FACET II Science Workshop | SLAC | October 15th, 2015

FLASHForward▸▸

a PWFA powered FEL experiment at DESY

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Mission and goals of **FLASH**Forward

FLASHForward is

- a fully approved DESY project since July 2014
- an extension to the FLASH FEL facility
- a new beamline for beam-driven plasma wakefield accelerator research

Mission

- to demonstrate beam quality from a plasma-based wakefield accelerator suitable for first applications in photon science as a stepping stone towards high-energy physics applications

Scientific goals

- the characterization of **externally injected** electron beams and their controlled release from a wakefield accelerator with **energies > 2.0 GeV** (→ *phase I)*
- the exploration of novel **in-plasma beam-generation**[1] and acceleration techniques to provide **> 1.6 GeV energy, < 100 nm transverse normalized emittance, fs duration,** and **> 1 kA current** electron bunches (→ *phase I)*
- **to demonstrate free-electron laser** gain with these beams at wavelengths on the few-nanometer scale (→ *phase II)*

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[1] A. Martinez de la Ossa *et al.*, "High-Quality Electron Beams from Beam-Driven Plasma Accelerators by Wakefield-Induced Ionization Injection", Physical Review Letters **111**, 245003 (2013)
A. Martinez de la Ossa *et al.*, "High-Quality Electron Beams from Field-Induced Ionization Injection in the Strong Blow-Out Regime of Beam-Driven Plasma Accelerators", NIM A **740**, 231 (2014)
J. Grebenyuk *et al.*, "Beam-Driven Plasma-Based Acceleration of Electrons with Density Down-Ramp Injection at FLASHForward", NIM A **740**, 246 (2014)
B. Hidding *et al.*, "Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout", Physical Review Letters **108**, 035001 (2012)

FLASHForward▸▸ builds on existing infrastructure at FLASH 2

- main beamline is being set up inside the FLASH 2 tunnel, installation started in May 2015
- laser and preparation infrastructure is situated in building 28m/O1 and O2

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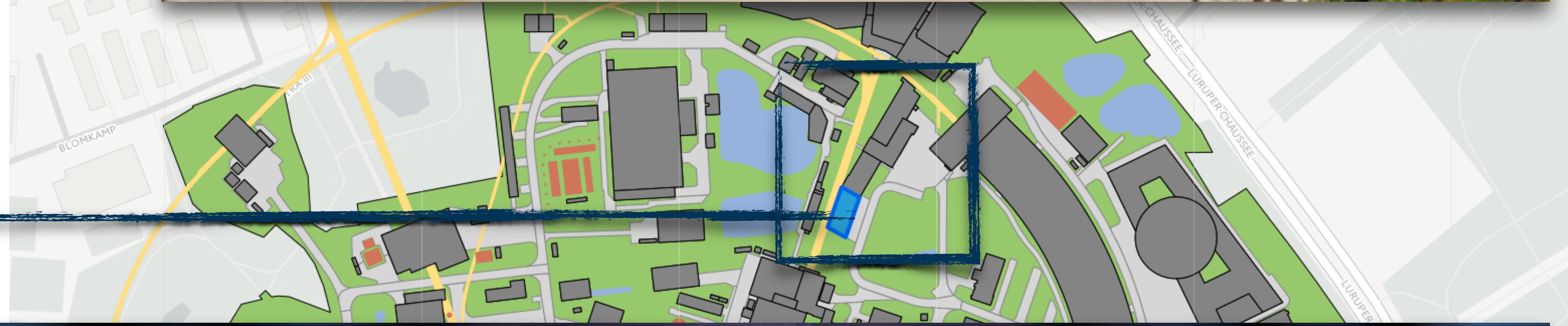
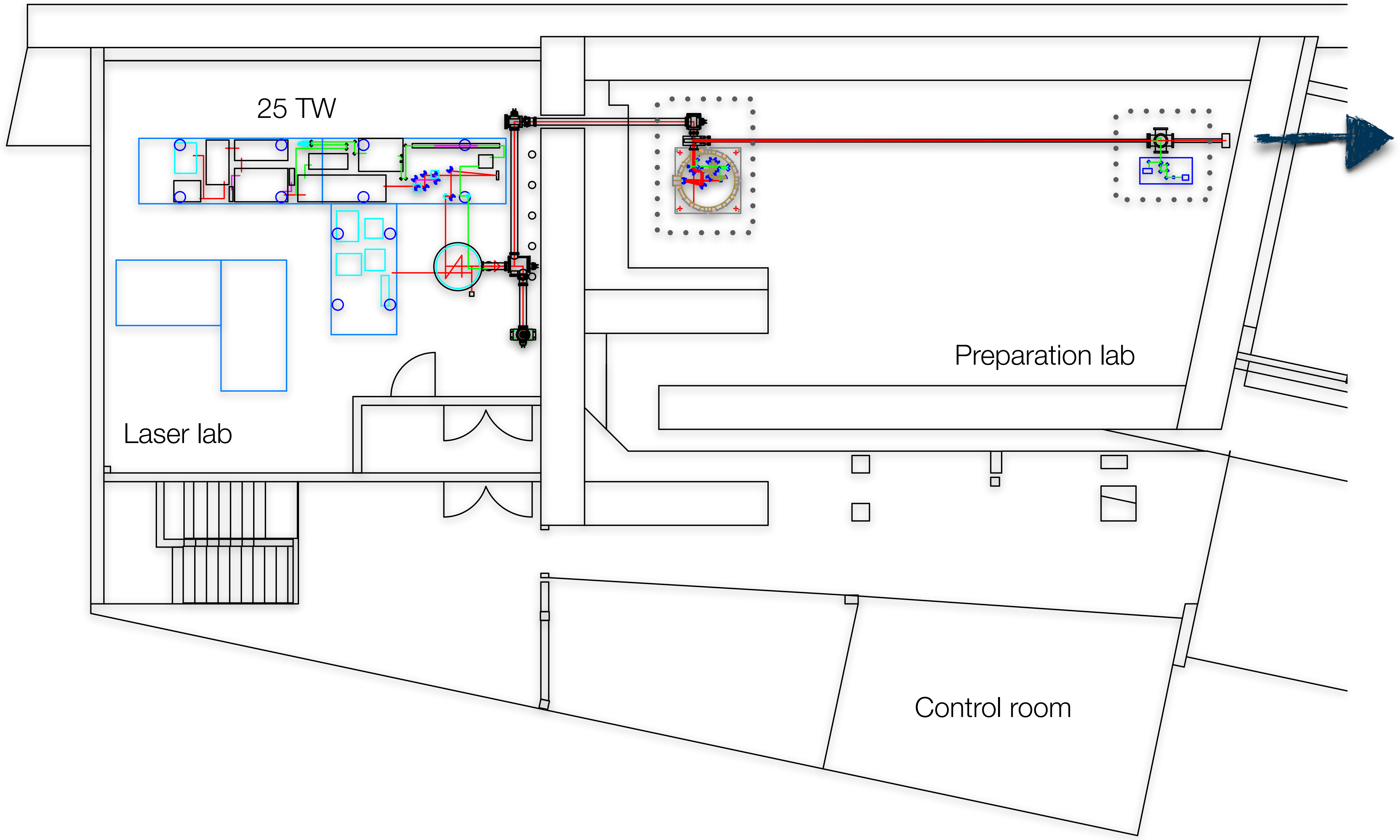
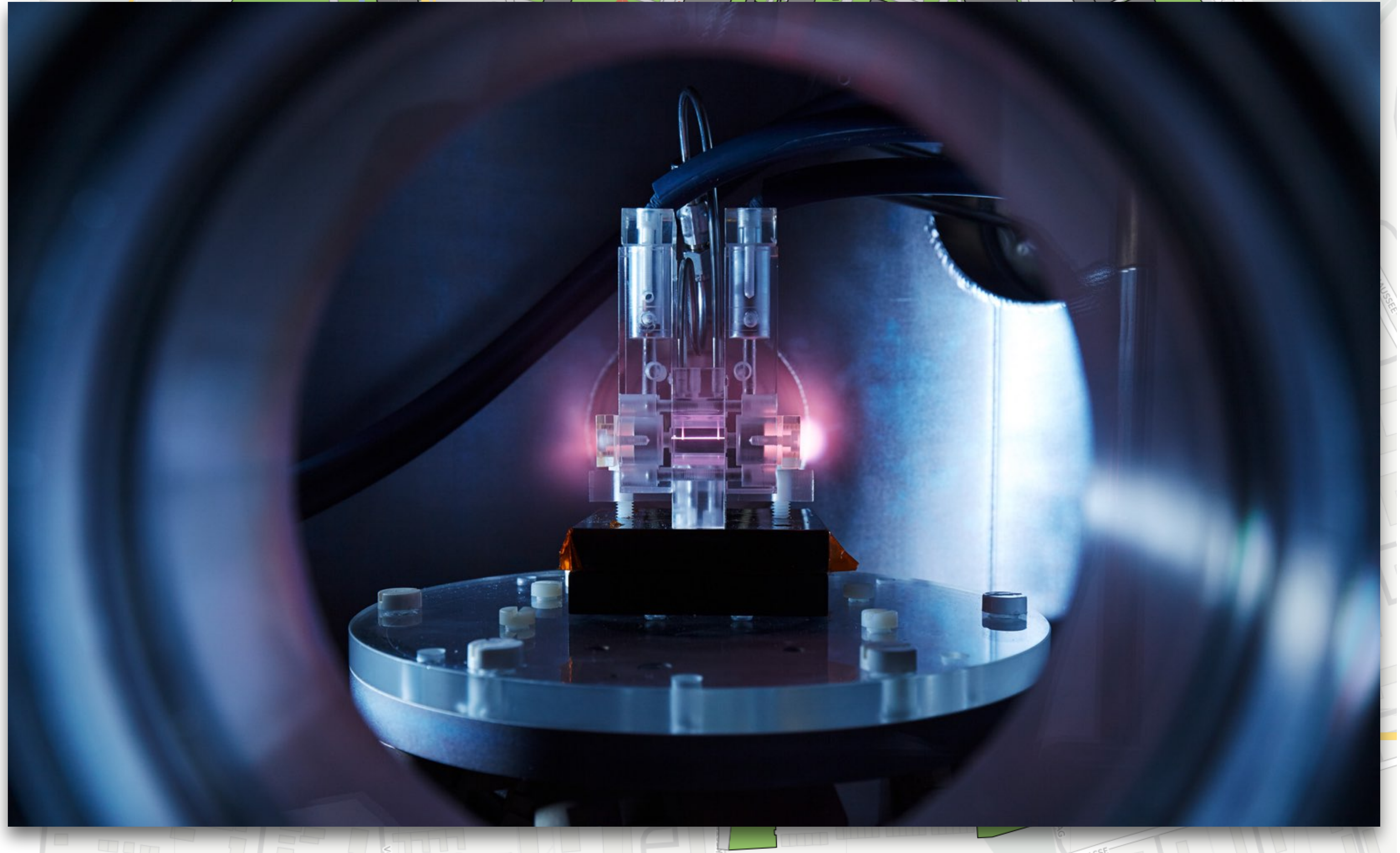
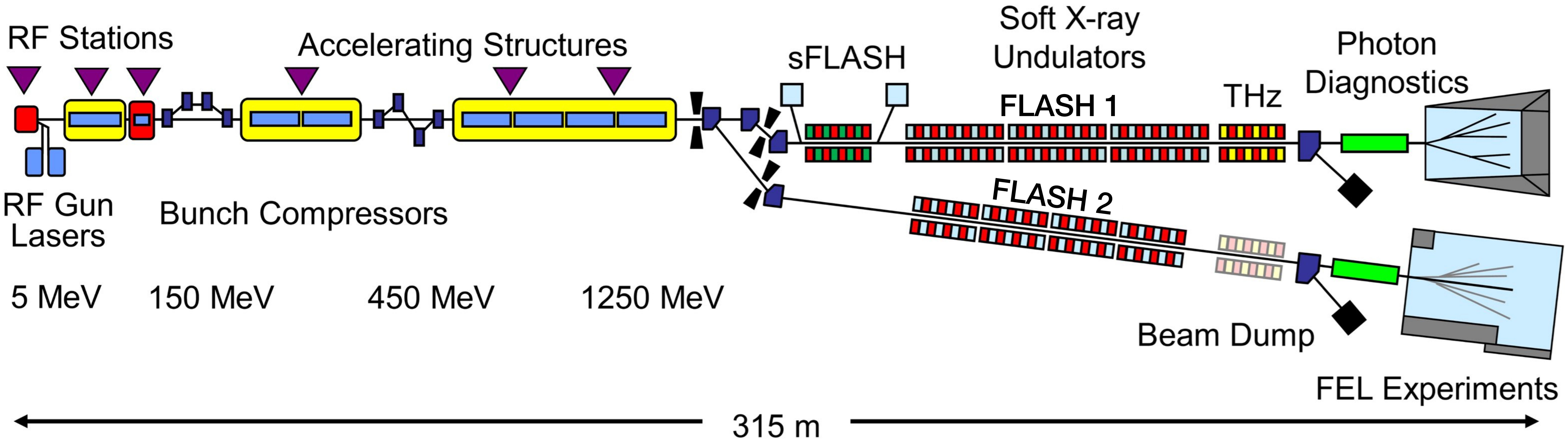


Laser and preparation laboratories (DESY 28m/O2)



