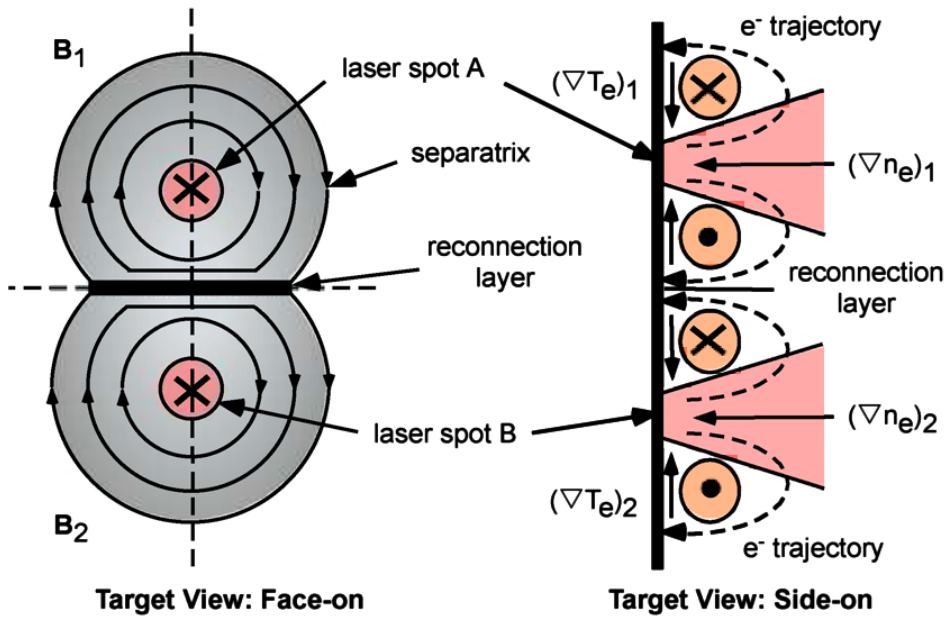
Magnetic Reconnection with High-Energy Petawatt Beams



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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.**

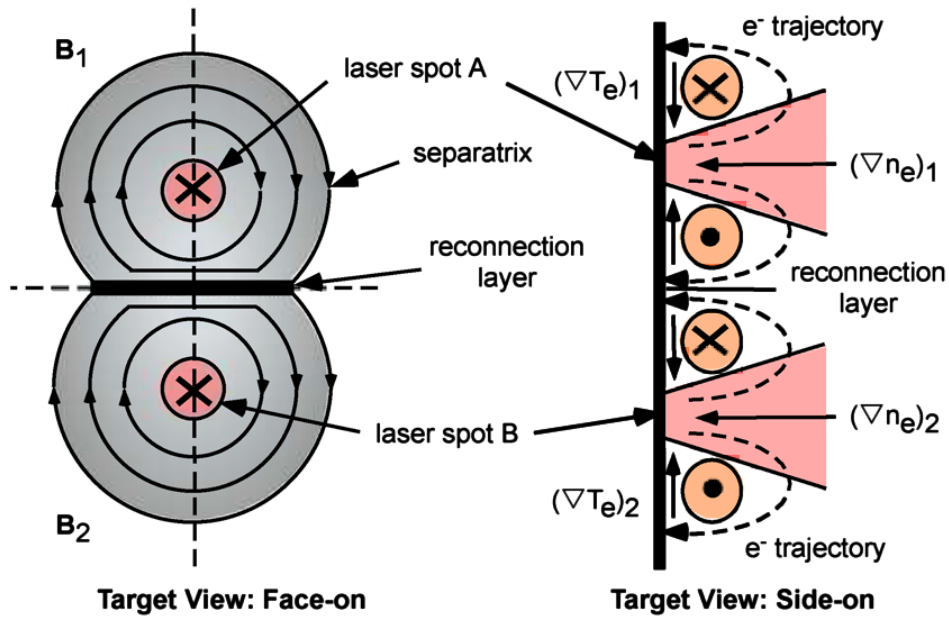
Experiments on OMEGA EP could provide important data for understanding the energized particle spectrum from collisionless magnetic reconnection.

Overview

- Review single-beam HEPW laser-solid interactions
  - target charging
  - particle acceleration without reconnection
- Magnetic reconnection with ps laser pulses
  - coronal plasma conditions
  - magnetic field measurements
- Example OMEGA EP experiment configuration
  - target geometry
  - diagnostics

Laser-driven magnetic reconnection with ns laser pulses has been observed[1-6]

- Proton probing showed MG-level field generation and reconnection layer formation[1-3]
- Optical probing showed bi-directional jet formation[1,4]
- Greater jet collimation was observed in higher-Z plasmas[4]
- Thomson scattering showed high electron temperatures in the reconnection layer[1]

