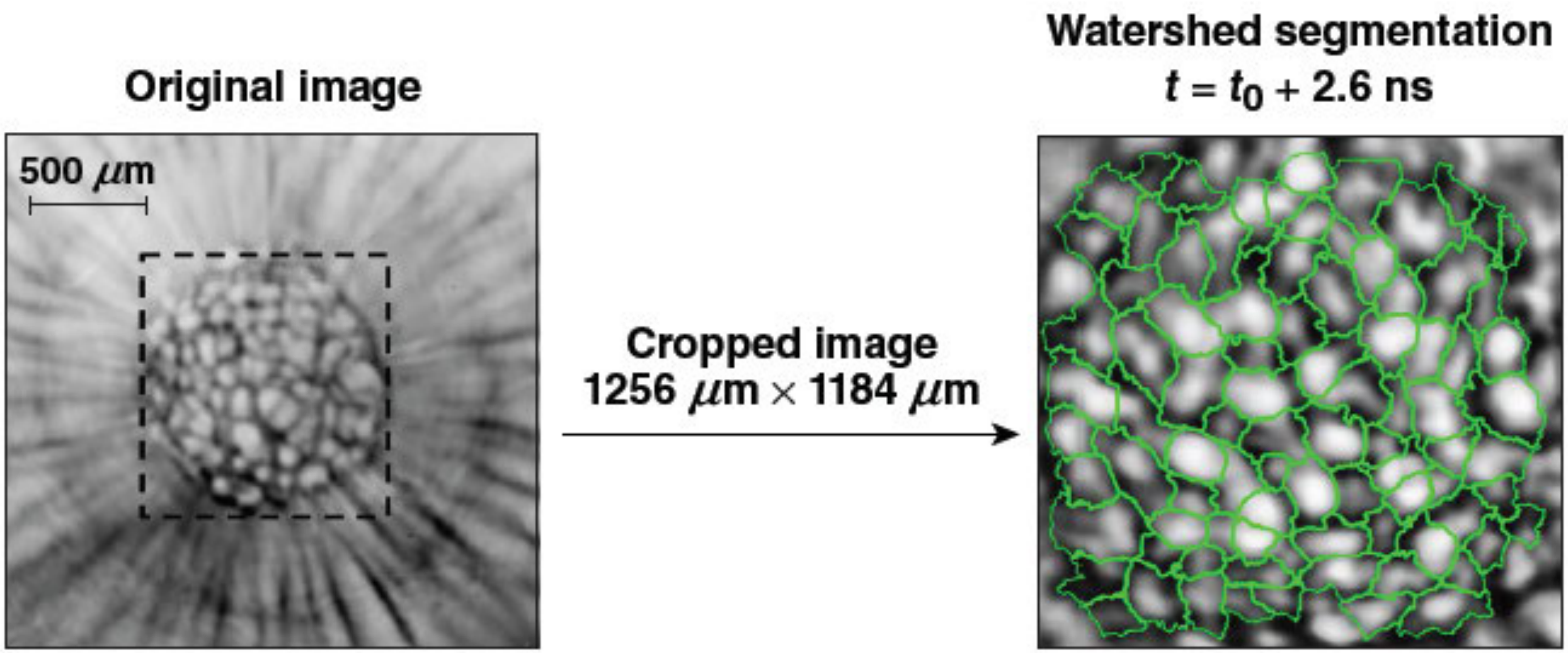


Proton radiograph

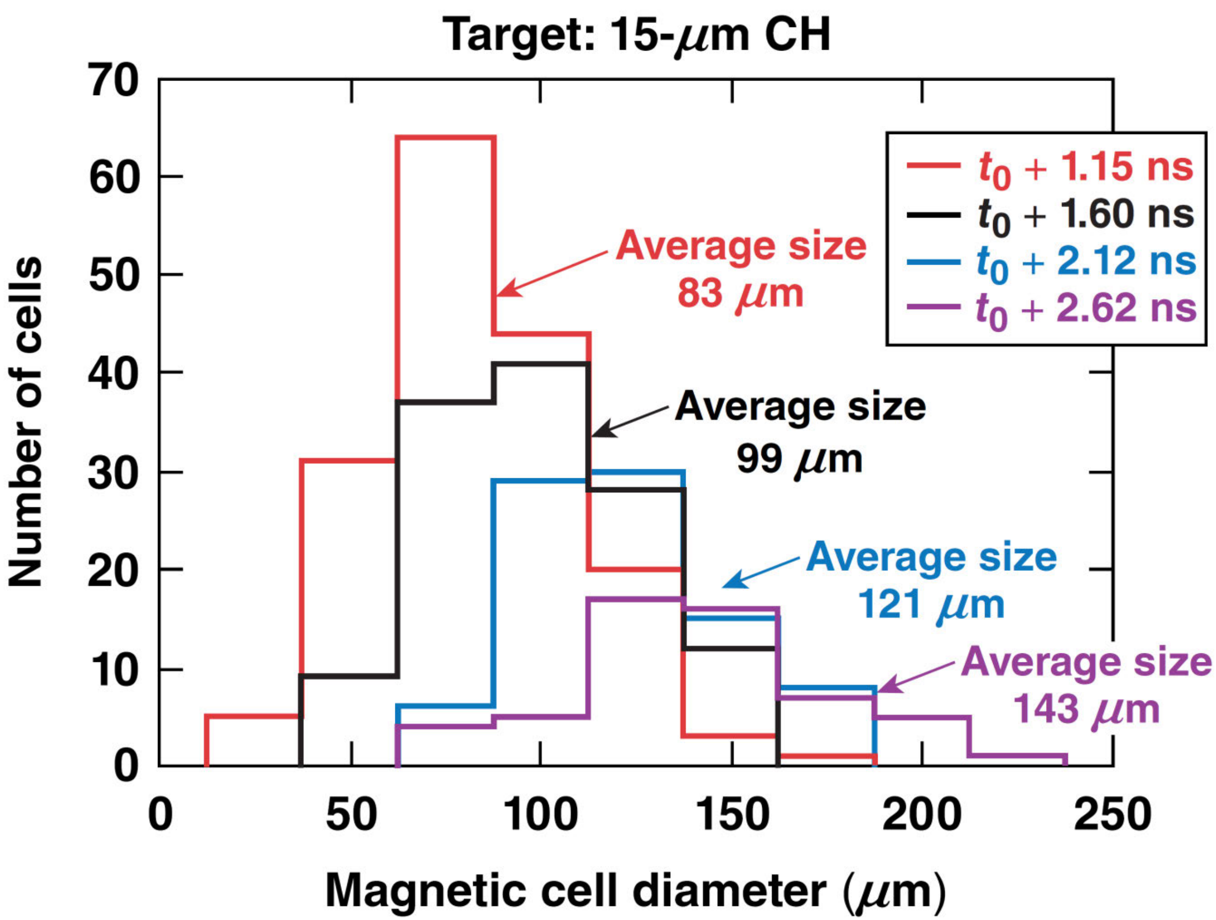


$t = t_0 + 2.6$ ns

The magnetic-field spatial distribution was