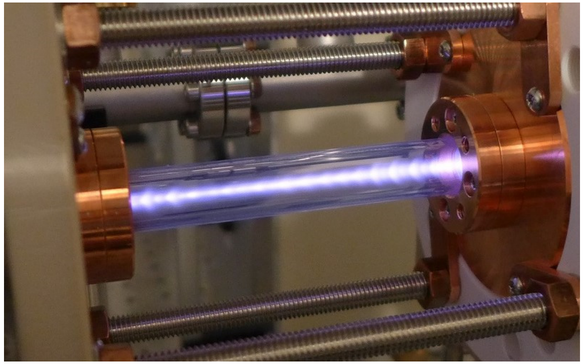
High Transformer Ratio PWFA Driven by Photocathode Laser Shaped Electron Bunches

Plasma acceleration experiments at DESY Zeuthen



Gregor Loisch

10th International Particle Accelerator Conference
Melbourne, 22.05.2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

IPAC19

PITZ Photo Injector Test Facility Zeuthen

DESY.

Outline

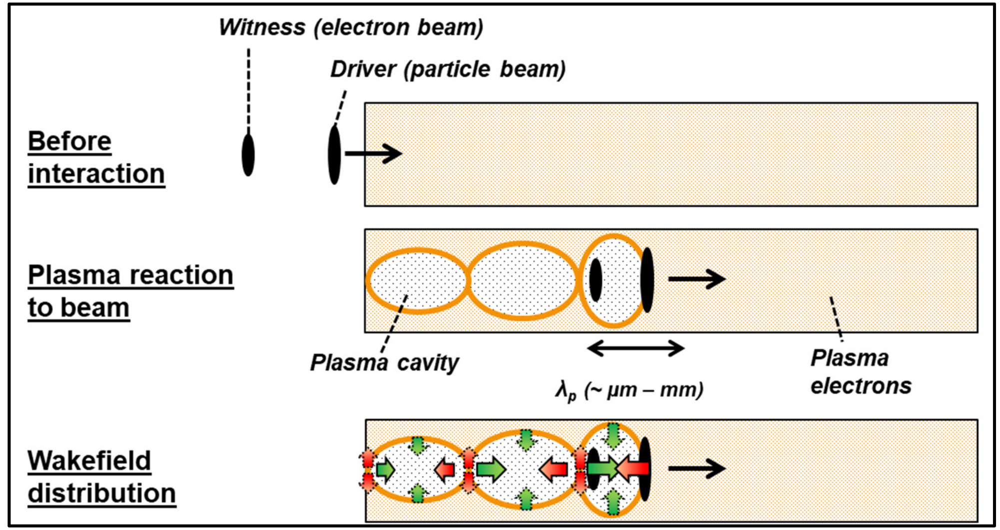
- Introduction to HTR PWFA
- Introduction to PITZ
- Self-Modulation Instability
- HTR PWFA at PITZ
- Advanced photocathode laser bunch shaping
- Outlook

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)

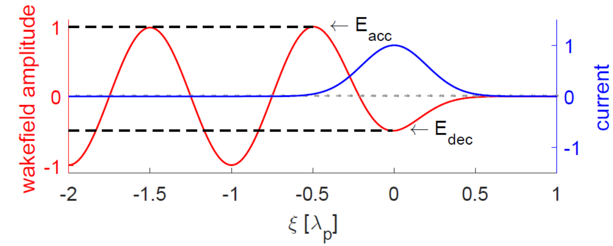
→ Wakefields have strong transverse components → **focusing & defocusing**

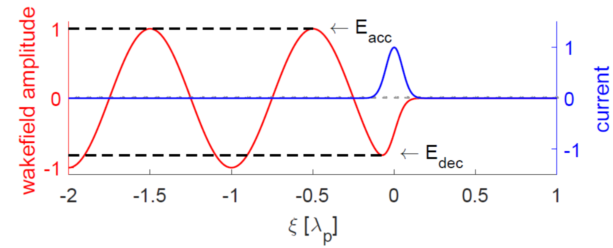
High Transformer Ratio (HTR) wakefields

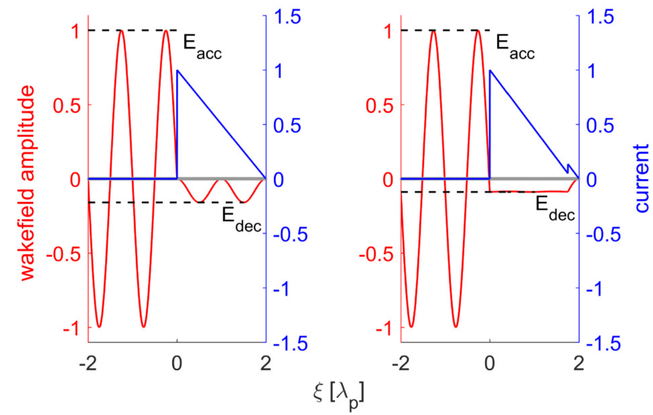
Increasing ratio of acceleration to deceleration

