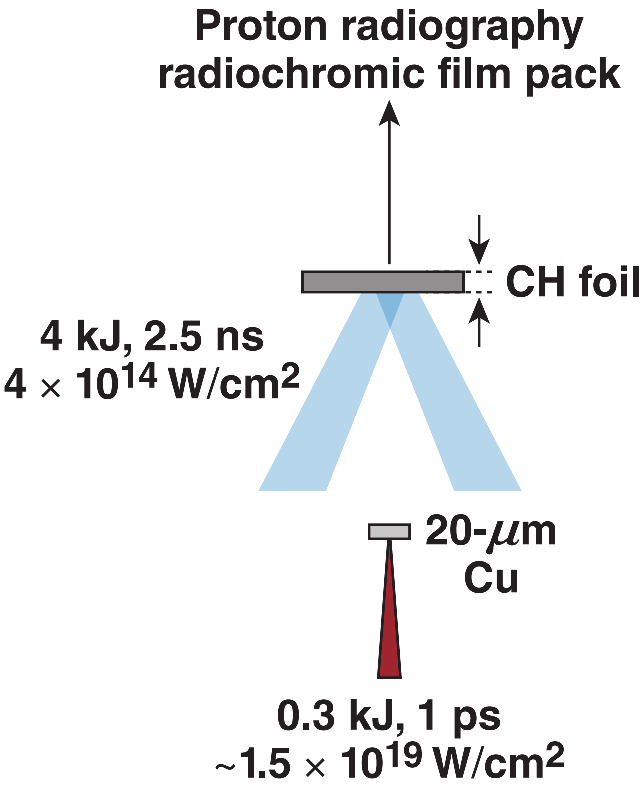
# Observation of Self-Similarity in the Magnetic Fields Generated by the Nonlinear Rayleigh–Taylor Instability



Proton radiography
radiochromic film pack

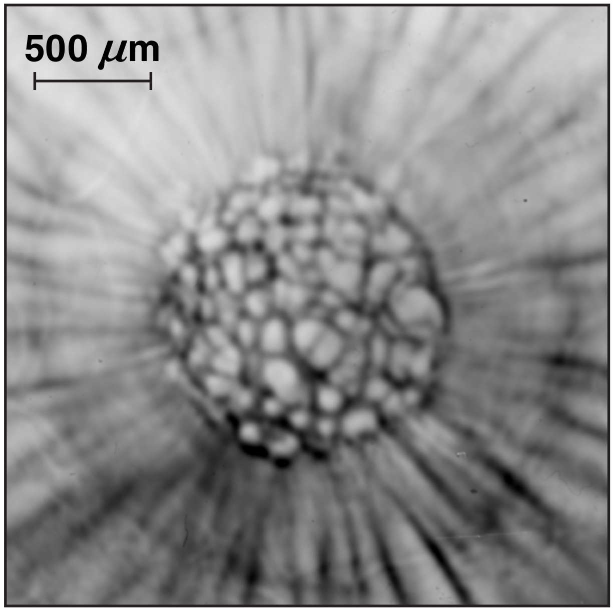
CH foil

4 kJ, 2.5 ns
$4 \times 10^{14}$ W/cm$^2$

20-$\mu$m
Cu

0.3 kJ, 1 ps
~$1.5 \times 10^{19}$ W/cm$^2$

Proton radiograph



$t = t_0 + 2.6$ ns

D. D. Meyerhofer
University of Rochester
Laboratory for Laser Energetics

Reconnection Workshop
Princeton Plasma Physics Lab
Princeton, NJ
4 April 2013

**Summary**

# The scale-invariant regime of nonlinear Rayleigh–Taylor (RT) instability has been probed with proton radiography

- The RT-generated magnetic-field distribution and its evolution were investigated using laser-driven CH targets
- The structural evolution was found to be scale invariant
- The data are consistent with a bubble competition and merger model;* the merger rate has been determined

**The role of magnetic reconnection in this process is unknown.**

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*O. Sadot *et al*., Phys. Rev. Lett. 95, 265001 (2005).

