Challenges for a PWFA-based linear collider

with a focus on plasma wakefield aspects

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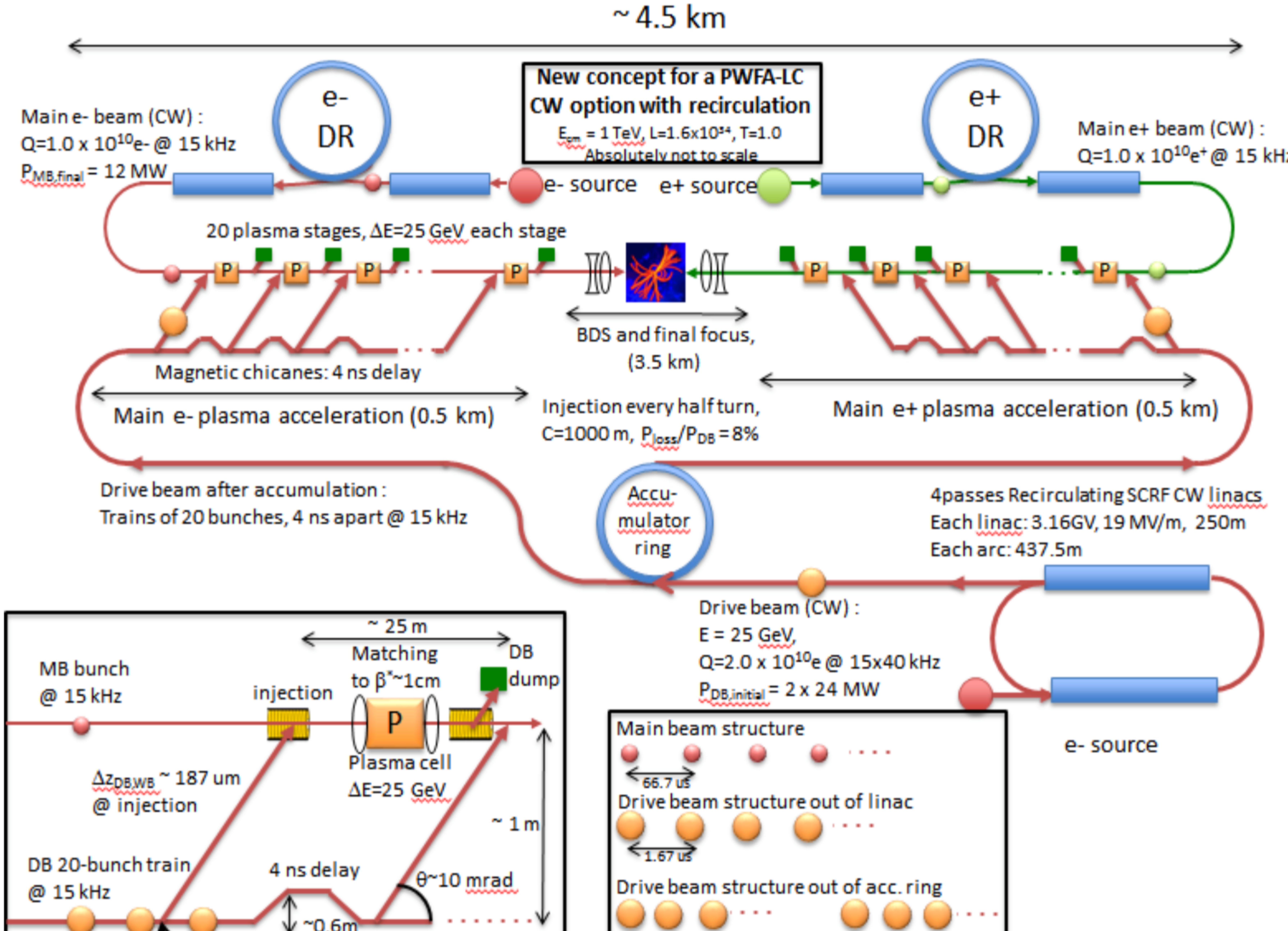
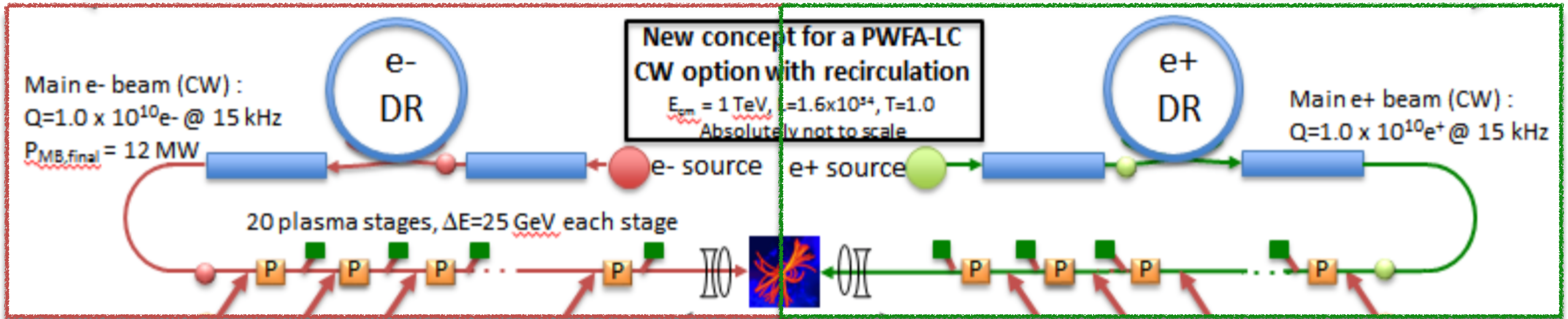
LAOLA.



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



Electrons

Positrons

Similar challenges for both particle types

> High luminosity → average power + beam quality

~3×10^{34} cm^{-2} s^{-1} *~10 MW*

high charge
~nC / pulse

high rep. rate
~10 kHz

wp efficiency
~10%

low energy bandwidth
sub %

low emittance
~10 nm rad

thermal management in plasma

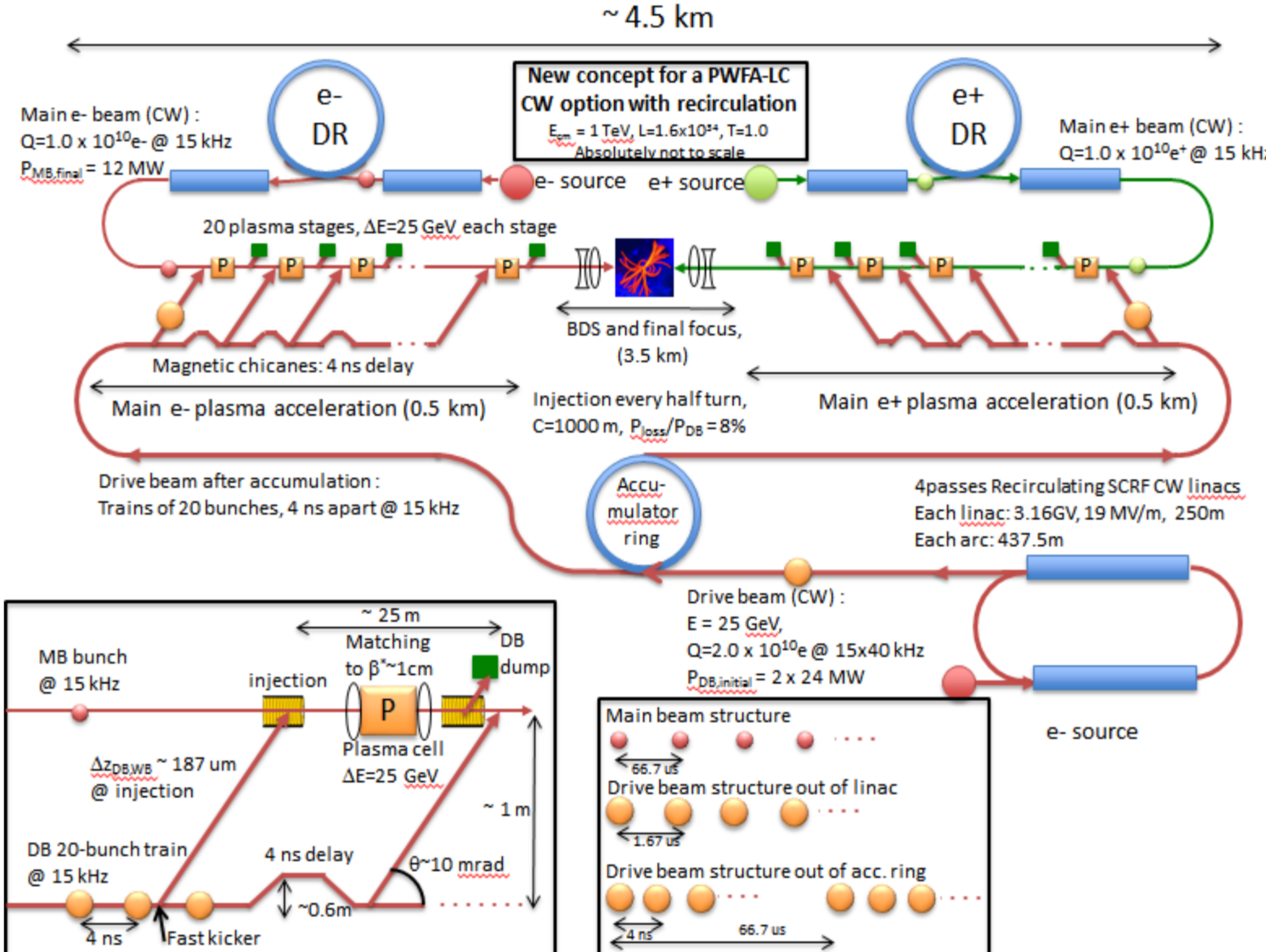
simultaneously

stability and control
not single shots!

> Staging and preserving beam quality

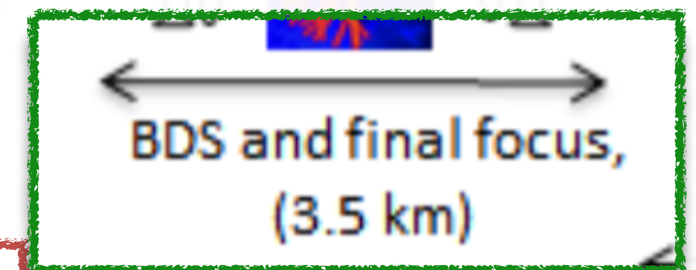
> Acceleration of polarized beams

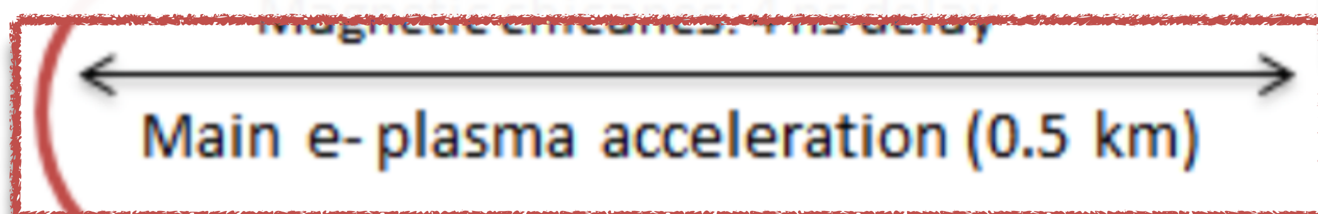
Key challenges


~ 4.5 km
New concept for a PWFA-LC
CW option with recirculation
E_cm = 1 TeV, L=1.6x10^34, T=1.0
Absolutely not to scale
Main e- beam (CW) :
Q=1.0 x 10^10 e- @ 15 kHz
P_MB,final = 12 MW
e-
DR
e- source
e+ source
e+
DR
Main e+ beam (CW) :
Q=1.0 x 10^10 e+ @ 15 kHz
20 plasma stages, ΔE=25 GeV each stage
P
BDS and final focus,
(3.5 km)
Magnetic chicanes: 4 ns delay
Main e- plasma acceleration (0.5 km)
Injection every half turn,
C=1000 m, P_loss/P_DB = 8%
Main e+ plasma acceleration (0.5 km)
Drive beam after accumulation :
Trains of 20 bunches, 4 ns apart @ 15 kHz
Accu-
mulator
ring
4passes Recirculating SCRF CW linacs
Each linac: 3.16GV, 19 MV/m, 250m
Each arc: 437.5m
Drive beam (CW) :
E = 25 GeV,
Q=2.0 x 10^10 e @ 15x40 kHz
P_DB,initial = 2 x 24 MW
e- source
~ 25 m
Matching
to β*~1cm
DB
dump
MB bunch
@ 15 kHz
injection
P
Plasma cell
ΔE=25 GeV
Δz_DB,WB ~ 187 um
@ injection
~ 1 m
DB 20-bunch train
@ 15 kHz
4 ns delay
θ~10 mrad
~0.6m
4 ns
Fast kicker
Main beam structure
66.7 us
Drive beam structure out of linac
1.67 us
Drive beam structure out of acc. ring
4 ns
66.7 us

