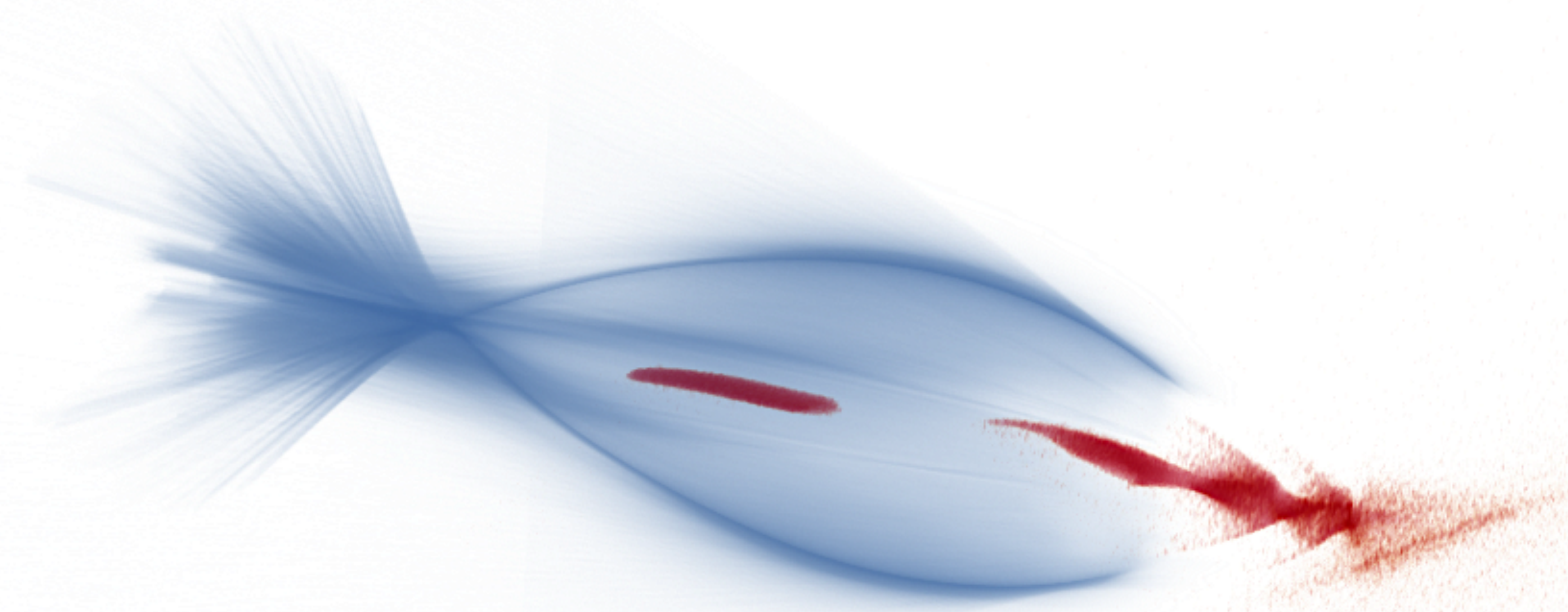


Plans at FLASHForward▸▸ relevant to ALIC

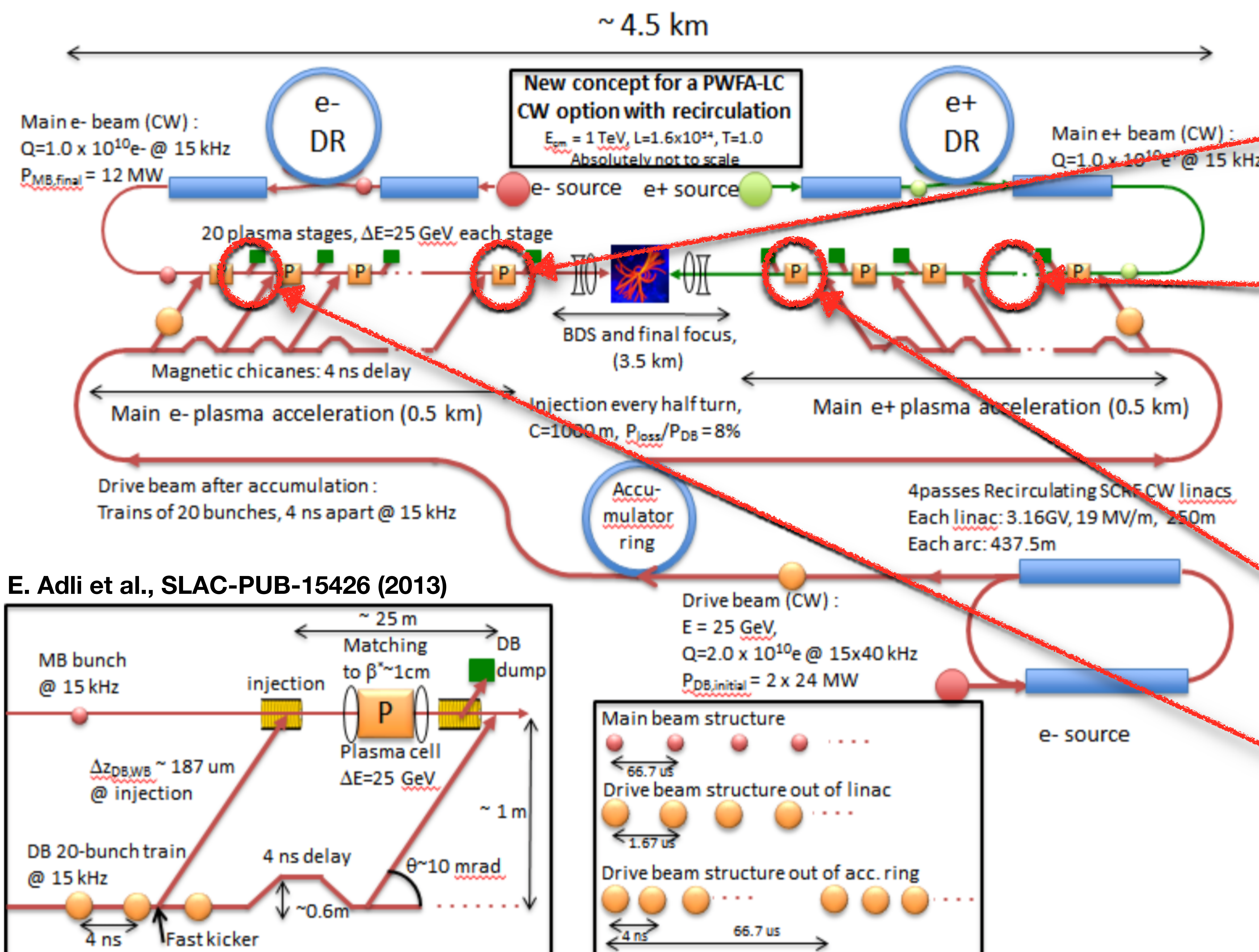
Richard D'Arcy

FLASHForward▸▸ Scientific Coordinator | Research Group for Plasma Wakefield Accelerators
Deutsches Elektronen-Synchrotron DESY, Particle Physics Division, Hamburg, Germany

Accelerator Research and Development, Matter and Technologies
Helmholtz Association of German Research Centres, Berlin, Germany

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

The ultimate application:
straw-man design of a TeV-class PWFA linear collider



E. Adli et al., SLAC-PUB-15426 (2013)

PWFA specific challenges & R&D

> **Single acceleration module**
support consistent high beam quality,
efficient energy transfer to witness

> **Coupling of plasma stages (staging)**
beam extraction and injection
with beam-quality preservation

> **High-average power operation**
plasma heat management,
drive-beam removal

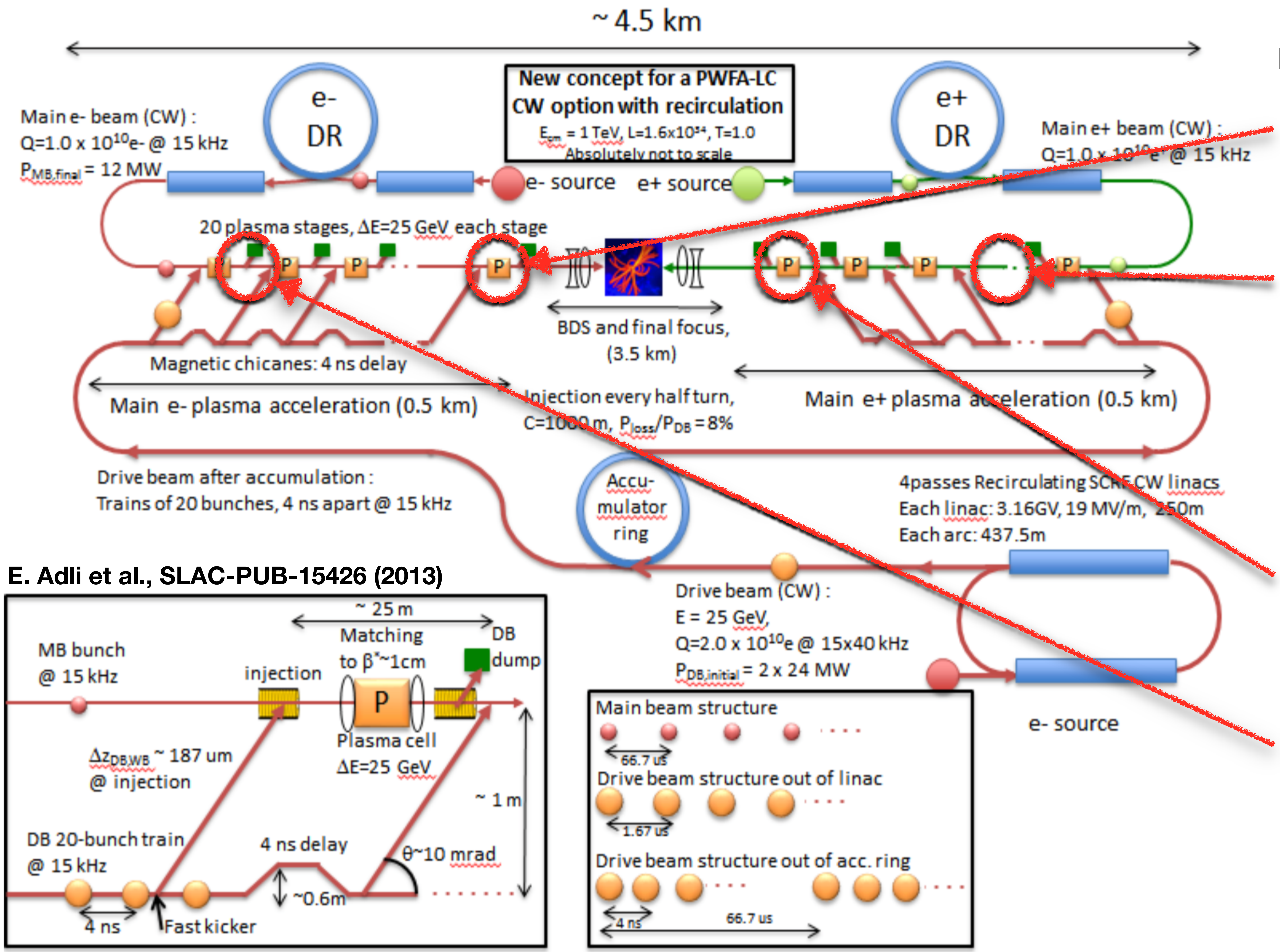
> **Positron acceleration**

> **Full characterisation of the beam**

> **Symmetric plasma optics**
coupling length minimisation,
positron capturing,
adiabatic focussing

> **Acceleration of polarised beams**

The ultimate application: straw-man design of a TeV-class PWFA linear collider



E. Adli et al., SLAC-PUB-15426 (2013)

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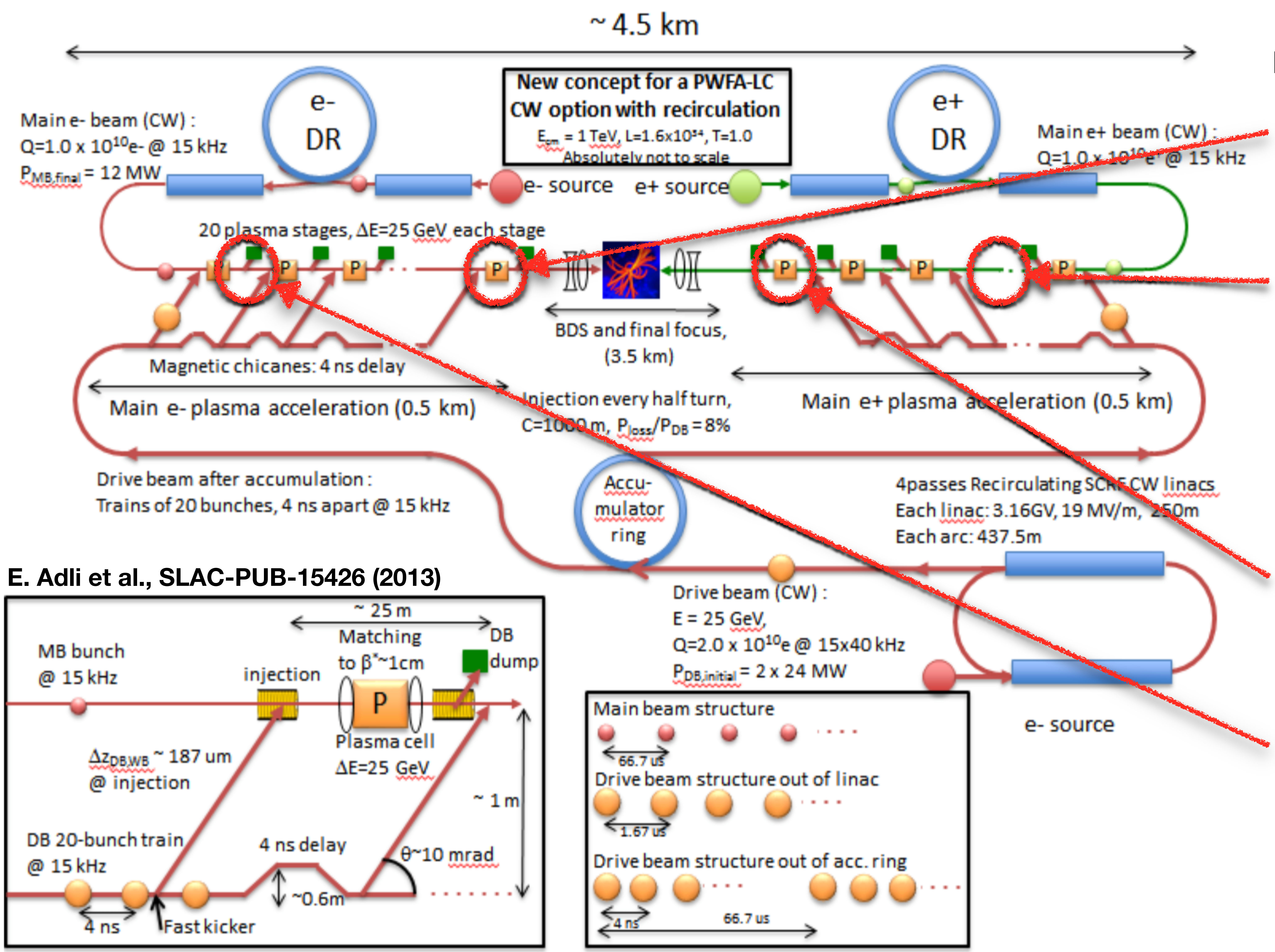
The ultimate application: straw-man design of a TeV-class PWFA linear collider

