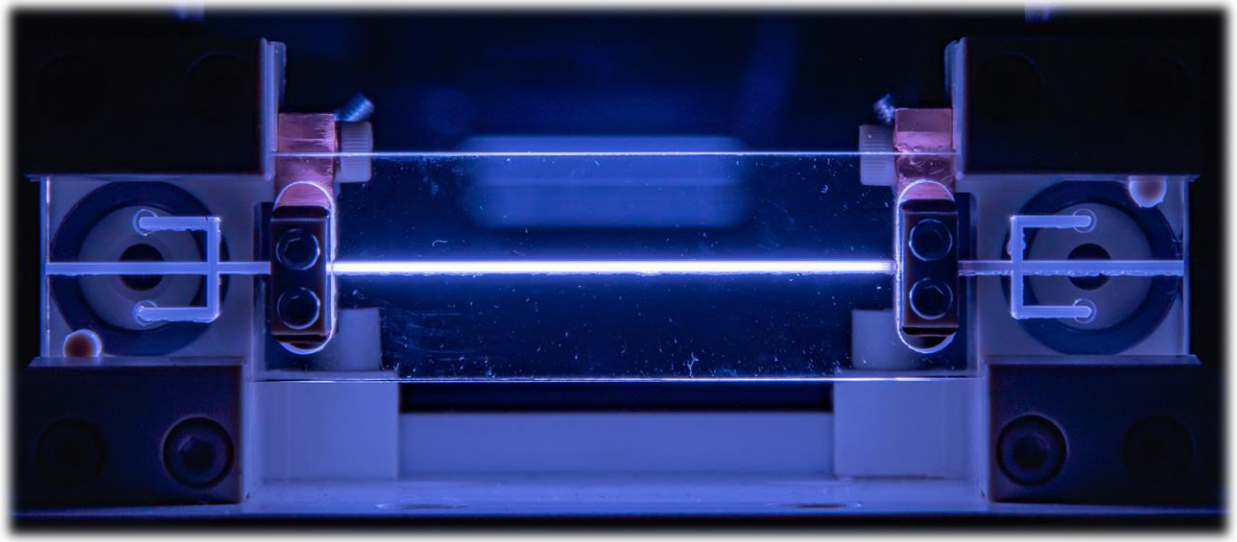
Beam-driven plasma wakefield acceleration at MHz repetition rates

Demonstrating competitive repetition rate PWFA at FLASHForward



G. Loisch, *S. Ackermann, J. Beinortaite, J. Björklund Svensson, G. Boyle, L. Boulton, M. Dinter, B. Foster, P. Gonzalez Caminal, M. J. Garland, H. Jones, J. Kahl, A. Kanekar, C. Lindstrøm, K. Ludwig, A. Martinez de la Ossa, F. Obier, F. Peña, T. Parikh, S. Pfeiffer, A. Rahali, A. Schleiermacher, S. Schreiber, S. Schröder, S. Wesch, M. Wing, J. Osterhoff, R. D'Arcy*

6th European Advanced Accelerator Concepts Workshop
La Biodola, Elba, 22.09.2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

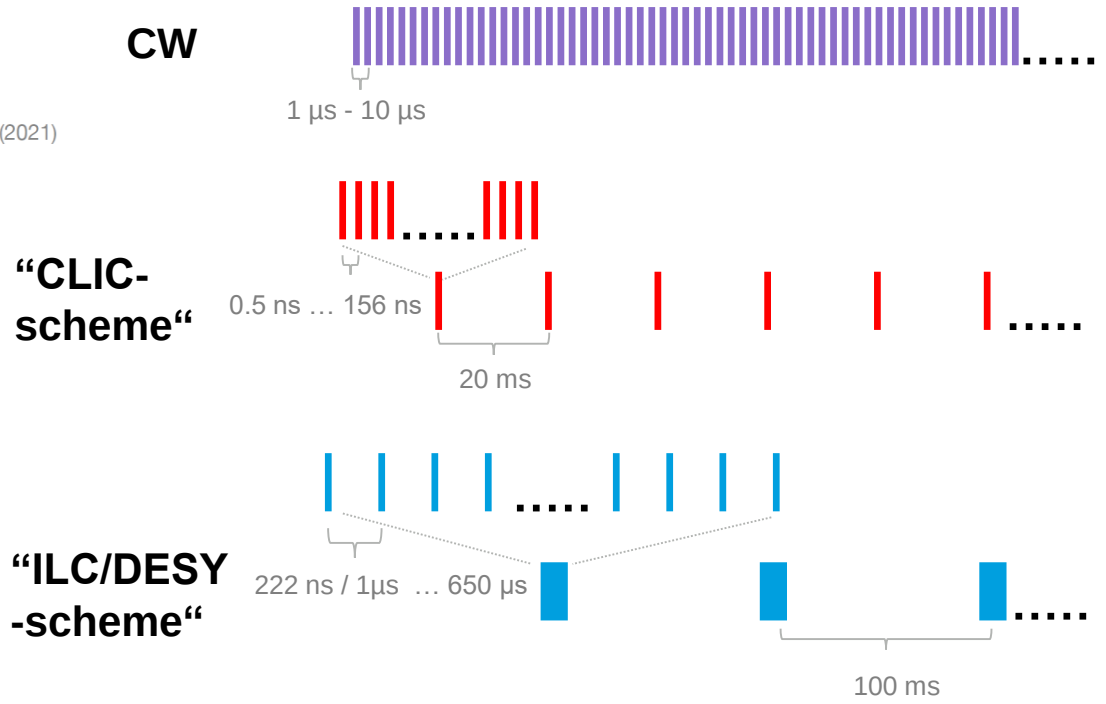
DESY.

