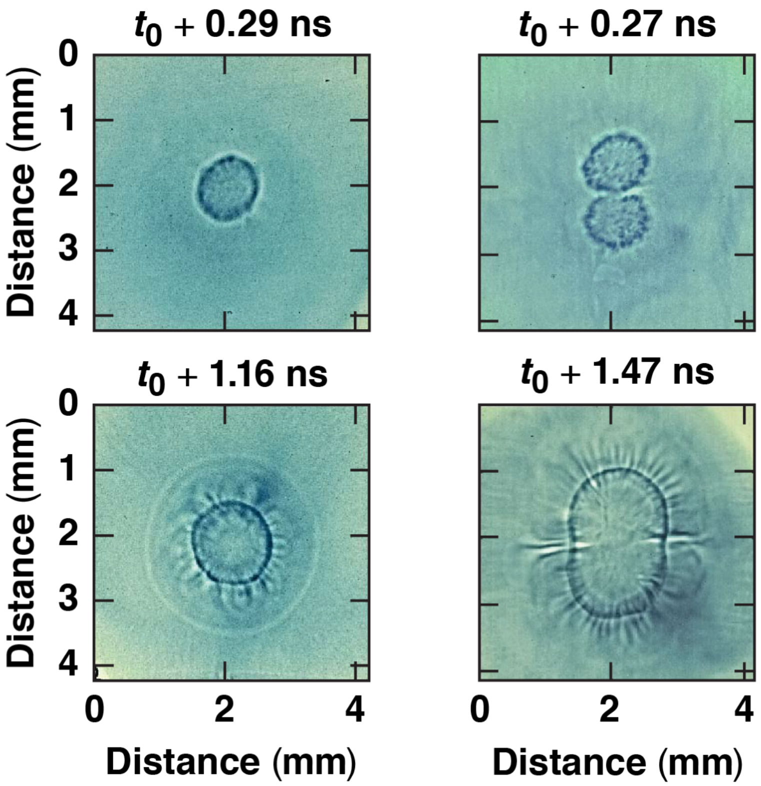
Magnetic Reconnection in the High-Energy-Density Regime



Laser Parameters

- Energy: 2 kJ
- Duration: 2.5 ns
- Intensity: >10^{14} W/cm^2

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Magnetic reconnection is demonstrated between two laser-produced plasmas that are generated one laser-spot diameter apart

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- Ultrafast proton radiography is used to provide detailed information on self-generated Biermann magnetic fields
  - location of fields
  - transport of fields
  - field merger and reconnection
- Single-beam interactions are used to map the magnetic fields
  - many features are reproduced by 2-D resistive MHD simulations
- Reconnection studies using an optimum laser-spot separation provide a complete time sequence of the reconnection process

Challenging the predictions of 3-D reconnection simulations is the next step.

MHD: magnetohydrodynamic

L. Gao, *et al.*, Phys. Rev. Lett. 114, 215003 (2015).

Collaborators

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Outline

- **Introduction**
- **Mapping laser-driven magnetic fields**
- **Gauging the optimum drive geometry**
- **Tracking magnetic connectivity changes**
- **Path forward**

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Laser-produced plasmas have emerged as a promising new paradigm for the creation and diagnosis of magnetic reconnection at high energy density (HED)

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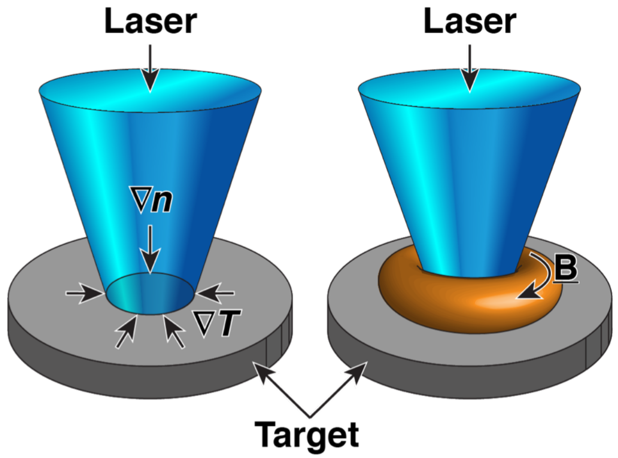
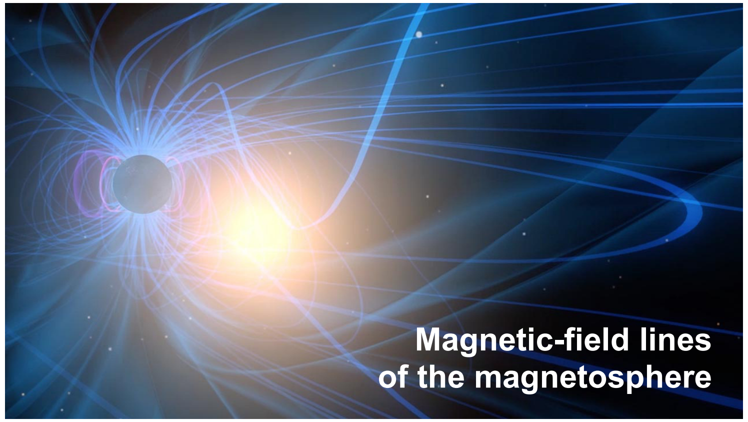
- Motivated by an improved understanding of reconnection theory and its application to
  - astrophysical environments
  - fusion plasmas and extreme radiation sources
  - fundamental HED plasma studies
- Important open questions concern the multiscale processes that lead to
  - reconnection onset
  - magnetic connectivity changes
  - the conversion of magnetic energy into other forms





New techniques are sought to recreate and study these processes under conditions of extreme energy density.

