FLASHForward▸▸

Future-oriented wakefield accelerator research and development at FLASH

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LAOLA.

Scientific project contributors

> Core FLASHForward team

Staff scientists

Eckhard Elsen
Bernhard Schmidt
Sven Karstensen

Engineers

Kai Ludwig
Frank Marutzky

Students

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

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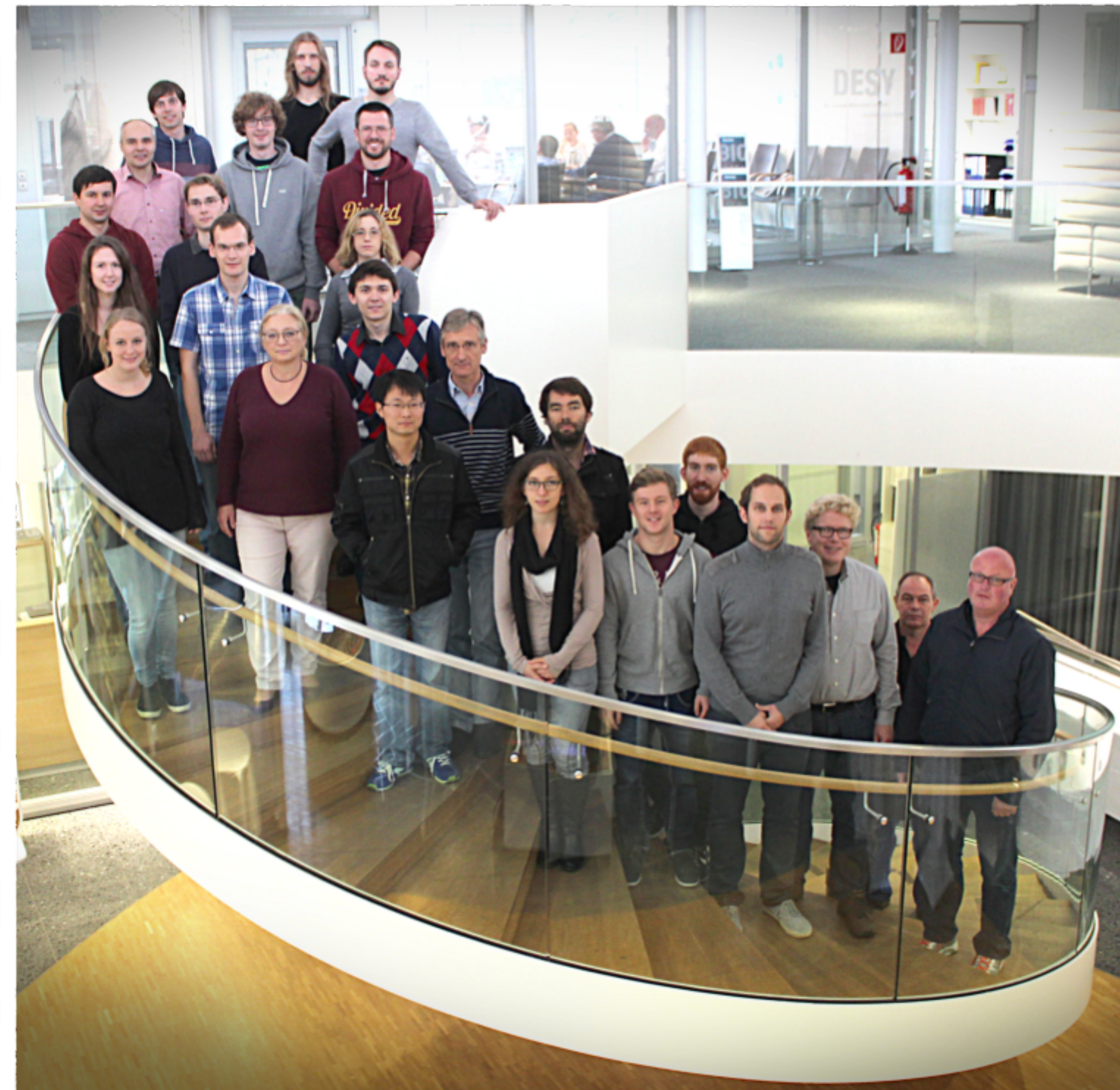
Johann Zemella
Matthew Streeter
Zhanghu Hu
Timon Mehrling
Christopher Behrens*
Laura di Lucchio

+ many DESY technical support groups



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> 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

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)*

[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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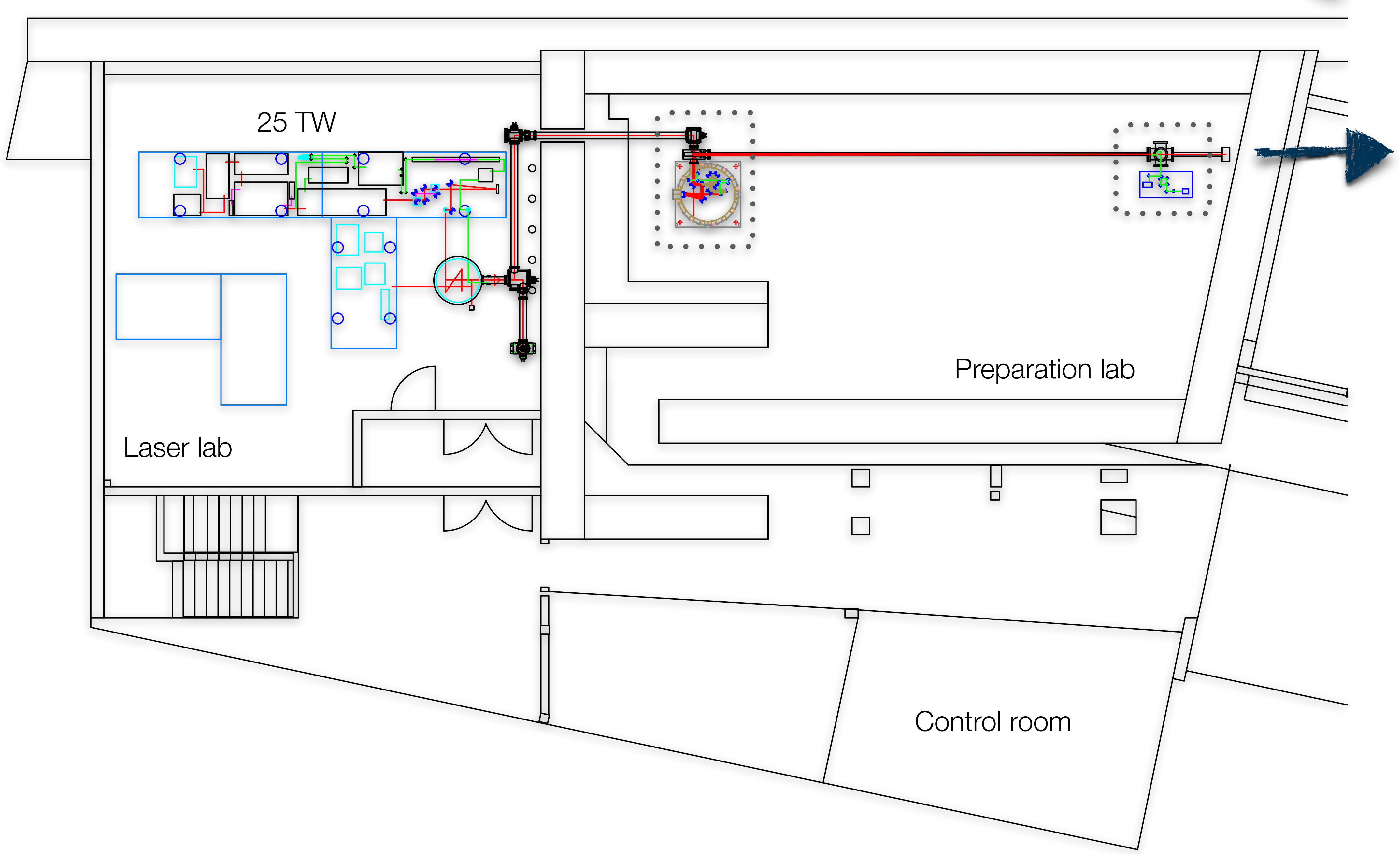
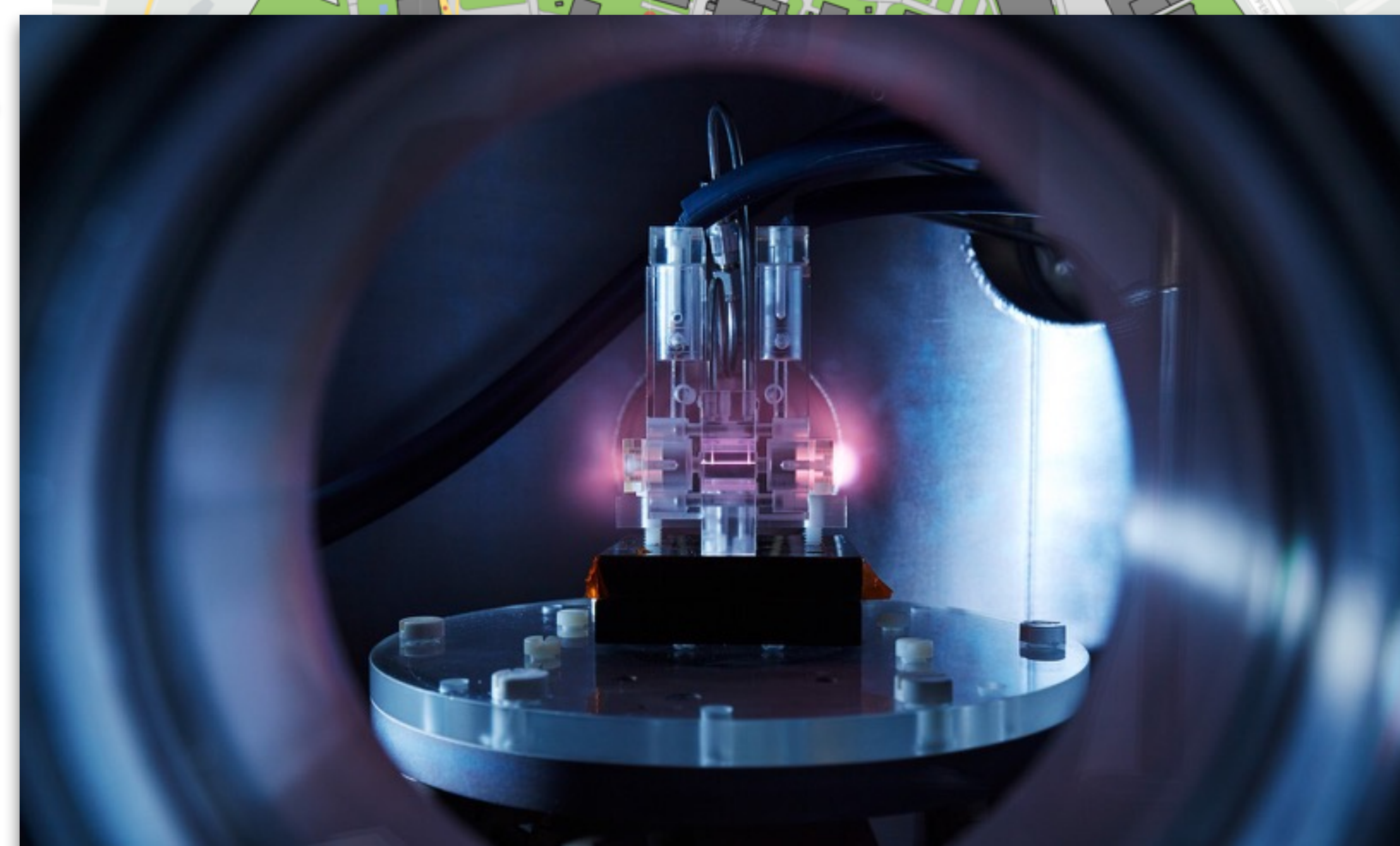
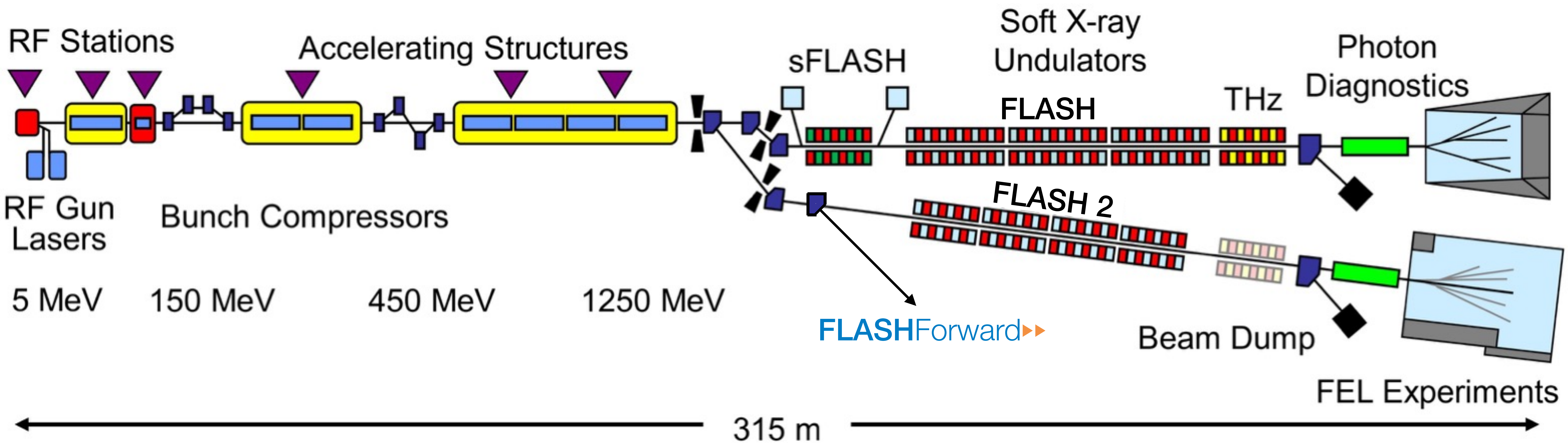
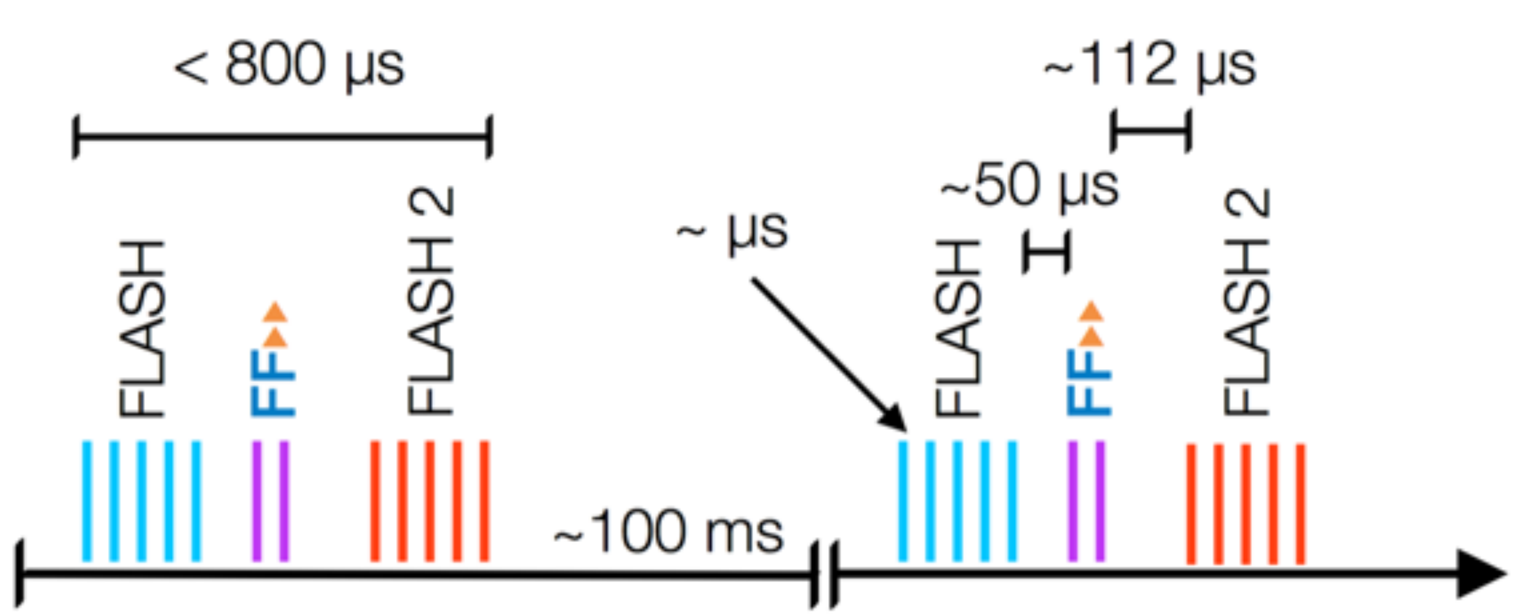
Laser and preparation laboratories (DESY 28m/O2)





