Ultrafast Electron Beam Radiography of Self-Generated Magnetic Fields from High Intensity Laser-Solid Interactions

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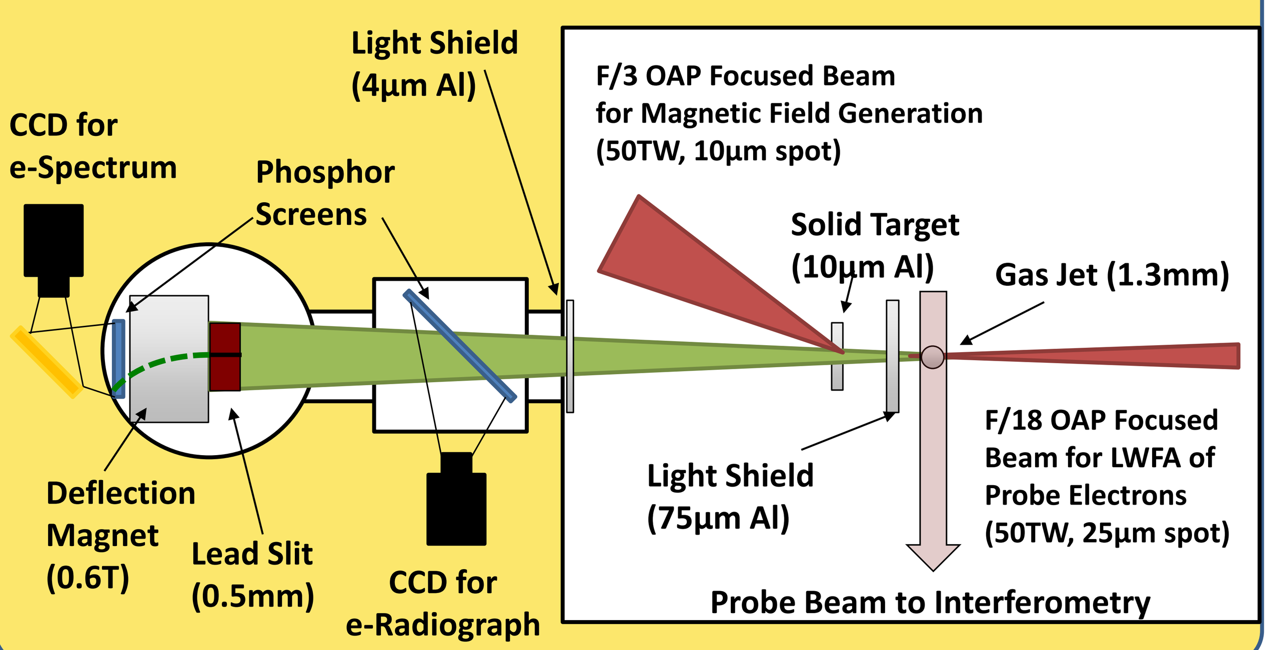
Abstract

