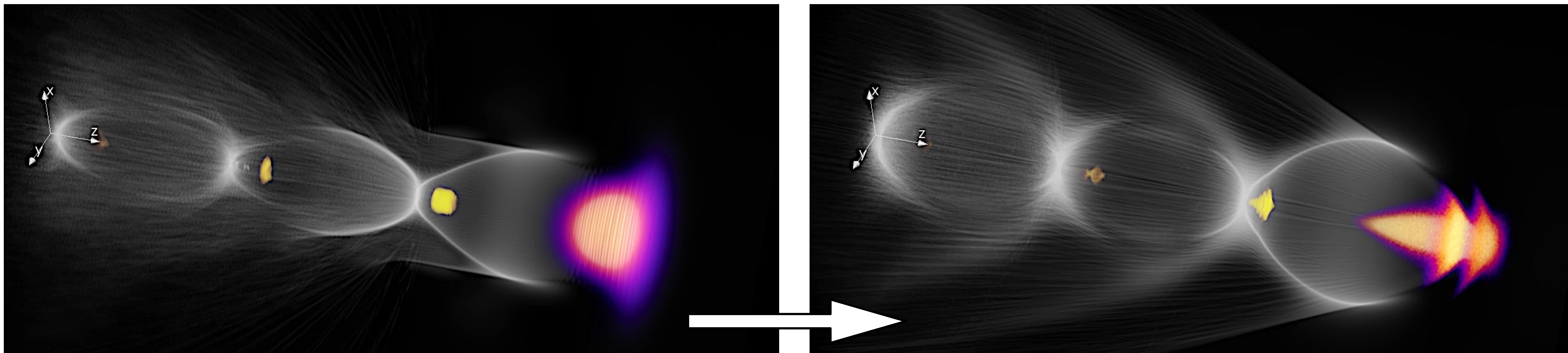
Hybrid LWFA | PWFA staging

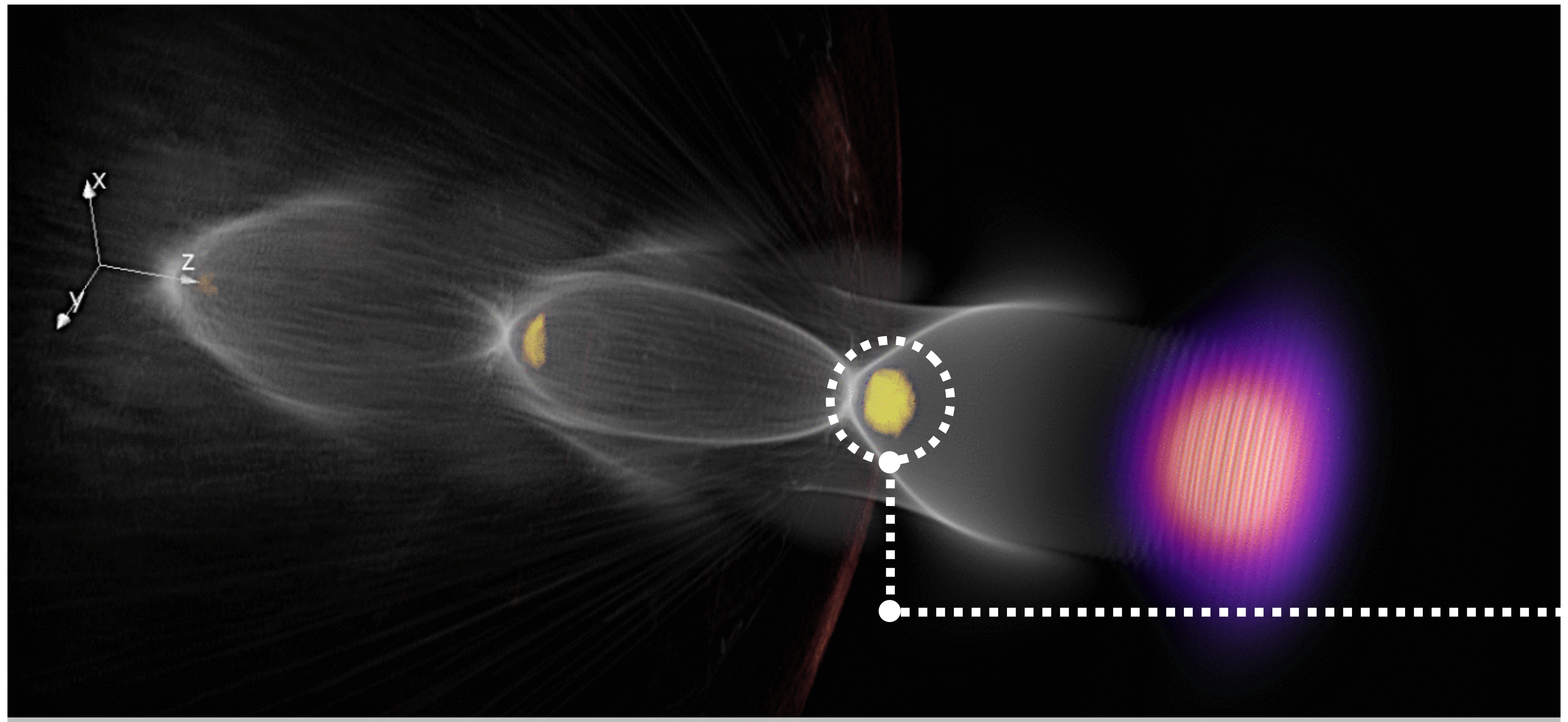


Laser-driven plasma wakefield accelerator (LWFA) Beam-driven plasma wakefield accelerator (PWFA)

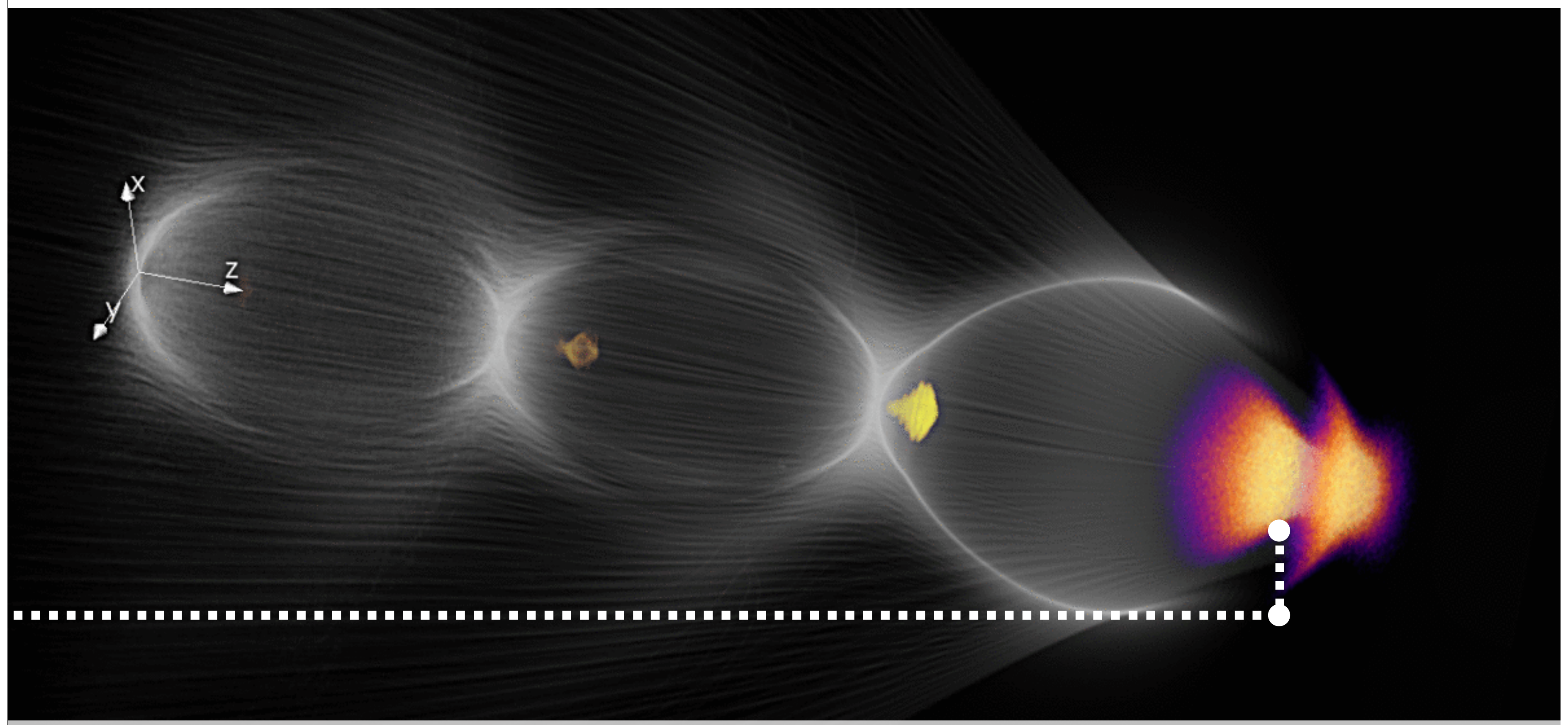
R. W. Aßmann, M. Bussmann, J. P. Couperus, A. Debus, T. Heinemann, B. Hidding,
A. Knetsch, T. Kurz, A. Koehler, J. Osterhoff, R. Pausch, U. Schramm,
A. Irman and A. Martinez de la Ossa.