J. A. Stamper and B. H. Ripin, Phys. Rev. Lett. 34, 138 (1975);
M. Yamada, R. M. Kulsrud, and H. Ji, Rev. Mod. Phys. 82, 603 (2010);
D. A. Uzdensky, Space Sci. Rev. 160; 45-71 (2011);
E. G. Zweibel and M. Yamada, Proc. Roy. Soc. A 472, 20160479 (2016);
www.nasa.gov

Previous experimental and computational studies have proposed, implemented, and studied key aspects of magnetic reconnection in HED plasmas

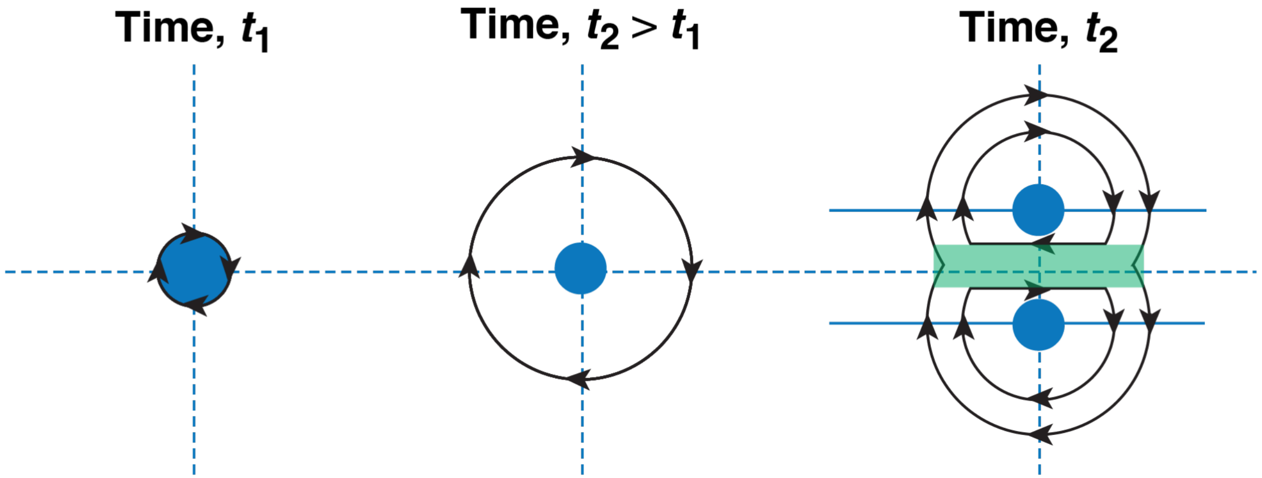
- Experiments have demonstrated
  - reconnection-layer formation
  - MG-field topology changes
  - reconnection stagnation
  - particle acceleration
  - the effects of asymmetric flows

- Computational studies have shown
  - strong reconnection drive and flux pile up
  - plasmoid formation
  - heat-flux effects
  - non thermal electron energization
  - vertically localized flux reconnection

To further challenge model predictions, detailed measurements are required with improved precision and accuracy.

C. K. Li *et al*., Phys. Rev. Lett. 97, 135003 (2006);
P. M. Nilson *et al*., Phys. Rev. Lett. 97, 255001 (2006);
C. K. Li et al., Phys. Rev. Lett. 99, 055001 (2007);
P. M. Nilson *et al*., Phys. Plasmas 15, 092701 (2008);
R. D. Petrasso *et al*., Phys. Rev. Lett. 103, 085001 (2009);
J. Zhong et al., Nat. Phys. 6, 984 (2010);
L. Willingale *et al*., Phys. Plasmas 17, 043104 (2010);
W. Fox, A. Bhattacharjee, and K. Germaschewski, Phys. Rev. Lett. 106, 215003 (2011);
W. Fox, A. Bhattacharjee, and K. Germaschewski, Phys. Plasmas 19, 056309 (2012);
Q.-L. Dong *et al*., Phys. Rev. Lett. 108, 215001 (2012);
M. J. Rosenberg *et al*., Phys. Rev. E 86, 056407 (2012);
L. Lancia *et al*., Phys. Rev. Lett. 113, 235001 (2014);
A. S. Joglekar *et al*., Phys. Rev. Lett. 112, 105004 (2014);
M. J. Rosenberg *et al*., Nat. Commun. 6, 6190 (2015);
M. J. Rosenberg *et al*., Phys. Rev. Lett. 114, 205004 (2015);
S. R. Totorica, T. Abel, and F. Fiuza, Phys. Rev. Lett. 116, 095003 (2016);
C. Liu *et al*., Phys. Rev. E 96, 043203 (2017);
J. D. Hare *et al*., Phys. Rev. Lett. 118, 085001 (2017);
K. V. Lezhnin *et al*., Phys. Plasma 25, 093105 (2018);
A. E. Raymond *et al*., Phys. Rev. E 98, 043207 (2018);
J. Matteucci *et al*., Phys. Rev. Lett. 121, 095001 (2018).

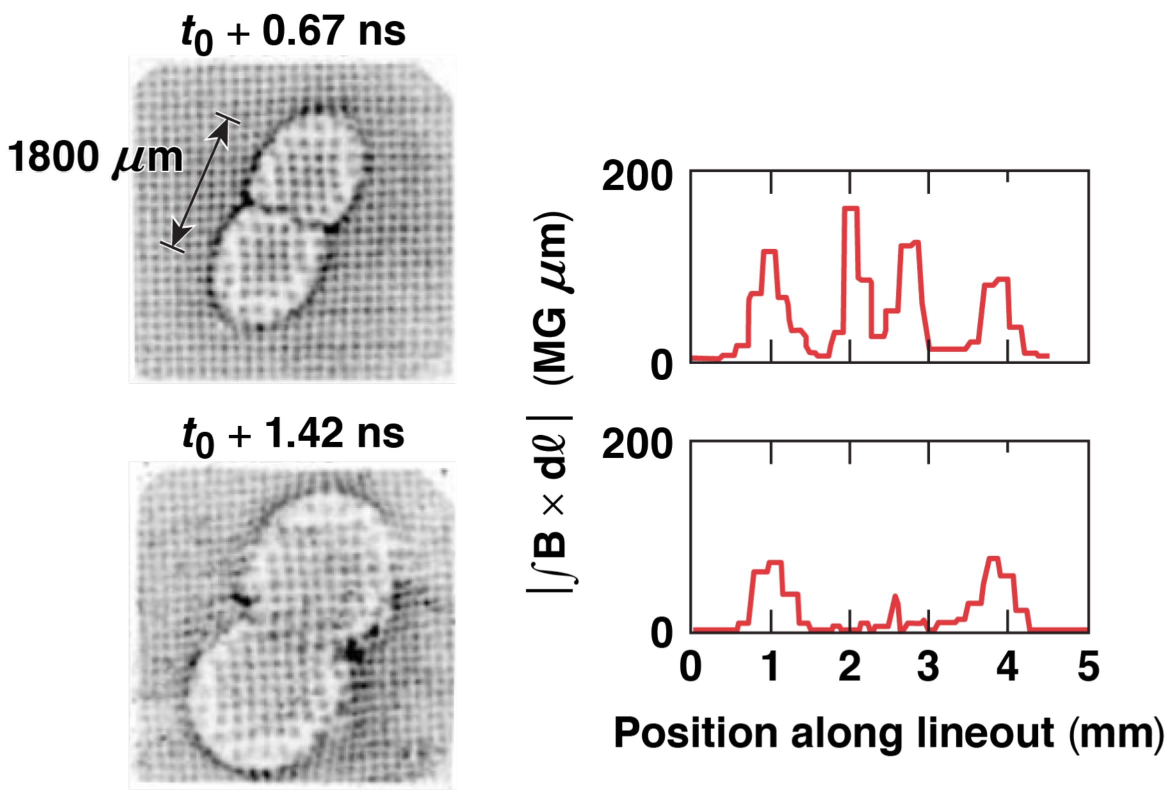
The standard picture says reconnection occurs when two expanding plasmas come together and opposing magnetic fields interact with each other