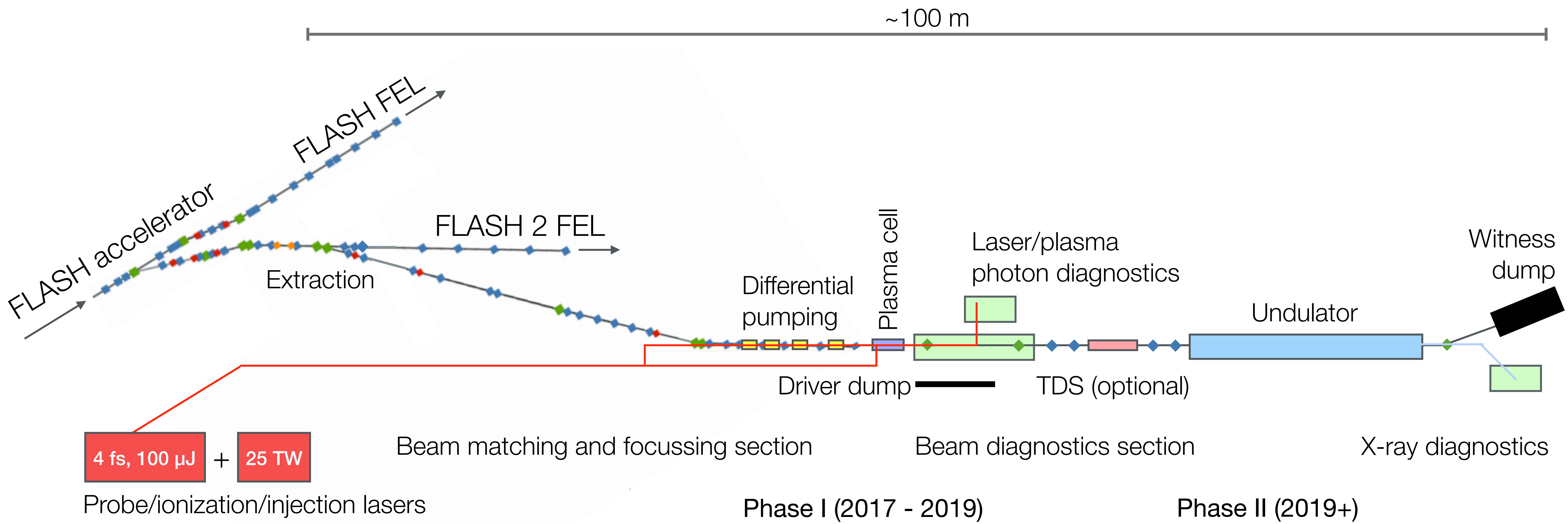
FLASHForward▸▸ shares the FLASH accelerator front-end





FLASH bunch train timing scheme

FLASHForward▸▸ beamline overview

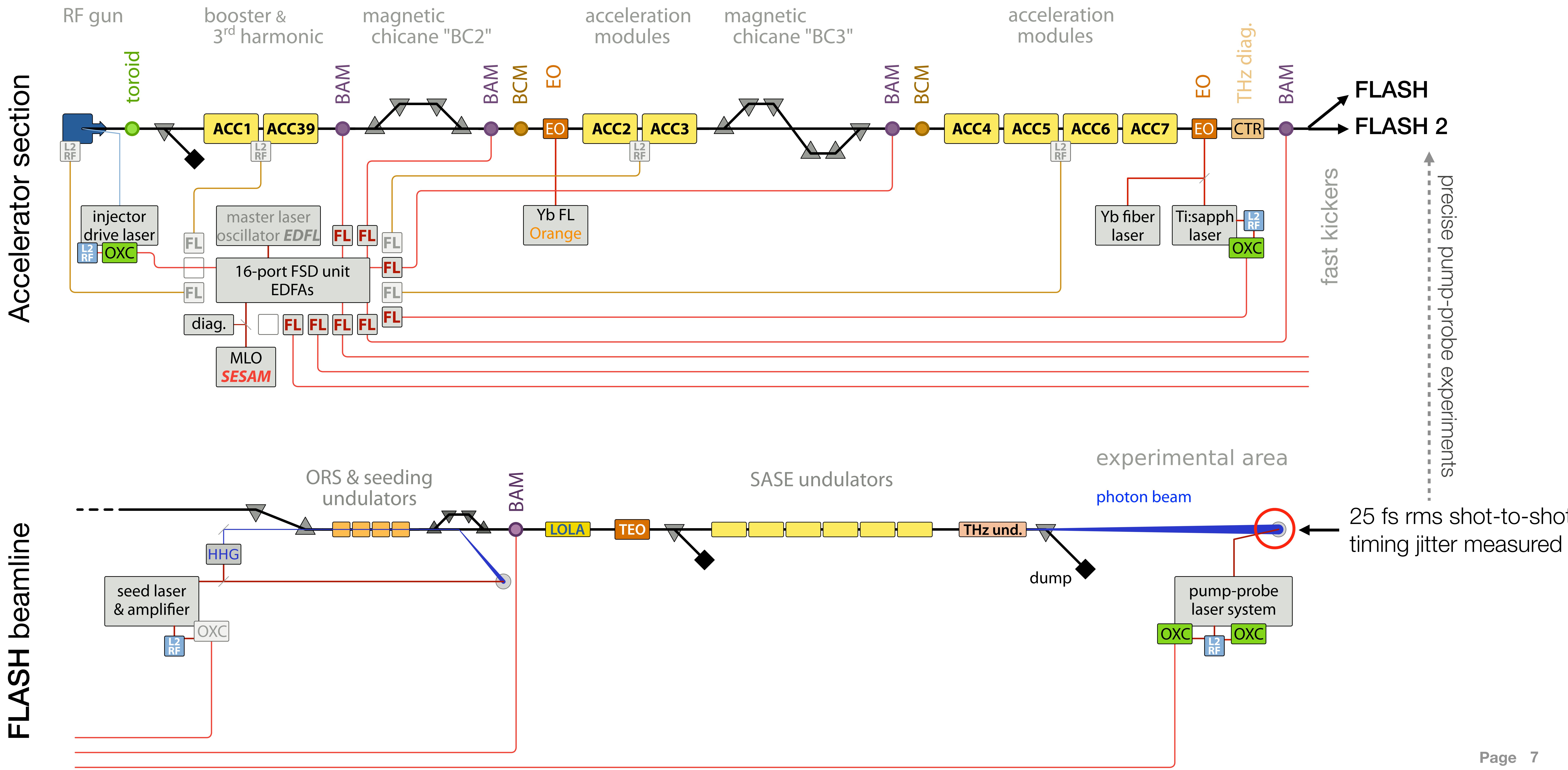


Capabilities of FLASH beams for FLASHForward

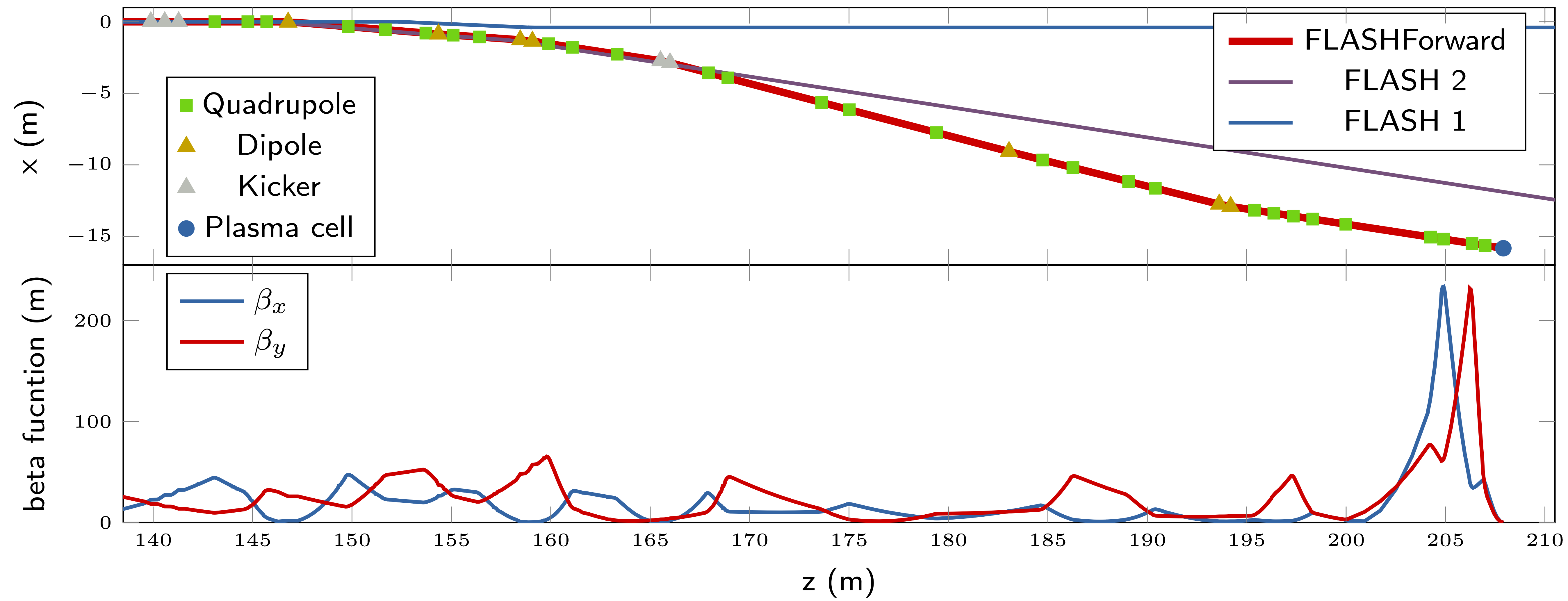
- FEL-quality (~1.25 GeV, ~0.1% energy spread, ~2 µm transverse norm. emittance), simultaneous with FLASH and FLASH 2
- Variable longitudinal beam shape (e.g. Gaussian, triangular), multi-kA peak current
- Sophisticated laser-to-beam synchronization for diagnostics/laser-triggered injection schemes
-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

FLASH timing system allows for beam-to-laser synchronization of ~25 fs rms

S. Schulz *et al.*, Nat. Comm. 6938, 1 (2015)



Pre-plasma cell lattice design for beam post-compression

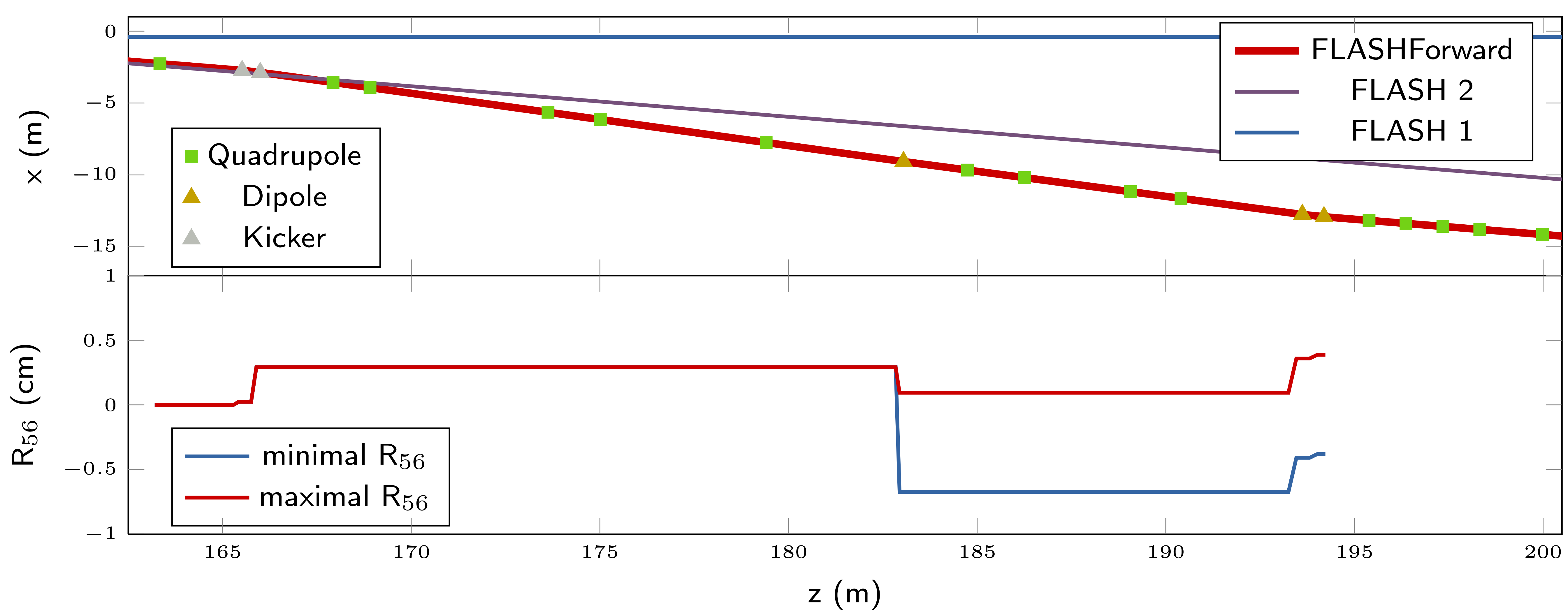


> *Concept:*
> C. Behrens, J. Zemella, M. Scholz (all MPY),
> V. Libov, J. Dale (all FLA)

> Fast kicker with 115 µs rise time for extraction

> W-shaped collimator/scraper in dispersive section

> Includes four differential pumping stations



Beamline optimized for

> $R_{16} \approx 0$ m, $R_{166} \approx 0$ m (trans. disp.)

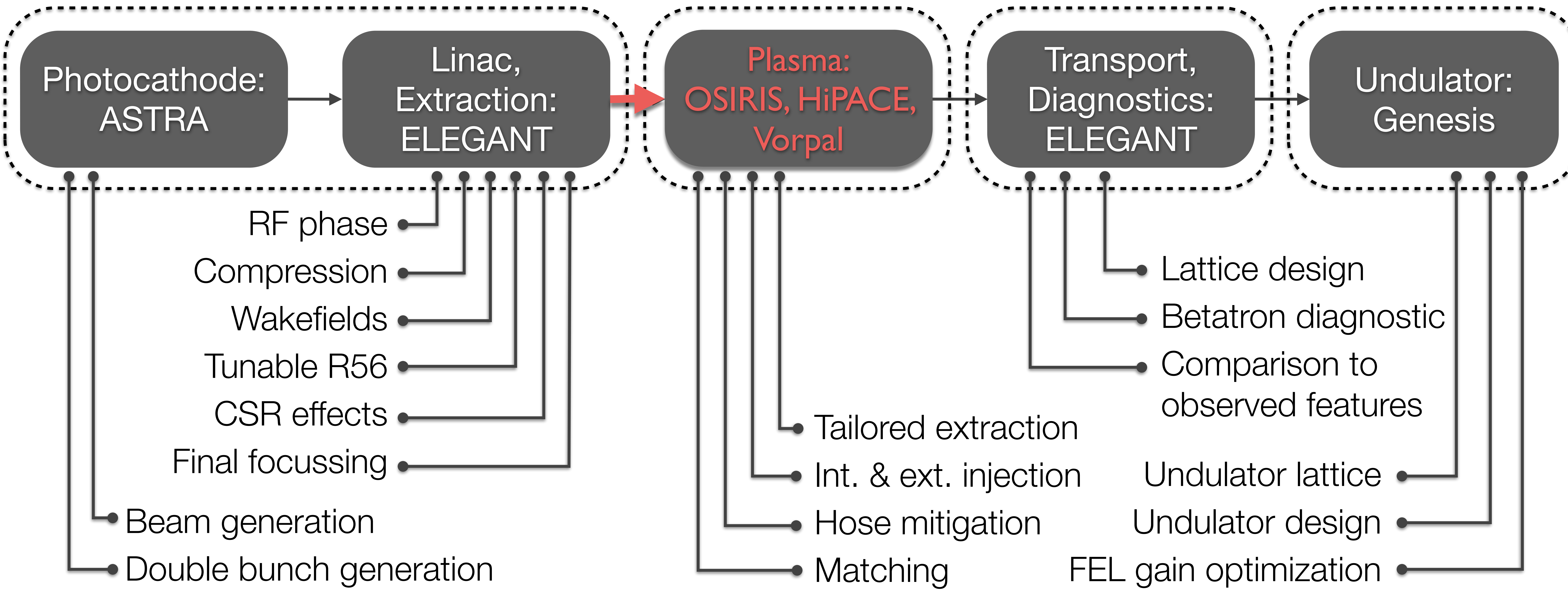
> $R_{26} \approx 0$ rad, $R_{266} \approx 0$ rad (trans. ang. disp.)

