FLASHForward▸▸

Challenges and Prospects for Beam-Driven Plasma-Wave Acceleration

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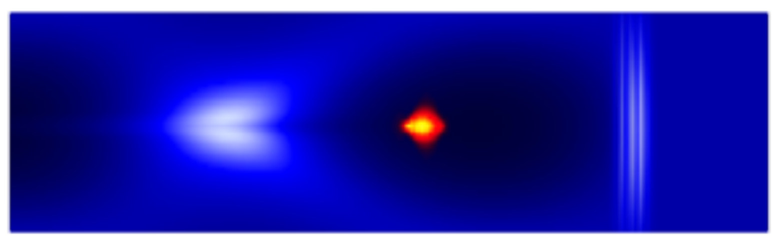
Project FLASHForward▸▸ | Research Group for Plasma Wakefield Accelerators FLA-PWA
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Alexander von Humboldt Stiftung/Foundation
HELMHOLTZ | GEMEINSCHAFT

Research Group for Plasma Wakefield Accelerators

Linear Accelerator Research Subdivision, High-Energy Physics Department

Core research

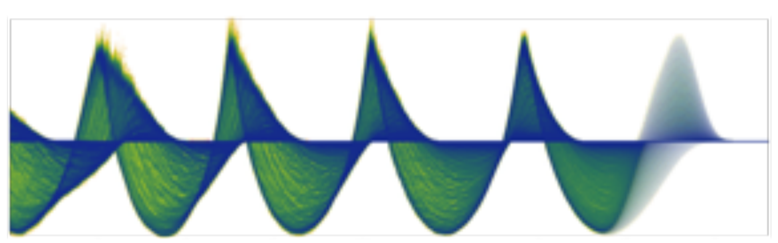


- Laser-driven plasma wakefield acceleration (LWFA)

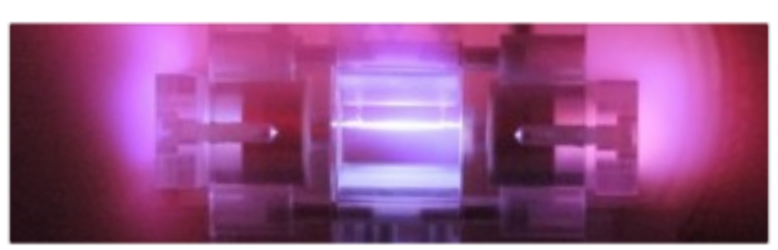
FLASHForward

- Beam-driven plasma wakefield acceleration (PWFA)

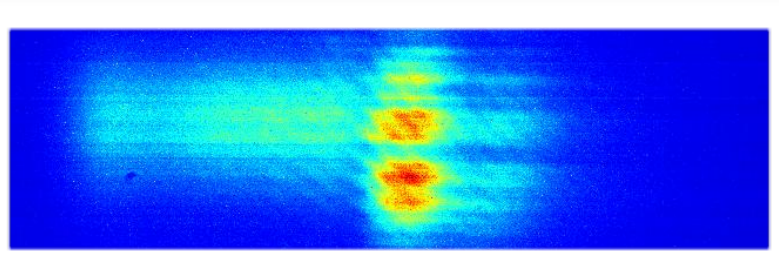
Fields of specialization



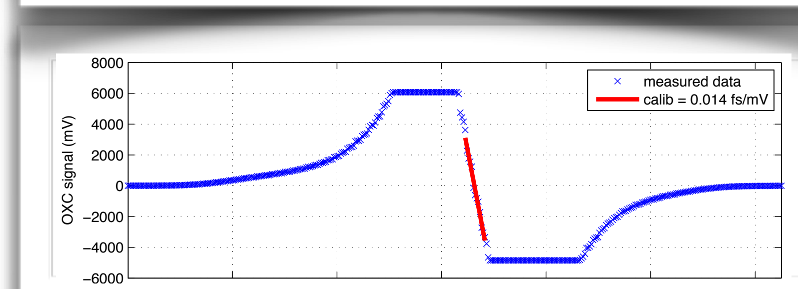
- Plasma theory and simulations



- Plasma-target and diagnostics development



- Ultrafast e⁻-beam characterization
  in collaboration with B. Schmidt's group at DESY



- High-intensity laser science and synchronization to accelerators
  in collaboration with H. Schlarb's group at DESY

Team leader

Jens Osterhoff

Postdocs

Lucas Schaper
Charlotte Palmer
Alberto Martinez de la Ossa
John Dale
Vladyslav Libov
Johann Zemella
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Students

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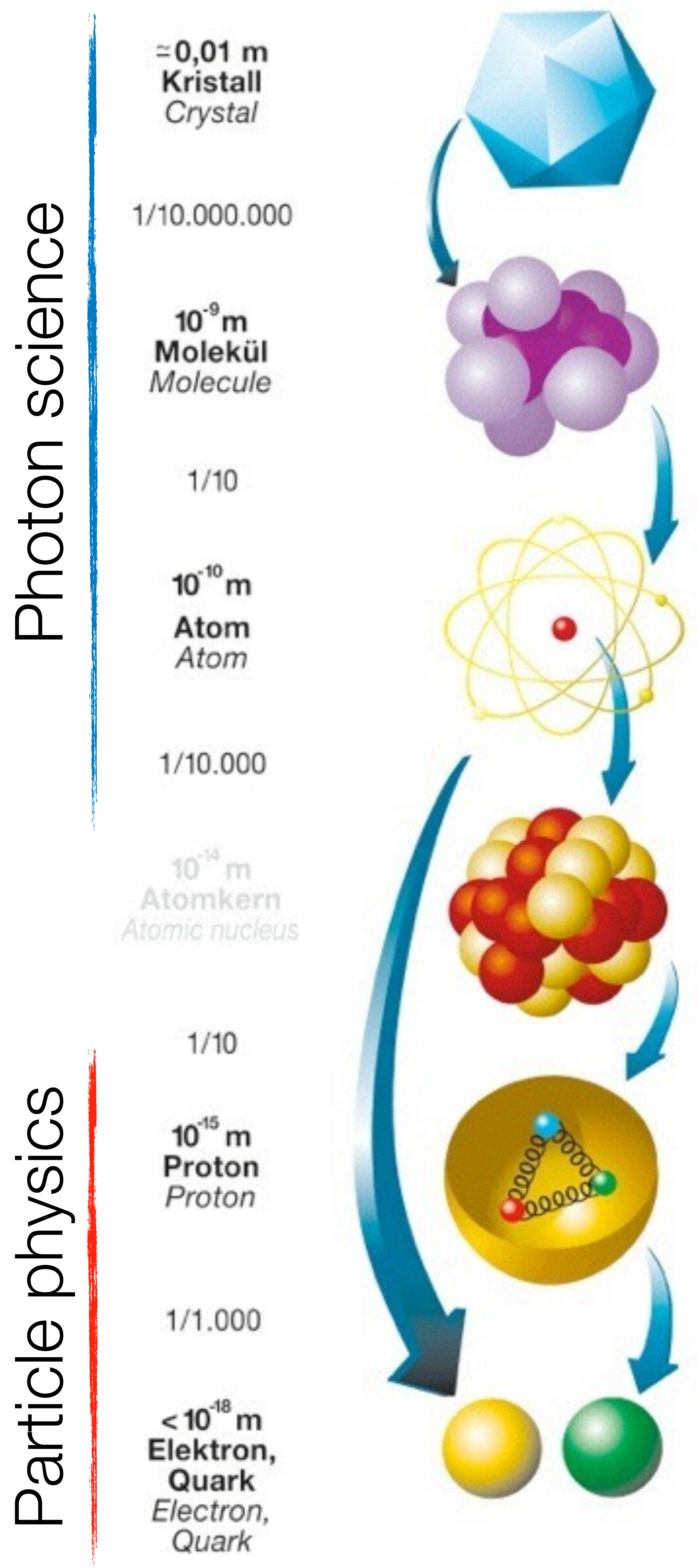
Steffen Wunderlich
Jan-Hendrik Erbe
Lars Goldberg
Olena Kononenko
Gabriele Tauscher
Violetta Wacker
Stefan Weichert

Outline

- Plasma accelerator projects at DESY
- What is plasma and plasma acceleration
- Plasma acceleration at FLASH
  - Mission and goals
  - Laser vs. beam-driven
  - Beam transport to FLASHForward
  - Different beam injection schemes
  - Mediated beam release
  - Beam capturing and diagnostics
  - Laser and preparation laboratories
- Summary and conclusion

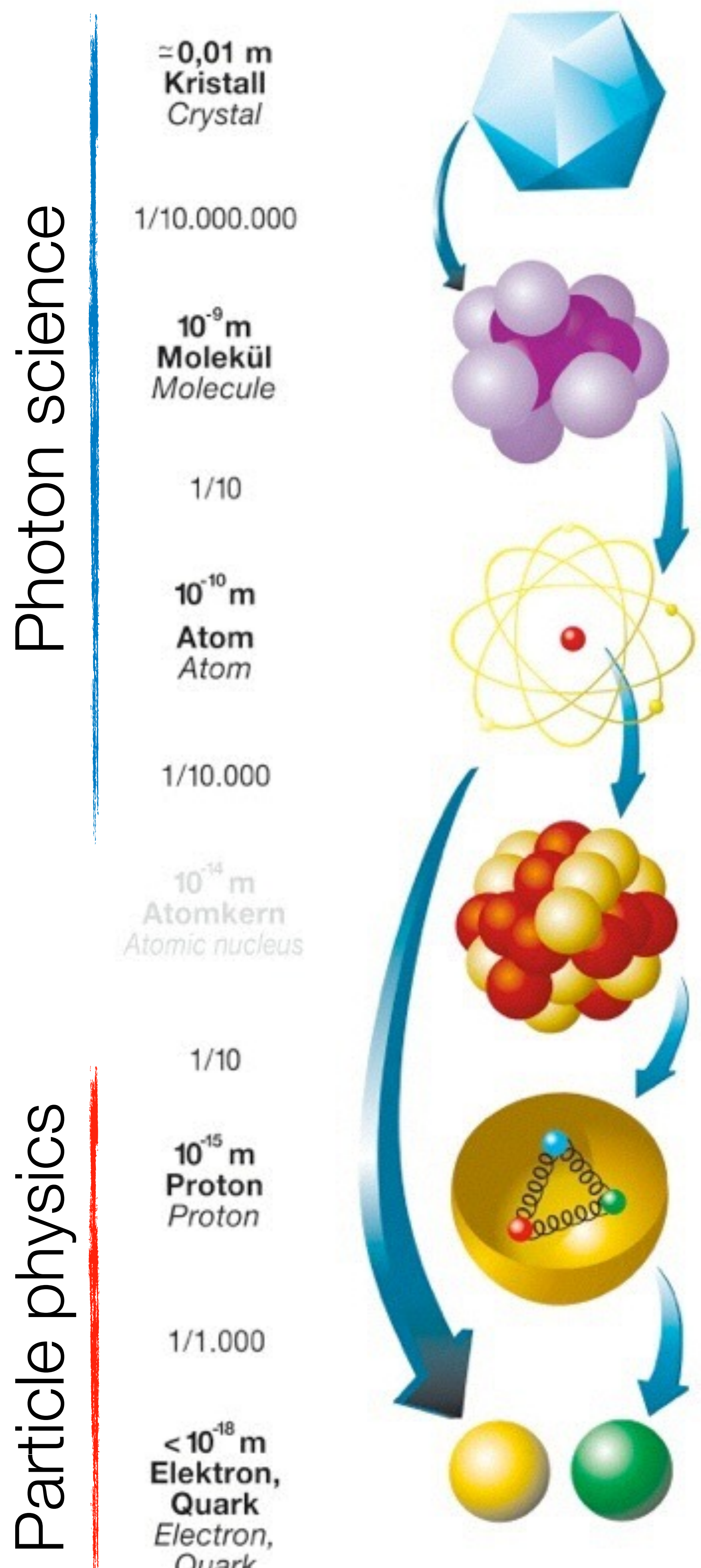
Deutsches Elektronen-Synchrotron DESY



The DESY mission:

develop and utilize particle accelerators
for the study of the structure of matter

Deutsches Elektronen-Synchrotron DESY



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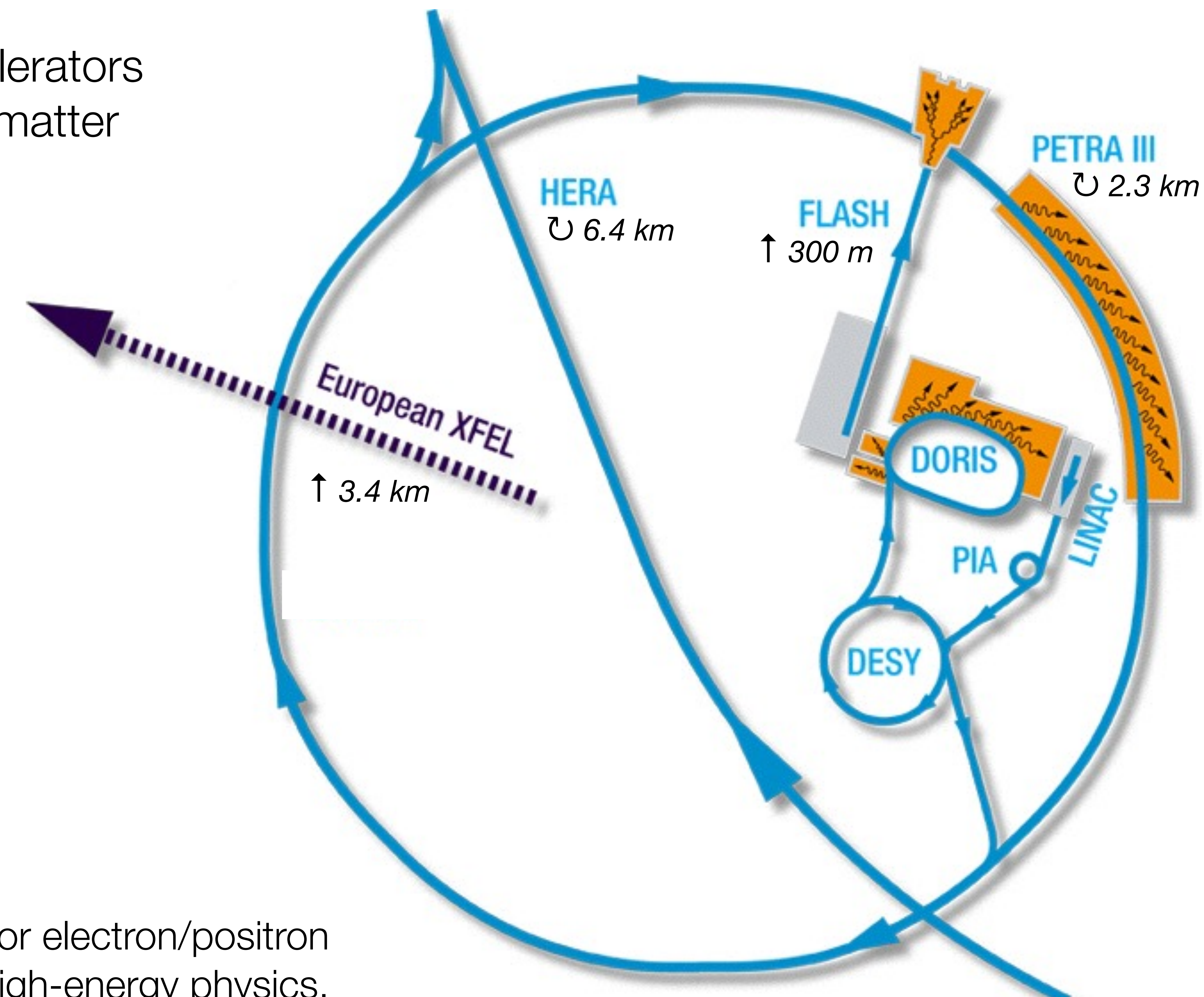

Accelerators at DESY, Hamburg

Leading center for electron/positron acceleration, high-energy physics, and free-electron laser science

Deutsches Elektronen-Synchrotron DESY

The DESY mission:

≈0,01 m
Kristall
Crystal
1/1.000
< 10^{-18} m
Elektron,
Quark
Electron,
Quark
Particle phy

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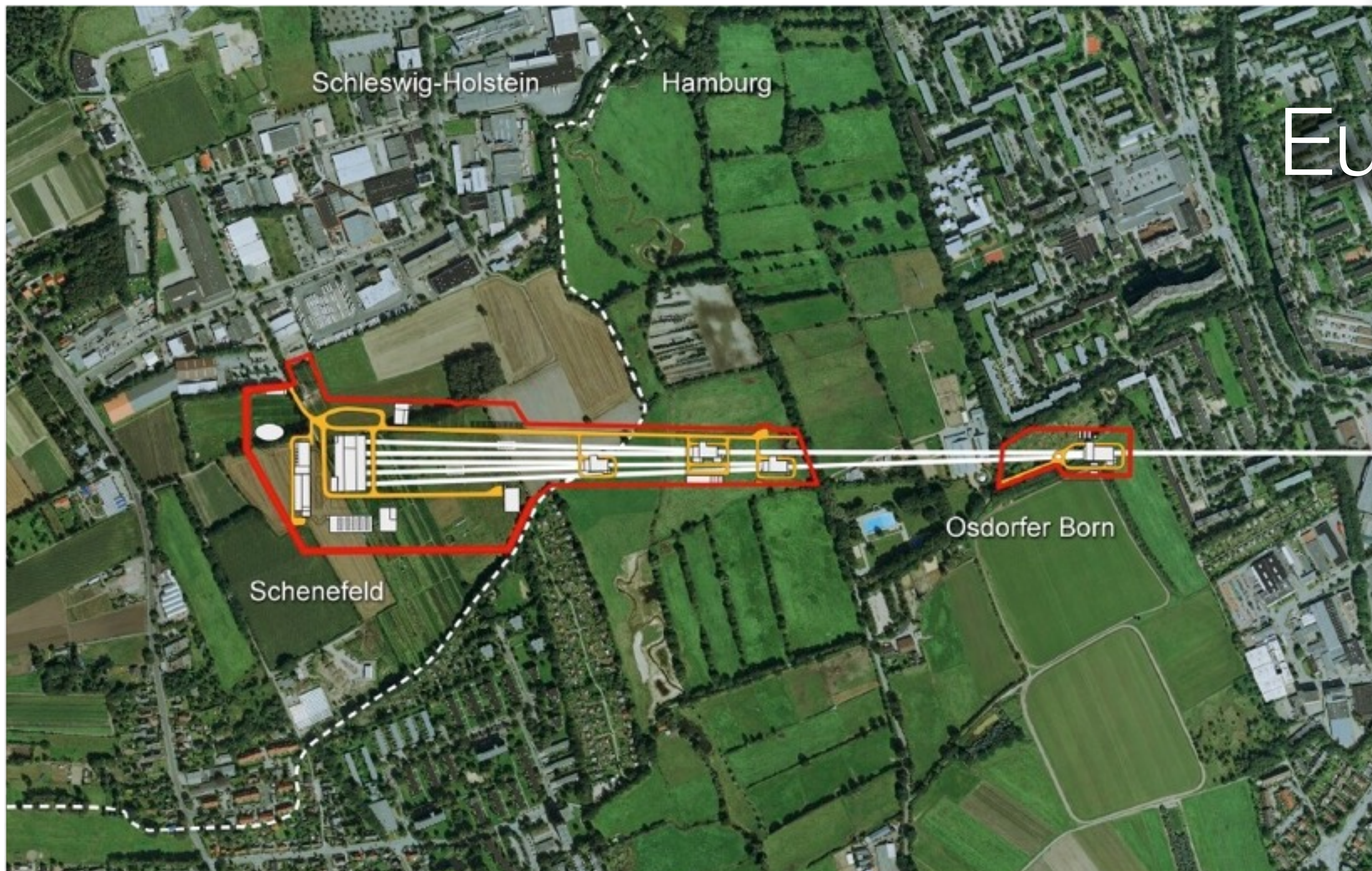

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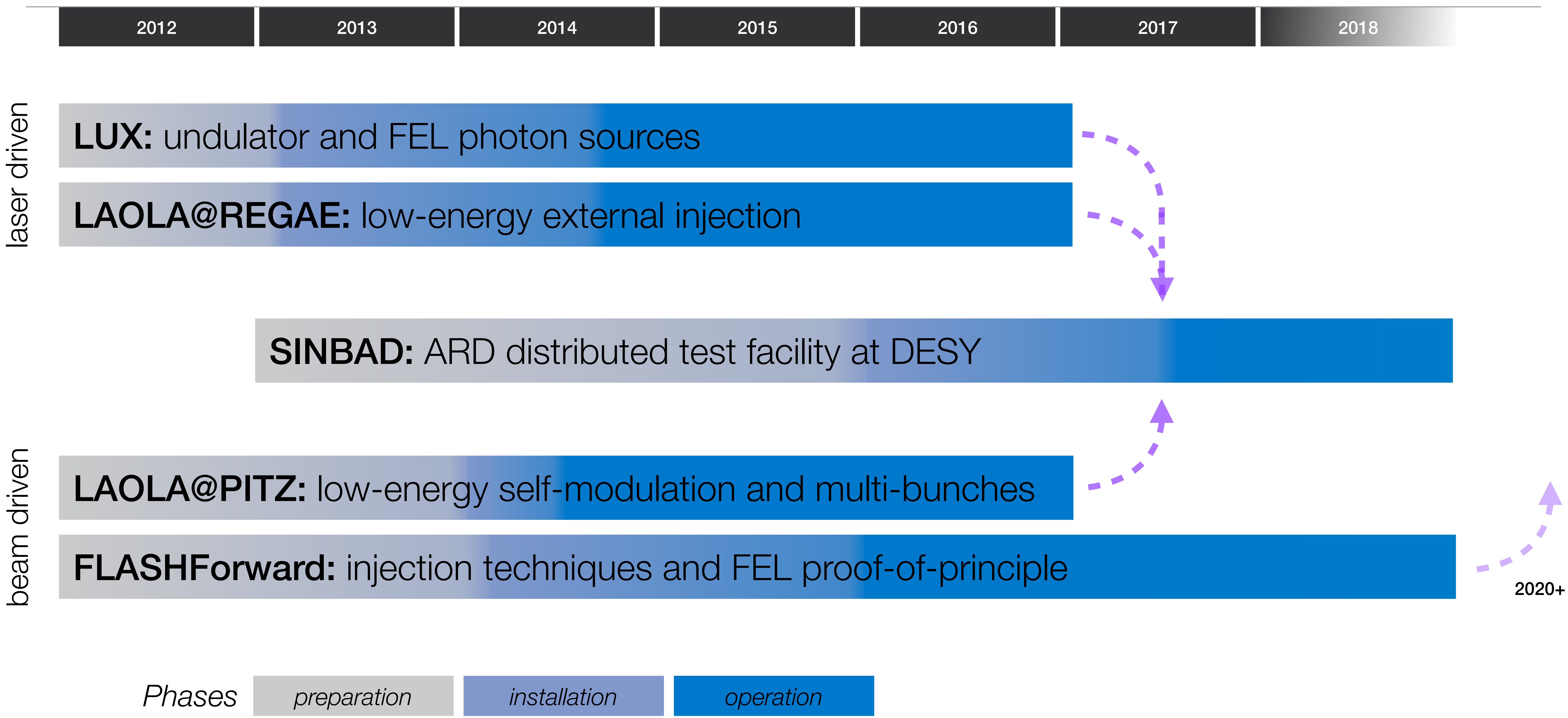
Accelerators at DESY, Hamburg

The LAOLA. collaboration and its plasma-wakefield strategy



LAOLA.

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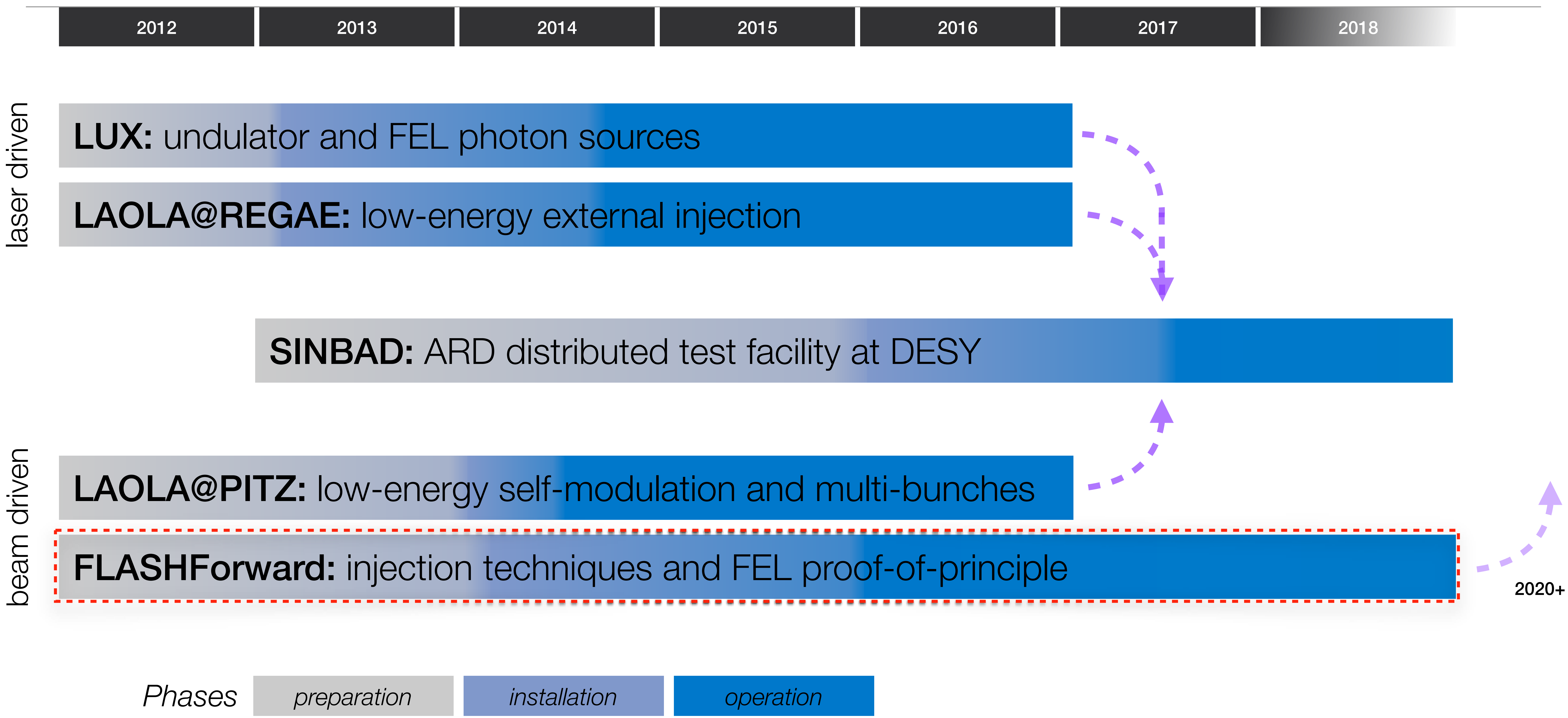
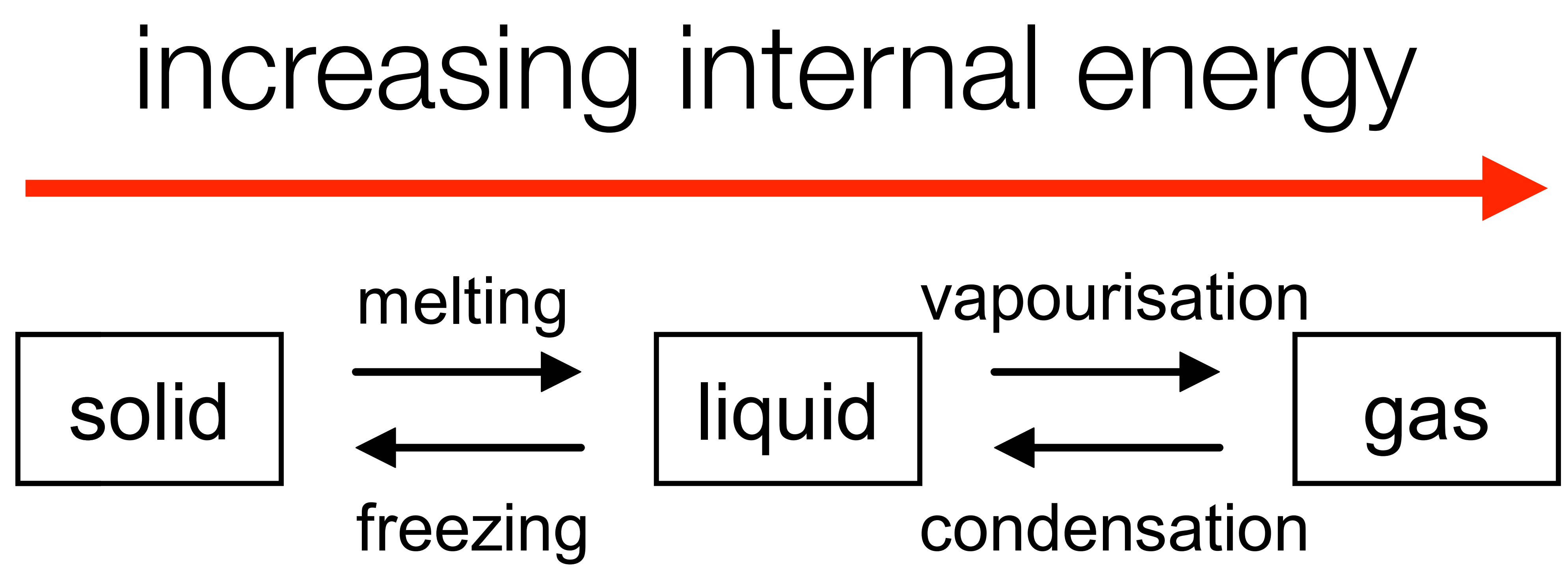


States of matter



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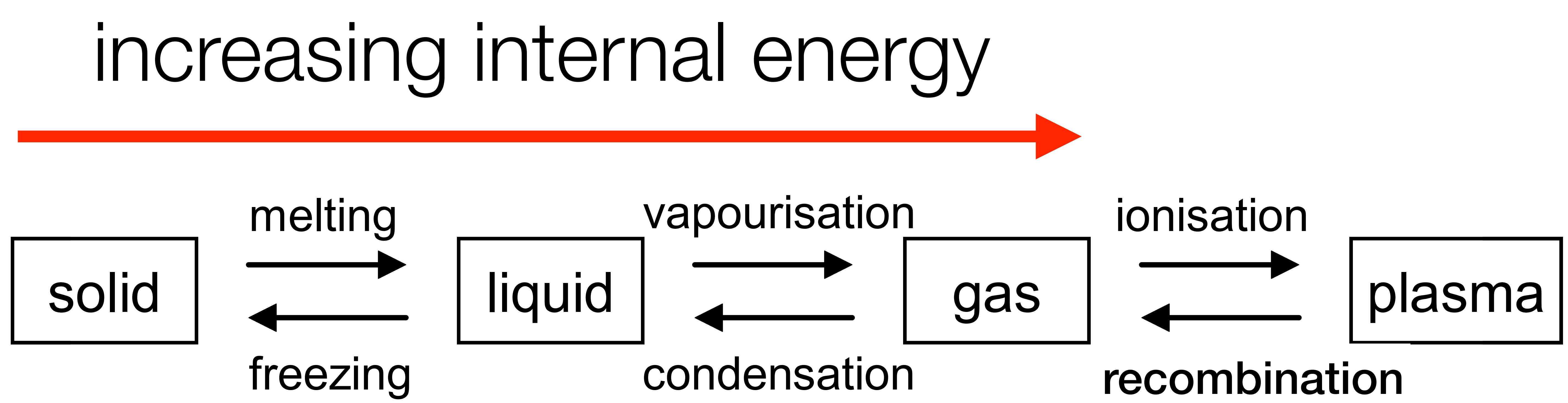
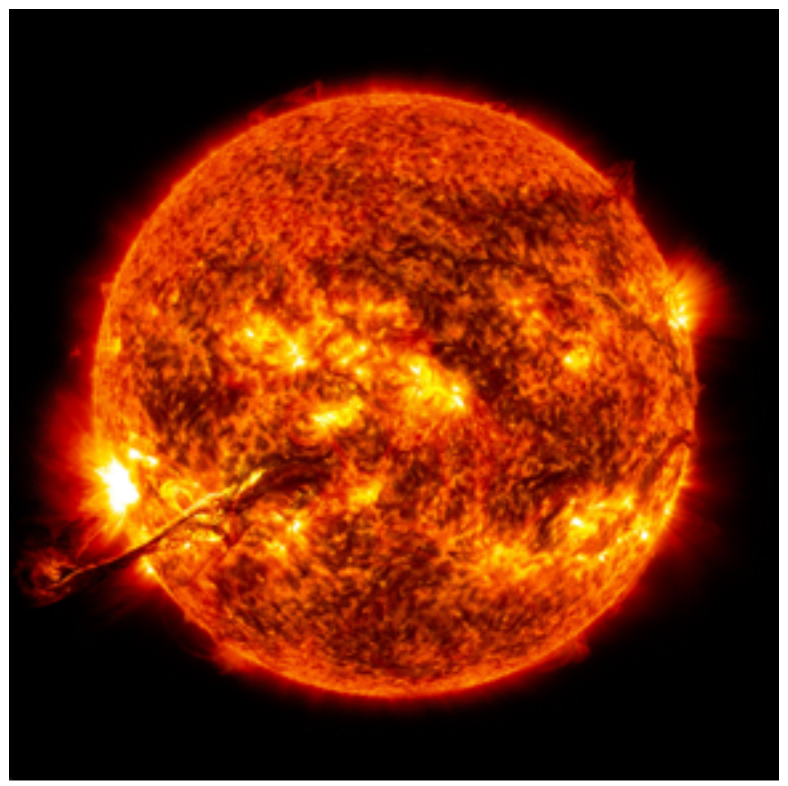


States of matter

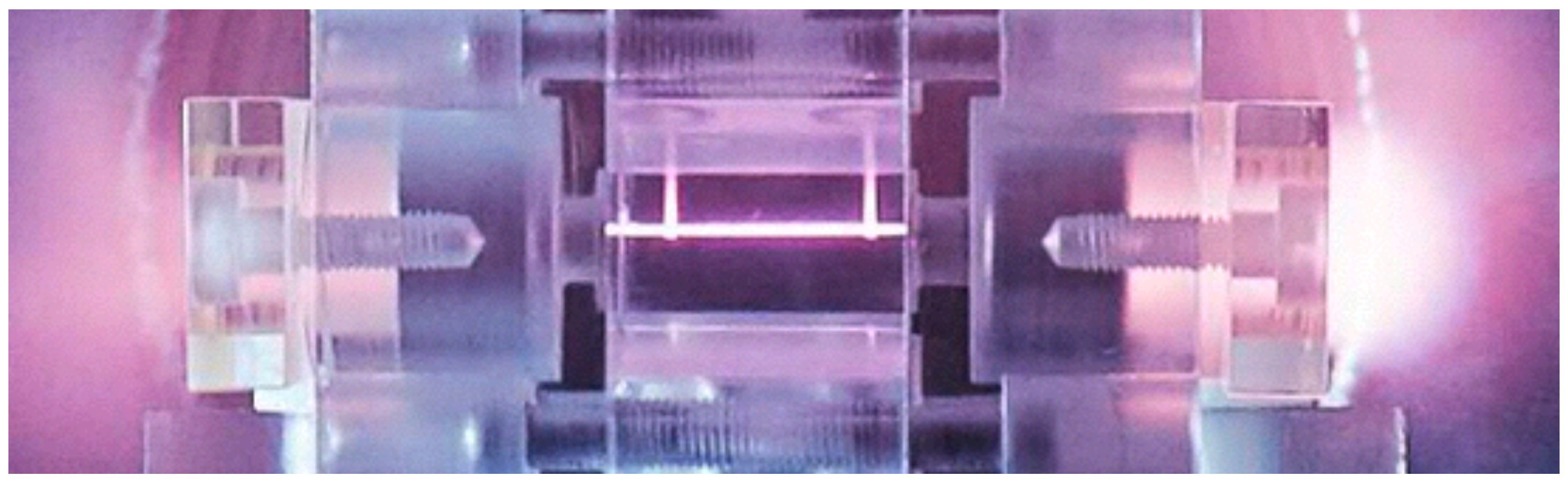
increasing internal energy →

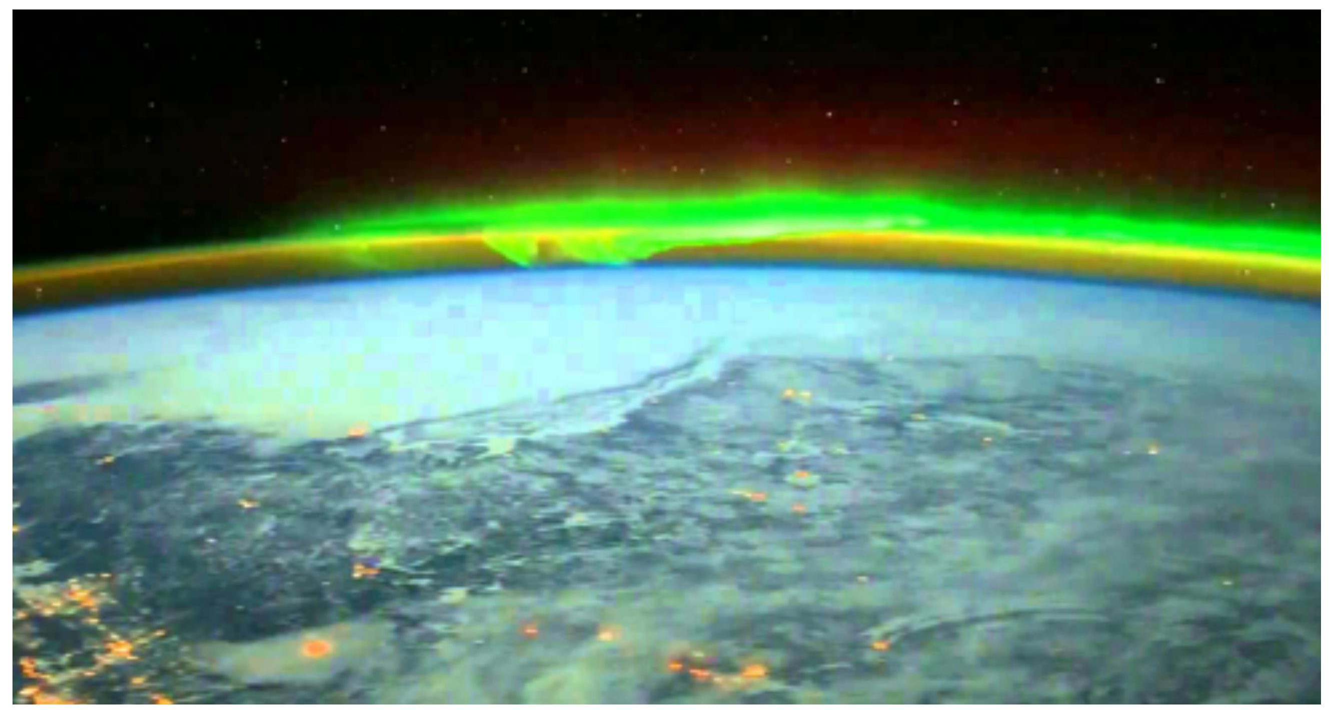
solid ⇄ liquid ⇄ gas ⇄ plasma

- solid → liquid: melting; liquid → solid: freezing
- liquid → gas: vapourisation; gas → liquid: condensation
- gas → plasma: ionisation; plasma → gas: **recombination**



- plasma most abundant state in universe (visible?)
- most manufacturing processes involve plasmas

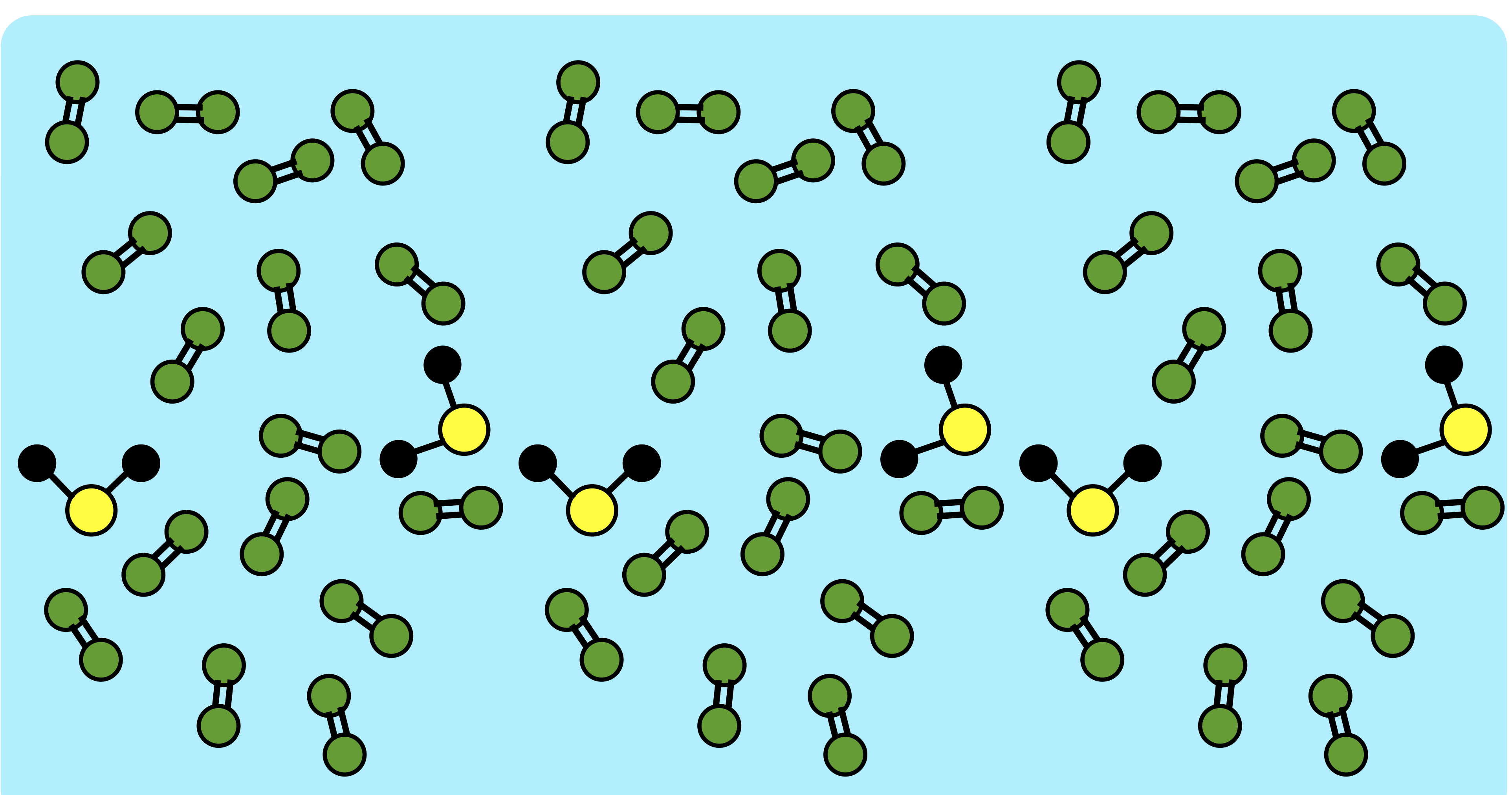




What is a plasma?

