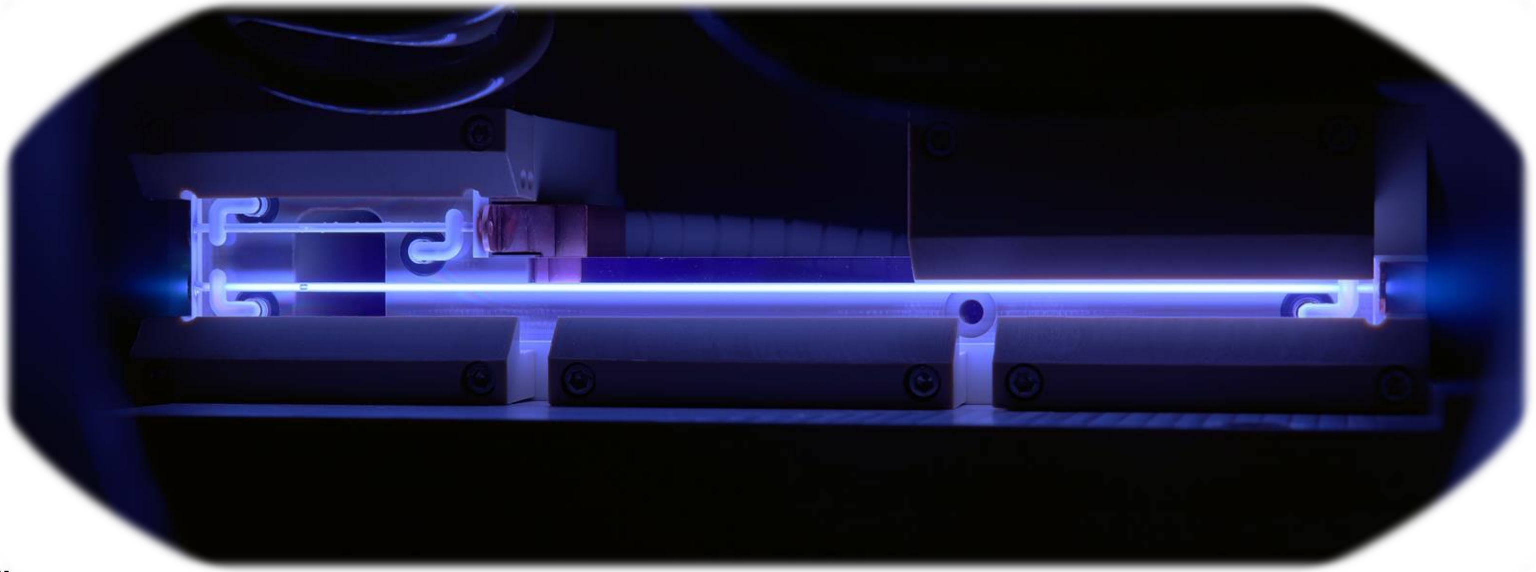
Experiments towards high-repetition-rate plasma-wakefield acceleration

First experimental results on fundamental repetition rate limits at FLASHForward



Gregor Loisch, J. Beinortaite, G. Boyle, J. Chappell, S. Diederichs, J. Garland, C. A. Lindstrøm, T. Parikh, S. Schreiber, S. Schröder, M. Thévenet, S. Wesch, M. Wing, P. Gonzalez-Caminal, B. Foster, J. Osterhoff, R. D'Arcy

IPAC 2022
Bangkok, 13.06.2022

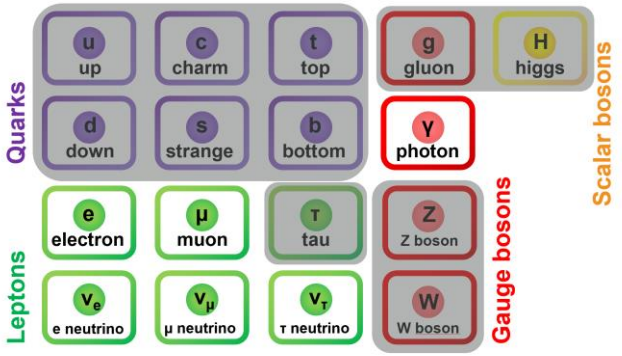
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

IPAC22

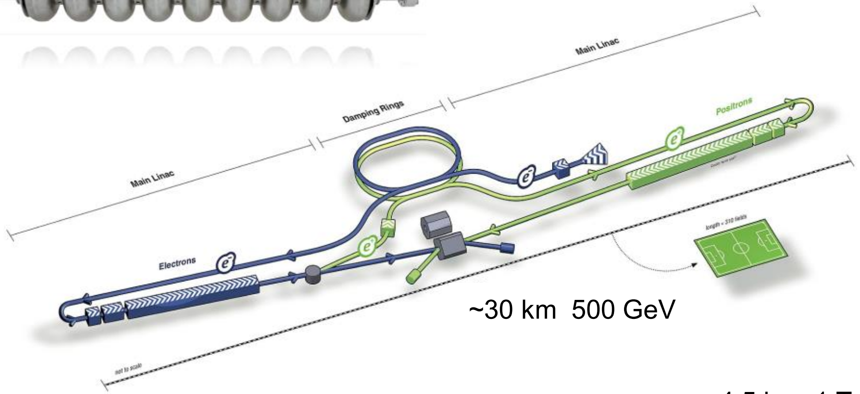
DESY.

