Determining the impact of LWFA injection schemes on electron bunch profiles and peak currents based on broadband, spectral CTR diagnostics at single shot

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Short electron bunches in LWFA

Pulse duration?  
Micro-structures?

- Knowledge on longitudinal electron bunch structures is key to bright radiation sources.
- Compact FELs require high peak currents for lasing

\[ \rho = \frac{1}{2\gamma} \left( \frac{I}{I_A} \cdot \left( \frac{f_c \cdot K \lambda_u}{2\pi \sigma_b} \right)^2 \right)^{1/3} \]

Ti:Sa Laser DRACO

- \( \lambda_0 = 800 \text{ nm} \)
- up to 4 J on target
- 27 fs pulse width (FWHM)
- Strehl-ratio > 0.9
- 20 \( \mu \text{m} \) FWHM

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Laser-Plasma Accelerator Workshop 2019 | MedILS, Split, Croatia | May 5th – 10th, 2019 | Dr. Alexander Debus
Self-truncated ionization injection regime of LWFA

consecutive shots

high bunch charges at several 100pC

2.5 J, 30 fs, plasma density $3.1 \times 10^{18}$ cm$^{-3}$, mixed He + 1% N$_2$, 3 mm gas jet


<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean ± Shot-to-shot jitter</th>
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<tbody>
<tr>
<td>Mean peak energy</td>
<td>250 MeV ± 22.5 MeV</td>
</tr>
<tr>
<td>Charge in FWHM</td>
<td>220 pC ± 40 pC</td>
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<tr>
<td>Abs. energy width</td>
<td>36 MeV ± 11 MeV</td>
</tr>
<tr>
<td>Divergence</td>
<td>7 mrad ± 1 mrad</td>
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</tbody>
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Visit talk of Jurjen Couperus Thu, 12:00
Coherent Transition Radiation in a nutshell

- Transition radiation (TR) is emitted when a relativistic charge passes through an interface between two dielectric media.

\[ \frac{d^2 W_e}{d\omega d\Omega} = \frac{e m_e c}{\pi^2} \frac{\beta^2 \sin^2 \theta}{(1-\beta^2 \cos^2 \theta)^2} \]

- Broadband radiation
- Radiation directional within $1/\gamma$-cone
- TR-beam is radially polarized

Useful for many (beam) diagnostics beyond pulse duration measurement

Diagnostics for plasma-based electron accelerators
M. C. Downer, R. Zgadzaj, A. Debus, U. Schramm, and M. C. Kaluza
Rev. Mod. Phys. 90, 035002 (2018)
Spectral CTR diagnostics:
A gateway to the fs-scale

Ultra-broadband UV-VIS spectrometer at single-shot

- single-shot capability
- 5.9 octaves frequency range
- 200 nm (UV) – 12 µm (MIR)
- high spectral resolution
- high-dynamic range
- detection limit ~ 50 fJ of CTR

Sim: 200 MeV, 20pC, 10 fs bunch length, 20 µm dia
Photometric calibration over the full spectrum for both polarizations

Absolute polarization dependent spectral calibration over 5.9 octaves needs lots of calibration sources!

- **Wavelength calibration**
  Mercury-Argon lamp, Argon lamp, absorption lines of Teflon foils

- **Relative response calibration**
  Halogen and Deuterium lamps, blackbody radiator

- **Absolute photometric calibration based on a range of laser sources**
  400nm, 532 nm, 800 nm, 1.5µm and 10.6µm
CTR foil target positioning & shielding close to source for full coherence

Tape drive + Steel foil  el.-spectrometer

CTR foil positioned 1 – 30 mm from jet

CTR spectrometer

Only the high energy peak contributes to CTR-spectrum

Only select shots that make it through the CTR spectrometer aperture without clipping.

CTR emission $\times 10^{-13} [\text{J}]$

charge [pC]

energy [MeV]

100µm  200µm

50µm
Data analysis
From the spectral to the time-domain

Form factor extracted from measured spectrum

Electron bunch length agrees with 3D-PIC simulations

Phase-retrieval including error analysis

Typical reconstructed electron bunch profile

| $\sigma_{\text{meas}}$ | $11.0 \text{ fs}$ | $+1.2 \text{ fs}$ | $-1.3 \text{ fs}$ |
| $\sigma_{\text{sub}}$ | $0.6 \text{ fs}$ | $+0.7 \text{ fs}$ | $-0.1 \text{ fs}$ |

FWHM: $18.9 \text{ fs}$

$\tau \sim 13 \text{ fs (rms)}$
Longitudinal bunch profiles at sub-fs resolution

**Ionization injection**

- Electron spectra
- 250 pC

**Self-injection**

- 50 pC

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**Longitudinal bunch profiles**

- \( \sigma_{\text{mean}} = 11.0 \text{ fs} \pm 1.2 \text{ fs} \) to \( -1.3 \text{ fs} \)
- \( \sigma_{\text{sub}} = 0.6 \text{ fs} \pm 0.7 \text{ fs} \) to \( -0.1 \text{ fs} \)

**Electron spectra**

- FWHM \~ 18.9 fs
- \( l = 14.5 \pm 3.5 \text{ kA} \)

**Current [kA]**

- 210 MeV energy @ 5% energy spread

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**Self-injection**

- \( \sigma_{\text{mean}} = 3.7 \text{ fs} \pm 0.5 \text{ fs} \) to \( -0.8 \text{ fs} \)
- \( \sigma_{\text{sub}} = 0.5 \text{ fs} \)

**Current [kA]**

- 260 MeV @ 15% energy spread

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**Bunch duration**

- 15 – 20 fs (FWHM)
- + distinct sub-fs substructure

- \~ 3 fs (FWHM)
- + less pronounced substructure
Systematical benchmarks of peak current in laser-wakefield accelerator experiments

Injection scheme: self-truncated ionization

Each data point denotes the statistics of 15 – 25 shots.
Coherent Optical Transition Radiation (COTR) imaging @ UV-NIR

- High-resolution, transverse CTR data acquired at 1mm behind the gas jet

- Observation of annular Point Spread Function
  - source size sub microns
  - hints at sub-structures

- Coherence observed at various wavelengths
  - bunch sub-structures
  - sub-fs length

- CTR (Wartski) Interferometry can analyze bunch sub-structure properties (e.g. emittance)
Outlook – 3D bunch profile diagnostics

- CTR spectra and images are complementary diagnostics of longitudinal and transverse electron beam distribution.

- All spectral and imaging measurements are simultaneously acquired at single shot.

- Our goal is to combine the analysis diagnose the 3D bunch profile at μm and fs-resolution.
Conclusions

▪ Single-shot, sub-fs resolution, energy independent spectral-domain bunch profile diagnostics for electron bunches down to the sub-pC charge scale.

▪ Enables characterizing longitudinal bunch profiles for different Laser-wakefield acceleration injection schemes, such as self-injection, self-truncated ionization injection,… .

▪ CTR spectra and imaging are complementary techniques, promising for 3D electron bunch reconstructions.

Self-Truncated Ionization injection
- Typical bunch duration 11fs (rms), 19 fs (FWHM)
- Typical bunch sub-structure duration 0.6 fs (rms)
- Typical peak current 15 kA
- Maximum peak currents of 20kA reproducibly attained using steep gas profiles and nitrogen doping concentrations of 1.5%.

Self-injection
- Typical bunch duration 3.7fs (rms), 2.9 fs (FWHM)
- Weak sub-structure with ~0.5 fs (rms) duration
- Typical peak current 10 kA