Relativistic Magnetic Reconnection Driven by High Intensity Lasers

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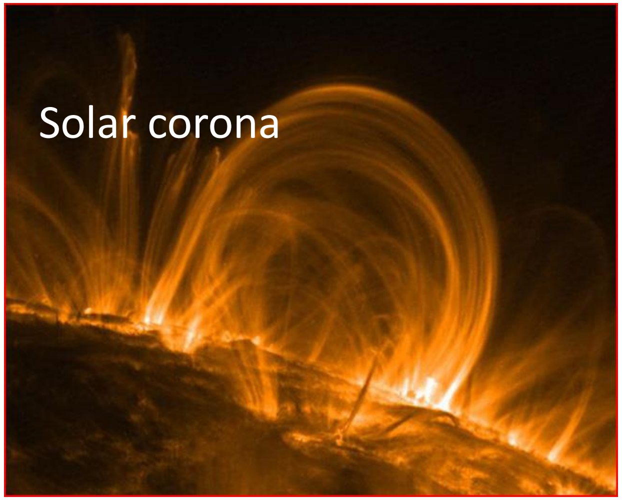
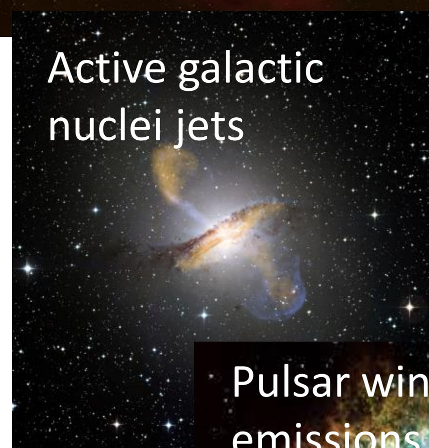
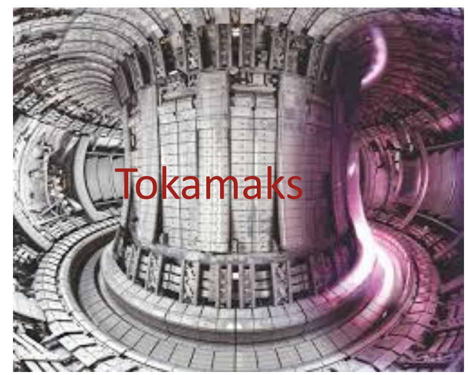
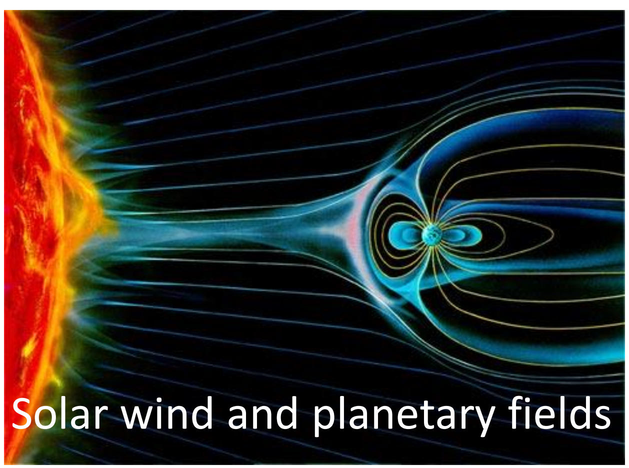
Magnetic Reconnection:
Topology changes that converts magnetic energy into plasma kinetic energy







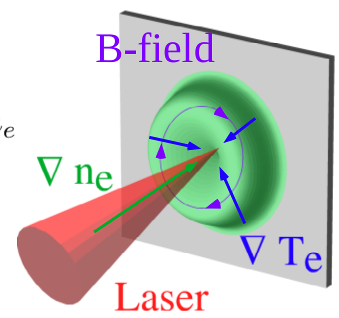


Laser driven magnetic reconnection experiments have been of significant interest over the past decade

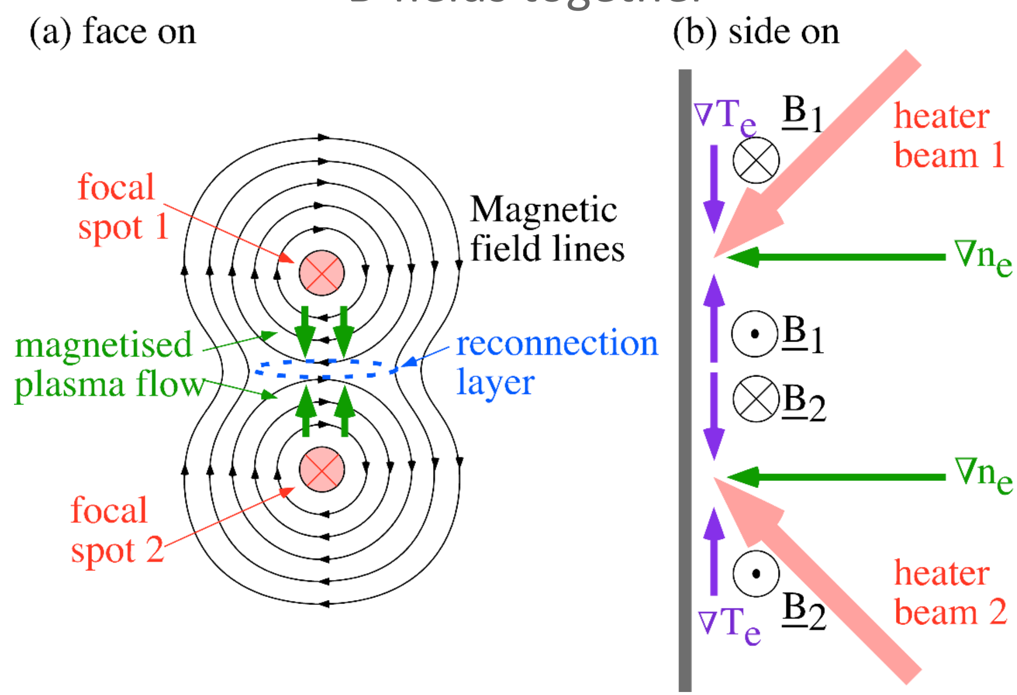
Biermann Battery effect:

$$\nabla P_e = -en_e\mathbf{E}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{k_B}{en_e}\nabla T_e \times \nabla n_e$$



Frozen-in-flow drives B-fields together



PM Nilson, et al, PRL, 97, 255001 (2006);
CK Li, et al, PRL, 99, 055001 (2007);
PM Nilson, et al, PoP, 15, 092701 (2008);
J Zhong, et al, Nature Physics, 6, 984 (2010);
W Fox, et al, PRL, 106, 215003 (2011);
MJ Rosenberg, et al, PRE, 86, 056407 (2012);
W Fox, et al, PoP, 19, 056309 (2012);
QL Dong, et al, PRL, 108, 215001 (2012);
AS Joglekar, et al, PRL, 112, 105004 (2014);
G Fiksel, et al, PRL, 113, 105003 (2014);
Plus more…..

B fields can be up to a MegaGauss or more are created by the hydrodynamic motion of the ablated plasma subsequent to the high intensity laser interaction and evolve on nanosecond timescales.

Relativistic magnetic reconnection

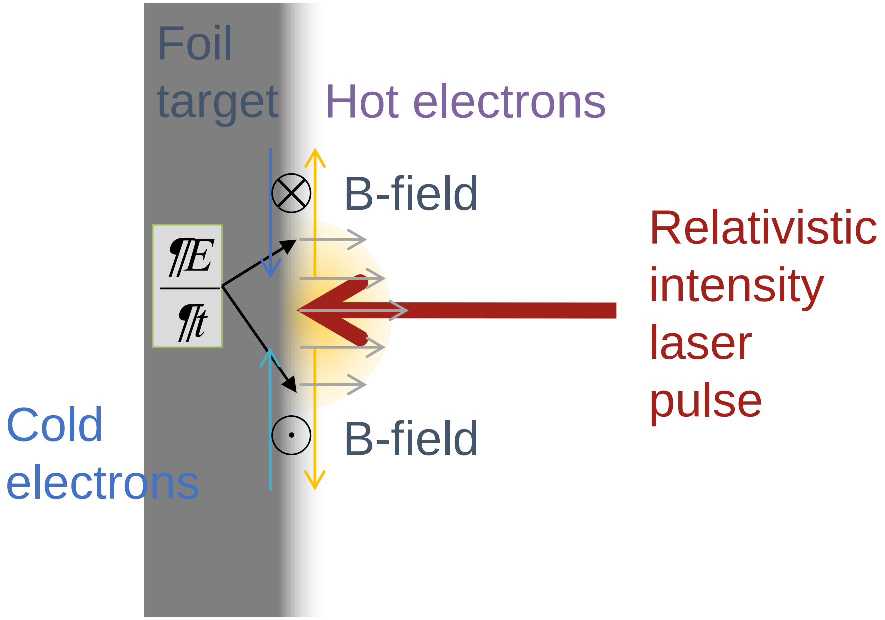
- The energy density of the reconnecting fields, $B^2/2\mu_0$, exceeds the rest mass energy density, $n_e m_e c^2$, or:

$$\sigma = \frac{B^2}{\mu_0 n_e m_e c^2} > 1$$

- Nanosecond laser driven reconnection: $\sigma < 0.01$

- High-intensity laser driven reconnection: $\sigma \sim ?$

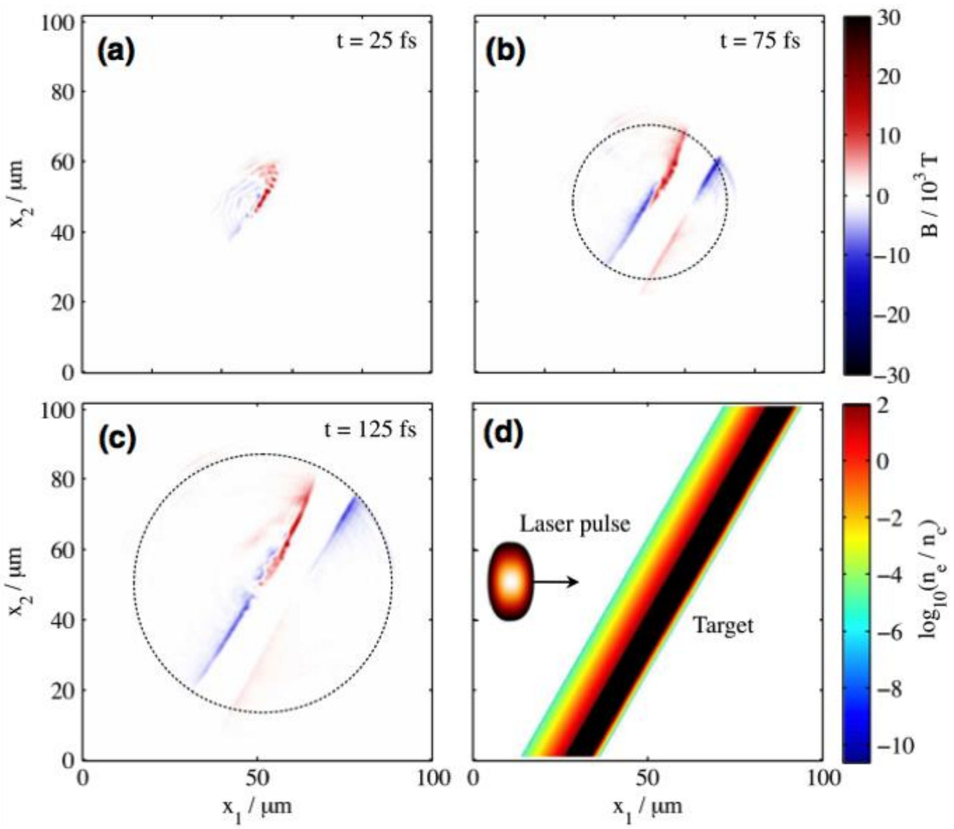
Magnetic field generation from a relativistic intensity interaction



- Electrons are heated to MeV energies
- Electron cloud expands into vacuum
- Large space-charge field is formed
  - confines the majority of the hot electrons to the target surface
  - Hot electron current spreads radially out along the target surface
  - Cold electron return current in bulk target
  - Azimuthal magnetic field is associated with these surface currents

W Schumaker, et al, PRL, 110, 015003 (2013)

Magnetic field expansion

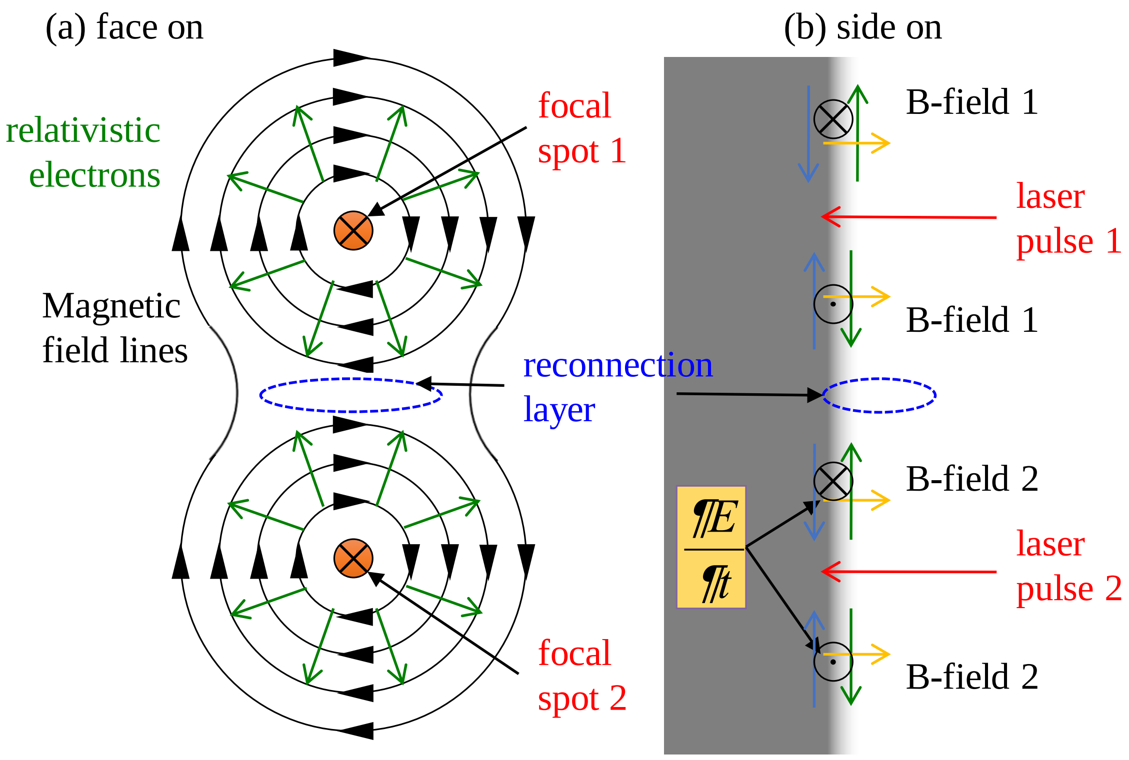


The relativistic energy electron surface current expands at a speed close to the speed of light.

Azimuthal magnetic fields expand radially at ~ c.

W Schumaker, et al, PRL, 110, 015003 (2013)

Relativistic Electron Driven Magnetic Reconnection



The azimuthal magnetic fields are in the same configuration, but the magnetic field lines are driven together at ~ c

Experimental 2 beam set up

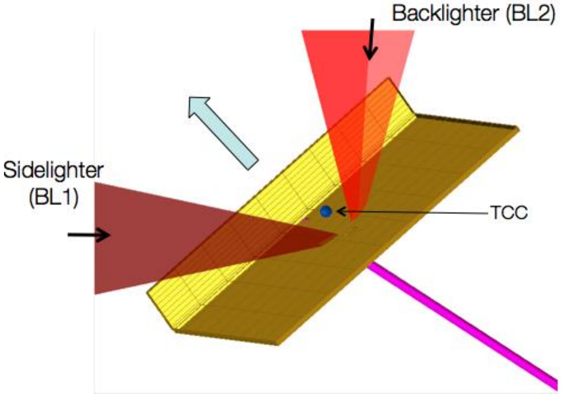
Hercules

Parabola cut in half with half on a translation stage. Deformable mirror required.

