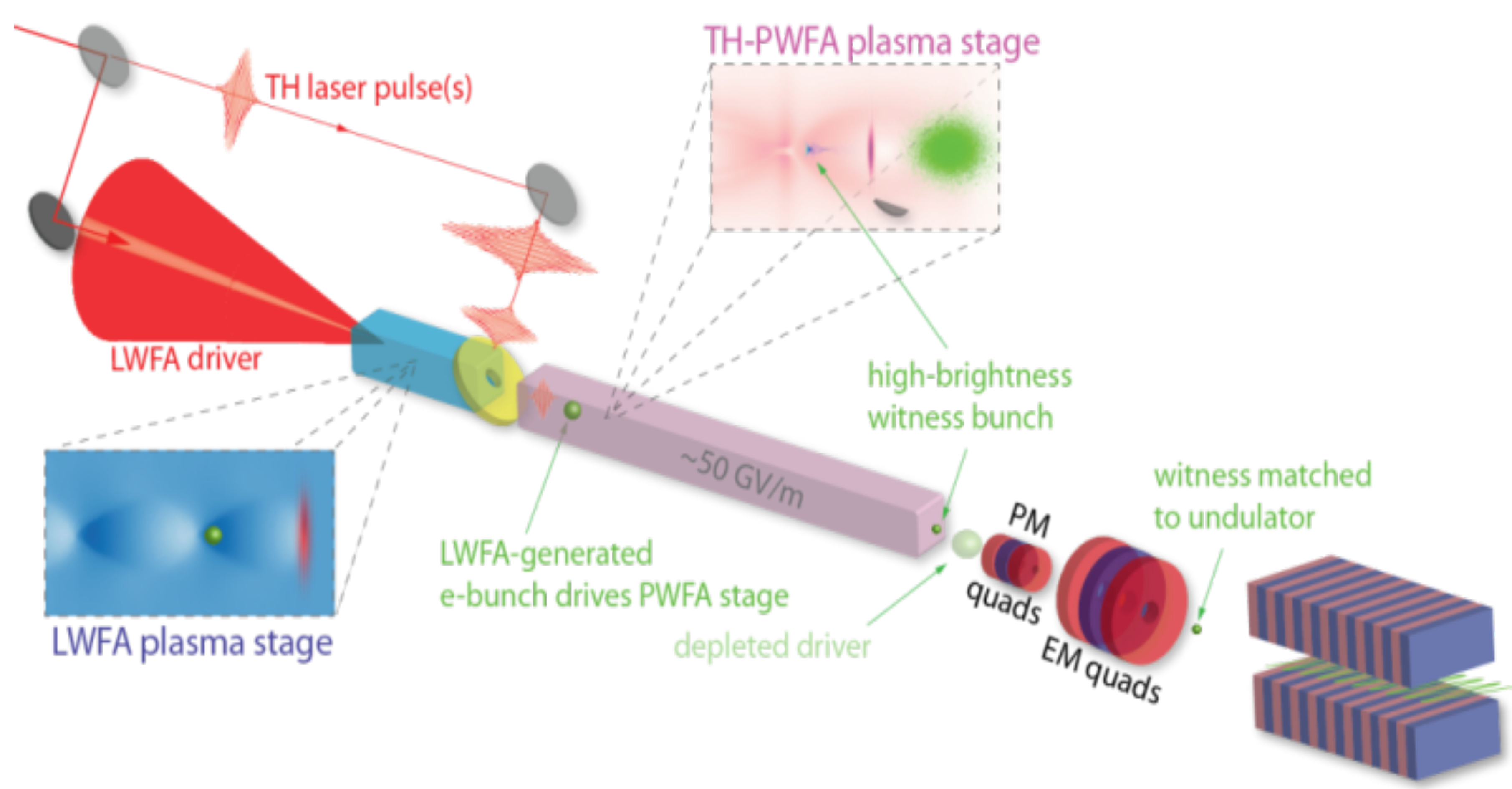
General goals

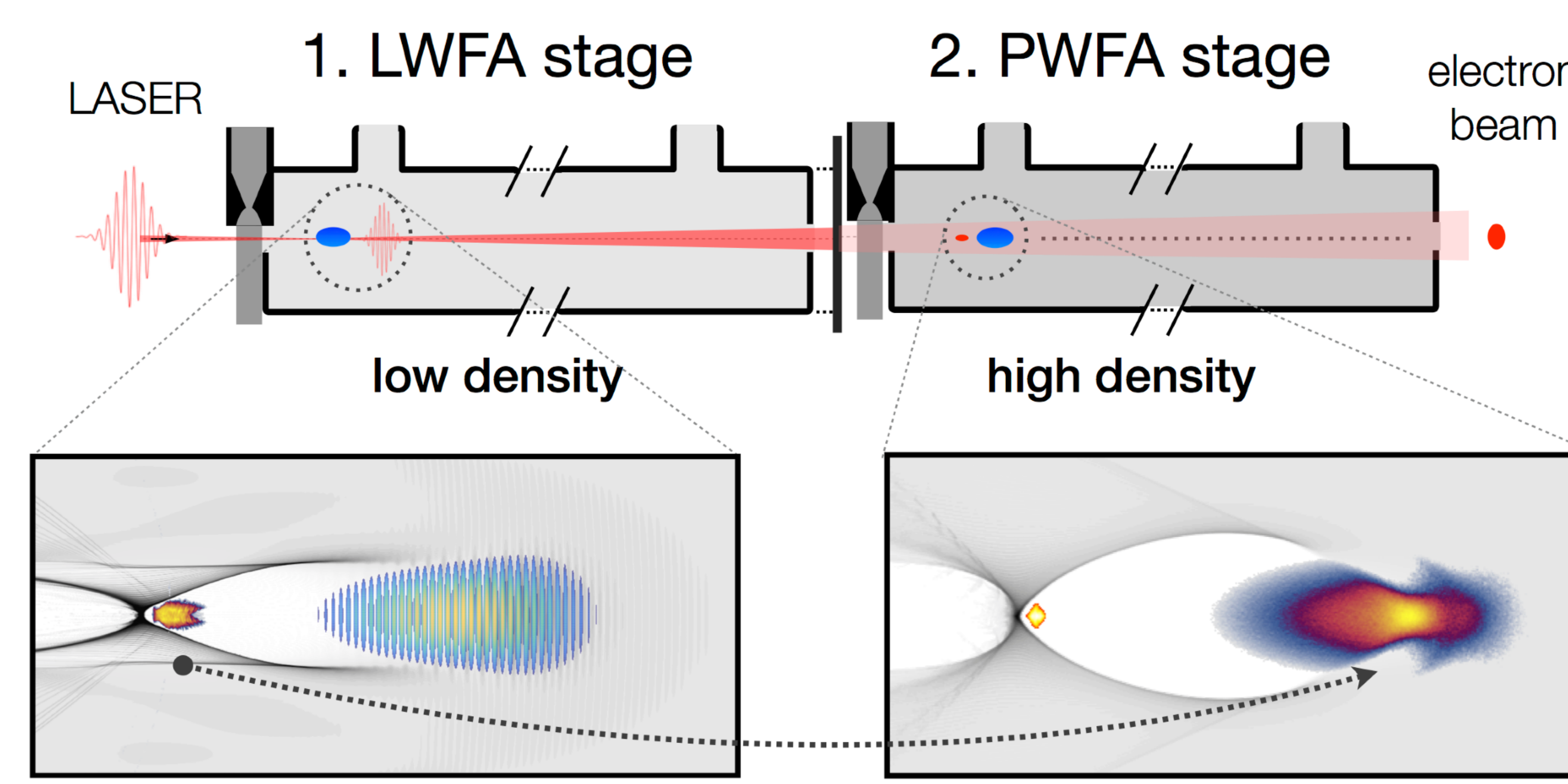
- ➤ Production of stable, high-current (≳ 8.5 kA), GeV-class electron beams from LWFA.
- ➤ Injection and acceleration of high-quality electron beams in a PWFA stage driven by the LWFA beam.