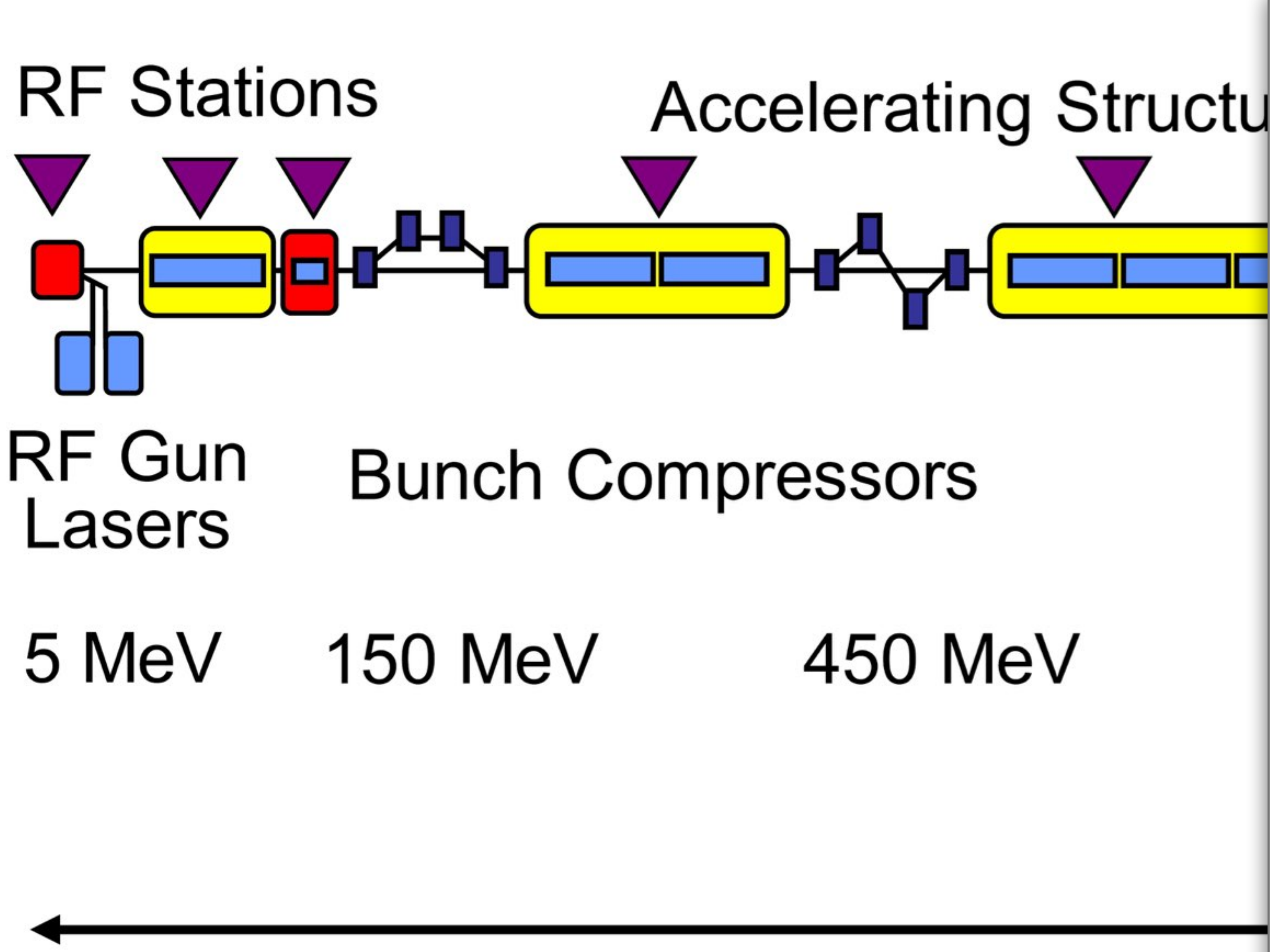


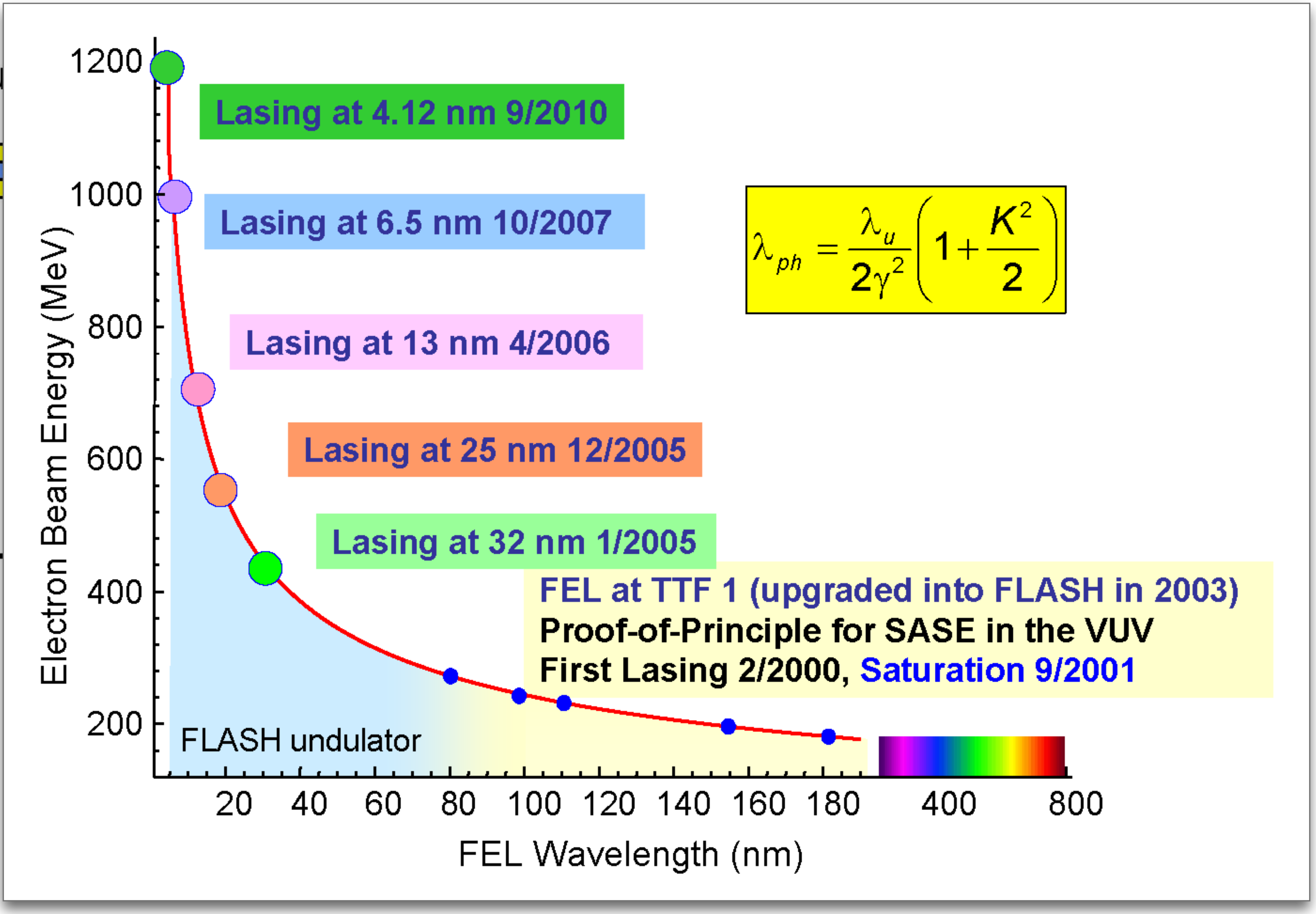
FLASH - The free-electron laser in Hamburg



- **FLASH is a water-window FEL user facility**

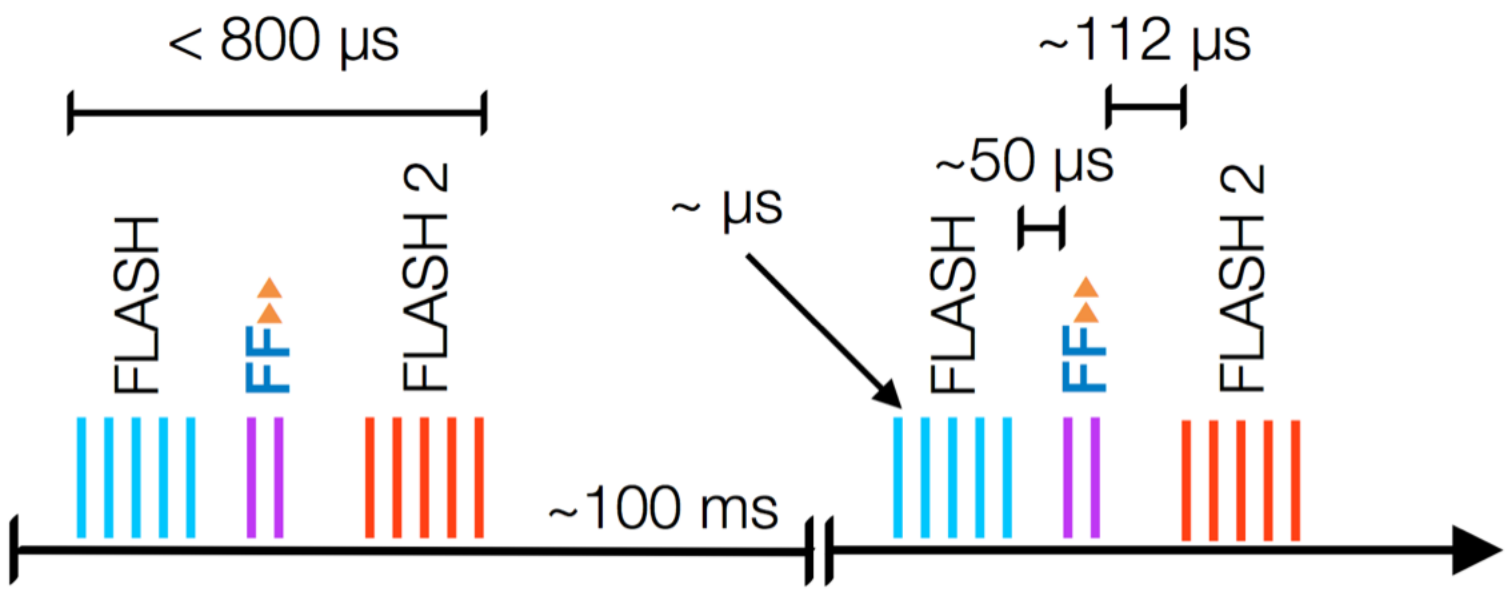
FLASH - The free-electron laser in Hamburg



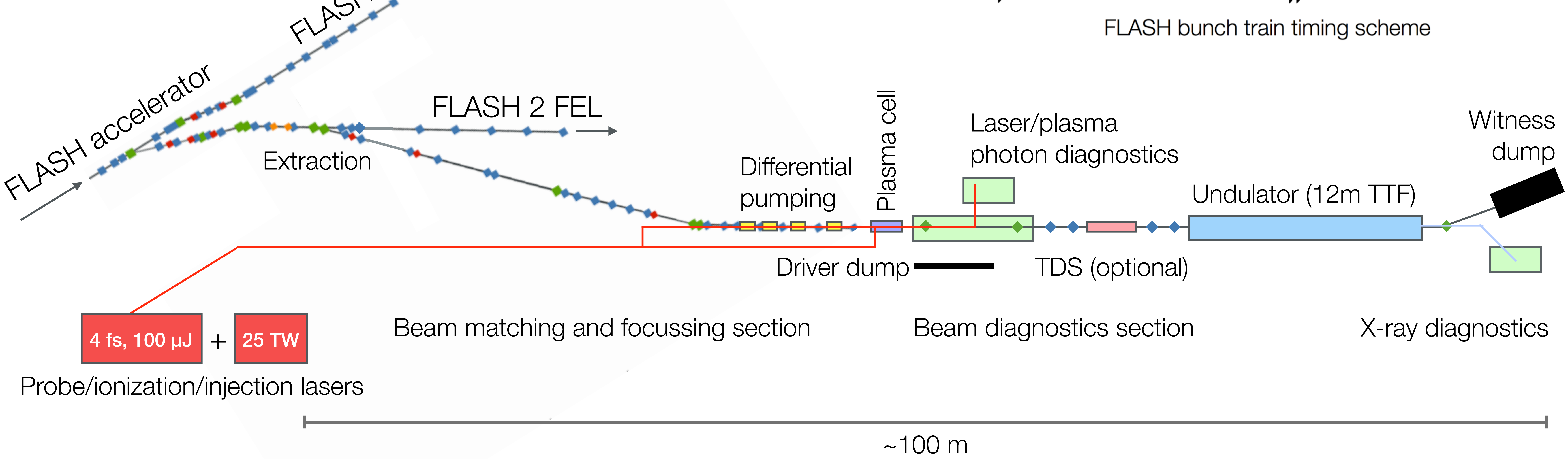


- FLASH is a water-window FEL user facility

FLASHForward▸▸ beamline overview



FLASH bunch train timing scheme

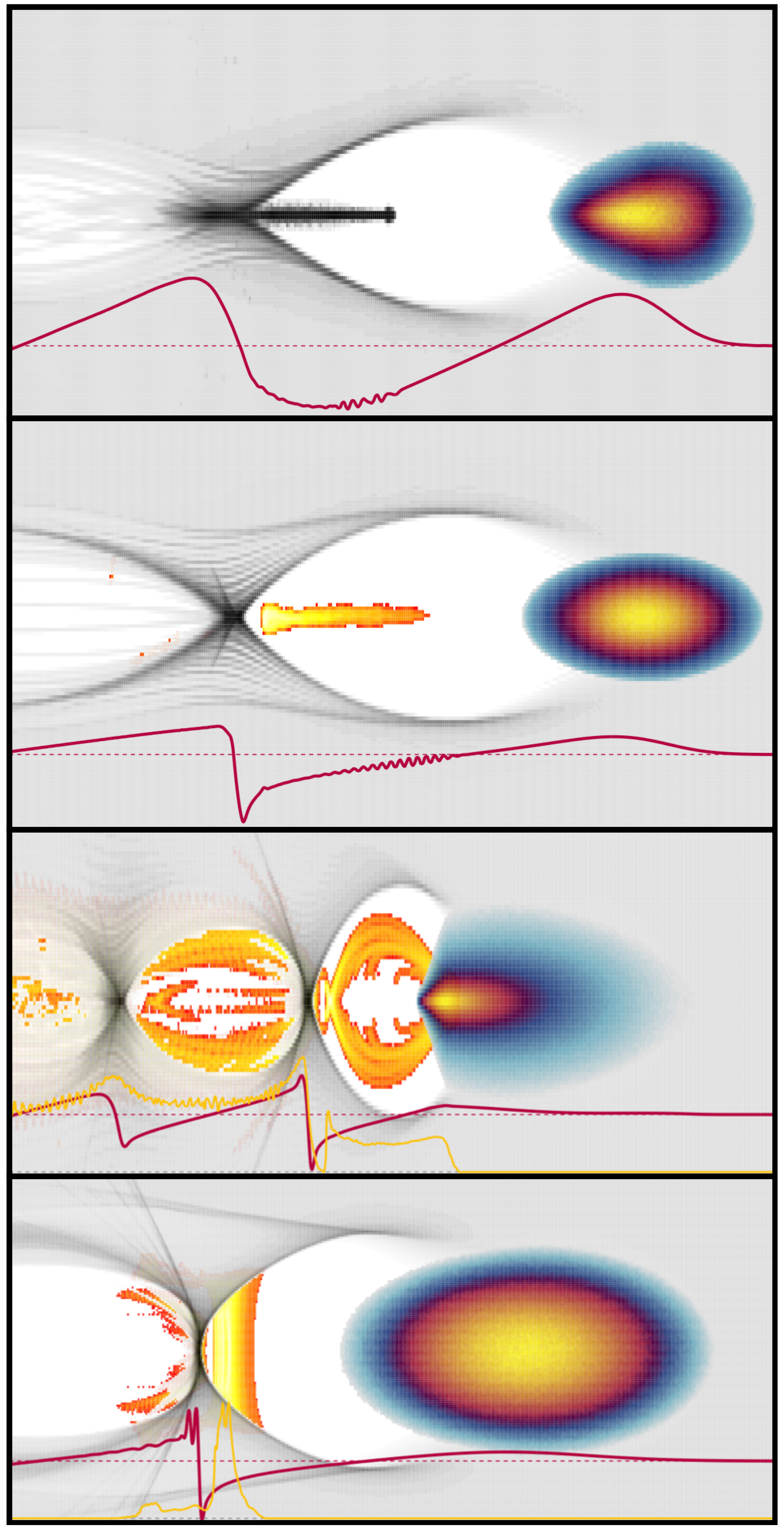


Capabilities of FLASH beams for FLASHForward

- FEL-quality (~1.25 GeV, ~0.1% energy spread, ~2 μm transverse norm. emittance), simultaneous with FLASH and FLASH 2
- Variable longitudinal beam shape (e.g. Gaussian, triangular), multi-kA peak current
- Sophisticated laser-to-beam synchronization for diagnostics/laser-triggered injection schemes
- 10 Hz repetition rate with up to 2 bunches at 1 μs separation + optional witness beam at ~100 fs separation (tunable)

Novel in-plasma beam-generation techniques for unprecedented beam properties

Quality of beams linked to control over initial population of wake-phase space at injection



- **Density down-ramp injection**
  J. Grebenyuk et al., NIM A 740, 246 (2014)

  $I_B \gtrsim 1\ \mathrm{kA}$

- **Laser-induced ionization injection (Trojan Horse injection)**
  B. Hidding et al., Physical Review Letters 108, 035001 (2012)