See Mark Hogan's talk later today for FACET-II



E. Adli et al., SLAC-PUB-15426 (2013)

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- **Acceleration of polarised beams**

Contributors

> **Core team**

Engineers, IT support, and technicians

Maik Dinter
Sven Karstensen
Kai Ludwig
Frank Marutzky
Amir Rahali
Andrej Schleiermacher
Sandra Thiele

Postdocs

Gregory Boyle
Theresa Brümmer
Jimmy Garland
Alexander Knetsch
Peng Kuang
Carl Lindstrøm
Zeng Ming
Pardis Niknejadi
Kristjan Põder
Lucas Schaper
Christopher Schlesiger

Scientists

Richard D'Arcy
Jens Osterhoff
Bernhard Schmidt
Stephan Wesch

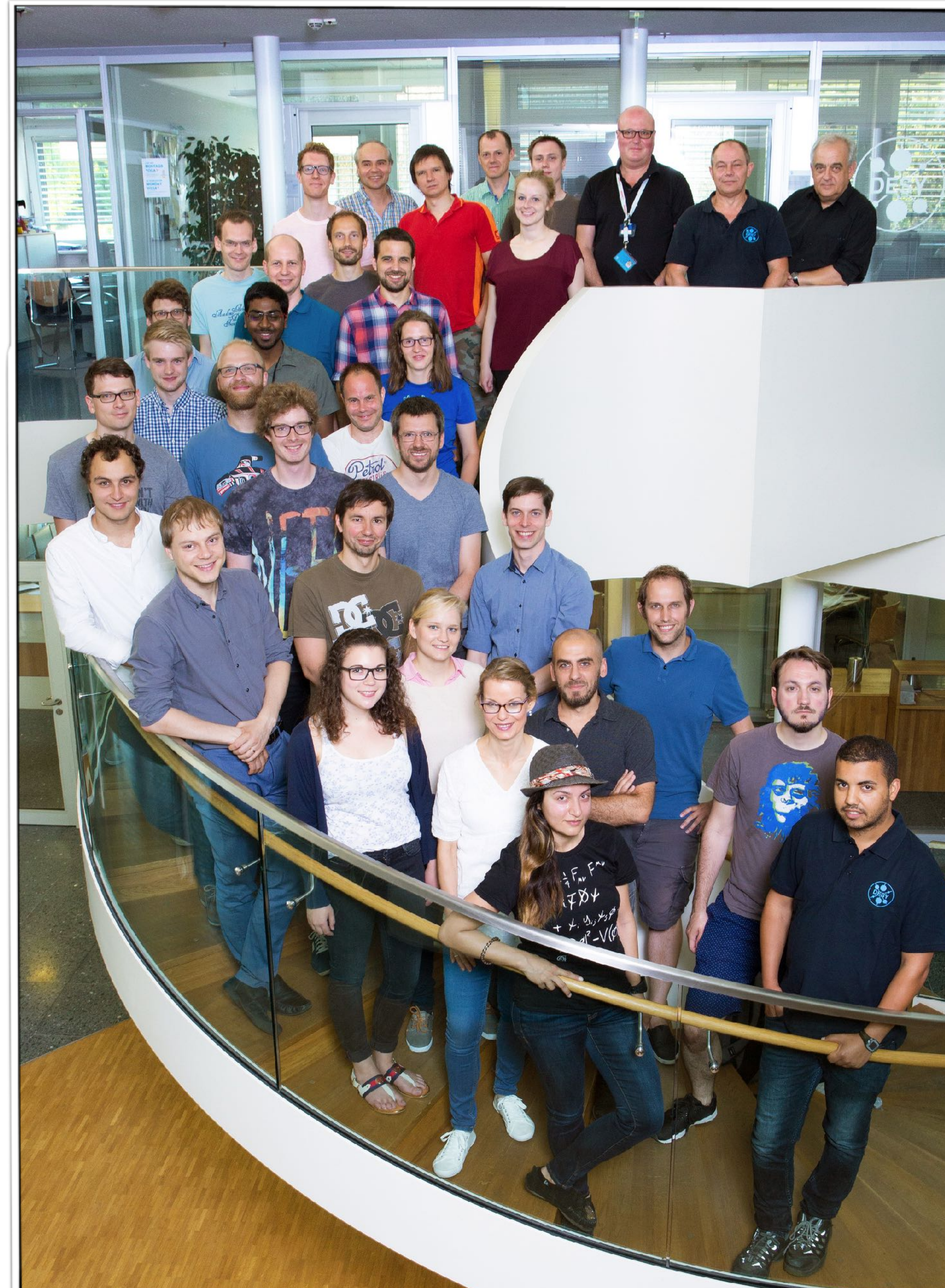
PhD students

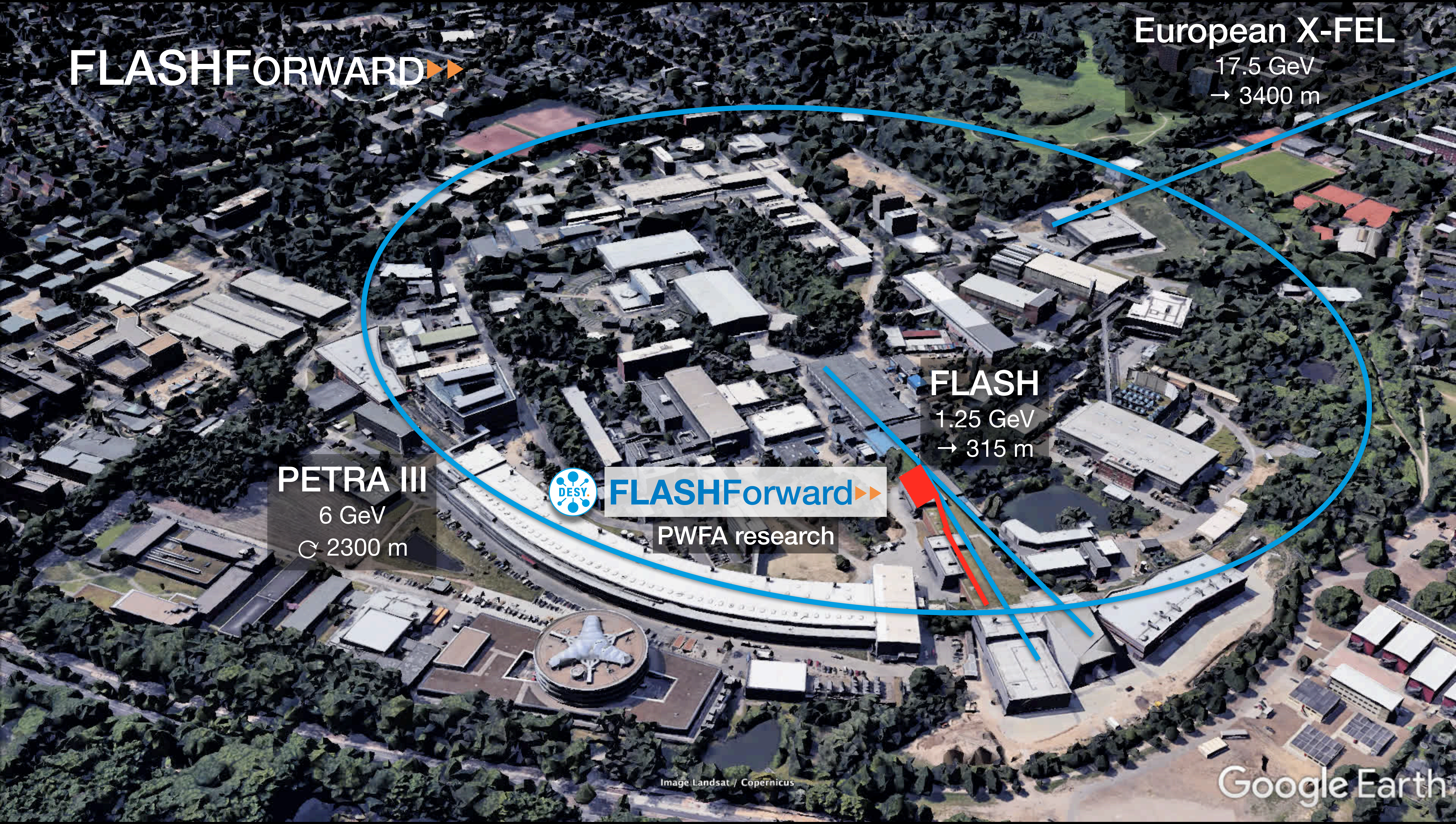
Alexander Aschikhin
Simon Bohlen
James Chappell
Pau Gonzalez
Martin Meisel
Sarah Schröder
Bridget Sheeran
Gabriele Tauscher

Students

Severin Diederichs
Artemis Kontogoula
Jonathan Targaczewski

> **...many DESY engineering & technical support groups**

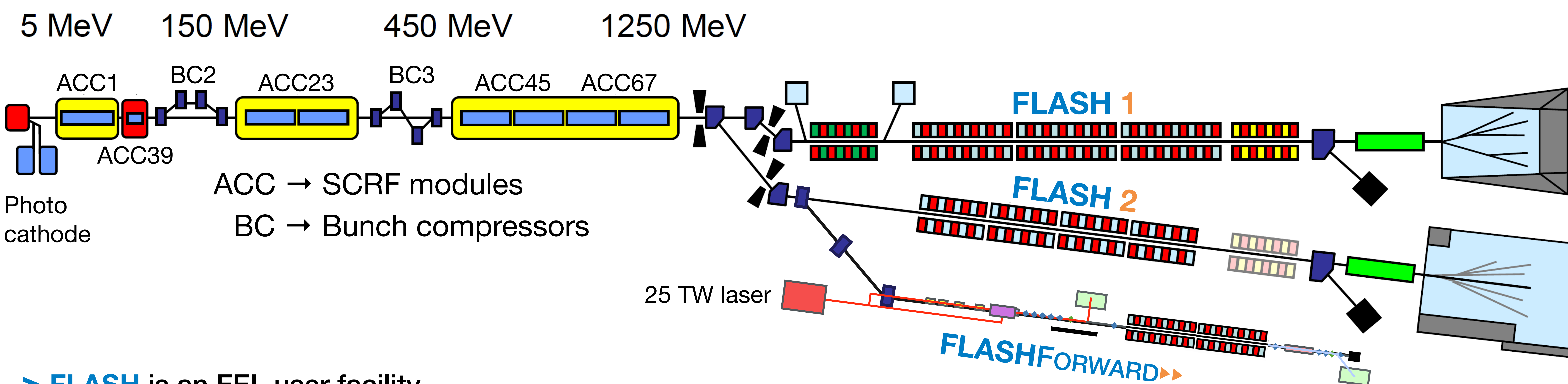




FLASHFORWARD
European X-FEL
17.5 GeV
→ 3400 m
FLASH
1.25 GeV
→ 315 m
PETRA III
6 GeV
2300 m
FLASHForward
PWFA research
Image Landsat / Copernicus
Google Earth

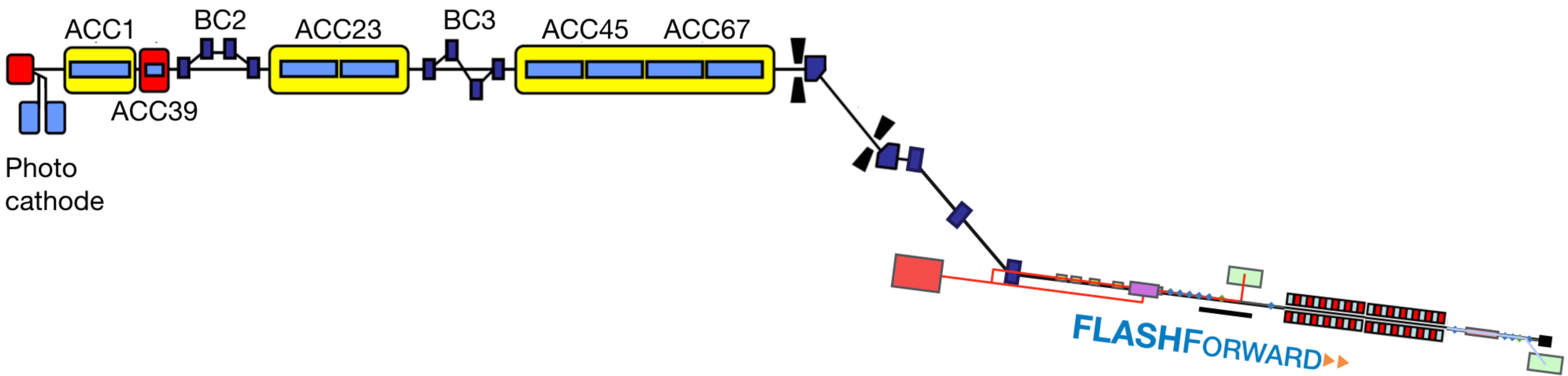
FLASHForward▸▸

The facility for high-quality, high-precision, high-average-power beam-driven PWFA science



- **FLASH is an FEL user facility**
  - 10% of beam time (750 h / year) dedicated to accelerator research
- **FLASHForward▸▸ is a beam line for PWFA research**
- **Both share the same superconducting accelerator based on ILC/XFEL technology. Typical electron beam parameters:**
  - ≲ 1.25 GeV energy with a few 100 pC at ~100 fs rms bunch duration
  - ~2 μm trans. norm. emittance
  - Exquisite stability, timing, and reproducibility through FEL-standard feedback systems