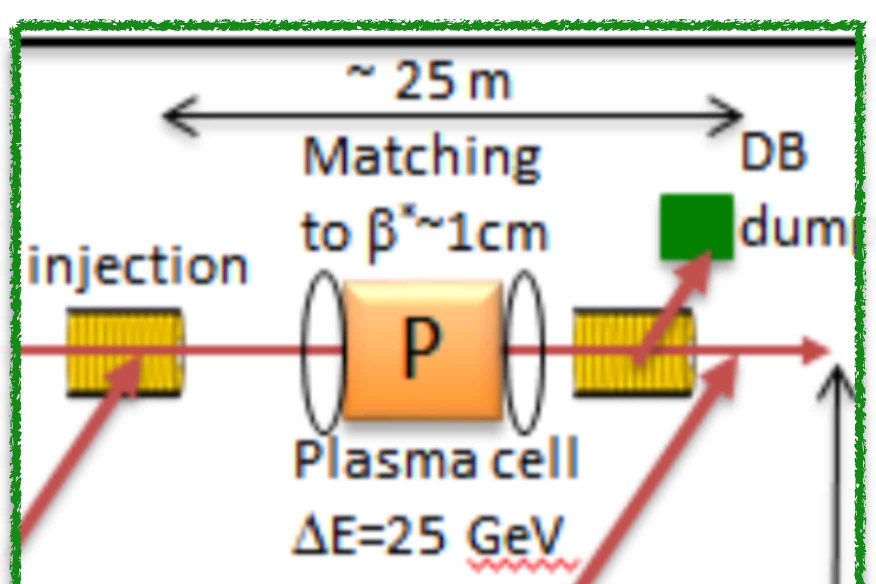
Appeal of plasma technology for HEP scales with cost: efficiency and average gradient

- Average gradient reduced by size of final focus system





- Average gradient reduced by coupling of stages



- Develop plasma based optics

Key challenges

How can FACET II help with these challenges?

> **Essential,** not planned anywhere else
  - Positrons!

> **Important contributions,** supplemented by activities at ATF II, FLASHForward, SPARC_Lab (+ LWFA labs, e.g. BELLA)
  - Beam quality (emittance, energy spread)
  - Beam quality preservation, in-coupling & extraction (+ simultaneous efficiency)
  - Plasma optics
  - Wall plug efficiency

> **Not planned (to my knowledge)**
  - High average power, thermal management → requires superconducting machine (maybe at FLASHForward)
  - True staging (for PWFA)
  - Polarized beams

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)

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
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Violetta Wacker
Stefan Weichert
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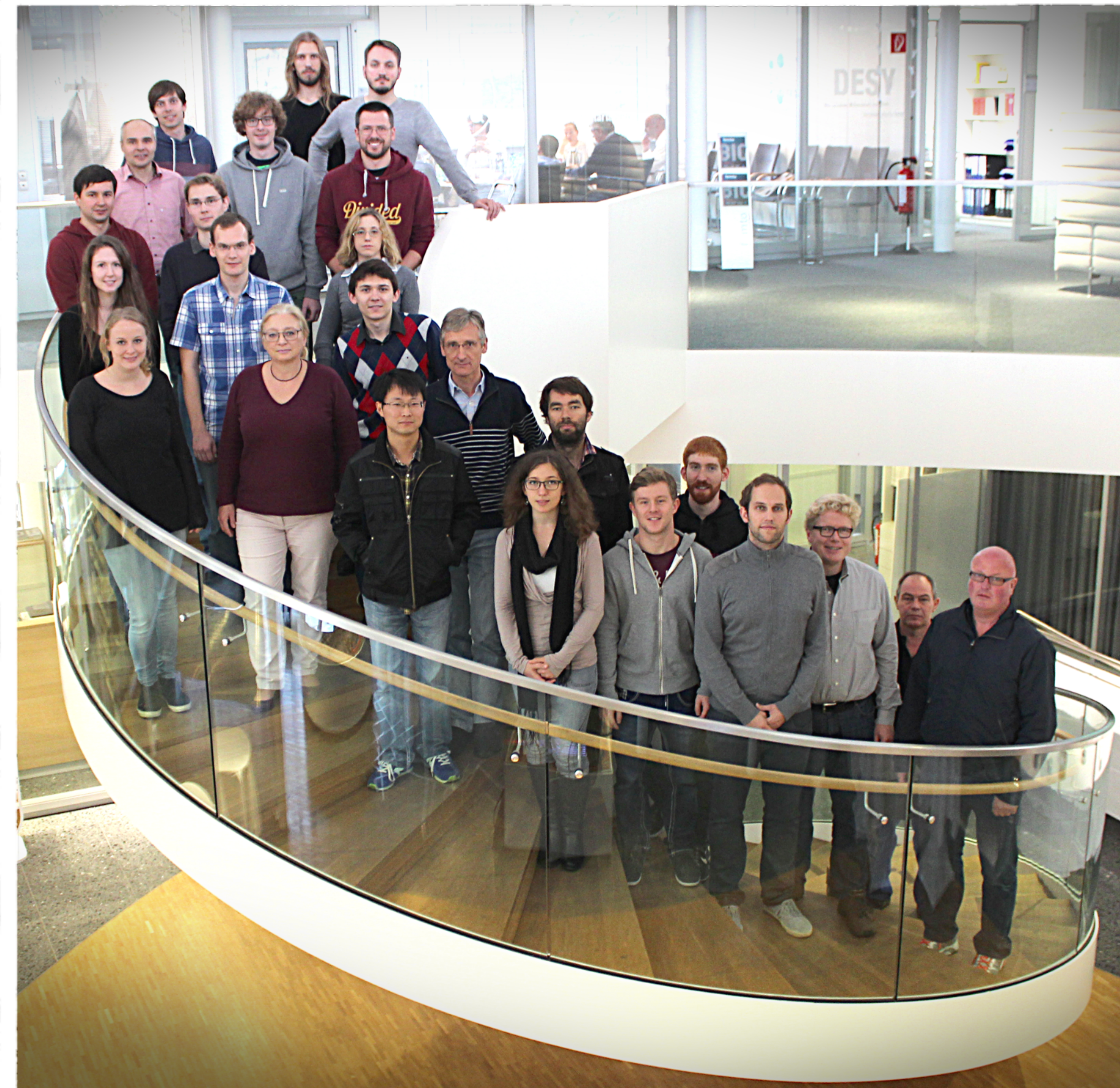
Matthew Streeter
Zhanghu Hu
Timon Mehrling
Christopher Behrens*
Laura di Lucchio

+ many DESY technical support groups



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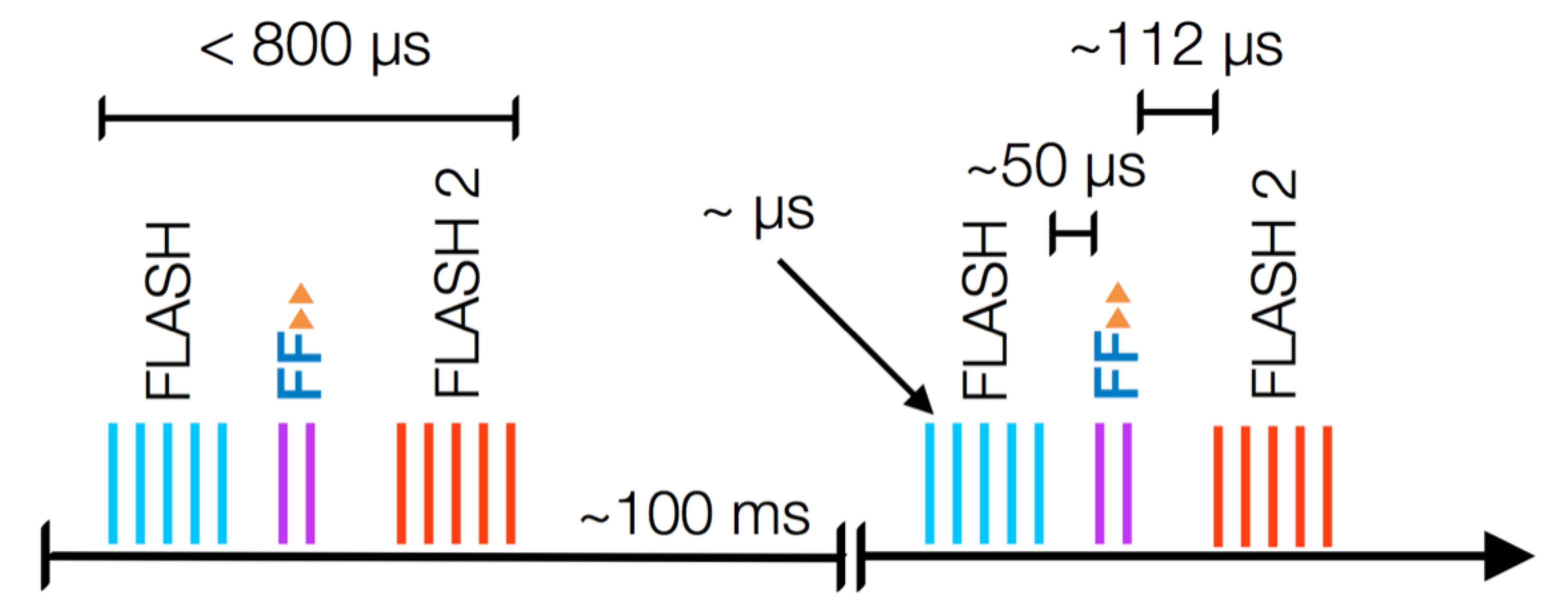
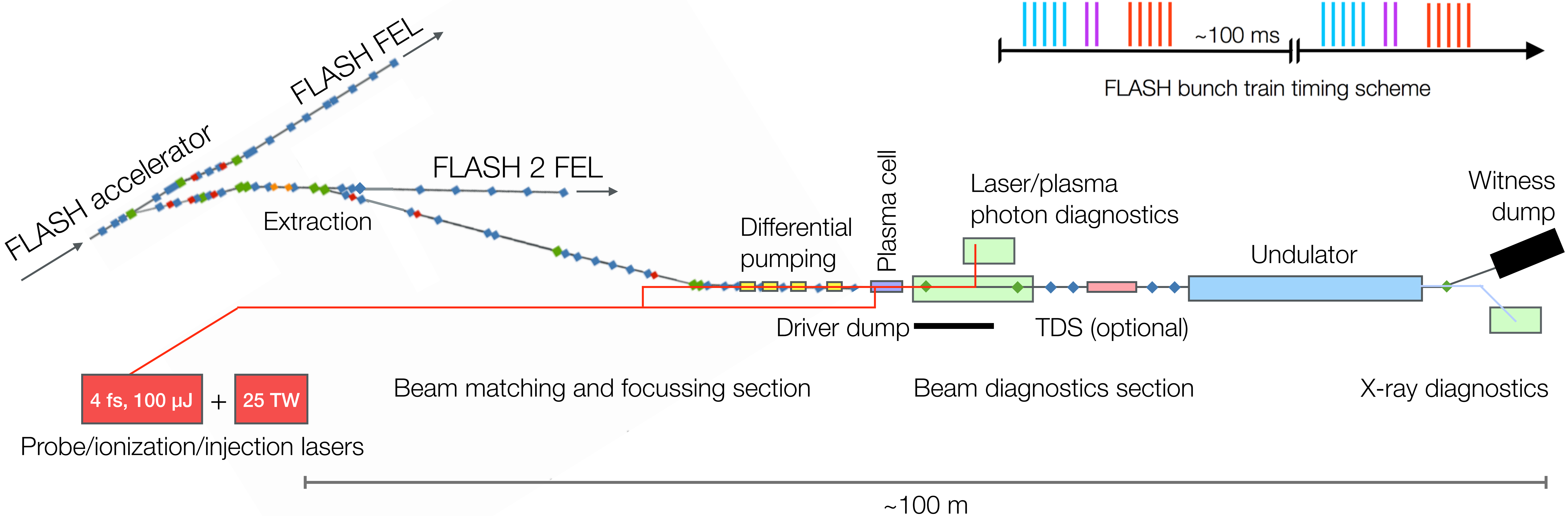
Collaborating institutes