Accelerators – an enabling technology…

…with limits



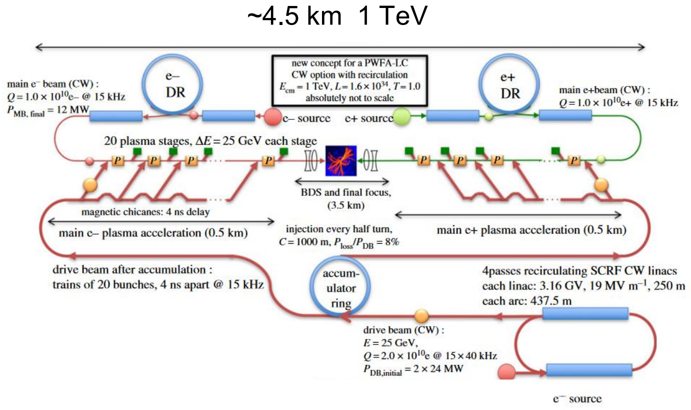
- Accelerators are a story of success
  - Enabled the establishment of standard model, …
  - Key tools in High-energy physics, Life sciences, Material sciences, Medical treatment, …
  - Supporting increasing number of industrial applications



- Radiofrequency cavities core technology of current machines
- Accelerating gradient in metal cavities limited

  → Large scale facilities

  → Future linear colliders 10's of km size



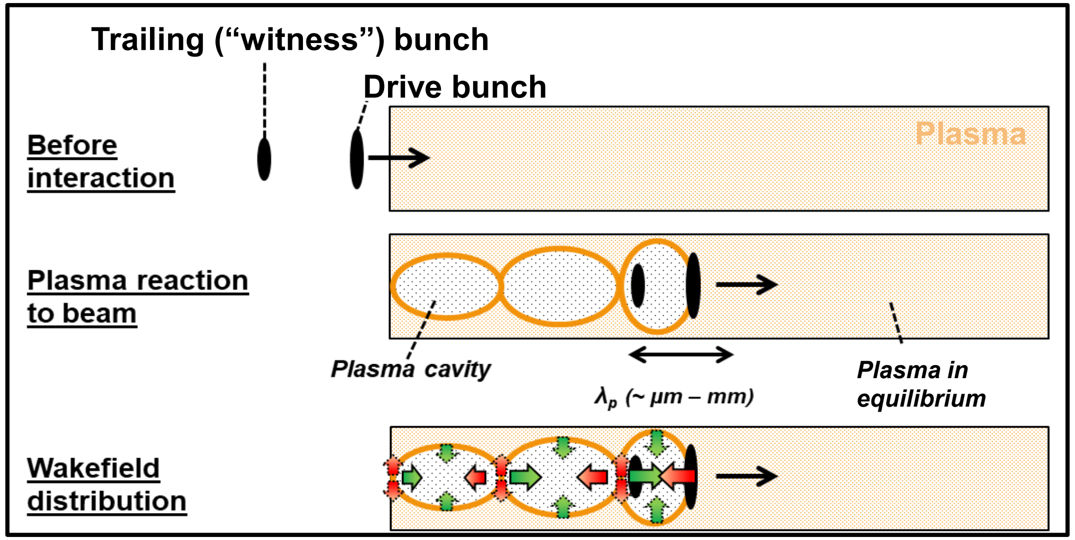
E. Adli, Phil. Trans. R. Soc. **377**, 20180419, 2019

→ Can we advance accelerators beyond current limits?

Plasma-wakefield acceleration (PWFA)

General introduction and state of the art

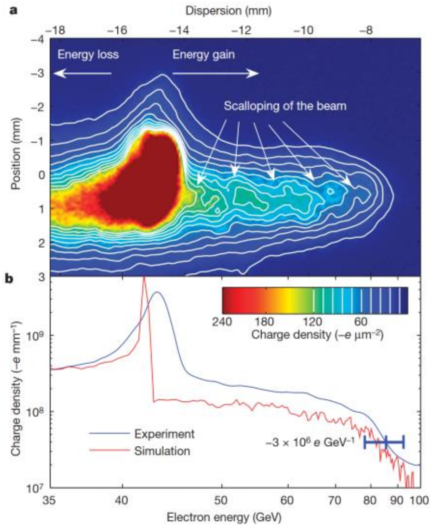
- Excitation of electron density oscillation in plasma by a particle bunch
- Charge separation → electrical fields
- Trailing bunch gains energy in wakefields



- Gradients ≤ 52 GV/m demonstrated
- Energy spread preservation demonstrated
- Experiments towards emittance preservation ongoing

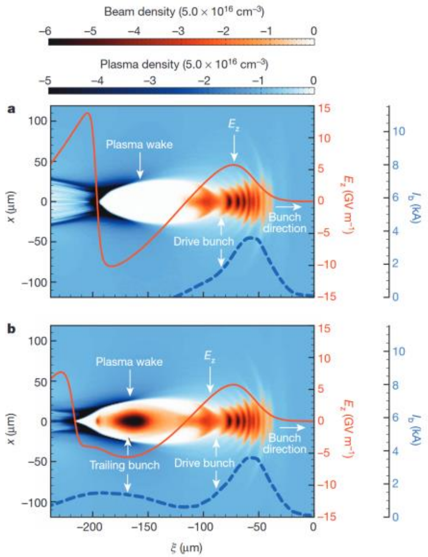
I. Blumenfeld *et al.*, Nature **445**, 741 (2007)

High gradient acceleration



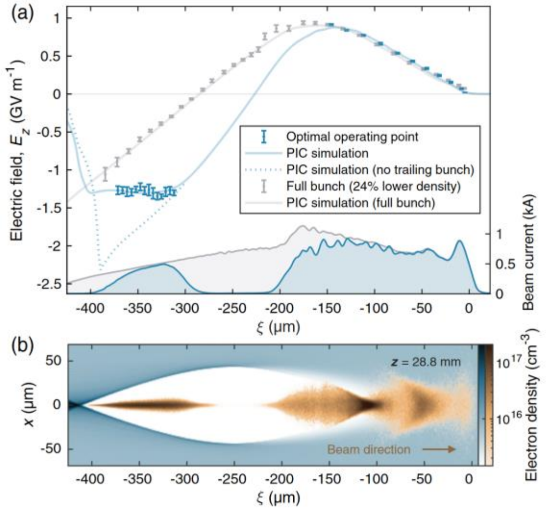
M. Litos *et al.*, Nature **515**, 92 (2014)

High instantaneous efficiency



C. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)