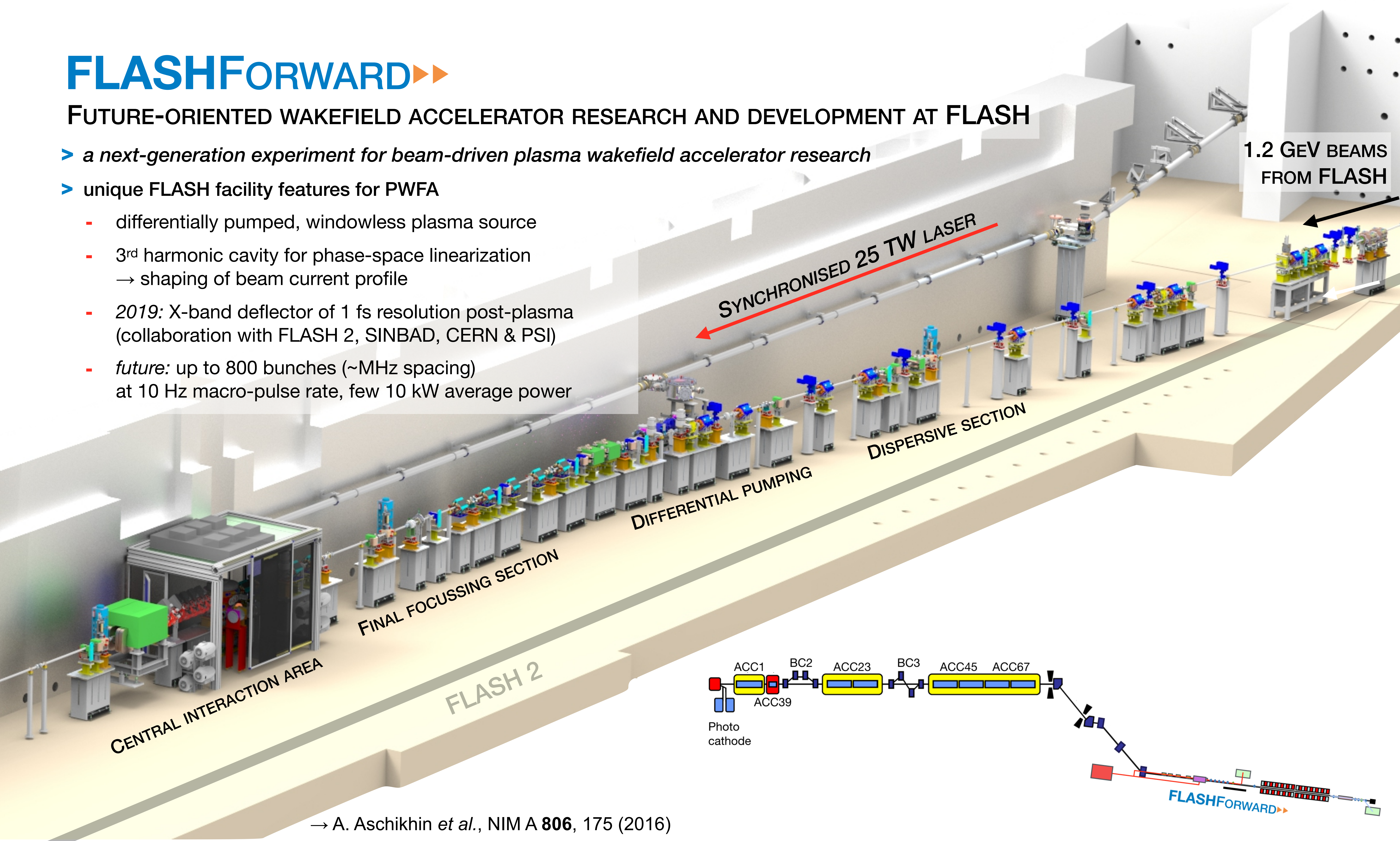
FLASHFORWARD



FLASHFORWARD▸▸

FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

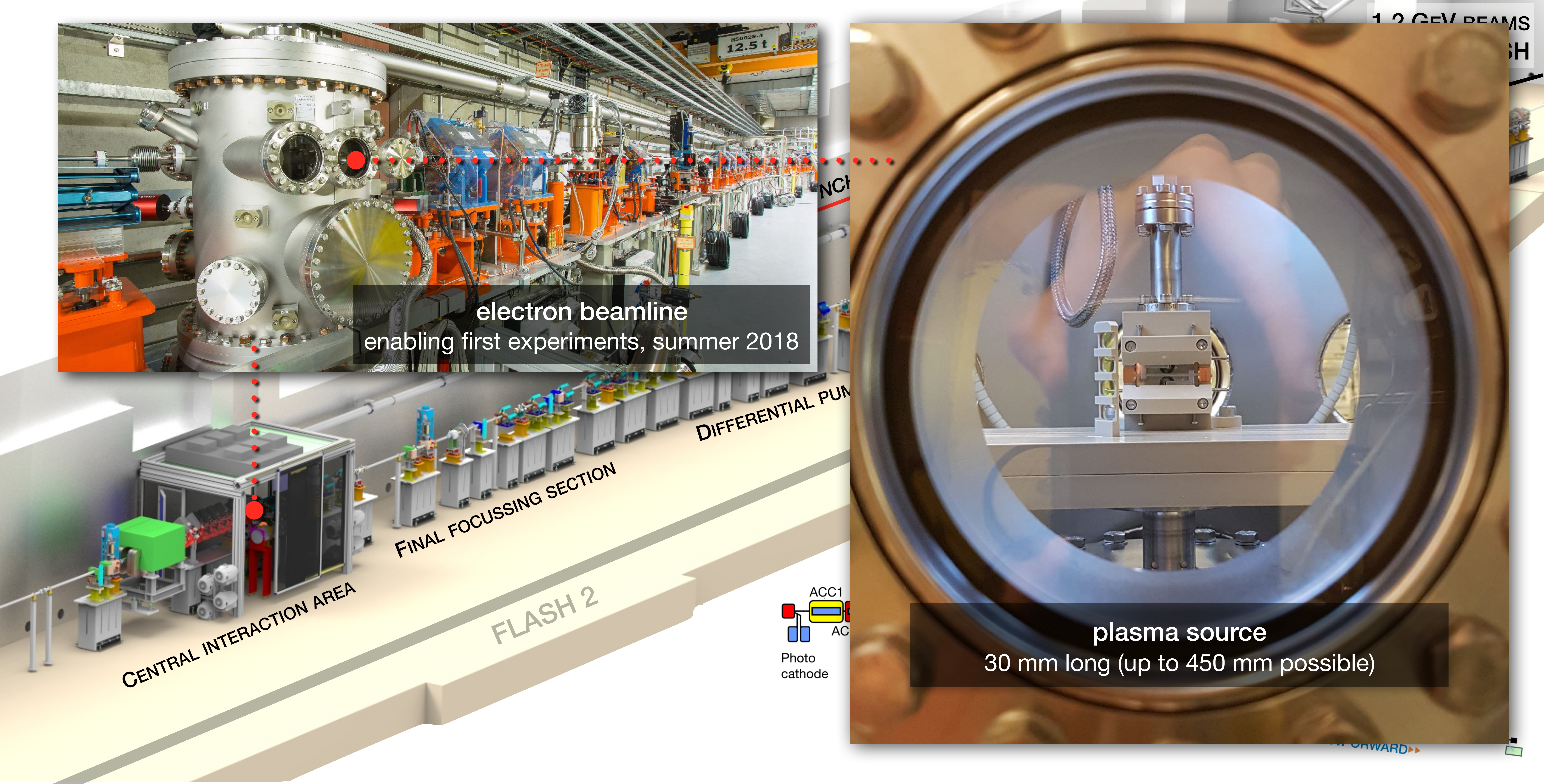
- *a next-generation experiment for beam-driven plasma wakefield accelerator research*
- unique FLASH facility features for PWFA
  - differentially pumped, windowless plasma source
  - 3rd harmonic cavity for phase-space linearization → shaping of beam current profile
  - *2019:* X-band deflector of 1 fs resolution post-plasma (collaboration with FLASH 2, SINBAD, CERN & PSI)
  - *future:* up to 800 bunches (~MHz spacing) at 10 Hz macro-pulse rate, few 10 kW average power



→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)

FLASHForward▸▸

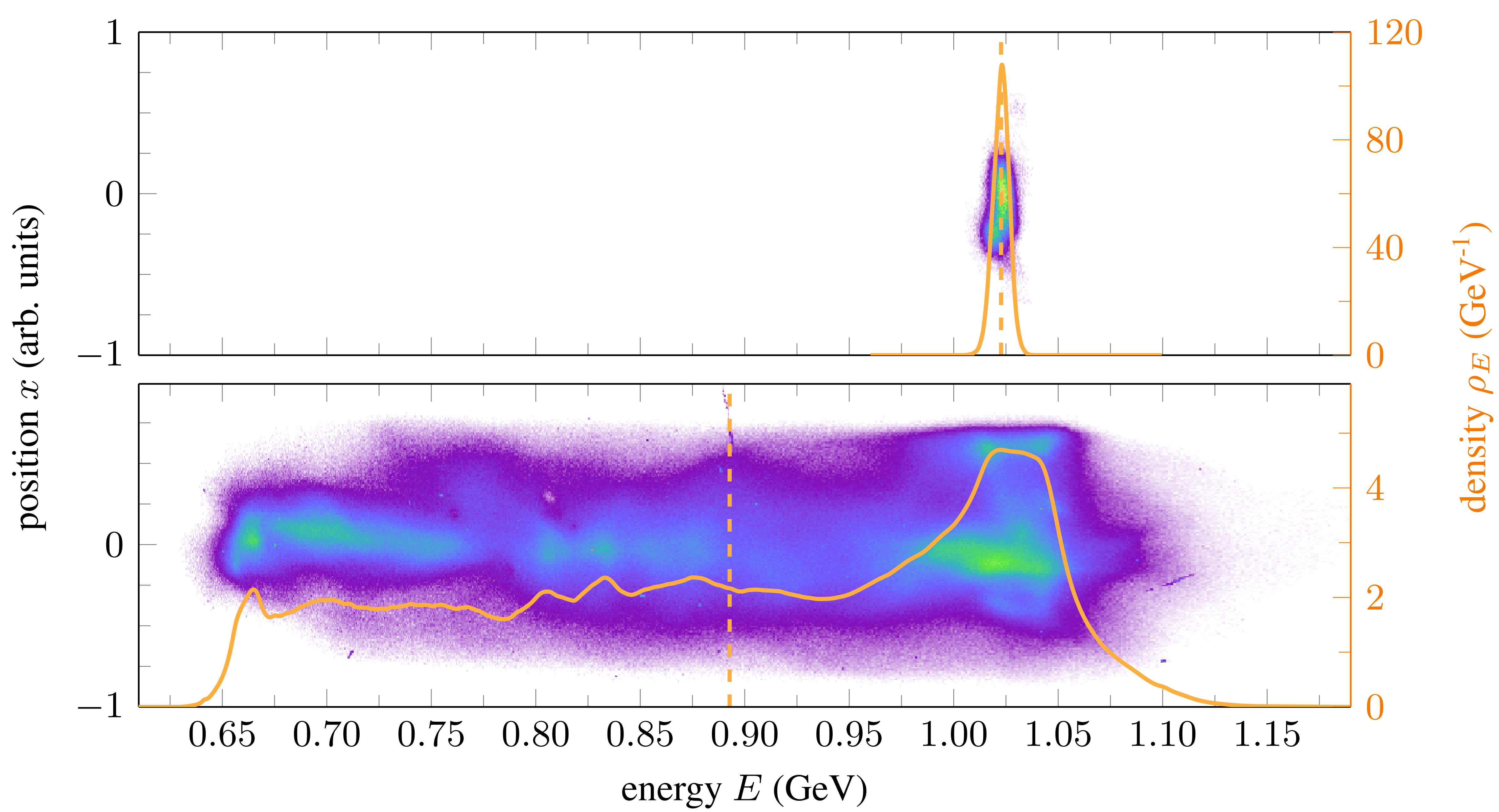
Future-oriented wakefield accelerator research and development at FLASH



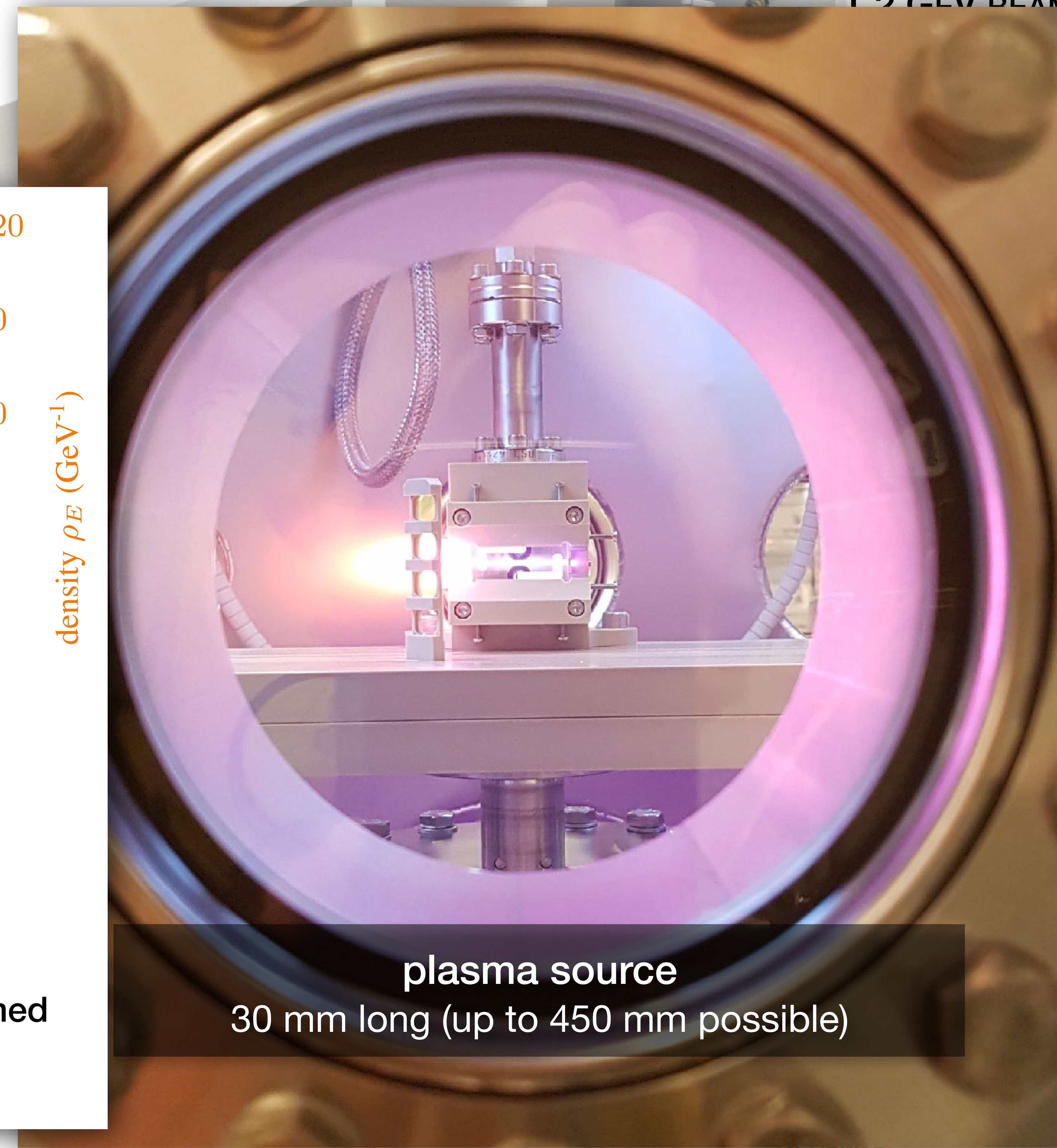
FLASHFORWARD▸▸

FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

- first PWFA beam-plasma interaction on June 19th, 2018
- commissioning successful and finished June 30th, 2018
- installation ready for first experiments since July 15th, 2018

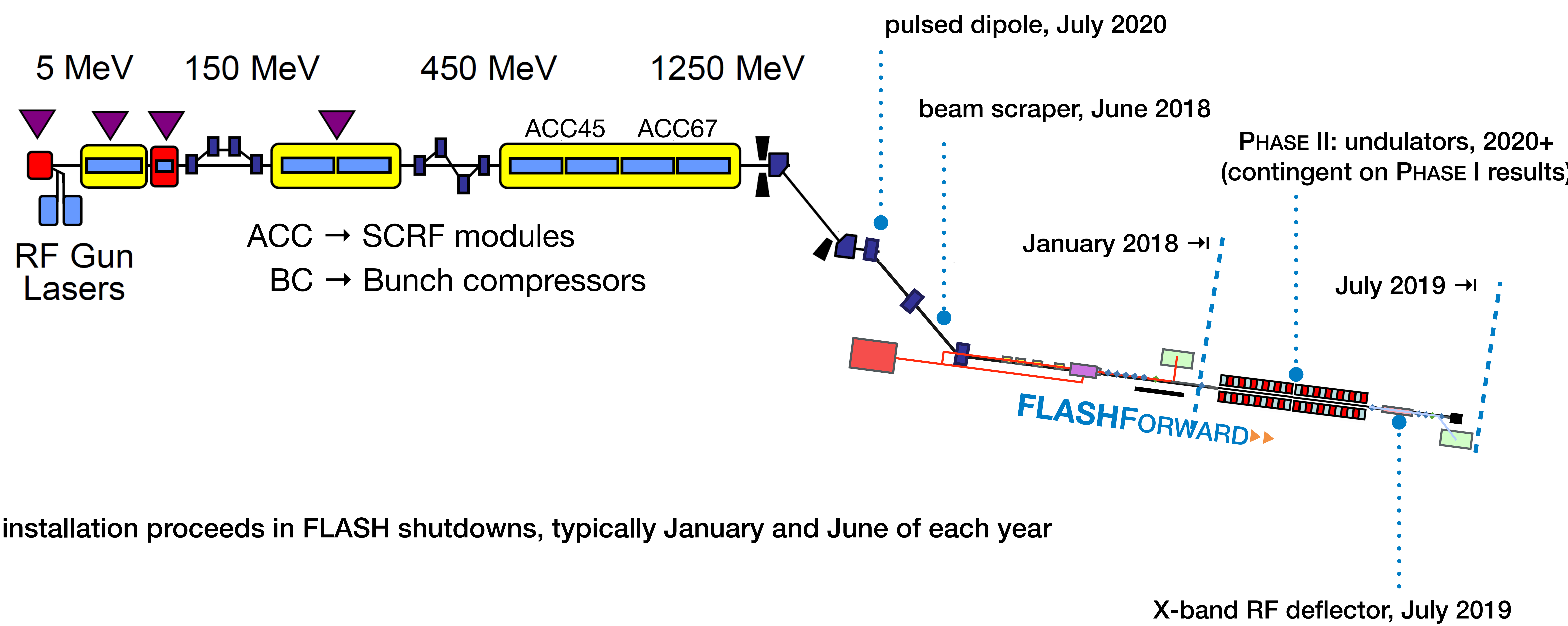


- (12.3 ± 1.7) GV/m wakefield generated in 30 mm plasma cell
  → plasma cell scale length ~100 mm for GeV energy gain confirmed
- 12.7% total energy loss to plasma wakefield



