LWFA: Electron Cyclotron Resonance Imaging

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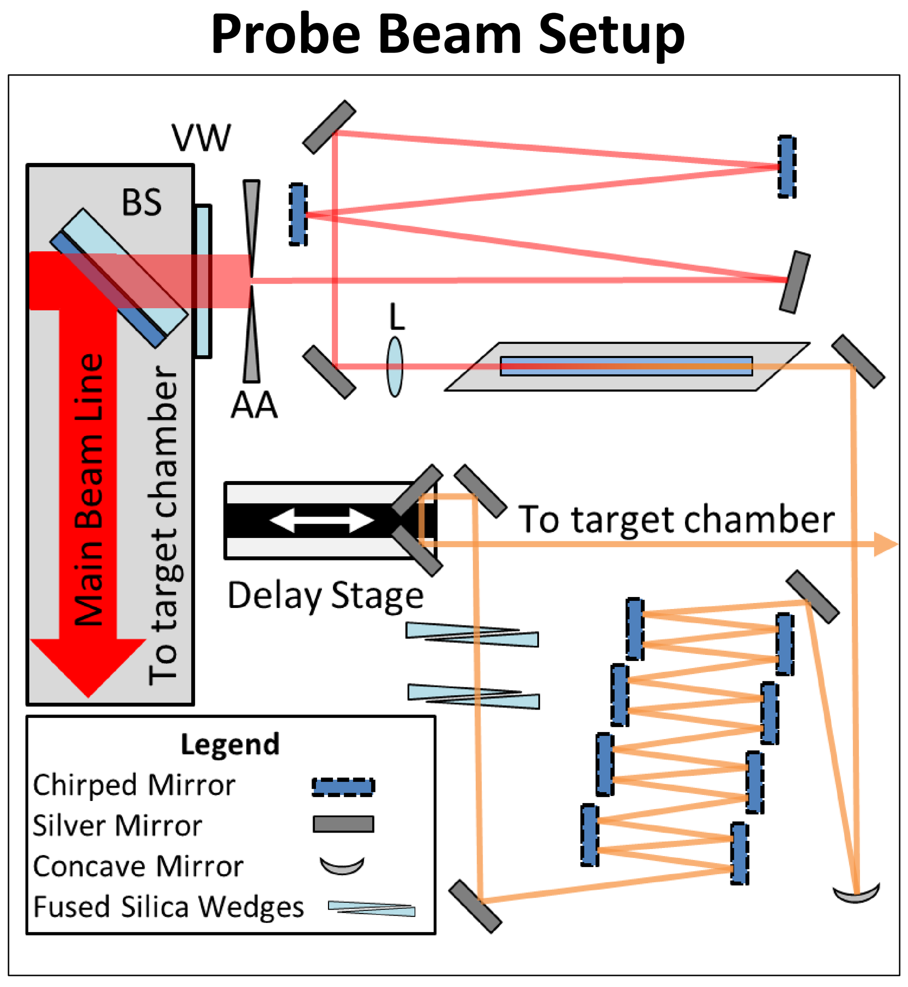
Motivation

Direct visualization of the plasma-wave in LWFA, due to its femtosecond dynamics and µm spatial scale, has previously been limited to simulations requiring idealized experimental conditions and significant computational efforts. Building on previous work employing few-cycle microscopy, we present a method of characterizing the evolving fields of the pump laser within the tenuous plasma by exploiting the broadband spectrum of a few-cycle probe. The technique relies on the relativistically intense pump laser (magnetic field strength of several tens of kilotesla) causing the electron cyclotron frequency of the local plasma to lie within the probe's spectrum.