- 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

FLASHForward▸▸ beamline overview



FLASH bunch train timing scheme



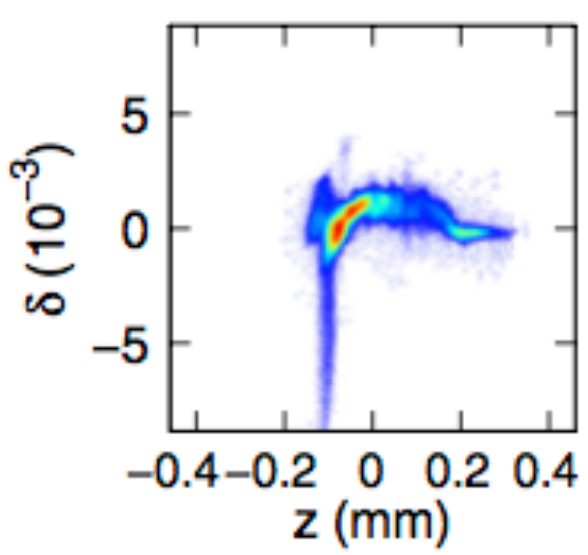
Capabilities of FLASH beams for FLASHForward

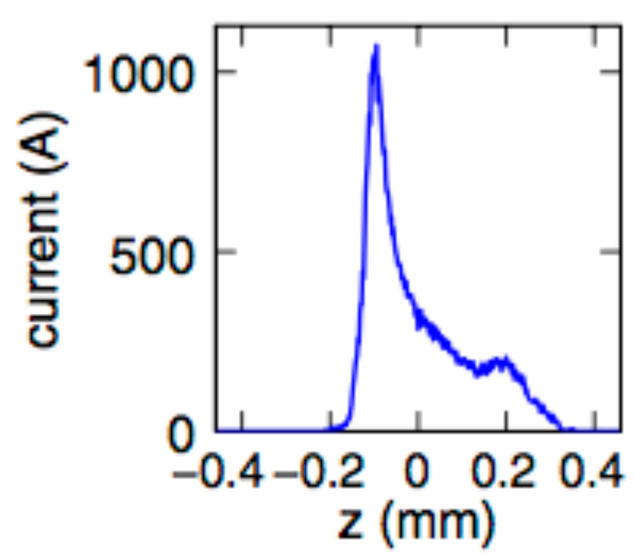
- FEL-quality (~1.25 GeV, ~0.1% energy spread, ~2 μm transverse norm. emittance), simultaneous with FLASH and FLASH 2
- Variable longitudinal beam shape (e.g. Gaussian, triangular), multi-kA peak current
- Sophisticated laser-to-beam synchronization for diagnostics/laser-triggered injection schemes
-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

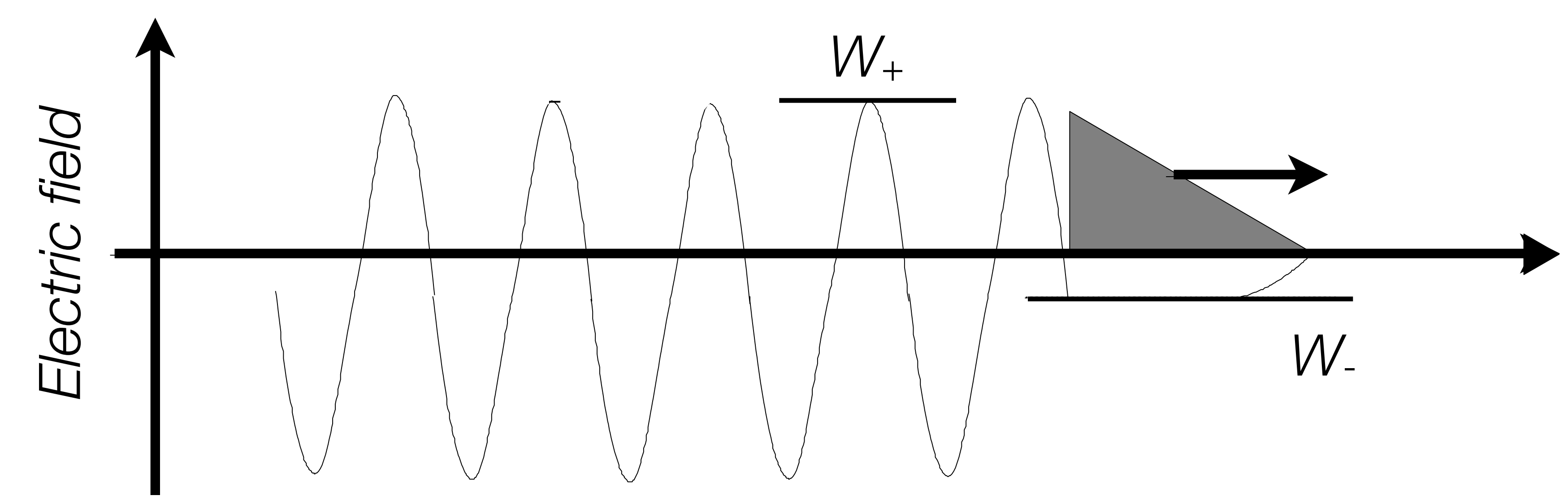
Versatile electron beams for transformer ratio studies

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 $R = W_+ / W_-$

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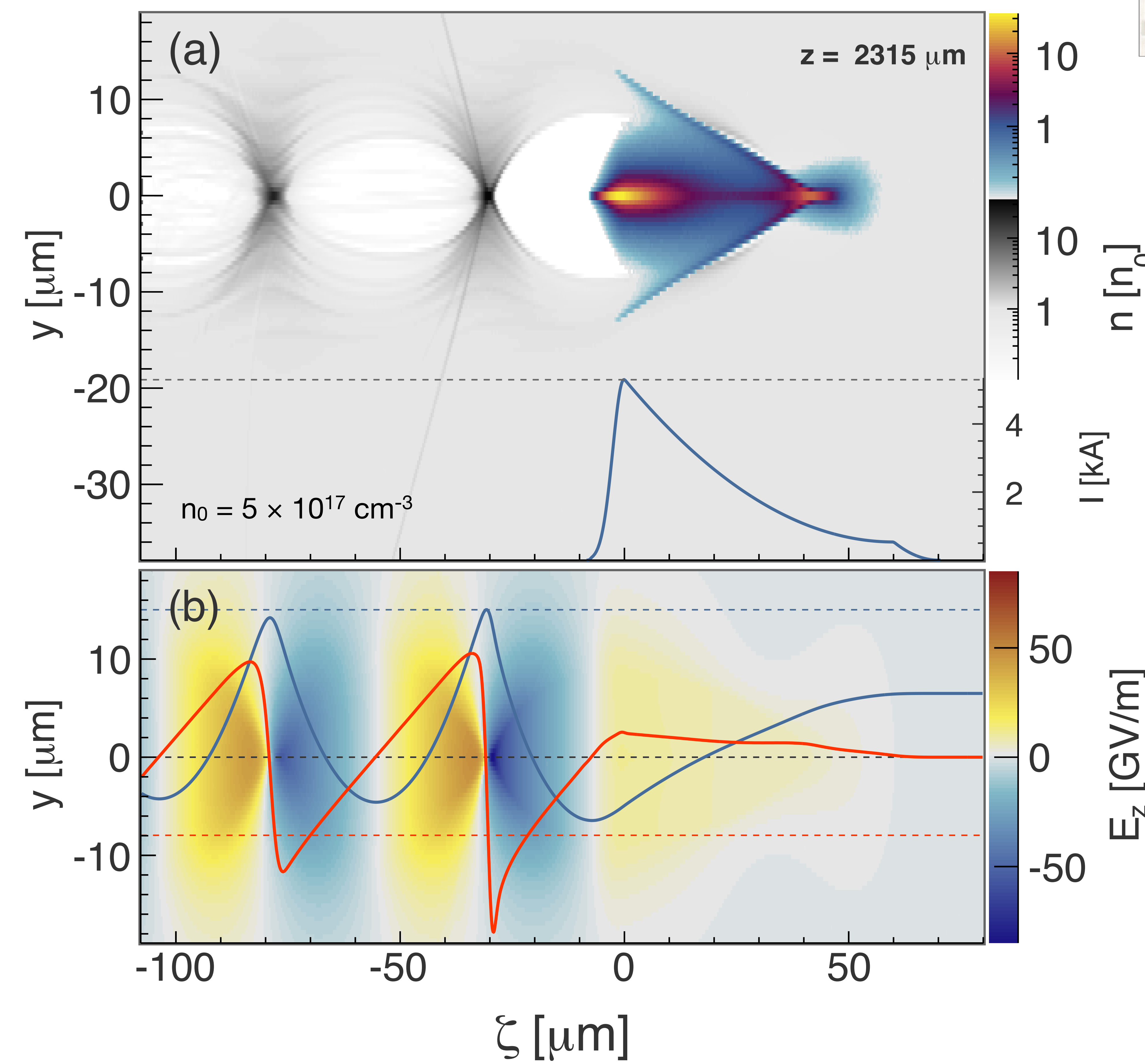
From OSIRIS 3D PIC simulations