High instantaneous efficiency + energy spread preserved



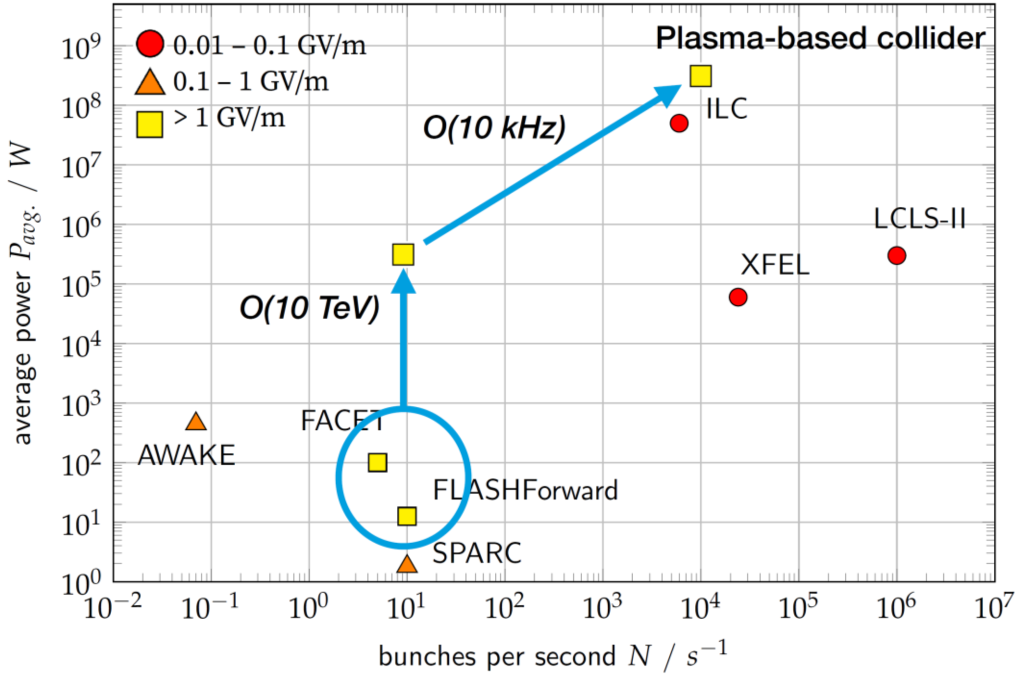
Applications and high repetition rates

Experimental demands in HEP and photon science

- Two main fields of application for PWFA
  - **High-energy physics** machines
  - Soft/hard X-ray **free-electron lasers**

→ luminosity and (int.) brightness **require high average power**, i.e., many bunches/sec

- Various bunch patterns used in conventional machines
  - *< ~100Hz CW* (LCLS I, SwissFEL, SACLA, PAL FEL, …)
  - *MHz burst @ 5-10 Hz* (Eu XFEL, FLASH, ILC)
  - *GHz bursts @ 50 Hz* (CLIC)
  - *MHz CW* (LCLS II, Eu XFEL)



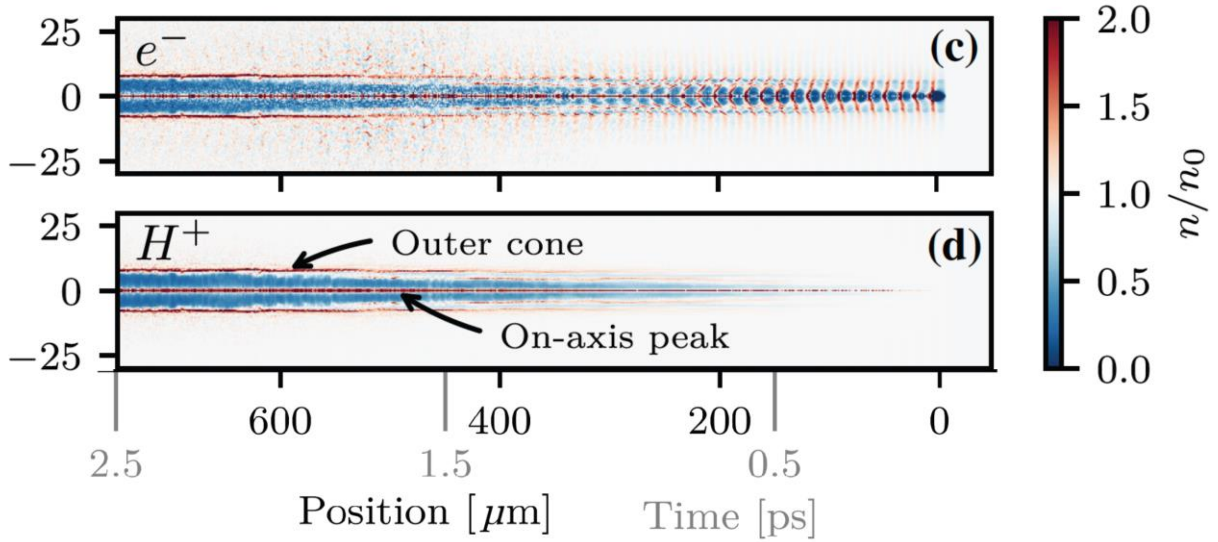
→ Advance PWFA from **O**(Hz) → **O**(kHz / MHz) !?

Fundamental limits for high-repetition-rate PWFA

Identifying possible operation modes

- Various constraints yet unknown
  - *Reset of plasma source* → Train repetition rate
  - *Plasma stability / heat accumulation / heat load on plasma source* → Bunch train length
  - **<u>Plasma recovery</u>** → Fastest repetition rate
- Electron redistribution to equilibrium ~few $1/\omega_{pe}$
- Plasma-ion & electron redistribution?
- Ion motion measured
  → how long is plasma affected?

