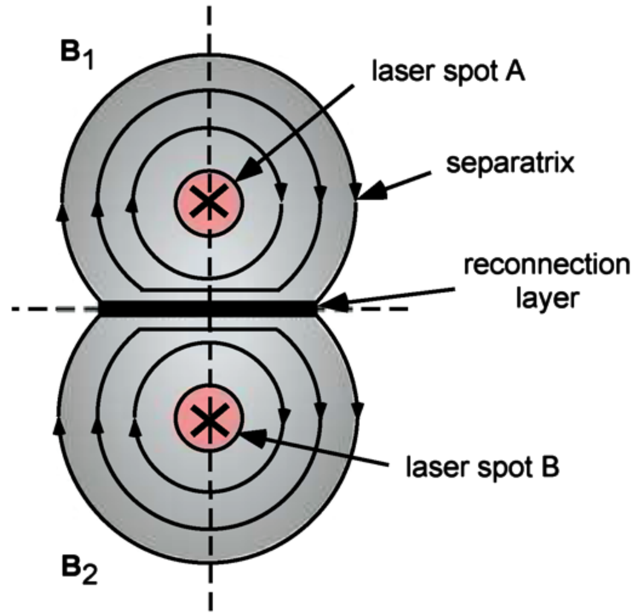
Past HED Reconnection Experiments in the UK and New Experiments with the OMEGA EP Laser System



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Laboratory for Laser Energetics

HED Meeting
PPPL
April 4-5, 2013

Summary

The plasma dynamics created by two heater beams at the surface of a planar solid target was studied

- A magnetic reconnection geometry was self generated with two closely focused laser spots: *10^{15} W/cm^2, 1-ns pulses*
- Observations consistent with a magnetic reconnection were made
  - the formation of a driven magnetic reconnection field distribution
  - the interaction of MG-level magnetic fields in a reconnection layer
  - collimated, high-velocity jet formation
  - high electron temperatures in the reconnection layer
- A magnetic reconnection experiment driven by high-energy petawatt (HEPW) lasers has been proposed (PI: Ji): *10^{18} W/cm^2, 10-ps pulses*
- The first shot day successfully demonstrated the timing and pointing capabilities necessary for these studies; an initial assessment of particle acceleration and jet formation was made

New diagnostics are required to probe the magnetic fields that are generated in these experiments

Collaborators: UK Experiments

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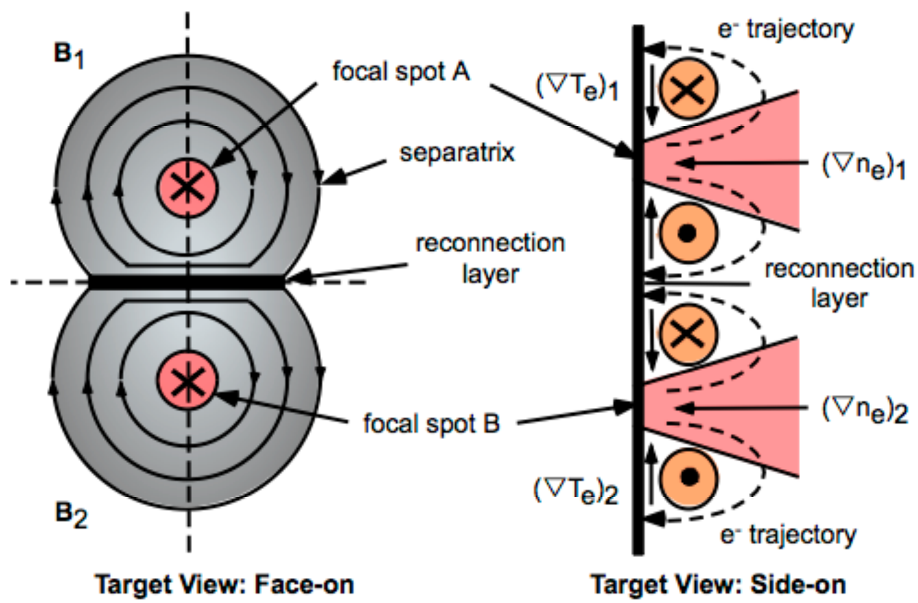
Laboratory for Laser Energetics

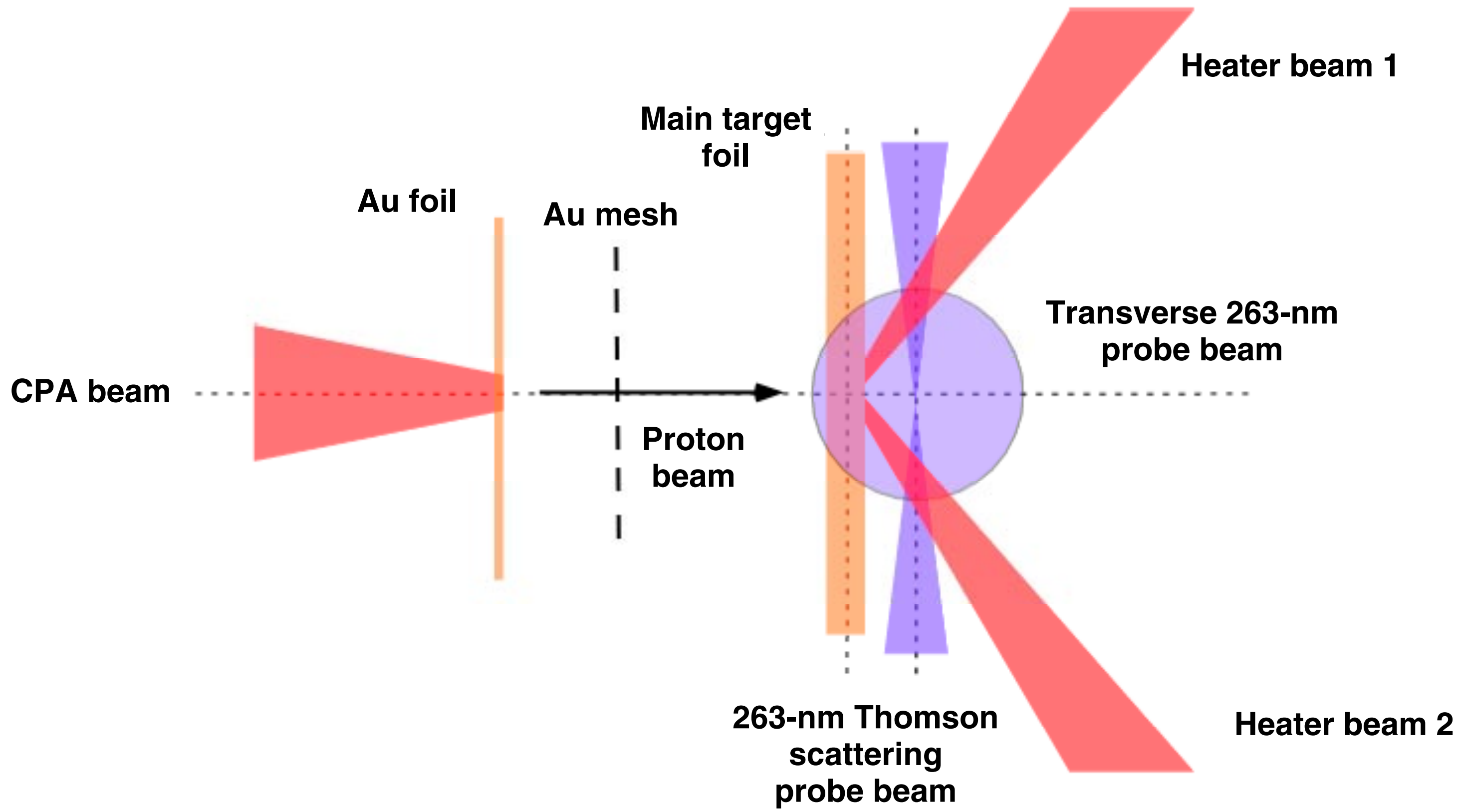
Magnetic fields are generated by non parallel electron density and temperature gradients