Energy and quality booster for the production of multi-GeV FEL capable beams

Conceptual designs



B. Hidding et al., Phys. Rev. Lett. 104, 195002 (2010).
B. Hidding et al., Phys. Rev. Lett. 108, 035001 (2012).



A. Martinez de la Ossa et al., Phys. Rev. Lett. 111, 245003 (2013).
A. Martinez de la Ossa et al., Phys. Plasmas 22, 093107 (2015).

WP14 Hybrid Laser-Electron-Beam Driven Acceleration: **Tasks and deliverables**

- **Task 14.1.** Selective ionization of plasma components.
  - ↳ Experimental determination of ionisation rates triggered by a laser.
  - ↳ Selection of most promising species for internal injection in both LWFA and PWFA modules.
  - ↳ **Deliverable 14.1.** Design of an optimized plasma ionization module. [M18]

- **Task 14.2.** Trojan Horse underdense photocathode witness bunch generation.
  - ↳ **Deliverable 14.2.** Underdense plasma photocathode design report. [M40]

    B. Hidding et al., Phys. Rev. Lett. 108, 035001 (2012).
    A. Knetsch et al., arXiv:1412.4844v1 [physics.acc-ph].

- **Task 14.3.** Wakefield-induced ionisation injection .
  - ↳ **Deliverable 14.3.** Design report with Wakefield induced ionisation technique. [M40]

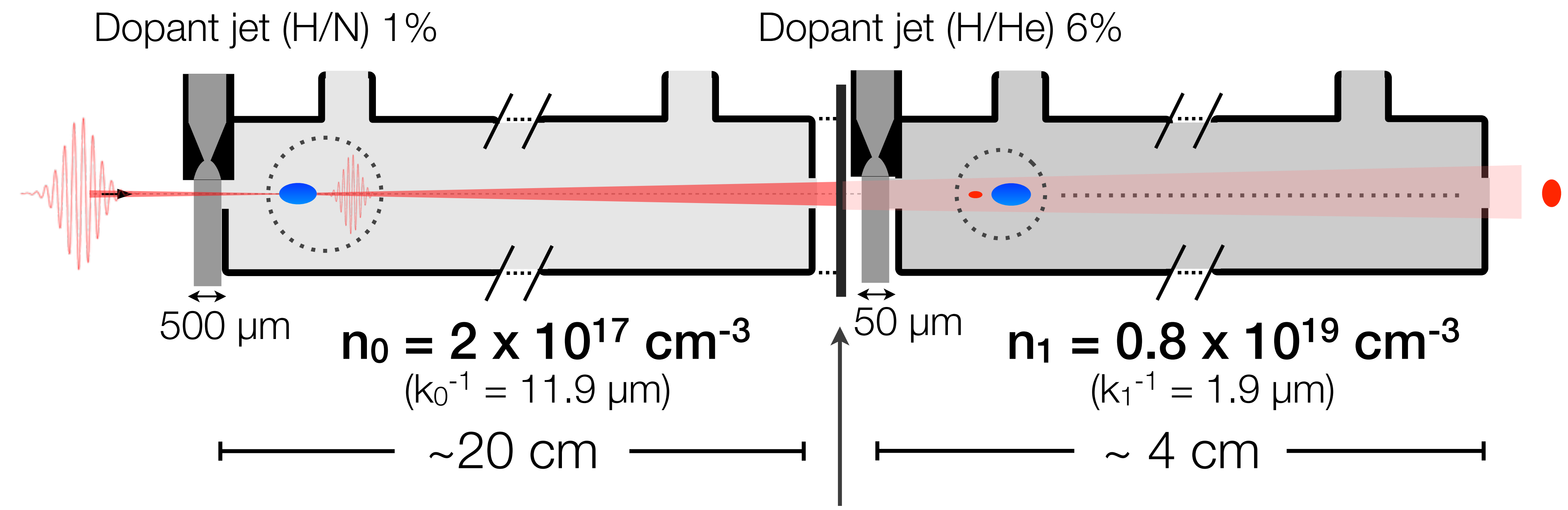
    A. Martinez de la Ossa et al., Phys. Plasmas 22, 093107 (2015).

- **Task 14.4.** Exploiting LWFA-generated electron bunches as drivers for PWFA.
  - ↳ <u>**Determination of a working point**</u> to enable internal injection in PWFA stage with LWFA produced beams.
  - ↳ <u>**Estimation of experimental tolerances**</u>
  - ↳ Studies on FEL gain capabilities with the generated bunches.
  - ↳ **Deliverable 14.4.** Conceptual design of optimized LWFA-source for PWFA-driver electron bunches. [M40]
  - ↳ **Deliverable 14.5.** Integration into EuPRAXIA Desing Report. [M46]

WP14 Hybrid Laser-Electron-Beam Driven Acceleration: **A working point (preliminary)**