FLASHFORWARD▸▸ follows a staggered installation plan

PROJECT PHASE I: PLASMA WAKEFIELD BEAMLINE AND DIAGNOSTICS — PHASE II: UNDULATOR INTEGRATION

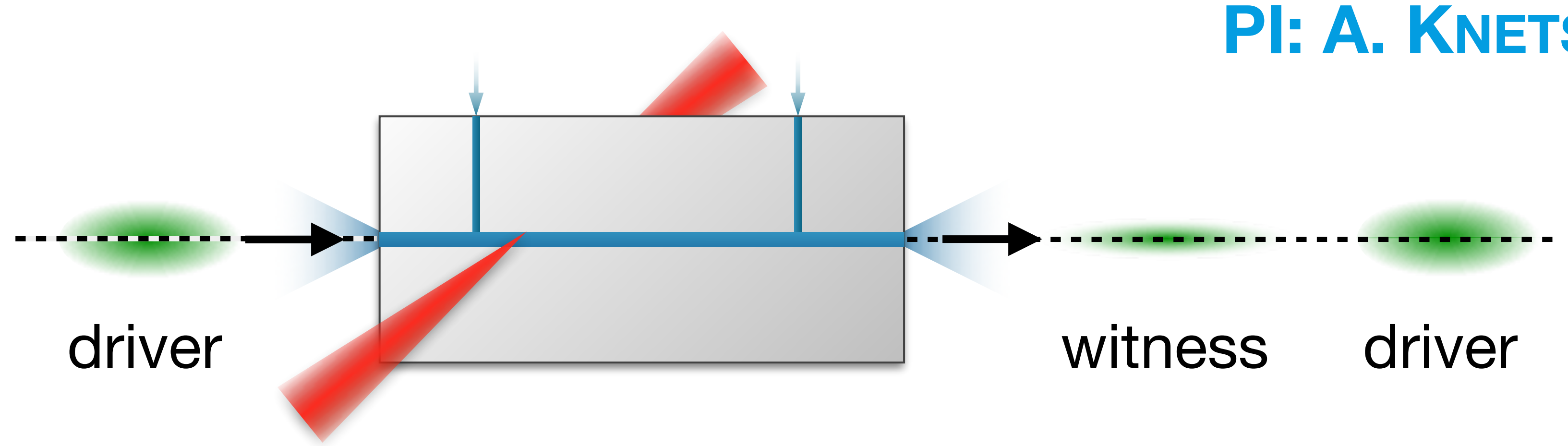


> installation proceeds in FLASH shutdowns, typically January and June of each year

FLASHFORWARD▸▸ collider-related scientific packages

CORE STUDY I — X-1: PLASMA CATHODE

PI: A. KNETSCH



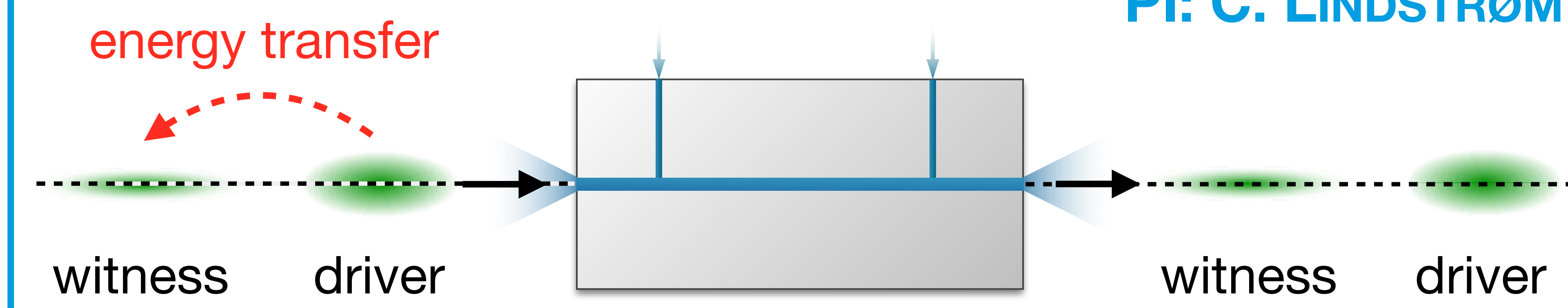
GOALS:

- 1 GeV energy gain of in-plasma injected beam
- transverse normalised beam emittance ~ 100 nm
- peak current ≳ 1 kA
- femtosecond bunch duration

> Beam generation for collider final focus

CORE STUDY II — X-2: PLASMA BOOSTER

PI: C. LINDSTRØM



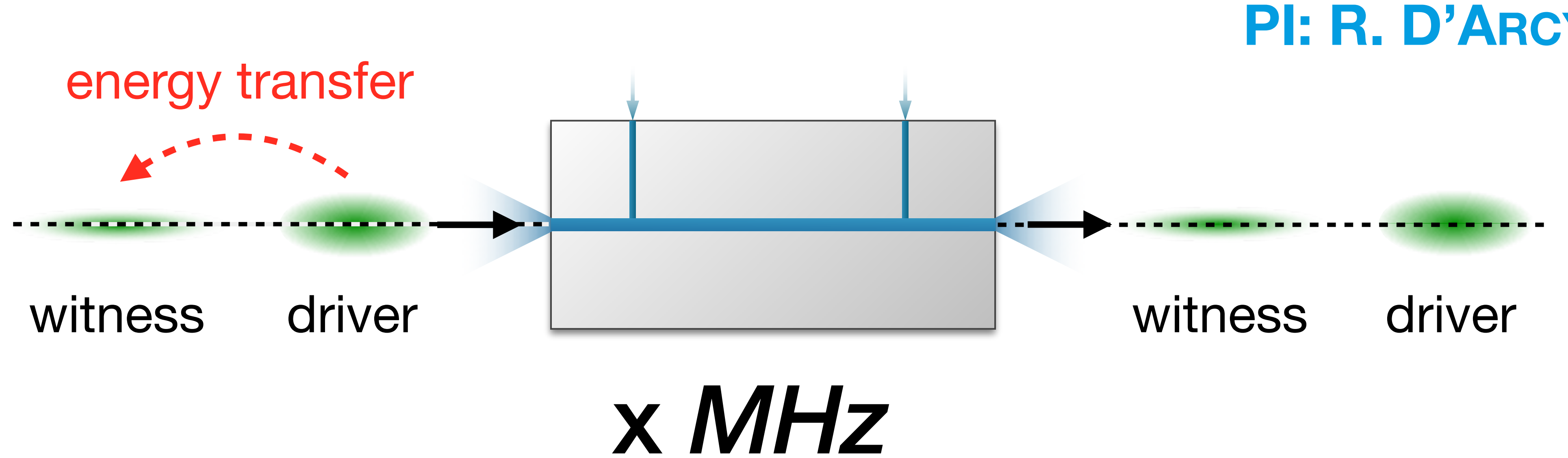
GOALS:

- 1 GeV energy gain
- conserve beam energy spread
- conserve beam normalised transverse emittance
- deplete drive beam energy
- 20% energy extraction efficiency from drive to witness

> Energy boosting section for collider staging

CORE STUDY III — X-3: HIGH-AVERAGE POWER PWFA

PI: R. D'ARCY



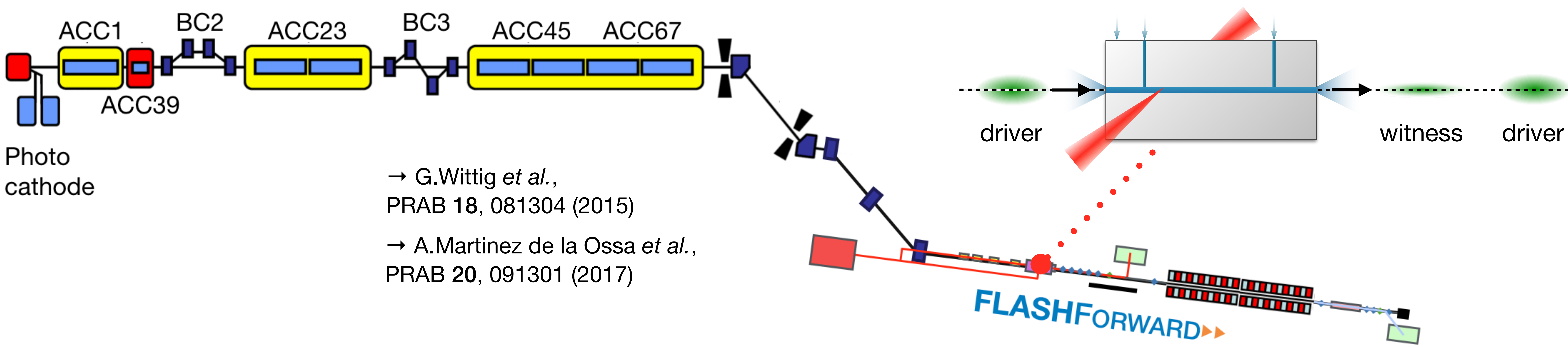
GOALS:

- GeV energy gain, beam quality preservation, depletion @ MHz
- plasma relaxation studies
- investigation into multi-discharge plasma recovery time
- MHz thermal management
- driver-witness beam separation

> Test bed to address high-average-power challenges

X-1: Plasma cathode for high-brightness beam generation

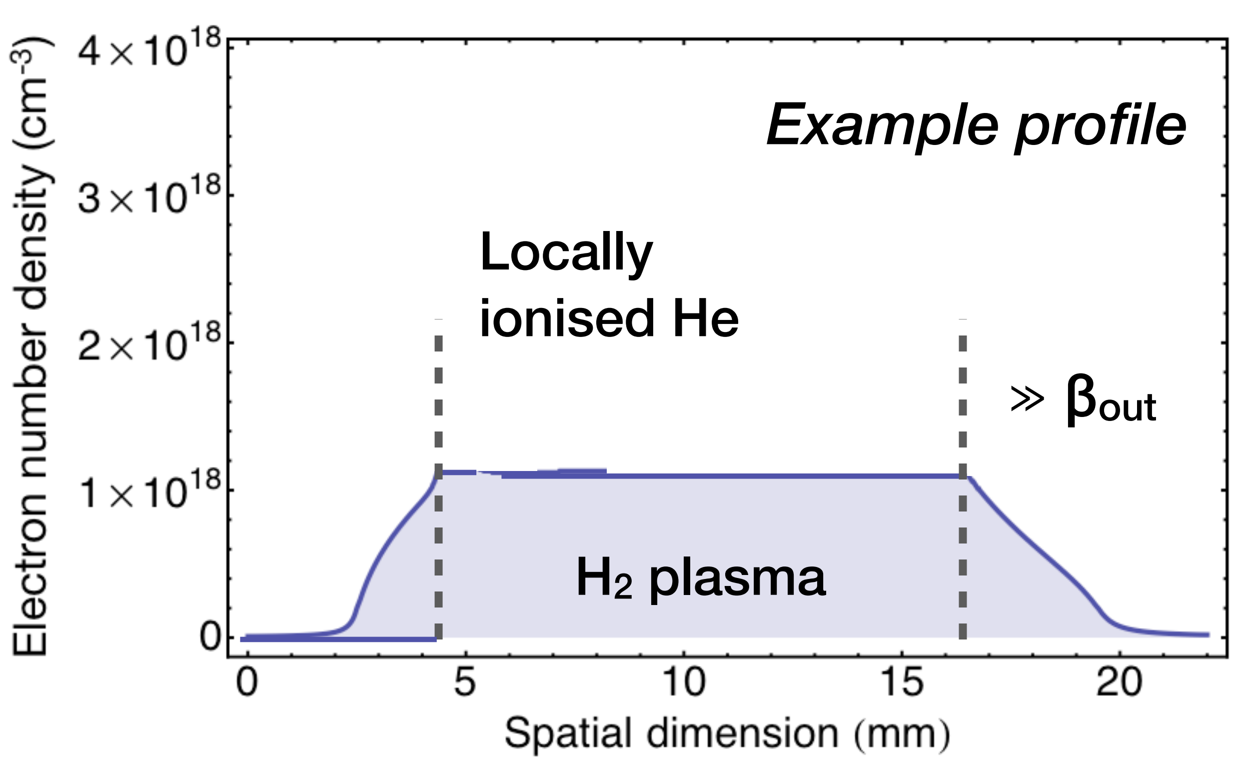
Generation of nm-scale normalised emittance beams for collider final focus



→ G.Wittig *et al.*, PRAB **18**, 081304 (2015)

→ A.Martinez de la Ossa *et al.*, PRAB **20**, 091301 (2017)

- **X-1 Plasma Cathode:** beam-brightness converter → emittance shrinker
  > 1.25 GeV energy, trans. norm. emittance ~100 nm, current ≳ 1 kA, ~fs bunch duration

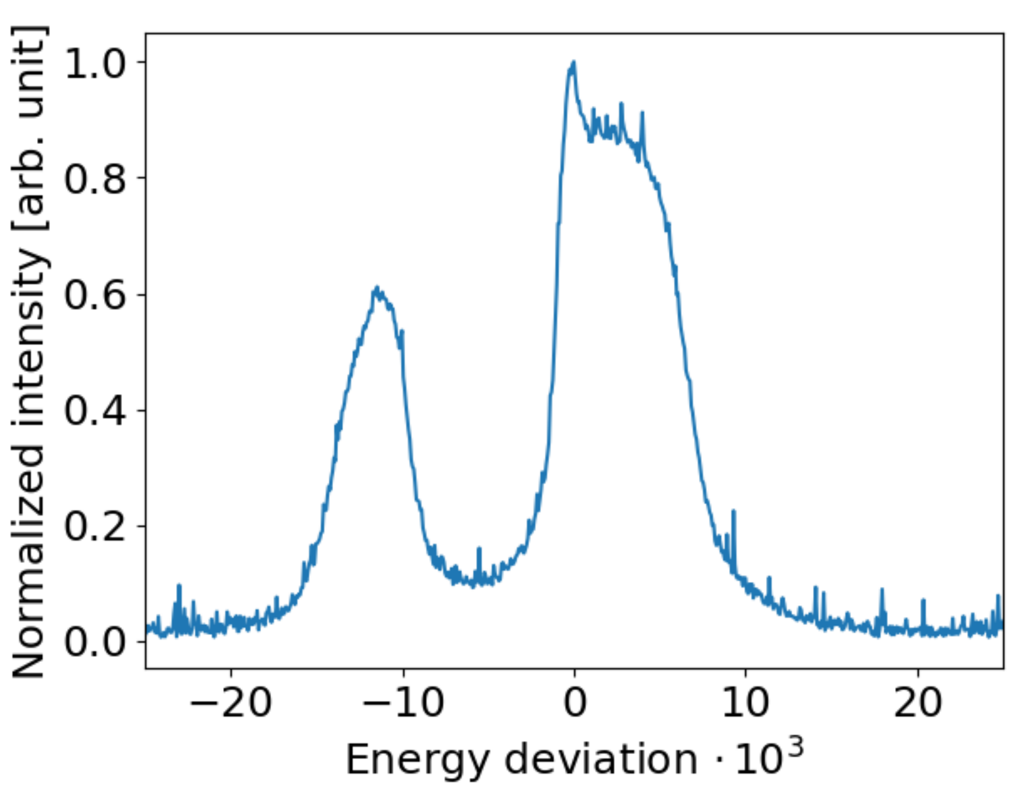


- first studies comparing laser- and HV discharge-generated plasma underway
- *in summer 2019*:
  → transverse laser in-coupling
  → 5 cm plasma cell with 300 µm transverse hole
  → accelerator of internally injected electrons