Gas:

- Atoms, molecules
- No order
- no strong intermolecular forces



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Gas:

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Energy →

Plasma:

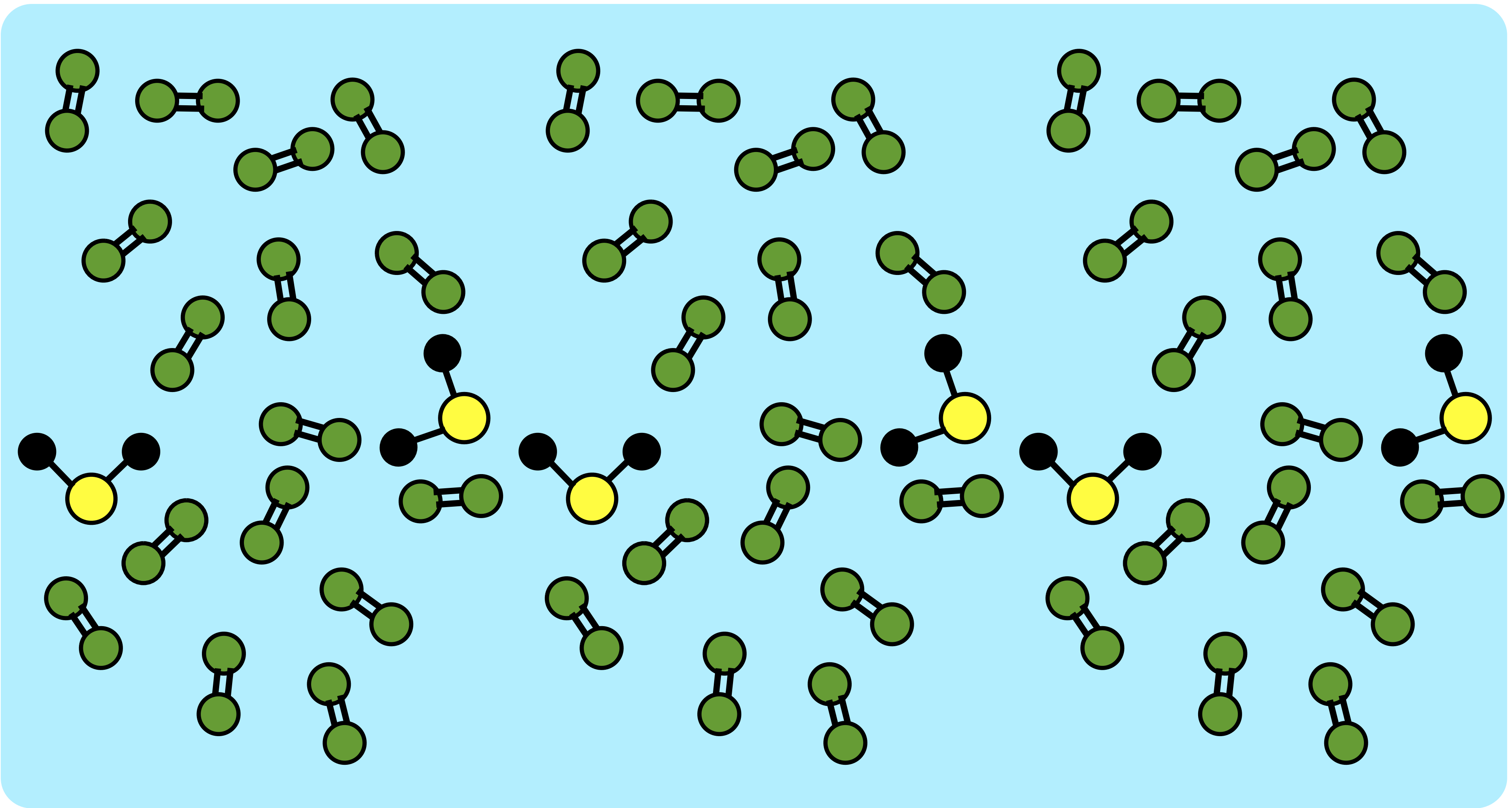
> Charged particles (electrons, ions)

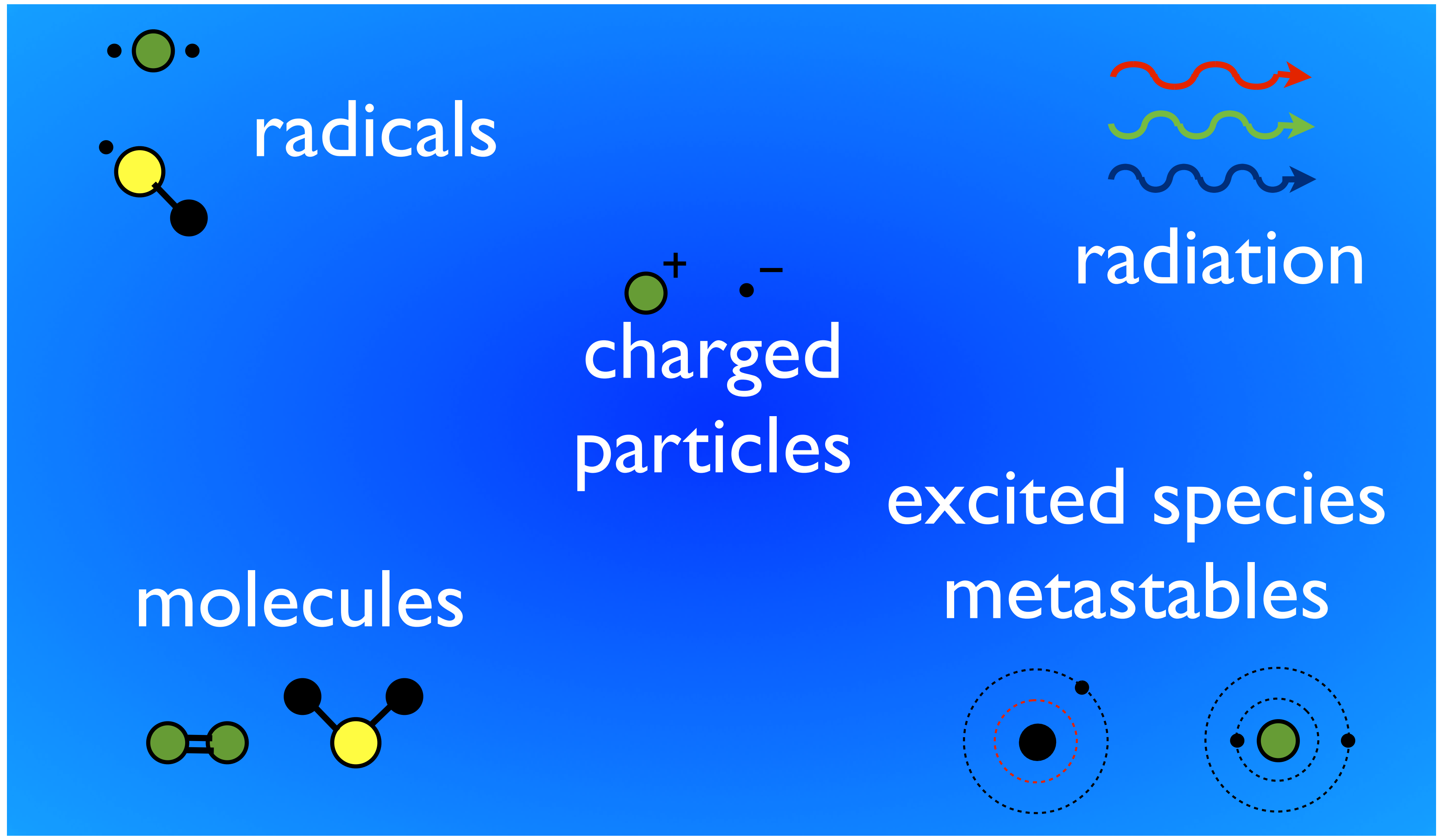
> macroscopically quasi neutral

> Coulomb interaction

> particles show collective behaviour

> conductive

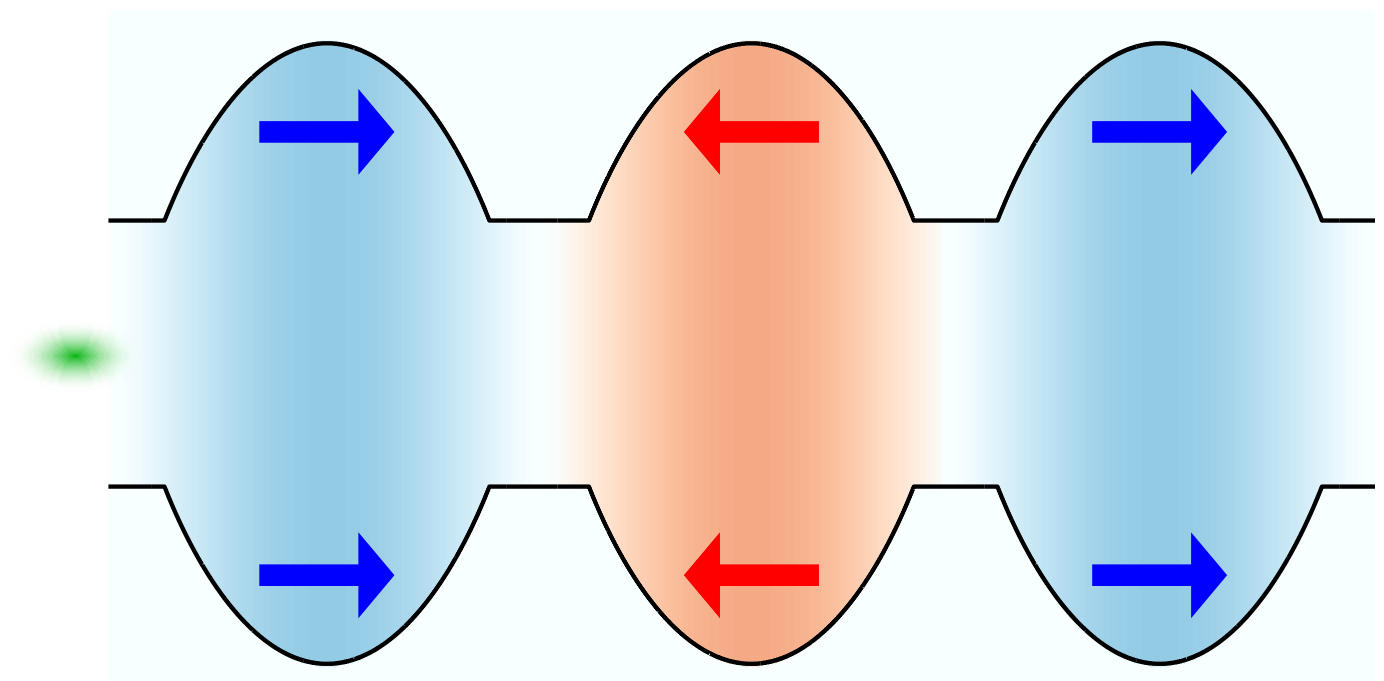




Conventional vs plasma based accelerators

Conventional accelerators (e.g. FLASH)

- field strength: 20 - 50 MV/m (limited by breakdown)
- length scale: m to km
- Fixed cavity structure "filled" with RF accelerating fields



Plasma based accelerators

- field strength: 10 - 1000 GV/m
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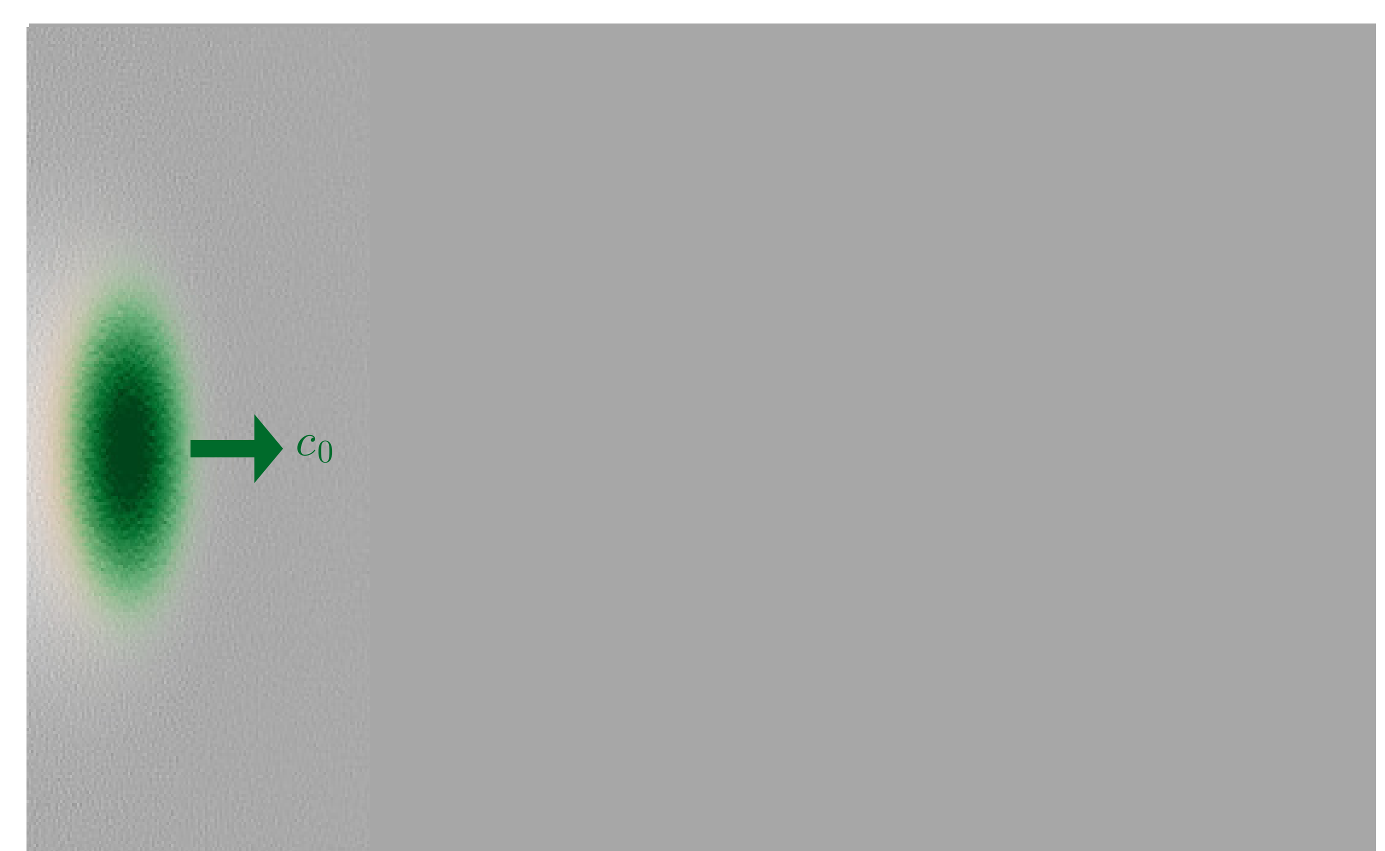
- accelerating fields "follow" the drive beam
- crucial parameter for plasma acceleration: electron density
  - plasma wavelength
  - field gradient



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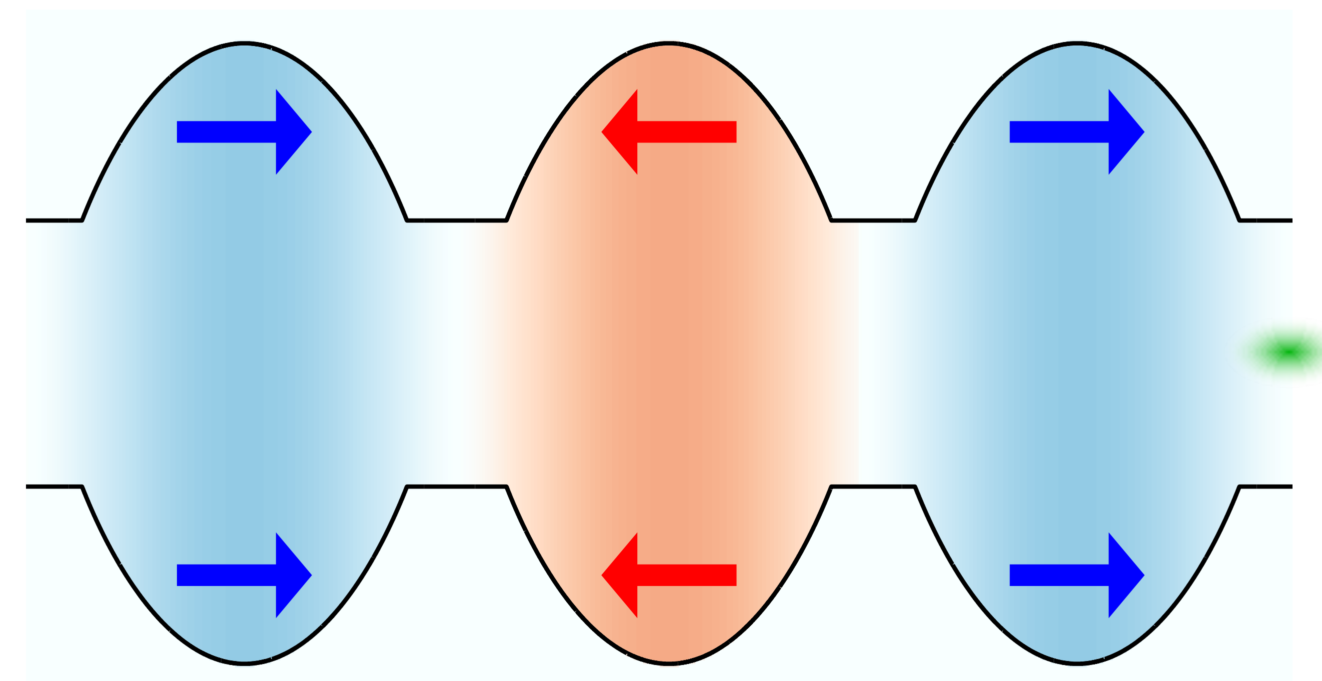

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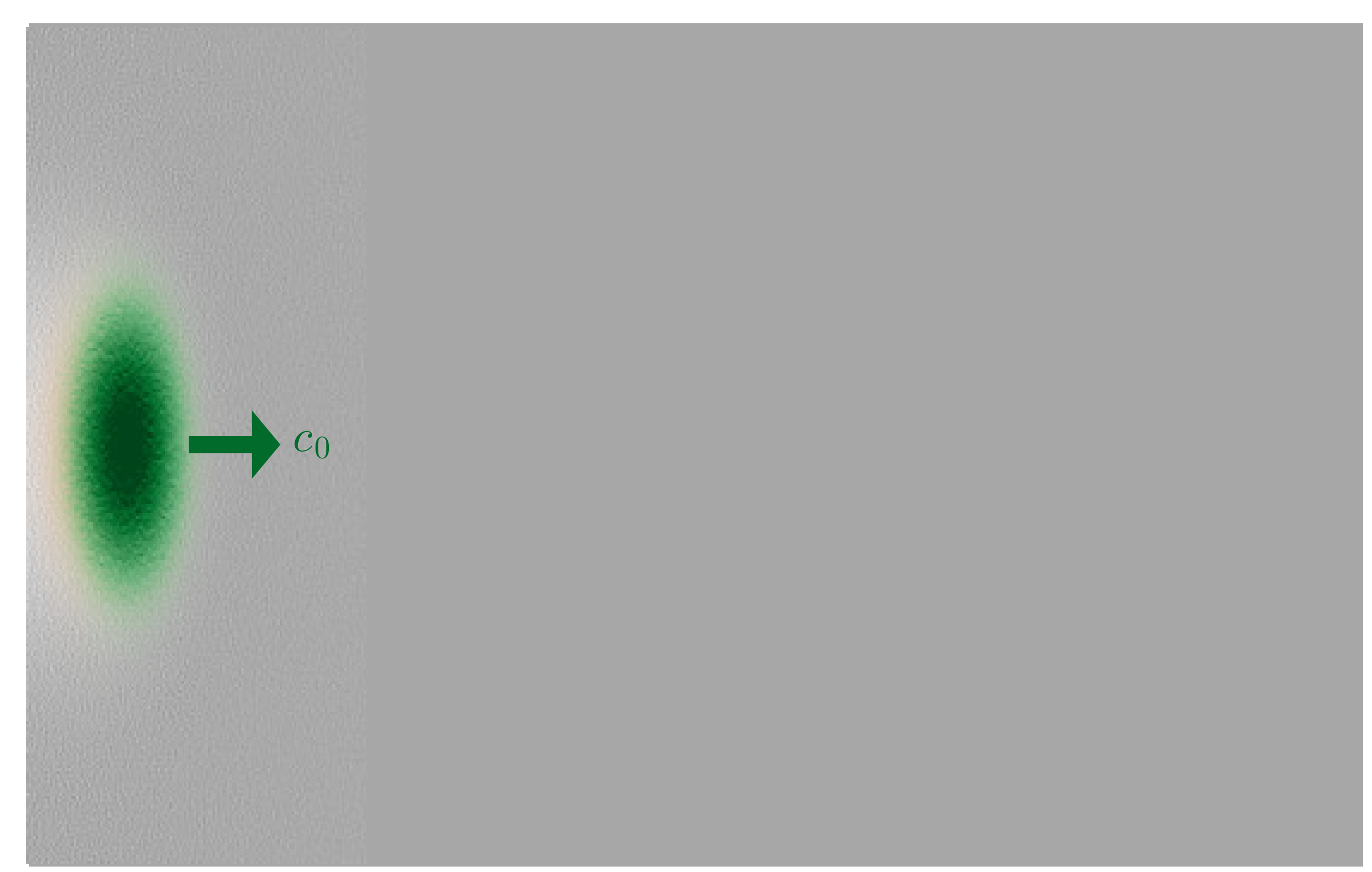

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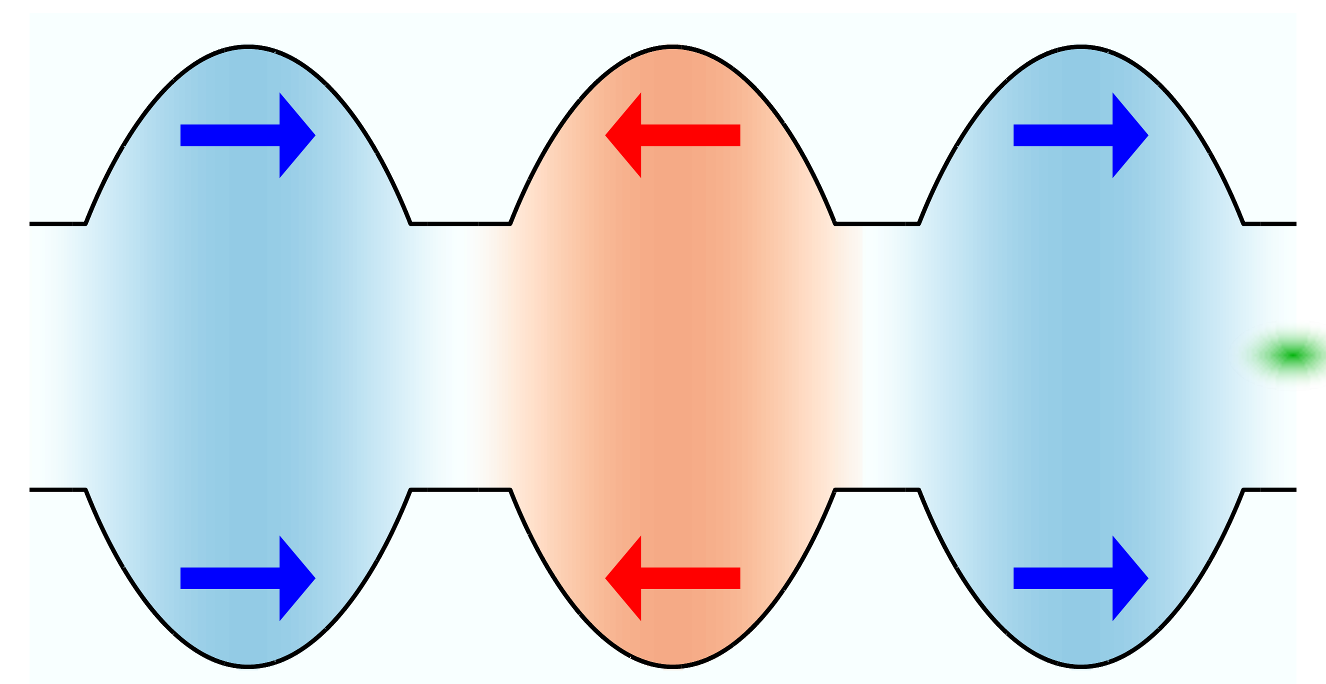

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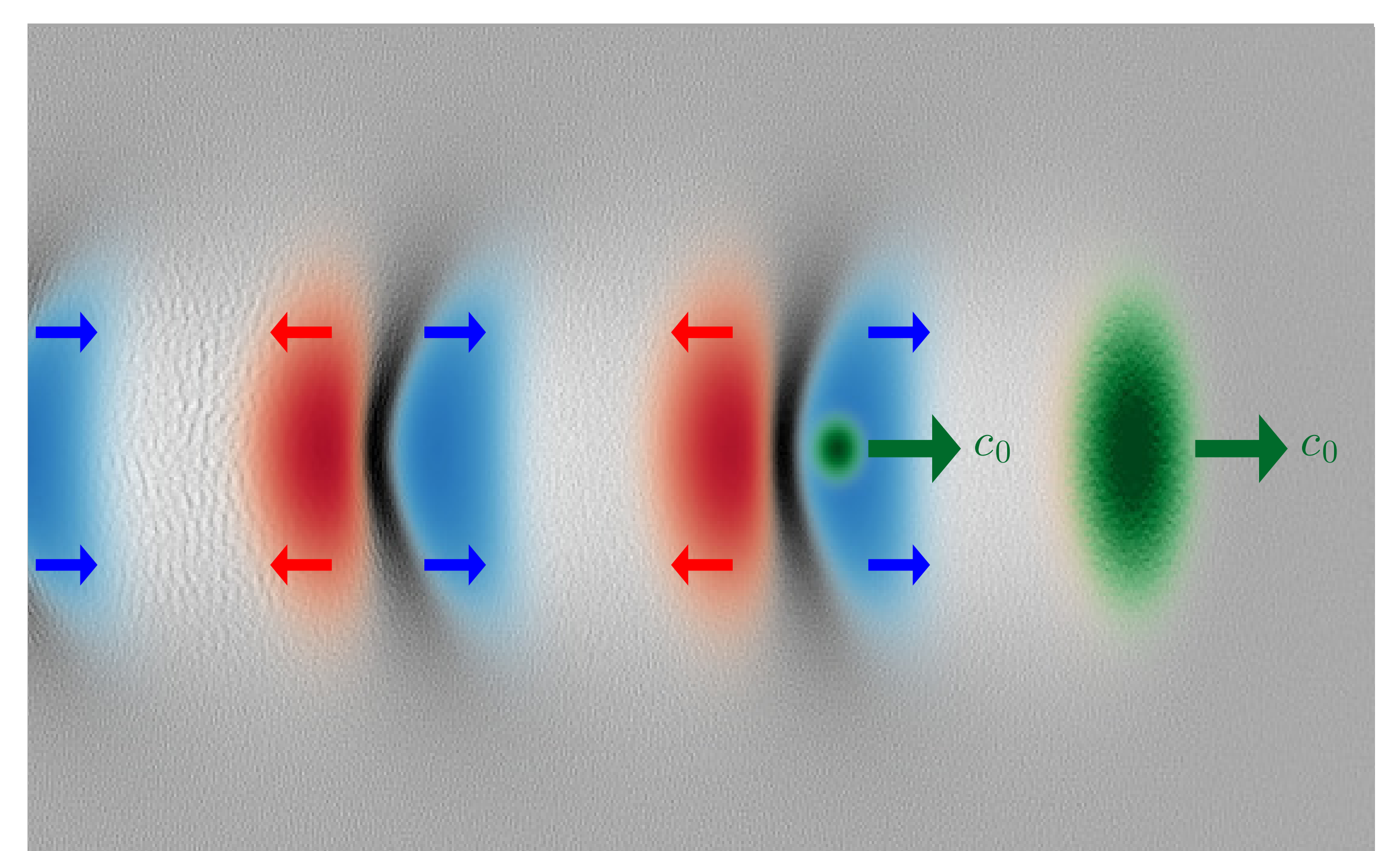
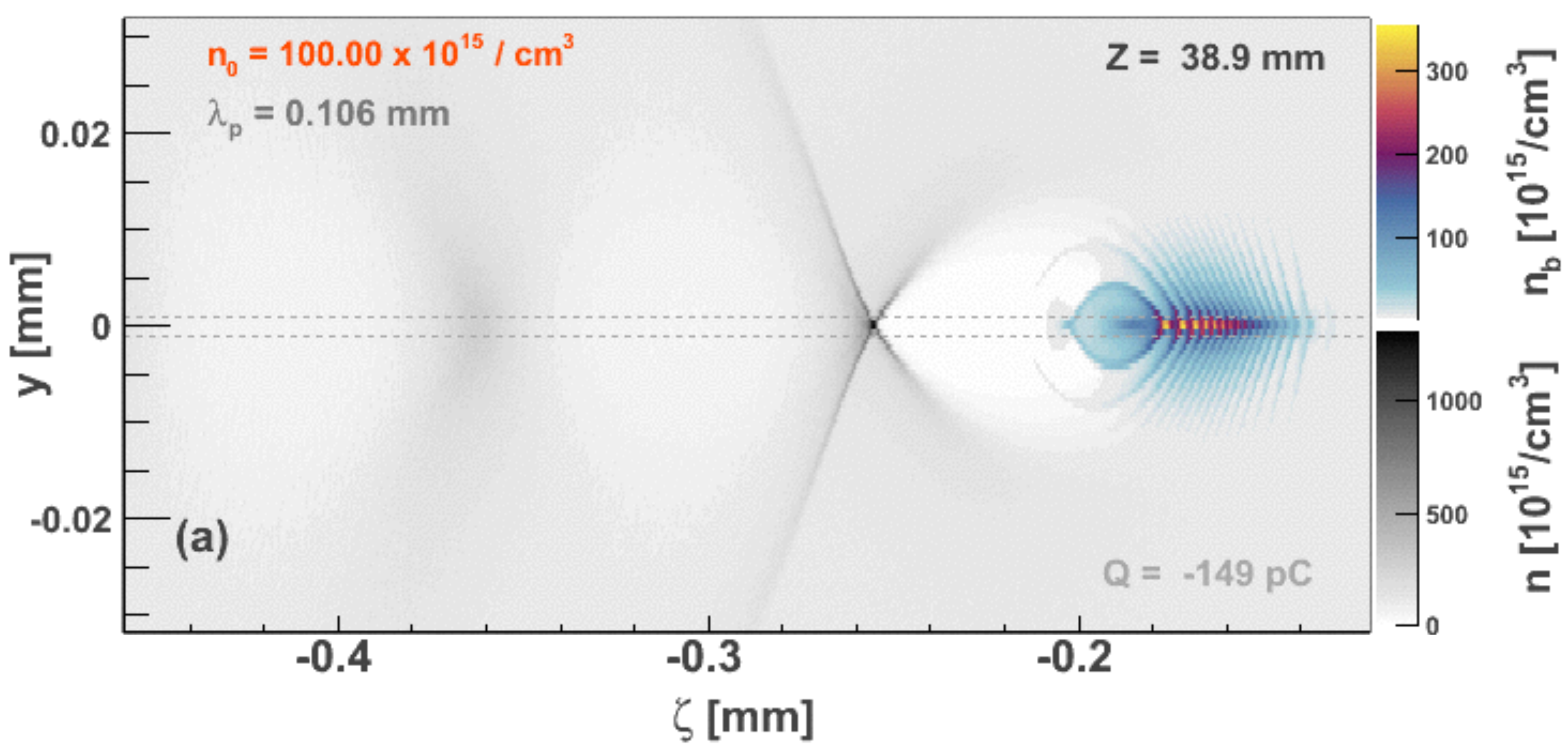
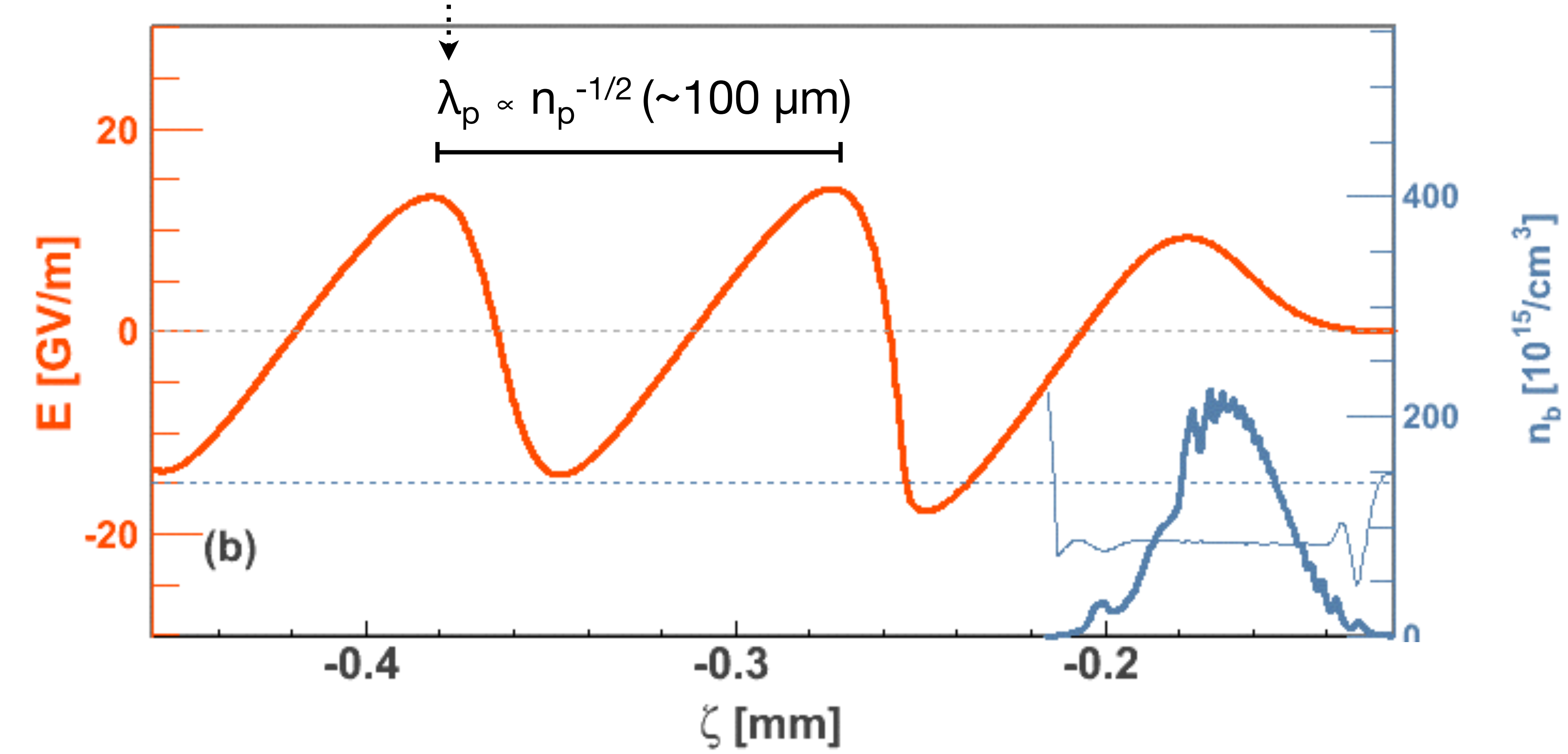


Standard FLASH beams well suited as plasma-wake drivers

3D OSIRIS PIC simulation



witness electron beams much shorter



Standard FLASH 2 beam: *2.5 kA peak current, 50 fs long, 10 µm focus size, 1.2 GeV, 0.1% energy spread, 1 µm normalized transverse emittance*

3D particle-in-cell (PIC) simulation

- High-current-density particle beam
  - pushes away plasma electrons by space-charge field (ions are too heavy, hardly move)
  - creates electron-depleted cavity, sets up charge separation
- Strong electrostatic fields pull back plasma electrons
- Electrons oscillate and create co-propagating wakefield

- Strong accelerating fields of > 10 GV/m are generated
- Conventional accelerators: Field <50 MeV/m

Mission and goals of the **FLASH**Forward▸▸ project

Mission

> To demonstrate the potential of beam-driven plasma wakefield accelerators for the production of high-quality electron beams supporting free-electron laser operation as a first step towards future high-energy physics applications

Scientific goals

Phase I (2016+)

> Characterization of **externally injected** electron beams and their release with energies **> 1.6 GeV**

> Exploration of novel **in-plasma whitnes-bunch generation** to energies **> 1.6 GeV**
Also: < 100 nm transverse normalized emittance,
~1 fs duration and
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> **Transformer ratios** of 2 and beyond yielding energies **> 4.0 GeV**

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Phase II (2018+)

- first demonstration of **FEL gain** with above beams at few nanometer wavelength-scale

Beam-driven acceleration compared to laser-driven schemes

Advantages

- **Particle beams may be produced at high average power** (up to MWs) for high-luminosity applications
  - $<$ 100 W average power of state-of-the-art TW to PW laser technology
- **Particle-beam production is efficient** (~10 % from the wall plug)
  - ≪ 1 % wall-plug efficiency for high-intensity lasers
- **Driver-beam stability** (≪ 1 %)
  - best high-power lasers fluctuate ~1% in intensity
- **No dephasing** of plasma wakefield and electron beam
  - laser pulse velocity less than *c*, electrons outrun wake
- **Diffraction lengths longer than energy depletion scales** for beams of µm normalized emittance
  - diffraction length of laser pulse shorter than depletion distances → limits witness beam energy

Disadvantage

- Requires a large conventional accelerator

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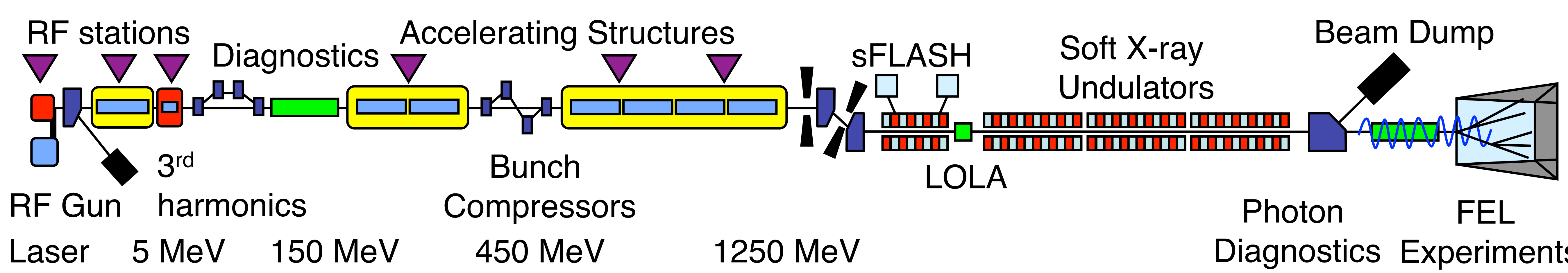
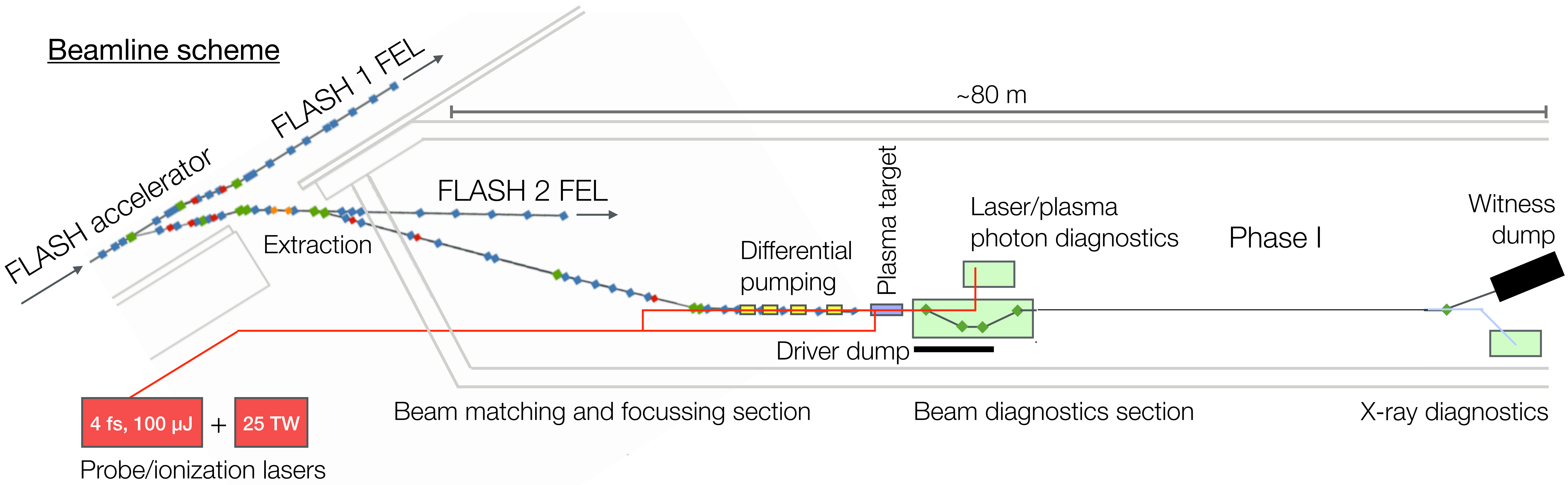


FLASHForward▸▸ : New beam-line attached to FLASH

Future-oriented wakefield-accelerator research and development at FLASH

Conceptual design close to finished, technical design / procurement started
Operation to start in ~2016, run for 4 years+

<u>Beamline scheme</u>



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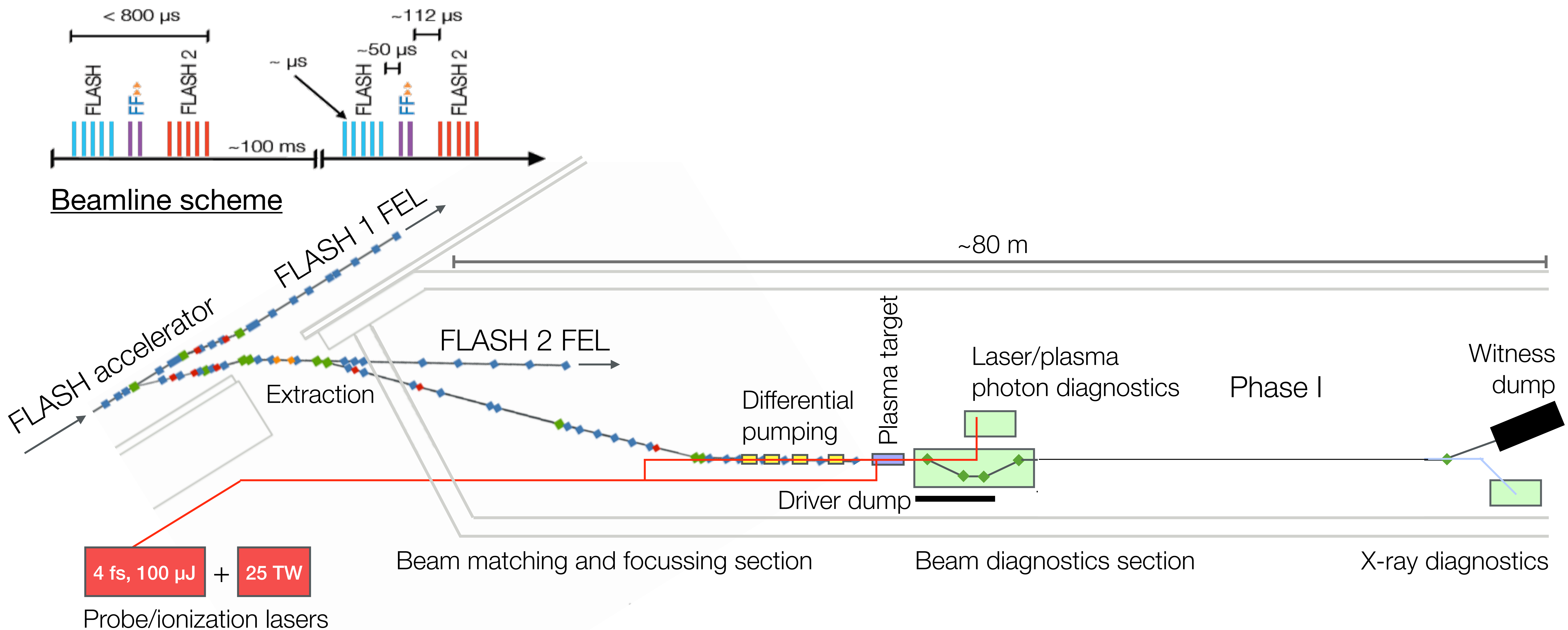

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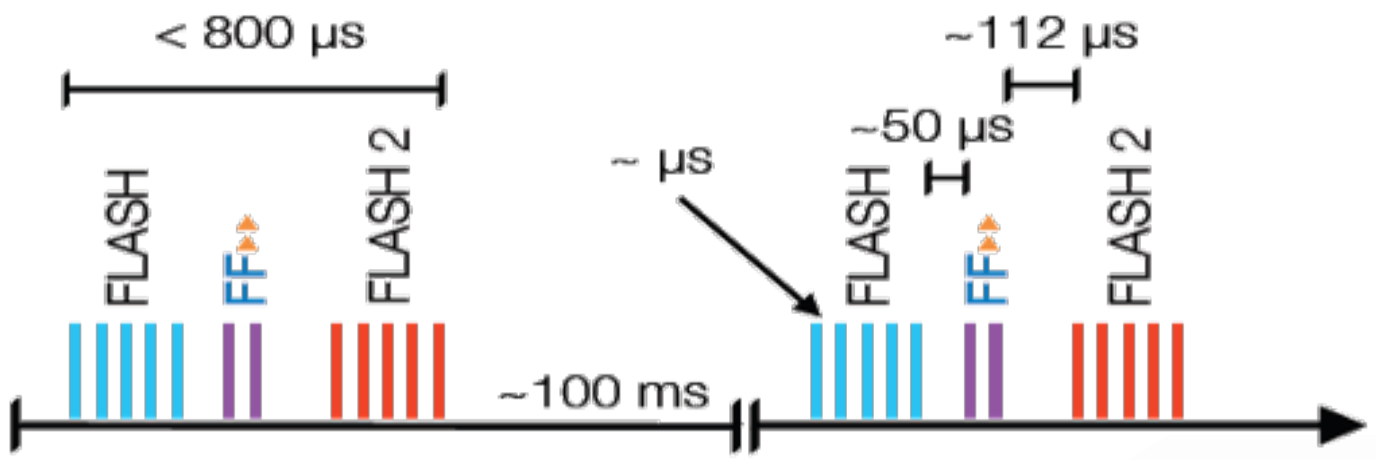

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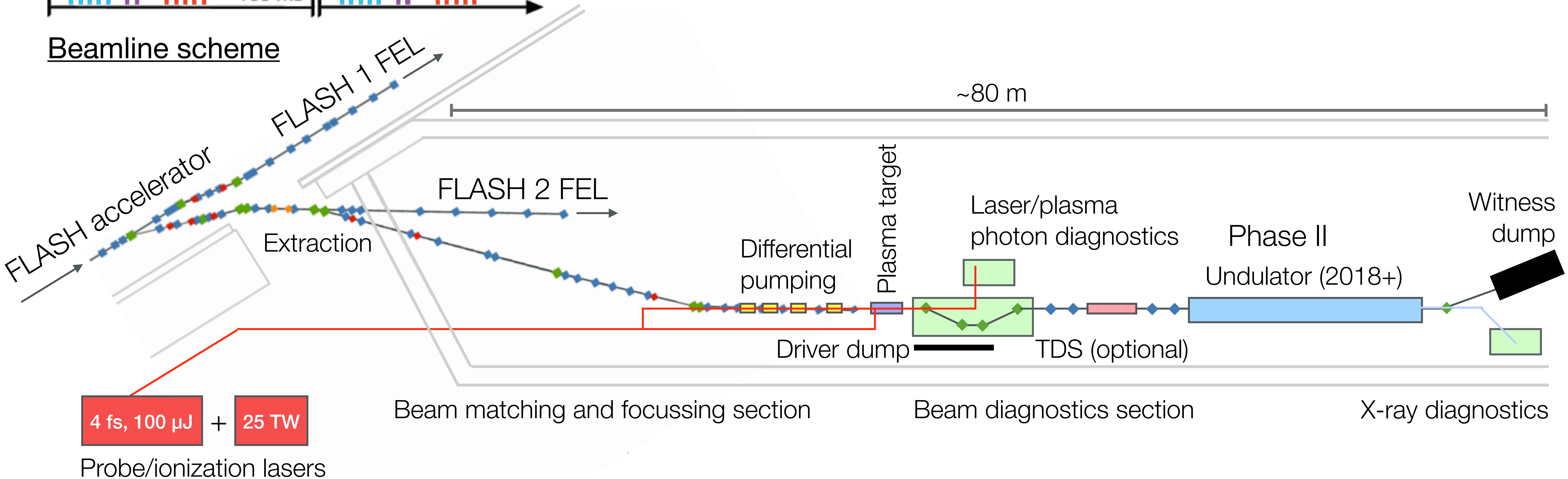

