Experimental progress in LWFA to PWFA staging

Sébastien Corde

On behalf of the hybrid collaboration
(HZDR, LMU, DESY, U. Strathclyde, LOA)

Work supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Miniature beam-driven Plasma Accelerators project, Grant Agreement No. 715807).

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INSTITUT POLYTECHNIQUE DE PARIS
loa
erc European Research Council Established by the European Commission

The LWFA-PWFA hybrid collaboration

S. Corde, O. Kononenko, G. Raj et al.

H. Ding, A. Döpp, M. Gilljohann, S. Karsch et al.

Y. Chang, J. Couperus Cabadag, A. Debus, A. Irman, T. Kurz, R. Pausch, S. Schöbel, U. Schramm et al.

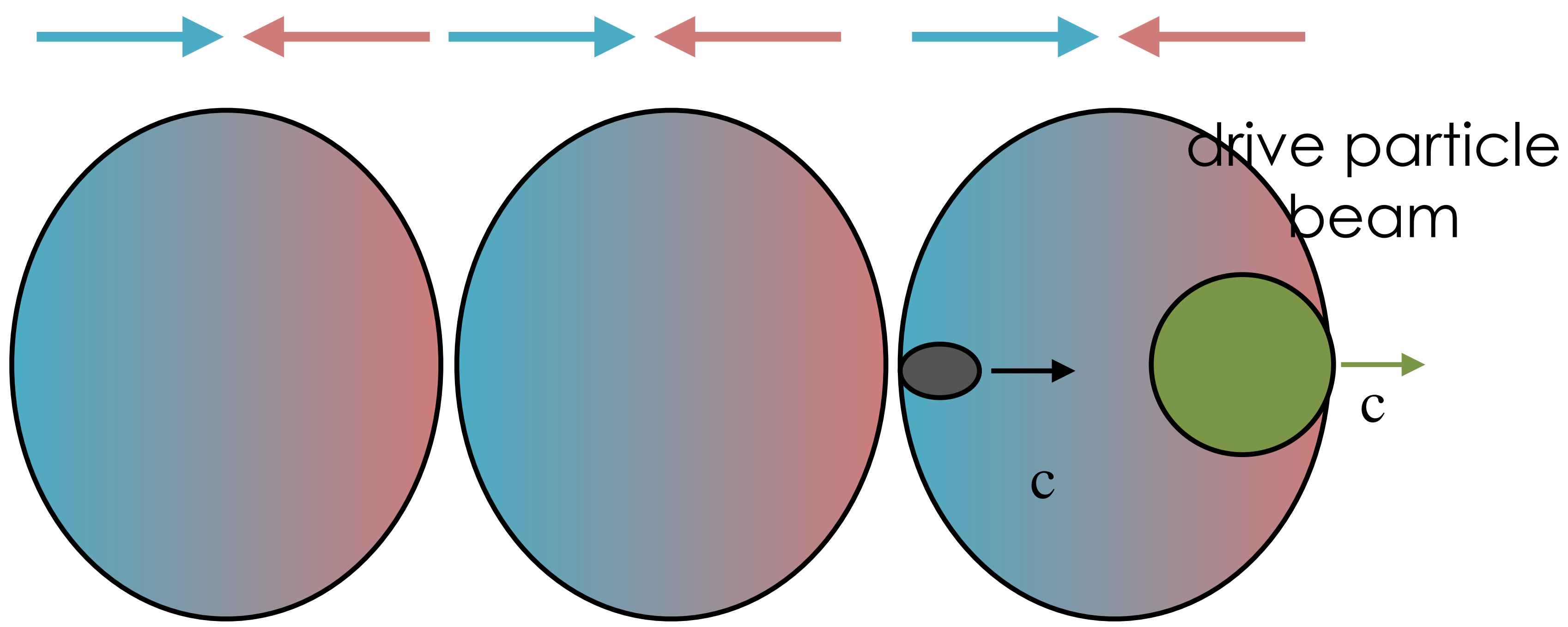
A. Martinez de la Ossa

B. Hidding et al.

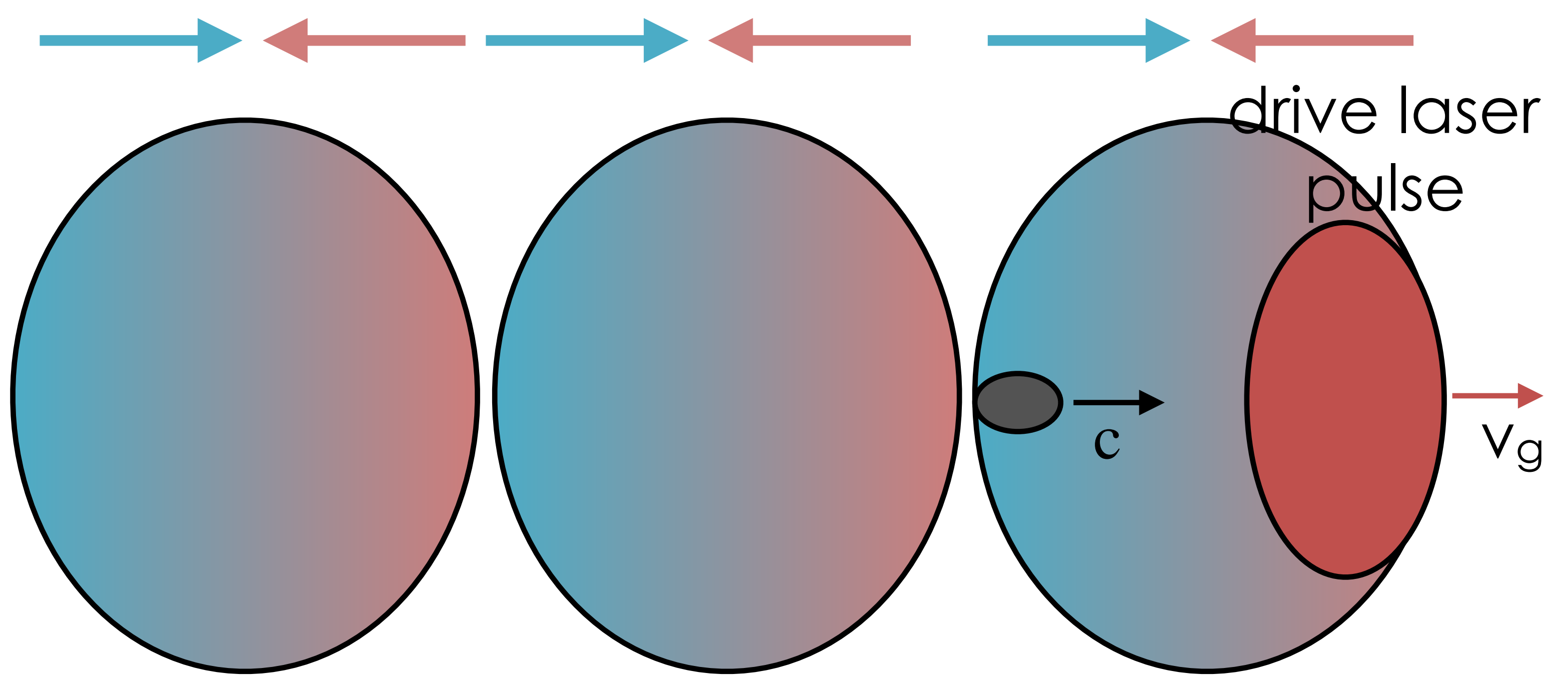
T. Heinemann

Particle acceleration in plasma

Plasma Wakefield Accelerator (PWFA)



Laser Wakefield Accelerator (LWFA)

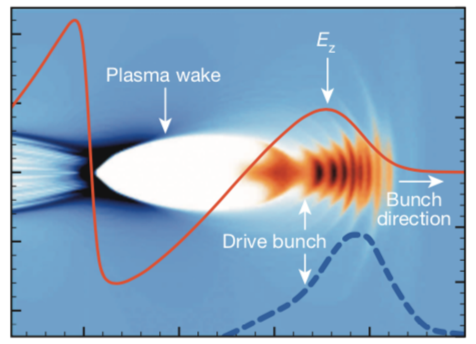


No dephasing and diffraction

Much more stable wakefield

Perspective for high-brightness beam generation

High energy efficiency and high rep rates



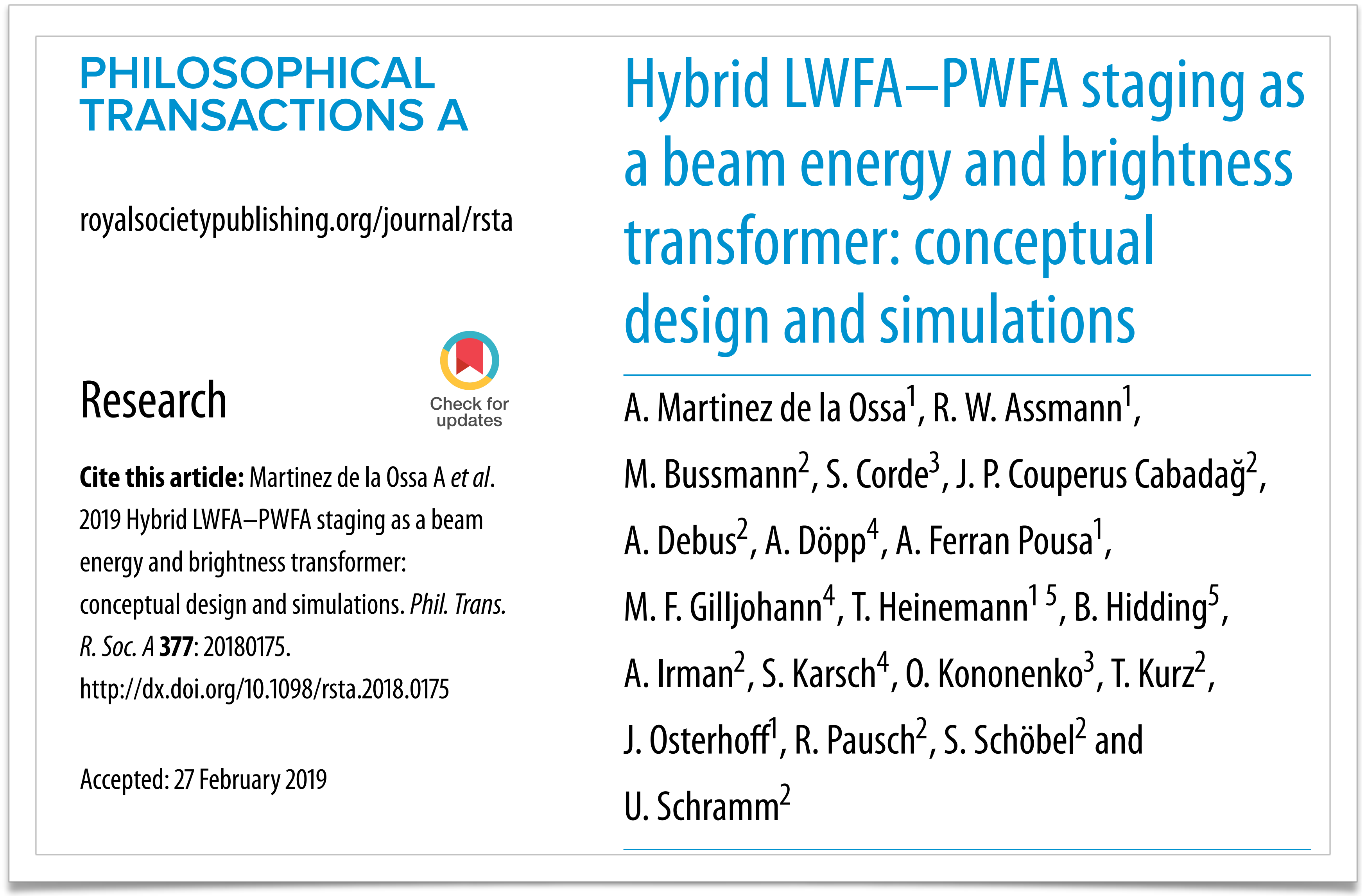
Limited acceleration length

Large shot-to-shot fluctuations of laser intensity profile in the plasma [S. Corde et al., Nat. Comm. 4, 1501 (2013)], and therefore of the wakefield

Optical tools readily available

Synergies between LWFA and PWFA - staging

- LWFA electron beams as injectors for PWFA: interesting but difficult to implement in reality, requires matured LWFA
- LWFA electron beams as drivers for PWFA: easier because spectral quality and matching is not critical
- Brightness transformer concept: generating higher brightness electron beams and light sources in a laser lab
- Complementary PWFA physics platform with optical tools from laser lab


PHILOSOPHICAL TRANSACTIONS A

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Research

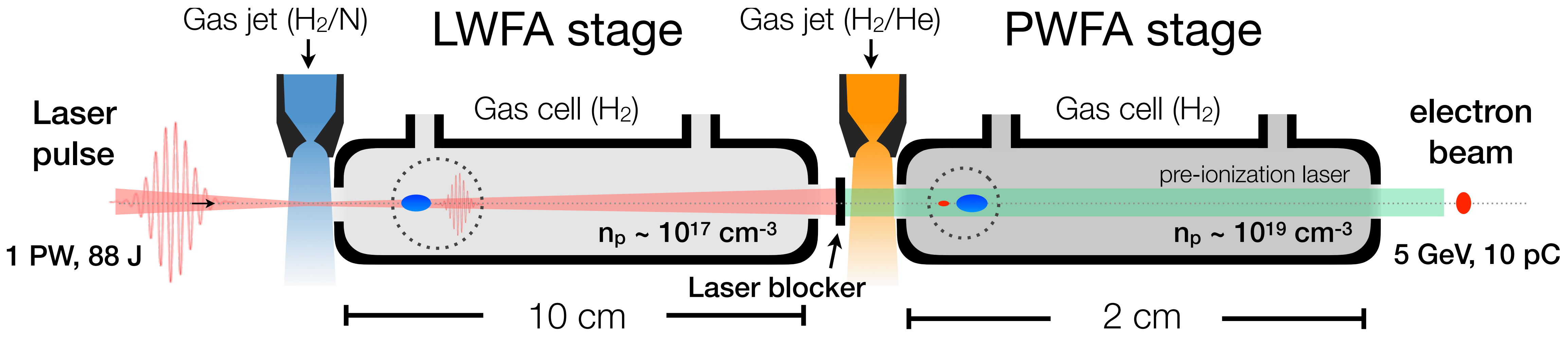
Check for updates

Hybrid LWFA–PWFA staging as a beam energy and brightness transformer: conceptual design and simulations

