Longitudinal phase space diagnostics for ultrashort bunches with a plasma deflector

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LAOLA. is a collaboration of
LUX Junior Research Group

Junior Research group at CFEL and Hamburg University

commission & operate 200 TW ANGUS laser system

build and operate the LUX beamline for laser-plasma driven undulator radiation

lux.cfel.de
Laser Plasma Acceleration (LPA)

- focus high power laser pulse into plasma target
- typical laser parameters:
  - 1 - 10 J pulse energy,
  - 30 fs pulse length,
  - 20 μm spot size

photo: N. Delbos

target chamber @ LUX
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- laser excites wakefield
  - charge separation
  - typical scale: plasma wavelength 10 - 100 μm
Laser Plasma Acceleration (LPA)

- high gradients

- University of Texas: 2 GeV over 7 cm

W. Leemans et al., PRL 113, 245002 (2014)
- LBNL: 4 GeV over 9 cm
Laser Plasma Acceleration (LPA) - Beam Quality

- challenges
  - stability
  - reproducibility
  - beam quality

- originate from
  - laser and plasma stability
  - injection mechanism
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- diagnose bunch for feedback
- external injection
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  diagnose bunch for feedback

  typical bunch length $\approx 2 \text{ fs rms}^{[1,2]}$

Plasma based current profile diagnostic

- laser drives linear wakefield
- inject electron bunch off-axis in y
- experiences streaking field

Advantages:
- strong fields
- short (plasma) wavelength
- short target

I. Dornmair et al., PRAB 19, 062801 (2016)
Plasma based current profile diagnostic

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I. Dornmair et al., PRAB 19, 062801 (2016)
Example: PIC simulations

- Electron beam from SINBAD LINAC [1]
  - $E_{\text{kin}} = 110$ MeV
  - $\varepsilon_{nx} = 0.09$ mm mrad
  - $\sigma_x = 17$ $\mu$m
  - detuned phase $\Rightarrow$ spiky current profile

- external injection setup
  - diagnose bunch at injection position

SINBAD LINAC: B. Marchetti et al., Proc. IPAC2015, Richmond, TUPWA030

I. Dornmair et al., PRAB 19, 062801 (2016)
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- Laser (3 J pulse energy)
  - $a_0 = 0.3$
  - $\tau = 41$ fs (FWHM)
  - $w_0 = 150$ $\mu$m

- Plasma:
  - $1 \cdot 10^{18} \text{ cm}^{-3}$
  - $l = 3.5$ mm
  - distance laser - beam: 34 $\mu$m
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- using WARP* in the boosted frame ($\gamma_{\text{boost}} = 10$)

* thanks to the WARP team: J.-L. Vay, R. Lehe (LBNL), D. P. Grote (LBNL/LLNL)

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Higher order field correlations

- $E_y$ is curved in $x$ and $y$
- streaking gradient smears over wide bunch
- independent of plasma length

$$\Delta \zeta \geq \frac{\sqrt{10}}{2} \left( \frac{2\sigma_y}{w_0} \right)^2 |\zeta|$$

![Graph showing phase space after interaction](image)

$E_y(x, \zeta) @ y = w_0/2$ [GV/m]
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- theoretical resolution: 96 attoseconds

$$\Delta \zeta \geq \frac{\varepsilon_{ny} m_e c^2}{\sigma_y e k V}$$
Temporal resolution - higher order correlations

- Resolution degradation from curvature:
  \[ \Delta \zeta \geq \frac{\sqrt{10}}{2} \left( \frac{2\sigma_y}{w_0} \right)^2 |\zeta| \]

- Theoretical resolution: 96 attoseconds
  \[ \Delta \zeta \geq \frac{\epsilon_{ny} m_e c^2}{\sigma_y e k V} \]

- Voltage \( V = 0.5 \text{MV} \)
- Wavenumber \( k = 1.9 \times 10^5 \text{m}^{-1} \)
Limitations - Beam Loading

- beam drives own wake
- modifies streaking field
- resolution degradation
  - for $Q = 0.5$ pC: $\Delta \zeta > 66$ as
  - for $Q = 10$ pC: $\Delta \zeta > 1.3$ fs
- if beam loading dominates:
  - increase laser spotsize
  - increase laser intensity

phase space after interaction
Limitations - Beam Loading

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simulated screen image
Limitations - Energy Spread

- slope of $E_z$
- like in TDS: induced energy spread
  - high temporal resolution $\leftrightarrow$ low energy spread resolution
- here: accumulated 1.4 % energy spread
Limitations - Arrival Time Jitter

- timing jitter:
  - shifts beam in phase of wake
  - remain at 10% of plasma wavelength
  - 10 fs rms

- synchronization: SASE FEL pulse to IR laser @ FLASH
  - 28 fs rms
  - limited by bunch duration

- also: seeded FEL @ FERMI
  - 6 fs rms

- ASTRA simulations
  - 10 fs rms jitter
  - 50 shots at each delay
  - rel. calibration error: 6%
Good

- comes for free in external injection experiments

Bad

- need high power laser system
Good

- comes for free in external injection experiments
- intrinsically synchronized in LPA

Bad

- need high power laser system
- synchronization to laser in conventional machines
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## Good

- comes for free in external injection experiments
- intrinsically synchronized in LPA
- calibration possible
- direct access to phase space
- compact
- tunable frequency
- low charge

## Bad

- need high power laser system
- synchronization to laser in conventional machines
- "active" structure
- limited to low charge
- small beam size required

**ugly:** no demonstration yet
Conclusion

- use plasma wakefield for bunch streaking
- strong fields and short wavelength
- temporal resolution below 1 fs
- high power laser system & synchronization needed
- well suited for laser plasma acceleration
Acknowledgement

funding

UNIVIE - M

partners

DESY - M

DESY FS-LA

LBNL

J.-L. Vay

WARP code

DESY

University of Strathclyde Glasgow

group

Florian Grüner

group

Brian McNeil

group

Jens Osterhoff

group Georg Korn

group

Johannes Bahrdt

group

LBNL

J.-L. Vay

WARP code

DESY FS-LA
Limitations: Pointing Jitter

- jitter in angle and offset:
  - shifts beam w.r.t. laser
  - streaking voltage drops
- laser stability at LUX
  - before compressor: 2 μrad rms pointing
  - after 40 m beam transport & focused: 40 μrad pointing, 6 μm offset
- good shot identification
  - center of screen
  - large extent in y
- ASTRA simulations:
  - jitter: 10 fs rms arrival time
    - 500 μrad pointing
    - 75 μm offset
  - 50 shots at each delay
  - rel. calibration error: 3 %
Laser-Driven Plasma Acceleration

ANGUS
new 200 TW laser

LUX
undulator radiation

60 m tunnel

see also lux.cfel.de
More longitudinal phase space diagnostics

- TDS cavities
  - down to 1 fs
    C. Behrens et al., Nat. Commun. 5, 3762 (2014)

- electro-optical monitors
  - around 50 fs
    R. Pompili et al., NIM A 740, 216 (2014)

- passive streaker
  - depending on charge, fs range
    S. Bettoni et al., PRAB 19, 021304 (2016)

- coherent transition radiation
  - depending on charge, no hard resolution limit
  - no unique reconstruction

- Faraday rotation
  - few fs
    A. Buck et al., Nat. Phys. 7, 543 (2011)

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