- 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



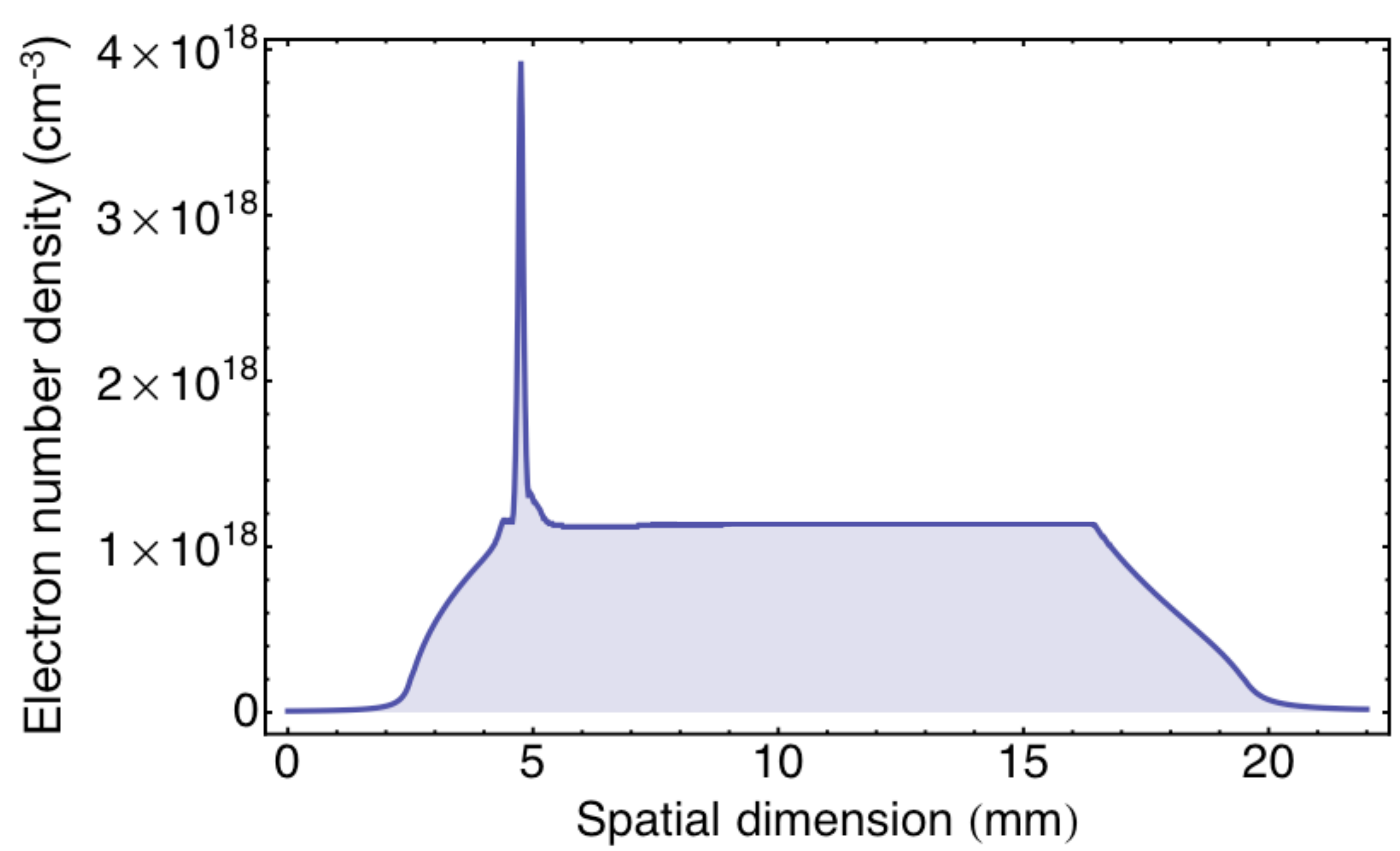
Plasma-cell design supports PWFA-injection schemes and emittance preservation

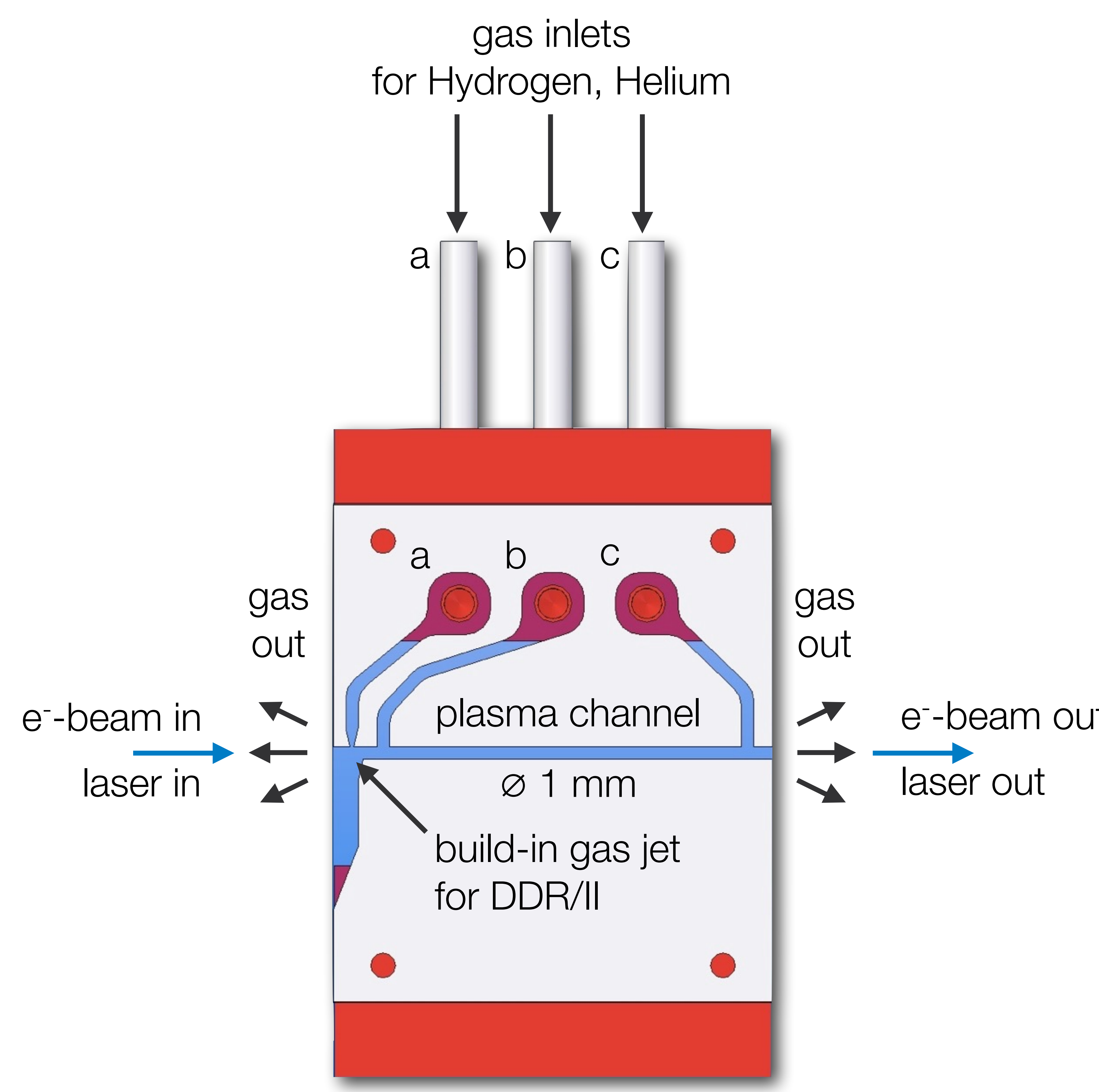
scheme by L. Schaper (DESY), N. Delbos, A. Maier (UHH)