characterized using the watershed algorithm

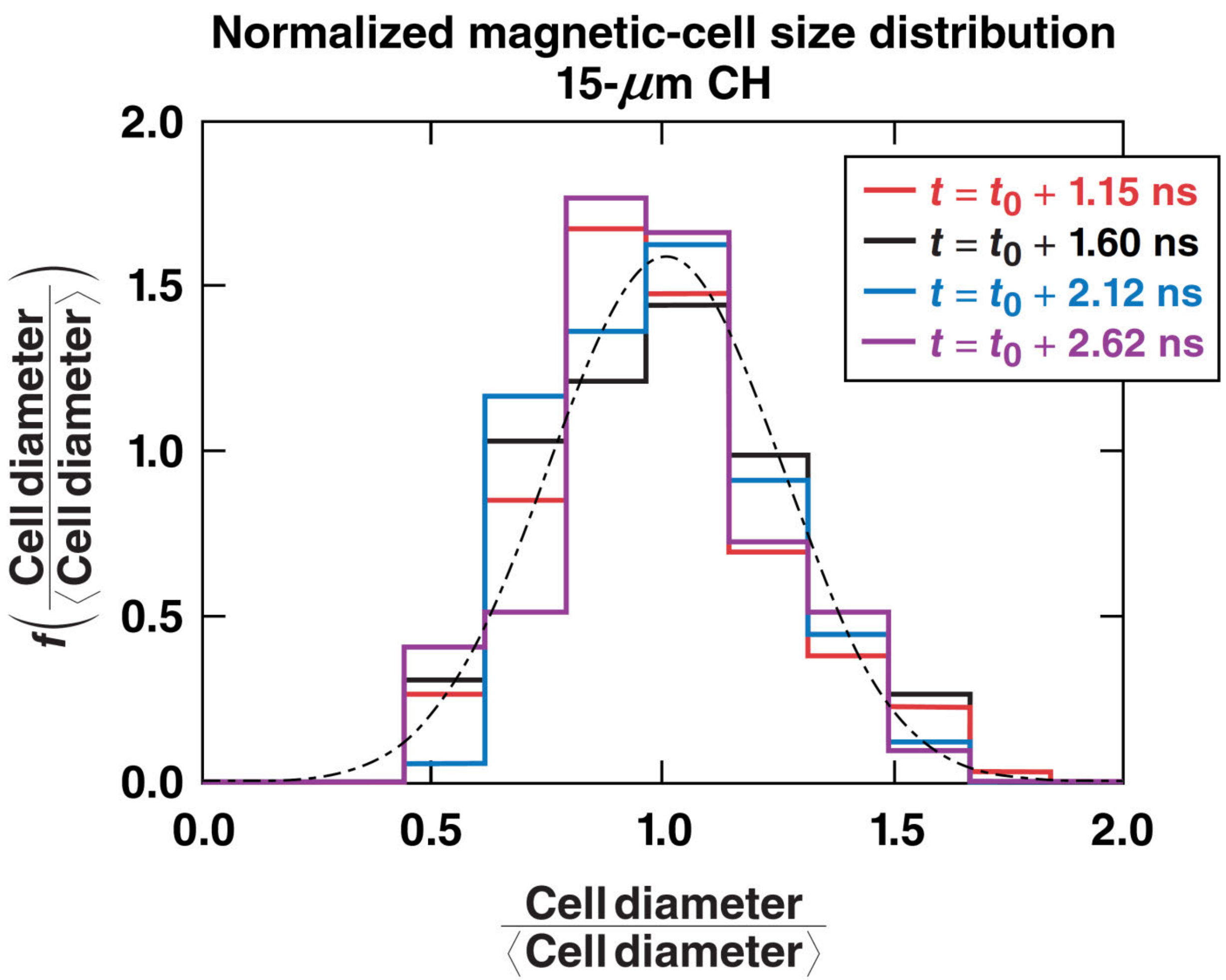


The number of magnetic cells decreases and the magnetic cell diameter increases with time