> final focus: radius < 8 µm,
> orbit jitter < 10 µm, pointing jitter < 0.5 mrad

> R_{12} and R_{22} such that jitter specifications are fulfilled with $\Delta B/B \approx 10^{-4}$ kicker fluctuations

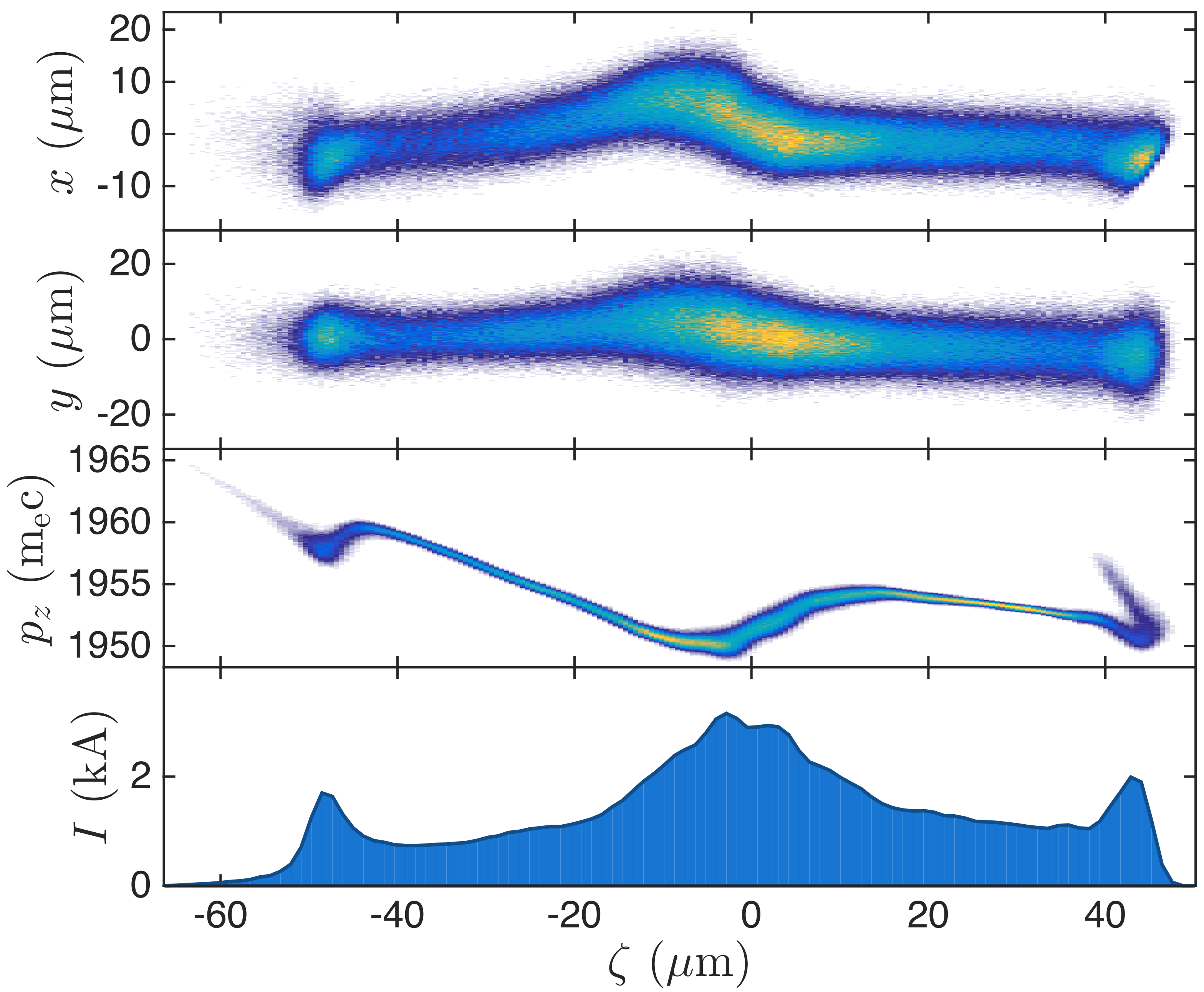
> Tunable R_{56} (long. disp.) between -0.5 and 0.4 cm

Full **FLASH** start-to-end simulations for realistic predictions

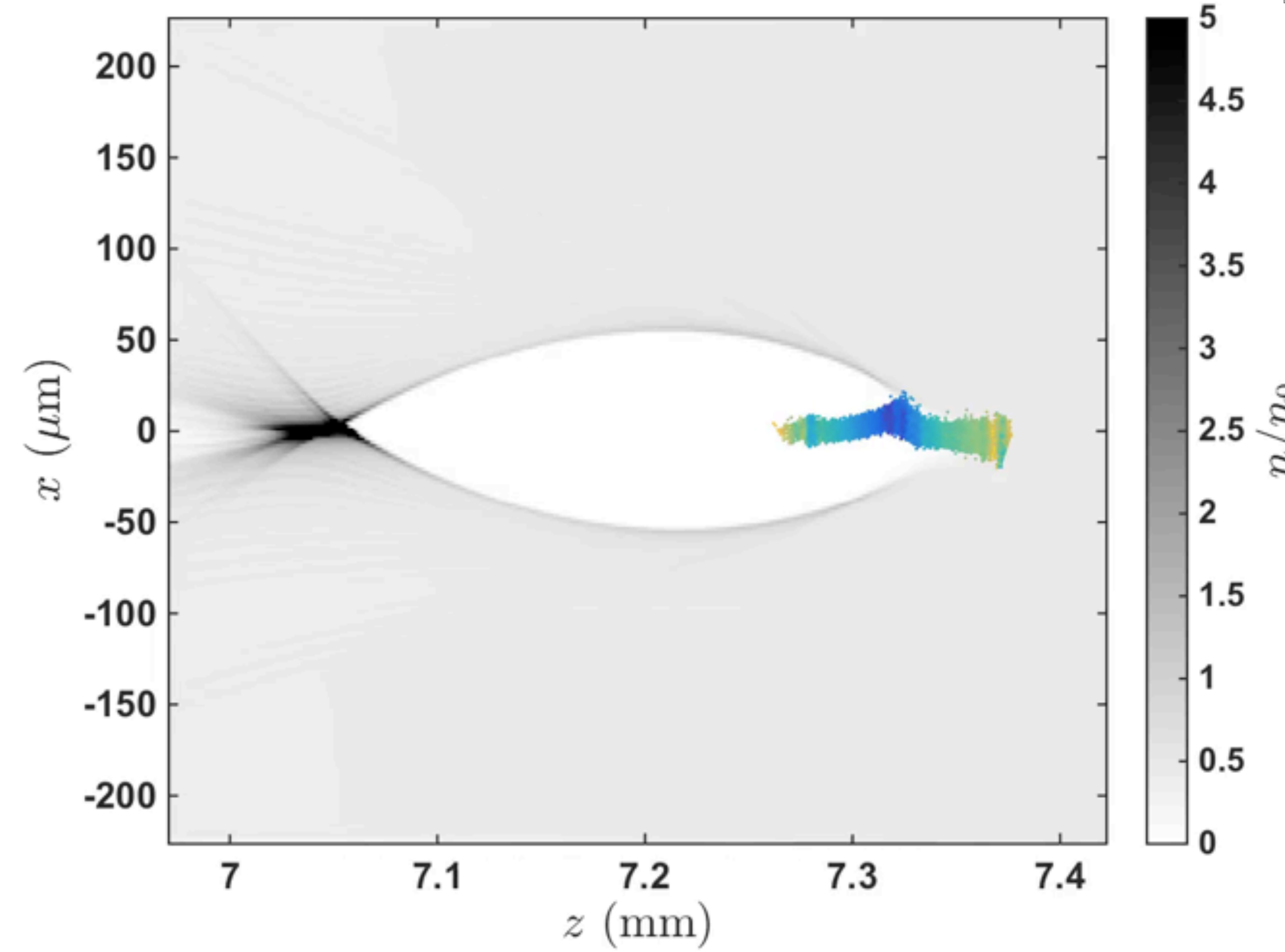


Mitigation of hose instability caused by CSR effects important

Example beam distribution from tracking codes



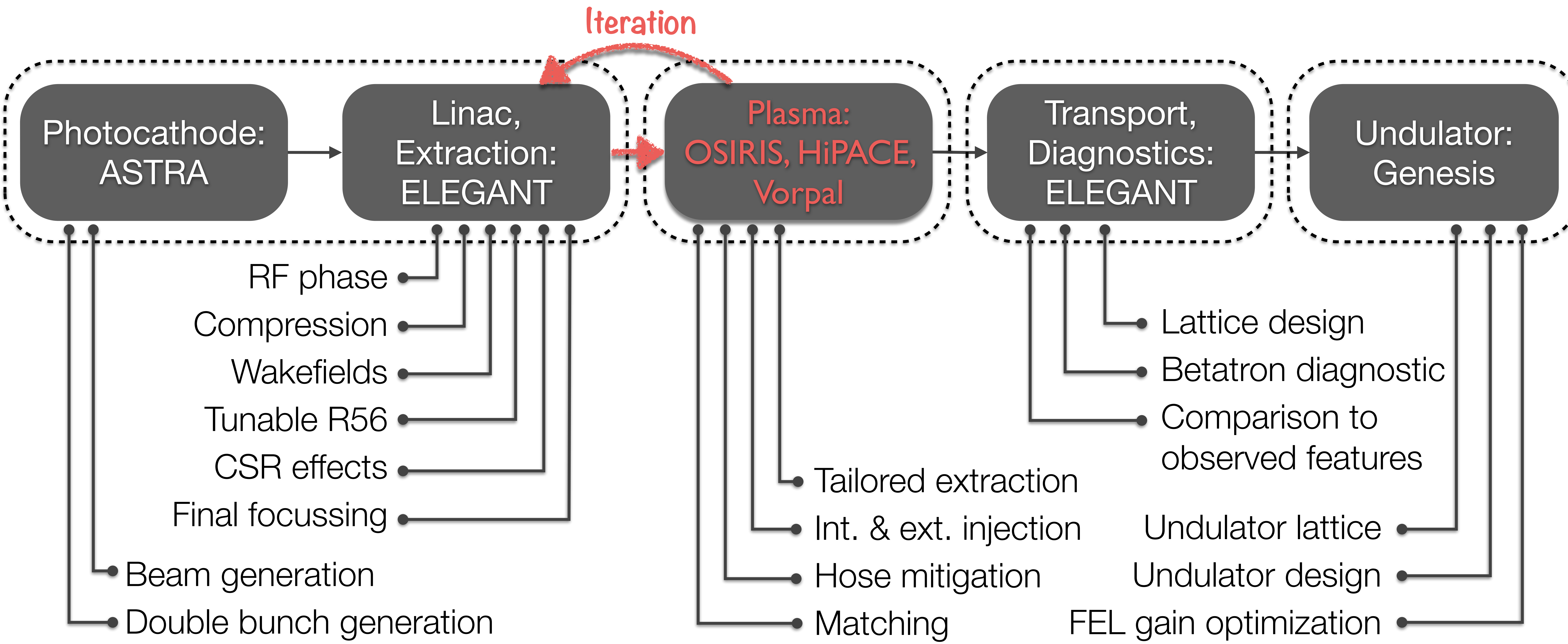
OSIRIS/HiPACE simulation



- Simulations allow for tracking of beams up to the plasma
- Realistic 6D beam phase space distribution affected by CSR

- Hose instability may severely affect quality and stability of accelerated beams
- Mitigation of hose instability crucial for FLASHForward

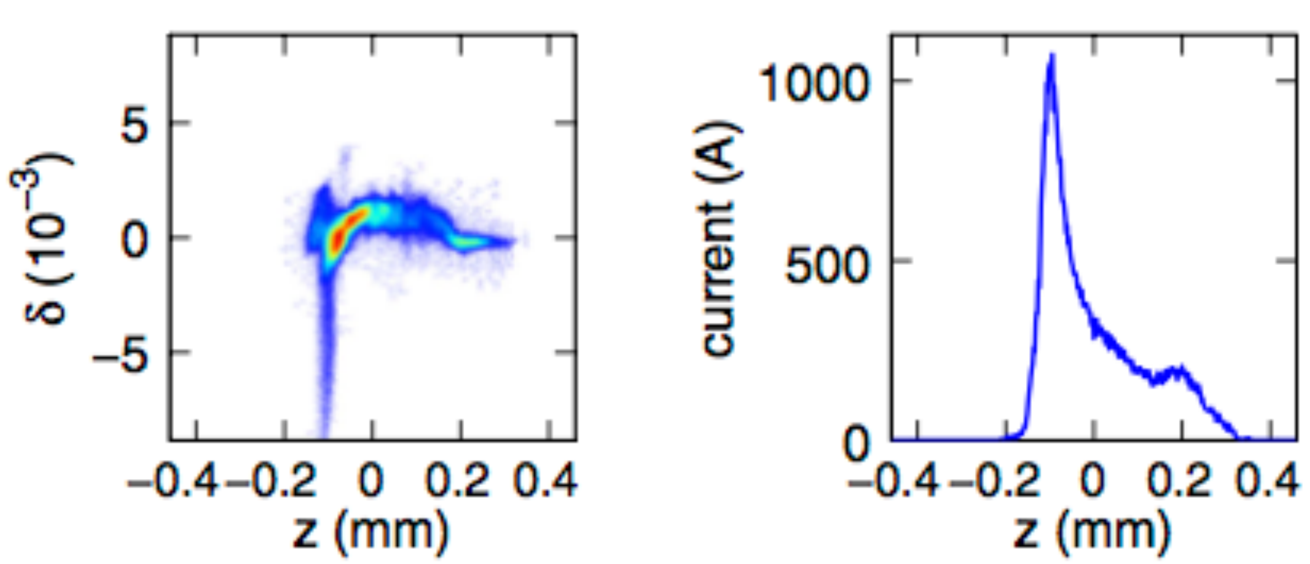
Full **FLASH** start-to-end simulations for optimized operation

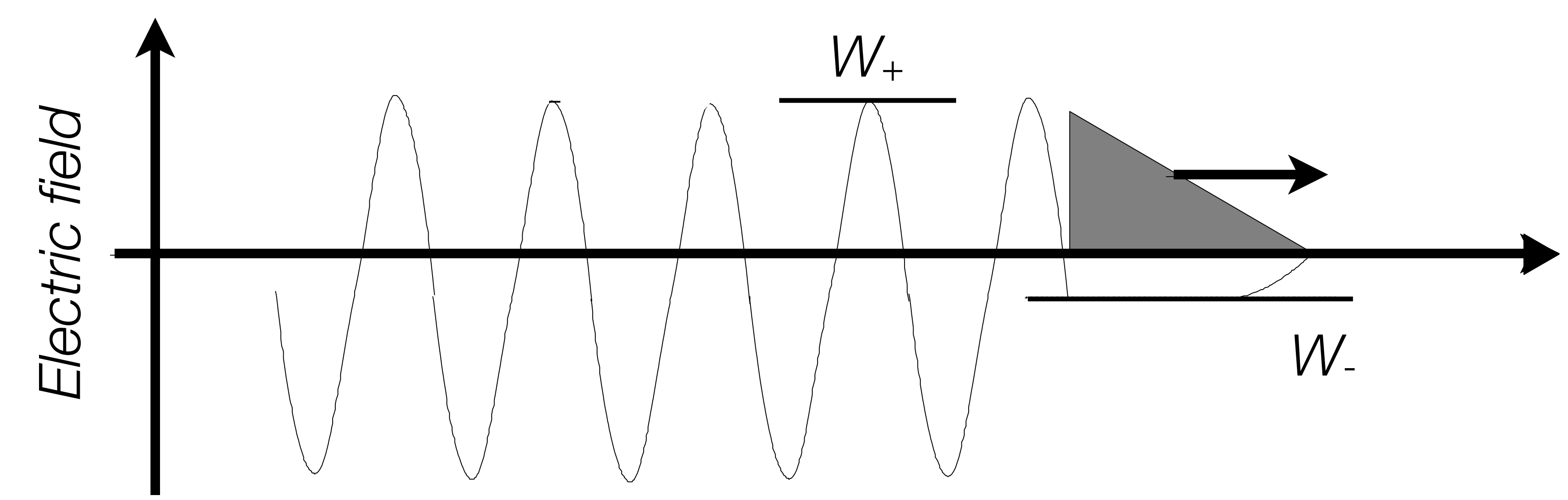


Versatile electron beams for transformer ratio studies

FLASH feature: tailored triangular beams for PWFA

- triangular current profile
- mode of operation demonstrated in Piot *et al.*, Phys. Rev. Lett. 108, 034801 (2012)
- pulse-shaping realized by 3rd harmonic RF cavity





from J.G.Power *et al.*, PAC Proceedings 115 (2001)

- maximum energy gain of a witness beam $\Delta E_W = R \times E_D$
- theoretical max. transformer ratio $R = W_+ / W_-$

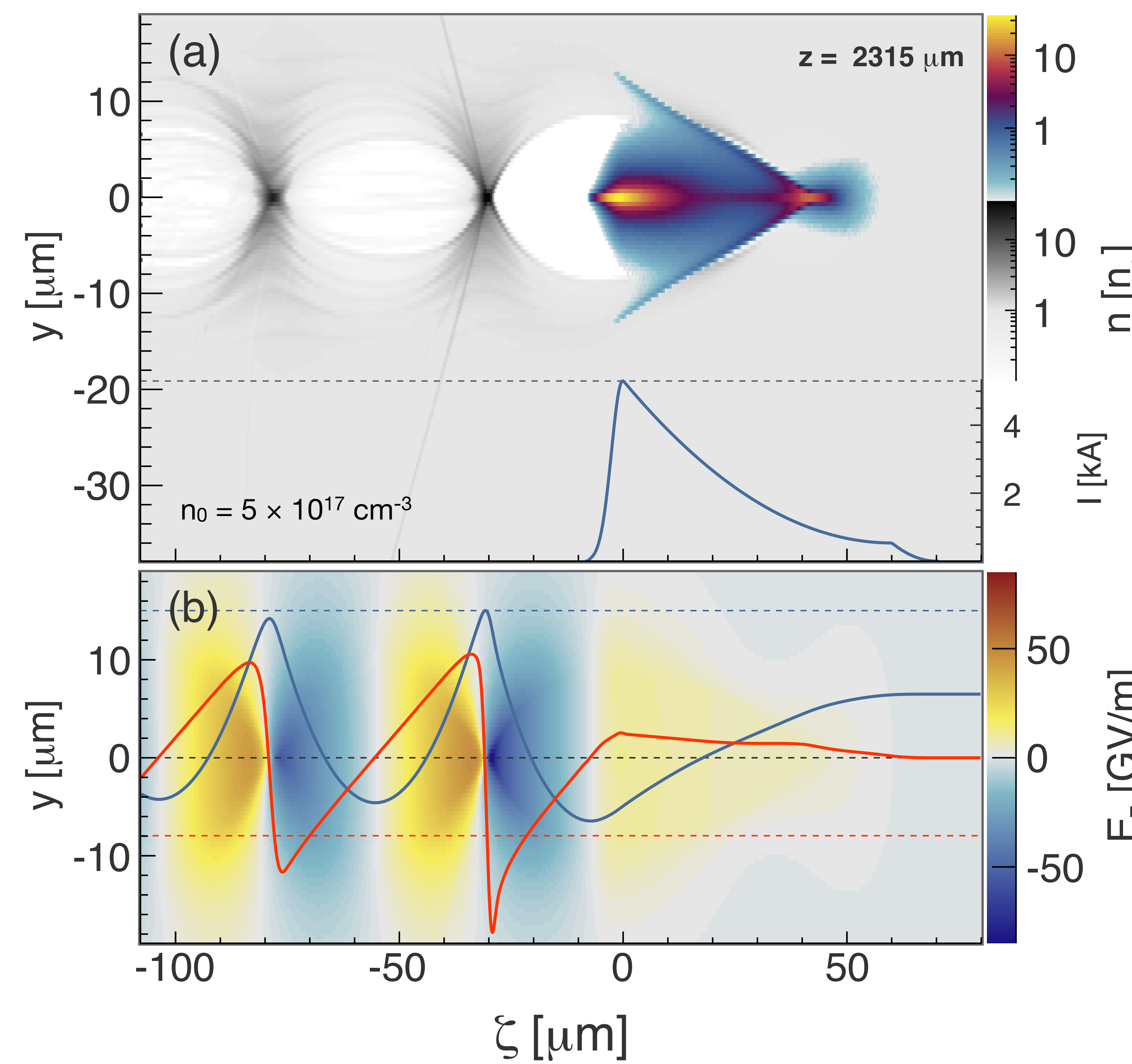
Versatile electron beams for transformer ratio studies