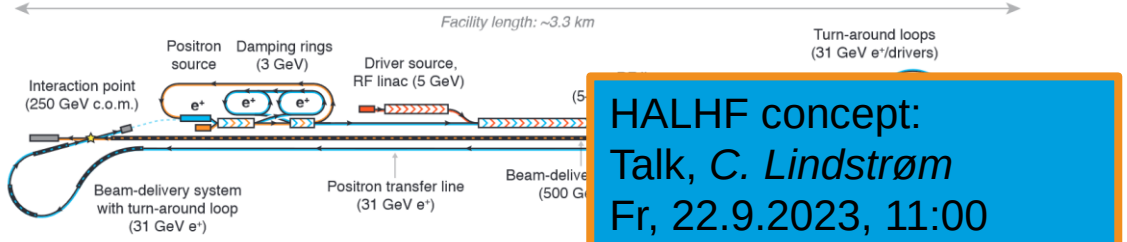
Repetition rates of plasma wakefield accelerators

… can plasma accelerators compete with conventional machines?

- Significant advance in plasma accelerator performance thus far
  - Gradients ≤ 52 GV/m demonstrated — I. Blumenfeld *et al.*, Nature **445**, 741 (2007)
  - Energy spread preservation demonstrated — C. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)
  - High energy transfer efficiency demonstrated — M. Litos *et al.*, Nature **515**, 92 (2014)
  - Emittance preservation demonstrated — C. Lindstrøm *et al.*, subm.
  - Ion motion recovery time measured — R. D'Arcy *et al.*, Nature **603**, 58-62 (2022)
- Applications (FELs, colliders, etc.) require high repetition rate
- So far PWFA using single bunch to ~10Hz
  (few experiments w/ 2-3 but dissimilar bunches)
- Different high repetition rate modes
  - CW (LCLS II, EuXFEL-cw)
  - Burst / bunch trains (CLIC, FLASH, EuXFEL, ILC, Argonne ATF)

→ **PWFA capabilities unknown**





HALHF concept:
Talk, *C. Lindstrøm*
Fr, 22.9.2023, 11:00

B. Foster *et al.* (2023), acc. at New J. Phys.

Repetition rates of plasma wakefield accelerators

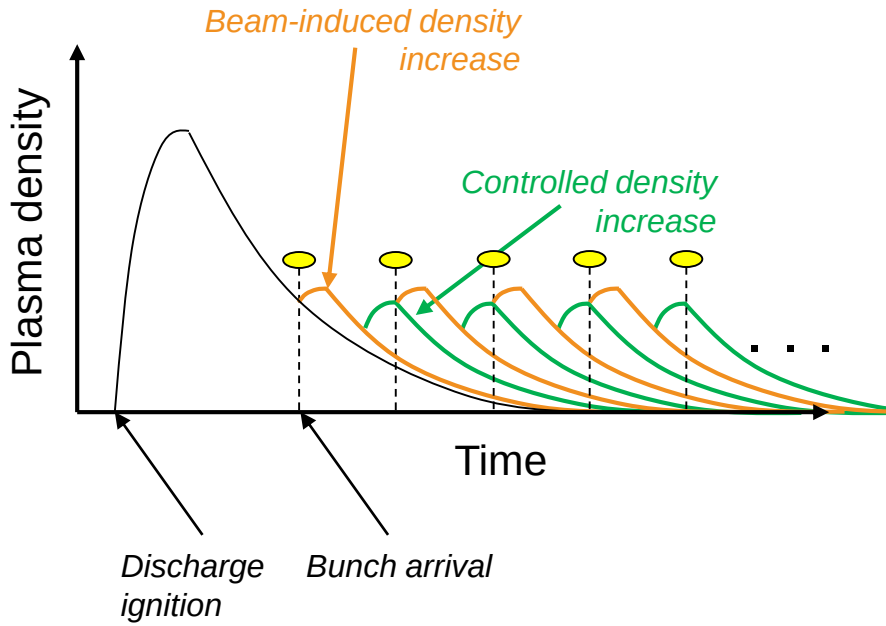
… can plasma accelerators compete with conventional machines?