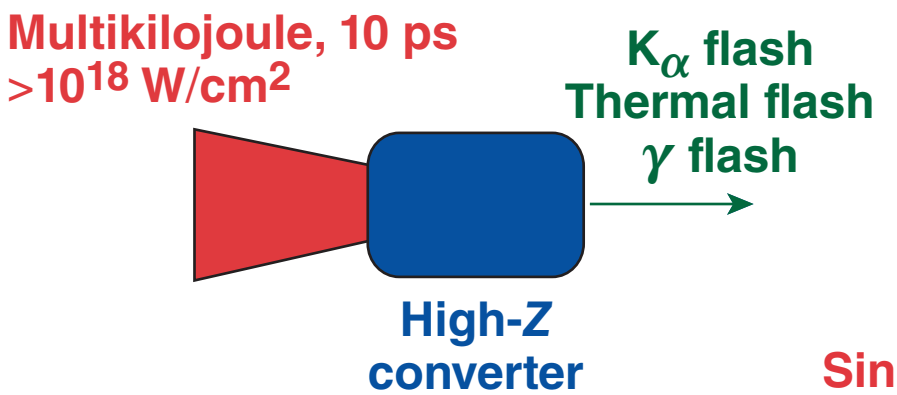


Dual-beam geometry

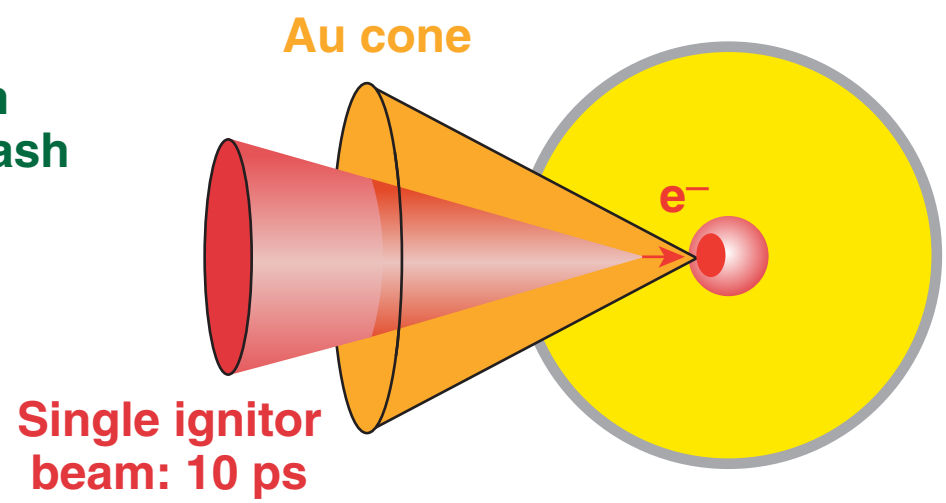
[1]P M Nilson et al, PRL 97, 255001 (2006)
[2]C K Li et al, PRL 99, 055001 (2007)
[3]L Willingale et al, PoP 17, 043104 (2010)
[4]P M Nilson et al, PoP 15, 092701 (2008)
[5]J Zhong et al, Nature Physics 6, 984987 (2010)
[6]W Fox et al, PRL 106, 215003 (2011)

High-energy petawatt laser-solid interactions generate powerful MeV electron sources

Laser-Driven Radiography[1,2]



Fast Ignition[3,4]



The energetic feasibility of these schemes relies on efficient energy coupling to hot electrons with 10-ps pulses.

[1]M. D. Perry *et al.*, Rev. Sci. Instrum. 70, 265 (1999).
[2]R. D. Edwards *et al.*, Appl. Phys. Lett. 80, 2129 (2002).
[3]M. Tabak *et al.*, Phys. Plasmas 1, 1626 (1994).
[4]M. H. Key *et al.*, Phys. Plasmas 5, 1966 (1998).

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HEPW-laser interactions with solid targets generate extreme high energy density conditions over picosecond timescales

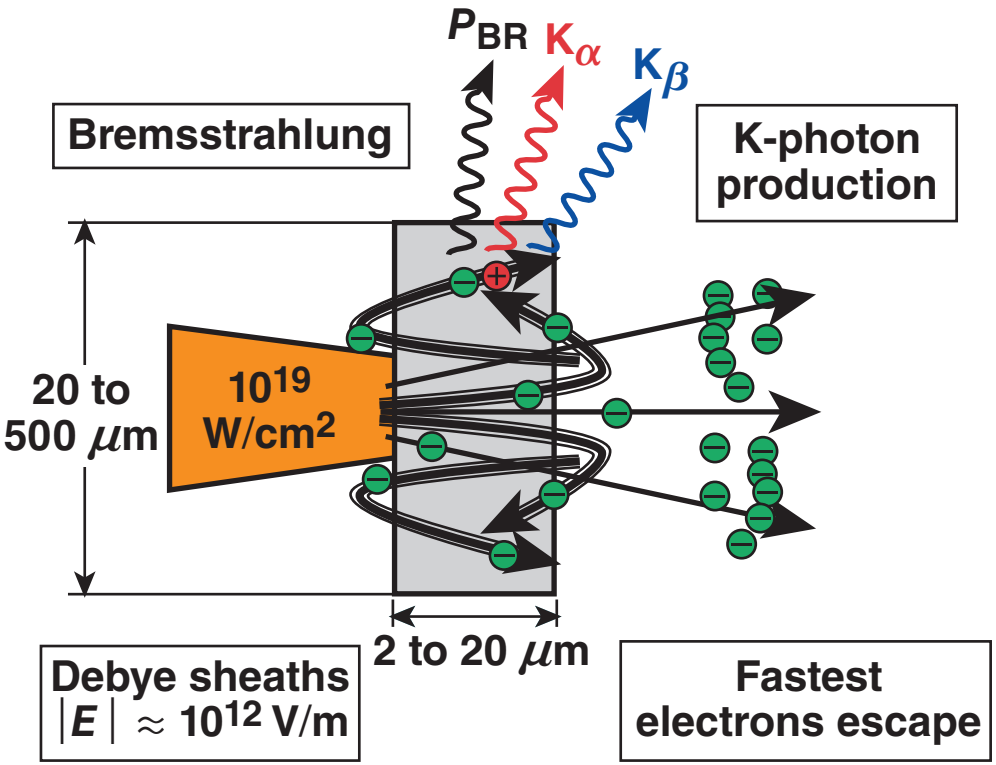
FSC

- **Laser parameters**
  - **energy: 100-J to 2.6-kJ @ 1 μm**
  - **pulse duration: 1- to 100-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**