  $I_B \gtrsim 5\ \mathrm{kA}$

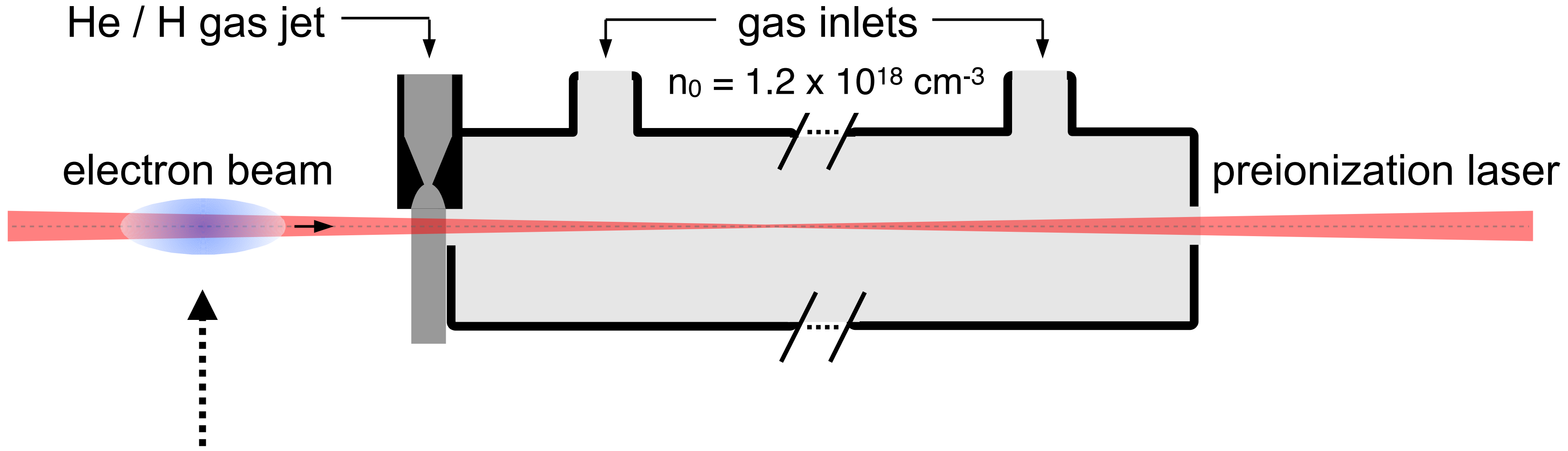
- **Beam-induced ionization injection**
  A. Martinez de la Ossa et al., NIM A 740, 231 (2014)

  $I_B \gtrsim 7.5\ \mathrm{kA}$

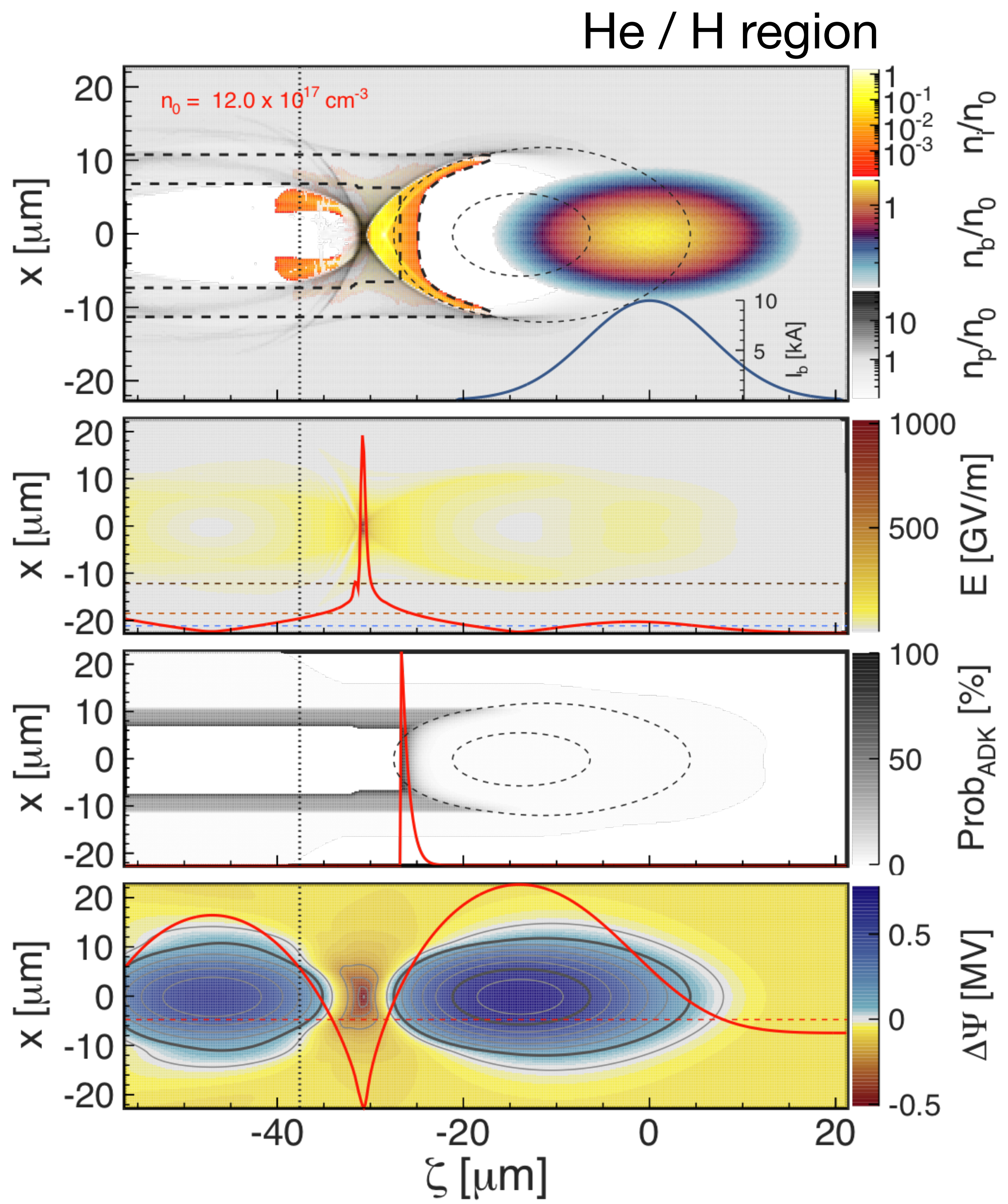
- **Wakefield-induced ionization injection**
  A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)

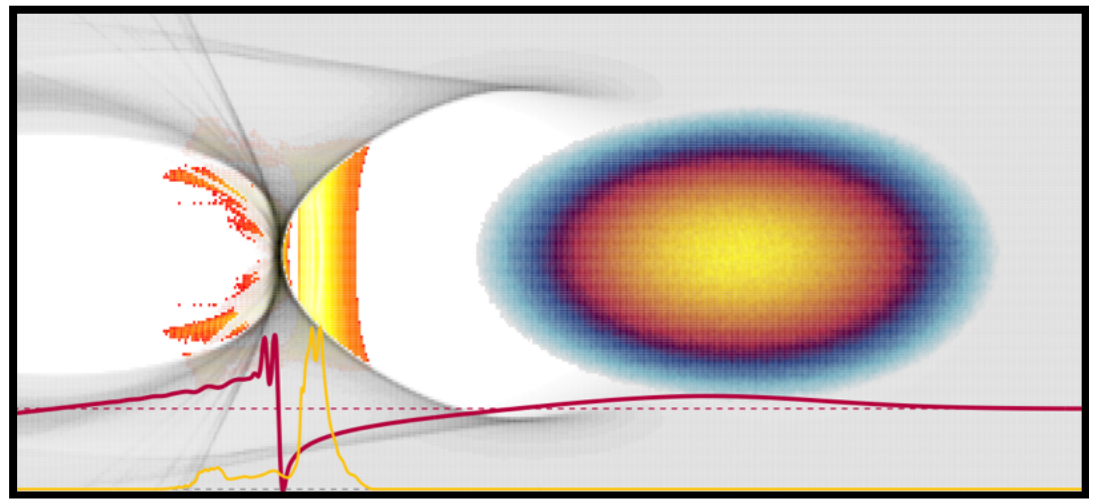
  $I_B \gtrsim 10\ \mathrm{kA}$

Wakefield-induced ionization injection utilizes strong fields of the generated wakefield to ionize dopant gas



Driver: E_b = 1 GeV, **I_b = 10 kA,** Q_b = 574 pC
σ_z = 7 μm, $\sigma_{x,y}$ = 4 μm, $\varepsilon_{x,y}$ = 1 μm





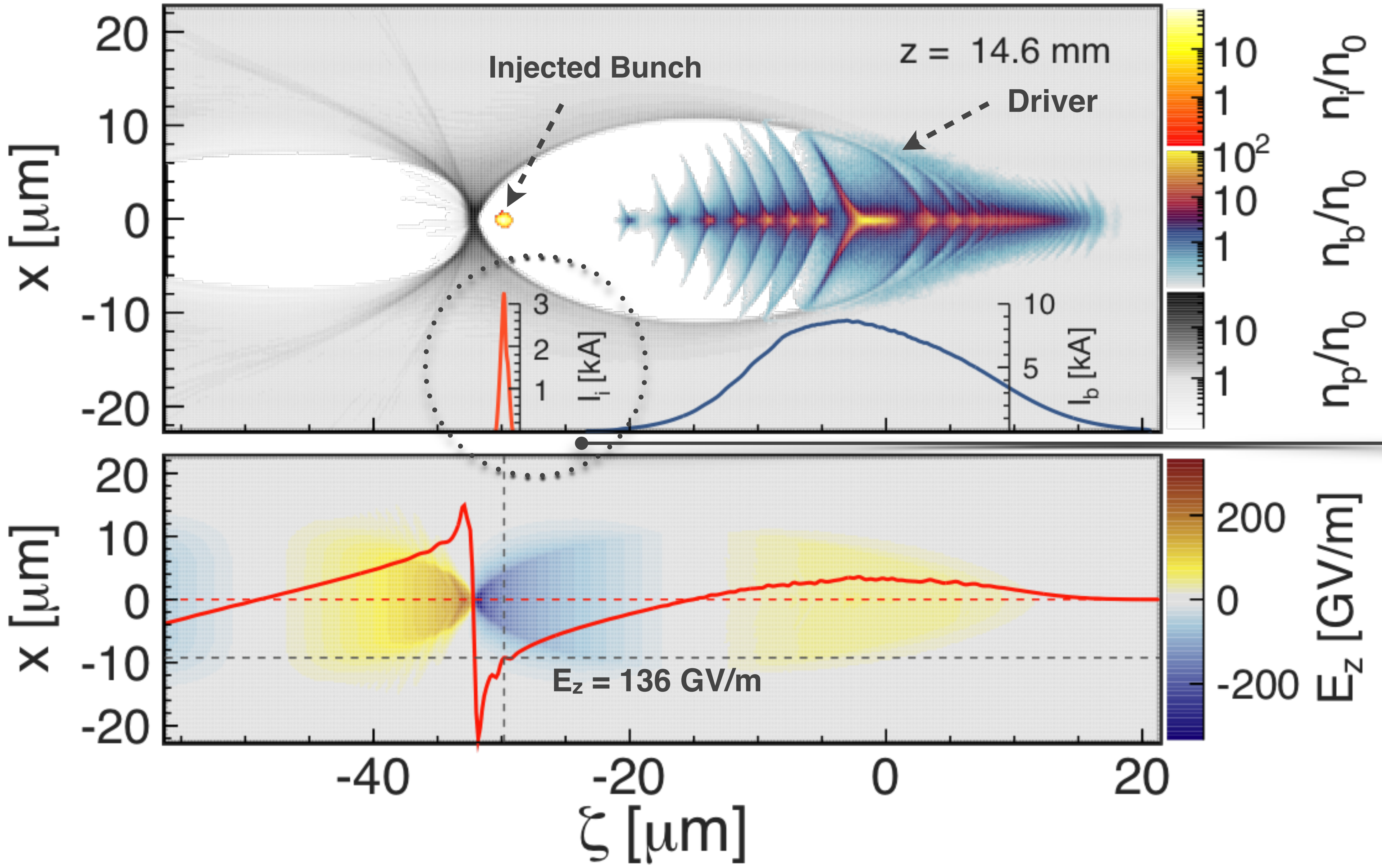
> **Wakefield-induced ionization injection**
A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)

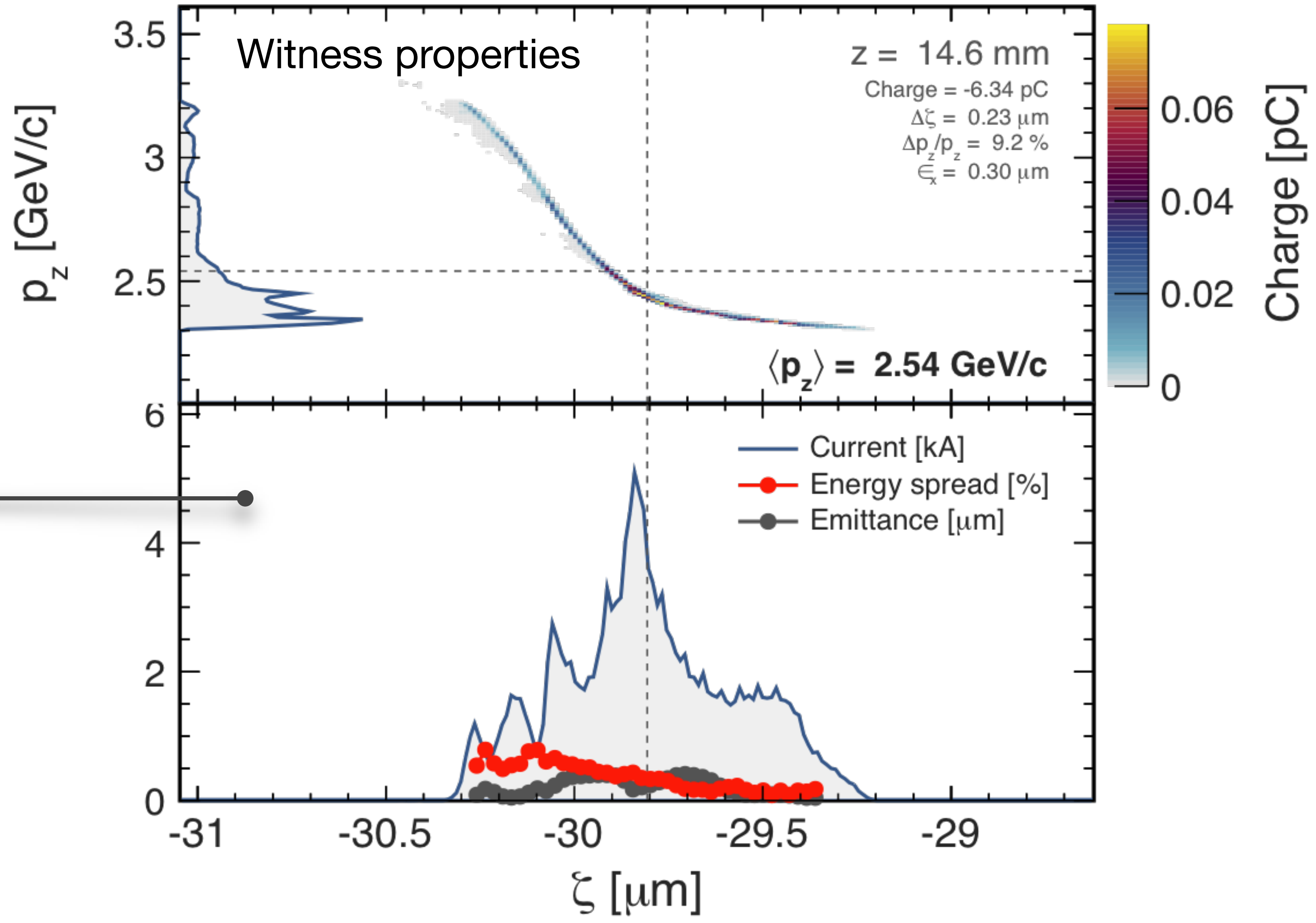
$$I_B \gtrsim 10\ \mathrm{kA}$$

Wakefield-induced ionization injection allows for beams with low emittance & sub-femtosecond durations