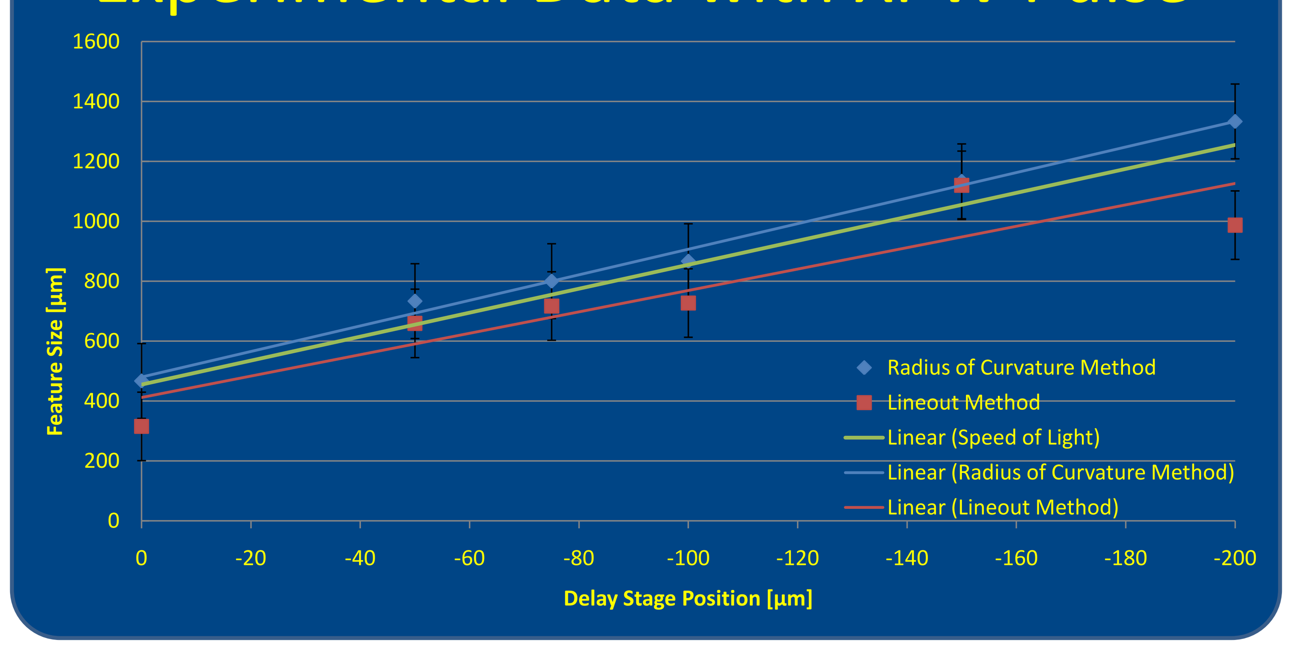
Using ~10 fs electron bunches generated with laser wakefield acceleration as a probe, the femtosecond temporal evolution of a 4×10^{19} W/cm^2 laser pulse interacting with solid targets has been studied experimentally. Magnetic fields on the order of 100 megagauss were observed travelling outward from the interaction point of the laser with the metallic foil at nearly the speed of light. These results are supported by OSIRIS particle-in-cell simulations.

Experimental Setup

For this experiment, the HERCULES laser was operated at 100 TW (3.5 J in 35 fs) with the XPW (cross-polarized wave) pulse cleaning technique, yielding 10^{-11} contrast for the Amplified Spontaneous Emission (ASE) pulse pedestal and 10^{-7} contrast for the picosecond pulse pedestal. A pick-off mirror sends half of the beam to a f/18 paraboloid mirror focusing the pulse to an intensity of 2×10^{19} W/cm^2 above a 1.3 mm gas jet nozzle ejecting a density of ~2×10^{19} cm^{-3}, generating a quasi-monoenergetic electron beam with ~100MeV energy. The remaining annular beam is sent to a delay stage and is focused with a 30 degree off-axis f/3 paraboloid mirror to an intensity of 4×10^{19} W/cm^2 onto a solid target of 10µm Al, generating intense magnetic fields on the surface.