# Collaborators

L. Gao, P. M. Nilson, I. V. Igumenshchev, G. Fiksel,
R. Yan, J. R. Davies, D. H. Froula, and R. Betti

Laboratory for Laser Energetics
University of Rochester

M. G. Haines

Imperial College London

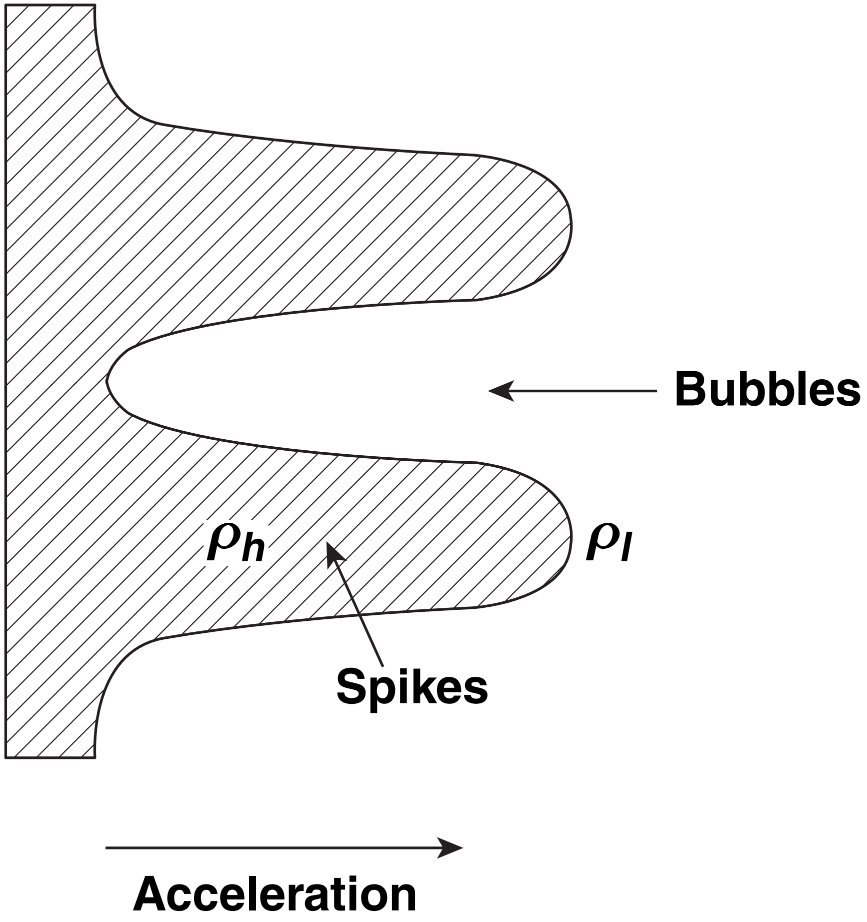
D. Martinez and V. A. Smalyuk

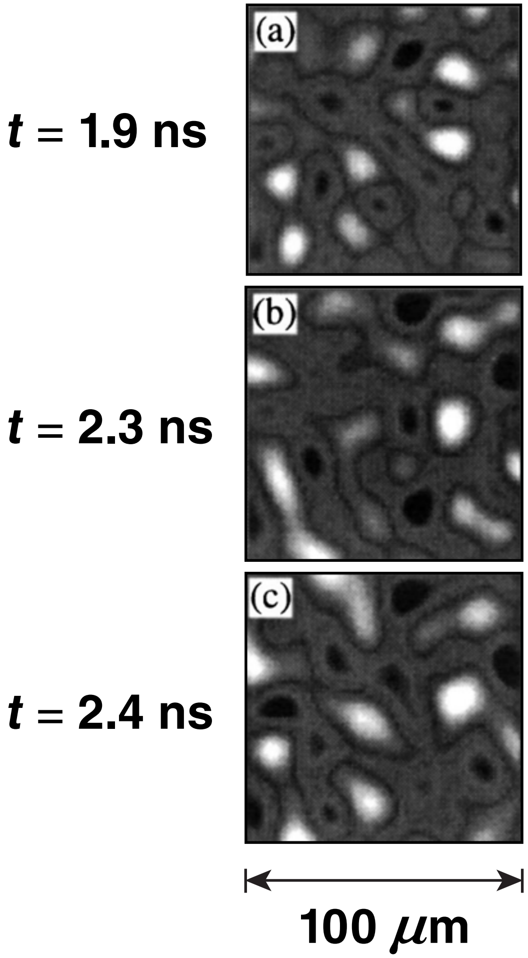
Lawrence Livermore National Laboratory

E. G. Blackman

University of Rochester

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

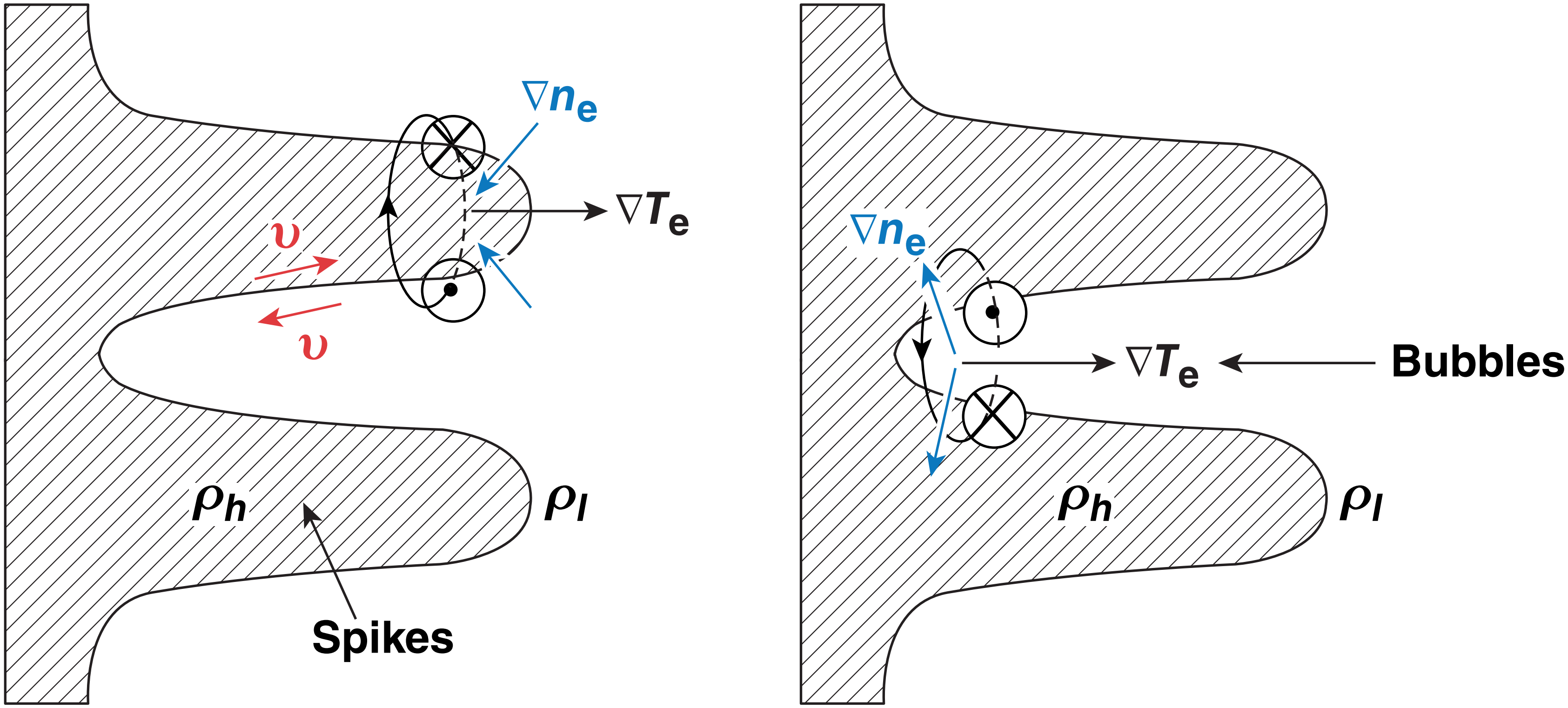




**X-ray photons are sensitive to density modulations.**

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

# The RT instability in laser-driven targets generates large amounts of fluid vorticity*



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

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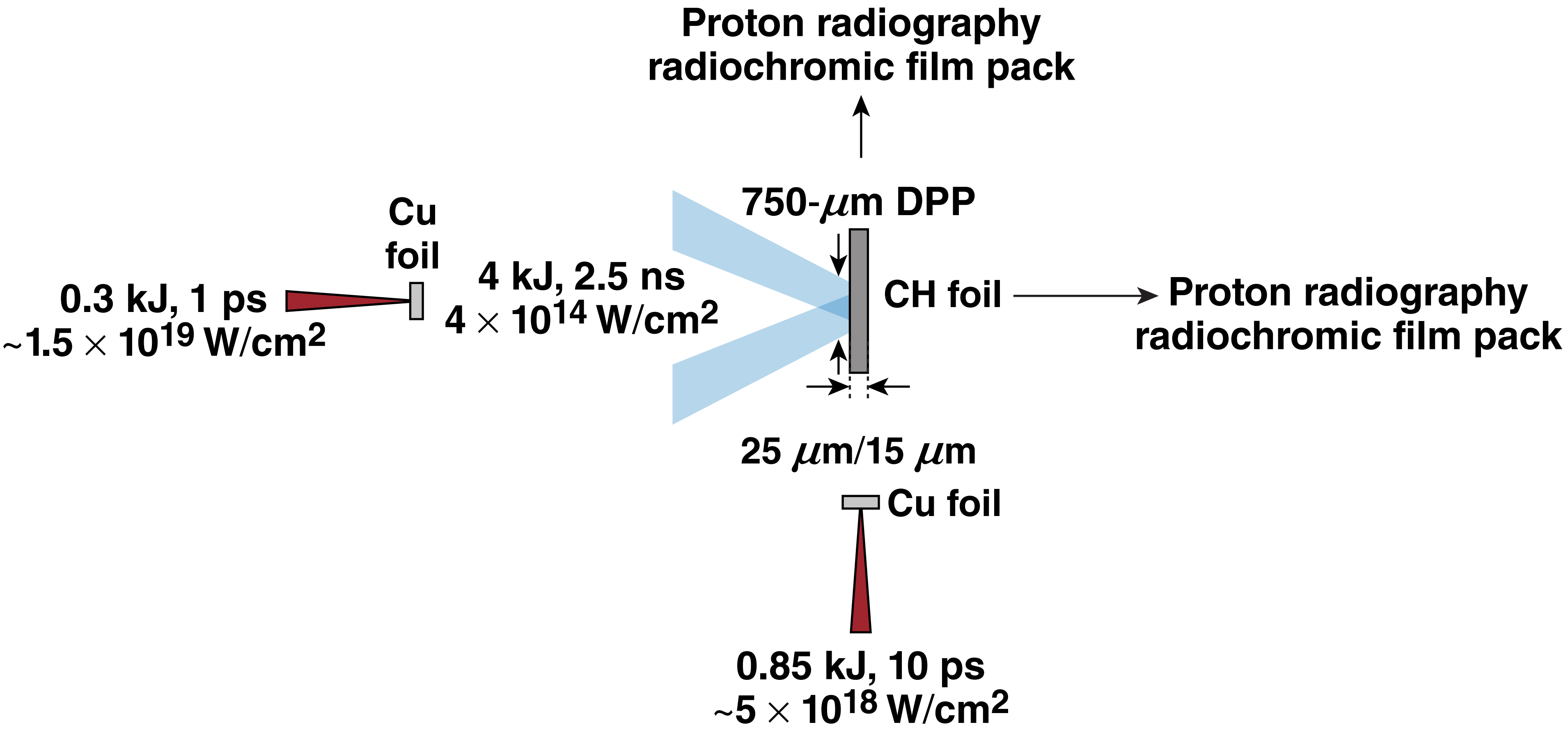
*K. Mima, T. Tajima, and J. N. Leboeuf, Phys. Rev. Lett. 41, 1715 (1978);