FLASH feature: tailored triangular beams for PWFA

- triangular current profile
- mode of operation demonstrated in Piot *et al.*, Phys. Rev. Lett. 108, 034801 (2012)
- pulse-shaping realized by 3rd harmonic RF cavity

From OSIRIS 3D PIC simulations

- maximum transformer ratio of **~6**
- **50 GV/m** peak field strength
- boosting the energy of a witness beam to ~5 GeV in less than 10 cm seems feasible

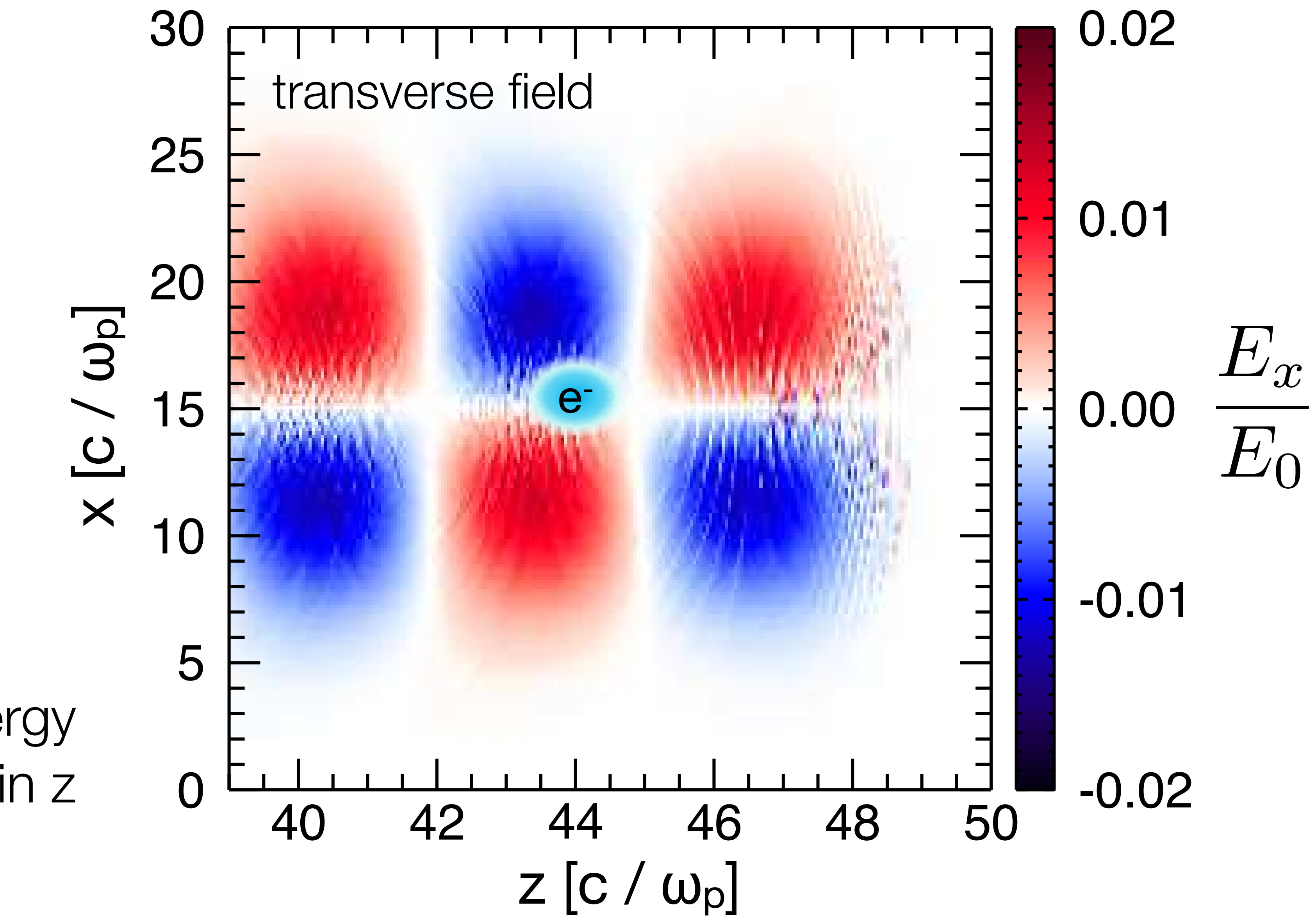


Beam injection: a challenge to preserve emittance

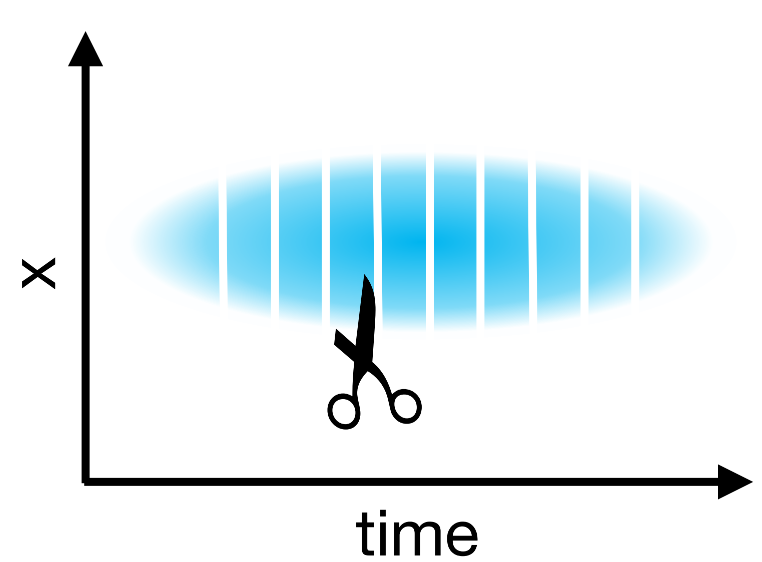
$$\epsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

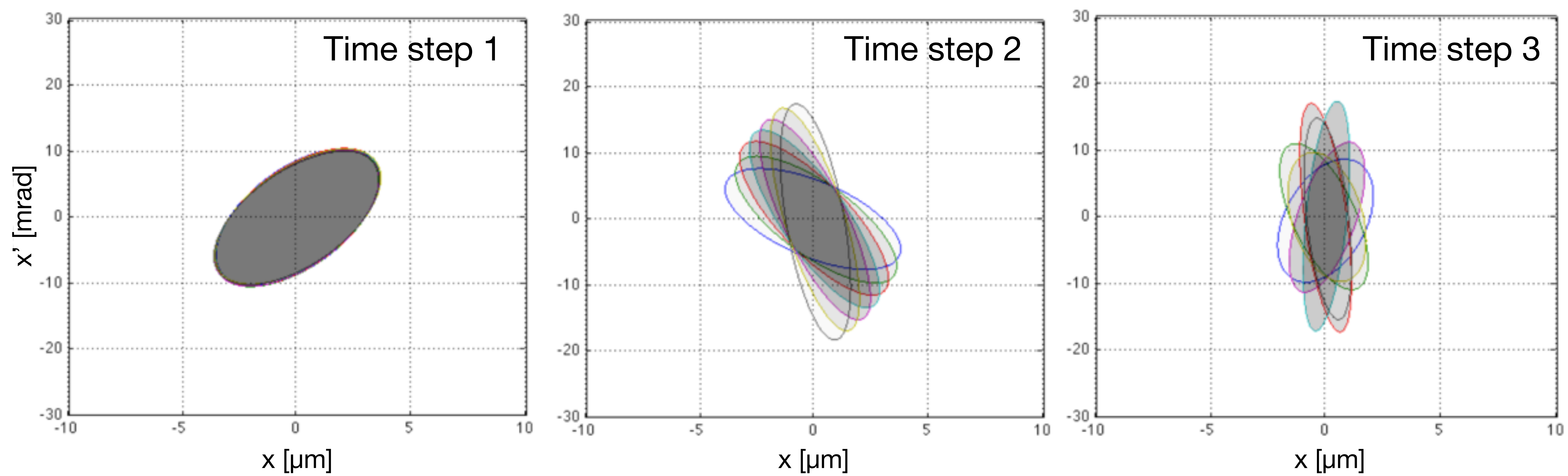
with $x' = p_x/p_z$

Beam focusing forces, slice energy may vary in plasmas in z



Slice rotation speeds vary along electron bunch





Beam injection: a challenge to preserve emittance

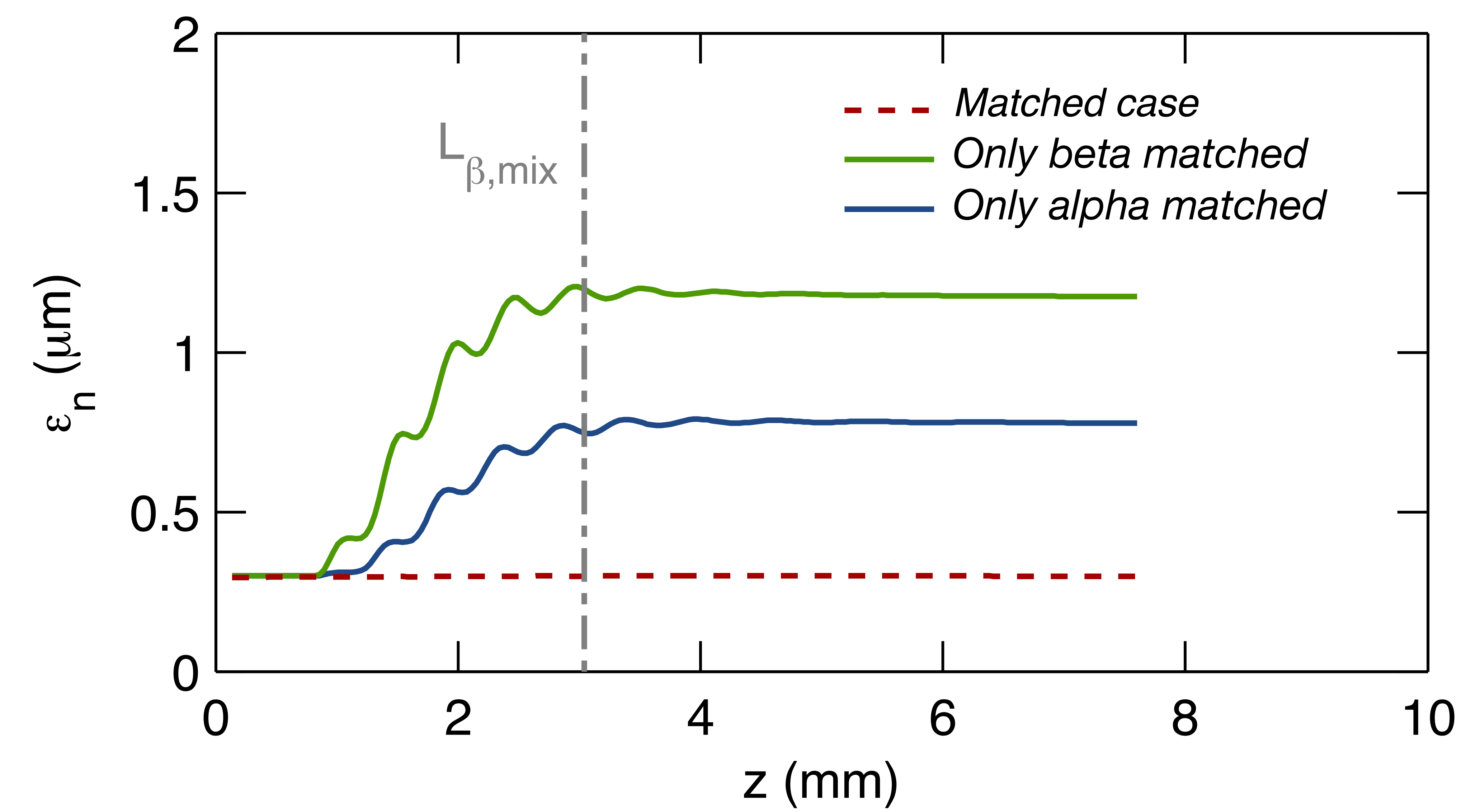
T. Mehrling *et al.*, Phys. Rev. STAB 15, 111303 (2012)

Total betatron phase mixing length

$$L_{\beta,\mathrm{mix}} \simeq \frac{\lambda_p}{a_0}\sqrt{\frac{8\pi\gamma_r}{k_p L_b}}$$