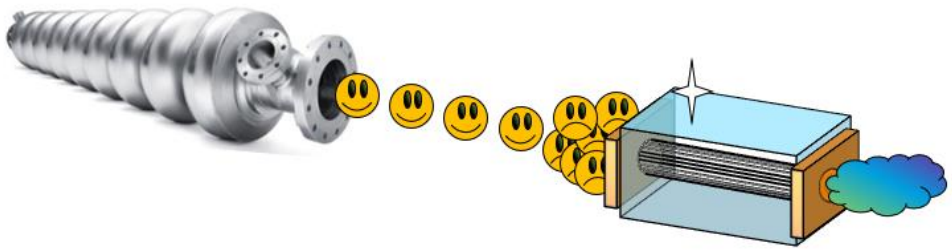
- What prevents PWFA from high rep. rates?
  - Drive linac → FLASH 1st PWFA drive linac capable of MHz bunch trains
    - Currently only ~10W beam power in FLASHForward beamline (radiation safety)
    - Bunches not identical along train: good enough for FEL, very obvious in PWFA

    → ongoing work

  - Beam impact on plasma?
    - Ion motion → <100ns, i.e. non-critical @MHz R. D'Arcy *et al.*, Nature **603**, 58-62, 2022
    - Beam-induced density increase → ?

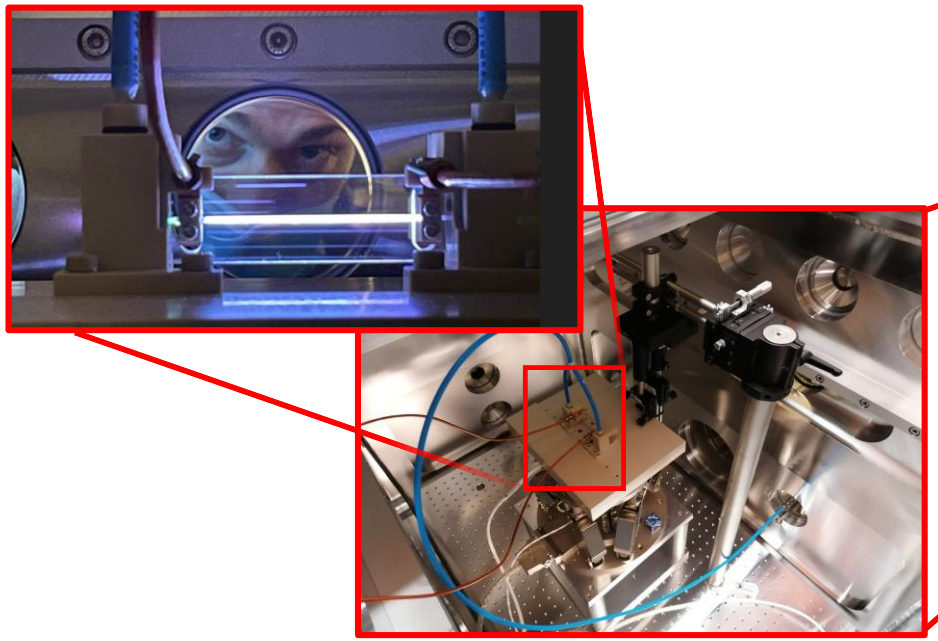
  - Plasma source → supply/replenish plasma medium @MHz !