A. Martinez de la Ossa[1], R. W. Assmann[1], M. Bussmann[2], S. Corde[3], J. P. Couperus Cabadağ[2], A. Debus[2], A. Döpp[4], A. Ferran Pousa[1], M. F. Gilljohann[4], T. Heinemann[1 5], B. Hidding[5], A. Irman[2], S. Karsch[4], O. Kononenko[3], T. Kurz[2], J. Osterhoff[1], R. Pausch[2], S. Schöbel[2] and U. Schramm[2]

Cite this article: Martinez de la Ossa A *et al.* 2019 Hybrid LWFA–PWFA staging as a beam energy and brightness transformer: conceptual design and simulations. *Phil. Trans. R. Soc. A* **377**: 20180175. http://dx.doi.org/10.1098/rsta.2018.0175

Accepted: 27 February 2019



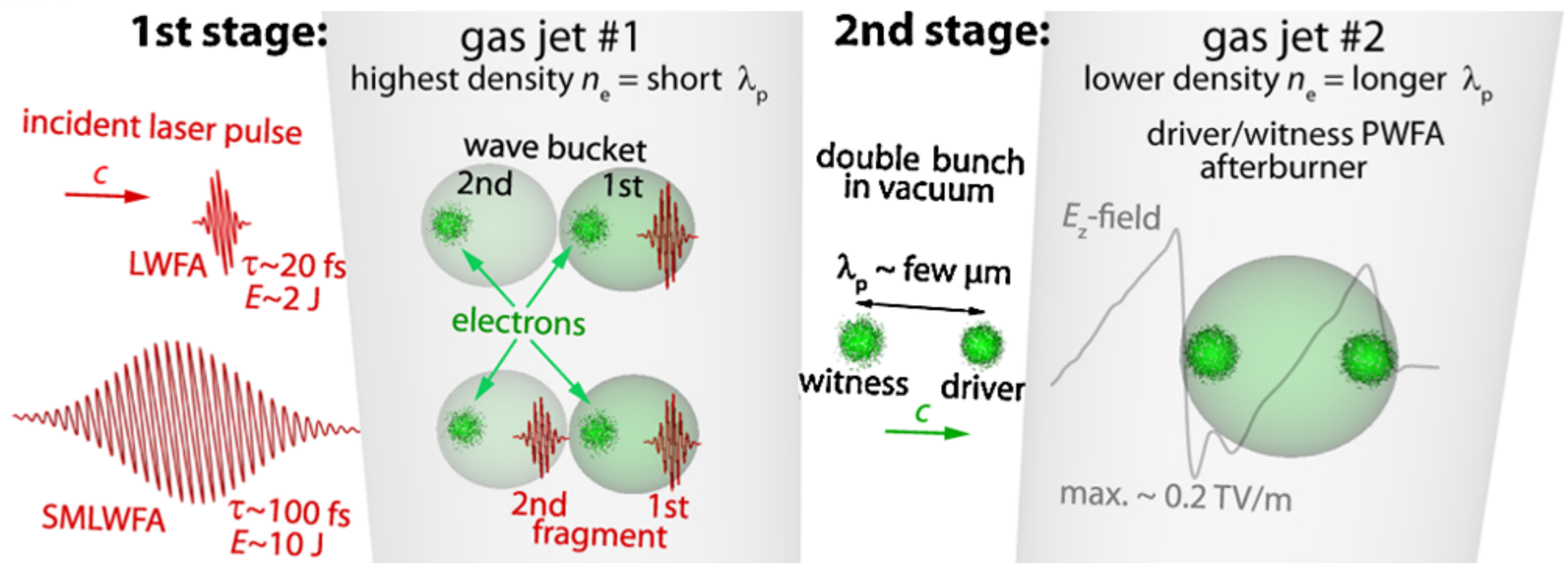
	Driver	Witness
Charge	190 pC	10 pC
Average energy	2 GeV	5 GeV
Energy spread	10%	3%
Sliced energy spread	10%	0.1%
Normalized emittance	15 μm	0.1 μm
Duration (fwhm)	18 fs	0.8 fs
Current	10 kA	15 kA
Brightness	0.044 kA/μm^2	1500 kA/μm^2

Pre-history of hybrid LWFA-PWFA collaboration

PRL 104, 195002 (2010) PHYSICAL REVIEW LETTERS week ending 14 MAY 2010

Monoenergetic Energy Doubling in a Hybrid Laser-Plasma Wakefield Accelerator

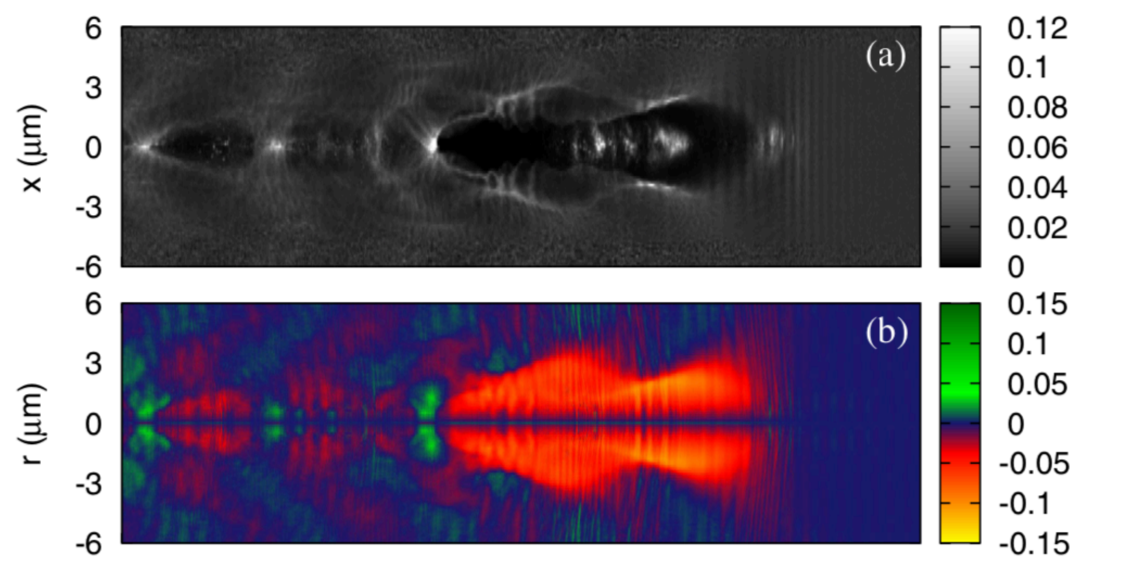
B. Hidding,[1] T. Königstein,[1] J. Osterholz,[1] S. Karsch,[2] O. Willi,[1] and G. Pretzler[1]



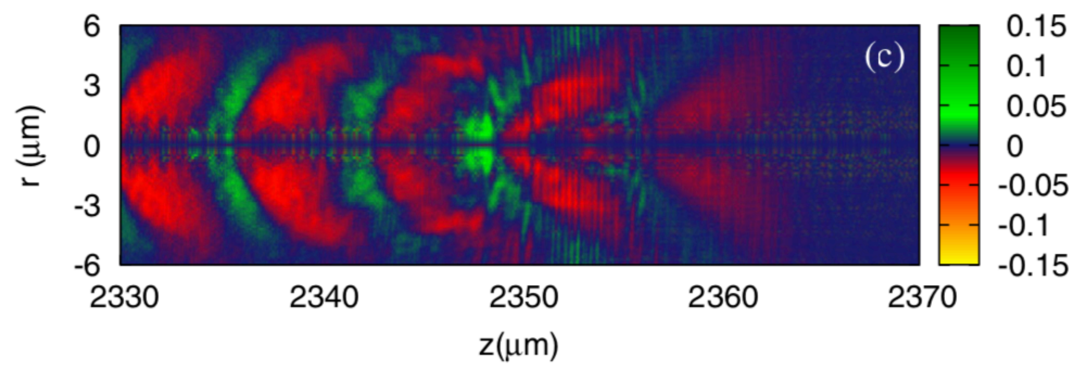
PRL 107, 215004 (2011) PHYSICAL REVIEW LETTERS week ending 18 NOVEMBER 2011

Mapping the X-Ray Emission Region in a Laser-Plasma Accelerator

S. Corde,[1] C. Thaury,[1] K. Ta Phuoc,[1] A. Lifschitz,[1] G. Lambert,[1] J. Faure,[1] O. Lundh,[1] E. Benveniste,[2] A. Ben-Ismail,[2] L. Arantchuk,[3] A. Marciniak,[1] A. Stordeur,[1] P. Brijesh,[1] A. Rousse,[1] A. Specka,[2] and V. Malka[1]



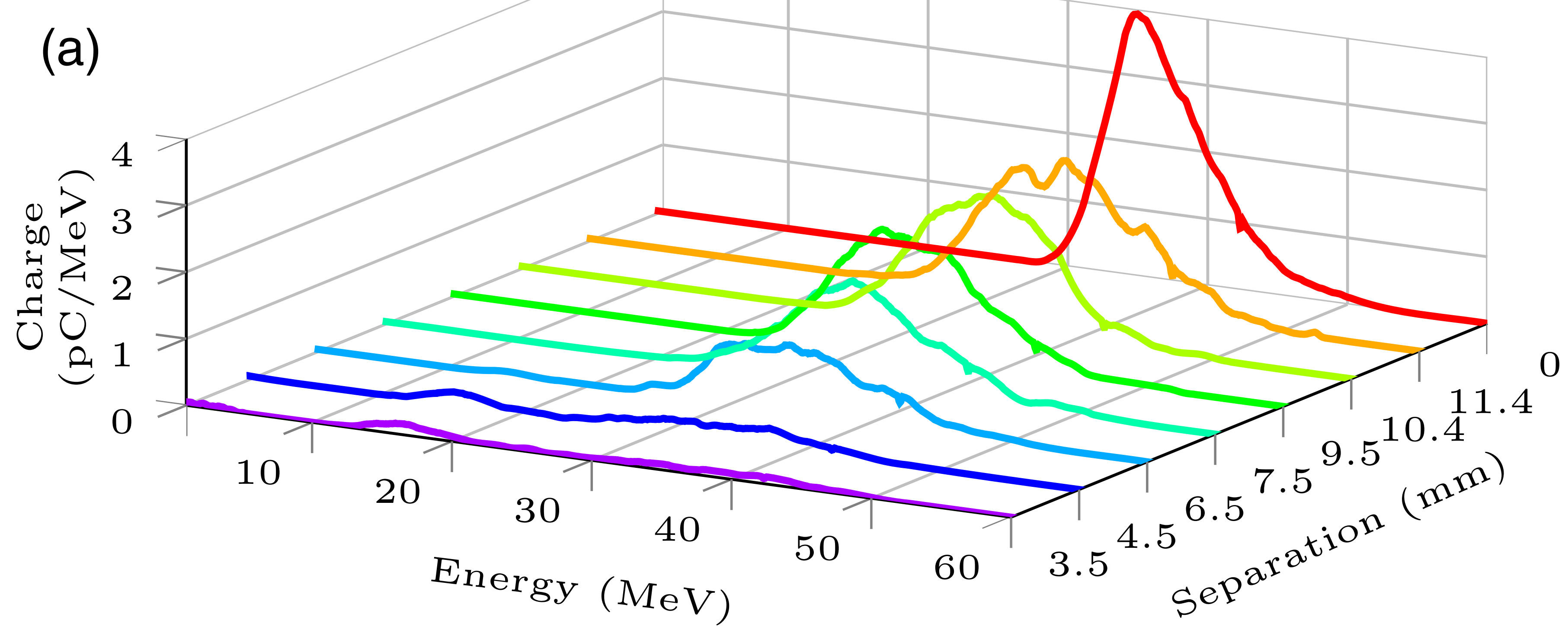
Self-transition from LWFA to PWFA



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

Collective Deceleration of Laser-Driven Electron Bunches

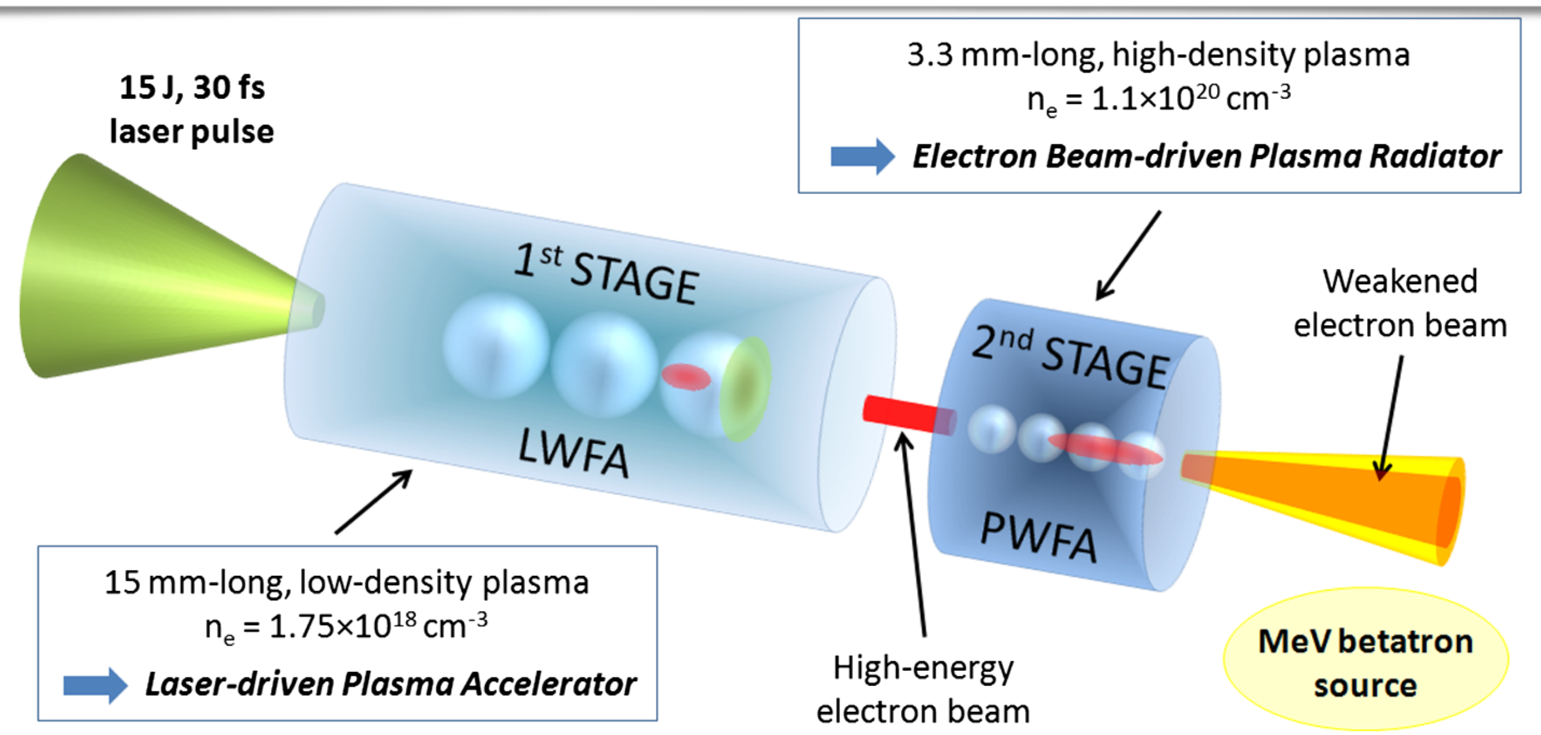
S. Chou (周紹暐),[1,2,*] J. Xu (徐建彩),[1,3] K. Khrennikov,[2] D. E. Cardenas,[1,2] J. Wenz,[2] M. Heigoldt,[2] L. Hofmann,[1,2] L. Veisz,[1,4] and S. Karsch[1,2]