- Plasma wakefield ~ transformer → Energy-transfer from driver to witness
- Fundamental theorem of beamloading: **$R = E_{acc}/E_{dec} < 2$** (symmetrical driver, linear theory)
- High R **enables high energy gain or high efficiency**
- Several **asymmetrical bunch shapes** proposed

  → $R \leq 2\pi\, L_{driver}/\lambda_{plasma}$







<u>HTR in PWFA</u>

- $\lambda_{plasma} \leq$ mm → **ps-scale bunch shaping**
- Driver length = several periods of wake → instability

  → operation in **(quasi-) nonlinear regime: $n_{bunch} > n_{plasma}$**

Shaping of picosecond electron bunches

Available bunch shaping schemes

- Several schemes for shaping high brightness electron bunches demonstrated
  - Masking in dispersive section
    D. C. Nguyen *et al.*, Phys. Rev. A **375**, pp. 597-601 (1996)
    P. Muggli *et al.*, Phys. Rev. Lett. **101**, 054801 (2008)
  - Nonlinear chromatic shaping with sextupoles
    R. J. England *et al.*, Phys. Rev. ST Accel. Beams **8**, 012801 (2008)
    R. J. England *et al.*, Phys. Rev. Lett. **100**, 214802 (2008)
  - Dual frequency linac bunch shaping
    P. Piot *et al.*, Phys. Rev. Lett. **108**, 034801 (2012)
  - Shaping by self-wakefields
    G. Andonian *et al.*, Phys. Rev. Lett. **118**, 054802 (2017)
  - Transverse-to-longitudinal emittance exchange (EEX)
    P. Piot *et al.*, Phys. Rev. ST Accel. Beams **14**, 022801 (2011)
    G. Ha *et al.*, Phys. Rev. Lett. **118**, 104801 (2018)
- Methods exhibit drawbacks
  - Additional beamline elements required
  - Some lead to large charge loss
  - Some introduce distortions to transverse phase space

M. Boscolo *et al.*, NIM A **577**, pp. 409-416 (2007)
G. Penco *et al.*, Phys. Rev. Lett. **112**, 044801 (2014)
F. Lemery *et al.*, Phys. Rev. ST Accel. Beams **18**, 081301 (2015)

→ **Photocathode laser based bunch shaping employed at PITZ**

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

C. Jing *et al.*, Phys. Rev. Lett. **98**, 144801 (2007)
C. Jing *et al.*, Phys. Rev. ST Accel. Beams **14**, 021302 (2011)

- 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

Q. Gao *et al.*, Phys. Rev. Lett. **120**, 114801 (2018)

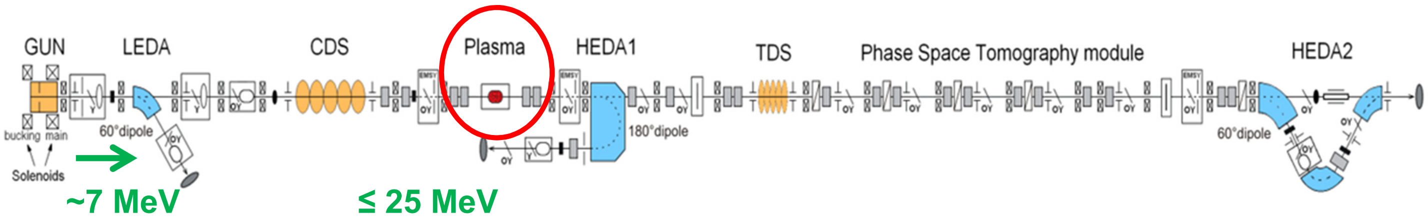
- Current other projects on HTR PWFA
  - SPARC @ INFN: ramped bunch train by pulse-stacking
  - ANL: EEX-shaped triangular bunches
  - FLASHForward: dual frequency shaped triangular bunches

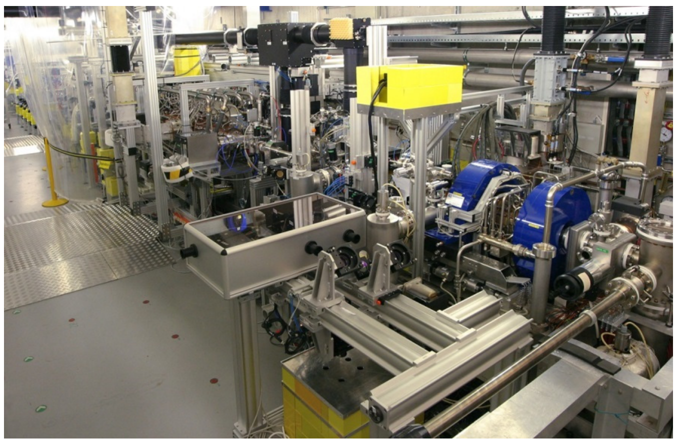
E. Chiadroni *et al.*, NIM A **865**, pp. 139-143 (2017)
R. J. Roussel, Poster @IPAC2019, **THPGW088**
A. Aschikhin *et al.*, NIM A **806**, pp. 175-183 (2016)

