International Beam Instrumentation Conference
Barcelona | September 13th, 2016

Beam Diagnostics Challenges in Plasma Wakefield Acceleration

Seminar

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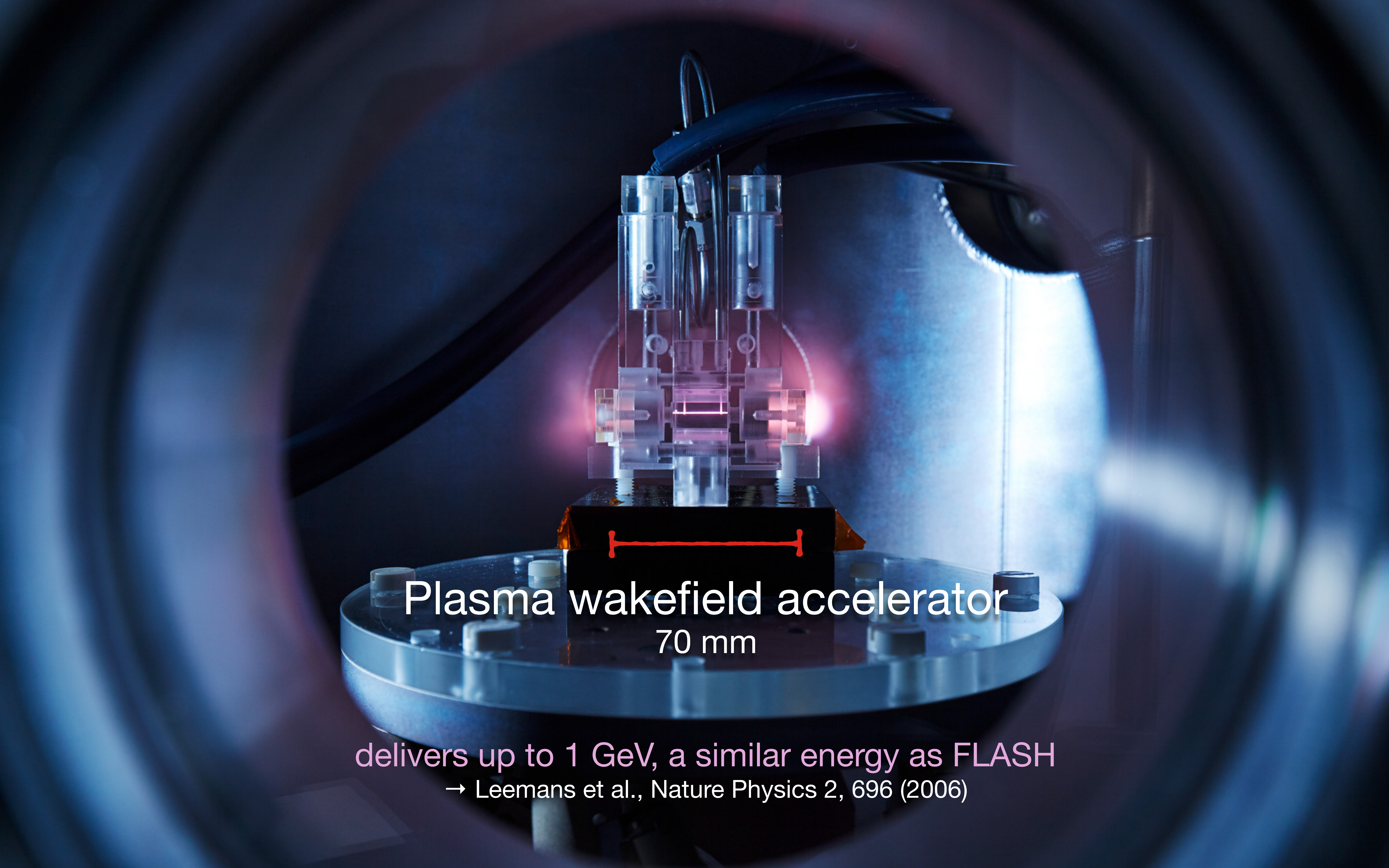
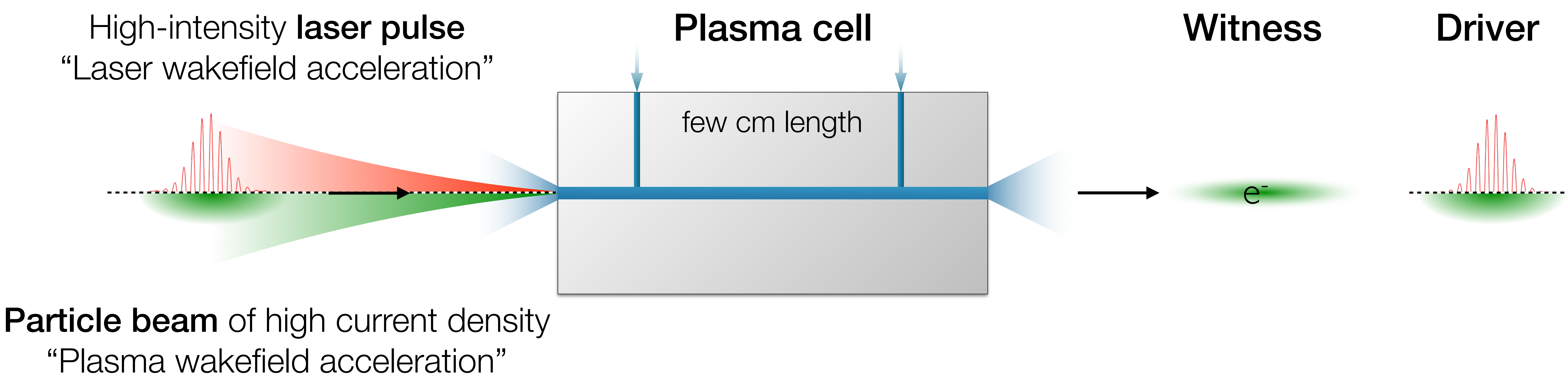
Outline

- Introduction to plasma wakefield acceleration (…and why we should care)
- *Example simulation:* expected beam parameters from wakefield-induced ionization injection
- *Example measurements:* state-of-the-art electron beams from plasma accelerators
- Advanced detection techniques
  - Bunch length
  - Transverse emittance
- What's next and summary


MODUL 6
DESY
FLASH FEL facility
315 m long with ~100 m 1.2 GeV SRF accelerator
Google earth

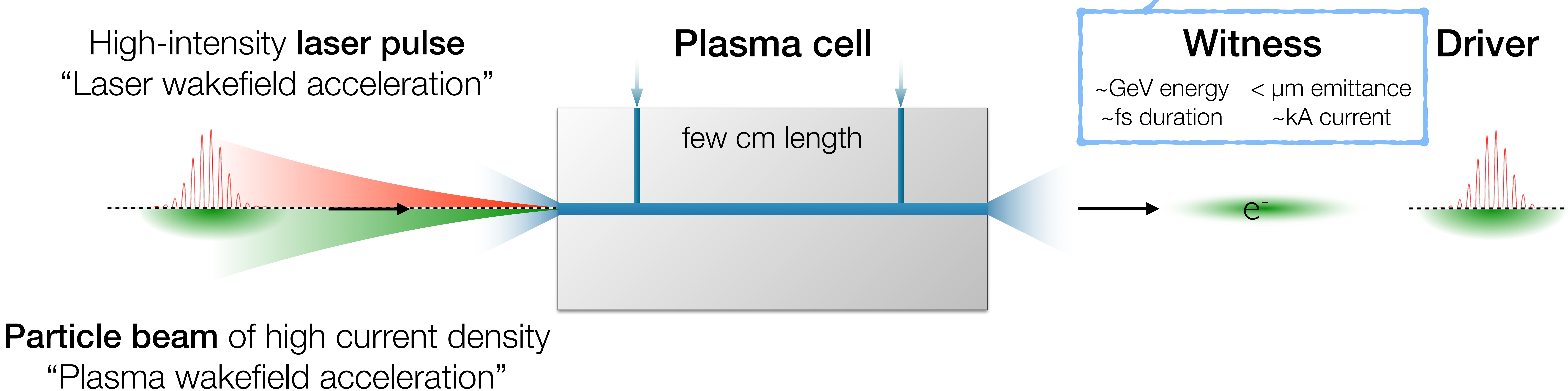

Plasma wakefield accelerator
70 mm
delivers up to 1 GeV, a similar energy as FLASH
→ Leemans et al., Nature Physics 2, 696 (2006)

Plasma wakefield acceleration in a nutshell



Plasma wakefield acceleration in a nutshell

Interesting for photon-science applications



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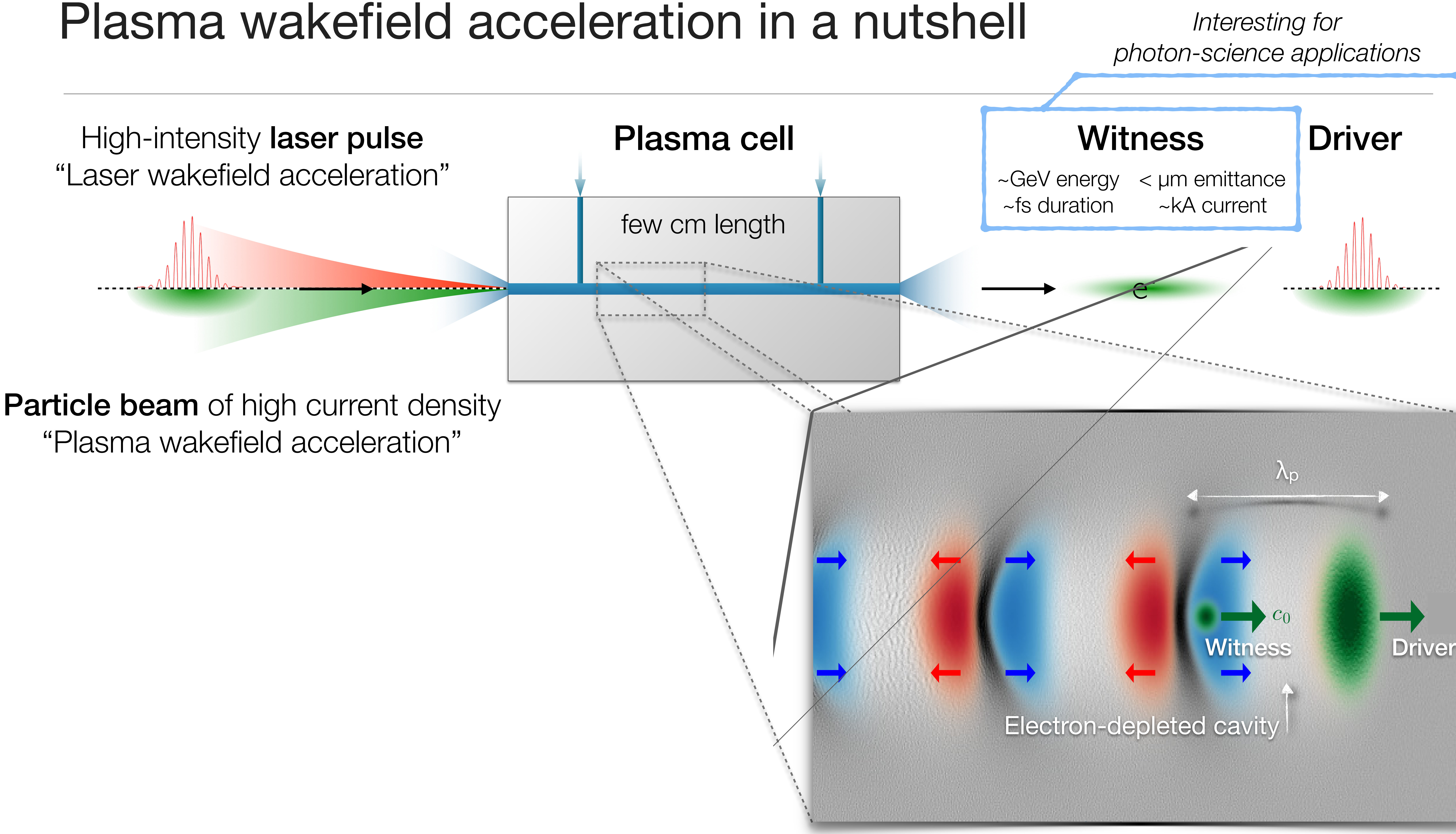
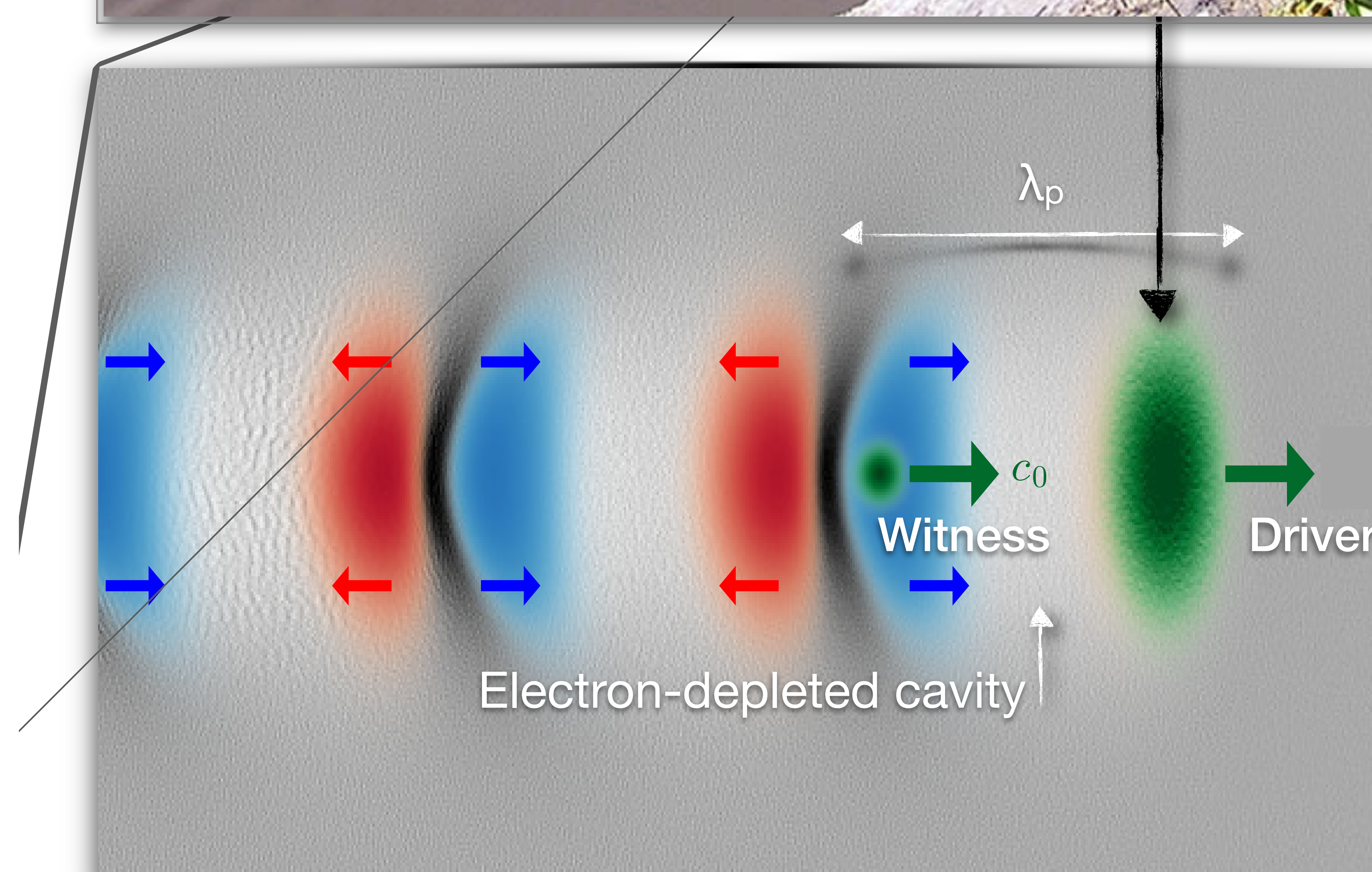


