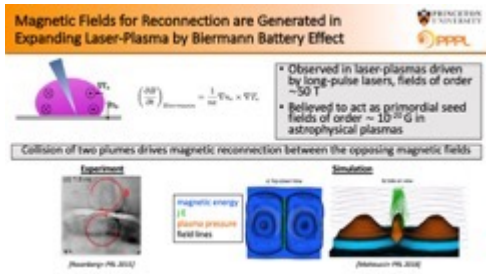
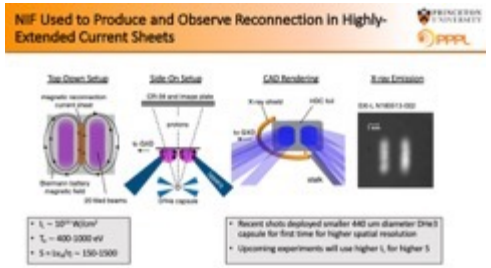
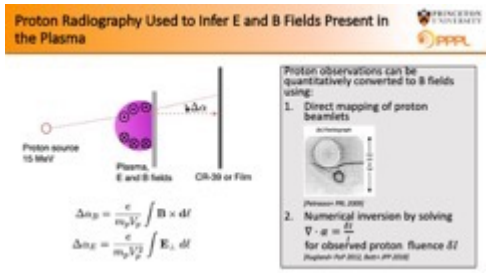
D.B. Schaeffer[1,2], W. Fox[3,1], M. Rosenberg[4], G. Fiksel[5], J. Matteucci[1], H.-S. Park[6], A.F. Bott[1], K.V. Lezhnin[1], A. Bhattacharjee[1,2,3], D. Kalantar[6], B.A. Remington[6], D. Uzdensky[7], C.K. Li[8], F.H. Seguin[8], and S.X. Hu[4]

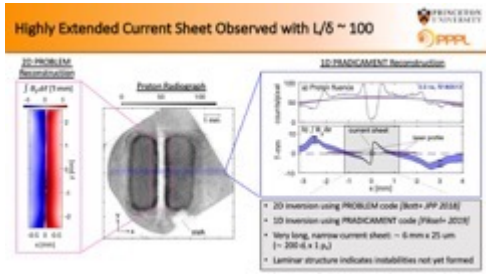
[1]Princeton University; [2]Princeton Center for Heliophysics; [3]PPPL; [4]LLE; [5]University of Michigan; [6]LLNL; [7]University of Colorado; [8]MIT Plasma Science & Fusion Center

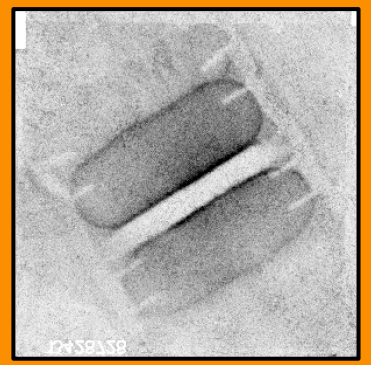
Large-Scale, Low Dissipation Magnetic Reconnection on the NIF

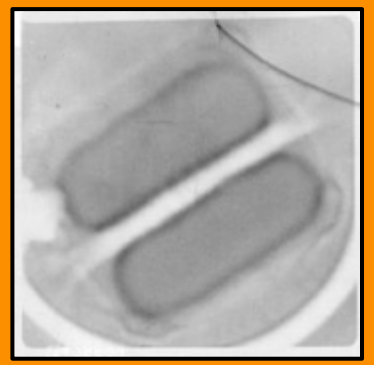


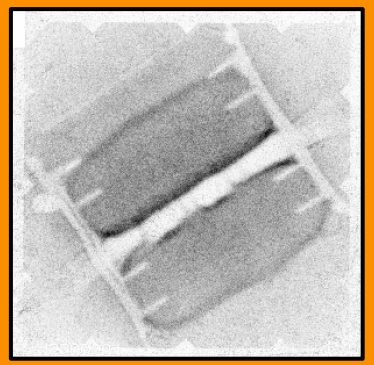








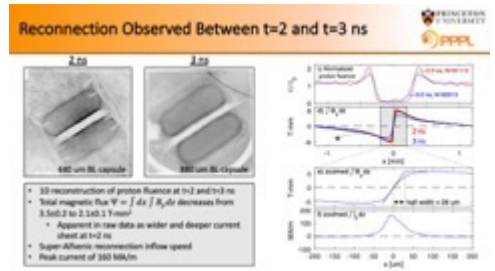


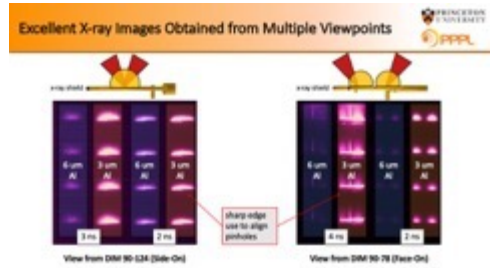


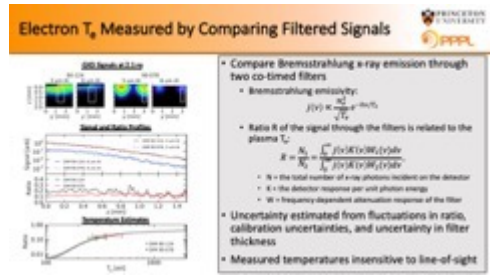
NIF-JLF User Group Meeting

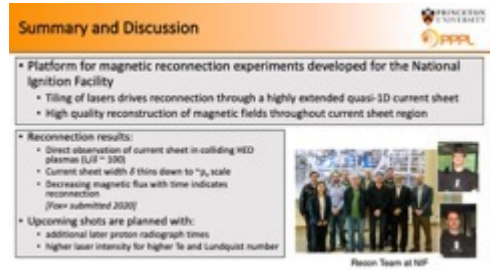
Feb. 7-9, 2022

Supported by the DOE FES & NNSA, NIF Discovery Science (experiments), and DOE INCITE (computation)









Summary

- Platform for magnetic reconnection experiments developed for the National Ignition Facility
  - Tiling of lasers drives reconnection through a highly extended quasi-1D current sheet
  - High quality reconstruction of magnetic fields throughout current sheet region
- Reconnection results:
  - Direct observation of current sheet in colliding HED plasmas ($L/\delta \sim 100$)
  - Current sheet width δ thins down to ~ρ_e scale
  - Decreasing magnetic flux with time indicates reconnection

  [Fox+ arXiv:2003.06351]

Magnetic Fields for Reconnection are Generated in Expanding Laser-Plasma by Biermann Battery Effect

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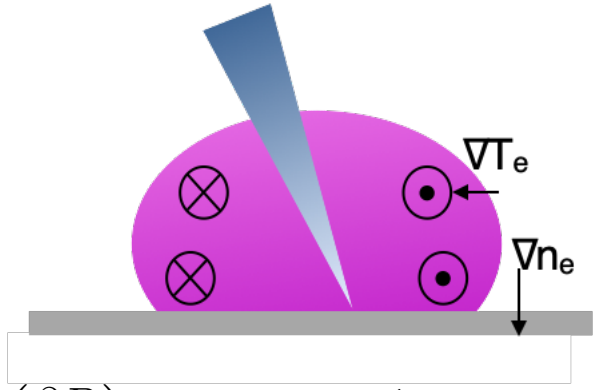
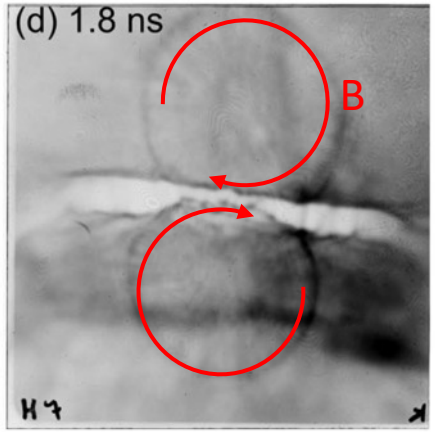
Biermann Battery