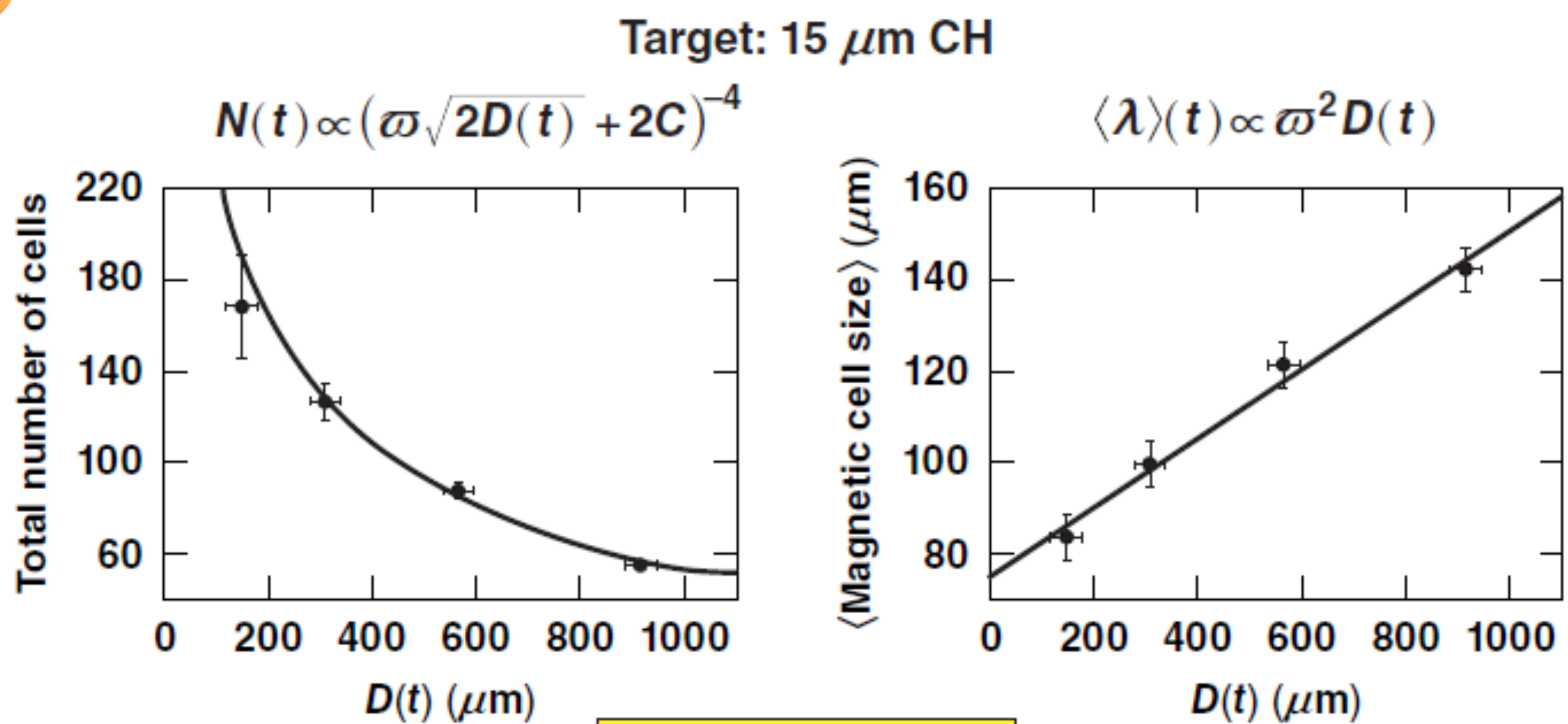


Face-on geometry

The normalized magnetic-field spatial distribution evolves self-similarly



The evolution of the magnetic-field spatial distribution is consistent with an RT bubble competition and merger model*



$\varpi_{CH} = 0.79 \pm 0.06$**

*O. Sadot *et al.*, Phys. Rev. Lett. 95, 265001 (2005);
D. Oron *et al.*, Phys. Plasmas 8, 2883 (2001);
U. Alon *et al.*, Phys. Rev. Lett. 72, 2867 (1994).

**L. Gao *et al.*, Phys. Rev. Lett. 110, 185003 (2013).

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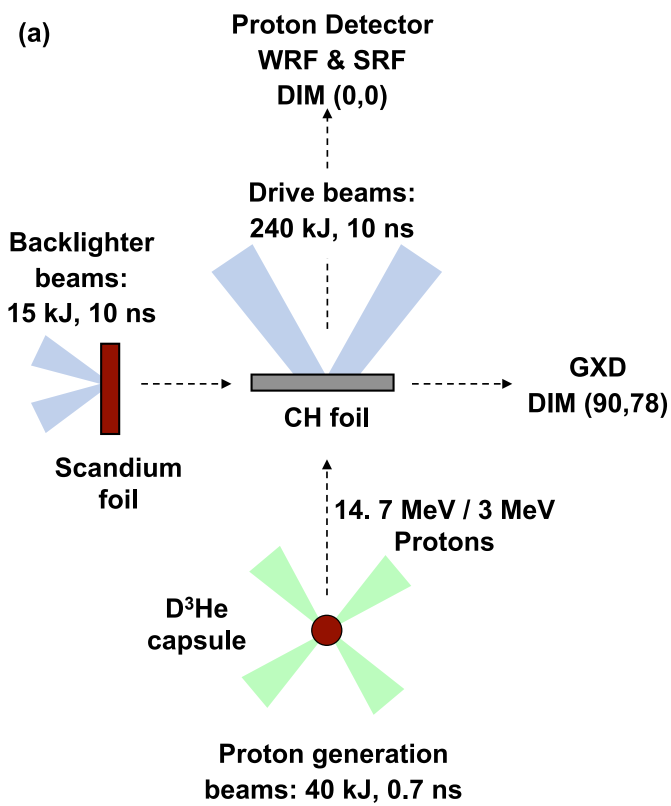
The origin and amplification of the magnetic field in the universe is a central astrophysical problem