- **Laser-pulse characteristics: 1 ns, 10^{15} W/cm^2**



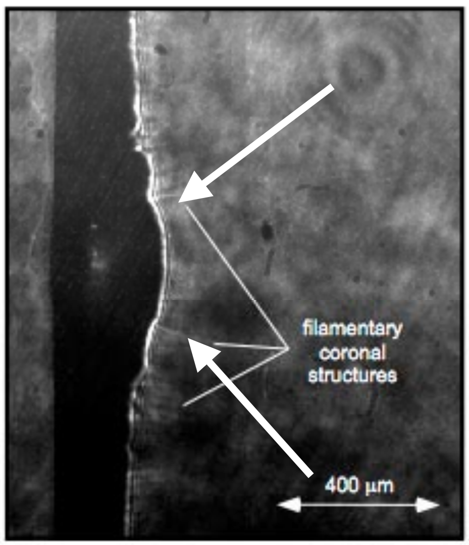
Self-generated magnetic reconnection in the HED regime

The experiments were carried out at the Vulcan Laser Facility at the Rutherford Appleton Laboratory

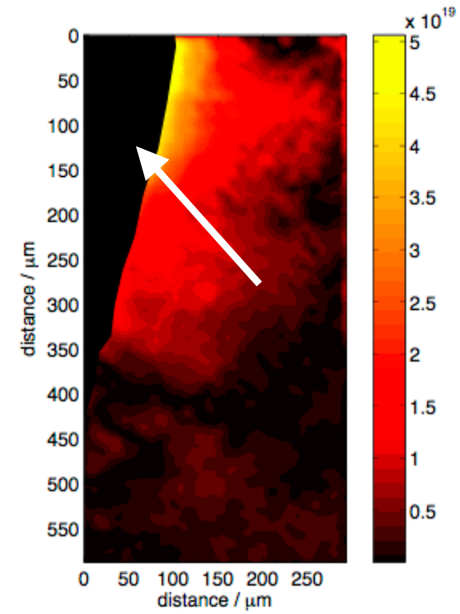


A single region of expanding plasma develops when the two heater beams are separated by ~200 μm

- **Shadowgram**
- **$t = t_0 + 1.5$ ns**



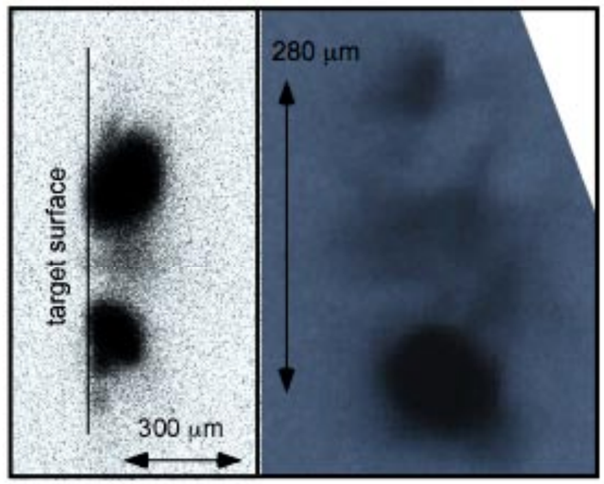
- **Interferogram**
- **$t = t_0 + 1.5$ ns**



- **Aluminum target foil**

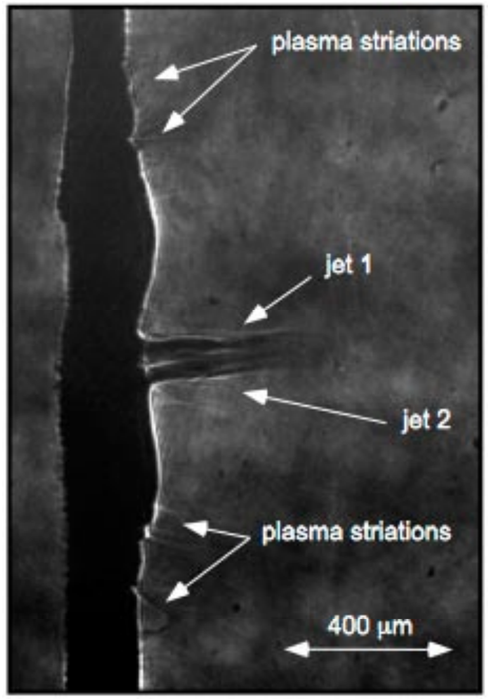
Time-integrated x-ray pinhole imaging shows heating due to a plasma collision

- **X-ray pinhole images (time-integrated)**
- **Al target (1-keV emission)**



- **Conversion of streaming ion kinetic energy into ion thermal energy**
- **Electrons gain energy through election–ion equilibration**