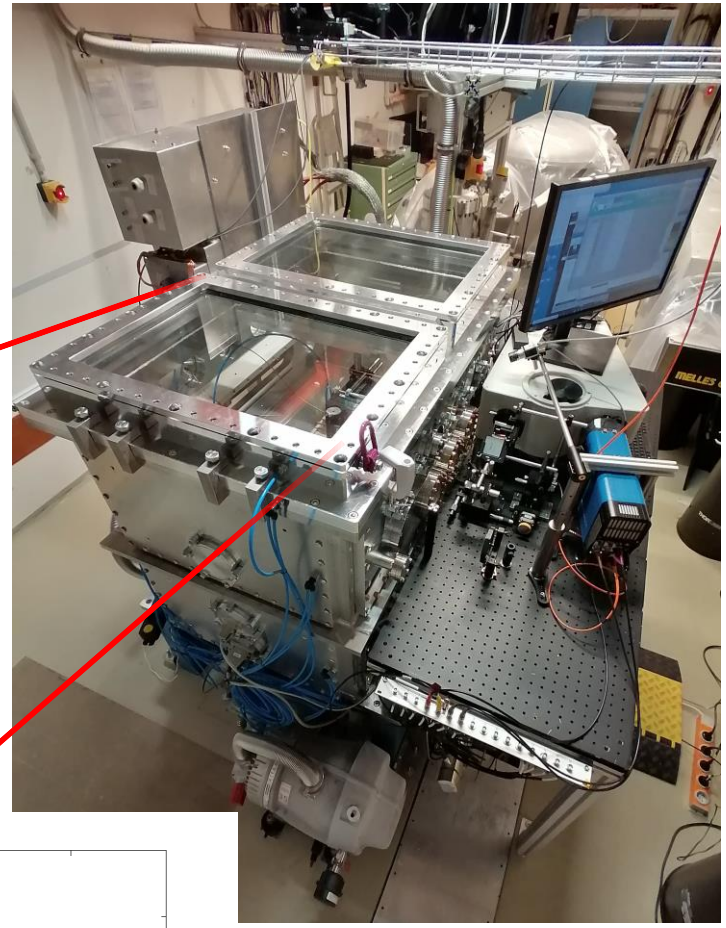




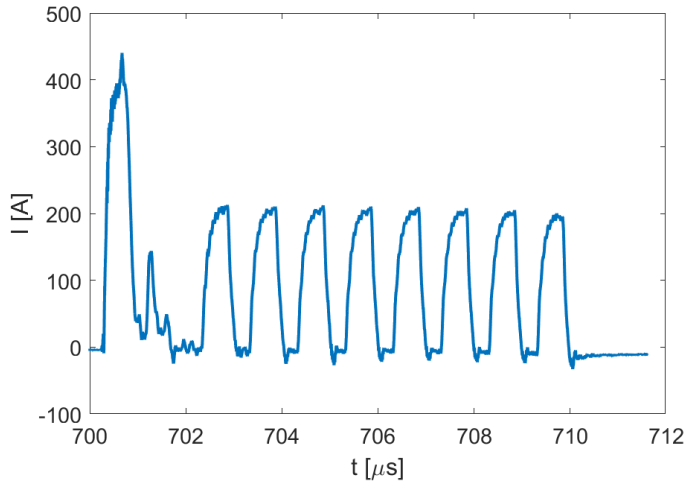
The ADVANCE laboratory

Dedicated lab for discharge plasma cell development





- Various diagnostics
  - Plasma spectroscopy
  - Interferometry
  - Fast cameras
  - High resolution ADCs
- Flexible infrastructure
  - Gas supplies (N2, He, ArH2, H2, Kr, ..)
  - Water cooling
  - High voltage pulsers (<27kV @10Hz, 12kV @~kHz, <5kV @MHz)



M. J. Garland *et al.*, Proc. IPAC2022, WEPOPT021

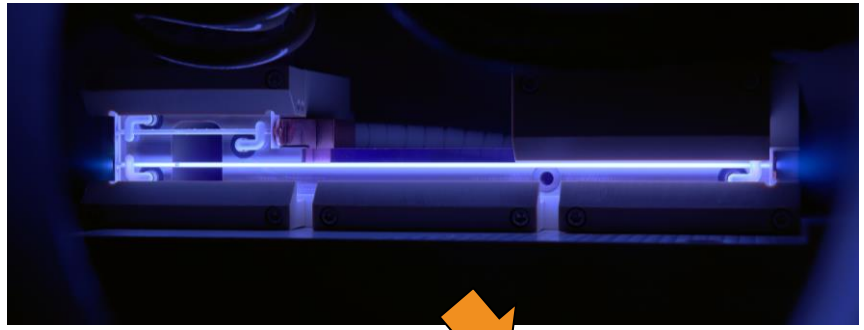
See also:
Poster, *H. Jones*
Tu, 19.9.2023