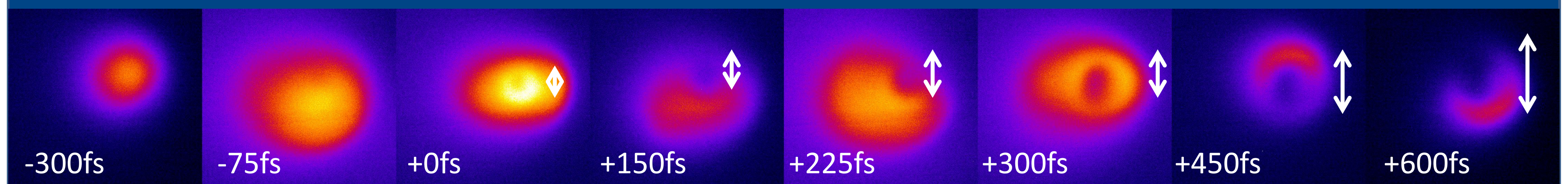
Experimental Data with XPW Pulse



Experimental Methods & Results

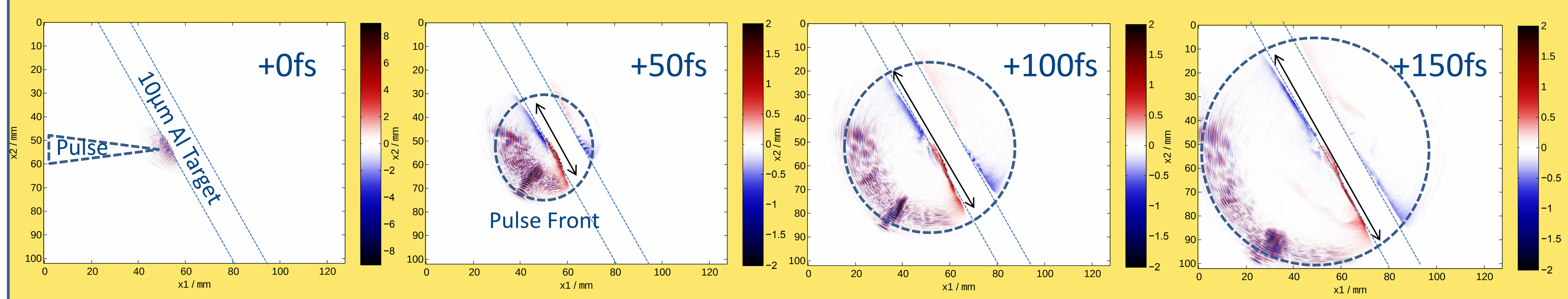
Using breakdown in air for our absolute timing calibration, we observed defocusing structures expanding after the pump pulse interacted with the target with good reproducibility (±100 fs delay, mainly due to target repositioning and critical surface errors) over a temporal window of 300 ps. Despite our small electron beam source size (around ~20µm), we are unable to resolve the ponderomotive force of the pump pulse due to the thick light-shielding (75µm) and low magnification geometry (6X).

Electron Radiographs of 10µm Aluminum with Clean Pulse (XPW)



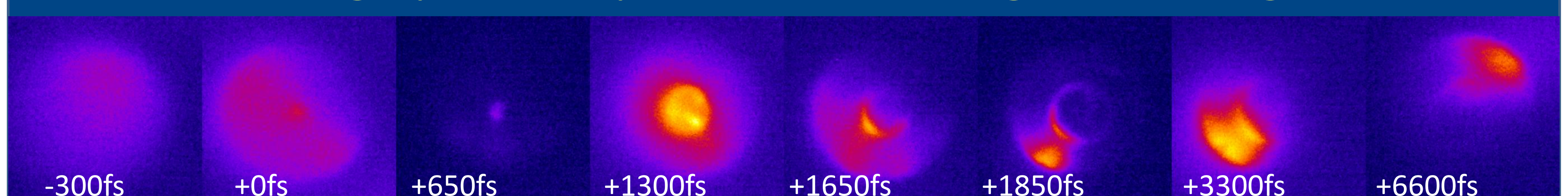
At early timesteps, we observed a strong de-focusing structure which quickly expanded linearly with increased delay (see chart/simulation below). This evidenced that the XPW pulse generated a strong enough field to completely deflect the electrons that was travelling at nearly the speed of light away from the focus.

B-fields in Particle-in-Cell Simulation of the Clean Pulse (XPW) Case



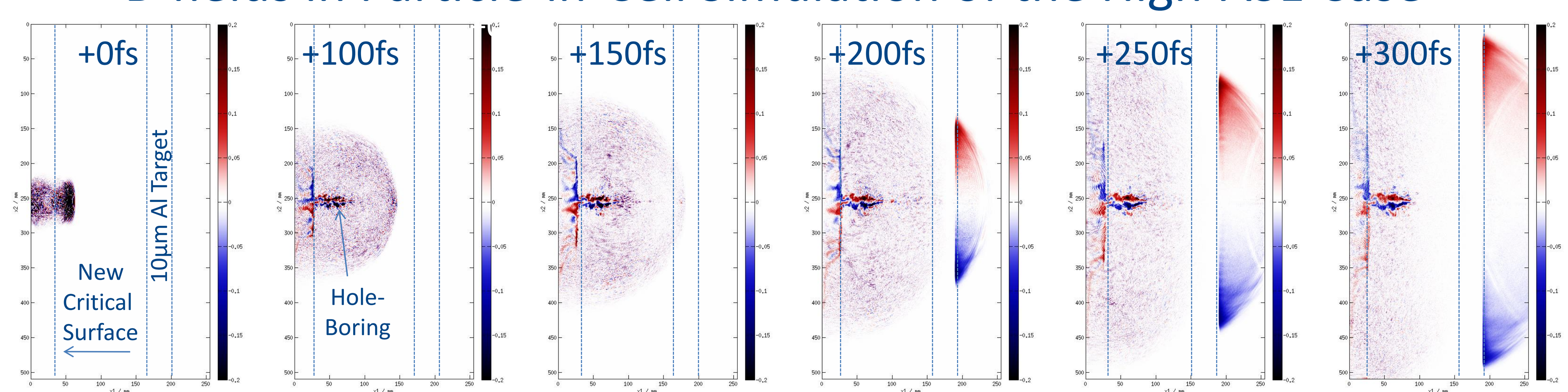
Note: the front surface magnetic fields are ~3-5 times larger in strength than the rear surface ones