PHYSICAL REVIEW LETTERS 120, 254802 (2018)

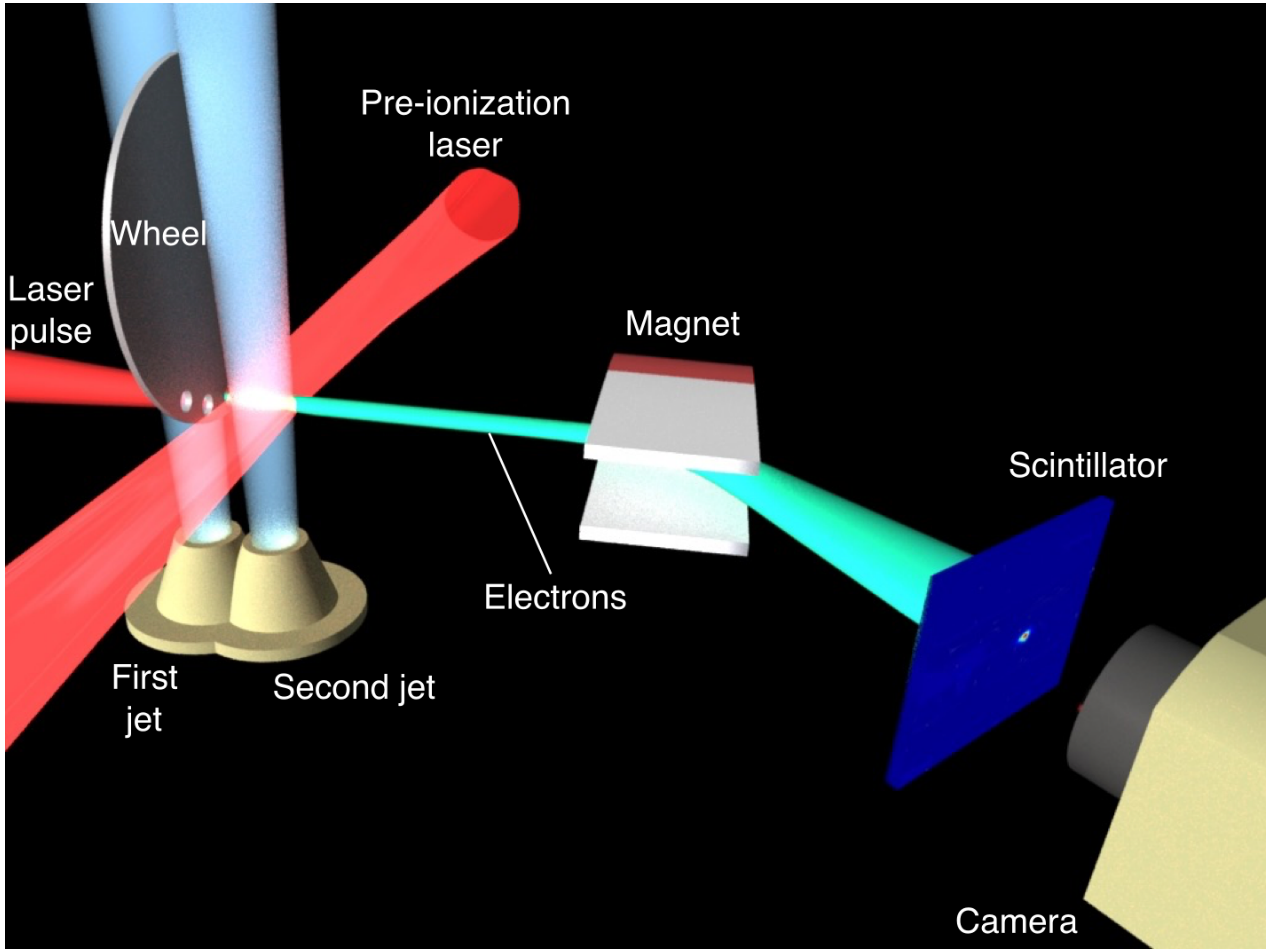
High-Brilliance Betatron γ-Ray Source Powered by Laser-Accelerated Electrons

J. Ferri,[1,2,6,*] S. Corde,[2] A. Döpp,[2,3] A. Lifschitz,[2] A. Doche,[2] C. Thaury,[2] K. Ta Phuoc,[2] B. Mahieu,[2] I. A. Andriyash,[4,5] V. Malka,[2,5] and X. Davoine[1]



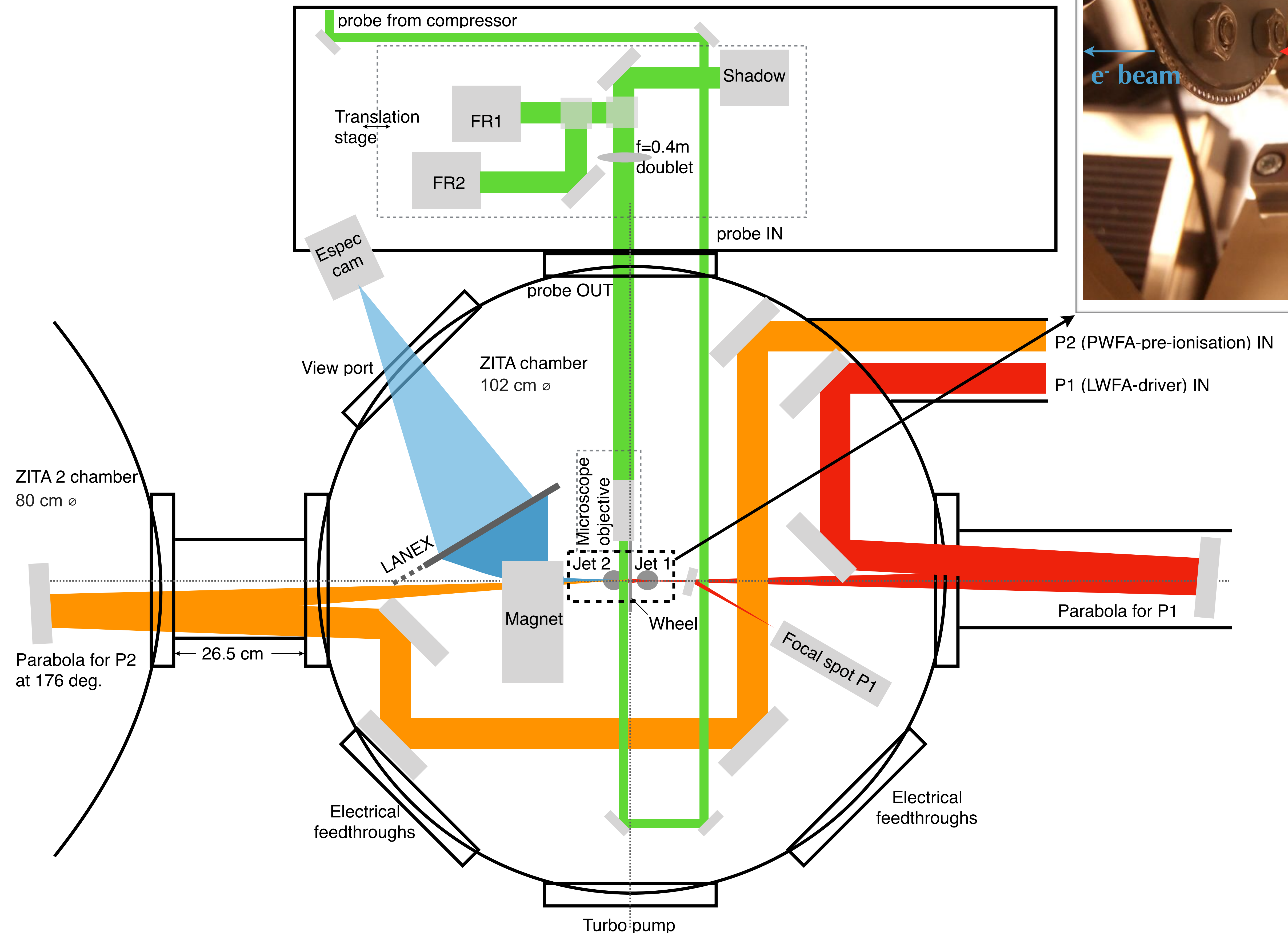
Experimental campaign in Salle Jaune (LOA)

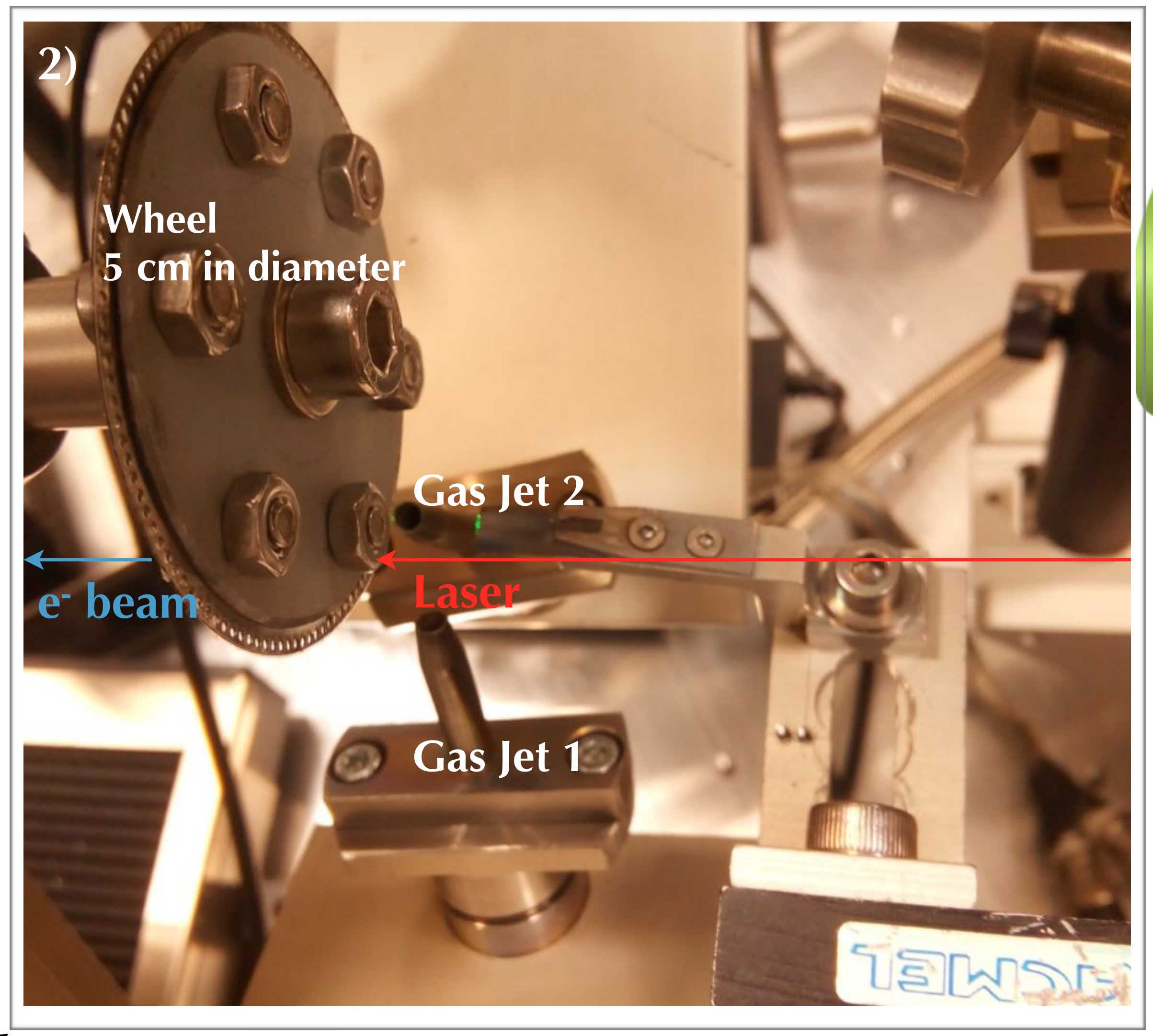
Experimental concept:

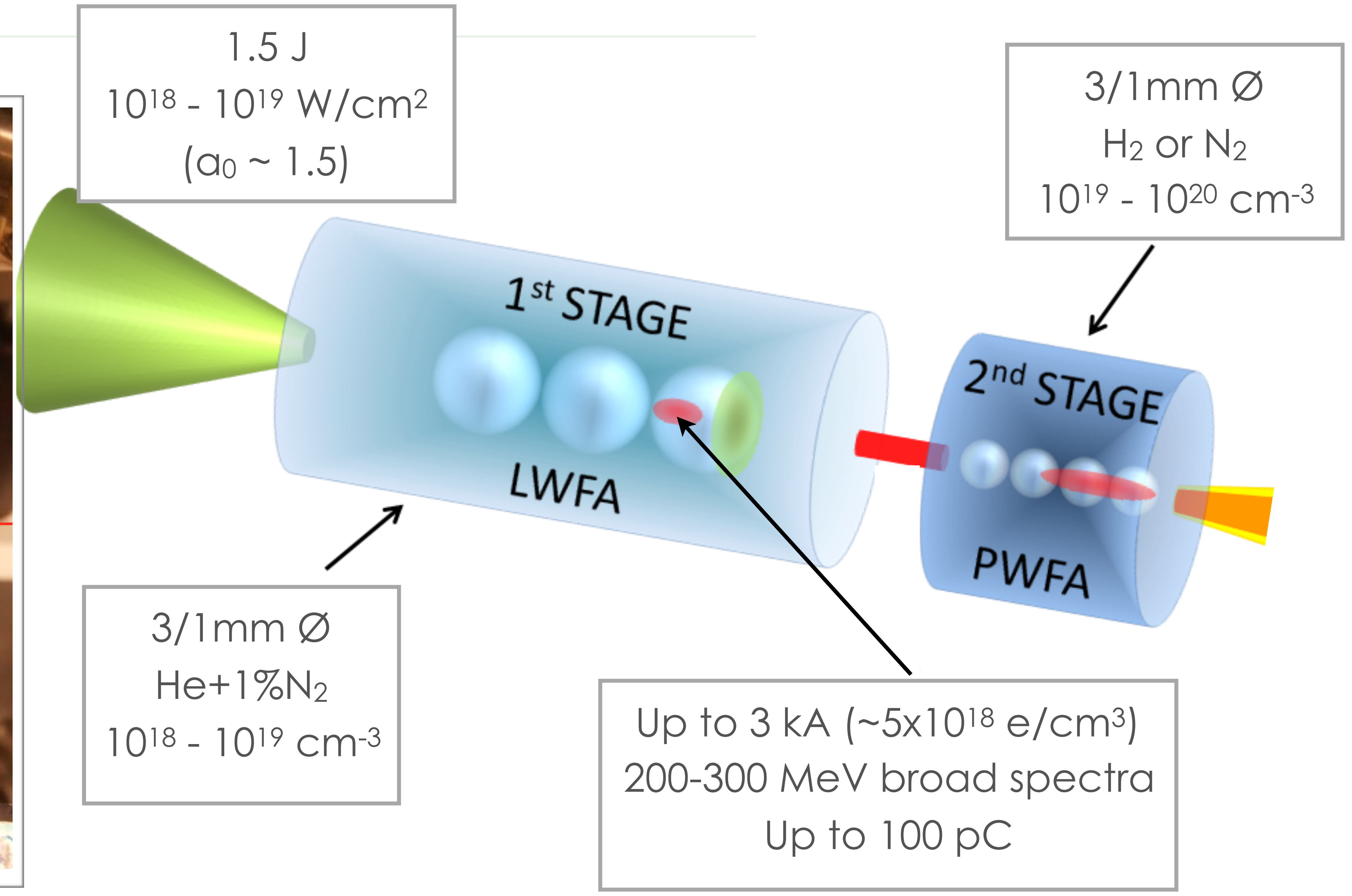


Experimental campaign in Salle Jaune (LOA)

- Three independent laser pulses
- Stable electron beam production (ionization injection)
- Significant flexibility of experimental setup







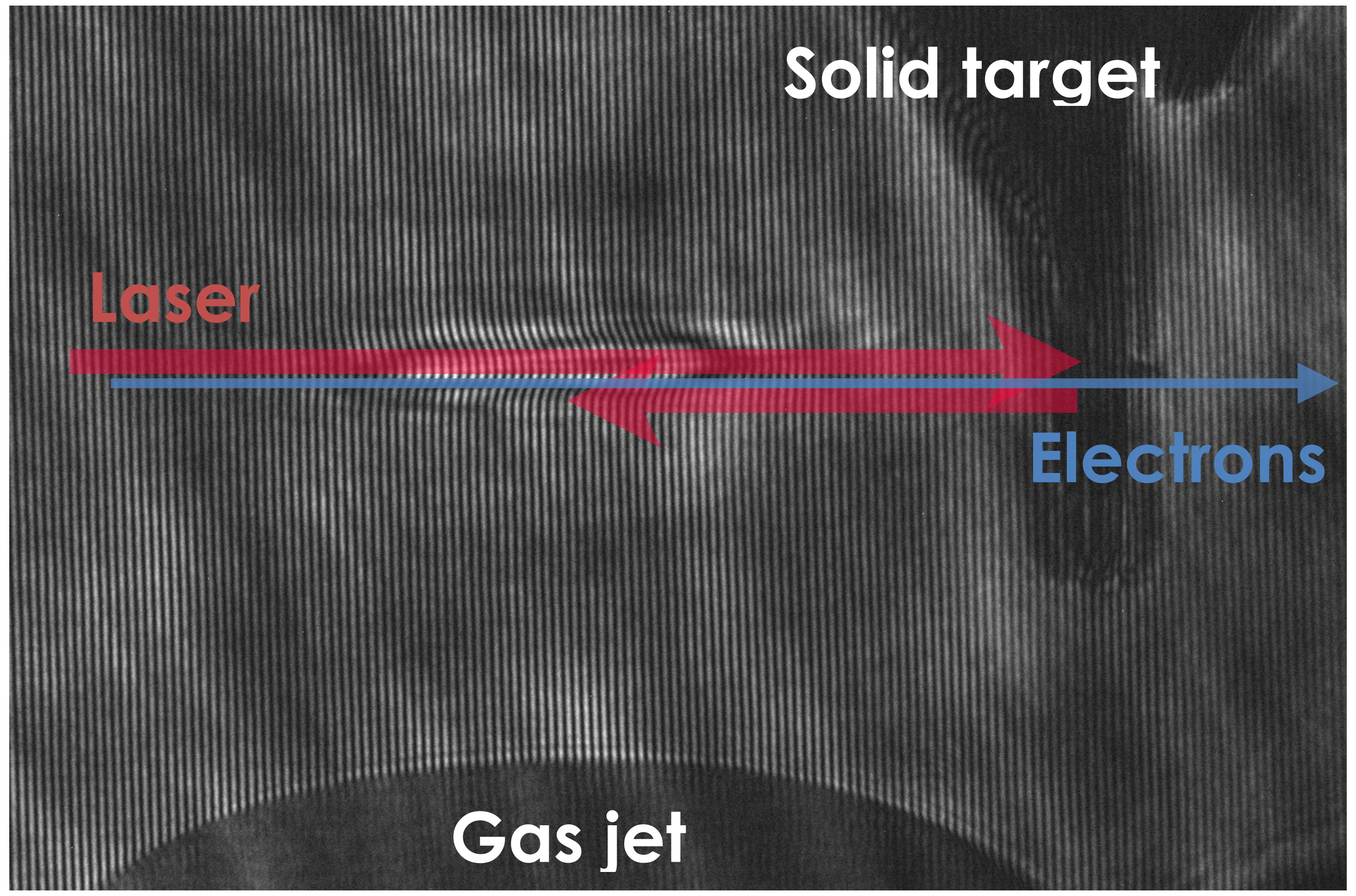
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{\delta n}{n_0} = c^2\frac{\nabla^2 a^2}{2} - \omega_p^2\frac{n_b}{n_0}$$

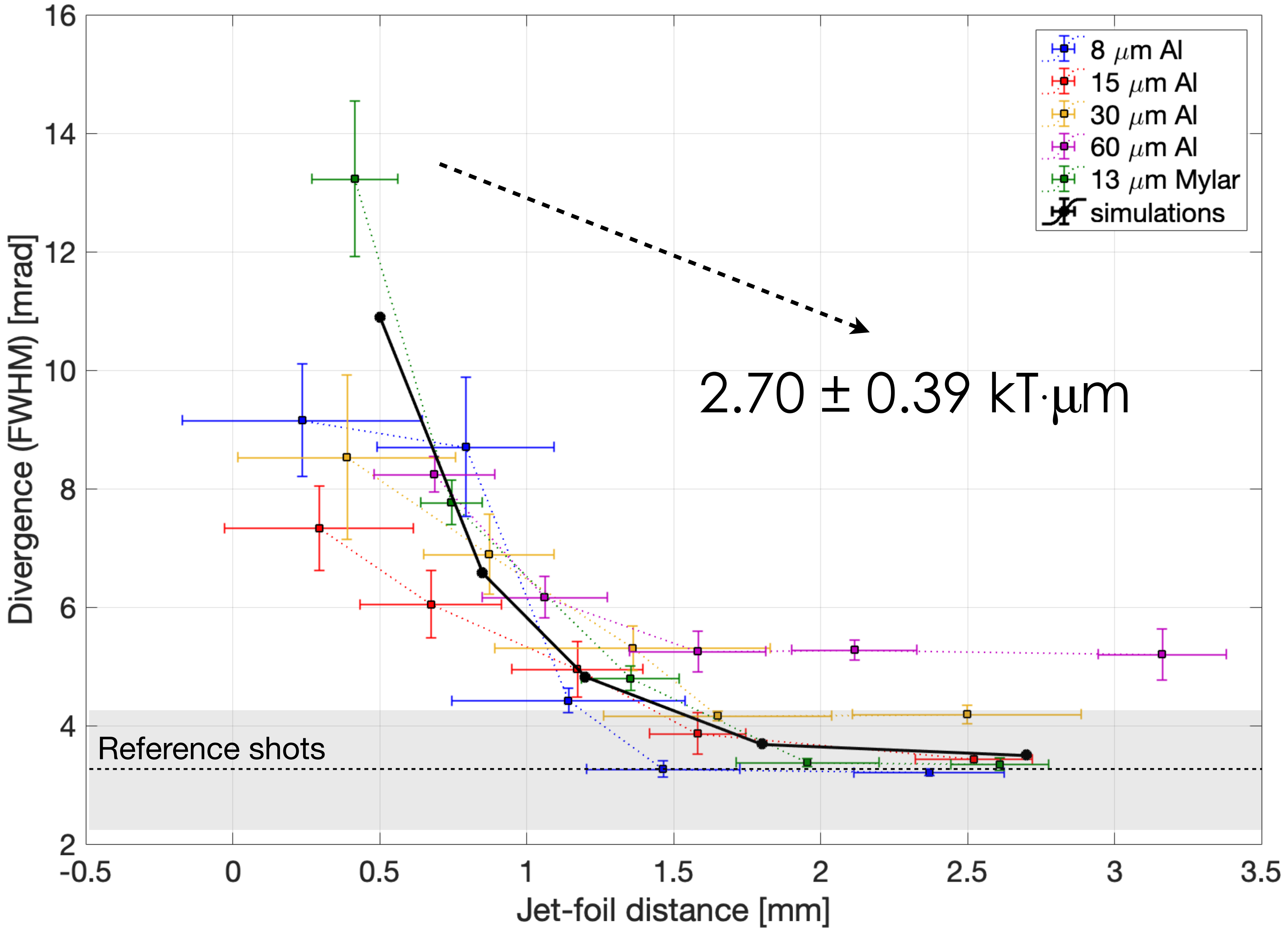
$n_b/n_0 \sim 10^{18}\text{-}10^{19}\ cm^{-3}/10^{19}\text{-}10^{20}\ cm^{-3} \sim 10\%$

Strong self-focusing required in order to drive a non-linear wake

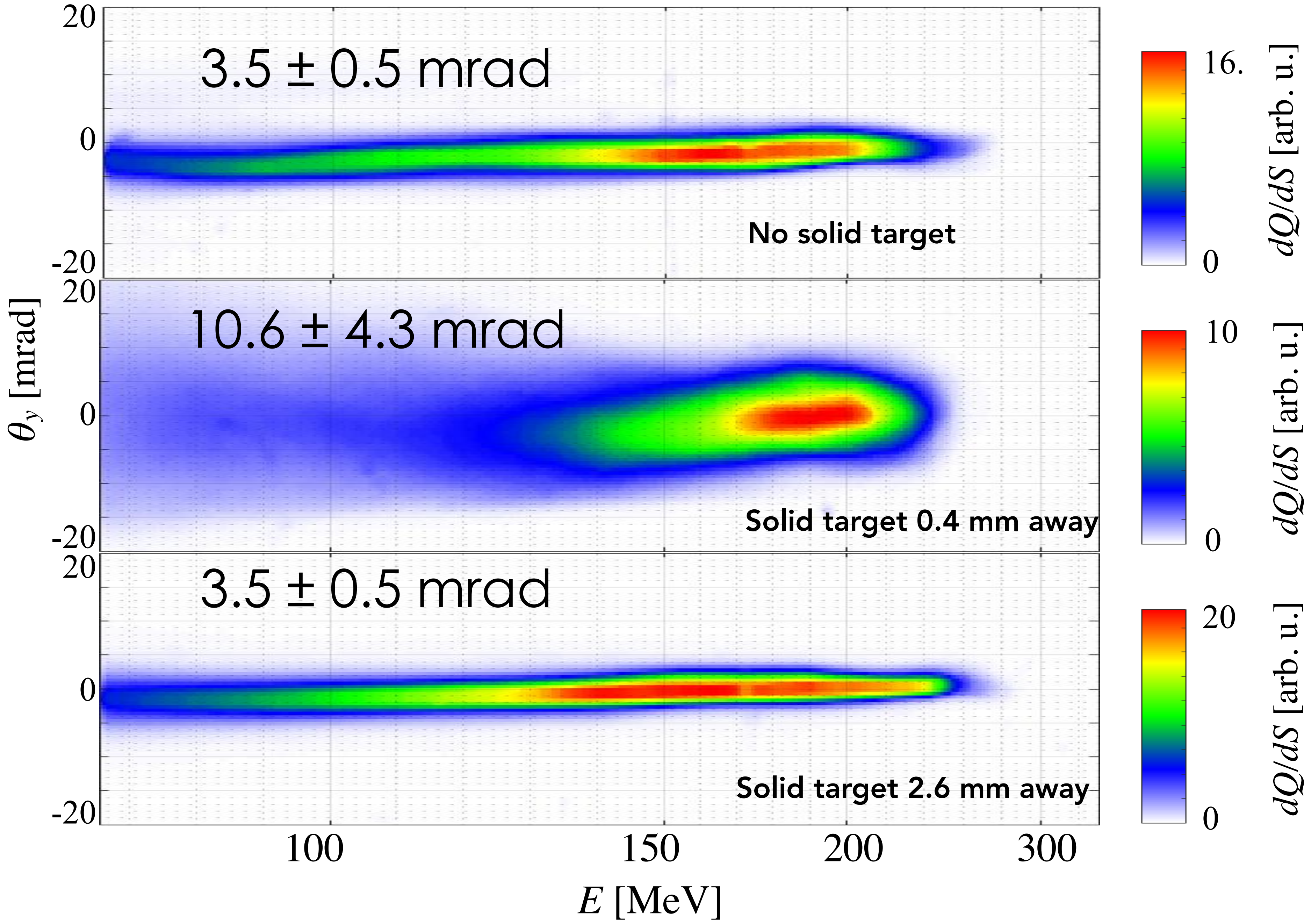
Interaction of the electron beam with irradiated foil