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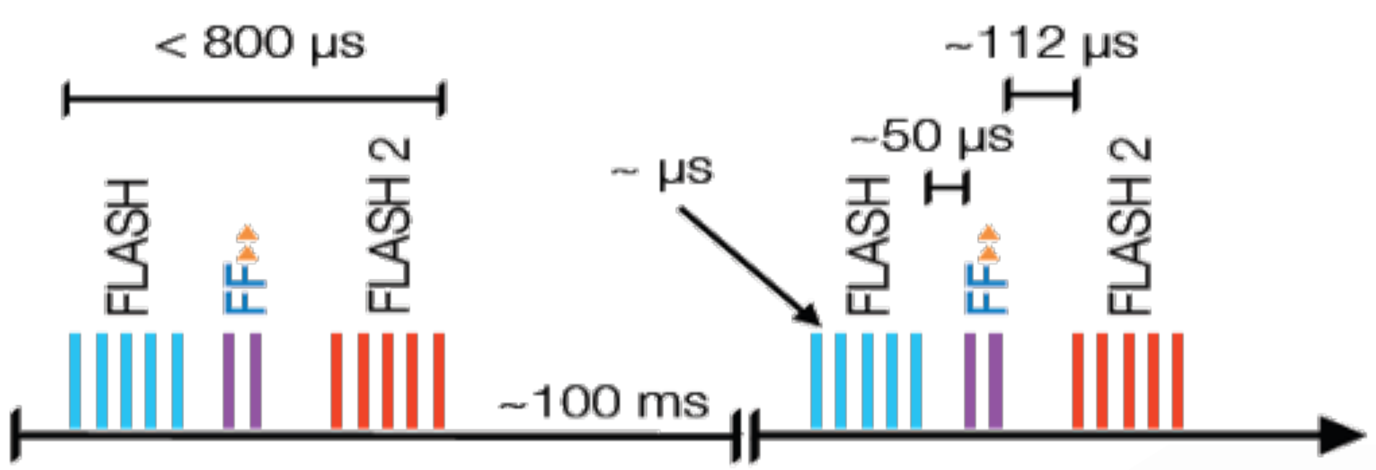

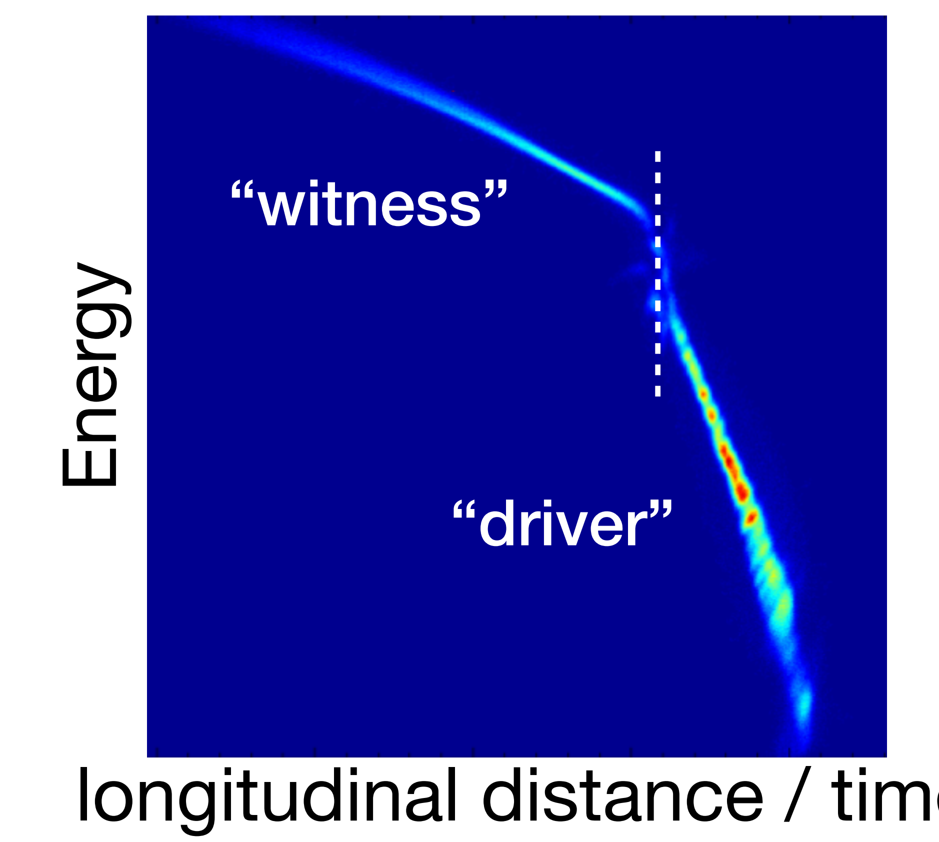

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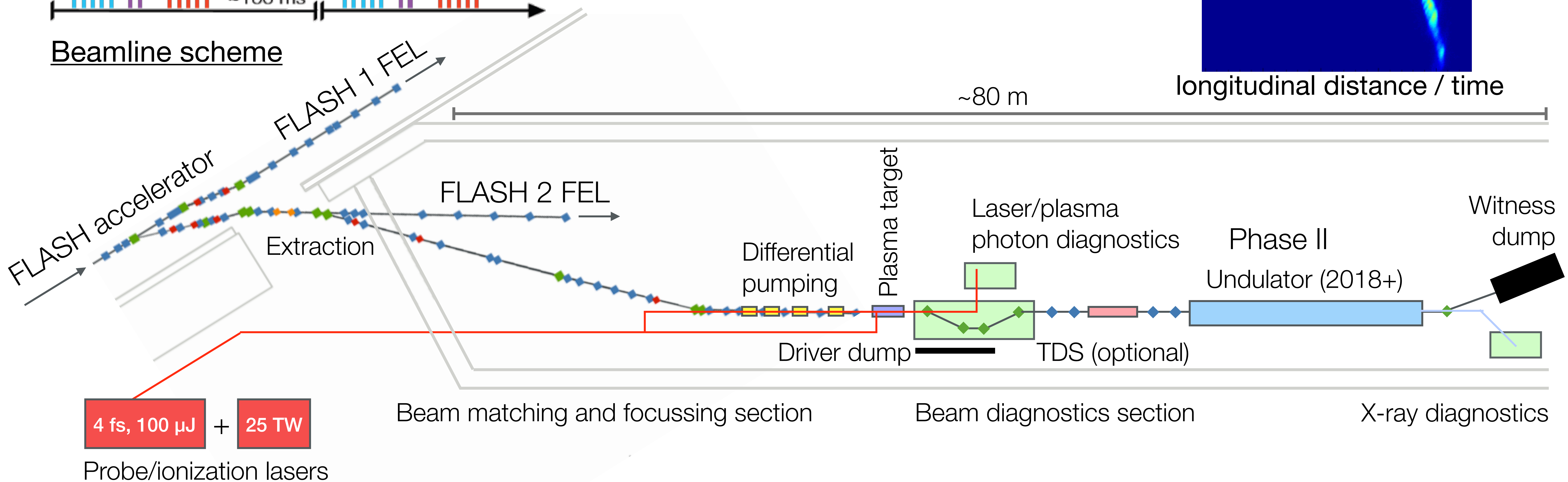

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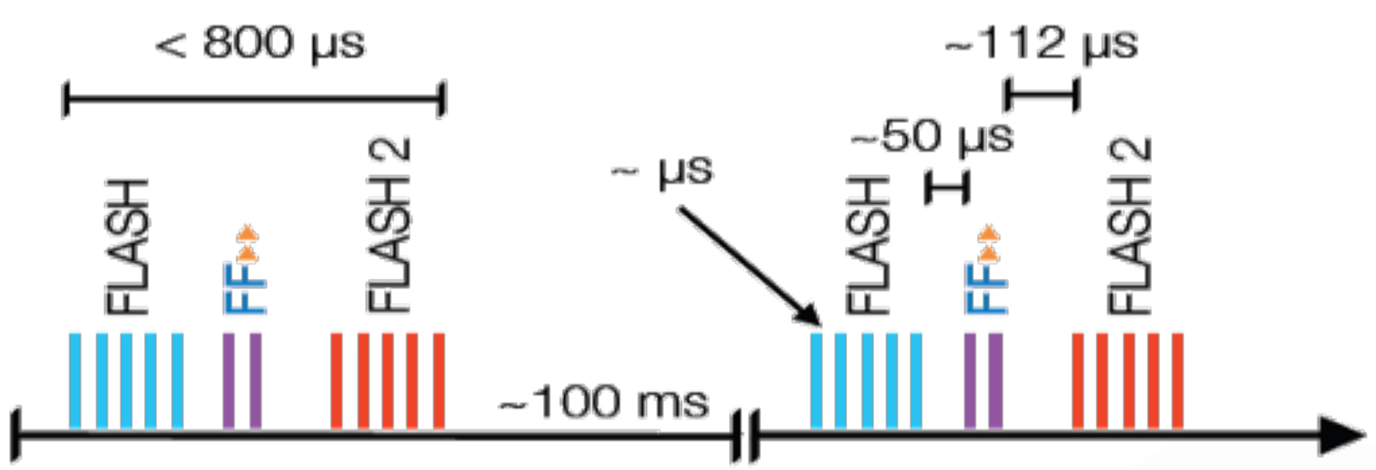

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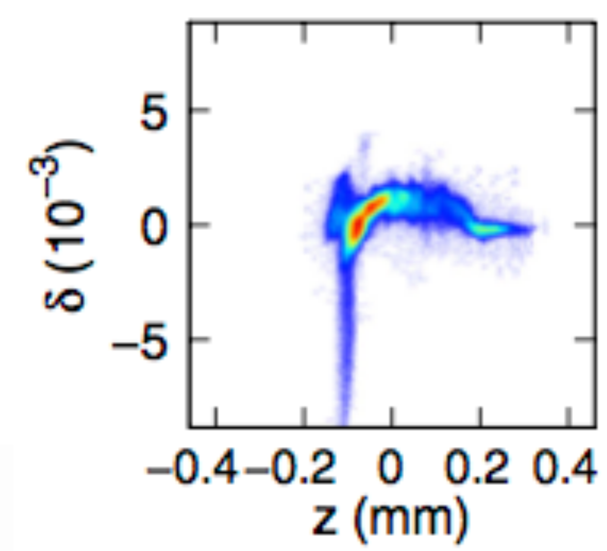

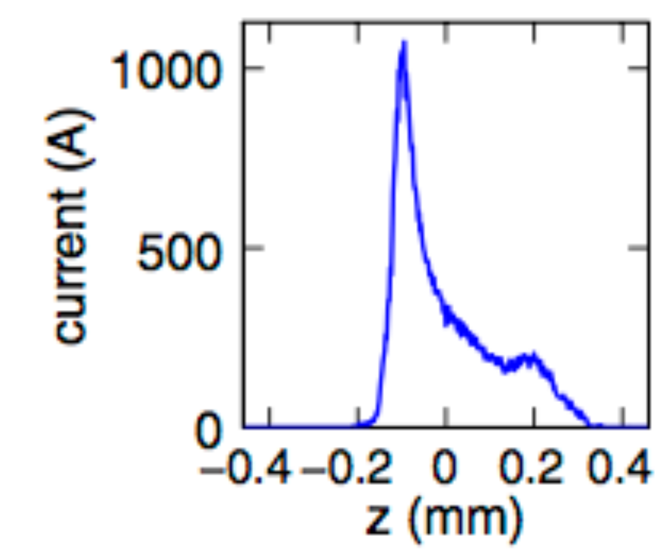

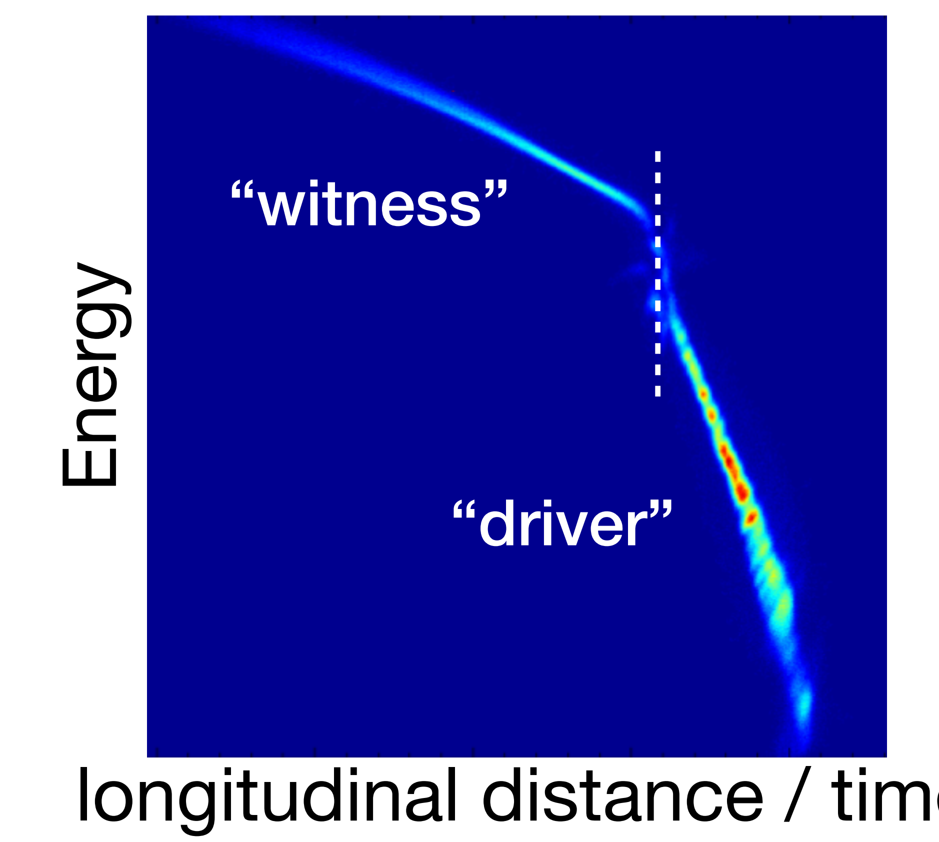

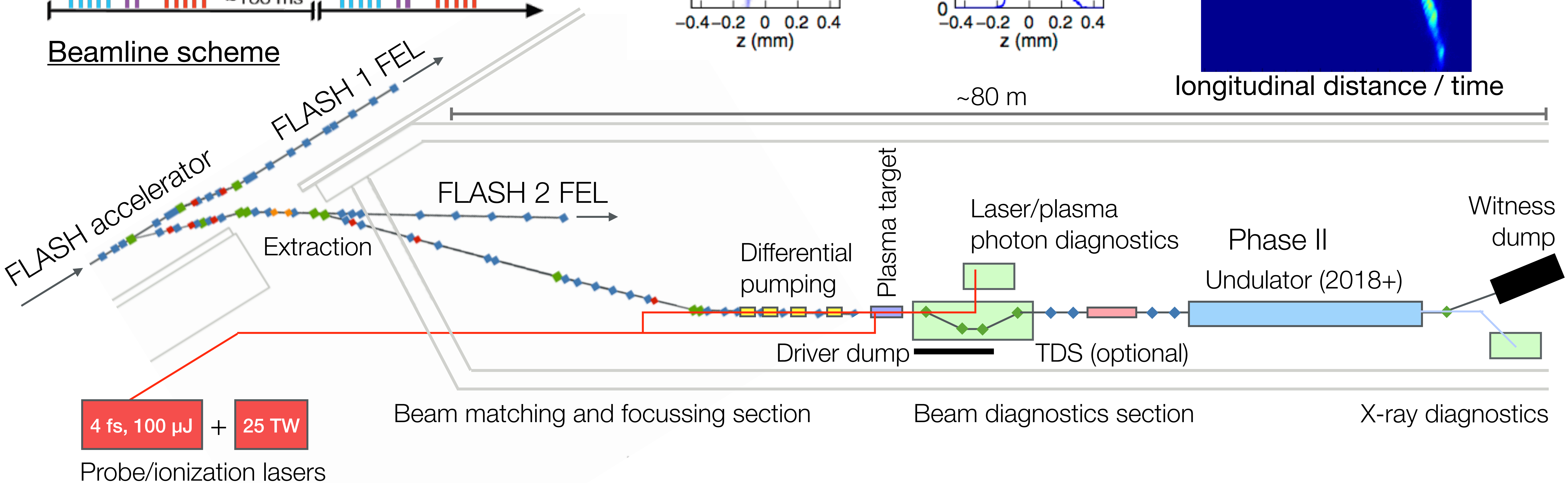

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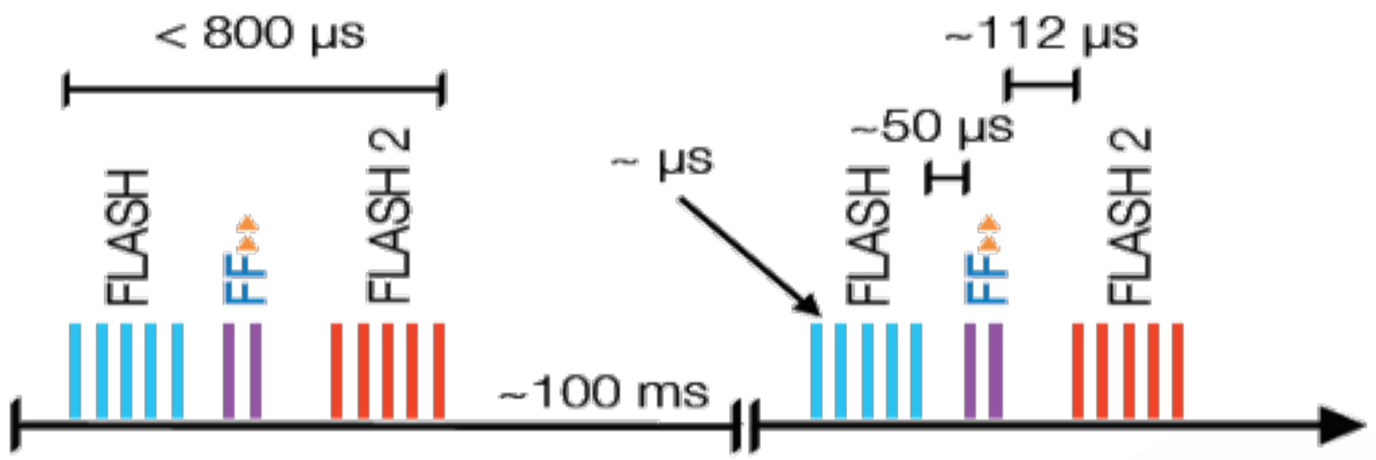

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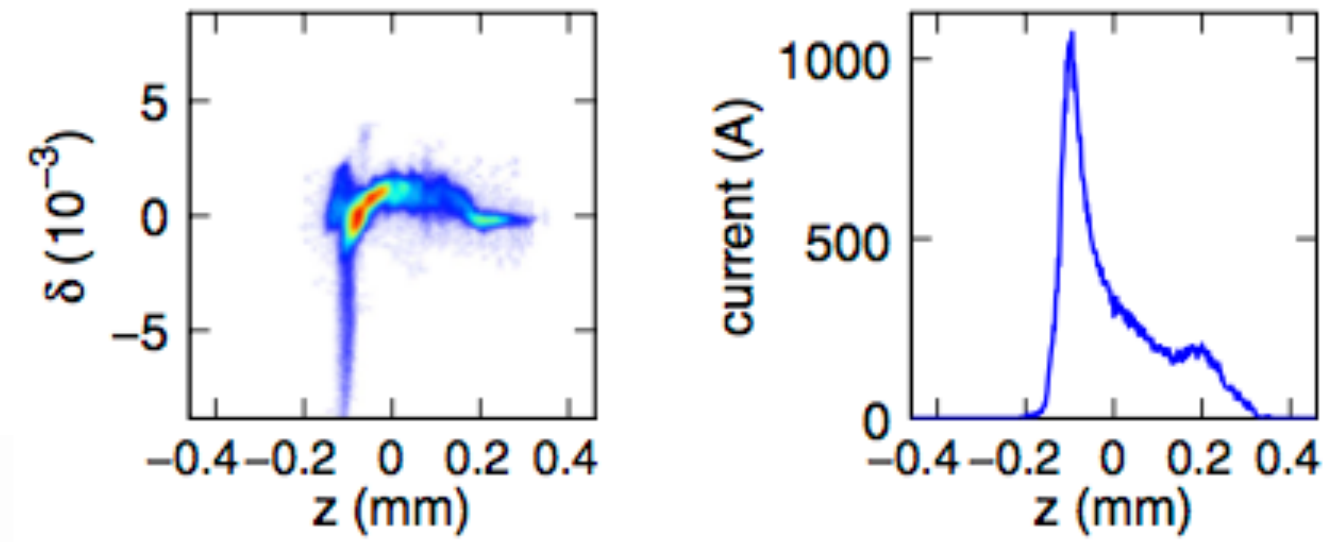
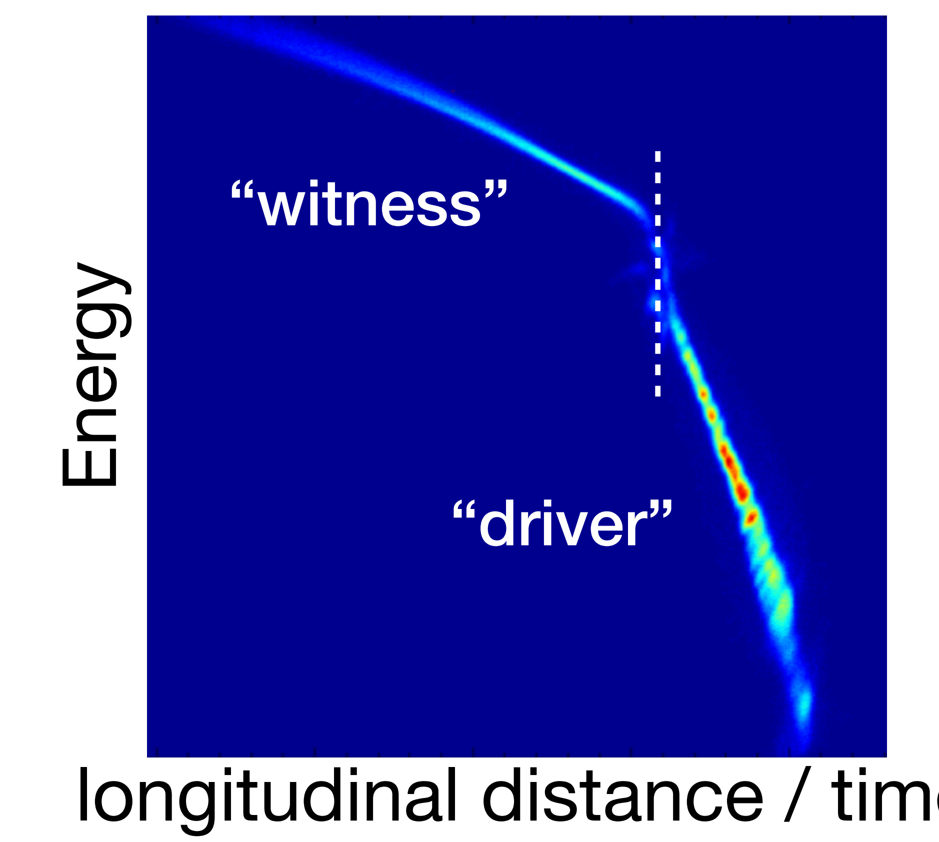
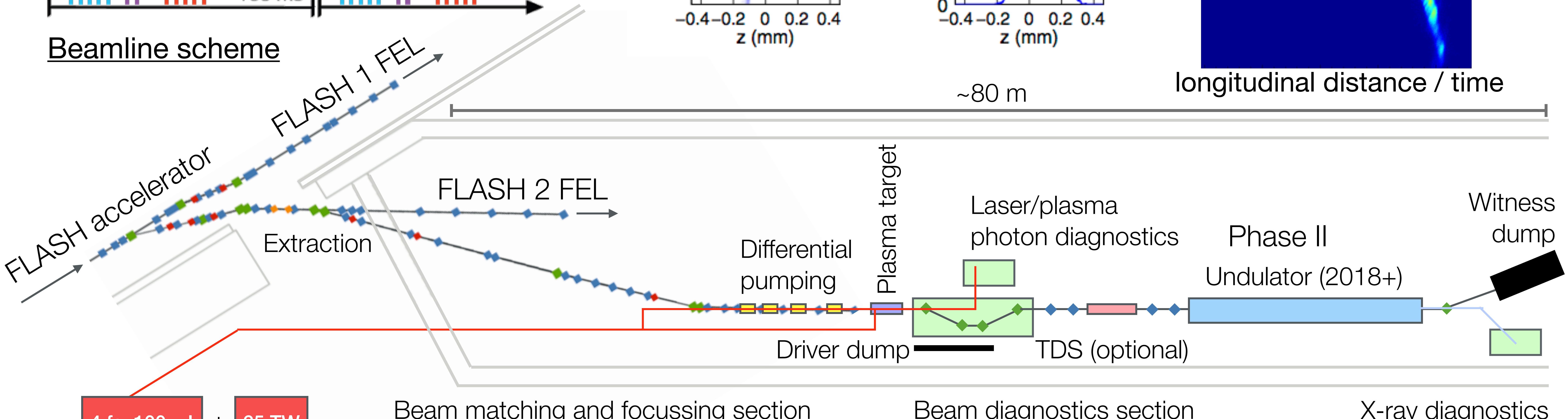


also: multi bunch excitation

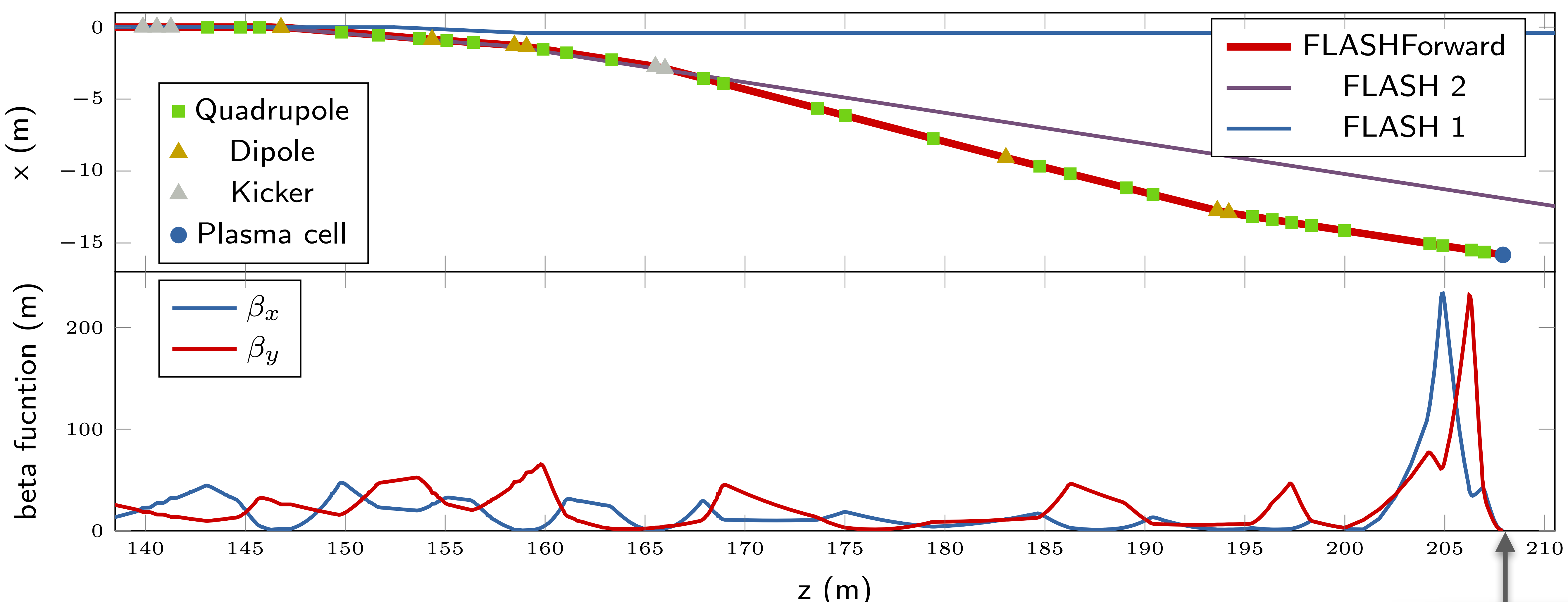




Smith Purcell detector (I. Konoplev)

undulator-based beam diagnostic (R. Bartolini)

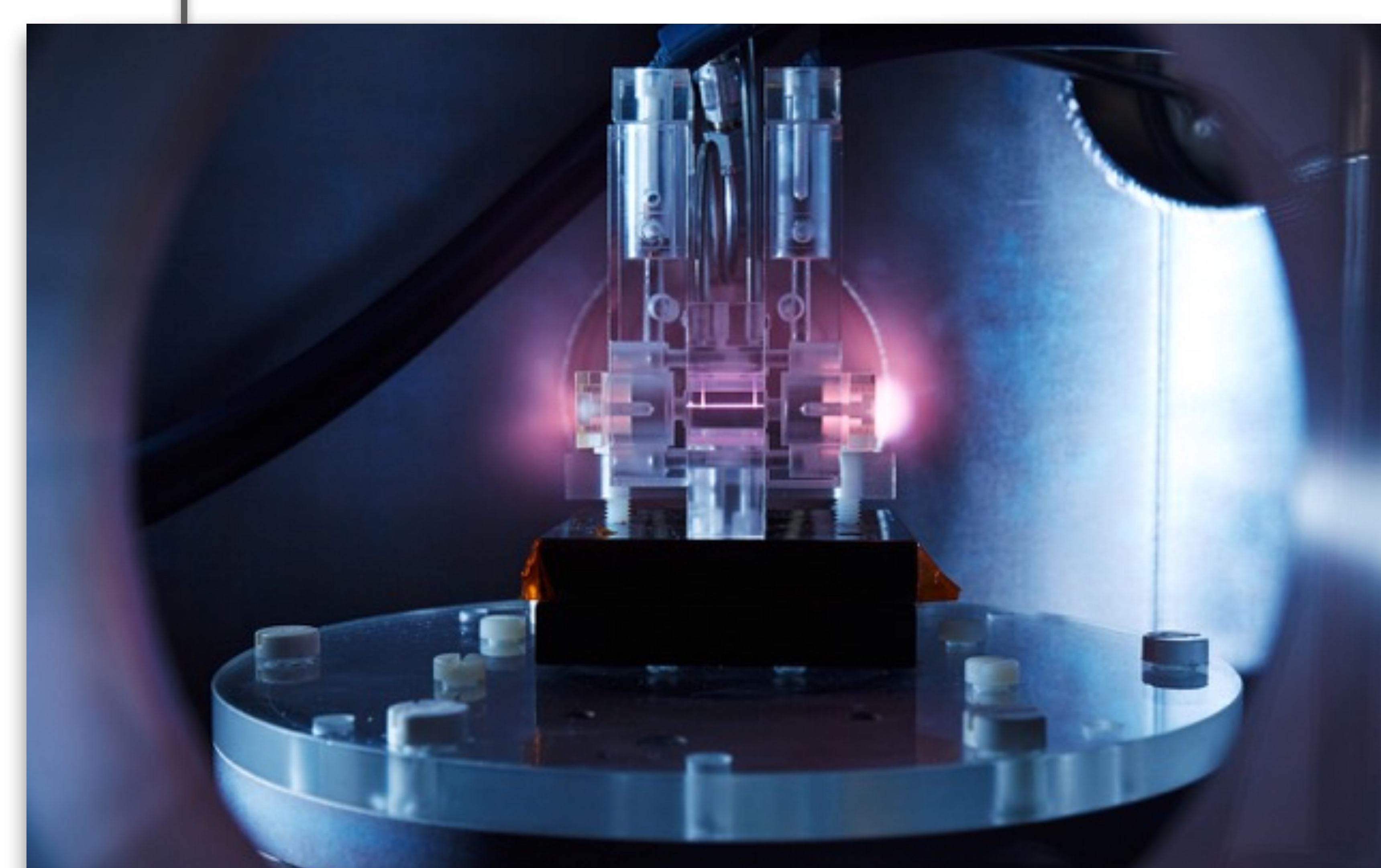
Lattice design for extraction and final focus section complete



- Concept: C.Behrens, J.Zemella, M.Scholz (MPY)
- Technical coordination: K.Ludwig (FLA)

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



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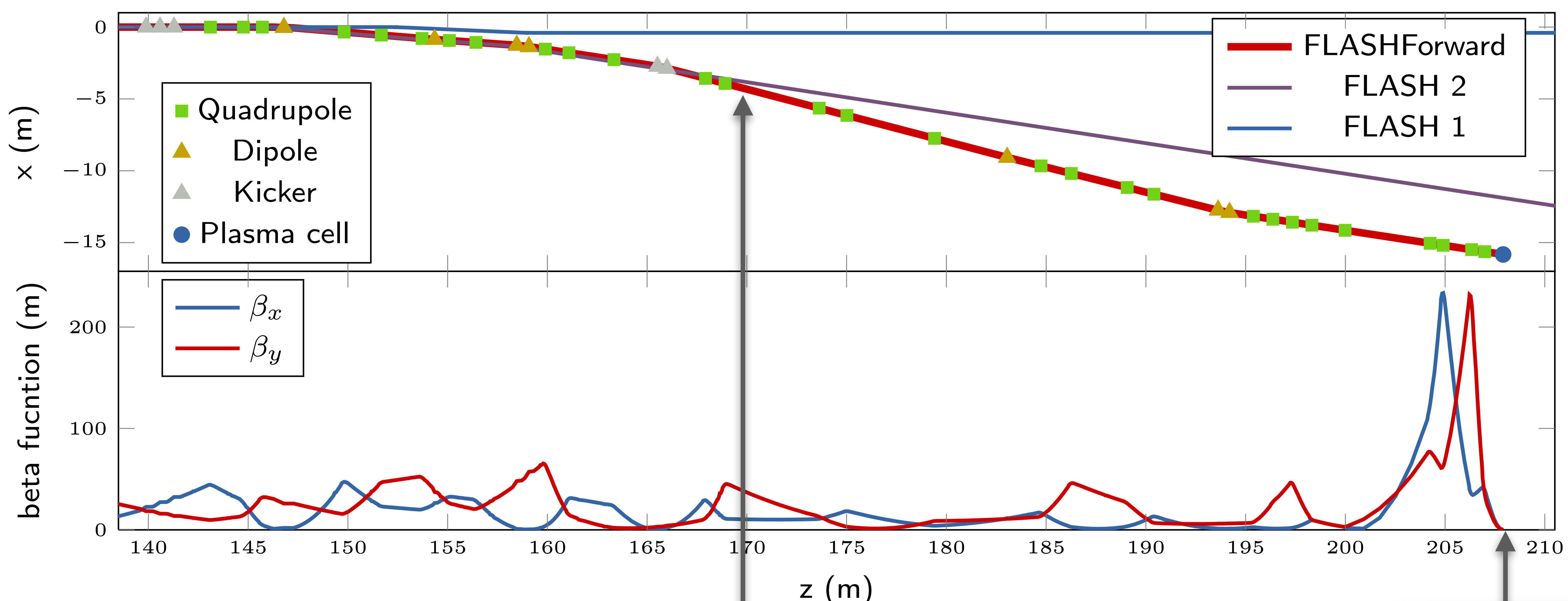

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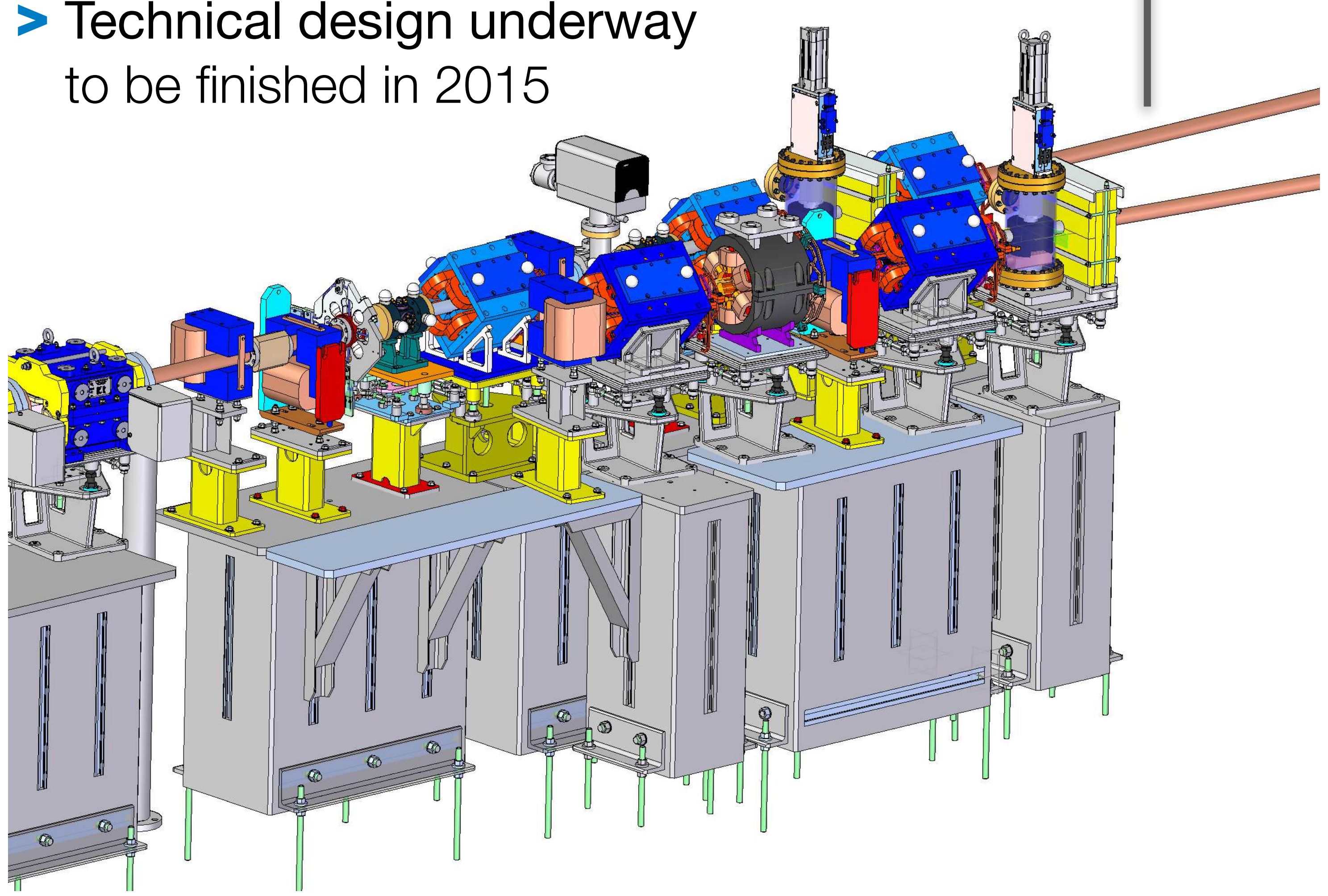
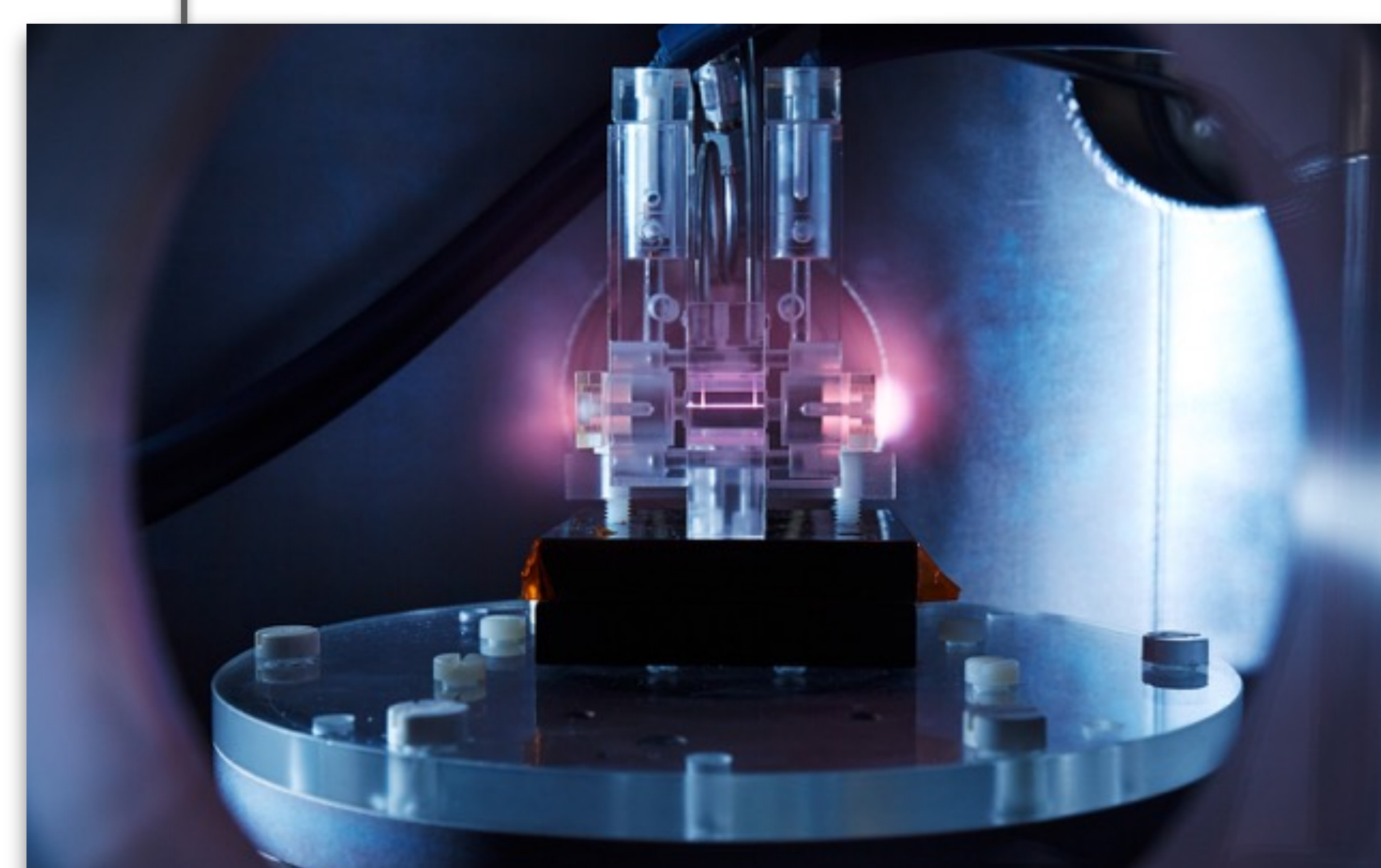
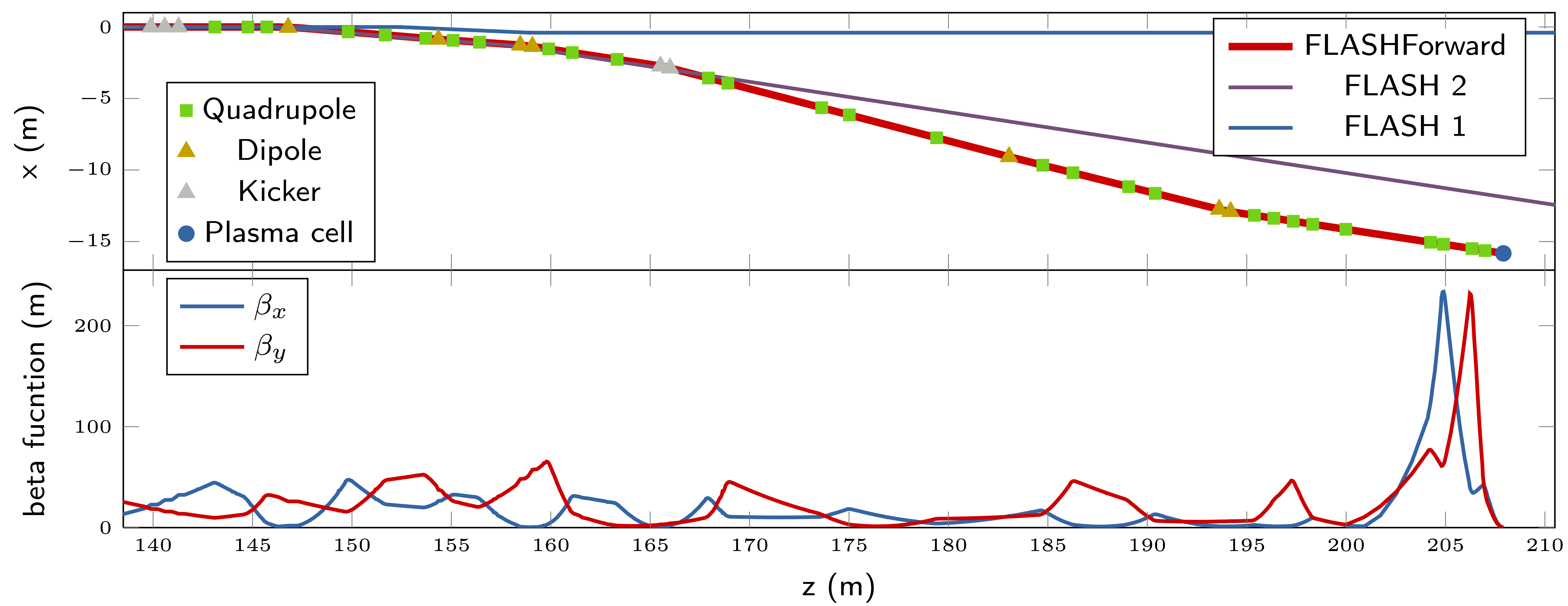
- Tunable R_{56} (long. disp.) between -0.5 and 0.4 cm

- Technical design underway to be finished in 2015





Lattice design for extraction and final focus section complete



- Concept: C.Behrens, J.Zemella, M.Scholz (MPY)
- Technical coordination: K.Ludwig (FLA)

