Working group 5

High-gradient plasma structures and Advanced beam diagnostics

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Contributions

19 talks + 20 posters

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Mozhgan Hayati (Uni Bern)  Paul Scherkl (Strathclyde Univ)
Topics

• Advanced beam diagnostics
• High-gradient structures and components
• Plasma lenses and laser waveguides
CTR based bunch length measurements

Electron spectrum

Omid Zarini, Monday, WG5


- \( E_{\text{peak}} \approx 300 \text{ MeV} \)
- \( \Delta E/E \approx 10\% \)
- \( Q_{\text{FWHM}} \approx 200 \text{ pC} \)

1st attempt for bunch length reconstruction

- \( \lambda_p/c \approx 78 \text{ fs} \)
- Bunch envelope: \( \tau_{\text{FWHM}} \approx 23 \text{ fs} \)
- Sub-structures: \( \tau_{\text{FWHM}} \approx 1-2 \text{ fs} \)

Observation of Point Spread Function

@730 nm, unpolarized

Peak Current (kA)

- \( l_p/c \sim 78 \text{ fs} \)

Bunch duration (fs)
Experimental setup @ SPARC_LAB

Motivations

- Single shot diagnostics on plasma accelerated electrons are needed to properly tune the source.
- We are studying a single shot emittance measurement based on incoherent optical transition radiation, exploiting its sensibility to beam divergence. In particular, the correlation term is reconstructed by using a microlens array.
- Zemax simulations have been performed and are in agreement with results.

Novel X-band TDS with variable polarization

New X-band TDS with variable polarization to be installed at several DESY and PSI facilities, incl. at SINBAD

Variable polarization allows bunch to be streaked in any transverse direction

Allows following measurements:
- Bunch length
- 3D charge density profile using tomographic reconstruction (real space)
- Slice emittance measurement (transverse phase space)
- Slice energy measurement using dipole (longitudinal phase space)

6D phase space characterization
Charge density reconstruction

- Streak bunches at 16 transverse angles
- Combine profiles using tomographic techniques to reconstruct the 3D charge profile distribution

Actual distribution at screen with TDS off

Reconstruction

Bunch energy measurement

- Combine TDS with dipole for slice energy measurement
- Energy spread is induced in TDS
- Can calculate and remove but this is very difficult for short (fs-scale) bunches

Simulations in elegant
Generated bunch for illustration

Proof-of-principle experiment for a sub-femtosecond electron bunch length diagnostic (M. Weikum et al.)

- Diagnostic device: laser modulator + RF deflecting cavity
- Strong horizontal streaking with laser modulator
- Vertical streaking to resolve streaking effect over full beam length

First proof-of-concept experiment at ATF (Brookhaven National Lab)

Increasing horizontal spread with increase in laser energy

Qualitative comparison with ELEGANT simulations:
- Strong focusing (sim.)
- Weak focusing (sim.)
- Strong focusing (exp.)
- Weak focusing (exp.)
Plasma-based spatiotemporal synchronization and alignment of electron and laser beams

Paul Scherkl, et al., EAAC 26-09-2017, WG5

Interaction of e-beam and confined plasma
- transfers energy into plasma
- ions remain and build up localized attracting potential
- continuous heating, excitation, impact ionization
- additional relaxation/recombination light

Temporal transition
- factor ~50 change in integrated counts
- r.m.s width ~470 fs
- slope ~ 1 fs / 0.1% change in intensity
- sensitive & robust beam arrival monitor

Spatial transition
- factor ~50 change in integrated counts
- r.m.s width ~58 µm
- response even for > 400 µm distance
- beam position monitor
- non-invasive
Calibration of Charge Diagnostics using LWFA Electrons

- Three different types of charge diagnostics installed for LWFA experiments at FLASHForward:
  - DRZ screens
  - DaMon
  - ICT