Side view interferometry





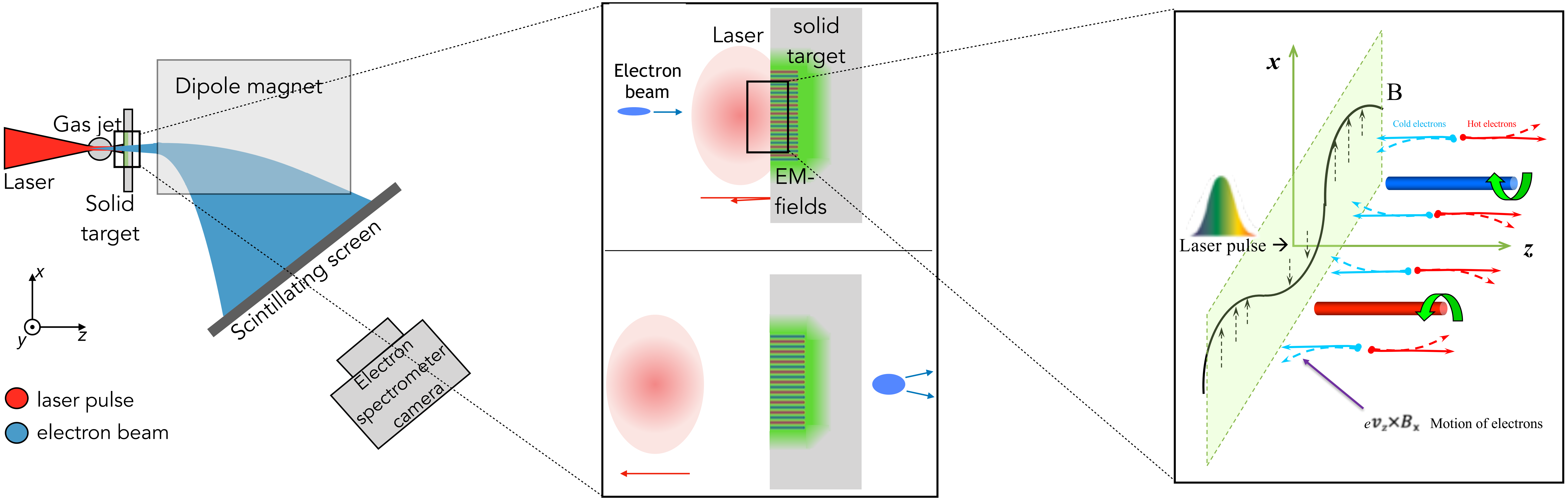
Electron spectra



- Sensitive to the jet-foil distance -> cannot be described by the scattering
- Effect of reflected laser ruled out
- Behaves similarly for different target thicknesses -> effect is happening only within limited penetration depth (in the vicinity of the surface of the solid target)

Current filamentation instability in hybrid accelerator

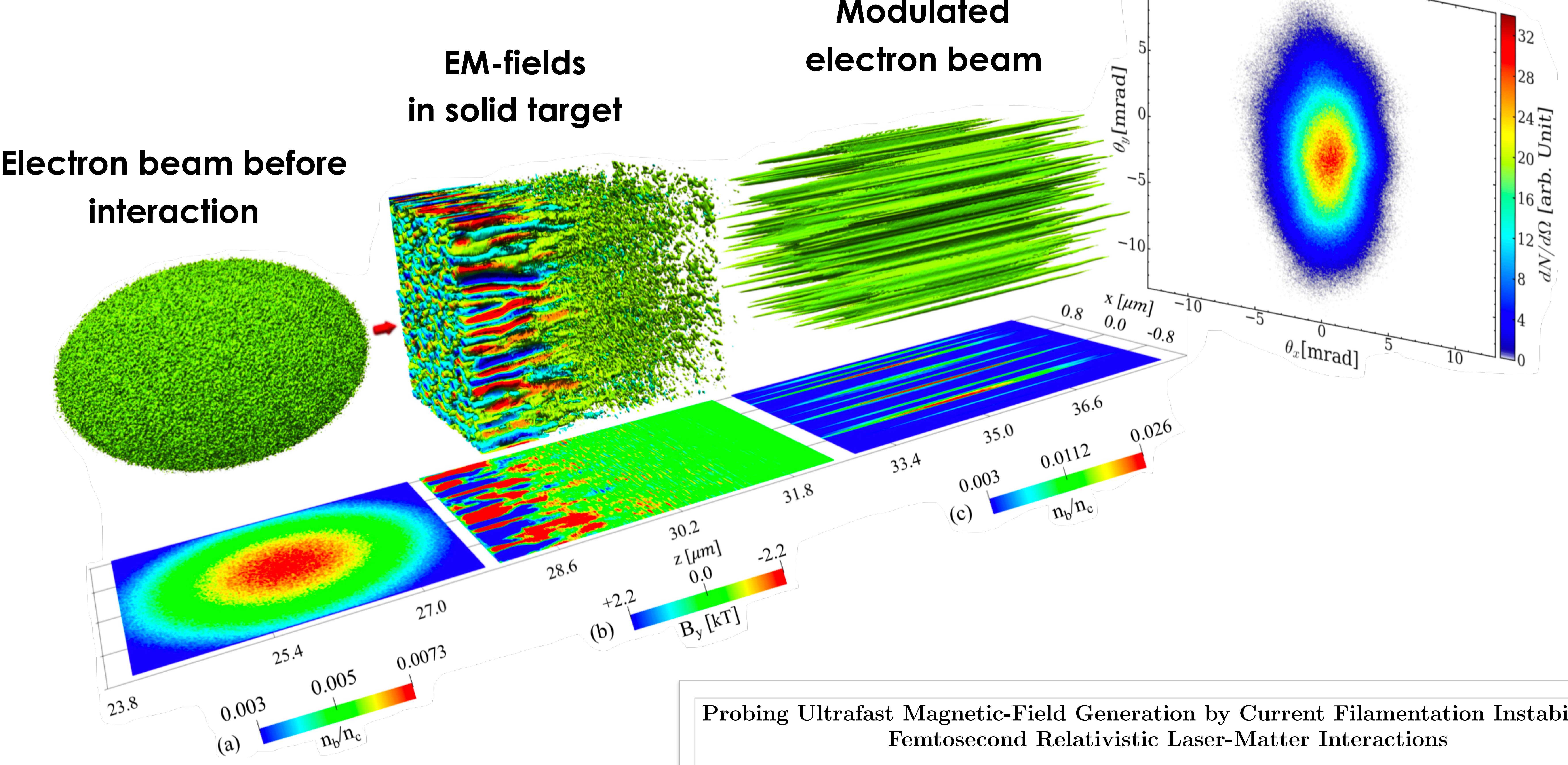
- After LWFA stage, laser is incident on the surface of the solid target, creating plasma with overcritical density
- Plasma mirror reflects the laser, letting the relativistic electron beam to pass through
- Electron beam after passing the solid target propagates towards the electron spectrometer



- Laser deposits energy within the skin depth
- This energy is transformed into distribution of hot electrons
- Current of hot electrons into the target triggers return current of the cold electrons from plasma
- Anisotropic system that is unstable to current filamentation instability

3D CALDER simulation of current filamentation instability

arXiv:1907.12052 (2019)

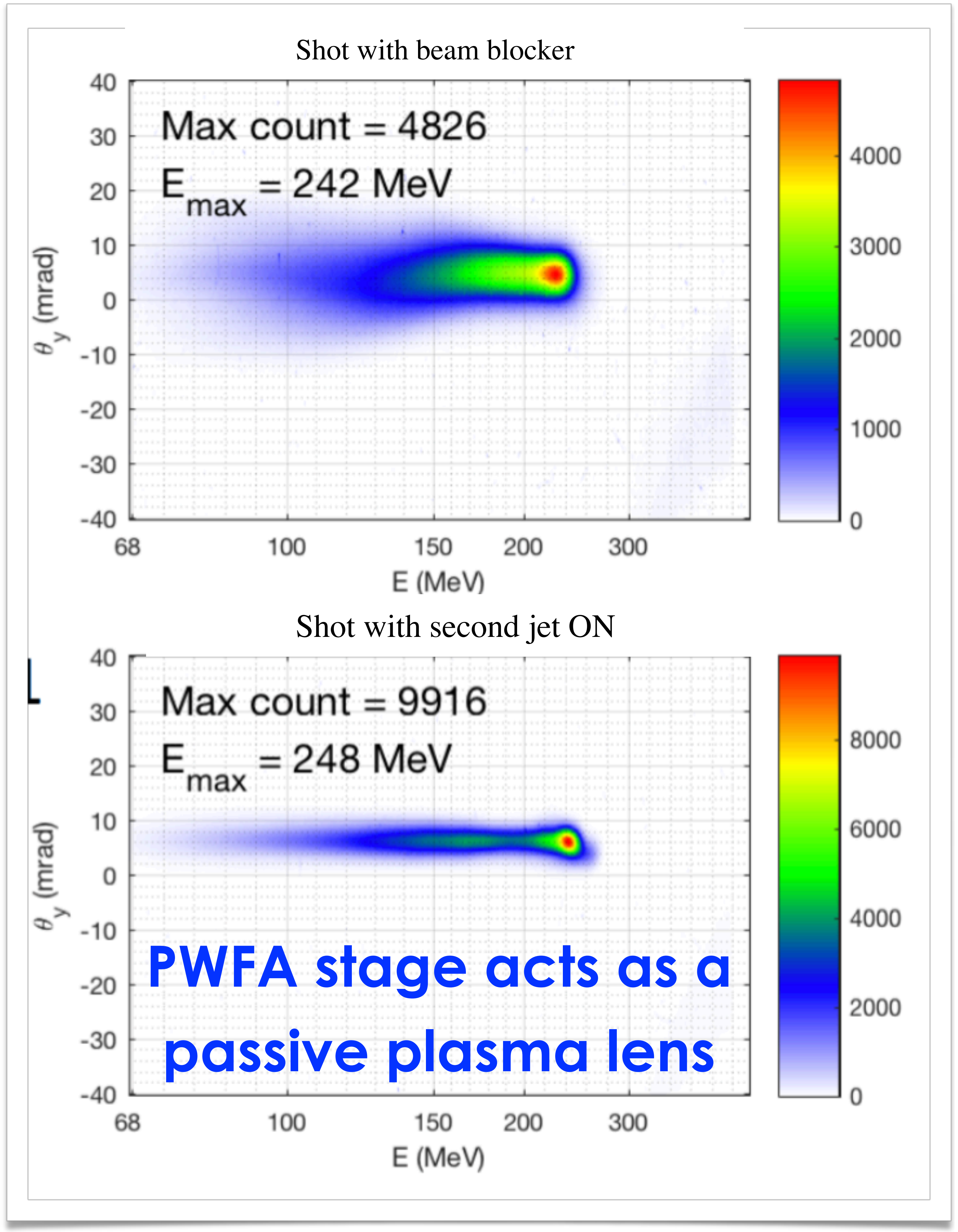


- Few kT.um integrated magnetic field
- Sub -µm transverse modulations
- Sub-µm length of the filaments

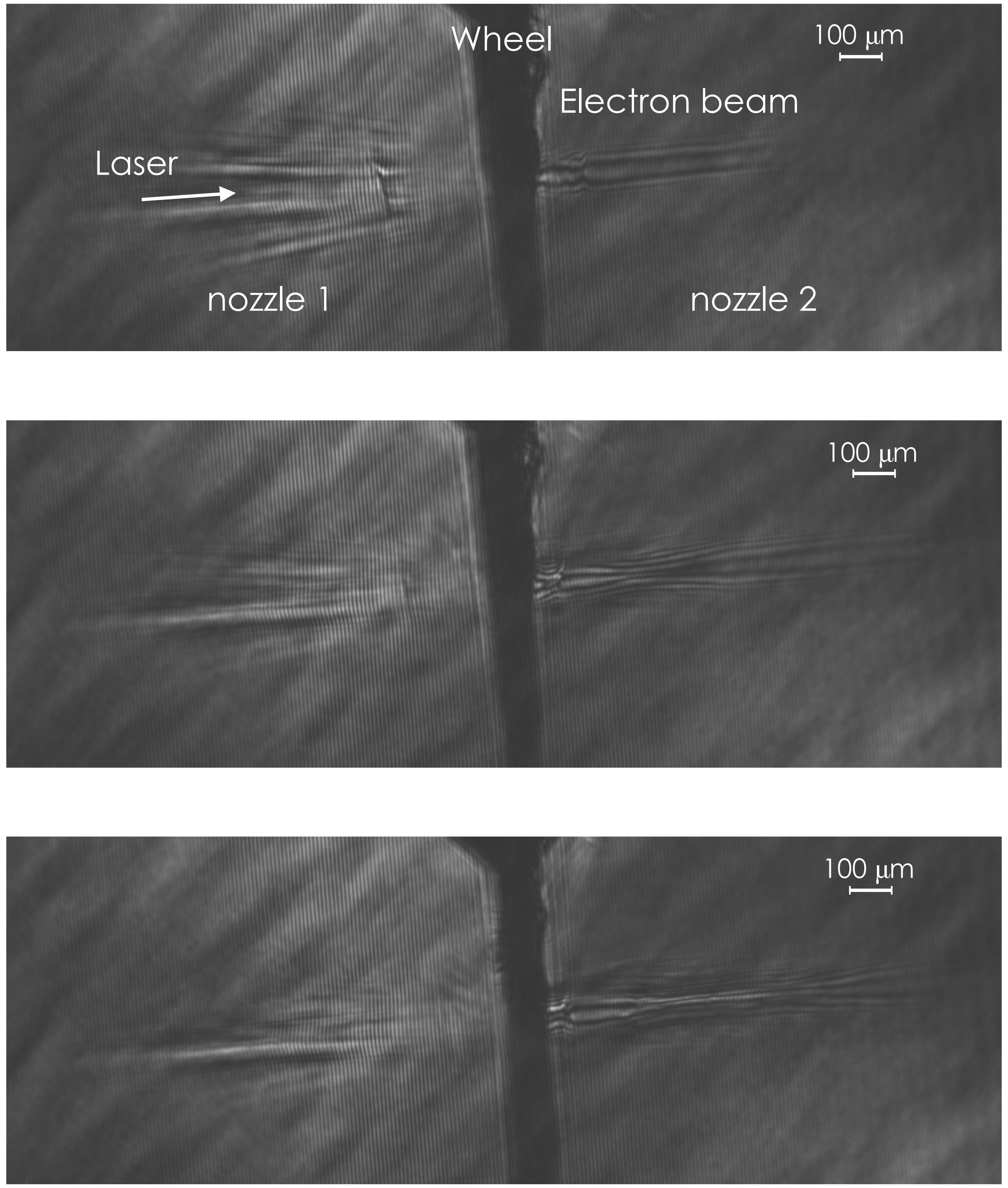
Probing Ultrafast Magnetic-Field Generation by Current Filamentation Instability in Femtosecond Relativistic Laser-Matter Interactions