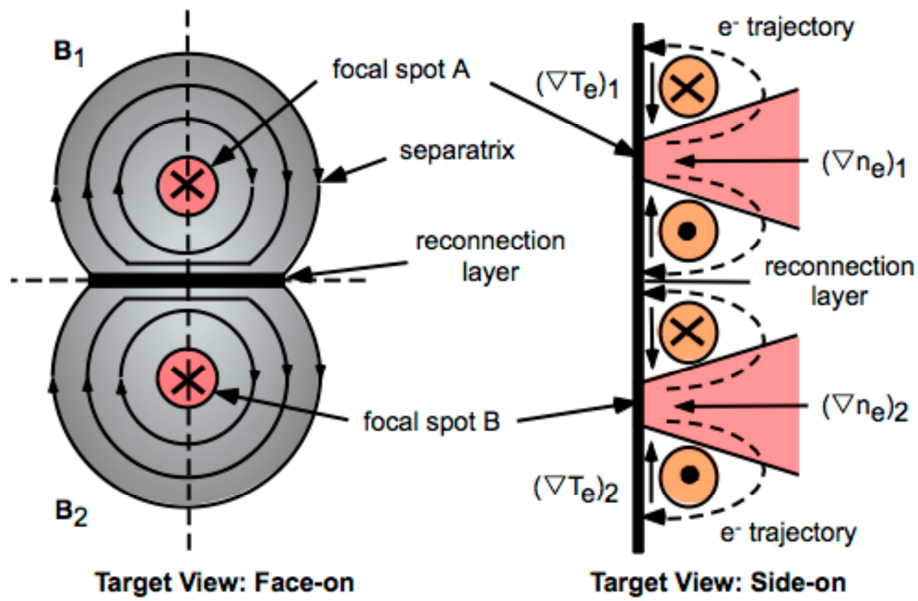
Sudden jet formation occurs for larger laser-spot separations of ~400 μm



- **Aluminum target foil**
- $t = t_0 + 1.5$ **ns**

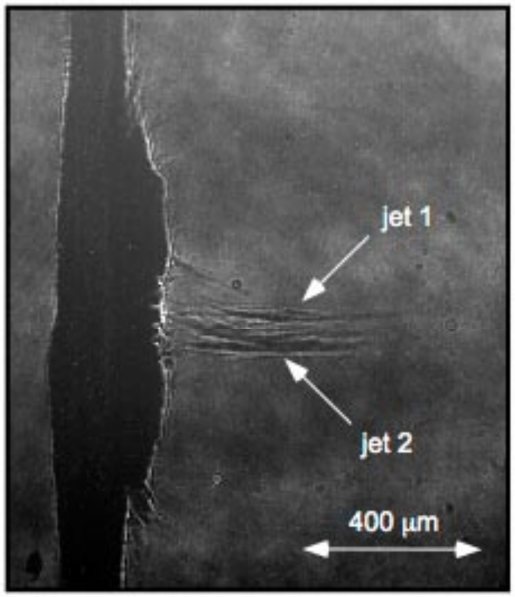
- **Jet formation occurs at an angle to the target surface**

Jet formation occurs at an angle to the target surface

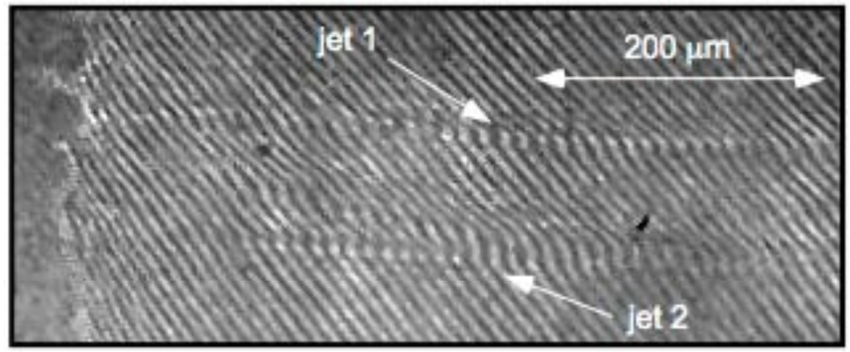


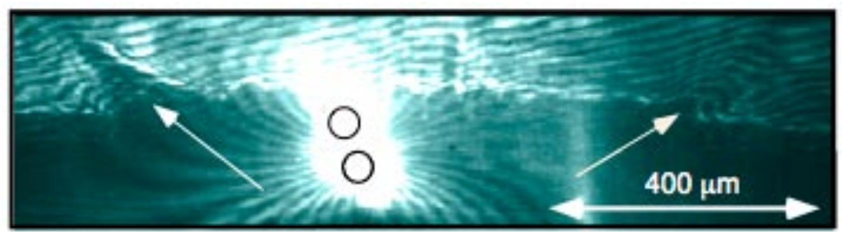
Greater jet collimation is observed in gold target interactions consistent with radiative cooling

$t = t_0 + 2.5$ ns



$t = t_0 + 0.7$ ns

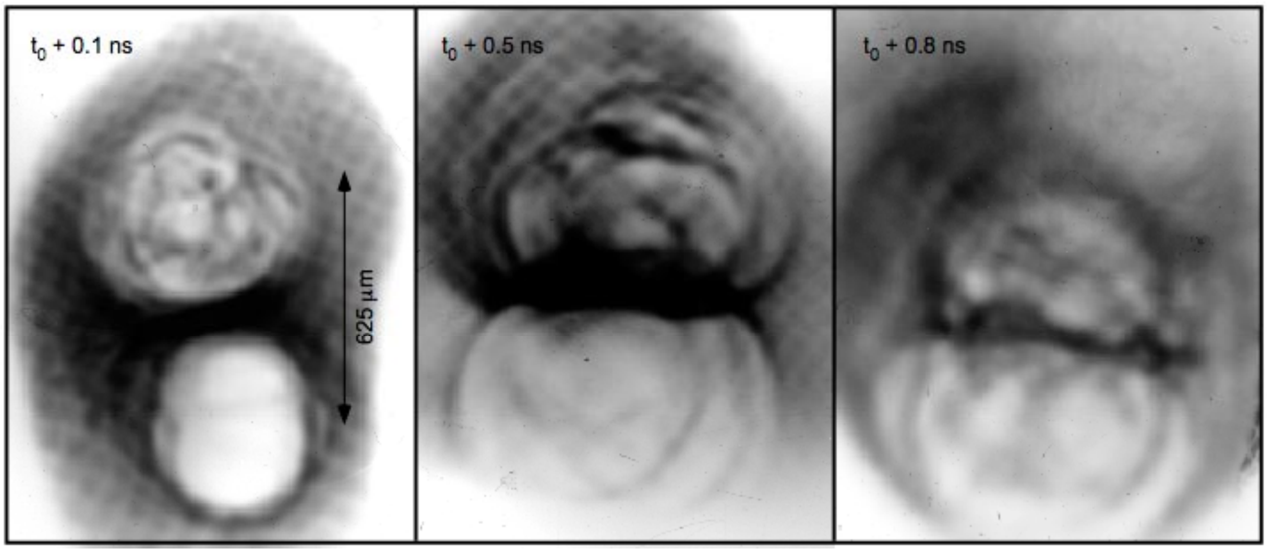




Gold target foil

Interacting MG-level azimuthal magnetic fields were measured with proton deflectometry