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF | University of Strathclyde Glasgow | UHH | DESY. | MT ARD MATTER AND TECHNOLOGIES ACCELERATOR RESEARCH AND DEVELOPMENT | HELMHOLTZ ASSOCIATION

Quick introduction: **Hybrid LWFA | PWFA staging**



Laser-driven plasma wakefield accelerator (LWFA)

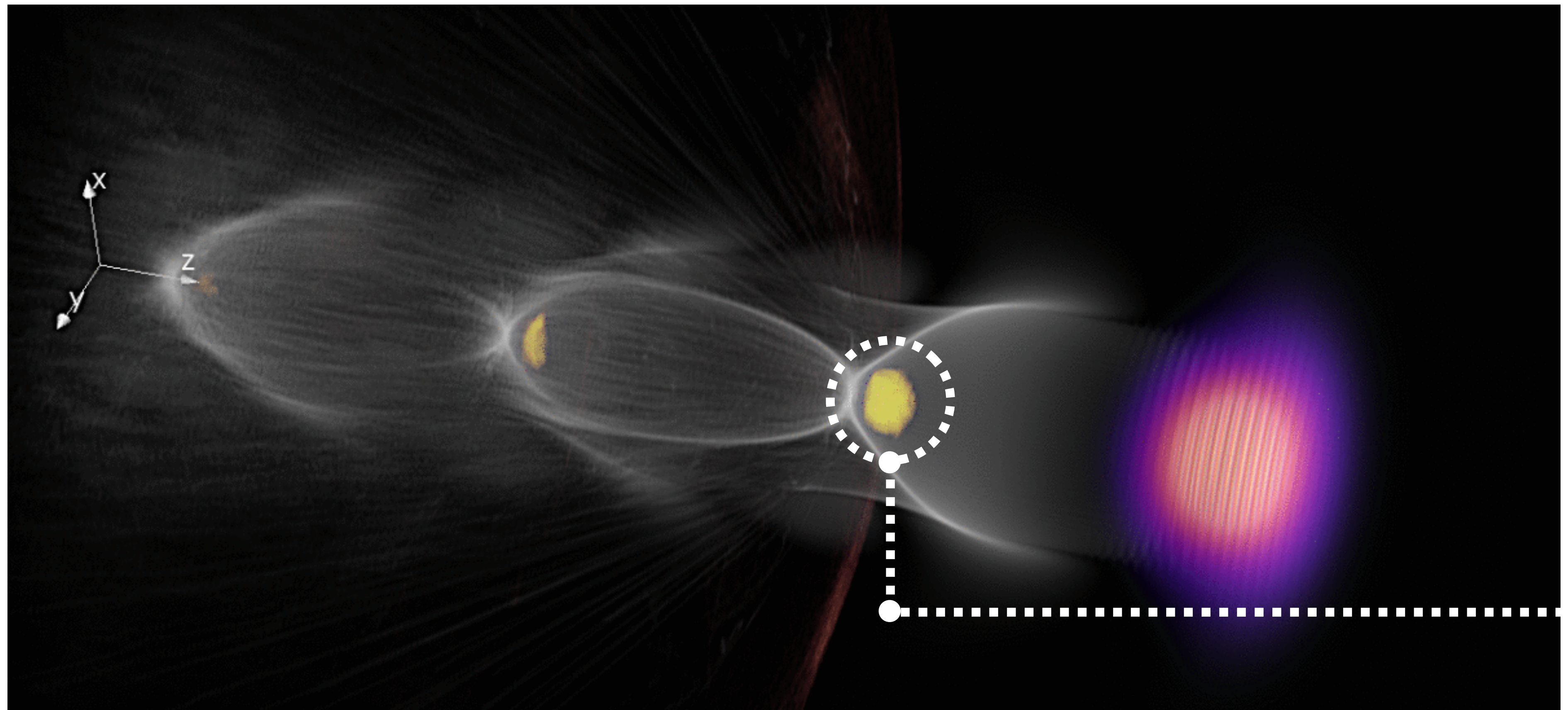


Beam-driven plasma wakefield accelerator (PWFA)

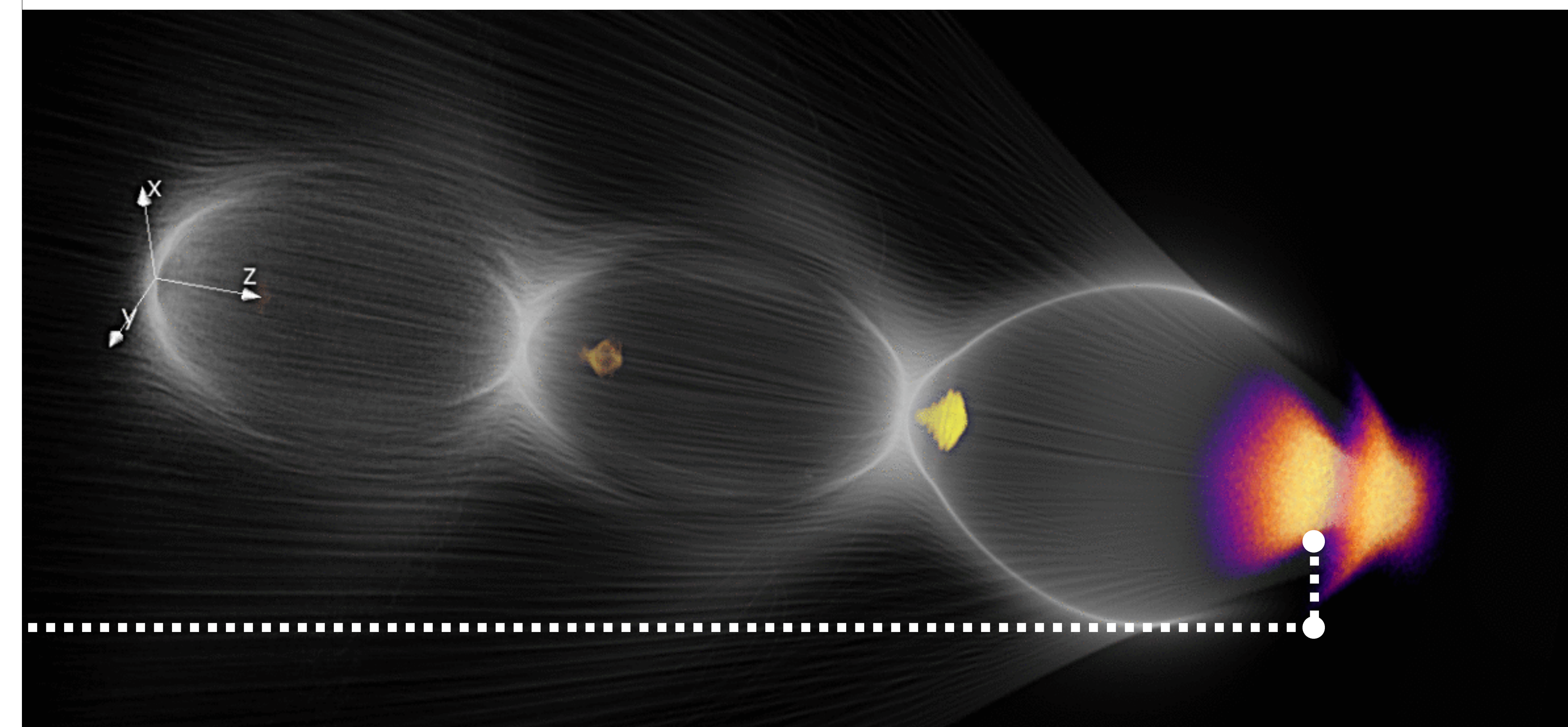
- ➤ Driven by high peak power lasers e.g.100 TW.
- ➤ Compact accelerator of the size of a <u>laser-lab</u>.
- ➤ Provides <u>high-current</u>, <u>GeV electron beams</u>.
- ➤ Greatly improved in <u>control and stability.</u>

- ➤ Driven by relativistic high-current beams e.g.10 kA.
- ➤ Uses km-scale <u>LINACs</u>: SLAC, FLASH, etc.
- ➤ Provides <u>energy boosted</u> electron beams.
- ➤ Special injection techniques for <u>high-quality beams</u>.