λ = 800 nm
2 J
40 fs
2×10^{19} Wcm^{-2}
Normal angle of incidence

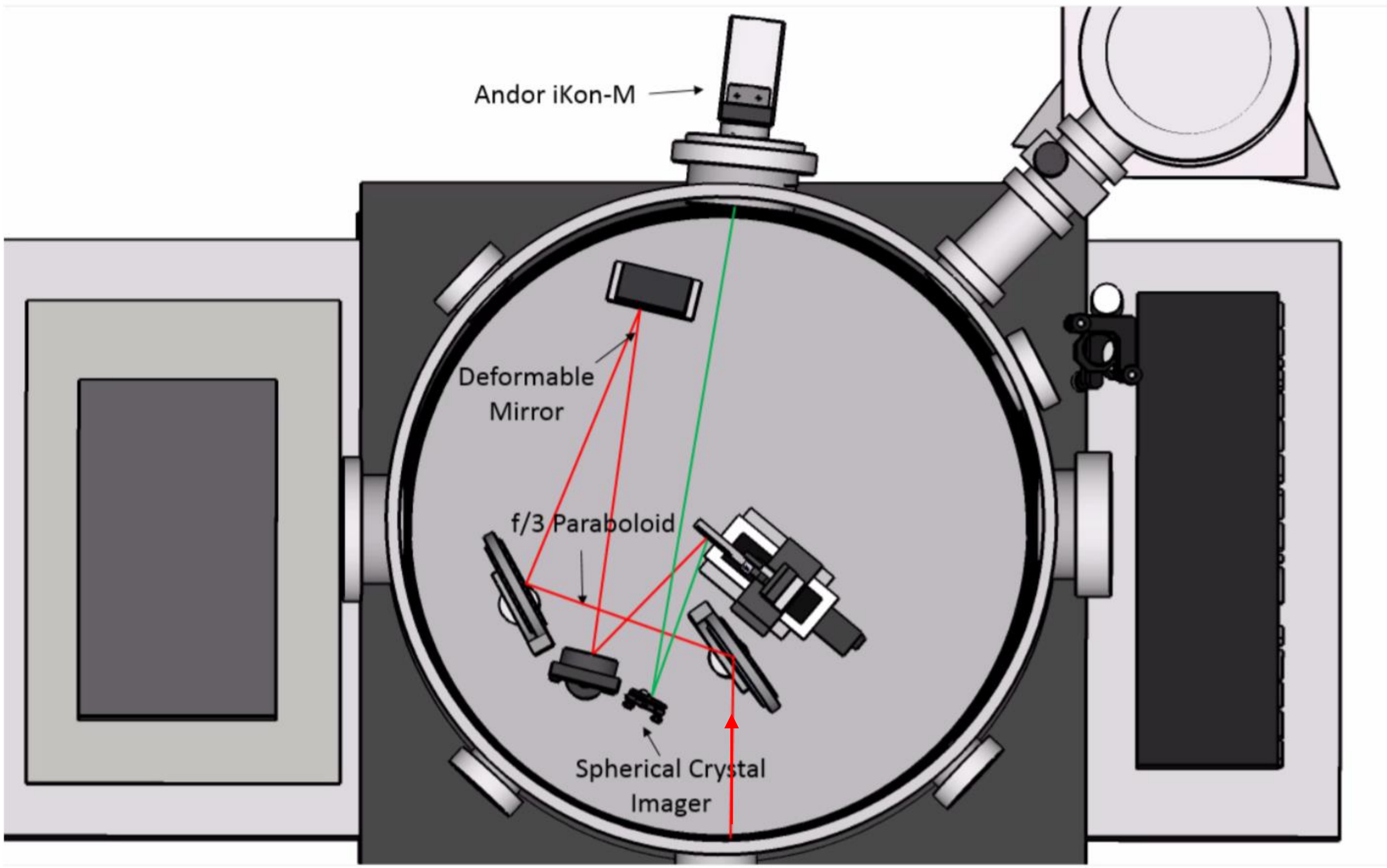
OMEGA EP

Two separate 20 ps beam lines. Co-timed to +/- 5ps.

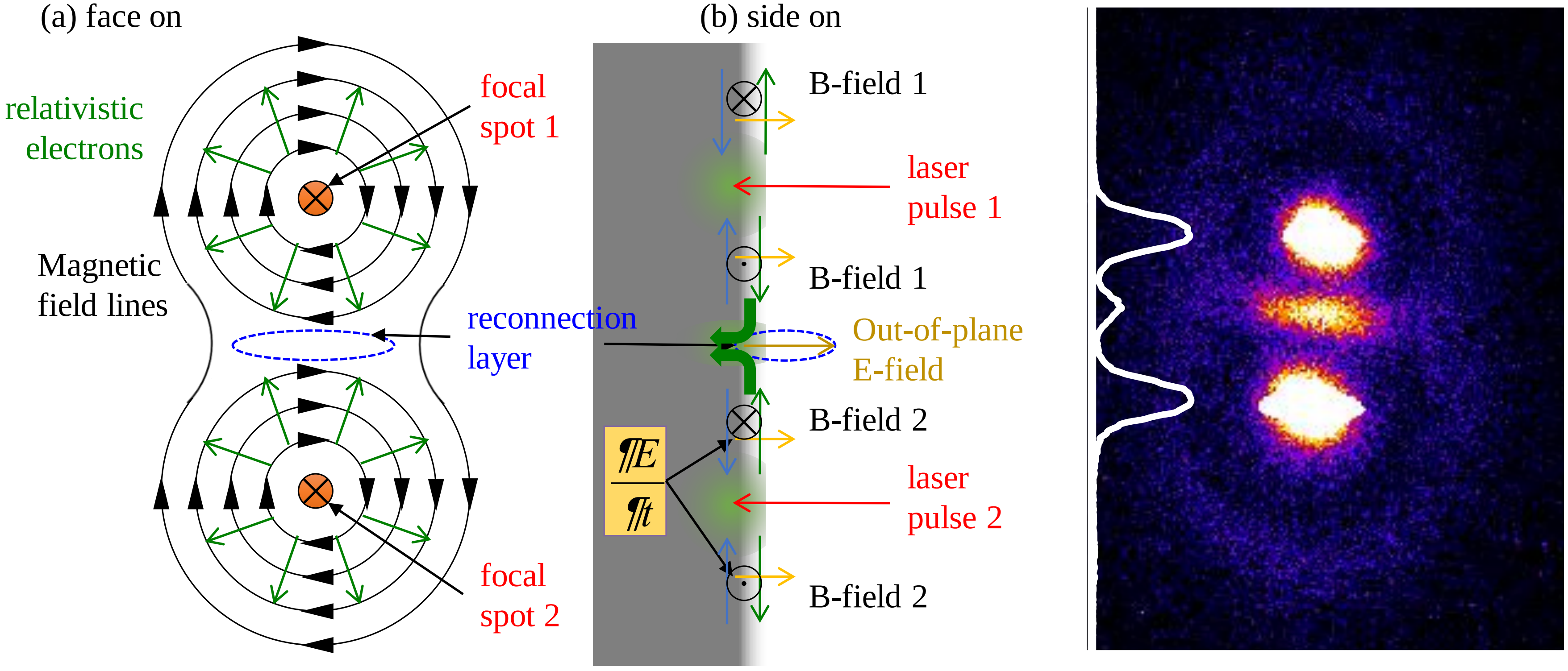


λ = 1.053 µm
500 J or 1000 J, 20 ps
$(1.2 – 2.5) \times 10^{18}$ Wcm^{-2}
45° angle of incidence