Plasma wakefield acceleration in



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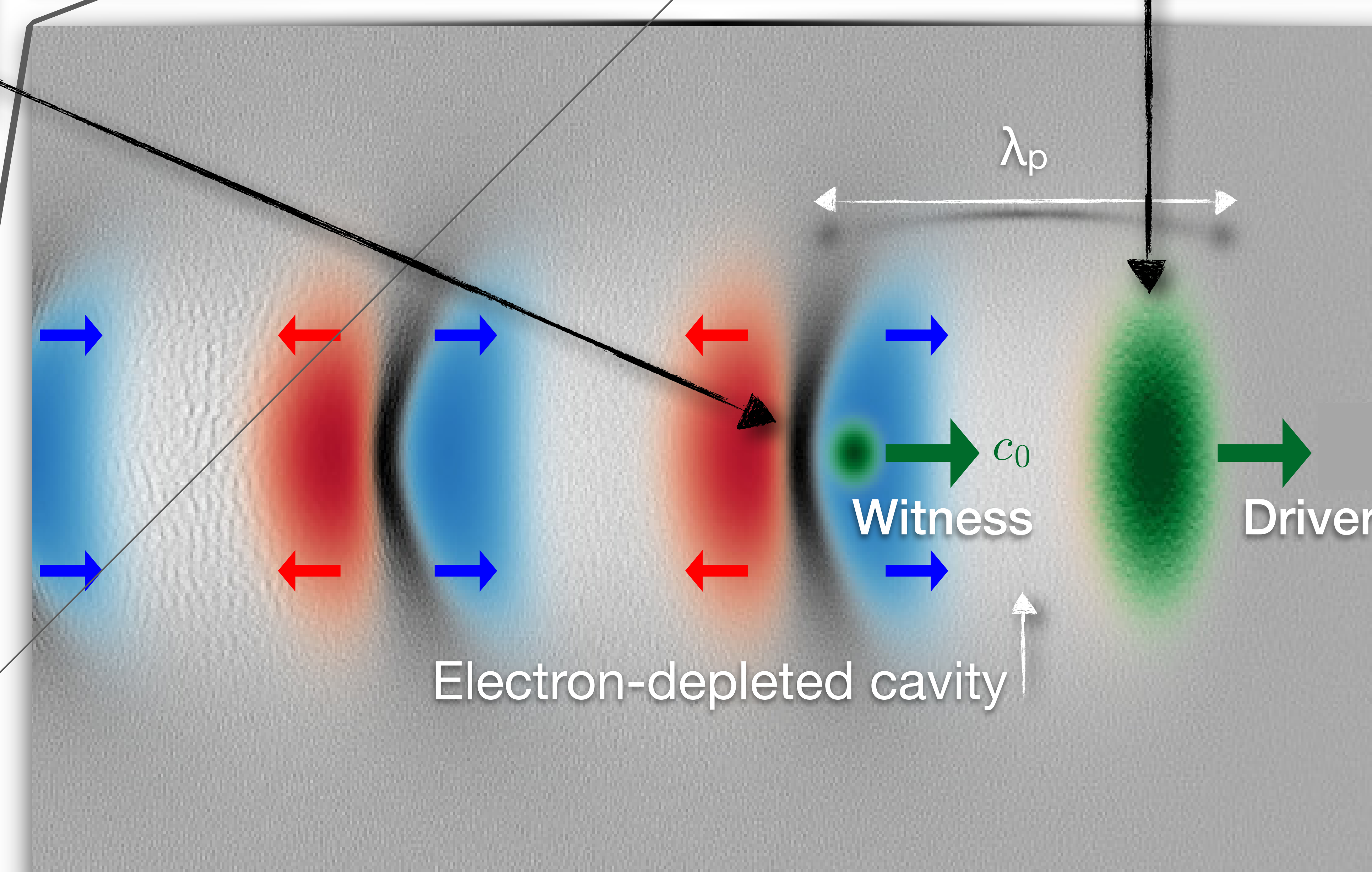


Plasma wakefield acceleration in

Bunch duration: fs

→ O. Lundh *et al.*, Nature Physics 7, 219 (2011)

→ A. Buck *et al.*, Nature Physics 7, 543 (2011)

Size of structure

$$\lambda_p \approx \frac{2\pi c}{\omega_p} \approx (33\ \mathrm{km})\sqrt{n_e^{-1}[\mathrm{cm}^{-3}]}$$

typically **λ_p ≈ 33 µm** (for $n_e \approx 10^{18}$ cm^{-3})

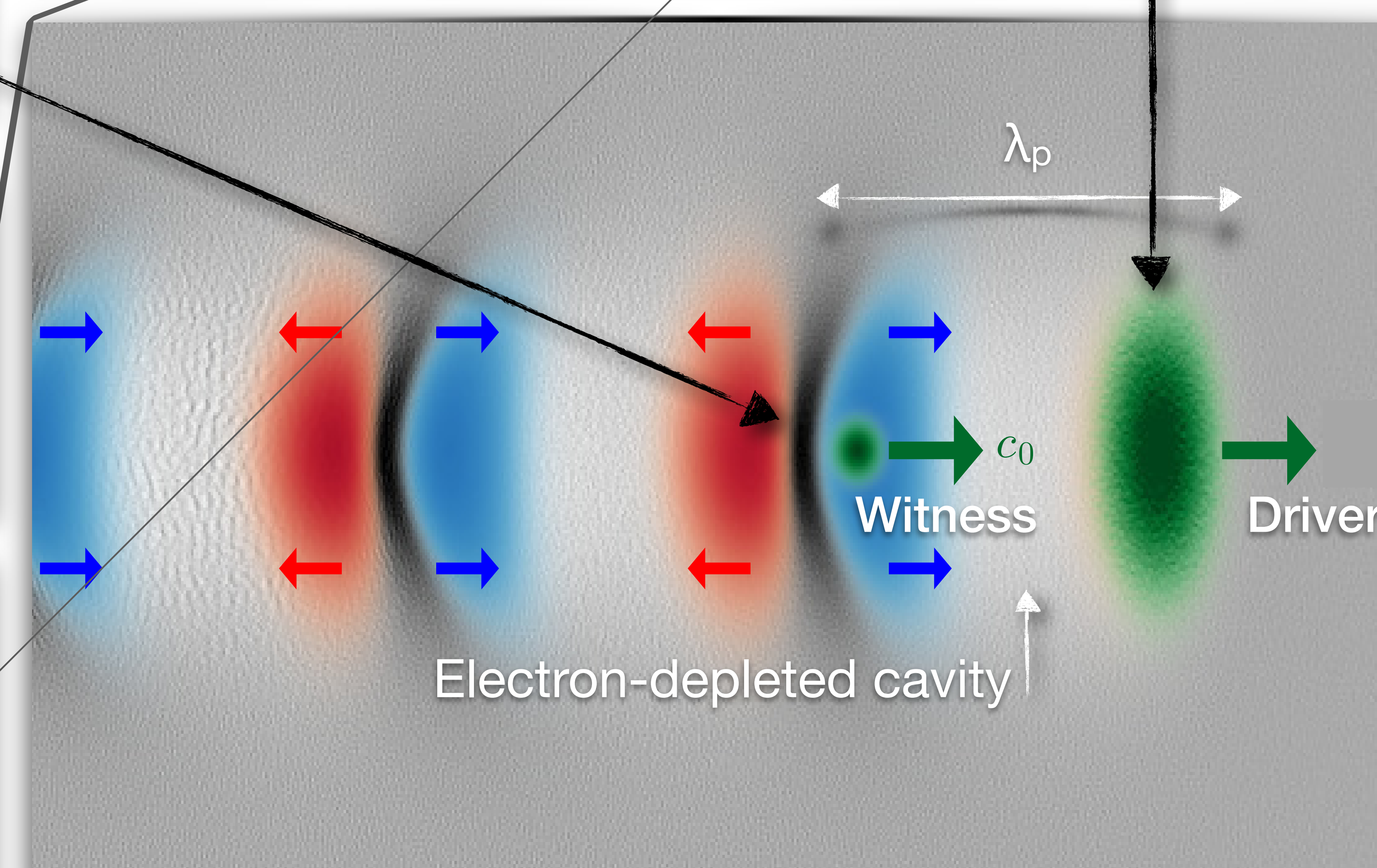
GeV energy gain over cm

→ W.P. Leemans *et al.*, Nature Physics 2, 696 (2006)

Electric field strength

$$E \approx \frac{mc\omega_p}{e} \approx (96\ \mathrm{V/m})\sqrt{n_e[\mathrm{cm}^{-3}]}$$

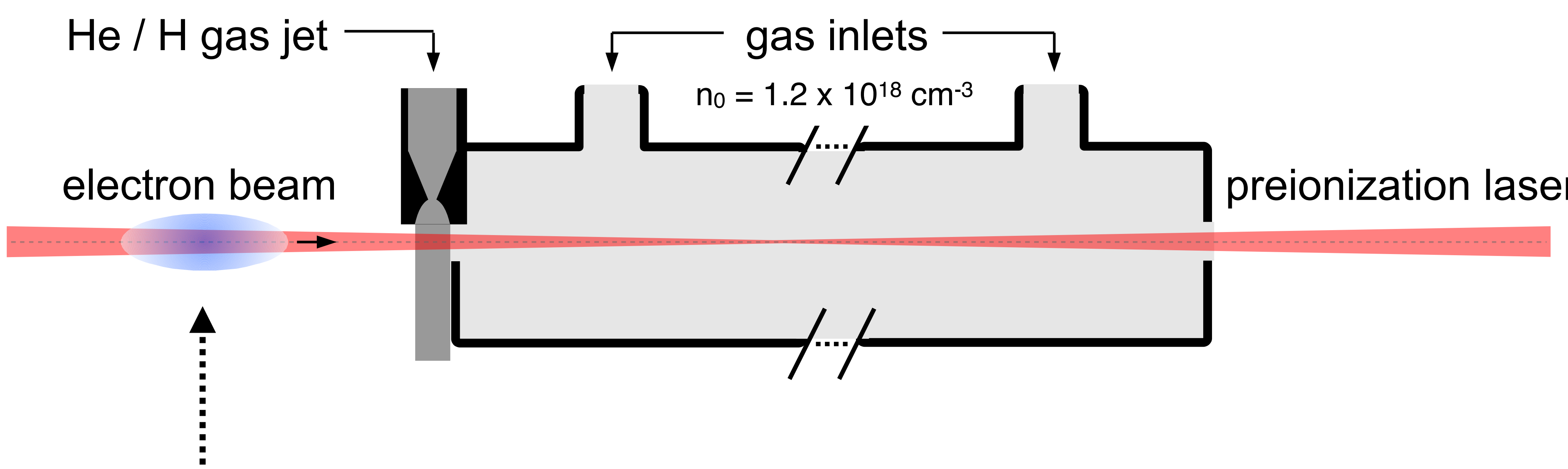
typically **E ≈ 100 GV/m** (for $n_e \approx 10^{18}$ cm^{-3})