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
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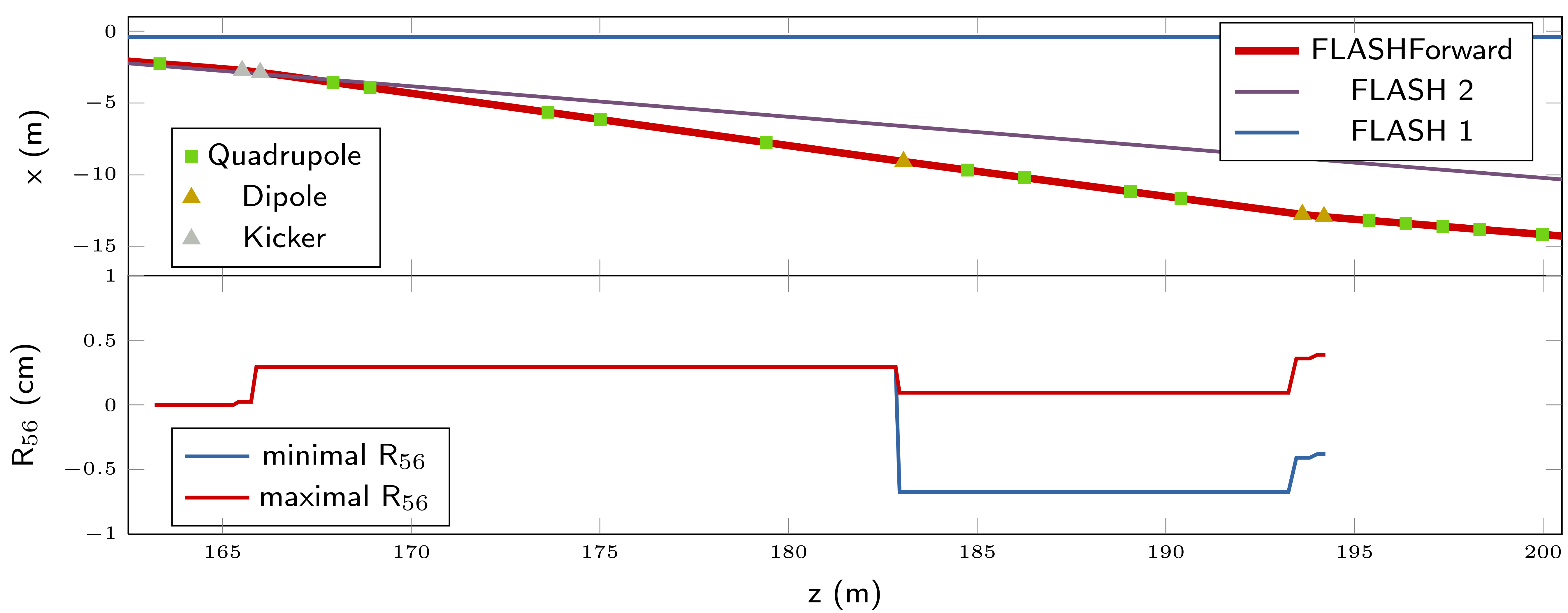
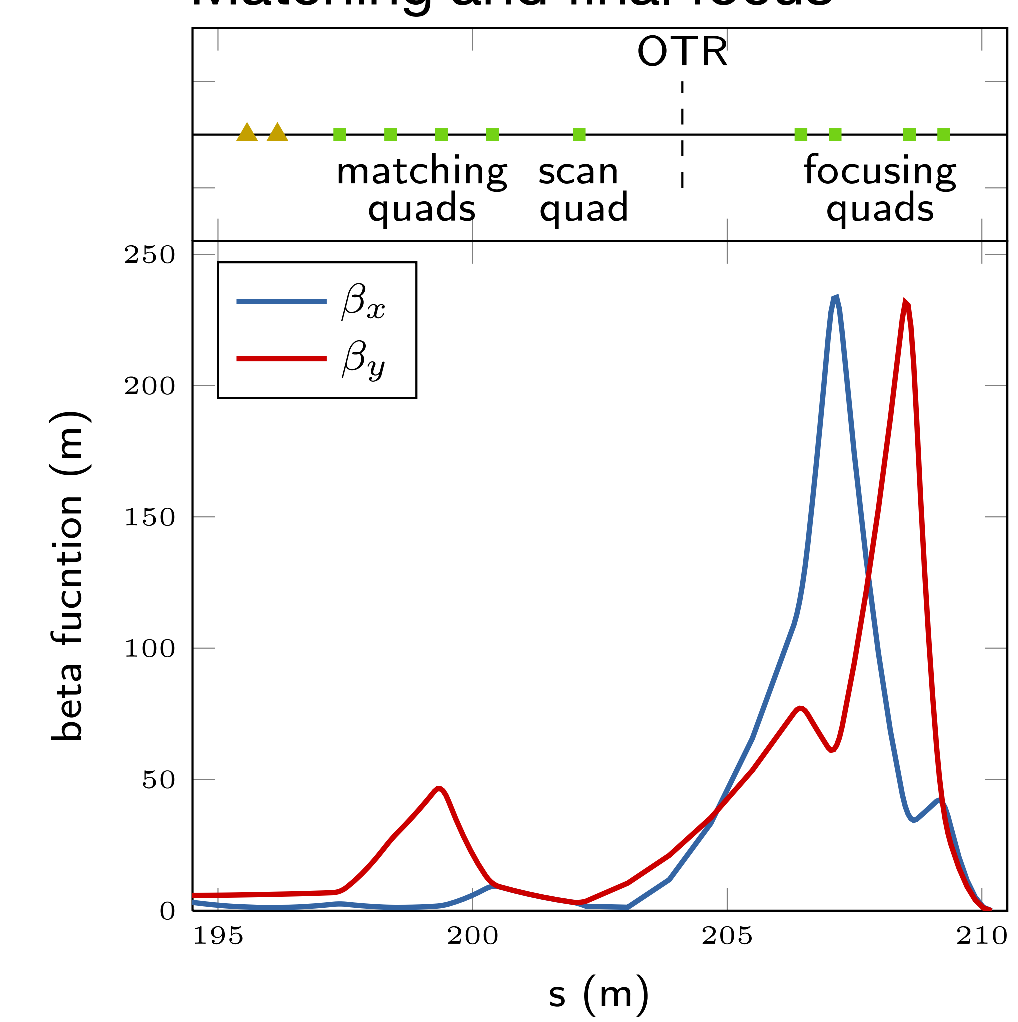
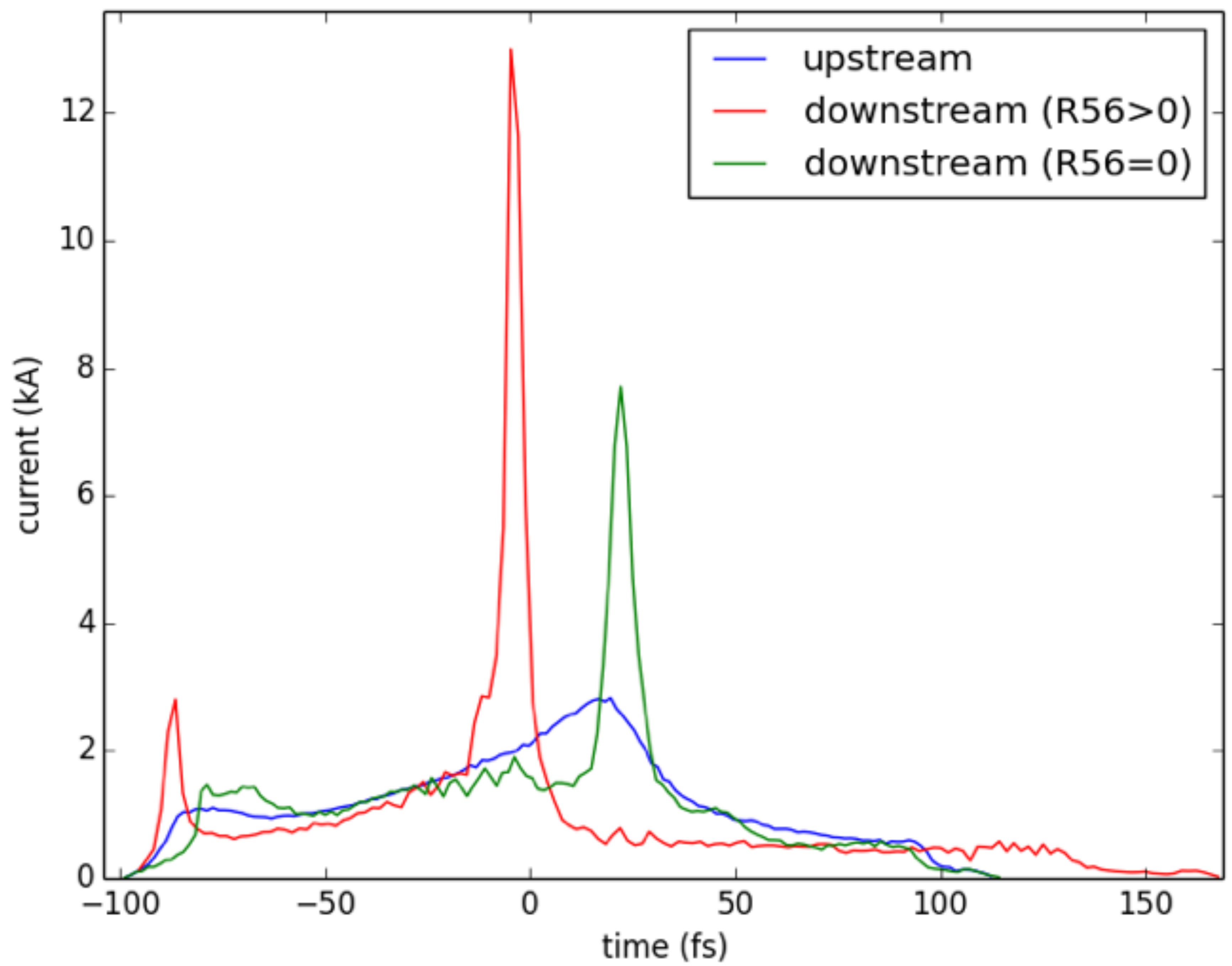
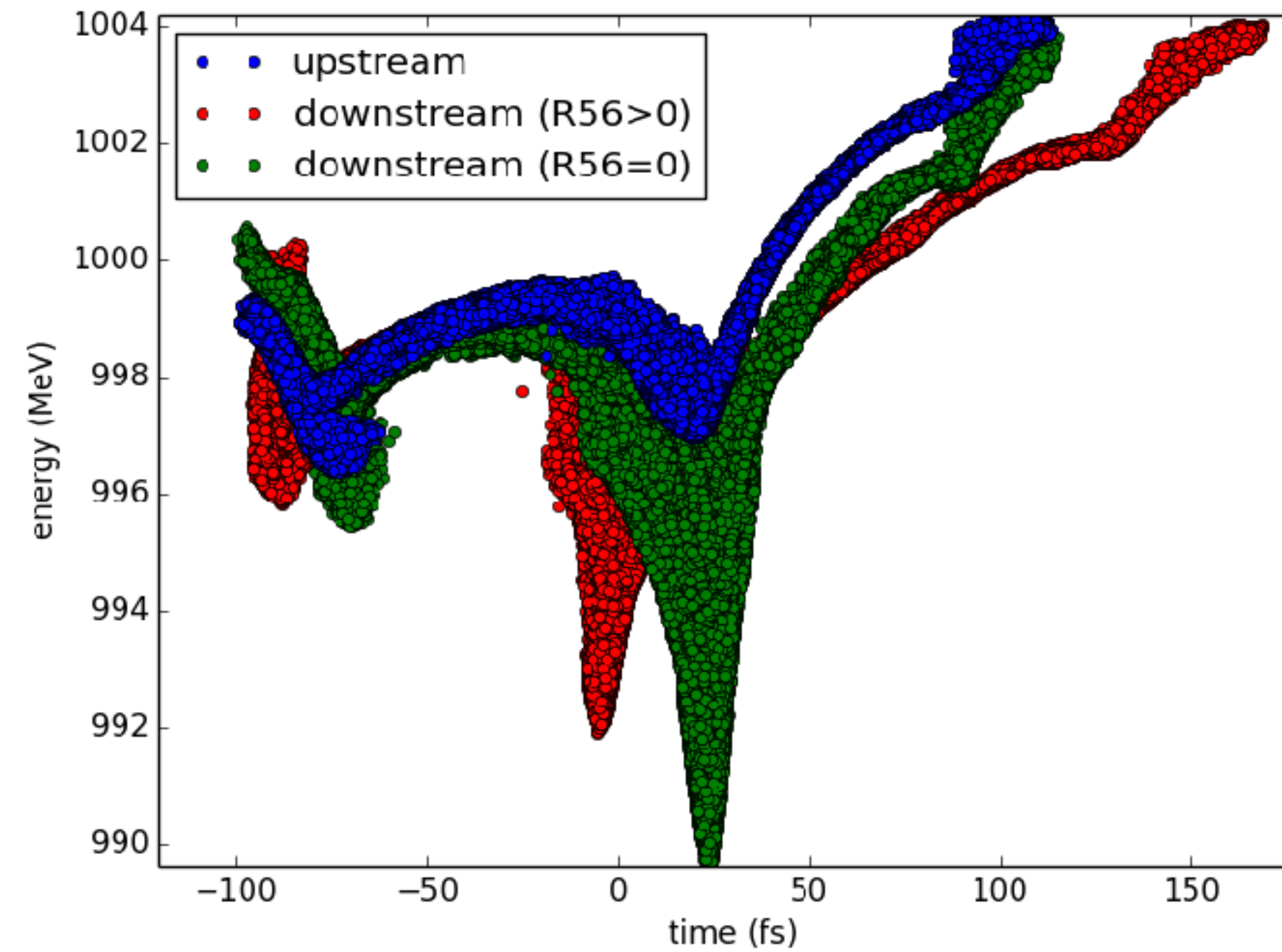


Matching and final focus



Tunable R_{56} in extraction dogleg for optimized peak current

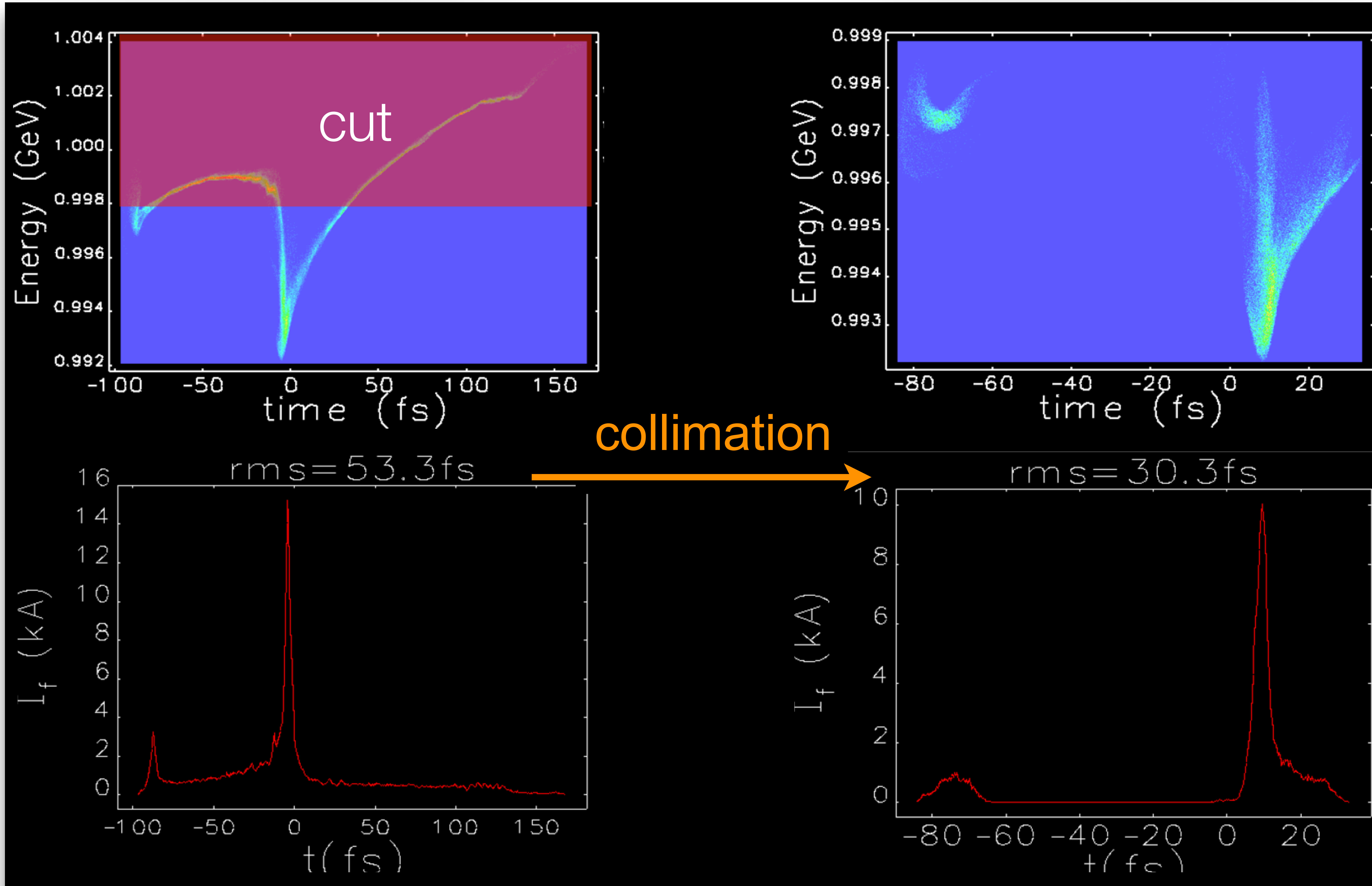




- Beams from FLASH at entrance of FLASHForward are close to maximum compression
- CSR in FLASHForward extraction section creates chirp

- **Our strategy:** compress the beam core for high peak current by
  - tuning R_{56} along the extraction beamline
  - tuning the RF-phase (not optimimized here)
- Further work
  - RF-phase parameter needs to be included in optimization
  - high-current mode needs to be examined at the interaction point including space charge effects

A collimator in the dispersive section can remove the wings



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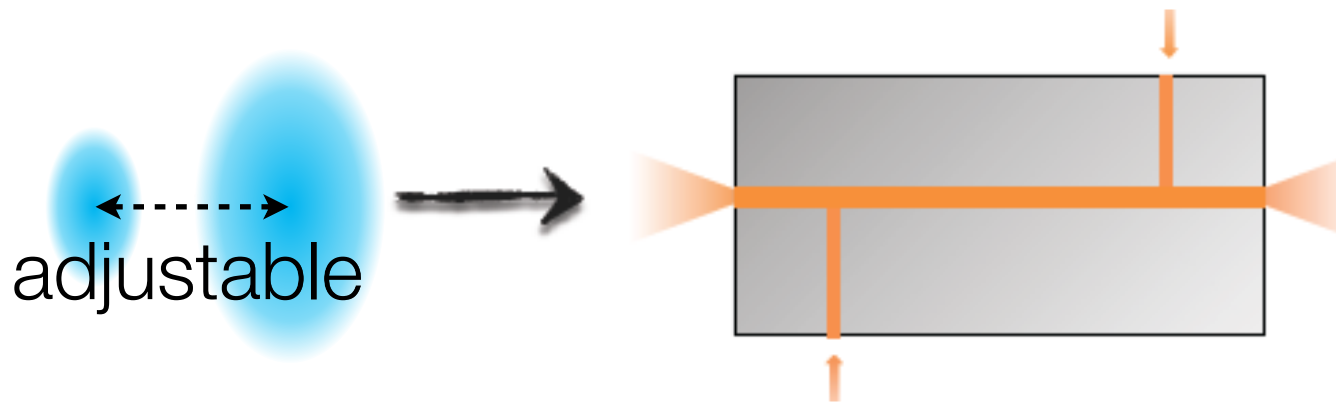

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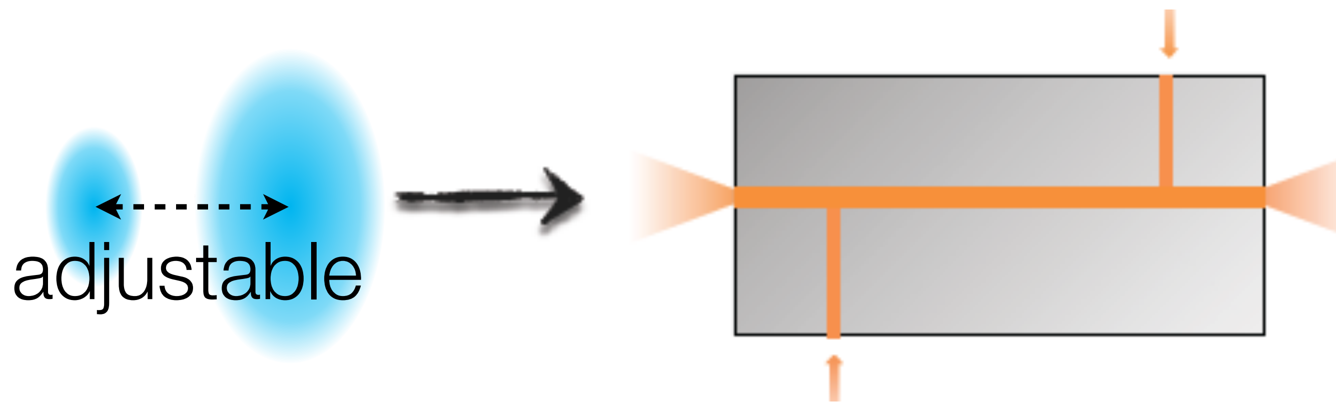

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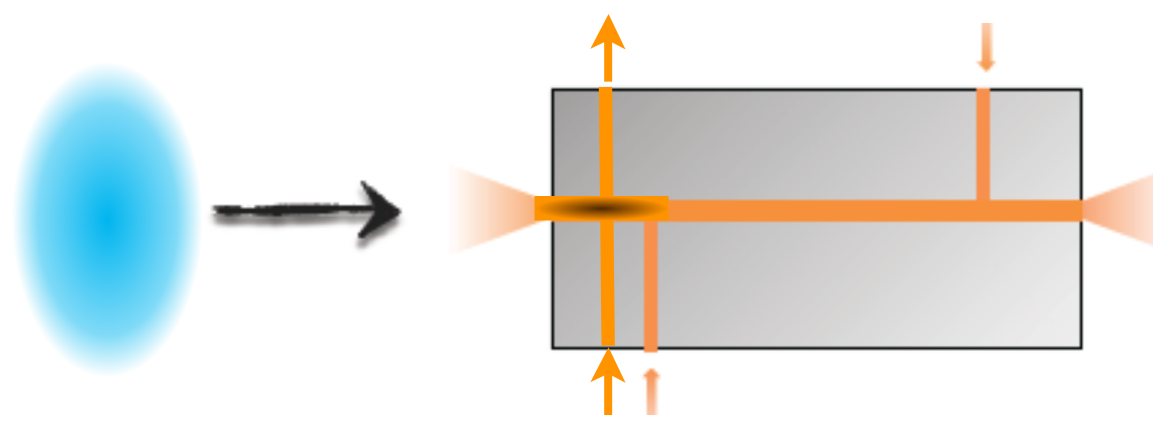

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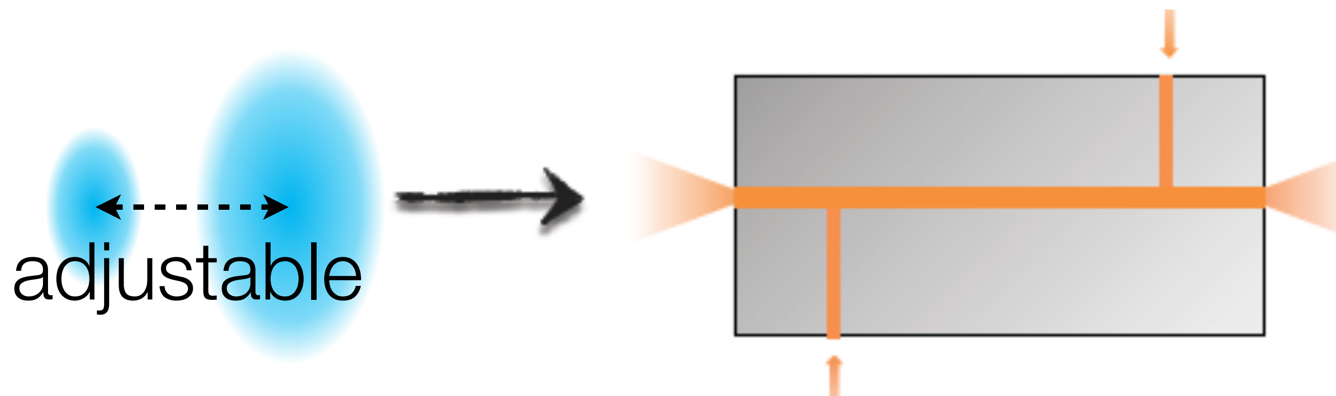

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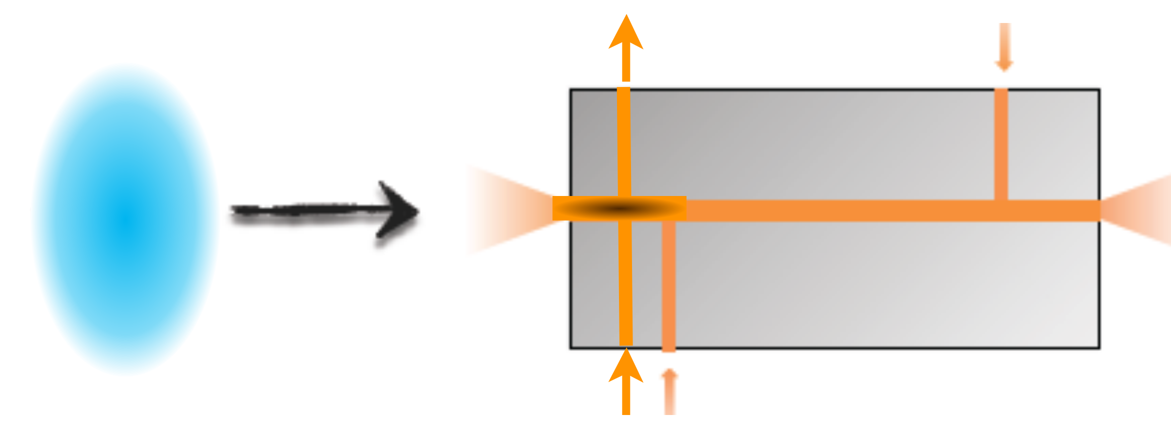

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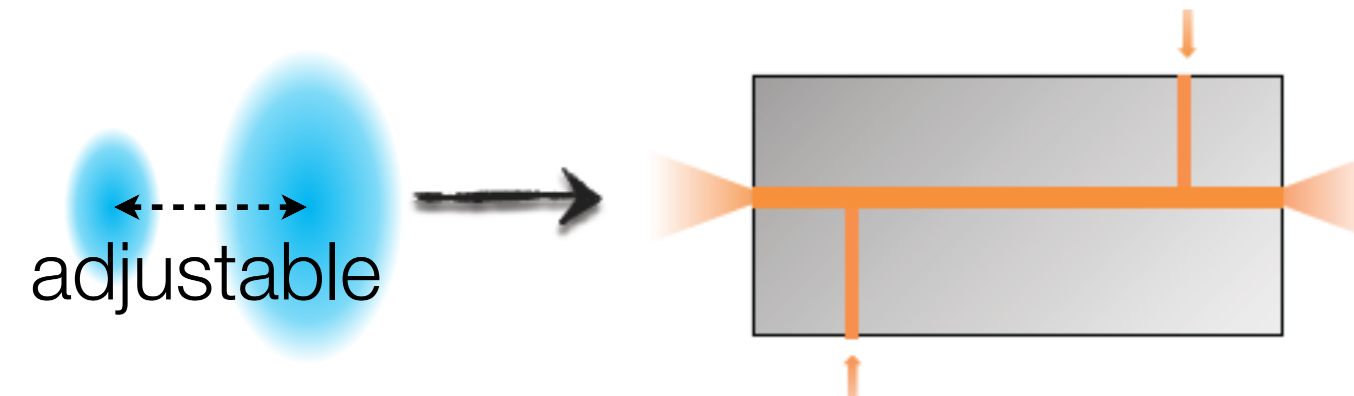

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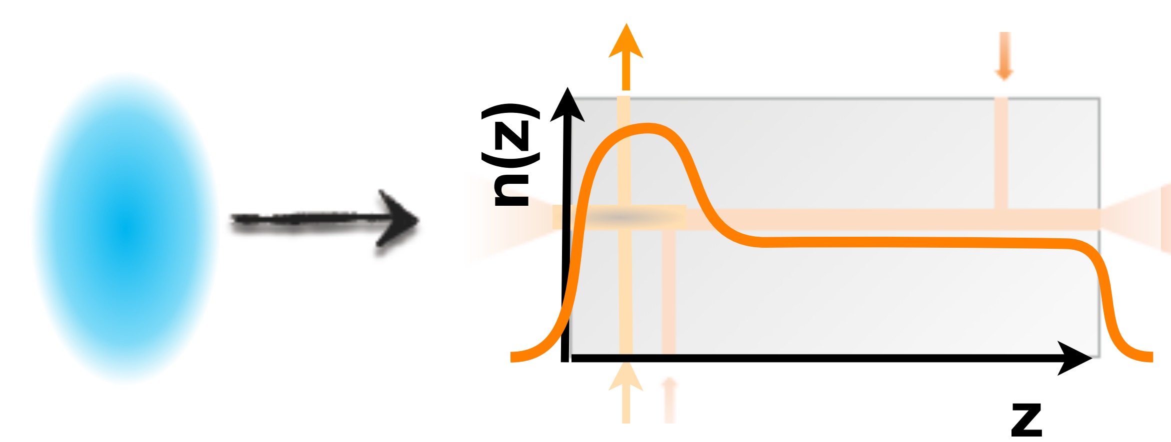

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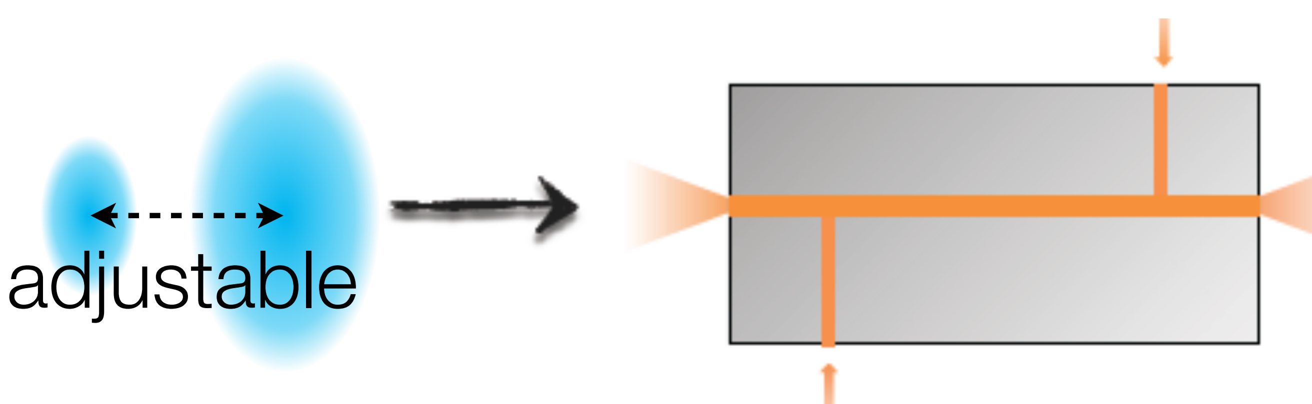

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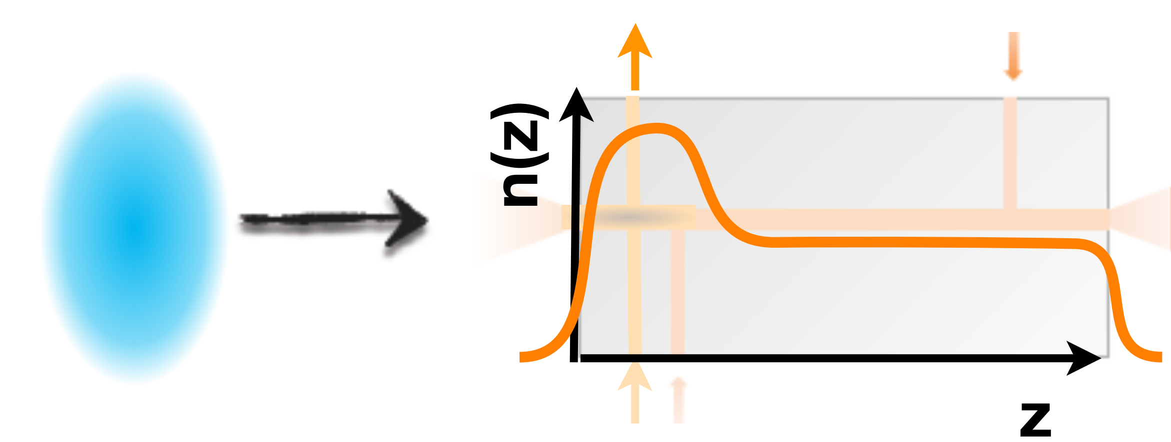

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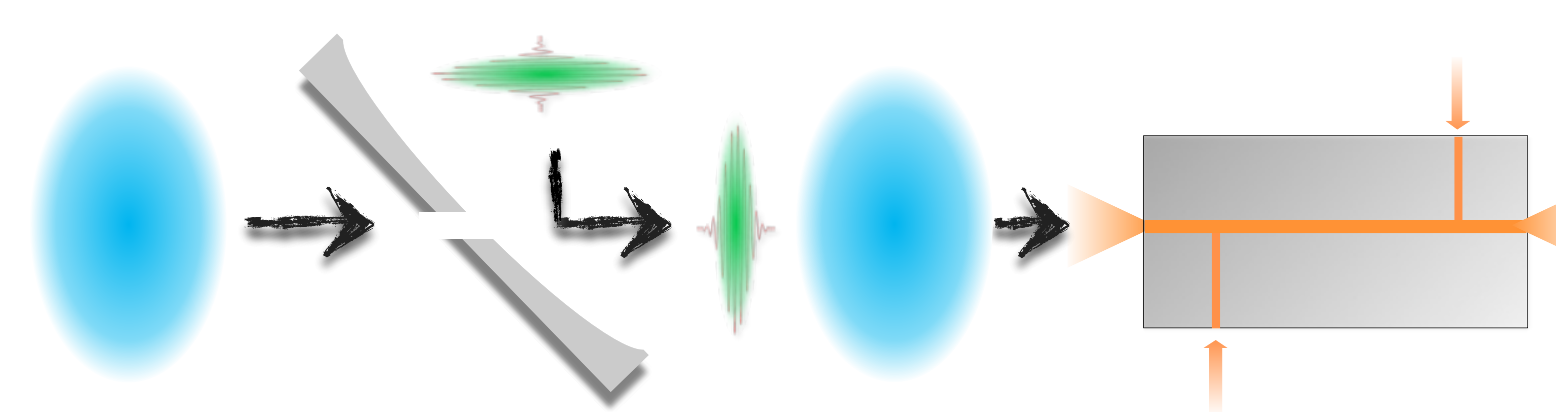

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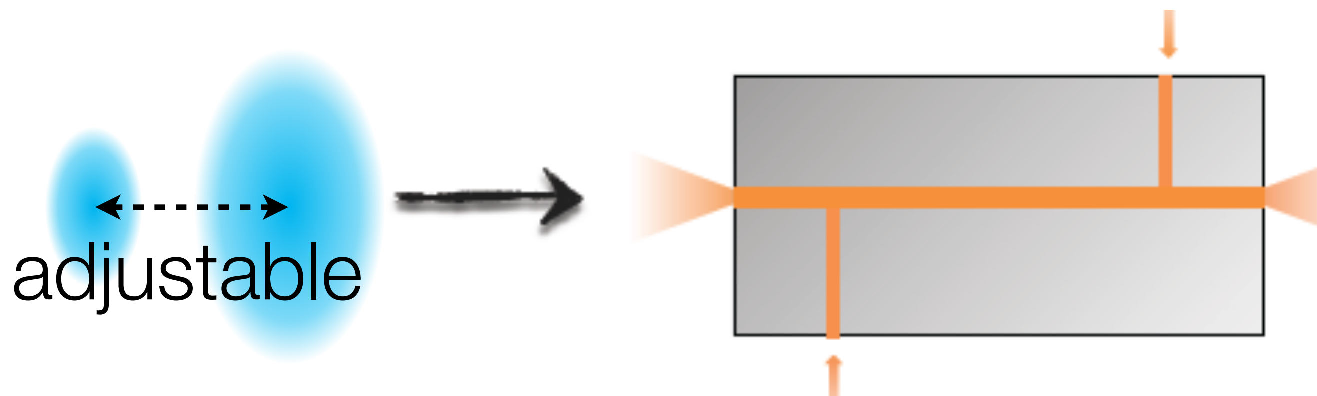

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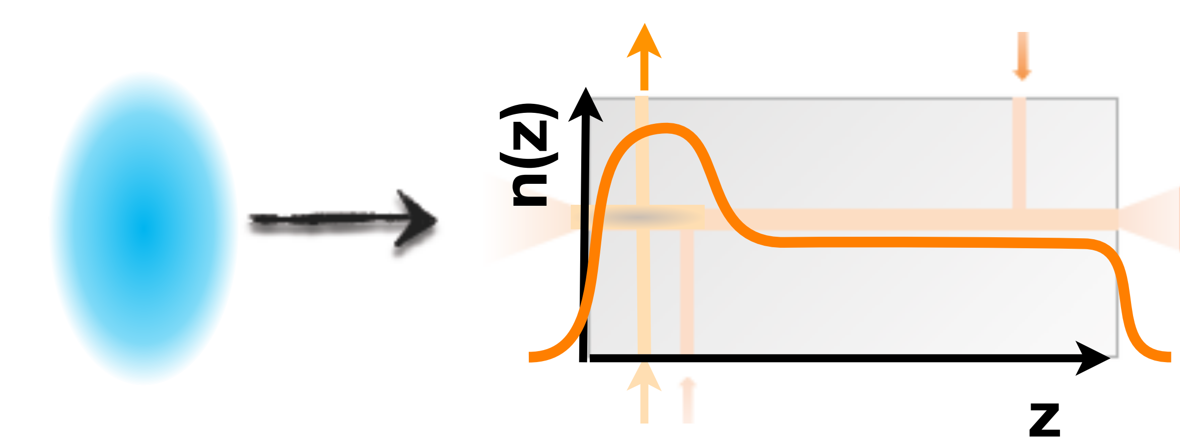

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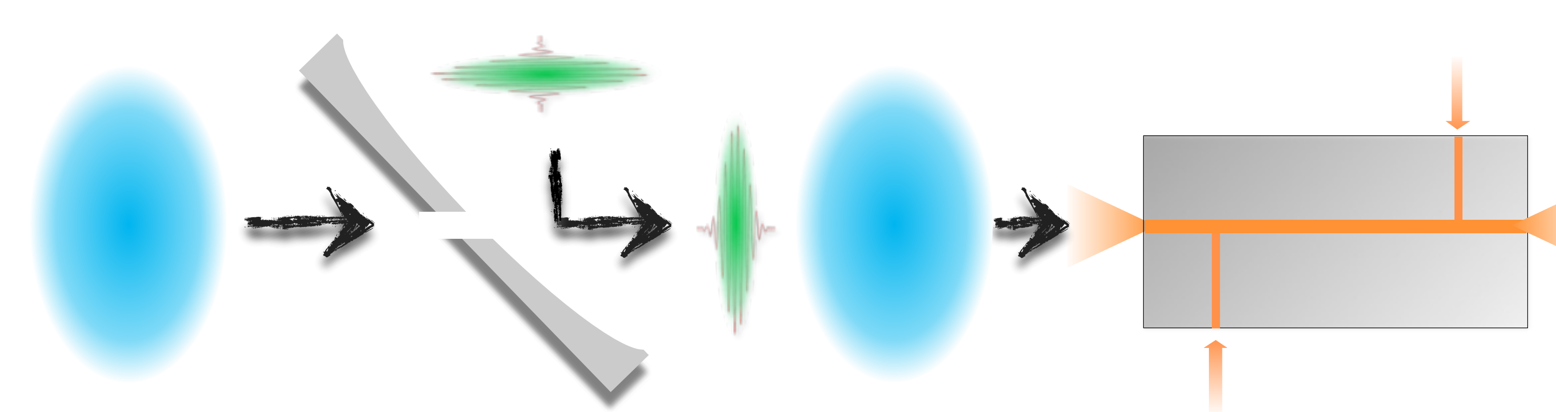

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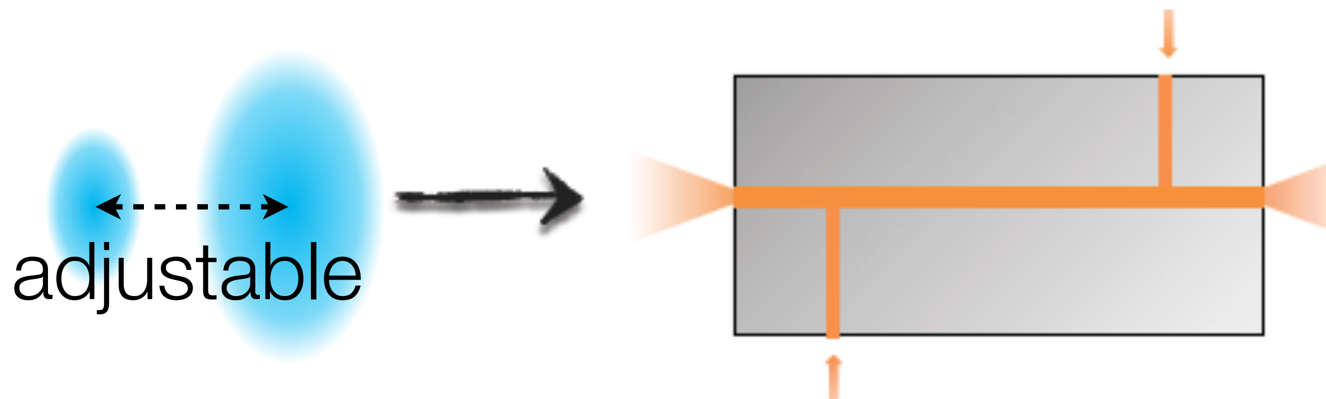

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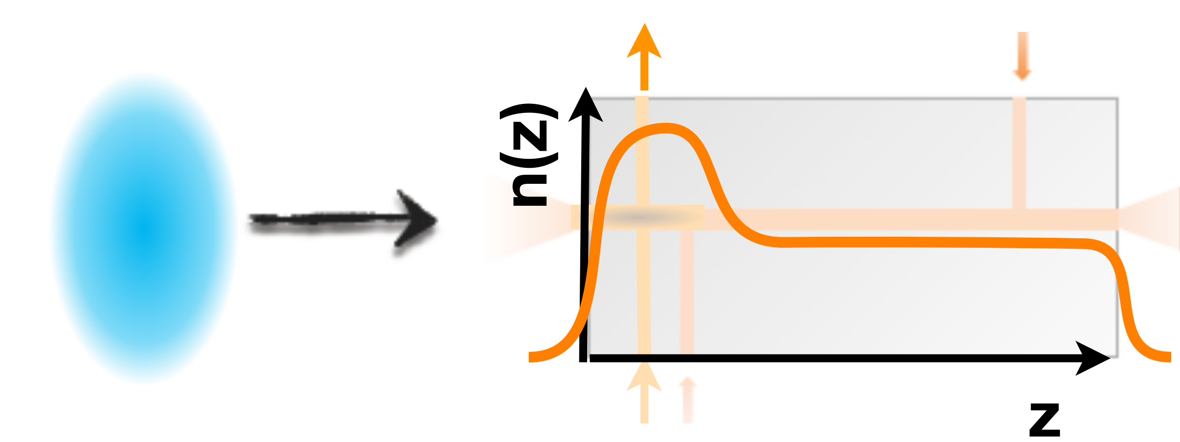

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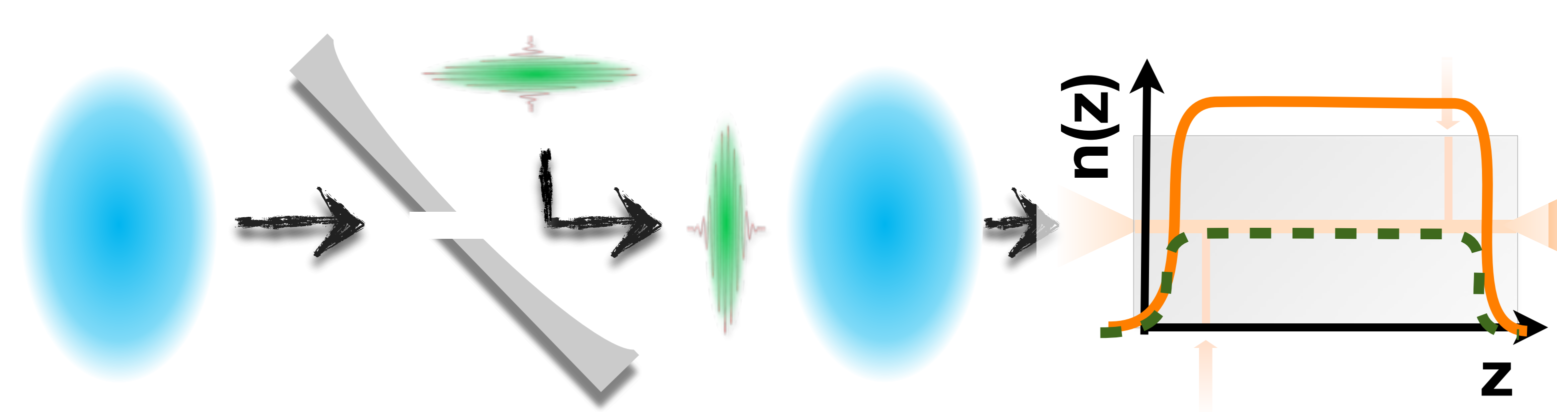

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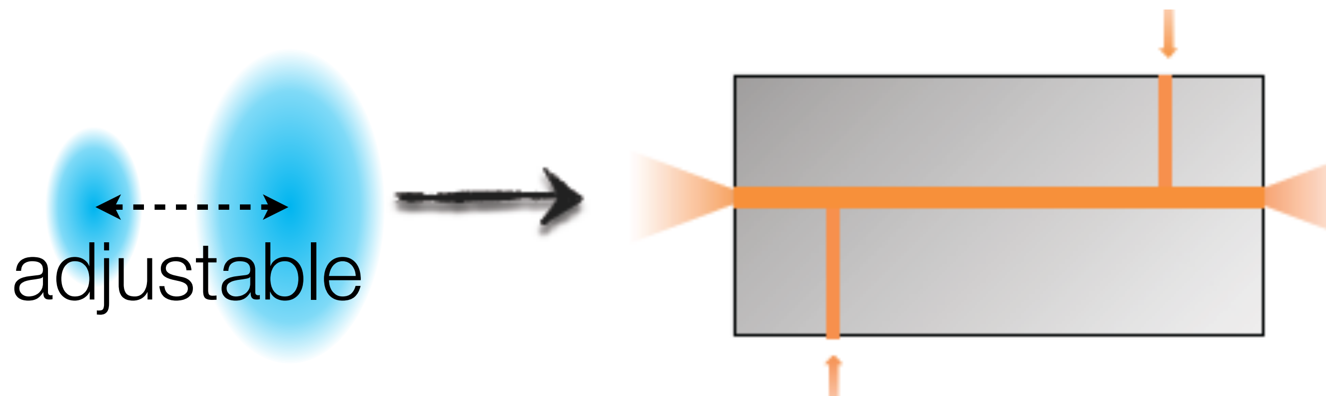