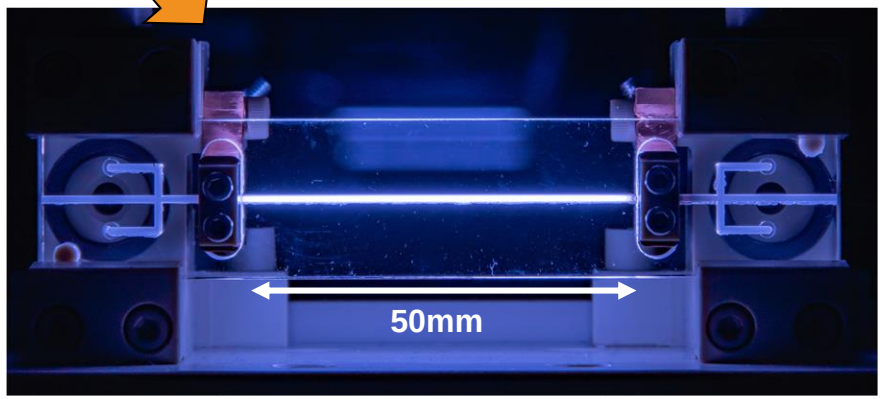
ADVANCE Lab

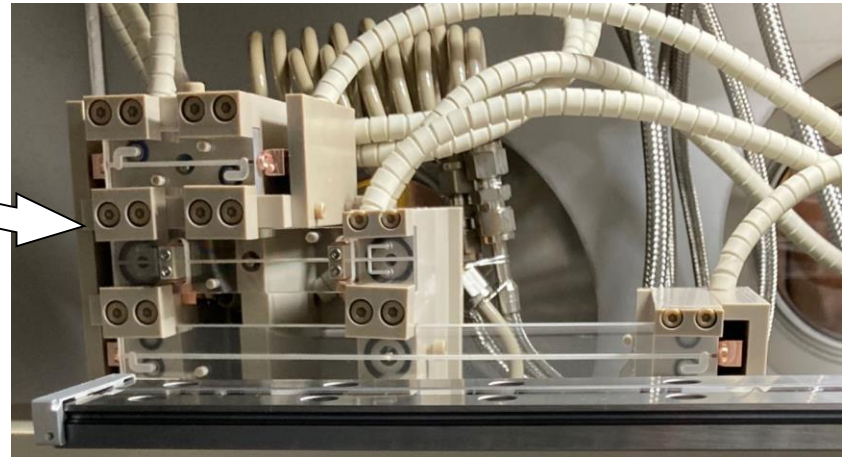
The FLASHForward MHz plasma sources

Key component for MHz acceleration

- Development of MHz plasma cells ongoing since 2020 @DESY
  - Build up of lab infrastructure for discharge cell development
  - Development of discharge HV electronics
  - Design, measurement & iteration of cell designs
- Open/window-less cells
  - No emittance degradation in beam windows
  - Continuous gas-flow
- Gas inlets moved outside electrodes
  - Create neutral gas buffer to mitigate expulsion
  - No expansion into gas inlets → homogeneous profile
  - Internal diameter (more) independent of exit diameter