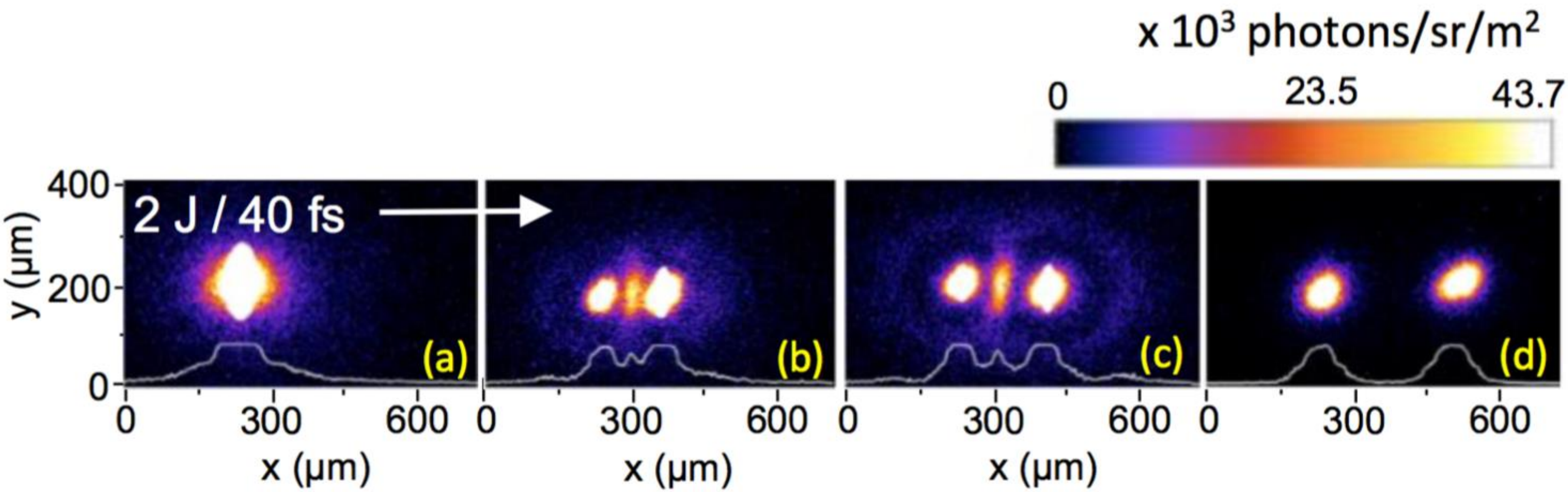
Hercules experimental setup



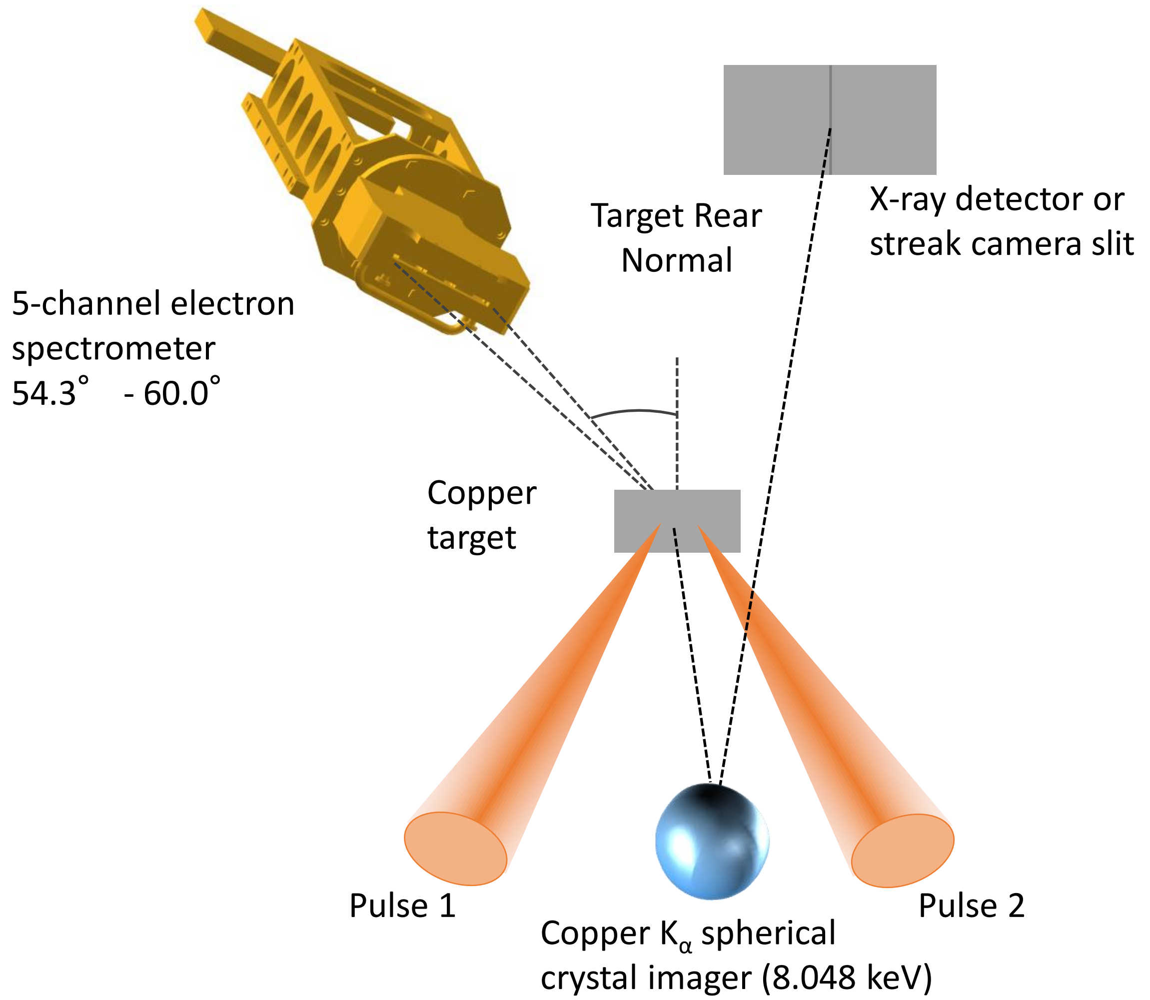
Mid-plane signal enhancement is due to reconnection fields



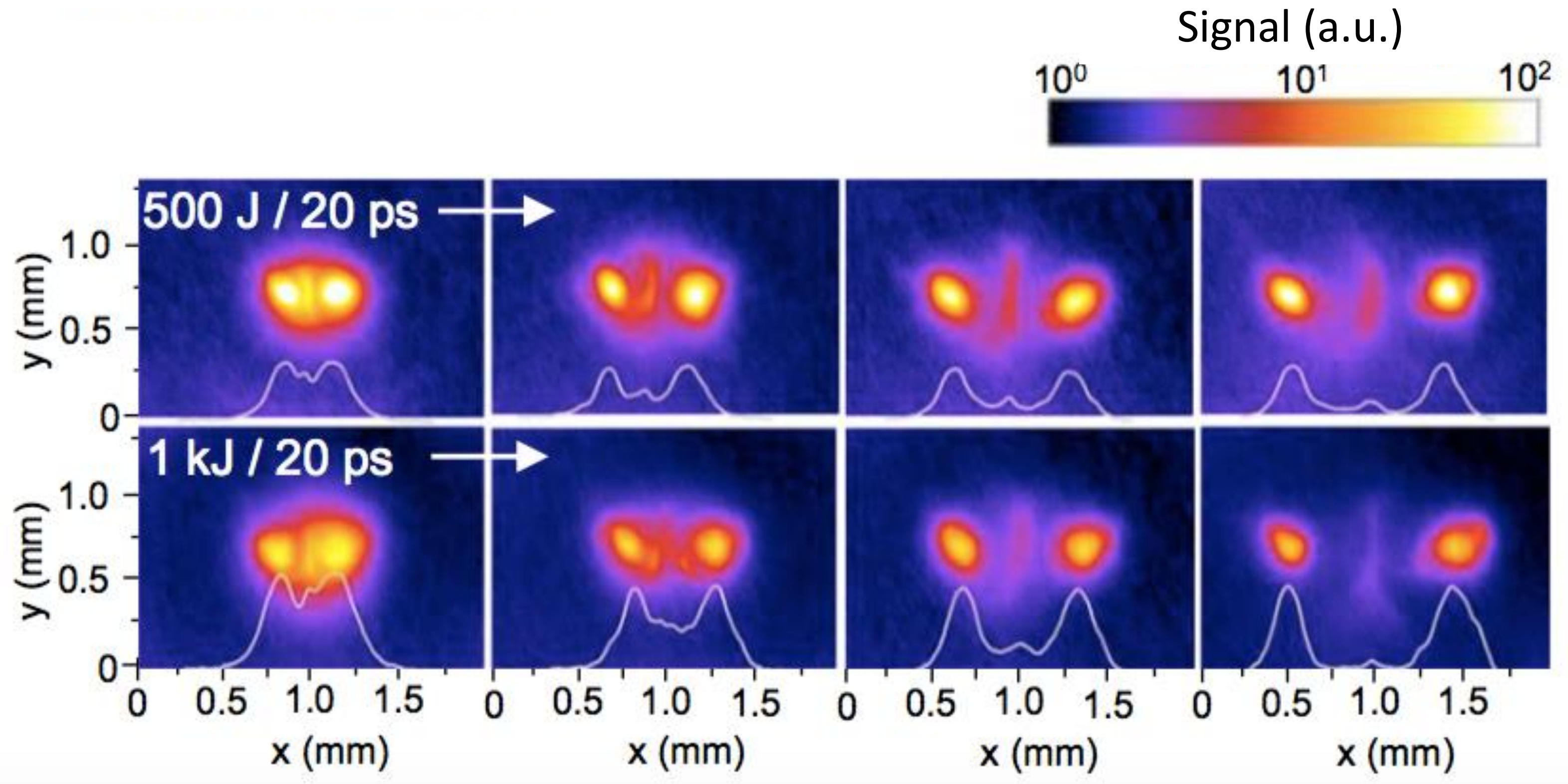
Hercules – midplane signal depends on focal spot separation