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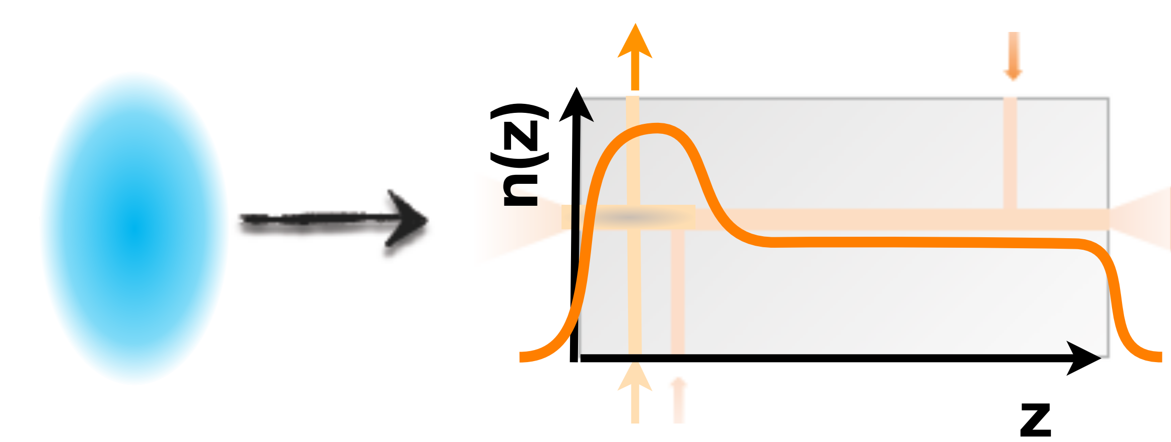

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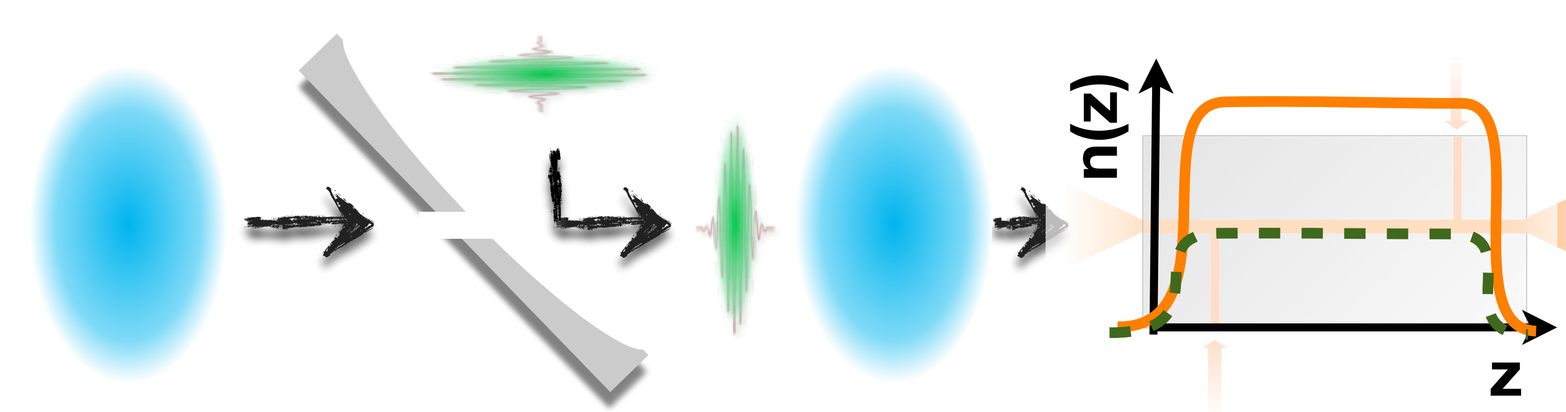

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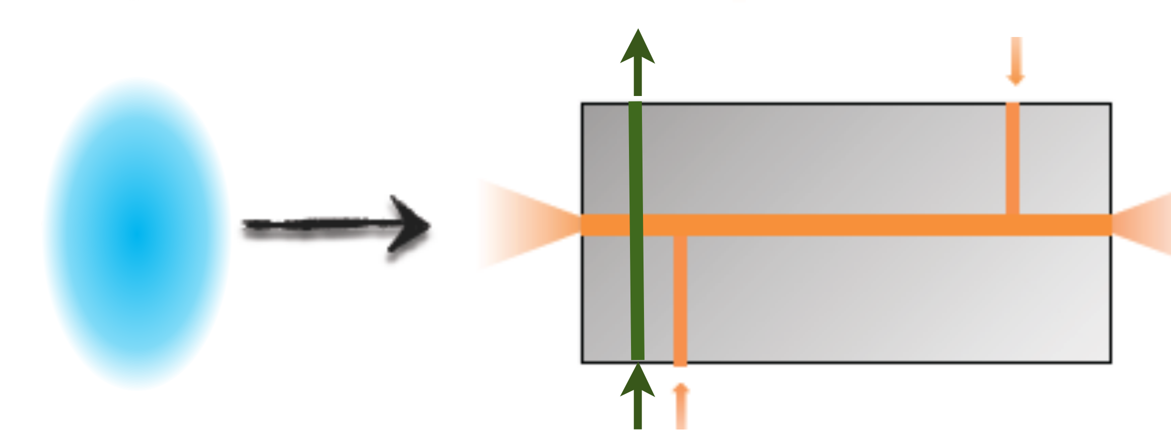

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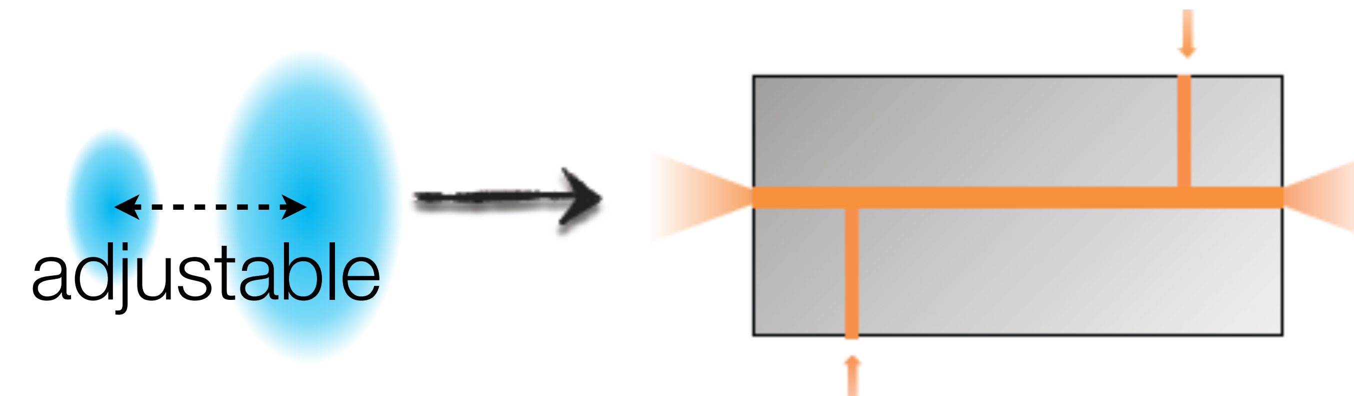

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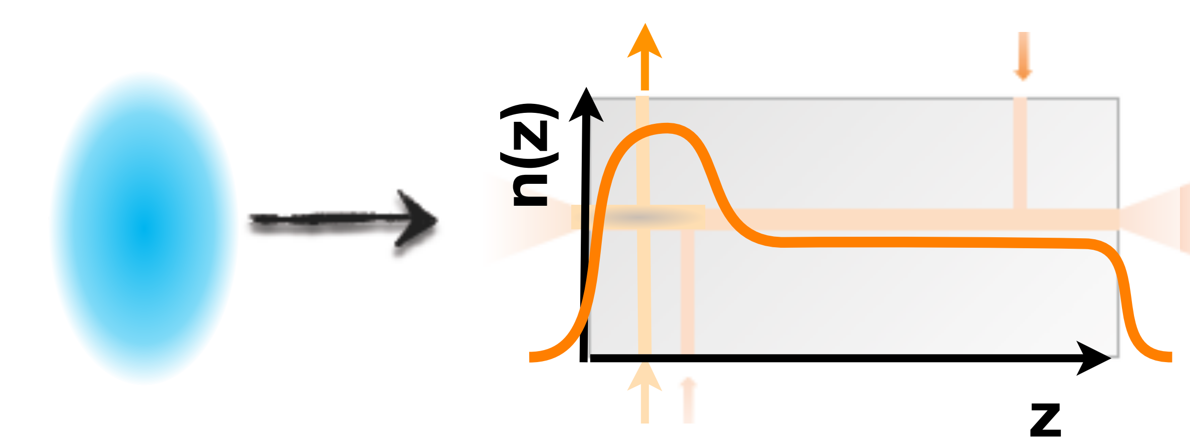

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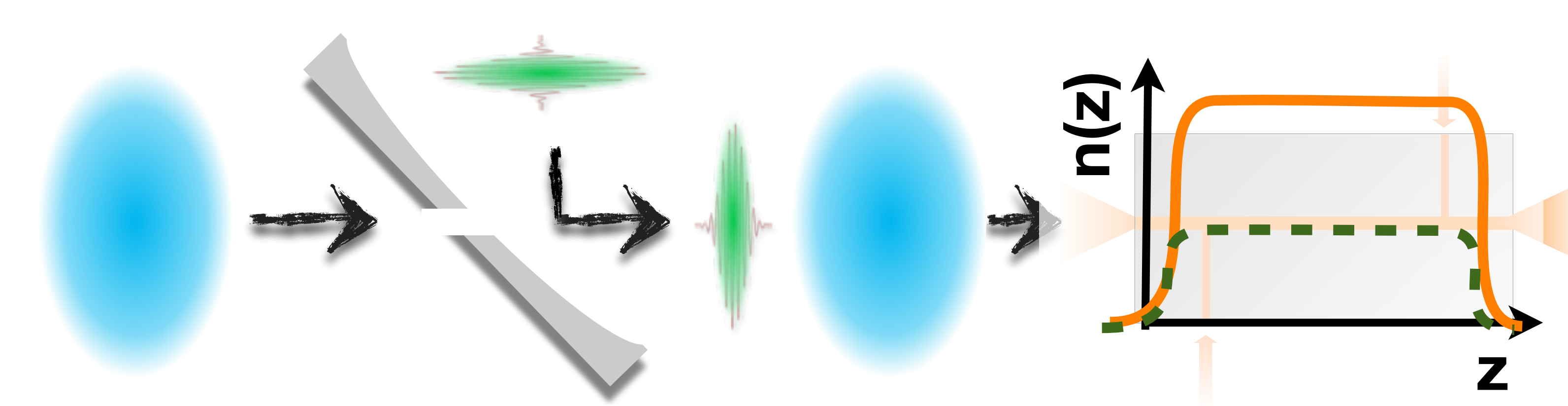

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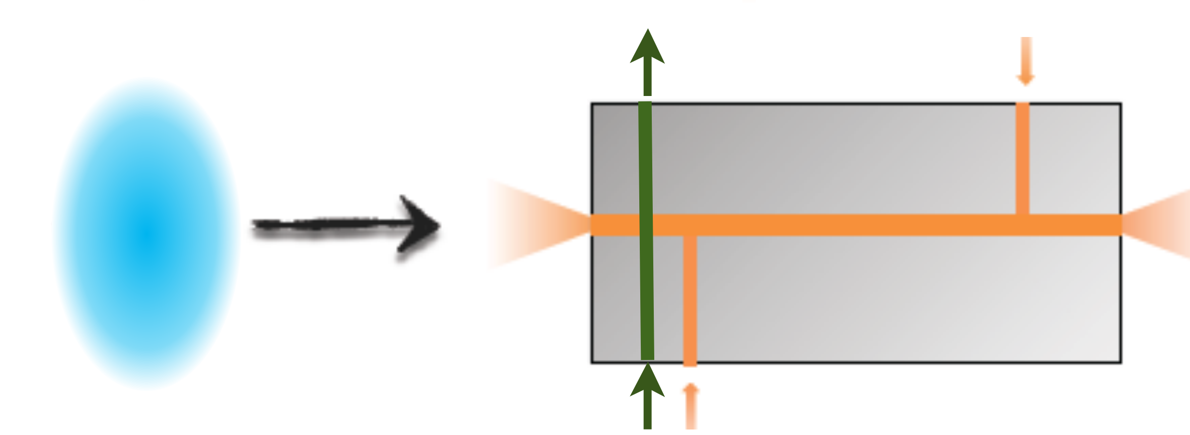

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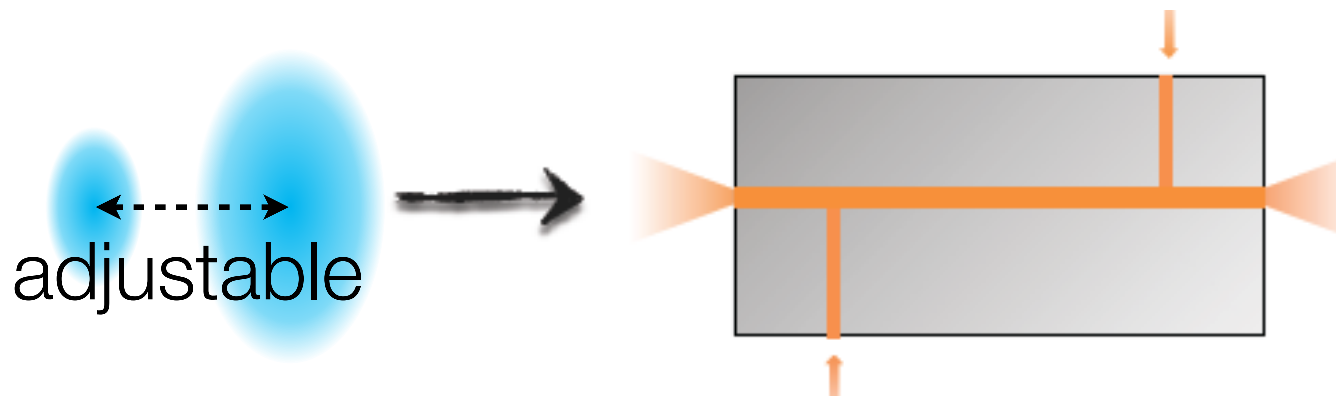

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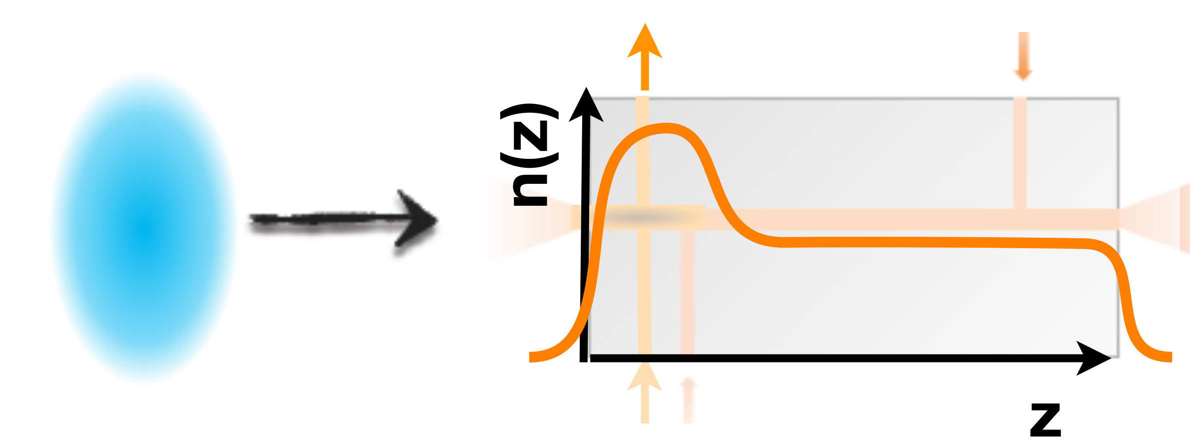

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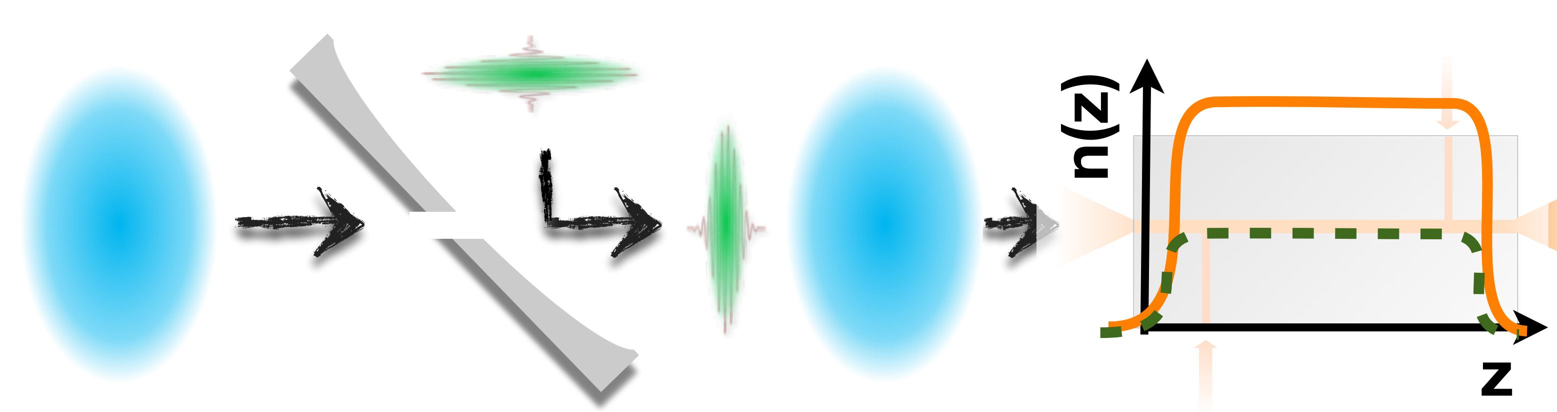

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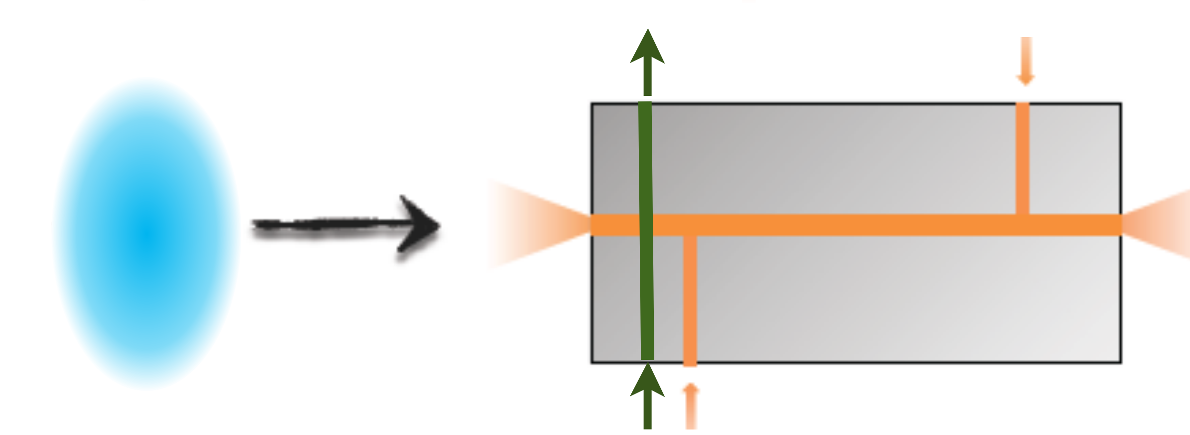

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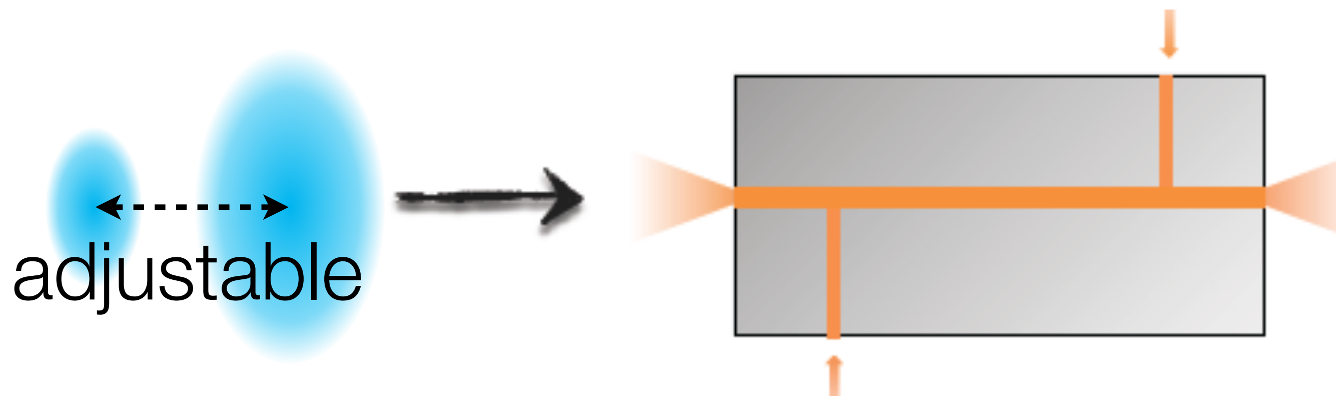

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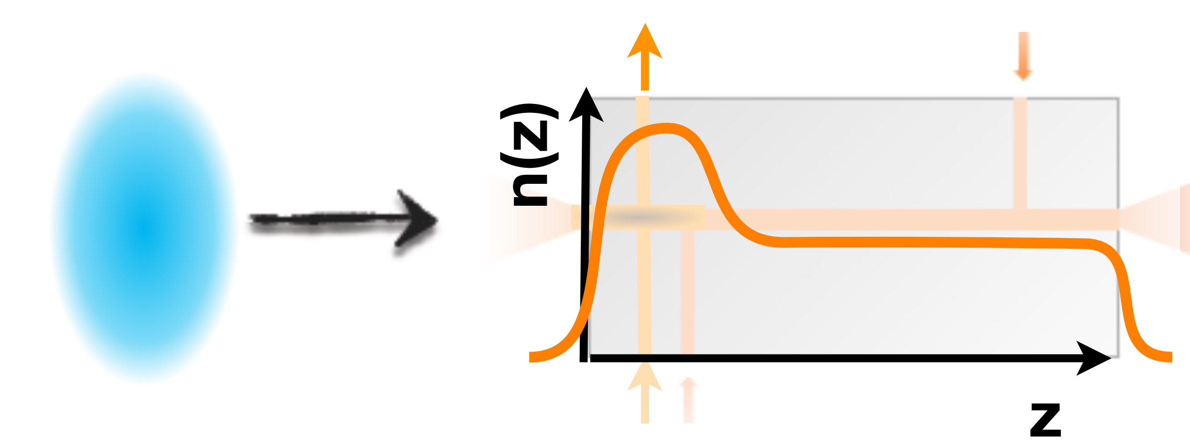

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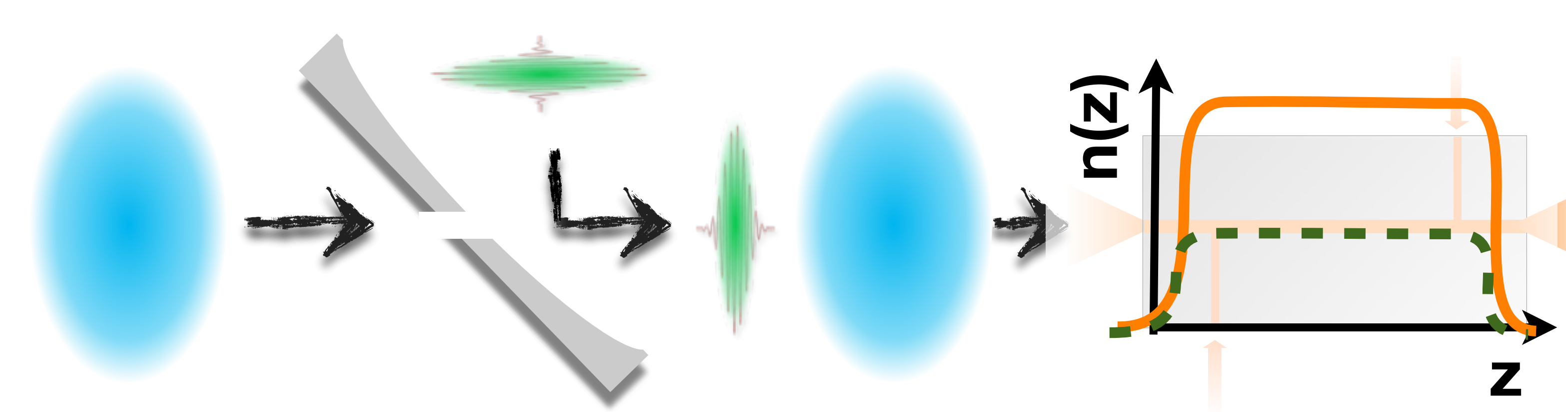

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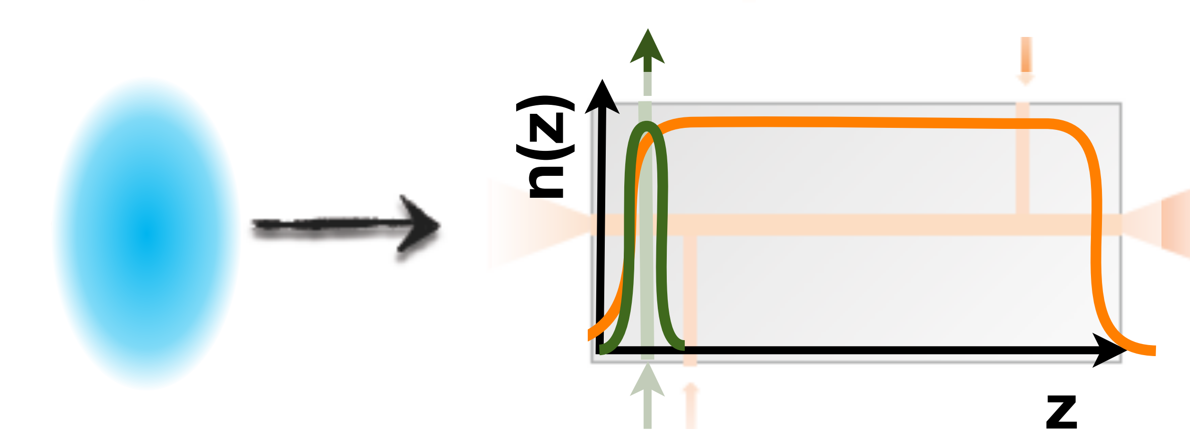

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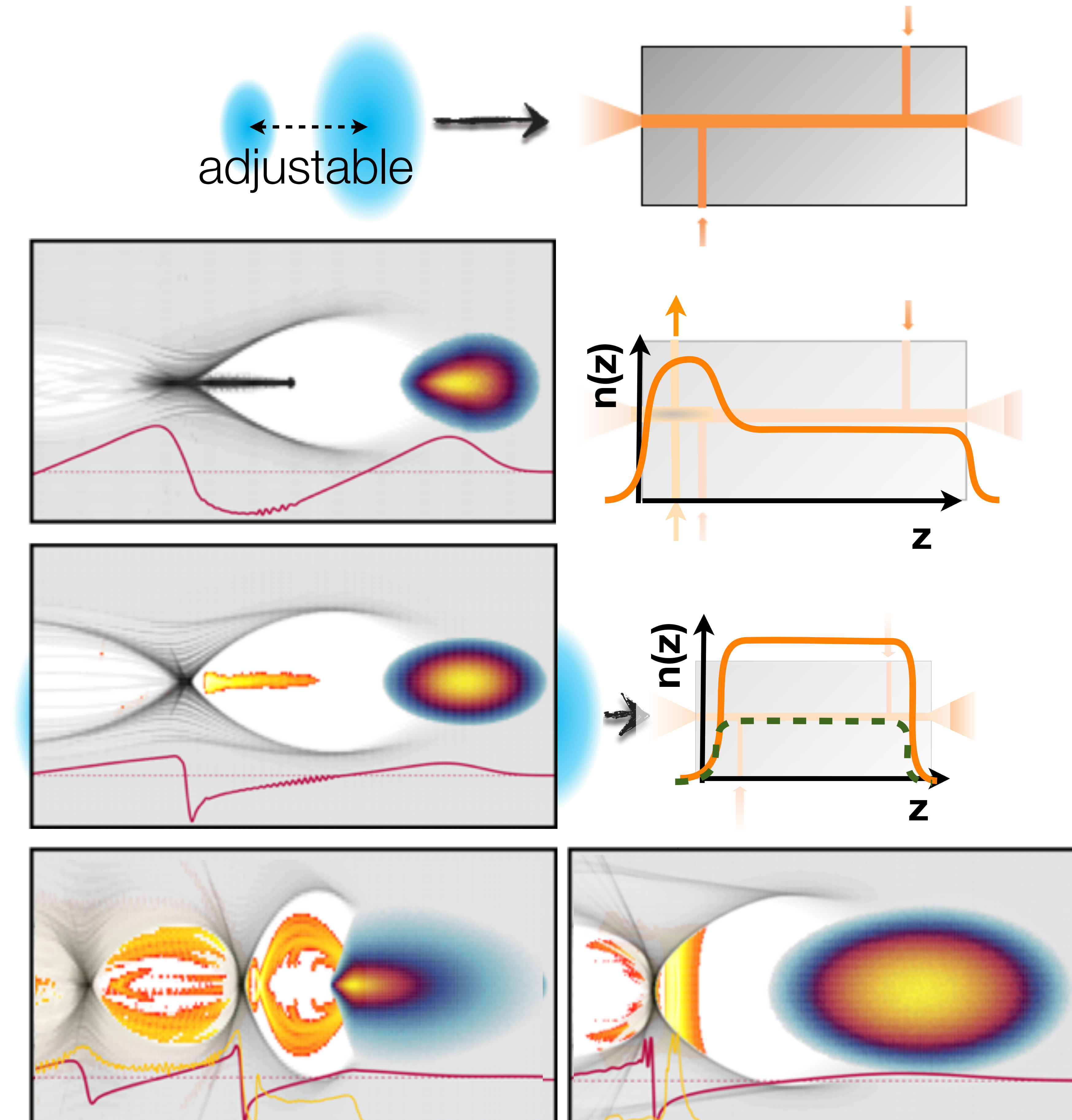
osiris v2.0
3D particle-in-cell (PIC) simulation



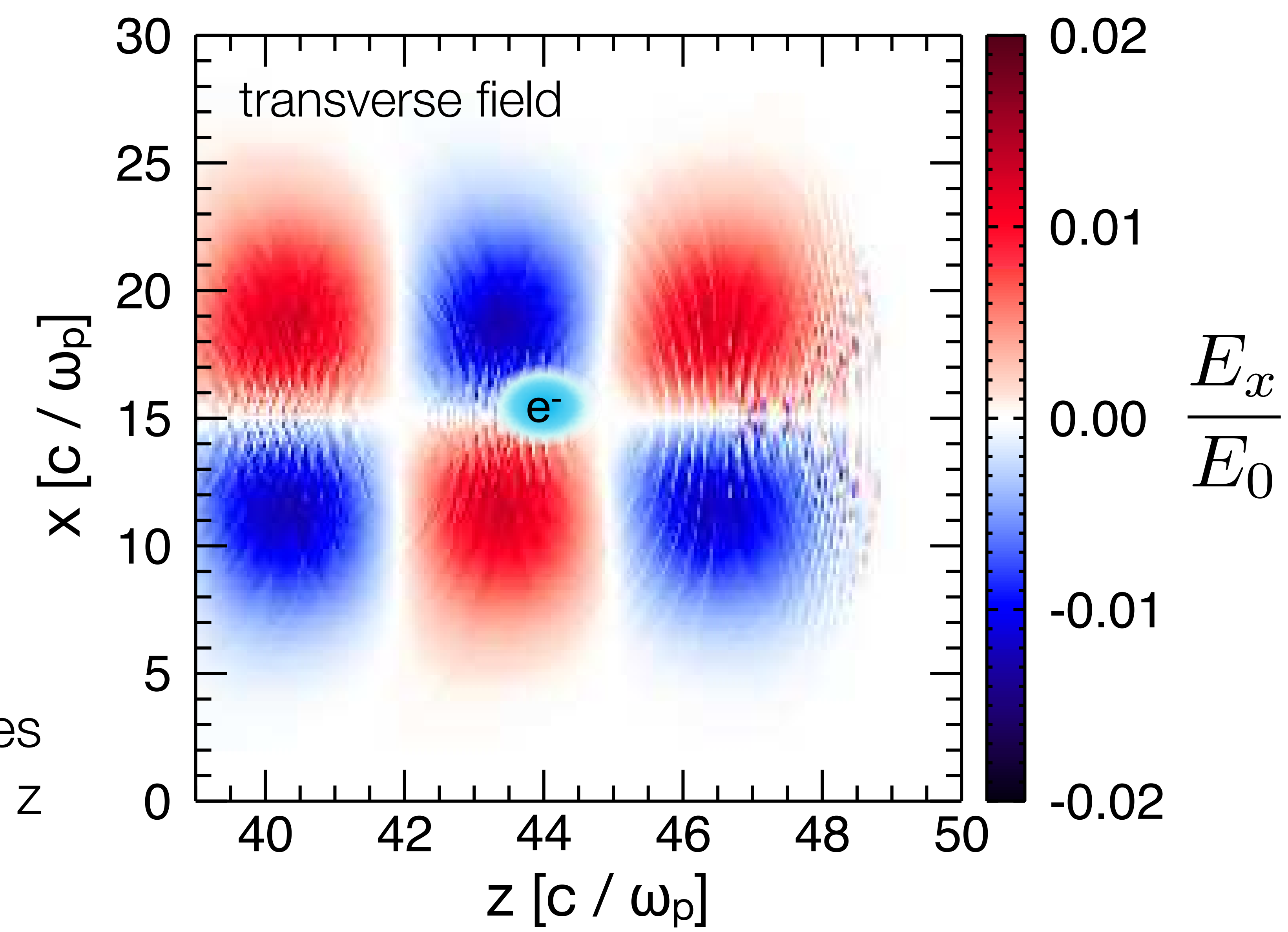
LAOLA.

External beam injection: Precursor to full staging
- A challenge to preserve beam emittance

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

with $x' = p_x / p_z$

Beam focusing forces
(in x) vary in plasmas in z

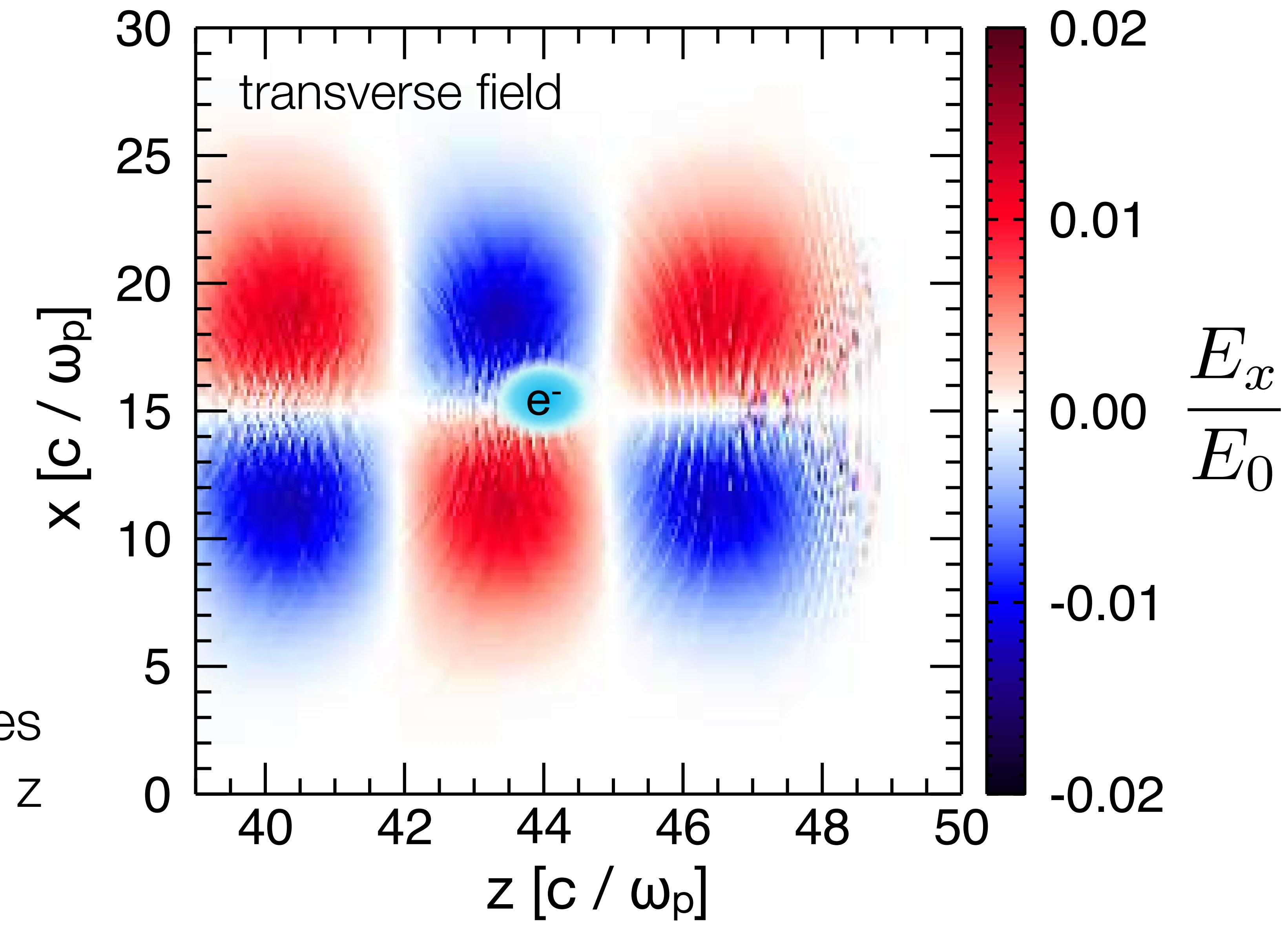


External beam injection: Precursor to full staging - A challenge to preserve beam emittance

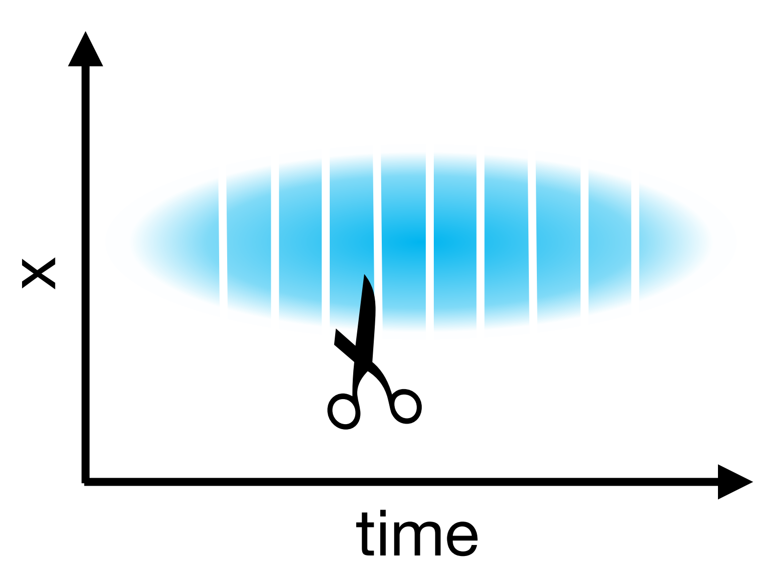
$$\epsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

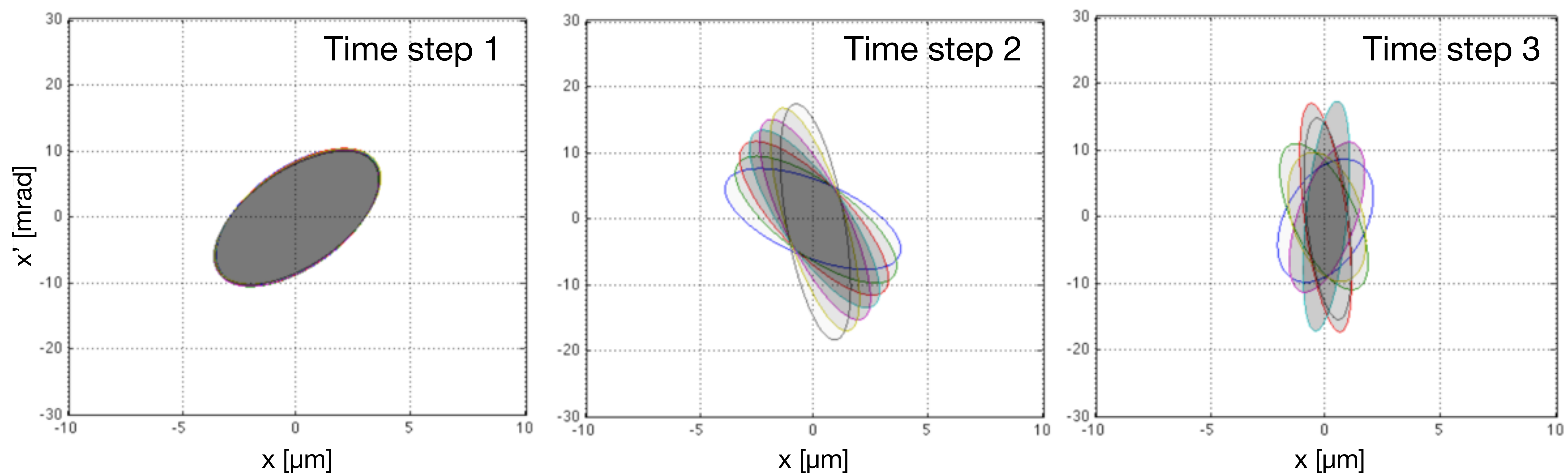
with $x' = p_x / p_z$

Beam focusing forces (in x) vary in plasmas in z



Slice rotation speeds vary along electron bunch





External beam injection: Precursor to full staging - A challenge to preserve beam emittance

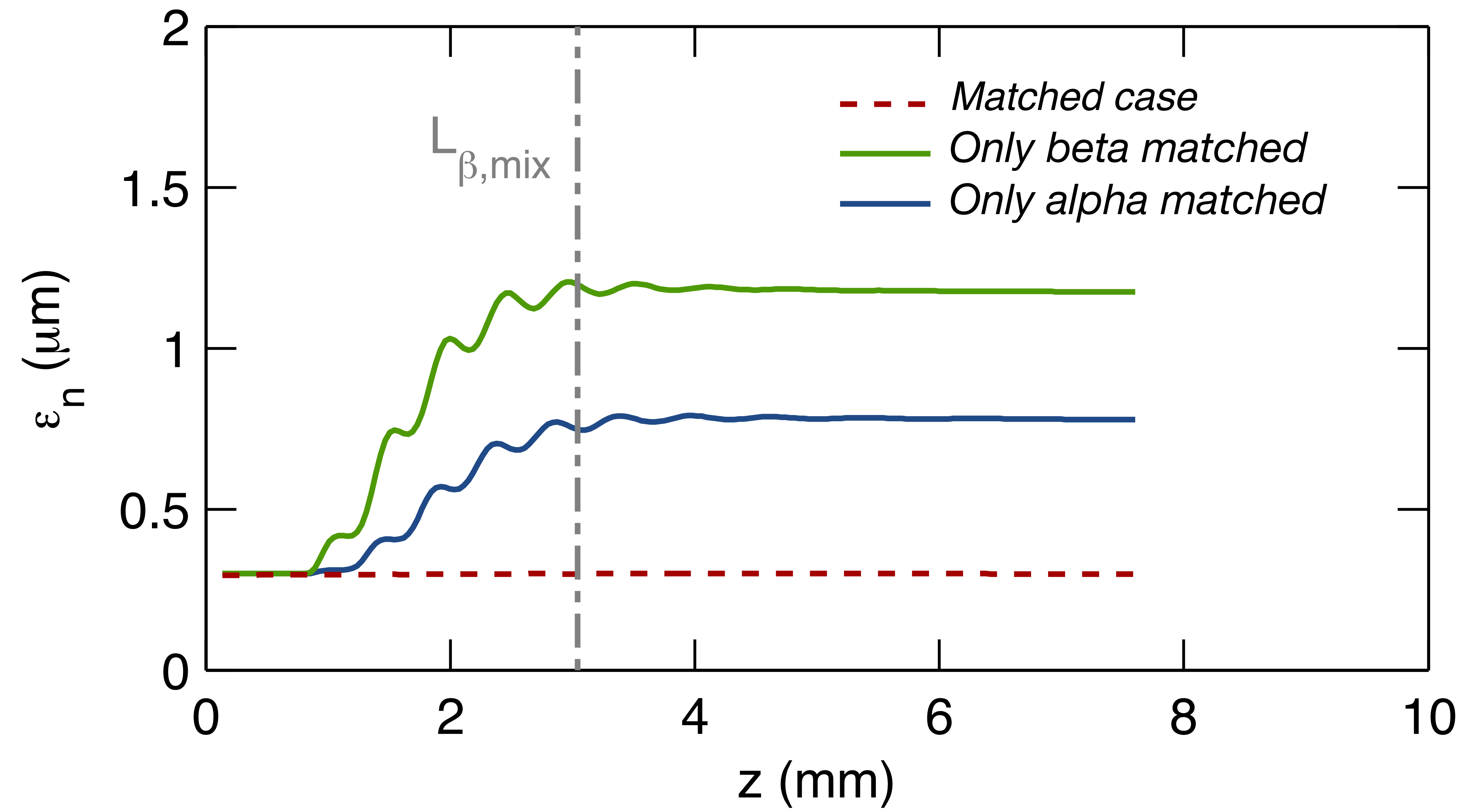
T. Mehrling *et al.*, Phys. Rev. STAB 15, 111303 (2012)

Total betatron phase mixing length

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

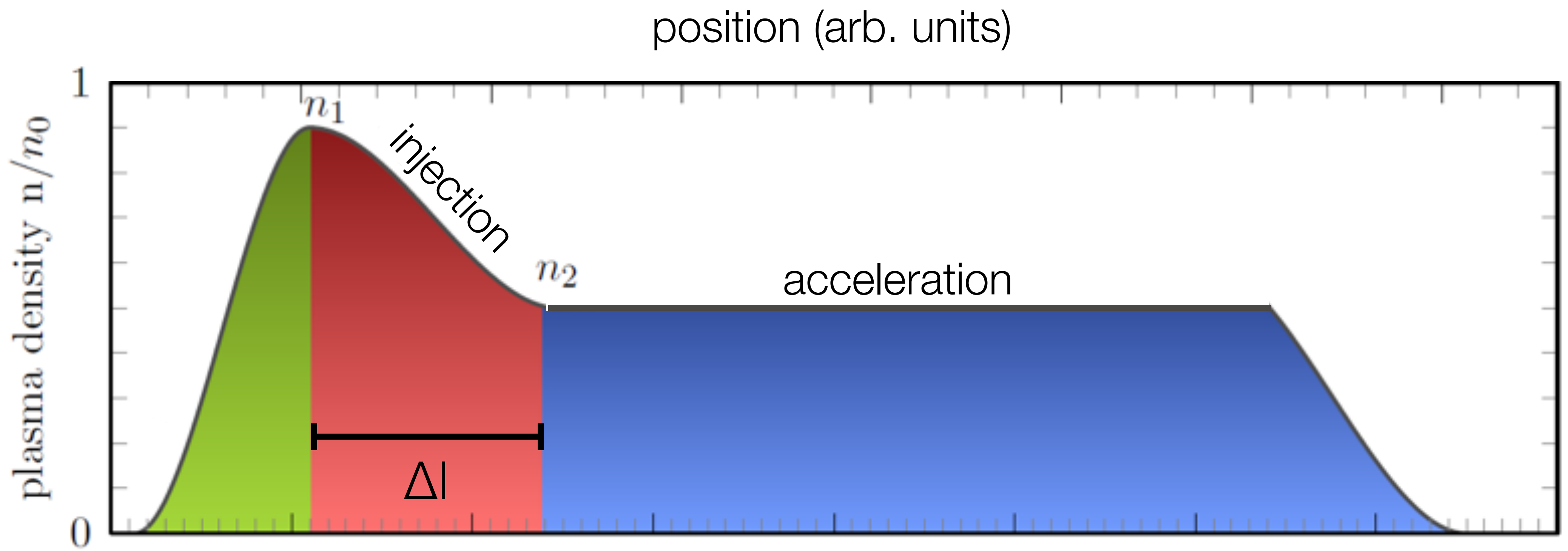
Matching conditions

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



- 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?