R. G. Evans, Plasma Phys. Control. Fusion. 28, 1021 (1986);
R. Betti and J. Sanz, Phys. Rev. Lett. 97, 205002 (2006).

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



Proton radiography radiochromic film pack

750-$\mu$m DPP

Cu foil

0.3 kJ, 1 ps

~$1.5 \times 10^{19}$ W/cm$^2$

4 kJ, 2.5 ns

$4 \times 10^{14}$ W/cm$^2$

CH foil

Proton radiography radiochromic film pack

25 $\mu$m/15 $\mu$m

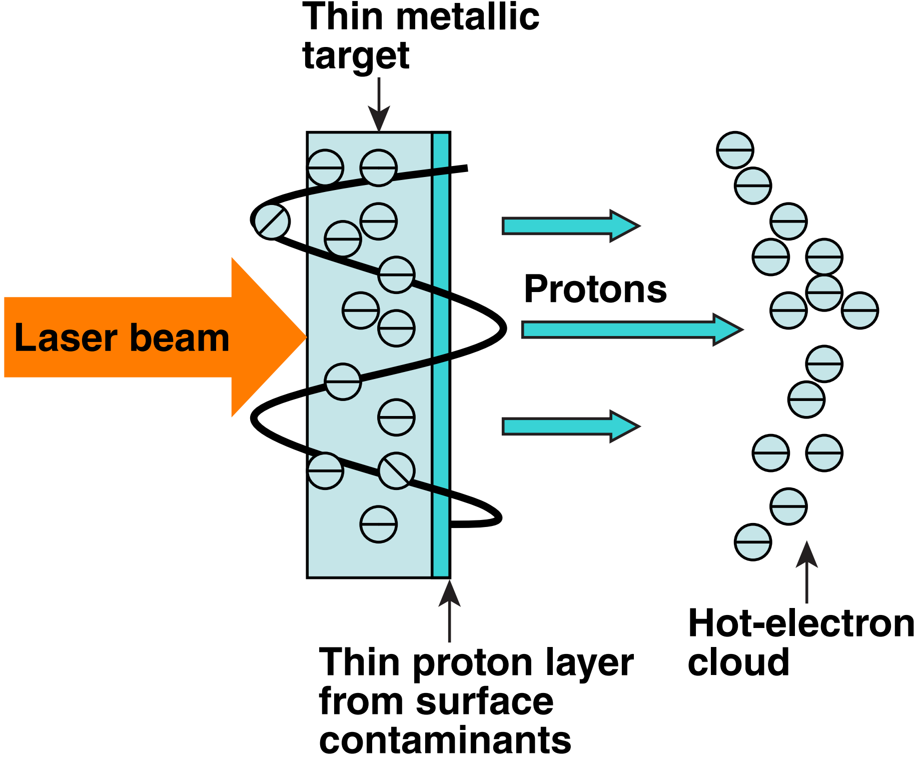
Cu foil

0.85 kJ, 10 ps

~$5 \times 10^{18}$ W/cm$^2$

# Target-normal sheath acceleration (TNSA)* generates MeV proton beams in intense ($>10^{18}$ W/cm$^2$) laser–solid interaction

- 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/$\mu$m
- 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).**

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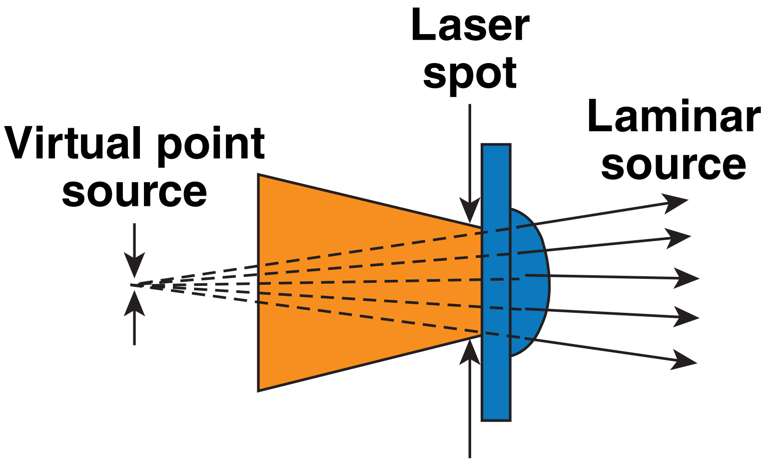
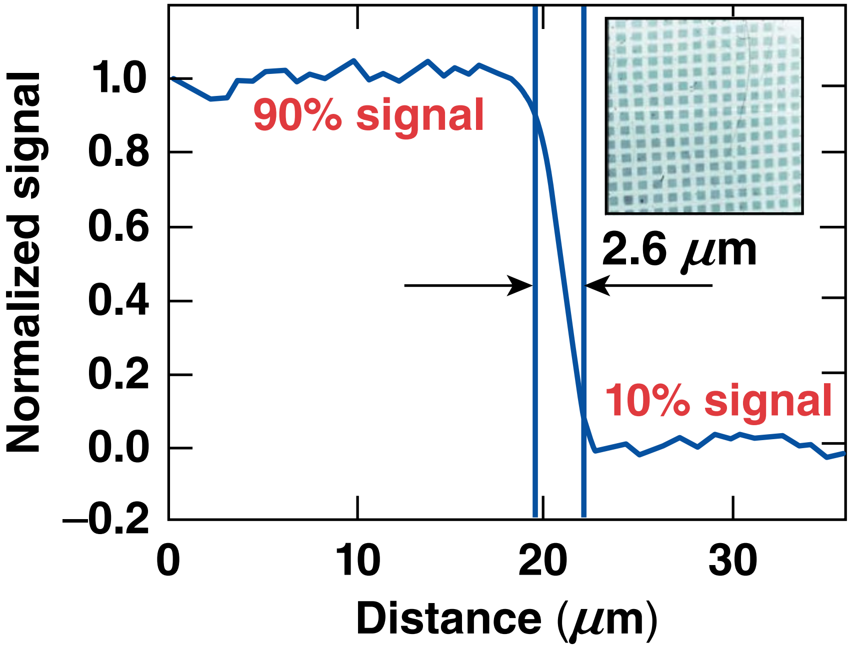
*S. C. Wilks *et al.*, Phys. Plasmas 8, 542 (2001).