- Sources of magnetic fields
- Amplification by the dynamo process
- Flow-dominated systems are common in astrophysics
- Particle acceleration, non-thermal emission

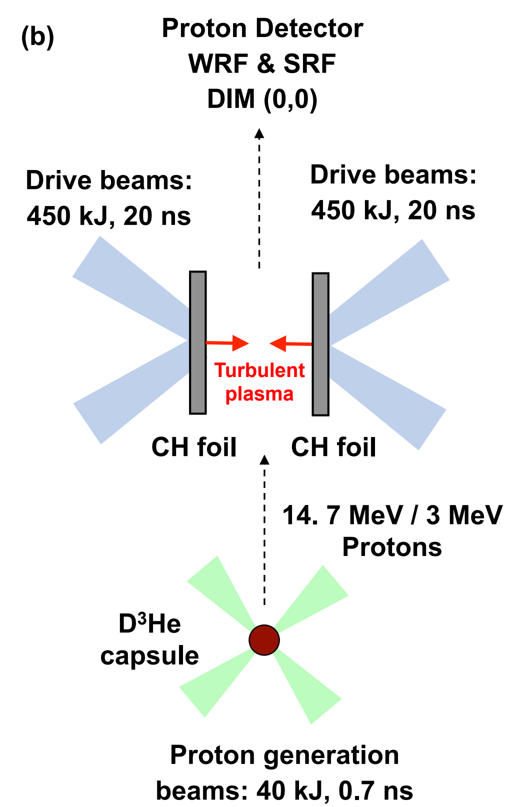
Dynamo

Two classes of experiments are proposed towards the first realization of a full MHD turbulence and dynamo in the HED systems using the NIF