- Absolute calibration of DRZ screens was performed at ELBE:
  - DRZ High was measured to have a very high light output of $1.05 \times 10^{10}$ photons / (sr * pC)
  - Factor of 13 more light yield compared to LANEX Fine
Calibration of Charge Diagnostics using LWFA Electrons

• ICT was tested in noisy environment:
  • Charge scaling factor of 0.33 required at our setup
  • Noise restricting measurement to charges above a few pC
  • Non-destructive measurement

• DaMon was first tested in LWFA setup:
  • Stainless steel cavity used as passive resonator
  • Amplitude of TM01 mode used for charge measurement
  • High dynamic range from ~ 10 fC up to 100 nC
  • Insensitive to electromagnetic noise from plasma
  • Non-destructive measurement
Topics

• Advanced beam diagnostics
• High-gradient structures and components
• Plasma lenses and laser waveguides
THz Field Enhancement Structures for Accelerators

- Electron streaking – single and multi-element structures
- Electron acceleration
- Electric field driven undulators

Resonant THz electric or magnetic field enhancement structures

Split ring resonator based device

Graphene plasmon based device

See also talk by Mozghan Hayati WG 5

Thomas Feurer (University of Bern)
We scan the time delay between the laser and the proton beam in order to learn about the SSM/SMI process. The proton beam is modulated at the plasma frequency, and therefore can be used to measure plasma density vs. time delay.

### Time Delay Scan Fourier Analysis

<table>
<thead>
<tr>
<th>Delay [ns]</th>
<th>FFT Peak [GHz]</th>
<th>Equivalent $n$ [$\times 10^{14}$ cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>141.2</td>
<td>2.47</td>
</tr>
<tr>
<td>350</td>
<td>141.2</td>
<td>2.47</td>
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<tr>
<td>1000</td>
<td>139.5</td>
<td>2.41</td>
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<td>2500</td>
<td>101.6</td>
<td>1.28</td>
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<tr>
<td>5000</td>
<td>70.6</td>
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<tr>
<td>10000</td>
<td>58.5</td>
<td>0.42</td>
</tr>
<tr>
<td>50000</td>
<td>39.2</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Chirp Mitigation of Plasma-Accelerated Beams by a Modulated Plasma Density

1. Modulate plasma wavelength (density)...

2. ...thereby oscillate between positive and negative slopes of the accelerating field...

3. ...while alternately focusing and defocusing the bunch for stable beam transport.

Particle-In-Cell case study

![Diagram showing modulated plasma and energy spread reduction](image)

-2π -3/2π -π -1/2π 0

\( K \)

\( E_z \)

\( \text{driver} \)

-100 -80 -60 -40 -20 0 0

\( \zeta [\mu m] \)

-3π -2π -π 0

![Diagram showing focusing and defocusing](image)

On average: Stable virtual on-crest acceleration
Compensation of energy chirp
Overview of the Plasma Source

Consists of 3 main sections

- a 10 m long 4 cm diameter liquid (Galden) heat exchanger
- 2 Rb reservoirs at the ends
- 2 Rb expansion chambers (buffer zones) for Rb collection

- Rb continuously flows through the system and exits the ends through 1 cm diameter apertures condenses in the expansion chambers located at the ends
- Density profile is adjusted by setting the reservoirs temperatures

- Plasma formed by laser ionization of Rubidium (Rb) Vapor. Above threshold (~10\(^{12}\) W/cm\(^2\)) we ionize % 100
  Plasma density = Vapor Density (n)
  Plasma density uniformity = Vapor Density uniformity
- Density is measured at both ends with a Mach-Zehnder interferometer 0.1 % accuracy
Summary of density control in the ELISA variable parameters gas cell

Interferometric measurements of the mean density inside the cell for various parameters

Fluid simulations with OpenFOAM: determination & control of the density profile along the laser axis.
Topics

• Advanced beam diagnostics
• High-gradient structures and components
• **Plasma lenses and laser waveguides**
Carl A. Lindstrøm, University of Oslo and CLEAR, CERN