Laser beam

P_0 = 500 TW
λ_0 = 800 nm
w_0 = 41 µm
a_0 = 3
τ = 100 fs
Energy = 53 J

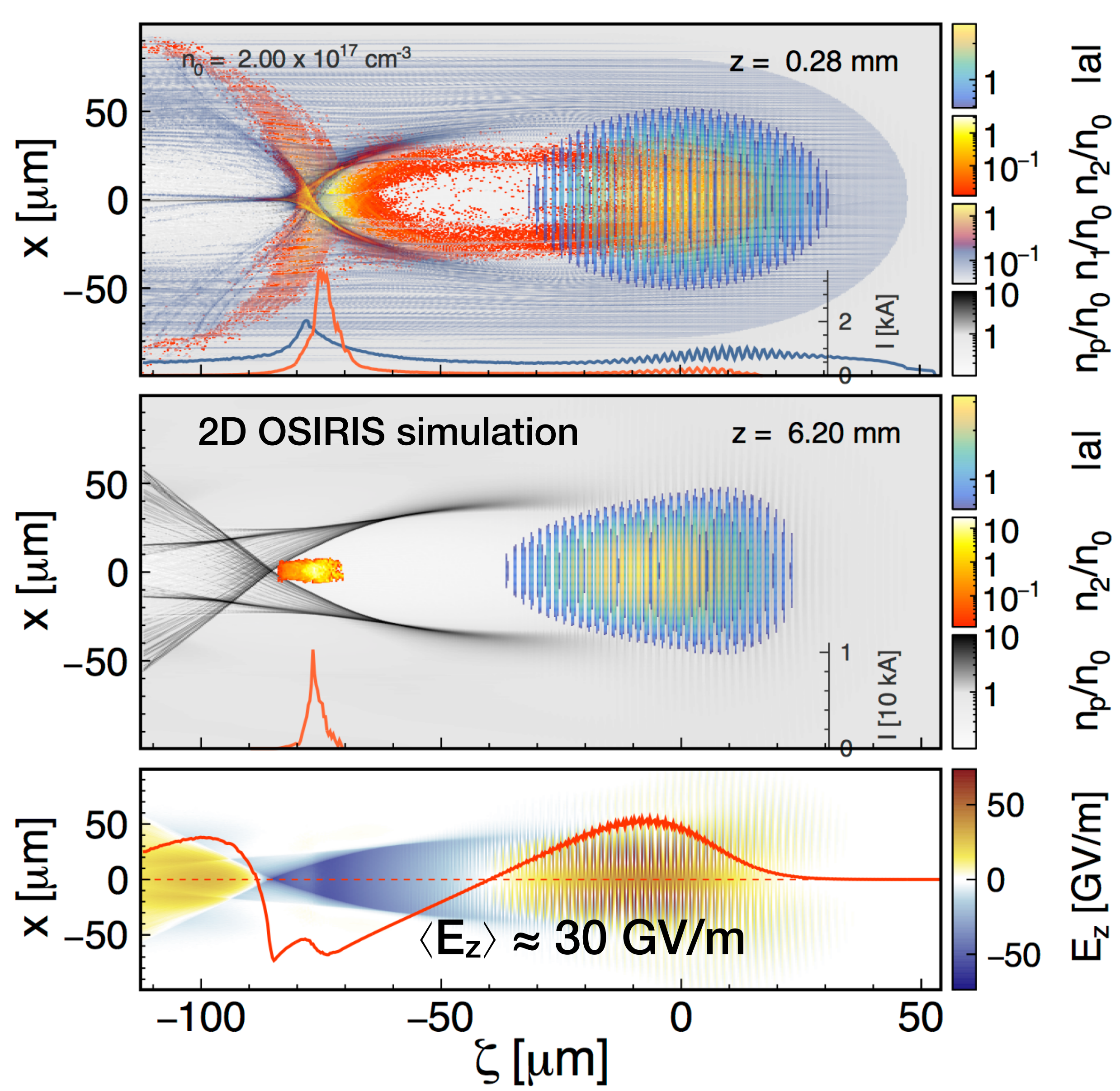


Electron beam

I_0 = 15 kA
ϵ_n = 130 nm
τ = 700 as
Υmc^2= 10 GeV
ΔΥ/Υ = 0.1 %
Charge = 10 pC

Laser barrier | Attenuates the laser below He^+ ionisation levels. Electron beam goes through.