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



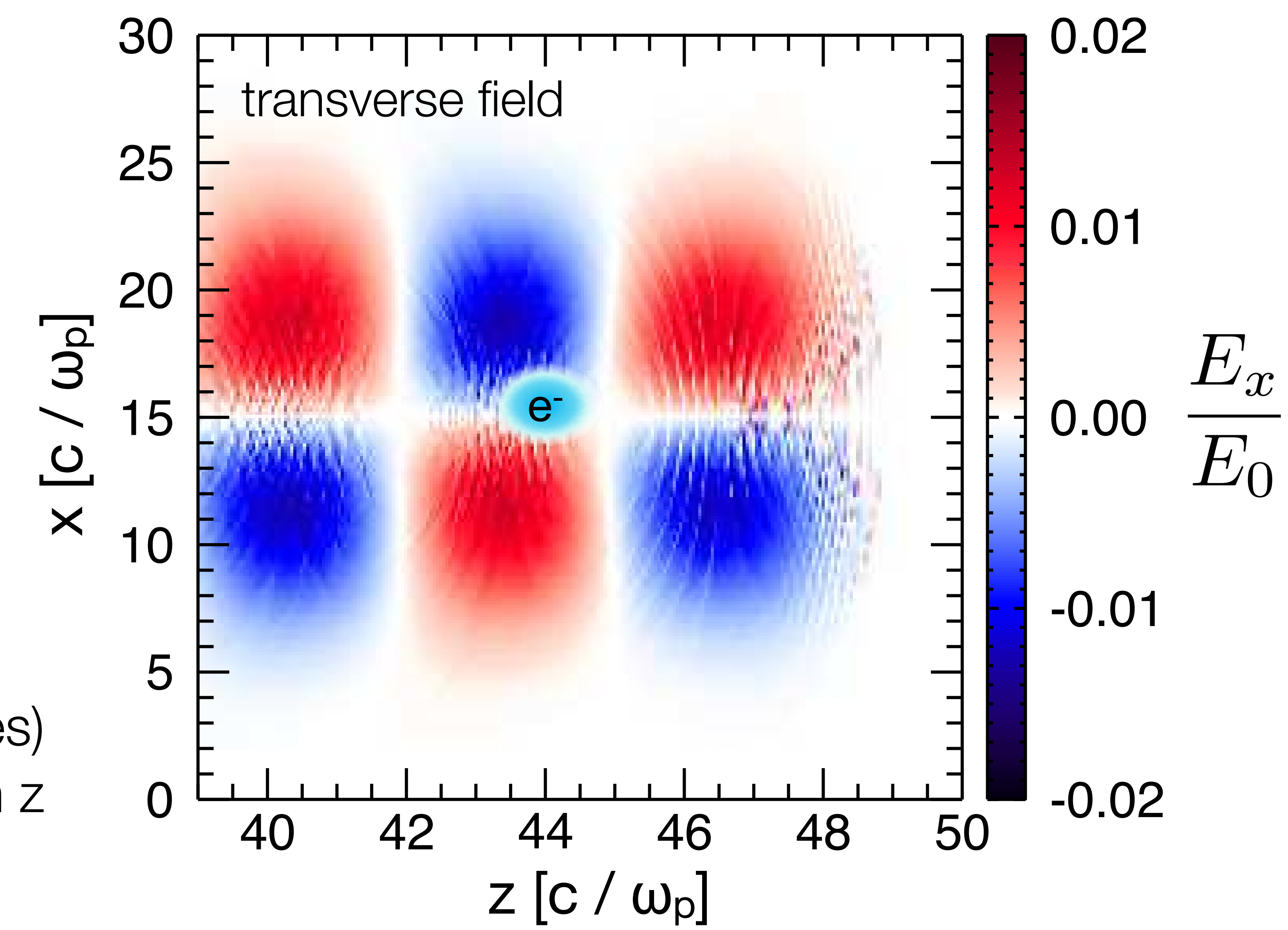


External beam injection: a challenge to preserve emittance

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

with $x' = p_x / p_z$

Beam slice energy (& focusing forces) may vary in plasmas in z



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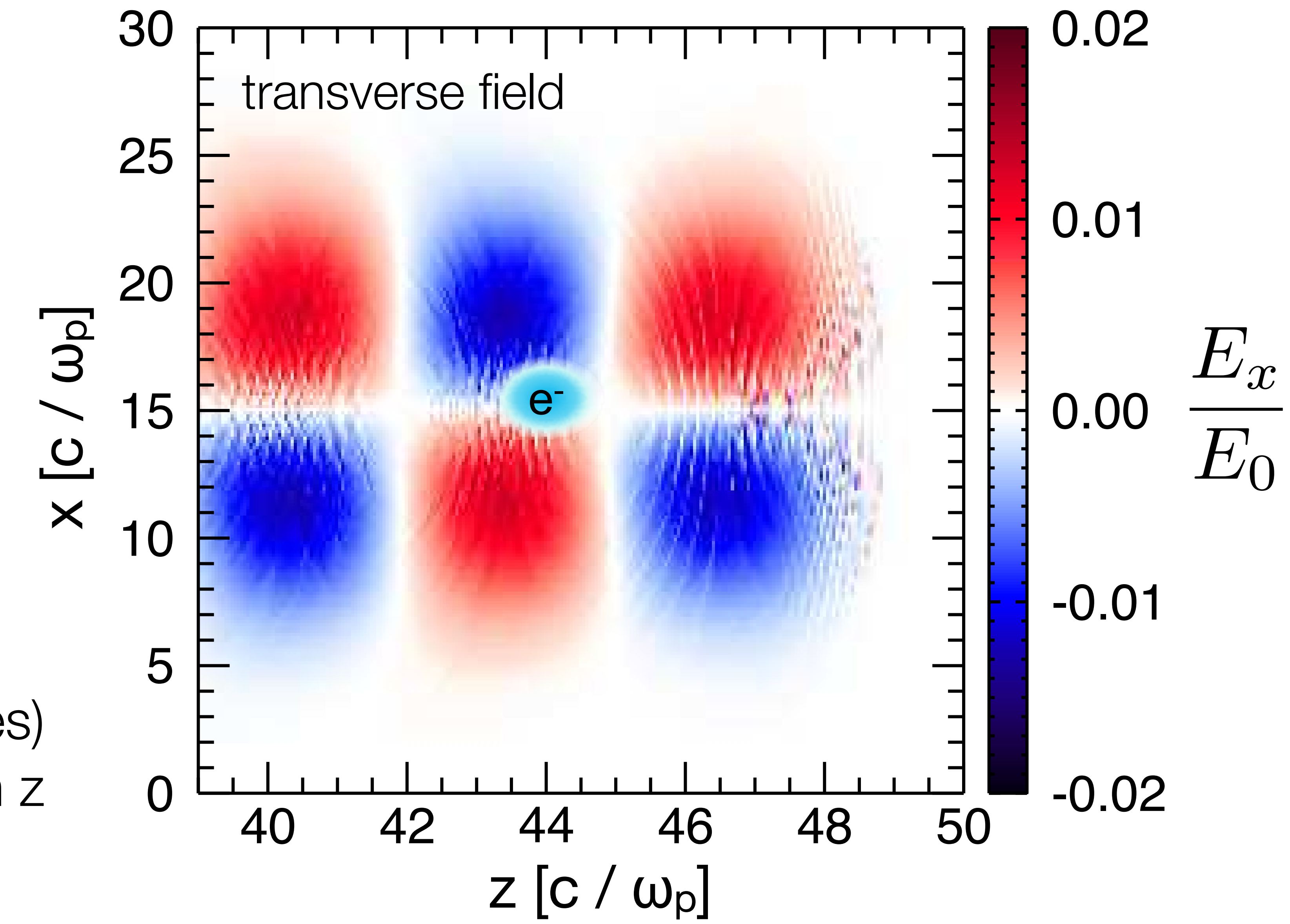
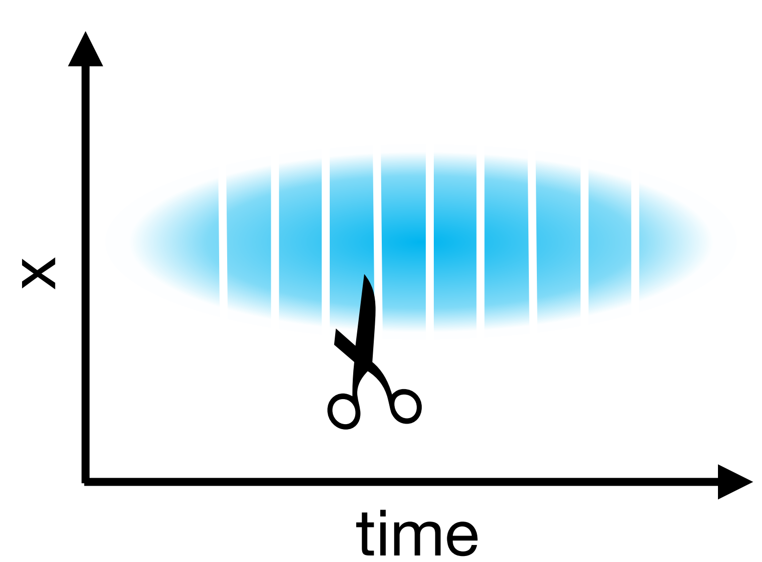
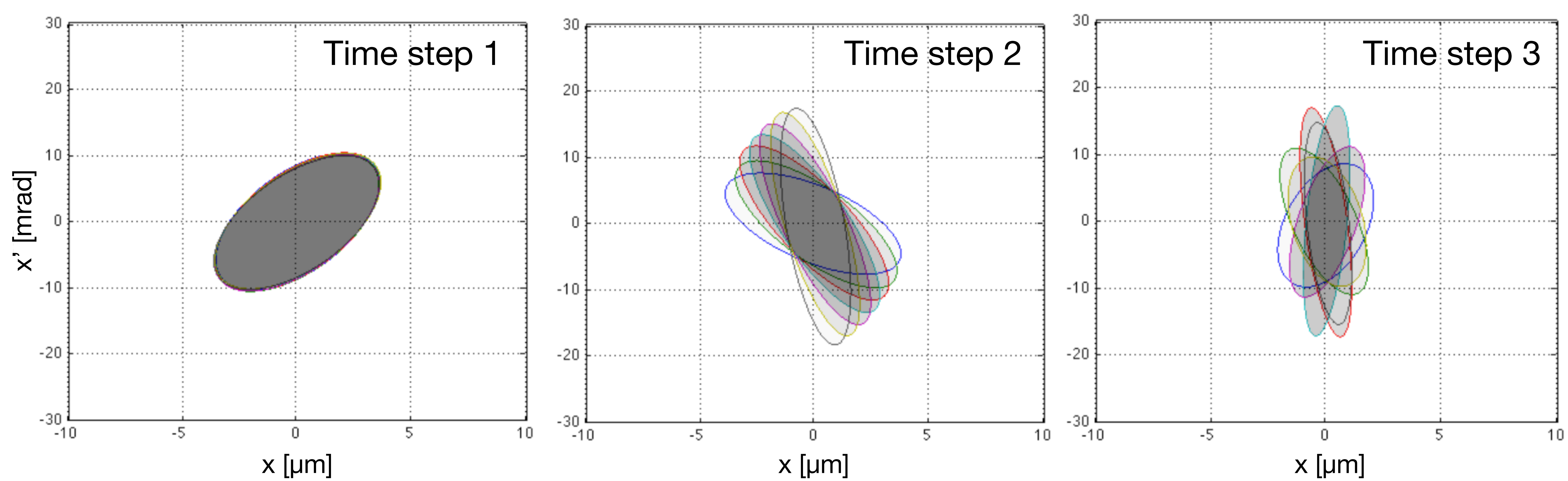


Beam slice energy (& focusing forces) may vary in plasmas in z

Slice rotation speeds vary along electron bunch



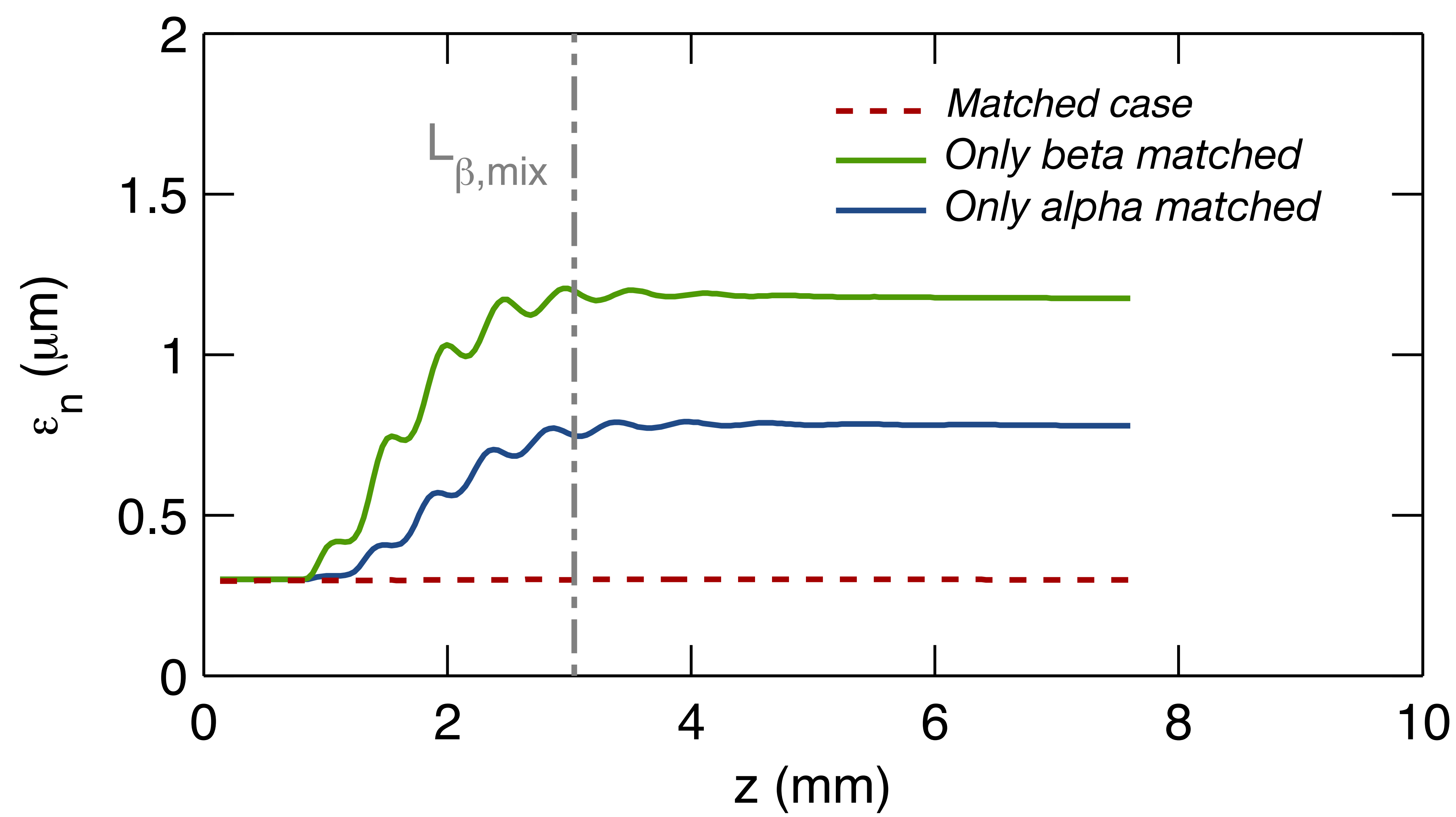


External beam injection: a challenge to preserve emittance

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

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)
- Matching sections between stages may require significant space with conventional technology
- Matched β can be challenging to achieve, β ≈ 1 mm at **FLASH**Forward▸▸