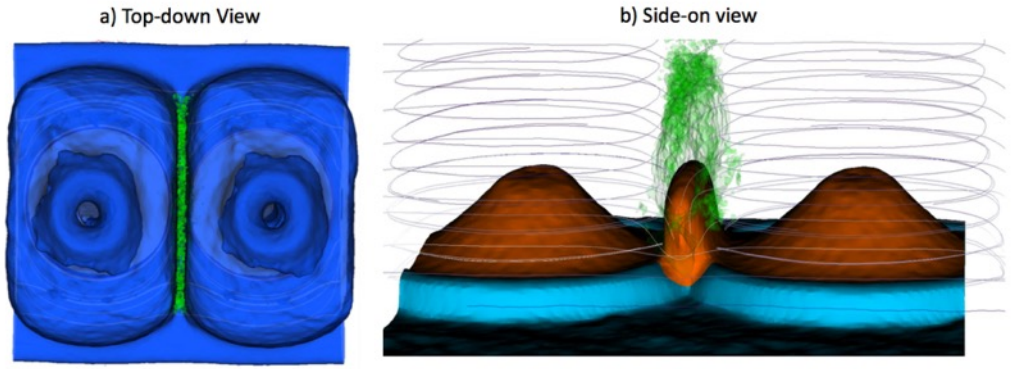
$$\left(\frac{\partial B}{\partial t}\right)_{Biermann} = \frac{1}{ne}\nabla n_e \times \nabla T_e$$

Experiment



[Rosenberg+ PRL 2015]

Simulation



[Matteucci+ PRL 2018]

magnetic energy
j·E
plasma pressure
field lines

- Observed in laser-plasmas driven by long-pulse lasers, fields of order ~50 T
- Believed to act as primordial seed fields of order ~ 10^{-20} G in astrophysical plasmas
- Collision of two plumes drives magnetic reconnection between the opposing magnetic fields

NIF Used to Produce and Observe Reconnection in Highly-Extended Current Sheets

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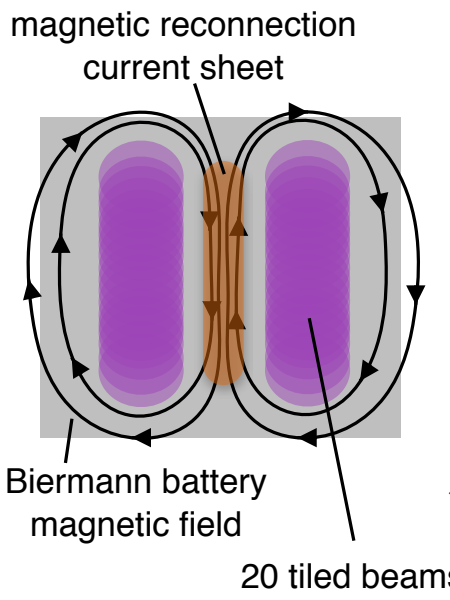
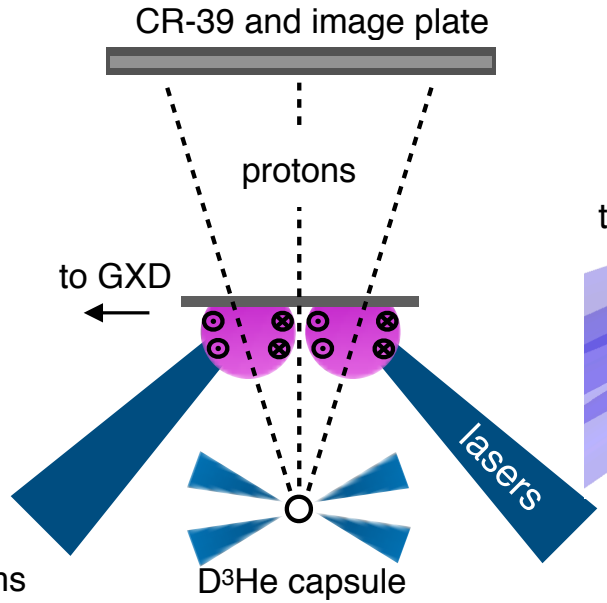
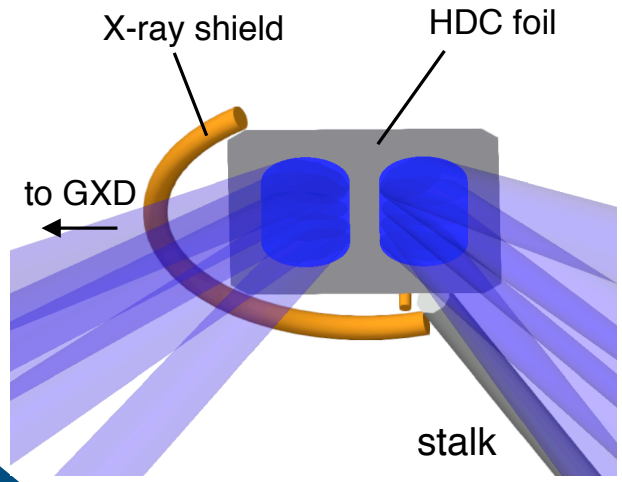
Top-Down Setup



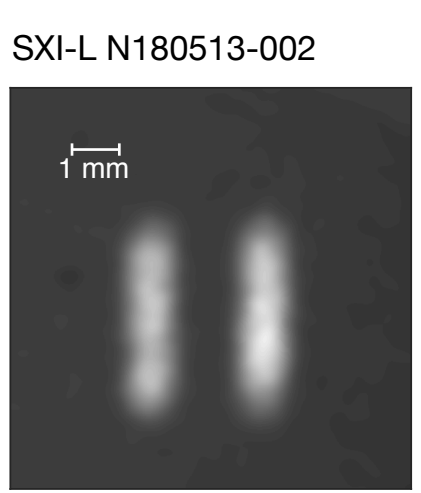
Side-On Setup



CAD Rendering



X-ray Emission



- $I_L \sim 10^{14}$ W/cm^2
- $T_e \sim$ 400-1000 eV
- $S = Lv_A/\eta \sim$ 150-1500

- Recent shots deployed smaller 440 um diameter DHe3 capsule for first time for higher spatial resolution
- Upcoming experiments will use higher I_L for higher S