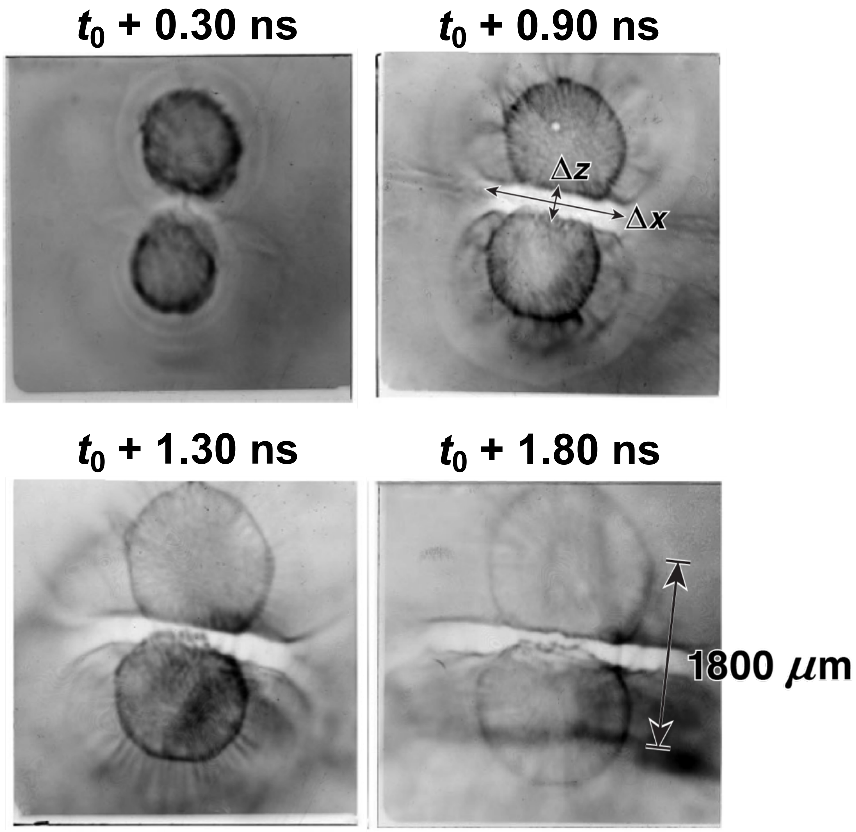
- MG-level Biermann fields surround each plume
- As the plasmas expand, the fields are forced together and reconnect

Reconnection layer formation and magnetic connectivity changes were previously observed using large laser-spot separations

OMEGA experiments*



OMEGA EP experiments**



* C. K. Li *et al.*, Phys. Rev. Lett. 99, 055001 (2007).
** M. J. Rosenberg *et al.*, Phys. Rev. Lett. 114, 205004 (2015).

Direct, high-resolution measurements are required to elucidate the physics of these strongly time- and space-dependent reconnection events*

- **Single-beam interactions**
  - **identify where in the plasma the Biermann fields exist as a function of time****
- **Multibeam interactions**
  - **determine the optimum drive geometry for allowing the largest fields to reconnect**
  - **track the magnetic connectivity changes**

* J. Matteucci *et al.*, Phys. Rev. Lett. 121, 095001 (2018).
** L. Gao *et al.*, Phys. Rev. Lett. 114, 215003 (2015).