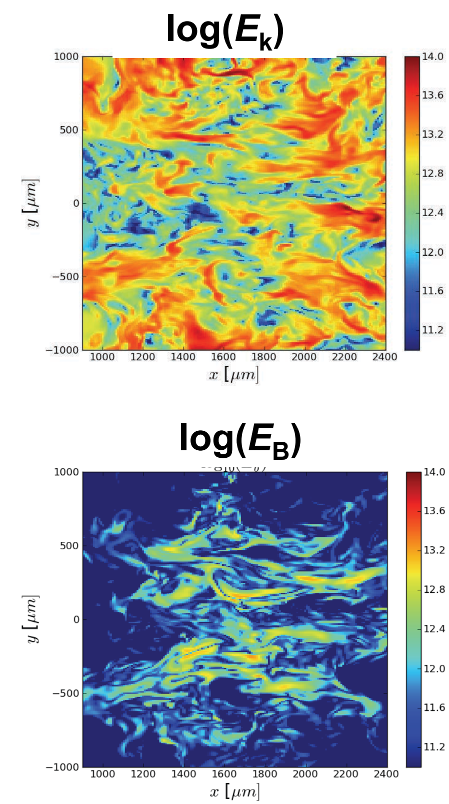
Single RT plume



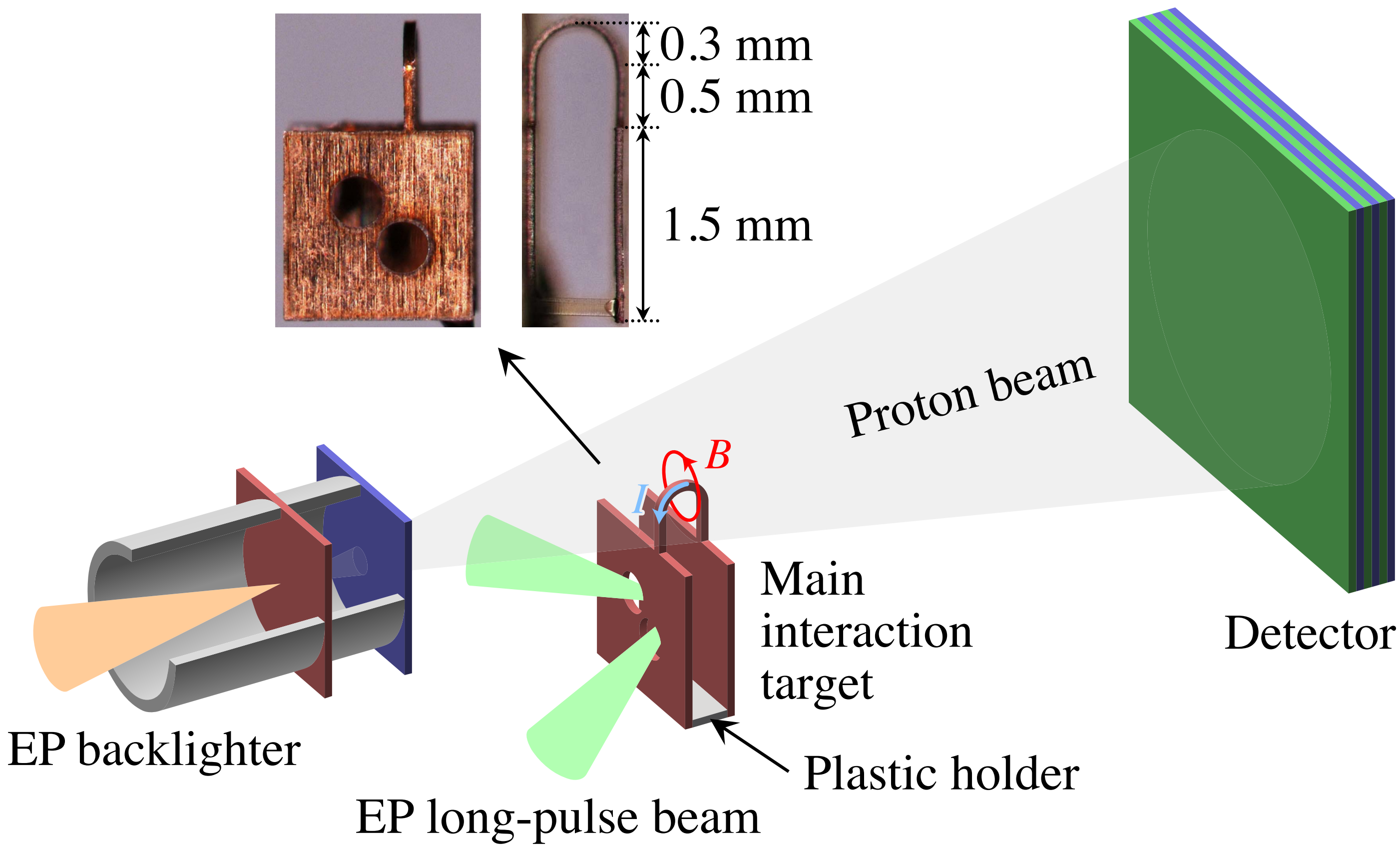
Colliding RT plumes



3D MHD simulation for the colliding case:



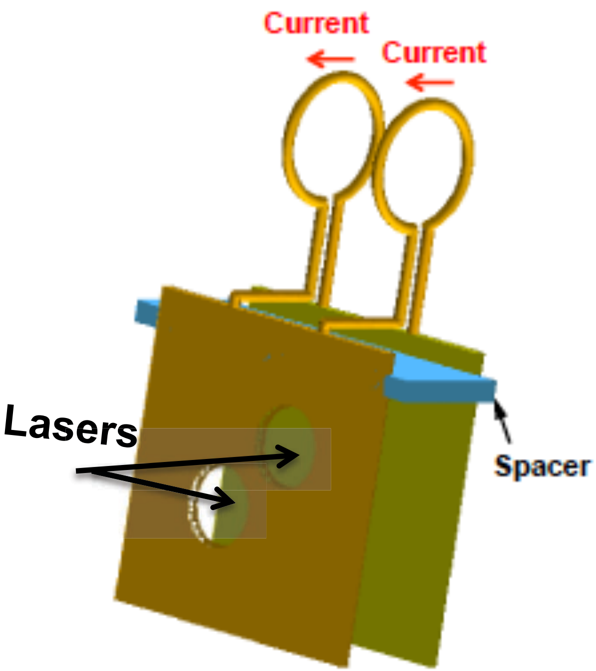
A novel technique has been developed to generate 100s of Tesla magnetic fields using powerful lasers



*L. Gao *et al.*, Phys. Plasma 23, 043106 (2016)

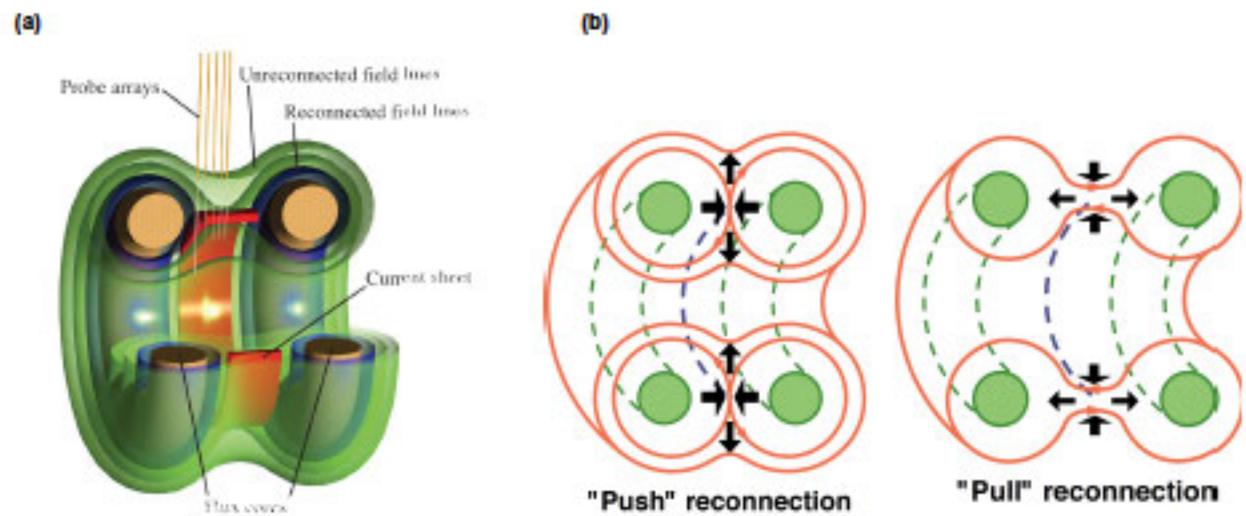
We are studying particle acceleration due to efficient axisymmetric magnetic reconnection