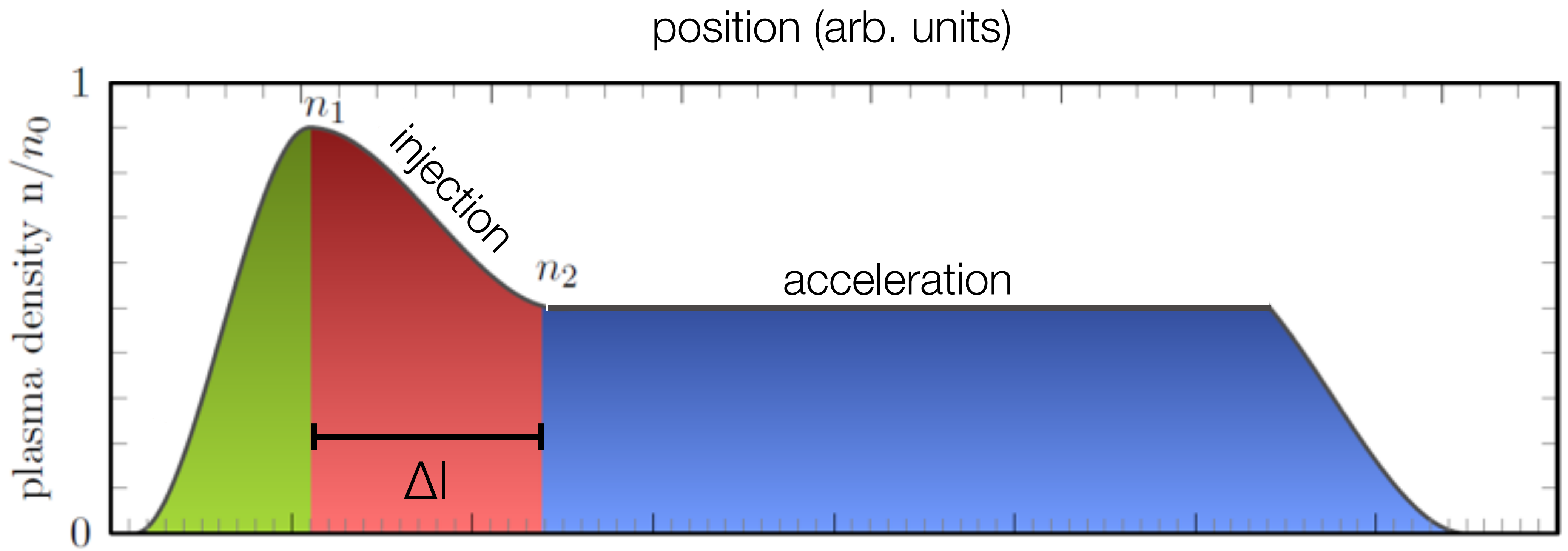
Density down-ramp injection for controlled electron beam generation in a PWFA



- demonstrated to work in LWFA, new concept for PWFA
- first experiments planned at FACET E-215
  → lessons learned will help to optimize experiment at FLASH
- simple: no injection laser necessary, just tailored plasma target
- injection occurs on density down-slope

S. Bulanov *et al.*, Phys. Rev. E **58**, R5257 (1998)

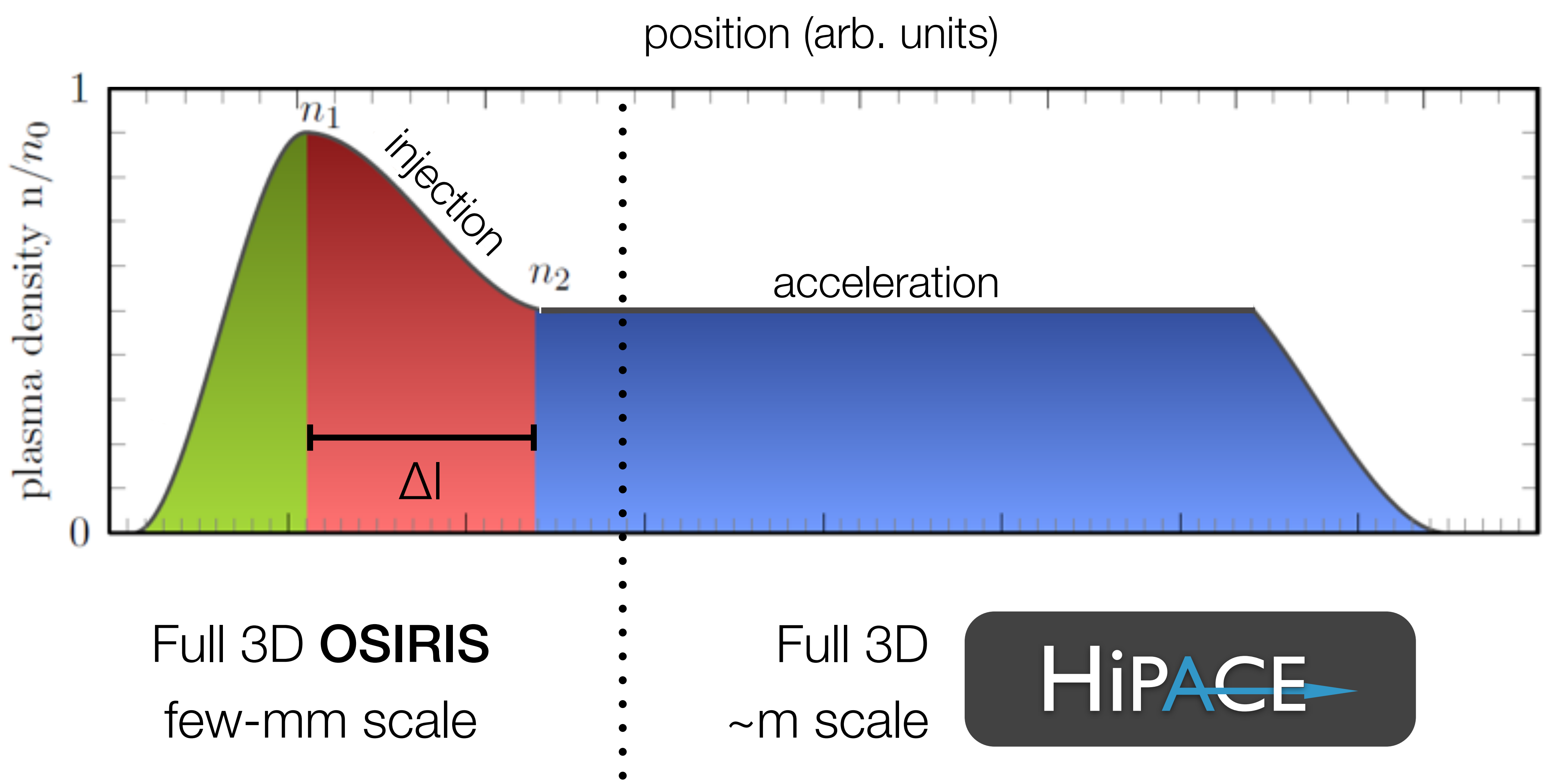
Challenges for 20 cm-scale down-ramp injection simulations



Computational challenge

- 20 cm-scale acceleration with ~100 nm spatial resolution
- capture physics of trapping → full PIC required
- cost: ~M core hours with full PIC

Challenges for 20 cm-scale down-ramp injection simulations



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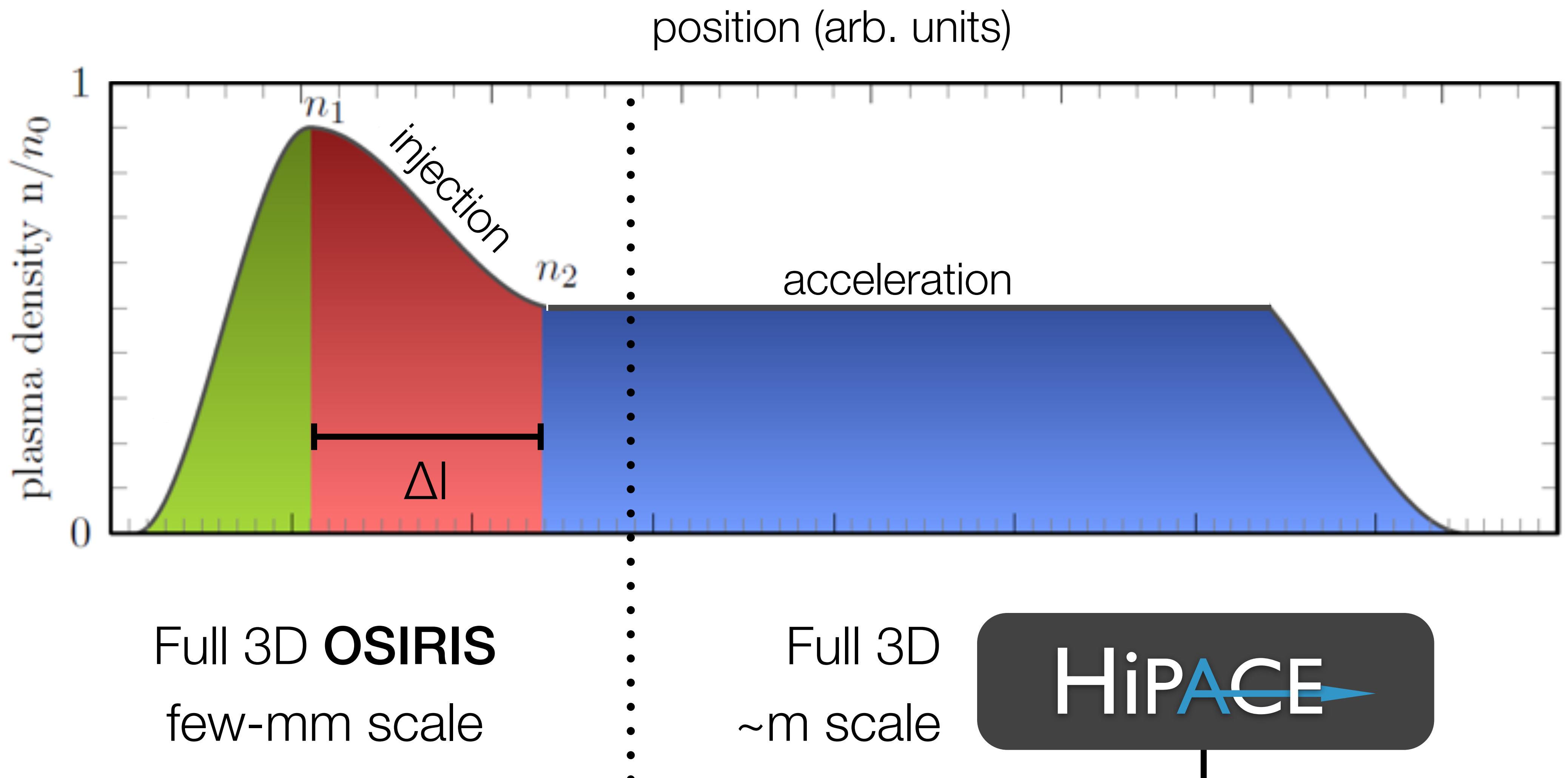


Computational challenge

- 20 cm-scale acceleration with ~100 nm spatial resolution
- capture physics of trapping → full PIC required
- cost: ~M core hours with full PIC

> T. Mehrling *et al.*, PPCF 56, 084012 (2014)

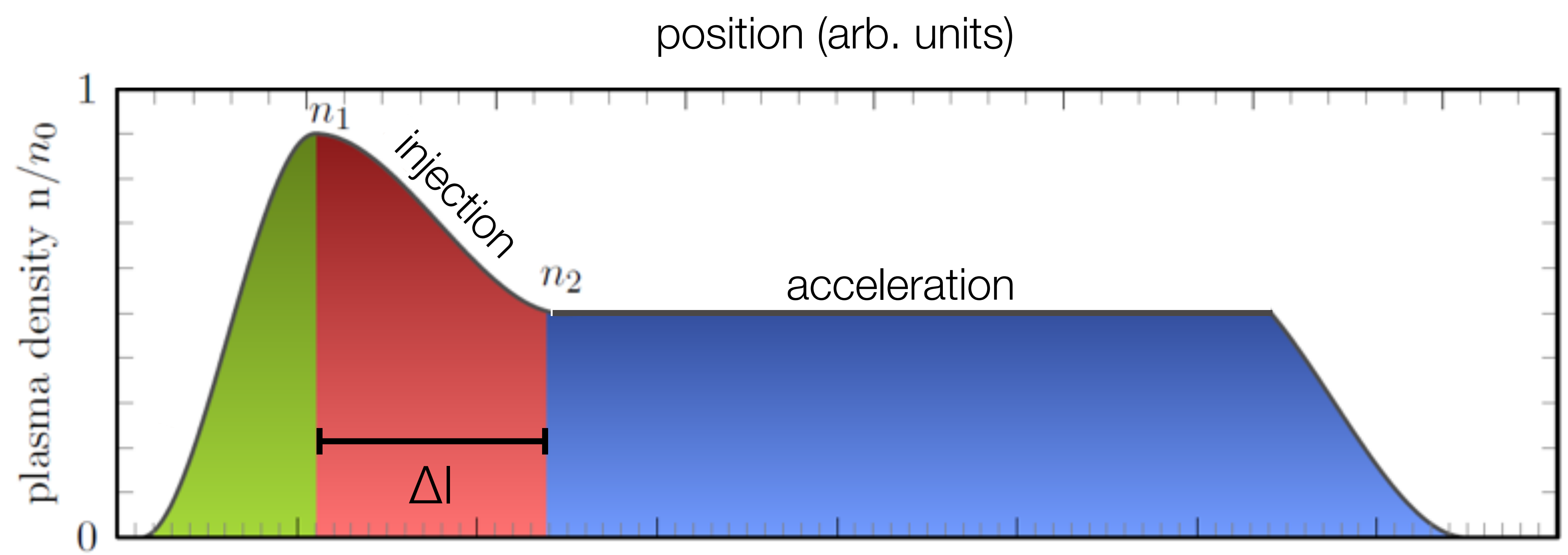
HiPACE - *a highly efficient plasma accelerator emulation*

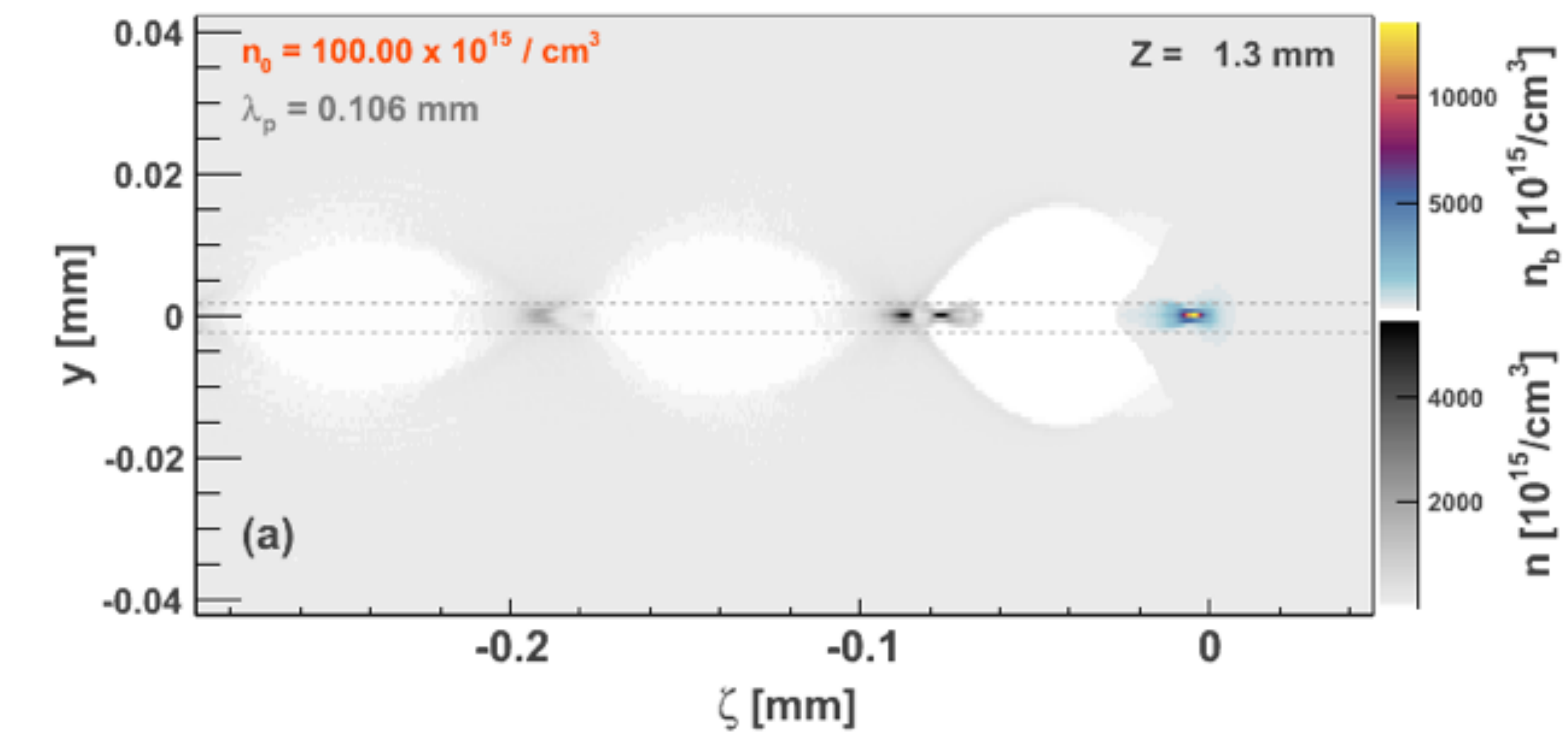
- 3D quasi-static particle-in-cell code
- fully parallelized and well scalable (tested up to 1024 cores)
- dynamic time-step adjustment
- allows **orders-of-magnitude speedup** for FLASHForward-type simulations vs. full PIC
- interfaces seamlessly with OSIRIS

developed in collaboration between DESY and LBNL

Density down-ramp injection produces low-transverse-emittance witness beams

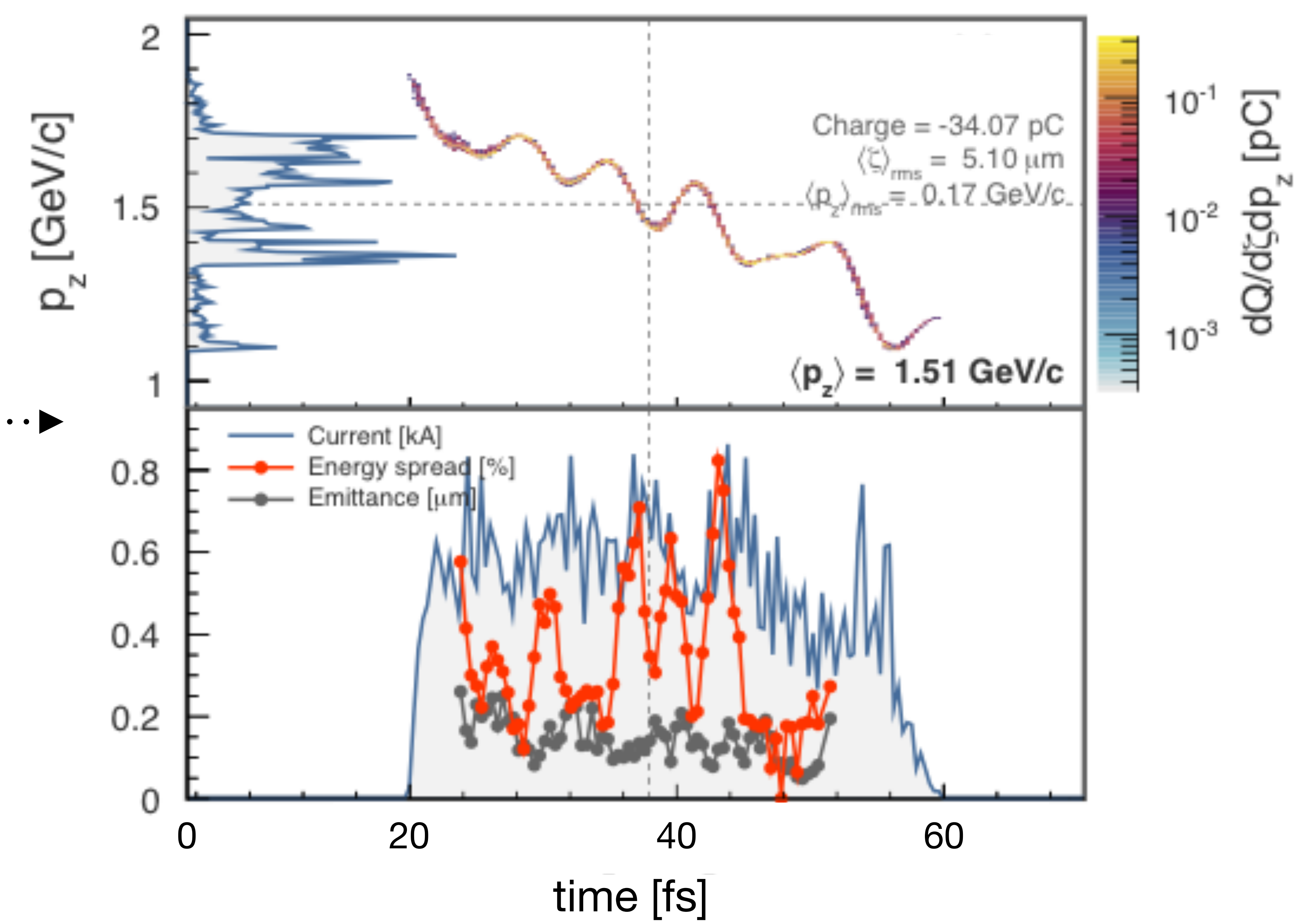
→ J. Grebenyuk et al., NIM A 740, 246 (2014)





Witness-beam parameters after 140 mm of propagation

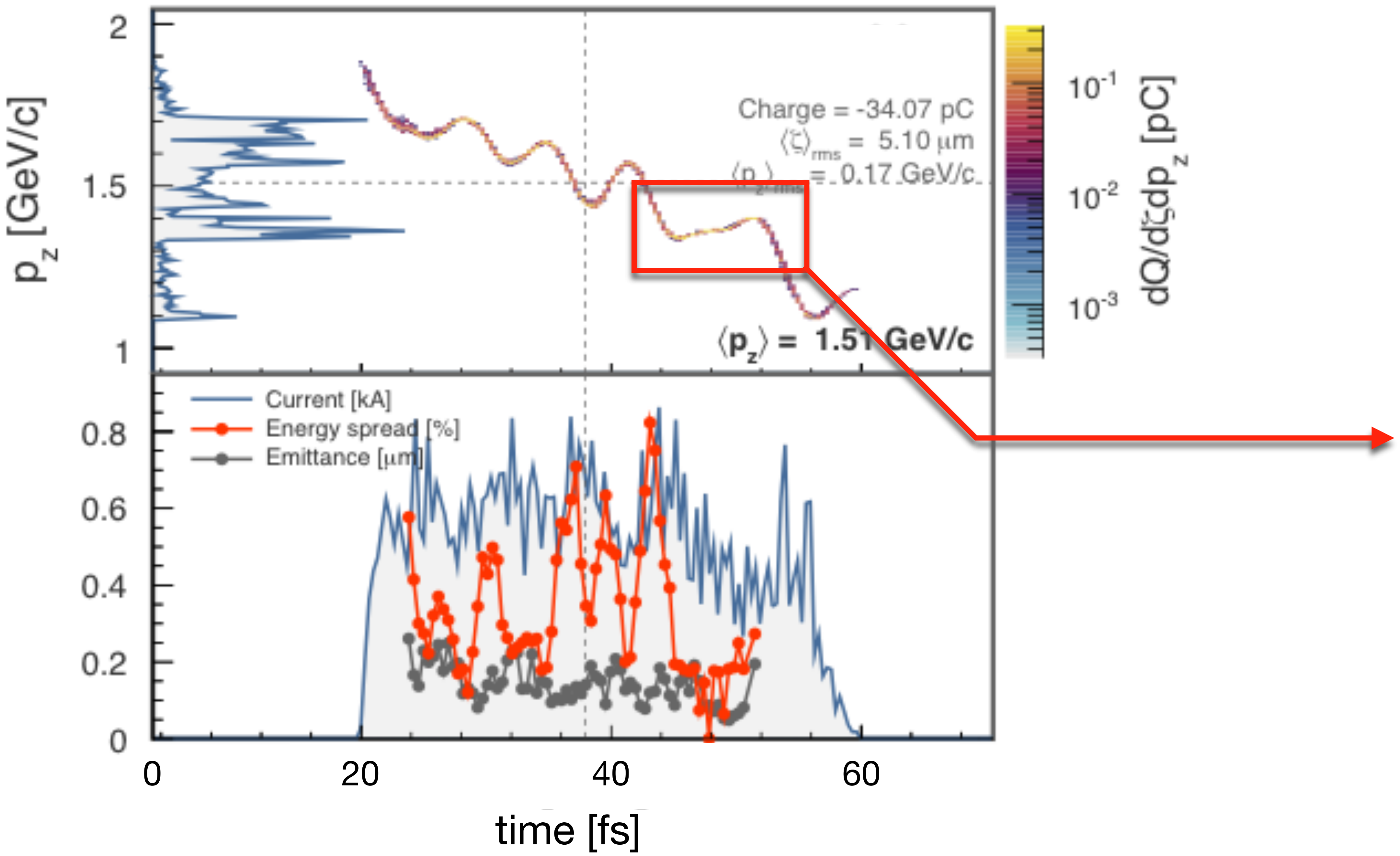
- standard FLASH driver beam at 2.5 kA
- witness beam at 1.5 GeV with 1.0 GeV driver
- further acceleration to ~2.5 GeV possible
- projected normalized transverse emittance < 0.5 μm
- strong longitudinal correlation



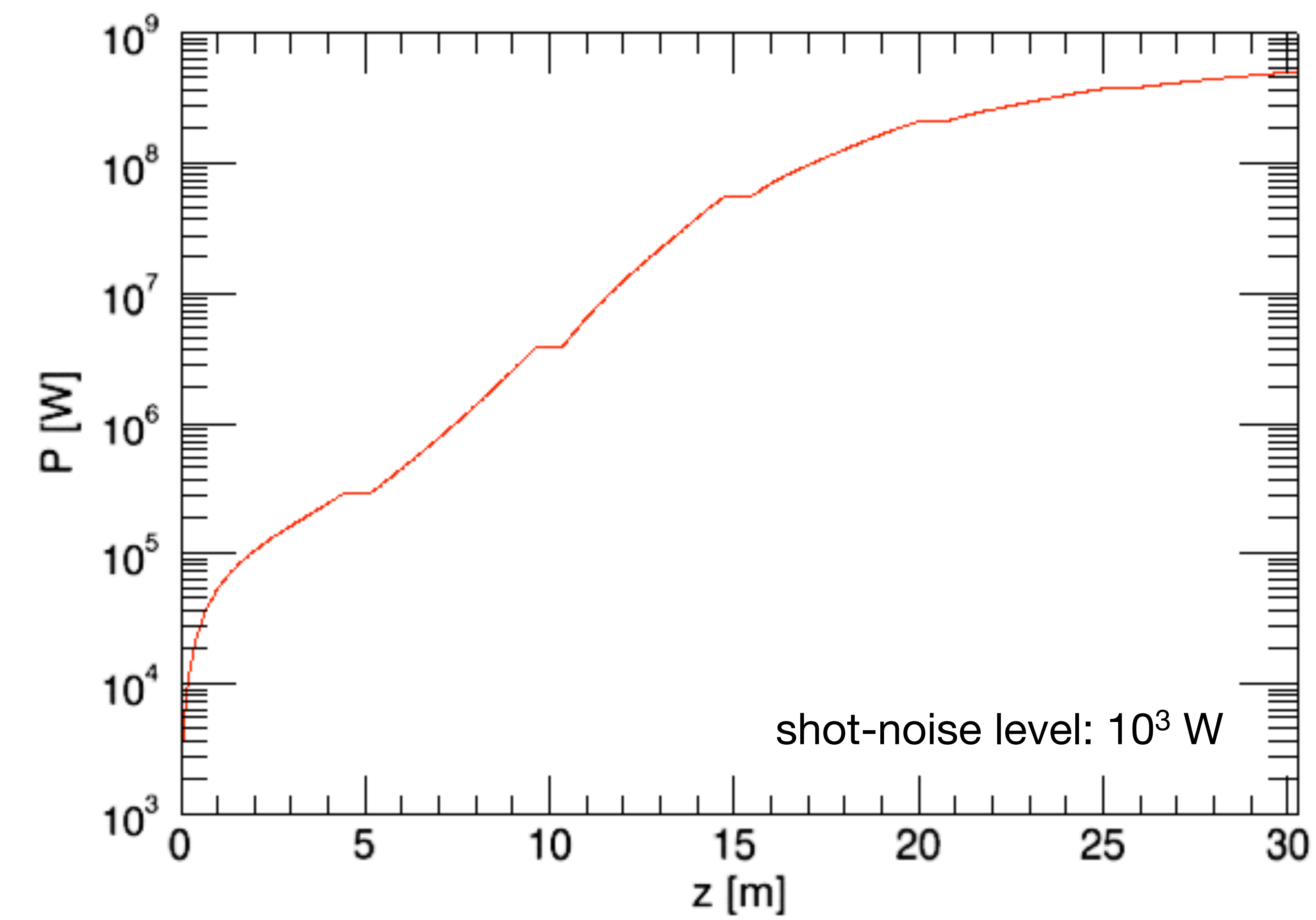
Can such beams drive an FEL?

Beams from density down-ramp injection show significant FEL gain in GENESIS simulations

→ simulations by C. Behrens



3D OSIRIS particle-in-cell simulation

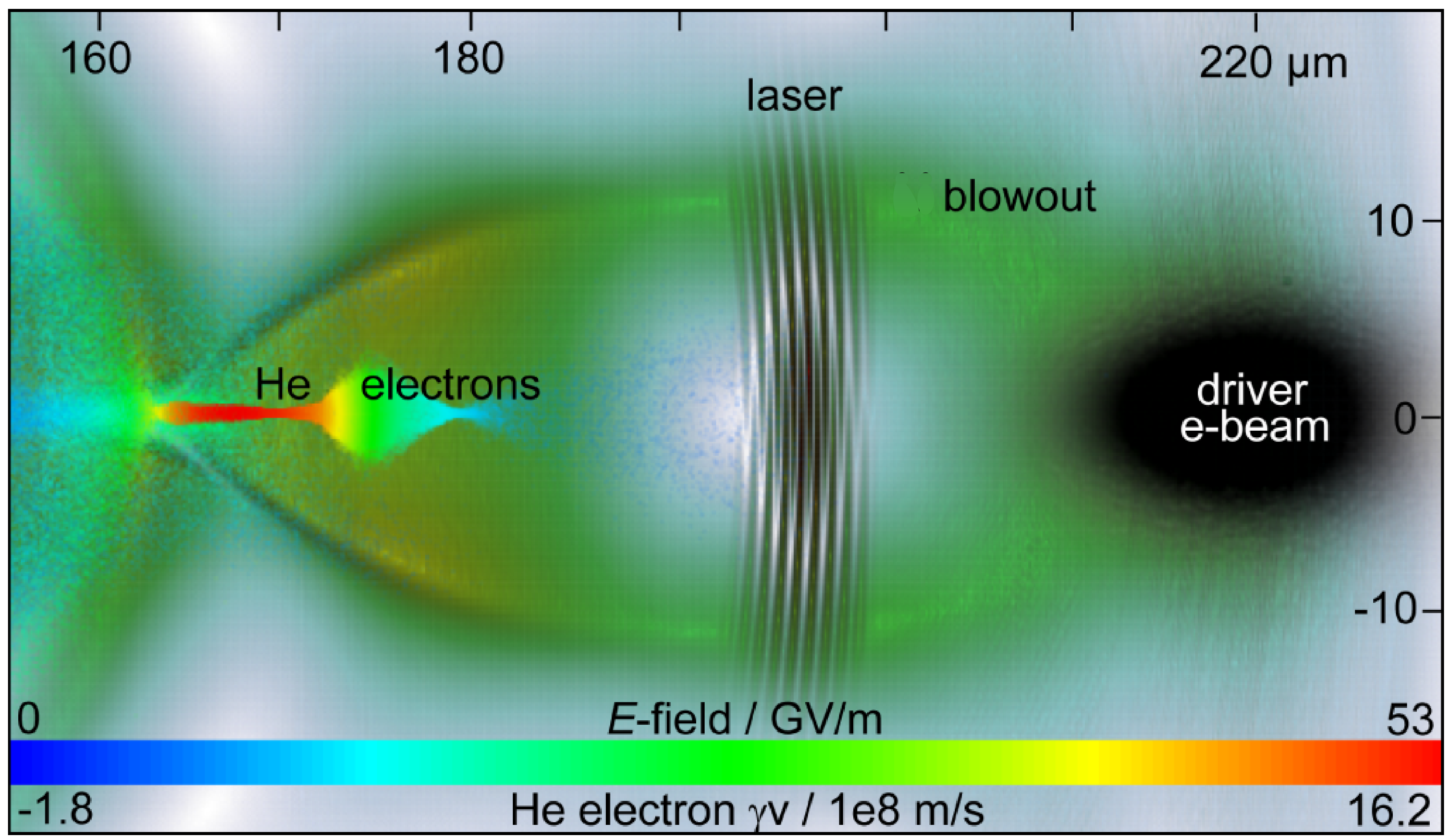


3D time-dependent GENESIS simulation

- part of beam matched through FLASH-type undulators
- gain length 1.7 m
- FEL signal at 3 nm ± 1 nm

Laser-triggered ionization injection for controlling electron trapping

> Simulations: A. Martinez de la Ossa (DESY), B. Hidding (UHH/U Strathclyde)

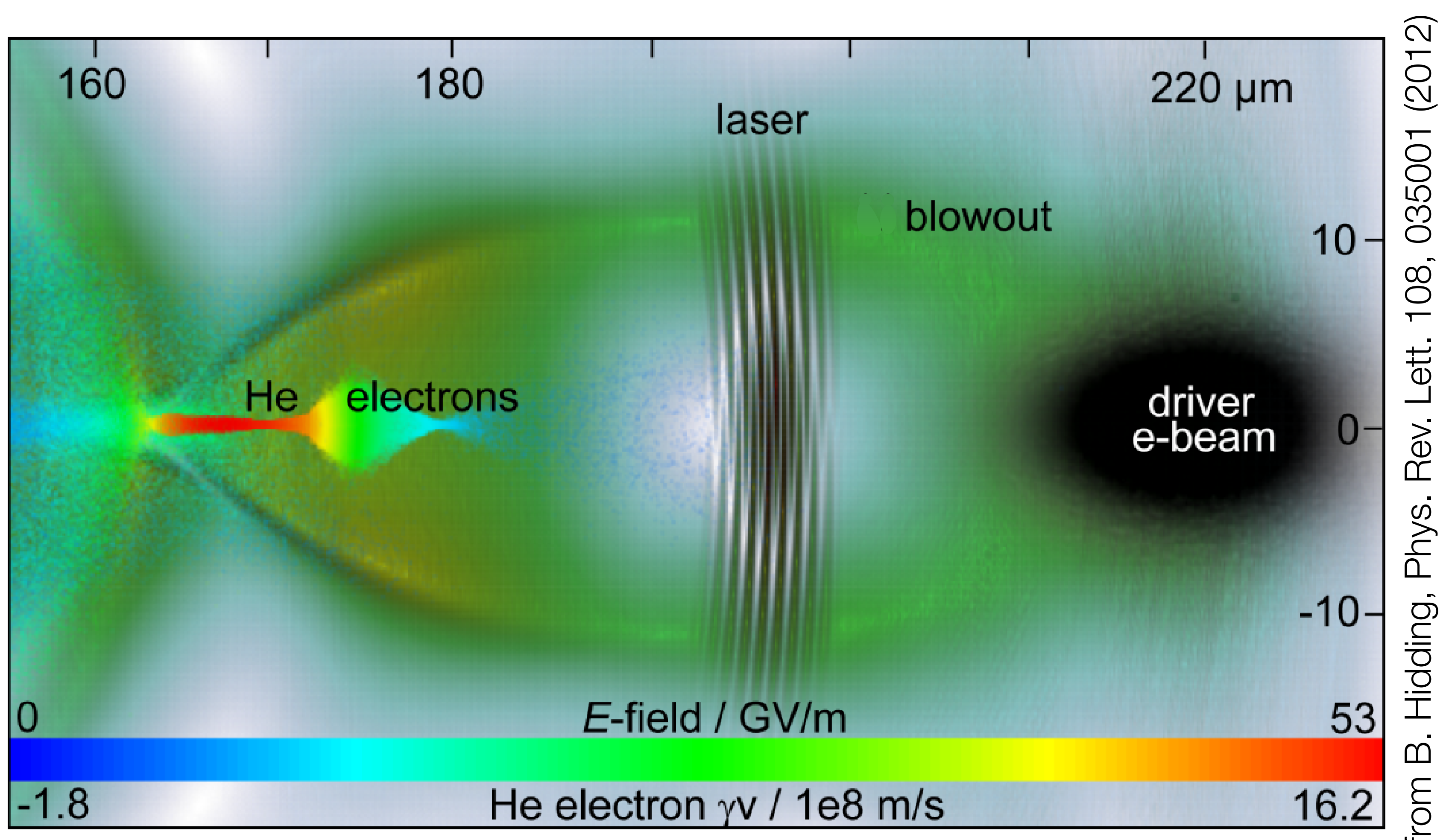


from B. Hidding, Phys. Rev. Lett. 108, 035001 (2012)

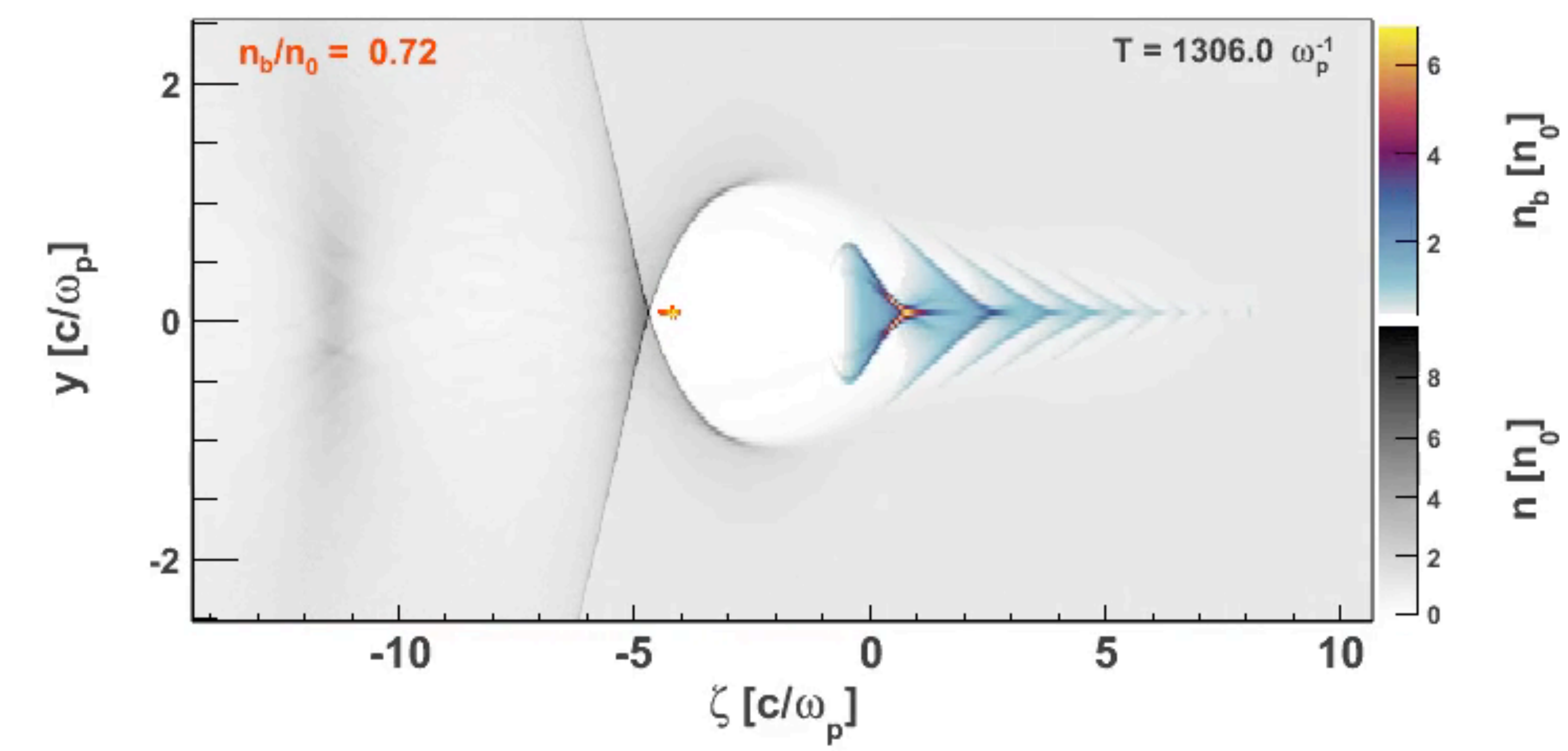
- laser triggers ionization and injection of electrons from He
- first experiments planned at FACET E-210
- laser-to-beam synchronization crucial

Laser-triggered ionization injection for controlling electron trapping

> Simulations: A. Martinez de la Ossa (DESY), B. Hidding (UHH/U Strathclyde)



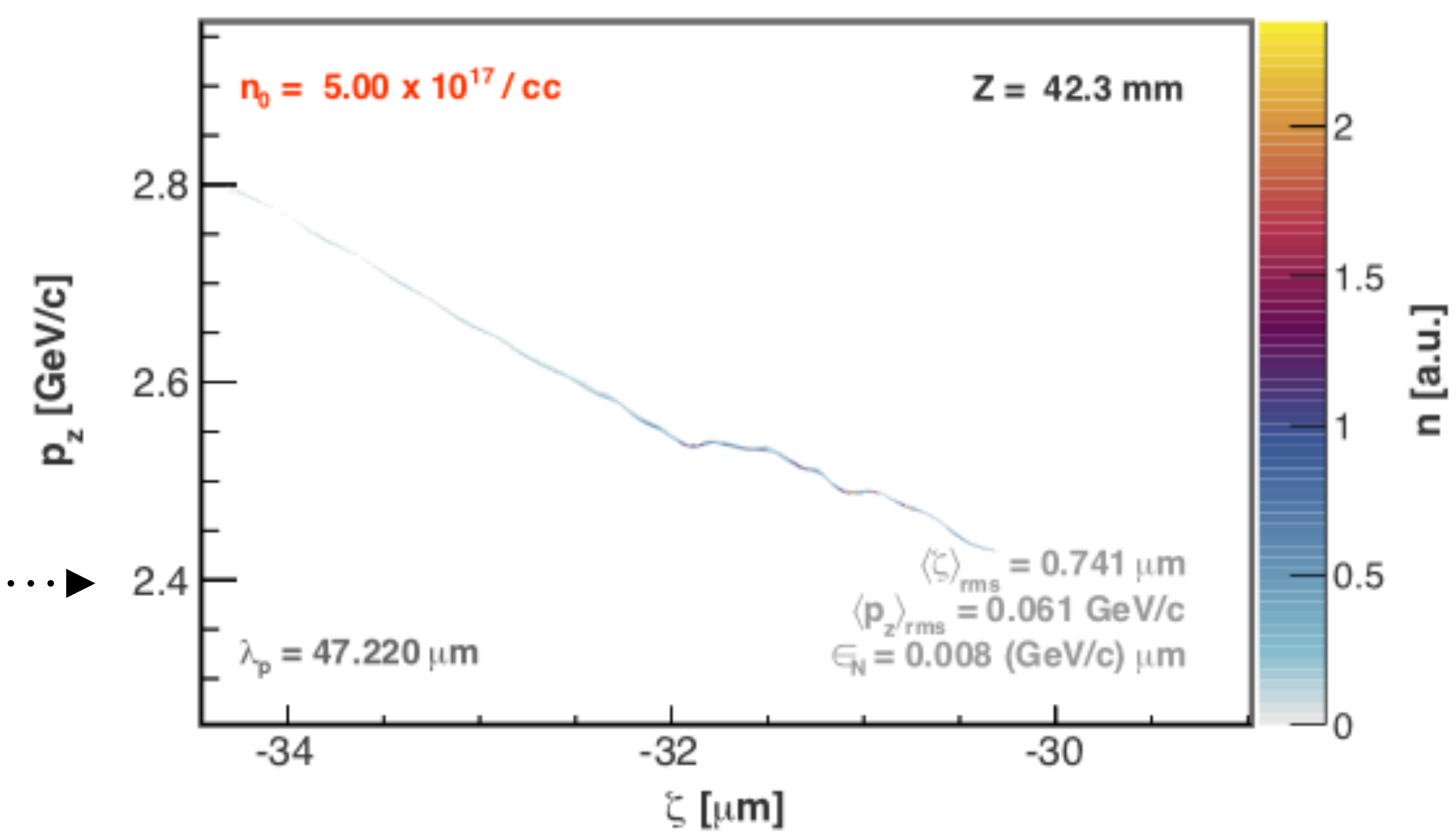
With **FLASH**Forward parameters



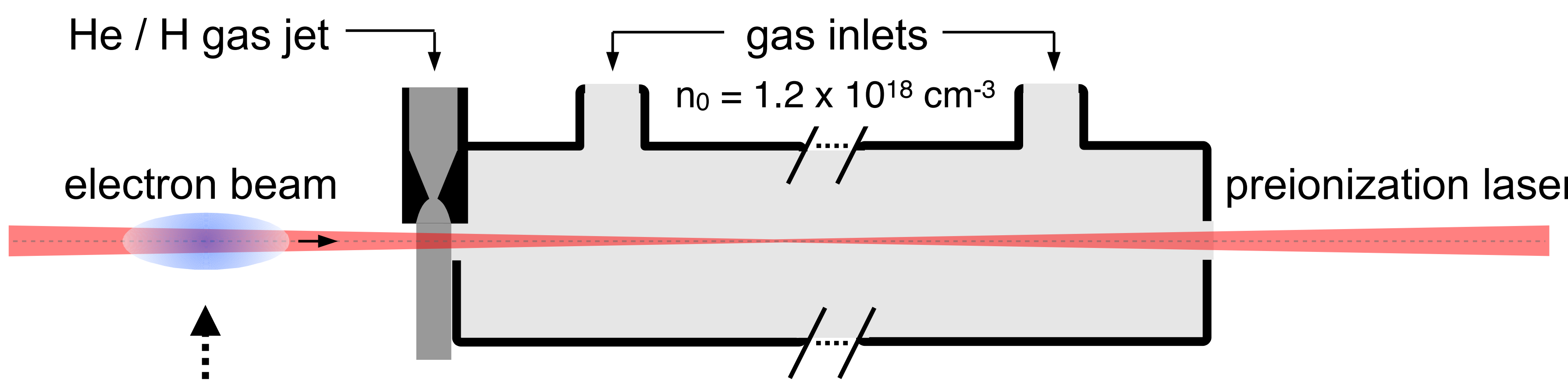
- laser triggers ionization and injection of electrons from He
- first experiments planned at FACET E-210
- laser-to-beam synchronization crucial