Low-emittance, ultra-short witness generation in plasma

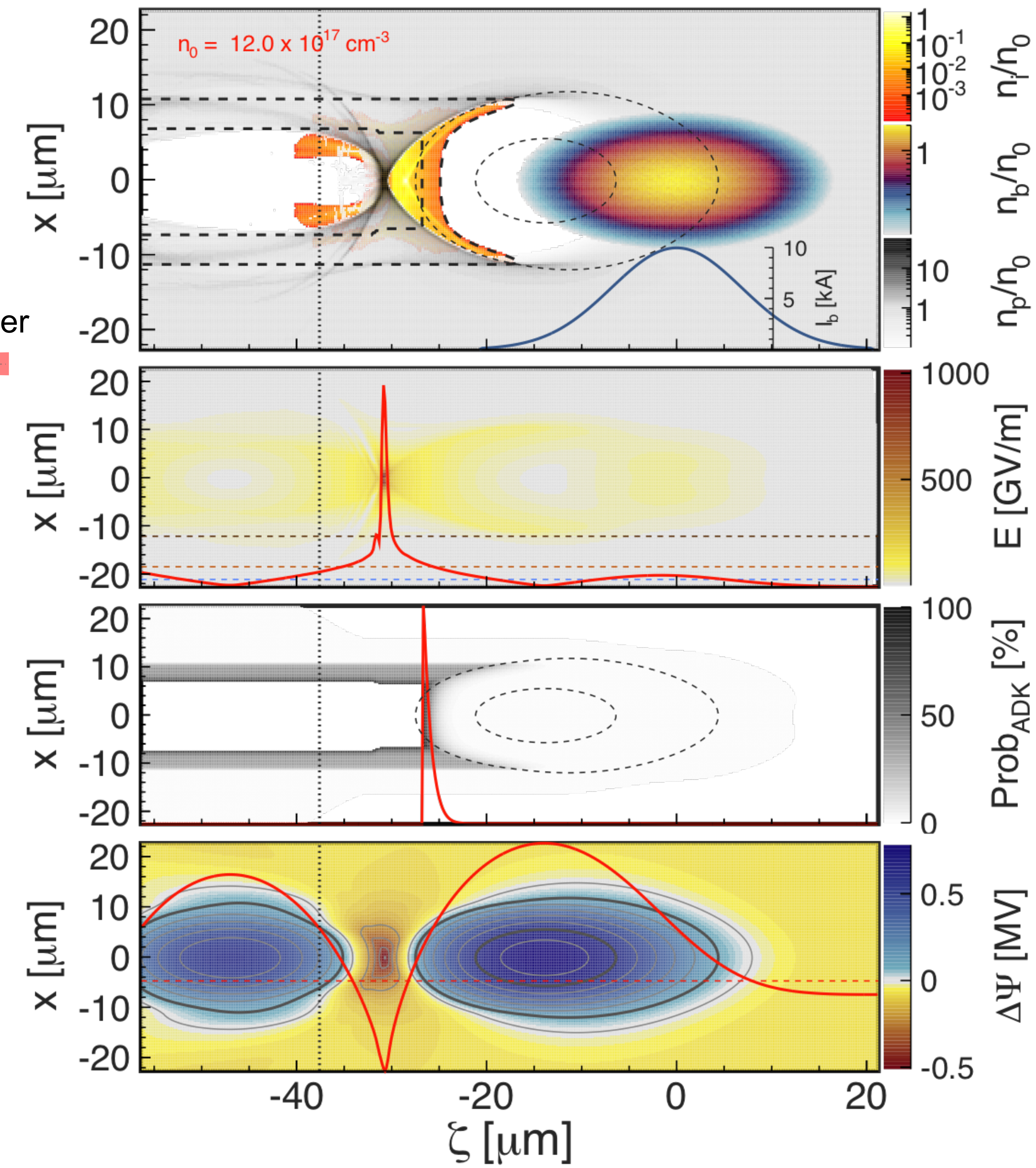
> Wakefield-induced ionization injection

A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)
A. Martinez de la Ossa et al., Phys Plasmas 22, 093107 (2015)



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_2 region

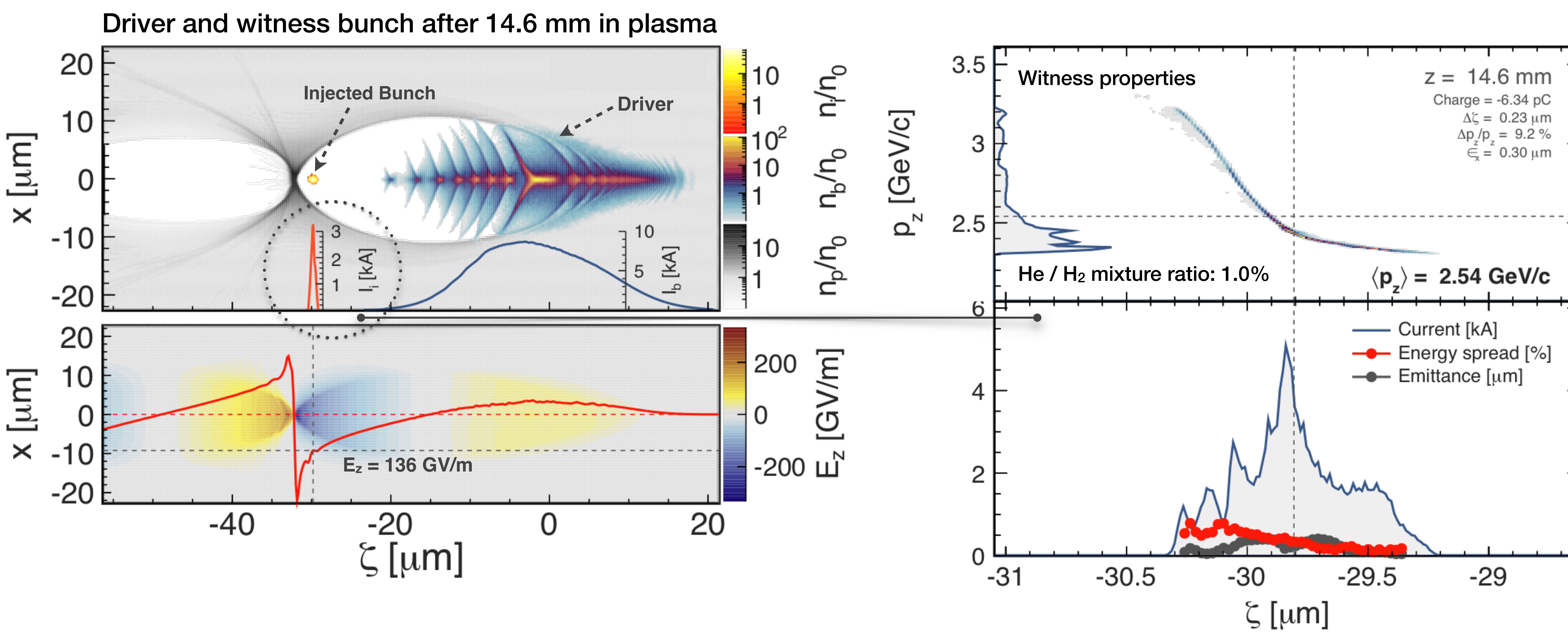


Low-emittance, ultra-short witness generation in plasma

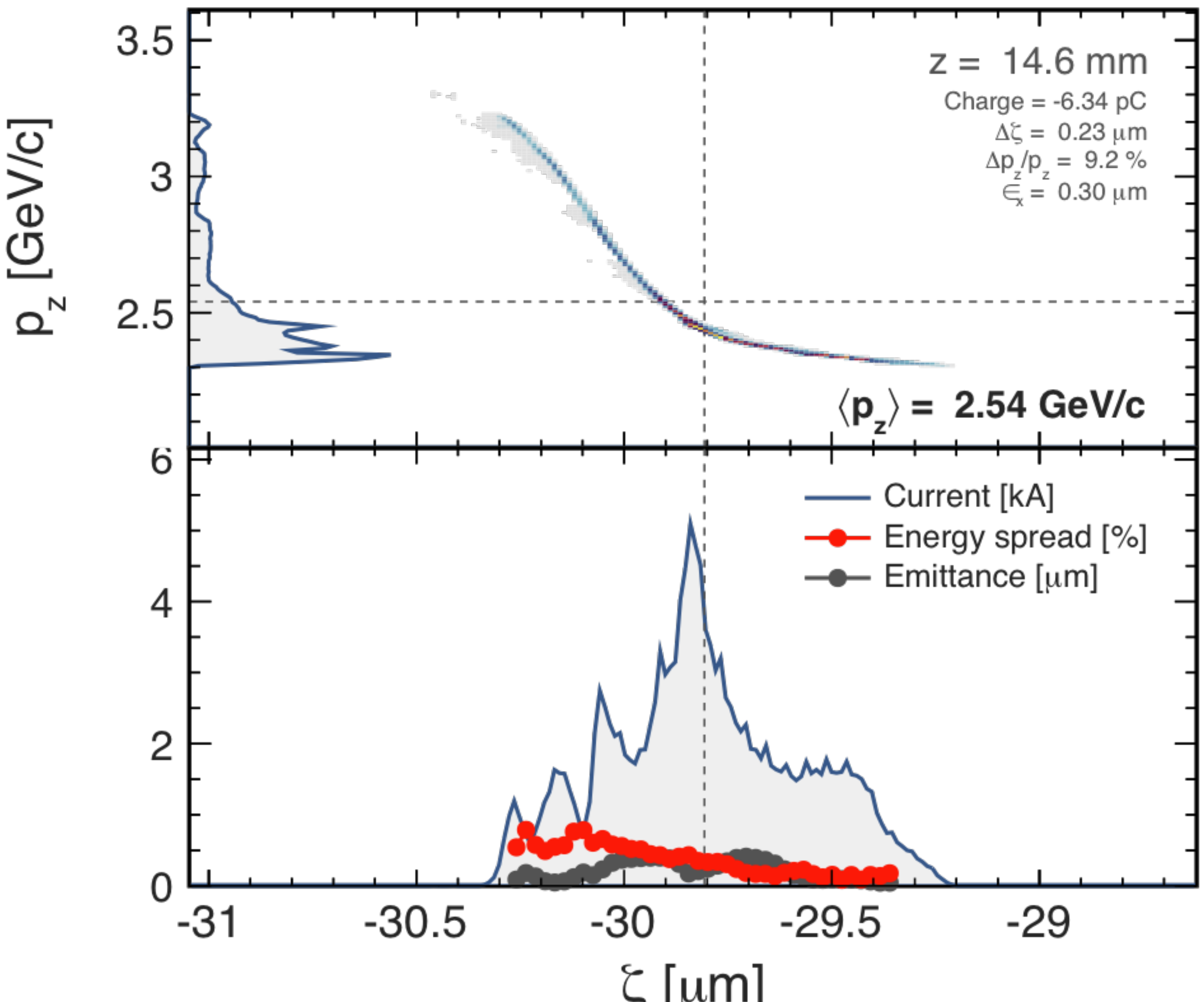
3D particle-in-cell (PIC) simulation

- Wakefield-induced ionization injection
  A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)
  A. Martinez de la Ossa et al., Phys Plasmas 22, 093107 (2015)

- Duration: 770 as rms
- Peak current: 5 kA
- Normalized emittance: 300 nm
- Uncorrelated energy spread: < 1%



Goal: generate and fully characterize such beams



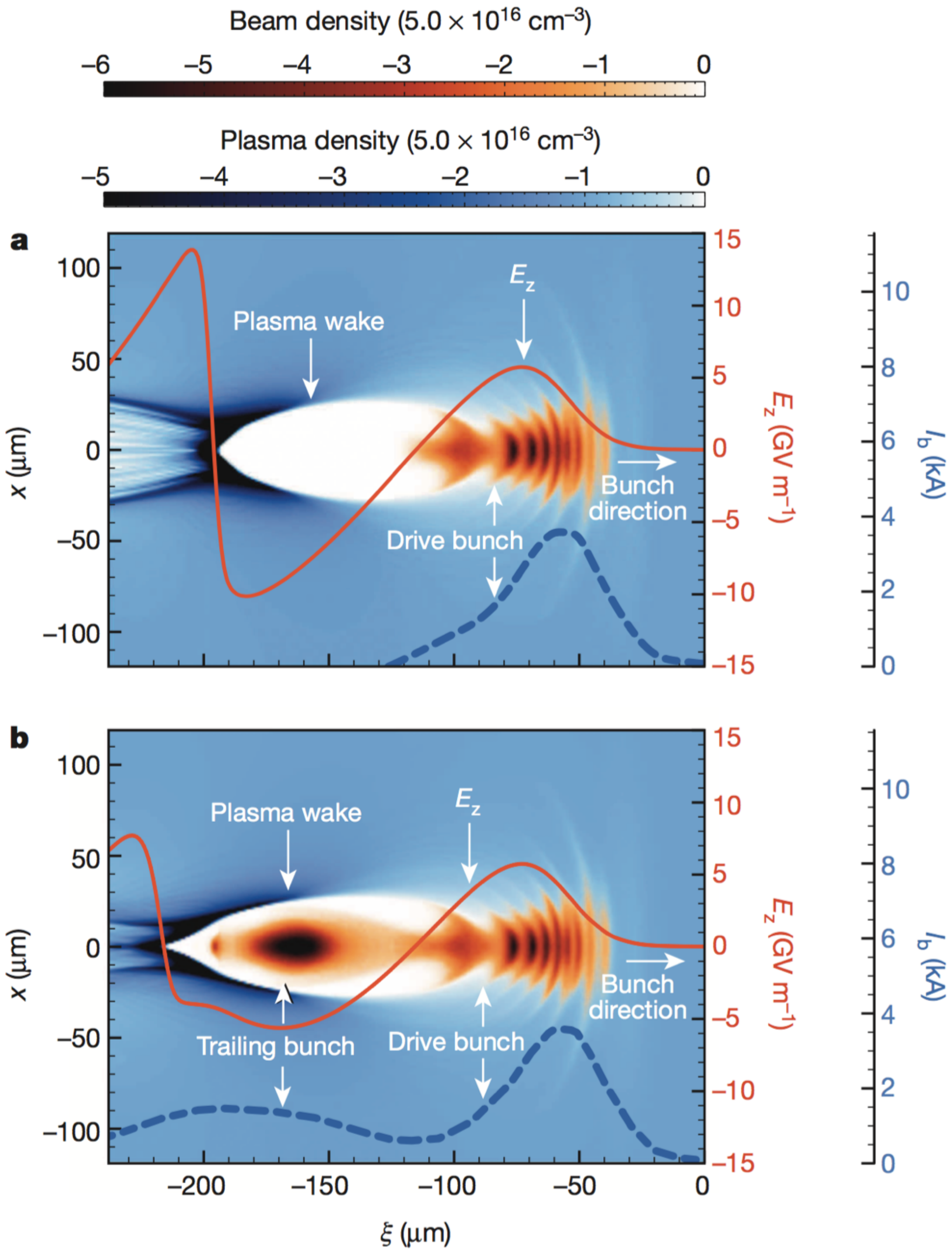
> **Standard measurements:**
- Energy spectrum
- Total charge
- Transverse beam-profile