LWFA stage with Ionisation injection

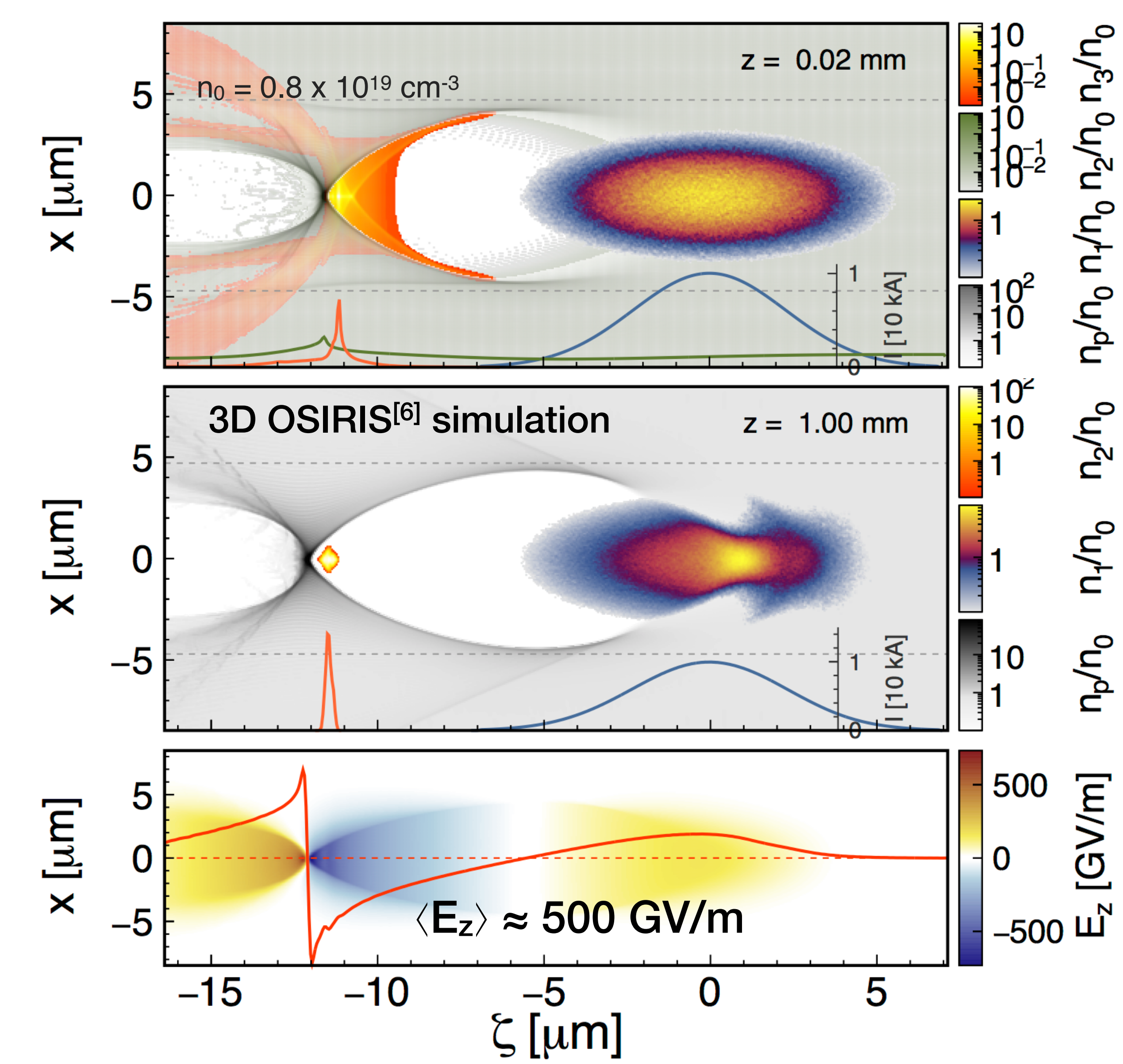


Electron driver
(from LWFA)

I_0 = 10 kA
ϵ_n = 10 µm
τ = 7 fs
Υmc^2= 5 GeV
ΔΥ/Υ = 10 %
Charge = 100 pC

Brightness booster $B \propto \frac{I_b}{\epsilon_n^2}$
x 10000

PWFA stage with WII injection



WP14 Hybrid Laser-Electron-Beam Driven Acceleration: **A working point (preliminary)**

Requires high-current beams
for internal injection:
$I_b \gtrsim 8.5$ kA

Laser driver

$P_0 = 500$ TW
$\lambda_0 = 800$ nm
$w_0 = 41$ μm
$a_0 = 3$
$\tau = 100$ fs
Energy = 53 J

LWFA stage →

Electron driver
(from LWFA)

$I_0 = 10$ kA
$\varepsilon_n = 10$ μm
$\tau = 7$ fs
$\gamma mc^2 = 5$ GeV
$\Delta\gamma/\gamma = 10$ %
Charge = 100 pC

PWFA stage →

Electron beam
(from PWFA)

$I_0 = 15$ kA
$\varepsilon_n = 130$ nm
$\tau = 700$ as
$\gamma mc^2 = 10$ GeV
$\Delta\gamma/\gamma = 0.1$ %
Charge = 10 pC

Energy booster $\Delta\gamma_w = R\ \gamma_d$
Transformer ratio
x 2

Brightness booster $B \propto \frac{I_b}{\epsilon_n^2}$
x 10000

Estimation of experimental tolerances through start-to-end simulations:

1. Close collaboration with **WP2 (Physics and simulations)**:
   - Needs of expensive 3D simulations and more realistic laser profiles.
   - 6D phase-space distributions for PWFA injection studies.
   - Dedicated computing grant for EuPRAXIA.
2. Continuous feedback with **WP3 and WP4** -> LWFA and Laser design and optimisation.
3. PWFA physics considerations parallel to **WP9** (Alternative e-beam driven plasma structure).
4. Close connection with **WP6** (FEL pilot application) for target design parameters and applications.

Estimation of experimental tolerances by doing actual experiments!

1. FACET (USA): Key experience on PWFA injection techniques through E210 experiment.
2. FLASHForward (Hamburg): Operating in 2017.
3. FSU (Jena): Passive plasma lensing experiment.
4. **HZDR (Dresden).**
5. LNF-INFN (Frascati).

WP14 Hybrid Laser-Electron-Beam Driven Acceleration: Experimental milestones

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 071301 (2016)

Demonstration of passive plasma lensing of a laser wakefield accelerated electron bunch

S. Kuschel,[1,2] D. Hollatz,[1,2] T. Heinemann,[3] O. Karger,[3] M. B. Schwab,[1] D. Ullmann,[1] A. Knetsch,[3] A. Seidel,[1] C. Rödel,[1,4] M. Yeung,[2] M. Leier,[1] A. Blinne,[2,5] H. Ding,[6] T. Kurz,[6] D. J. Corvan,[7] A. Sävert,[1] S. Karsch,[6] M. C. Kaluza,[1,2] B. Hidding,[8,3] and M. Zepf[1,2,7]