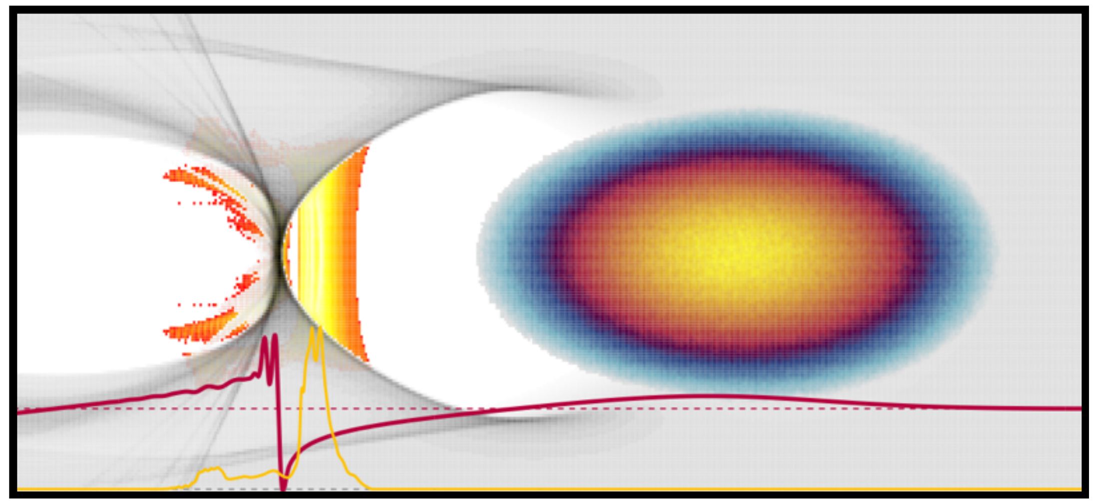
A. Martinez de la Ossa *et al.*, Phys Plasmas **22**, 093107 (2015)

Driver and witness bunch after 14.6 mm in plasma





- Duration: 770 as rms
- Current: 5 kA (tunable)
- Normalized emittance: 300 nm
- Uncorrelated energy spread: < 1%



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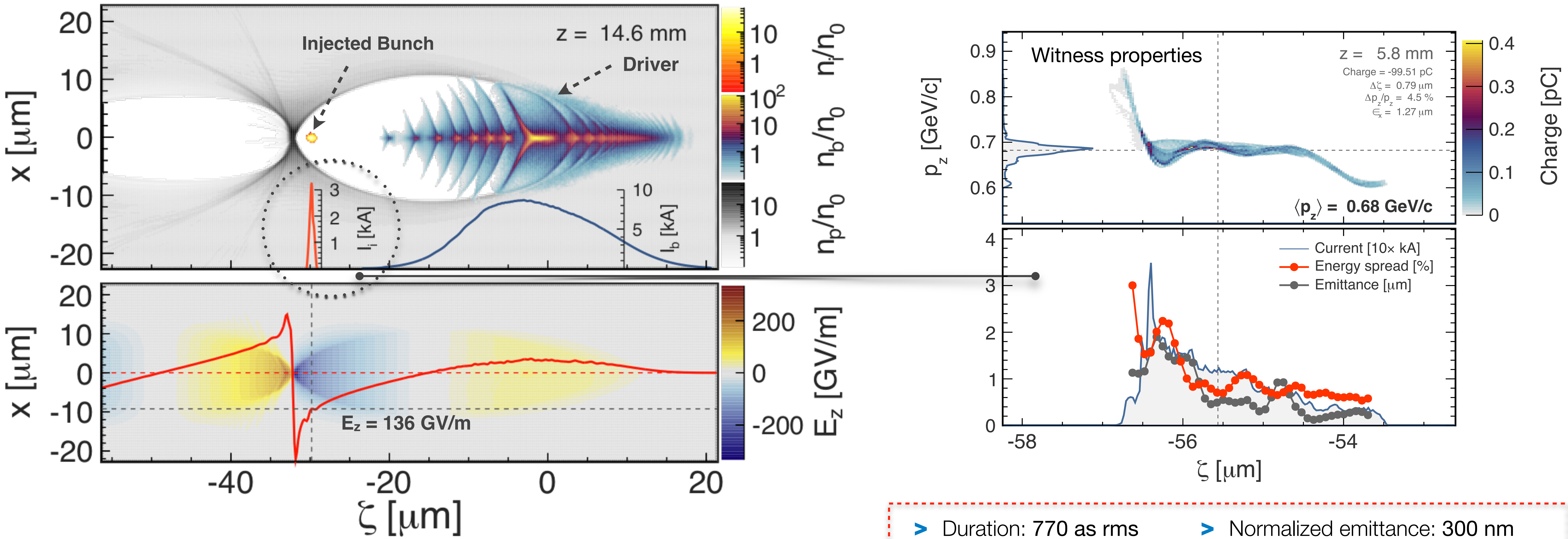

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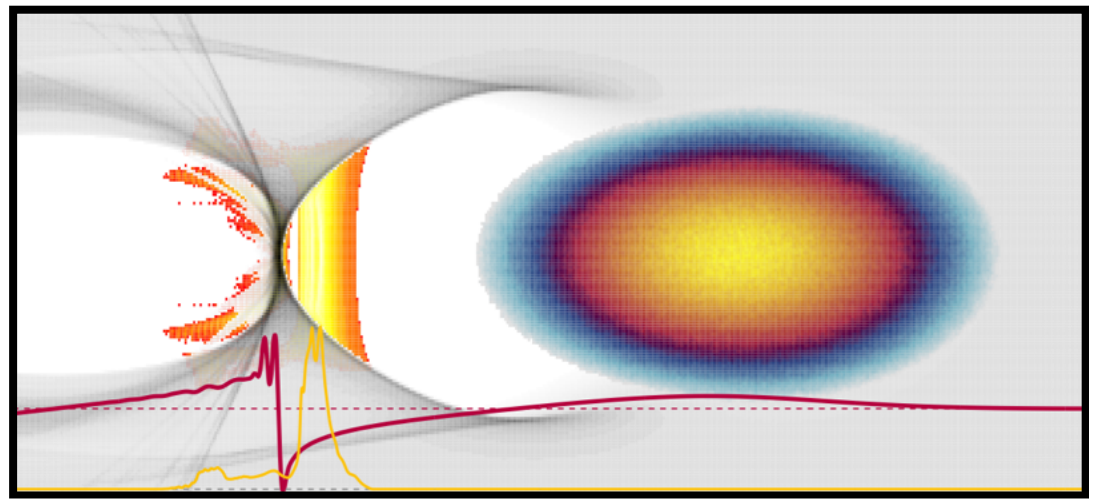

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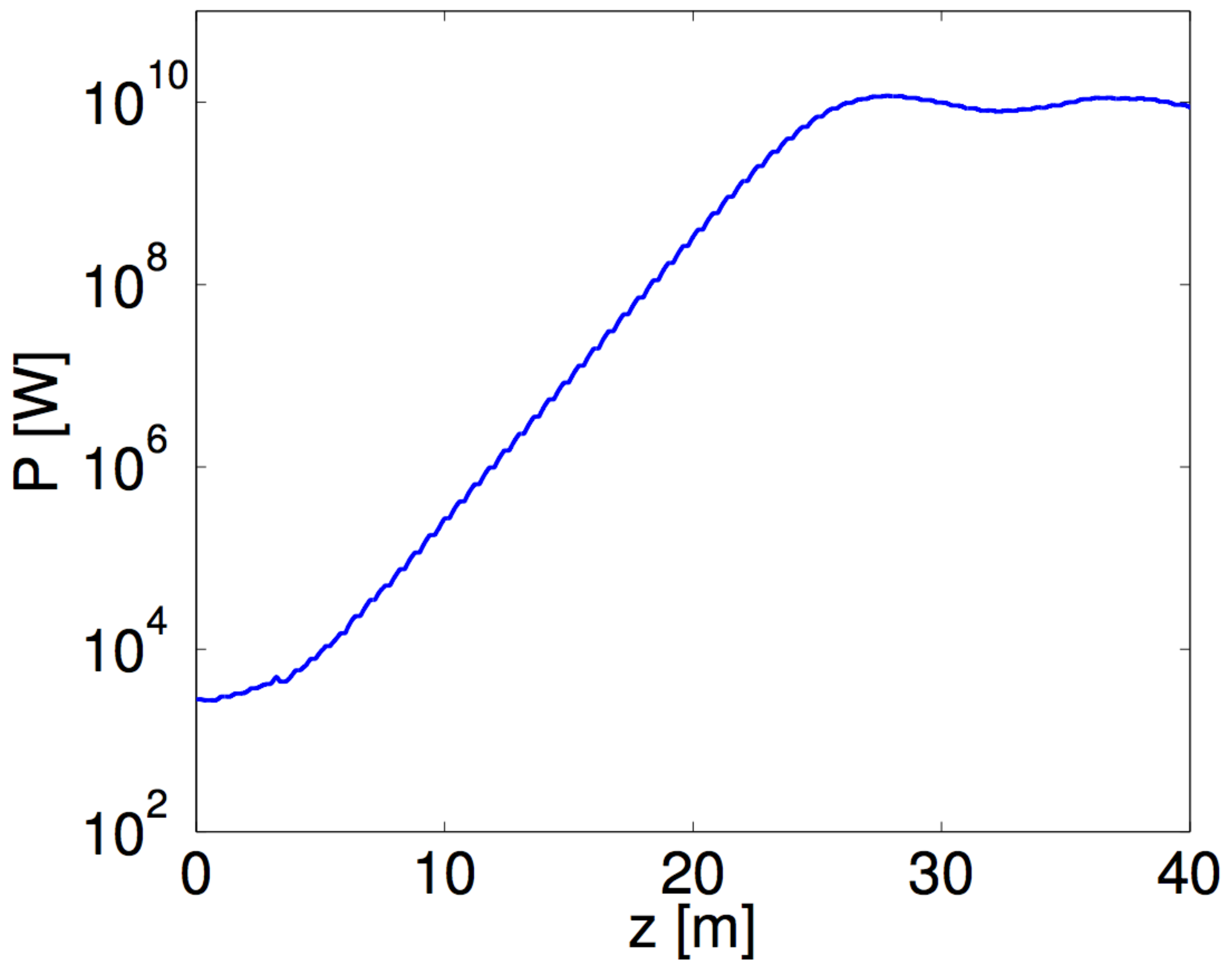
- Time-independent GENESIS simulation



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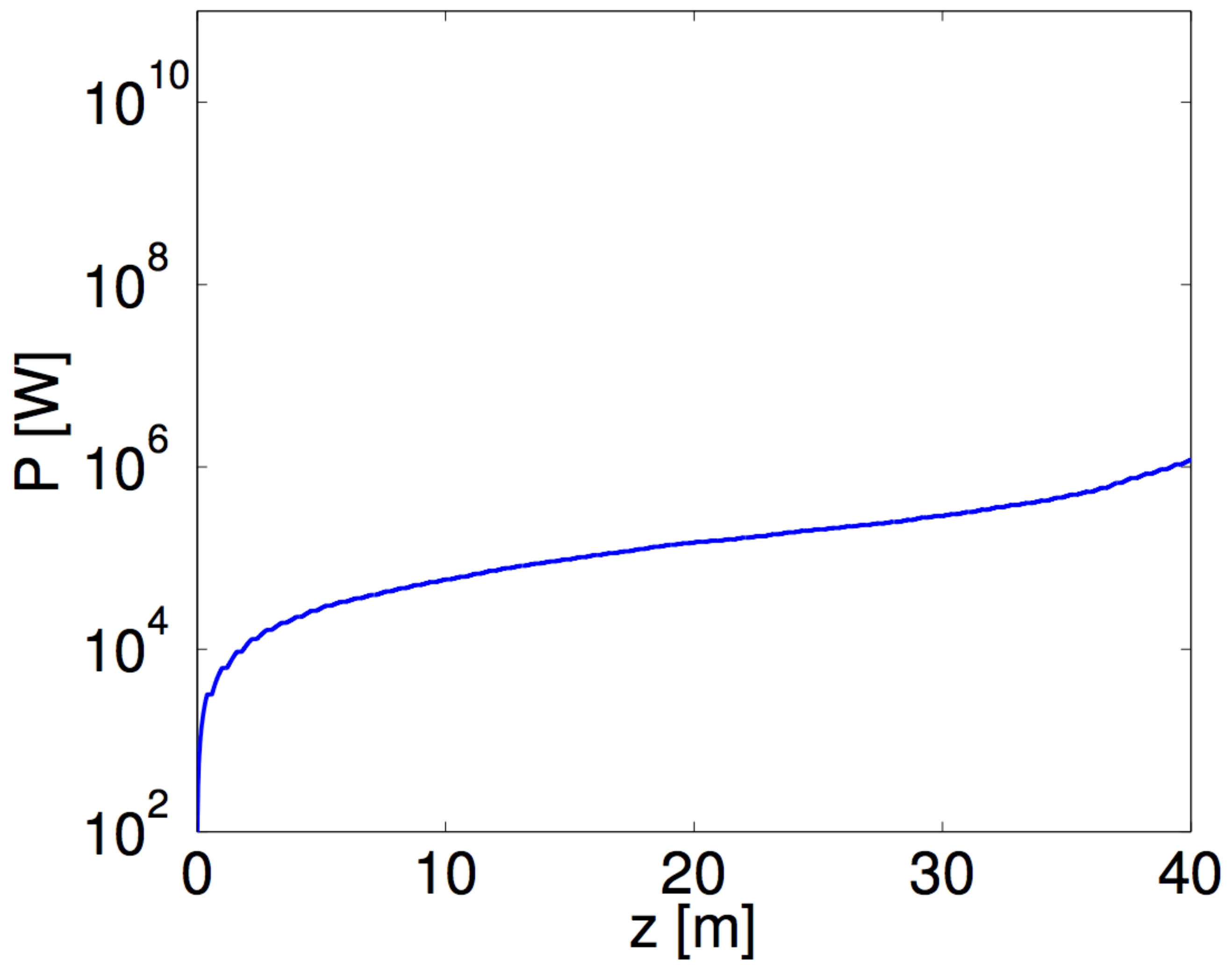
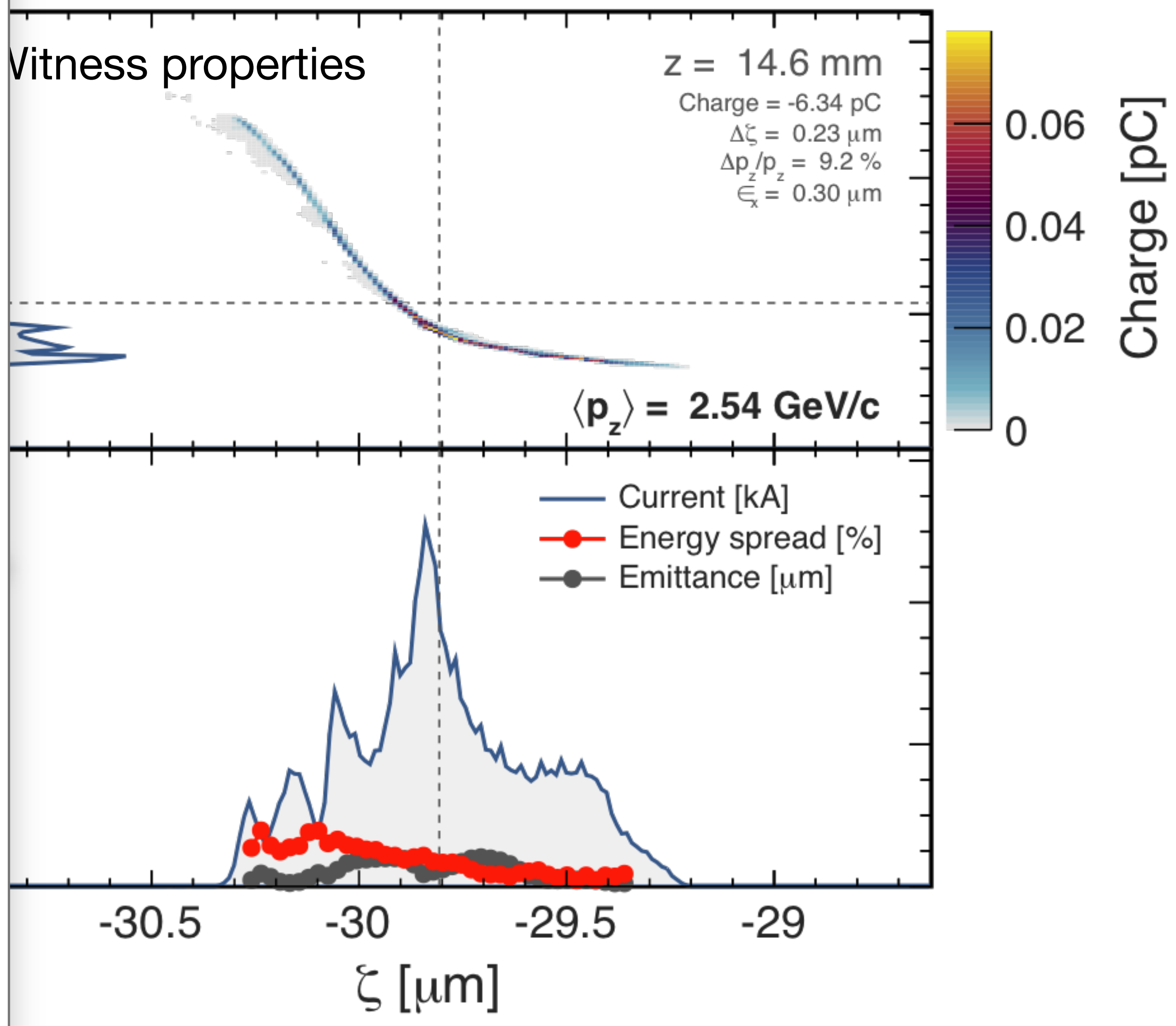
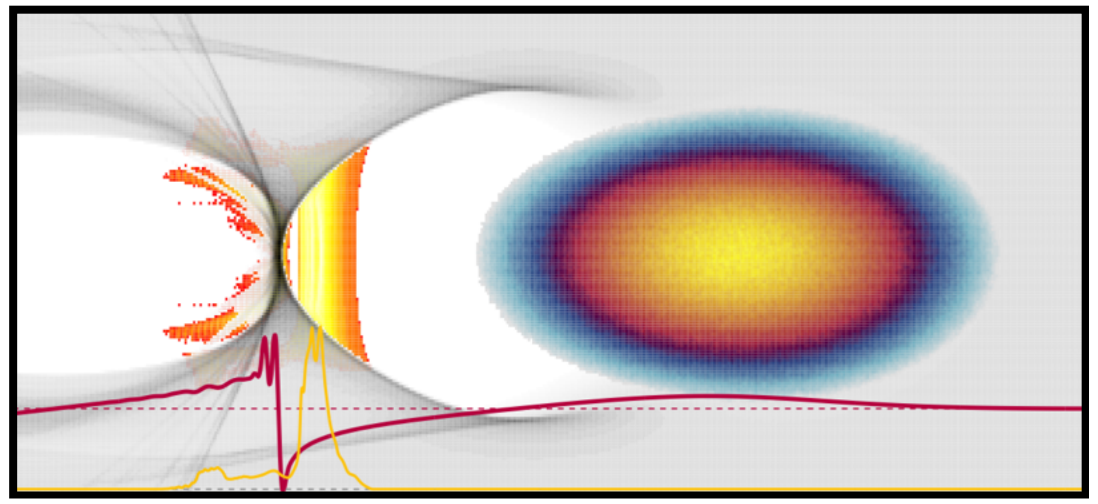