Witness-beam parameters after 42 mm of propagation

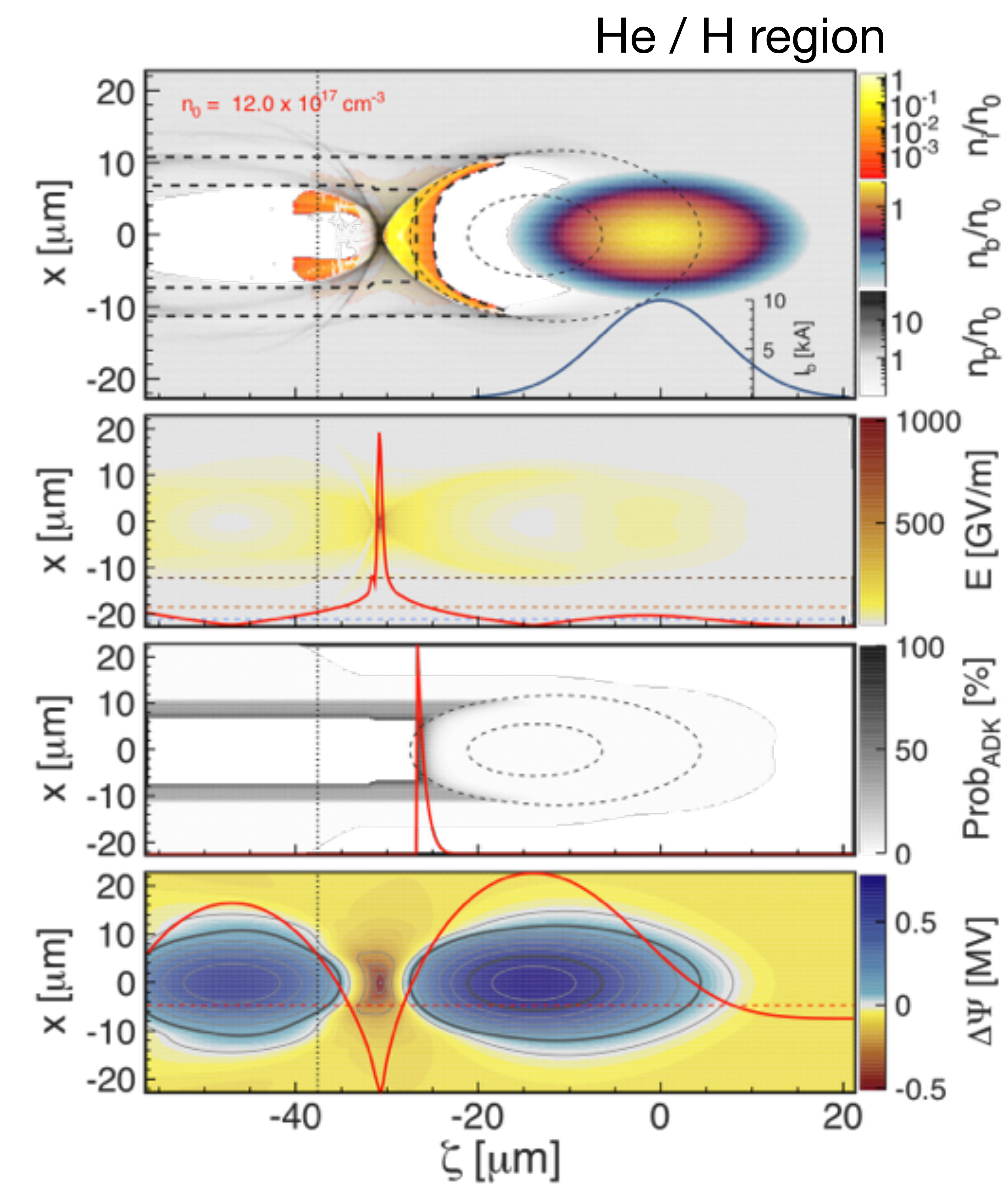
- beam at 2.5 GeV with 1.0 GeV driver, few-fs duration
- small uncorrelated energy spread (~‰ level), emittance (~100 nm), ~kA current
- strong longitudinal correlation

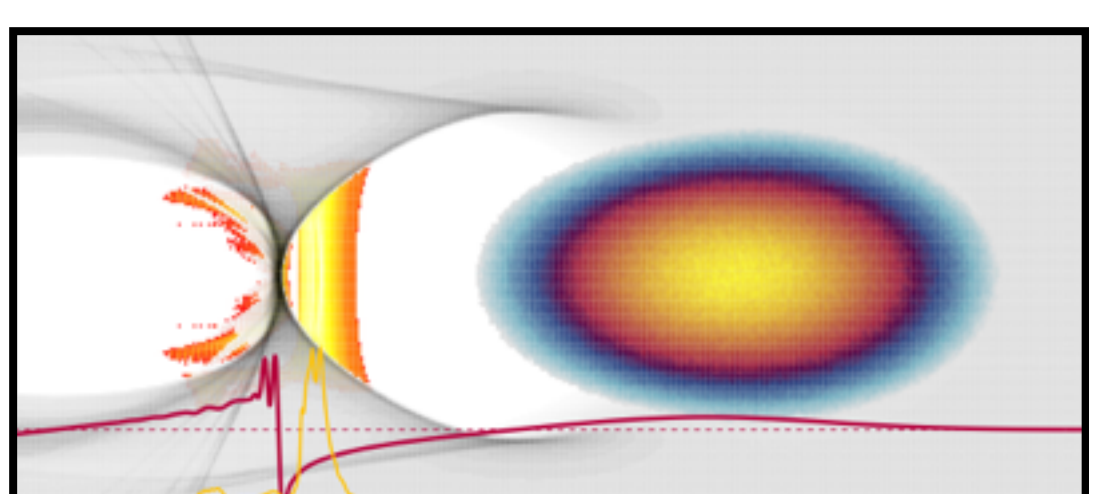


Wakefield-induced ionization injection utilizes strong fields of the generated wakefield to ionize dopant gas



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





> Wakefield-induced ionization injection

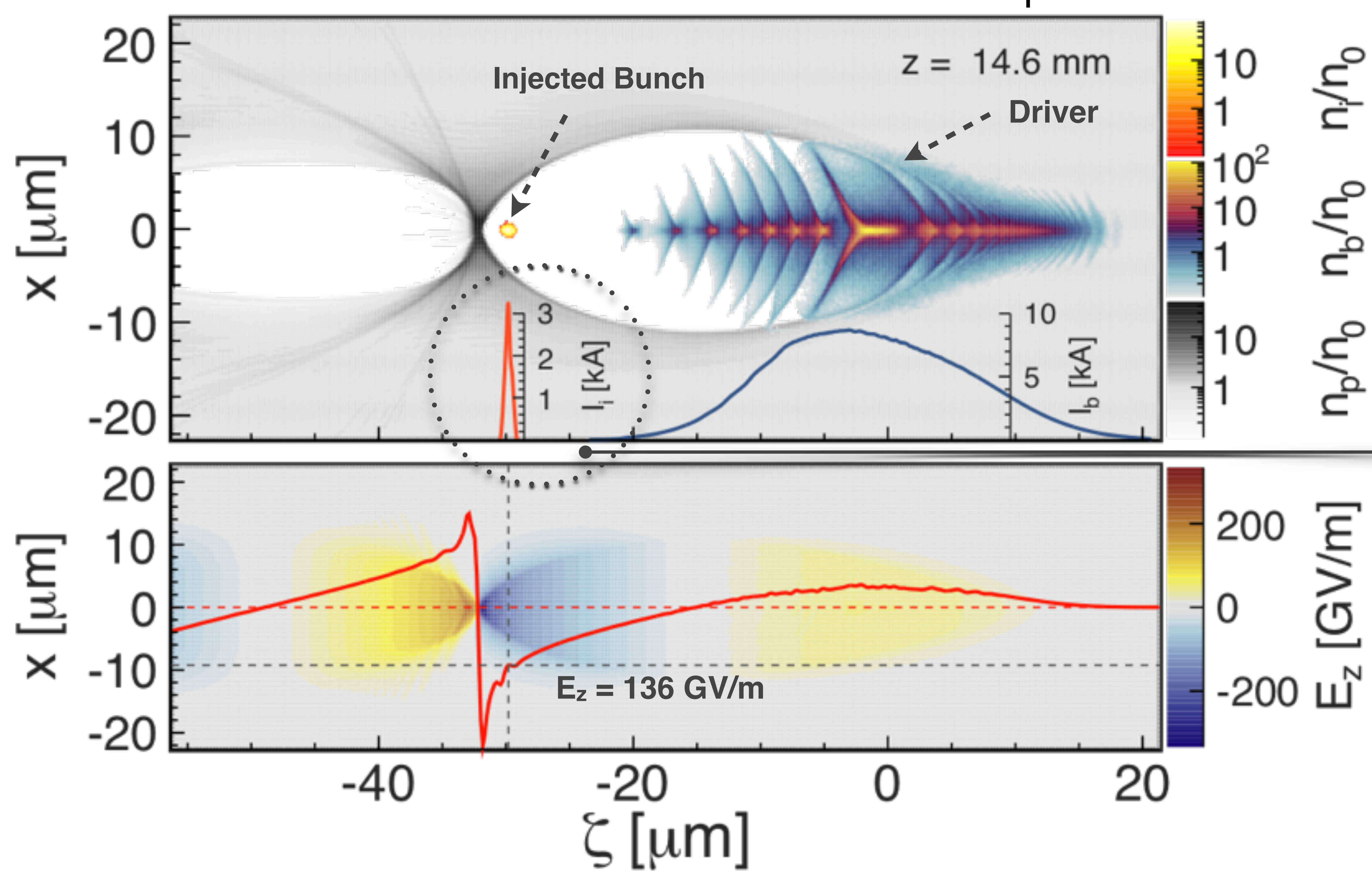
A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)

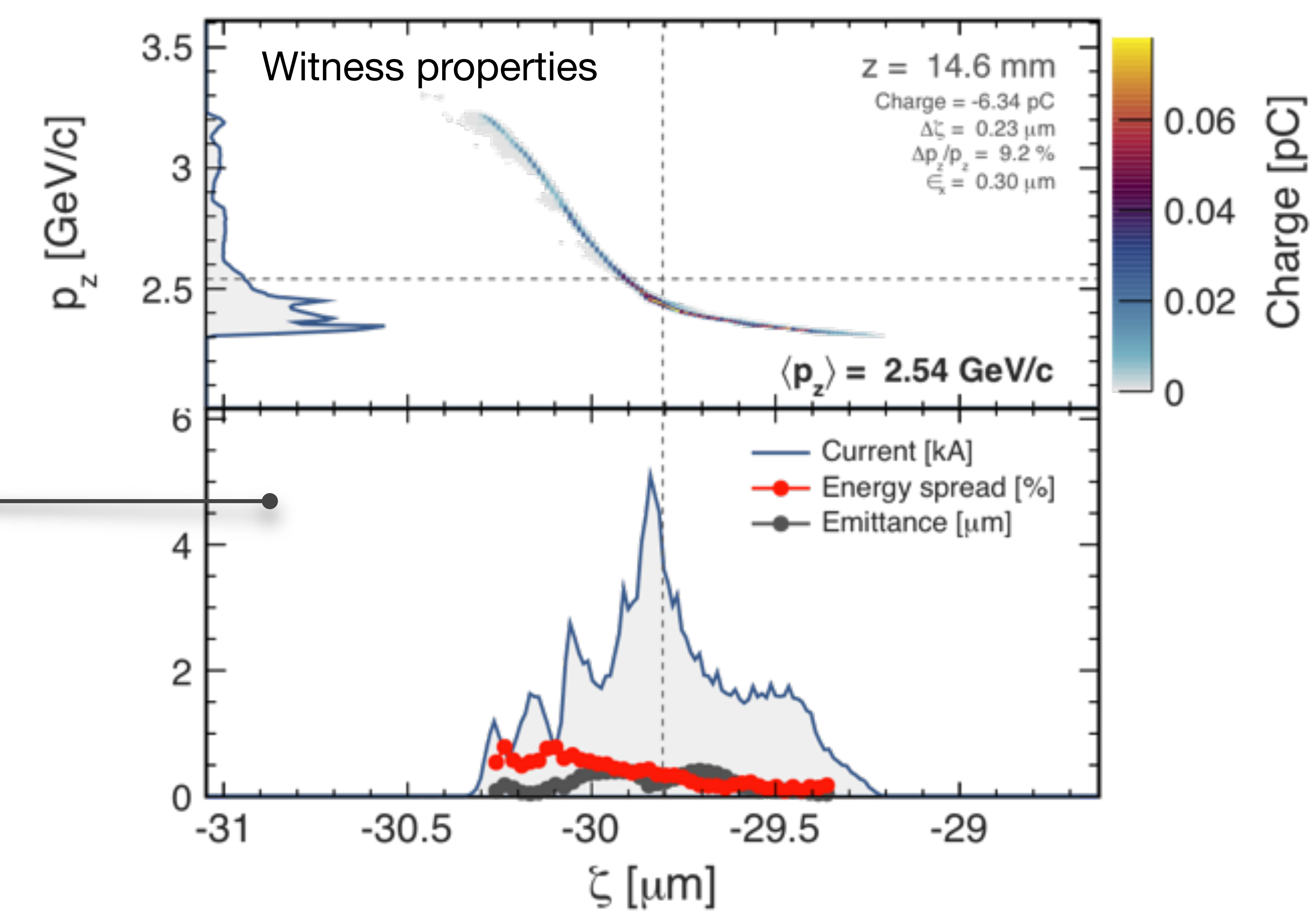
$I_B \gtrsim 10$ kA

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

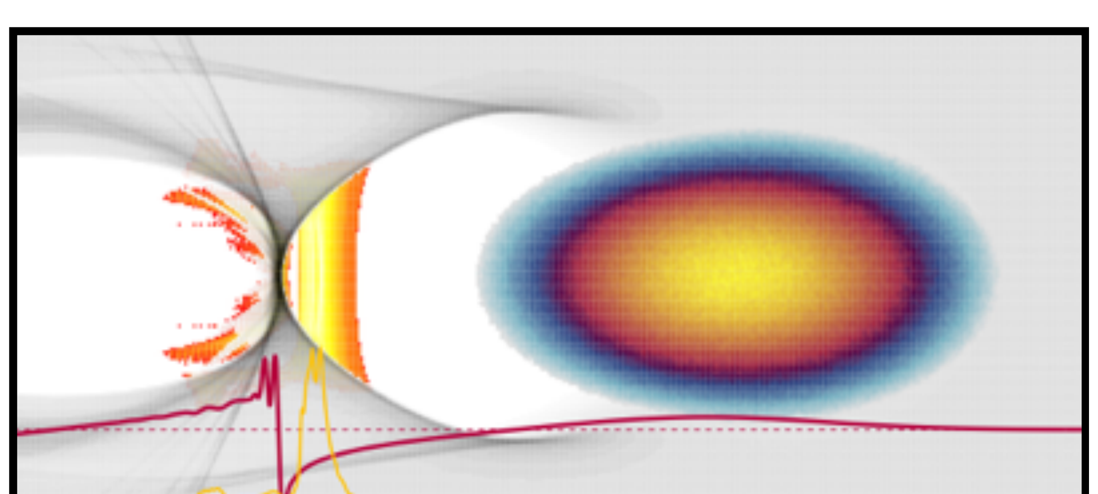
A. Martinez de la Ossa *et al.,* to be published

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%



- **Wakefield-induced ionization injection**

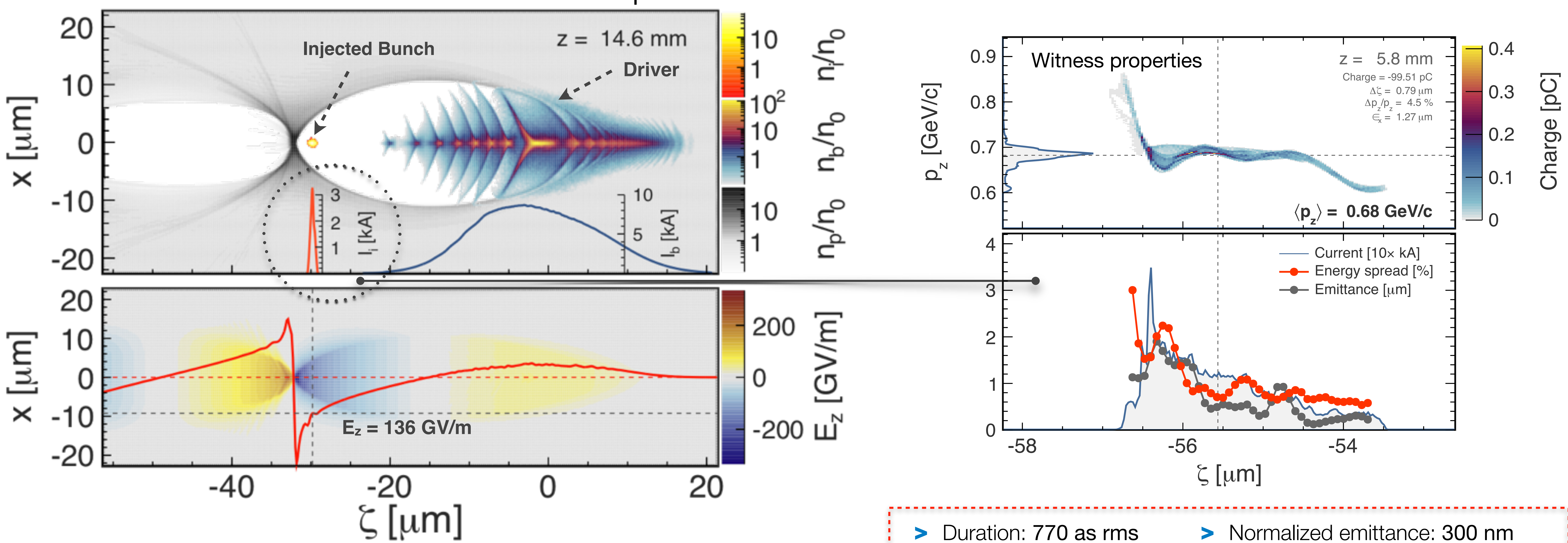
  A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)

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

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

Driver and witness bunch after 14.6 mm in plasma

A. Martinez de la Ossa *et al.,* to be published



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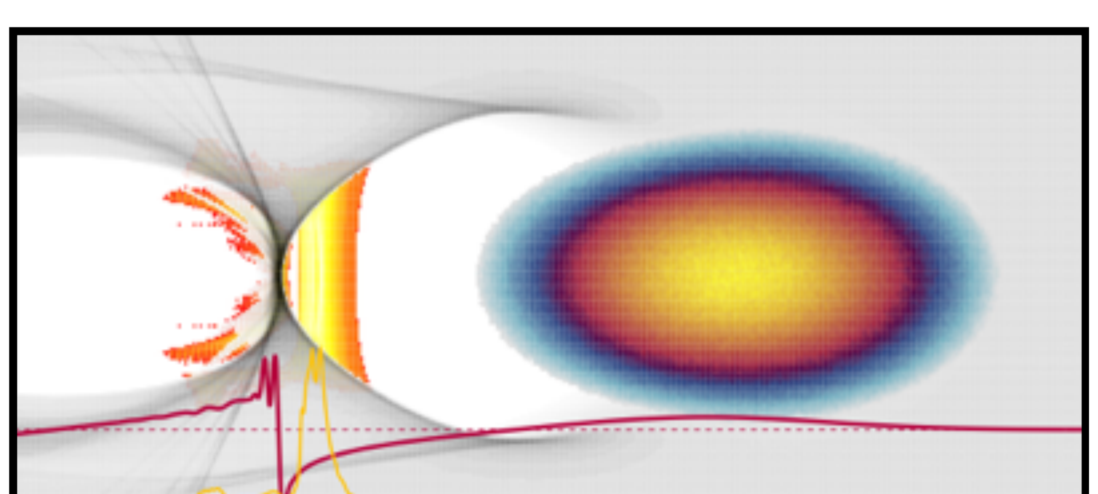


> Wakefield-induced ionization injection
A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)

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

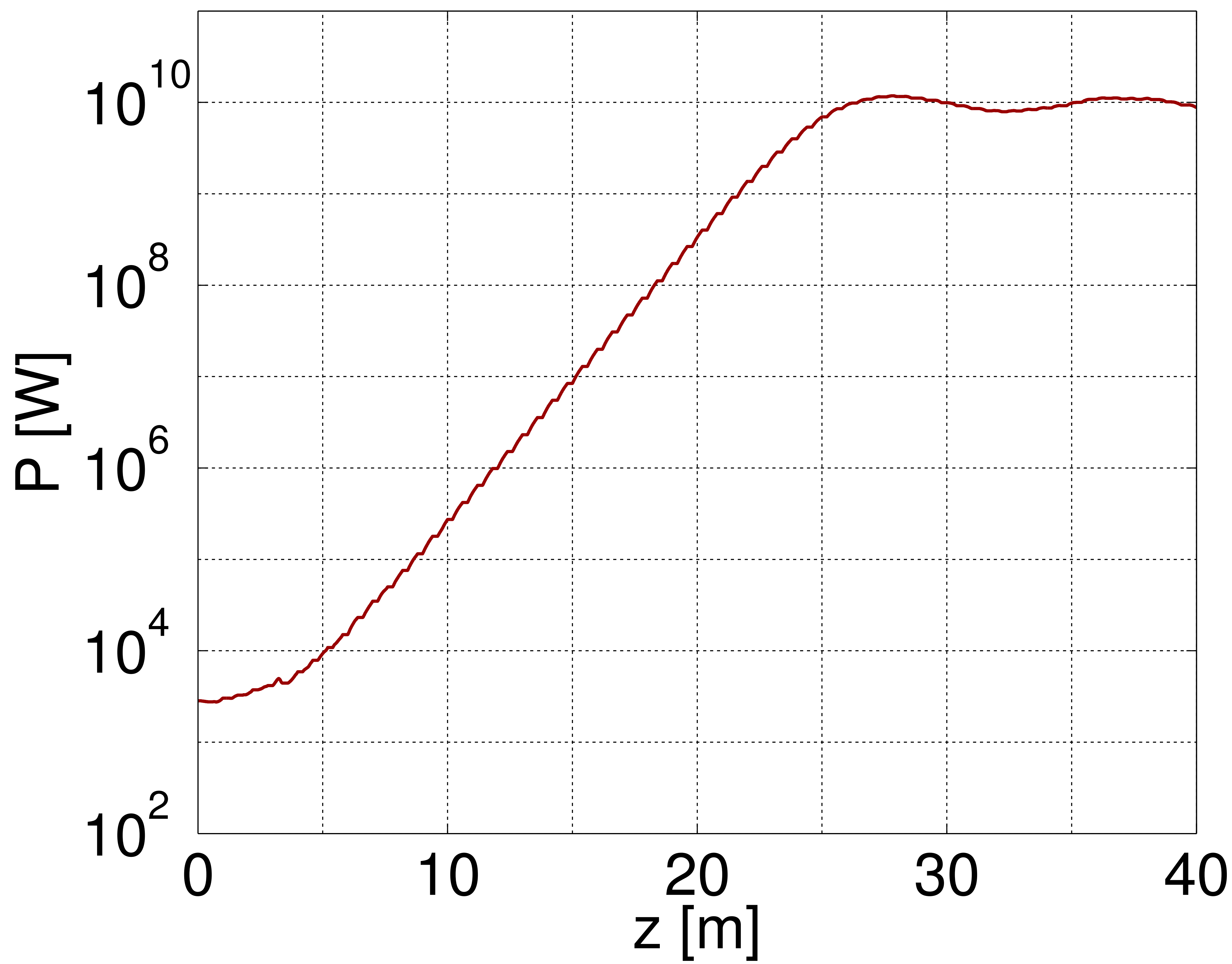
Beams from wakefield-induced ionization injection show significant FEL gain in GENESIS simulations

→ thesis by F. Pannek

- Undulator optimised for short gain length with Wakefield-Induced Ionization Injection beam
- Saturation observed after 28 m, producing 11.8 GW at 12 nm

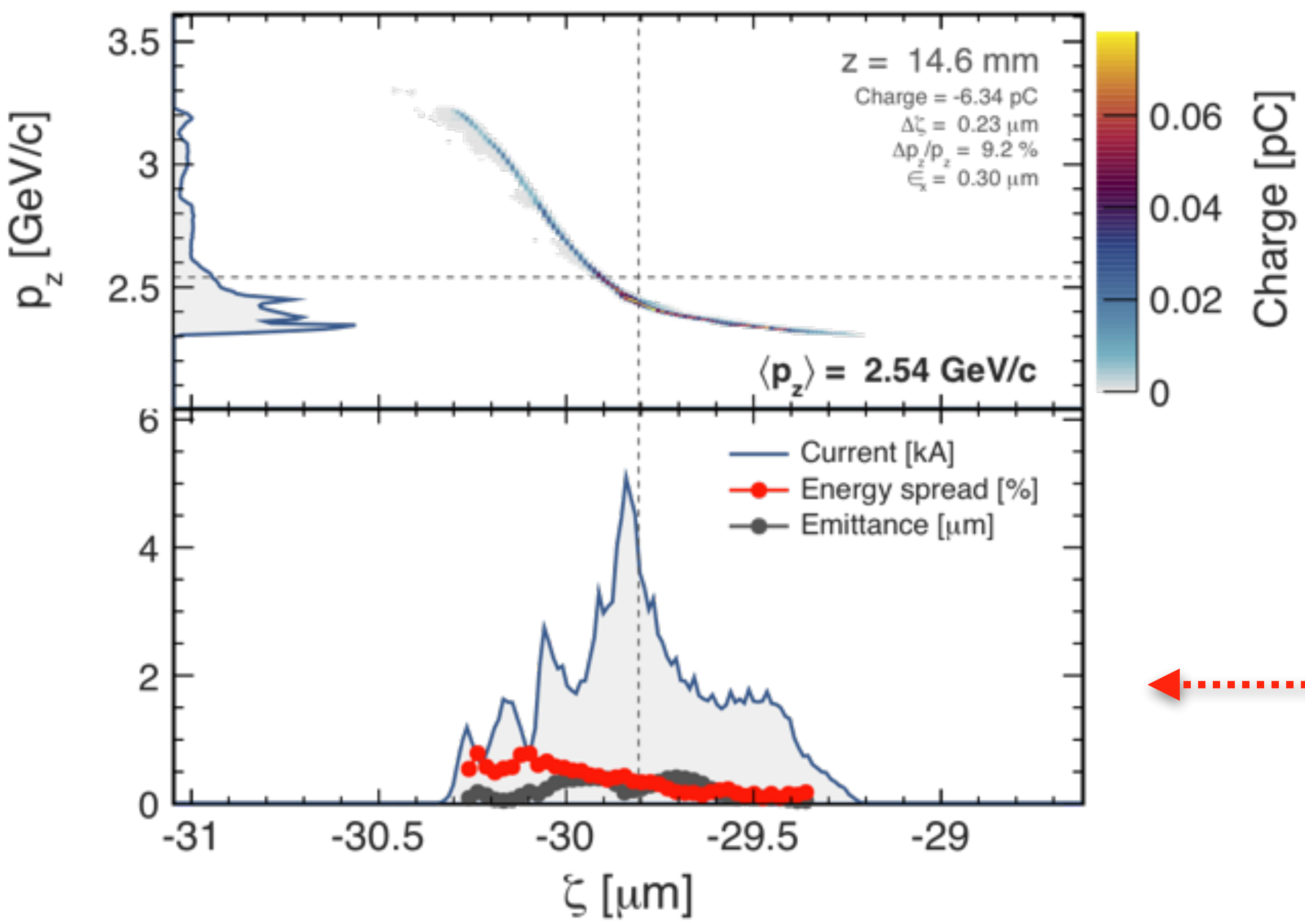
$$E = 2.5 \text{ GeV}$$
$$I_e = 5 \text{ kA}$$
$$\epsilon_n = 0.3\ \mu\text{m}$$
$$\sigma_\Delta = 0.5\ \%$$

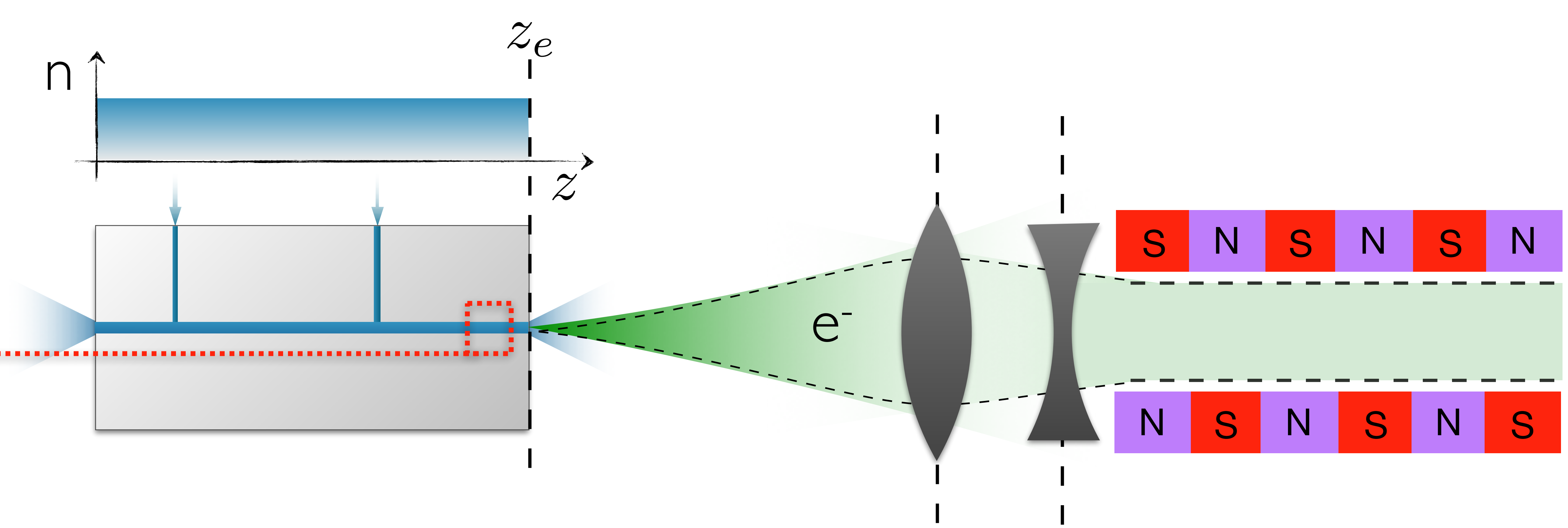
$$\lambda_u = 4 \text{ cm}$$
$$K_0 = 5 \text{ kA}$$
$$\bar{\beta} = 1.2 \text{ m}$$



3D time-dependent GENESIS simulation

Capturing and transport while preserving beam properties is a key challenge for free-electron-laser and HEP applications





Witness beam in plasma

- **Parameters:**
  Energy ~2.5 GeV
  Peak current 5 kA
  Bunch duration 770 as
  Transverse emittance ~300 nm
  Uncorrelated energy spread < 1%
- Correlated energy spread 9 %
- Beta function ~1 mm

Extraction from plasma

- **Main scientific challenge:**
  How to preserve beam properties in plasma-to-vacuum transition?
- **Small beta function, large energy spread:**
  - (a) emittance growth[1]
  - (b) bunch lengthening

Application in FEL

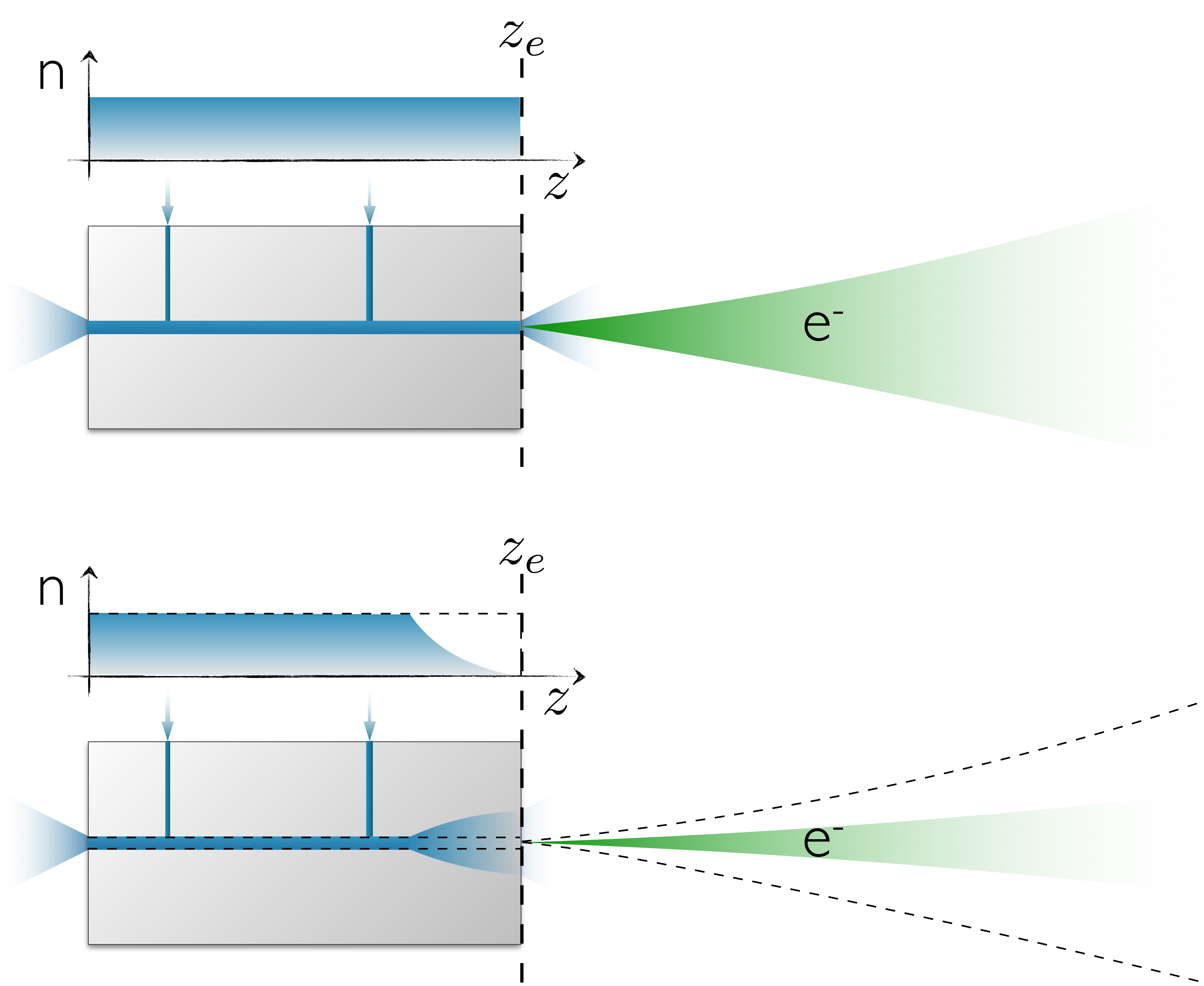
- **Goal:** demonstration of gain
- Requires excellent properties, low emittance, high current, low energy spread

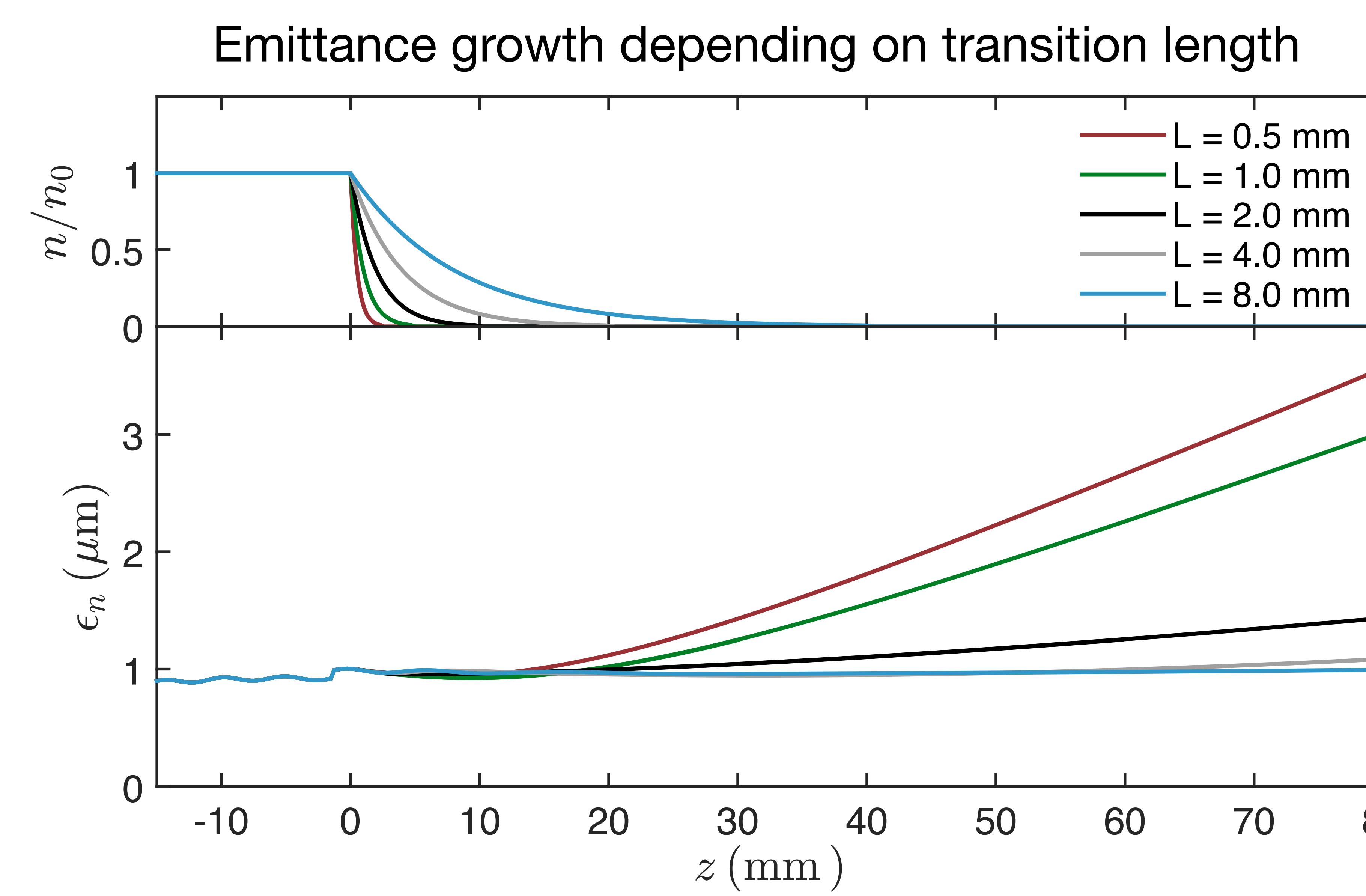
Scientific challenge

[1] K. Floettmann, Phys. Rev. ST Accel. Beams 6, 034202 (2003)

FLASHForward strategy: tailored plasma-to-vacuum transition to adiabatically increase beta, minimize emittance growth

> Concept, theory: T. Mehrling (DESY), to be published



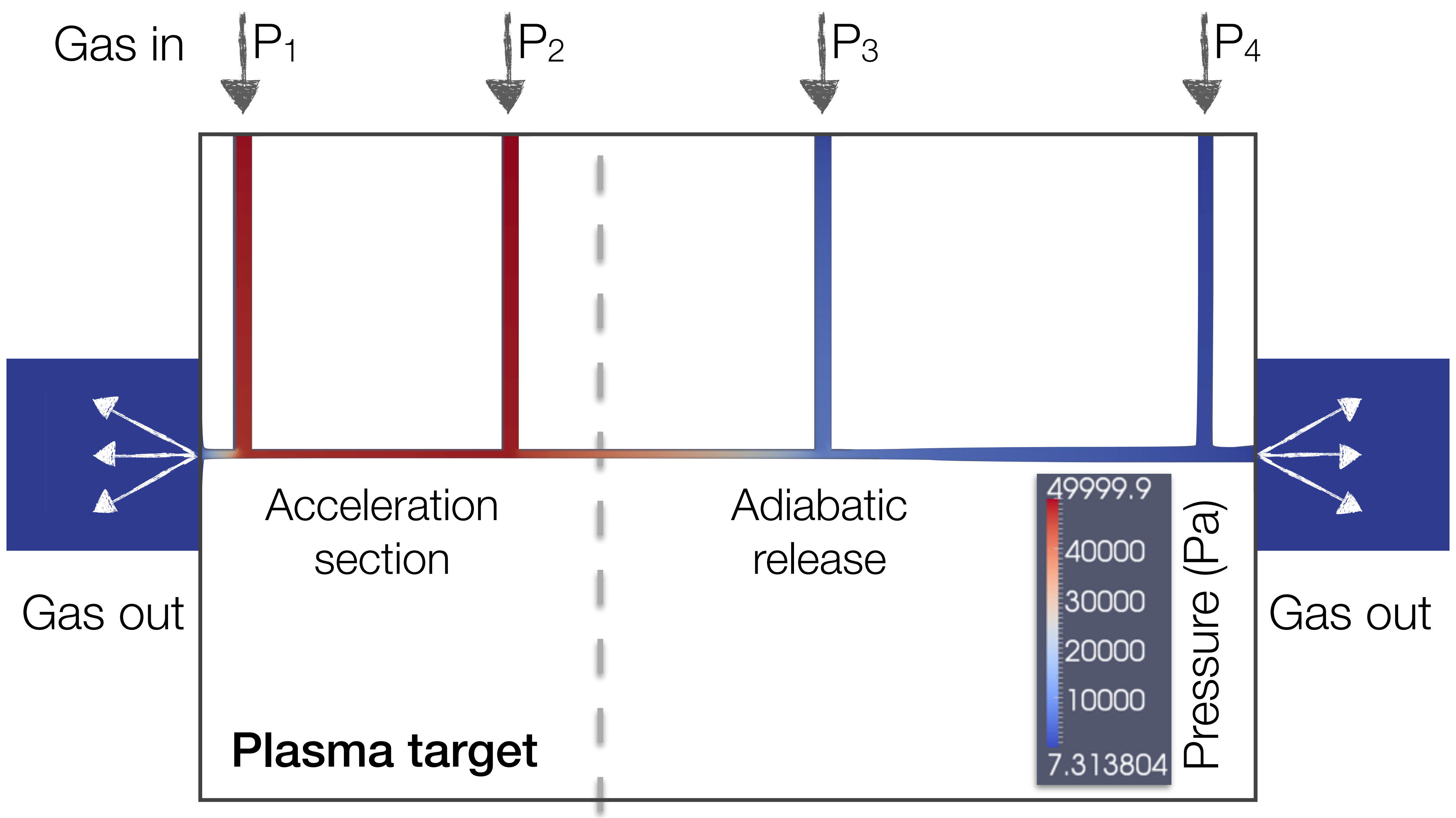


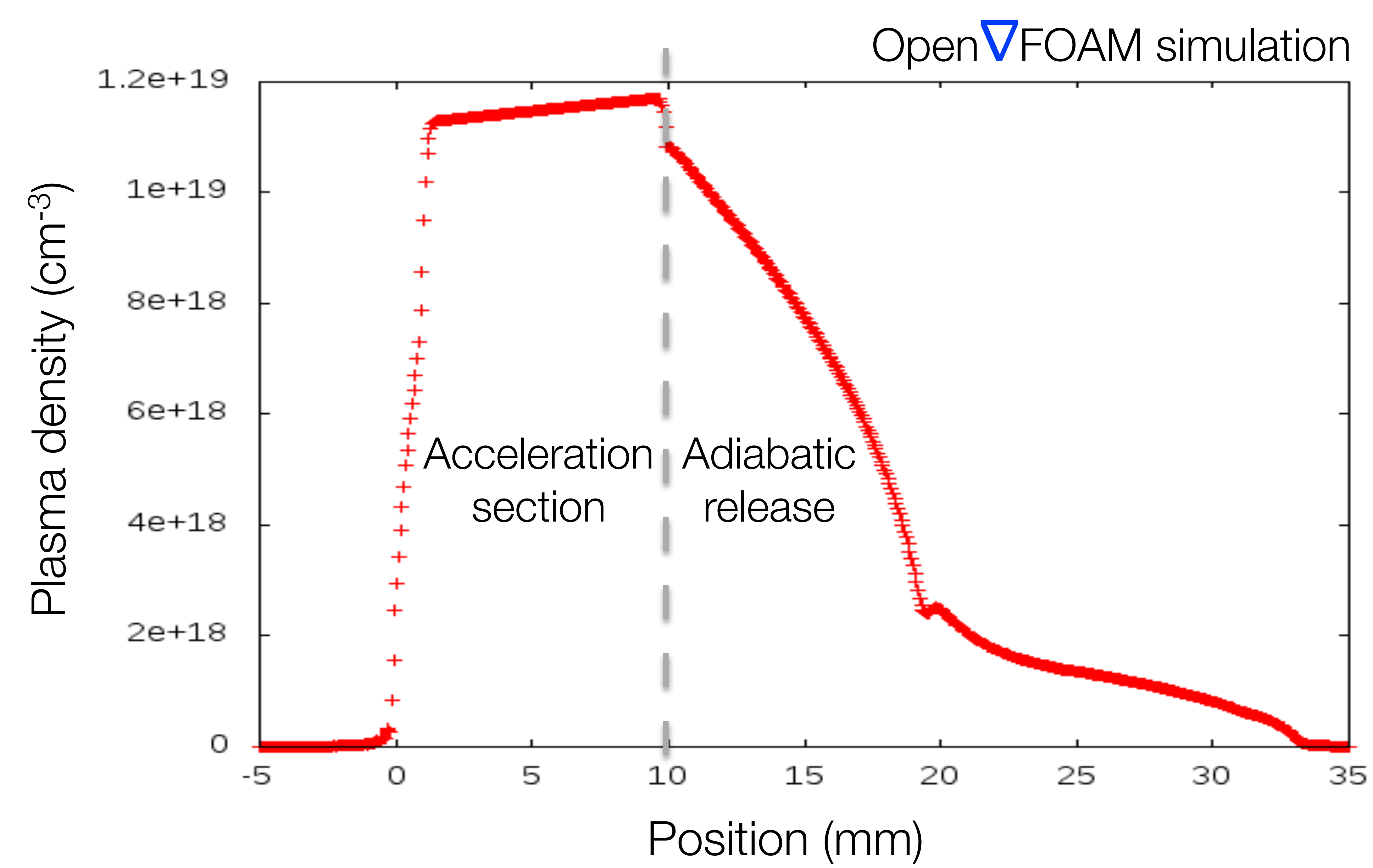
> Plasma-to-vacuum transition » beta for emittance preservation