Introduction to PITZ

Photo-Injector Test facility at DESY in Zeuthen (PITZ)

Experimental environment

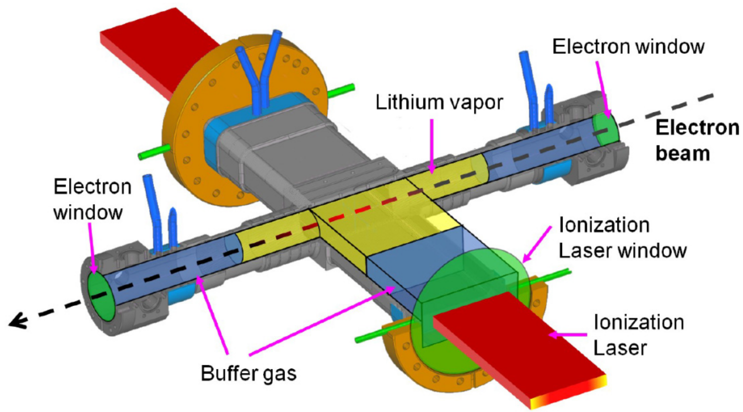




- Test stand for photo electron guns of FLASH and European XFEL
- ≤ **25 MeV** bunch energy
- High brightness
- Bunch charges **1 pC - 4000 pC**
- **Various diagnostics**
  - Emittance
  - Longitudinal profile (TDS)
  - Longitudinal phase space, …
- Flexible electron bunch shapes

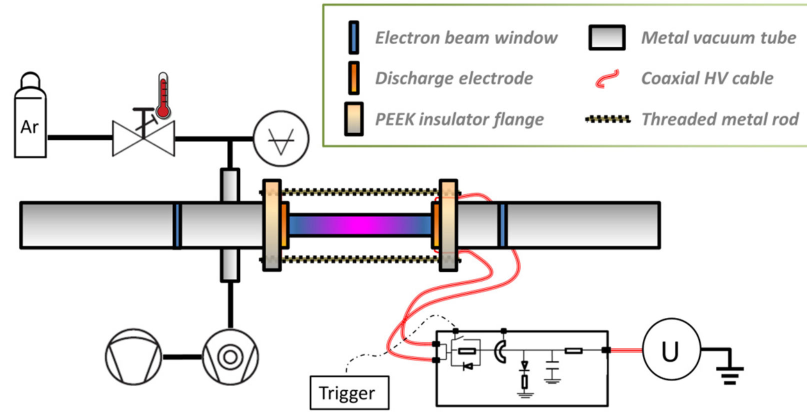
PITZ plasma cells

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

O. Lishilin *et al., NIM A* **829**, pp. 37-42 (2016)



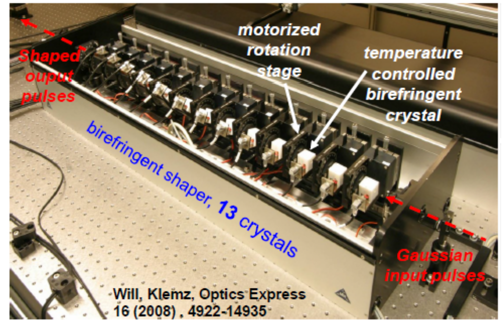
- **Gas discharge** in ~1 mbar Argon
- 10 mm diameter, **~100 mm plasma** column length
- 2 µs, ~300 A peak current pulses
- µm-thin polymer electron beam windows
- Densities **<10^{13} cm^{-3} up to 3×10^{16} cm^{-3}**

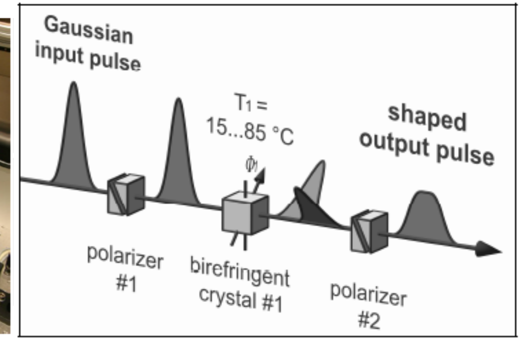
G. Loisch *et al., J. Appl. Phys.* **125**, 063301 (2019)

Production of HTR-capable bunches

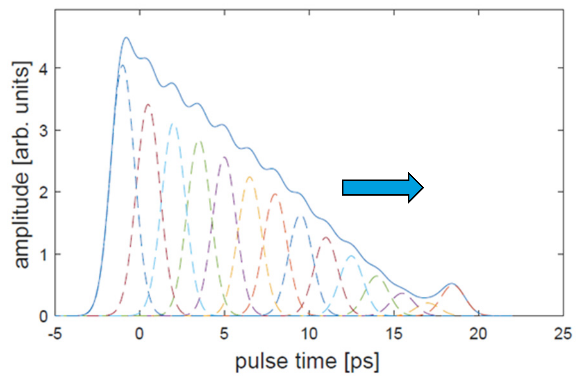
Photocathode laser-based bunch shaping

- Bunch shaping by **photocathode laser pulse shaping**
- Shaping by adding 14 Gaussian quasi-pulses *("Ṡolc 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**