Fast-electron refluxing in thin-foil targets accesses high temperature matter at solid density



- Refluxing is caused by Debye-sheath field effects[1–5]
- Majority of fast electrons are stopped in the target
- Efficient radiators
  - K_α, K_β
  - thermal emission
- No fluor layers

Fast-electron "calorimeter"

[1]S. P. Hatchett *et al.*, Phys. Plasmas 7, 2076 (2000).
[2]R. A. Snavely *et al.*, Phys. Rev. Lett. 85, 2945 (2000).
[3]W. Theobald *et al.*, Phys. Plasmas 13, 043102 (2006).
[4]J. Myatt *et al.*, Phys. Plasmas 14, 055301 (2007).
[5]P. M. Nilson *et al.*, Phys. Rev, E 79, 016406 (2009).

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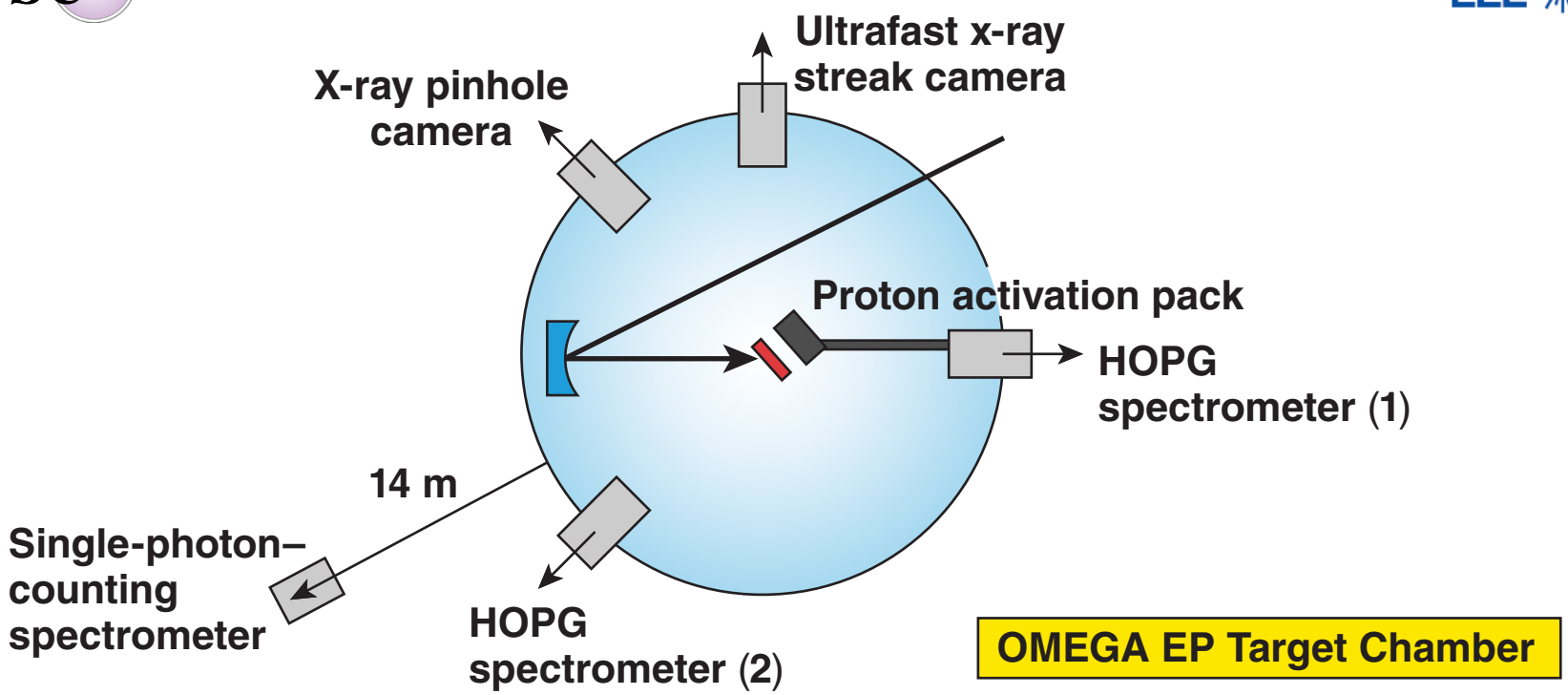
Single-beam experiments were performed on OMEGA EP with up to 2.1-kJ, 10-ps laser pulses



- Laser intensities $I \sim 5 \times 10^{18}$ W/cm^2
- Copper-foil targets
- Target volumes:
  $500 \times 500 \times 50\ \mu m^3$ to $75 \times 75 \times 5\ \mu m^3$