FLASHForward strategy: tailored plasma-to-vacuum transition → specialized gas targets are under development

> Concept, target: J.-H. Erbe, L. Schaper (DESY)

- Example: $P_1 = P_2 = 500$ mbar, $P_3 = P_4 = 0.1$ mbar

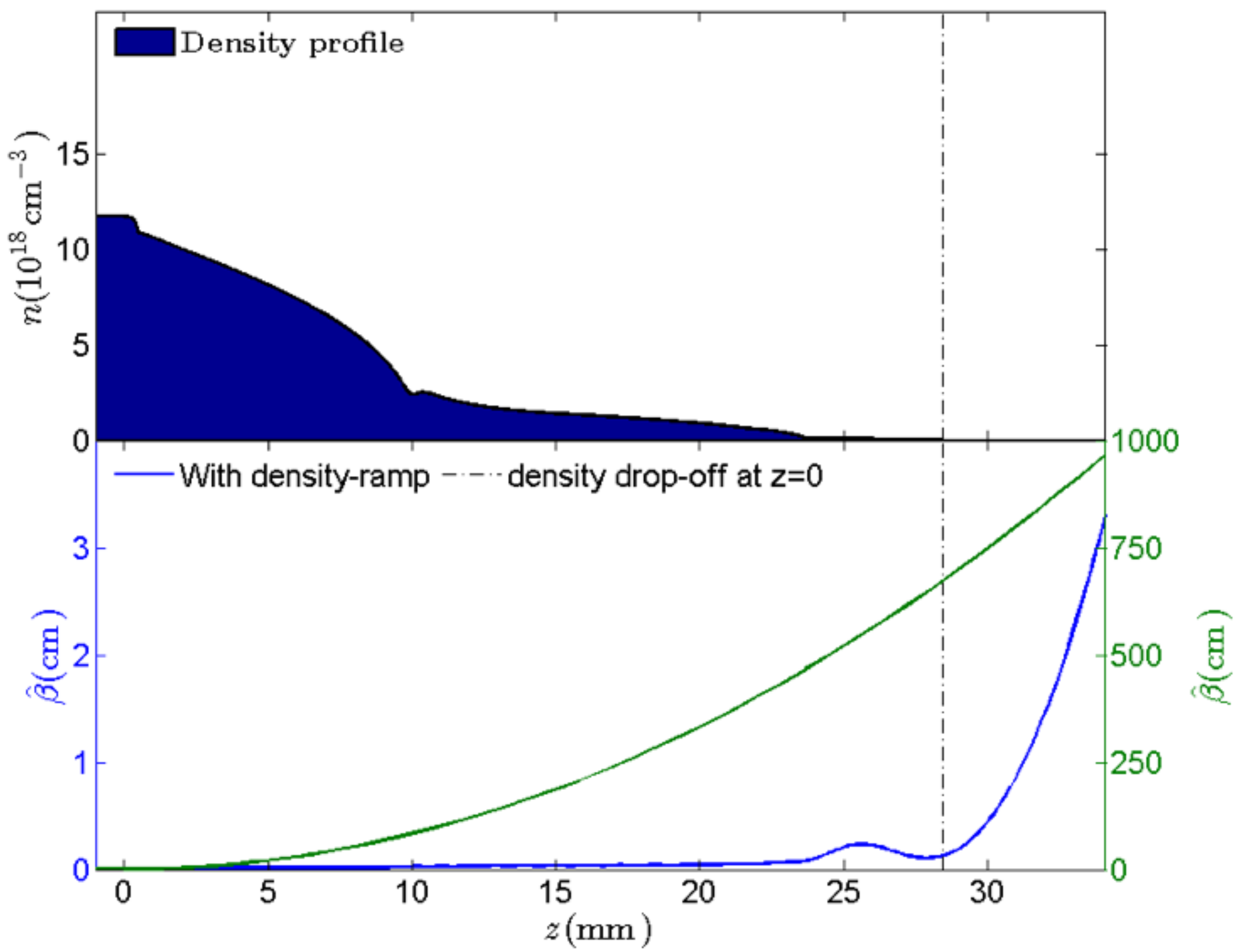


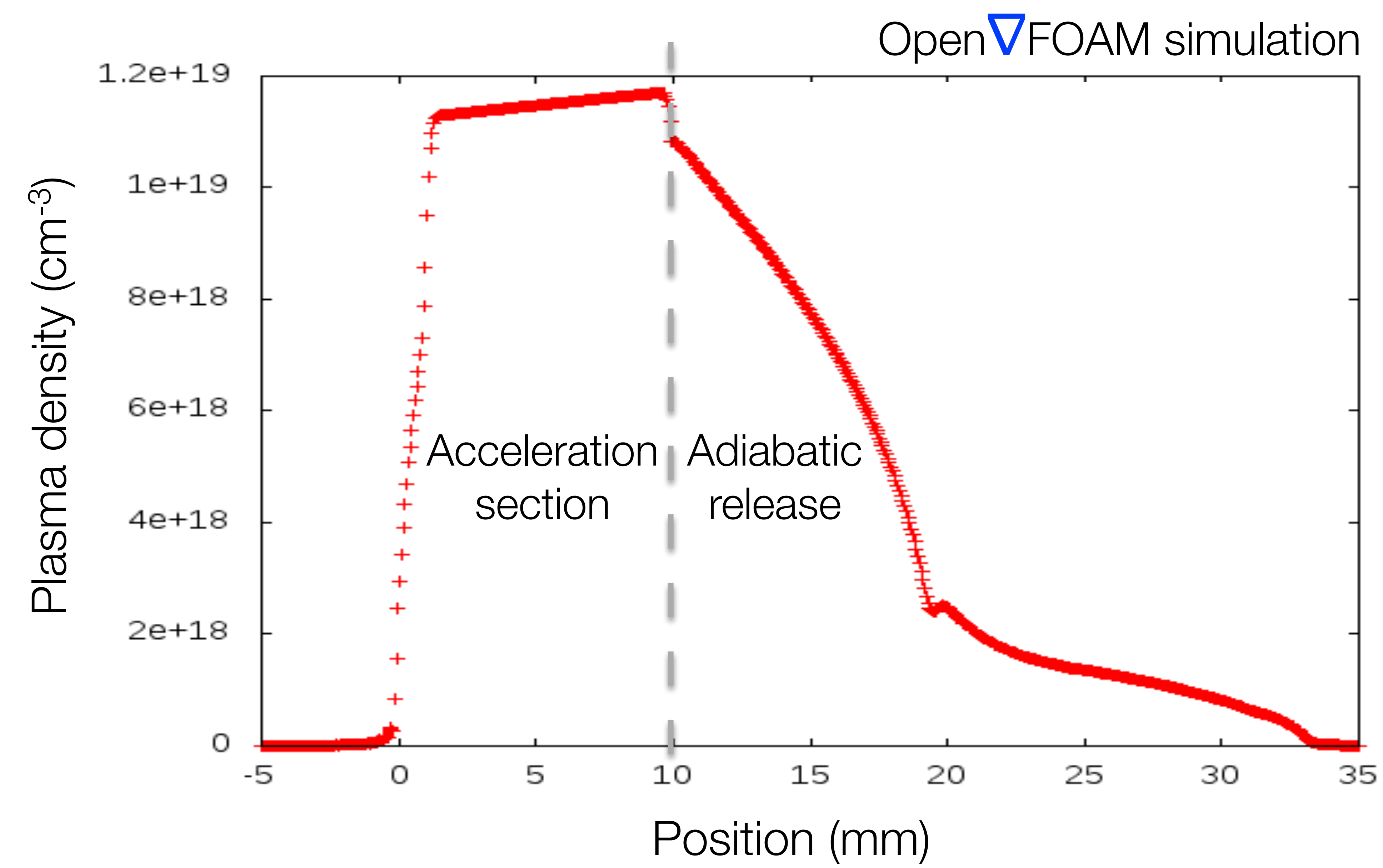


- Targets are under construction, to be tested in first half of 2015

FLASHForward strategy: tailored plasma-to-vacuum transition → specialized gas targets are under development

> Concept, target: J.-H. Erbe, L. Schaper (DESY)





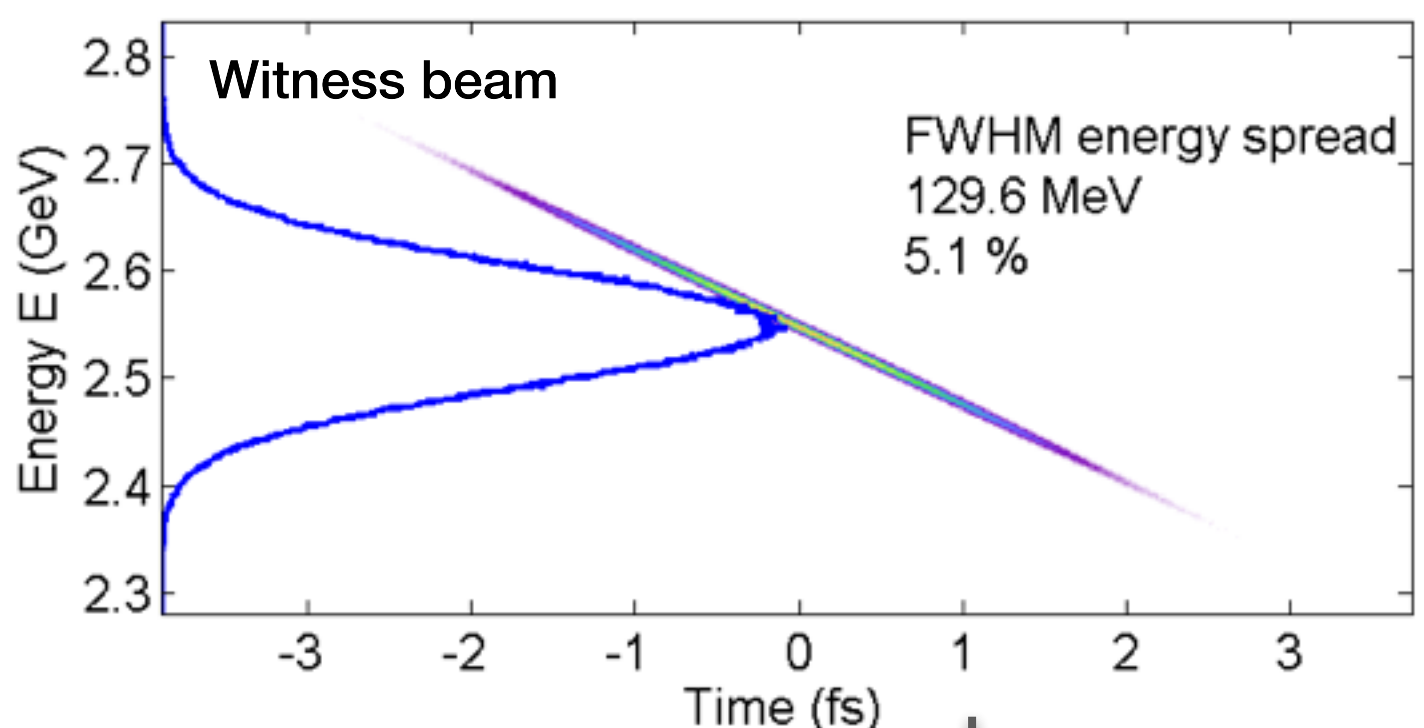
FLASHForward strategy: tailored plasma-to-vacuum transition to compensate for correlated energy spread

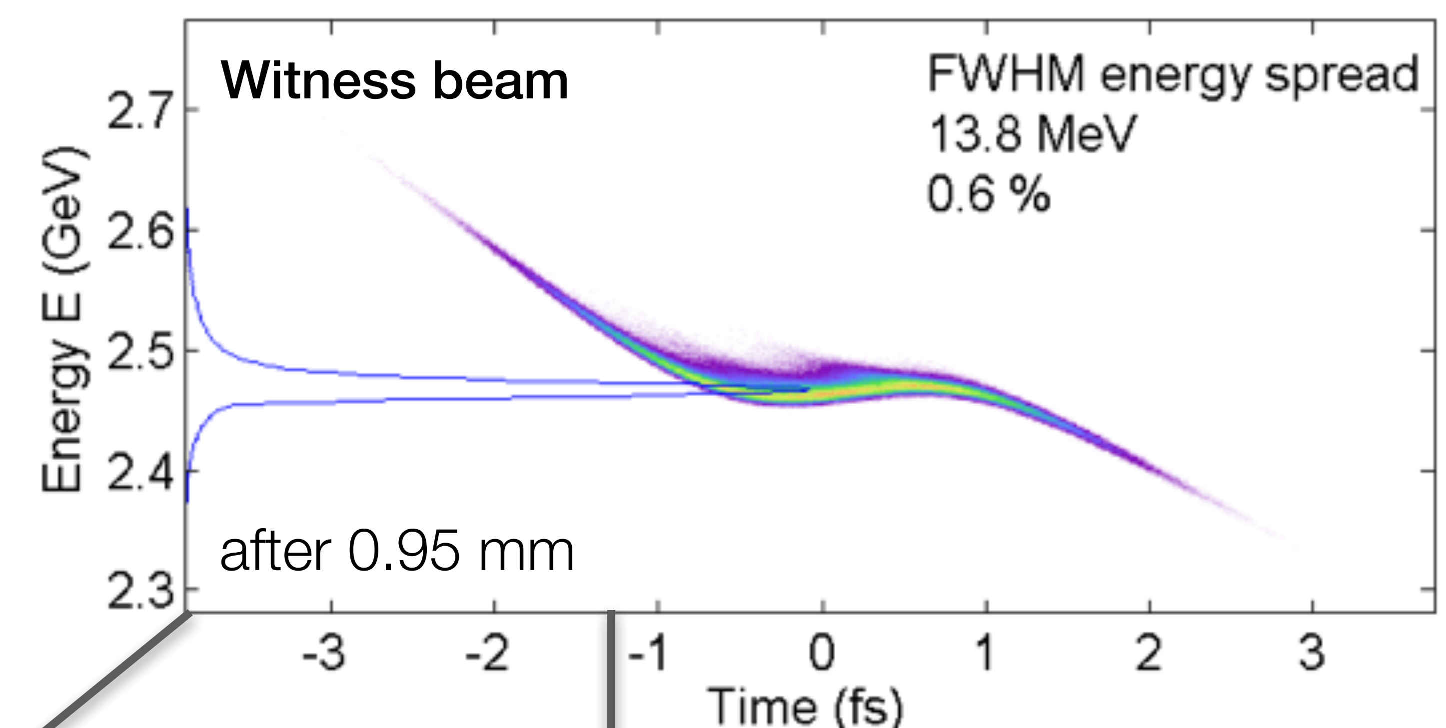
> Concept, theory: V. Wacker, C. Behrens (DESY), to be published

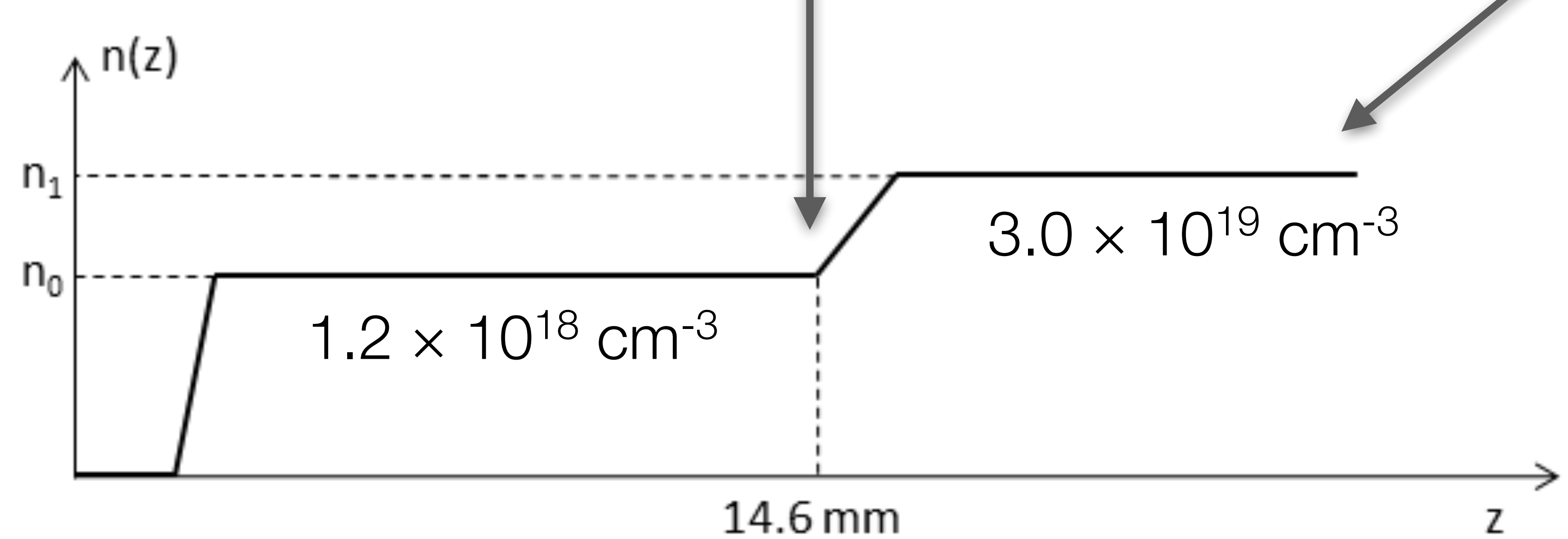
- Dechirping in plasma analogous to corrugated pipe[1] and dielectric structure[2]
- *Example:* beam from wakefield-induced ionization injection

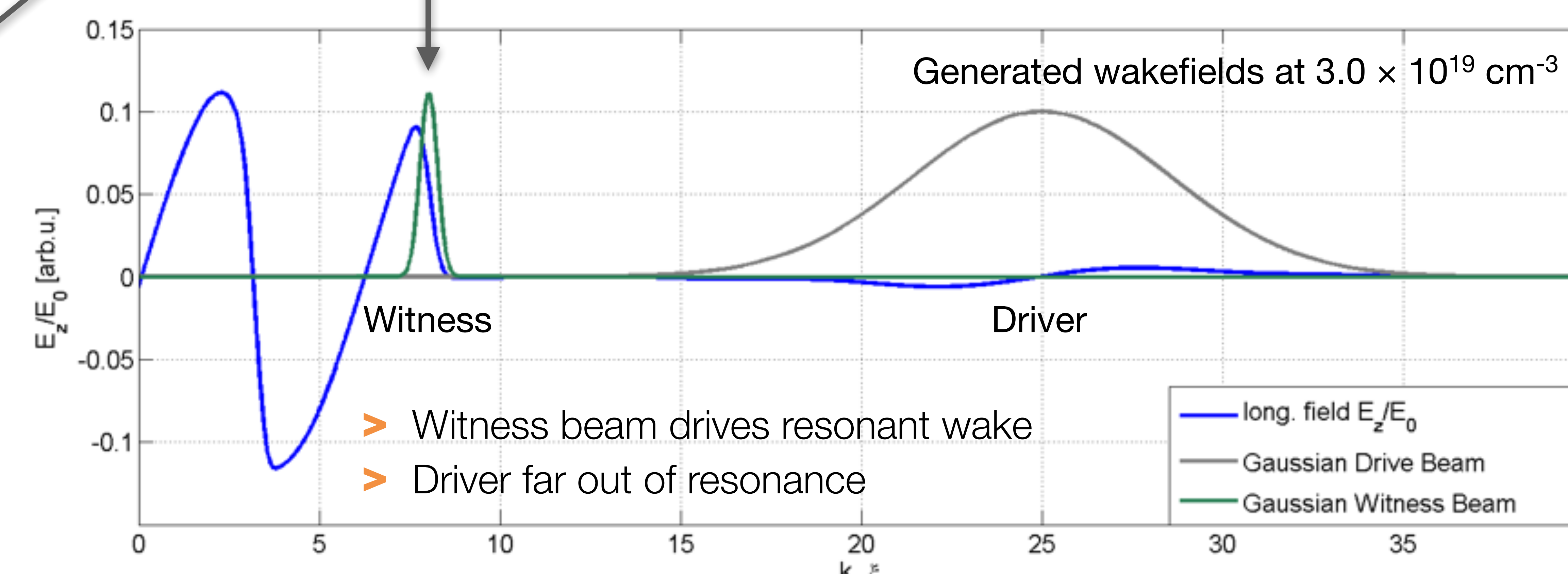
Drive beam
σ_z = 7 µm, $\varepsilon_{x,y}$ = 1 µm, I_B = 10 kA, Q = 574 pC, E = 1 GeV

Witness beam
σ_z = 0.23 µm, $\varepsilon_{x,y}$ = 10.3 µm, I_B = 5 kA, Q = 32 pC, E = 2.5 GeV







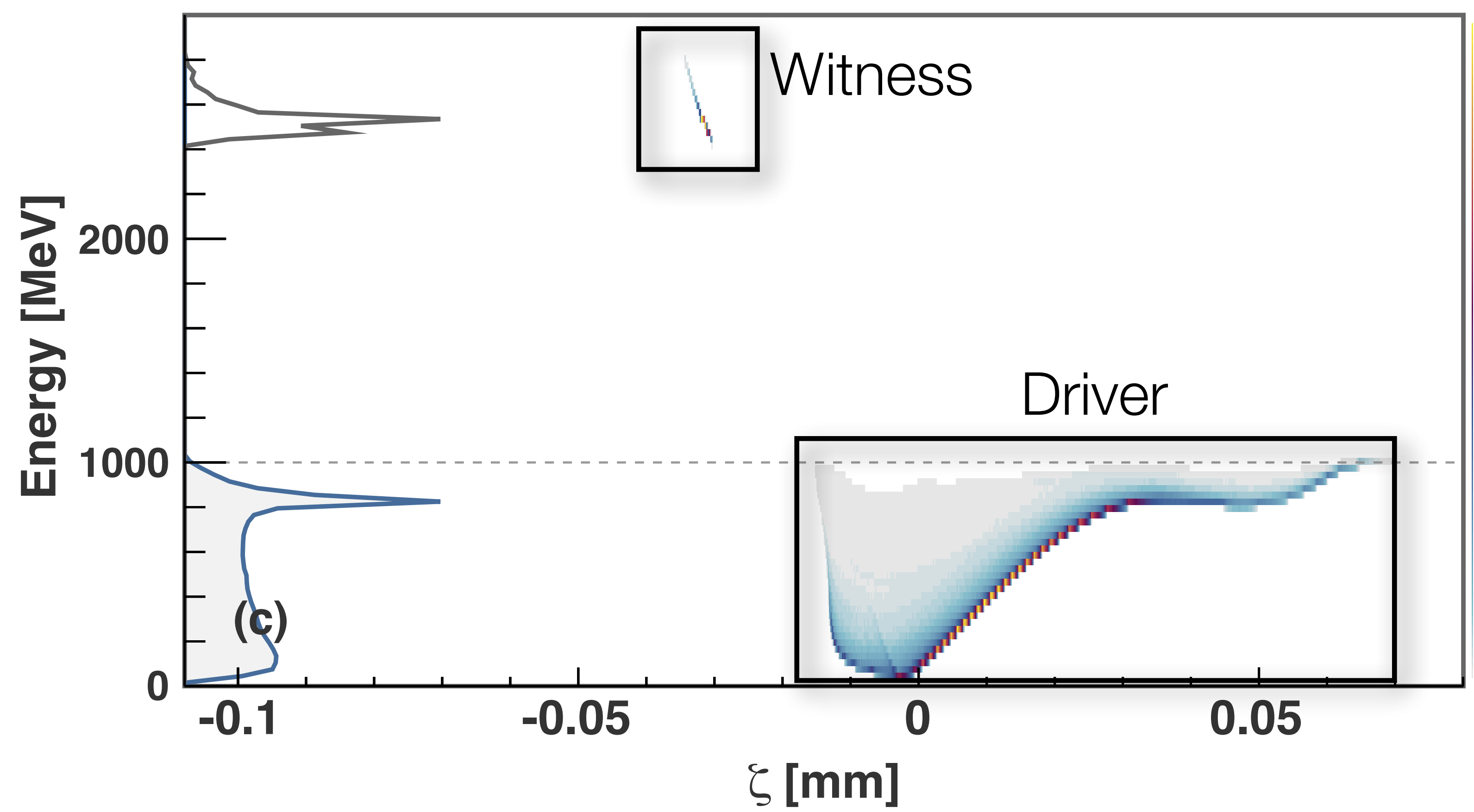


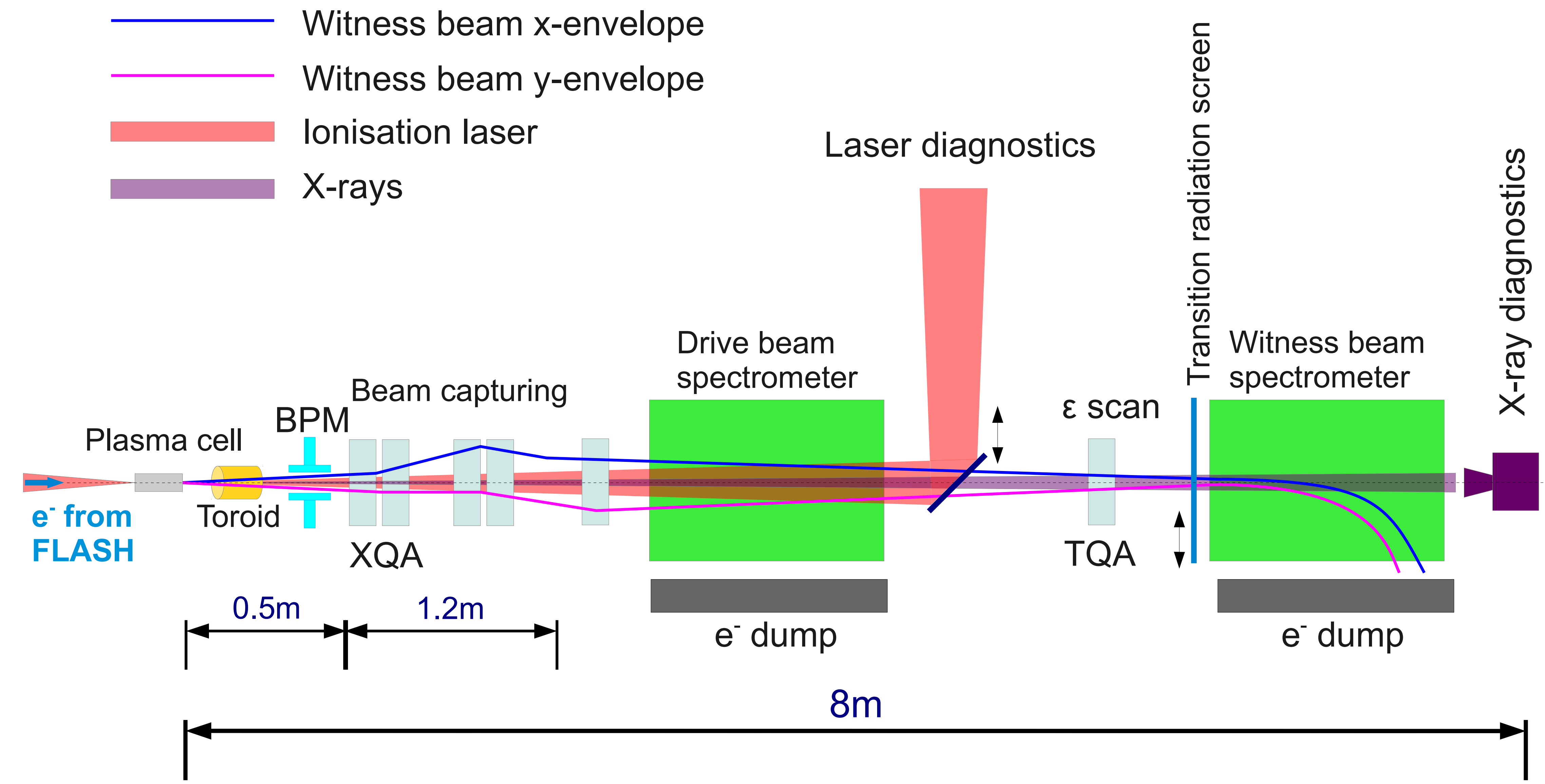
[1] K.L.F. Bane and G. Stupakov, NIM A 690, 106 (2012)
[2] S. Antipov et al., Phys. Rev. Lett. 112, 114801 (2014)

Layout of beam capturing and diagnostics section for phase I

> Scientific concept: V.Libov (FLA), C.Behrens (MPY)

Example: longitudinal phase-space after plasma interaction (from a PIC simulation)





Common witness features

- strong longitudinal correlation
- projected energy spread in the few % range
- uncorrelated energy spread in the ‰ range
- < 1 to 20 fs rms duration
- projected norm. emittances of ≪1 µm

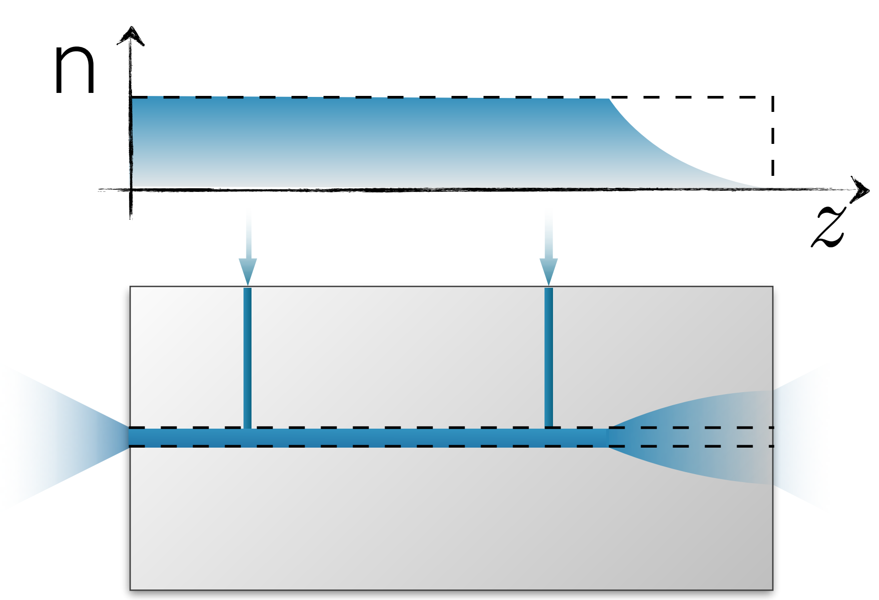
High-gradient quadrupoles and tailoring mitigate emittance degradation and bunch lengthening

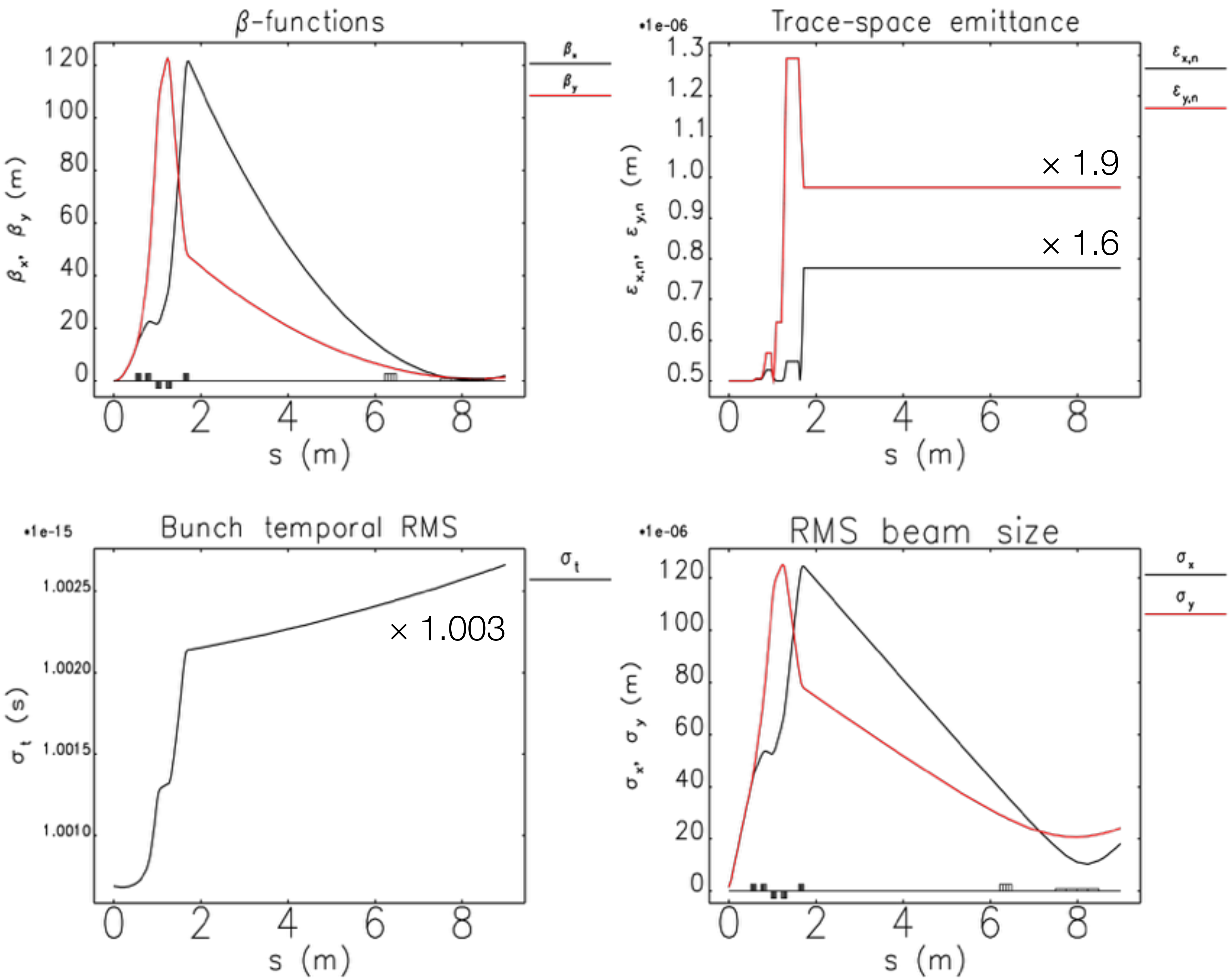
> Scientific concept: V.Libov (FLA), C.Behrens (MPY)

> **Witness parameters**
> E = 2 GeV, σ_E = 1%, ε_0 = 0.5 μm, $\sigma_{t,0}$ = 1 fs,

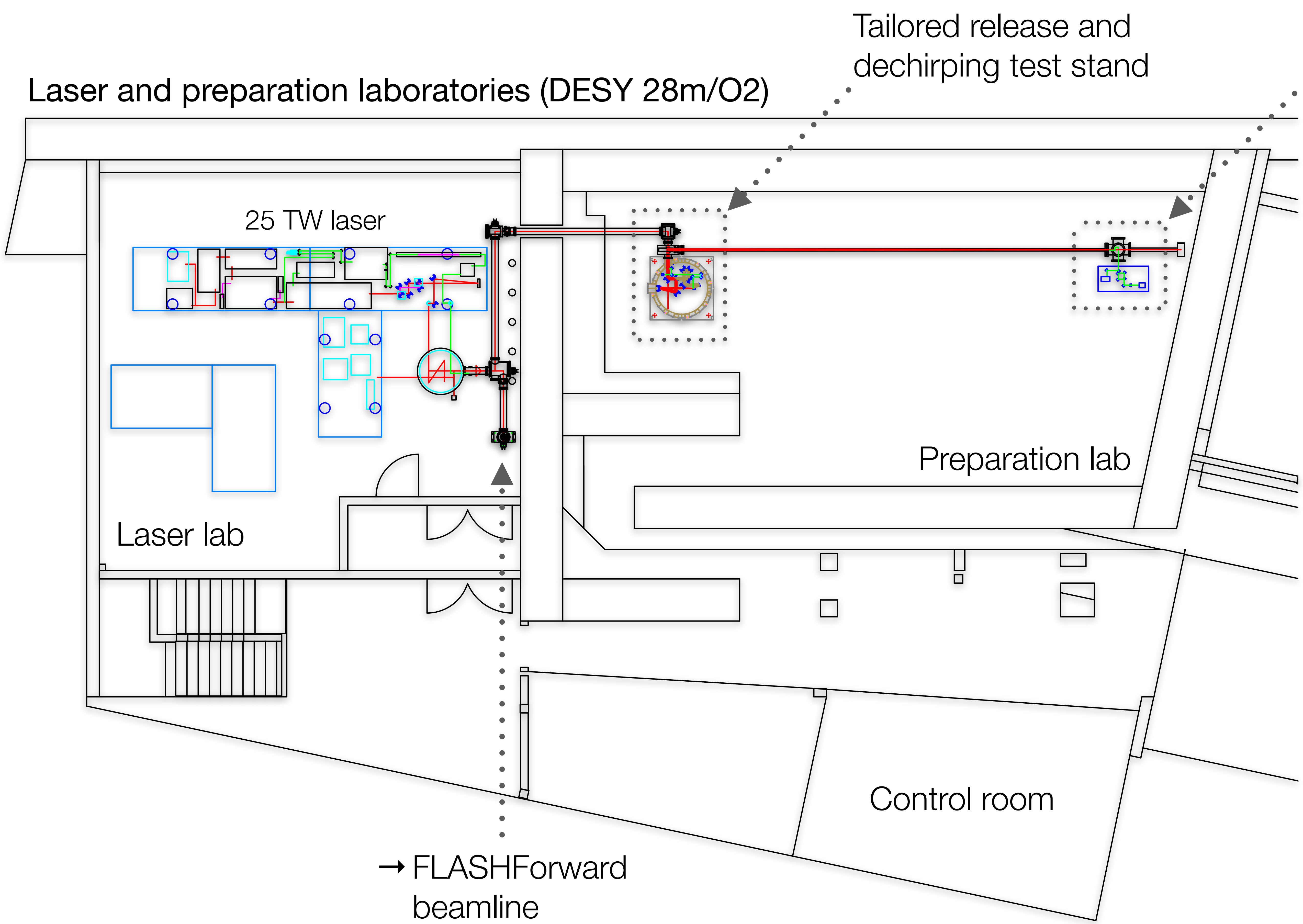
> **XQA magnets** with 100 T/m for capturing

> **Tailored plasma profile** for β = 20 mm at plasma exit





FLASHForward laser to test plasma targets in 2015



- **>** Plasma targets will be tested and characterized
  - laser ionization
  - longitudinal density profile
  - tailored release for adiabatic beta increase
  - dechirping by density upramp
- **>** Test stands useful for diagnostic tests prior to start of FLASHForward experiments
- **>** Optimization of laser for FLASHForward
  - synchronization to FLASH
  - reliability / control
- **>** Laser to be delivered in December 2014, installed in January/February 2015

Broad scientific program investigates crucial PWFA issues

FLASHForward▸▸ *core studies*

- novel types of witness-bunch generation for unprecedented PWFA beam quality
  - laser-triggered ionization injection
  - beam and wake-triggered ionization injection
  - density down-ramp injection
  - external injection (two pulses from photo gun)

normalized witness beam emittances of ≲ 100 nm expected with multi-kA peak currents at 1.5 to 4+ GeV in few-fs duration

- transformer ratios of 2 and beyond
  - boost beams to ~2.5 GeV
  - boost beams to ~4+ GeV Triangular driver

- acceleration in dielectric structures

- assess potential to show FEL gain at wavelengths of ~1 nm
- bunch-quality for photon-science applications
  - emittance, current, duration measurements
  - first measurement of slice parameters *(with TDS)*
- stability/reproducibility of the process
  - beam- and plasma-parameter influence on stability

In addition, the beamline will be well equipped to study a plethora of scientific problems in novel and conventional accelerator R&D (e.g. Thomson scattering, novel diagnostic and timing schemes, components…)

We are open to collaborations and new ideas…

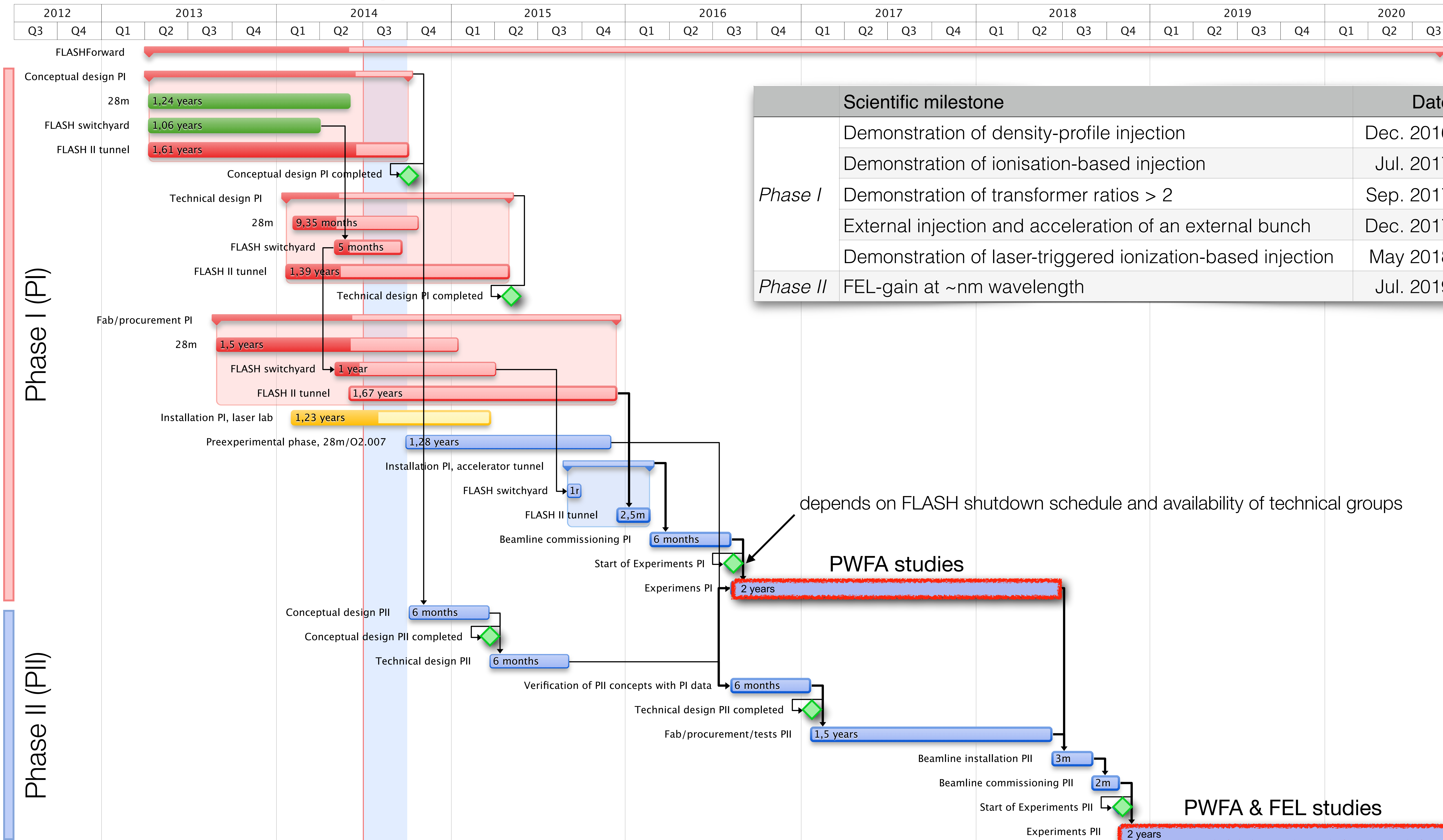
Summary and conclusions

- **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 as first 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

Backup material…

FLASHForward project schedule



	Scientific milestone	Date
Phase I	Demonstration of density-profile injection	Dec. 2016
	Demonstration of ionisation-based injection	Jul. 2017
	Demonstration of transformer ratios > 2	Sep. 2017
	External injection and acceleration of an external bunch	Dec. 2017
	Demonstration of laser-triggered ionization-based injection	May 2018
Phase II	FEL-gain at ~nm wavelength	Jul. 2019

The FLASHForward collaboration network

FLASHForward▸▸

local

- LAOLA.

national

- HELMHOLTZ ASSOCIATION
- Helmholtz-Zentrum Dresden-Rossendorf
- Helmholtz-Institut Jena

international

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