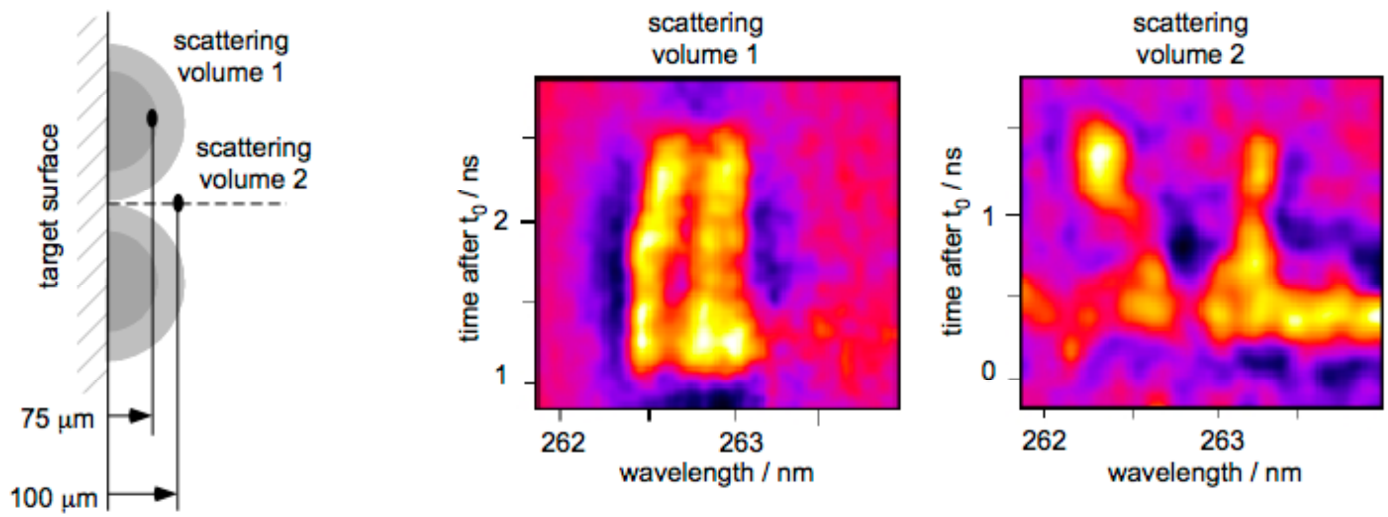
$t = t_0 + 0.1$ ns $\quad t = t_0 + 0.5$ ns $\quad t = t_0 + 0.8$ ns



- **0.7- to 1.3-MG magnetic fields**
- **Stressed magnetic-field lines**

More detail: JO2.00009 Willingale

Thomson scattering measurements show keV electron temperatures in the Al interaction layer



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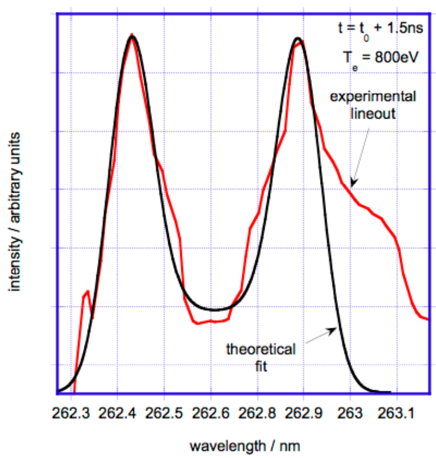
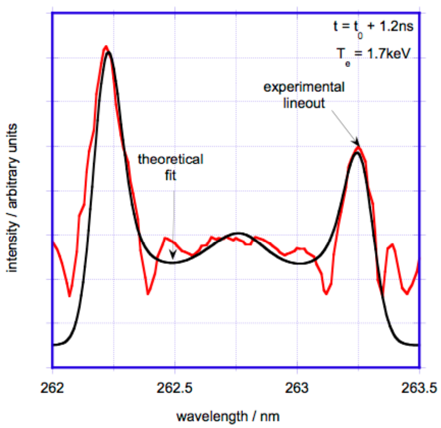


- **Scattering volume 1: plume**
- **T_e = 800 eV at $t = t_0$ + 1.5 ns**

- **Cooling due to hydrodynamic expansion**



- **Scattering volume 2: interaction region**
- **T_e = 1700 eV at $t = t_0$ + 1.2 ns**

- **Assumes an ion-distribution function represented by the sum of two Maxwellians shifted by the beam flow velocity**

Summary: UK Experiments

The plasma dynamics created by two heater beams at the surface of a planar solid target was studied

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- Observations consistent with a magnetic reconnection were made
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- Much is to be understood in these interactions
  - magnetic field dynamics
  - jet formation
  - 'bursty' dynamics over long drive times (>10 ns)
  - heating dynamics

[1] P M Nilson et al, PRL 97, 255001 (2006)
[2] C K Li et al, PRL 99, 055001 (2007)
[3] L Willingale et al, PoP 17, 043104 (2010)
[4] P M Nilson et al, PoP 15, 092701 (2008)
[5] J Zhong et al, Nature Physics 6, 984987 (2010)
[6] W Fox et al, PRL 106, 215003 (2011)

OMEGA EP offers exciting potential for studying particle acceleration in collisionless magnetic reconnection

- **The most interesting astrophysical environments for particle acceleration by magnetic reconnection are collisionless, magnetically dominated, and have a system size much larger than the ion skin depth.**

- **These conditions can be approached with picosecond laser-solid Interactions at intensities of more than 10^{18} W/cm^2.**

- **The OMEGA EP laser facility uniquely combines two HEPW-class beam lines capable of generating a collisionless magnetic reconnection geometry.**

- **A suite of high-energy particle and x-ray diagnostics exists.**

Experiments on OMEGA EP could provide important data for understanding the energized particle spectrum from collisionless magnetic reconnection.

