Diagnostics Tools for Laser-Driven Plasma-Accelerators

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Outline

• Motivation: Why plasma diagnostics necessary
• Pump-probe scenarios:
  Which different types of probe pulses can be applied?
• Electro-magnetic probe pulses:
  o Shadowgraphy
  o Interferometry
  o E- and B-field sensitive techniques
• Particle probe pulses:
  o Proton probing
  o Detection of magnetic and electric field distributions
Motivation

- Laser-produced plasmas:
  - formation and modulation occurring on time scales of driving laser
  - density distribution?
  - temperature?
  - internal fields?
- High relevance for particle accelerators
  - plasma-wakefield accelerators: detect details of plasma wave
  - plasma ion accelerators: e.g. sheath field of accelerating fields from solid targets
- Pump-probe geometry well suited: probe interaction driven („pumped“) by main pulse

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Electromagnetic Probe Pulses

- Generation of synchronized optical probe pulses:
  - split off part of the main pulse
  - guide it towards interaction along different path
  - adjust temporal delay
  - perfect synchronization
  - probe pulse duration similar to main pulse
  - record movie from subsequent shots at different delays

Electromagnetic Probe Pulses

- Delay scan of interaction of 10-TW laser pulse with preformed plasma at different shots:
  - How can we deduce the plasma density from these images?
  - Use interferometry!
Interferometry

- Refractive index of a plasma:
  \[ \eta = \sqrt{1 - \left( \frac{\omega_p}{\omega_L} \right)^2} = \sqrt{1 - \frac{n_e}{n_c}} \]

- Integrated optical path length or integrated phase \( \phi \) depends on plasma density distribution seen by light rays:

- Visualize phase difference between probe ray and ray going through vacuum:
  interferometer

- Challenge for short pulses: rays’ path lengths need to be identical within pulse length (few \( \mu \)m)!
  easier: Wollaston prism

Interferometry

- Wollaston prism = polarizing beam splitter, combination of two birefringent prisms
- Probe pulse: polarization under 45° w.r.t. both optical axes
- Two replica separated by \( \alpha \), polarized perpendicularly to each other
- Imaging system: generation of two images shifted transversely
- Polarizer under 45°: interference between to replica possible, „mixing“ of beam parts going through interaction region and through vacuum
- Separation distance \( i \) of fringes on CCD:
  \[ i = \frac{\lambda_{\text{probe}}}{\alpha} \frac{p'}{b} \]
Interferometry

• Deduce plasma density distribution by assuming cylindrical symmetry:

$$\Delta \varphi(y_0) = \Phi(y_0) = \frac{2\pi}{\lambda_L} \int_{x_1}^{x_2} [1 - \eta(x)] \, dx$$

$$\approx \frac{\pi}{n_{ct} \lambda_L} \int_{x_1}^{x_2} n_e(x) \, dx = \frac{2\pi}{n_{ct} \lambda_L} \int_{y_0}^{R} \frac{n_e(r)r}{\sqrt{r^2 - y_0^2}} \, dr$$

• Deduce plasma density via Abel inversion:

$$n_e(r) = -\frac{n_{ct} \lambda_L}{\pi^2} \int_{R}^{r} \frac{d\Phi(y)}{dy} \cdot \frac{dy}{\sqrt{y^2 - r^2}}.$$ 

**Interferometry**

- Deduce plasma density distribution by assuming cylindrical symmetry:

![Image of plasma density distribution](image)

- Density given in units of $n_{cr}$

**Electromagnetic Probe Pulses**

- 2-color probe pulses: visualize different time steps of evolution during a single shot by taking 2 images at different times
- 2 pulses ($1\omega$ and $2\omega$) go through window at different speed (GVD) => separation by few ps
- Separate pulses after interaction: get 2 images of the same interaction at 2 different times
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**TNSA (Target Normal Sheath Acceleration)**

- laser pulse generates relativistic electrons,
- they propagate through the foil and form an electric sheath field
  \[
  \varepsilon_{\text{front}}(t) \approx 2 \frac{k_B T_e n_e}{\varepsilon_0 (2eN + \omega_{\text{pi}}^2 t^2)}
  \]
- charge distribution starts to expand,
- acceleration length \( \approx \mu m \)
- Debye-length \( \lambda_D = \frac{\varepsilon_0 k_B T_e n_e}{n_e e^2} \)
- lifetime of electric field \( \approx f(\tau_L) \)
- max. ion energies

\[
E_{\text{max}} = 2Zk_BT_e \left[ \ln \left( \frac{\omega_{\text{pi}} t}{\sqrt{2eN}} + \sqrt{\left( \frac{\omega_{\text{pi}} t}{\sqrt{2eN}} \right)^2 + 1} \right) \right]^2
\]

Investigation of rear-surface TNSA-sheath at onset of acceleration process:
optical probing with fs and μm resolution

reflective geometry

Investigation of rear-surface TNSA-sheath at onset of acceleration process:
optical probing with fs and μm resolution

transverse geometry
Plasma Diagnostics

Electromagnetic Probe Pulses

Phase shift (measured tangentially) ⇒ 2D signal
\[ \Delta \phi = \frac{\omega}{c} \int (\eta - 1) ds = \frac{\omega}{c} \int \left( \sqrt{1 - \frac{n_e}{n_c}} - 1 \right) ds \]
\[ \approx \frac{\omega}{2cn_e} \int n_e ds \]

Abel inversion
\[ h(y) = 2 \int_{y}^{R} f(y) \frac{r}{\sqrt{r^2 - y^2}} dr \]

3D electron density distribution (cylindrical symmetry)
\[ n_e(r, z, t) \sim \exp \left[ -\frac{r(t)^2}{w_0^2} \right] \exp \left[ -\frac{z(t)}{\lambda_D} \right] \]

- spatial resolution ~ 1.1 µm
- temporal resolution ~ 100 fs
⇒ match dimensions of accel. process!