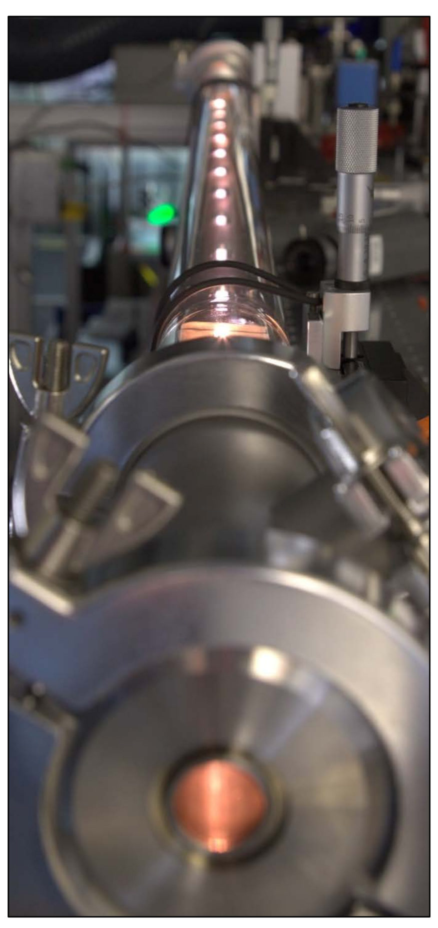
Objectives

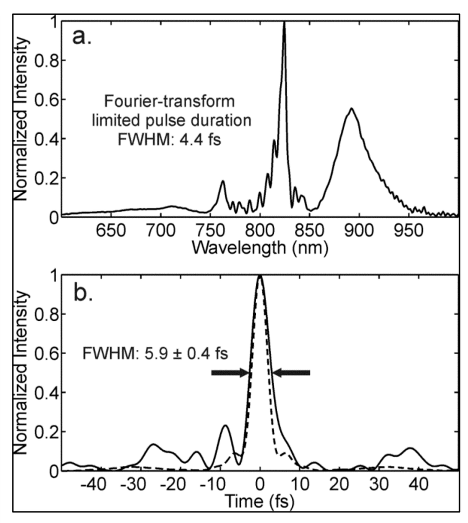
- Real time visualization of wakefield evolution and surrounding area
- Polarization and spectrally filtered shadowgraphic imaging to gain quantitative characterization of pump laser's dynamics.
- Comparison of experimental results to 3D-PIC or plasma fluid simulations

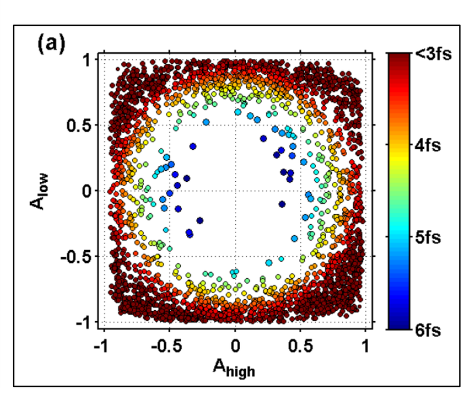
Probe Beam Setup



Characterization



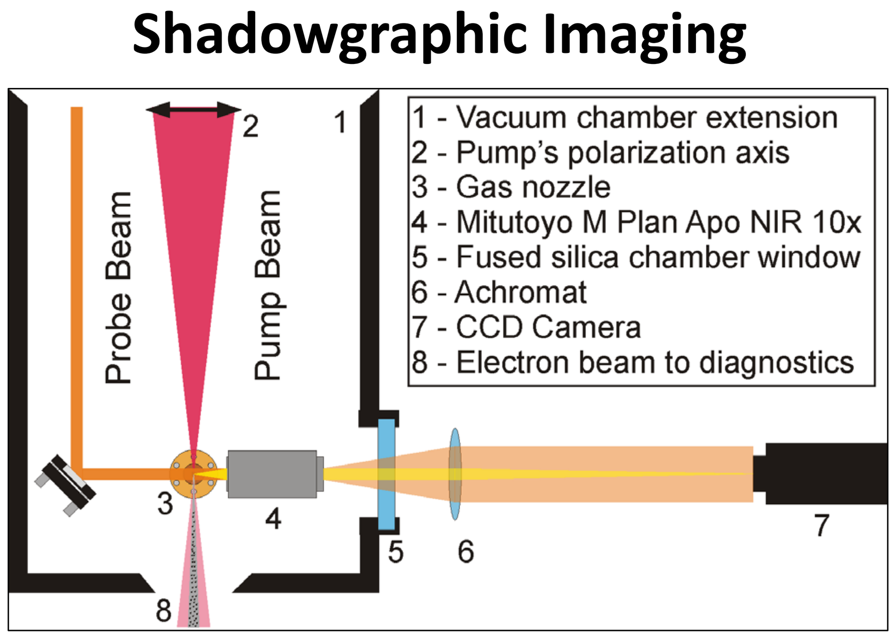




Experimental Setup

- Hollow core fiber (HCF) pulse compression system [**1,2**], ~1 mJ energy from a 26 fs, 40 Terawatt-class pump laser, synchronized pump and probe
- Spectral broadening in HCF with Neon or Argon gas
- Spectral phase correction via dielectric chirped mirrors
- Resulting probe pulses <5 fs FWHM duration [**3**] and ~250 µJ energy
- Target gas: He:N_2, mixed at 95:5, electron plasma density ~10^{19} e^-/cm^3
- Relativistic pump pulse (~10^{19} W/cm^2) ionizes target gas and drives wakefield, probe propagates transversely through the plasma distribution
- Shadowgraphic imaging via few-cycle VIS-NIR corrected microscopy
- Parameter scans: target gas pressure/type, target length, driver polarization/energy/duration and probe polarization/wavelength
- Probe images correlated to varying parameters and measurables, e.g. accelerated e^- bunch properties, emitted radiation properties, etc. [**4**]
- Combination of polarization and spectral filtering allows isolation of electron cyclotron effects on the probe's propagation through the plasma
- Similar to electron cyclotron emission diagnostics on fusion devices