Quick introduction: **Hybrid LWFA | PWFA staging**



Laser-driven plasma wakefield accelerator (LWFA)



Beam-driven plasma wakefield accelerator (PWFA)

Combine both in a **LWFA-driven PWFA**

LWFA for the generation of GeV-class, high-current beams → PWFA for the production of energy and brightness boosted beams

"Exploit individual benefits of both schemes in a truly compact setup to generate high-brightness beams on a university laboratory-scale"

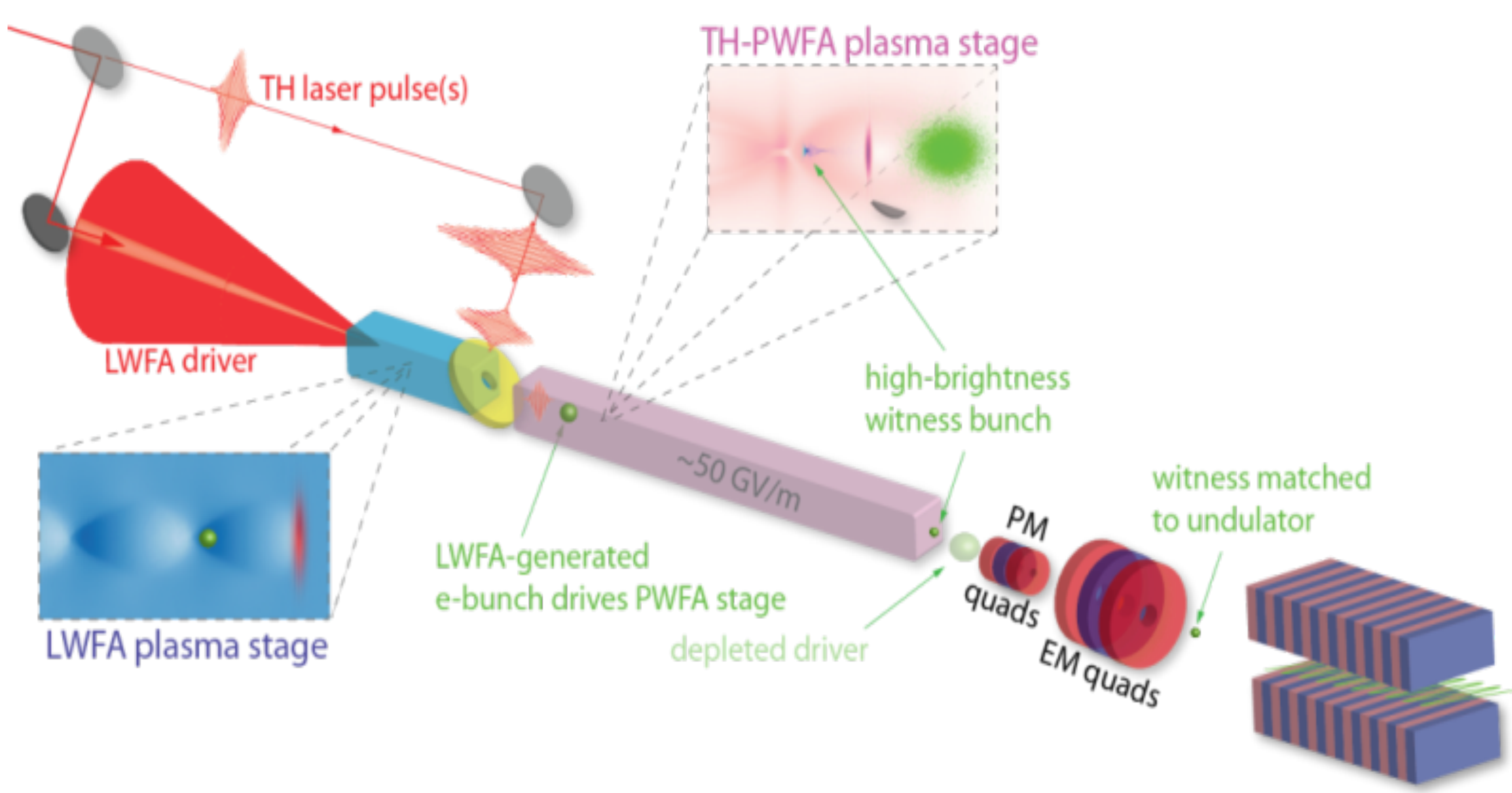
Towards LWFA-driven PWFAs: **Hybrid plasma accelerators**

LWFA | PWFA

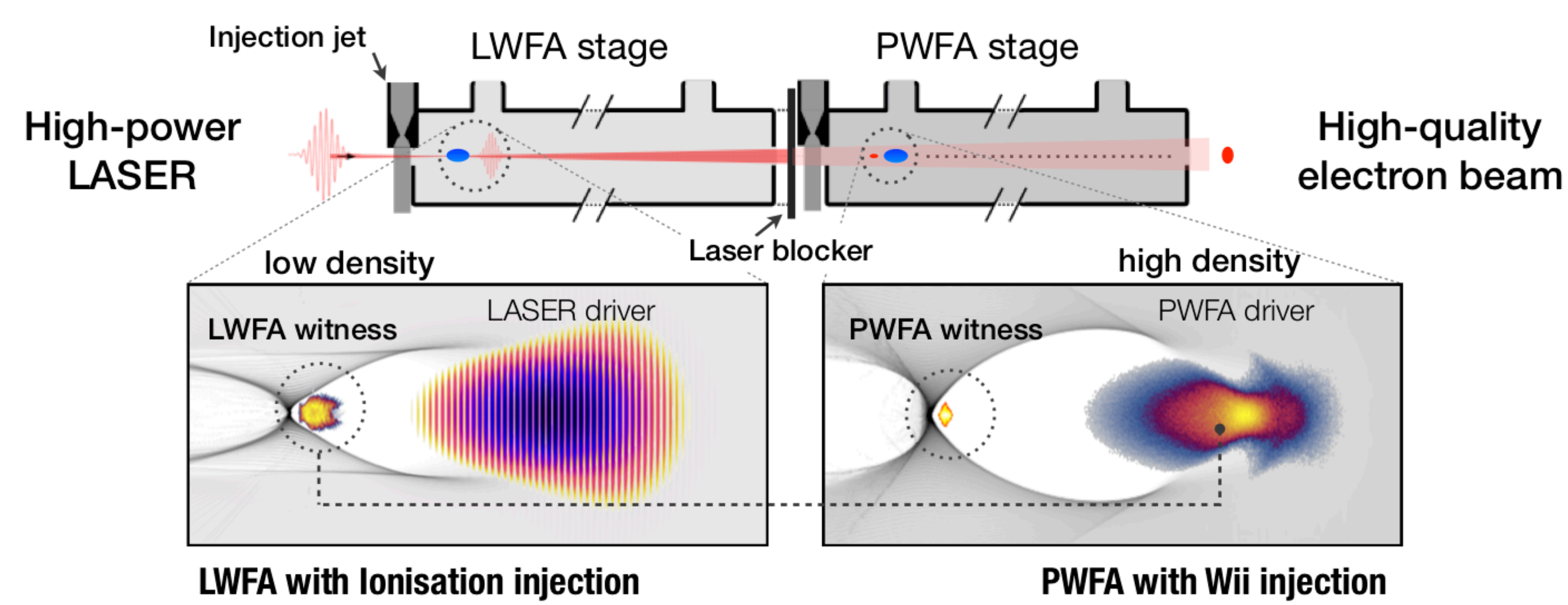
Energy and brightness booster
for the production of multi-GeV FEL-capable beams

EuPraxia Working Package 14:
Hybrid Laser-Electron-Beam Driven Acceleration
B. Hidding and A. M. de la Ossa