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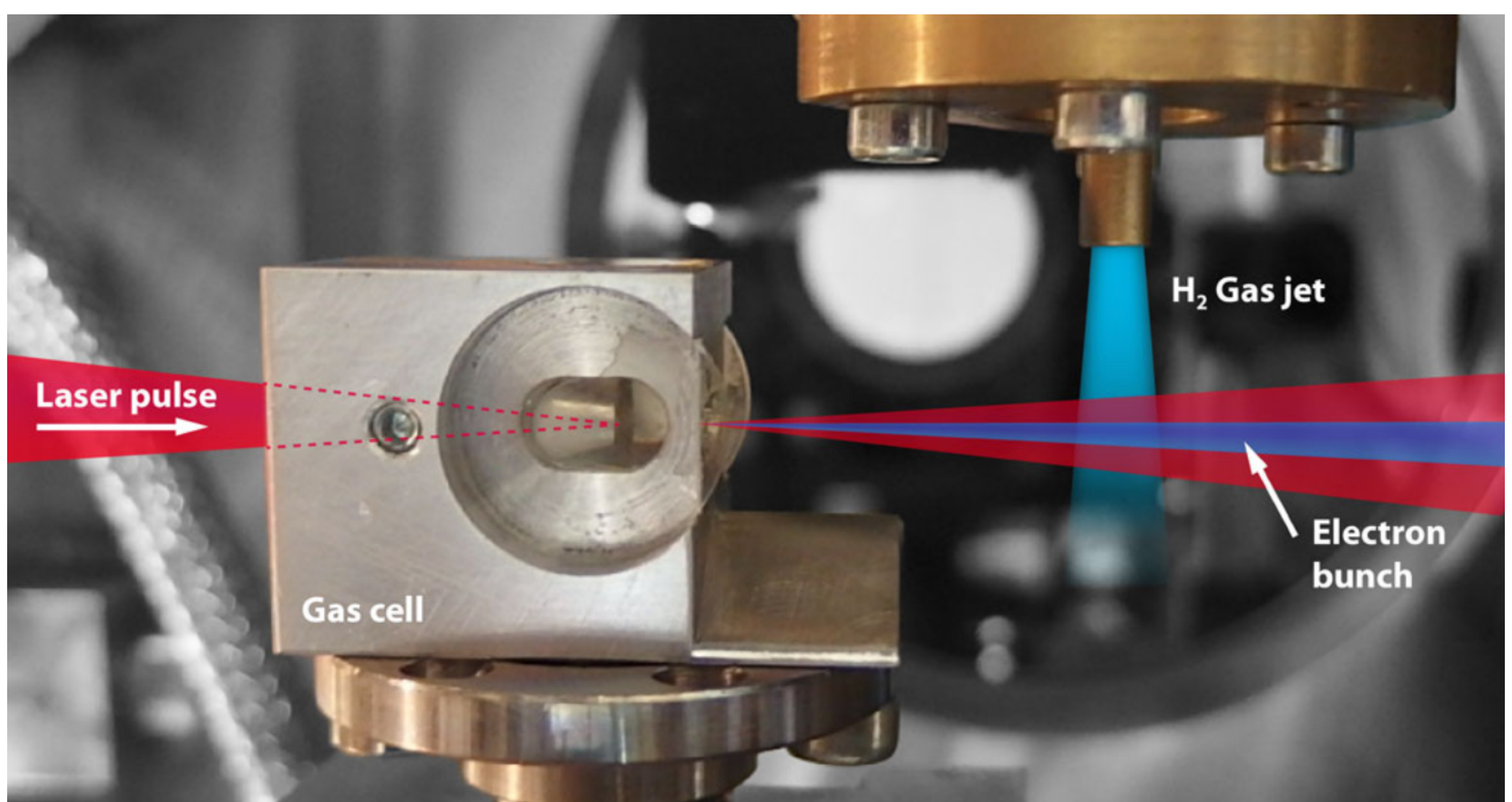
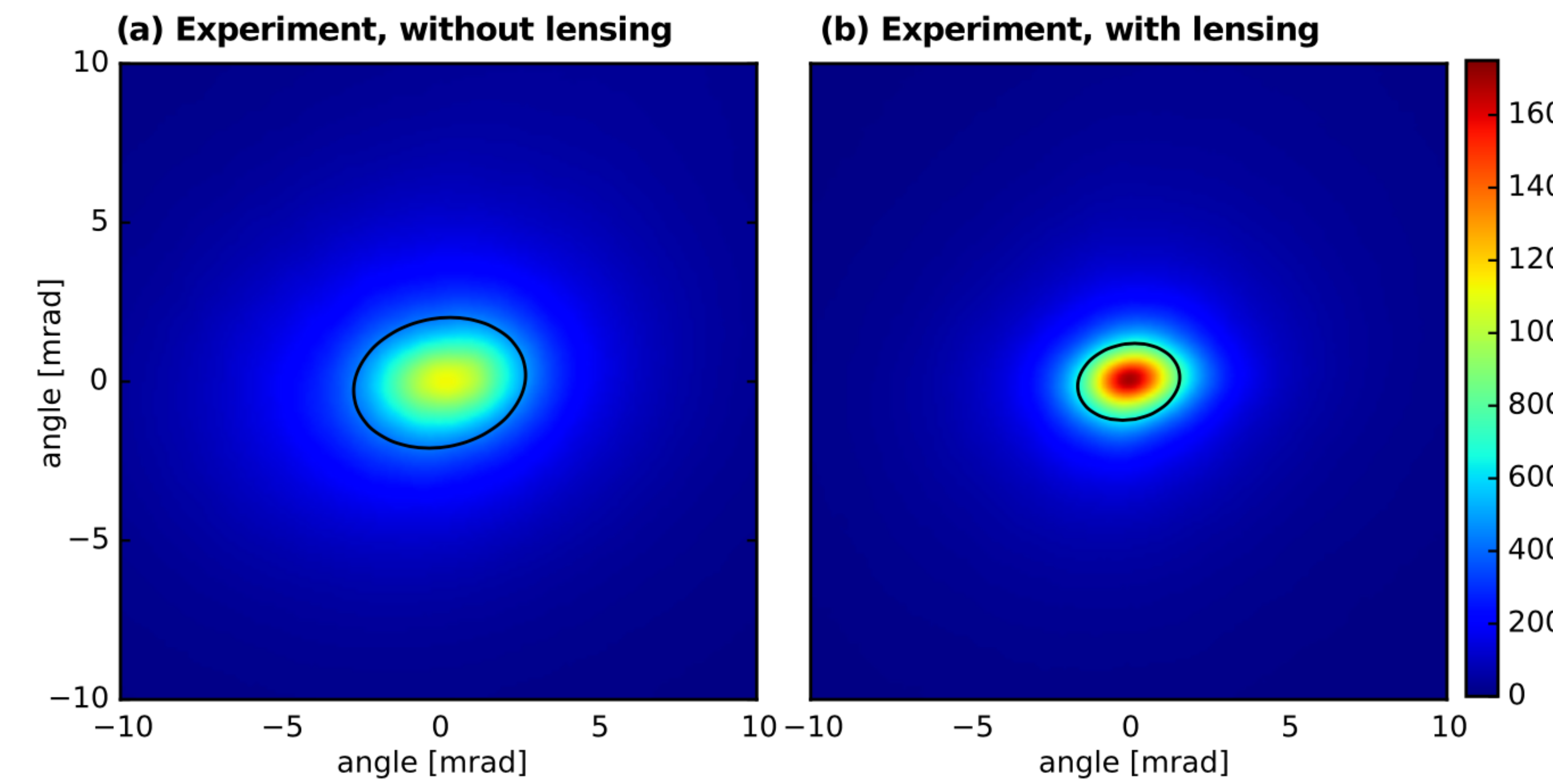
(Received 15 January 2016; revised manuscript received 12 April 2016; published 20 July 2016)

We report on the first demonstration of passive all-optical plasma lensing using a two-stage setup. An intense femtosecond laser accelerates electrons in a laser wakefield accelerator (LWFA) to 100 MeV over millimeter length scales. By adding a second gas target behind the initial LWFA stage we introduce a robust and independently tunable plasma lens. We observe a density dependent reduction of the LWFA electron beam divergence from an initial value of 2.3 mrad, down to 1.4 mrad (rms), when the plasma lens is in operation. Such a plasma lens provides a simple and compact approach for divergence reduction well matched to the mm-scale length of the LWFA accelerator. The focusing forces are provided solely by the





Electron beam can be recaptured in a second plasma target

WP14 Hybrid Laser-Electron-Beam Driven Acceleration: Experimental milestones

PRL **117,** 144801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Collective Deceleration of Laser-Driven Electron Bunches

S. Chou (周紹暐),[1,2,*] J. Xu (徐建彩),[1,3] K. Khrennikov,[2] D. E. Cardenas,[1,2] J. Wenz,[2] M. Heigoldt,[2] L. Hofmann,[1,2] L. Veisz,[1,4] and S. Karsch[1,2]