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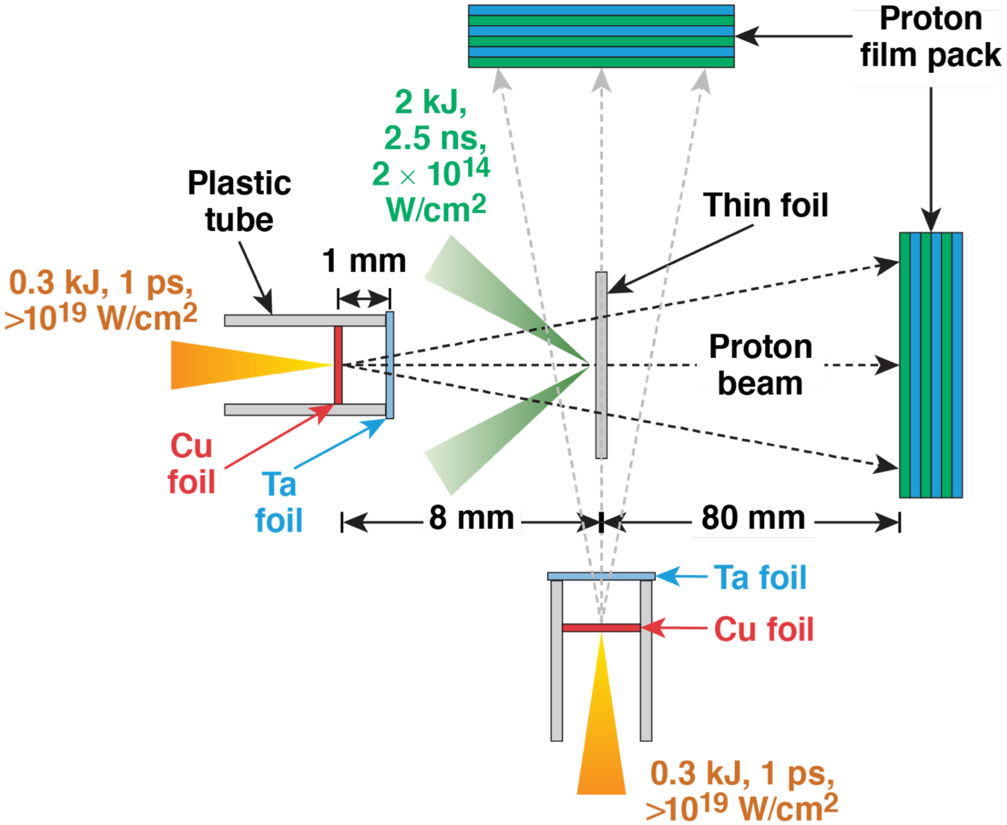
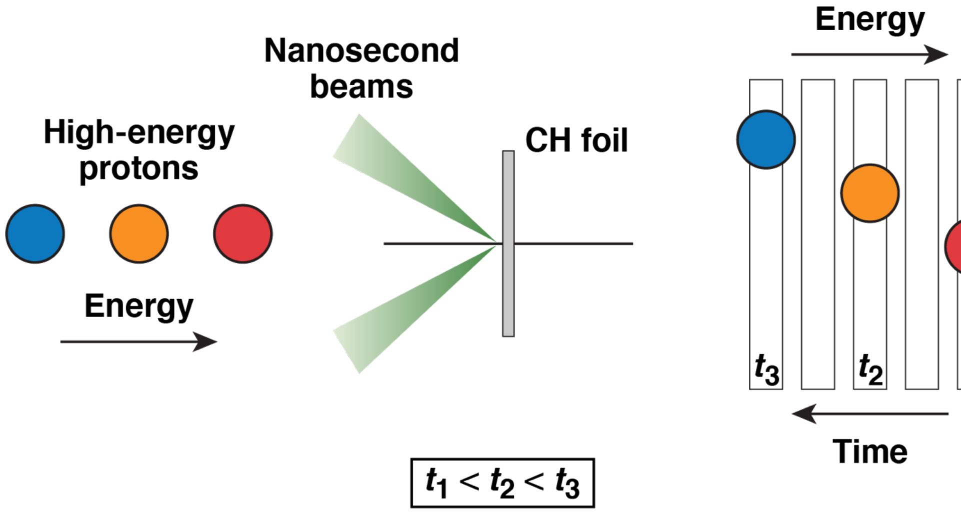
OMEGA EP can generate a long-pulse–driven reconnection geometry while probing the system dynamics with two ultrafast, laser-driven proton beams





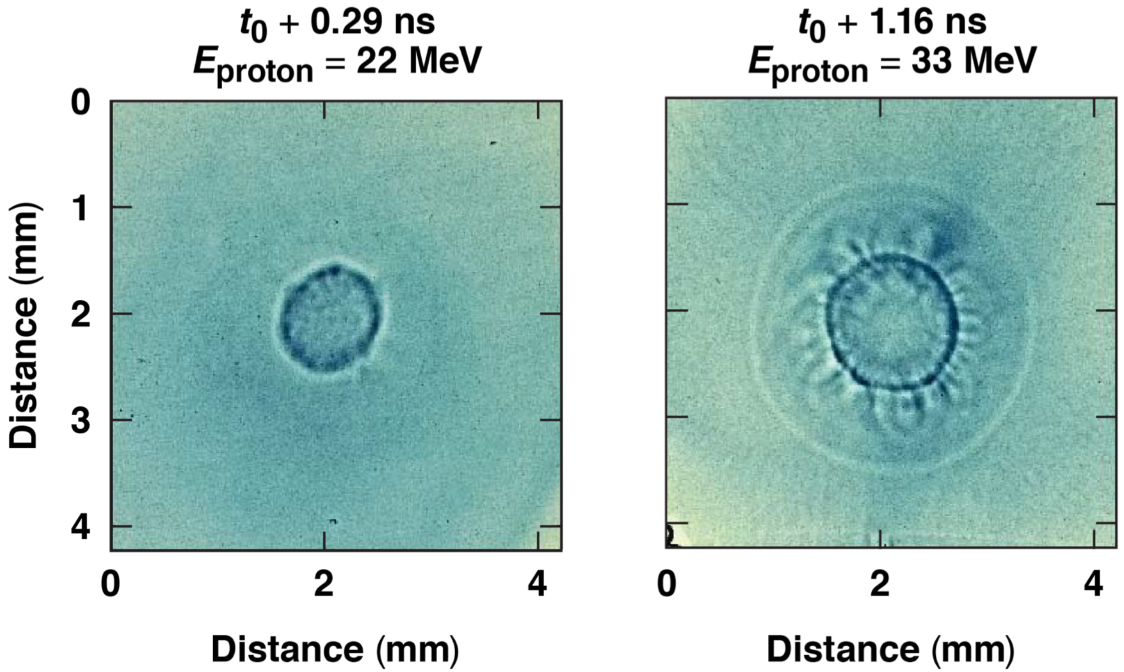
Ultrafast proton radiography*

- Short temporal burst: few ps
- High energy: up to 60 MeV
- Virtual proton source much smaller than the high-intensity laser spot

Time-of-flight dispersion and a filtered stack detector produces a multiframe imaging capability.

* S. C. Wilks *et al.*, Phys. Plasmas. 8, 542 (2001);
M. Borghesi *et al.*, Phys. Rev. Lett. 92, 055003 (2004);
T. E. Cowan *et al.*, Phys. Rev. Lett. 92, 204801 (2004);
L. Romagnani *et al.*, Phys. Rev. Lett. 95, 195001 (2005).

Face-on proton radiography measurements show where the Biermann fields are generated and to where they are transported during the laser drive



- **Darker regions indicate a higher detected proton flux**

The data show two circular structures that grow in time.