Laser-based reconnection



Reconnection target

MRX at PPPL

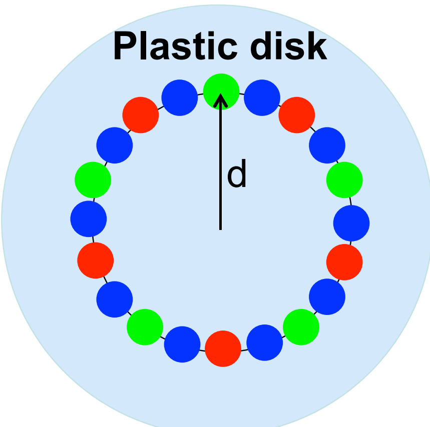


Magnetized jet

A strong, fast propagating, magnetized jet has been created at the OMEGA Laser Facility

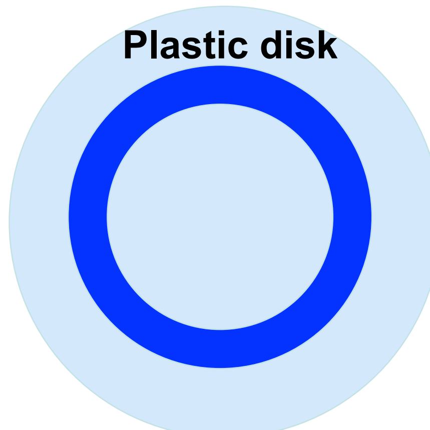
Magnetized Jet and the Collisionless Shock

OMEGA Experiment



- P1 axis, Ring 1, 5 beams
- P1 axis, Ring 2, 5 beams
- P1 axis, Ring 3, 10 beams

Form a ring of plasma →



d = 0, 400 um, and 800 um

Magnetized Jet

Plastic disk

- Collisionless shocks are believed to sites for cosmic ray acceleration
- A magnetized, supersonic jet has been successfully demonstrated in the FY16 campaign, in collaboration with Rice, LLE and MIT
- The next goal is to collide the jets for collionless shock

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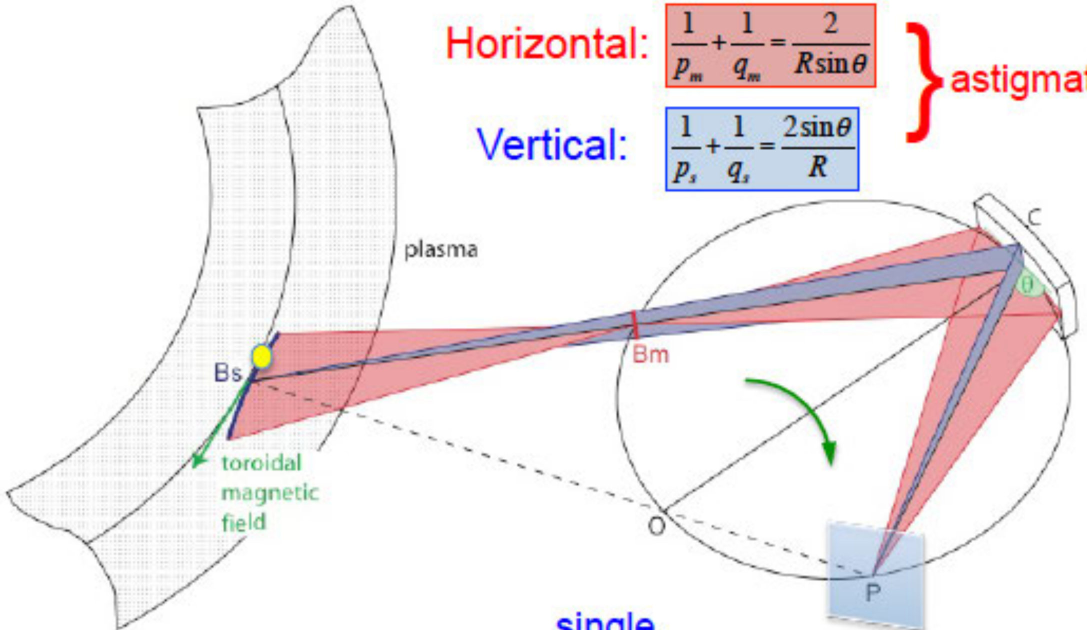
High-resolution x-ray spectroscopy is well-established on Tokamaks for measuring plasma conditions

Horizontal: $\frac{1}{p_m}+\frac{1}{q_m}=\frac{2}{R\sin\theta}$

Vertical: $\frac{1}{p_s}+\frac{1}{q_s}=\frac{2\sin\theta}{R}$

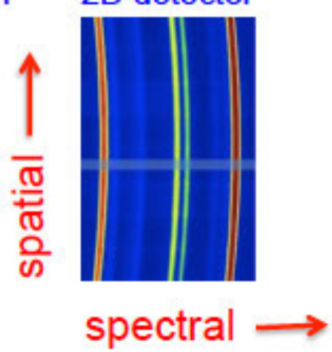
} astigmatism (different H/V focal lengths)



spherically bent crystal

single wavelength

2D detector



Bragg relation

$n\lambda=2d\sin\theta$

Enabling Principles

- Astigmatism of a spherical reflector
- Bragg relation
- Rotational symmetry of a spherical reflector about the normal axis, CO

Can obtain spatial resolution for small sources if the source is located on the sagittal focal line at Bs.