Conceptual designs

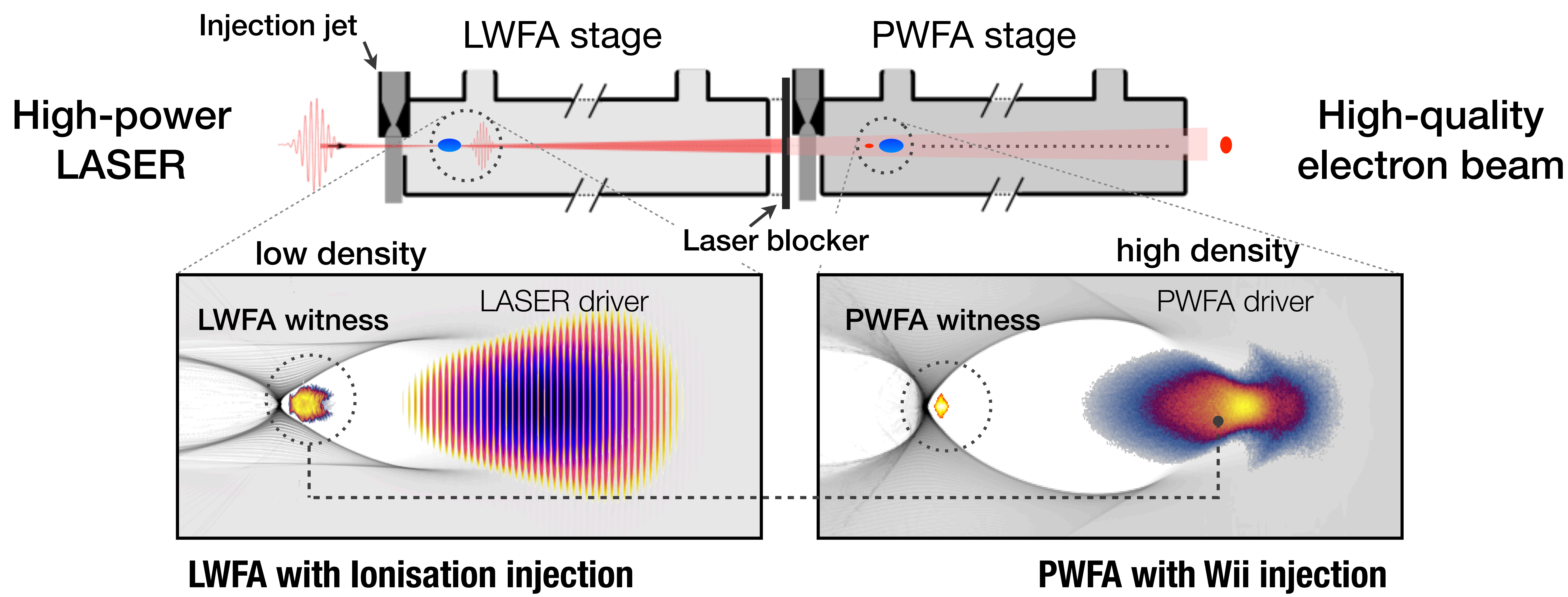


B. Hidding et al., Phys. Rev. Lett. 104, 195002 (2010).
B. Hidding et al., Phys. Rev. Lett. 108, 035001 (2012).



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).

Hybrid LWFA | PWFA design with ionization injection



Why adding a PWFA stage?

- **Energy boost**: High transformer ratio in blowout regime.
- **Emittance reduction:** Novel injection techniques in PWFA for the generation of low emittance beams.
- **High-current, low energy spread**: Energy chirp balance by means of beam-loading requires high-current witness.

High-brightness (6D), GeV class electron beams

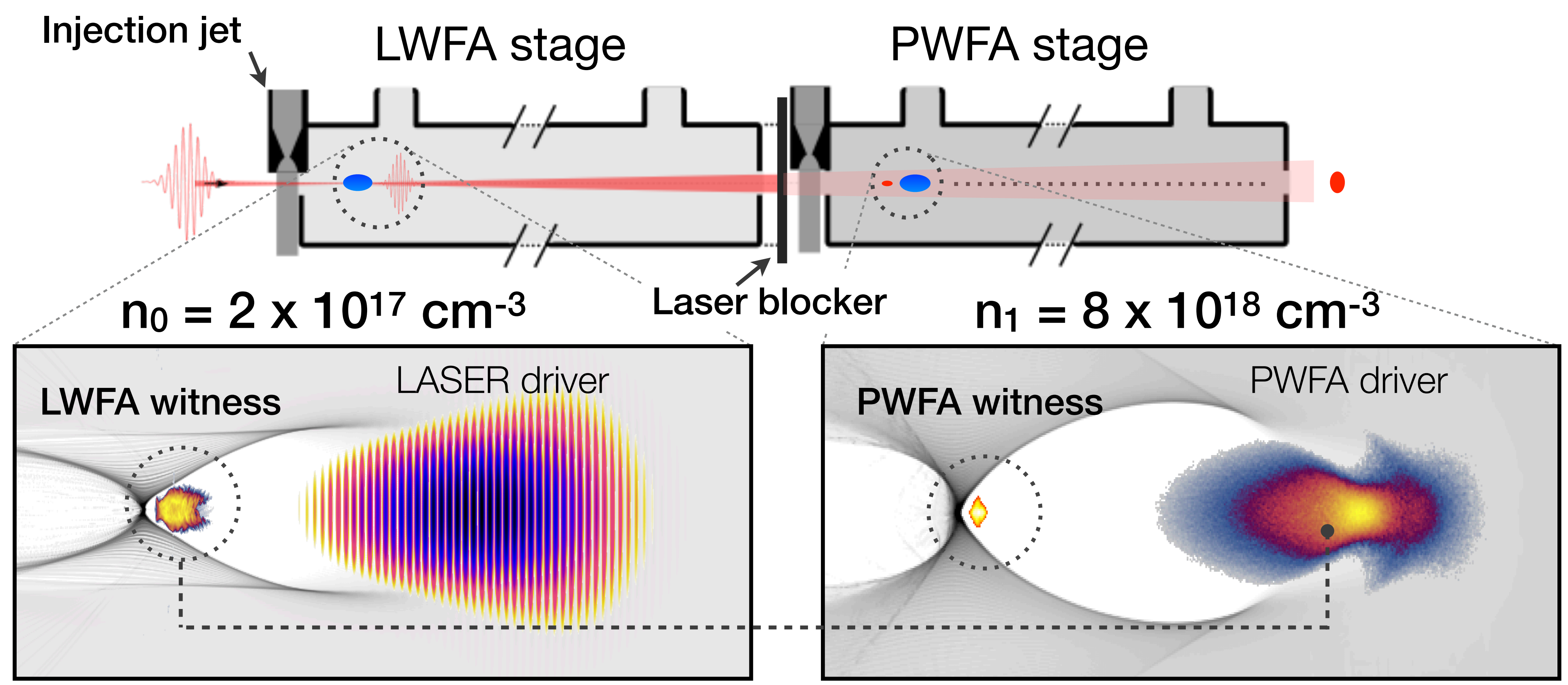
for applications demanding high-quality e.g. FELs.

High 6D brightness $B_{6\mathrm{D}} \propto \dfrac{I_b}{\epsilon_n^2(\sigma_\gamma/\bar{\gamma})}$