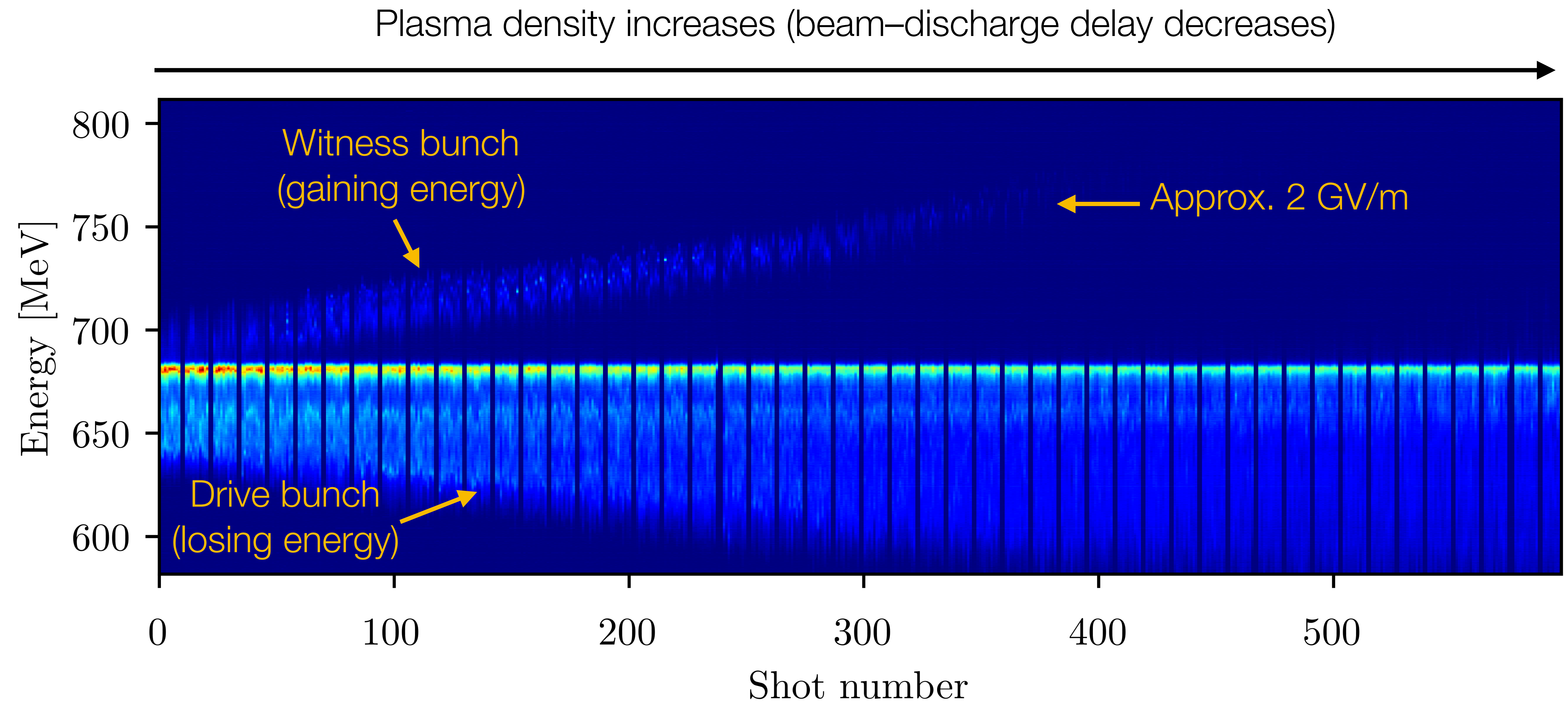
X-2: Plasma-based energy booster module

HIGH GRADIENT ENERGY BOOSTING, BEAM-QUALITY PRESERVATION, AND STABILITY STUDIES

Driver/witness creation using a wedge-shaped scraper in a dispersive section



plasma interaction



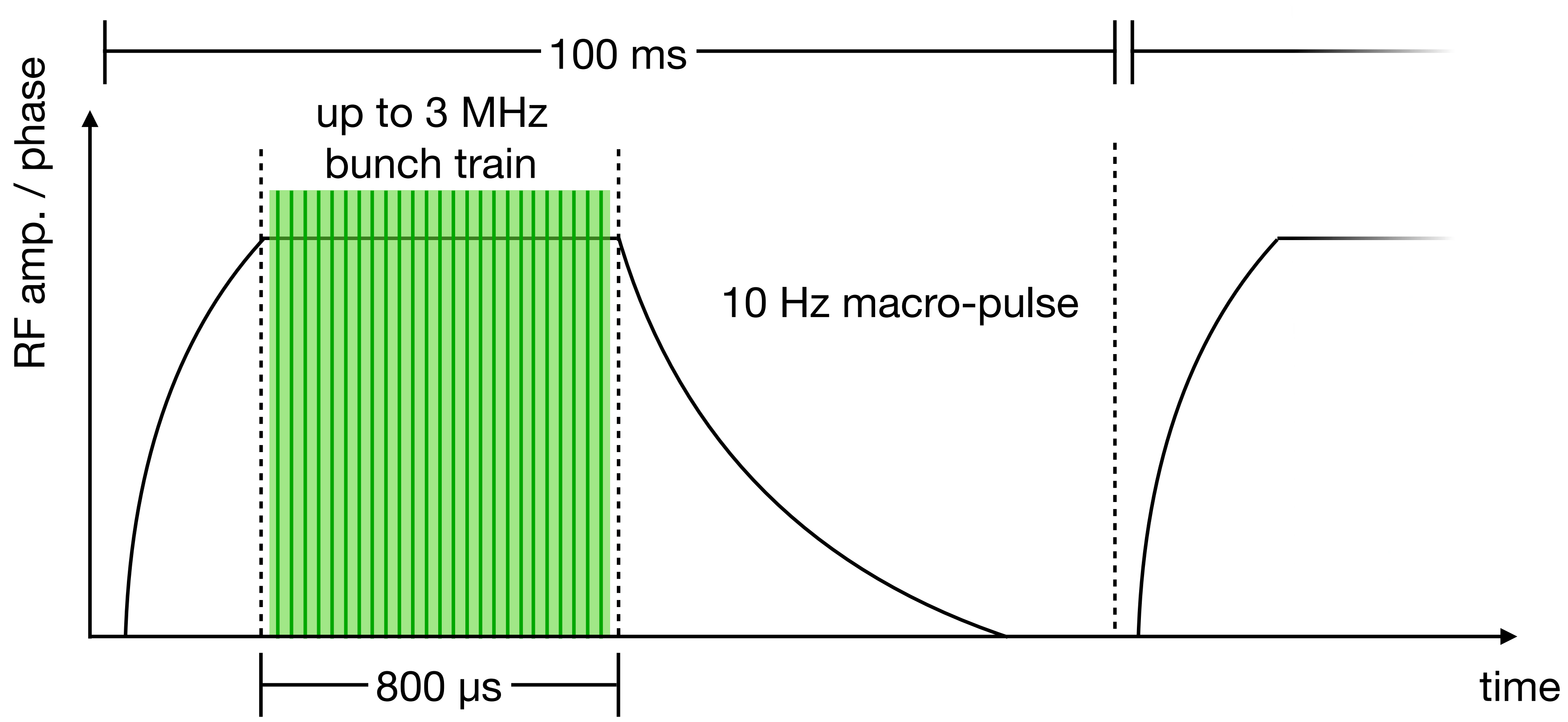
Double-bunch plasma interaction

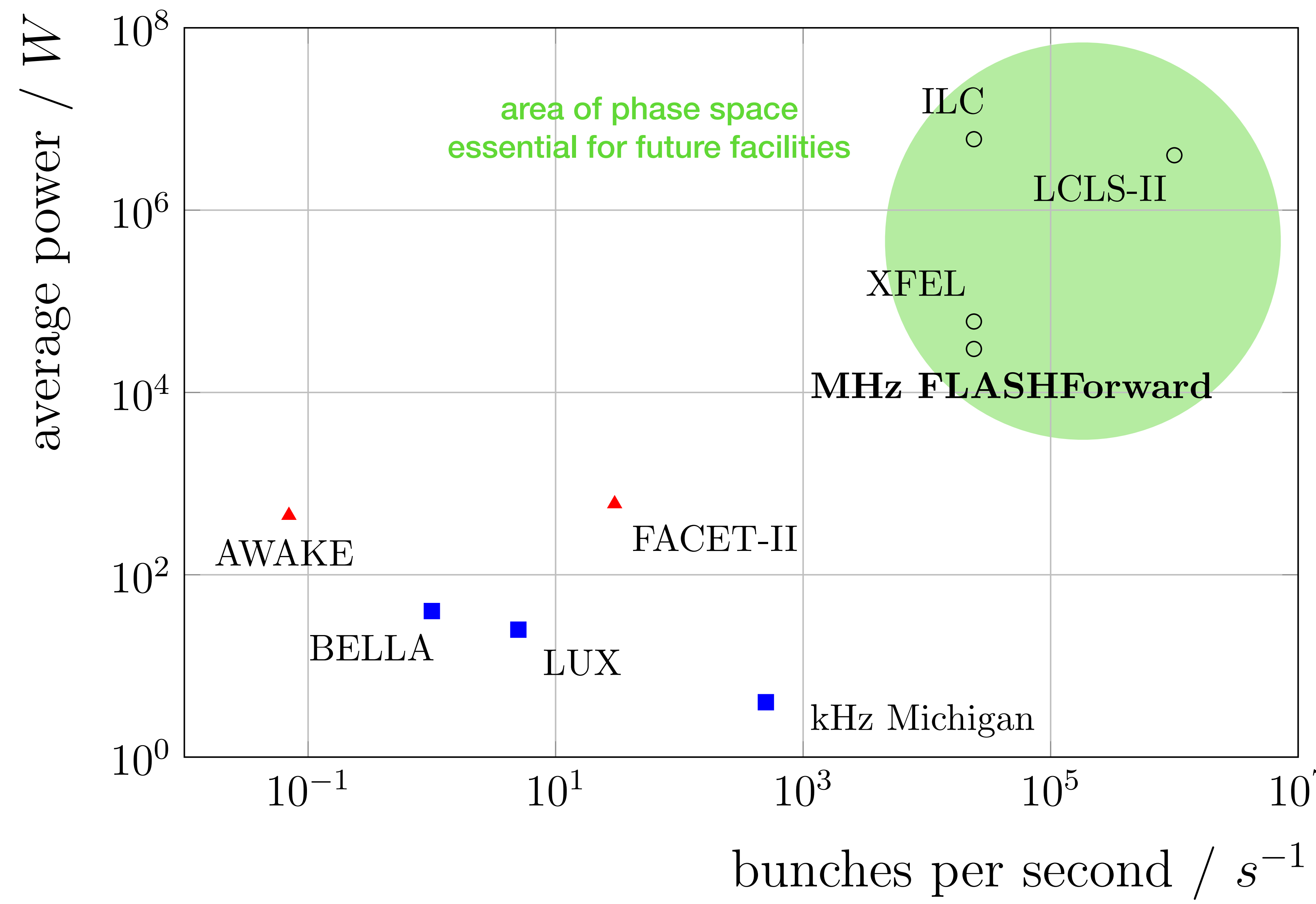
- **First observation of witness acceleration with GV/m fields** (parameters: 1 kA driver peak current, 30 mm plasma cell, 10^{15} - 10^{16} cm^{-3} plasma density)
- ***in summer 2019:* 20 cm plasma cell → multi-100 MeV energy gain + drive depletion; beam loading control → explore energy spread and emittance conservation**

- **No shot selection or preferential ordering**
- **Excellent stability over short and long term (multiple hours) thanks to stability of the SCRF cavities and FEL-quality feedback systems**