G. Raj,[1,*] O. Kononenko,[1,*] A. Doche,[1] X. Davoine,[2] C. Caizergues,[1] Y.-Y. Chang,[3] J. P. Couperus Cabadağ,[3] A. Debus,[3] H. Ding,[4,5] M. Förster,[4,5] M. F. Gilljohann,[4,5] J.-P. Goddet,[1] T. Heinemann,[6,7,8] T. Kluge,[3] T. Kurz,[3,9] R. Pausch,[3] P. Rousseau,[1] P. San Miguel Claveria,[1] S. Schöbel,[3,9] A. Siciak,[1] K. Steiniger,[3] A. Tafzi,[1] S. Yu,[1] B. Hidding,[7,8] A. Martinez de la Ossa,[6] A. Irman,[3] S. Karsch,[4,5] A. Döpp,[4,5] U. Schramm,[3,9] L. Gremillet,[2] and S. Corde[1,†]

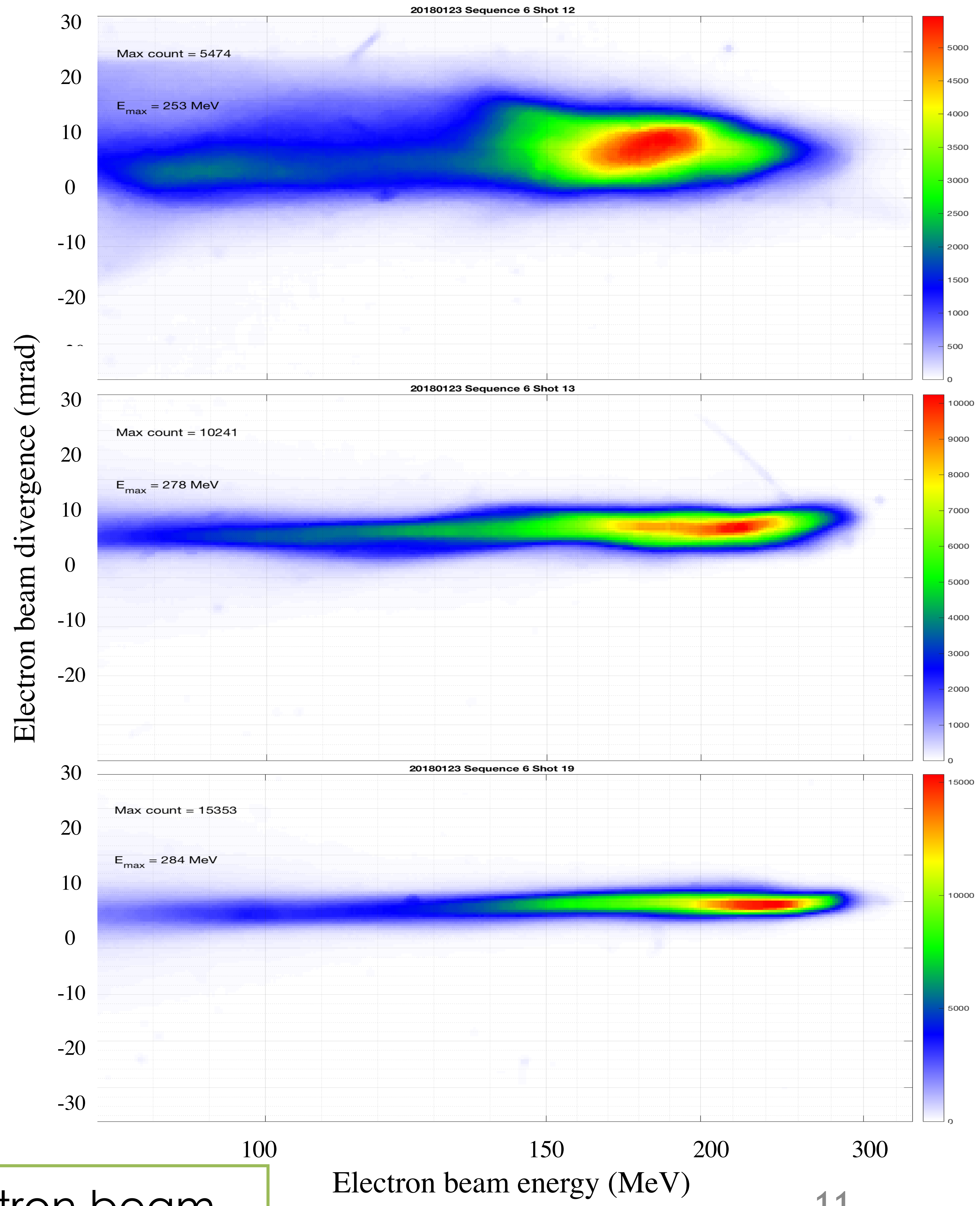
LWFA electron beams in second PWFA jet



Side view interferometry

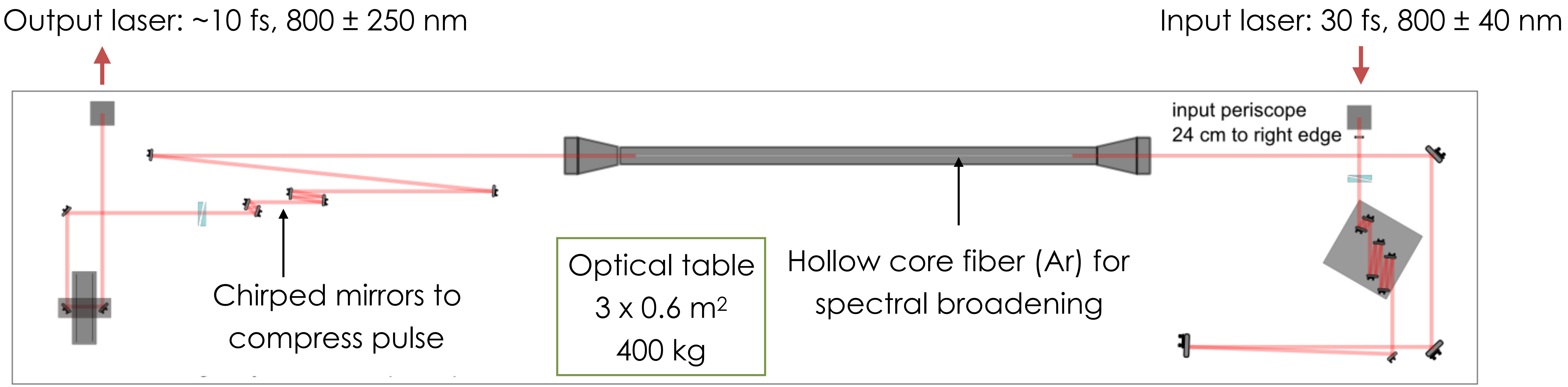


Electron spectroscopy



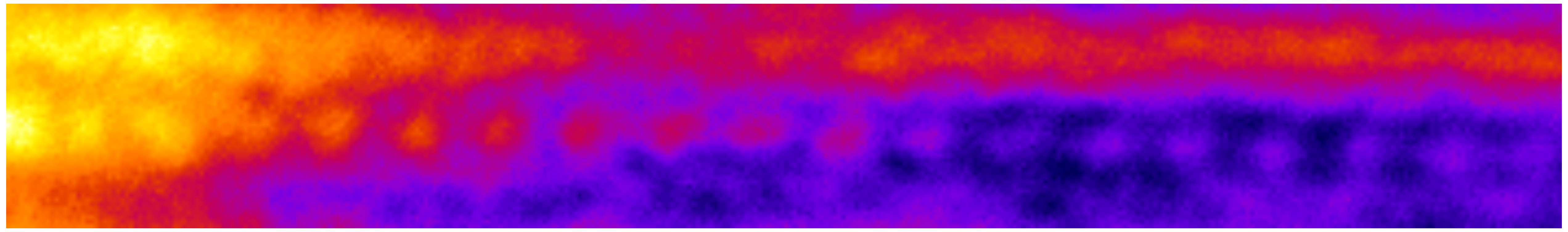
Plasma wave, excited by electron bunch in the second stage, works as a lens for electron beam

Few cycle optical probe for plasma wave imaging



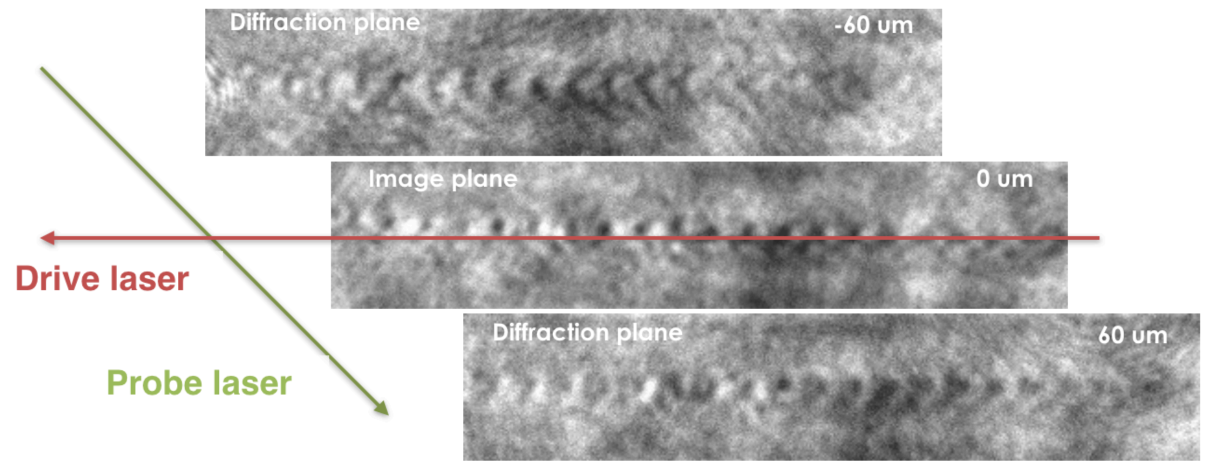
- Spectral broadening in hollow core fibre filled with Argon (self-phase modulation)
- Compression using chirped mirrors
- Transverse probing of the plasma wave with variable delay
- Imaging onto cameras using achromatic microscope (x10) objective and lens

One of the first LWFA plasma wave shadowgraphy in SalleJaune

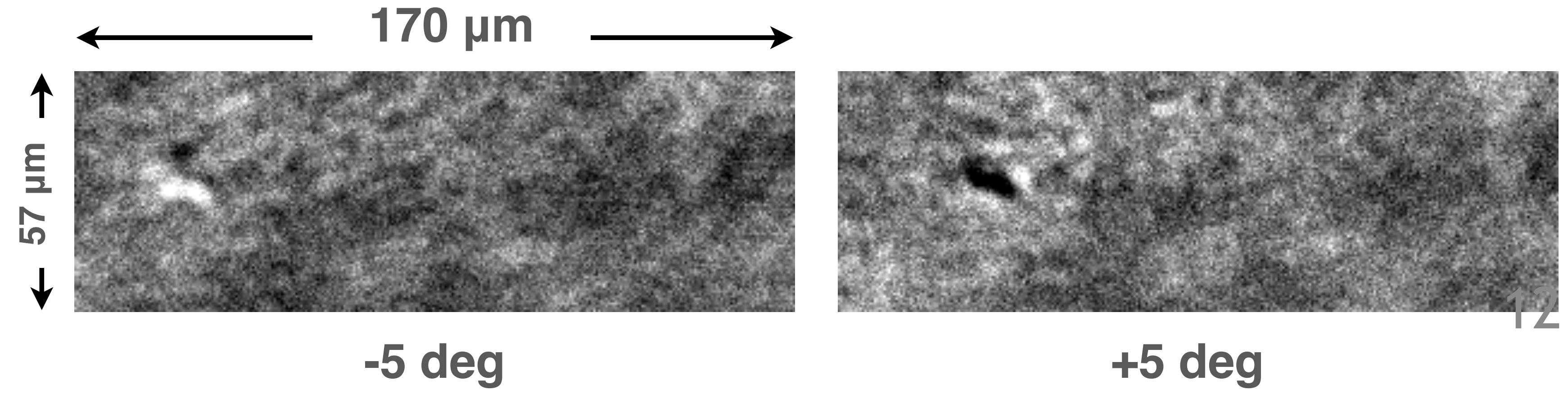


PWFA plasma wave too weak to be observed, Salle Jaune currently under upgrade to double the on-target laser energy to 2.5-3.5 J