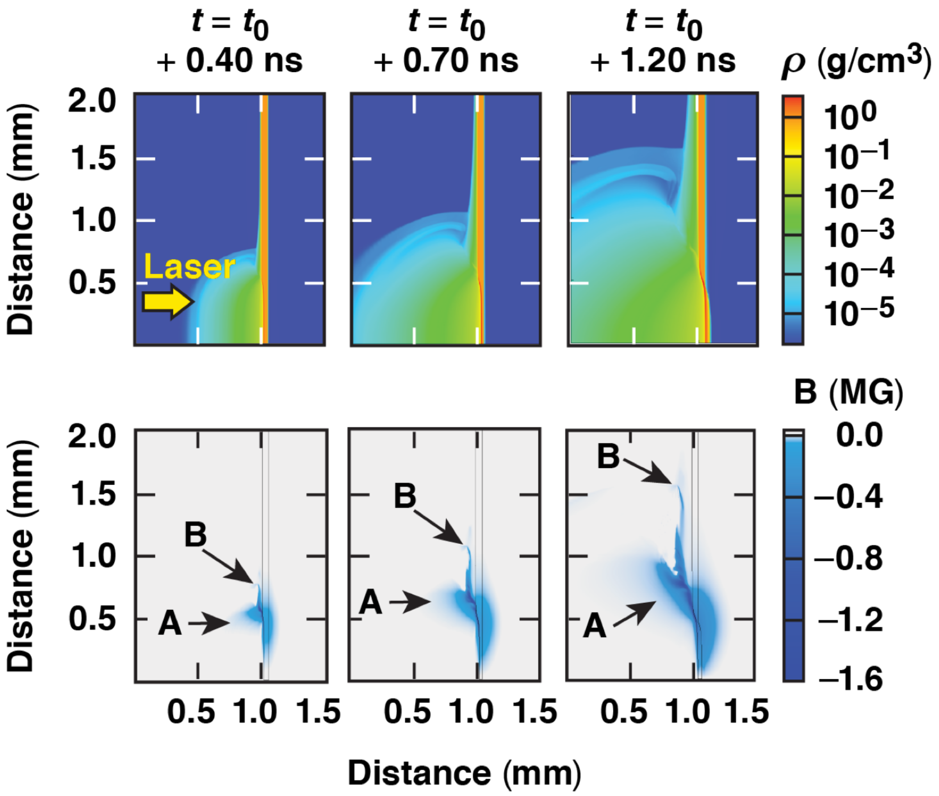
Self-generated magnetic fields and magnetic-dependent heat fluxes in laser-ablated plasma were calculated using the Braginskii formulation*

- The 2-D code *DRACO*** uses the induction equation with all Braginskii's terms

Flow convection — Source — Pinch — Nernst — Diffusion

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{V} \times \vec{B}) + \frac{c}{e}\left[\nabla \times \frac{\nabla p_e}{n_e} - \nabla \times \frac{(\nabla \times \vec{B}) \times \vec{B}}{4\pi n_e} - \nabla \times \frac{\vec{R}_T + \vec{R}_u}{n_e}\right]$$

The largest magnetic fields have MG magnitude and bound the laser-focal region.

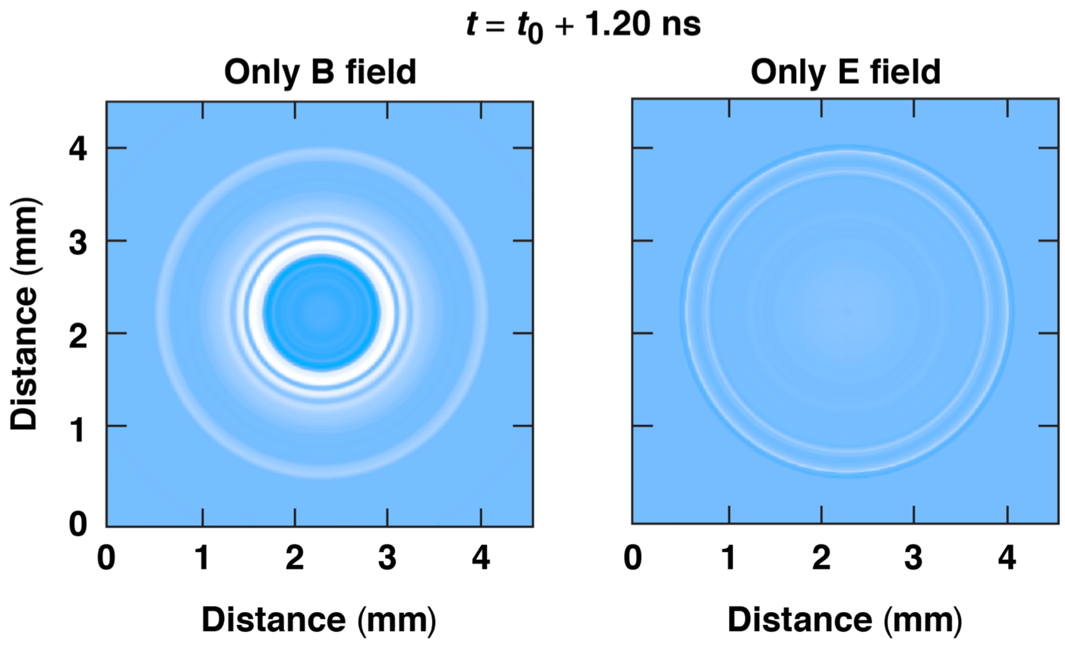


R_u: friction force
R_T: thermal force

* S. I. Braginskii, in *Reviews of Plasma Physics*, edited by M. A. Leontovich (Consultants Bureau, New York, 1965), Vol. 1, pp. 262–276.
** P. B. Radha *et al.*, Phys. Plasmas 12, 032702 (2005);
I. V. Igumenshchev *et al.*, Phys. Plasmas 21, 062707 (2014);
M. G. Haines, Can. J. Phys. 64, 912 (1986).