The CLEAR Plasma Lens Experiment - Summary

- **Active plasma lens experiment** at the CLEAR Test Facility at CERN.
  - 15 mm long, 1 mm diameter sapphire capillary (made by DESY)
  - Compact Marx Bank HV short-pulse discharge source of peak current ~500 A (made by Uni Oxford)

- **Experimental goals:**
  - Successful operation: First step towards a multi-plasma lens apochromatic lattice for a emittance preserving PWFA/LWFA staging
  - Measurement of radial field non-uniformity with high resolution (small beam)
  - Probing limits set by plasma wakefields using short, intense particle beams

- **Current progress and plans:**
  - Successfully tested plasma discharge (no beam, Aug 2017)
  - Successfully transported beam through capillary (no discharge, Sep 2017)
Mapping active plasma lenses

Direct detection of linear and nonlinear focusing fields

- Plasma lens experiment at Mainz Microtron (855 MeV; 1.5 mm mrad)
- No pointing or orbit stability degradation through plasma lens
- Direct magnetic field gradient measurements performed
- Emittance measured after plasma lens interaction
- Results confirm predictions from MHD and particle tracking sims
- Future studies will focus on reducing gradient nonlinearity

Magnetic field scans

Modeling

Emittance measurements

<table>
<thead>
<tr>
<th>Current [A]</th>
<th>Simulated Norm. Emitt. [mm mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>188</td>
<td>3.3 ± 0.3</td>
</tr>
<tr>
<td>368</td>
<td>4.7 ± 0.1</td>
</tr>
<tr>
<td>740</td>
<td>7.4 ± 0.2</td>
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Low-density plasma channels capable of high repetition rate operation

- Hydrodynamic expansion of plasma columns can generate channels suitable for guiding which:
  - Are capable of **multi-kHz operation**
  - Are **immune to damage**
  - Can be made **long** (several hundred mm)

- To date initial plasma columns have been heated collisionally
  - Requires high initial density for efficient heating
  - Thus limits on-axis density to \( > 1 \times 10^{18} \text{ cm}^{-3} \)

- Desirable to decrease on-axis density to \( \sim 10^{17} \text{ cm}^{-3} \) for \( \sim 10 \text{ GeV} \) stages

- **Optical field ionization** can create hot electrons independent of initial density
Low-density plasma channels capable of high repetition rate operation

Interferometric measurements of OFI channels show:
- On-axis densities as low as \(2 \times 10^{17} \text{ cm}^{-3}\)
- Matched spot sizes 35-55 \(\mu\text{m}\)
- Calculated low-loss guided mode
- Attenuation length of order 900\(\text{mm}\)

Radial expansion of shock front in excellent agreement with blast-wave theory and fluid simulations.
Summary

► Plasma channels \( \sim r^\alpha \) for \( \alpha = 6 \) or larger are suitable for propagation of long trains of laser pulses. Matching spot size doesn’t depend on \( \alpha \).

► A train of 10 laser pulses with total energy of 800 mJ @ 1 \( \mu \) m was propagated (EPOCH 2D PIC) over 25 cm in a plasma channel with \( \alpha = 10 \) and the density on axis = \( 1.75 \times 10^{17} \) cm\(^{-3} \) demonstrating that MP-LWFA accelerating electrons to GeV energies at low density in a plasma channel is possible.

► Red and blue frequency shifts are significant and eventually limit accelerator energy and amount of usable pump laser energy. This has been demonstrated at the pump wavelength increased to 8 \( \mu \) m. For \( a_0 = 3 \), possible accelerator length is about factor 2 shorter than the dephasing length.

\[ E_x \text{ longitudinal electric field on axis in V/m after 25 cm propagation} \]

\[ \lambda_0 = 1 \mu \text{m} \]

\[ \lambda_0 = 8 \mu \text{m} \]
Thanks!

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