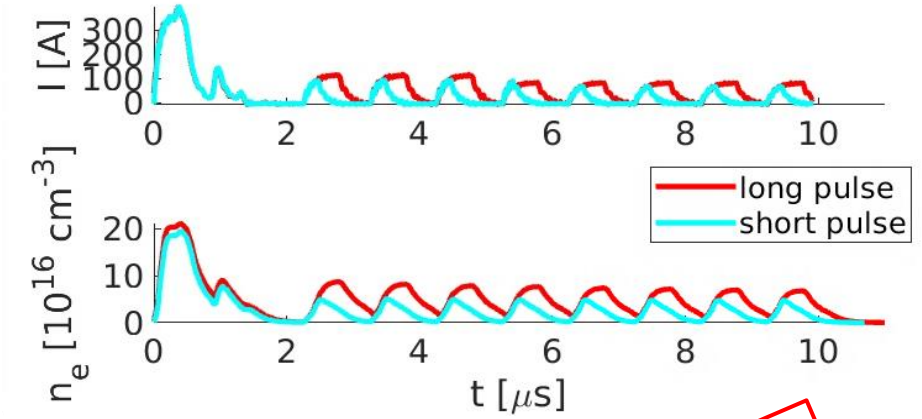


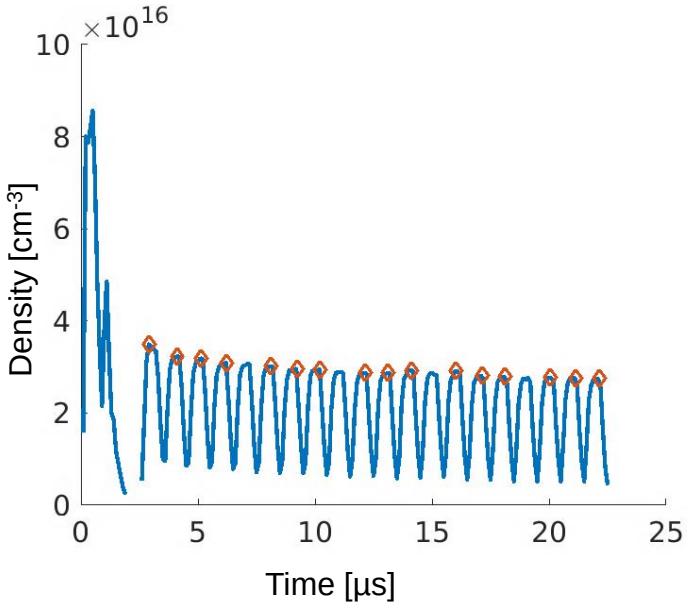


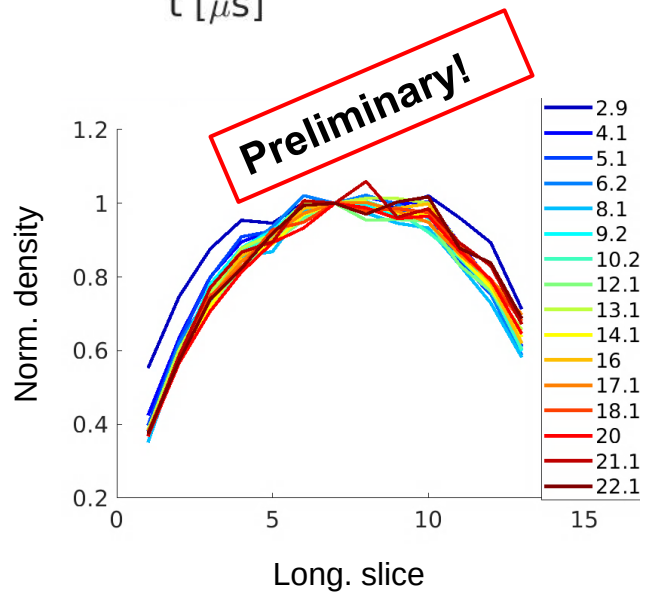
The FLASHForward MHz plasma sources

1st PWFA plasma cells operating @MHz bursts

- Plasma produced w/ ignition pulse (typ. >10kV)
- Electron density control w/ MHz “heating” pulses
  - U < 5kV
  - Variable rep. rate/timing
  - Variable pulse length
- Slow droop observed over 10’s of µs
  - Optimisation possible via current pulse shape → ongoing work
- Longitudinal profiles constant
- Various cell geometries investigated