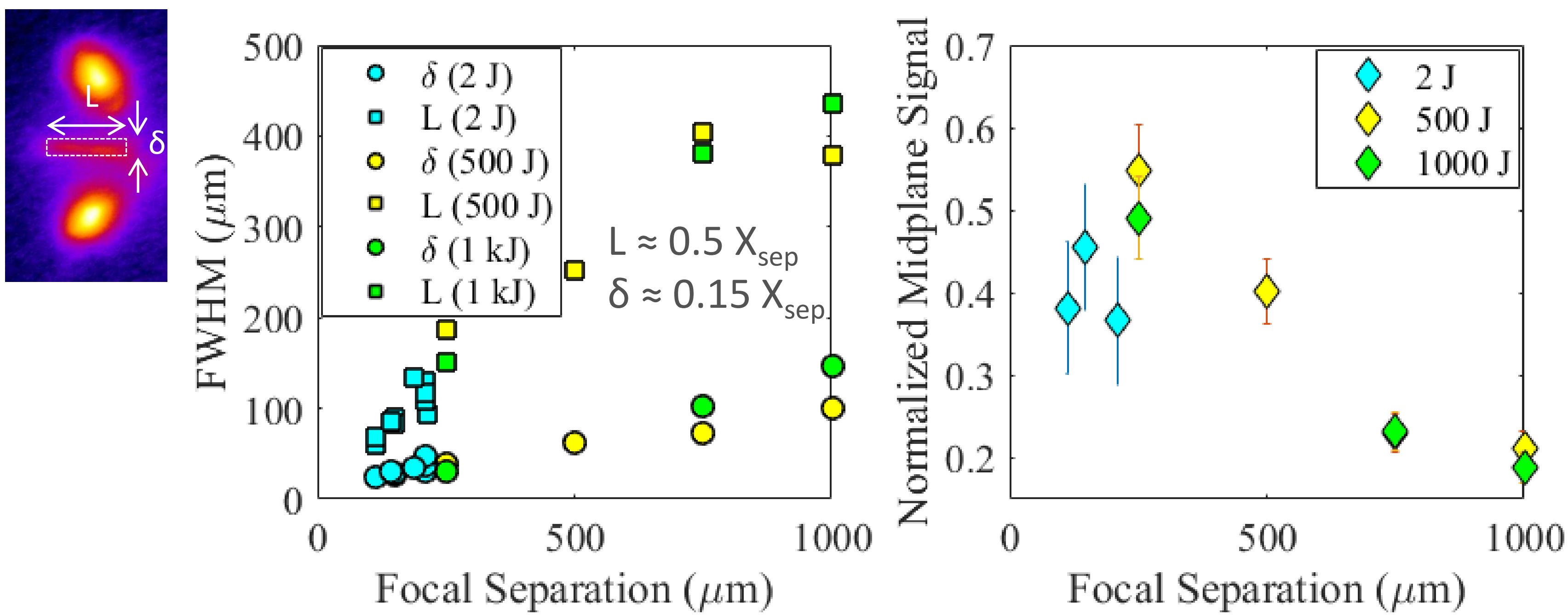
Omega EP Experimental configuration



Omega EP copper K_α imaging data



Copper K_α imaging trends for midplane signal

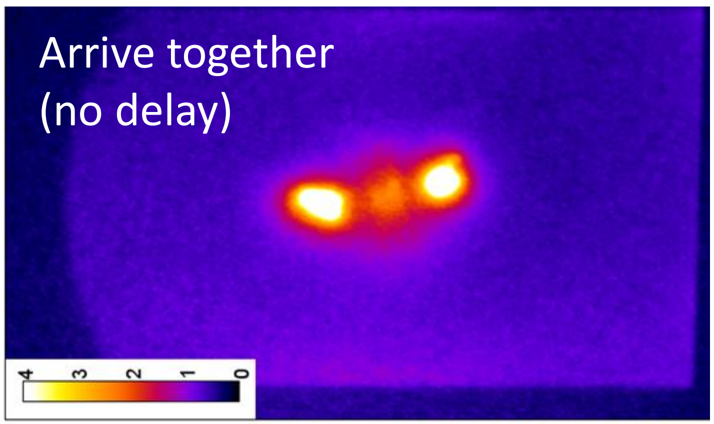


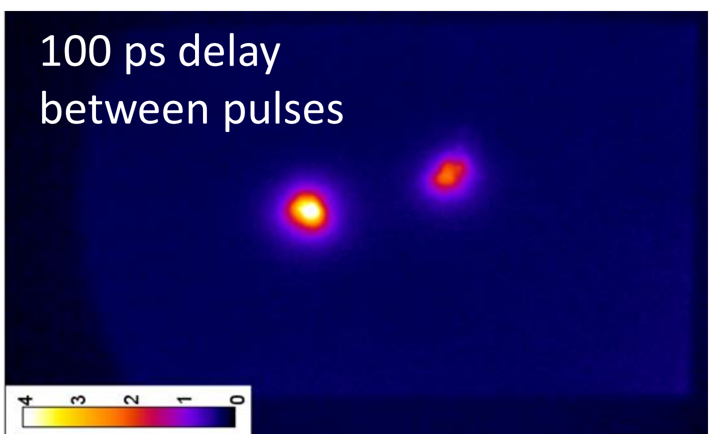
The ratio δ / L ≈ 0.3 over the whole region of focal spots separation

Linear trends were observed for both the length L and width δ of the reconnection region versus focal separation suggesting the regime accessed at either facility are comparable, despite the drastic change in pulse parameters.

Deliberate 100 ps offset between pulse 1 and pulse 2

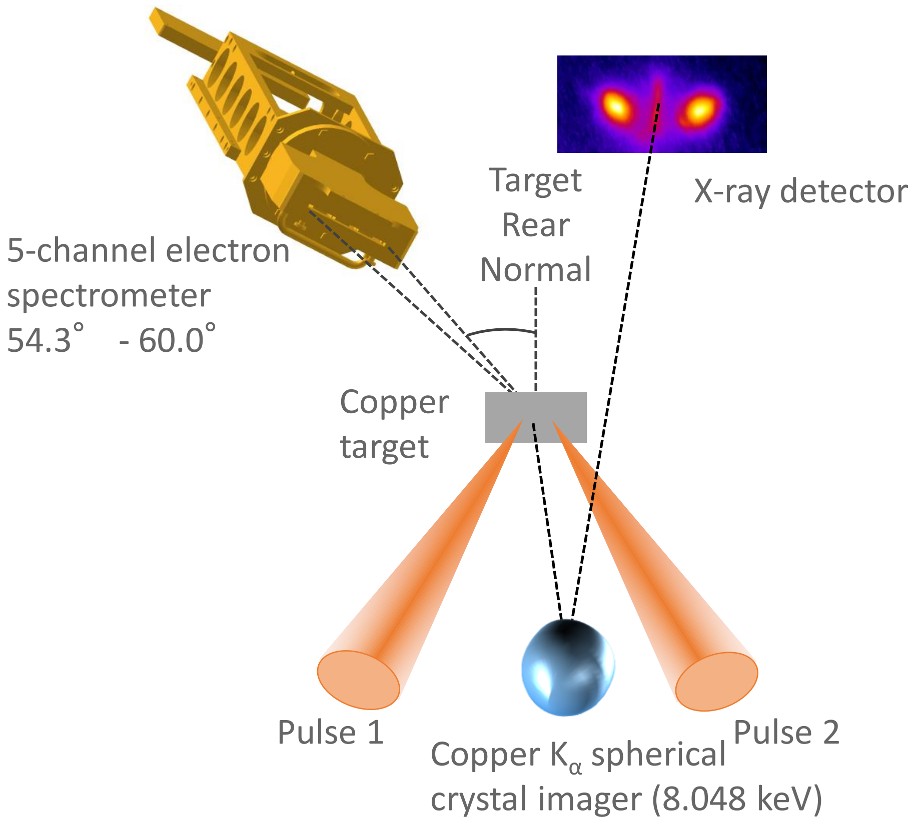
Copper K_α imaging of the rear of the target