Electron Radiographs of 10µm Aluminum Targets with High-ASE Pulse



At early timesteps, we observed slight focusing which slowly transitioned to defocusing. This evidenced that the ASE pulse generated a focusing - but weaker - field, corroborated by simulations (see below).

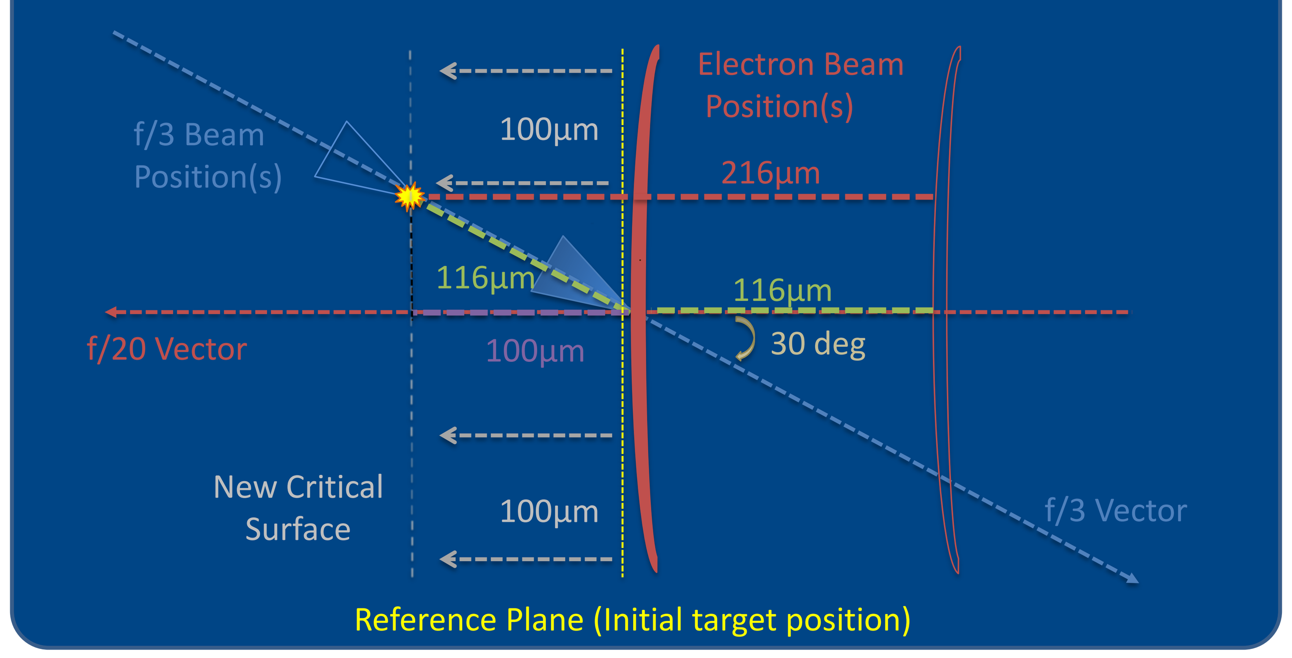
B-fields in Particle-in-Cell Simulation of the High-ASE Case



Note: the scale of the ASE magnetic fields are roughly an order of magnitude weaker than the XPW case!