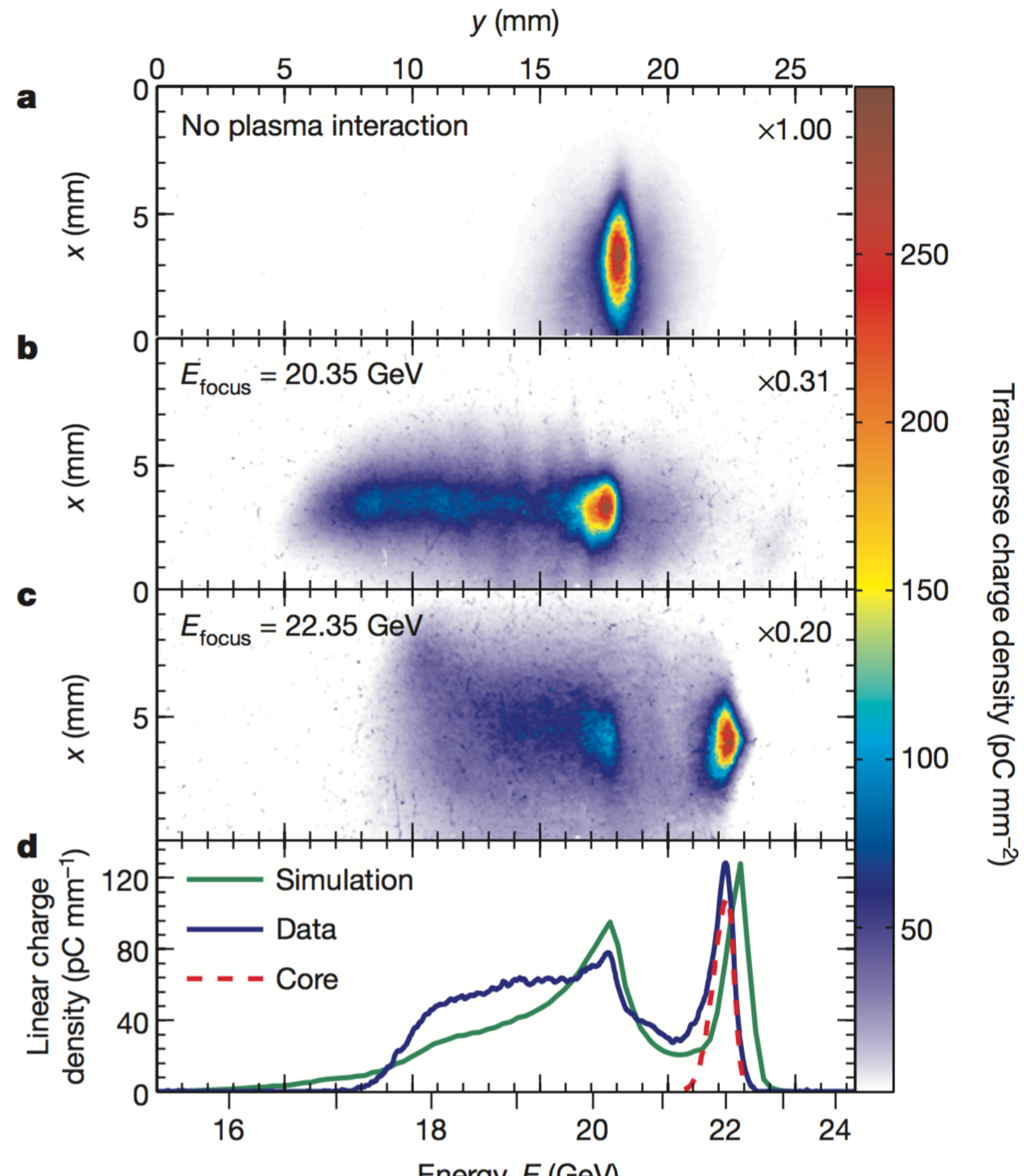
> **Challenging measurements:**
- Pulse length, average current
- Transverse emittance

> **Unmeasured properties:**
- Longitudinal phase-space
- Slice emittance

State-of-the-art in beam-driven plasma wakes: efficient witness acceleration at FACET

→ M. Litos et al., Nature 515, 92 (2014)





Driver bunch

- 20.35 GeV energy
- 4.9 kA peak current
- 1 nC charge

Witness bunch

- accelerated by 1.7 GeV with gradient of 5 GV/m
- energy transfer efficiency from driver to witness exceeding 30%
- down to 0.7% rms energy spread

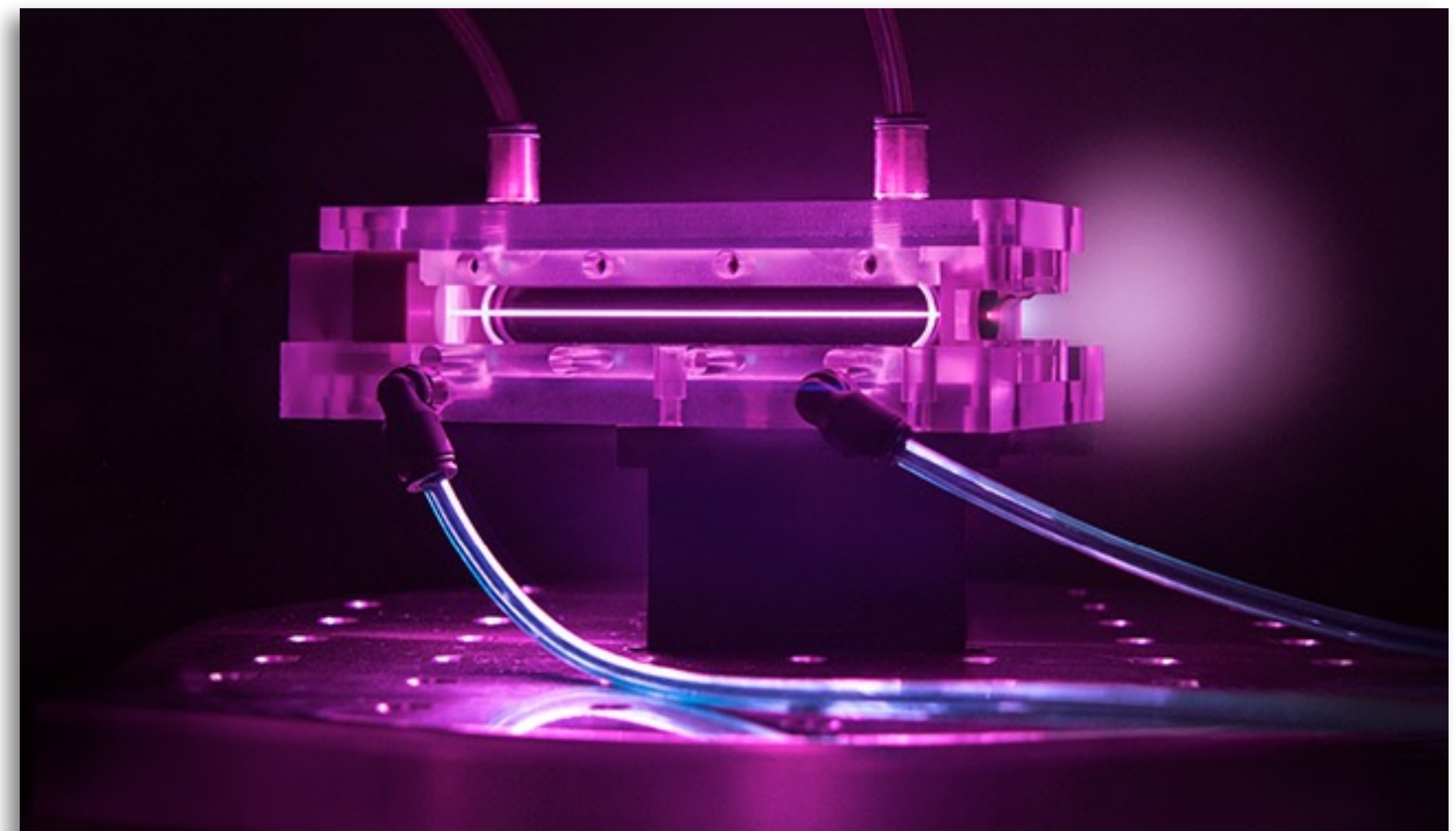
Not detected

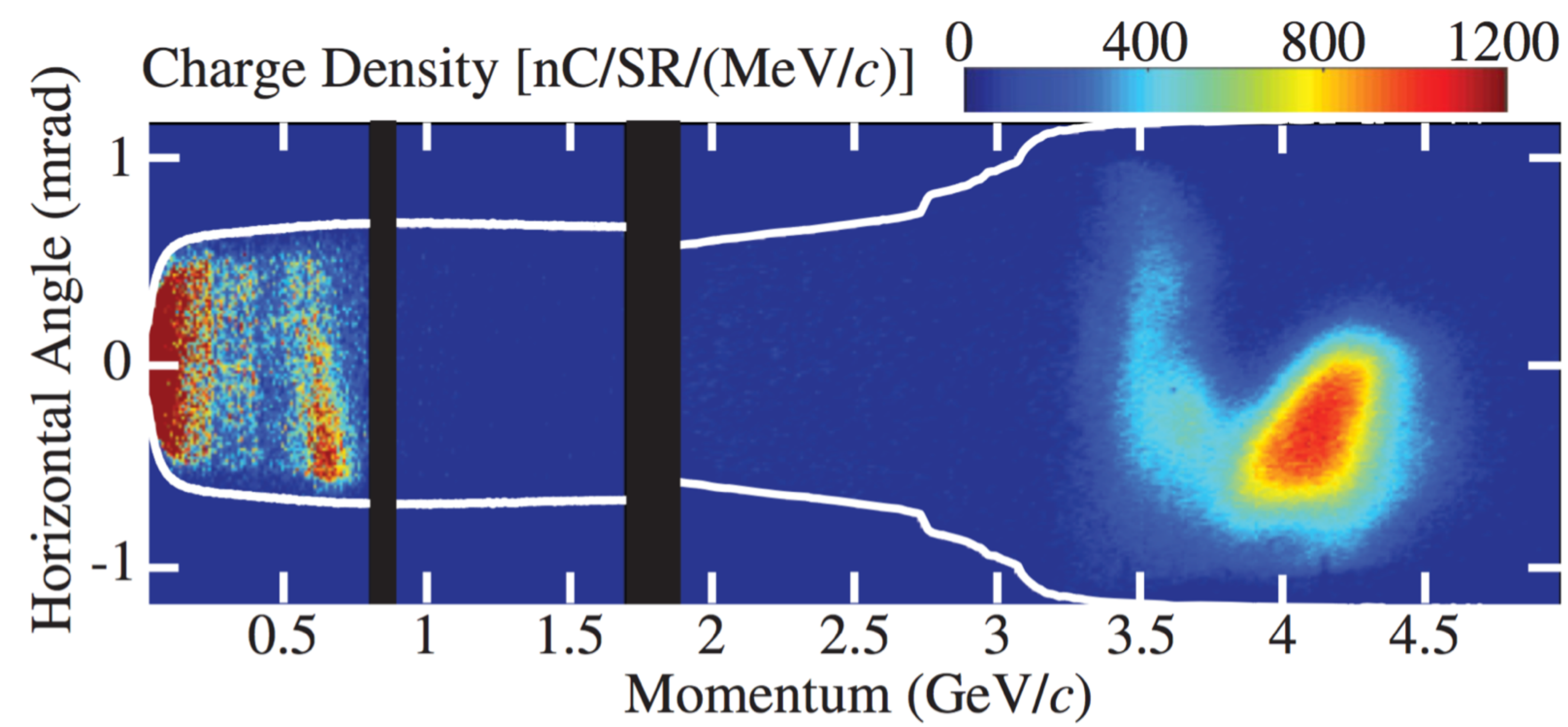
- witness emittance
- longitudinal properties

State-of-the-art in laser-driven plasma wakes: energy record at BELLA

→ W.P. Leemans et al., Phys. Rev. Lett. 113, 245002 (2014)

Capillary discharge waveguide, 9 cm





Laser

- 300 TW peak power, 16 J, 40 fs FWHM
- Ti:sapphire

Electron bunch

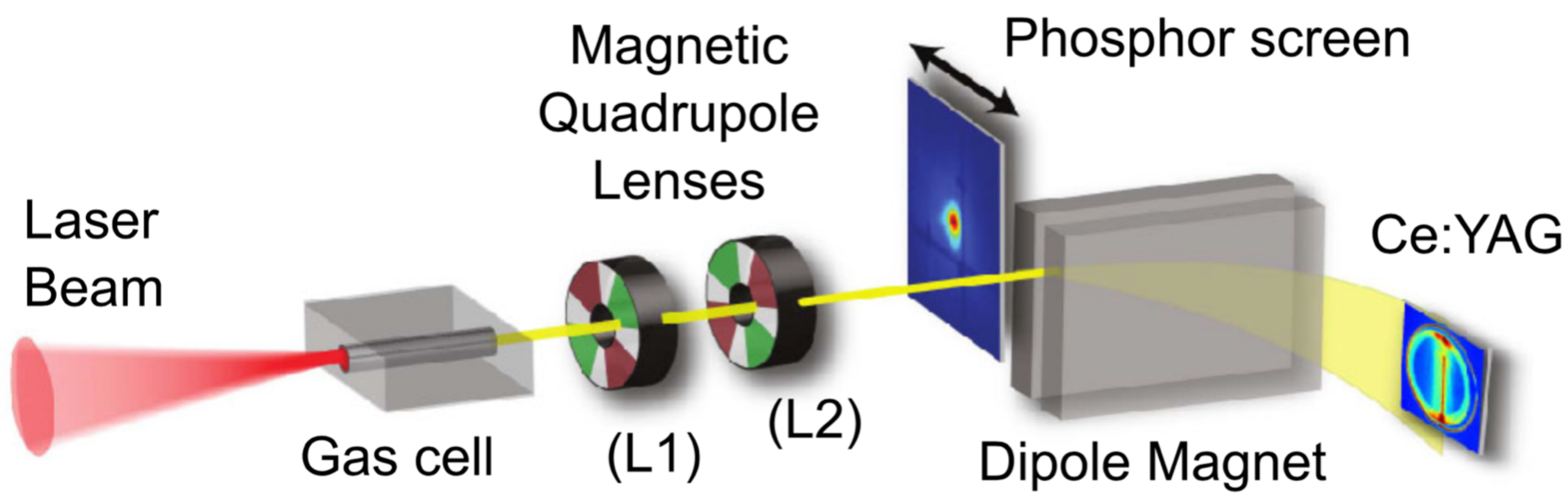
- acceleration with 47 GV/m
- here: 4.2 GeV, 6% rms energy spread, 6 pC charge
- up to 180 pC at 3 GeV