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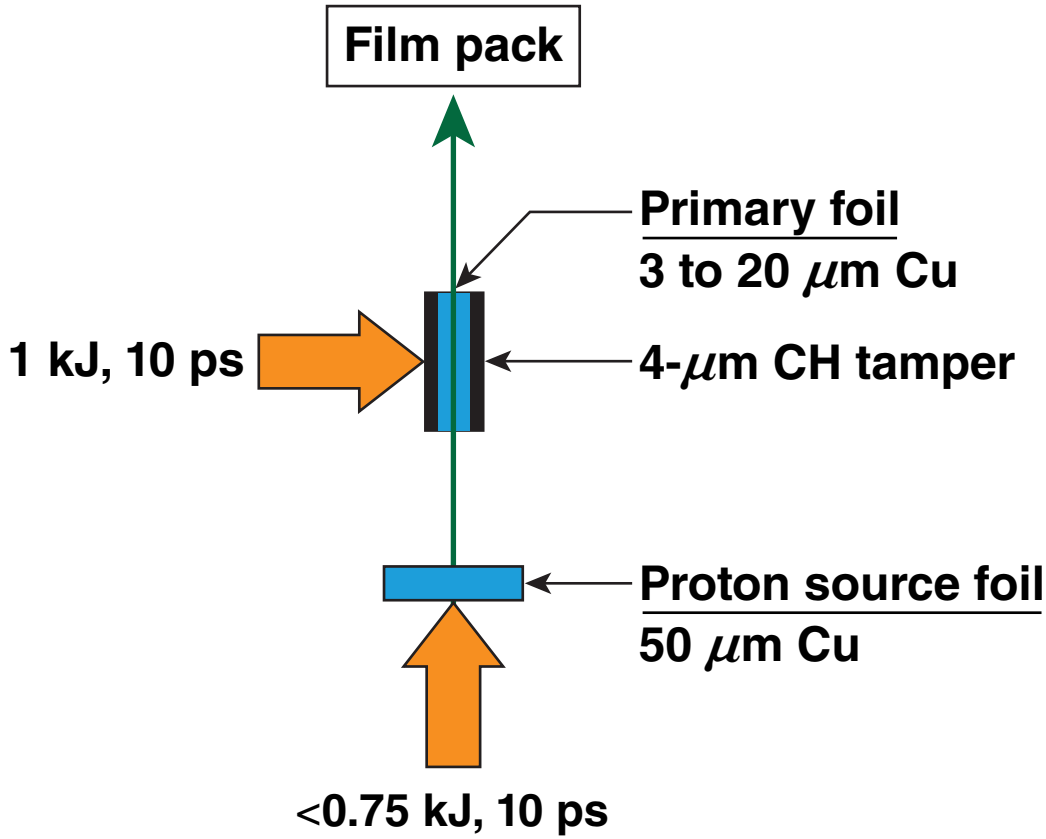
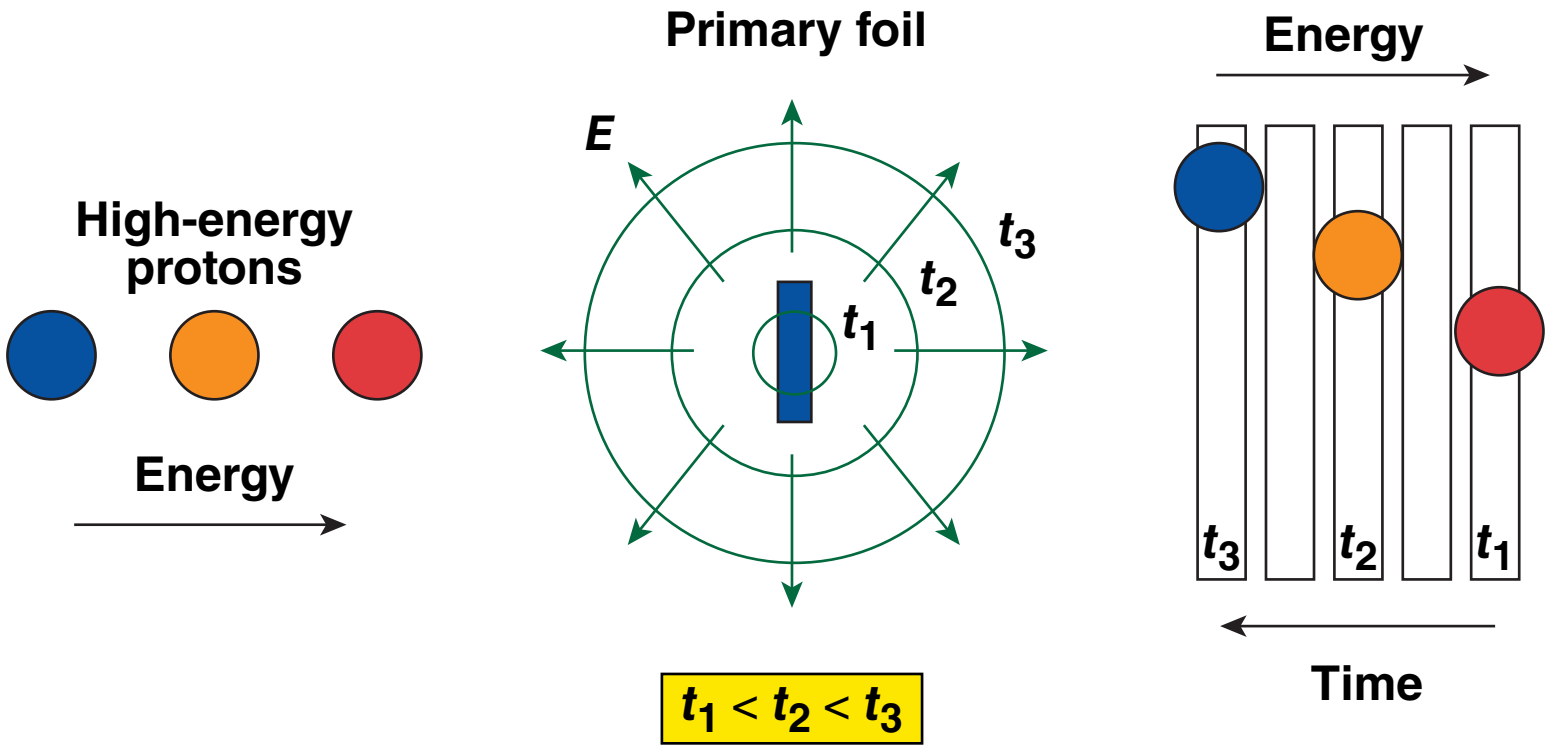
Proton radiography was used to study target charging



Single-shot, multiframe imaging is achieved with μm-scale spatial resolution and ps-scale temporal resolution.