Matching conditions

$$\alpha_{match} = 0 \qquad \beta_{match} \simeq \frac{c}{\omega_\beta}$$

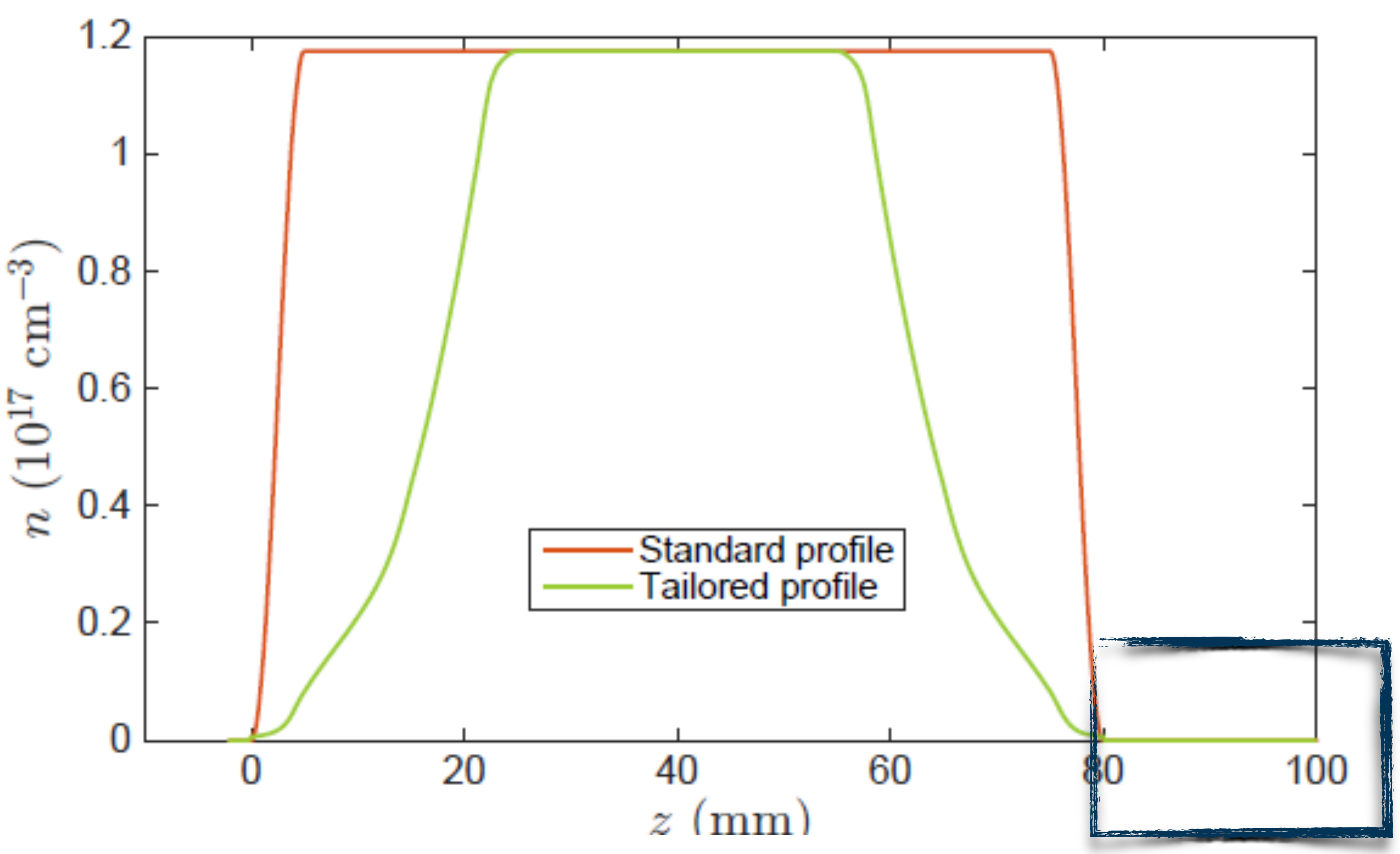


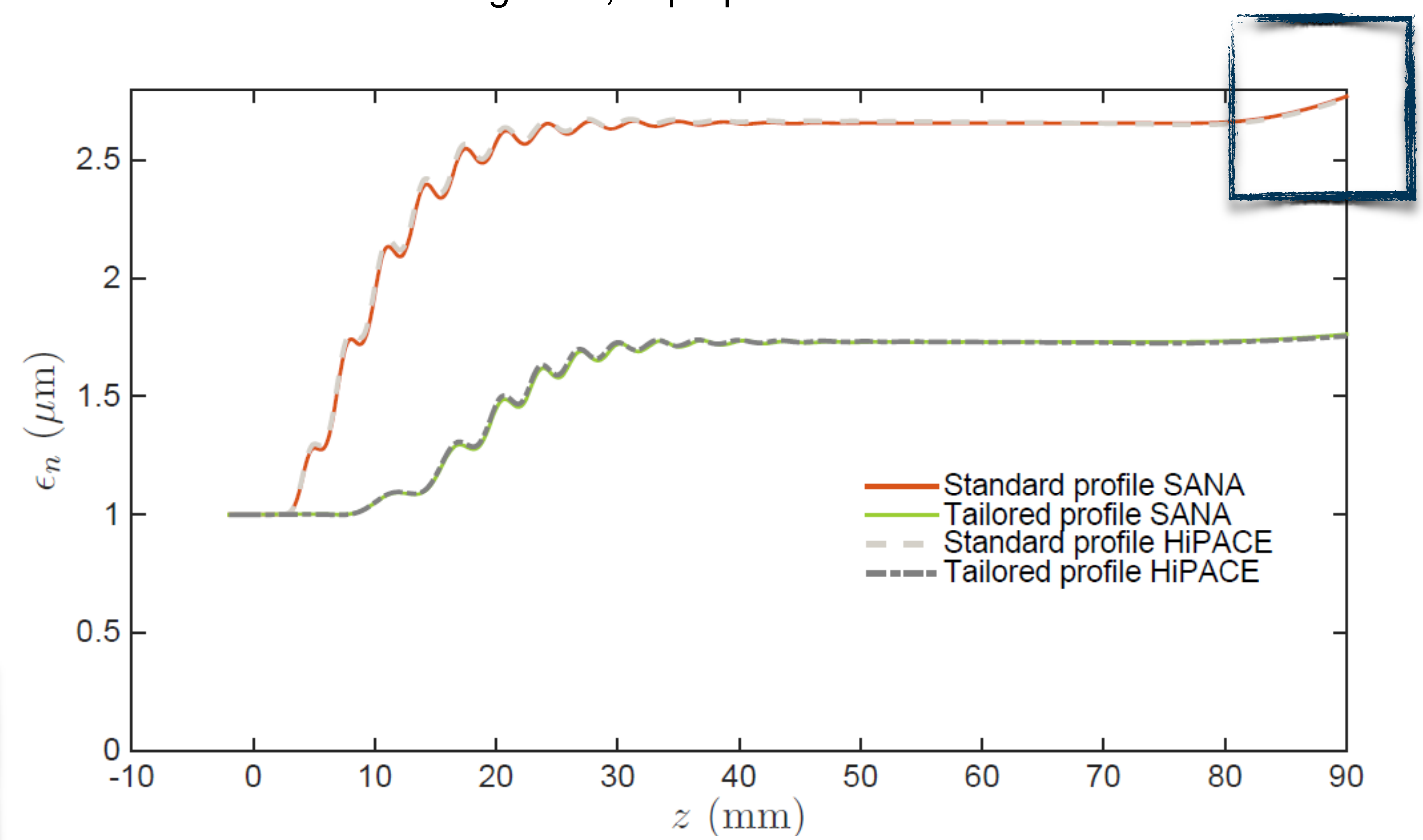
- Significant phase mixing occurs up to ~TeV energies within acceleration length
(with plasma density 10^{17} cm^{-3}, quasi-linear wake, λ = 800 nm)
- Matching sections between stages require significant space with conventional technology → Plasma optics to maintain average gradient?
- Matched β can be challenging to achieve, β ≈ 1 mm at **FLASH**Forward▸▸

Analytic models for emittance evolution

>> New semi-analytical approach based on beam-envelope equations

R. Robson *et al., Annals of Physics* **356,** 306 (2015)
T. Mehrling *et al.*, in preparation



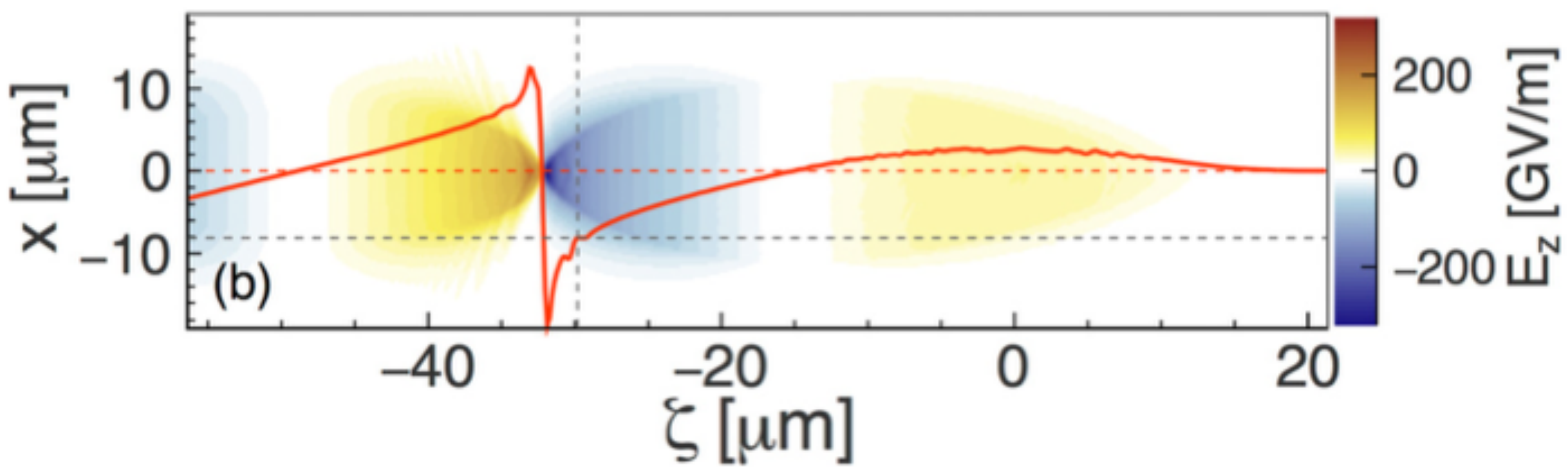


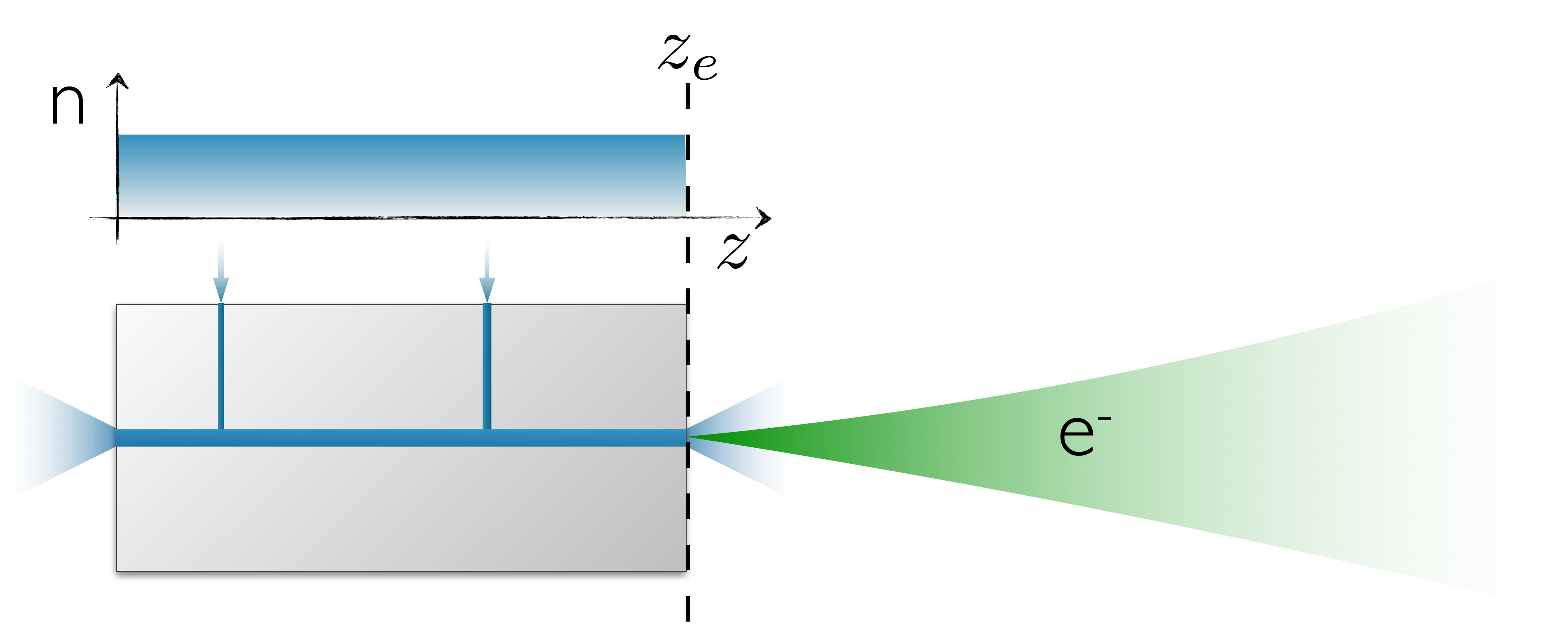
- Allows for accurate calculation of emittance evolution in arbitrary plasma profiles

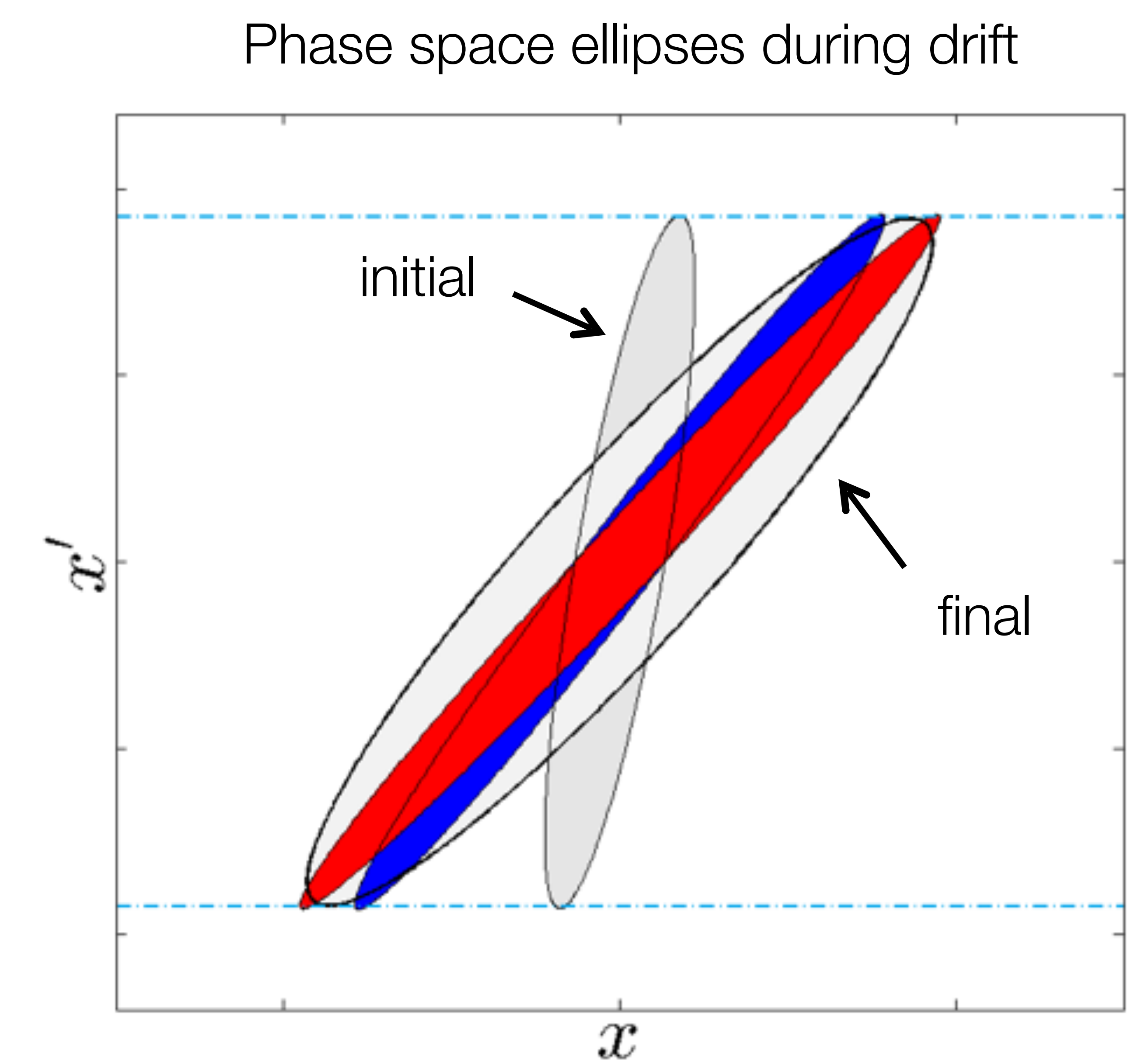
$$\overline{\gamma} = 2000 \qquad n_0 = 10^{23}\ \mathrm{m}^{-3}$$

$$\sigma_\gamma/\overline{\gamma} = 0.05$$

Energy spread and small β complicate emittance preservation







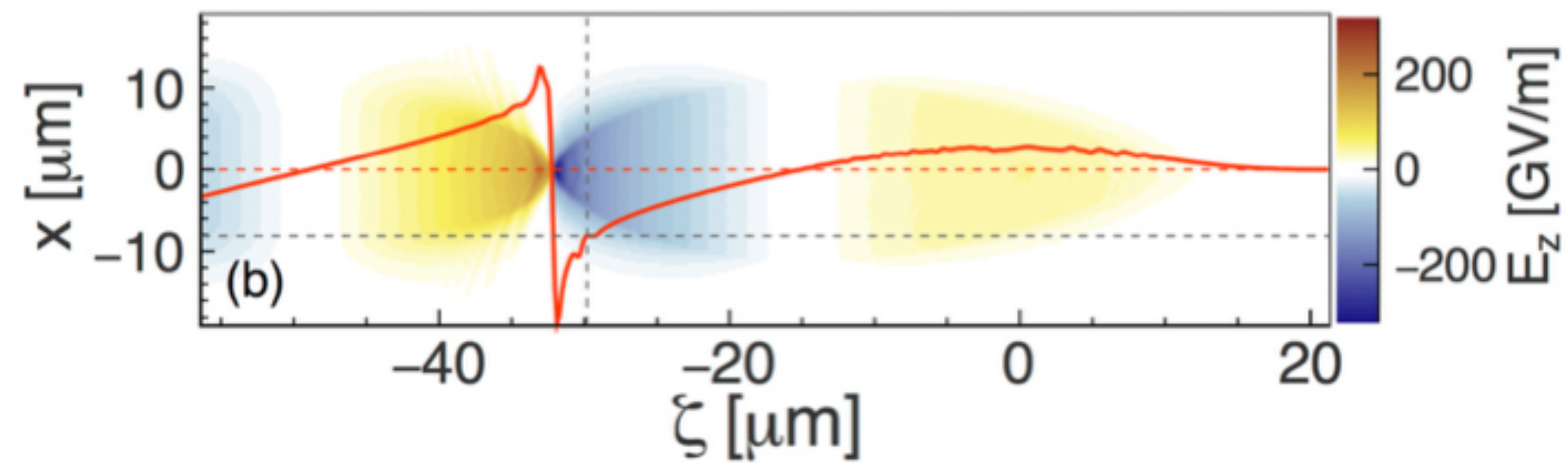
$$\varepsilon_n{}^2 \cong \langle\gamma\rangle^2 \cdot (\sigma_E{}^2 \sigma_{x'}{}^4 s^2 + \varepsilon^2)$$

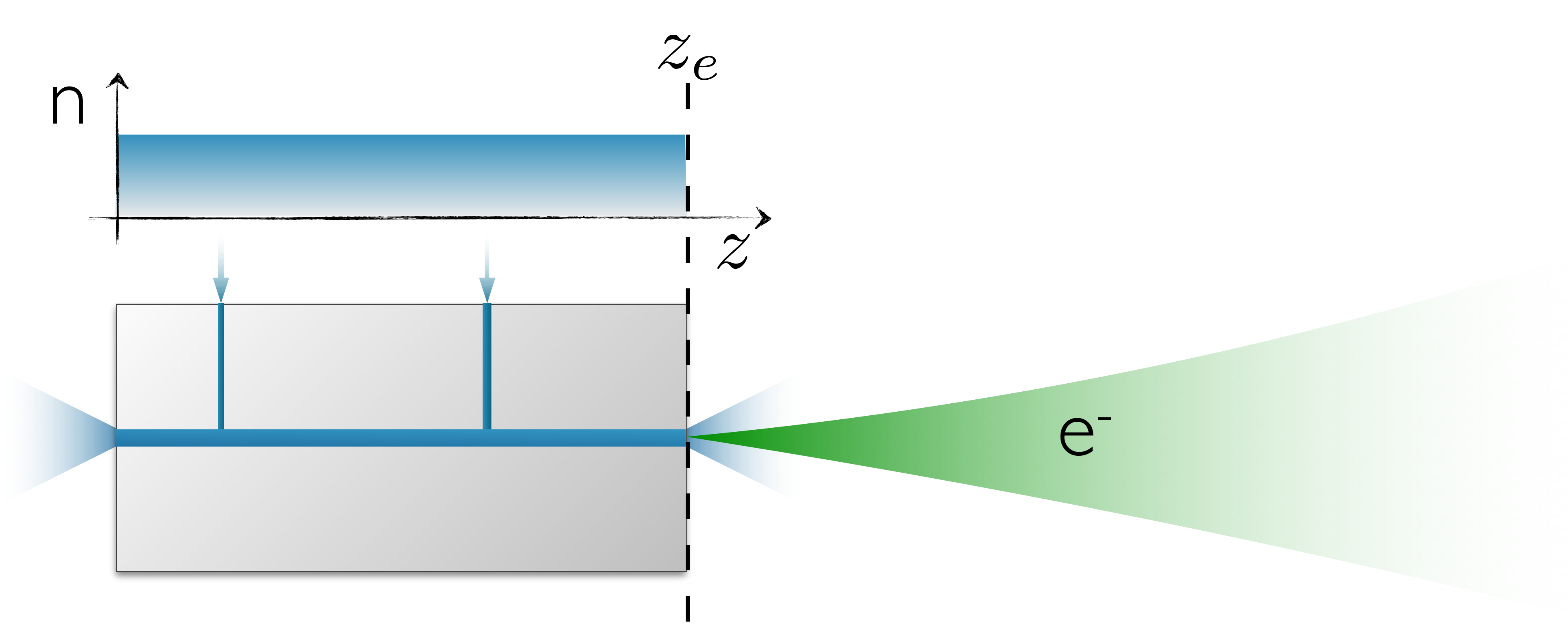
- beams at plasma exit:
  - ~% level energy spread
  - small beta function, mrad divergence
- leads to transverse emittance growth in free drift

