High Transformer Ratio PWFA Driven by Photocathode Laser Shaped Electron Bunches

Plasma acceleration experiments at DESY Zeuthen

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Outline

► Introduction to HTR PWFA
► Introduction to PITZ
► Self-Modulation Instability
► HTR PWFA at PITZ
► Advanced photocathode laser bunch shaping
► Outlook
Beam-driven plasma wakefield acceleration (PWFA)

PWFA principles, characteristics, implications

**Basic principle**

- Relativistic driver enters plasma
- Pushes plasma electrons away due to space charge
- $\sigma_z \sim \lambda_p$: plasma electrons oscillate around immobile ions
- Trailing witness accelerated in wakefields

**PWFA features**

- Very **high fields** achievable (~50 GV/m demonstrated)
- Wakefields have strong transverse components $\rightarrow$ **focusing & defocusing**
High Transformer Ratio (HTR) wakefields

Increasing ratio of acceleration to deceleration

- Plasma wakefield \( \sim \) transformer \( \Rightarrow \) Energy-transfer from driver to witness

- Fundamental theorem of beamloading: \( R = \frac{E_{\text{acc}}}{E_{\text{dec}}} < 2 \) (symmetrical driver, linear theory)

- High \( R \) enables high energy gain or high efficiency

- Several asymmetrical bunch shapes proposed
  \[ R \leq 2\pi \frac{L_{\text{driver}}}{\lambda_{\text{plasma}}} \]

**HTR in PWFA**

- \( \lambda_{\text{plasma}} \leq \text{mm} \) \( \Rightarrow \) ps-scale bunch shaping

- Driver length = several periods of wake \( \Rightarrow \) instability
  \[ \Rightarrow \text{operation in (quasi-) nonlinear regime: } n_{\text{bunch}} > n_{\text{plasma}} \]
Shaping of picosecond electron bunches

Available bunch shaping schemes

► Several schemes for shaping high brightness electron bunches demonstrated

- Masking in dispersive section
- Nonlinear chromatic shaping with sextupoles
- Dual frequency linac bunch shaping
- Shaping by self-wakefields
- Transverse-to-longitudinal emittance exchange (EEX)


► Methods exhibit drawbacks

- Additional beamline elements required
- Some lead to large charge loss
- Some introduce distortions to transverse phase space

→ Photocathode laser based bunch shaping employed at PITZ

M. Boscolo et al., NIM A 577, pp. 409-416 (2007)
Status of HTR wakefield acceleration

Projects and measurements for achieving HTR

► Enhanced and high transformer ratios first observed at Argonne National Laboratory
  ➢ Dielectric structure based wakefield
  ➢ Ramped bunch train by stacking of UV laser pulses
  ➢ TR of 3.4 achieved

► HTR with shaped bunches also observed at ANL
  ➢ Dielectric structure based wakefield
  ➢ Triangular bunch shaping by transverse-longitudinal EEX
  ➢ TR of up to ~5 achieved

► Current other projects on HTR PWFA
  ➢ SPARC @ INFN: ramped bunch train by pulse-stacking
  ➢ ANL: EEX-shaped triangular bunches
  ➢ FLASHForward: dual frequency shaped triangular bunches

E. Chiadroni et al., NIM A 865, pp. 139-143 (2017)
R. J. Roussel, Poster @IPAC2019, THPGW088
A. Aschikhin et al., NIM A 806, pp. 175-183 (2016)
Introduction to PITZ
Photo-Injector Test facility at DESY in Zeuthen (PITZ)

Experimental environment

- Test stand for photo electron guns of FLASH and European XFEL
- ≤ 25 MeV bunch energy
- High brightness
- Bunch charges 1 pC - 4000 pC
- Various diagnostics
  - Emittance
  - Longitudinal profile (TDS)
  - Longitudinal phase space, …
- Flexible electron bunch shapes
PITZ plasma cells

Lithium heat pipe oven and Argon gas discharge

- Cross-shaped metal vapour oven
- **Side ionisation** with UV-laser
- Max. design plasma density $10^{15}$ cm$^{-3}$
- Longitudinal profile shaping of plasma density possible
- Gas-vacuum separation with µm-thin polymer windows


- **Gas discharge** in ~1 mbar Argon
- 10 mm diameter, **100 mm plasma** column length
- 2 µs, ~300 A peak current pulses
- µm-thin polymer electron beam windows
- Densities $10^{13}$ cm$^{-3}$ up to $3 \times 10^{16}$ cm$^{-3}$