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



M. Borghesi *et al.*, Phys. Plasmas 9, 2214 (2002).

Many open questions exist about plasma formation and magnetic field generation from solid targets in the HEPW regime

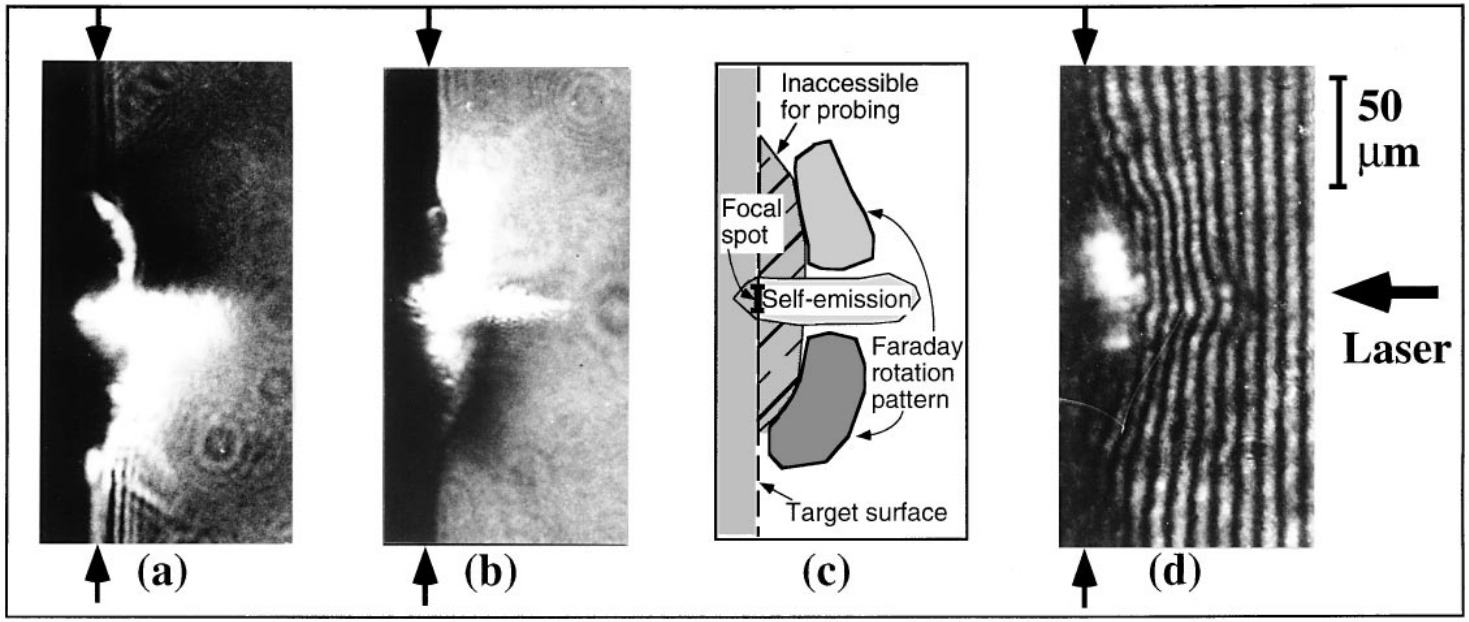
- **What is the preplasma and coronal plasma density profile?**
  - **intrinsic prepulse-driven plasma conditions?**
  - **effect of target-Z and laser-pulse duration?**
  - **plasma-formation with ns heater beams?**

- **What is the magnitude of the azimuthal grad n_e × grad T_e fields?**
  - **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?**

These considerations reveal a large parameter space for designing an experiment

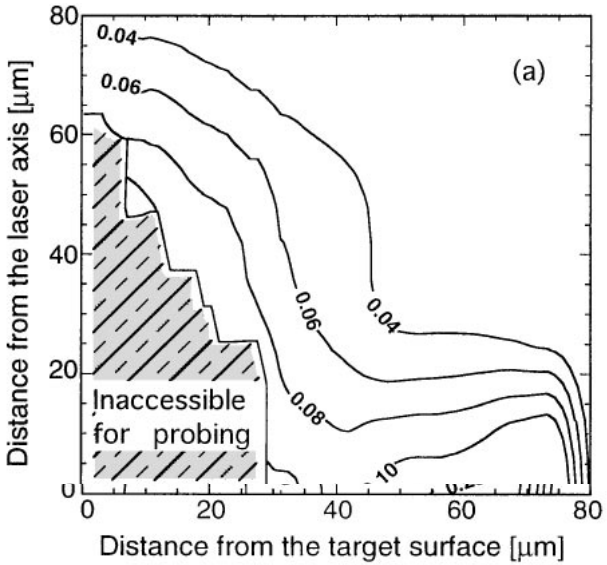
The spatial and temporal evolution of B fields in ps laser-solid interactions were measured using Faraday rotation