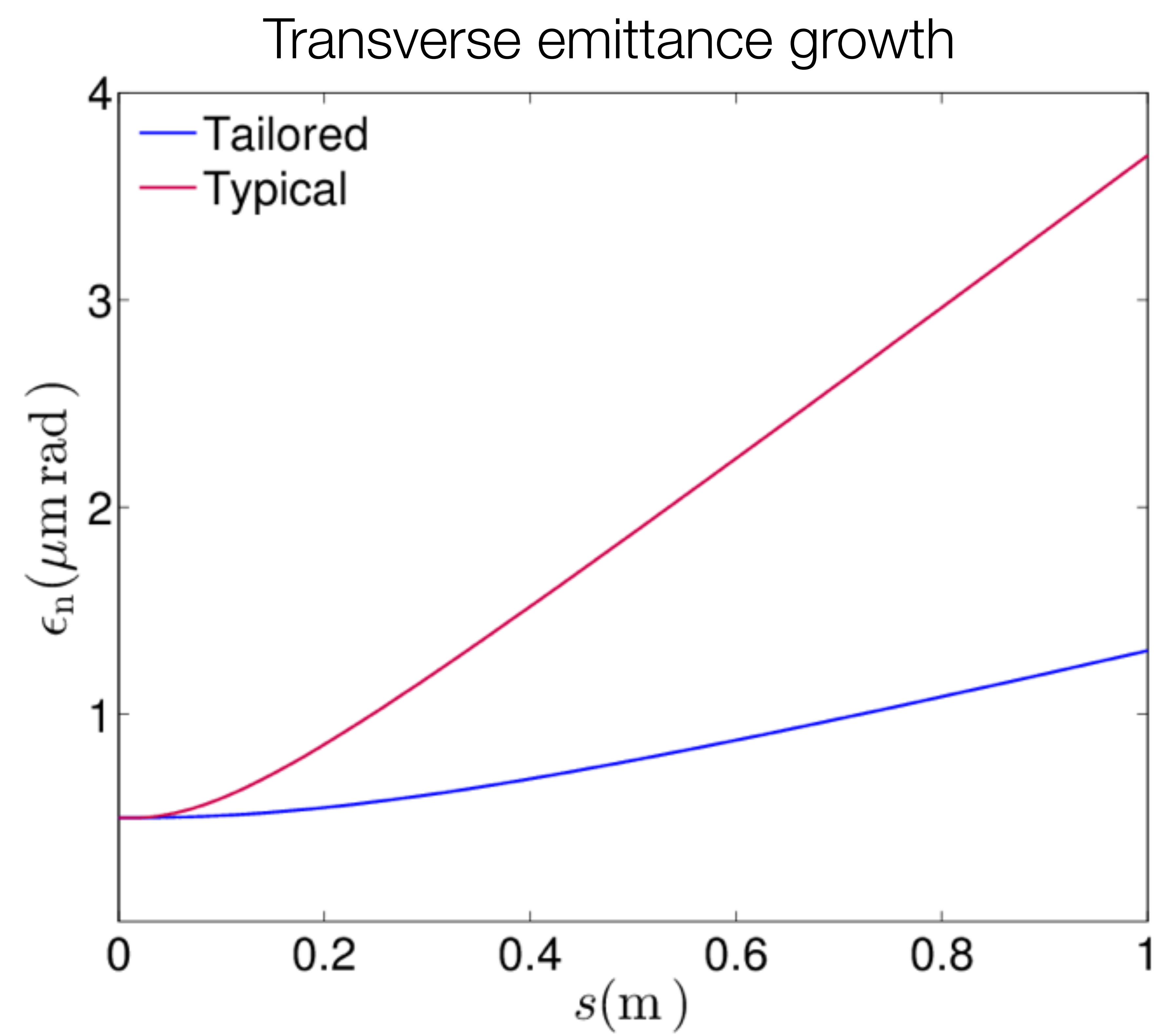
→ K. Floettmann, Phys. Rev. STAB 6, 034202 (2003)

- **quality preserving capturing is a challenge**

Energy spread and small β complicate emittance preservation







E = 1.5 GeV, σ_E = 1%, $\epsilon_{n,0}$ = 0.5 µm rad, $\sigma_{\tau,0}$ = 1 fs

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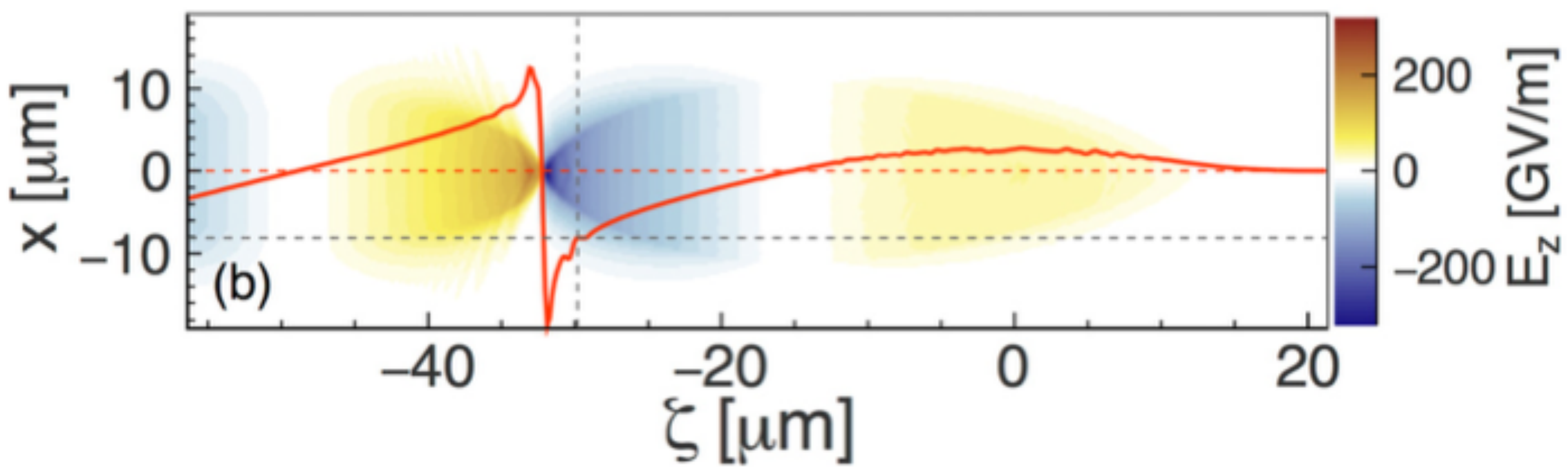

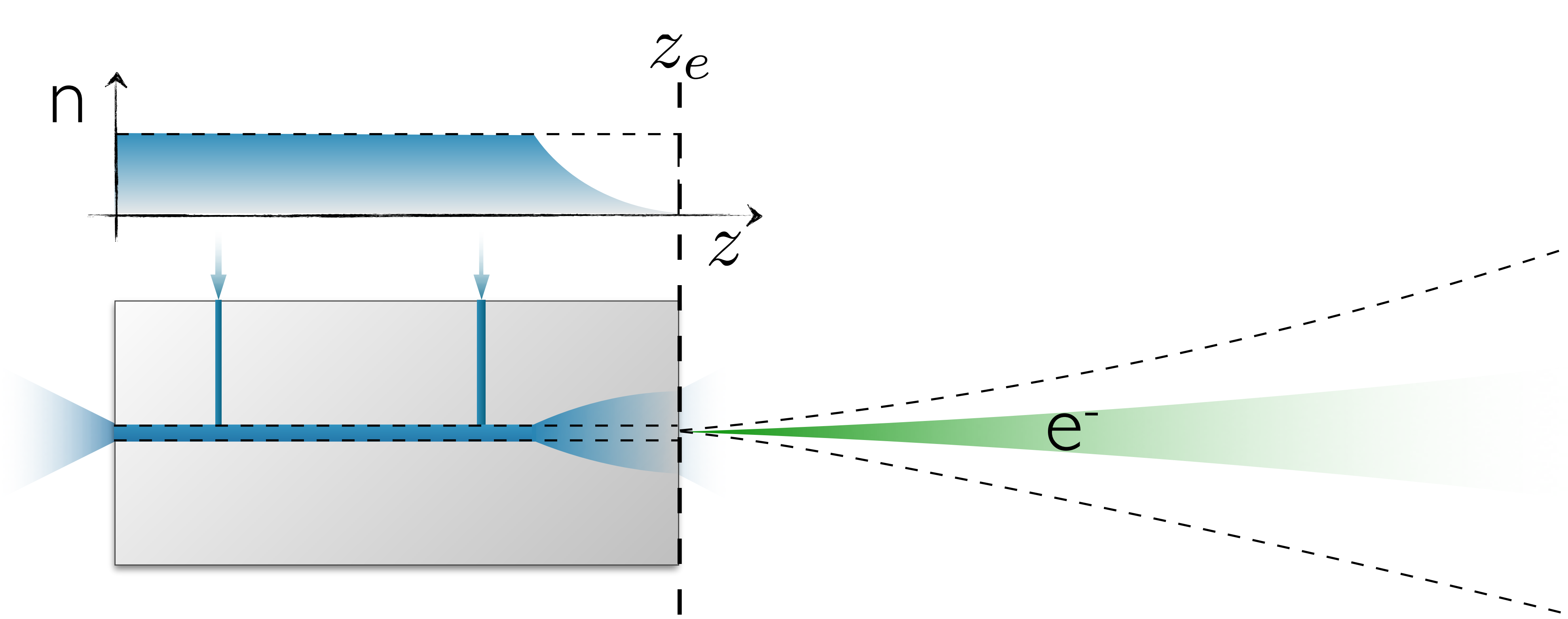

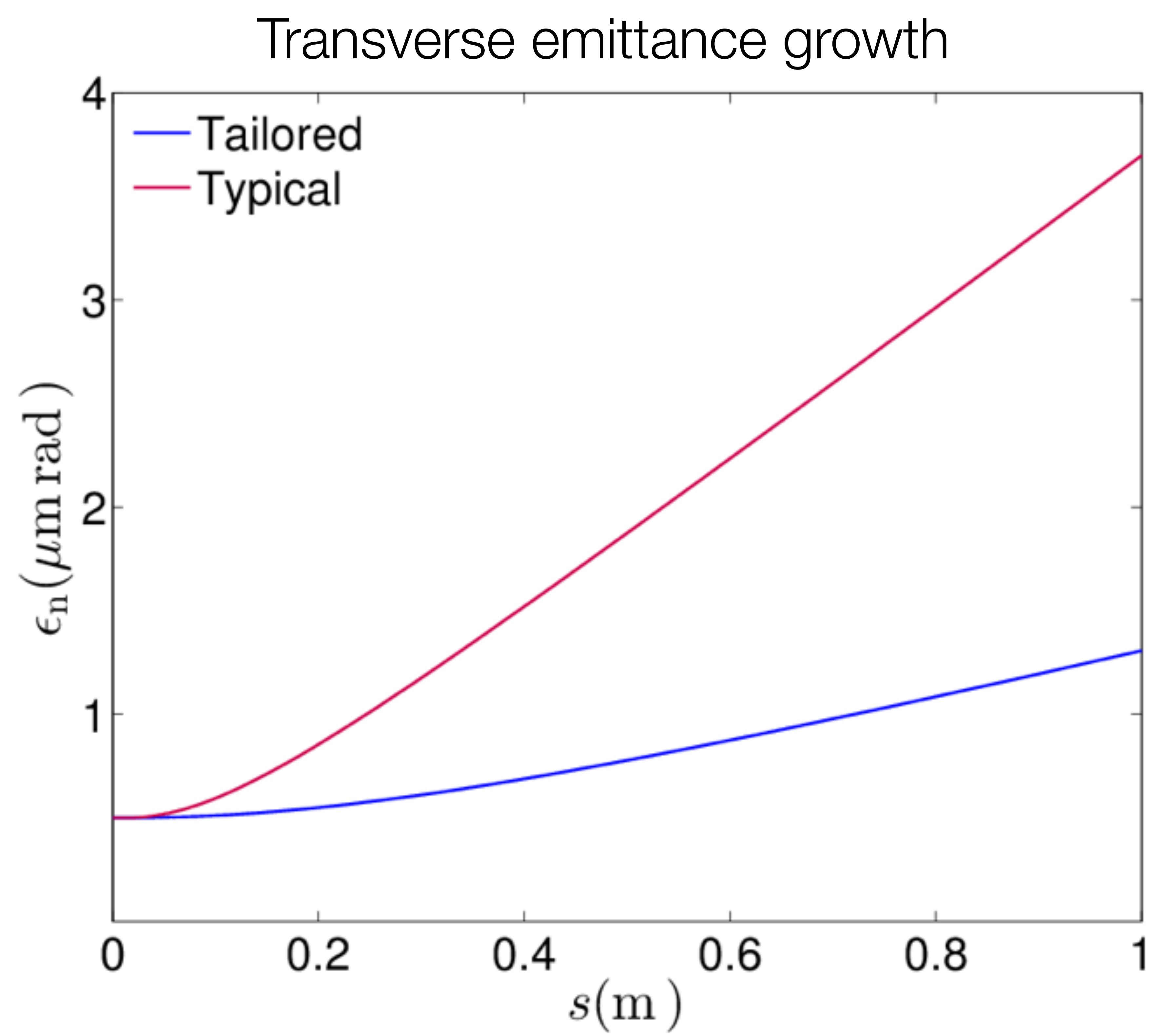

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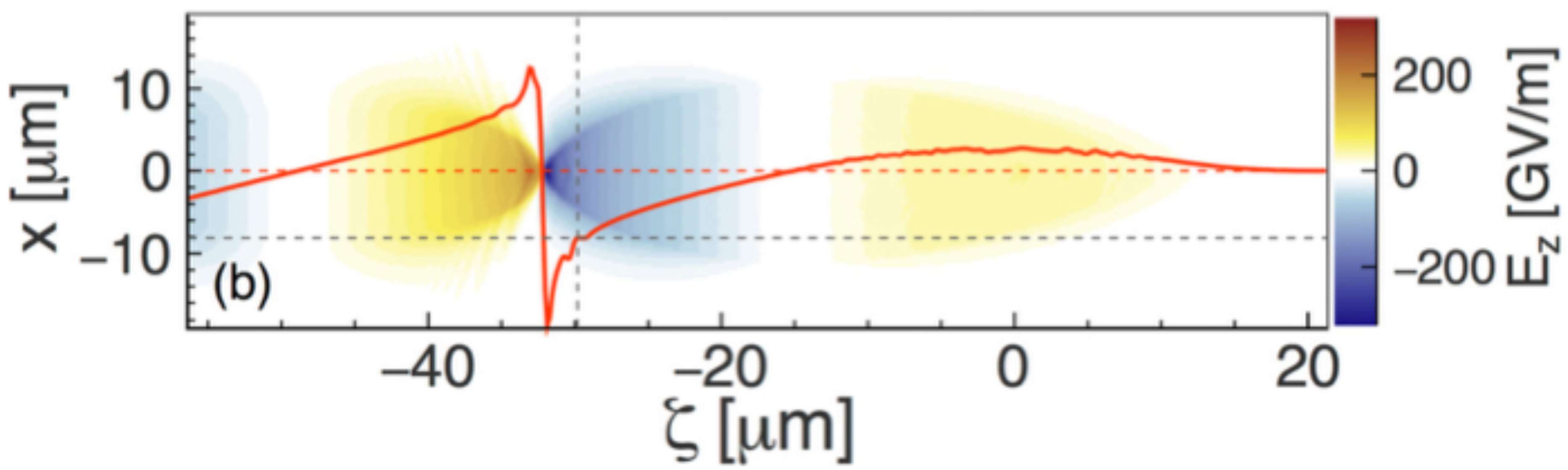