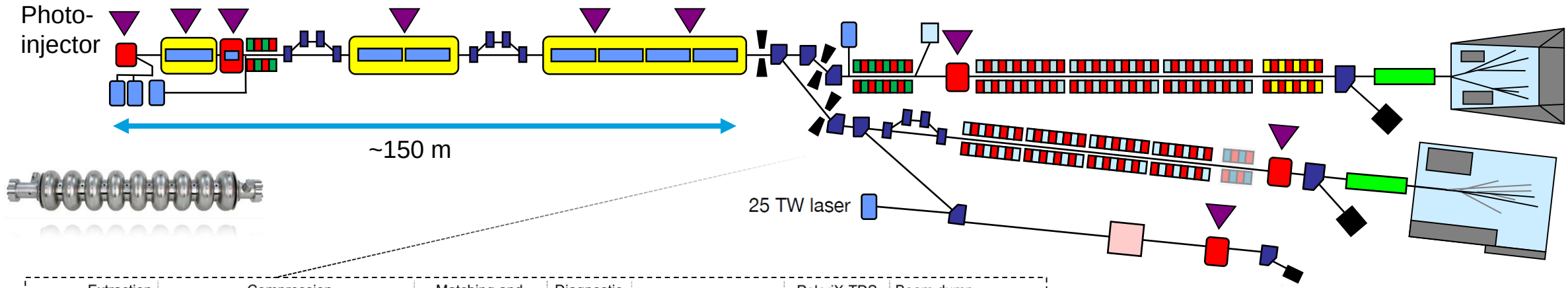


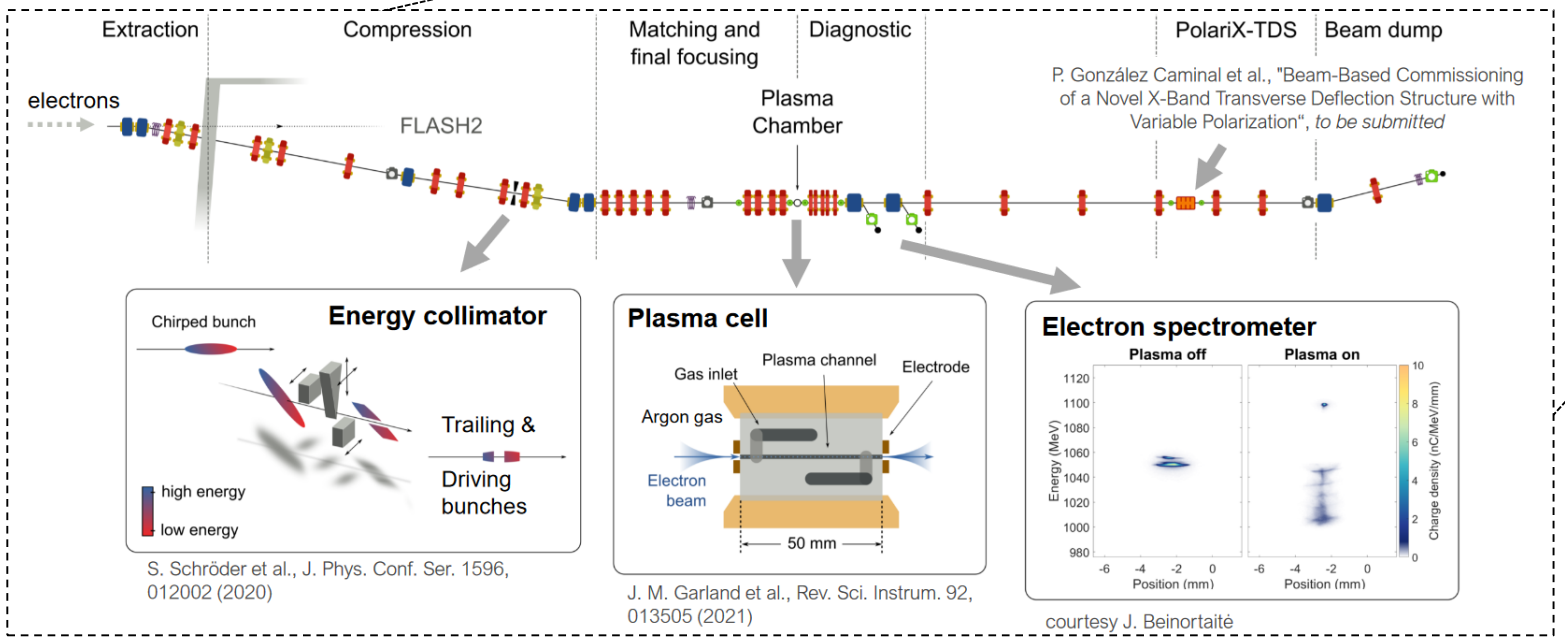
Detailed information:
Poster, *G. Loisch*
Tu, 19.9.2023