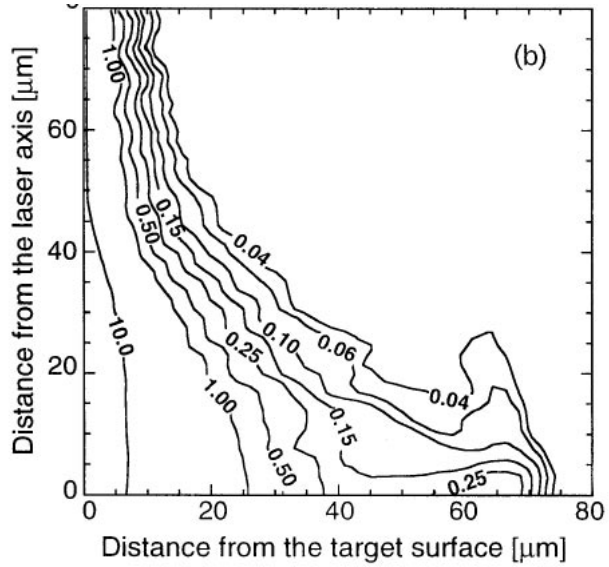


Laser: 10 J, 1.5 ps
Intensity: 5×10^{18} W/cm^2
Target: Al foil
Timing: $t_0 + 12$ ps

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

The electron density distribution in the laser focal region was measured with interferometry



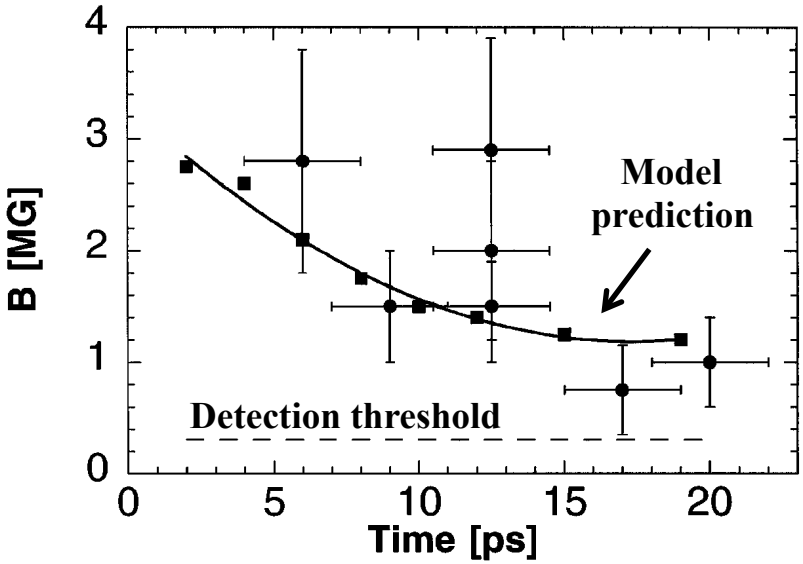


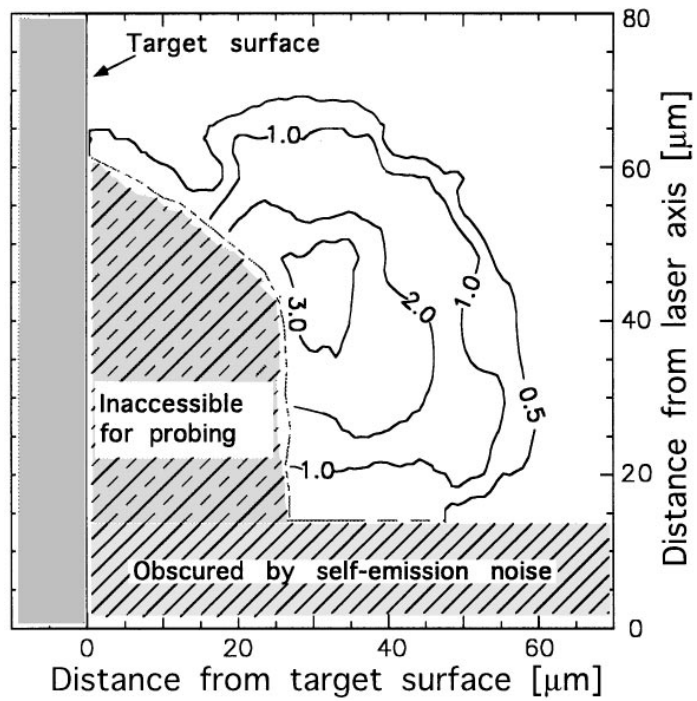
Laser: 10 J, 1.5 ps
Intensity: 5×10^{18} W/cm^2
Target: Al foil
Timing: t_0 + 12 ps