Source: M.F. Gilljohann *et al.*, Phys. Rev. X **9**, 011046 (2019)

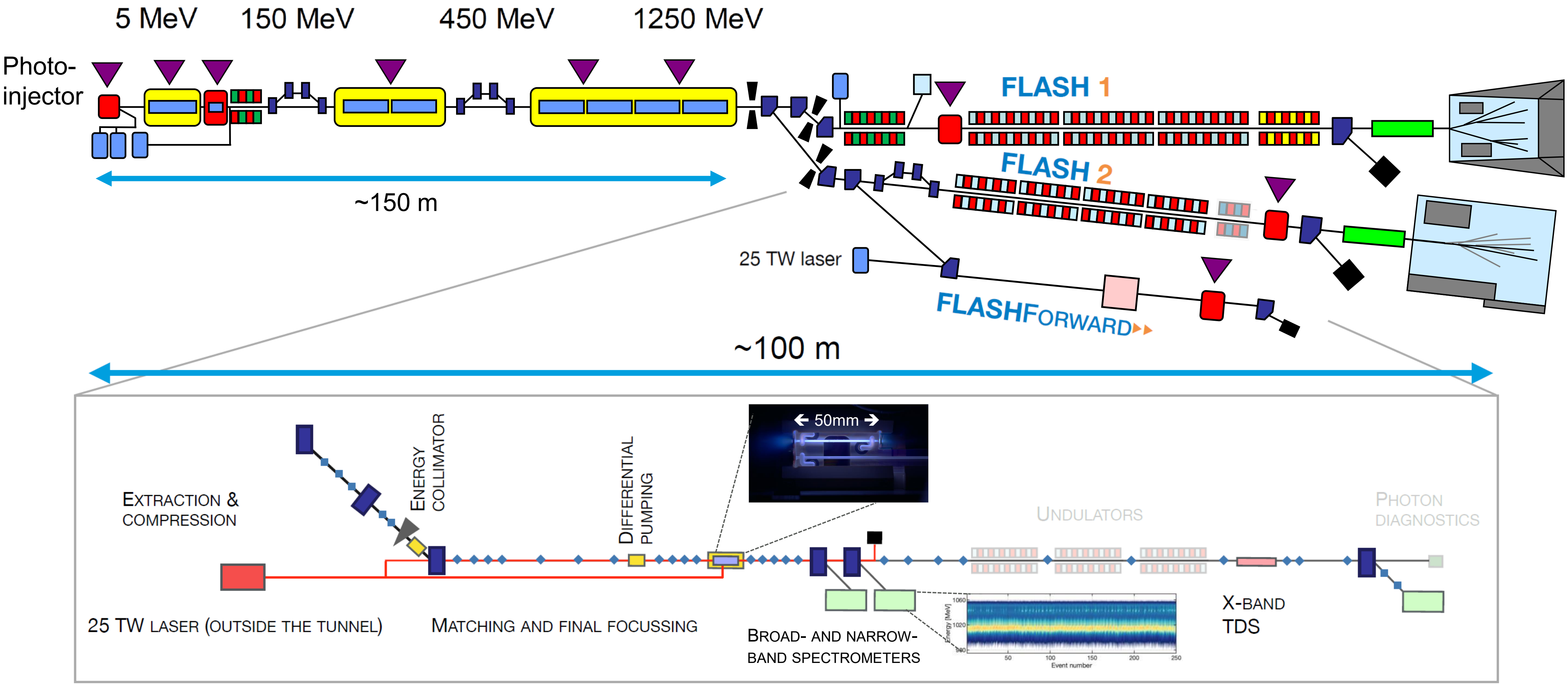


The FLASHForward facility

PWFA at the FLASH FEL drive linac

ACC → SCRF modules
BC → Bunch compressors

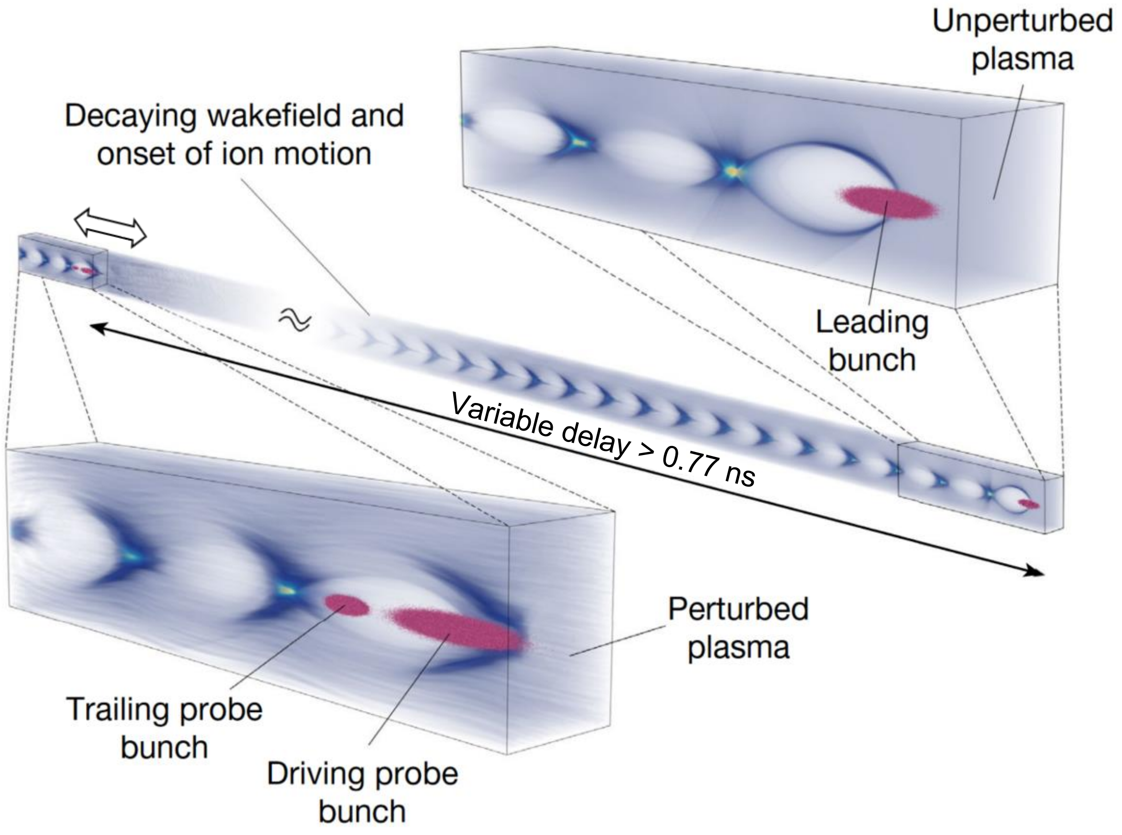
Poster WEPOST033
S. Schröder *et al.*
Wednesday 16:20-18:20