HEPW-laser interactions with solid target generate extreme HED conditions over ps timescales

- Laser parameters
  - energy: 100-J to 2.6-kJ @ 1 μm
  - pulse duration: 1- to 100-ps (20-ps)
  - spot diameter: tens of microns
  - focused intensities: >10^{18} W/cm^2

- Targets
  - mm × mm planar foils
  - μm to several-hundred μm thick
  - various Z: CH, Al, Au

- Plasma parameters
  - tenuous coronal plasma >$0.05n_{cr}$
  - MG to GG (?) magnetic fields
  - MeV hot electrons
  - MeV proton beams
  - eV to keV thermal temperatures @ solid density

Many open questions exist in HEPW-laser interactions with solid targets

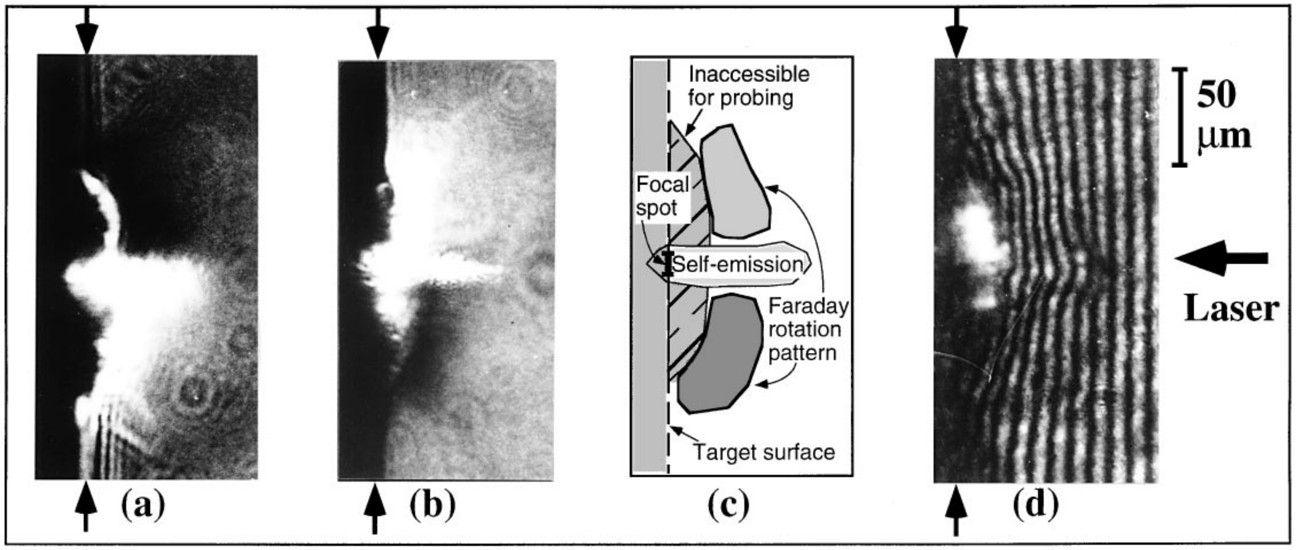
- What is the magnitude of the azimuthal grad $n_e \times$ grad T_e field?
  - spatial extent of the magnetic field distribution?
  - temporal evolution of the magnetic field distribution?
  - defines the optimum spot separation for reconnection

- Are there larger magnetic fields at the critical surface?
  - 100's MG to GG?
  - what is the magnetic field topology in this region?

- ** Do PIC models predict magnetic reconnection in this regime? **

These considerations reveal a large parameter space for designing experiments

The evolution of B fields in ps laser-solid interactions were measured with Faraday rotation

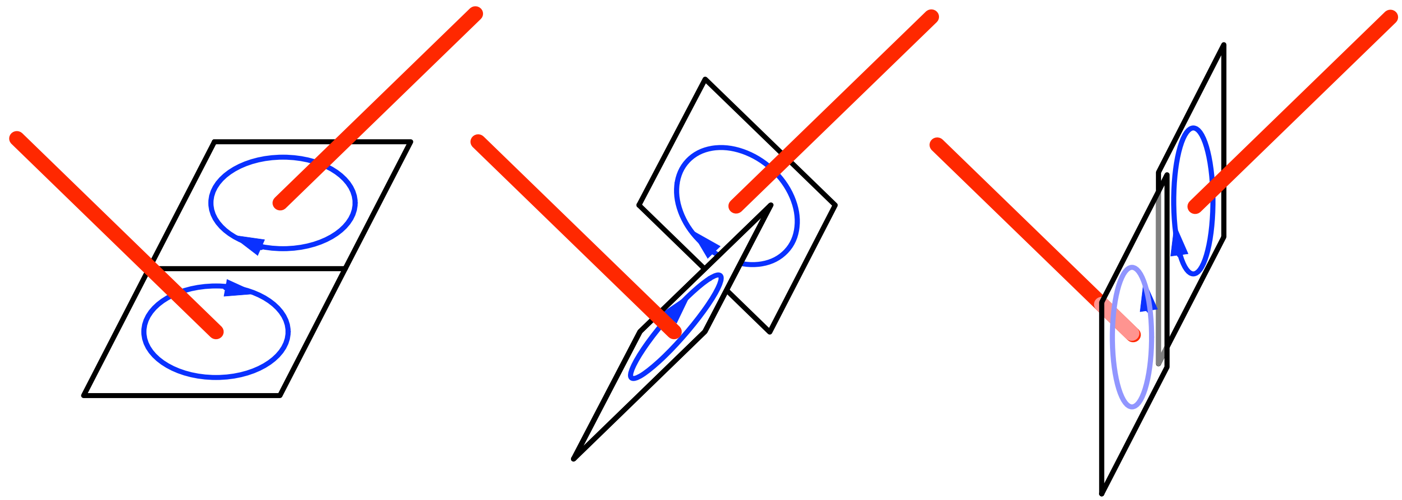


Laser: 10 J, 1.5 ps
Intensity: 5 × 10^{18} W/cm^2
Target: Al foil
Timing: t_0 + 12 ps