Proton Radiography Used to Infer E and B Fields Present in the Plasma

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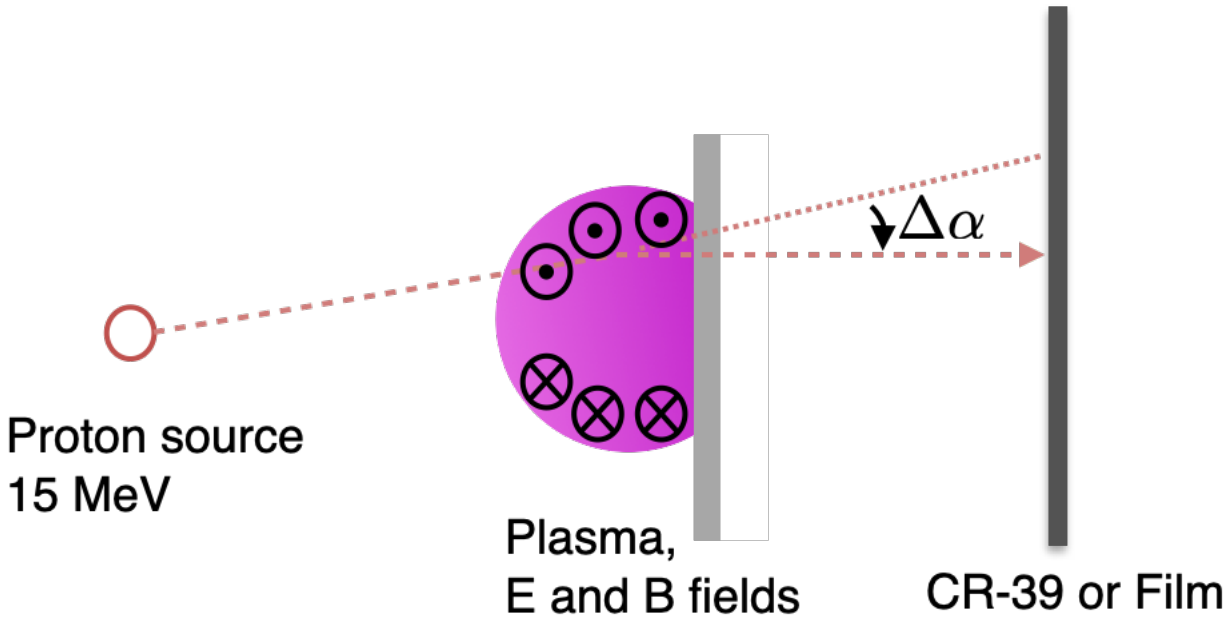
Proton Radiography

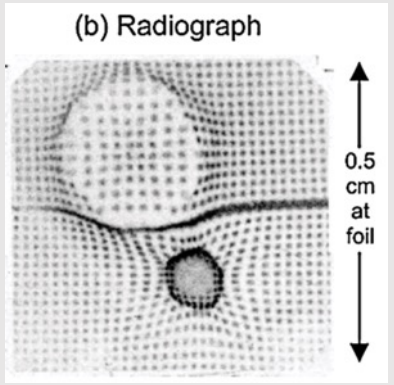


$$\Delta\alpha_B = \frac{e}{m_p V_p} \int \mathbf{B} \times \mathbf{d}\ell$$

$$\Delta\alpha_E = \frac{e}{m_p V_p^2} \int \mathbf{E}_\perp \, d\ell$$

Proton observations can be quantitatively converted to B fields using:

1. Direct mapping of proton beamlets

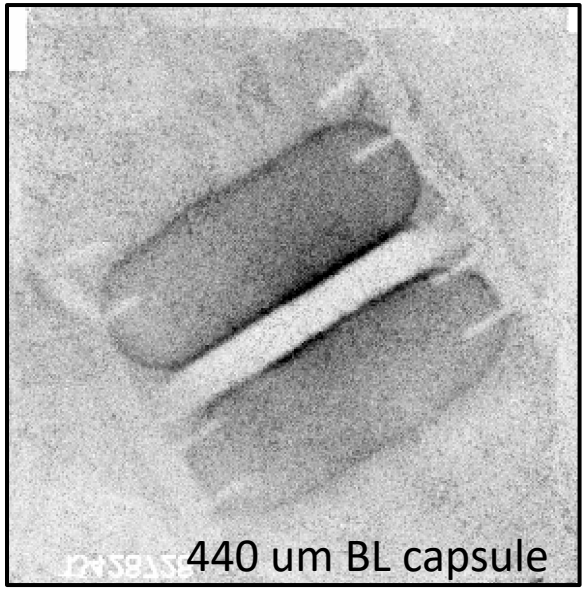
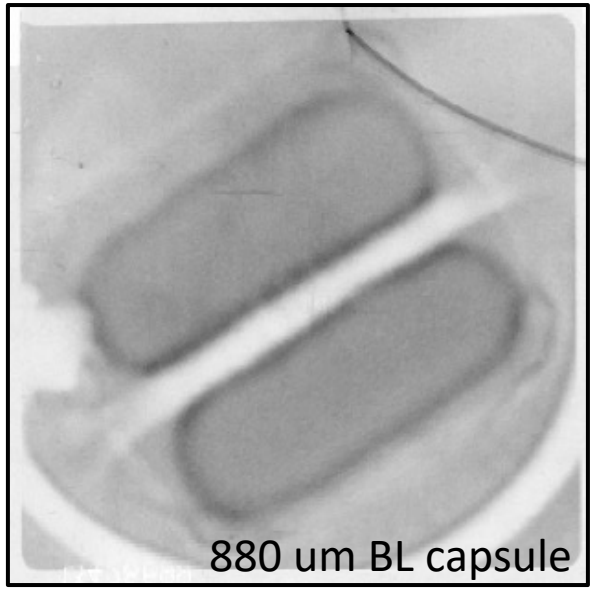
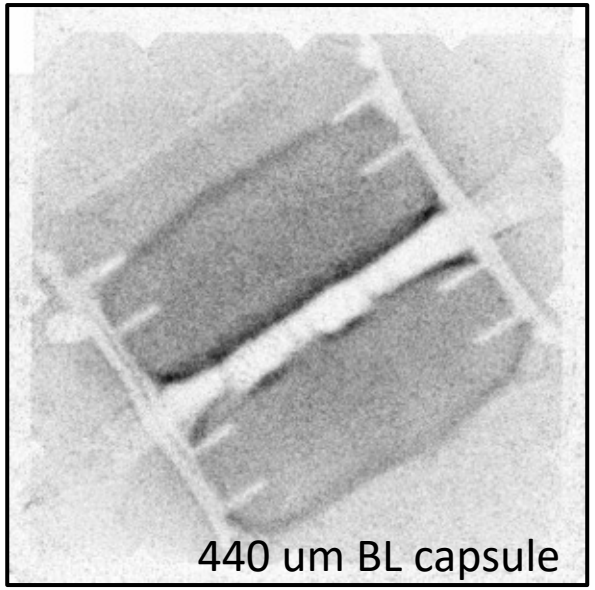
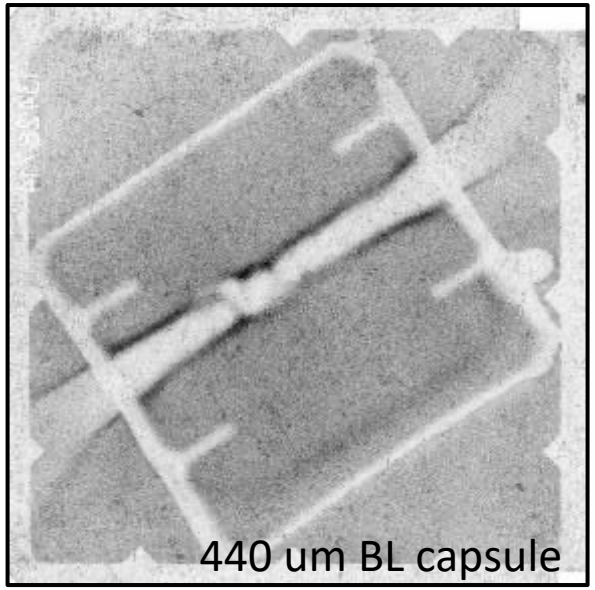


[Petrasso+ PRL 2009]

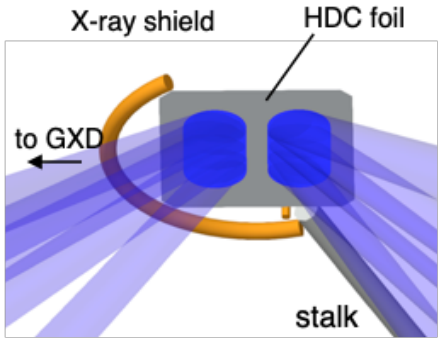
2. Numerical inversion by solving $\nabla \cdot \alpha = \frac{\delta I}{I}$ for observed proton fluence δI