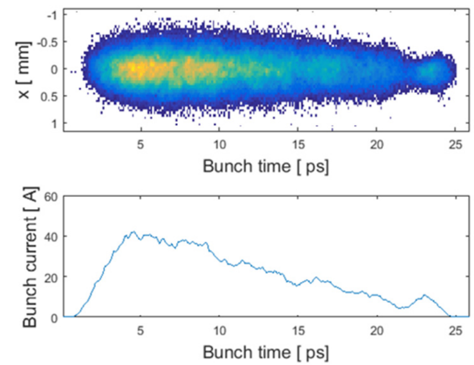




Laser pulse simulation



Bunch measurement



G. Loisch *et al.*, *NIM A* **909**, pp. 107-110 (2018)

Self-Modulation Instability

Self-modulation instability (SMI)

Background & scope of experiments

Instability physics

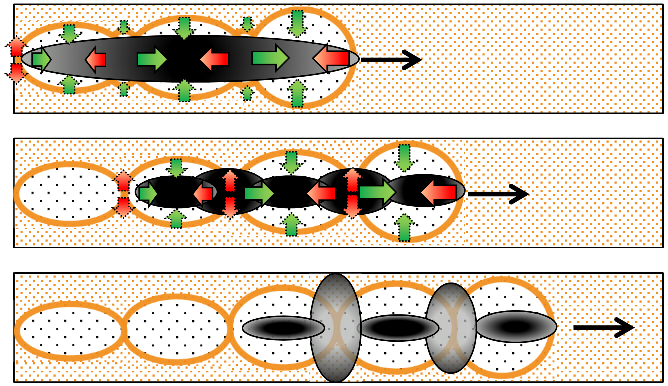
- **Transverse modulation** of long bunches ($L_{bunch} > \lambda_{plasma}$)
- Initiated by inhomogeneities in focusing forces
- Proposed to **provide proton driver** trains for PWFA (AWAKE@CERN)