Magnetic fields generated by OMEGA EP have not been characterised

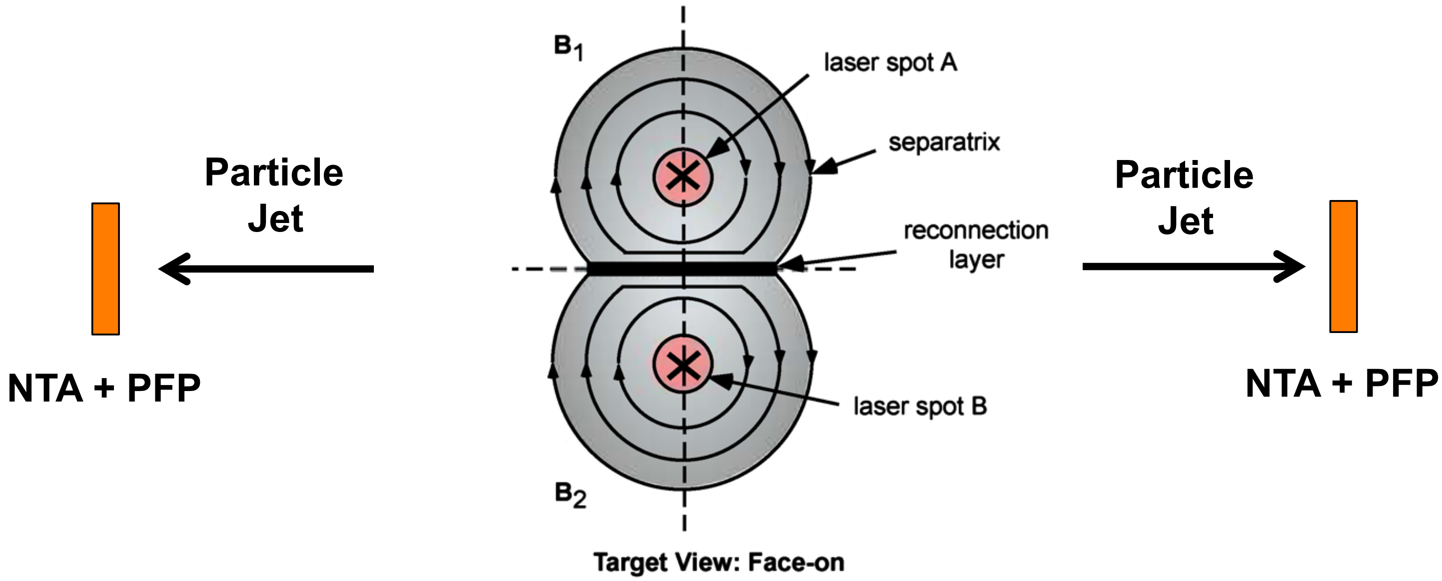
M Borghesi et al, PRL 81, 1 (1998)

A magnetic reconnection experiment driven by high-energy petawatt lasers was proposed (PI: Ji)



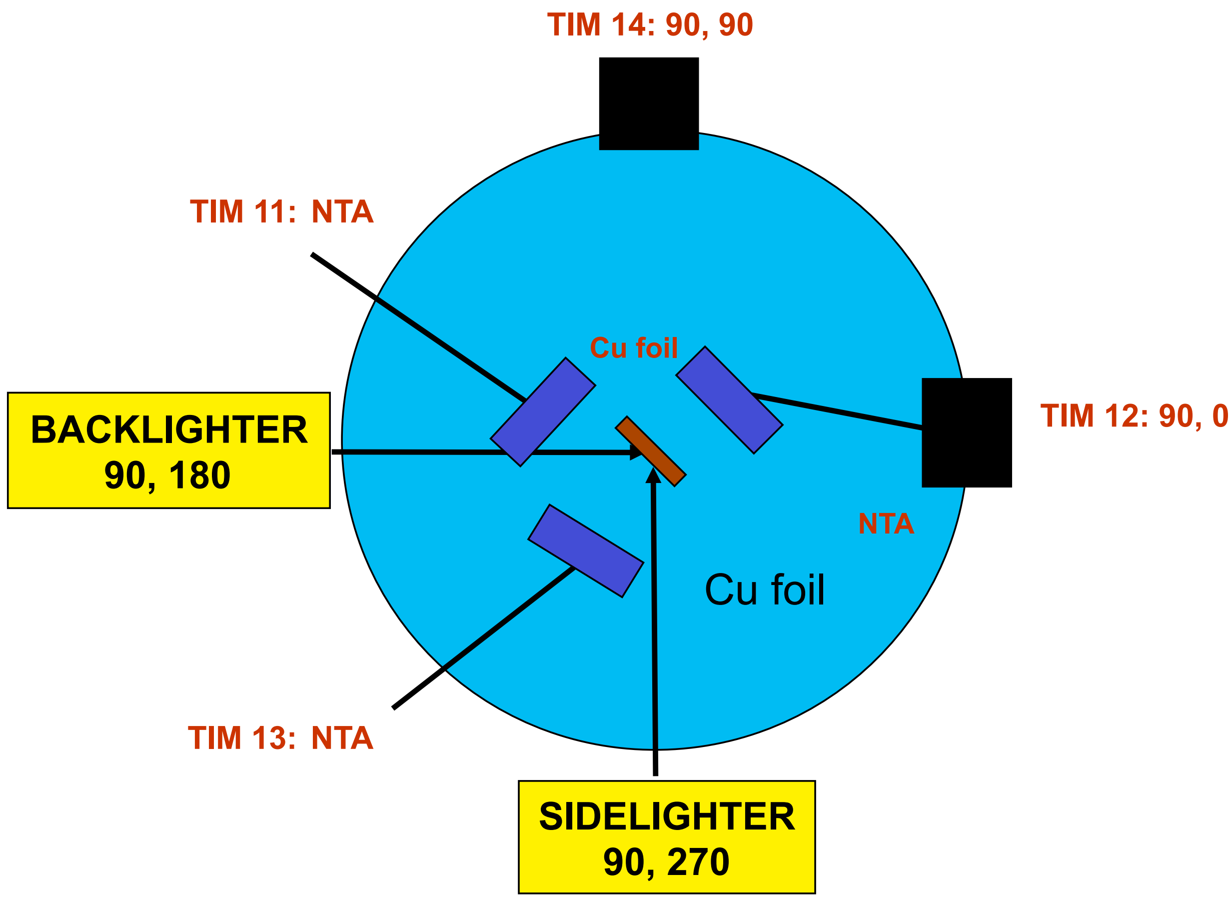
Anti parallel fields for reconnection	Field reconnects at an angle	No reconnection expected

The first OMEGA EP experiment demonstrated the required pointing and timing accuracy