Not detected

- witness emittance
- longitudinal properties

Beam emittance measurement by quadrupole scan

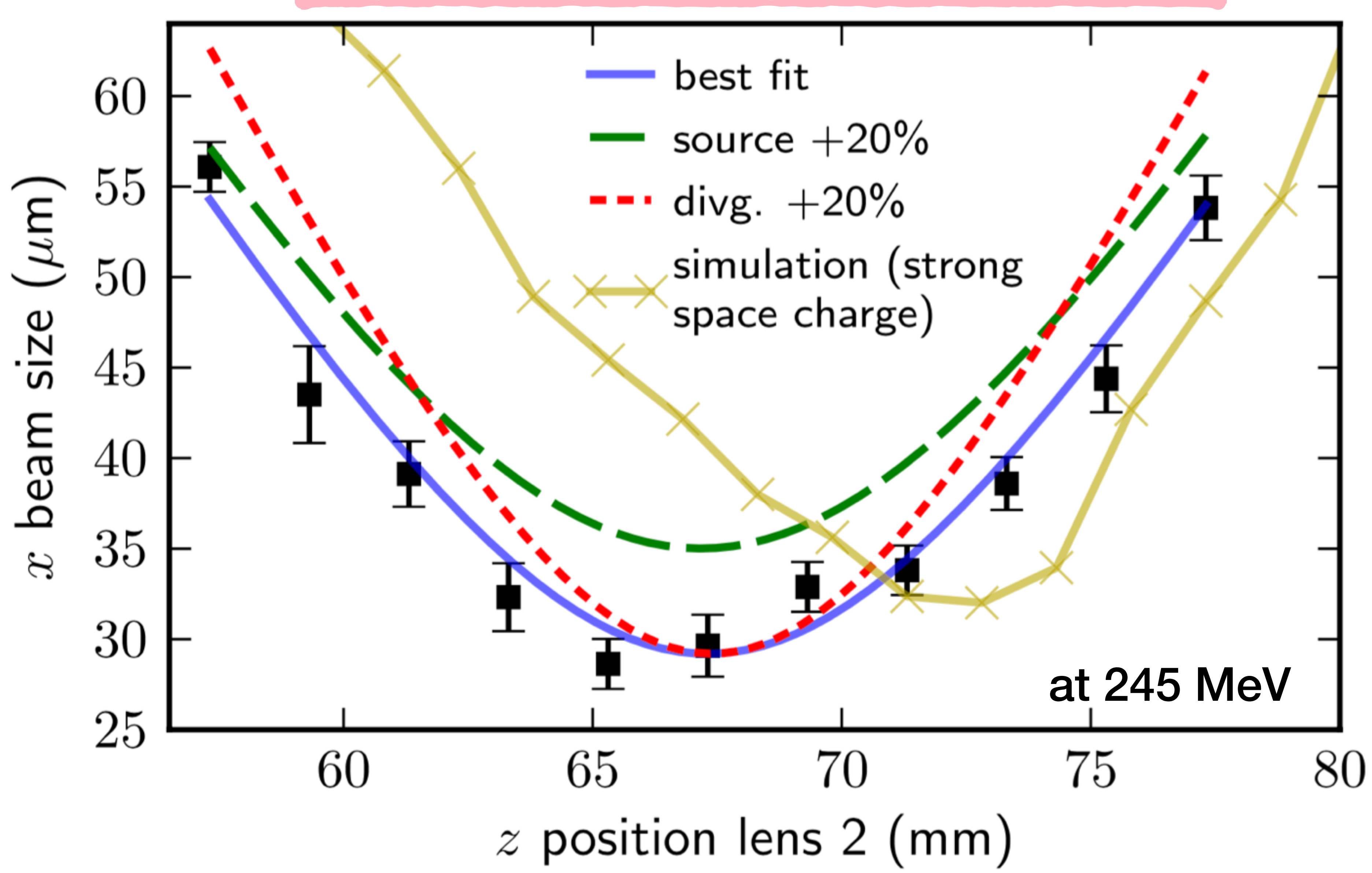
→ R. Weingartner et al., PRSTAB 15, 111302 (2012)



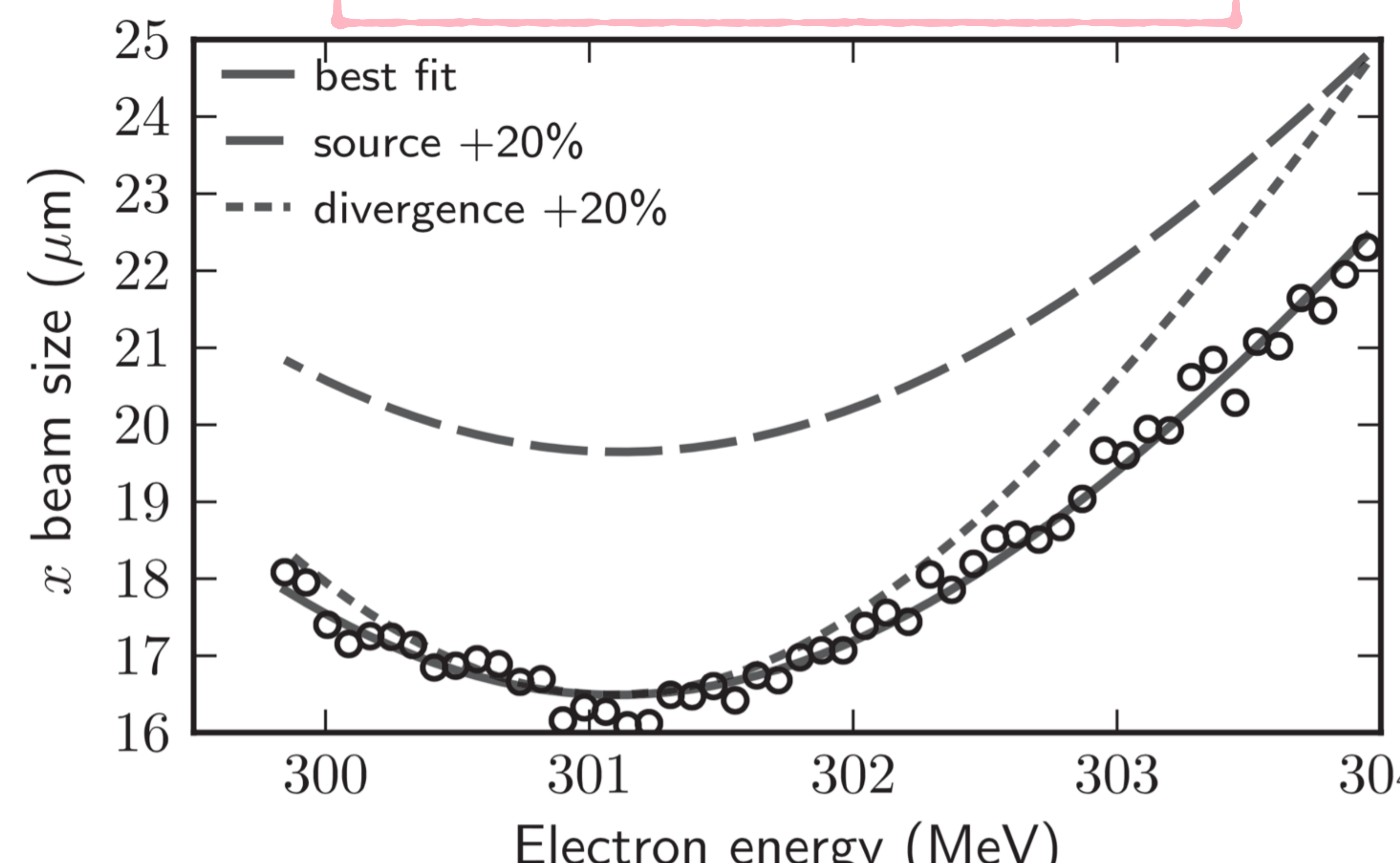
- Beam envelope

$$\sigma(s_1)^2 = M_{11}^2 \epsilon\beta(s_0) - 2M_{11}M_{12}\epsilon\alpha(s_0) + M_{12}^2 \epsilon\gamma(s_0).$$

$$\epsilon_0 = 0.21 \pm 0.02 \text{ mm mrad}$$

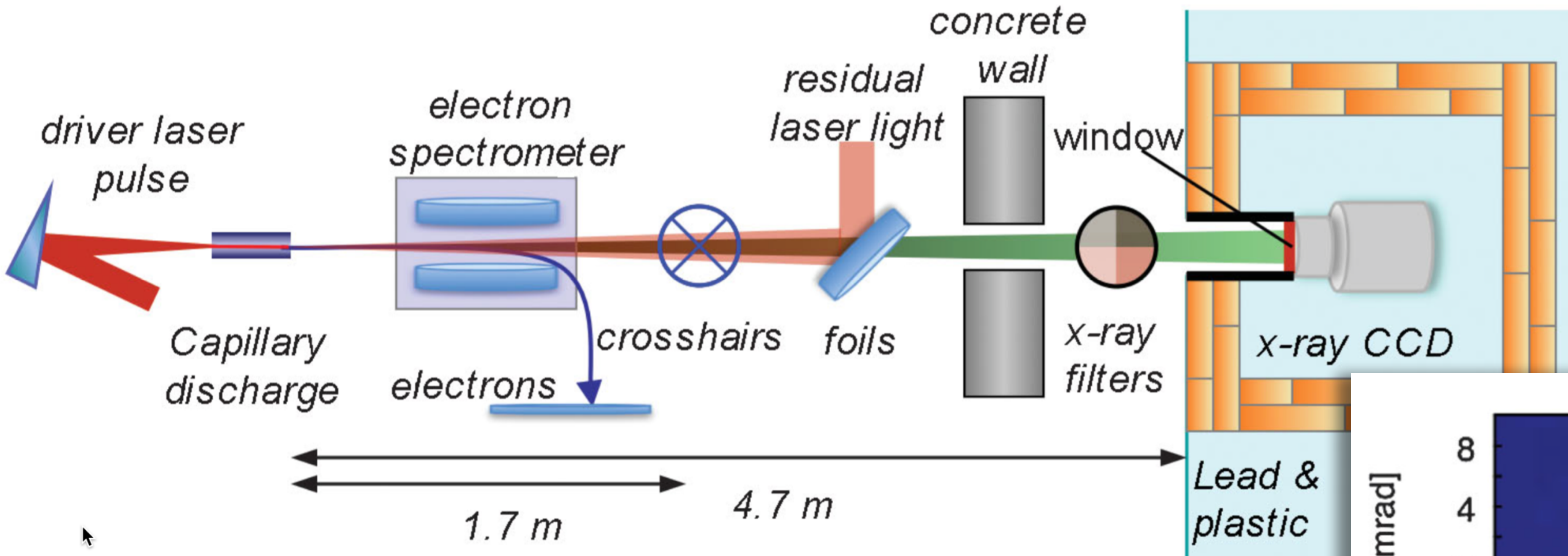


$$\epsilon_0 = 0.14 \pm 0.01 \text{ mm mrad}$$



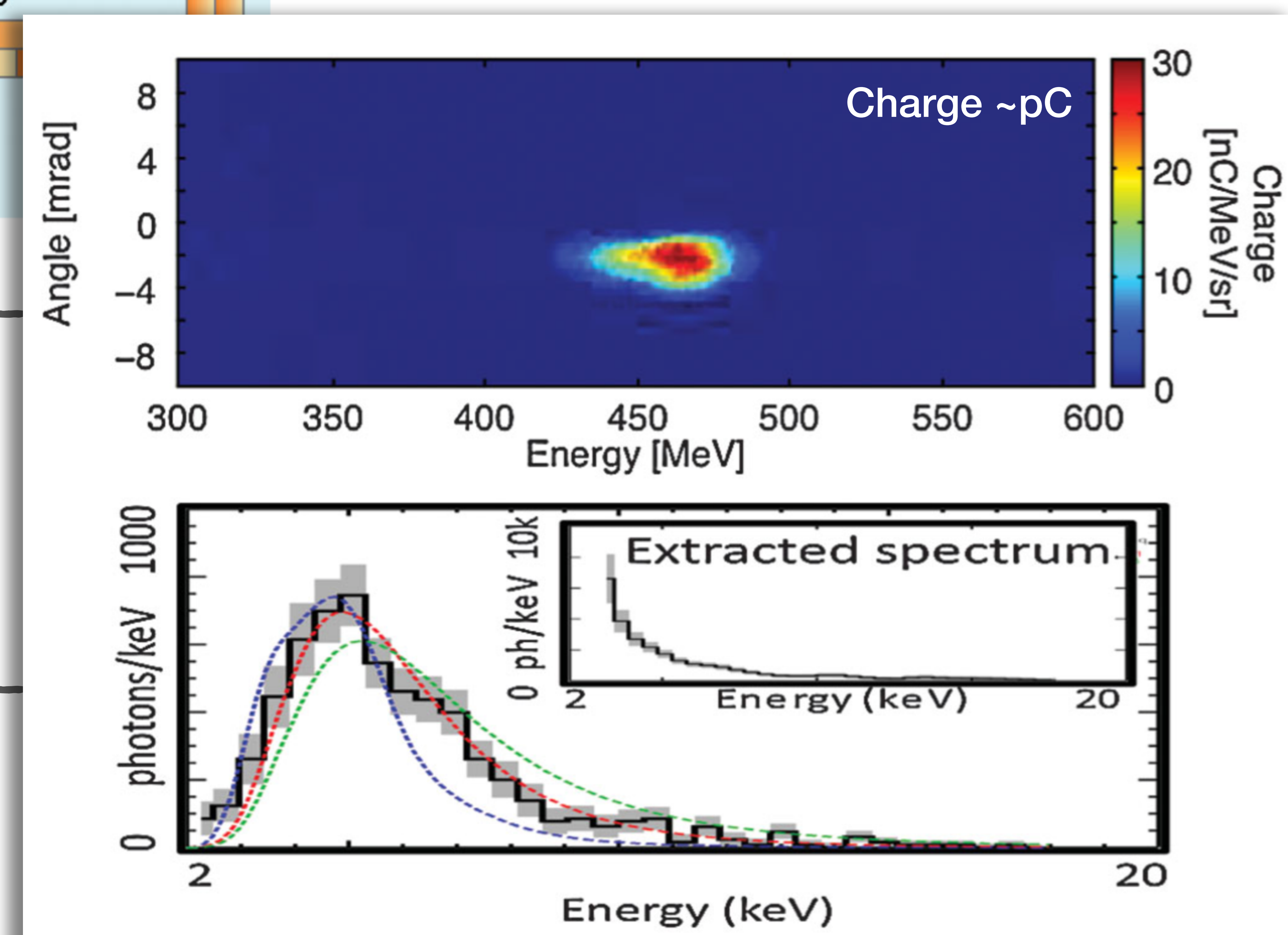
Betatron-radiation based source-size detection