Production of HTR-capable bunches

Photocathode laser-based bunch shaping

► Bunch shaping by photocathode laser pulse shaping
► Shaping by adding 14 Gaussian quasi-pulses ("Solc fan filter")
► Originally used for flattop bunches
► Powerful but complicated tuning
► Witness bunch by splitting pulse upstream of pulse shaper
► Efficient way of bunch shaping

Self-Modulation Instability
Self-modulation instability (SMI)

Background & scope of experiments

Instability physics

- **Transverse modulation** of long bunches ($L_{\text{bunch}} > \lambda_{\text{plasma}}$)
- Initiated by inhomogeneities in focusing forces
- Proposed to **provide proton driver** trains for PWFA (AWAKE@CERN)


Self-modulation at PITZ

- **Proof-of-principle** experiments
- Modulate **flat-top electron bunches**
- Investigate dynamics of instability, test theory models

PITZ SMI experiments
First direct measurement of SMI

- Flat-top electron bunches
- ~1 nC bunch charge
- Interaction with Lithium plasma
- Use rf-deflector to measure time resolved transverse profile and energy
- Clear modulation visible
- Simulations show exponential growth of instability
- Also used for density measurements

See also Posters on Thu by O. Lishilin THPGW016 & THPGW017


High transformer ratio
PWFA
HTR PWFA Experiments

First demonstration of HTR PWFA

- TR calculated from slice energy gain/loss
- Plasma density of $\sim 2 \times 10^{13}$ cm$^{-3}$
- HTR also observed at other densities
- Simulations show TR of 4.3
- $\sim 70\%$ of witness particles lost

$TR = 4.6^{+2.2}_{-0.7}$

HTR PWFA issues

Beam-plasma instabilities

► Measured max. TR of 5.0

► Long electron bunches prone to instabilities (self-modulation & hosing)
  ➢ Focus driver as much as possible
  ➢ Operate at low plasma density

► Simulations predict stable transport at 2 x 10^{14} cm^{-3} max. density

► BUT: Only reached stable transport up to \sim 8 x 10^{13} cm^{-3}

TR = 5.0^{+1.5}_{-0.4}
HTR PWFA issues

Driver slice envelope oscillations

- Large witness charge losses due to defocusing wakefields (& subsequent apertures)
  - Different focal spots of driver & witness
- BUT: Witness focusing not sufficient
- → Betatron oscillations of driver envelope
  - Cause: uneven slice matching due to inhomogeneous focus of driver

- Also measured inhomogeneous driver deceleration:
  - Min. deviation of 62% from mean deceleration in driver measured
HTR PWFA issues

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HTR PWFA issues

Beam transport with Šolc filter shaping

► Inhomogeneous slice focus due to different space charge forces in slices at emission
  ➢ Enhances SMI
  ➢ Betatron oscillations of bunch envelope due to uneven matching

► Further issue: Very long driver shape tuning times

→ Need different, transverse & longitudinal laser pulse shaping technique
Advanced photocathode laser pulse shaping
Advanced photocathode laser shaping

Improvement of HTR PWFA @PITZ

► New photocathode laser in commissioning
► Originally designed to provide ellipsoidal laser pulses for beam emittance reduction

► Transverse & longitudinal bunch shaping based on Spatial Light Modulator (SLM) masking of chirped pulses
  ➢ Independent **shaping in x-λ and y-λ-planes**
  ➢ **Direct control** (fast & more accurate shaping)
  ➢ Control slice parameters (homogeneous focusing)

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Outlook

Ongoing work on SLM-based shaping

► Preliminary simulations show strongly reduced slice misalignment
► SLM shaping in IR set up
► First measurements show fast, stable and accurate shaping in frequency domain
► UV conversion being commissioned
► First shaped bunches expected this summer/fall

→ Bunch characterisation (& measurement of TR/efficiency)

Final goal: readiness of photocathode bunch shaping for high energy accelerator
Summary

Future PWFA activities at PITZ

► High transformer ratios (~5) achieved at different facilities/in different wakefield schemes

► Not yet demonstrated HTR accelerator at parameters for application

► Studies ongoing to overcome current limitations

► Future studies at PITZ:
  ➢ Direct observation of SMI growth
  ➢ Demonstrate transverse & longitudinal photocathode laser bunch shaping of HTR-capable bunches based on SLMs
  ➢ Optimisation of TR & efficiency

See also Posters on Thu by O. Lishilin THPGW016 & THPGW017
Thank you for your attention!

Contact

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