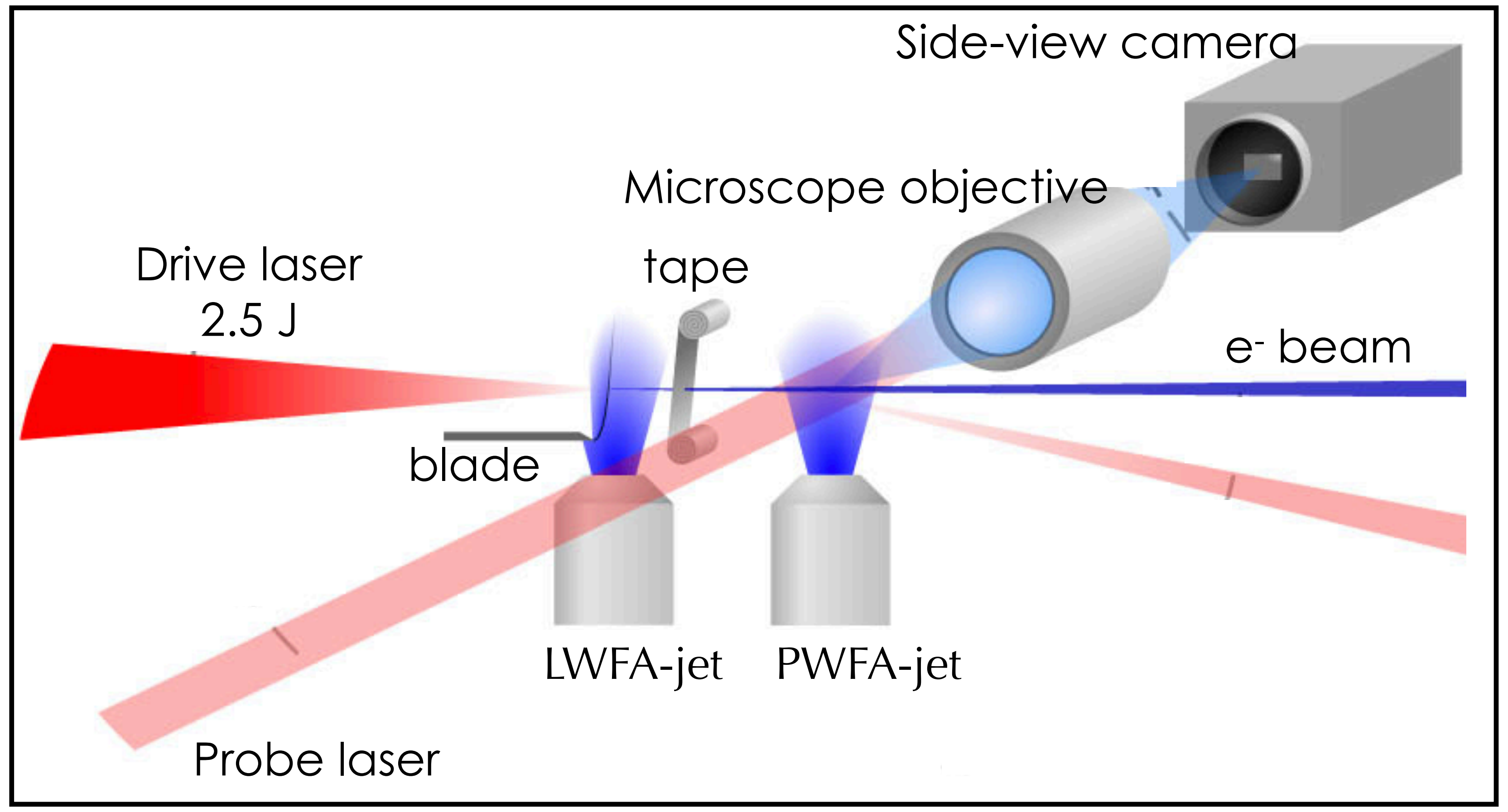
Multi-plane shadowgraphy

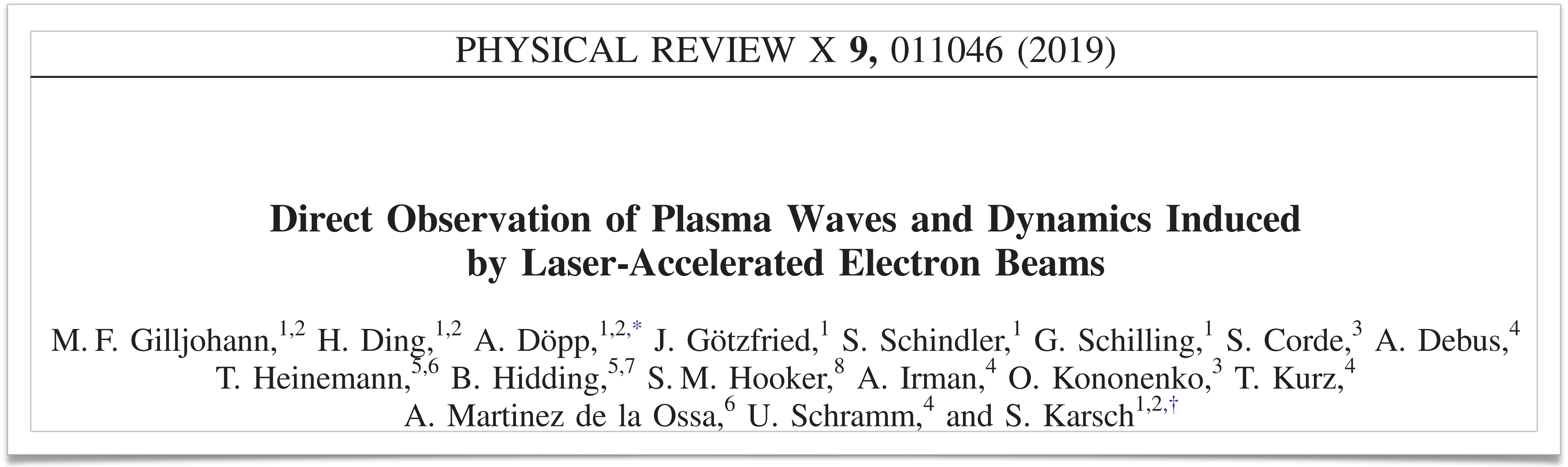


Faraday polarisation rotation - to detect the magnetic fields from plasma wave or electron beam



Study of PWFA plasma dynamics in hybrids (LMU)

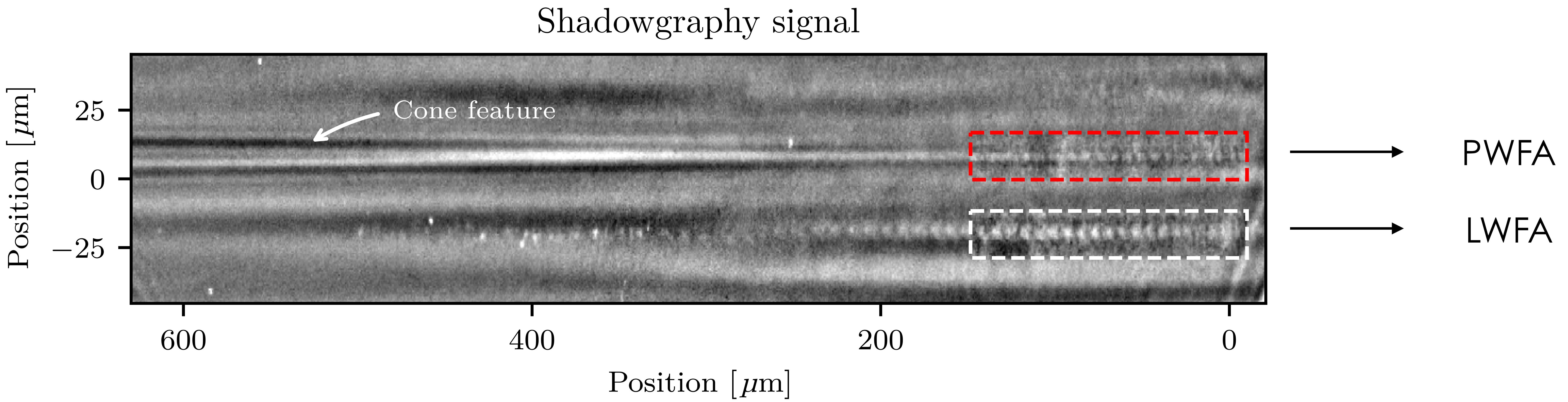




PHYSICAL REVIEW X 9, 011046 (2019)

Direct Observation of Plasma Waves and Dynamics Induced by Laser-Accelerated Electron Beams

M. F. Gilljohann,[1,2] H. Ding,[1,2] A. Döpp,[1,2,*] J. Götzfried,[1] S. Schindler,[1] G. Schilling,[1] S. Corde,[3] A. Debus,[4] T. Heinemann,[5,6] B. Hidding,[5,7] S. M. Hooker,[8] A. Irman,[4] O. Kononenko,[3] T. Kurz,[4] A. Martinez de la Ossa,[6] U. Schramm,[4] and S. Karsch[1,2,†]

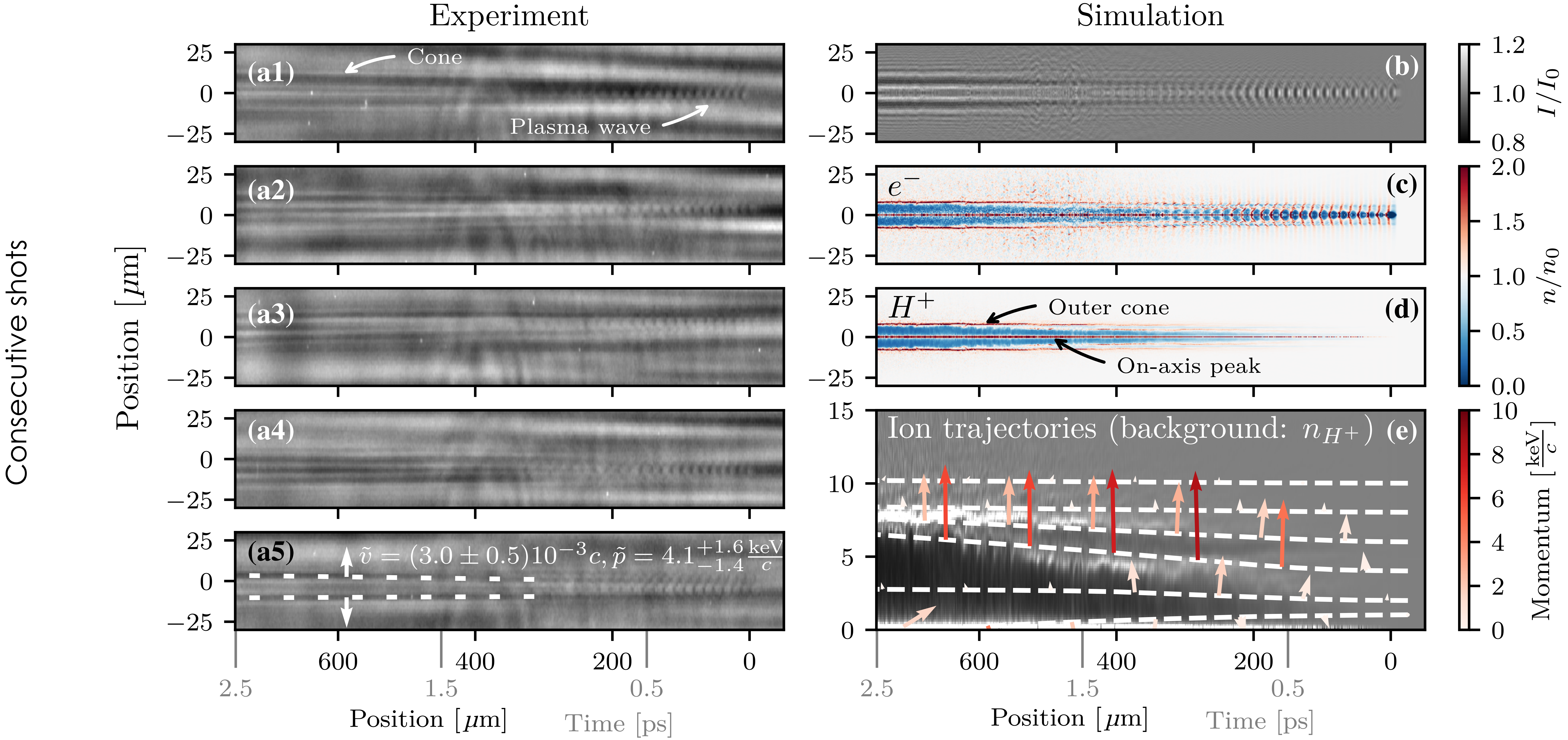


Shock injection:
$Q = 200$ pC
$E = 150$ MeV
Divergence 0.6 mrad (FWHM)
3 mm gap between jets

First direct observation of PWFA plasma waves

For PWFA plasma wave: strong plasma wave ponderomotive force acts on plasma ions causing their transverse expansion and a cone feature

Study of PWFA plasma dynamics in hybrids (LMU)



Direct visualisation of PWFA-induced ion dynamics at ps time scales

Direct relationship to the talk from Thales Silva: self-generated hollow channels and associated ion dynamics can be visualised

High peak current driver from LWFA (HZDR)

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

nature COMMUNICATIONS

Demonstration of a beam loaded nanocoulomb-class laser wakefield accelerator

J.P. Couperus[1,2], R. Pausch[1,2], A. Köhler[1,2], O. Zarini[1,2], J.M. Krämer[1,2], M. Garten[1,2], A. Huebl[1,2], R. Gebhardt[1], U. Helbig[1], S. Bock[1], K. Zeil[1], A. Debus[1], M. Bussmann[1], U. Schramm[1,2] & A. Irman[1]