→ G.R. Plateau et al., PRL 109, 064802 (2012)



Spectral shape determined by betatron strength parameter

$$a_\beta \propto \sqrt{\gamma n_e} r_\beta$$



$$\sigma_\theta = 1.2\,\mathrm{mrad\ rms}$$

$$\boxed{\epsilon_{0,x} \approx \beta\gamma\sigma_x\sigma_\theta \sim 0.1\ \mathrm{mm\ mrad}}$$

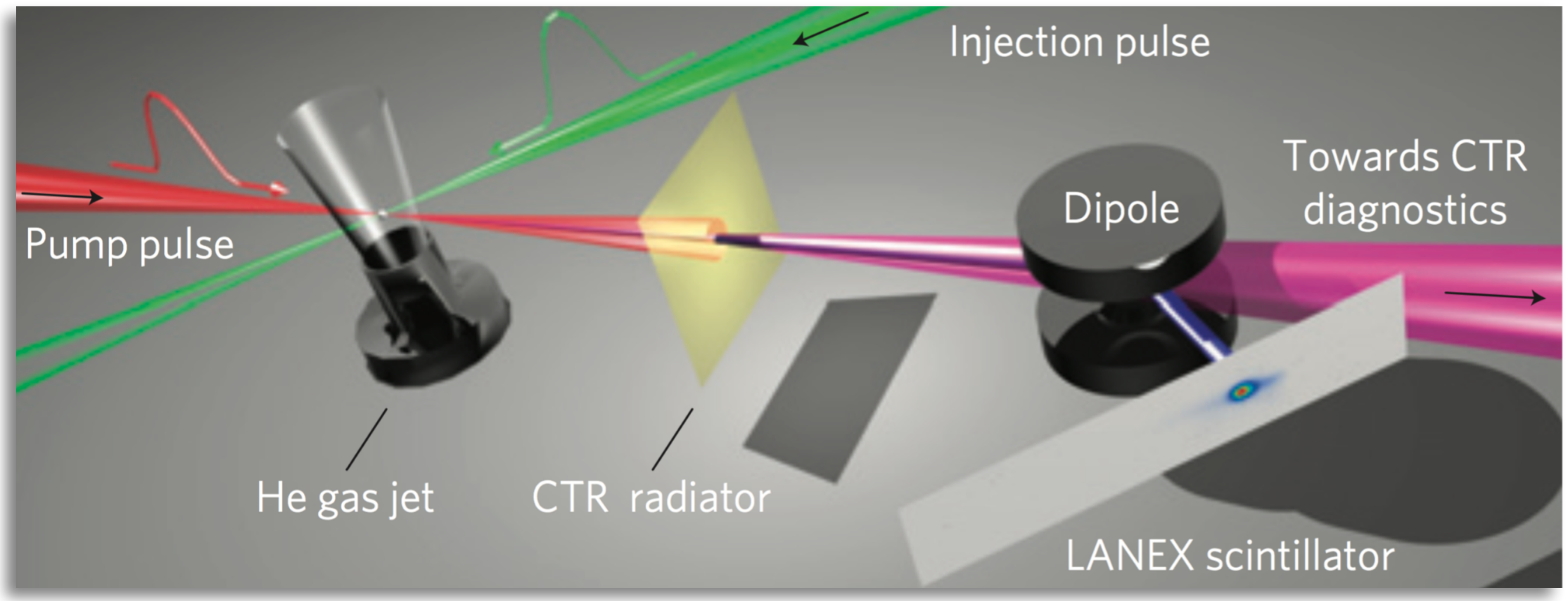
$$\sigma_x = 0.1\ \mu\mathrm{m}$$

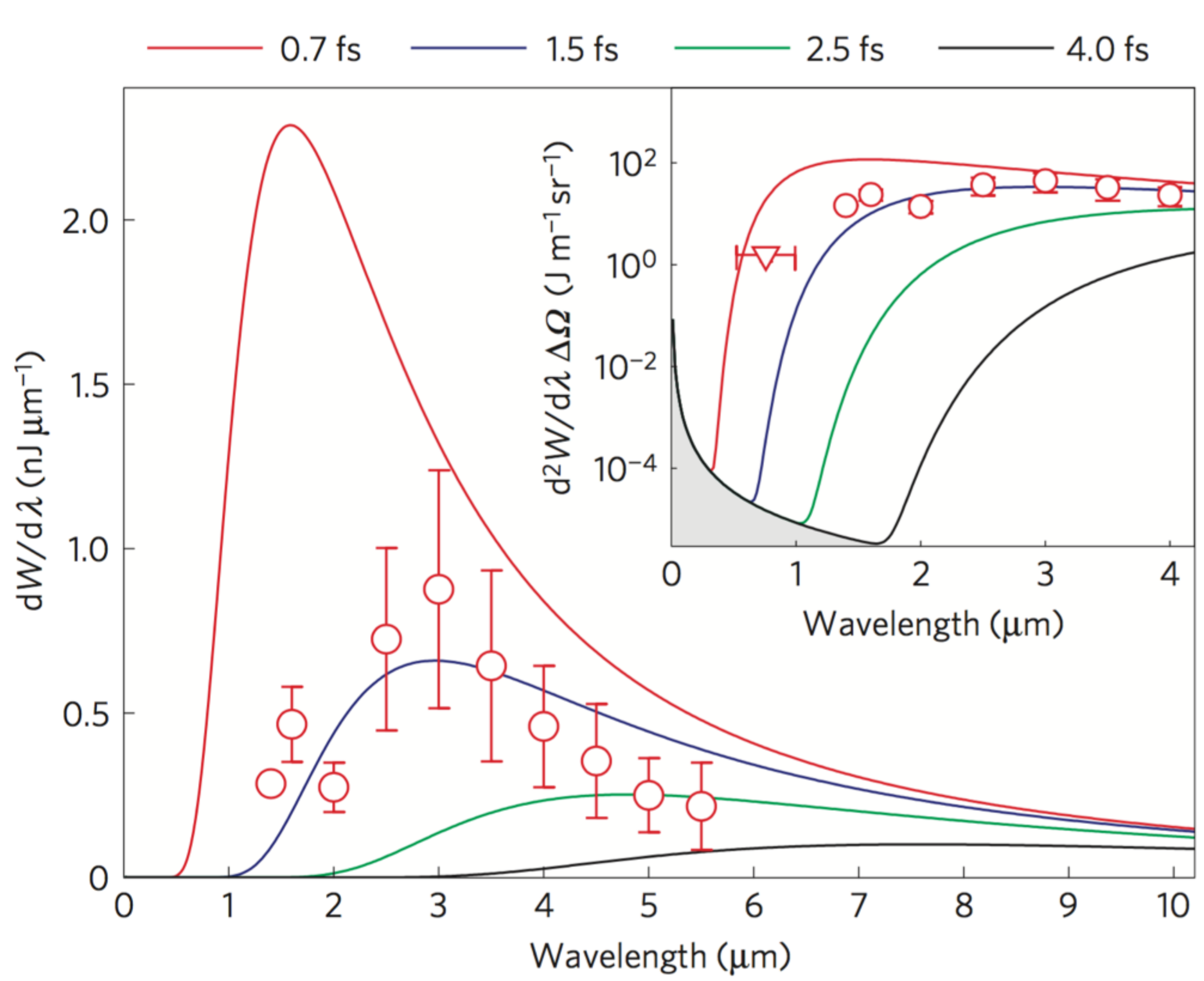
error ~50%

Assumptions

- Insignificant influence of plasma transition on beam divergence
- Beam matched to plasma wake (is at waist)

Form factor measurements by coherent transition radiation spectroscopy





Longitudinal bunch properties

- 1.4 to 1.8 fs rms bunch length
- 3 to 4 kA peak current

→ O. Lundh et al., Nature Physics 7, 219 (2011)

$$\frac{d^2W}{d\omega d\Omega} = \left[N + N^2 F(\omega,\theta)\right] \frac{d^2w}{d\omega d\Omega}$$

From factor contains information about bunch length and shape

- Form factor is squared amplitude of Fourier transform of electron bunch distribution
- Exact bunch shape reconstruction requires solution to 1D phase-retrieval problem

  Not solvable!
  → E. J. Akutowicz, Trans. Am. Math. Soc. 83,234 (1956)
- Phase retrieval algorithms (e.g. Kramers Kronig) give idea about bunch duration, sub-structure, but are ambiguous
- Thus, time-domain measurements preferable
  → transverse RF-deflector with sub-fs resolution
  → has not been done yet

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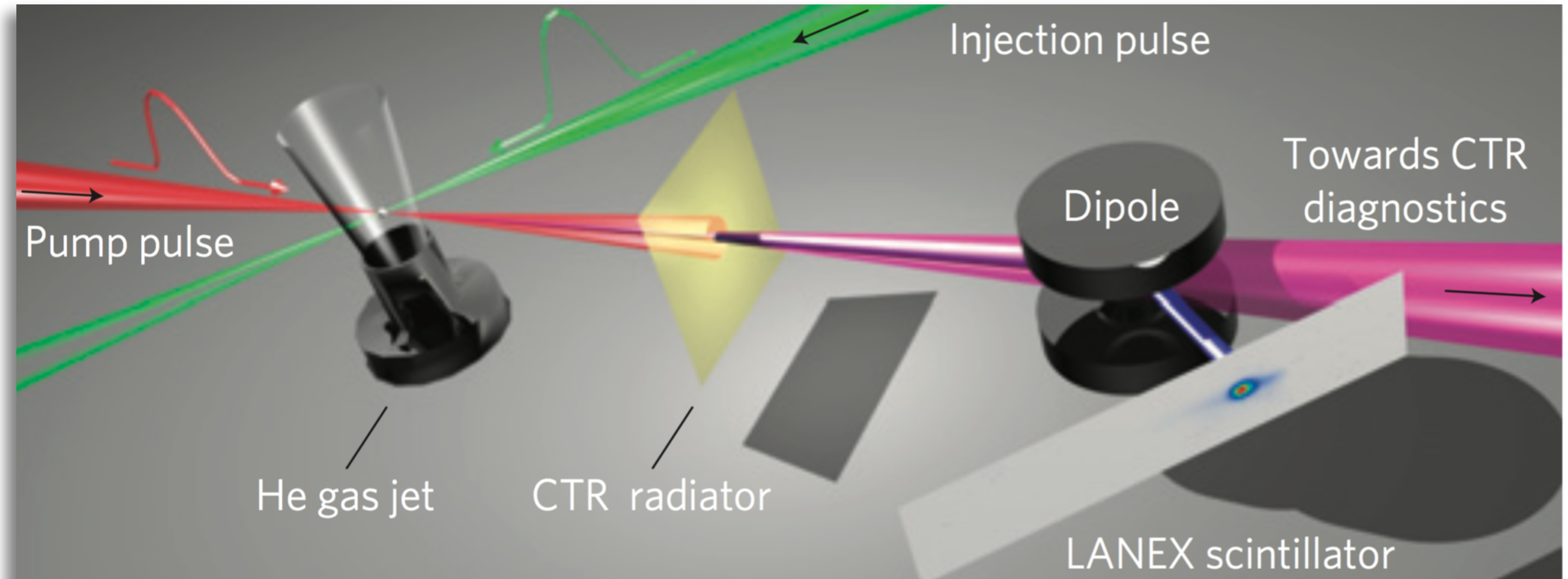