The FLASHForward facility

PWFA at the FLASH FEL drive linac

FLASHForward overview:
Talk, *F. Peña*
We, 20.9.2023, 09:00



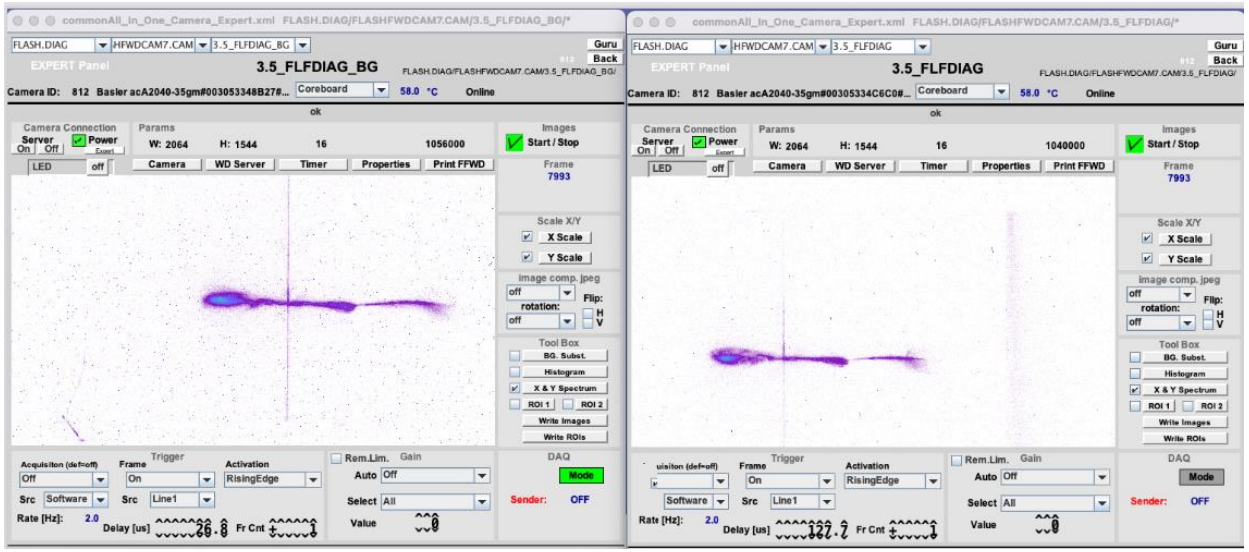


→ FLASH allows experiments @MHz (3MHz), ≤ 800 bunches

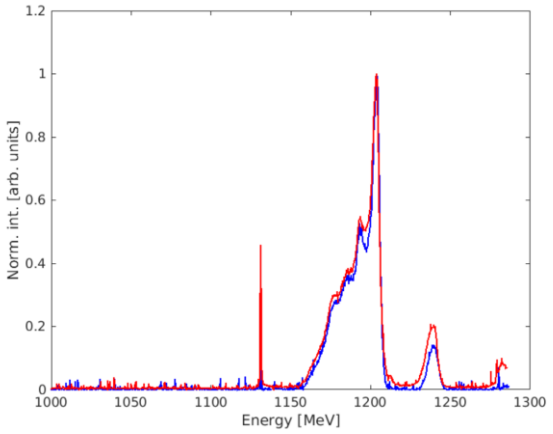
1st MHz experiments

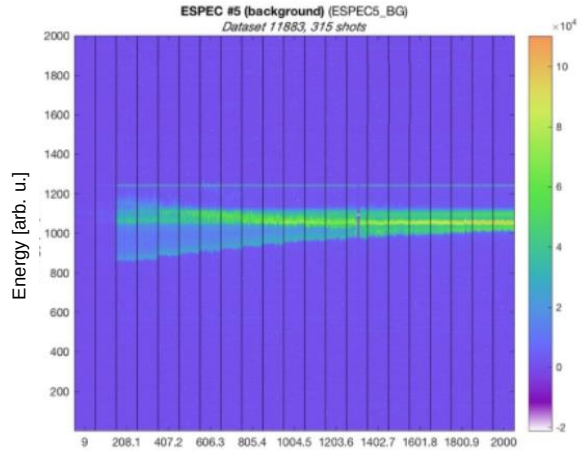
2 bunch experiments in 2021 & 2022

- Only 2 bunches / train allowed in FLASHForward beamline
- Did measurements in Argon & H2
- Did measurements in old and new design plasma cells
- Also used a 2nd discharge pulse to control plasma density for 2nd bunch
- ~similar energy spectra observed
  - → very promising
  - Only one consecutive bunch → singular meas. point → could be „coincidence“
- Also performed beam-based density evolution measurements
  - Recorded clear density increase after bunch
  - Complex beam dynamics → difficult analysis



2 bunch pairs 1µs apart





2nd bunch delay

MHz bunch train acceleration

Performing 1st bunch train measurements in a PWFA

- Measurements this August
- Trains of ≤ 12 bunches (@1 Hz)
- Various measurements performed
- Analysis ongoing

Preliminary results! Analysis ongoing

Summary & Outlook

Where are we at the repetition rate frontier?

- 1st acceleration in a plasma w/ MHz repetition rate
  - Burst of 12 bunches (currently limited by radiation safety)
  - First parameter studies started (e.g. Repetition rate → Potential bunch train length (>) =44 µs (!?), gas species, …)
  - Detailed analysis ongoing
- Many challenges opening up
  - Understanding of beam-induced perturbation (e.g. ionisation & plasma recombination)
  - Scaling to longer burst lengths, macropulse repetition rates (i.e. high average power) & higher energies
  - Reproducibility of bunches within train & plasma acceleration medium
  - Thermal effects on plasma cell

  → Iterative optimisation process…
- Significant development & resources required
- MHz PWFA is possible! → competitive accelerator performance seems feasible

Thank you for your attention!

Contact

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