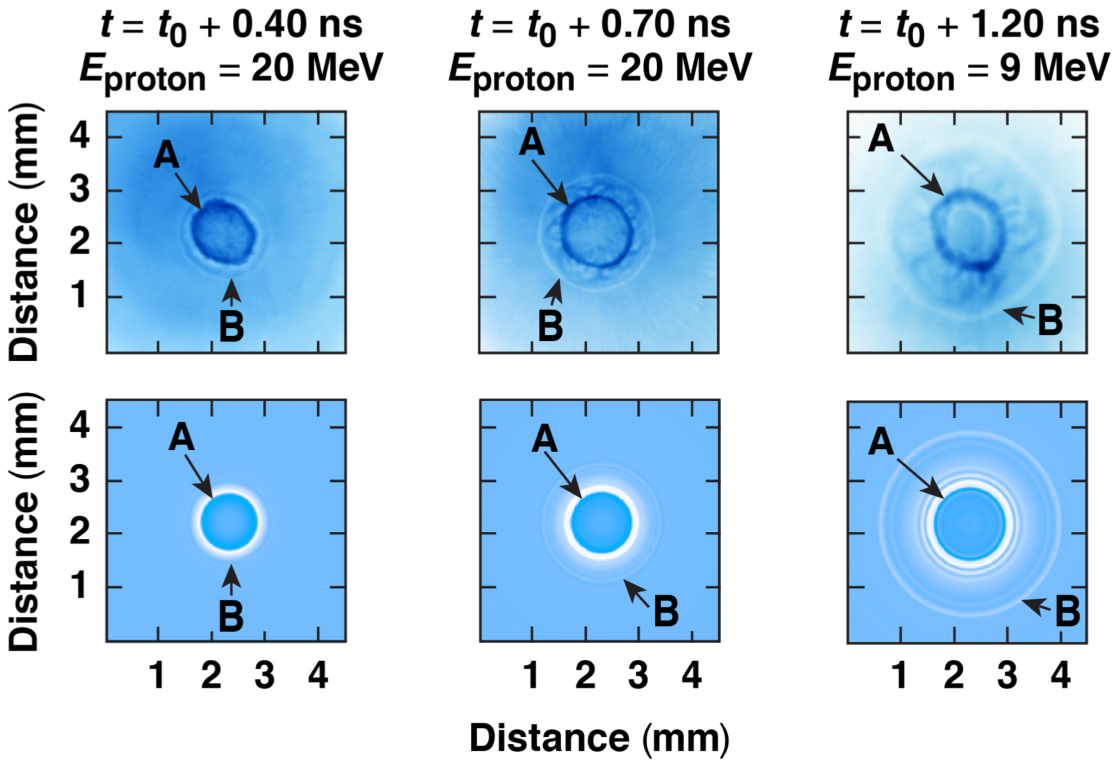
The electromagnetic-field distributions from *DRACO* were post-processed with a proton tracking code that used the same geometry as the experiment

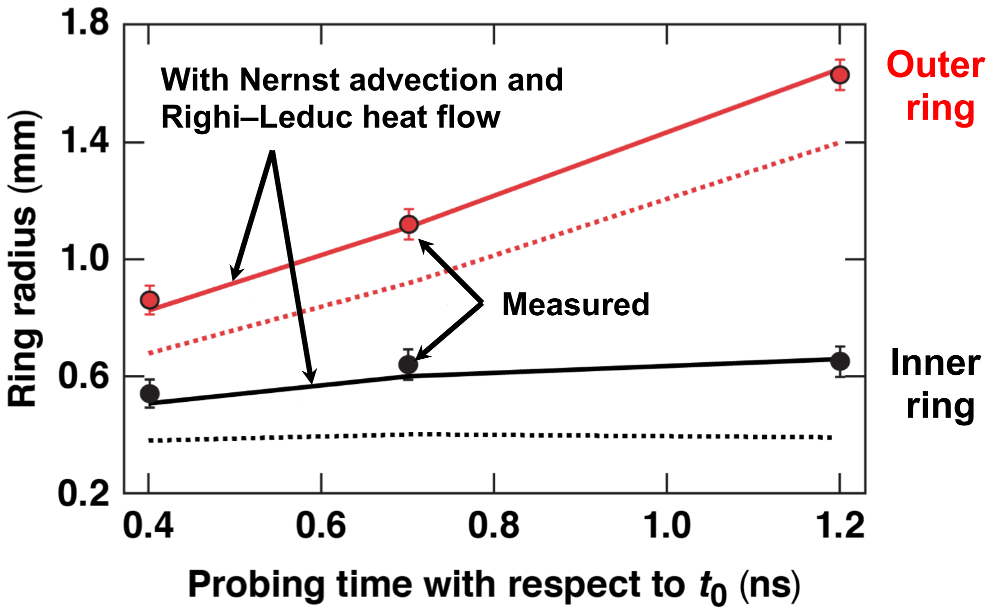
- At the coronal-plasma front
  - electric fields deflect protons
  - magnetic fields focus protons
  - causes a local proton flux deficit
- At the laser-focal region
  - magnetic fields focus protons
  - creates the inner dark ring



Getting the field magnitudes correct at the edge of the coronal plasma requires the consideration of kinetic effects not included in *DRACO*.

The synthetic radiographs reproduce the main features that were observed experimentally, aiding interpretation of the magnetic-field distribution





The light and dark rings provide a metric to understand the effect of spot separation in defining the reconnection geometry.

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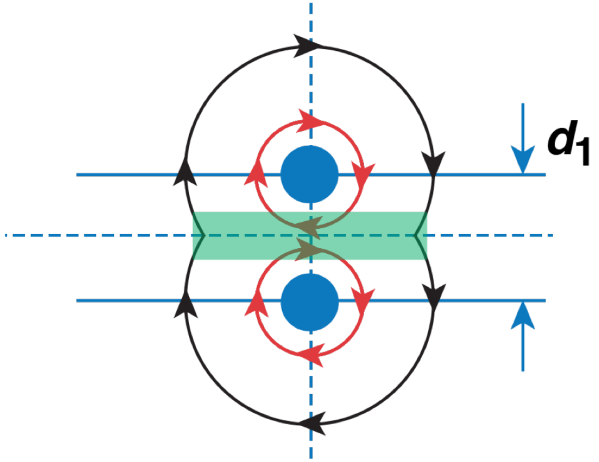
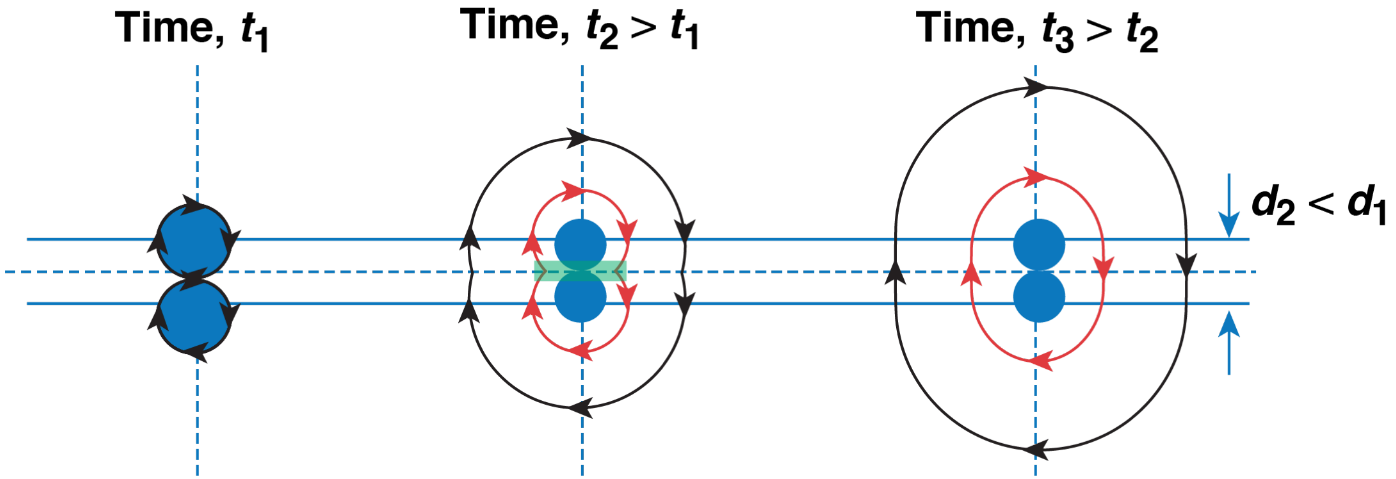
Larger laser-spot separations increase the time for expansion before the fields at the edge of each plume can meet and form a reconnection layer