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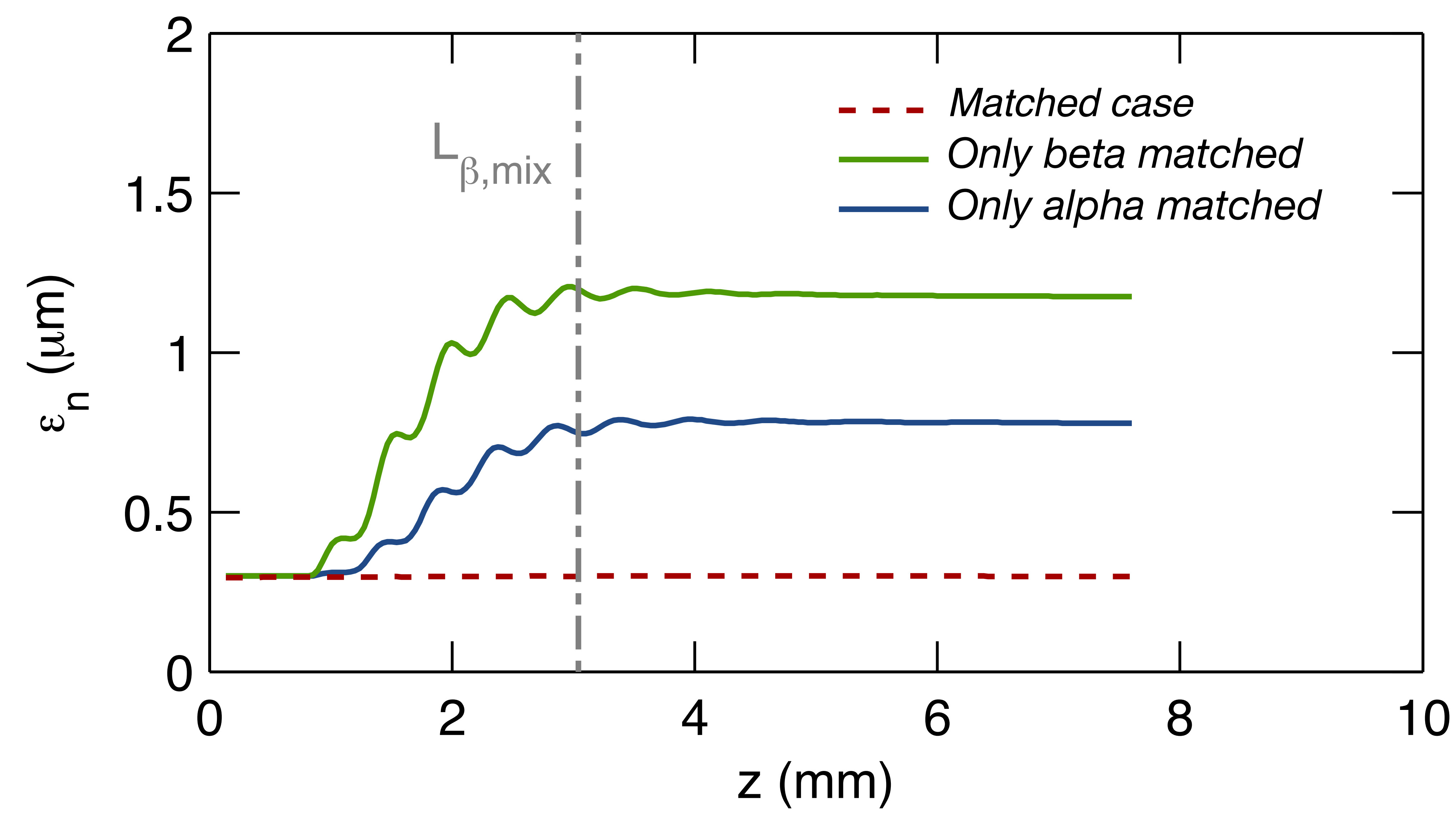

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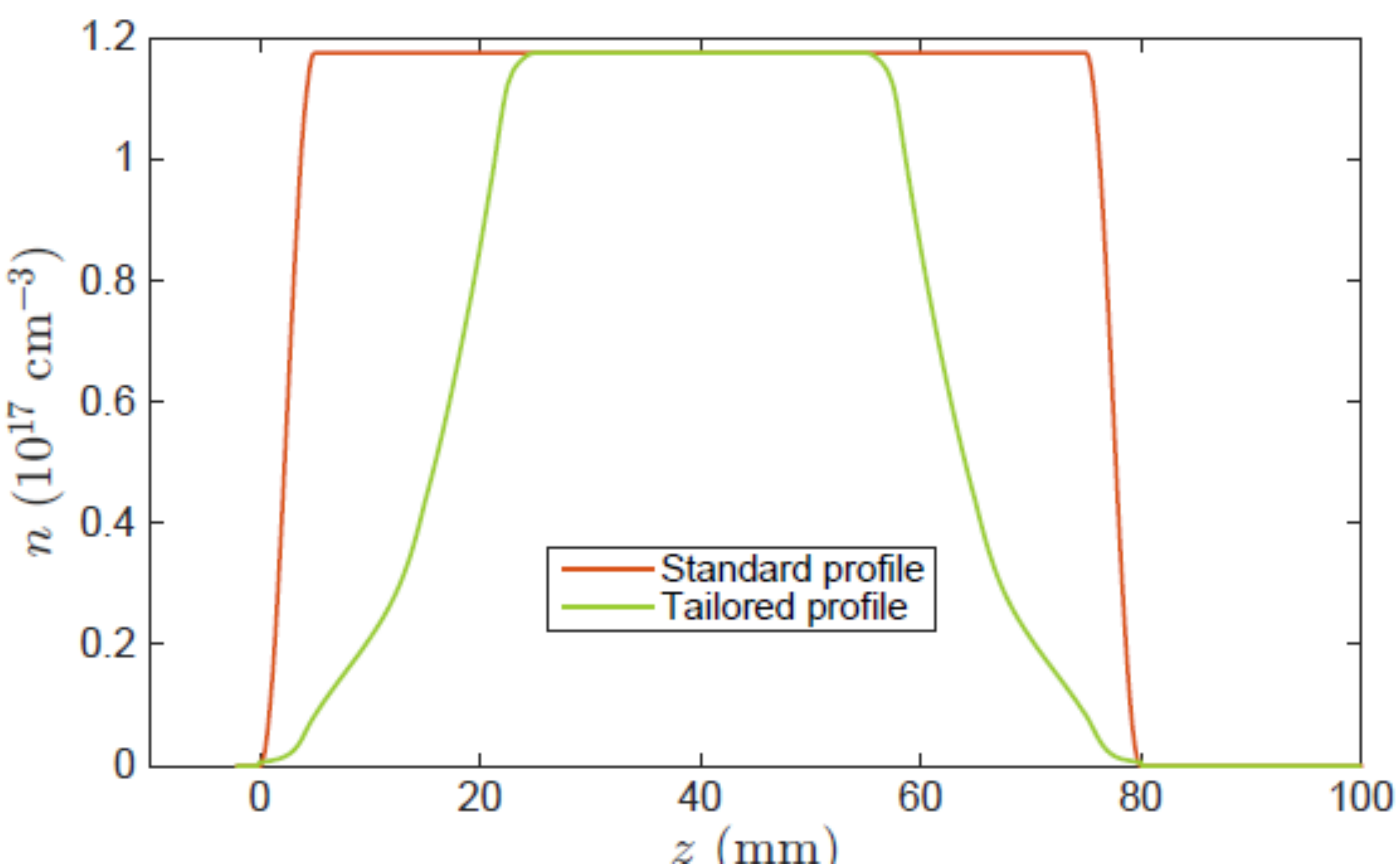
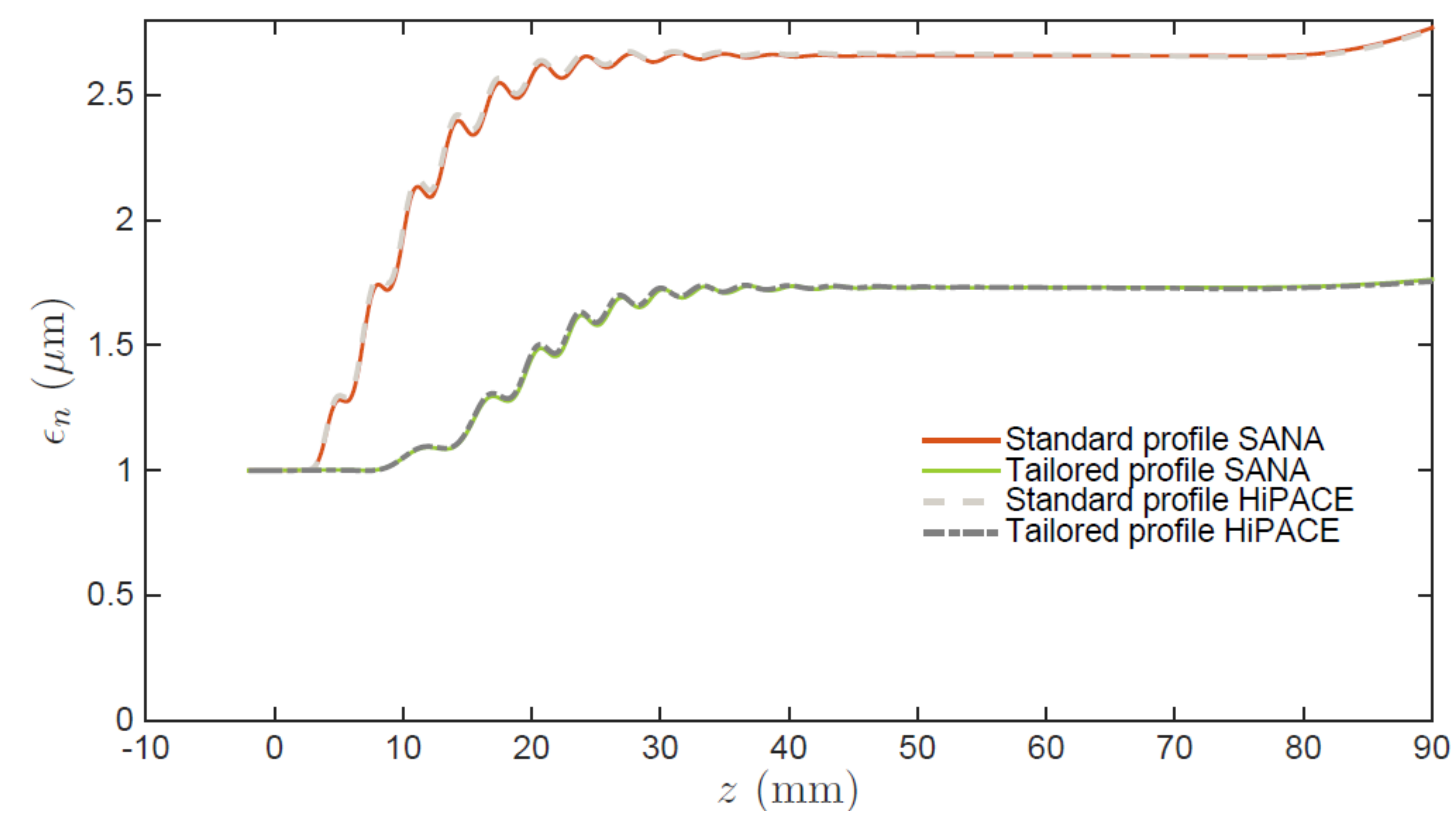
→ Plasma optics to maintain average gradient?