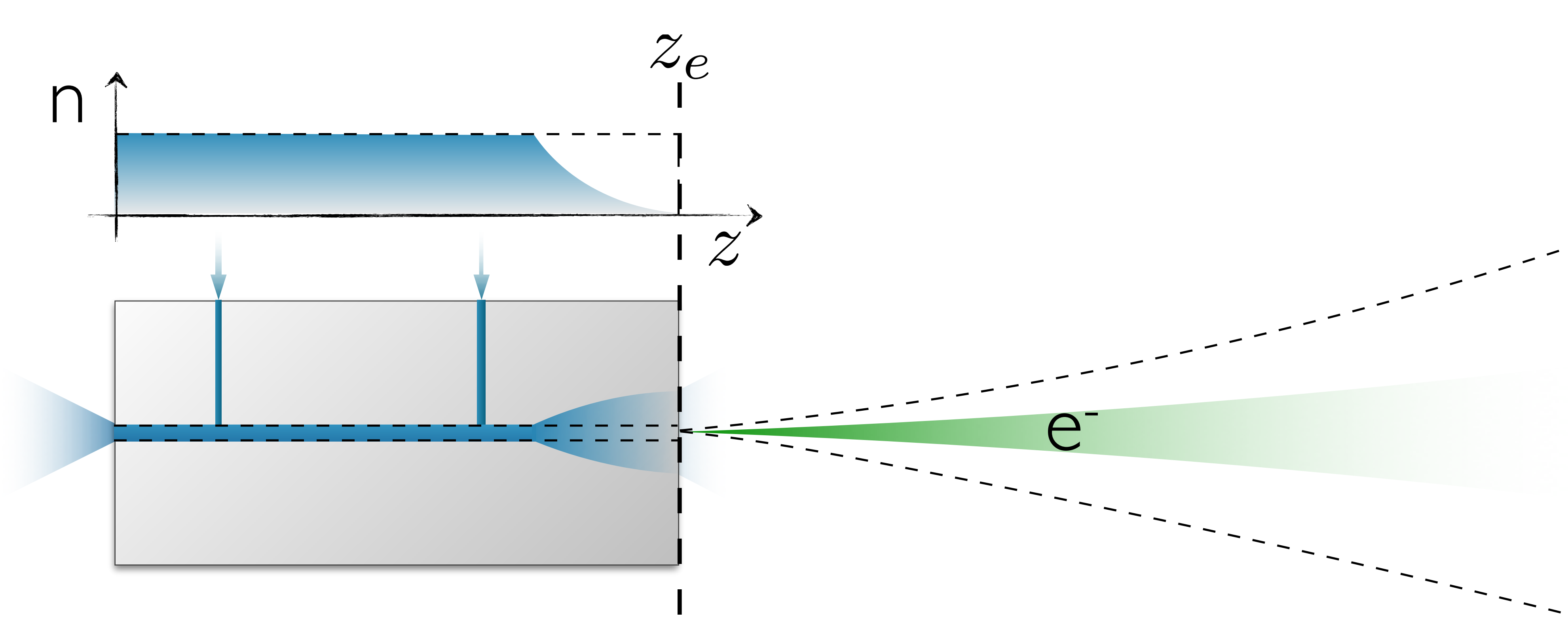

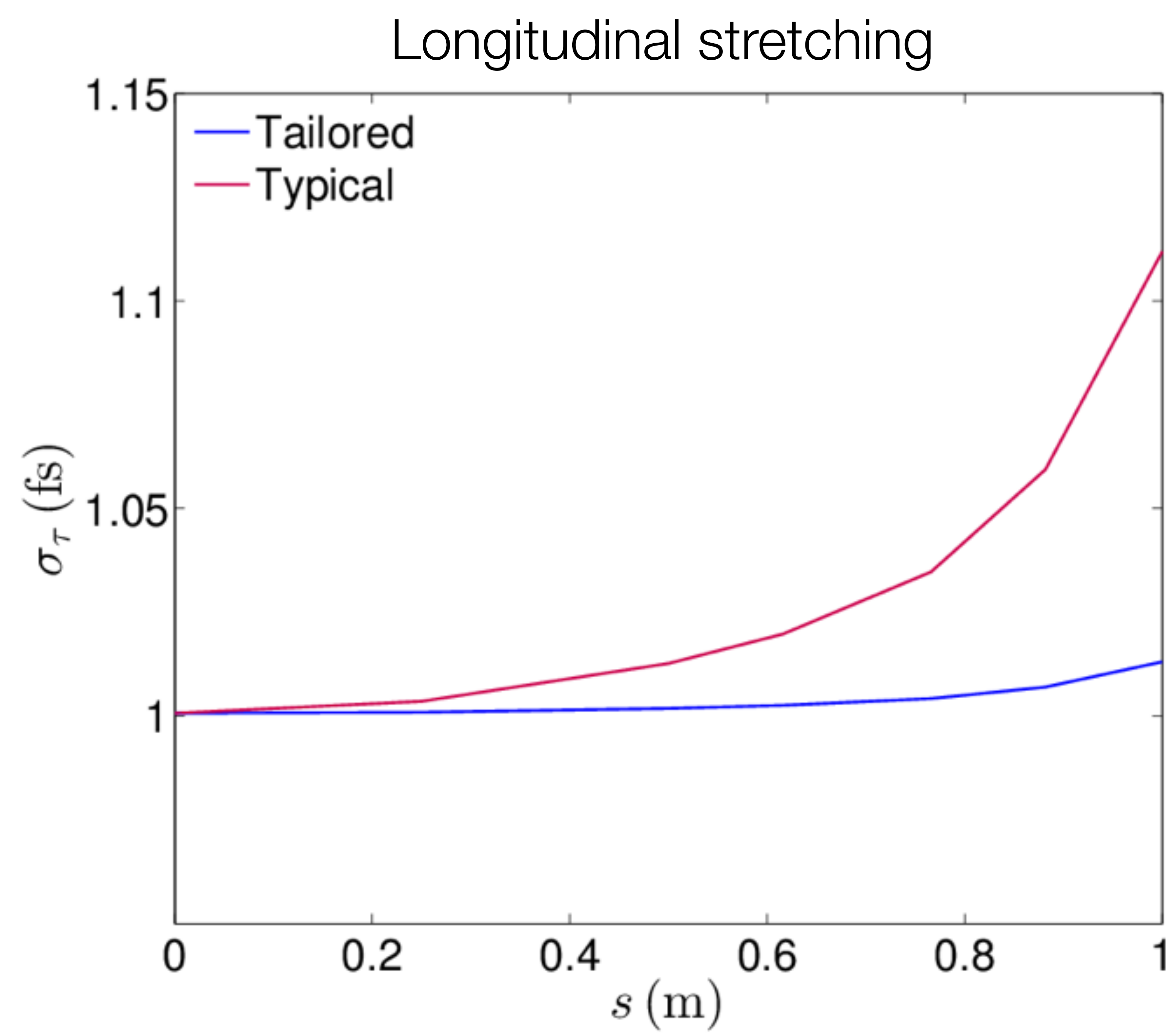

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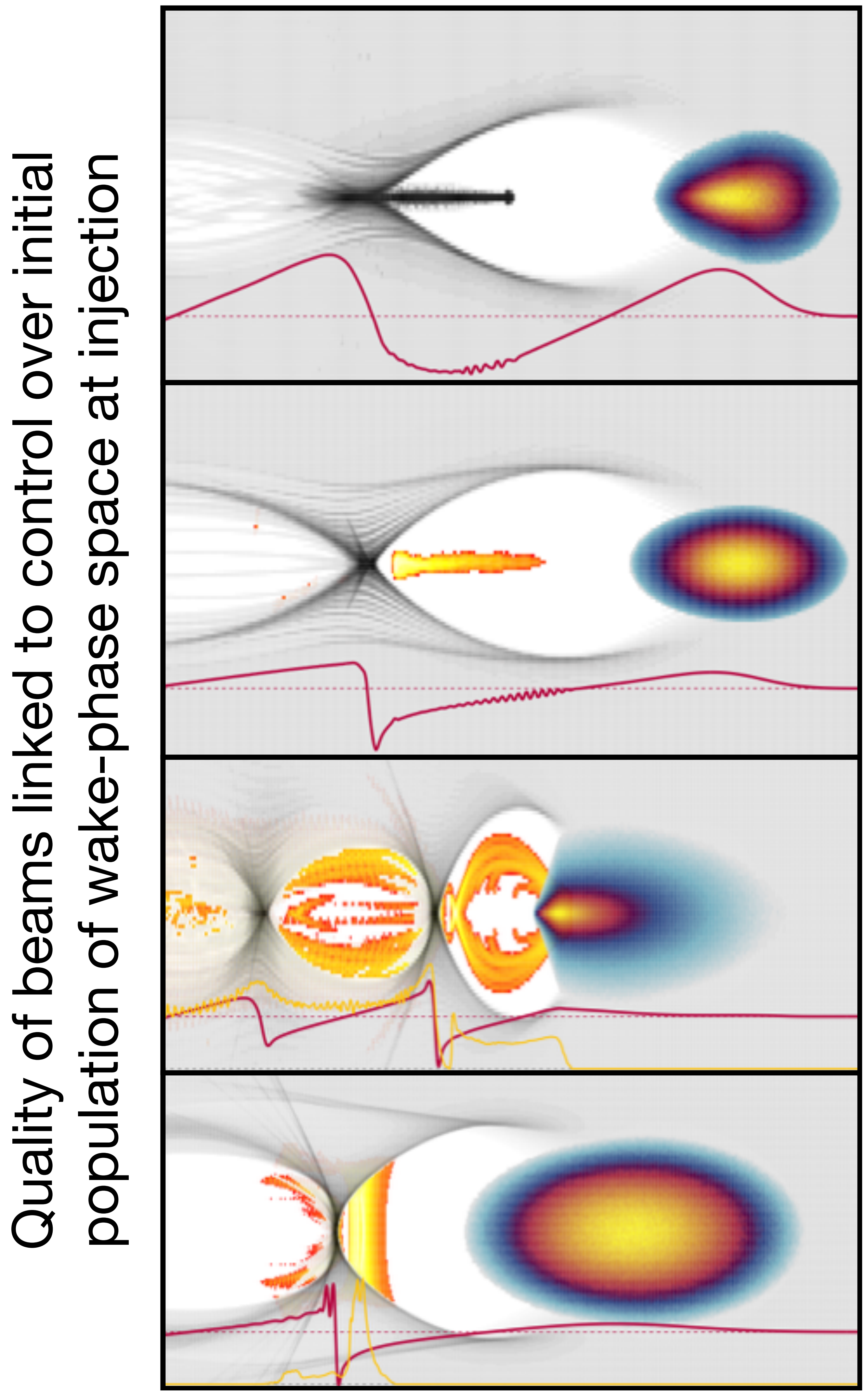
Novel in-plasma beam-generation techniques for unprecedented beam properties



- **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)

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

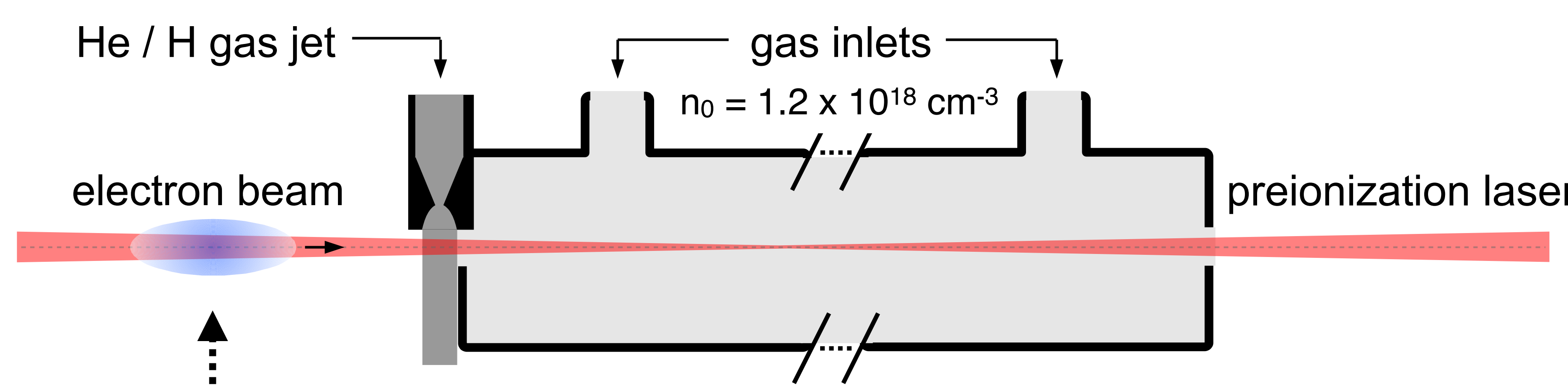
- **Beam-induced ionization injection**
  A. Martinez de la Ossa et al., NIM A 740, 231 (2014)

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

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

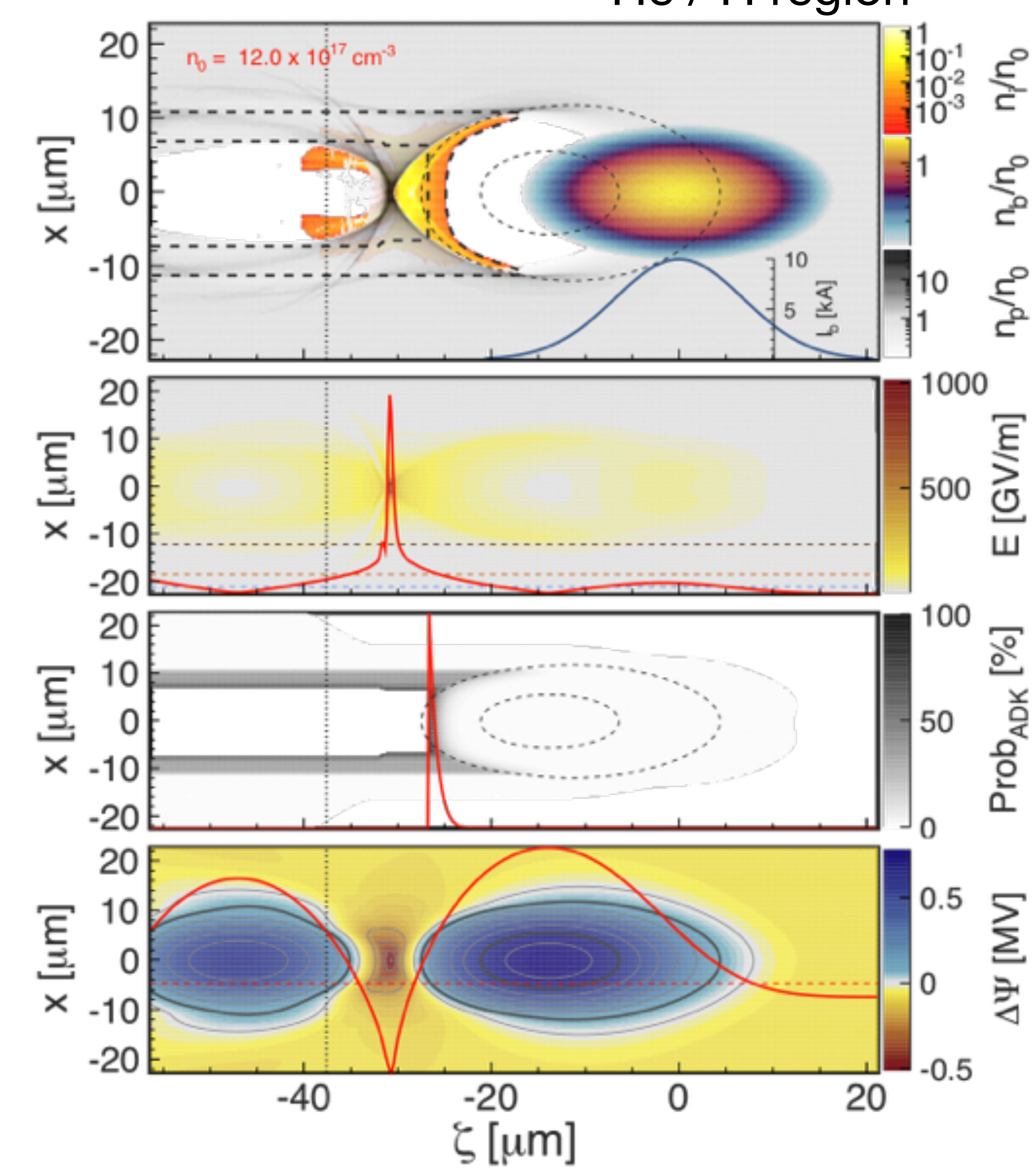
  $I_B \gtrsim 10\ \mathrm{kA}$

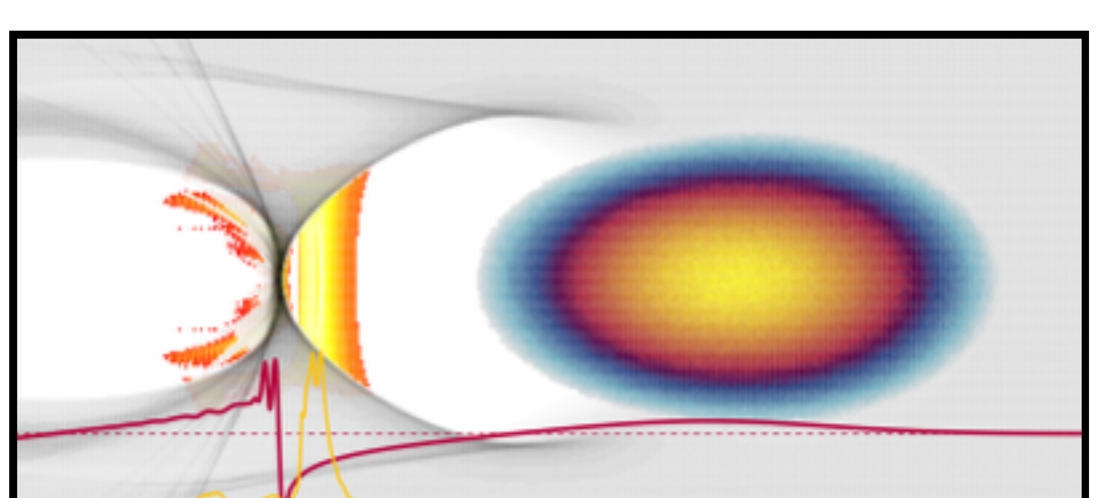
Wakefield-induced ionization injection utilizes strong fields of the generated wakefield to ionize dopant gas