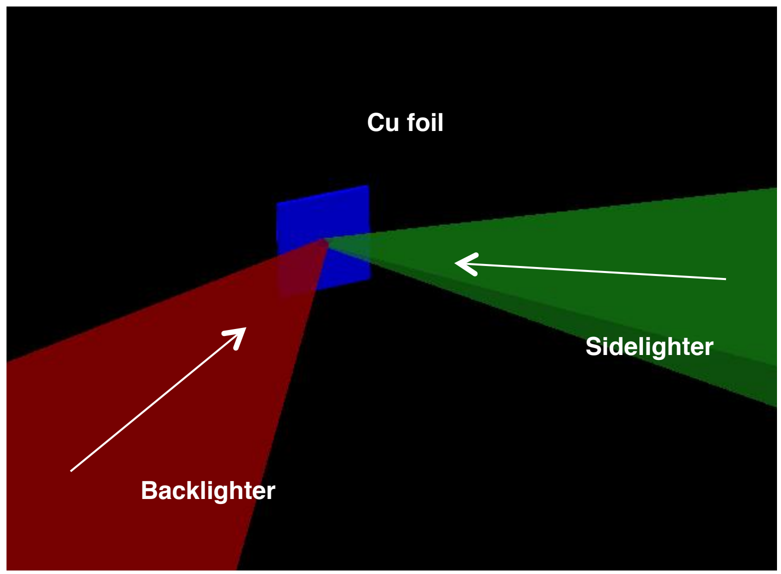


An initial assessment of particle acceleration and jet formation was made

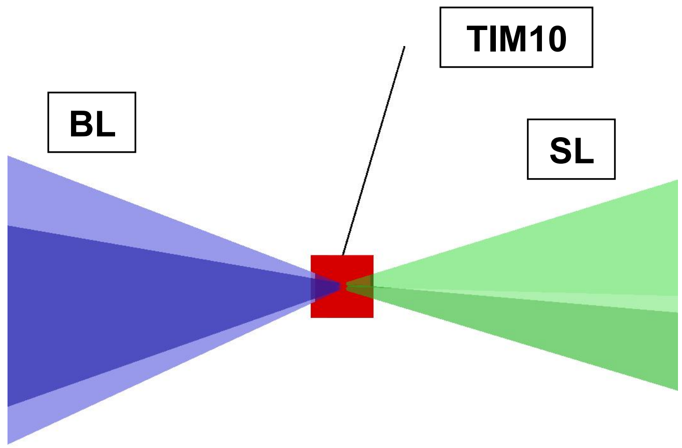
Three radiochromic film detector packs were deployed

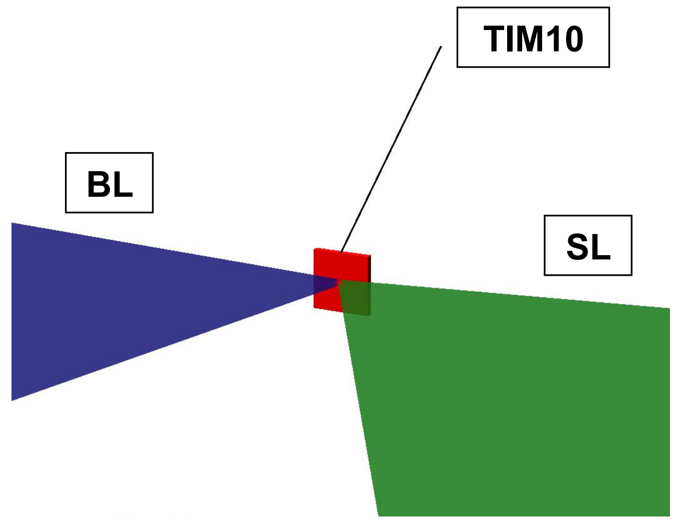


Each laser spot was focused to the same location and separated on each shot up to a few focal spot diameters



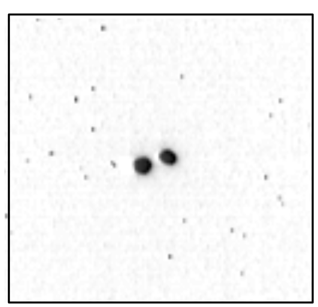
Two x-ray pinhole cameras verified the focal spot alignment