Plasma recovery experiment at FLASHForward

Probing perturbed plasma time evolution

- 2 independent bunches from linac
  - 1st bunch directly to plasma
  - 2nd bunch collimated into driver/trailing pair
  - Separation tunable in 0.77 ns steps (→ <800 μs)
- 1st bunch drives wake / perturbs plasma
- 2nd bunch pair probes evolution
- Can vary exp. conditions
  - Gas species
  - Plasma density
  - Bunch charge/current

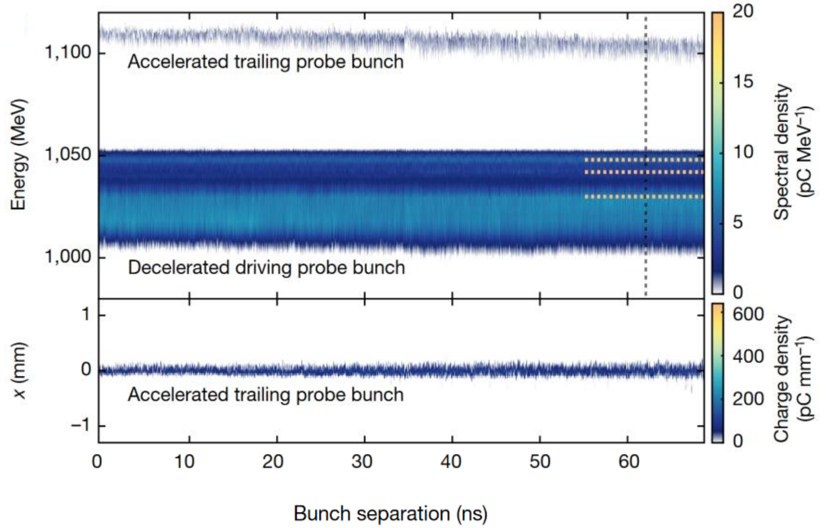


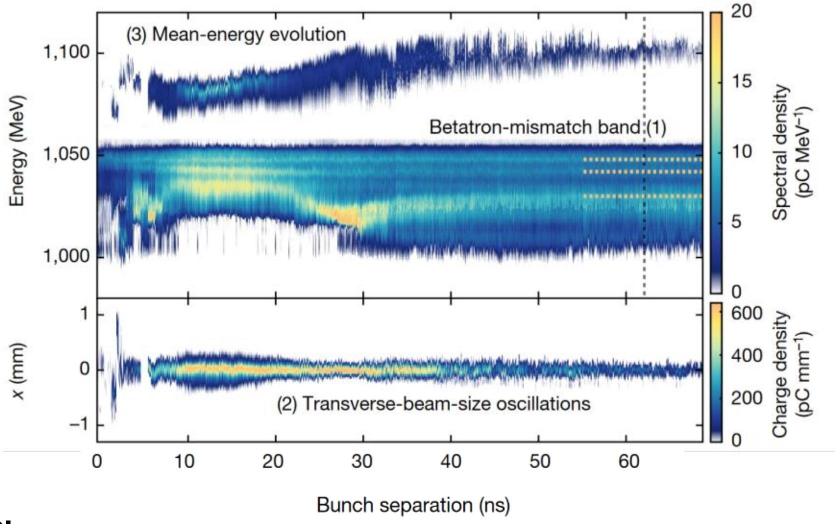
R. D'Arcy *et al.*,
Nature **603**, 58-62, 2022

Plasma recovery time

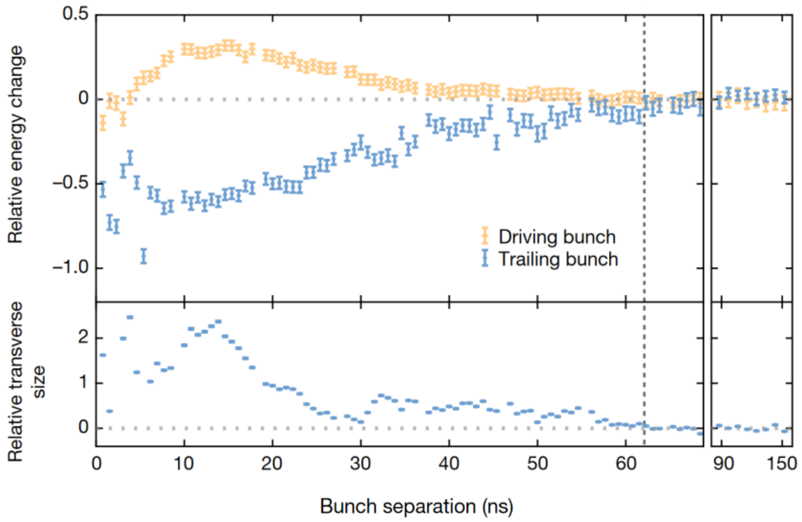
First measurement of evolution time of plasma perturbation

- Compare perturbed & unperturbed cases
  - Compensate plasma density evolution
- Observed evolution of
  - Trailing probe bunch energy
  - Trailing probe bunch transverse size
- Measured **recovery time of 63 ns**
  - Argon plasma
  - Initial density 1.75 x 10^{16} cm^{-3}
  - 1.5 kA bunch perturbing plasma