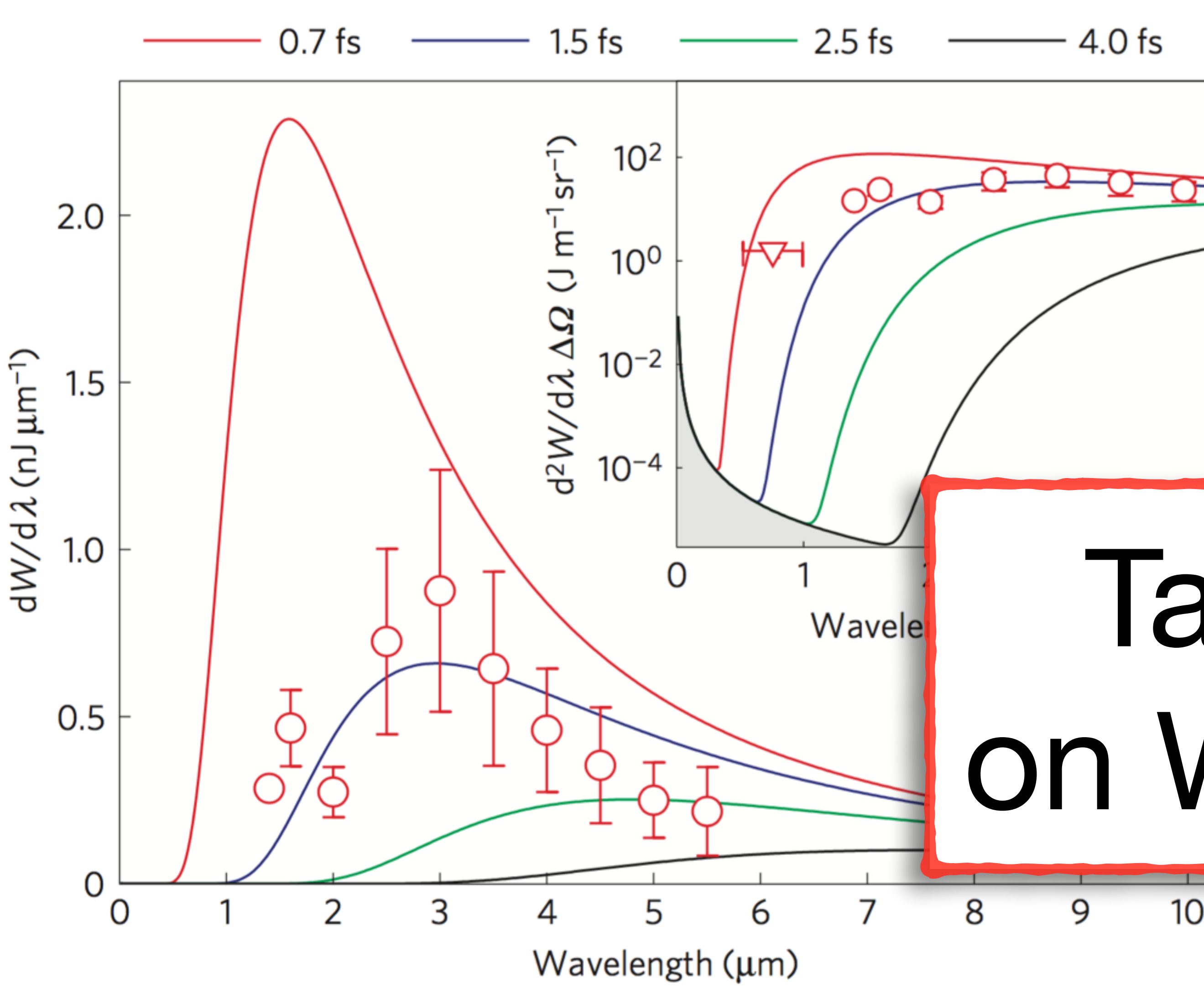

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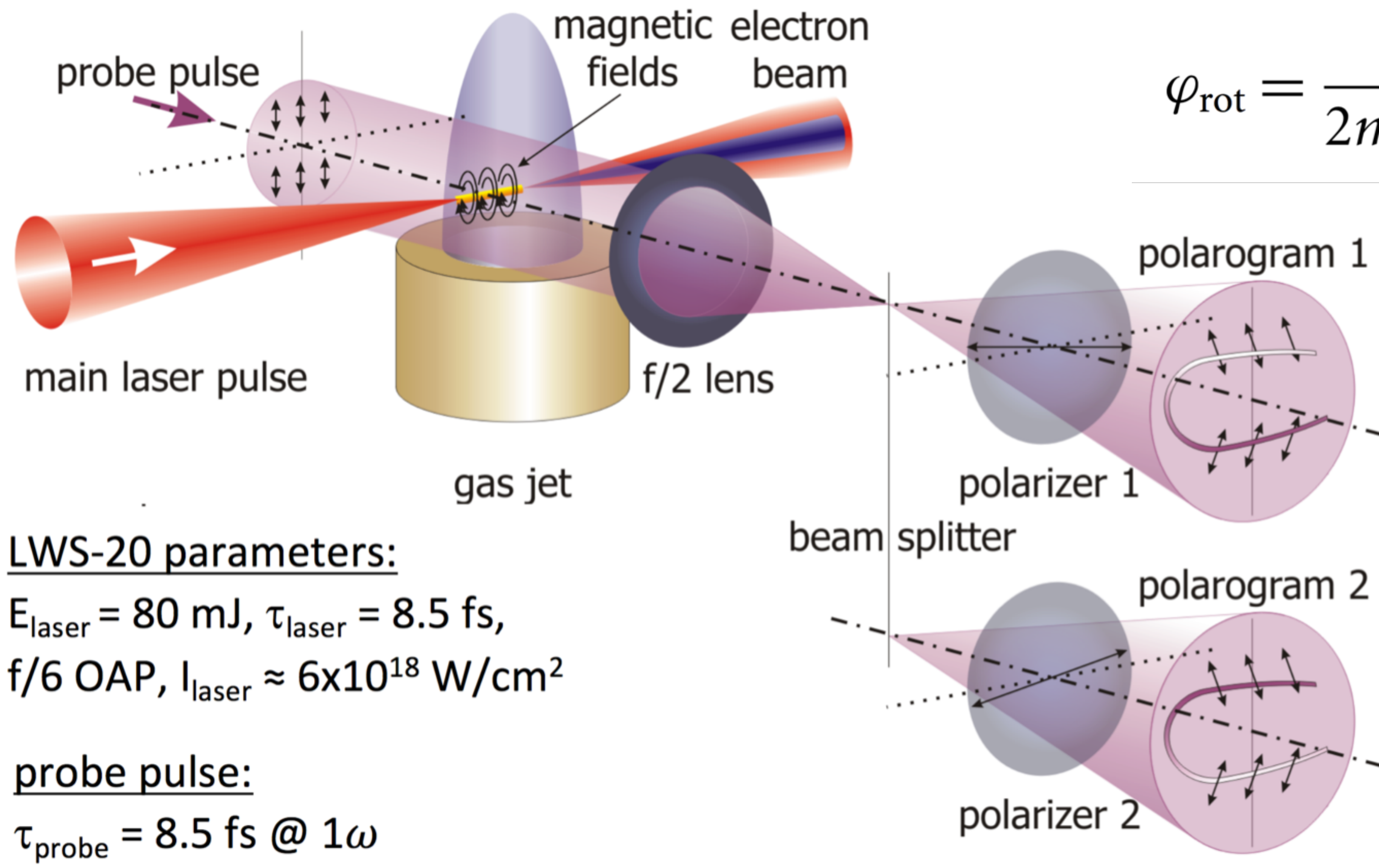
Talk by I. Dornmair, on Wednesday 2:30pm

Thus, time-domain measurements preferable
→ transverse RF-deflector with sub-fs resolution
→ has not been done yet

In-plasma bunch duration measurements by transverse laser probing

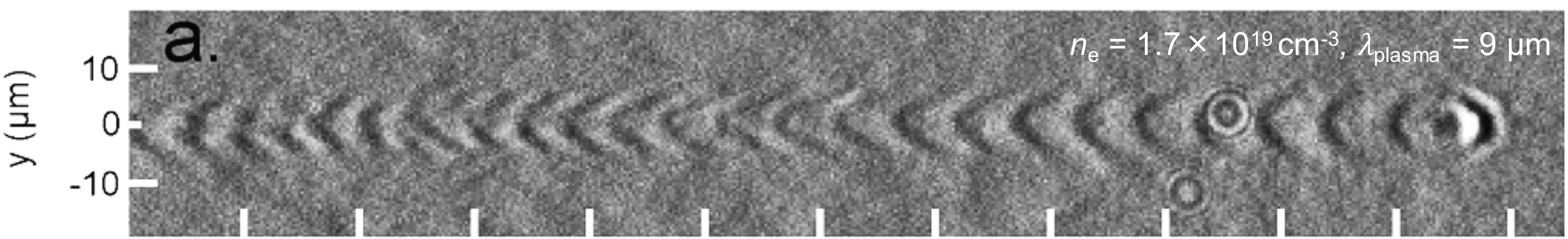
→ A. Buck et al., Nature Physics 7, 543 (2011)



$$\varphi_{\mathrm{rot}} = \frac{e}{2m_e c n_c}\int_l n_e \mathbf{B}_\varphi \cdot d\mathbf{s}$$

<u>LWS-20 parameters:</u>
E_{laser} = 80 mJ, τ_{laser} = 8.5 fs,
f/6 OAP, $I_{laser} \approx 6\times10^{18}$ W/cm^2

<u>probe pulse:</u>
τ_{probe} = 8.5 fs @ 1ω



M. Schnell *et al.*, Nat. Comm. **4**, 2421 (2013)

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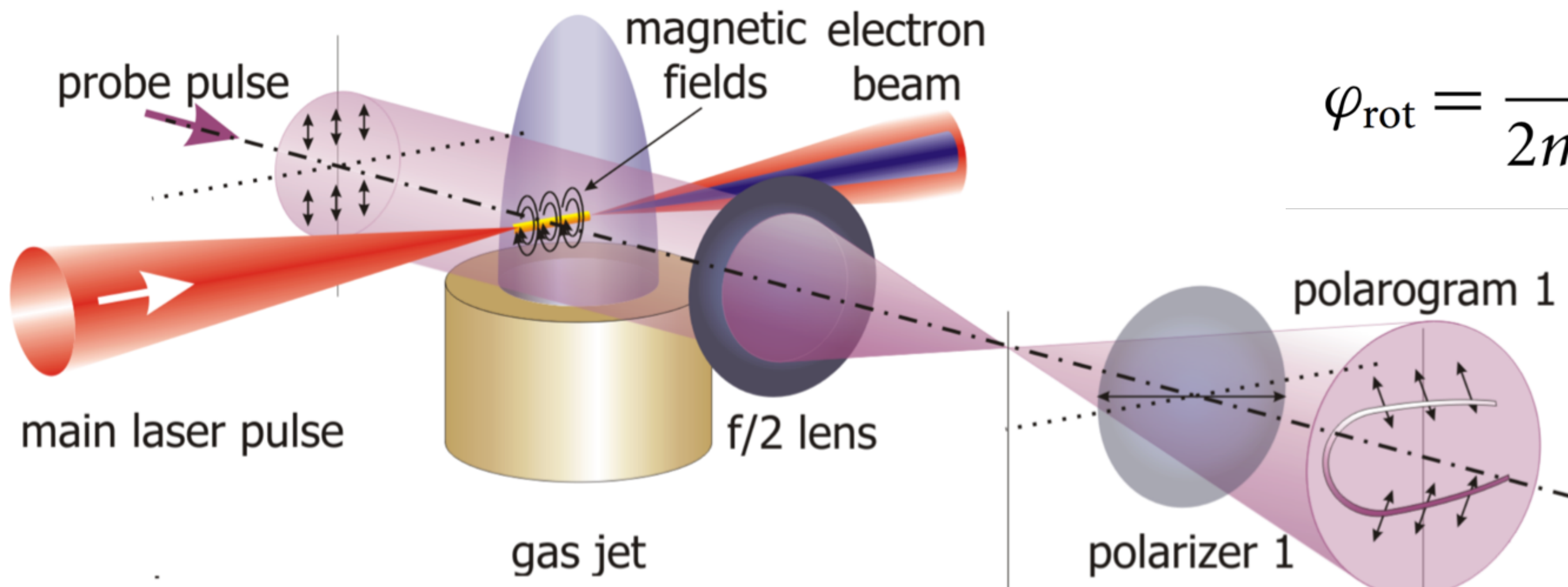

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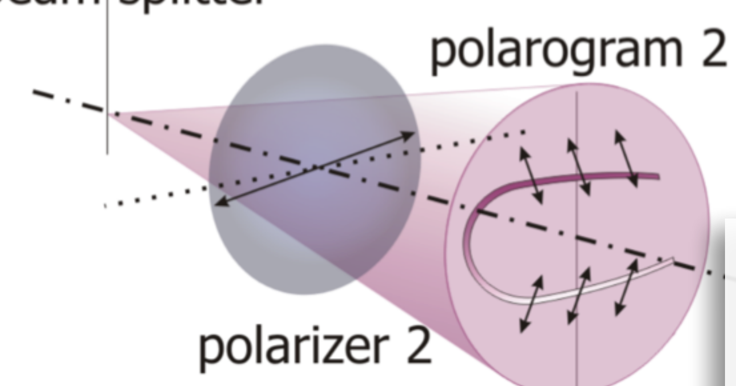