Model prediction
Units: 10^{21} cm^{-3}

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

The temporal evolution of the maximum magnetic field was determined



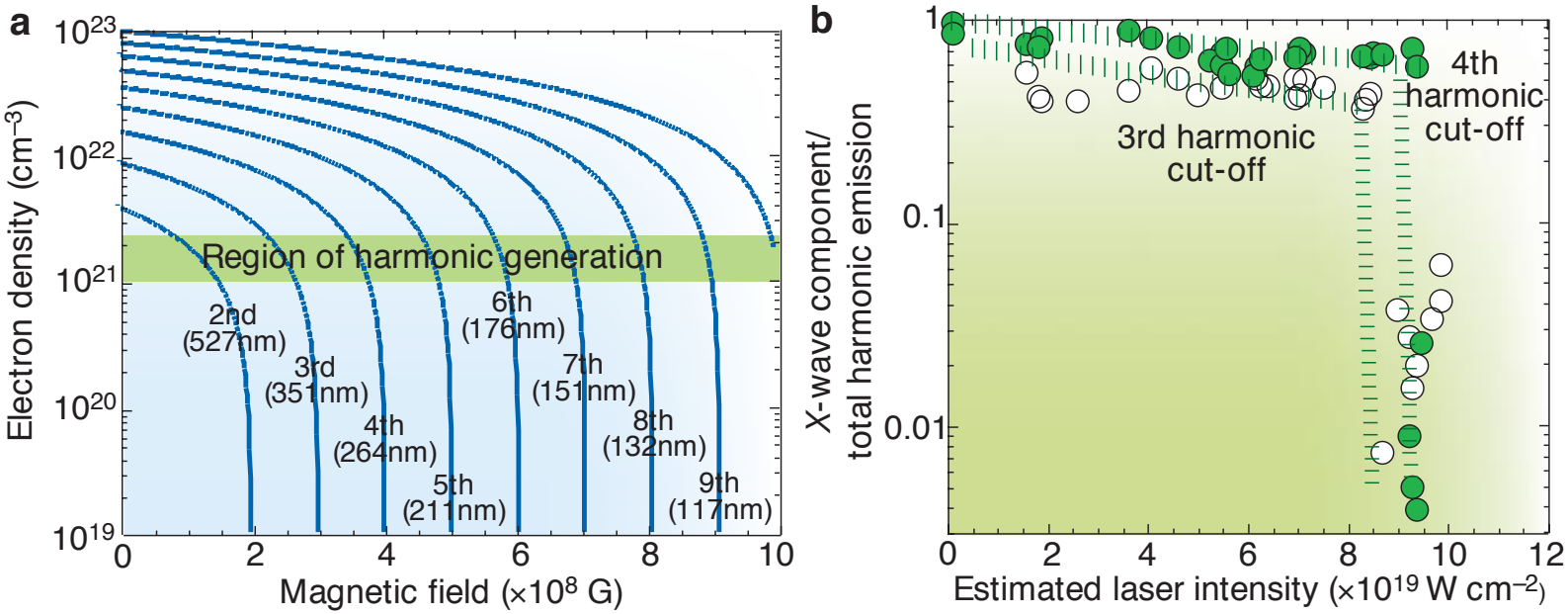


Laser: 10 J, 1.5 ps
Density: 4×10^{19} cm^{-3}

Maximum spot separation of 10's μm

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

340 – 460 MG fields have been measured at higher densities



The magnetic field is inferred from X-wave cutoffs for various harmonics

M Tatarakis et al, Nature 415, 280 (2002)

The OMEGA EP beams can generate collisionless magnetized plasma plumes that will reconnect as the expand

Primary objective

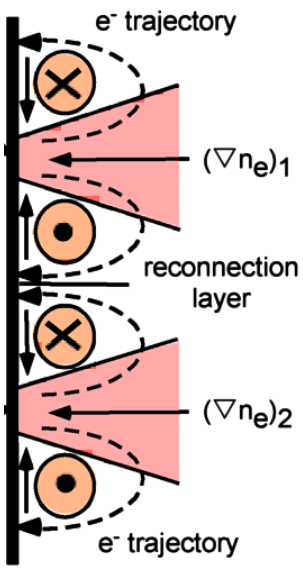
- **Characterize particle acceleration from collisionless magnetic reconnection**

Laser parameters

- **0.1- to 2.6-kJ, 1- to 100-ps pulses, >10^{18} W/cm^2**
- **>25-µm diam. spot, 10- to 100-µm spot separation**

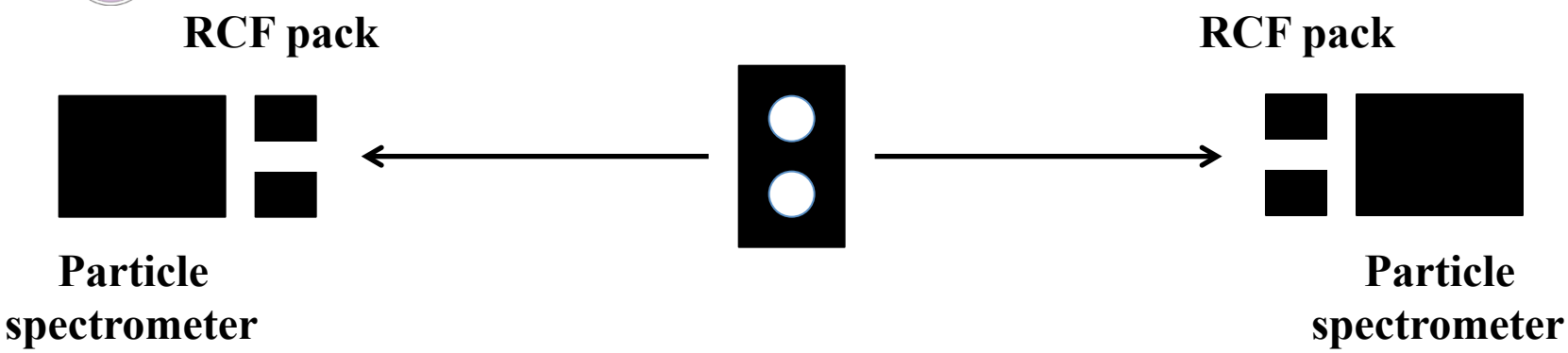
Plasma parameters

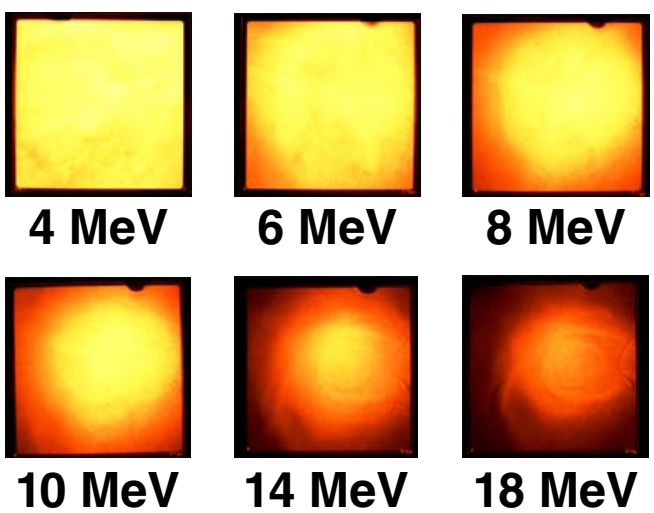
- **Target Z: CH, Al, Au**
- **kT ~ 100 keV, L_T ~ 50 µm, L_n ~ 10 µm, n_e ~ 10^{19} cm^{-3}**
- **Plasma β ~ 0.1; $L/d_i \geq 1$**