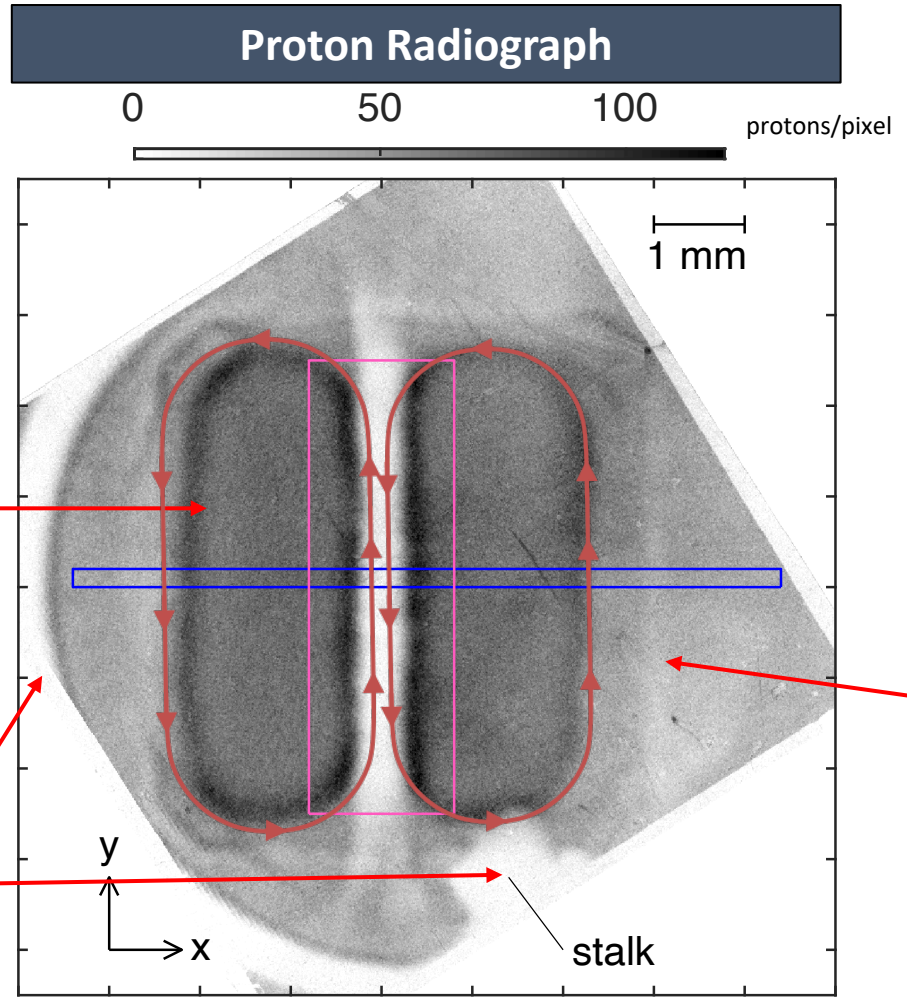
[Kugland+ PoP 2012, Bott+ JPP 2018]

Proton Image Sequence Between 2 – 6 ns

2 ns	3 ns	4 ns	6 ns
			
440 um BL capsule	880 um BL capsule	440 um BL capsule	440 um BL capsule

Excellent Proton Radiograph Obtained at t = 3 ns



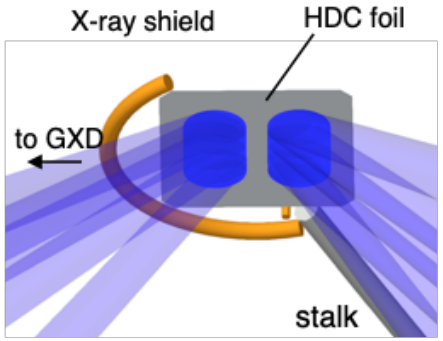


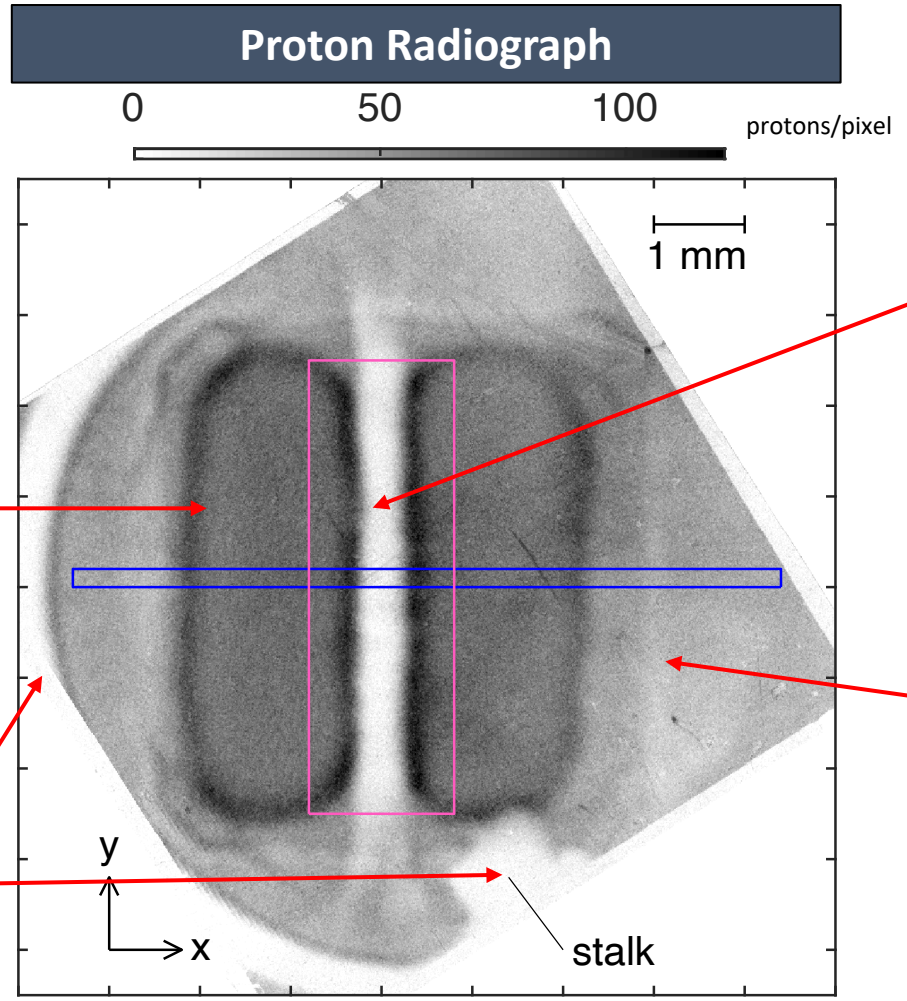
proton focusing from global Biermann field

target features (x-ray shield, stalk)

target edge

Excellent Proton Radiograph Obtained at t = 3 ns





proton depletion: current sheet

proton focusing from global Biermann field

target edge

target features (x-ray shield, stalk)