LPWFA design with ionization injection: EuPRAXIA example

Laser beam

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



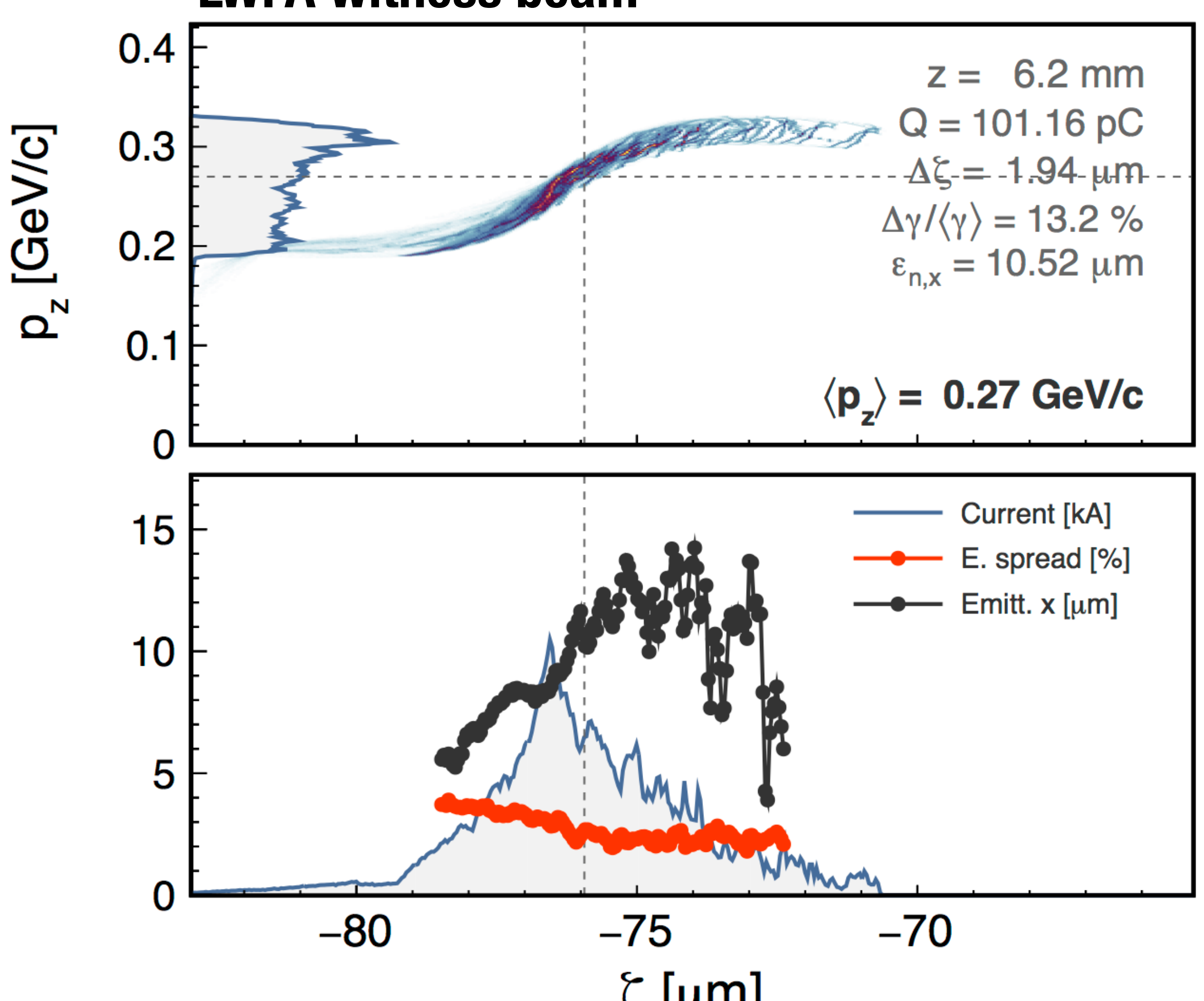
LWFA with Ionisation injection

PWFA with Wii injection

Electron beam

$I_0 = 15$ kA
$\epsilon_n = 130$ nm
$\tau = 700$ as
$\gamma mc^2 = 5$ GeV
$\Delta\gamma/\gamma = 0.2$ %
Charge = 10 pC

LWFA witness beam

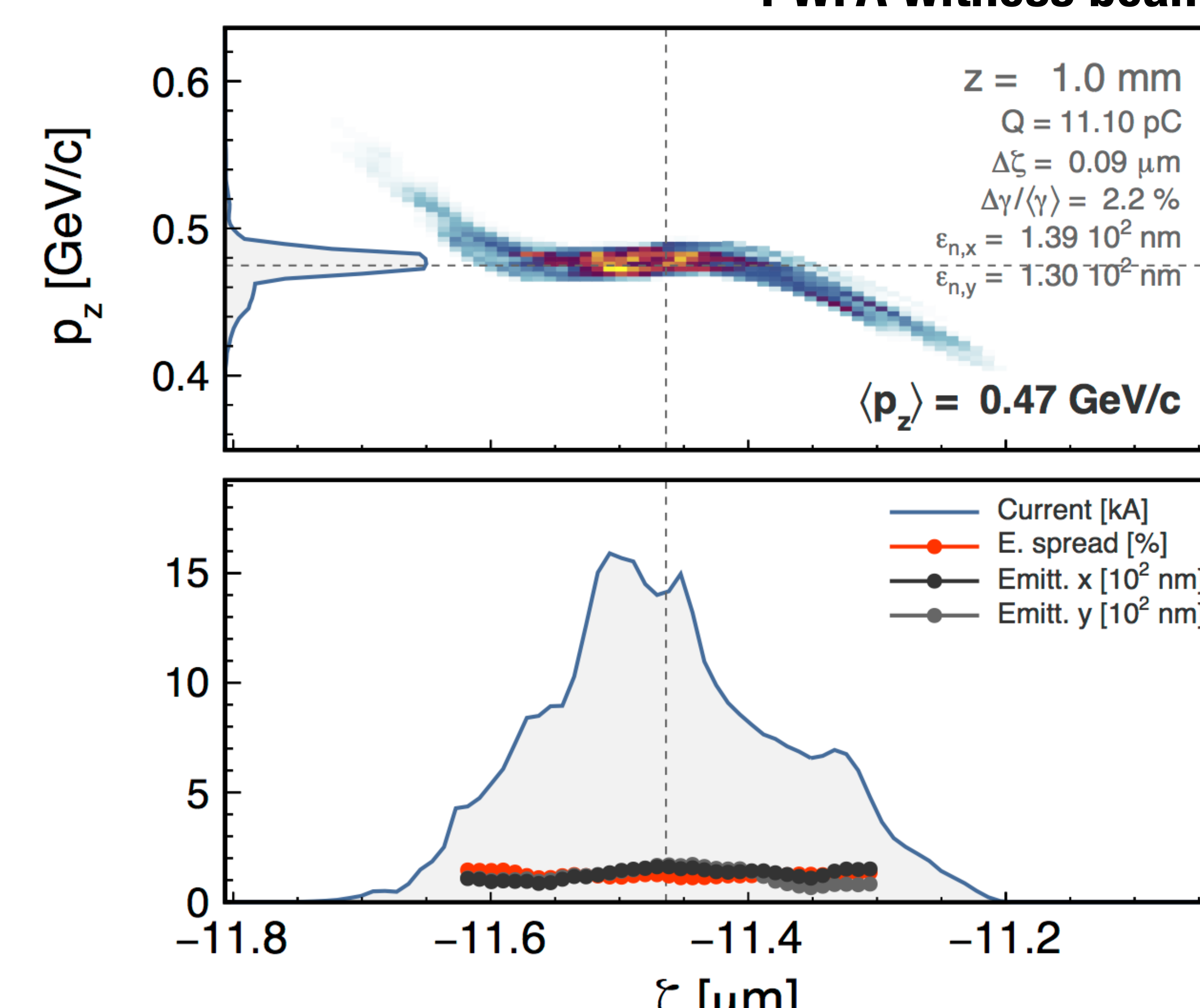


Energy doubling $\Delta\gamma_w = R\,\gamma_d$

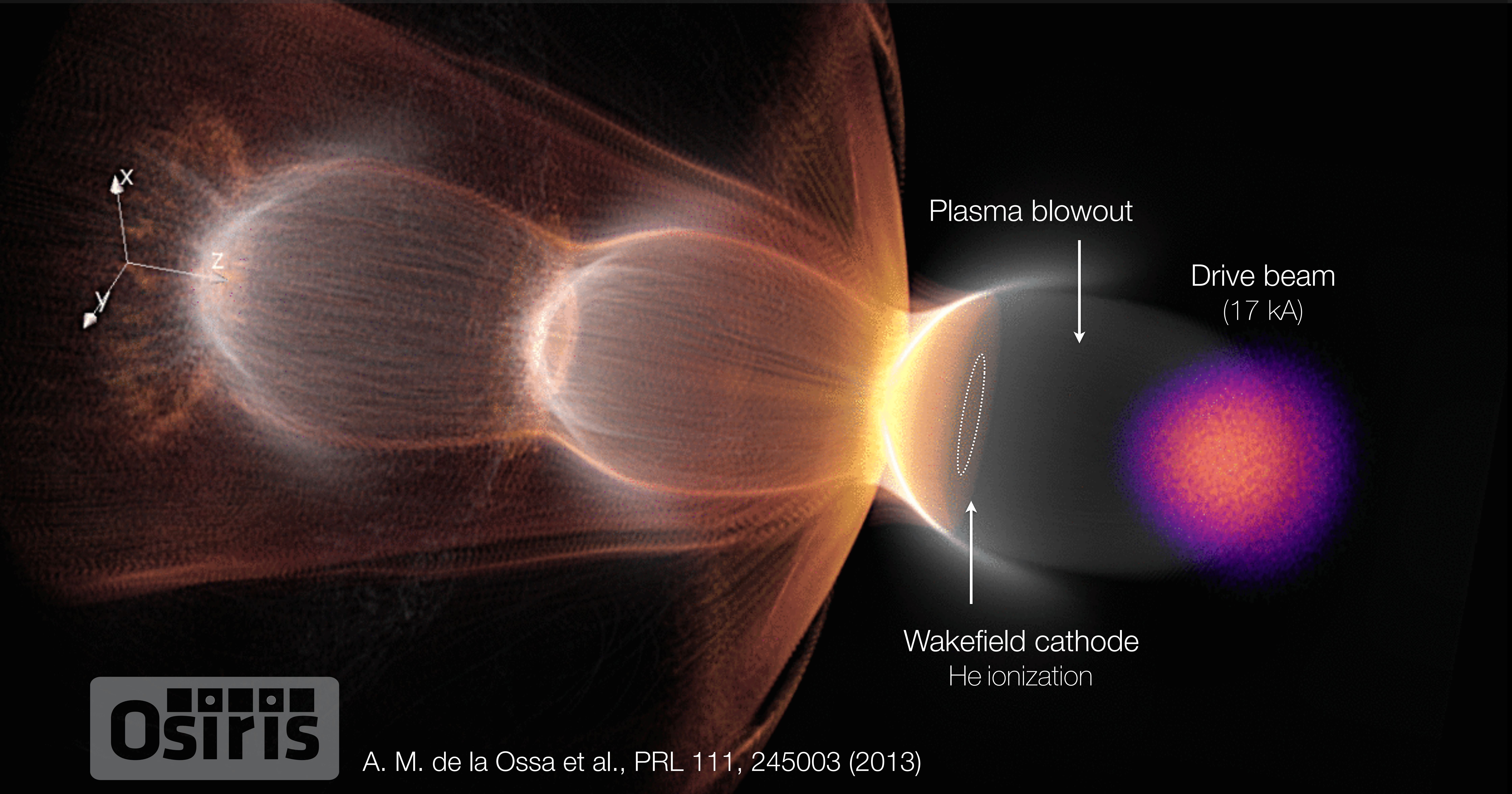
Brightness booster $B \propto \frac{I_b}{\epsilon_n^2}$