The largest magnetic fields likely do not meet.

Smaller laser-spot separations reduce the time for expansion, allowing the Biermann fields at the edge of each laser-focal region to interact



- The interaction occurs earlier in time
- The distance the largest magnetic fields must be transported is reduced
- The system is less perturbed by plasma accumulation at the mid plane

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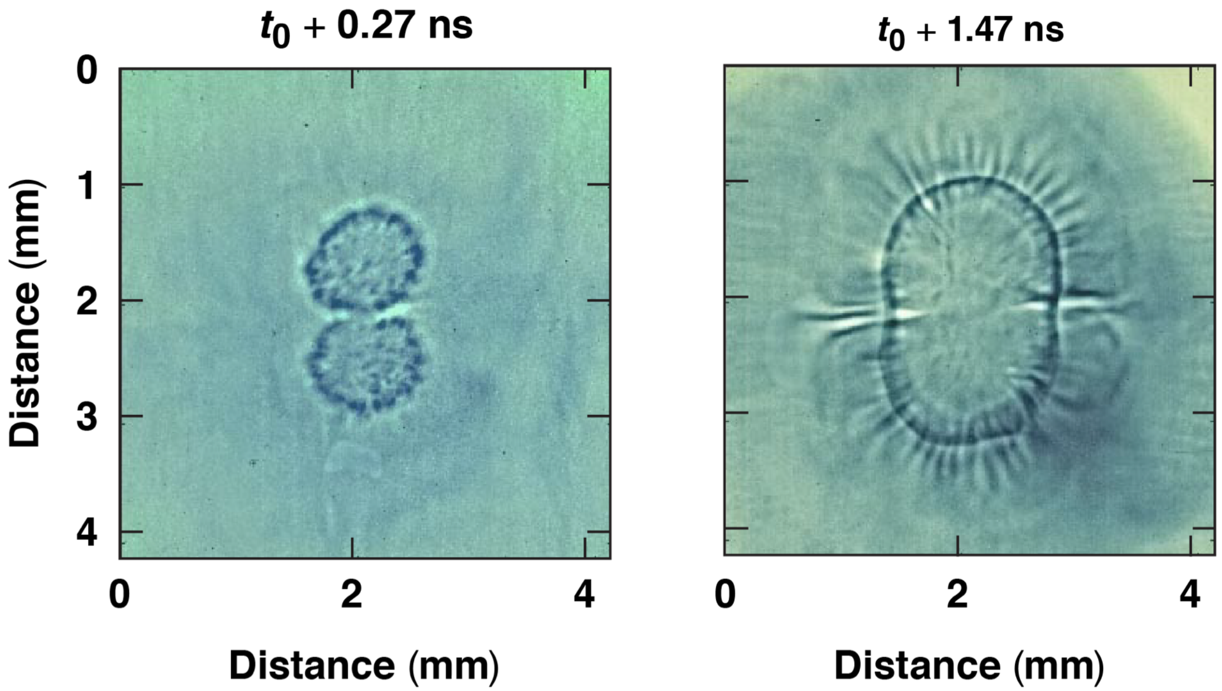
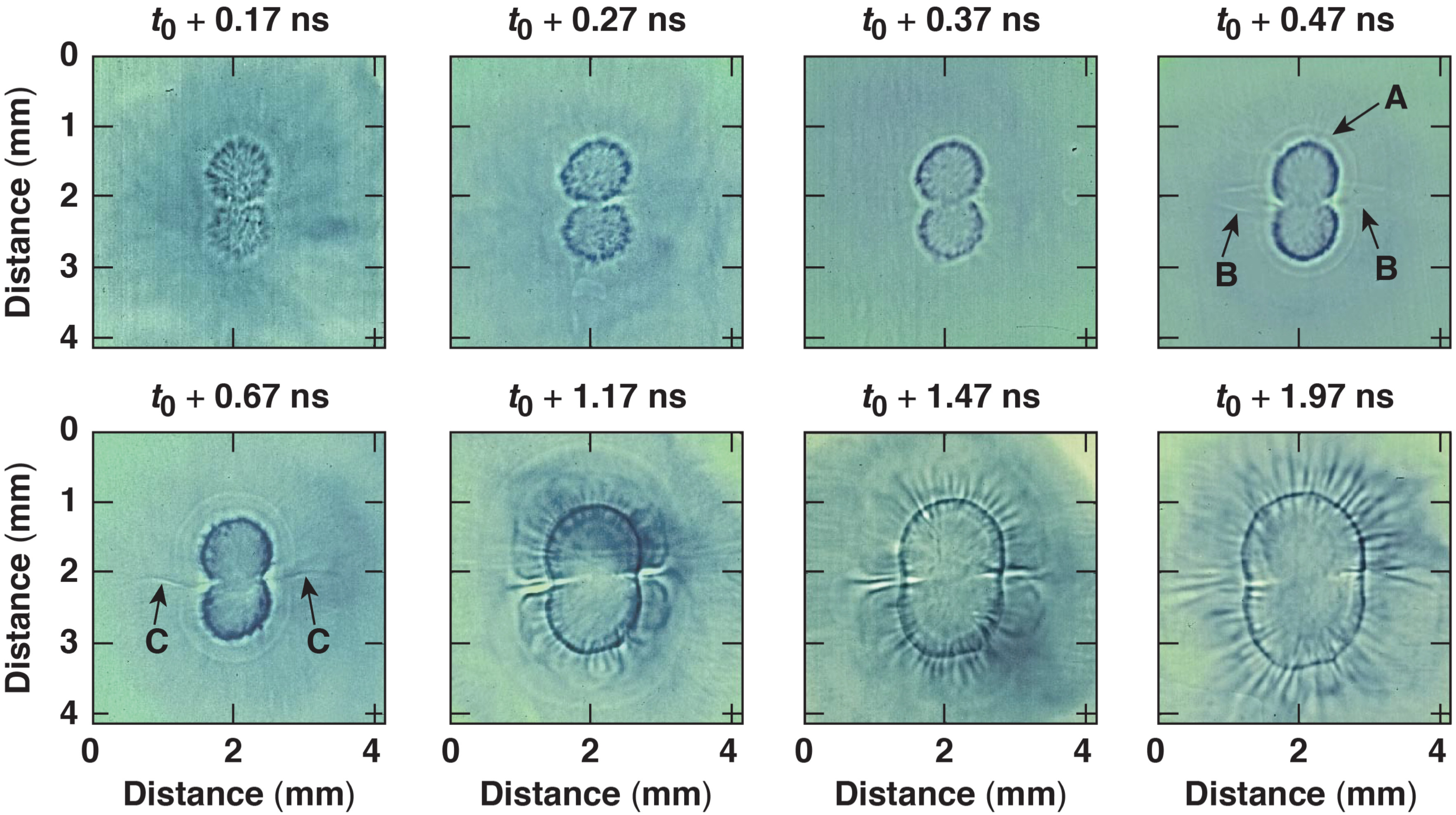
As a result of the closer spot separation, magnetic reconnection is driven between the magnetic fields that exist at the edge of each laser-focal region