# The virtual proton source is much smaller than the laser spot*



**Virtual source size: 4±2 μm**



5-MeV protons
26-μm wire, 35-μm hole

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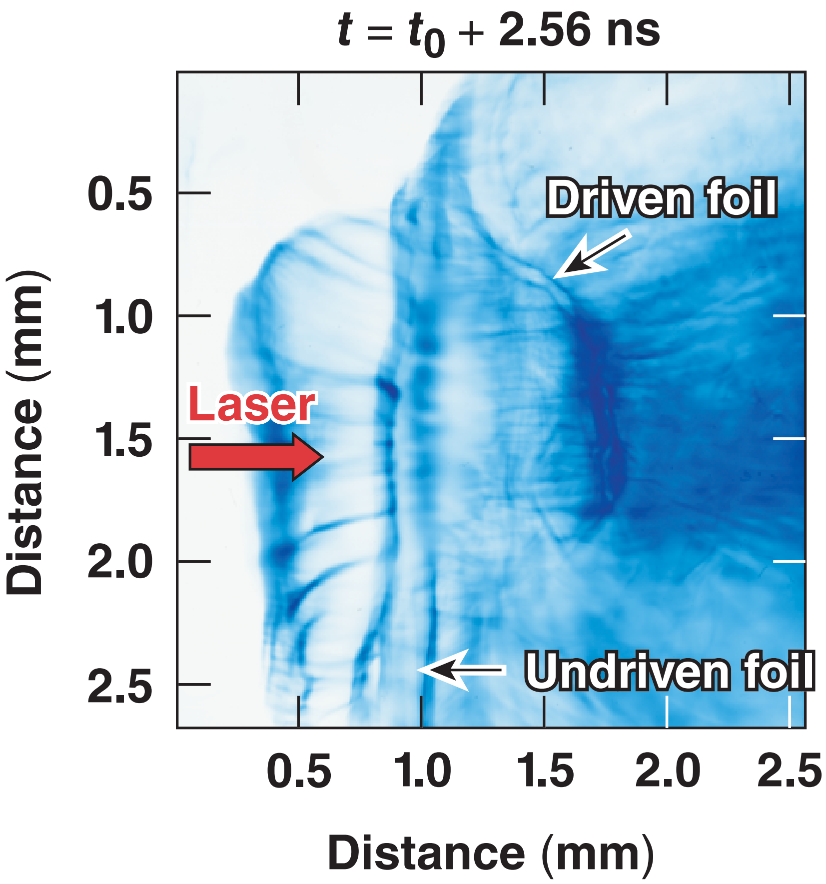
*M. Borghesi *et al*., Phys. Rev. Lett. 92, 055003 (2004);
T. E. Cowan *et al*., Phys. Rev. Lett. 92, 204801 (2004).

**Side-on geometry**

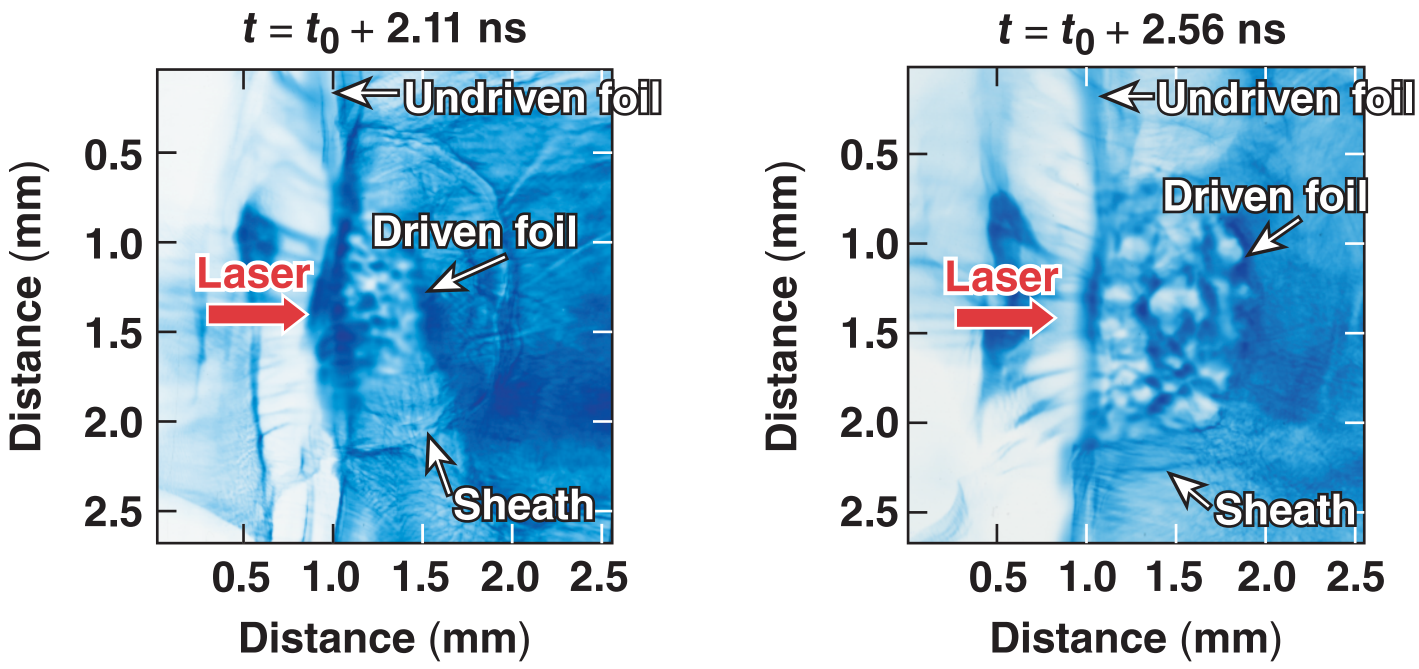
# 25-$\mu$m-thick CH targets were unbroken by instability formation