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

He / H region





> Wakefield-induced ionization injection

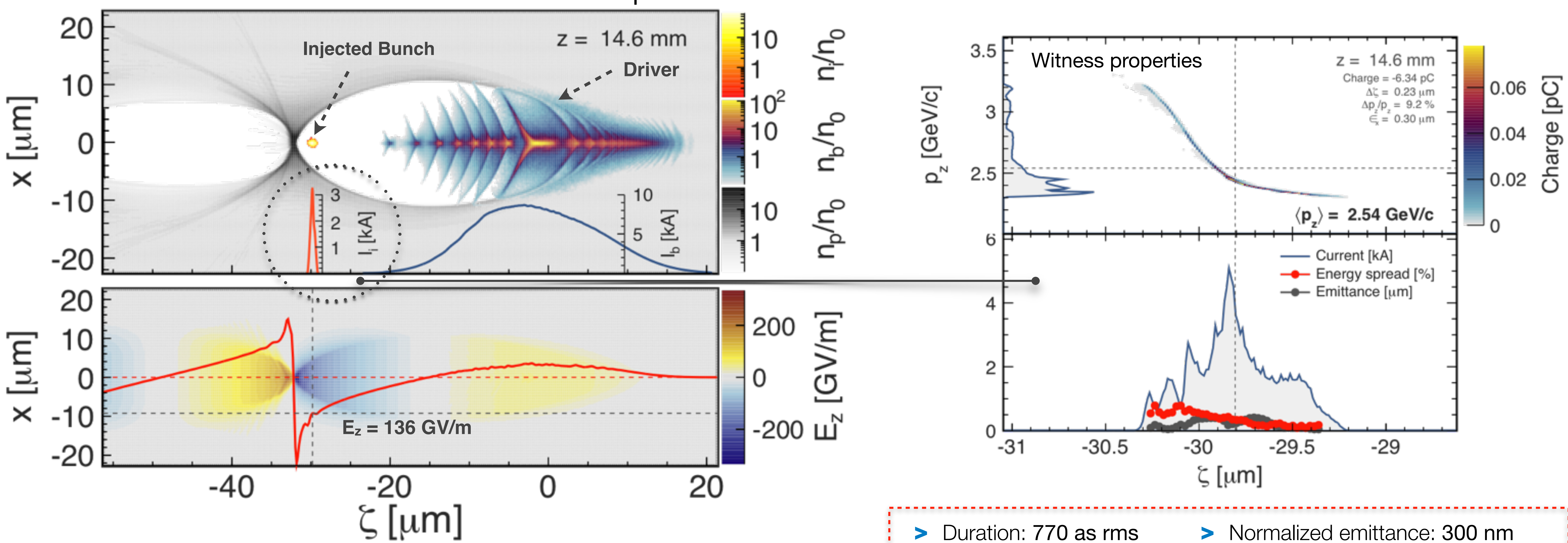
A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)

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

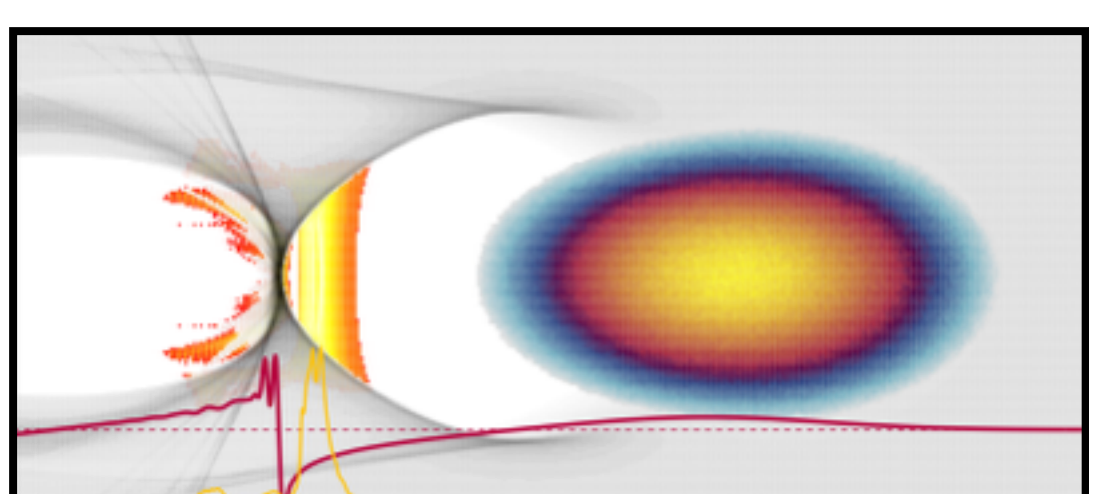
Wakefield-induced ionization injection allows for beams with low emittance & sub-femtosecond durations

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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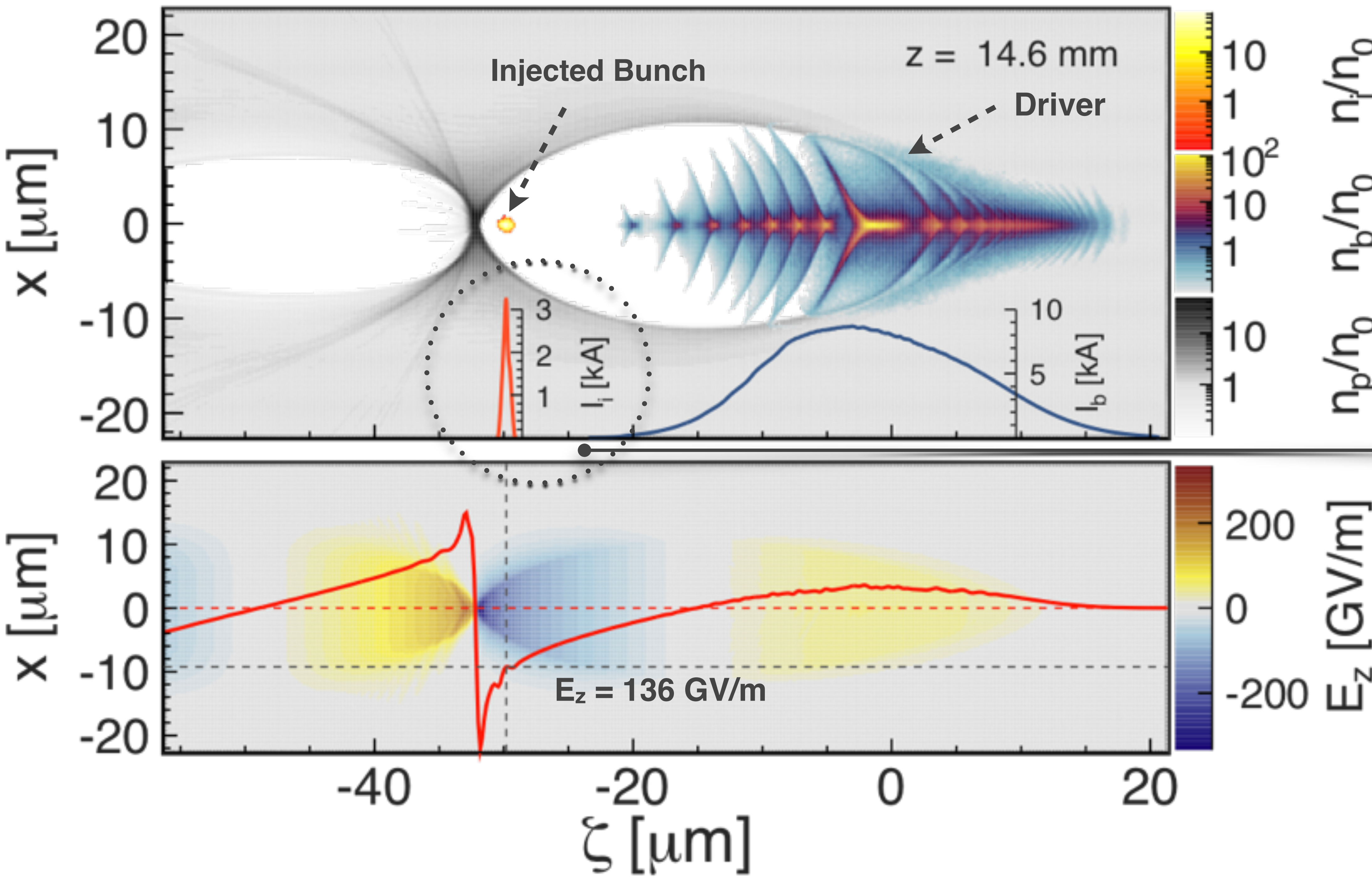

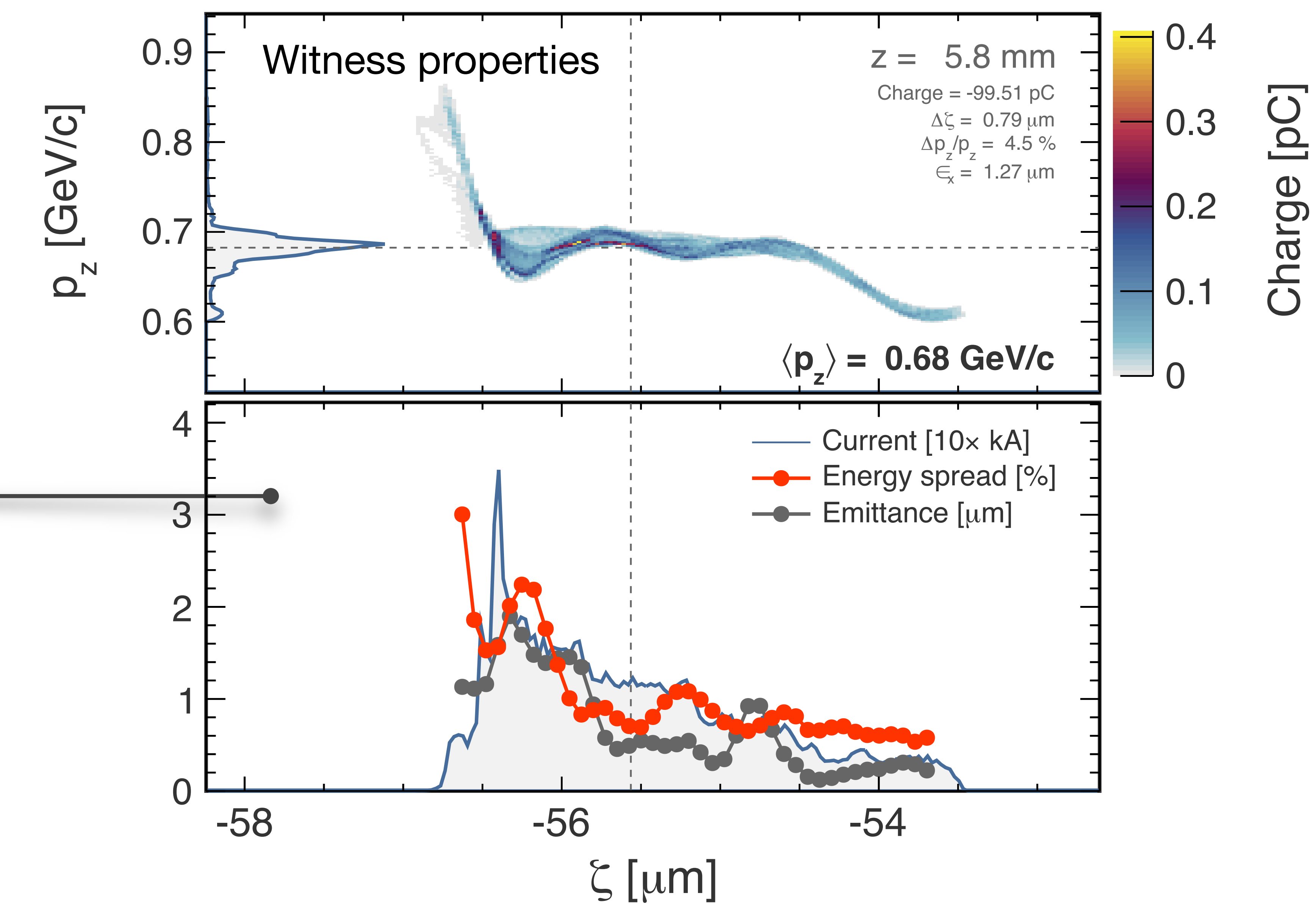

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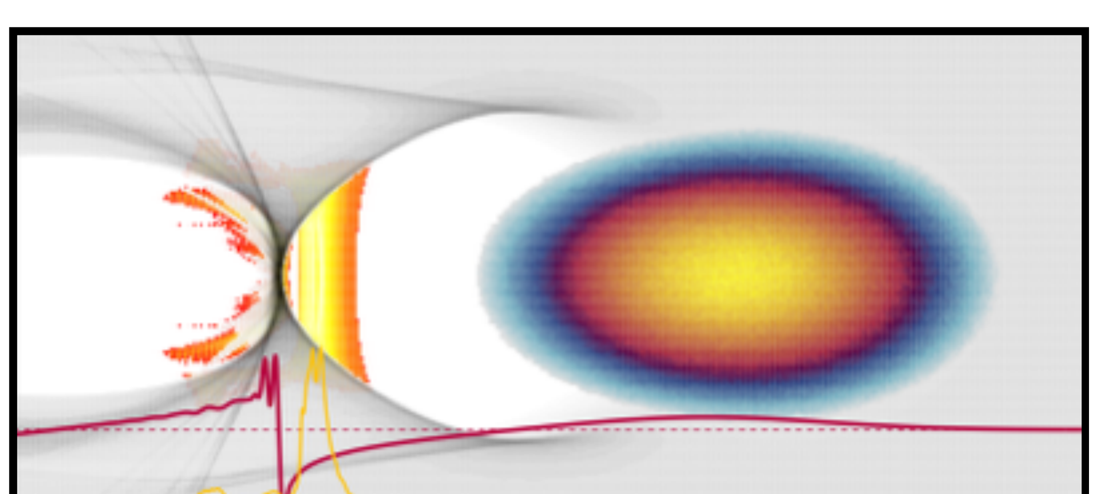

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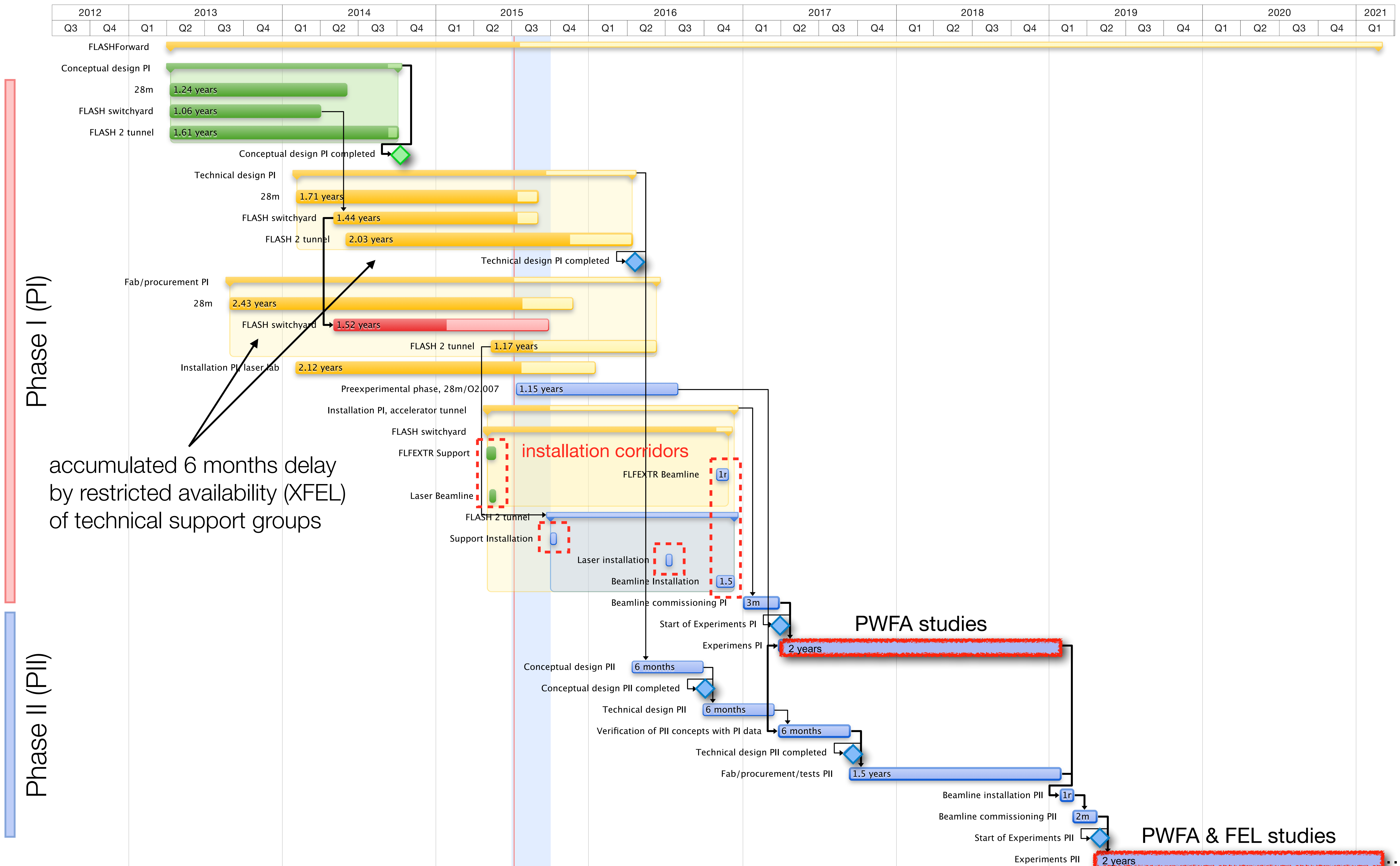
  $I_B \gtrsim 10$ kA

Experiments to start in January 2017



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
- External injection and extraction experiments are foreseen as a precursor to staging studies, important for HEP
- FLASHForward is an important step to explore beam-driven wakefield acceleration and prepare it for applications

Goal: plasma accelerator research → usable plasma accelerators