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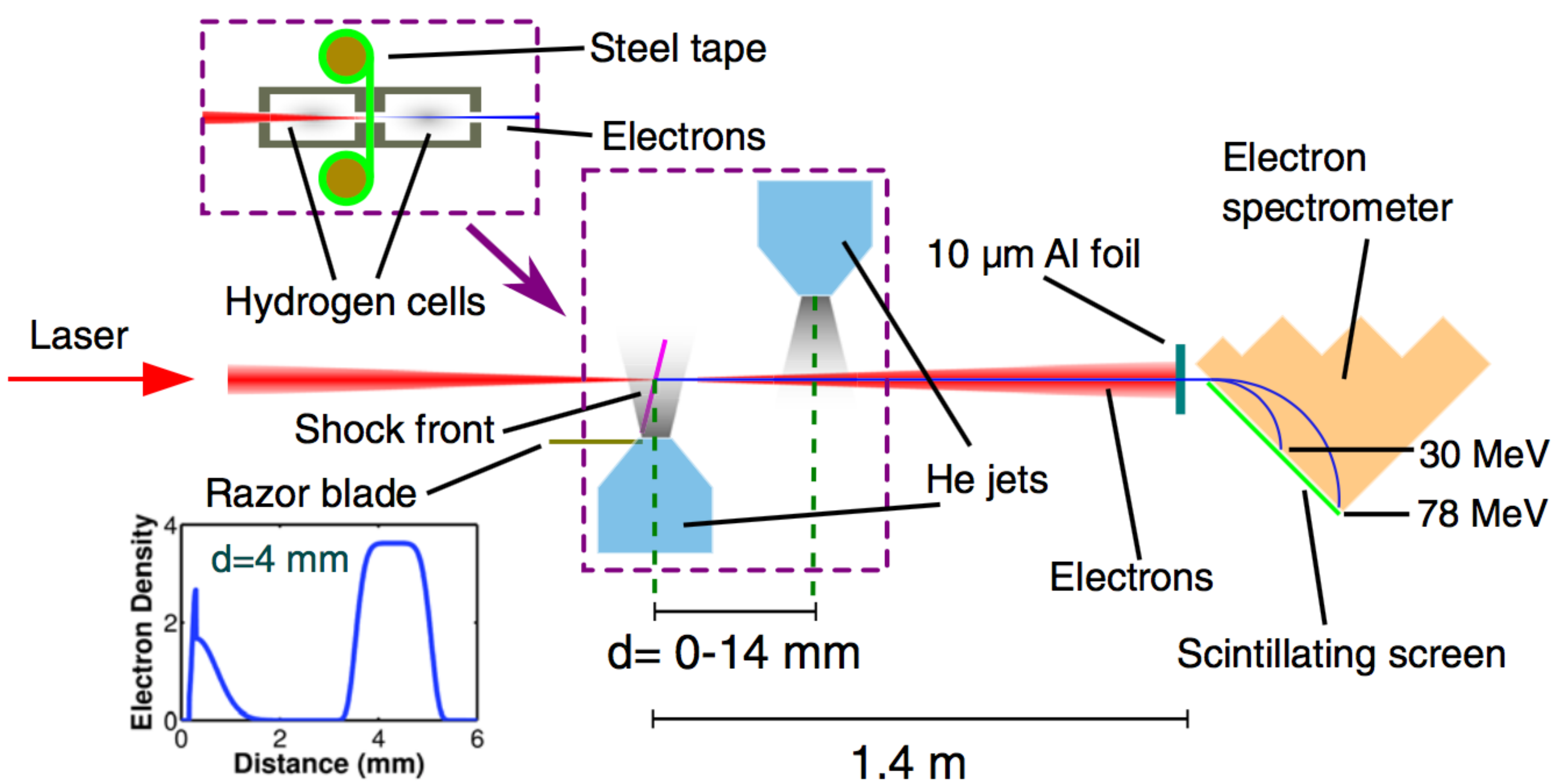
(Received 1 March 2015; revised manuscript received 19 August 2016; published 27 September 2016)

Few-fs electron bunches from laser wakefield acceleration (LWFA) can efficiently drive plasma wakefields (PWFs), as shown by their propagation through underdense plasma in two experiments. A strong and density-insensitive deceleration of the bunches has been observed in 2 mm of 10^{18} cm^{-3} density plasma with 5.1 GV/m average gradient, which is attributed to a self-driven PWF. This observation implies that the physics of PWFs, usually relying on large-scale rf accelerators as drivers, can be studied by tabletop LWFA electron sources.