Proton energy: 13 MeV

**Side-on geometry**

# Proton radiography of 15-$\mu$m-thick foils reveals magnetic-field generation and its evolution*



Proton energy: 13 MeV

**Magnetic-field cell size doubles in 500 ps.**

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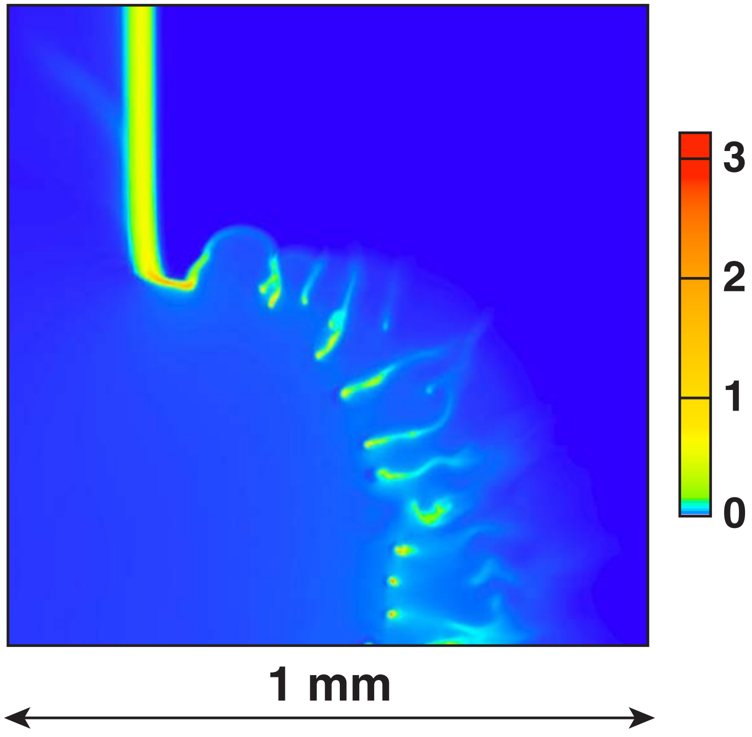
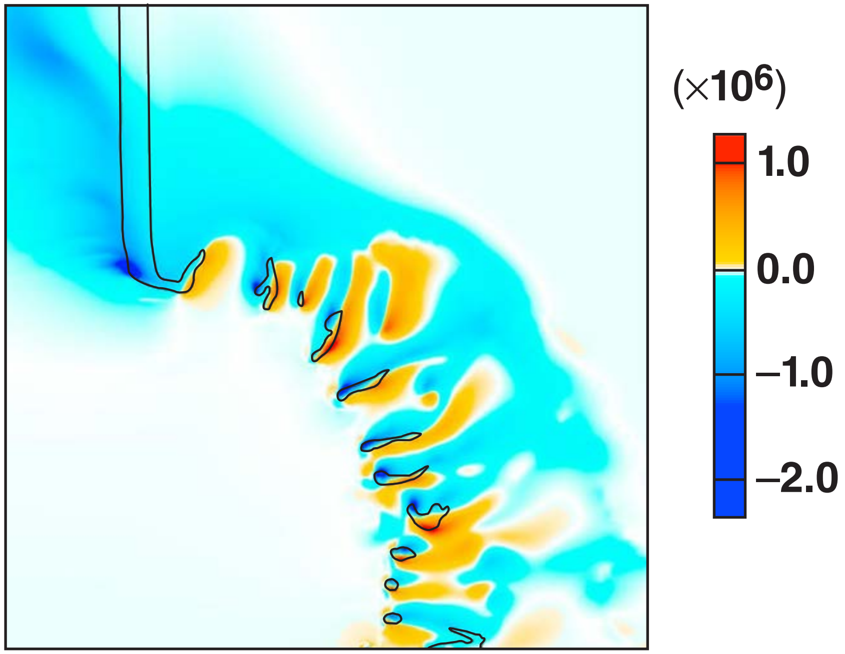
*L. Gao *et al*., Phys. Rev. Lett. 109, 115001 (2012).

# MG-level magnetic fields are predicted in a broken 15-$\mu$m-thick CH foil using 2-D magnetohydrodynamic (MHD) *DRACO** simulations

**Density (g/cm$^3$)**



**Magnetic induction (toroidal component) (Gauss)**



**Black line: density contour at 0.05 g/cm$^3$**

$t = t_0 + 2.1$ ns

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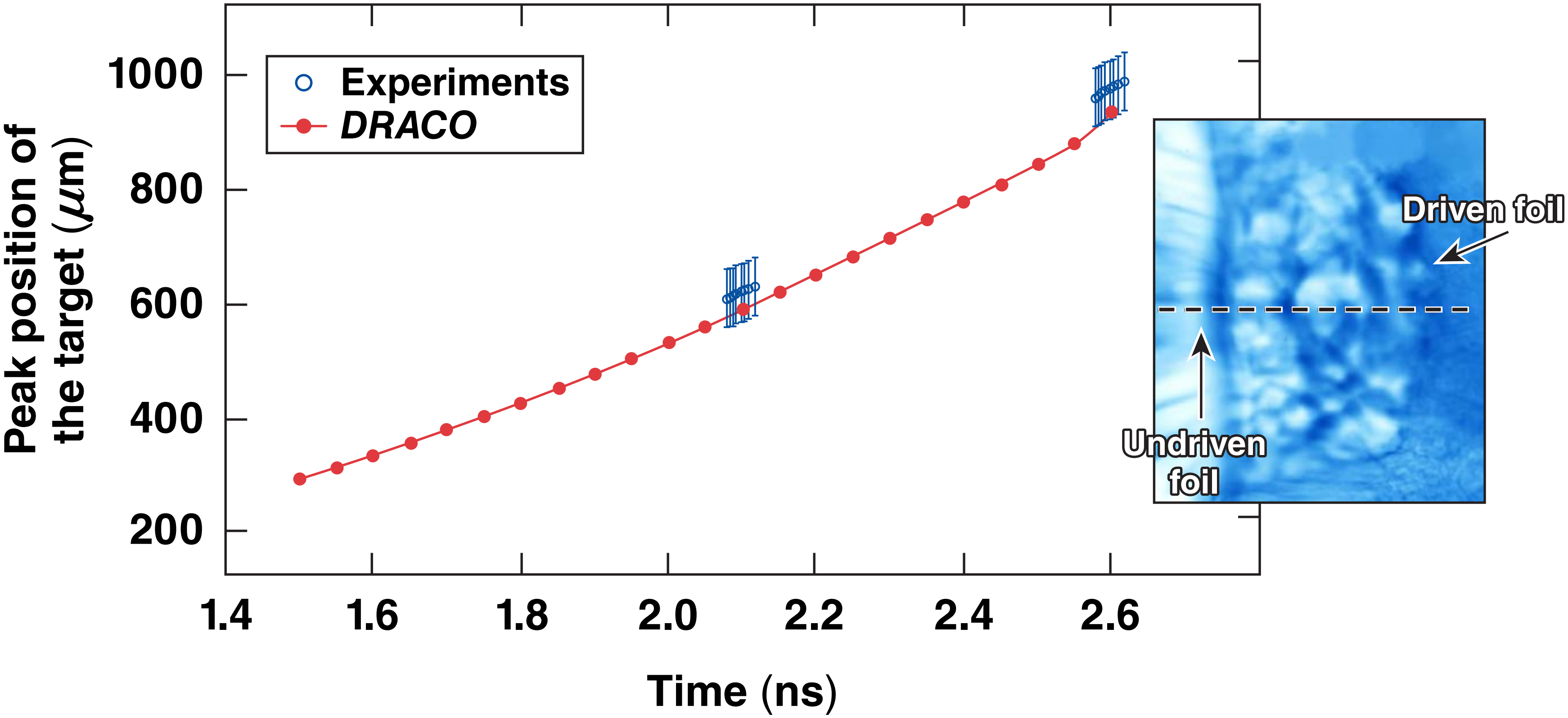
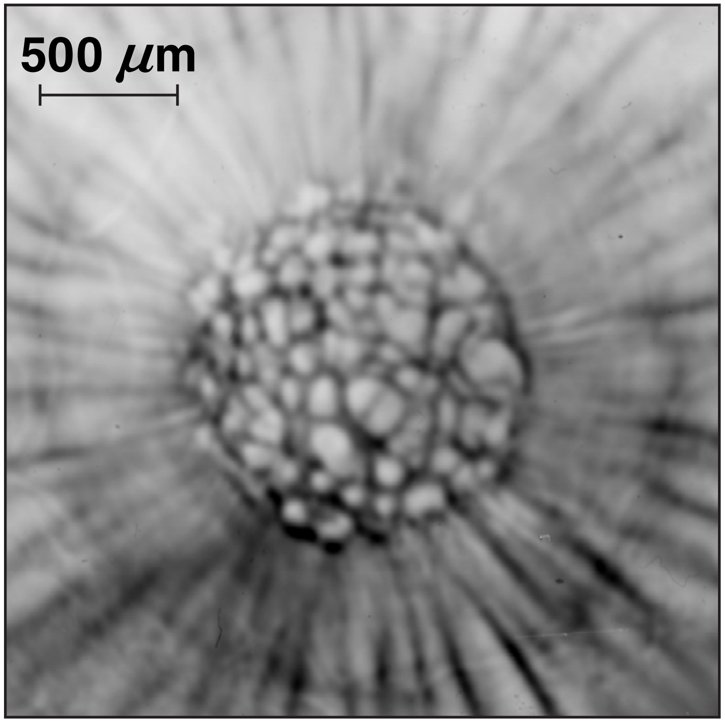
*D. Keller *et al.*, Bull. Am. Phys. Soc. 44, 37 (1999); P. B. Radha *et al.*, Phys. Plasmas 12, 032702 (2005).