x 10000

PWFA witness beam

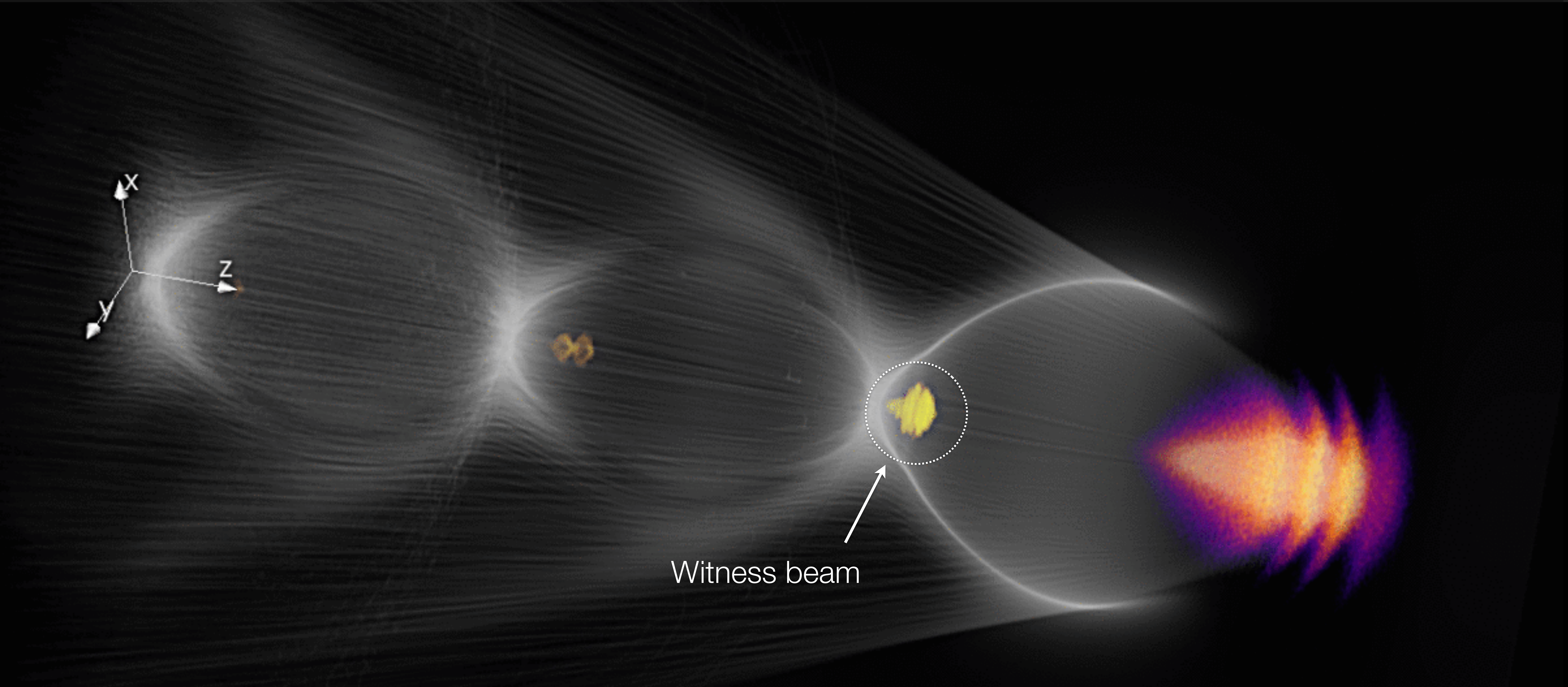


Simulation: **PWFA stage with Wii injection**



A. M. de la Ossa et al., PRL 111, 245003 (2013)

Simulation: PWFA stage with Wii injection



A. M. de la Ossa et al., PRL 111, 245003 (2013)

PWFA with Wii injection and **Self-Similar Staging**

Requirements:

- **<u>High-current</u> (>10 kA) relativistic drivers:**
  Needs a strong blowout regime for trapping.
- **Appropriate dopant species:**
  Ionisation is triggered by the wakefields only.

Features:

- **Self-synchronization:** Wakefield "cathode".
- **Low emittance witness:** $\varepsilon_n \approx 0.1/k_p$
- **High transformer ratio:** $\Delta E_{wit} \approx R\, E_{dri}$
- **<u>High-current</u> and low energy spread witness:**
  energy chirp balance by beamloading.

High 6D brightness $B_{6\mathrm{D}} \propto \dfrac{I_b}{\epsilon_n^2(\sigma_\gamma/\bar{\gamma})}$

Self-Similar Staging

Witness beams from Wii injection
can drive Wii injection
in a higher density plasma

⇩

Order of magnitude reduction of
emittance in each stage.
Brightness x 100.
Energy x 2.

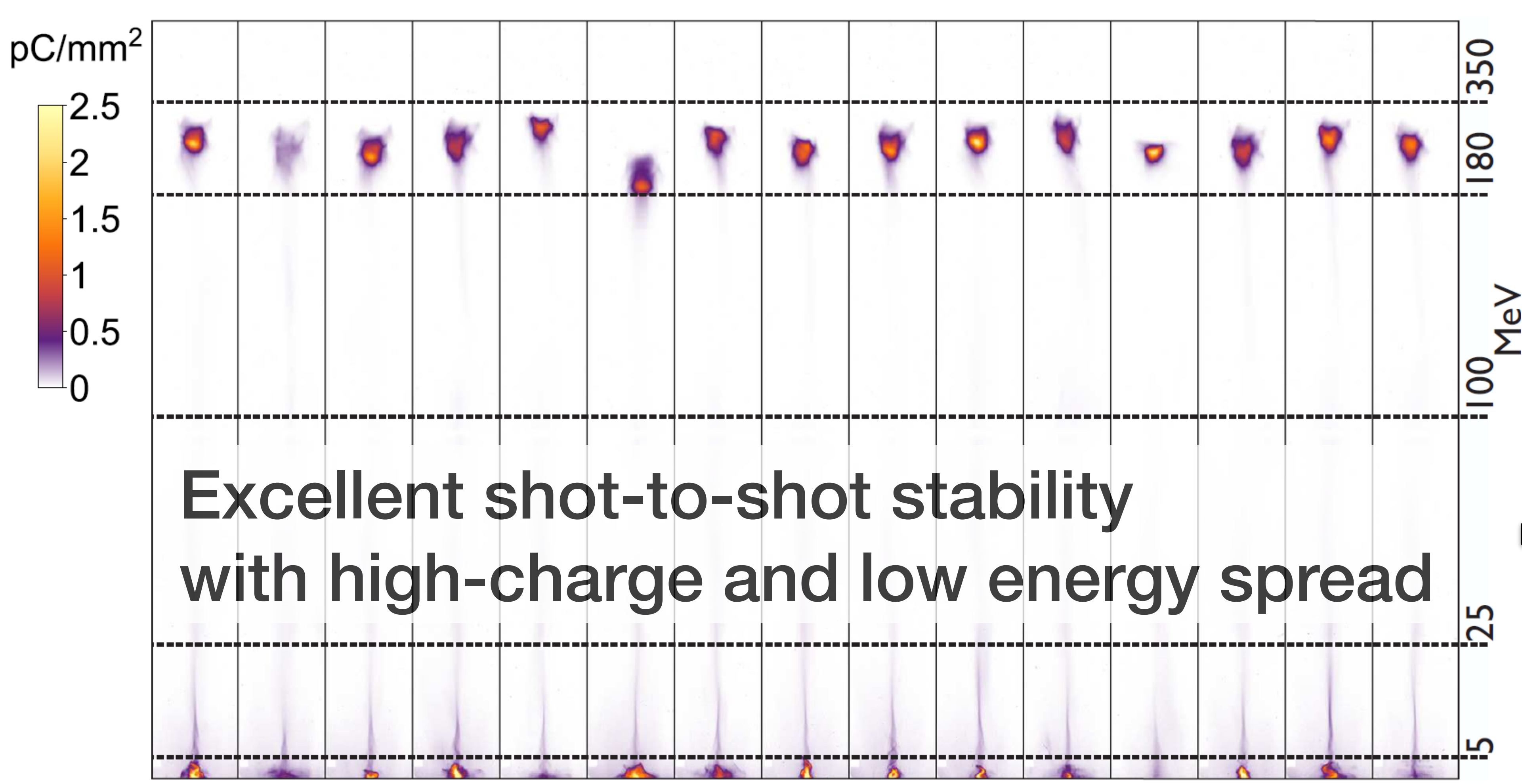
Can LWFA beams drive PWFA with Wii injection?