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**

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

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

HiPACE

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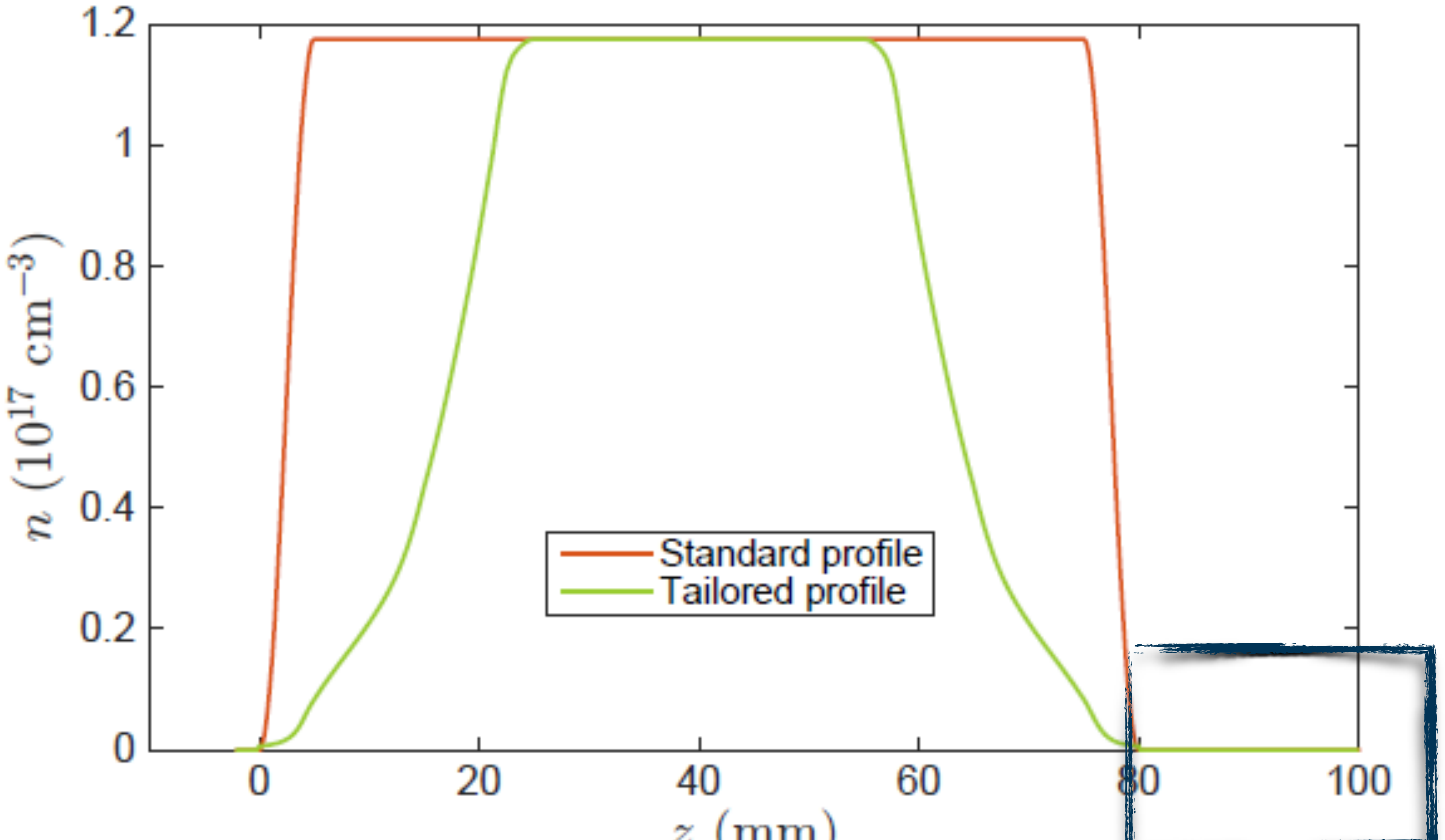

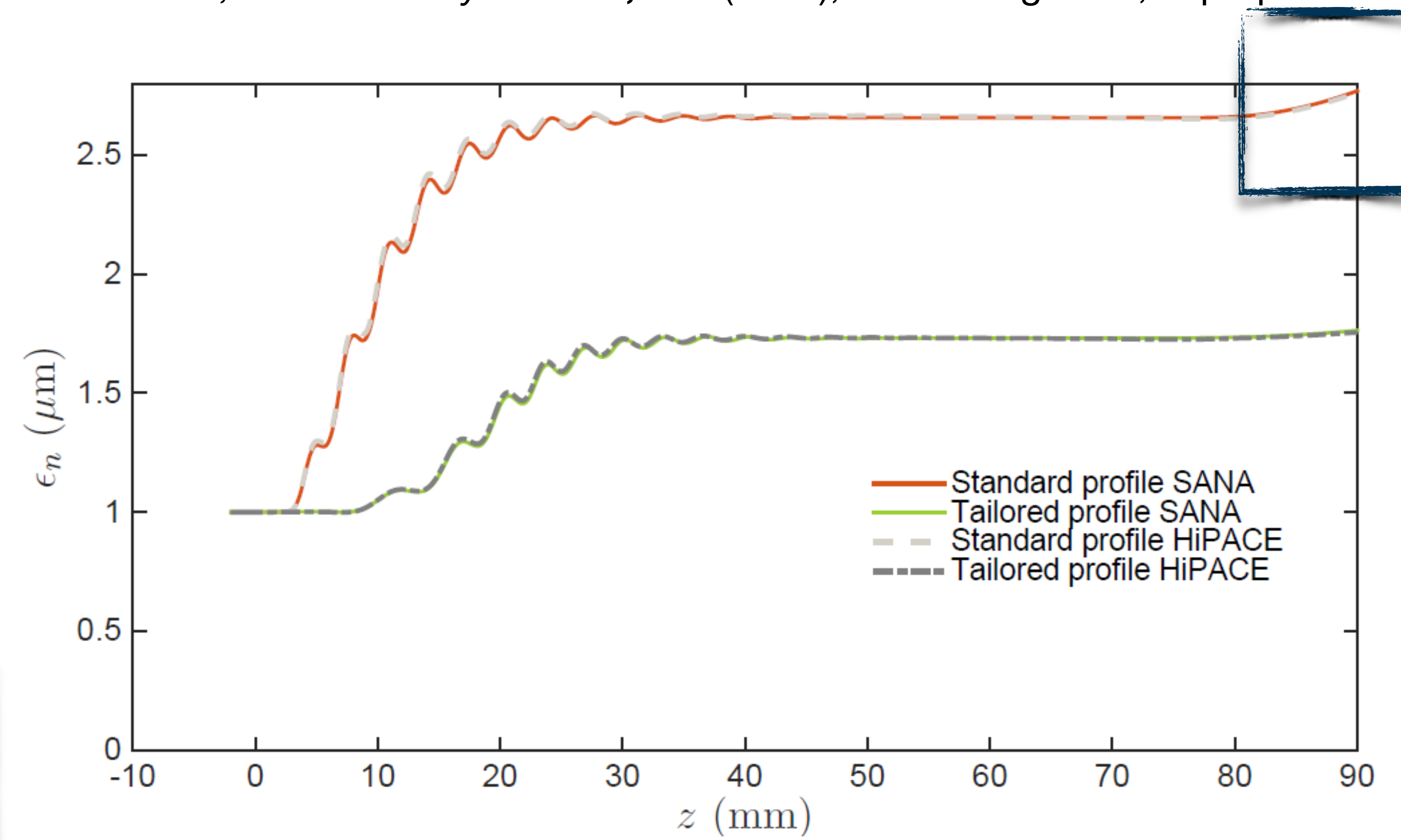

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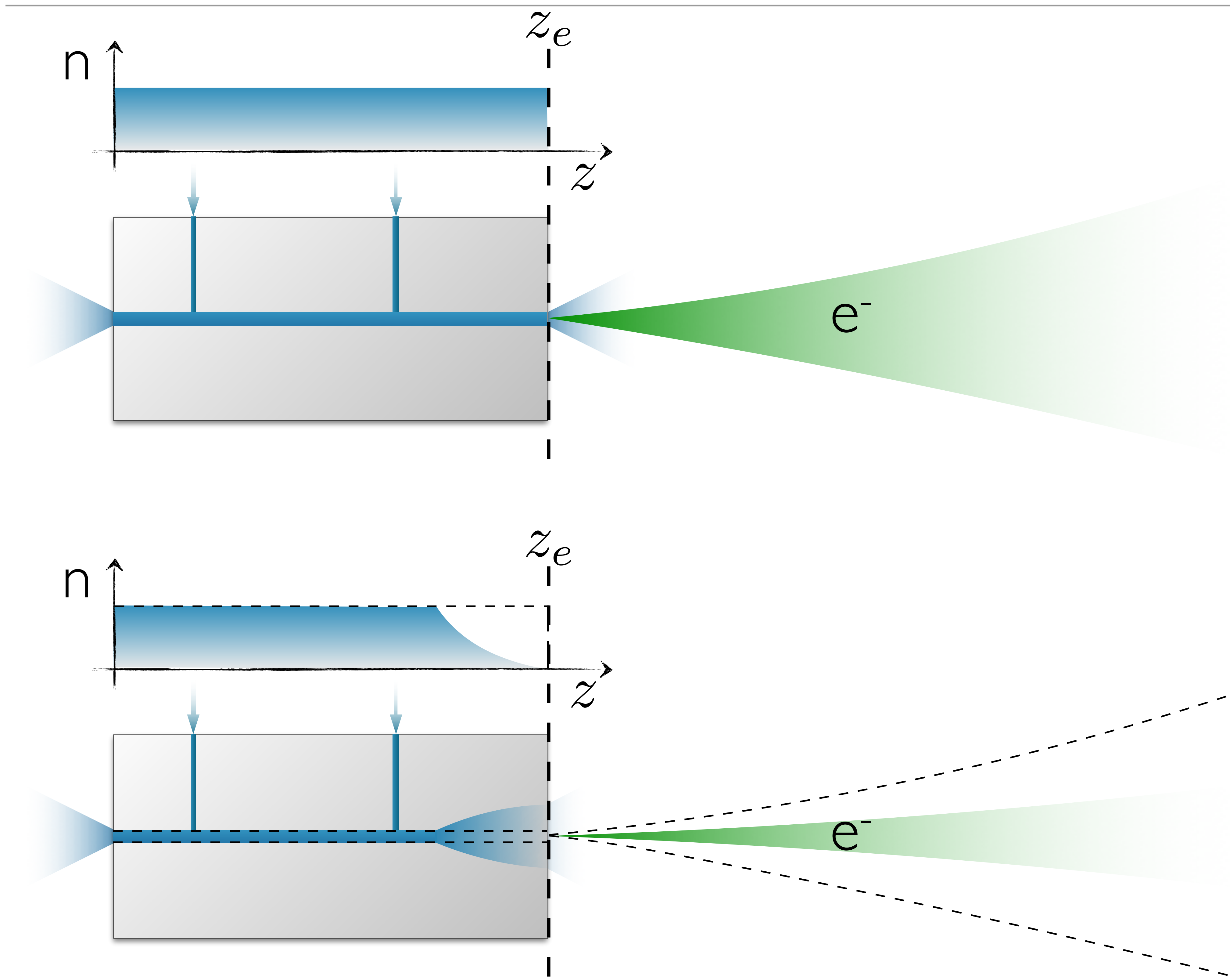
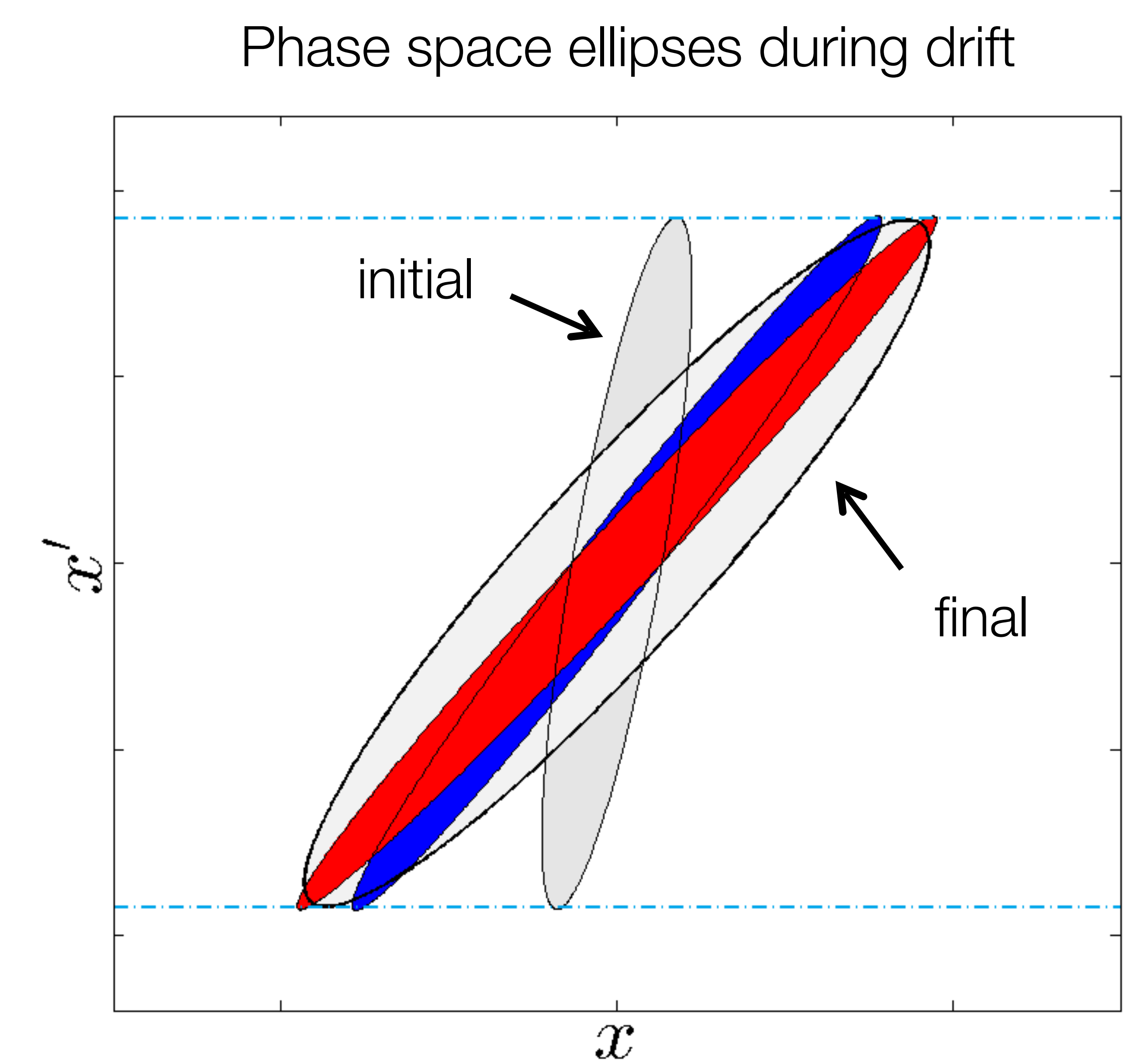
HiPACE