Highly Extended Current Sheet Observed with L/δ ~ 100

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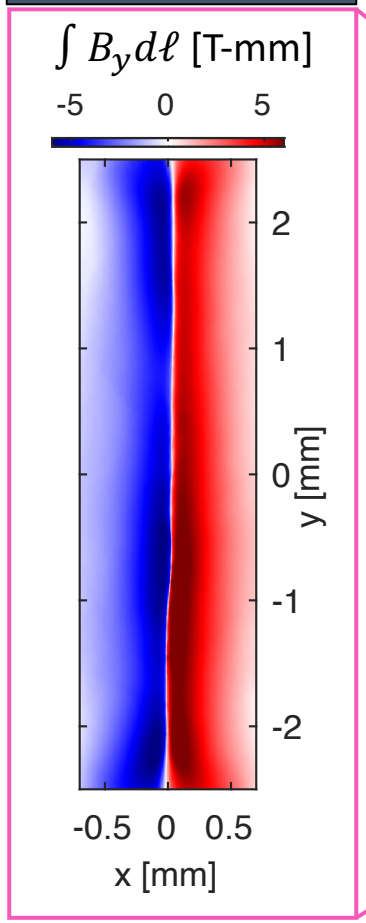
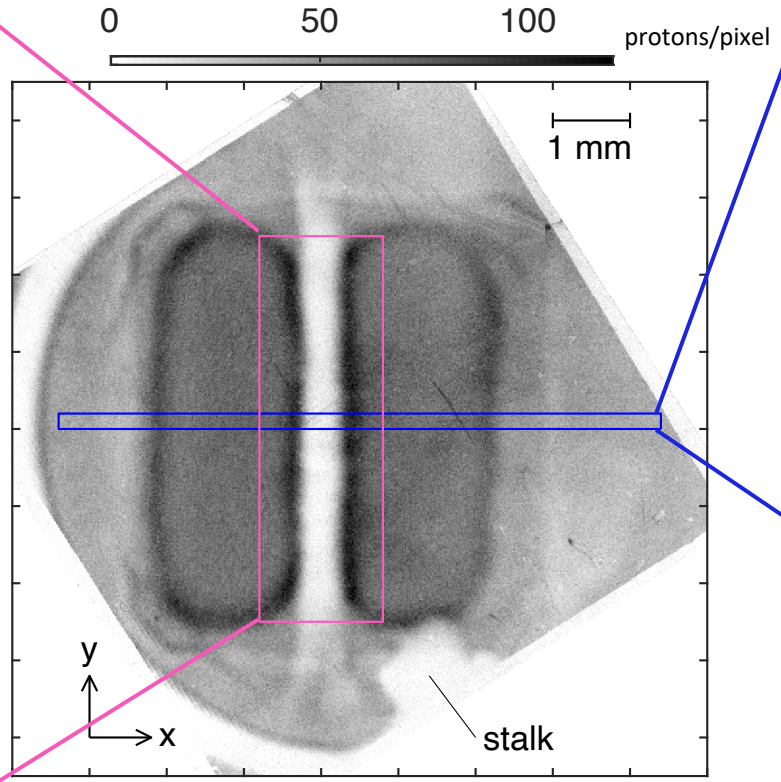
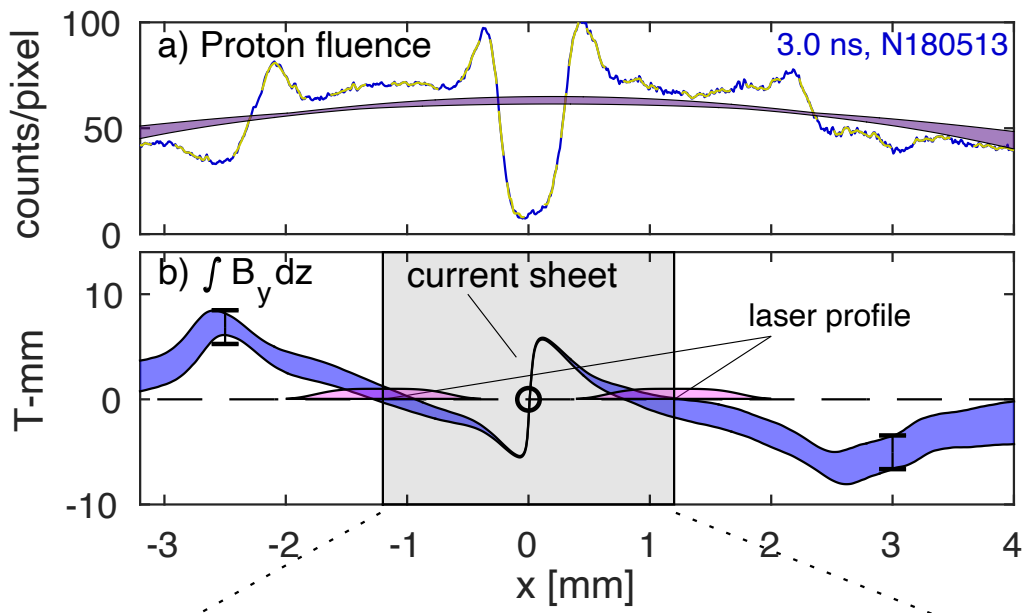
2D PROBLEM Reconstruction



Proton Radiograph



1D PRADICAMENT Reconstruction



- 2D inversion using PROBLEM code *[Bott+ JPP 2018]*
- 1D inversion using PRADICAMENT code *[Fiksel+ 2019]*
- Very long, narrow current sheet: ~ 6 mm x 25 um (~ 200 d_i x 1 ρ_e)
- Laminar structure indicates instabilities not yet formed

Reconnection Observed Between t=2 and t=3 ns

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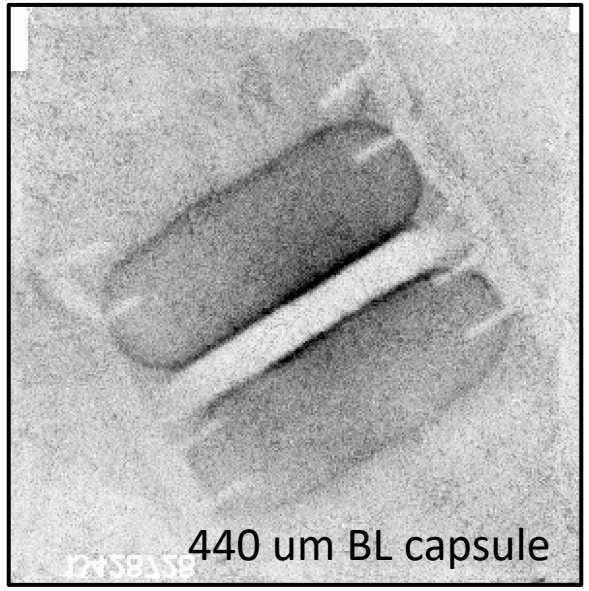
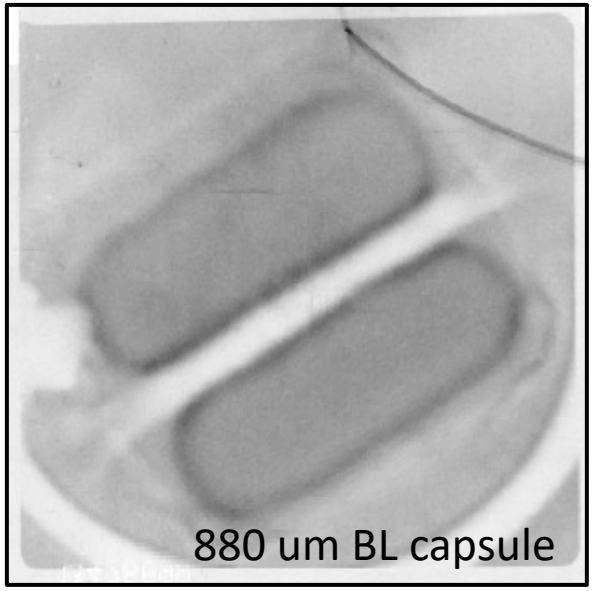
2 ns