Beam: E = 2.5 GeV, σ_Δ = 0.5%, I_e = 5 kA, ε_n = 0.3 μm, σ_z = 0.23 μm

TTF undulators: K_0 = 1.21, λ_u = 2.73 cm, β = 5 m



- 70 as rms
- Normalized emittance: 300 nm
- Current: 5 kA (tunable)
- Uncorrelated energy spread: < 1%



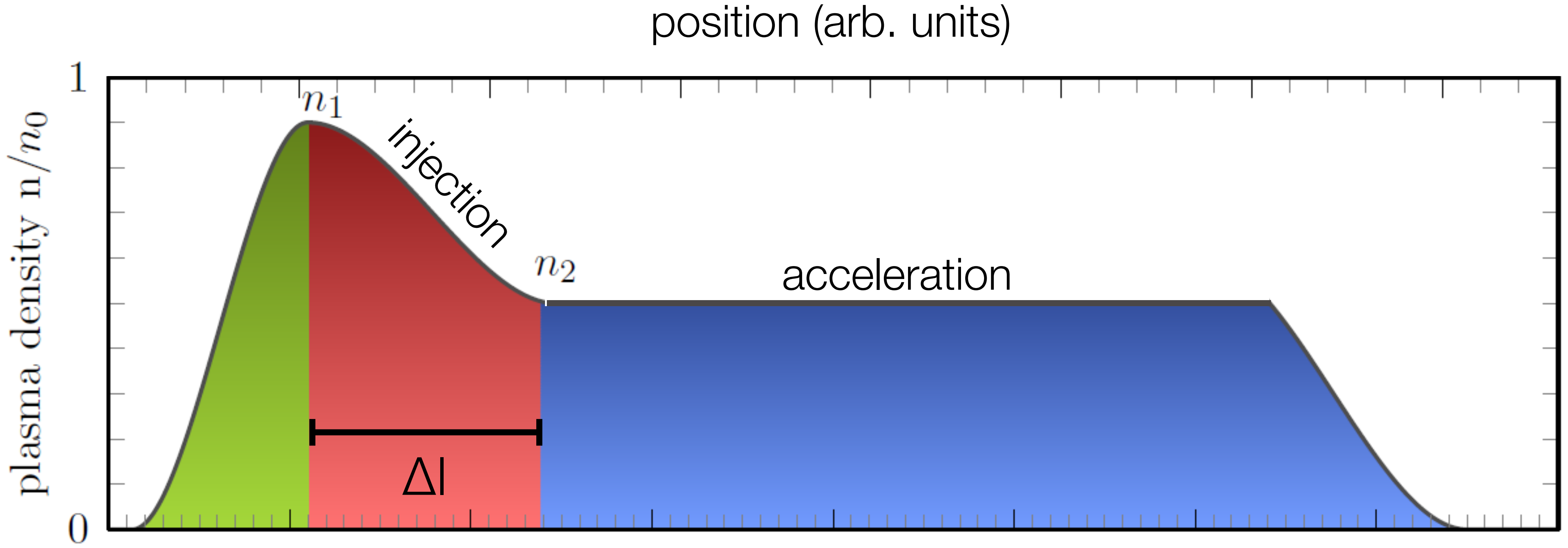
- Wakefield-induced ionization injection

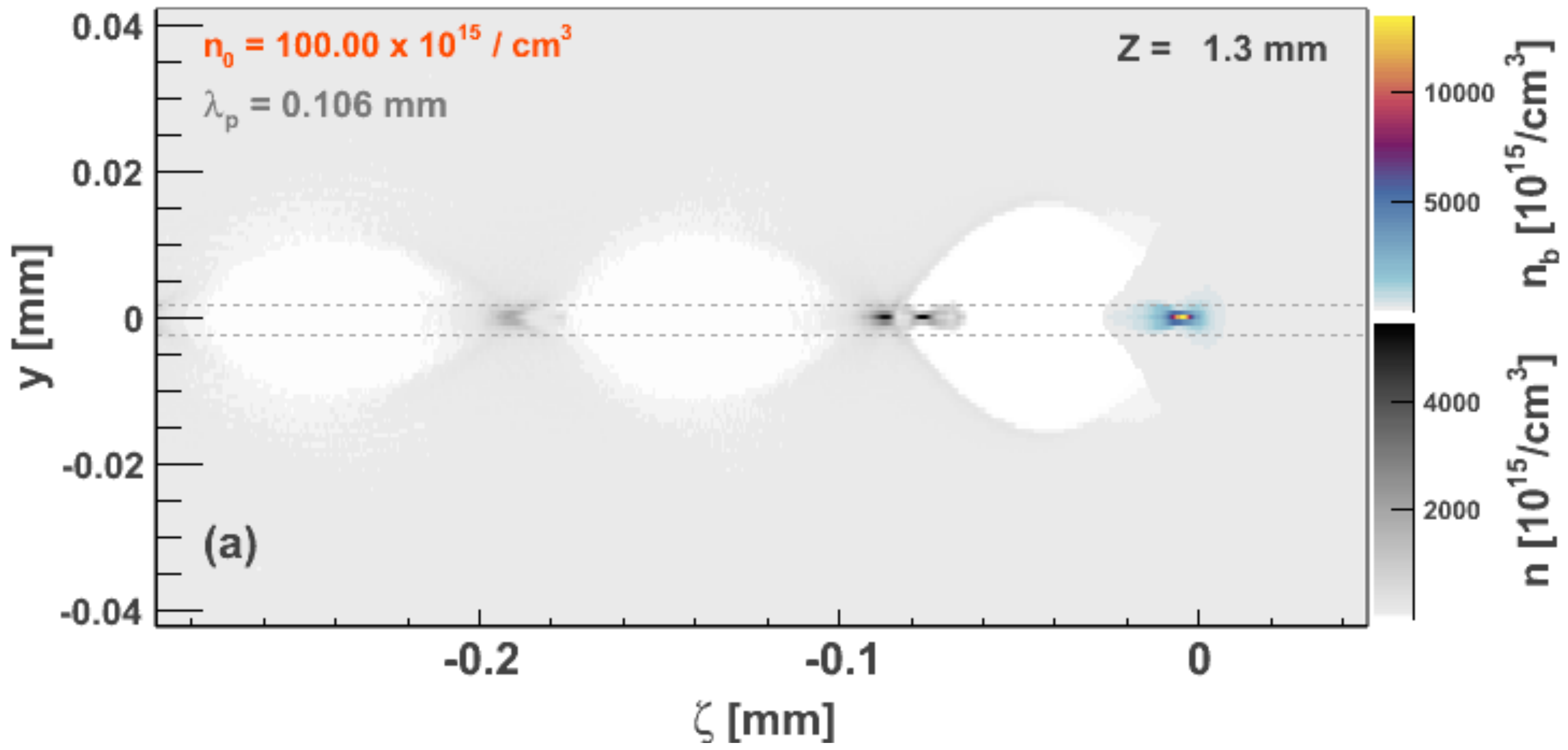
A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)

$$I_B \gtrsim 10\ \mathrm{kA}$$

Density down-ramp injection produces longer pulse duration, low-transverse-emittance witness beams

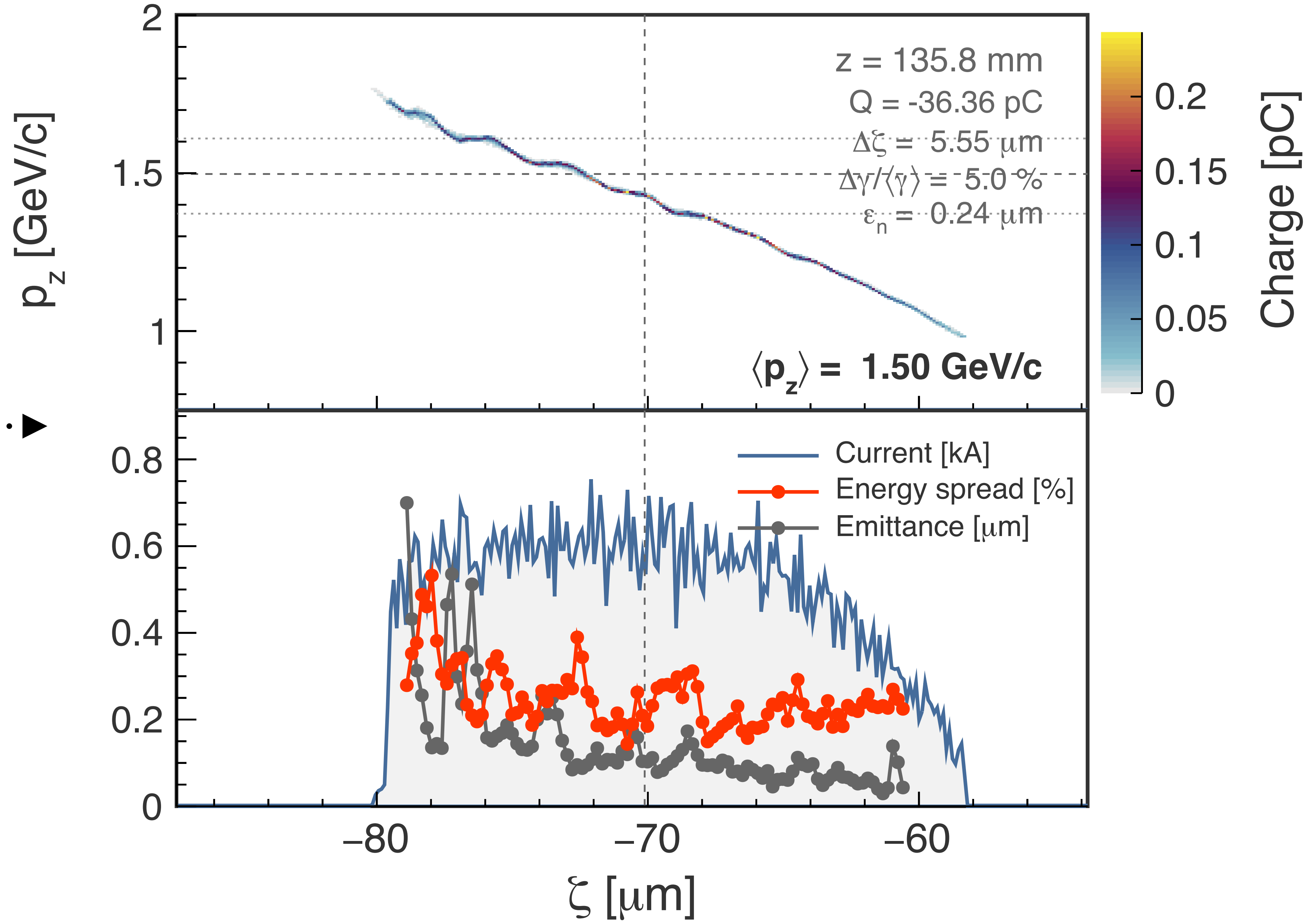
→ J. Grebenyuk et al., NIM A 740, 246 (2014)





Witness-beam parameters after 136 mm of propagation

- standard FLASH driver beam at 2.5 kA
- witness beam at 1.5 GeV with 1.0 GeV driver
- further acceleration to ~2.5 GeV possible
- projected normalized transverse emittance 0.24 µm
- bunch duration 18 fs rms
- strong longitudinal correlation