X-3: High-average-power PWFA research

MHz repetition rate PWFA for high-average-power applications

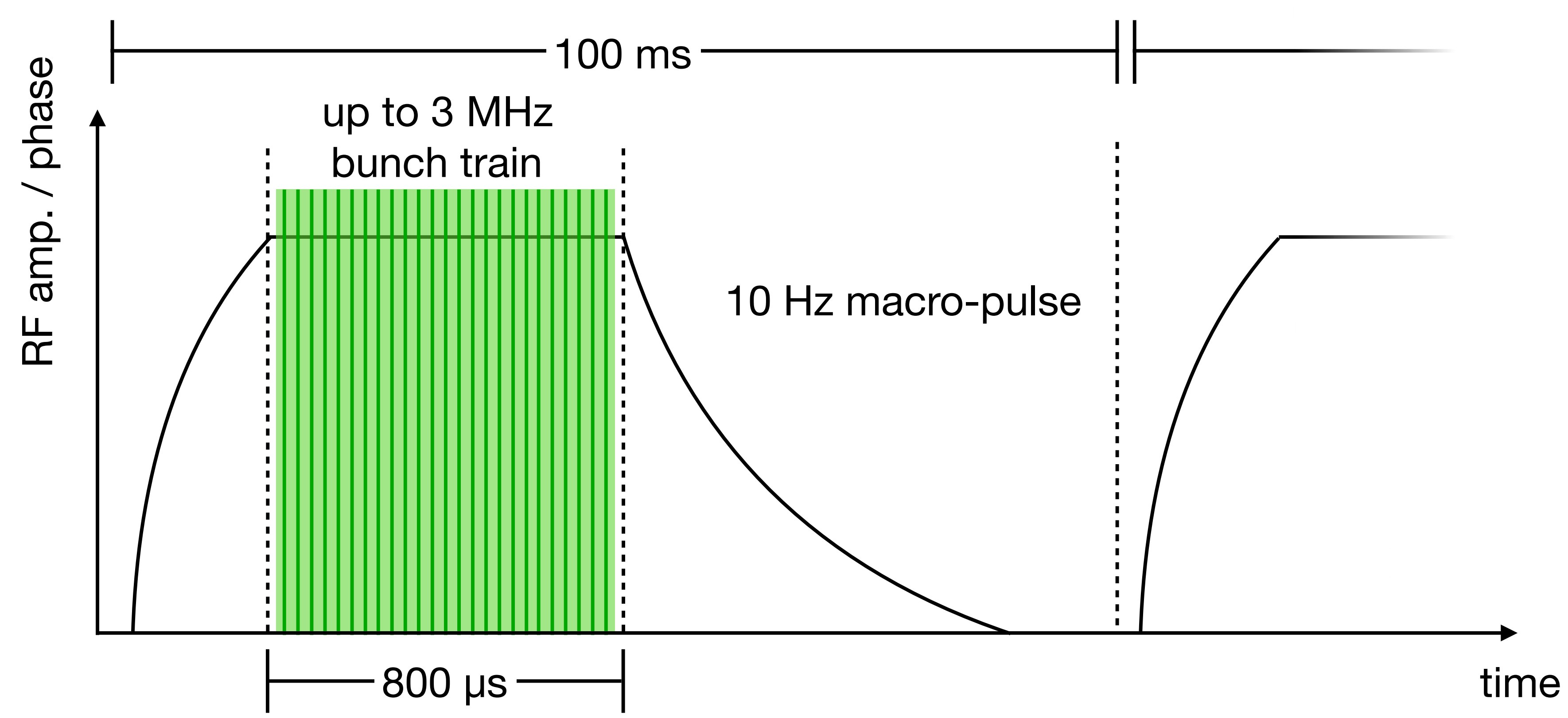


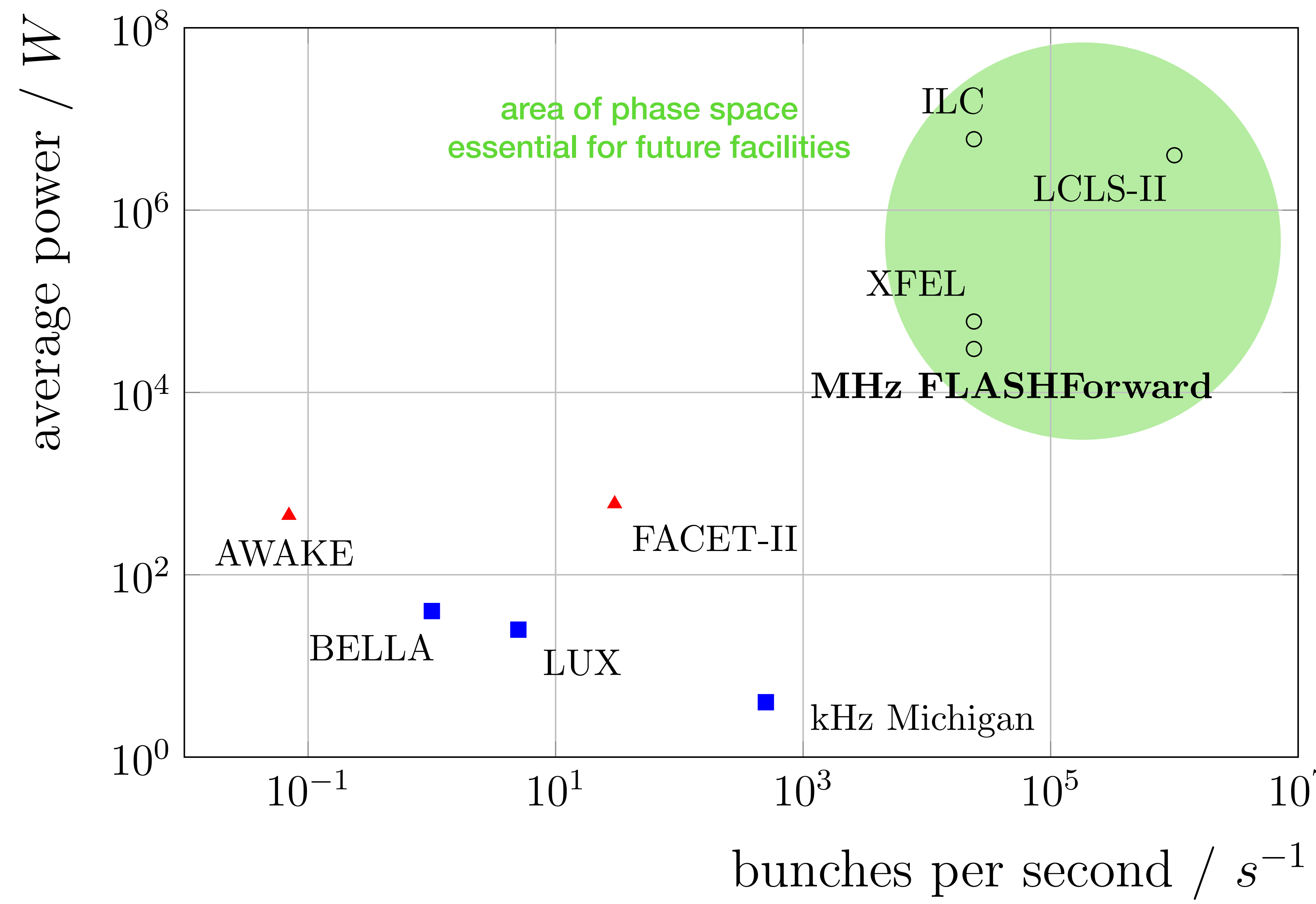


- Up to 3 MHz bunch train structure, provided by the FLASH SCRF front-end, places FLASHForward in a unique position to explore the high-average-power regime necessary for future facilities

X-3: High-average-power PWFA research

MHz REPETITION RATE PWFA FOR HIGH-AVERAGE-POWER APPLICATIONS





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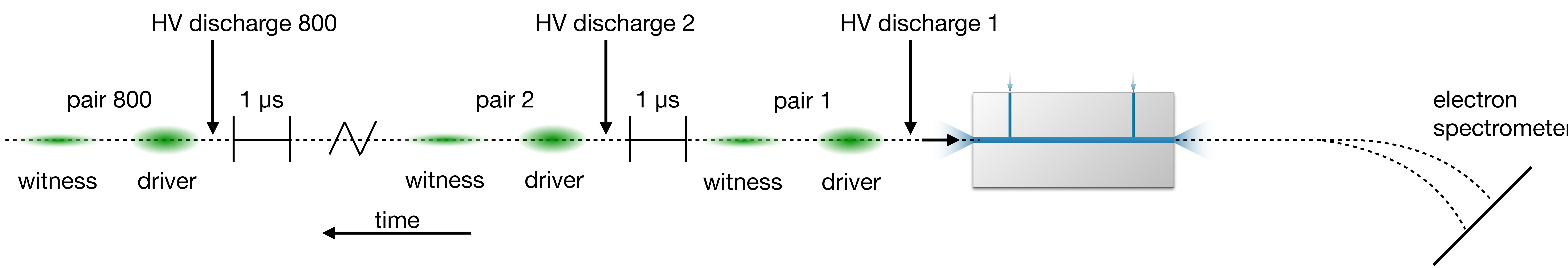


X-3: High-average-power PWFA research

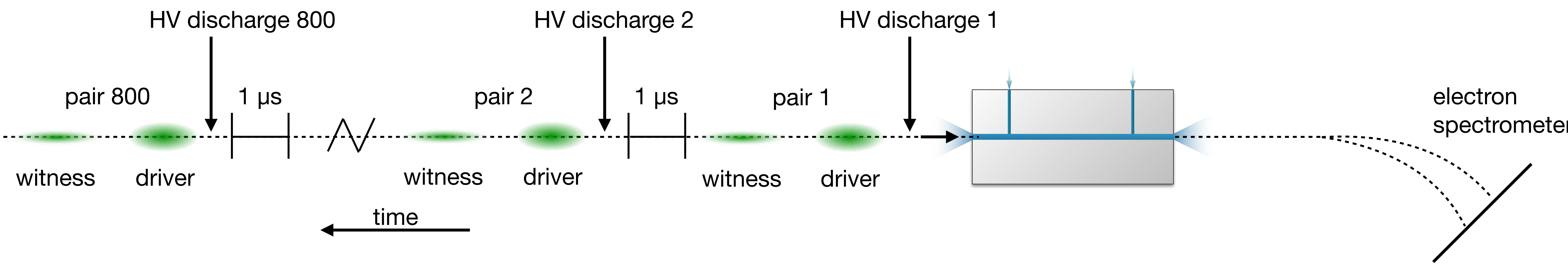
MHz REPETITION RATE PWFA FOR HIGH-AVERAGE-POWER APPLICATIONS

Technical challenges

- MHz repetition rate plasma discharge
- Driver and witness beam separation
- Gas flow and high rep. rate plasma cell
- Imaging diagnostics with high temporal resolution

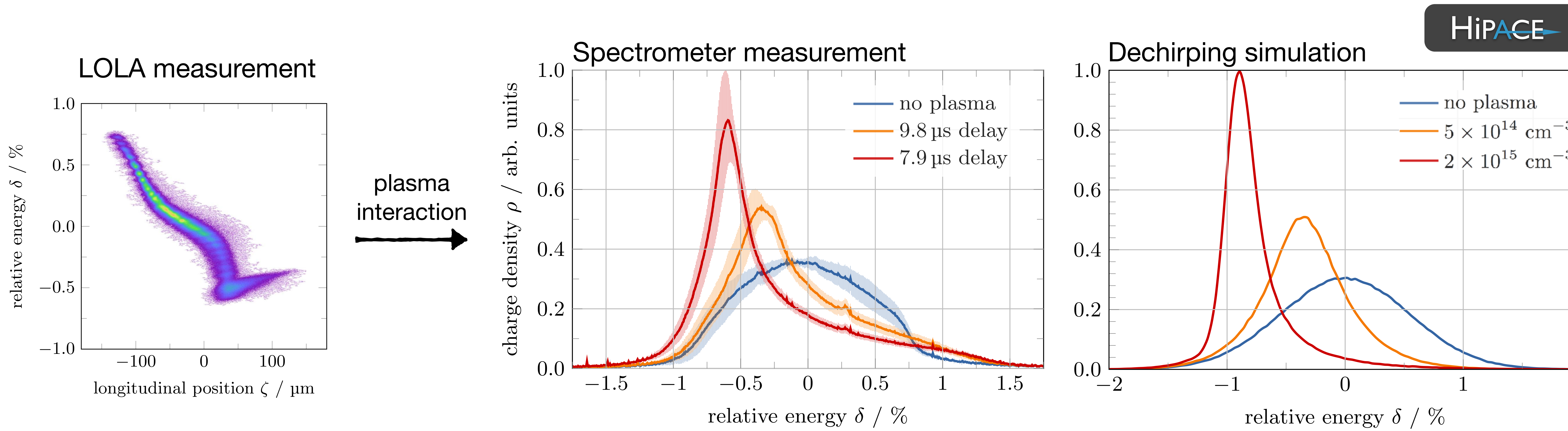
Scientific questions

- How is the lifetime of plasma relaxation affected by perturbations generated by a particle beam driving a wakefield?
- What is the recovery time of the system between the generation of a first plasma through a high-voltage discharge and a second?
- Can the deposition of heat into the plasma from the drive bunch be managed at MHz rates?

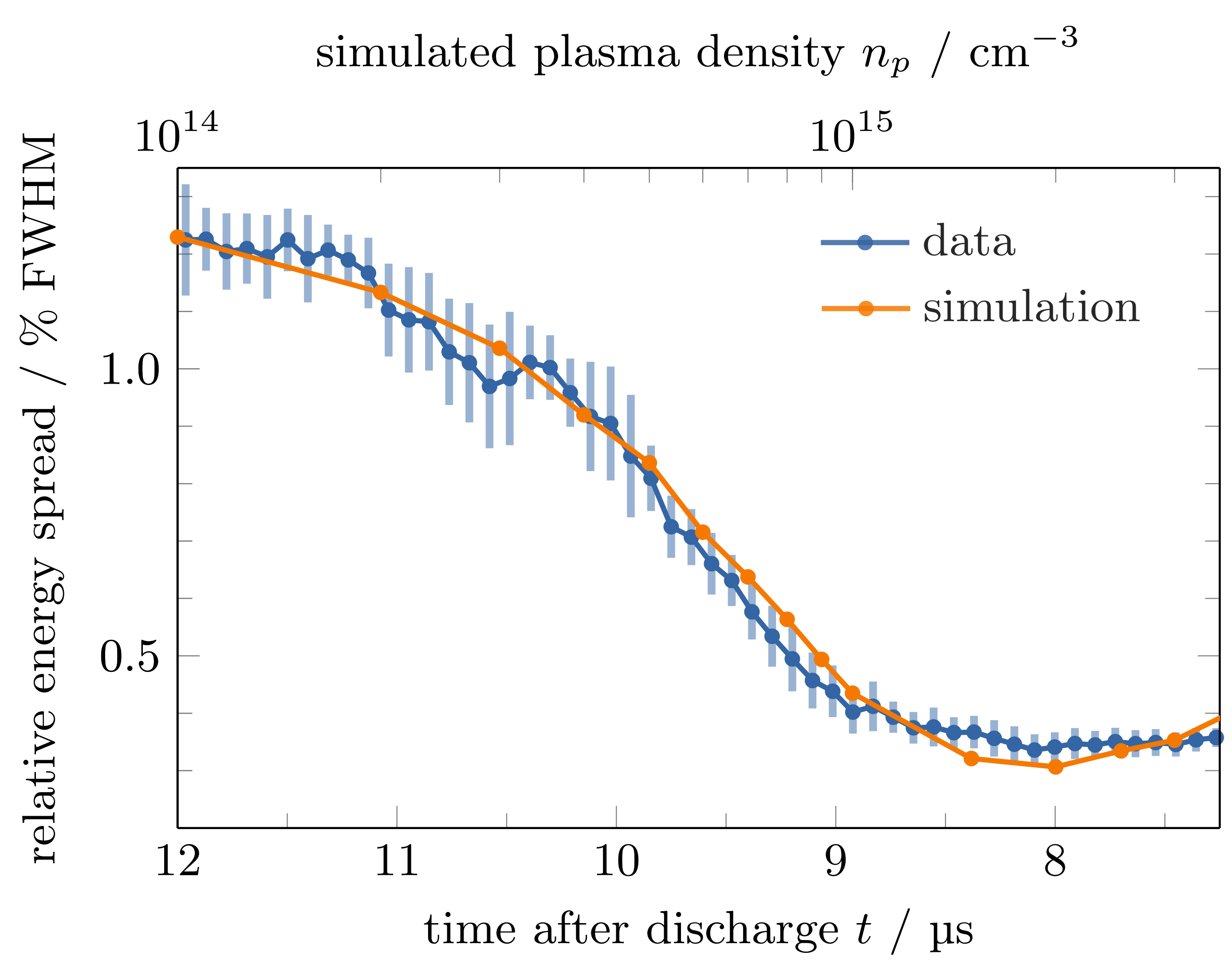


Scientific highlight: Tunable plasma-based energy dechirper

REMOVE REMANENT ENERGY CHIRP FOR INTRA-STAGING AND COLLIDER FINAL FOCUS



- Reduction of energy spread from 1.3% to 0.3% FWHM
- Experimental demonstration of 1.8 GeV/mm/m dechirping strength, orders of magnitude higher than other state-of-the-art devices
- May dramatically improve applicability of PWFA beams to future facilities