# *DRACO* reproduces the measured foil trajectory



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

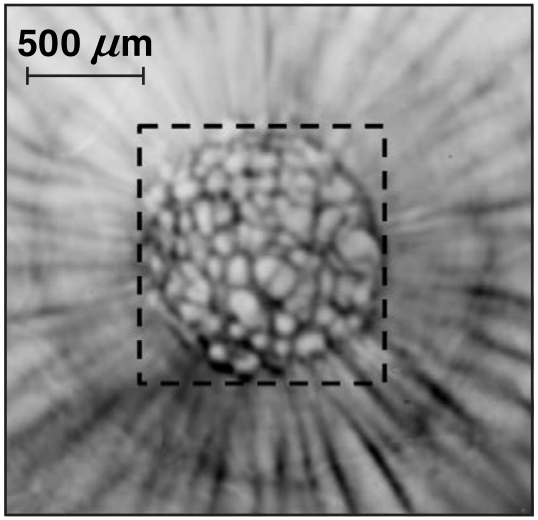
Proton radiograph



$t = t_0 + 2.6$ ns

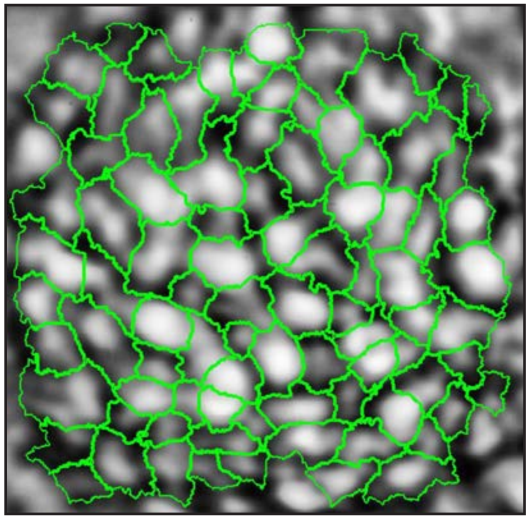
# The magnetic-field spatial distribution was characterized using the watershed algorithm