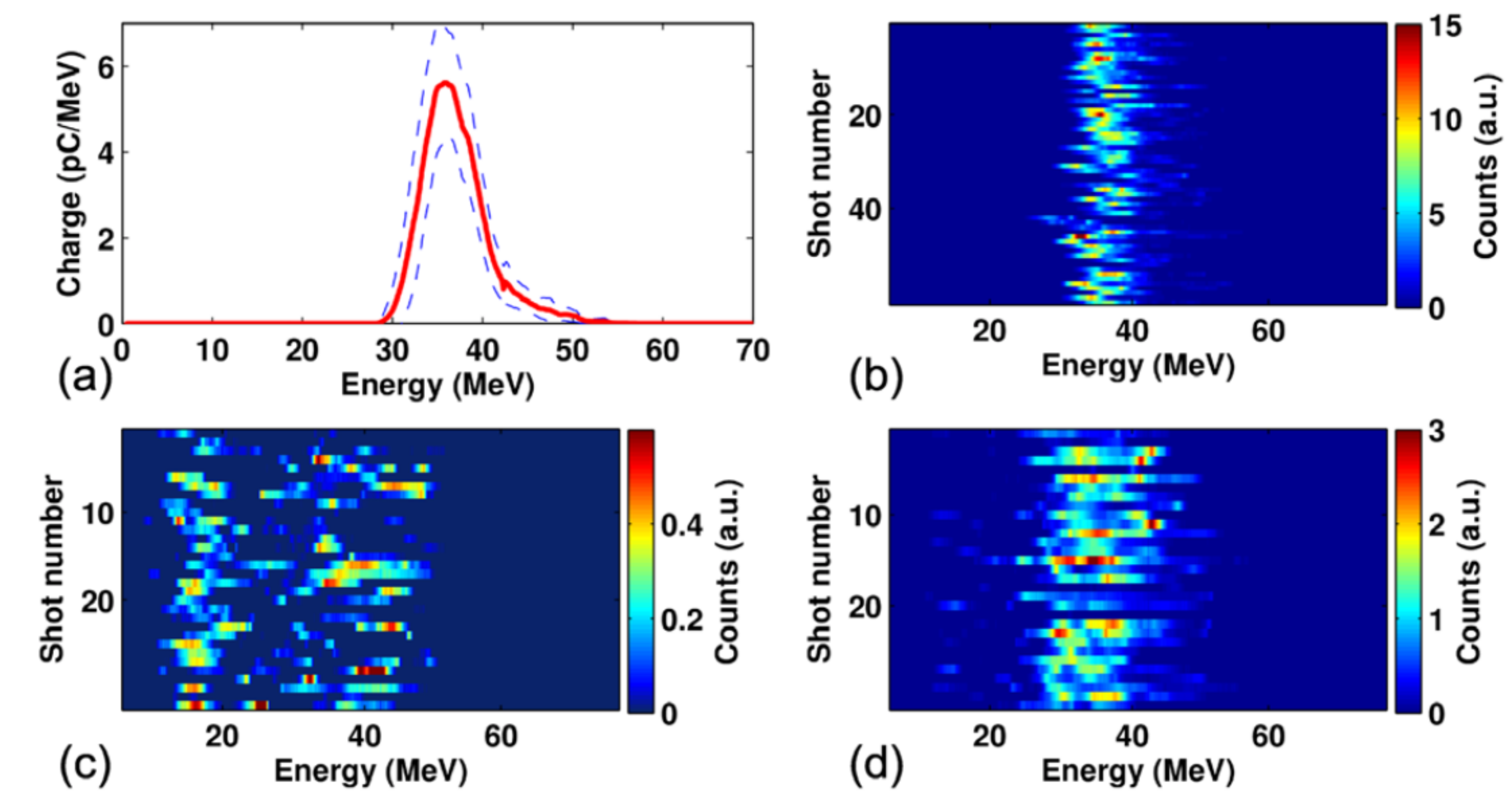
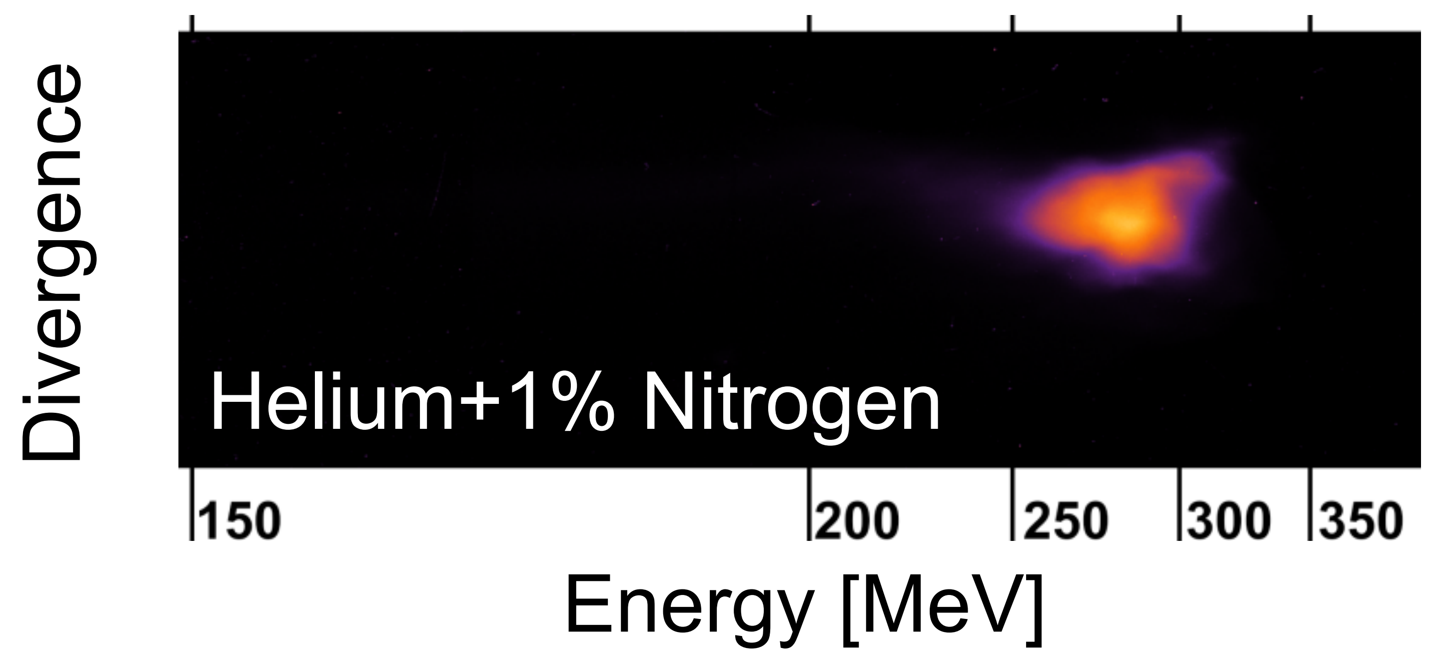


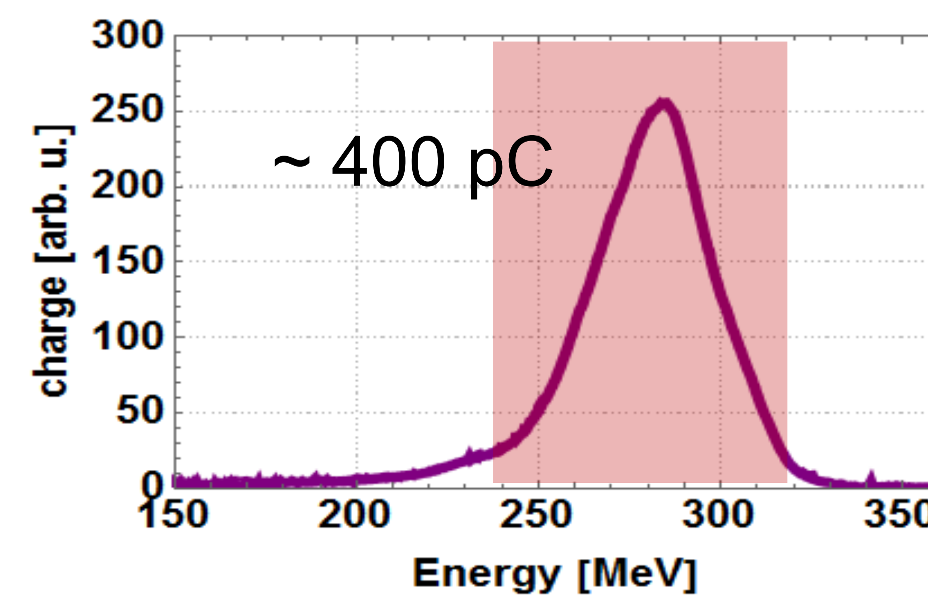
FIG. 2. Electron spectra. (a) Average spectrum (solid line) and root-mean-square (dashed line) from over 60 consecutive shots. The shock-front configuration was used to generate 35.8 ± 0.3 MeV, 44.3 ± 1.5 pC electrons with an average FWHM divergence 6.9 ± 0.17 mrad. (b) Consecutive shots of stable shock-front injected bunches without jet 2. (c) Decelerated spectra with $d = 3.5$ and 3.6×10^{18} cm^{-3} electron density in jet 2. (d) Decelerated spectra with $d = 6.5$.