Plasma recovery time

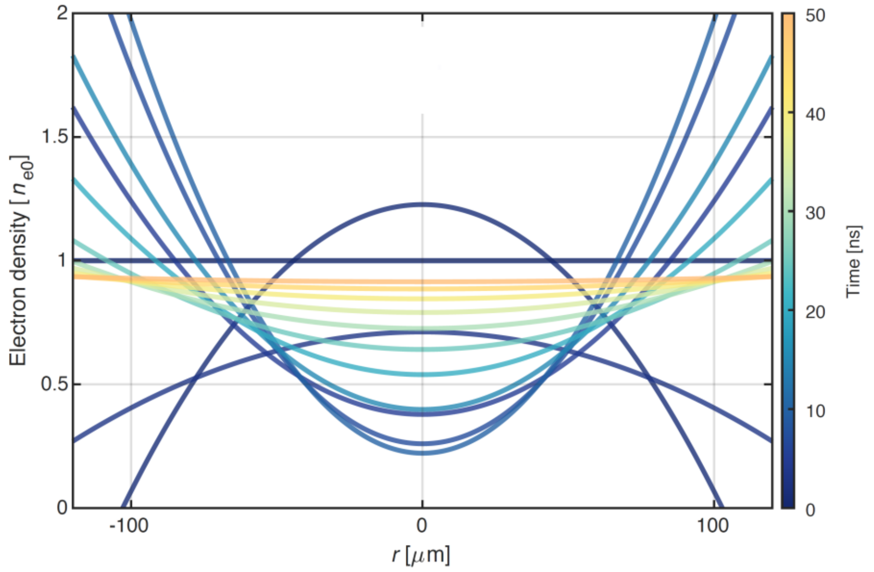


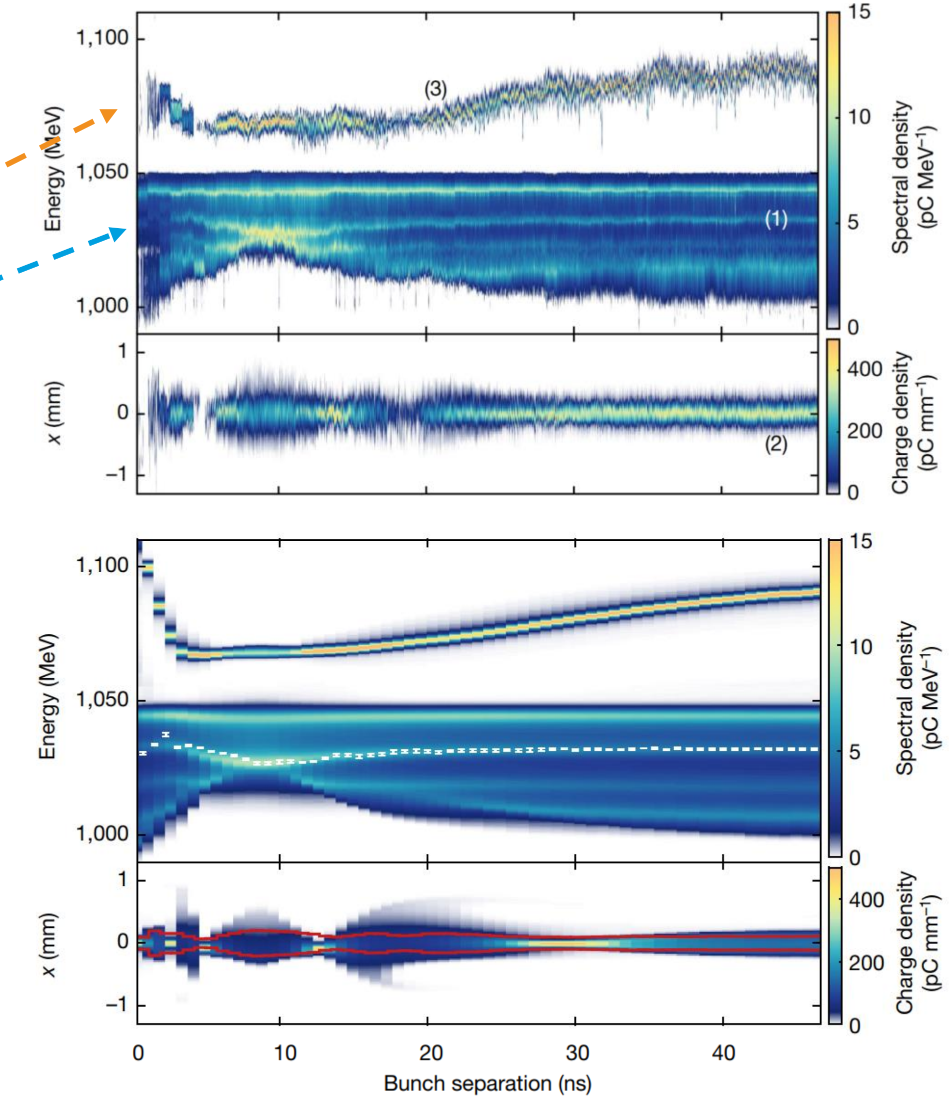
R. D'Arcy *et al.*,
Nature **603**, 58-62, 2022

Modeling of plasma recovery

Understanding the measured beam evolution

- Deduce transverse plasma properties from
  - Probe witness beam energy gain (→ on-axis density)
  - Focal lines of beam (→ transverse density curvature)
- Measurements reproduced well in simulation
- Plasma channel w/ shape evolving over 63 ns



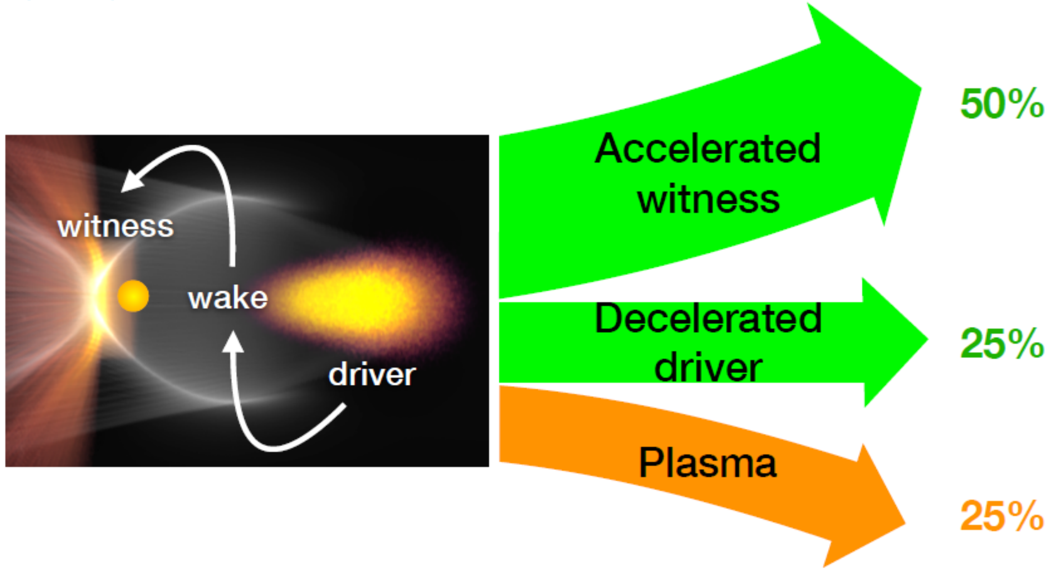


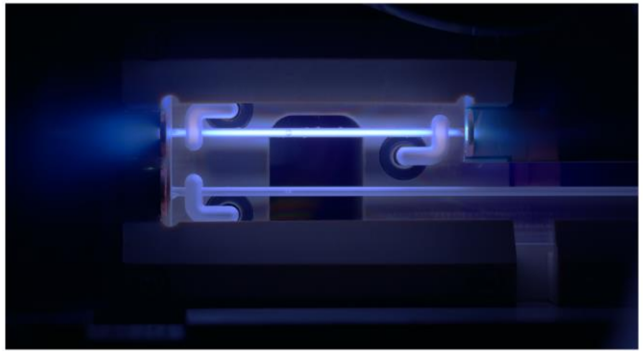
R. D'Arcy *et al.*,
Nature **603**, 58-62, 2022