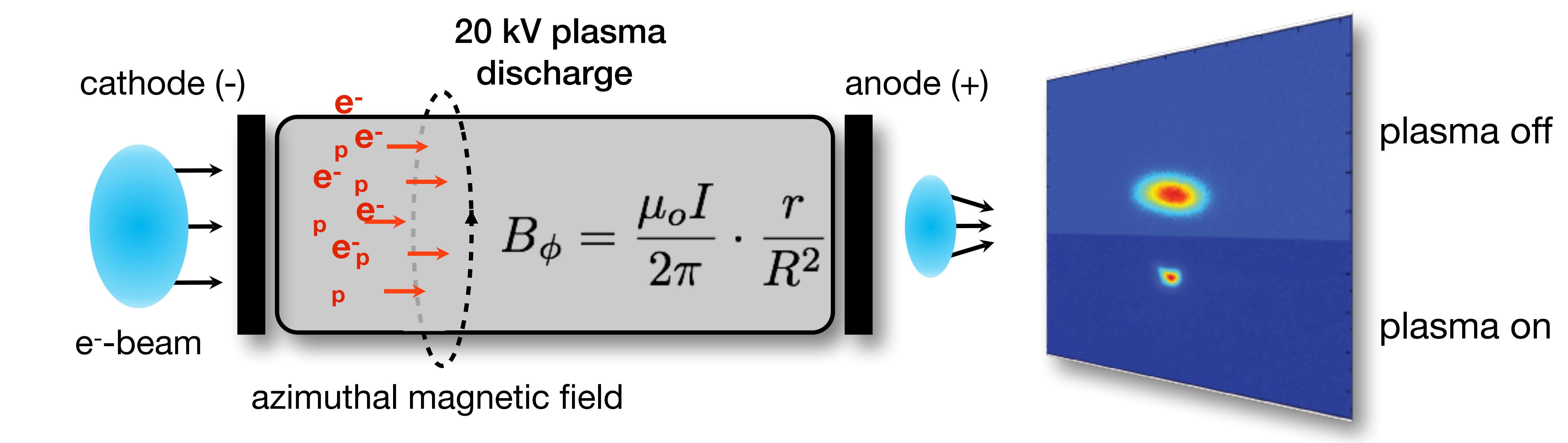
- First experimental demonstration of dechirping in plasma
- Proof of principle results, utilising an artificially chirped FLASH beam, published in January

R. D'Arcy et al.,
Phys. Rev. Lett. 122, 034801 (2019)

Scientific highlight: Aberration-free active plasma lenses

EMITTANCE PRESERVING FOCUSSING ELEMENTS FOR BEAM CAPTURE AND FINAL FOCUSSING

in collaboration between



→ F = I x B, tunable and symmetric focussing force for e⁻beam

→ multi-kT/m focussing gradients, much higher than conventional magnets

J. van Tilborg et al., Phys. Rev. Lett. ***115****, 184802 (2015)*

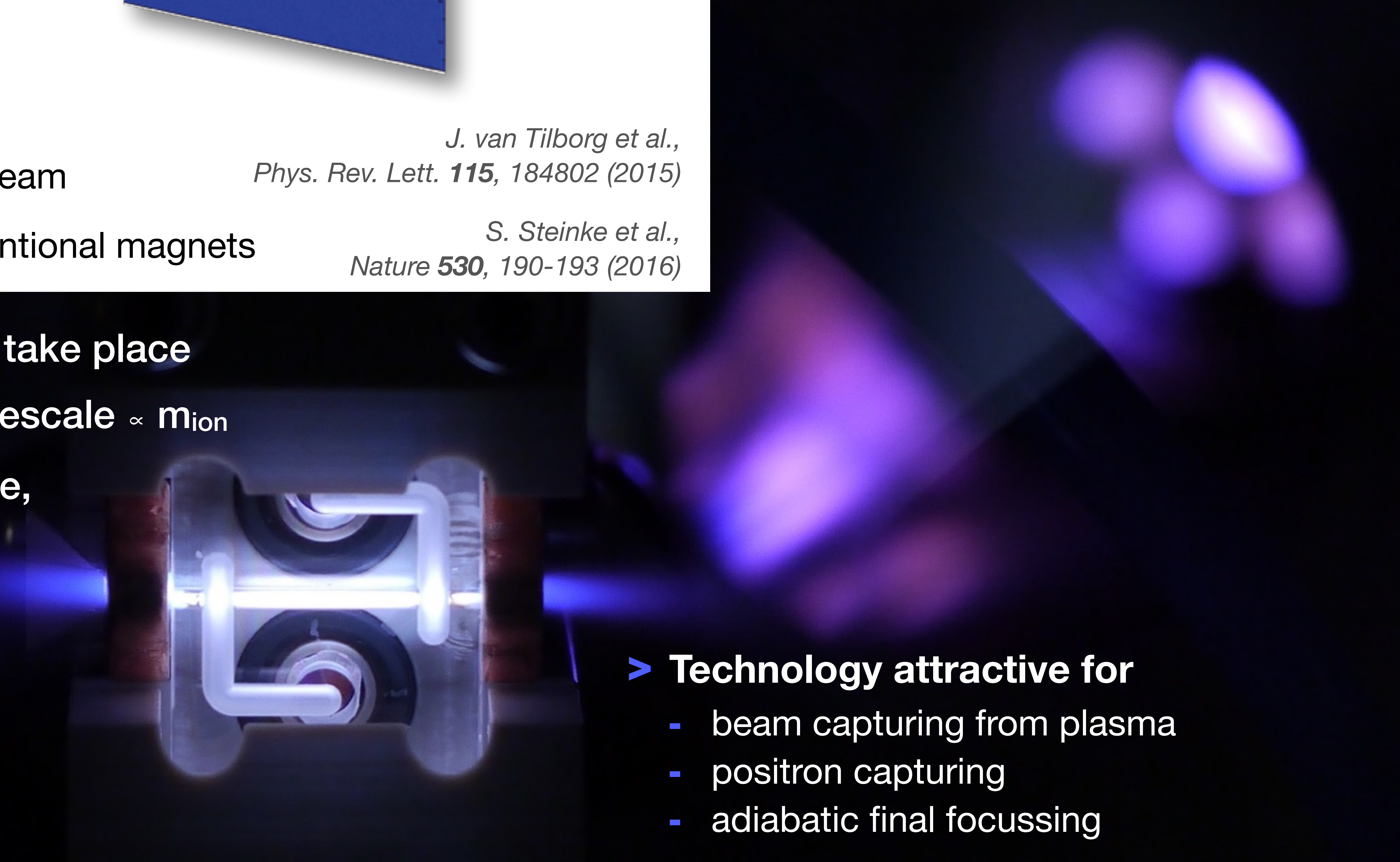
S. Steinke et al., Nature ***530****, 190-193 (2016)*

> *Idea:* utilize APL before temperature equilibration can take place

> Substitute Hydrogen/Helium with Argon to extend timescale $\propto m_{ion}$

> Experiment at CLEAR, CERN: 216 MeV, 50 µm rms size, 3 µm trans. norm. emittance, 410 A current at 70 ns

> Argon: emittance conservation demonstrated
Helium: emittance not conserved

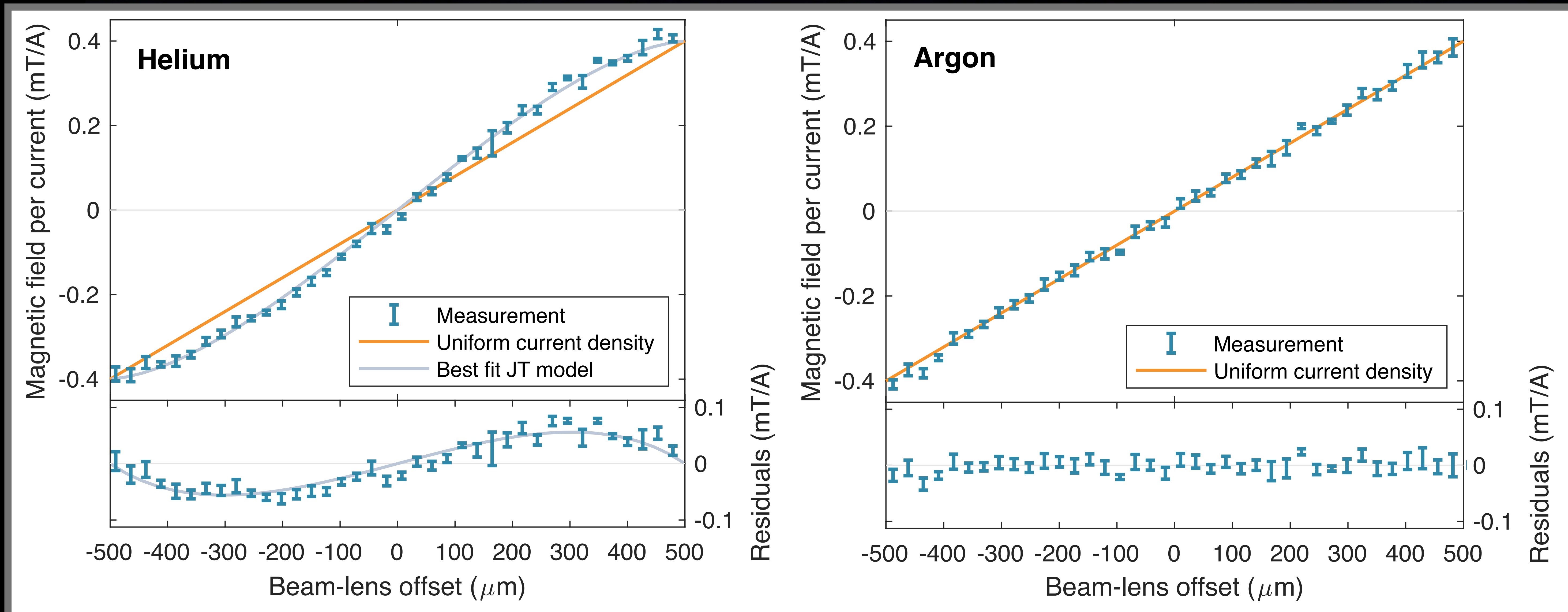


> **Technology attractive for**
- beam capturing from plasma
- positron capturing
- adiabatic final focussing

Scientific highlight: Aberration-free active plasma lenses

Emittance preserving focussing elements for beam capture and final focussing

in collaboration between



C. A. Lindstrom *et al.*,
Phys. Rev. Lett. 121, 194801(2018)

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- Substitute Hydrogen/Helium with Argon to extend timescale ∝ m_{ion}
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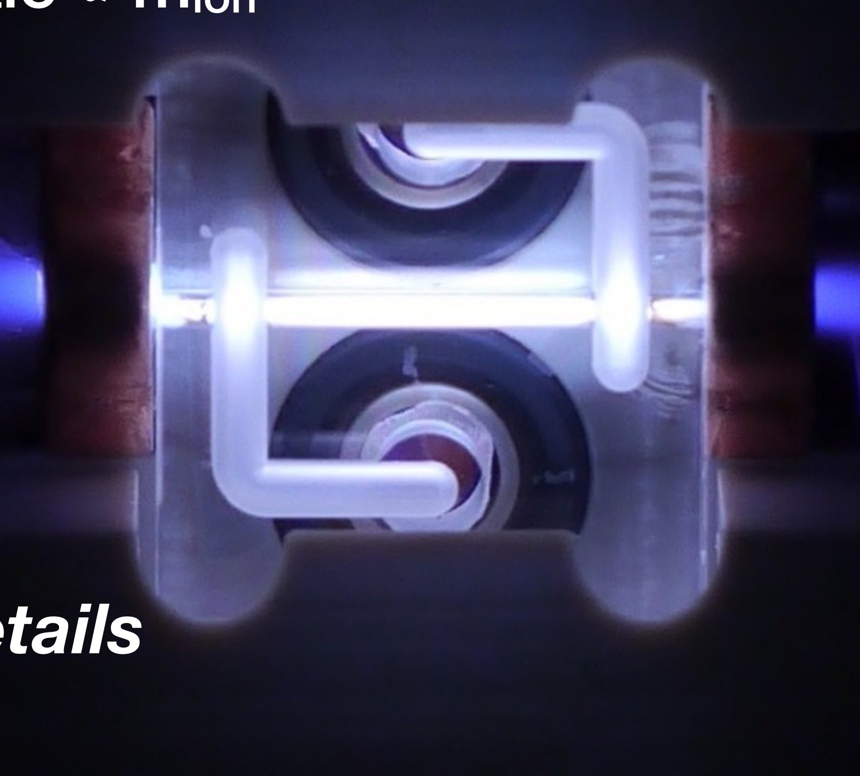
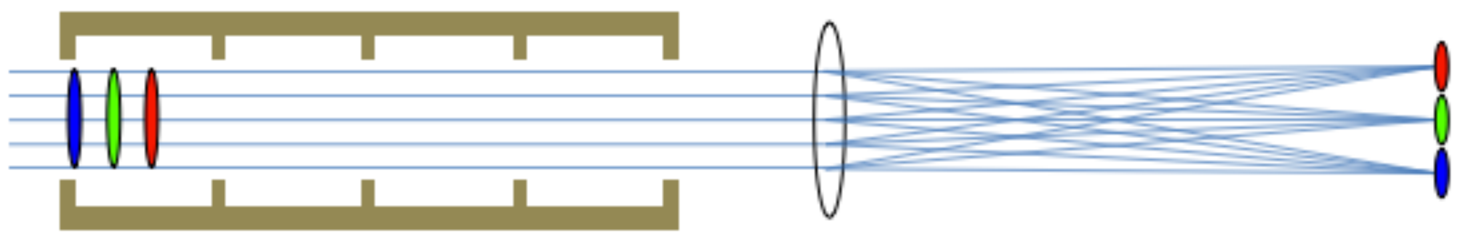


- **Technology attractive for**
  - beam capturing from plasma
  - positron capturing
  - adiabatic final focussing

See Carl's presentation tomorrow afternoon for further details

Scientific highlight: fs-level resolution of beam parameters

X-BAND TRANSVERSE DEFLECTOR FOR PHASE-SPACE CHARACTERISATION



- A collaboration between DESY, CERN, and PSI to share expertise and develop X-band technology
- A novel dual-polarisation RF deflecting cavity → tomographic reconstruction of phase space

- Resolutions witness* and driver** beam working points:

$$R_z = \frac{\sigma_y}{S} = \sqrt{\frac{\varepsilon_y(s)}{\beta_y(s_0)}} \frac{1}{|\sin \mu_y|} \frac{E}{eVk}$$