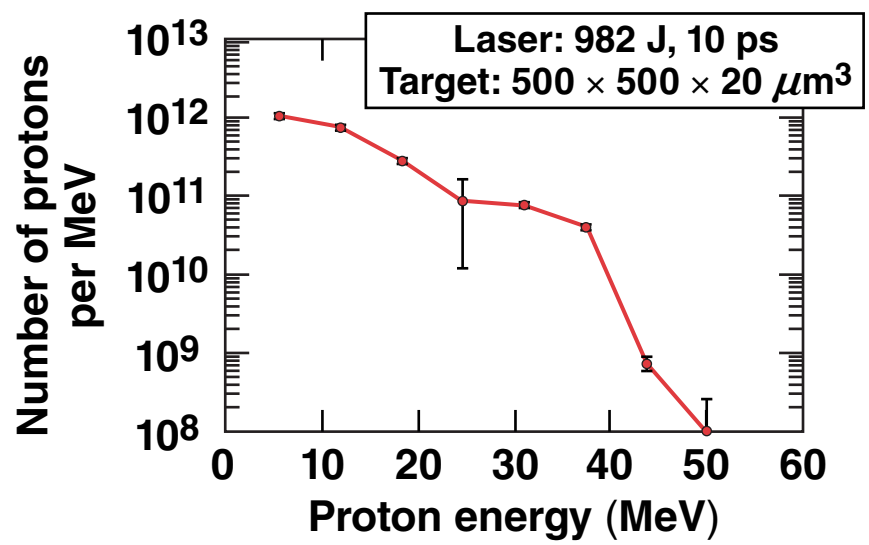
The interaction between two high-intensity laser-produced plasmas has not previously been studied in any regime

OMEGA EP experimental configuration





Example RCF pack data



Example proton spectra

A wide range of particle and x-ray diagnostics are available

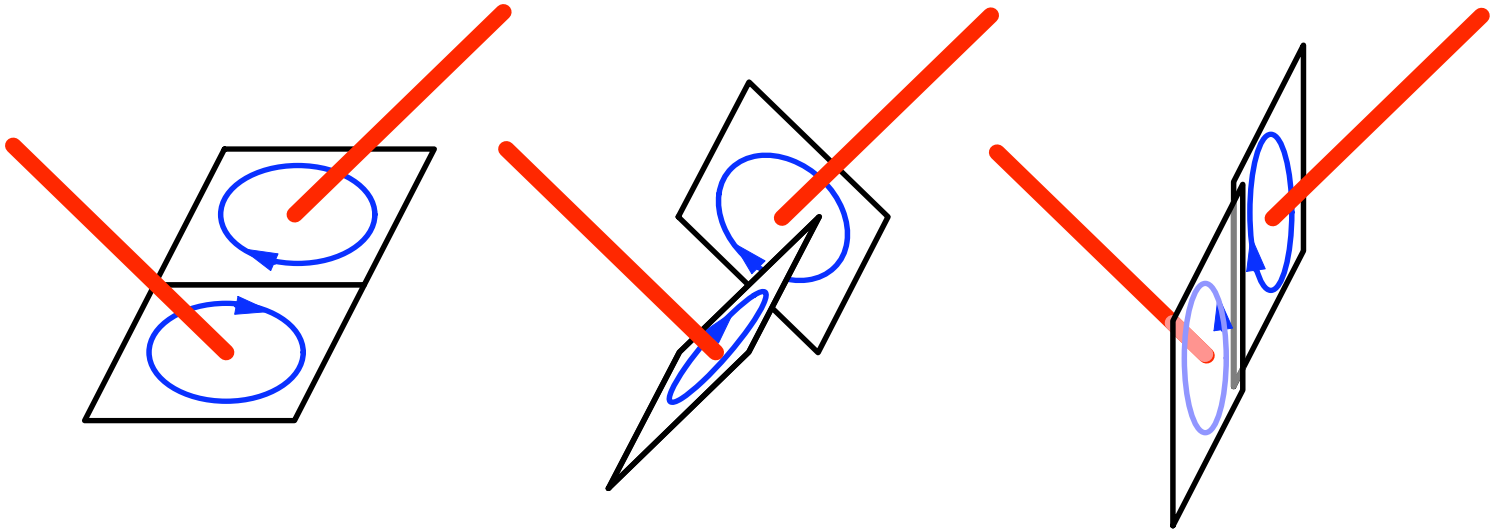
- Radiochromic film (RCF) packs – proton beam profile
- Modified RCF packs and near-target arm (NTA)
- Electron spectrometers (10's MeV)
- Thomson parabola (10's MeV protons)

- Optical probe: Schlieren imaging, interferometry, and polarimetry

- Thomson scattering: Z, T_e, flow velocity; imaging Thomson scattering

- X-ray spectrometers (> keV; time integrated and time resolved)
- X-ray crystal imagers (> keV)
- Time-integrated KB x-ray microscope (3-8 keV)
- Time-integrated x-ray pinhole cameras

Anti-parallel and co-parallel magnetic fields can be studied with different target geometries



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

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