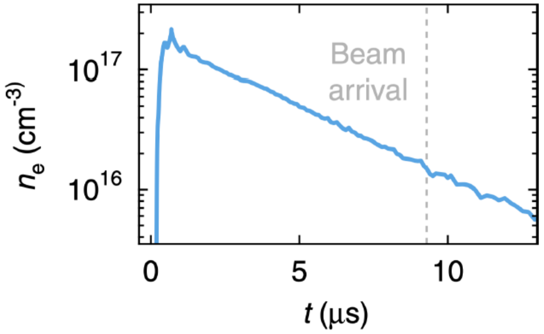
Plasma recovery in the bigger context

Next hurdles towards high average power PWFA

- Measured recovery time allows repetition rate of **O**(10 MHz)
  → **O**(1 MHz) operation mode of various machines
- Various physics issues to tackle
  - Further understanding of dependencies of recovery
  - Supply of similar plasma media at MHz
    - Source technology?
    - Containment of plasma/gas?
  - Target PWFA efficiency ~50%
    → manage/remove excess heat from plasma source







J.M. Garland *et al.*, Rev. Sci. Instrum. **92** 013505 (2021)

FLASHForward roadmap

Path towards demonstration of a ready-to-use PWFA stage

- Aiming at ΔE= 1 GeV, 10 kW average power PWFA stage
- Plasma discharge sources development lab now operational at DESY

Poster WEPOPT021
J. Garland
Wednesday 16:20-18:20

2018
Plasma dechirper
- D'Arcy *et al.*, **PRL** 122, 034801 (2019)

2019
Energy depletion and energy doubling

Wakefield sampling
- Schröder *et al.*, **Nat. Commun. 11 5984** (2020)

Energy spread preservation by beam loading control
- Lindstrøm *et al.*, **PRL** 126, **014801** (2021)

2022
Recovery Time
- D'Arcy *et al.*, **Nature** 603, 58-62 (2022)

Emittance preservation

High overall efficiency & gain for sustainable operation

2024
kHz-to-MHz operation

2026
FEL gain studies

10 kW stage with 40% efficiency & witness property conservation

→ FLASH: increase FEL energies, access oxygen K-edge at 2.33 nm wavelength

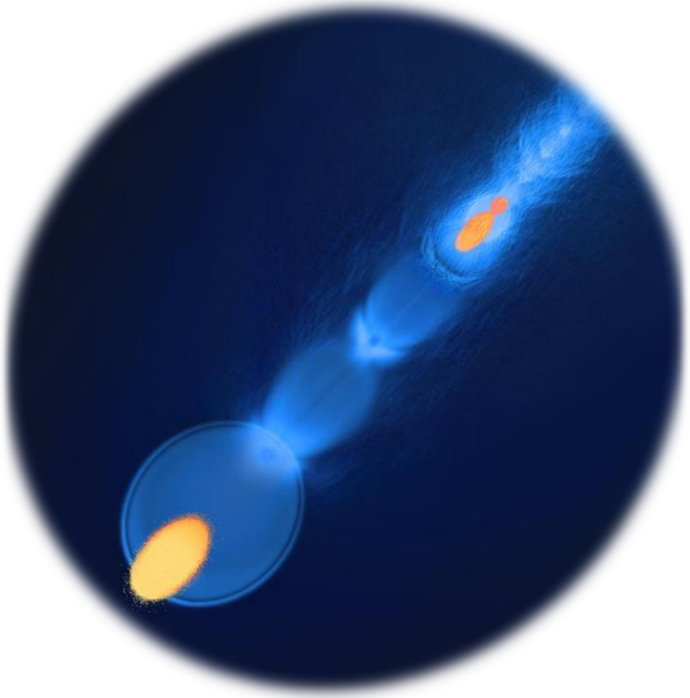
2030

complete
planned

Summary & Outlook

Status and prospects

- First **measurement of fundamental repetition rate limit** in a PWFA
  → Repetition rates of ***O***(10 MHz) in principle possible
- FLASH provides ideal conditions for these studies
- **Further studies** on repetition rate limiting effects commencing
  - **Parameter dependencies** of ion motion limits
  - Bunch **train stability**
  - **Plasma sources**
  - Beam induced **effects on longer time scales**



➔ **FLASHForward now in full motion towards high-average-power PWFA!**

Summary & Outlook

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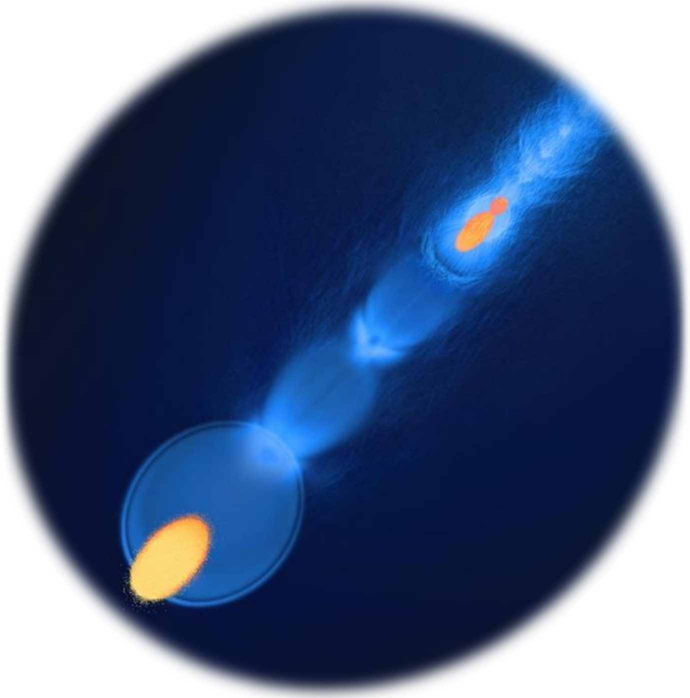

→ **FLASHForward now in full motion towards high-average-power PWFA!**

Thank you for your attention!