R. Assmann *et al.*, Plasma Phys. Contr. Fusion **56**, 084013 (2014)

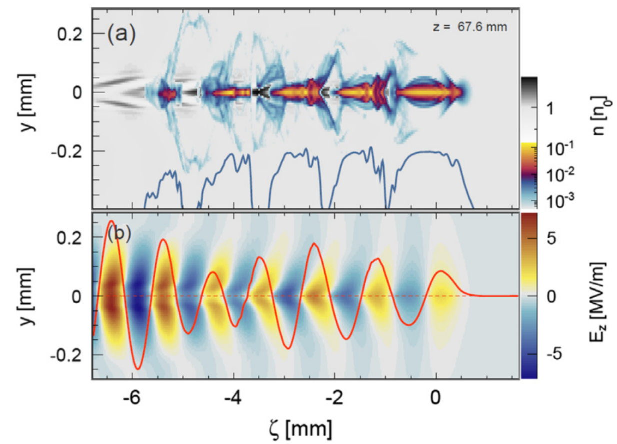
Self-modulation at PITZ

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

SMI principle



Preliminary simulations



M. Gross et al., *NIM A* **740**, pp. 74-80 (2018)

OSIRIS

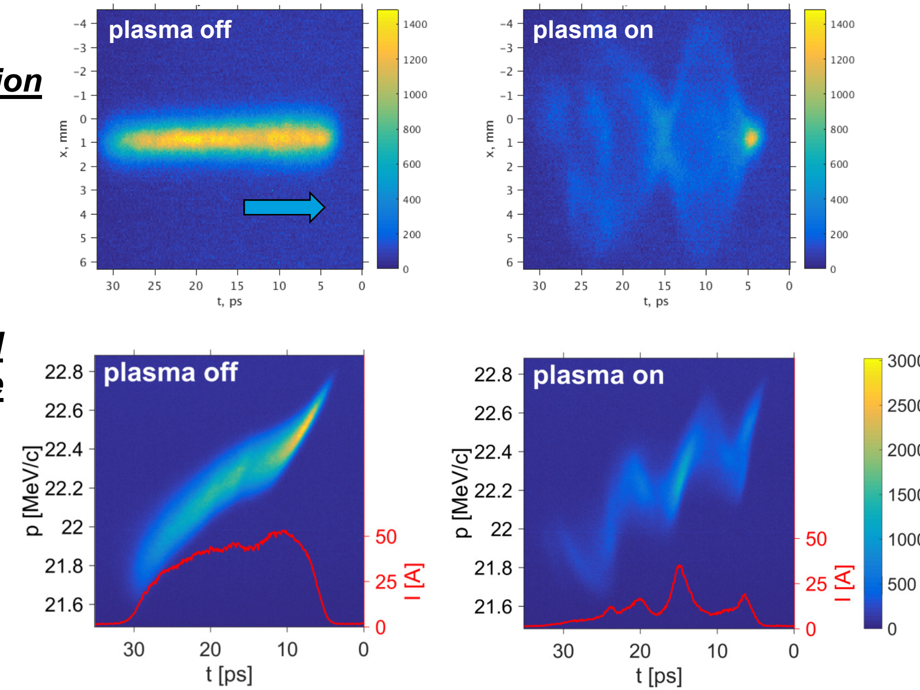
PITZ SMI experiments

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

x-z projection

Longitudinal phase space



M. Gross et al., *Phys. Rev. Lett.* **120**, 144802 (2018)

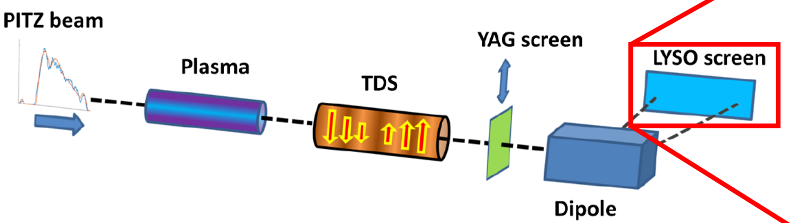
See also Posters on Thu by O. Lishilin THPGW016 & THPGW017

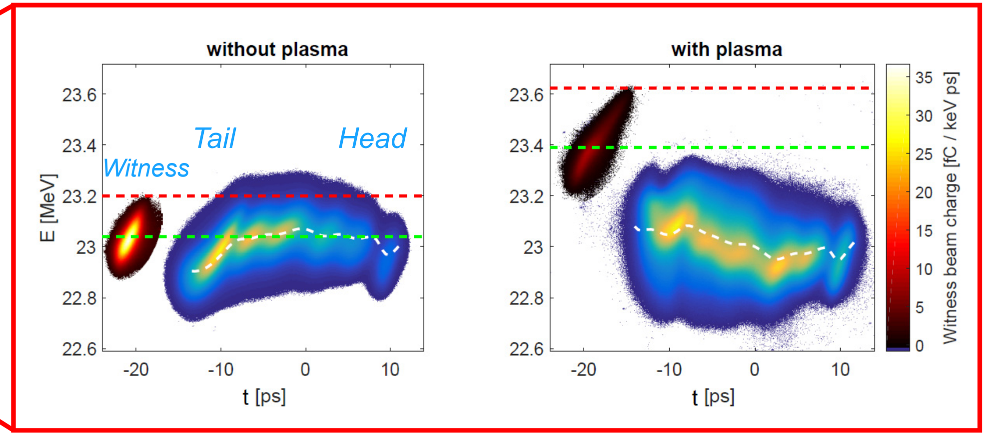
G. Loisch *et al., Plasma Phys. Contr. Fusion* **61**, 045012 (2019)

High transformer ratio PWFA

HTR PWFA Experiments

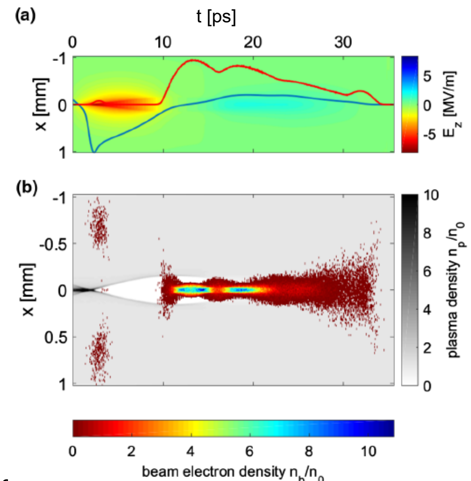
First demonstration of HTR PWFA

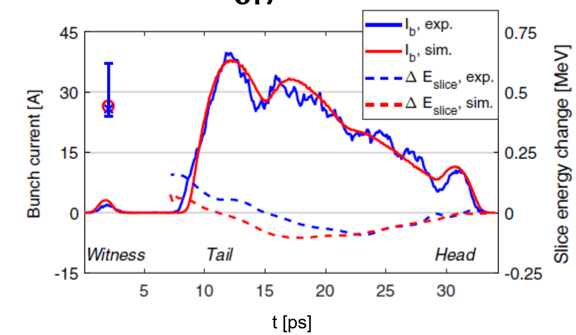




- TR calculated from slice energy gain/loss
- Plasma density of ~2 x 10^{13} cm^{-3}
- HTR also observed at other densities
- Simulations show TR of 4.3
- ~70% of witness particles lost