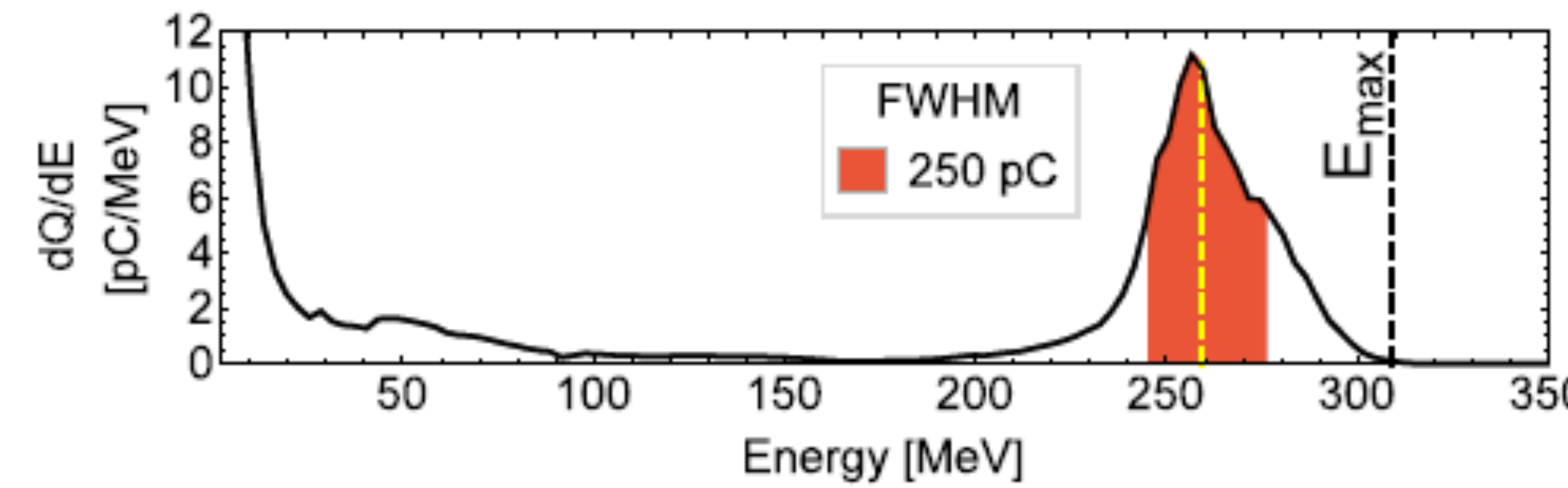
A. Martinez de la Ossa et al., Phys. Plasmas 22, 093107 (2015)

Beams from LWFA with self-truncated ionization injection in HZDR

HZDR
LWFA with ionization injection

J. Couperus et al., Nature Comm. 8, 487 (2017)





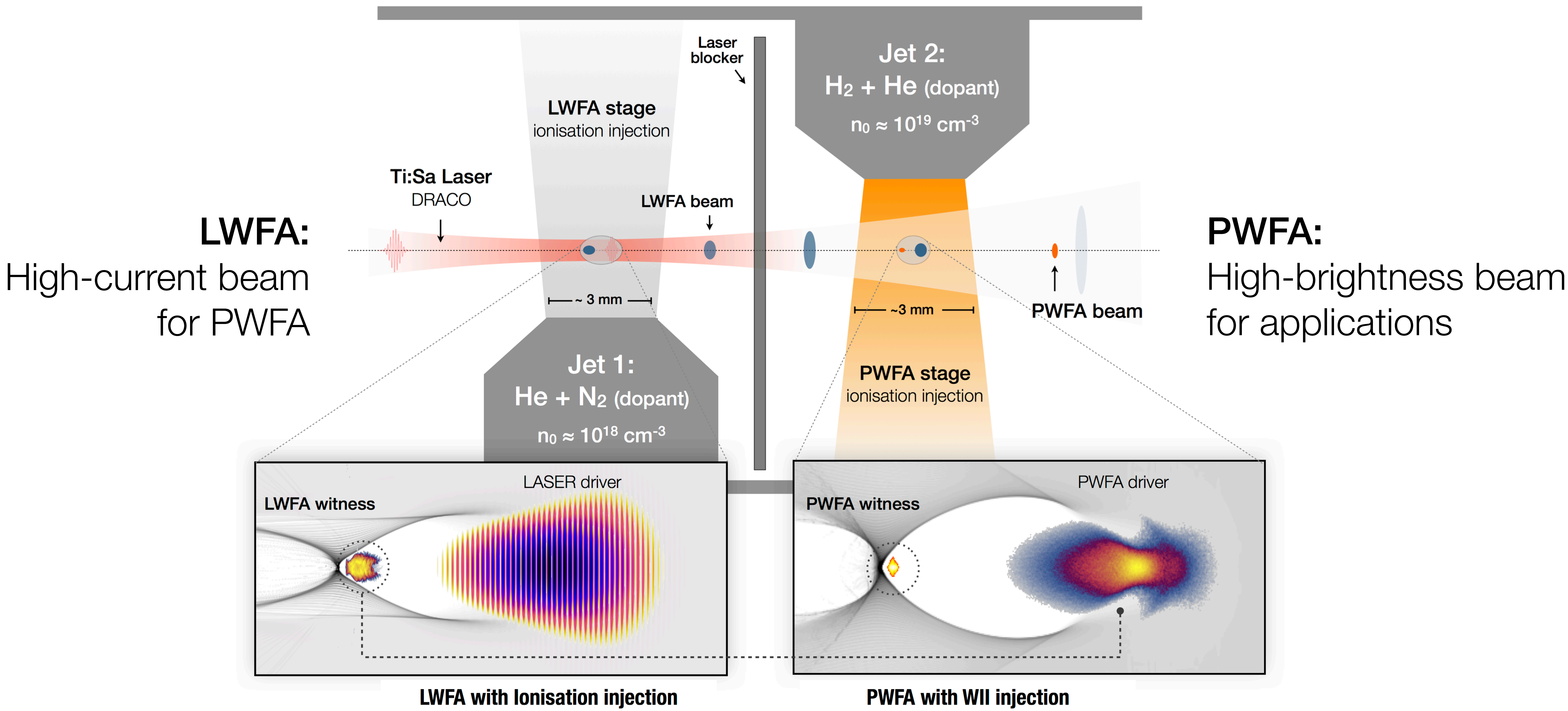
Electron beams from LWFA at HZDR
Average energy: **270 MeV** ± 9% shot-to-shot.
Energy spread (rms): **20 MeV** (7 %)
Charge (fwhm): **250 pC** ± 20 % shot-to-shot.
Duration (fwhm): **10 fs**
Estimated peak current: **30 kA**

“Ionization injection enables loading of ~0.5 nC within a mono-energetic peak”

High-current (≳ 30 kA), relativistic electron beams from LWFA !!