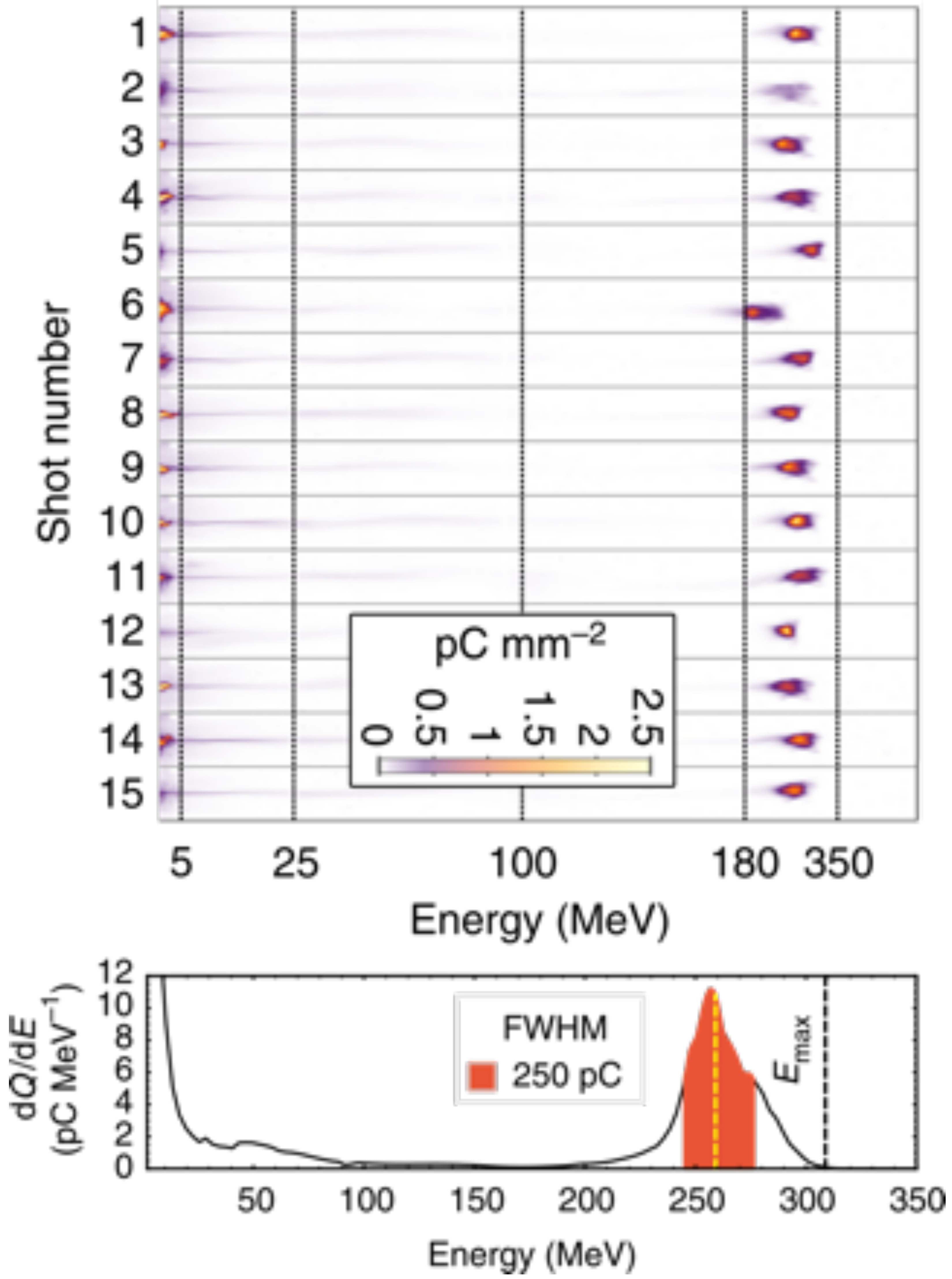
Self truncated ionisation injection:

$Q = 220 \pm 40$ pC

$E_{peak} = 250 \pm 23$ MeV

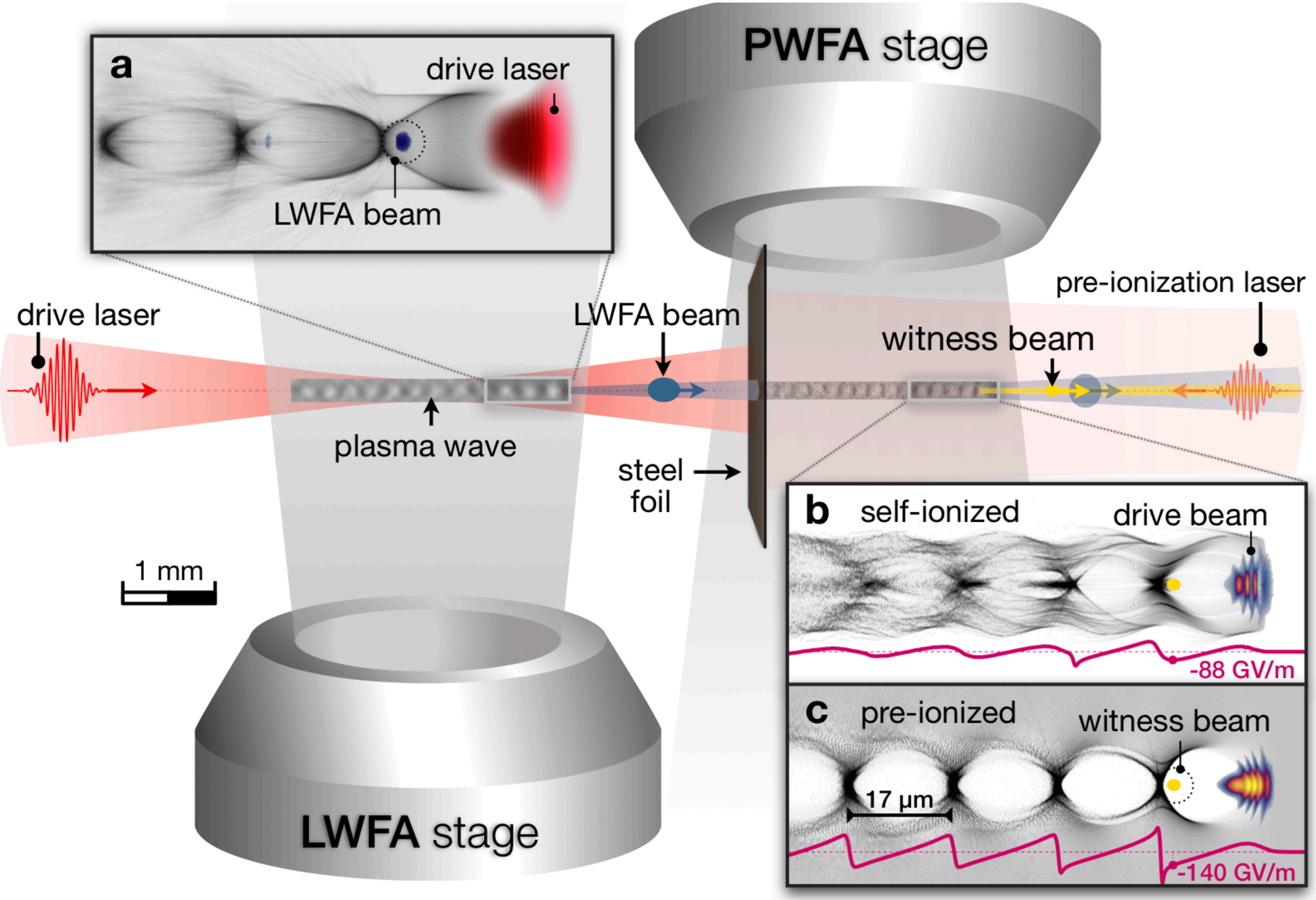
$\Delta E = 32$ MeV (8%)

Divergence ~ 7 mrad



Acceleration of an electron beam in a PWFA powered by LWFA electron beams

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



OSIRIS 3D PIC simulations demonstrating more pronounced PWFA in pre-ionized case

Deutsches Elektronen-Synchrotron

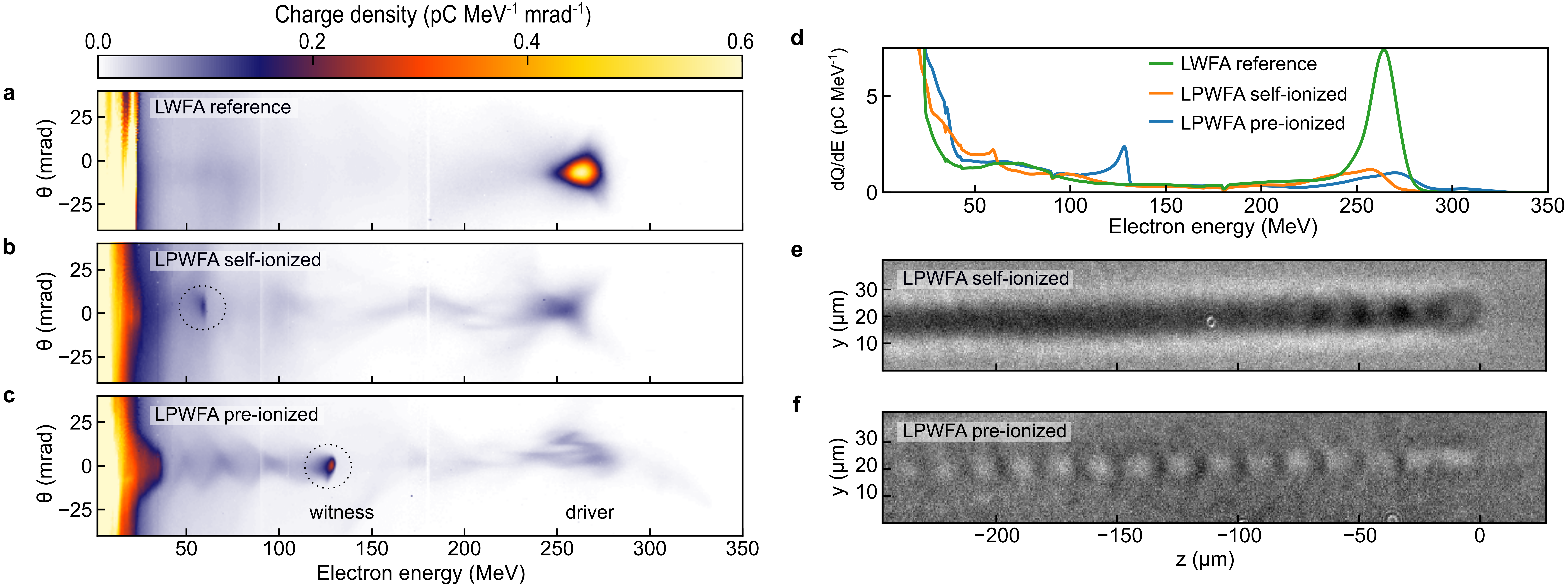
Accelerating gradient in PWFA stage can exceed 100 GeV/m

Acceleration of an electron beam in a PWFA powered by LWFA electron beams

Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams

T. Kurz,[1,2,*] T. Heinemann,[3,4,5,*] M. F. Gilljohann,[6,7] Y. Y. Chang,[1] J. P. Couperus Cabadağ,[1] A. Debus,[1] O. Kononenko,[8] R. Pausch,[1] S. Schöbel,[1,2] R. W. Assmann,[3] M. Bussmann,[1] H. Ding,[6,7] J. Götzfried,[6,7] A. Köhler,[1] G. Raj,[8] S. Schindler,[6,7] K. Steiniger,[1] O. Zarini,[1] S. Corde,[8] A. Döpp,[6,7] B. Hidding,[4,5] S. Karsch,[6,7] U. Schramm,[1,2] A. Martinez de la Ossa,[3] and A. Irman[1]

arXiv:1909.06676 (2019)



Experimental data: electron spectra (a-c) and shadowgraphy (e-f) in hybrid accelerator

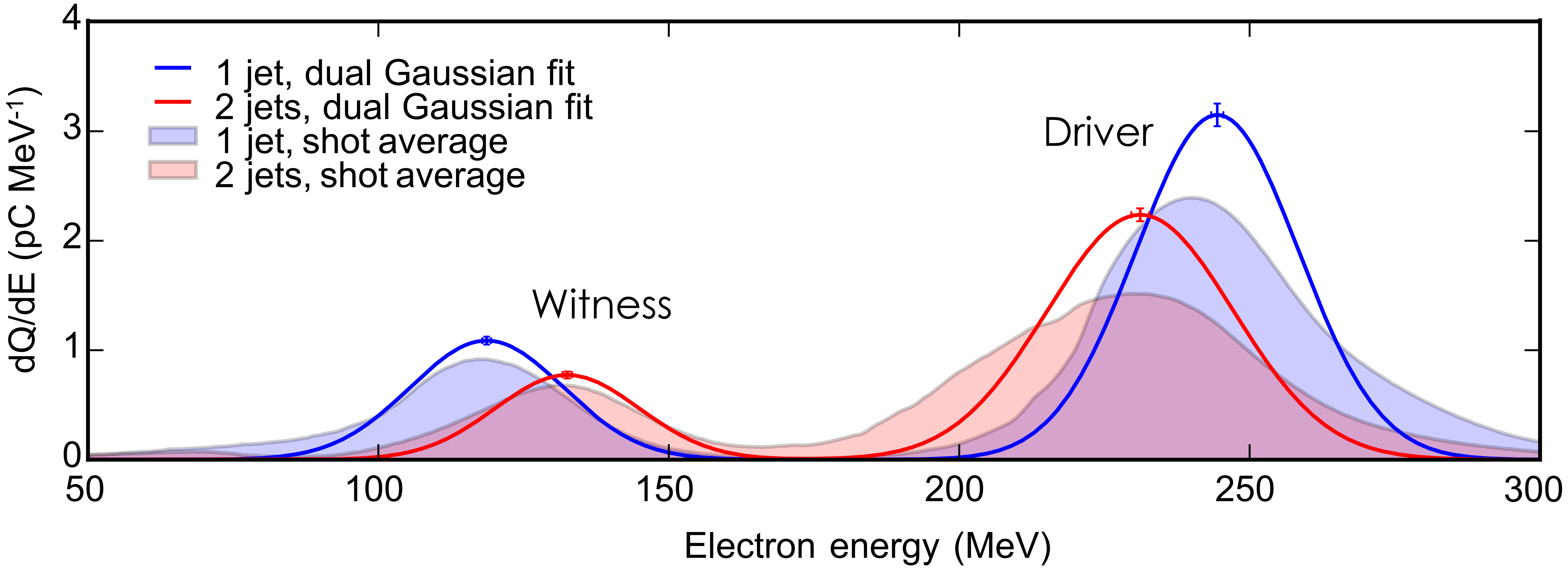
Acceleration of an electron beam in a PWFA powered by LWFA electron beams

Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams

T. Kurz,[1,2,*] T. Heinemann,[3,4,5,*] M. F. Gilljohann,[6,7] Y. Y. Chang,[1] J. P. Couperus Cabadağ,[1] A. Debus,[1] O. Kononenko,[8] R. Pausch,[1] S. Schöbel,[1,2] R. W. Assmann,[3] M. Bussmann,[1] H. Ding,[6,7] J. Götzfried,[6,7] A. Köhler,[1] G. Raj,[8] S. Schindler,[6,7] K. Steiniger,[1] O. Zarini,[1] S. Corde,[8] A. Döpp,[6,7] B. Hidding,[4,5] S. Karsch,[6,7] U. Schramm,[1,2] A. Martinez de la Ossa,[3] and A. Irman[1]

arXiv:1909.06676 (2019)

Dual drive-witness beam from LWFA by shock injection in two consecutive plasma buckets



Reproducible simultaneous deceleration of the drive bunch and acceleration of the witness bunch

Summary

- Current filamentation instability in solid target separating LWFA and PWFA stages
- First direct observation of PWFA plasma waves, PWFA physics with few-cycle shadowgraphy
- PWFA-induced ion dynamics at ps time scales
- Acceleration of an electron beam in a PWFA powered by LWFA electron beams
- Work presented on behalf of the hybrid collaboration:

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
CALA
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
DESY Deutsches Elektronen-Synchrotron
l'X ÉCOLE POLYTECHNIQUE
INSTITUT POLYTECHNIQUE DE PARIS
University of Strathclyde