The geometry modifies where, when, and how reconnection occurs.

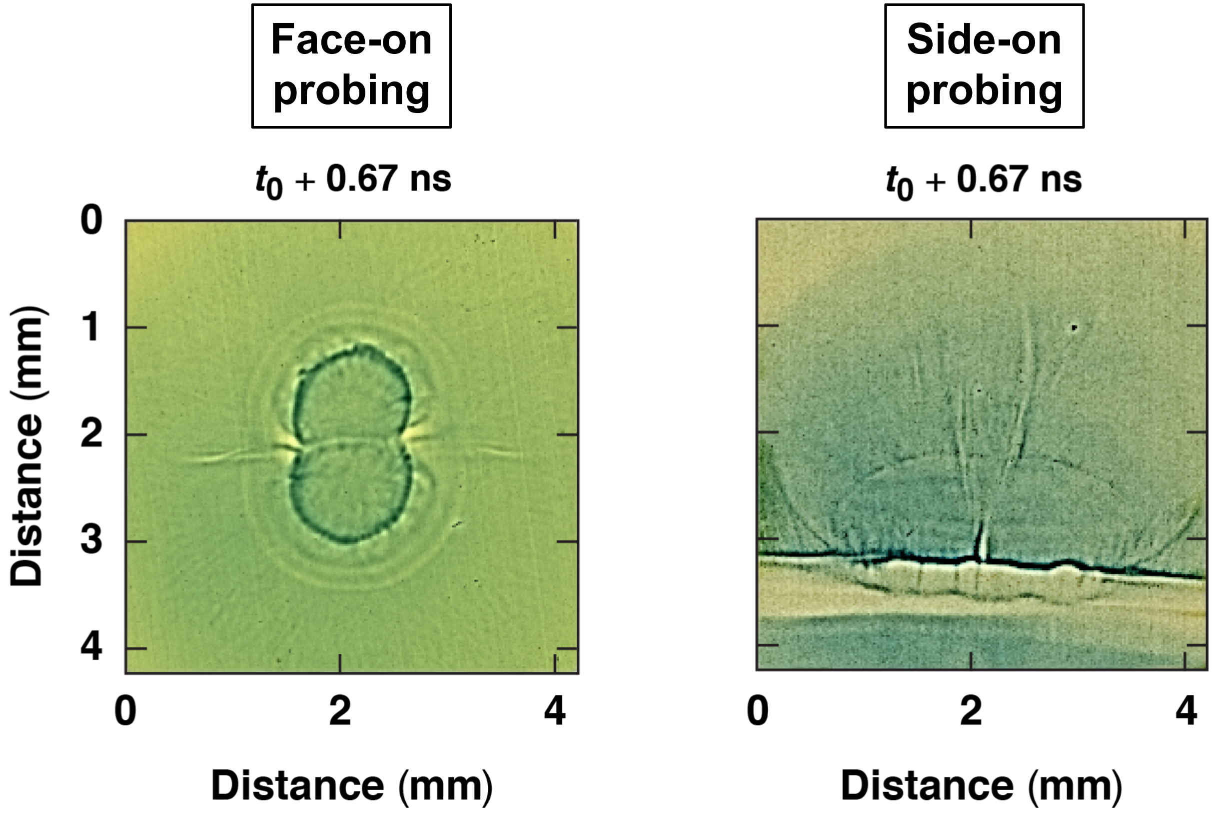
The change in magnetic connectivity was tracked in time



The merging plasmas do not behave as a single asymmetric plume

- The collision region has a proton deficit
- Protons are deflected out of the current sheet
- Provides a lower bound on the path-integrated magnetic-field strength

Reconnection layer width = 100 μm
Maximum proton energy = 30 MeV
Path-integrated field strength > 60 MGμm
Integrated path legend = 500 μm
Inferred magnetic field > 0.1 MG



The reconnection layer forms before significant plasma accumulation can occur at the mid plane.

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Outstanding questions about the location and interaction of the Biermann fields have been reconciled; uncertainties exist in the integrated-system dynamics

- **Multidimensional implications**
  - **the Biermann generation and reconnection zones coincide**
- **An improved understanding of the 3-D collision and merging process is required**
- **Multidimensional plasma characterization must be revisited in this geometry**
  - **optical Thomson scattering**
  - **x-ray imaging**
  - **high-energy particle detection**
  - **field reconstruction***

* C. Graziani et. at., Rev. Sci. Instrum. 88, 123507 (2017).

Summary/Conclusions

Magnetic reconnection is demonstrated between two laser-produced plasmas that are generated one laser-spot diameter apart

- Ultrafast proton radiography is used to provide detailed information on self-generated Biermann magnetic fields
  - location of fields
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- Single-beam interactions are used to map the magnetic fields
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