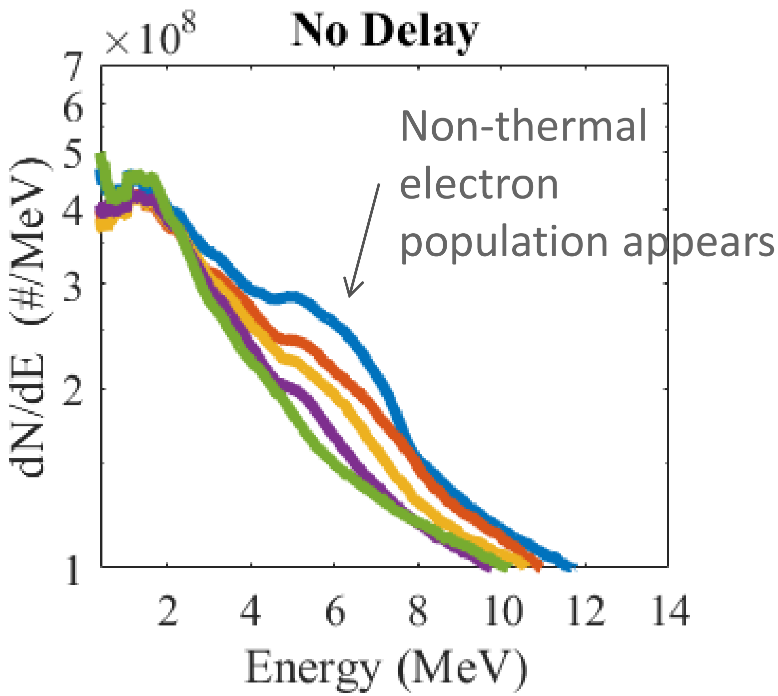




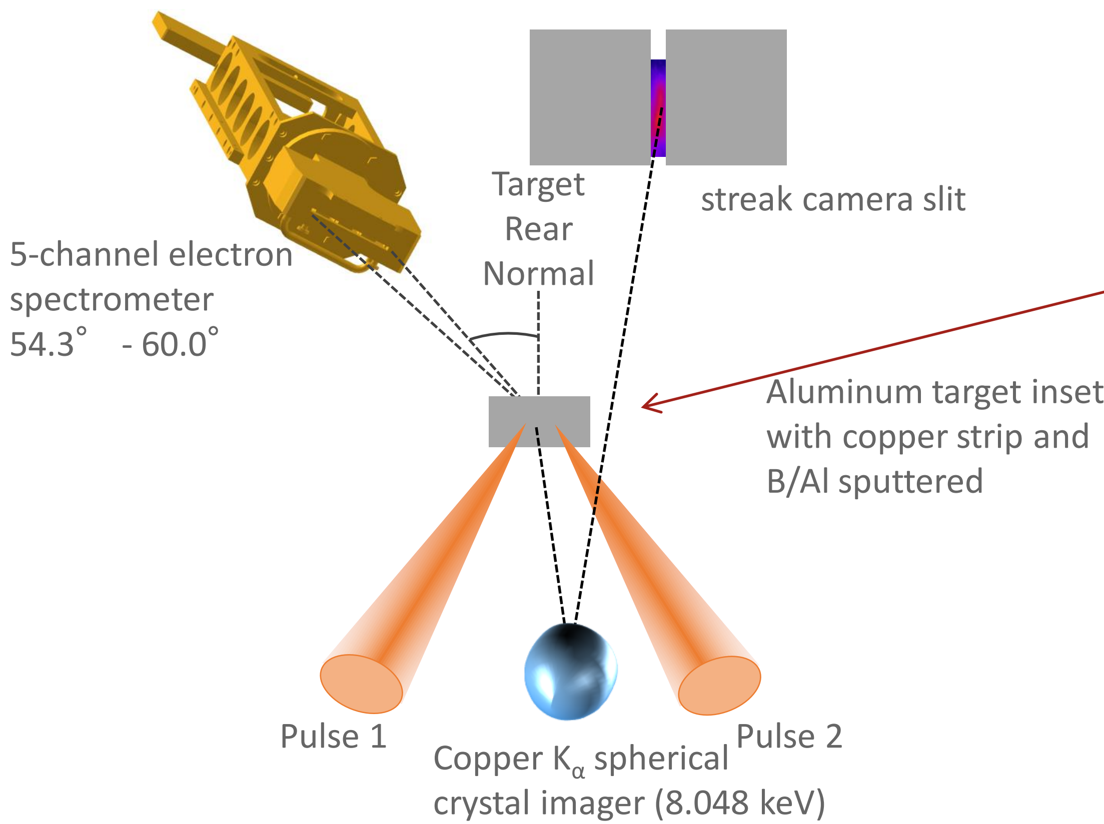
Pulses must arrive together for the magnetic fields to interact and reconnect.

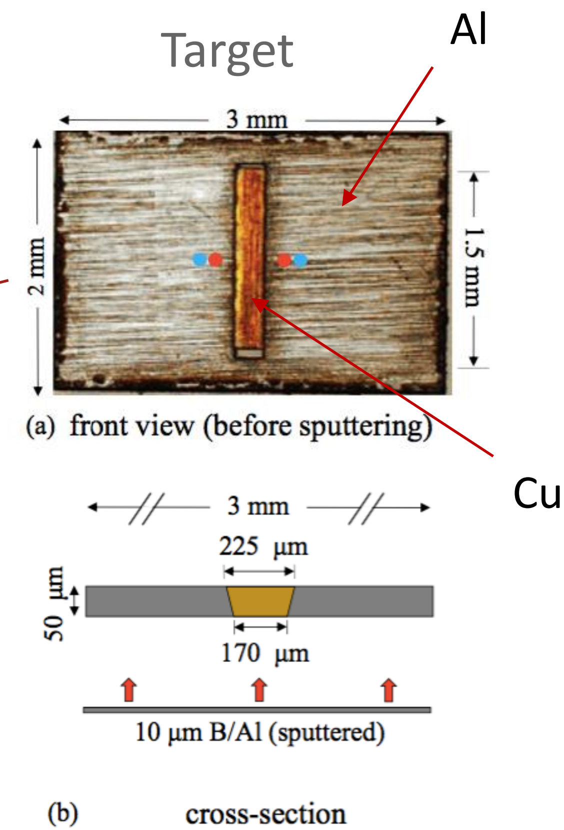
Electron spectra measurements





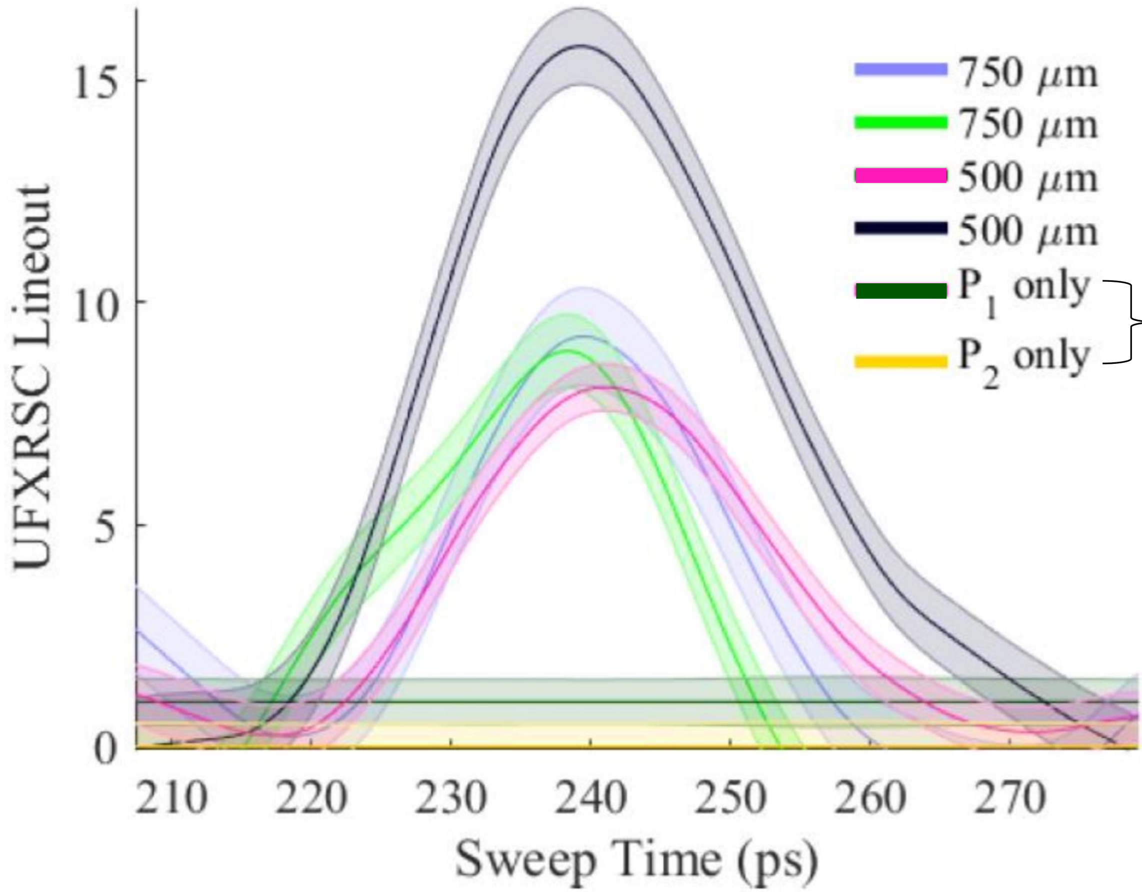
Temporal duration measurements





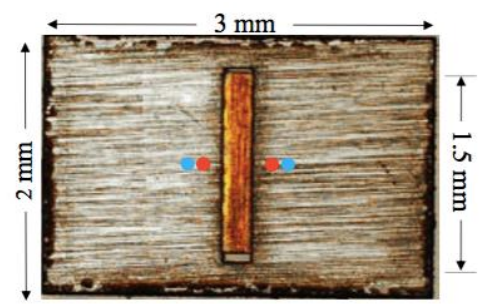
Temporal duration measurements

Midplane emission lasts for (25 ± 5) ps, equivalent to the signal duration from the focal spot region on a plane copper target