Electron beams generate wakefields in a second plasma target

LWFA experiment at HZDR: Stable production of high current beams

LWFA with ionization injection





DRACO Laser: 2.8 J, 28 fs, 20 μm

Peak energy: ~ 283 MeV
Energy spread: ~ 40 MeV (14%)
Charge: 292 ± 59 pC (fwhm).
Duration: ~ 10 fs
Estimated peak current: ~ 30 kA

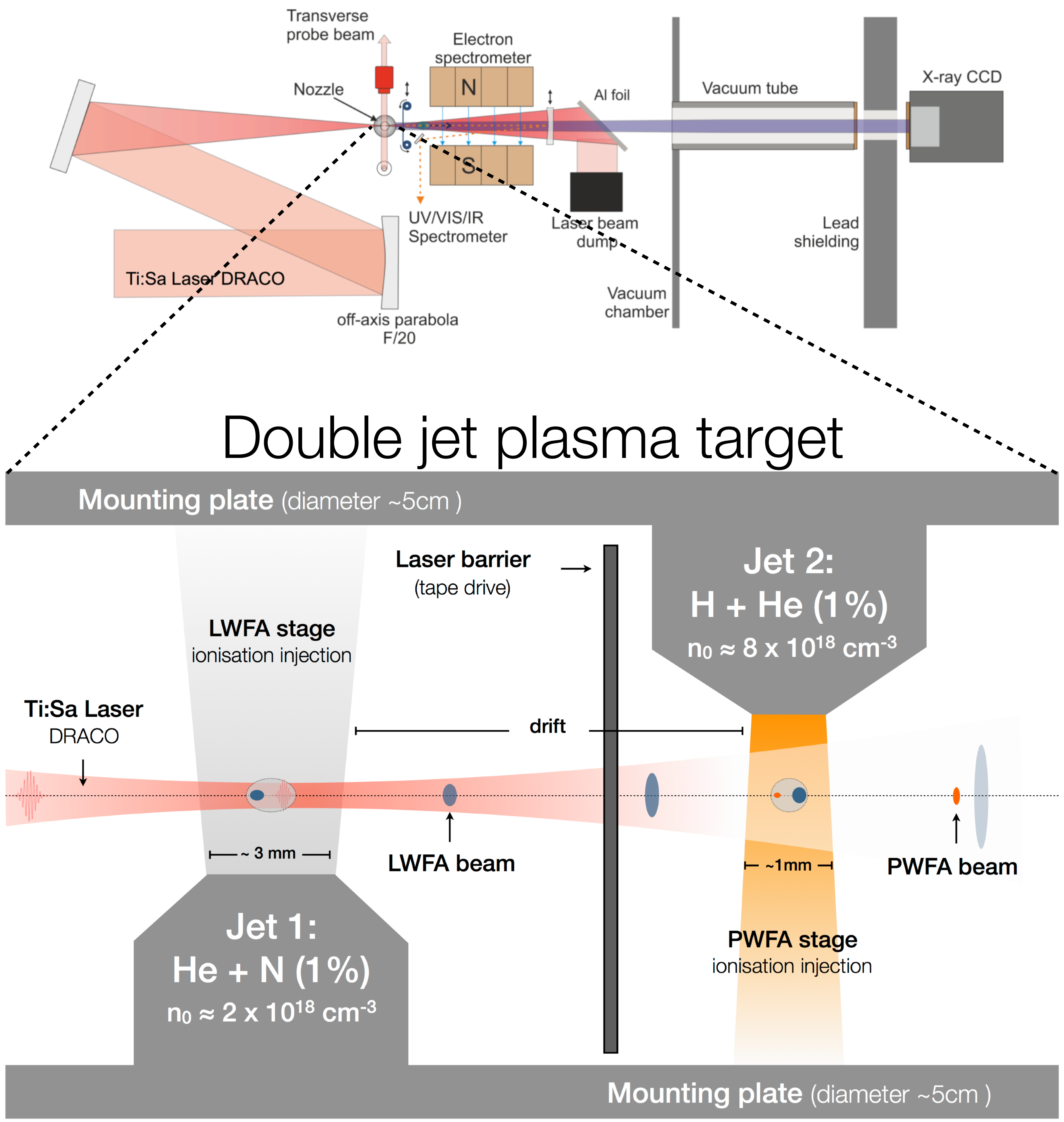
Dr. Arie Irman and Prof. Dr. Ulrich Schramm

Stable production of
high current beams

→ **Proof of concept experiment at Dresden**
Demonstration of injection and acceleration
of electrons in a PWFA stage driven by a LWFA beam.

Proof of concept experiment at HZDR: Towards laser-beam plasma accelerators

HZDR
Laser - beam WFA: LPWFA



LPWFA experiment

- Experimental design.
- Technical realisation and equipment.
- Diagnostics and observables.
- Theoretical/simulation studies.
- Experimental program.

Acceleration of a witness beam in a PWFA stage driven by a LWFA electron beam.

A. Irman, J. Couperus, A. Koehler, O. Zarini, T. Kurz, T. Heinemann, O. Kononenko, A. Knetsch, A. Ferran-Pousa, U. Schramm, J. Osterhoff, R. Aßmann, B. Hidding, A. Martinez de la Ossa.

WP14 Hybrid Laser-Electron-Beam Driven Acceleration: Summary

Conceptual designs for staged LWFA + PWFA setups available:
For the production of multi-GeV, high-brightness, FEL capable beams.

Preliminary working point achieved by means of PIC simulations
Energy and brightness booster: 2 x energy, 10000 x brightness.

Experimental milestones published in 2016
FSU (Jena): Recapturing of electron beams from LWFA.
MPQ (Garching) : Generation of wakefields by electron beams from LWFA.

Next milestone: Proof of concept experiment in HZDR (Dresden)
Injection of electron beams in a PWFA driven by electron beams from LWFA.

Research personnel

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Gabriele Tauscher (Hamburg/DESY). PhD student.

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