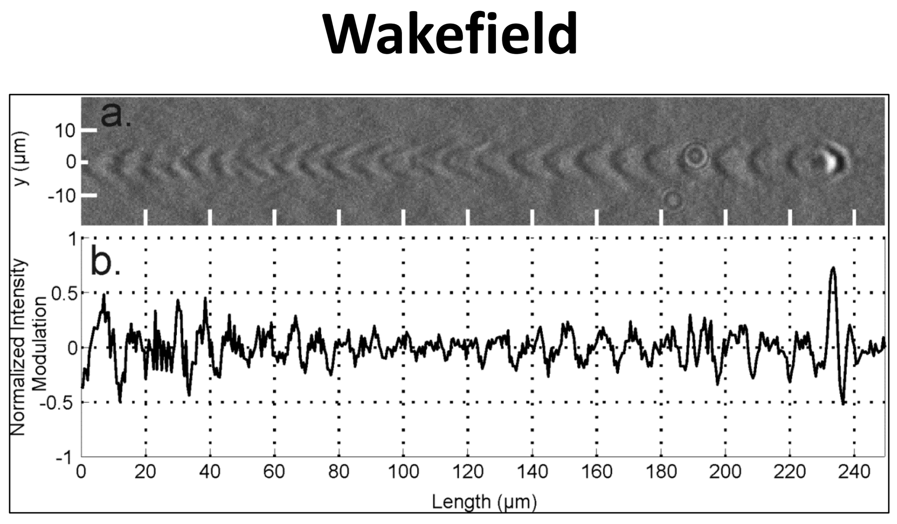
Shadowgraphic Imaging



Gas Cell Target

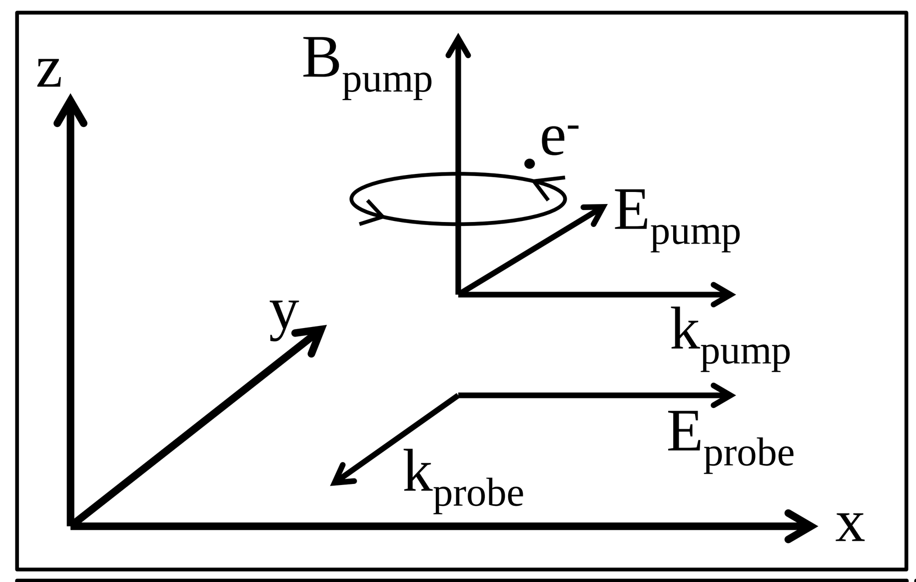
Gas Jet Target

Wakefield



Magnetoionic (Appleton-Hartree) Theory

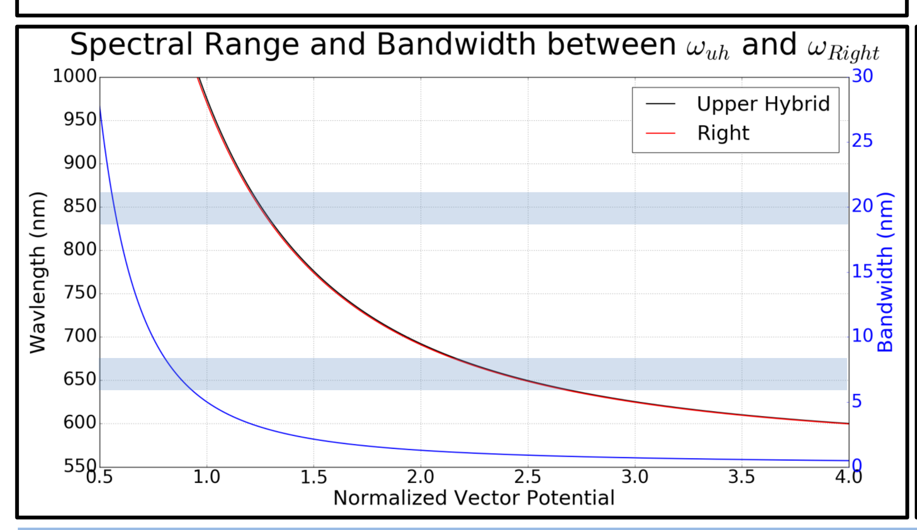
- Cold, collisionless, magnetized, under-dense plasma, cyclotron motion
- EM-wave (probe) propagating perpendicular to pump's magnetic field
- Ordinary-(O)wave sees no modification of the plasma's refractive index
- Extraordinary-(X)wave experiences resonance/cutoff frequencies due to electron motion in plasma (ions are assumed to be static)
- Relativistic pump shifts resonance/cutoff into the VIS-NIR spectrum
- X-wave's refractive index, n_x, is highly dependent on local pump intensity

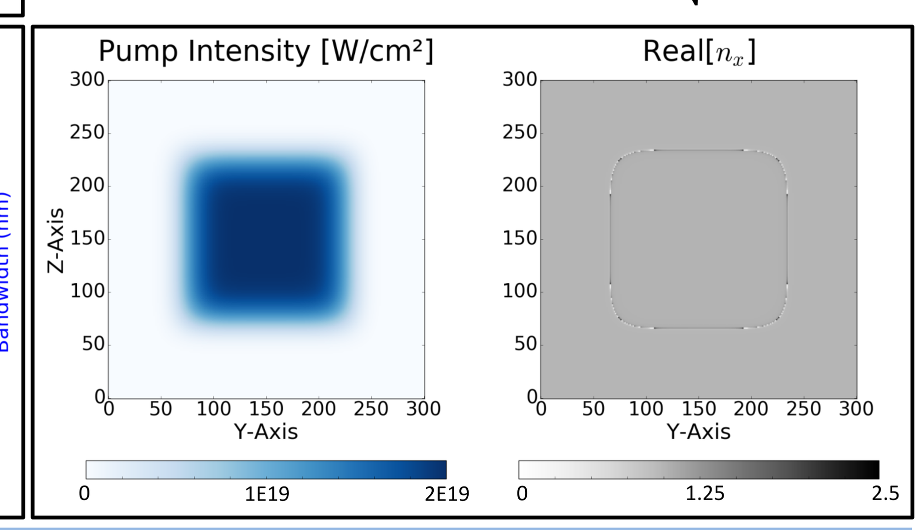


$$n_X^2 = \frac{(\omega^2 - \omega_{Left}^2)(\omega^2 - \omega_{Right}^2)}{\omega^2(\omega^2 - \omega_{uh}^2)}$$

$$\omega_{Left}, \omega_{Right}, \omega_{uh} = f(\Omega_{ce}, \omega_{pe})$$

$$\Omega_{ce} = \frac{qB}{\gamma m_e} \qquad \omega_{pe} = \sqrt{\frac{n_e e^2}{\gamma m_e \varepsilon_o}}$$





Experimental Results

- Images recorded at constant electron plasma density and varying propagation distances in target; 850±20 nm and 660±20 nm filters used
- Polarization of probe is oriented along electrons' plane of gyration (perpendicular to pump's B-field), causing the probe to be strongly refracted/absorbed in the vicinity of the pump depending on the spectrum

Gas Cell Entrance 0-200 µm

Gas Cell Middle 400-600 µm

Gas Cell Exit 800-1000 µm

Summary and Outlook

- A method for imaging the evolving pump laser in LWFA experiments based on electron cyclotron resonances and few-cycle probing is described
- Further development of the imaging technique including modeling [**5**] few-cycle microscopy in magnetized plasma via 3D-PIC or fluid simulations could lead the way to quantitative measurements of the pump laser's evolution and its influence on plasma dynamics inside the interaction

Acknowledgments

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