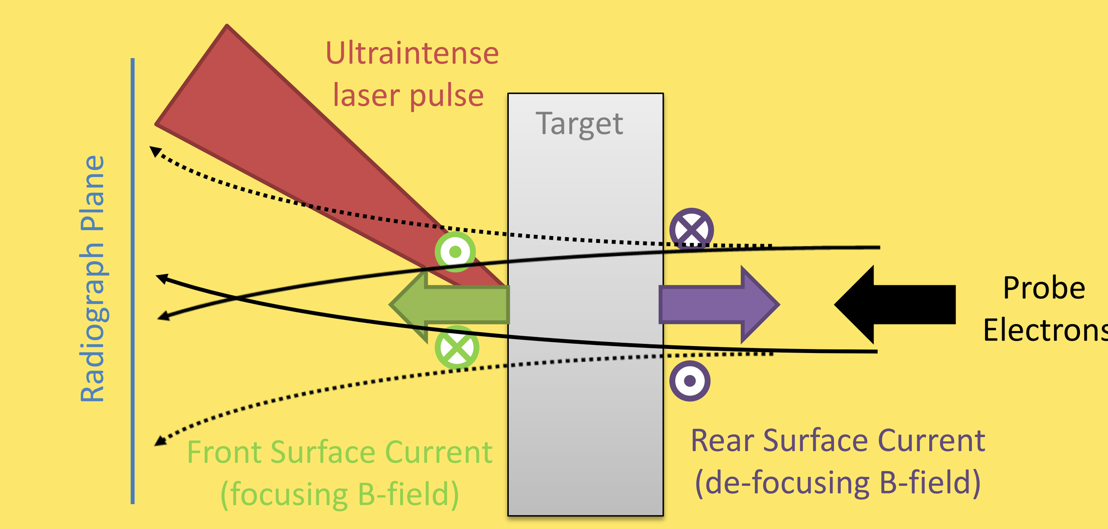
Timing & the Critical Surface

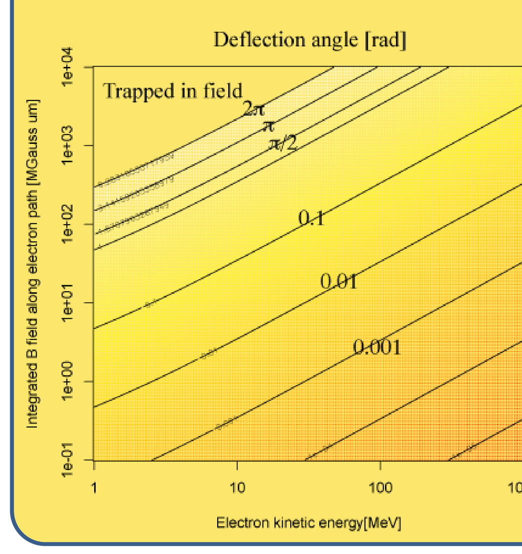
This geometry details where the beams are overlap if the critical surface was ejected in front of the target by 100µm. The total delay of the electron beam with respect to the interaction is 216µm spatially, or about 720 fs temporally!



Deflection Mechanism & Pattern

In our temporal window, the relevant mechanisms are:
- Ponderomotive force of the laser pulse (~30 fs)
- Sheath currents moving outward from target surface (100s of fs)





Assuming a ~2µm thick field, and given a 100MeV beam and 60mrad deflection, this yields a field strength of 100 megaguass!

$$\int_L \mathbf{B}\times dl = \frac{m_0 c\theta_d}{e}\sqrt{\left(\frac{m_0c^2+\varepsilon_k}{m_0c^2}\right)^2-1}$$

θ_d : deflection angle
ε_k : kinetic energy

Summary

- Magnetics fields on order 100 megagauss were measured
- An absolute timing diagnostic was critical for the accurate determination of scale length effects
- Varying the pre-pulse level had significant effects on the magnetic fields and observed radiographs
- PIC simulations provided crucial insight in deciphering the underlying field structure and its evolution
- Higher magnification and electron beam charge will be necessary to see more detailed structures