500µm separation positions

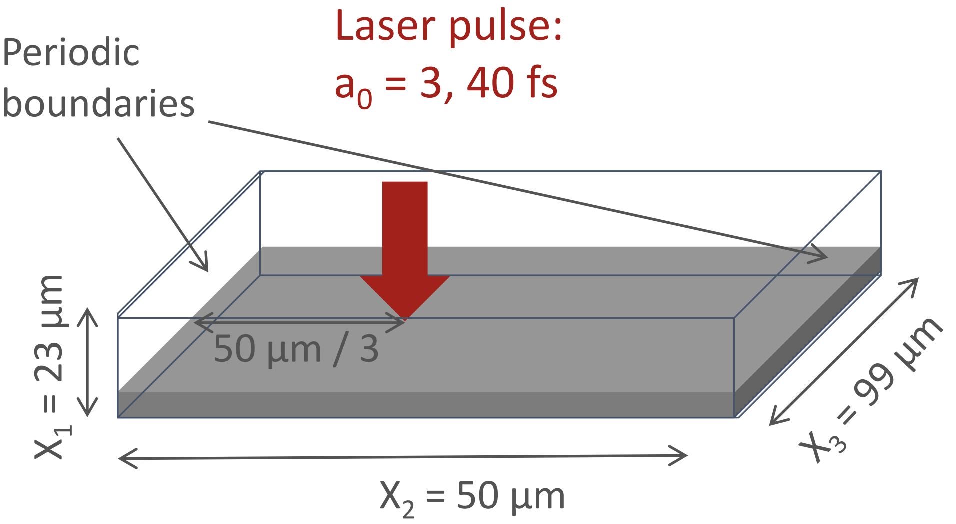
500µm 750µm



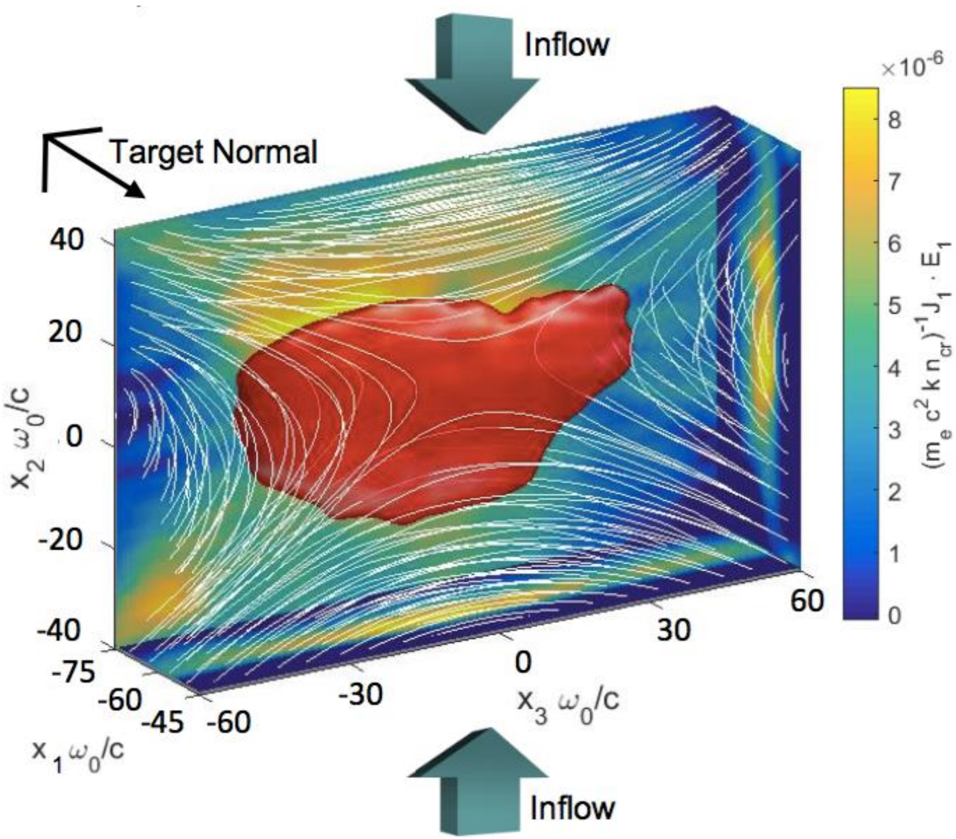
(a) front view (before sputtering)

3D OSIRIS Simulation (using 34,848 nodes of the NASA Pleiades supercomputer)

- (x_1, x_2, x_3) = (23 µm, 50 µm, 99 µm)
- 40 cells per λ
- 3 x 3 x 3 particles per cell
- $n_{max} = 30\ n_c$
- Plasma scalelength of λ
- Stationary ions
- Single pulse with periodic boundary create an effective spot separation of 50 µm
- Thermal boundaries were utilized in the laser longitudinal direction x_1 to prevent electron refluxing through the target



3D simulation results



Magnetic streamlines (white)

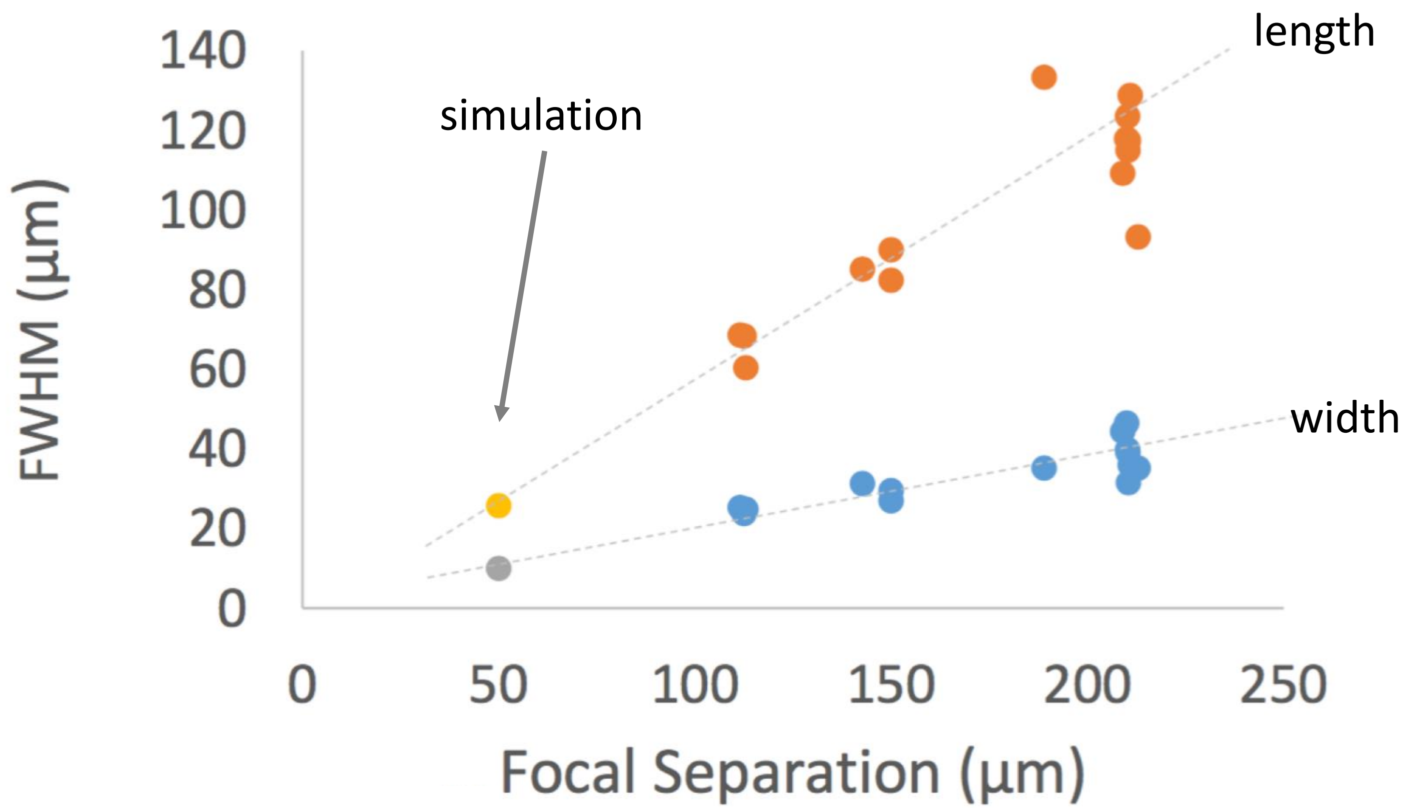
Hot electrons with Te~1 MeV are generated;