High-resolution x-ray spectroscopy is well-established on Tokamaks for measuring plasma conditions

PPPL digest
PRINCETON PLASMA PHYSICS LABORATORY
A United States Department of Energy Facility
AUGUST 2007

X-ray Crystal Spectrometer Makes Debut at C-Mod

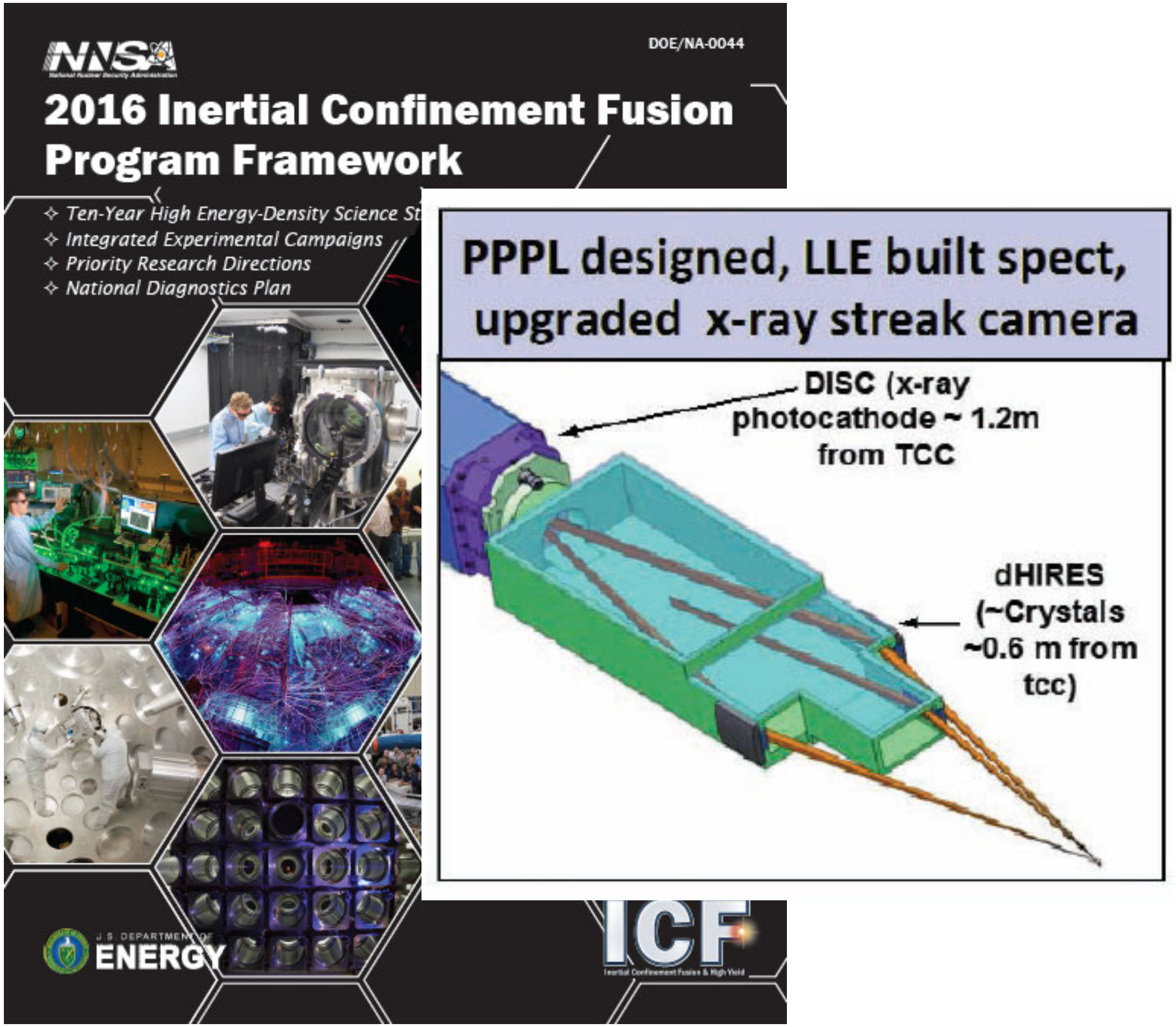
New Technique a Major Advance for ITER

A PPPL/Alcator C-Mod collaboration has resulted in the demonstration of a greatly improved X-ray crystal spectrometer for application to ITER and fusion reactors. Experiments conducted by a PPPL/MIT team in April mark the beginning of a new era in the ability of such devices to determine radial profiles of the ion temperature and the rotational velocity of high temperature plasmas without the need for diagnostic beams. Their success will benefit substantially ITER and other advanced fusion energy systems.

From the left are: Alex Ince-Cushman, MIT; Ken Hill, PPPL; Manfred Bitter, PPPL; John Rice, MIT; and Christian Broennimann of the Paul Scherrer Institute in Switzerland.