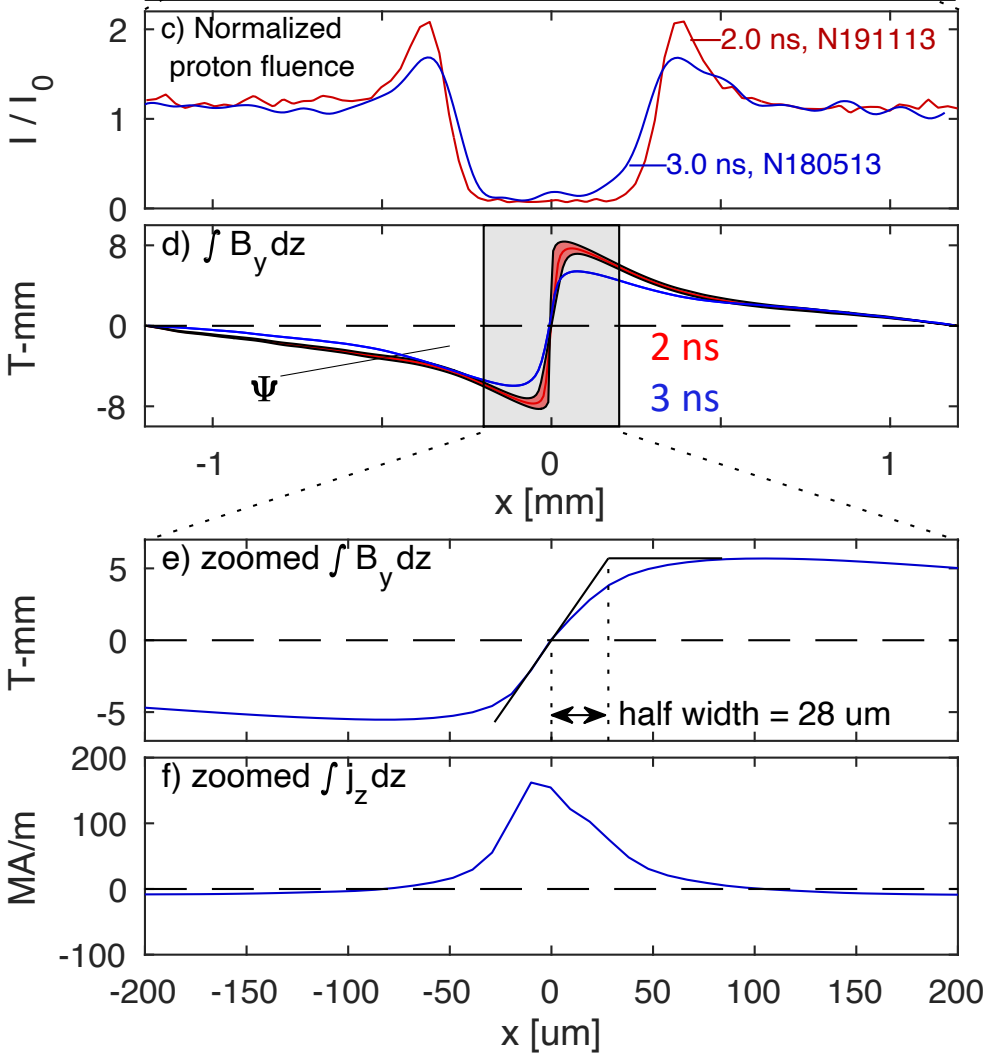


3 ns



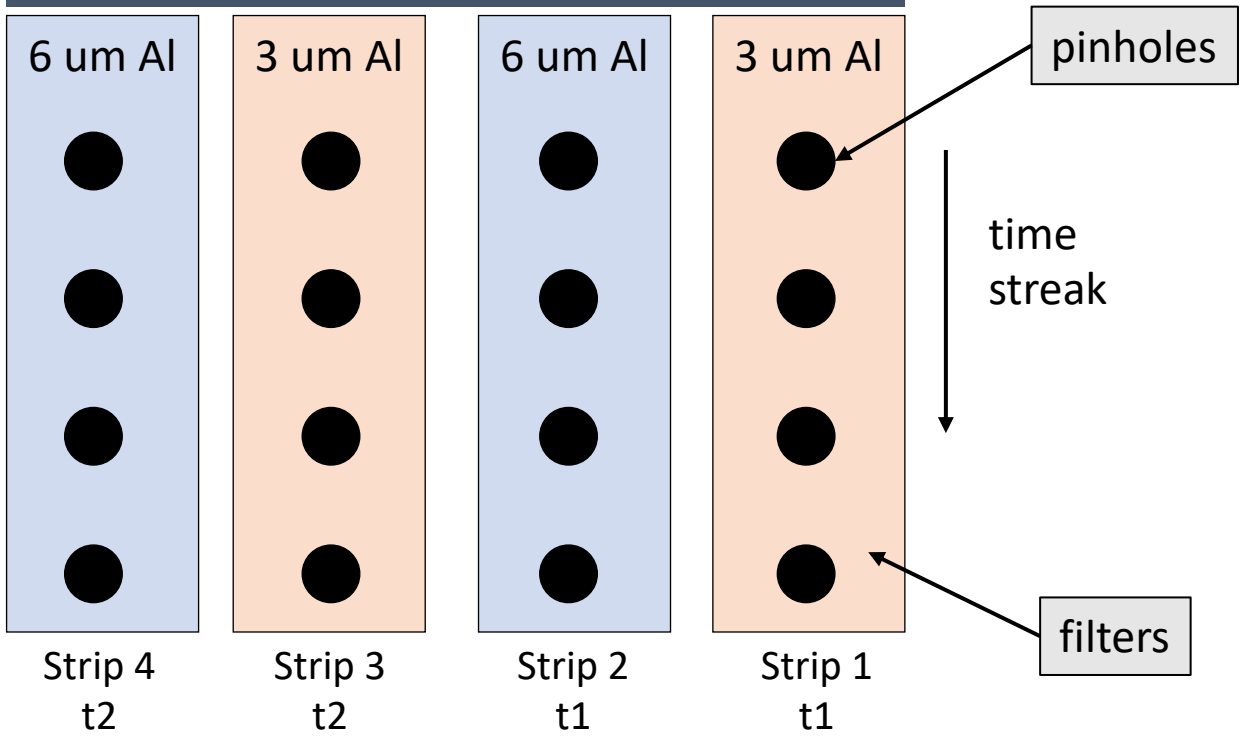
- 1D reconstruction of proton fluence at t=2 and t=3 ns
- Total magnetic flux $\Psi = \int dx \int B_y dz$ decreases from 3.5±0.2 to 2.1±0.1 T-mm^2
  - Apparent in raw data as wider and deeper current sheet at t=2 ns
- Super-Alfvenic reconnection inflow speed
- Peak current of 160 MA/m

1D Reconstructions



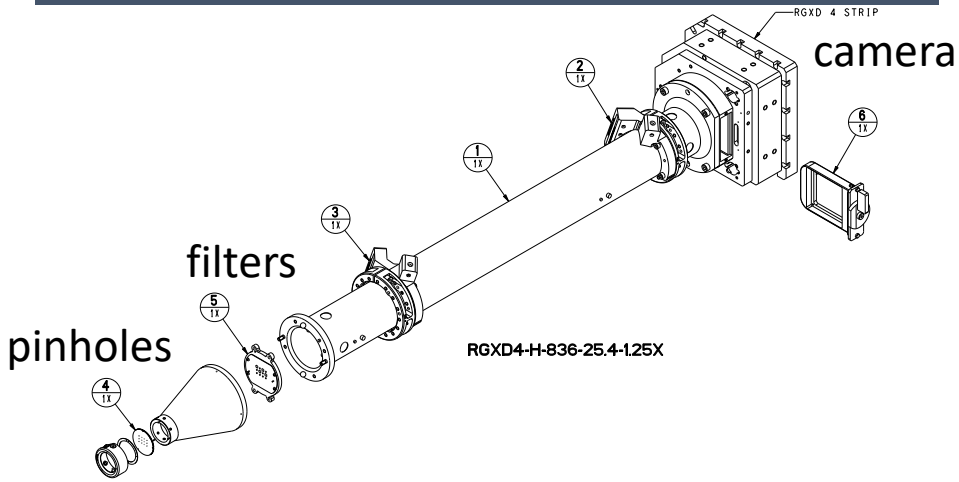
Plasma Self-Emission Measured with Gated X-ray Detector (GXD)