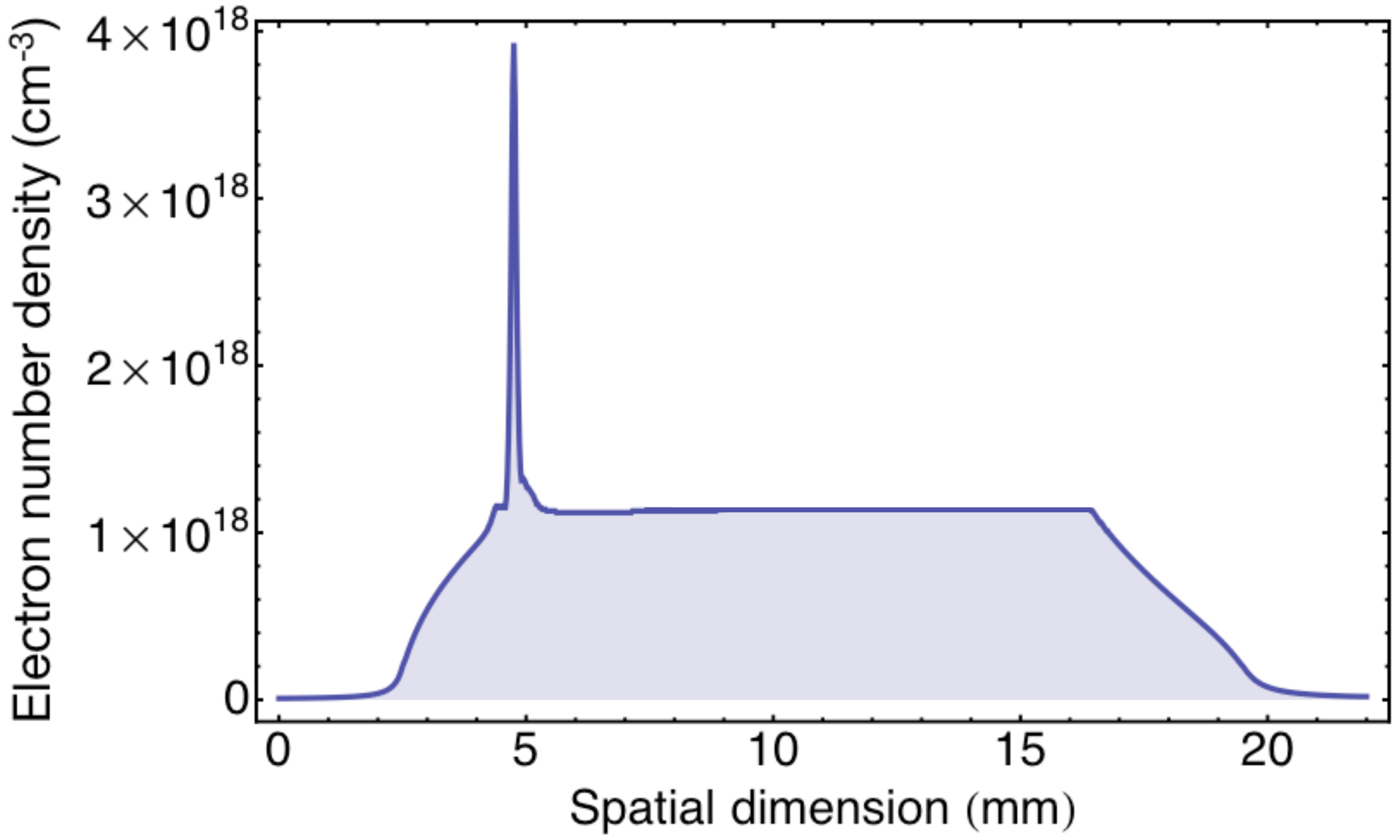
Plasma-cell design supports PWFA-injection schemes and emittance preservation

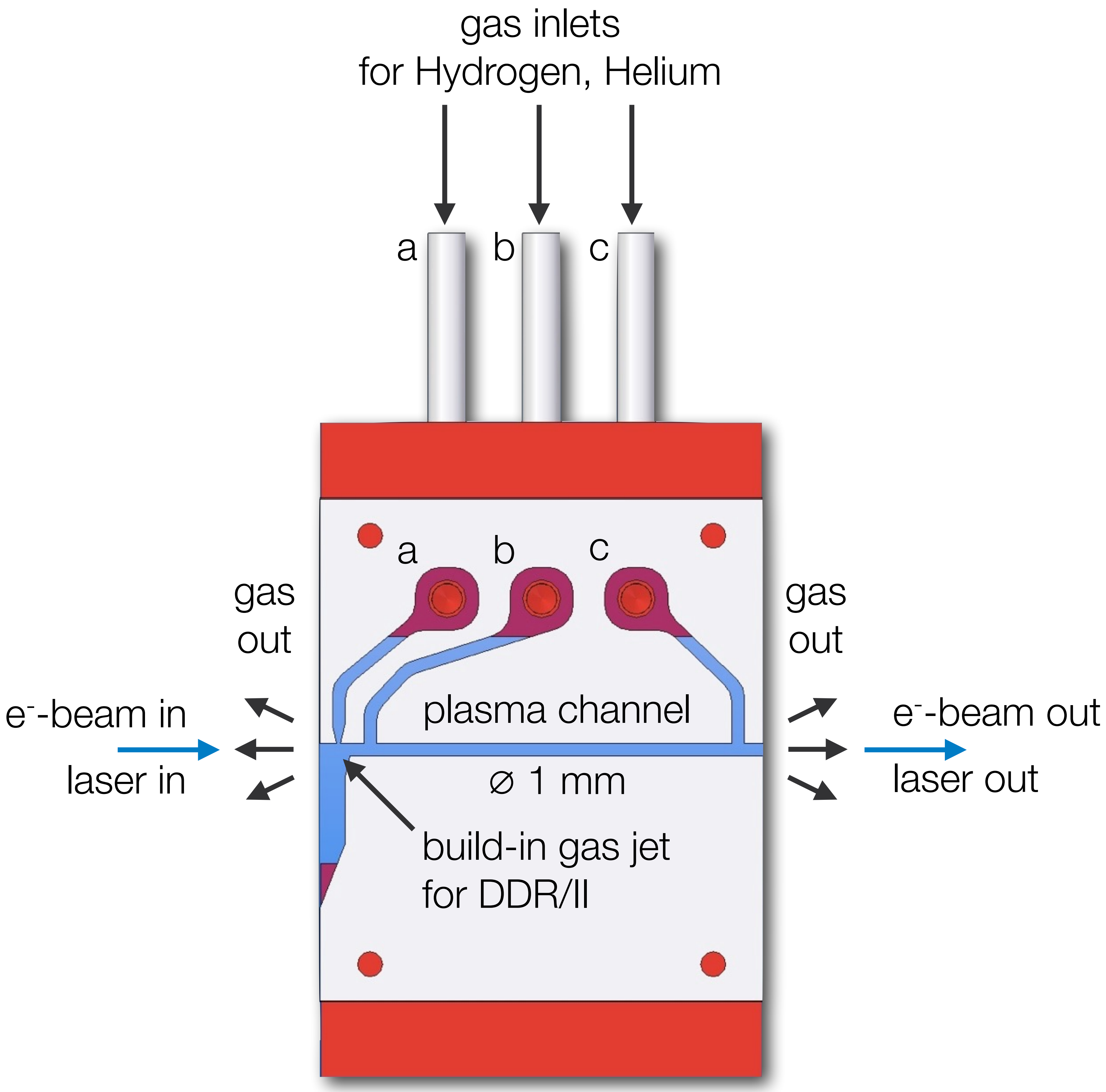
scheme by L. Schaper (DESY), N. Delbos, A. Maier (UHH)

Design

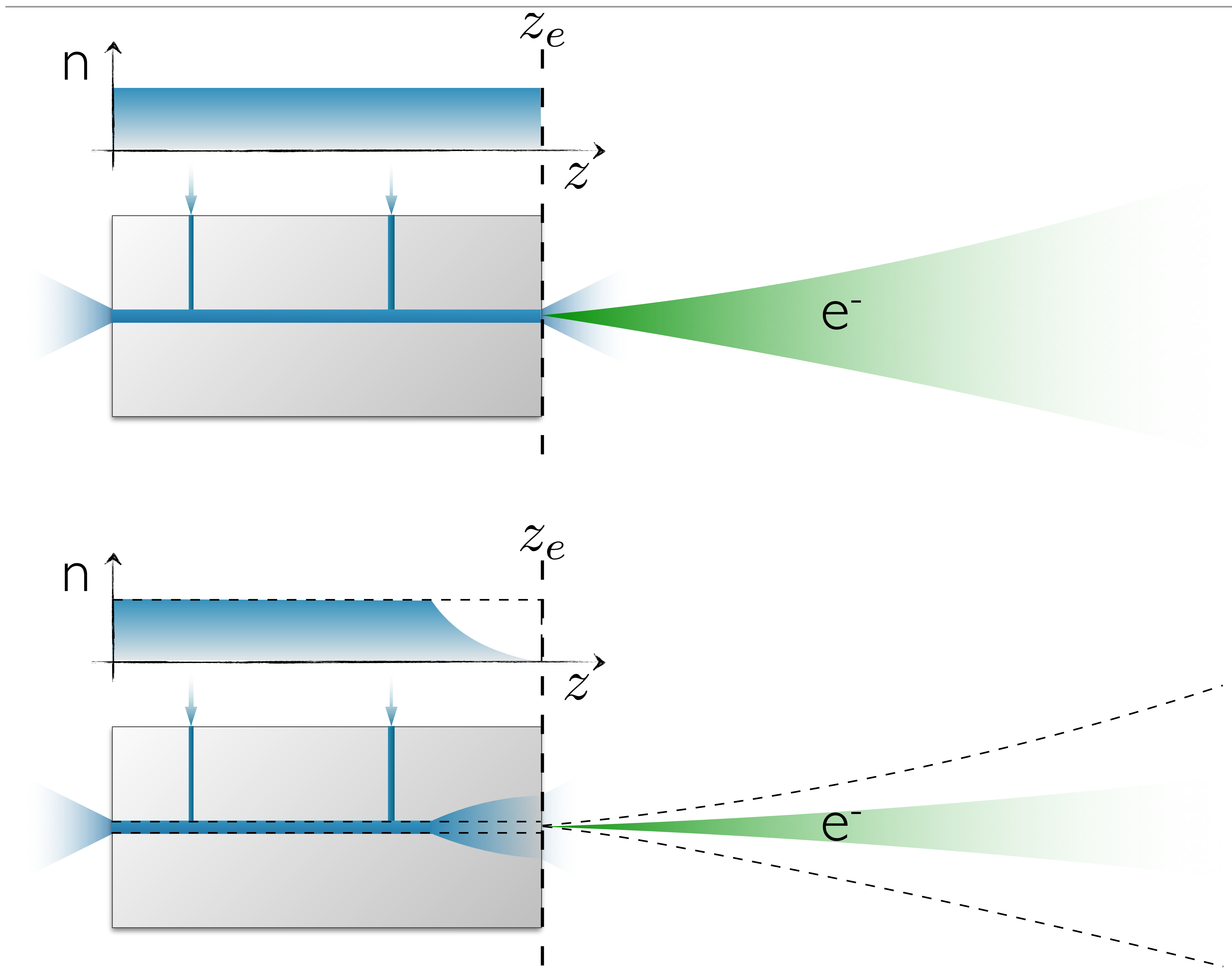
- window-less to avoid emittance growth
- compatible with plasma creation by ionization laser, electric discharge, or beam electric fields
- transverse laser probing possible
- redundant installation inside vacuum chamber possible
- source operated from **10^{14}** to **10^{19} cm^{-3}**

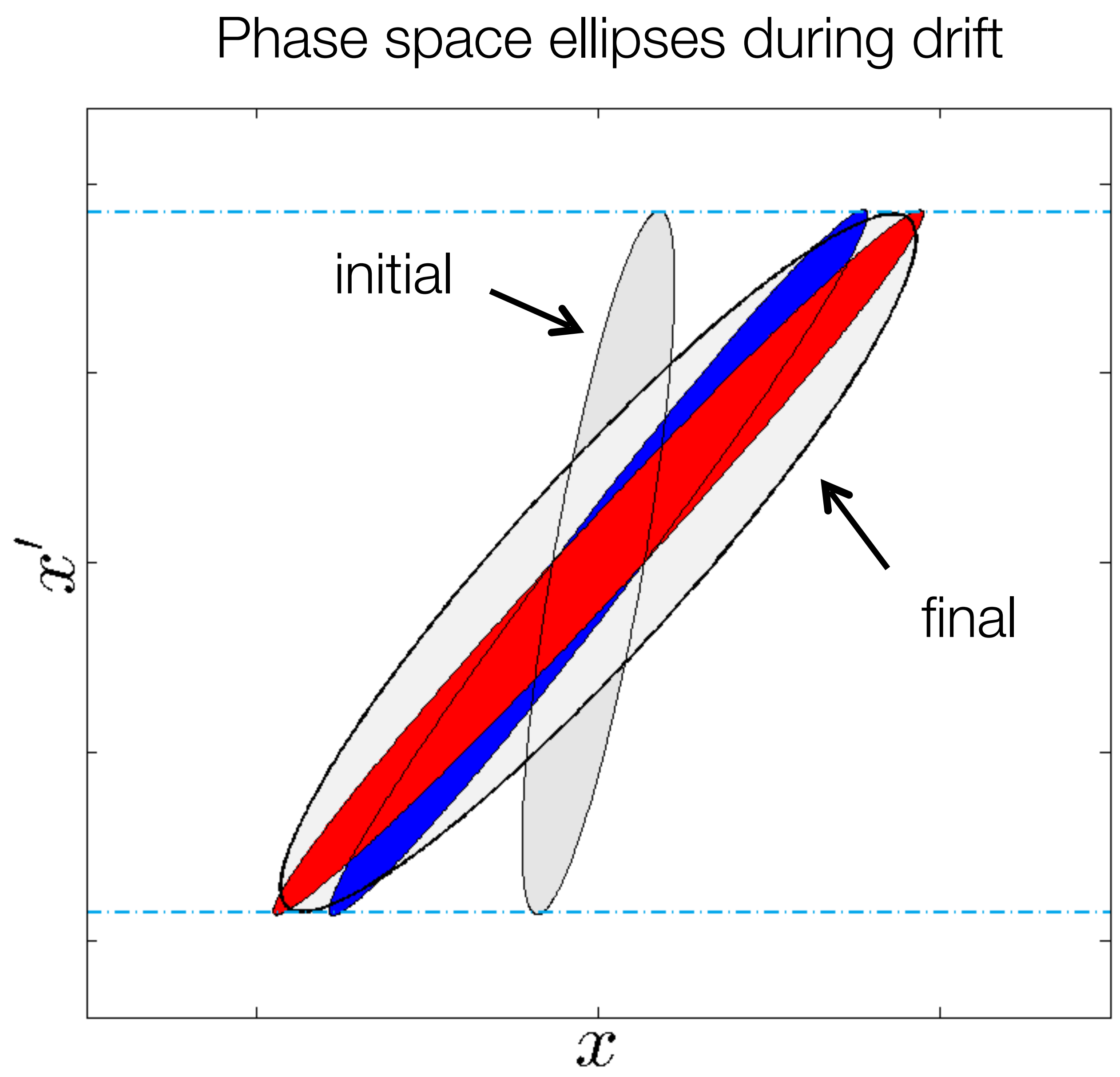
- example longitudinal density profile, short cell





Beam release I: tailored plasma-to-vacuum transition to adiabatically increase beta, minimize emittance growth




Phase space ellipses during drift

- beams at plasma exit:
  - ~% level energy spread
  - small beta function, mrad divergence
- leads to transverse emittance growth in free drift

$$\varepsilon_n{}^2 \cong \langle \gamma \rangle^2 \cdot \left(\sigma_E{}^2 \sigma_{x'}{}^4 s^2 + \varepsilon^2\right)$$