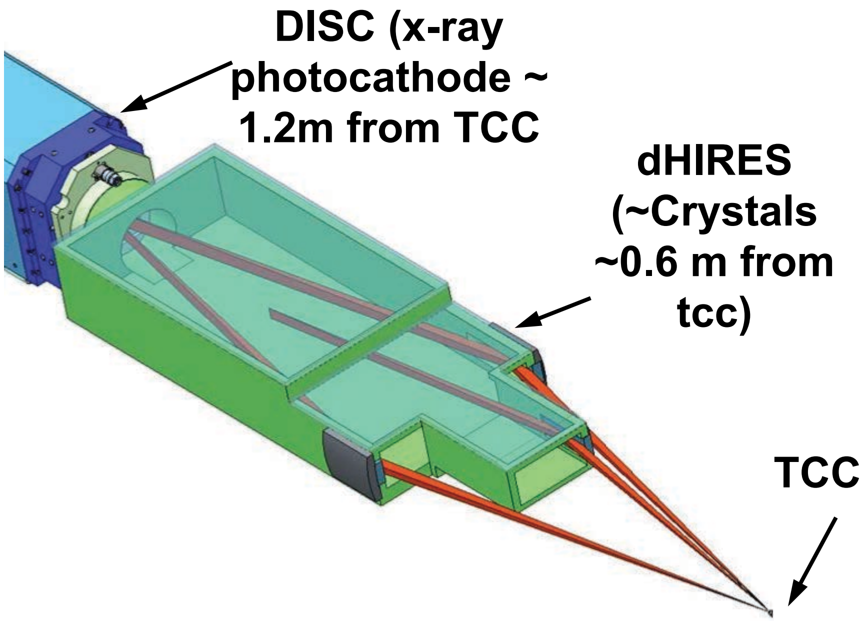
impurity by the pattern of frequencies, or spectrum, of the light emitted and they can determine the

PPPL designed high-resolution x-ray spectrometer has been identified as one of the 8 National Transformative Diagnostics



NIF DIM-based high-resolution x-ray spectrometer (dHIRES)

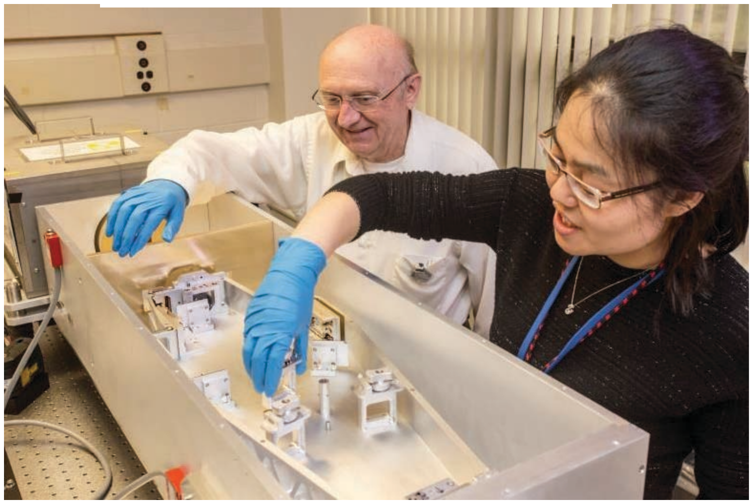
- Three crystals are fit in the same plane inside a cassette, covering a large range of x-ray energies
- Detectors are the DISC streak camera and image plate: measure time-resolved and -integrated spectra simultaneously
- dHIRES will be used to measure n_e and T_e in implosion and benchmark n_e and T_e derived from neutrons



*K. W. Hill *et al.*, 26th IAEA Fusion Energy Conference, Kyoto, Japan, 2016

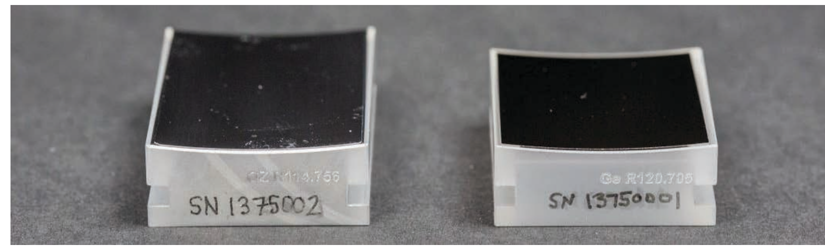
dHIRES is being calibrated at the x-ray lab at PPPL (L123)

K. Hill and L. Gao

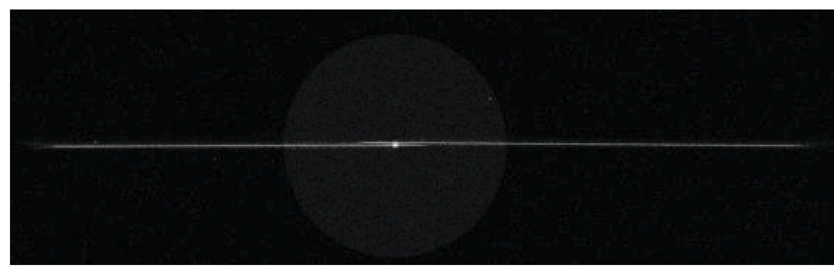


- **Alignment**
- **Energy calibration**
- **Throughput**
- **Filter**

dHIERS crystals



Sample spectra



dHIRES will be shipped to NIF in the week of August 14, and deployed on NIF for experiments on Sept. 27, 2017

Summary/Conclusions

A wide range of HED physics are being studied at PPPL related to fusion and astrophysics

- The nonlinear phase of the RT instability generates magnetic fields that could be of astrophysics importance*
- A strong, fast propagating, magnetized jet has been demonstrated ready for astrophysics applications**
- A novel axisymmetric reconnection platform based on a strong external magnetic field source generated by high-power lasers is being pursued***
- The NIF high-resolution spectrometer will be fielded on NIF for actual shot end of September****

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*L. Gao *et al.,* Phys. Rev. Lett. 109, 115001 (2012).
L. Gao *et al.,* Phys. Rev. Lett. 110, 185003 (2013).
**L. Gao *et al.,* in preparation.
***L. Gao *et al.,* Phys. Plasma 23, 043106 (2016)
****K. W. Hill et al., 26th IAEA Fusion Energy Conference, Kyoto, Japan, 2016