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Contact

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Machine Injection Group MIN
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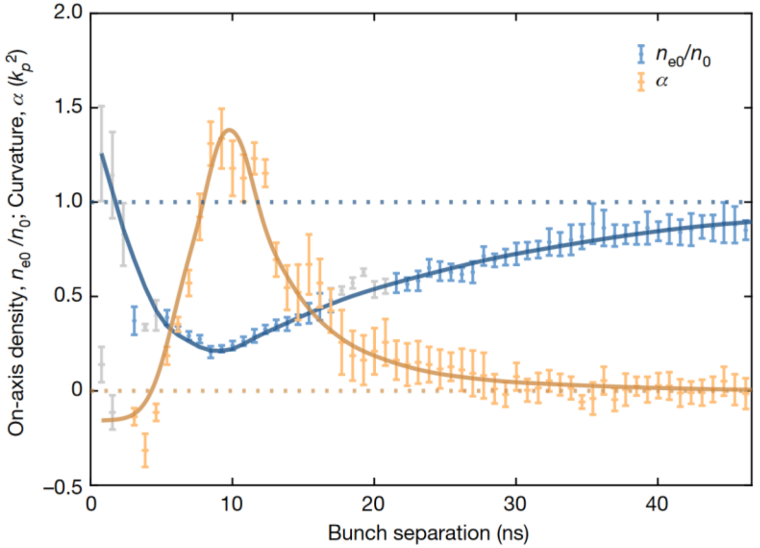
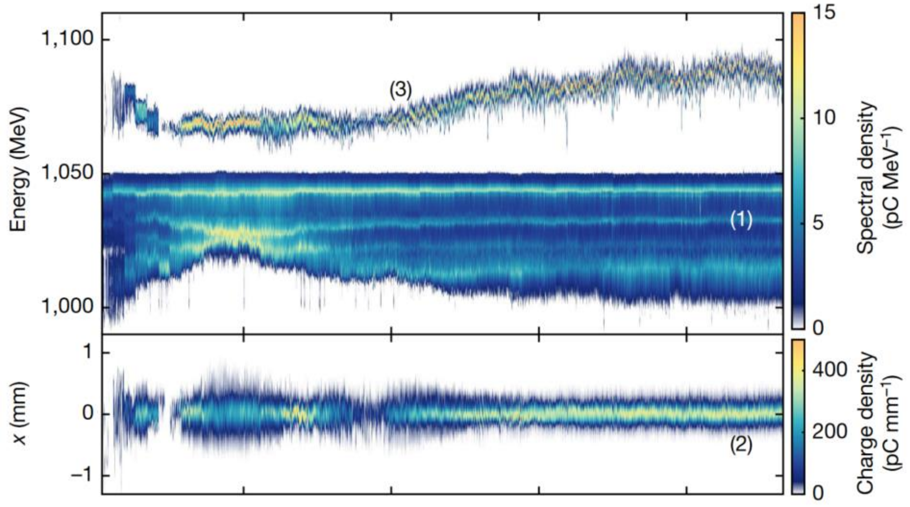
Tel. +49 8998 - 4961

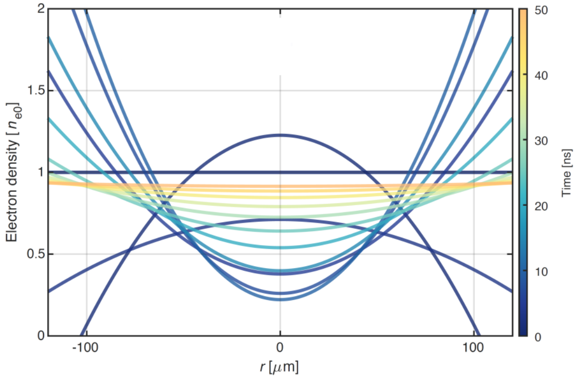
Modeling of plasma recovery

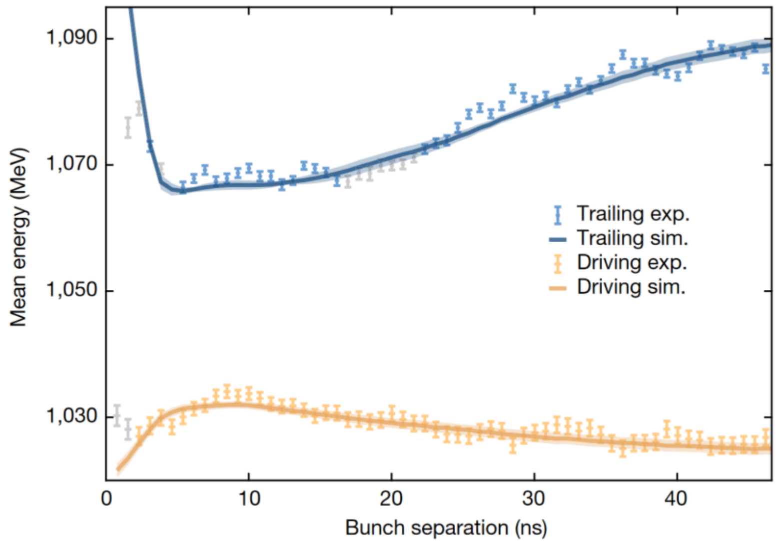
Understanding the measured beam evolution

- Deduce transverse plasma properties from
  - Focal lines of beam (→ transverse density curvature)
  - Probe witness beam energy gain (→ on-axis density)
- Very good agreement w/ simulations
- On-axis density spike evolving into “hollow” channel









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