Example Filter Setup



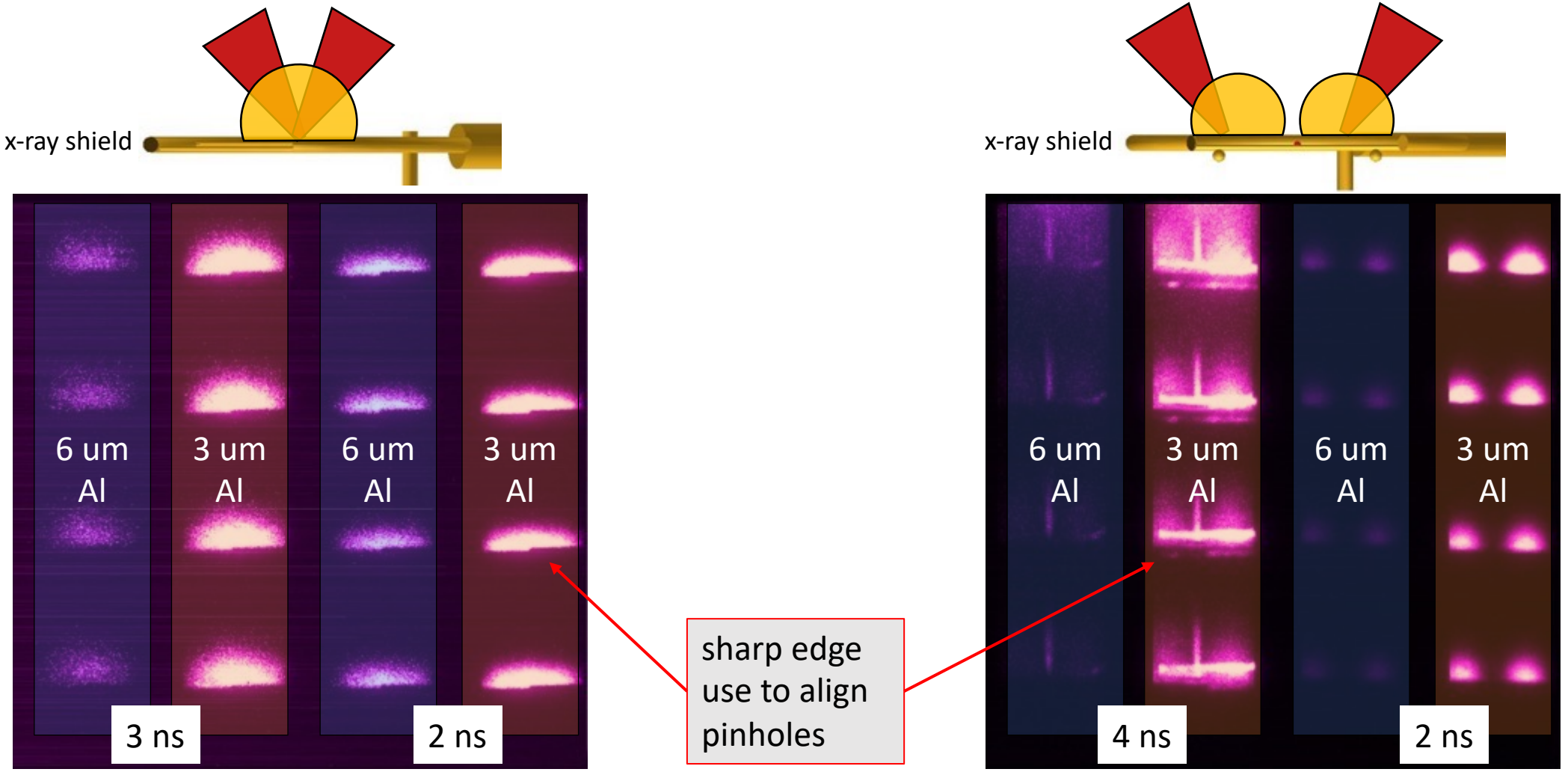
- X-rays pass through filtered pinhole array
- Pinhole images collected on streaked detector
  - 4 independently timed strips embedded in MCP
  - Signal integrated from 200-600 ps
  - Images projected onto CCD (spaced to avoid overlap)

GXD Snout



	90-78	90-124
Camera	RGXD4F	RGXD3F
Snout	H-836-25.4-1.75x	H-836-25.4-1.25x
Magnification	1.75x	1.25x
Pinhole Size	150 um	150 um
Sweep speed	600 ps	200 ps
Relative Gain	176x	5x

Excellent X-ray Images Obtained from Multiple Viewpoints

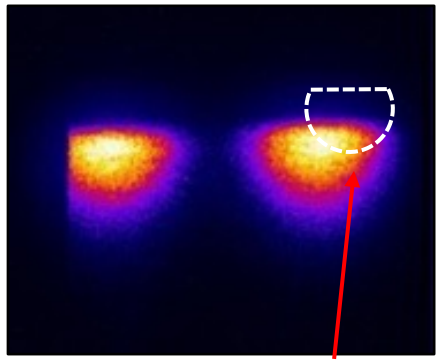


View from DIM 90-124 (Side-On)

View from DIM 90-78 (Face-On)