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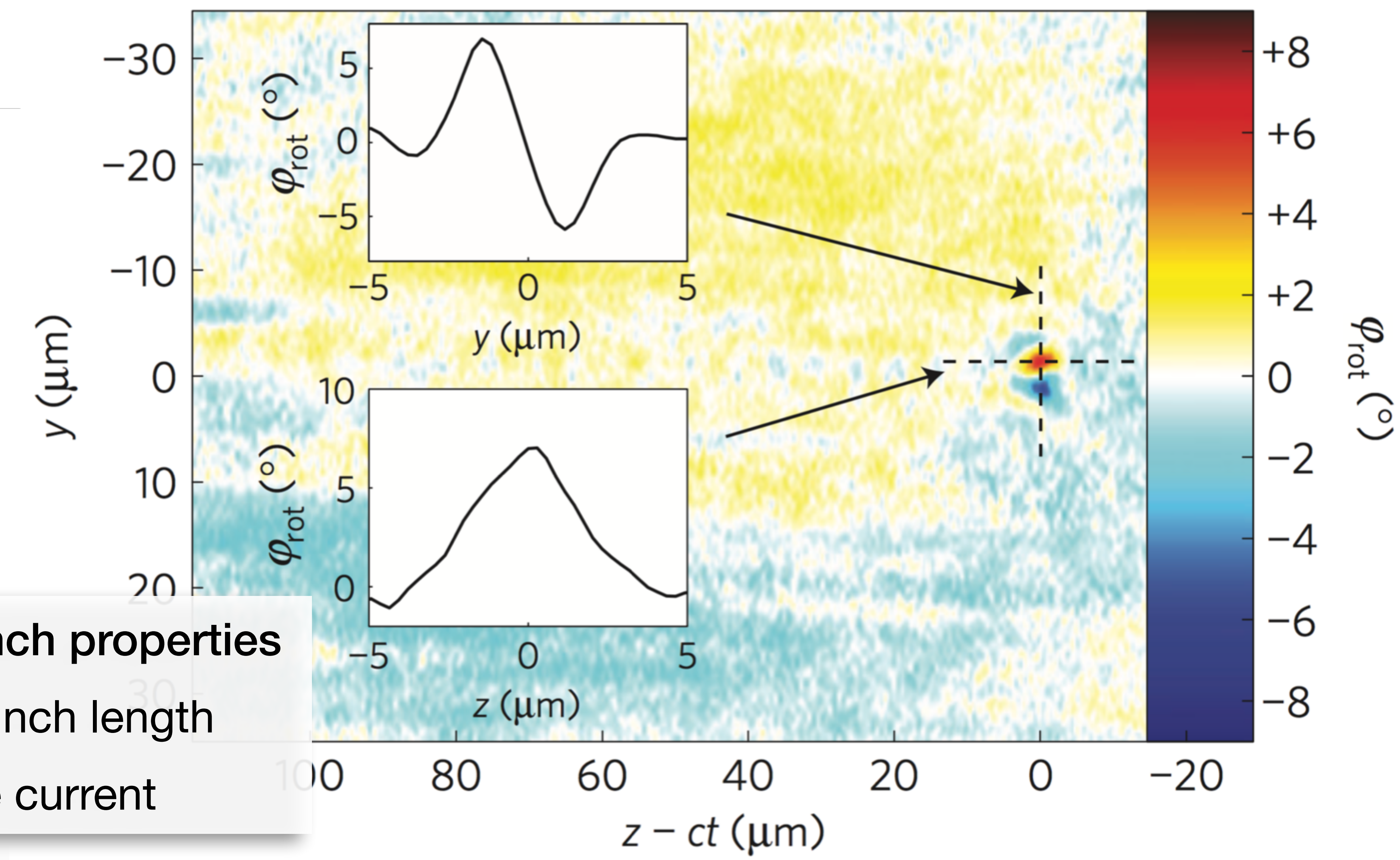
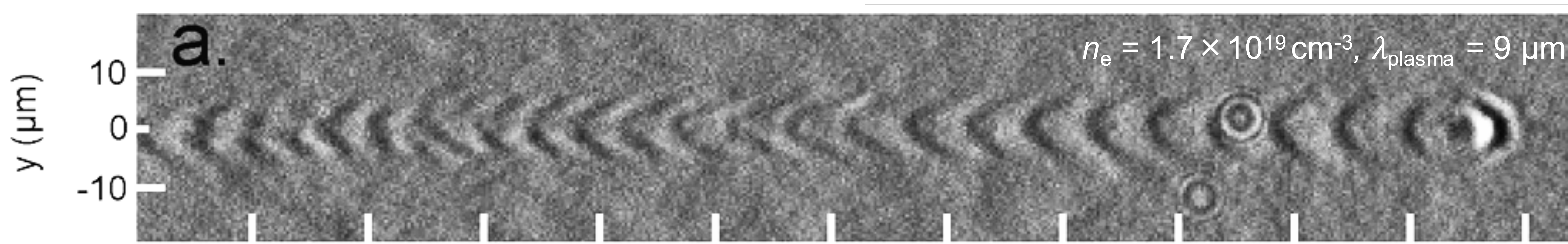


Longitudinal bunch properties

- 2.5 fs rms bunch length
- 1 kA average current



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The next-generation beam-driven plasma accelerator: FLASHFORWARD▸▸ at DESY

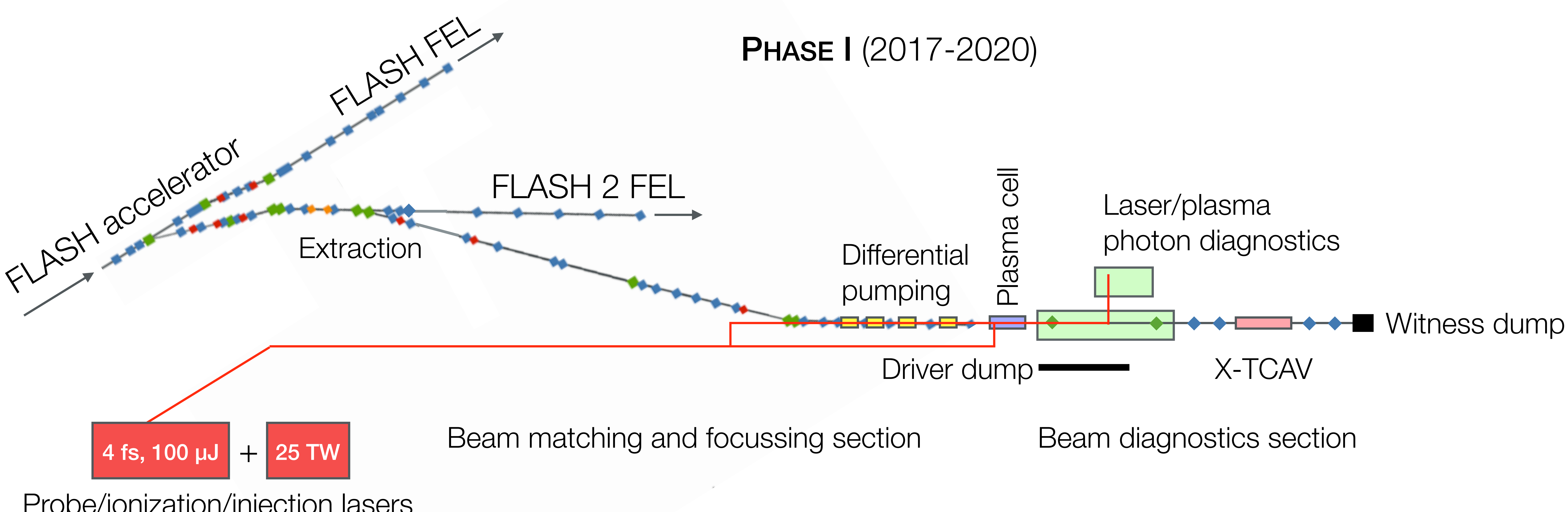
→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)

FLASHForward is

- an extension to the FLASH 1.2 GeV superconducting RF FEL facility
- a new ***experiment for beam-driven plasma wakefield accelerator research***

Scientific 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



- boost FLASH to ~2 GeV with high efficiency (30%), **conserve emittance and energy spread**
- generate **high-quality beams** in plasma with **low emittance** (≤ 100 nm) **at** > 1.5 GeV
- **characterize longitudinal phase-space and slice emittance properties**

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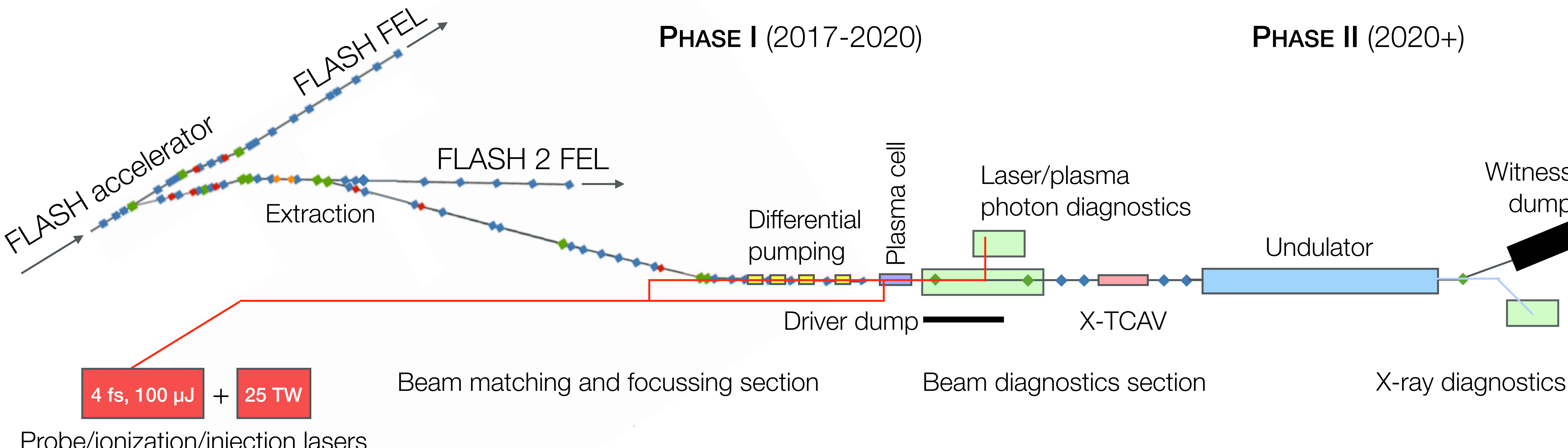

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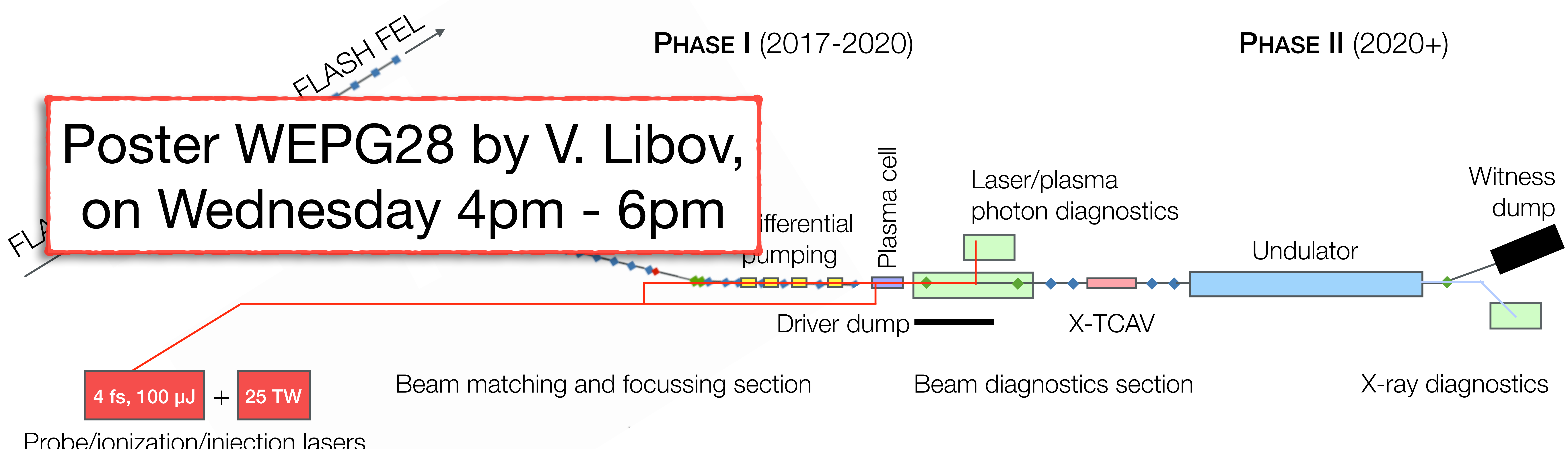

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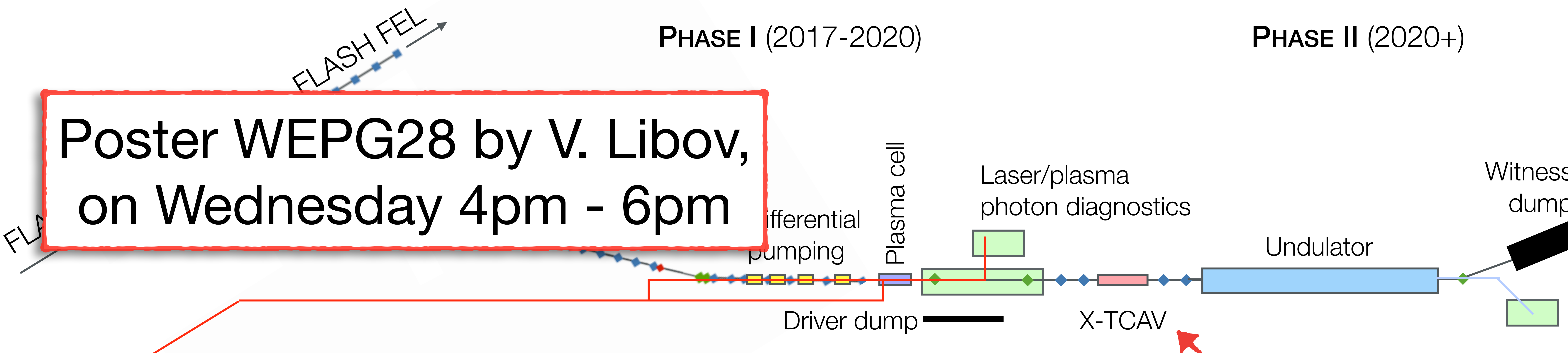

Poster WEPG28 by V. Libov, on Wednesday 4pm - 6pm

Poster WEPG51 by R. D'Arcy, on Wednesday 4pm - 6pm

- boost FLASH to ~2 GeV with
- generate **high-quality beams**
- characterize longitudinal phase-space and slice emittance properties

Summary

- Plasma wakefield technology offers a promising path to compact accelerators with > 10 GV/m fields
- Two alternative driver technologies: laser- and beam-excited plasma wakes
- Both techniques may generate beams of extreme properties: sub-fs duration, kA currents, 100 nm emittance

- **Existing diagnostic techniques have been adapted**
  - form-factor detection down to ~1 fs bunch length
  - quadrupole scans for emittance measurements

- **Innovative diagnostic techniques have been developed**
  - ultra-short-laser imaging of electron beams in plasma by Faraday rotation
  - betatron-radiation-based source size measurements

- **A full temporal characterization is challenging**
  - sub-femtosecond resolution required → longitudinal phase space
  - diagnostics exist (X-band deflector), require accelerator know-how, and are expensive (comparable to complete laser-plasma accelerator!)

FLASHForward▸▸ scientific project contributors

> Core FLASHForward team

Engineers and technicians

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Sven Karstensen
Frank Marutzky
Amir Rahali
Andrej Schleiermacher

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John Dale
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Alberto Martinez de la Ossa
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Jan-Patrick Schwinkendorf
Gabriele Tauscher

Students

Dennis Borrisenko
Gregor Indorf
Paul Pourmoussavi
Martin Quast
Jelto Thesinga
Stefan Weichert

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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
Friedrich-Schiller-Universität Jena, Germany

> DESY technical support groups