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





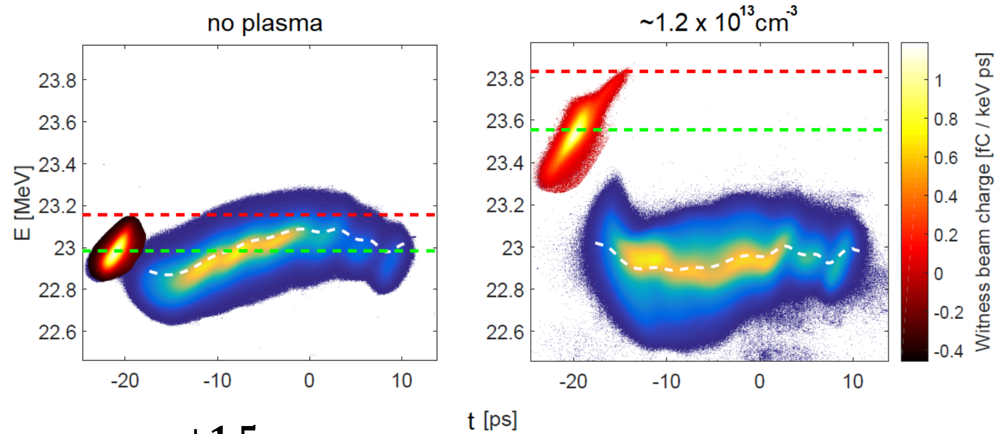
G. Loisch *et al.*, *Phys. Rev. Lett.* **121**, 064801 (2018)

ASTRA HiPACE

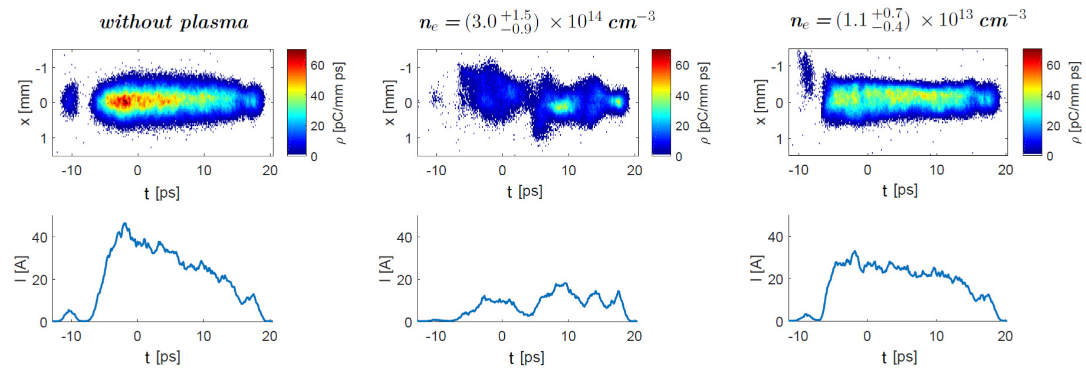
HTR PWFA issues

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 $2 \times 10^{14}\ cm^{-3}$ max. density
- BUT: Only reached stable transport up to ~$8 \times 10^{13}\ cm^{-3}$