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



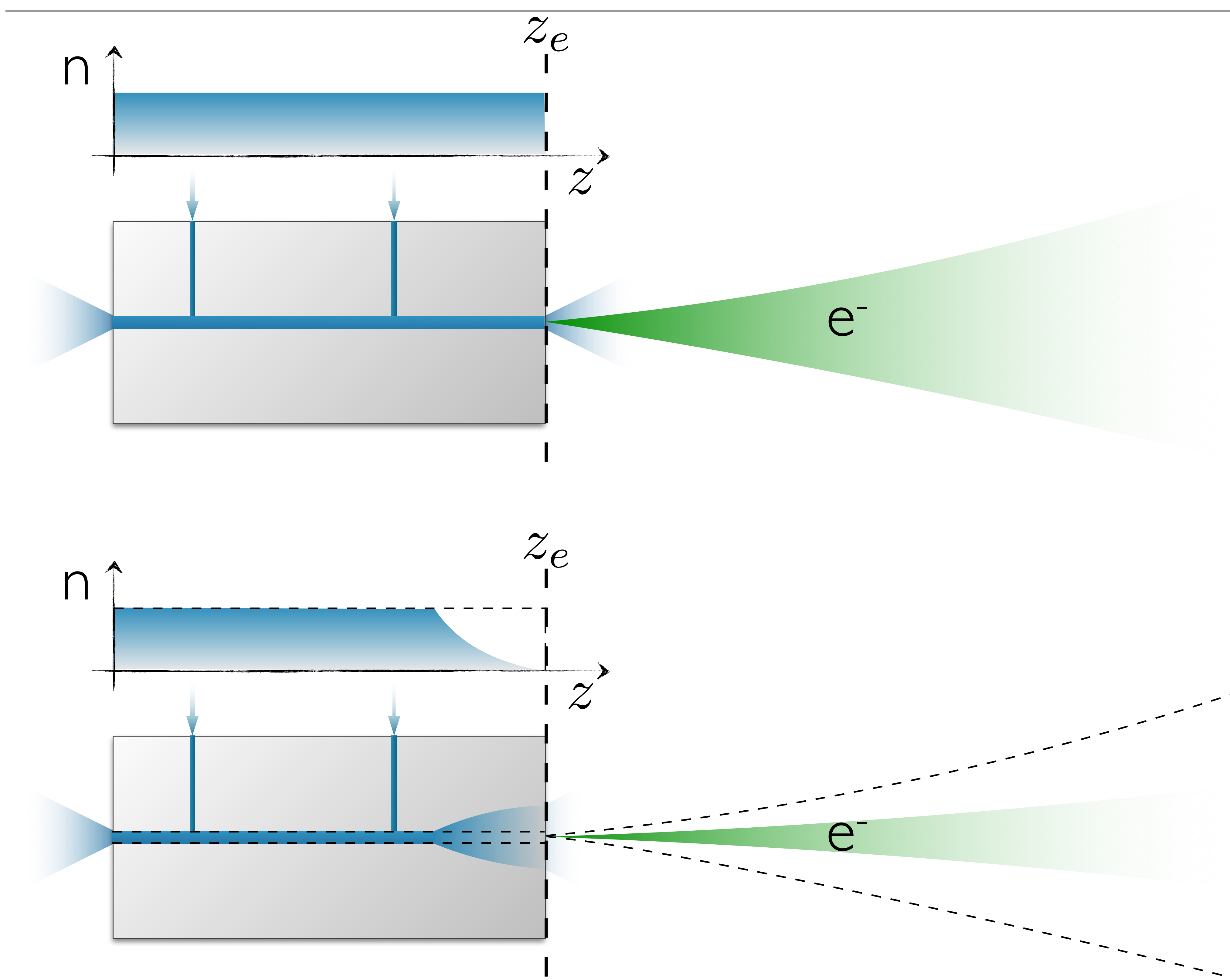


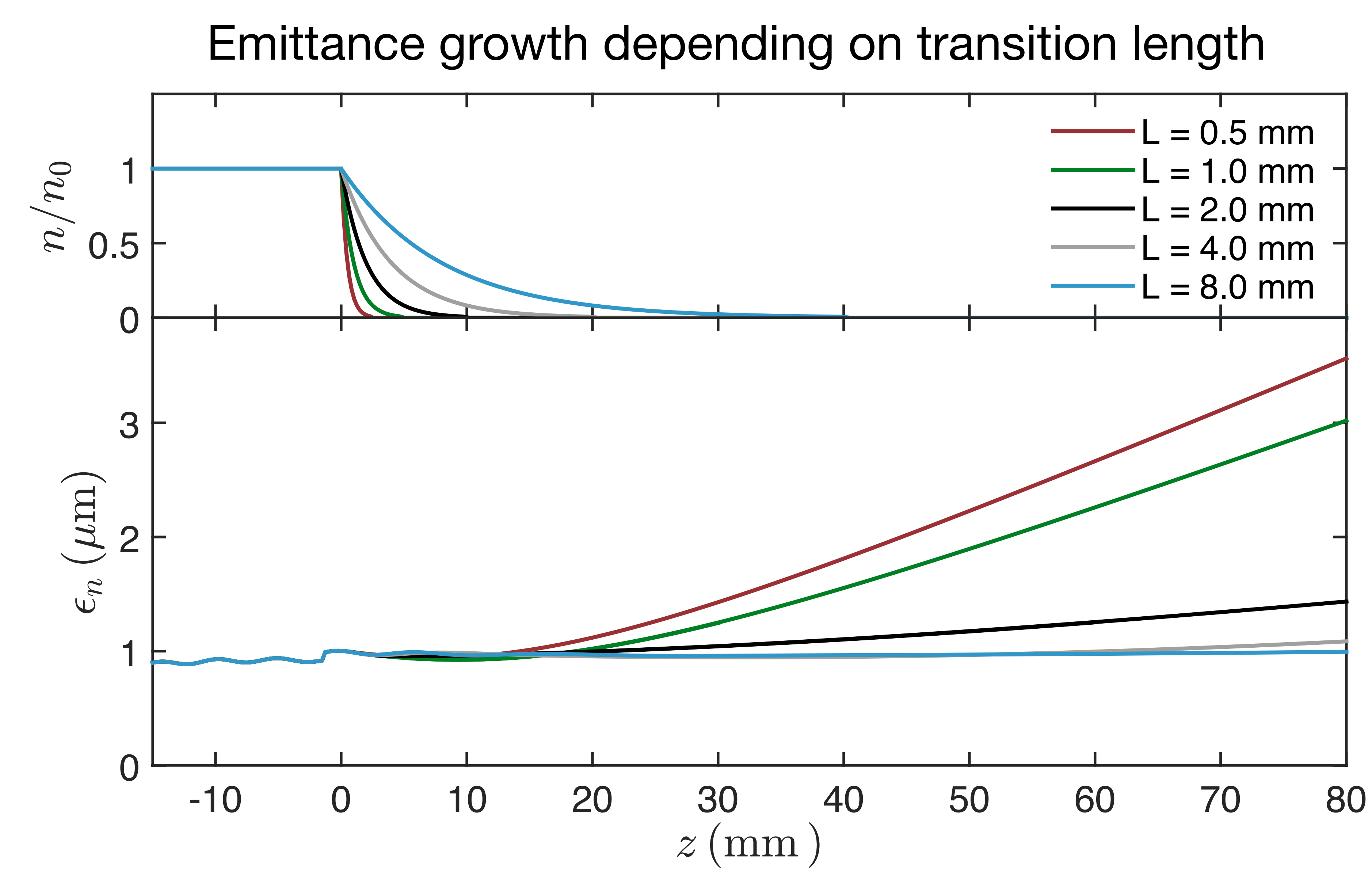
$$\varepsilon_n{}^2 \cong \langle\gamma\rangle^2 \cdot (\sigma_E{}^2 \sigma_{x'}{}^4 s^2 + \varepsilon^2)$$

- 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)

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





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

Summary

- Beam-driven plasma wakefield accelerators are an interesting option for future HEP applications
- Critical to have a programmatic, coordinated approach (best: worldwide)
- Plasma technology faces many challenges before plasma-based colliders become reality. We need to demonstrate
  - high beam quality
  - at high average power
  - with high wall plug efficiency
  - for electrons and positrons
  - with beam quality incl. polarization being maintained in multiple stages
  - operated under stable and controllable conditions

Goal: plasma accelerator research → usable plasma accelerators

- Money is important!
  - plasma accelerators/plasma optics allow to increase average gradient, reduce length
  - high efficiency to lower operation cost

Key challenge: plasma technology needs to be less costly than conventional schemes to be competitive