→ K. Floettmann, Phys. Rev. STAB 6, 034202 (2003)

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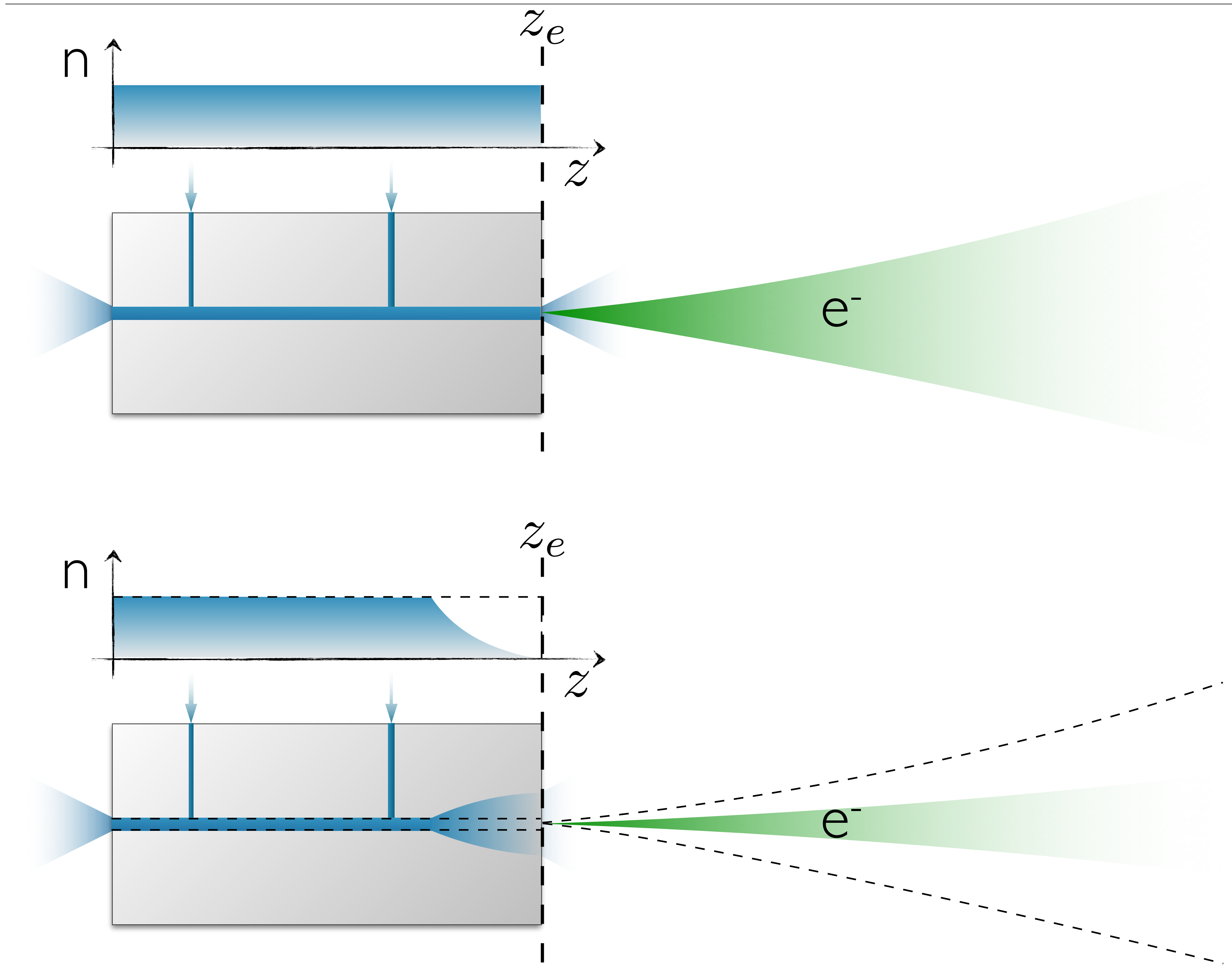

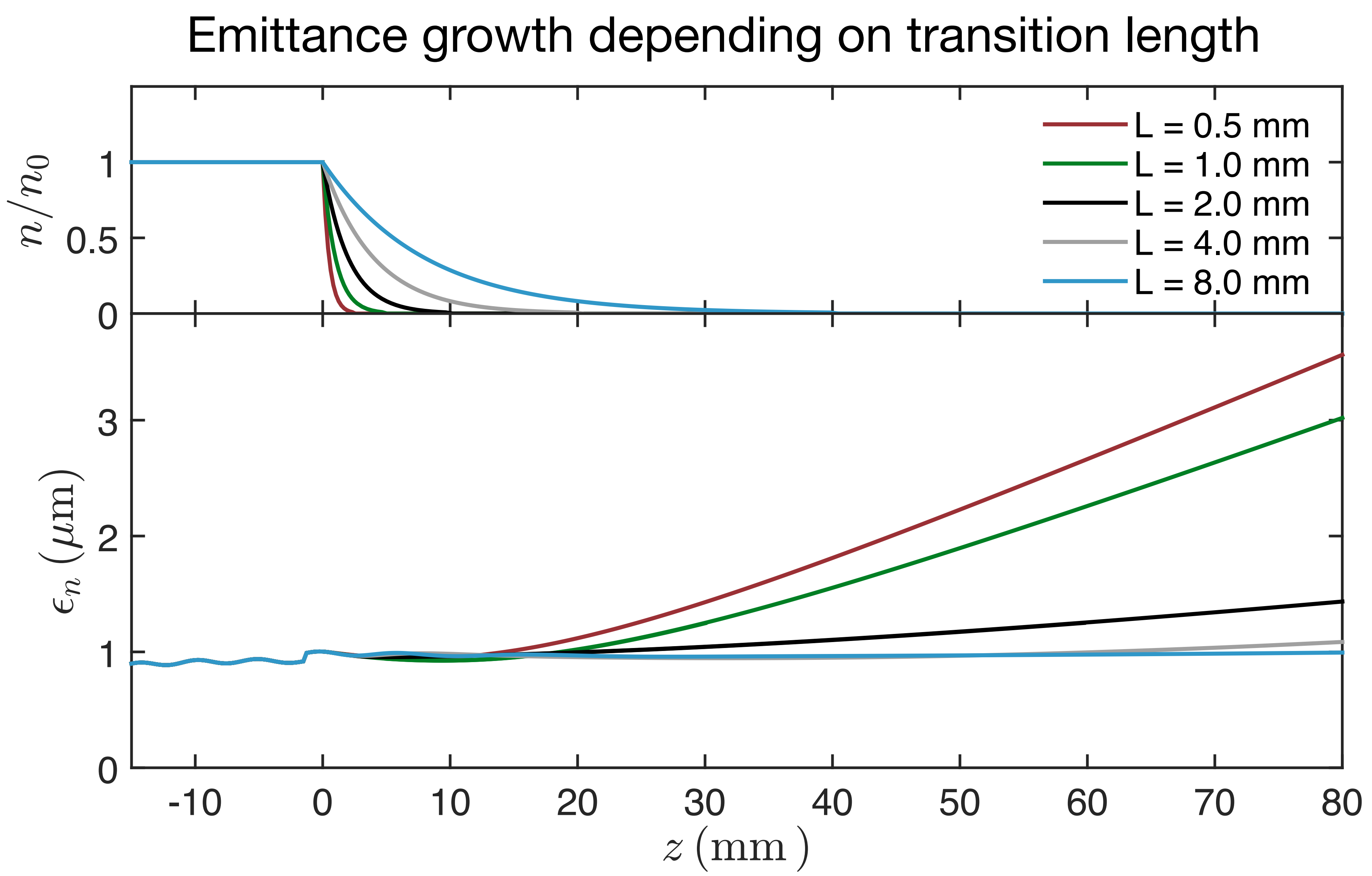

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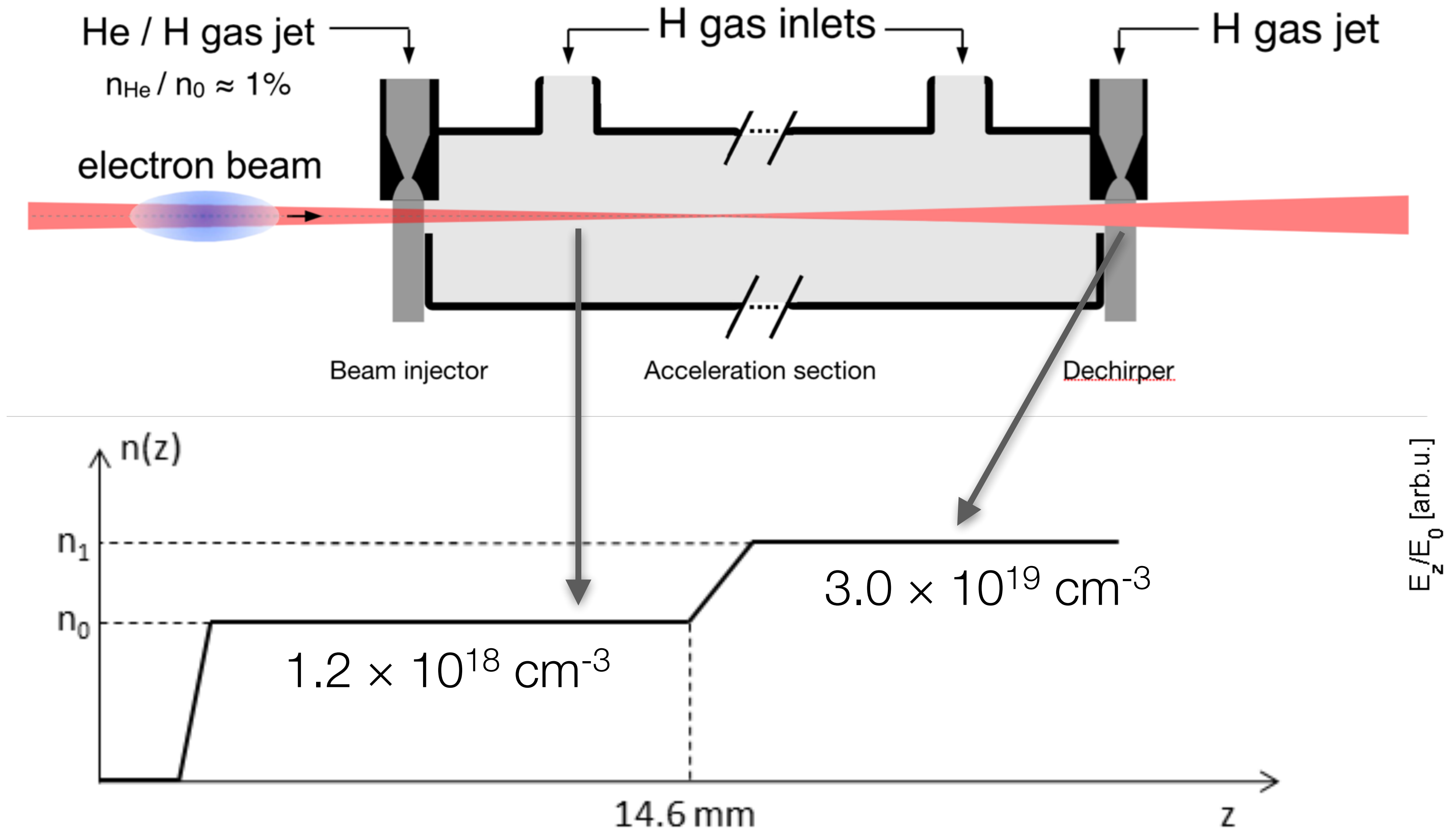
- Plasma-to-vacuum transition » beta for emittance preservation

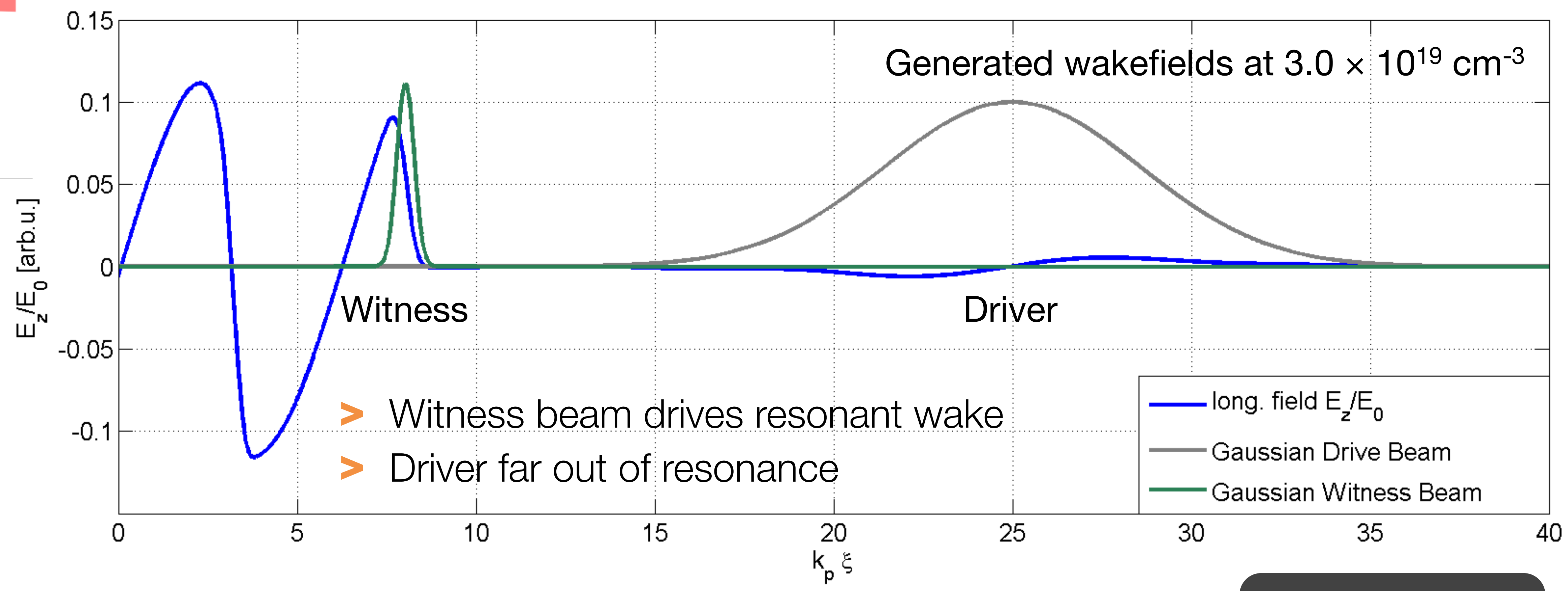
Beam release II: tailored plasma-to-vacuum transition to dechirp beams