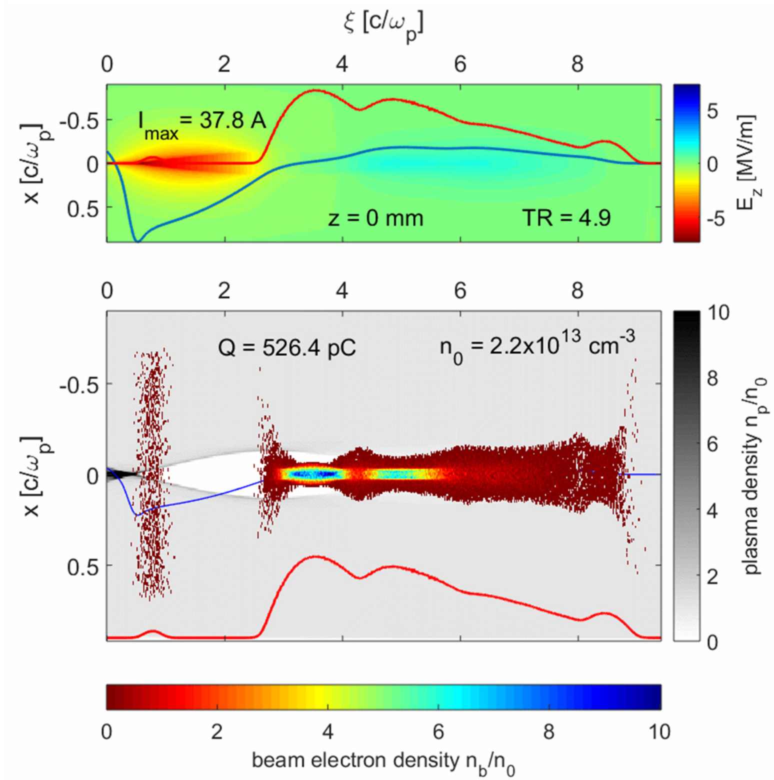
TR = $5.0^{+1.5}_{-0.4}$



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



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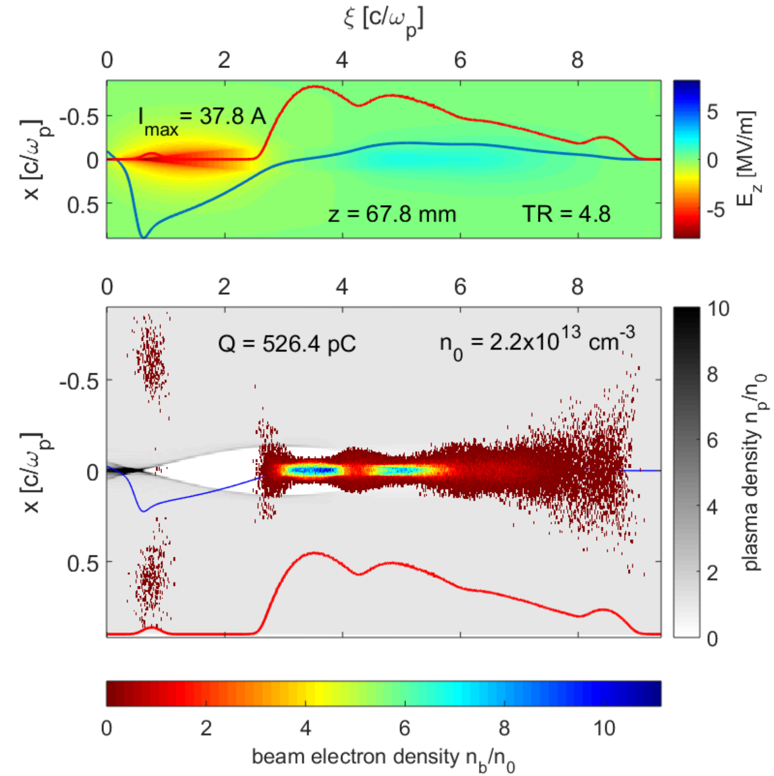
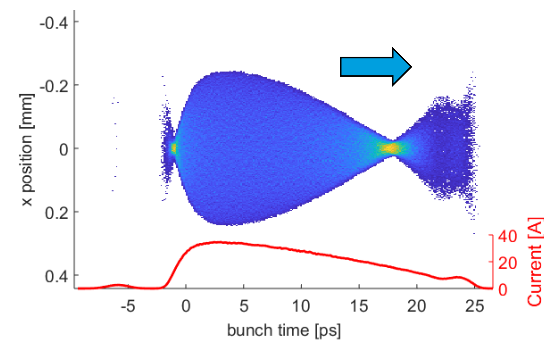