R. Benattar et al. (1979); G. Prettler et al. (1992)
1st all-optical measurement of $n_e$-distribution driving laser ion acceleration!


Comparsion with numerical simulations

3D-PIC results by A. Pukhov for comparable laser conditions

⇒ comparable shape
⇒ deviation of absolute numbers (measured density smaller by a factor of 5)

A. Pukhov, PRL 86, 16 (2001)
Energy content of electron sheath: \( E_{e^-} = k_B T_e N_e \)

Conversion efficiency
\( E_{\text{laser}} \Rightarrow \text{hot electrons:} \)
\[
\eta = \frac{E_{e^-}}{E_{\text{L,eff}}} = \frac{k_B T_e N_e}{E_{\text{L,eff}}}
\]
\( \eta_{\text{sheath}} = (3.7 \pm 1.2)\% \)
\( \eta_{\text{total}} = (9 \pm 3)\% \)
(deduced from sheath’s electron density and radial extent, assuming similar hot-e-density inside the target)

Electromagnetic Probe Pulses

Two polarograms from two (almost) crossed polarizers:

340 µm

560 µm
Electromagnetic Probe Pulses

Two polarograms from two (almost) crossed polarizers:

\[ I_{\text{pol}1} = I_0 \left[ 1 - \beta_1 \sin^2(90^\circ - \theta_{\text{pol}1} - \phi_{\text{rot}}) \right] \quad I_{\text{pol}2} = I_0 \left[ 1 - \beta_2 \sin^2(90^\circ + \theta_{\text{pol}2} - \phi_{\text{rot}}) \right] \]

Deduce rotation angle \( \phi_{\text{rot}} \) from pixel-by-pixel division of polarogram intensities:

\[ \frac{I_{\text{pol}1}(x, y)}{I_{\text{pol}2}(x, y)} \]

Experimental evidence for B-fields from MeV electrons and bubble!

Electron bunch length: $\Delta z = 4 \mu m$

$\tau_{\text{FWHM}} = (6 \pm 2) \text{ fs}$, $\tau_{\text{RMS}} = (2.5 \pm 0.9) \text{ fs}$

A. Buck et al., Nature Physics 7, 543 (2011)

- Polarimetry: visualize e-bunch via associated B-fields
- change delay between pump and probe ⇒ movie of e-bunch formation
- observe e-bunch formation on-line!

A. Buck et al., Nature Physics 7, 543 (2011)
• **Polarimetry:** visualize e-bunch via associated B-fields

• change delay between pump and probe ⇒ movie of e-bunch formation

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A. Buck *et al.*, Nature Physics 7, 543 (2011)

• **Shadowgraphy:** visualize plasma wave

• change electron density ⇒ change plasma wavelength

A. Buck *et al.*, Nature Physics 7, 543 (2011)
Electromagnetic Probe Pulses

- Few-cycle probe pulses
- Similar resolution with 35-fs driver laser:
  - frequency-broadening of probe pulse
    (in gas-filled hollow fiber)
  \[ \Rightarrow \text{shorter } \tau_{\text{probe}} \]

\[ \Rightarrow \text{sub-main pulse temporal resolution,} \]
\[ 1.1 \, \mu m \text{ spatial resolution with optimized imaging system} \]

Electromagnetic Probe Pulses

- Length of 2nd plasma period vs. density after ~ 1.1 mm propagation

\[
\alpha P \frac{P_c}{P_e} > \frac{1}{16} \left[ \ln \left( \frac{2n_c}{2n_e} \right) - 1 \right]^3
\]

S. P. D. Mangles et al., PRSTAB 15, 011302 (2012)

Above threshold: increase of \( \lambda_p \) (beam loading)
Electromagnetic Probe Pulses

• After plasma wave evolution into single bubble:

\[ \frac{\Delta E}{E} \approx 3\% \]

4 pC

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Particle Probe Pulses

- Probing with laser-accelerated proton beams:
  - broad energy spectrum (up to few 10’s of MeV)
  - laminar flow -> excellent imaging properties

Energy spectrum in forward direction

Transverse beam profile for different energies

protons from POLARIS @ 20 TW


Particle Probe Pulses

- Probing with laser-accelerated proton beams:
  - broad energy spectrum (up to few 10’s of MeV),
  - laminar flow -> excellent imaging properties
  - energies detected separately in radiochromic film stack

L. Willingale, PhD thesis
Imperial College (2007)
Particle Probe Pulses

- Probing with laser-accelerated proton beams:
  - broad energy spectrum (up to few 10’s of MeV)
  - laminar flow -> excellent imaging properties
  - energies detected separately in radiochromic film stack
  - initial duration ≈ few times laser pulse duration, stretching due to different velocities

- Different images from different proton energies = snapshots from different times during the interaction
- Record movie of evolution of field distribution!

Particle Probe Pulses

- Transverse probing with laser-accelerated proton beams:
  - proton deflection mainly due to electric fields

  ![Diagram](image)

  L. Romagnani, PRL (2005)

- record TNSA-sheath evolution in single shot,
- deduce sheath-field strength from mesh warping:
  \[ E_{\text{TNSA}} \geq 3 \times 10^{10} \text{ V/m} \]
Particle Probe Pulses

- Longitudinal probing with laser-accelerated proton beams:
  - proton deflection mainly due to magnetic fields

P. Nilson, PRL (2006)

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Particle Probe Pulses

- Longitudinal probing with laser-accelerated proton beams:
  - visualize B-field geometry in 2-beam interaction
  - see merging of B-field structures between two plasma plumes
  - example of magnetic reconnetion

P. Nilson, PRL (2006)
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