**Original image**

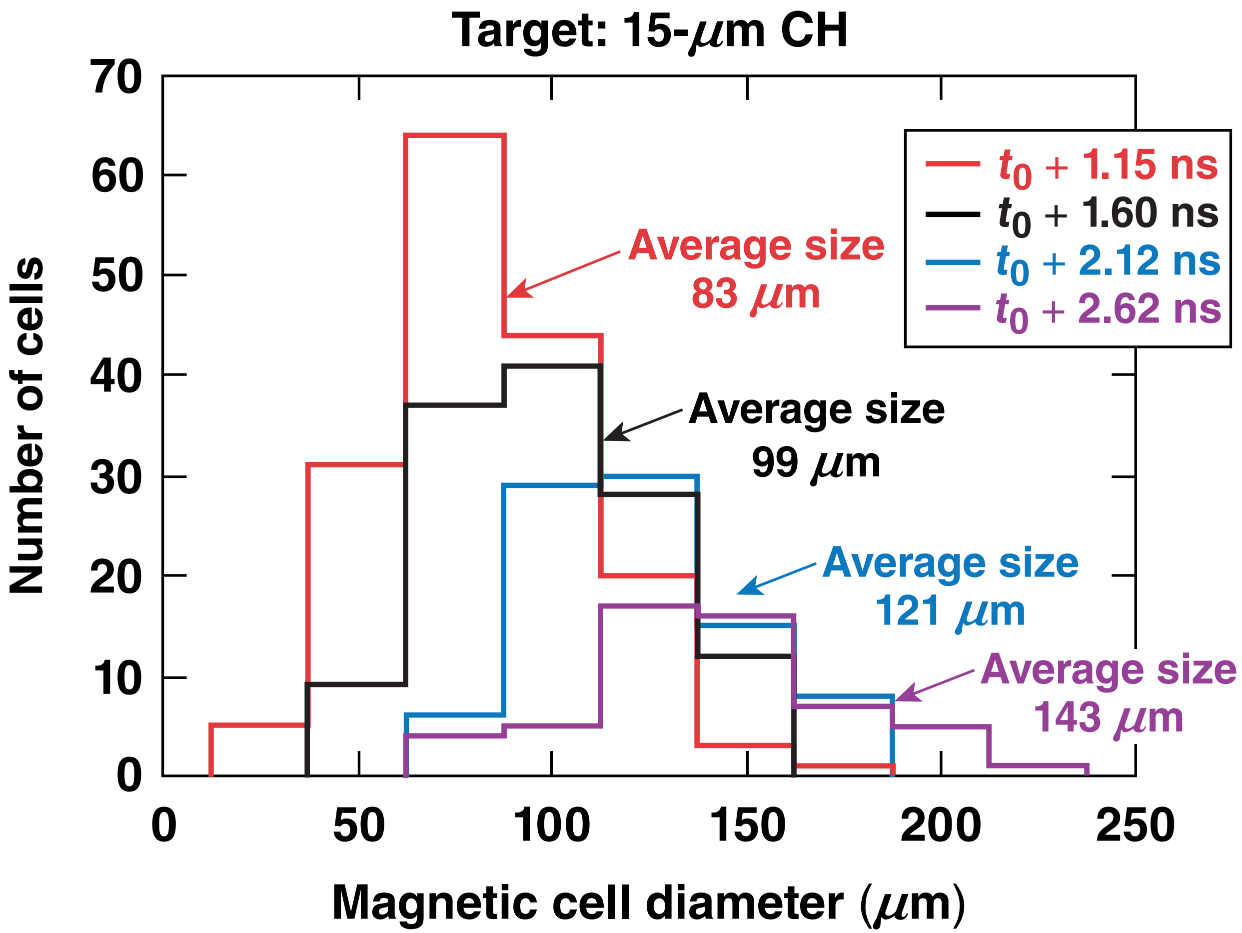


**Cropped image**
**1256 $\mu$m × 1184 $\mu$m**

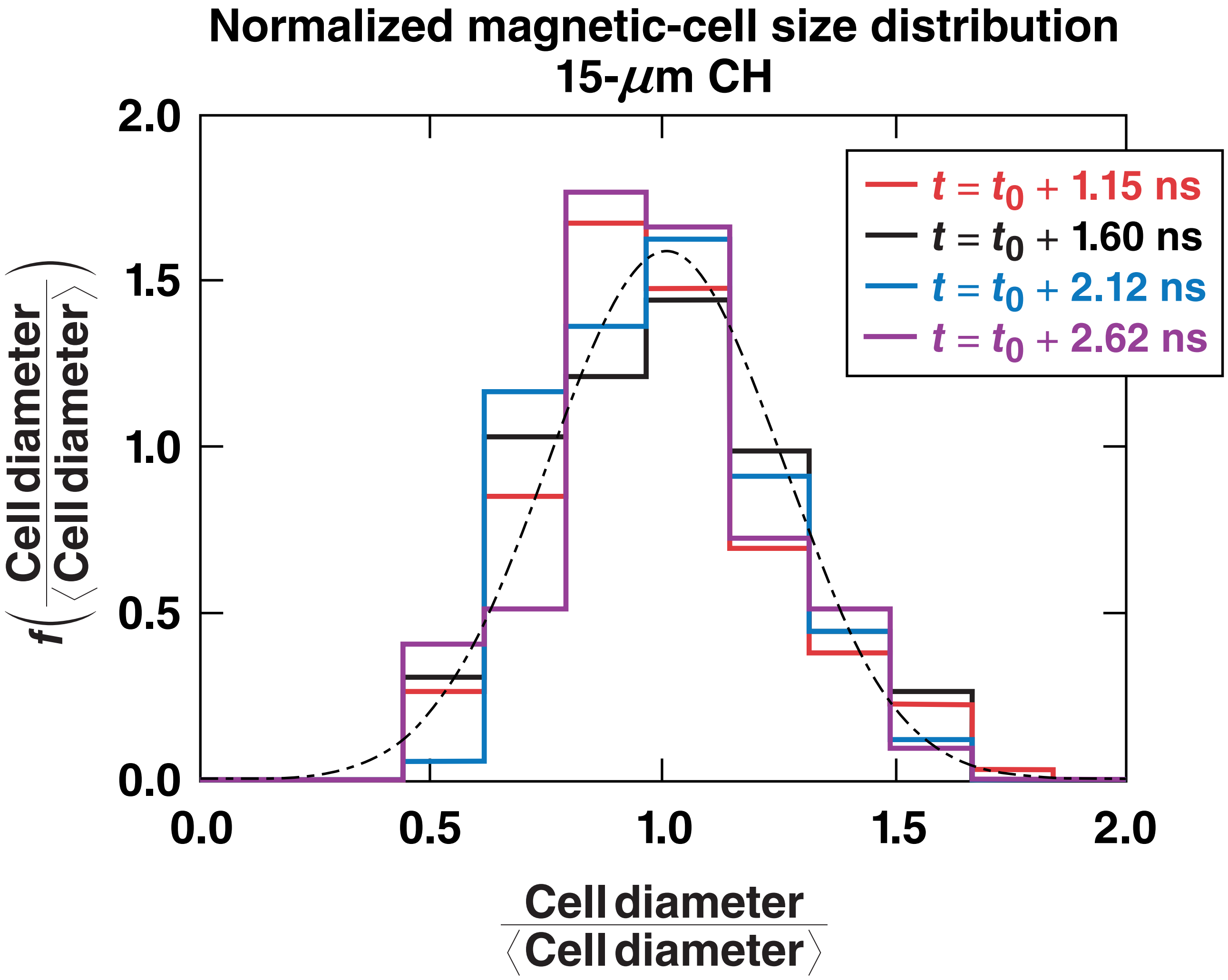
**Watershed segmentation**
**$t = t_0 + 2.6$ ns**