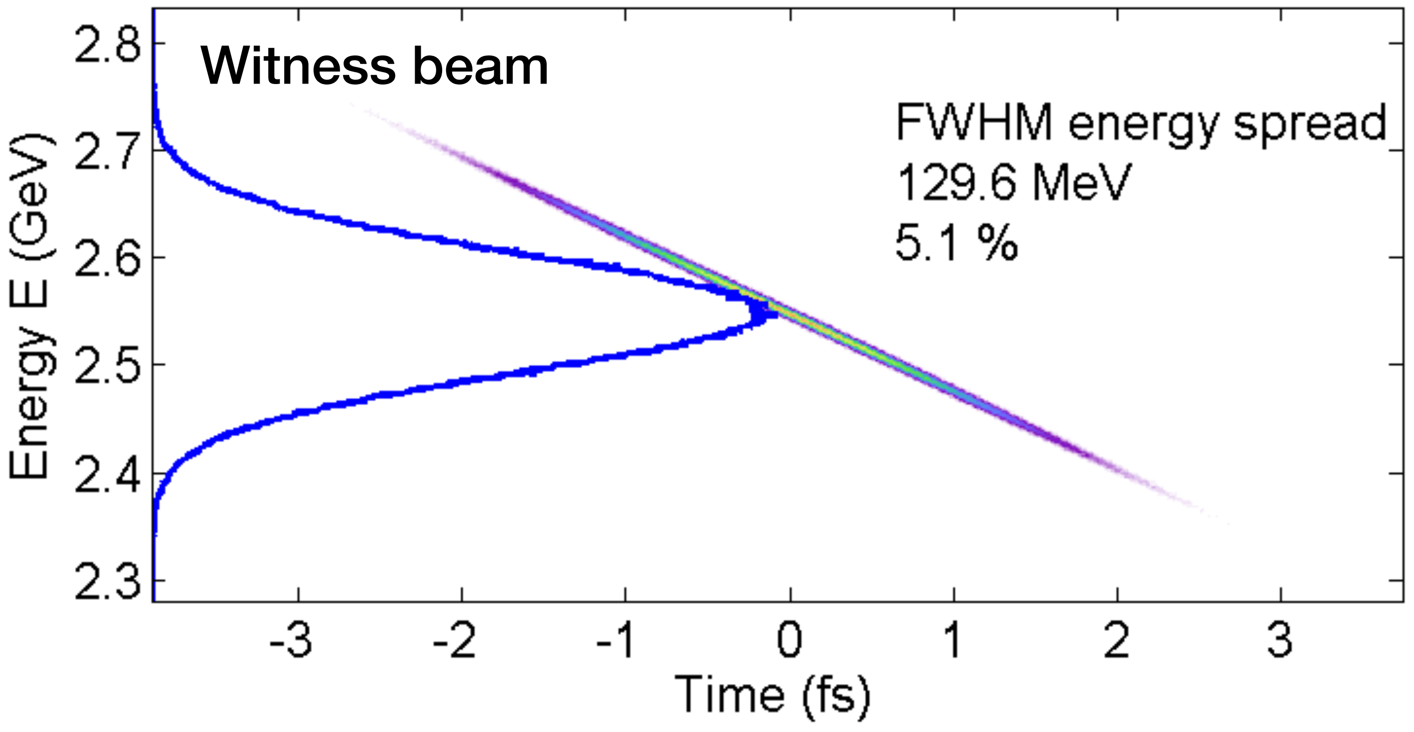
- Dechirping in plasma analogous to corrugated pipe[1] and dielectric structure[2]

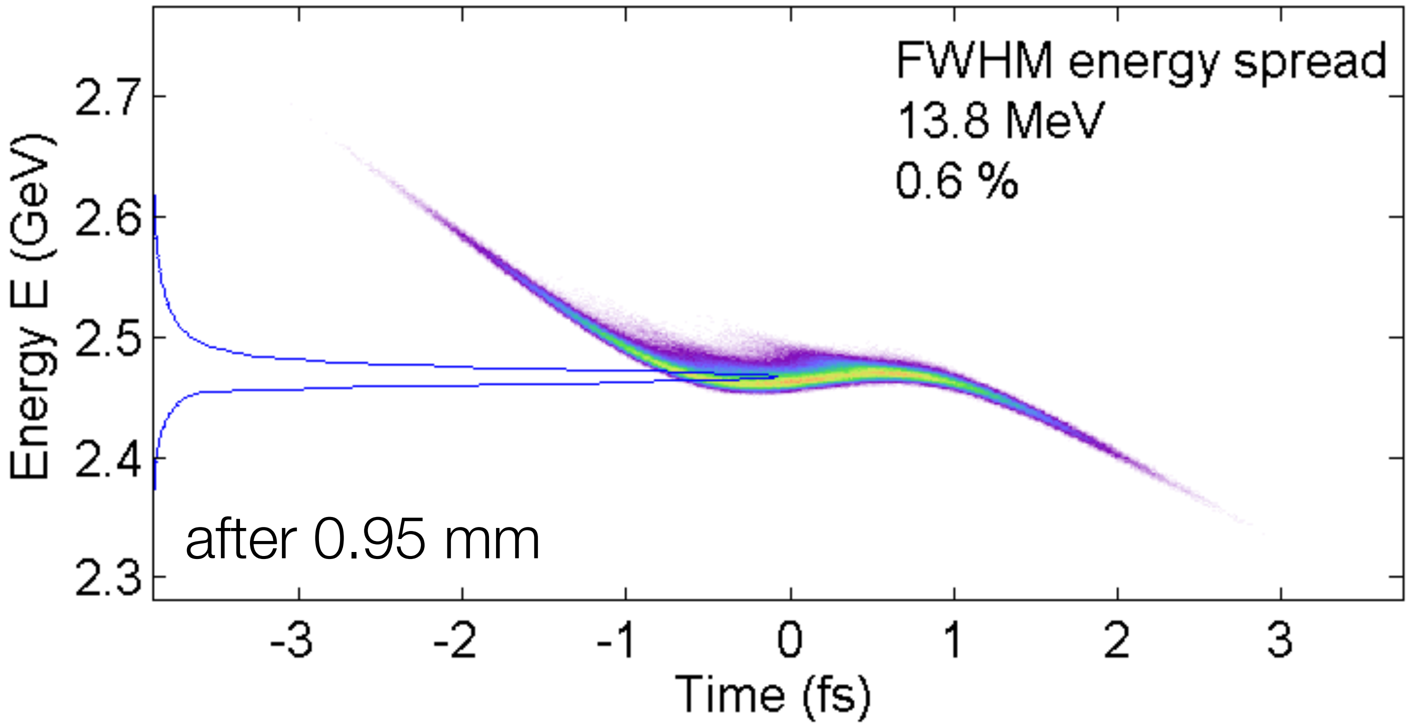
[1] K.L.F. Bane and G. Stupakov, NIM A 690, 106 (2012)

[2] S. Antipov et al., Phys. Rev. Lett. 112, 114801 (2014)



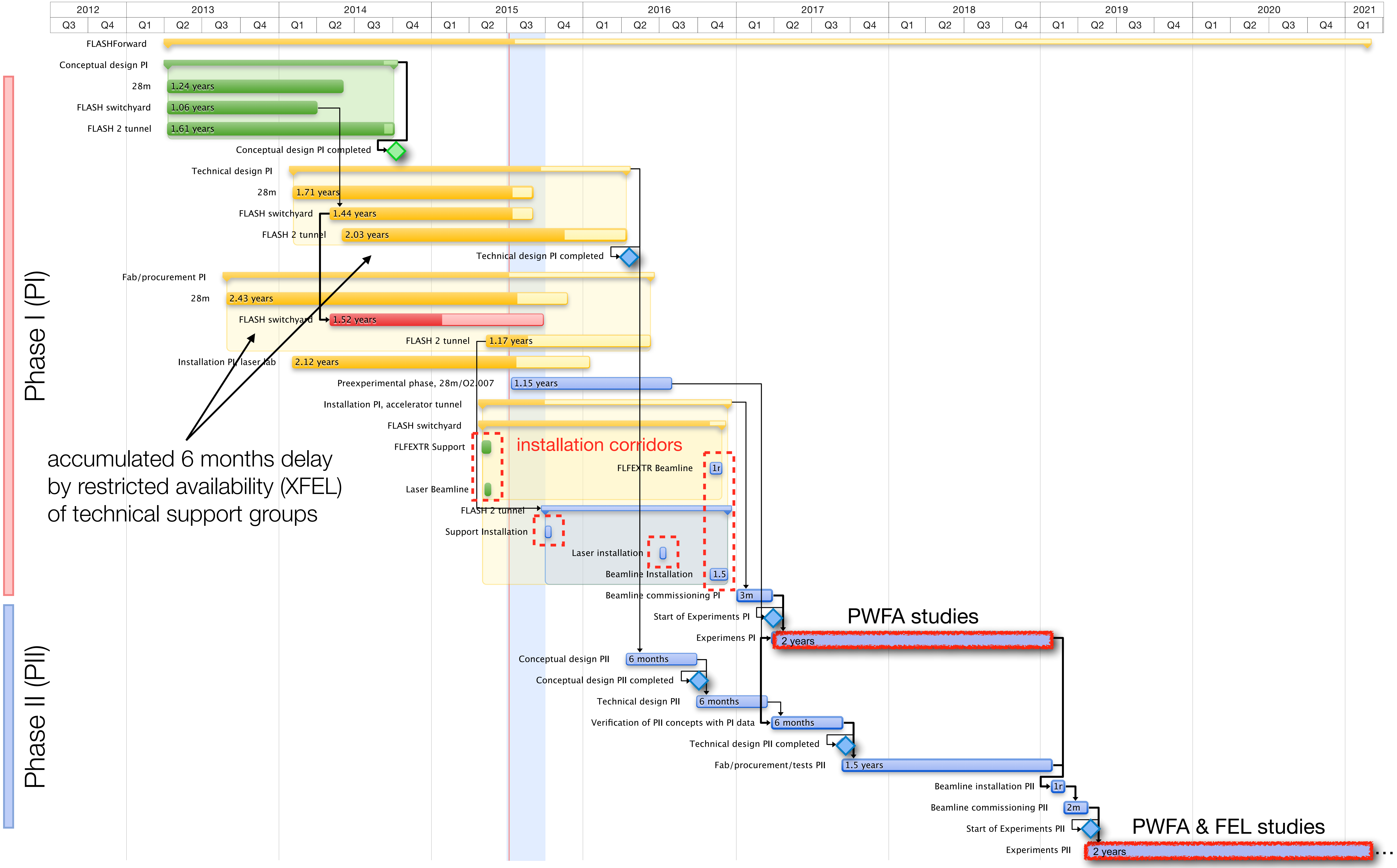
- Witness beam drives resonant wake
- Driver far out of resonance





- Drive beam
  $\sigma_z = 7$ μm, $\varepsilon_{x,y} = 1$ μm, $I_B = 10$ kA,
  $Q = 574$ pC, $E = 1$ GeV
- Witness beam
  $\sigma_z = 0.23$ μm, $\varepsilon_{x,y} = 10.3$ μm, $I_B = 5$ kA,
  $Q = 32$ pC, $E = 2.5$ GeV

Experiments to start in January 2017



accumulated 6 months delay by restricted availability (XFEL) of technical support groups

PWFA studies

PWFA & FEL studies

…

Summary

- **FLASH**Forward▸▸ aims at advancing novel-accelerator science by exploring plasma-wakefield acceleration
  - various external and internal witness-beam-injection schemes to achieve usable beam quality
  - the extraction of accelerated beams from plasma without significant quality degradation
  - the assessment of the usability of these beams in a free-electron laser
- Photon science applications will be pursued first as litmus test for plasma-accelerator technology
- FLASHForward is an important step to explore beam-driven wakefield acceleration and prepare it for applications

Goal: plasma accelerator research → usable plasma accelerators

Scientific project contributors

- Core FLASHForward team

Staff scientists

Eckhard Elsen
Bernhard Schmidt
Sven Karstensen

Engineers

Kai Ludwig
Frank Marutzky

Students

Jan-Patrick Schwinkendorf
Jan-Hendrik Erbe
Lars Goldberg
Olena Kononenko
Gabriele Tauscher
Violetta Wacker
Stefan Weichert
Alexander Aschikhin
Simon Bohlen
Jan-Niclas Gruse
Fabian Pannek
Dennis Borrisenko

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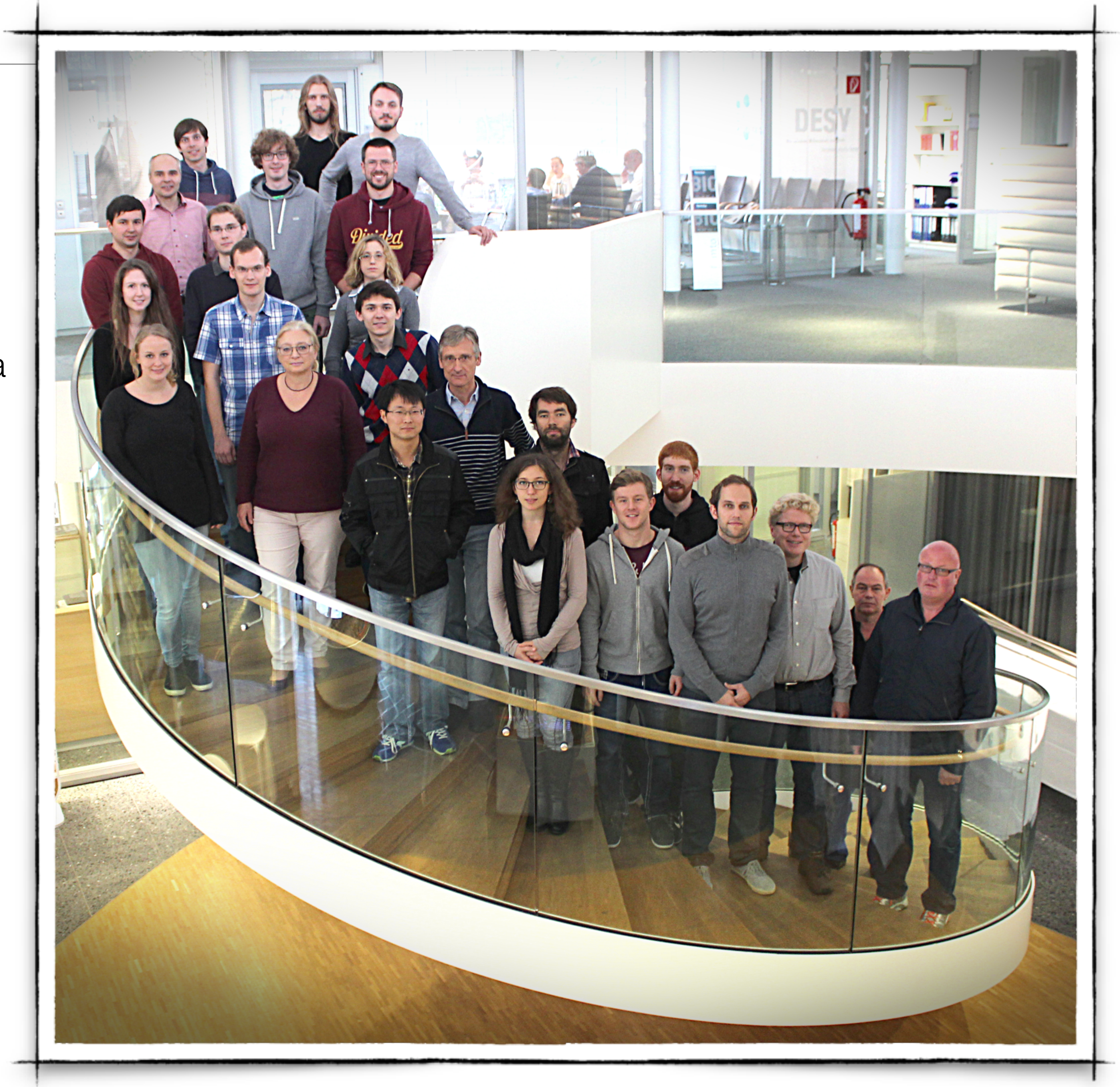
Charlotte Palmer
Alberto Martinez de la Ossa
John Dale
Vladyslav Libov
Johann Zemella
Matthew Streeter
Zhanghu Hu
Timon Mehrling
Christopher Behrens*
Laura di Lucchio

+ many DESY technical support groups



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+ many DESY technical support groups

> Collaborating institutes

Universität Hamburg, Germany
John Adams Institute, UK
Lawrence Berkeley National Laboratory, US
Stanford Linear Accelerator Center, US
James Cook University, Australia
Max Planck Institute for Physics, Bavaria
CERN, Switzerland
Laboratori Nazionali di Frascati, Italy
University of California Los Angeles, US
Instituto Superior Técnico Lisboa, Portugal