Azimutal magnetic fields within the interaction site ~35 MG

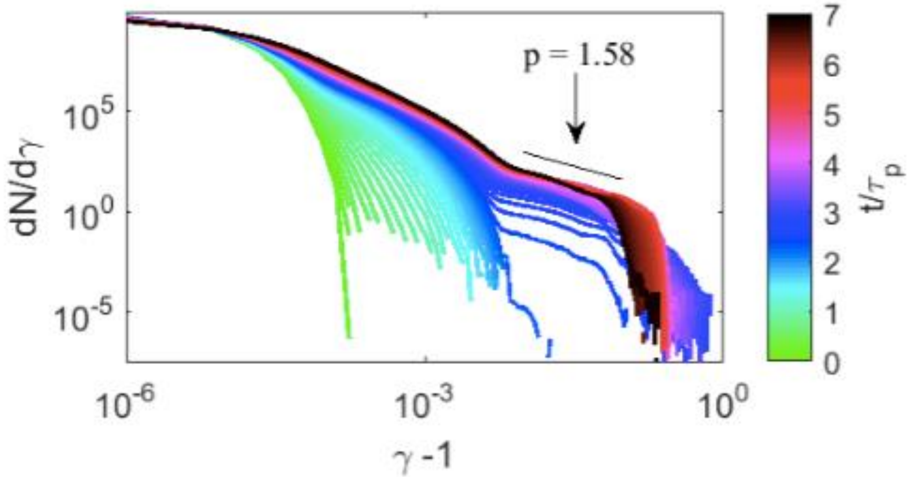
Electric field associated with the reconnection shown as a red isosurface with magnitude 95 GV/m

$E_1.J_1$ (work done on the electrons) evaluated through the center are shown on the box-faces

3D simulation results: reconnection layer dimensions

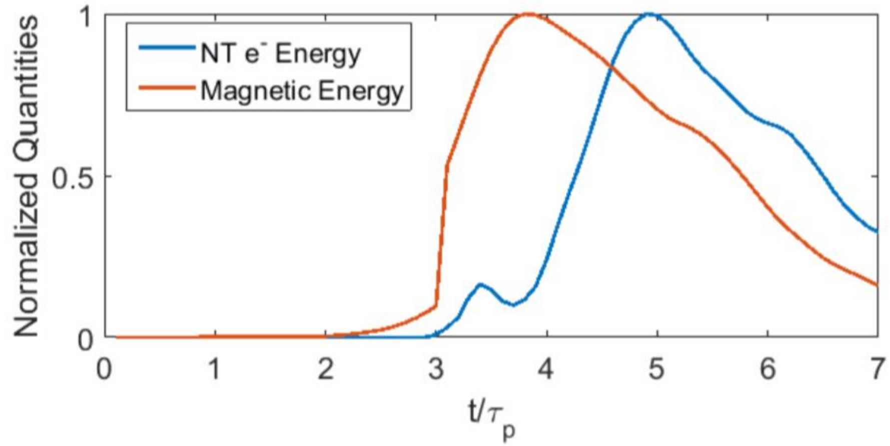


3D simulation results



Nonthermal spectral component develops: power law fit $\frac{dN}{d\gamma} \propto \gamma^{-1.6}$

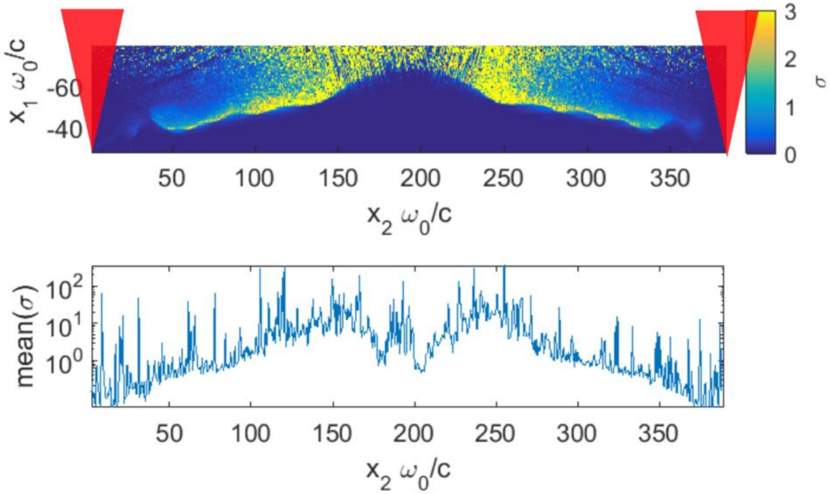
Consistent with relativistic reconnection



Temporal evolution of magnetic potential energy and the energy in nonthermal electrons

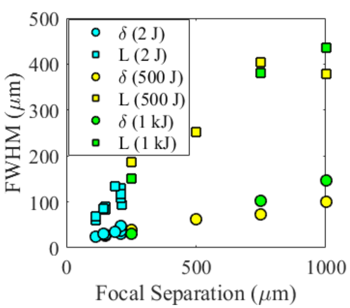
3D simulation results summary

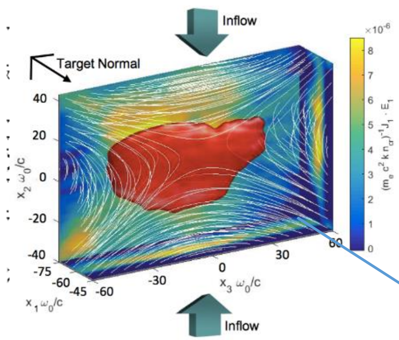
- Simulations indicate **relativistic reconnection**: $\mathcal{O}(40\%)$ of σ > 1 on target surface
- **Hall-like** features observed
- Reconnection rate is **fast**, comparable to experimental results and magnetic energy conversion time is $\approx 2\tau_p$
- **Suprathermal electrons** injected into the midplane

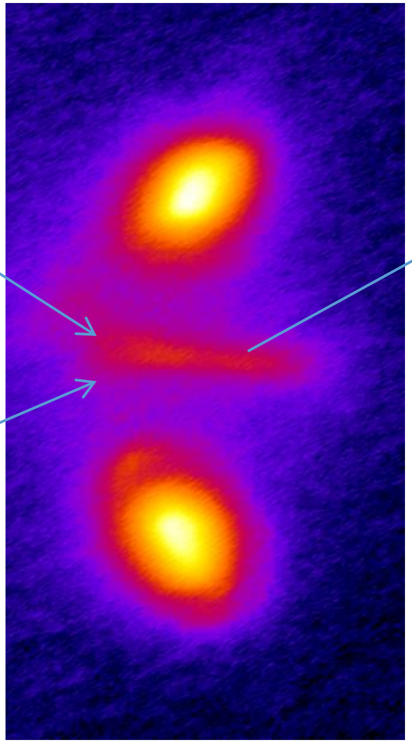


Relativistic magnetic reconnection in the laboratory

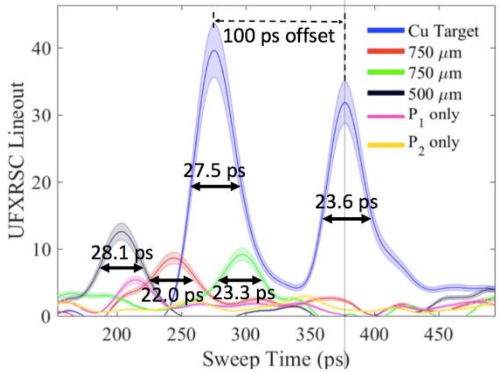
Current sheet formation



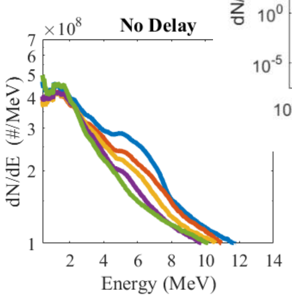


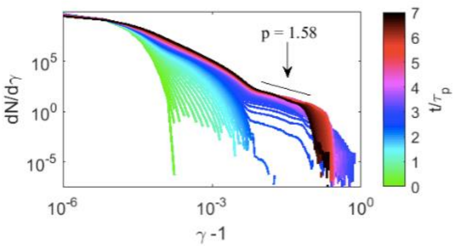


Fast reconnection timescale



Electron acceleration and heating





Simulations show reconnecting field structure and plasma parameters