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

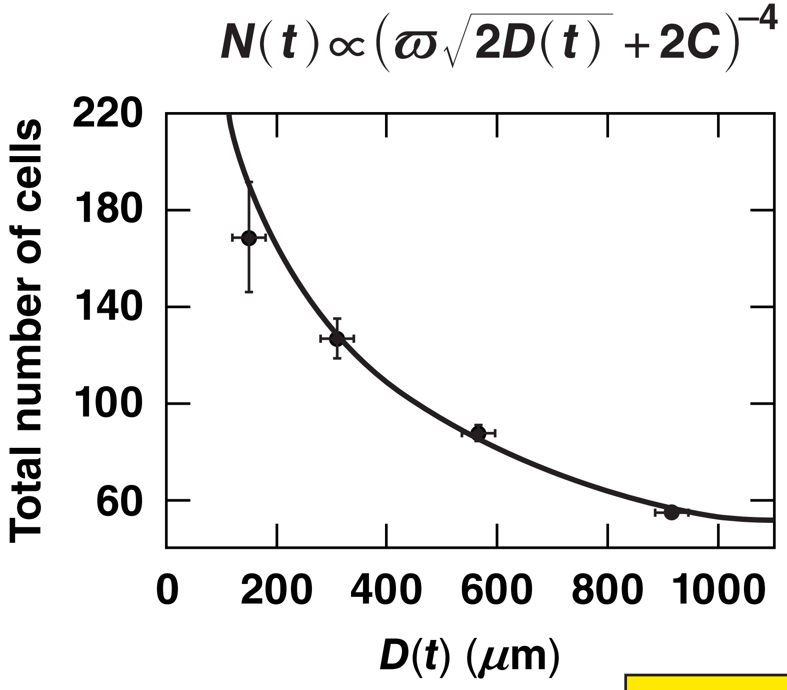


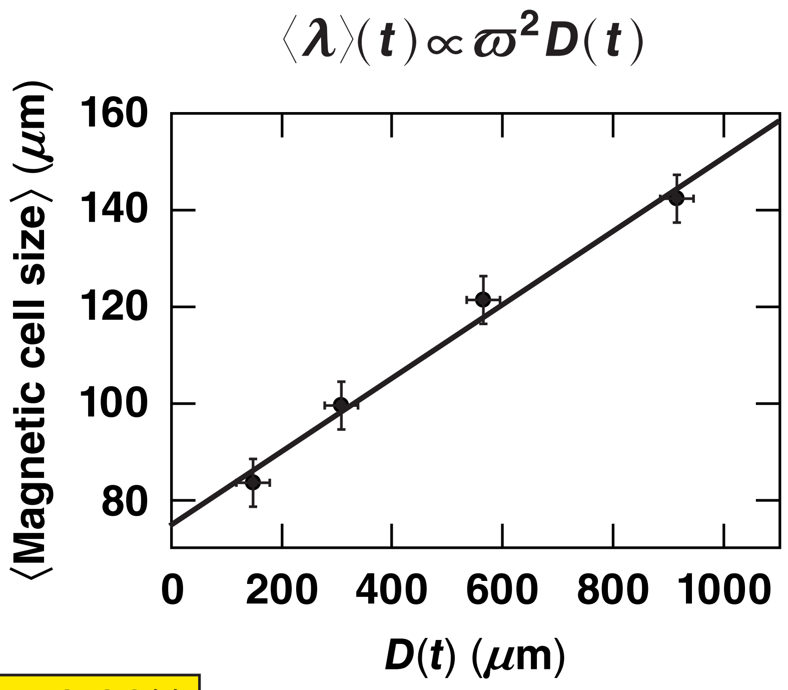
# The normalized magnetic-field spatial distribution evolves self-similarly



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

**Target: 15-$\mu$m CH**





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

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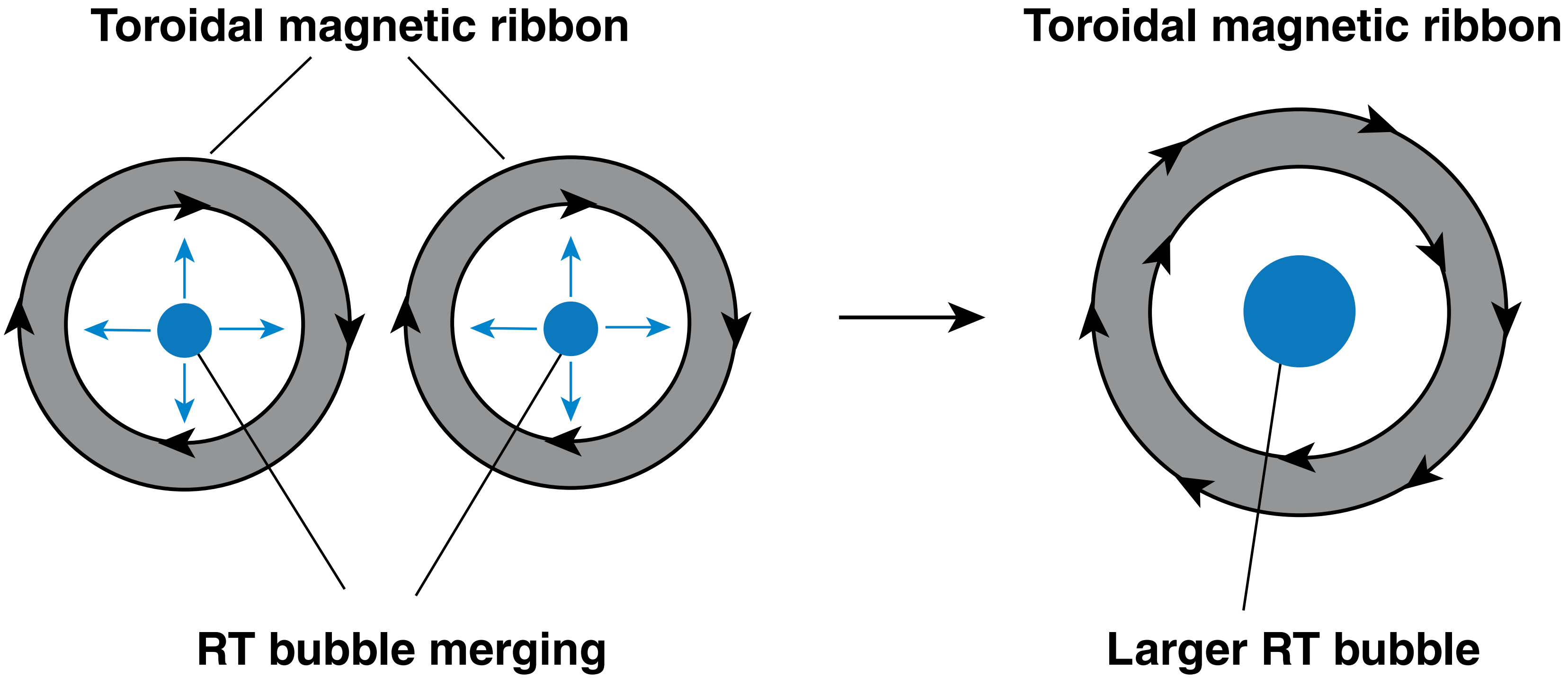
*O. Sadot *et al*., Phys. Rev. Lett. 95, 265001 (2005);
D. Oron *et al*., Phys. Plasmas 8, 2883 (2001);
U. Alon *et al*., Phys. Rev. Lett. 72, 2867 (1994).

**L. Gao *et al*., "Observation of Self-Similarity in the Magnetic Fields Generated by the Ablative Nonlinear Rayleigh–Taylor Instability," submitted to Physical Review Letters.

# The high-energy-density plasma is flow dominated

| Parameter | Symbol | OMEGA EP |
|---|---|---|
| Peak plasma density | $n_{e0}$ | $5 \times 10^{22}$ cm$^{-3}$ |
| Temperature | $T_e$ | 50 eV |
| Magnetic field | $B$ | $10^6$ G |
| Alfven speed | $V_A$ | $7 \times 10^3$ m s$^{-1}$ |
| Sound speed | $C_s$ | $6 \times 10^4$ m s$^{-1}$ |
| Estimated inflow | $V_{in}$ | $\sim C_s$ |
| Plasma beta | $\beta$ | 100 |
| Lundquist number | $S_0$ | 0.06 to 0.2 |
| Hall parameter | $\omega_{ce}/\nu_{e0}$ | 0.1 |
| Magnetic Reynolds number | $R_m$ | 0.5 to 1.0 |
| Diffusion time | $\tau$ | 0.1 to 1.0 ns |

# Global magnetic organization occurs as a result of diffusive magnetic reconnection



Toroidal magnetic ribbon

Toroidal magnetic ribbon

RT bubble merging

Larger RT bubble

**Summary/Conclusions**

# The scale-invariant regime of nonlinear Rayleigh–Taylor (RT) instability has been probed with proton radiography

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**The role of magnetic reconnection in this process is unknown.**

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*O. Sadot *et al*., Phys. Rev. Lett. 95, 265001 (2005).

# The distribution of magnetic-field ringlets in CH targets shifts to longer wave lengths