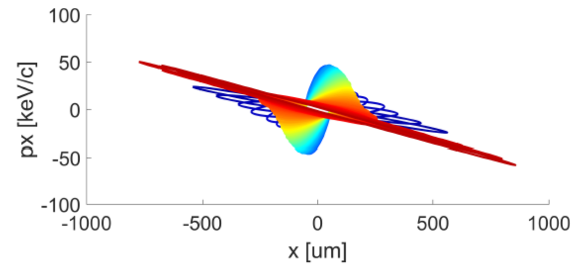
HTR PWFA issues

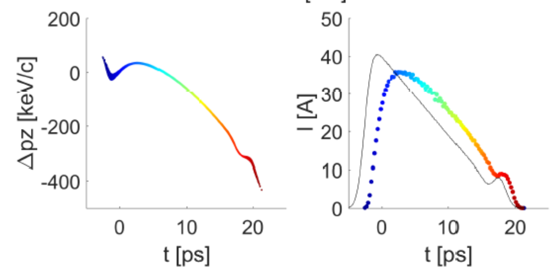
Beam transport with Śolc filter shaping

- 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







ASTRA

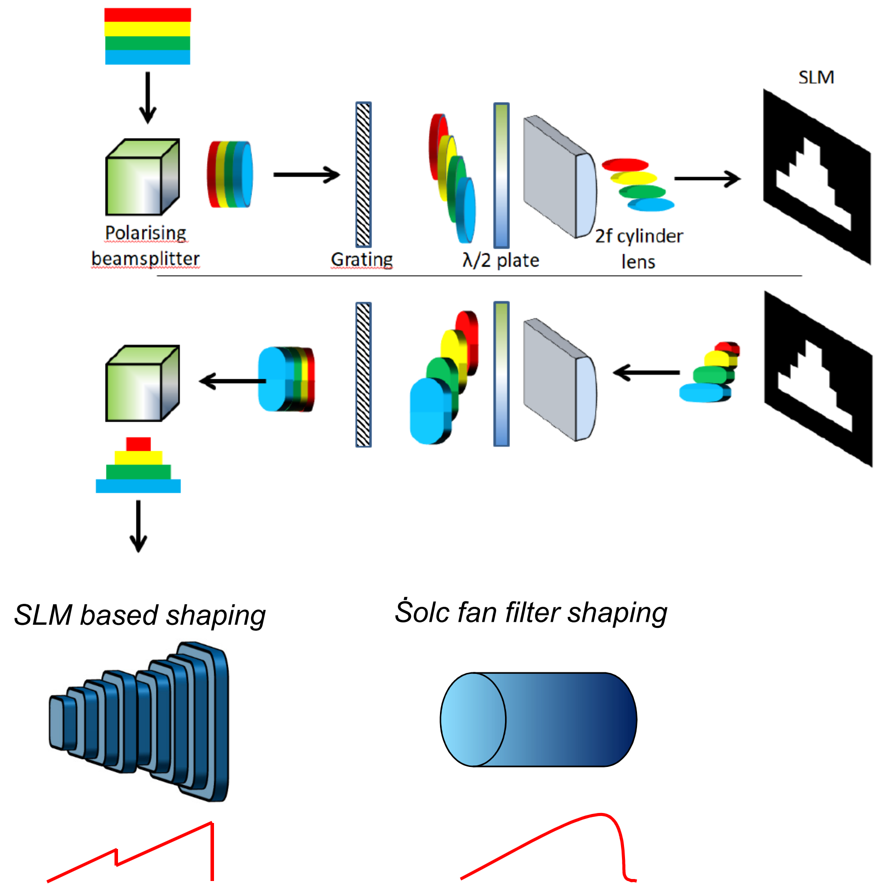
Advanced photocathode laser pulse shaping

Advanced photocathode laser shaping

Improvement of HTR PWFA @PITZ

- New photocathode laser in commissioning
- Originally designed to provide ellispoidal 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)



I. Kuzmin *et al.*, Laser Phys. Lett. **16**, 015001 (2018)
G. Loisch *et al.*, *NIM A* **909**, pp. 107-110 (2018)
I. Kuzmin *et al.*, Appl. Opt. **58**, pp. 2678-2686 (2019)

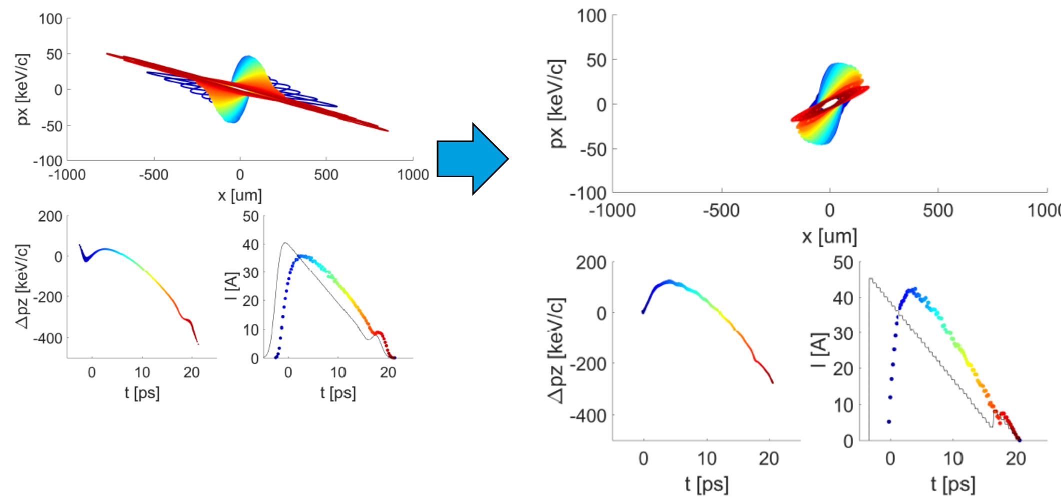
Outlook

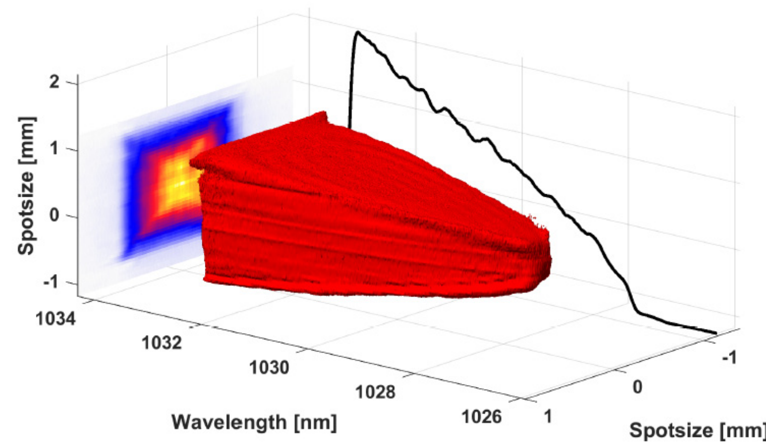
Ongoing work on SLM-based shaping

- 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)

Ṡolc fan filter shaping | *SLM-based shaping*





<u>Final goal</u>: 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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