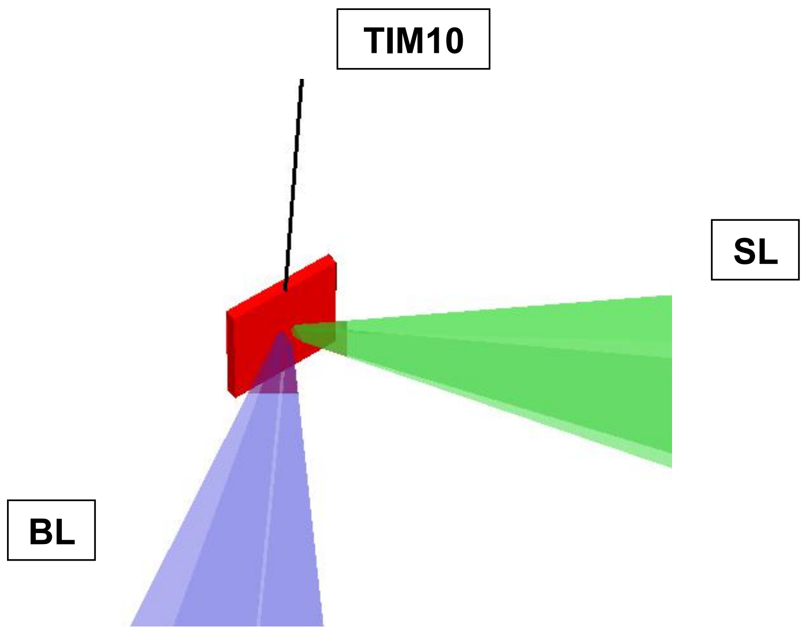
EP39

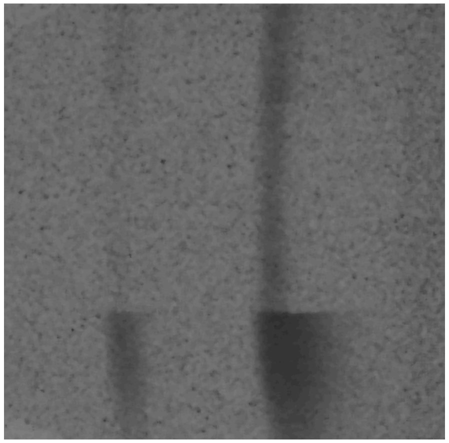
EP52-A



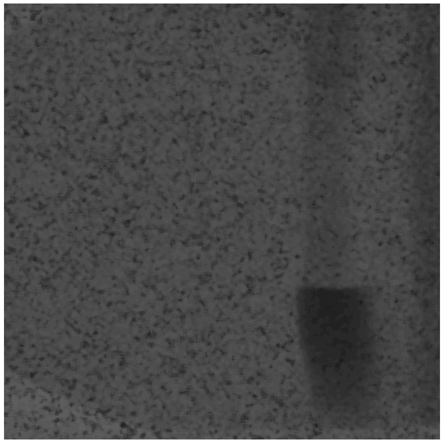
Shot: 14038
Spot separation: ~100µm

The ultrafast x-ray streak camera verified beam timing; the view is from TIM11



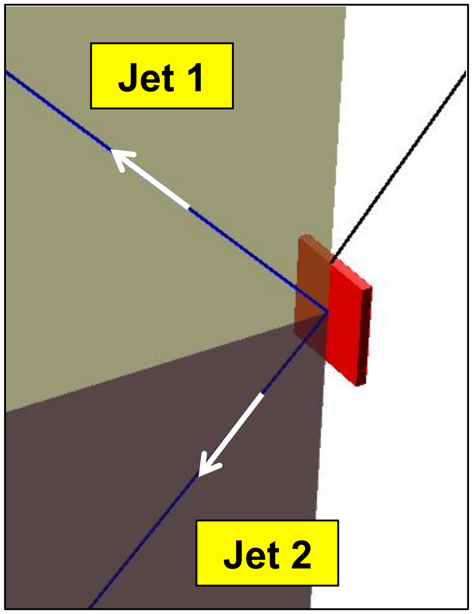


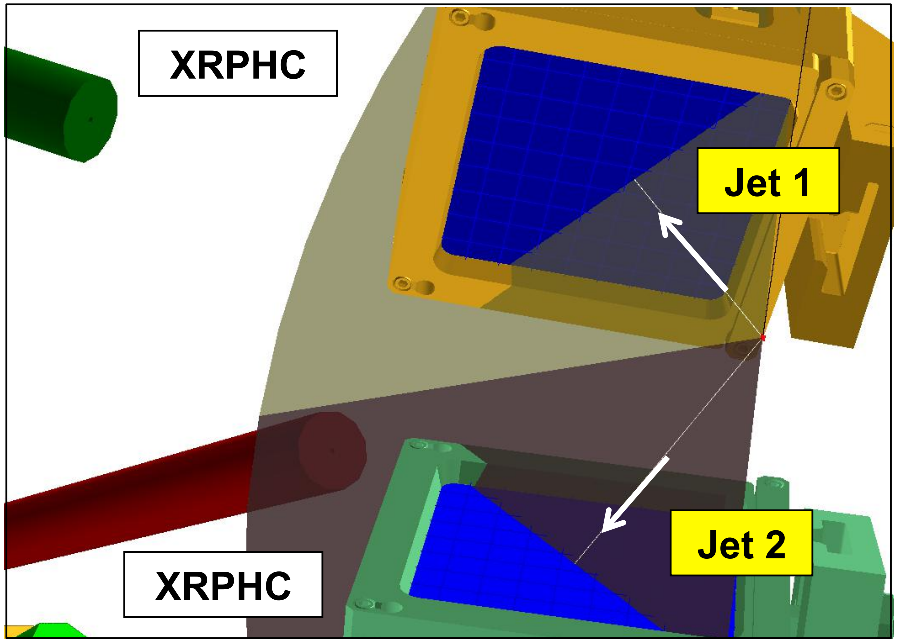
Separated: ~125 ps apart



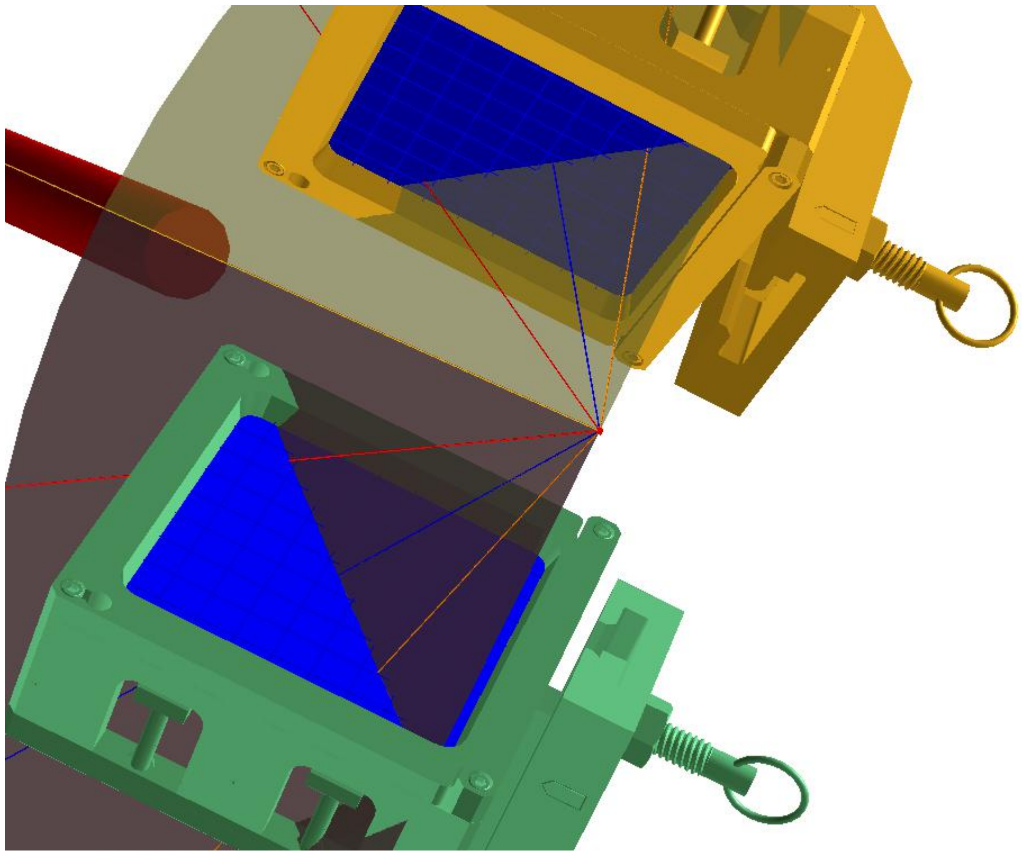
Co timed

Film pack alignment optimized the angular coverage





The proton film packs were placed to confirm symmetry



Future experiments require modeling predictions and more diagnostics for characterizing the interaction layer

- PIC modeling
  - Magnetic field predictions for OMEGA EP drive conditions
  - Is magnetic reconnection observed in the modeling?
  - Particle acceleration predictions?
- Particle diagnostics
  - Radiochromic film stacks
  - Thomson parabola (angular coverage)
  - Electron spectrometers (angular coverage)
- Optical probing
  - Interferometry
  - Faraday rotation
- X-ray diagnostics
  - X-ray imaging
  - Time-resolved x-ray spectroscopy

Summary: OMEGA EP Experiments

A magnetic reconnection experiment driven by HEPW lasers was proposed (PI: Ji)

- **The first shot day successfully demonstrated the timing and pointing capabilities necessary for these studies**
- **An initial assessment of particle acceleration and jet formation was made**
- **PIC modeling of two-beam interactions in the high-intensity regime is required**

New diagnostic opportunities exist to probe the magnetic fields that are generated in these experiments