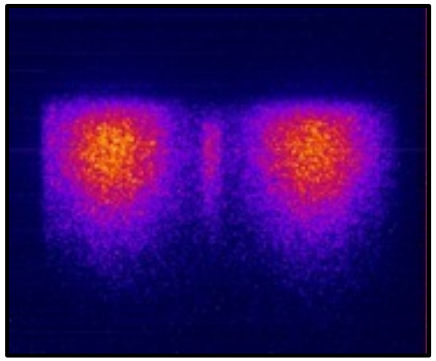
X-ray Image Sequence Between 2 – 8 ns

T0+2ns

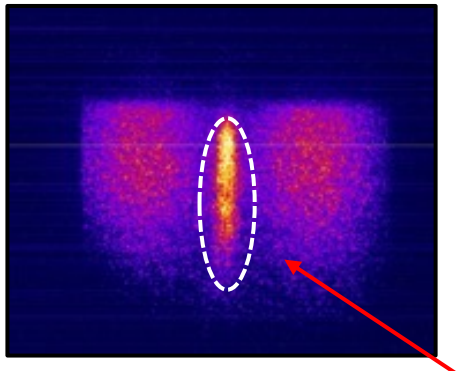


laser plasma plume

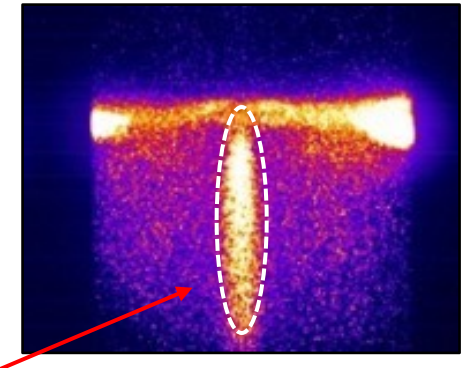
T0+3ns



T0+4ns



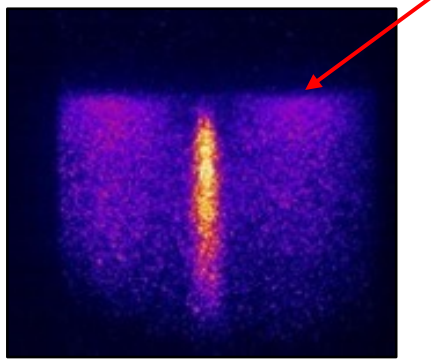
T0+5ns



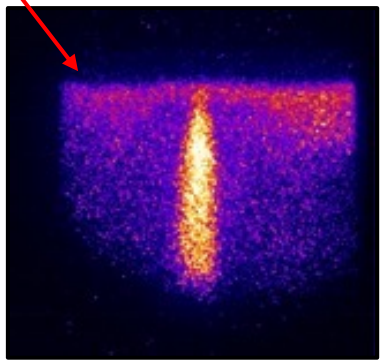
stagnating hot plasma

HDC target edge

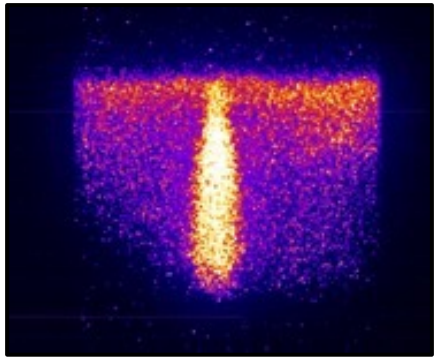
T0+6ns



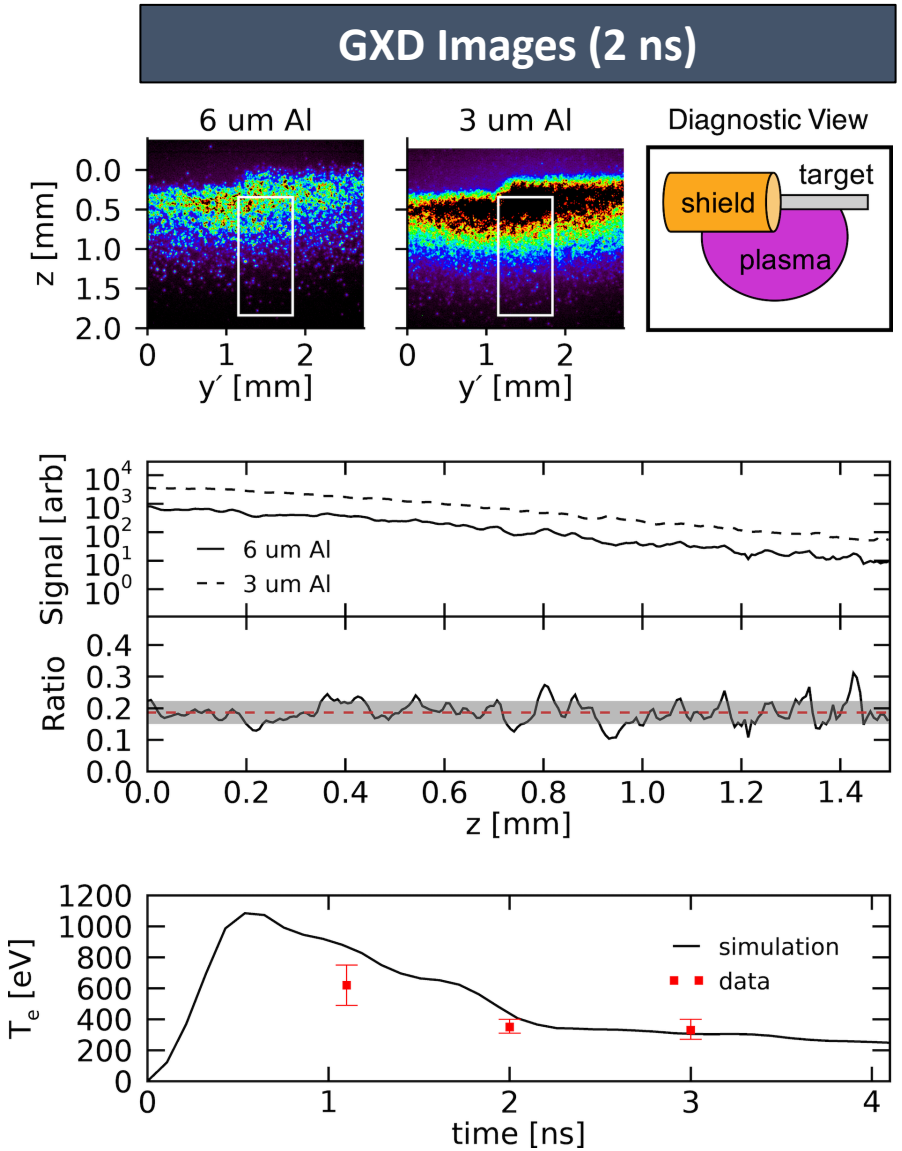
T0+7ns



T0+8ns



Plasma Temperature Measured with X-ray Pinhole Imaging



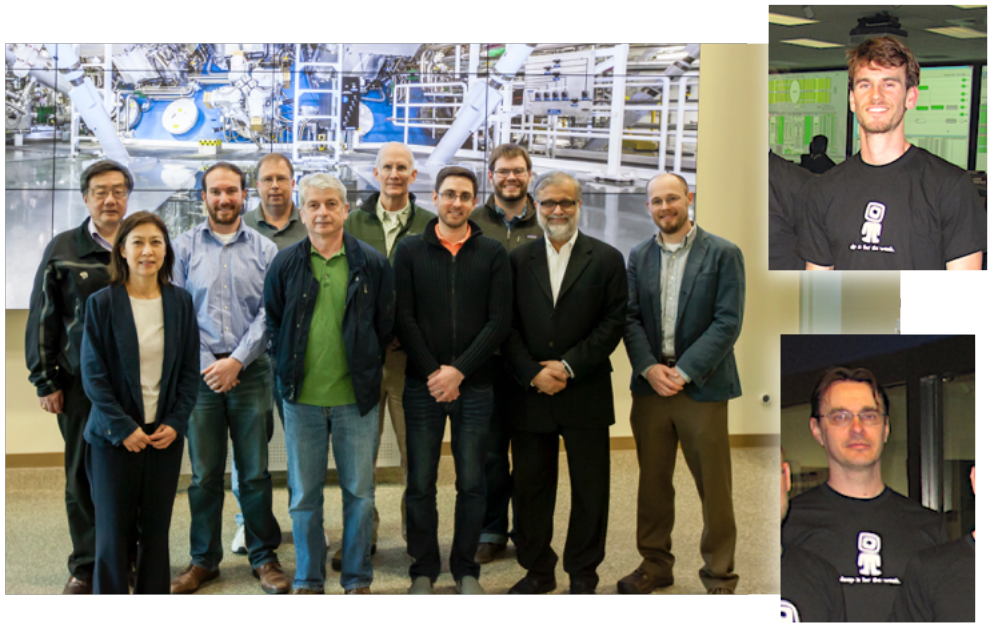
- Compare Bremsstrahlung x-ray emission through two co-timed filters, e.g. 3 and 6 um Al
  - Ratio of the signal through the filters is related to the plasma T_e
- Measured T_e varies from ~700 eV at 1.1 ns to ~400 eV at 2-3 ns
- These temperatures and scale lengths were used to constrain PSC particle-in-cell simulations
- GXD images also indicate that:
  - plasma is reproducible
  - line-integration in side-on imaging (90-124 view) does not significantly affect measured temperature compared to face-on image (90-78 view)

[Schaeffer+ RSI 2021]

Summary and Discussion

- Platform for magnetic reconnection experiments developed for the National Ignition Facility
  - Tiling of lasers drives reconnection through a highly extended quasi-1D current sheet
  - High quality reconstruction of magnetic fields throughout current sheet region
- Reconnection results:
  - Direct observation of current sheet in colliding HED plasmas (L/δ ~ 100)
  - Current sheet width δ thins down to ~ρ_e scale
  - Decreasing magnetic flux with time indicates reconnection

  [Fox+ arXiv:2003.06351]
- Upcoming shots are planned with:
  - higher laser intensity for higher Te and Lundquist number



Recon Team at NIF