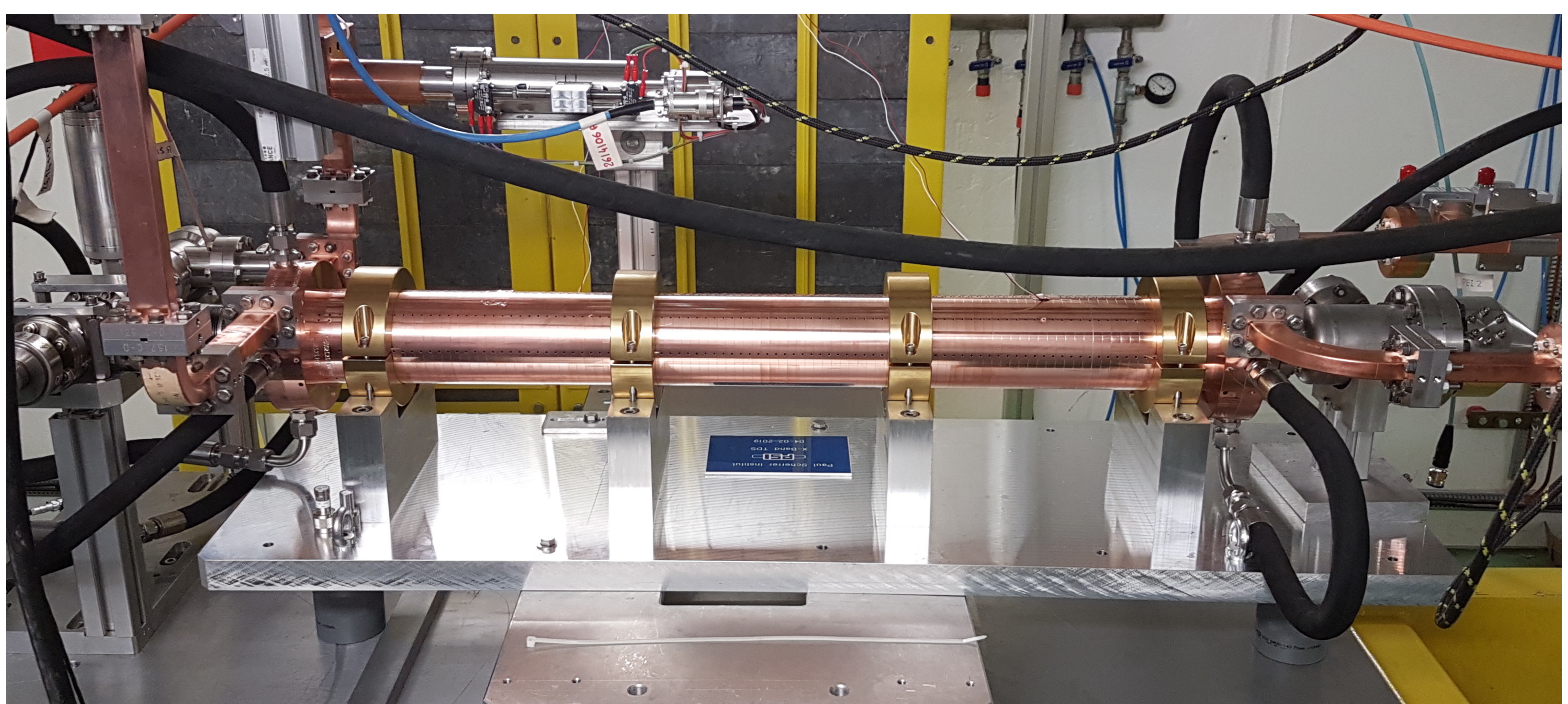
$R_t > 0.9$ fs (witness)
$R_t > 1.5$ fs (driver)

$$R_\delta = \frac{\sigma_x}{|D_x|} = \sqrt{\varepsilon_x} \frac{\sqrt{\beta_x}}{|D_x|}$$

$R_\delta > 2\text{x}10^{-4}$ (witness)
$R_\delta > 1\text{x}10^{-4}$ (driver)

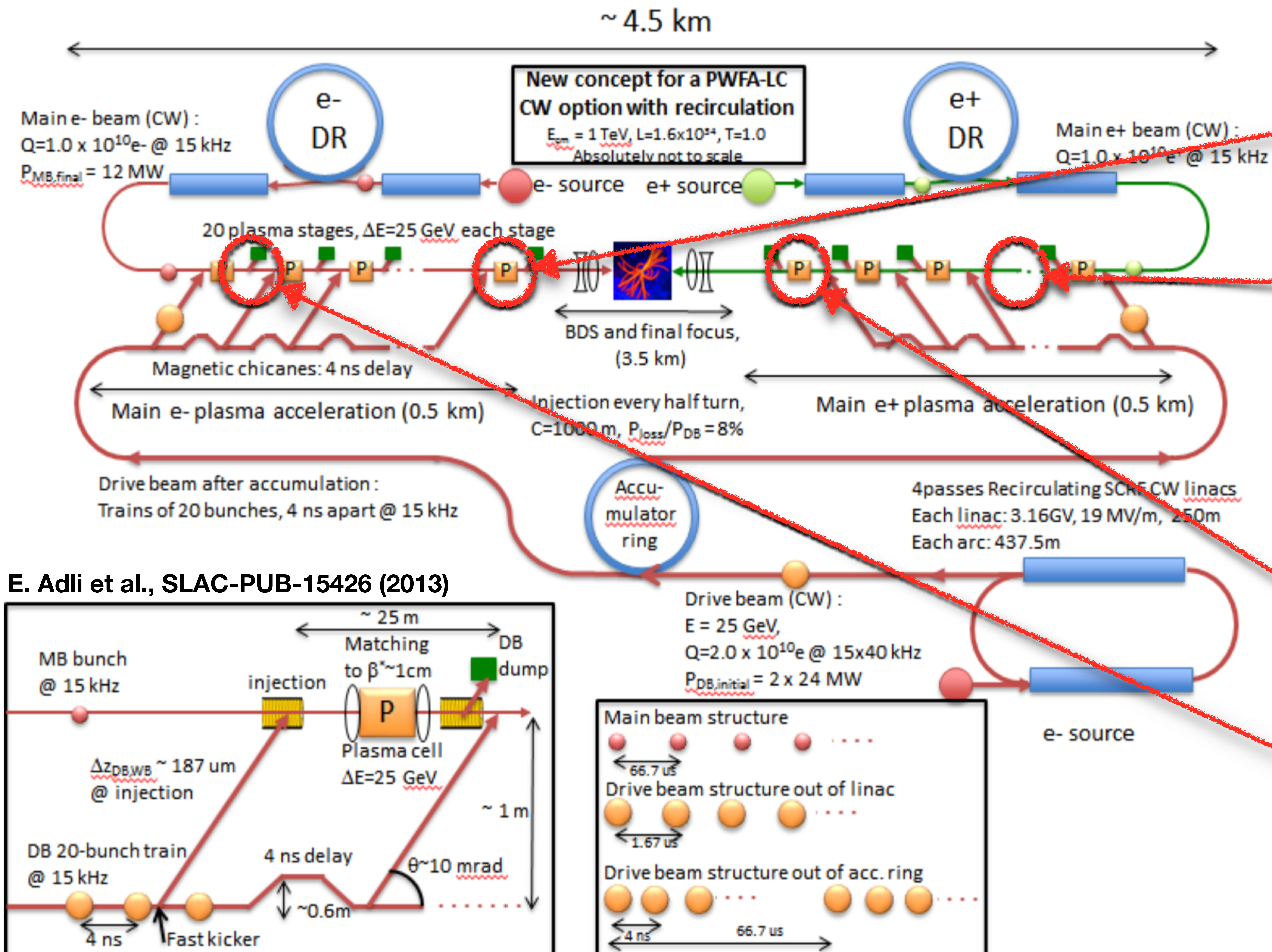
* E = 1.5 GeV, ε = 0.5 μm

** E = 1.0 GeV, ε = 2.0 μm



- Cavity currently being high-power conditioned at the Xbox facility here at CERN
- Due for installation at FLASHForward in the summer shutdown
- Commissioning with beam to commence in August 2019

The ultimate application:
straw-man design of a TeV-class PWFA linear collider



PWFA specific challenges & R&D

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  → FACET-II
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  plasma heat management,
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The ultimate application:
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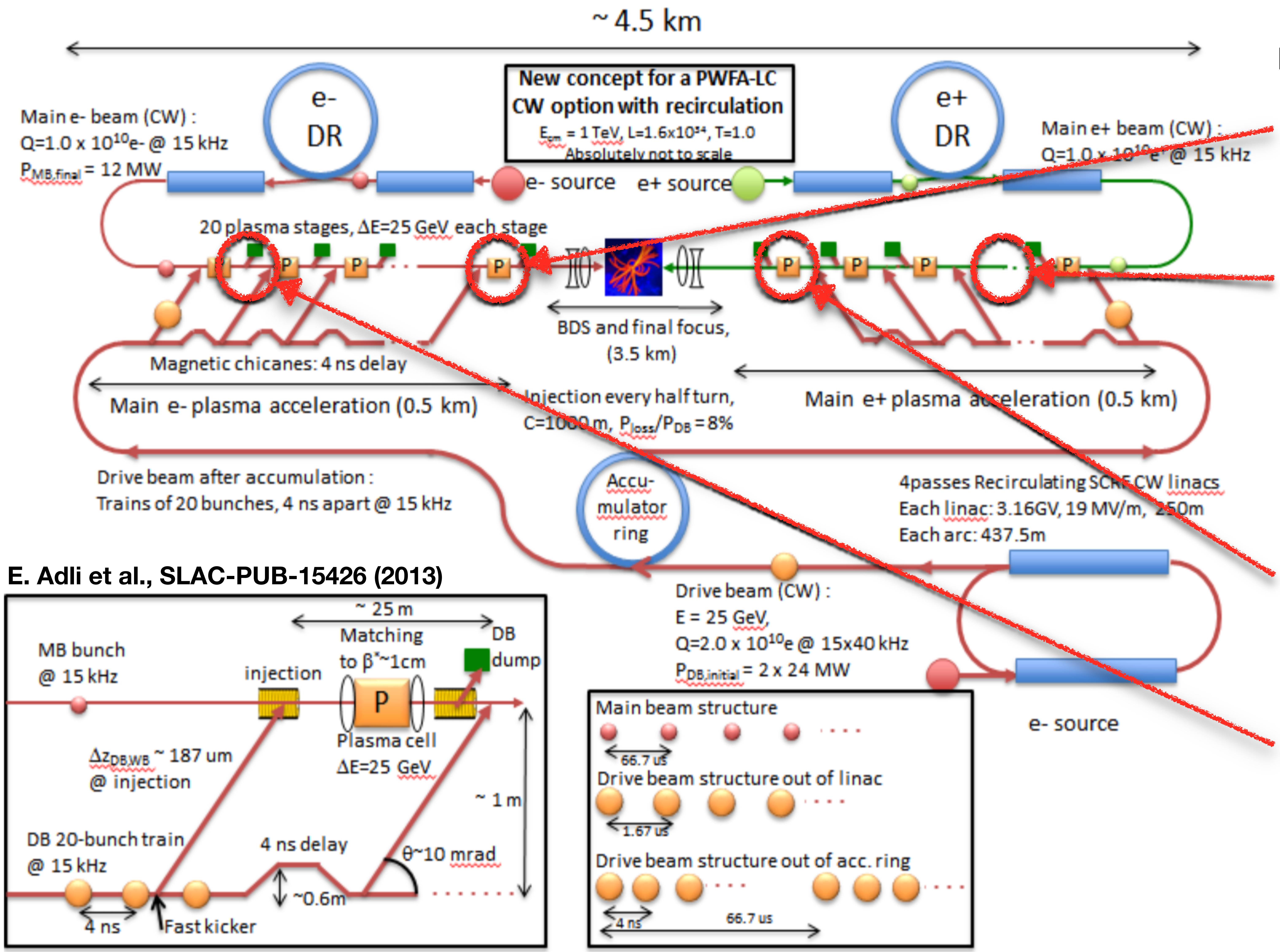

PWFA specific challenges & R&D

- **Single acceleration module**
  support consistent high beam quality,
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  → **FACET-II, FF▸▸**
- **Coupling of plasma stages (staging)**
  beam extraction and injection
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  → **FACET-II, FF▸▸**
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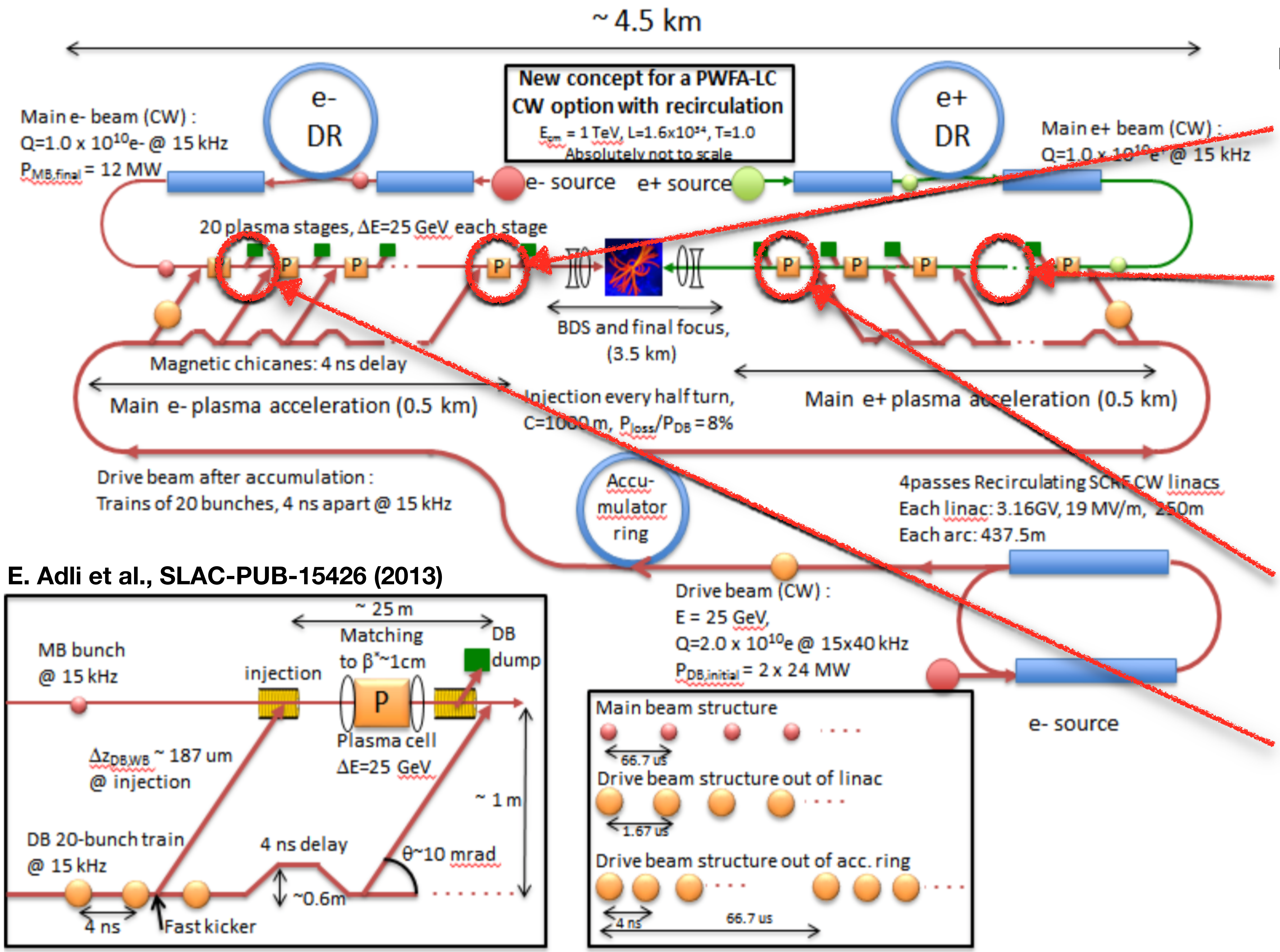
  plasma heat management,
  drive-beam removal
  → **FF▸▸**
- **Positron acceleration**
  → **FACET-II**
- **Full characterisation of the beam**
  → **FF▸▸**
- **Symmetric plasma optics**
  coupling length minimisation,
  positron capturing,
  adiabatic focussing
  → **FF▸▸**
- **Acceleration of polarised beams**

The ultimate application:
straw-man design of a TeV-class PWFA linear collider



PWFA specific challenges & R&D

- **Single acceleration module**
  support consistent high beam quality,
  efficient energy transfer to witness
  → **FACET-II, FF▸▸**
- **Coupling of plasma stages (staging)**
  beam extraction and injection
  with beam-quality preservation
  → **FACET-II, FF▸▸** (both only partially)
- **High-average power operation**
  plasma heat management,
  drive-beam removal
  → **FF▸▸**
- **Positron acceleration**
  → **FACET-II**
- **Full characterisation of the beam**
  → **FF▸▸**
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  coupling length minimisation,
  positron capturing,
  adiabatic focussing
  → **FF▸▸**
- **Acceleration of polarised beams**
  → **?**

Summary

- A lot of exciting electron beam-driven PWFA milestones towards a future TeV-class collider have already been reached
- Many many more challenges need to be addressed in the coming years → FLASHForward▸▸
- Further upgrades to existing experiments and new facilities required to tick off the remaining boxes → necessary to take PWFA research from ‘Nature’ to next generation