10 - 20 fs beams drive (resonantly) PWFA at higher densities: 5 - 10 x 10^{18} cm^{-3}

A LWFA-driven PWFA (**LPWFA**): **Proof-of-concept experiment at HZDR**



Proof of concept experiment at HZDR

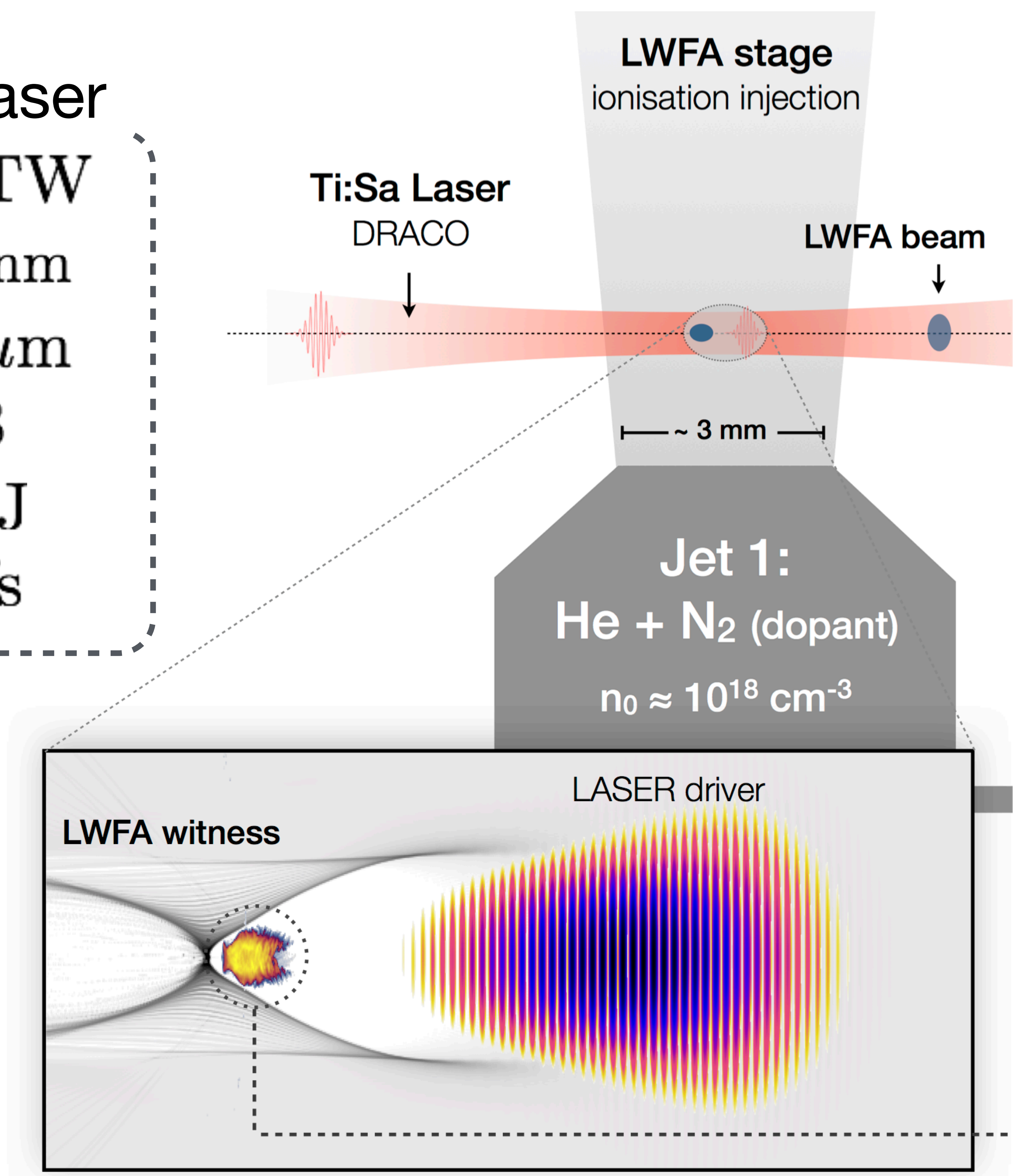
- ➤ Demonstration of injection and acceleration in a PWFA stage driven by a LWFA beam.
- ➤ Demonstration of energy and quality transformer.

Simulation: **LWFA with ionization injection**

First jet: LWFA with DRACO laser

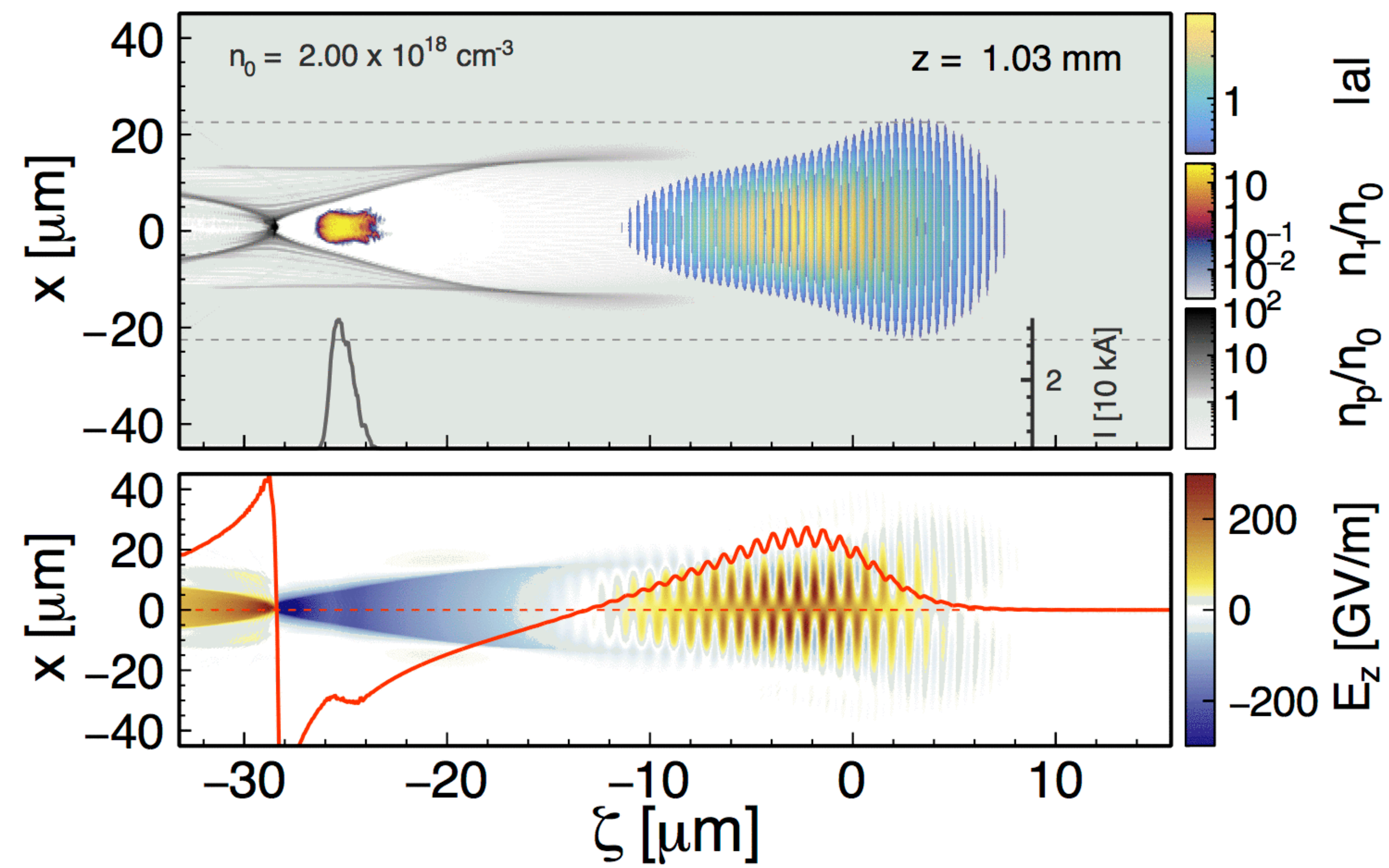
DRACO laser

$P_0 = 98$ TW
$\lambda_0 = 800$ nm
$w_0 = 17\ \mu m$
$a_0 = 3.18$
$\mathcal{E} = 2.8$ J
$\tau = 27$ fs



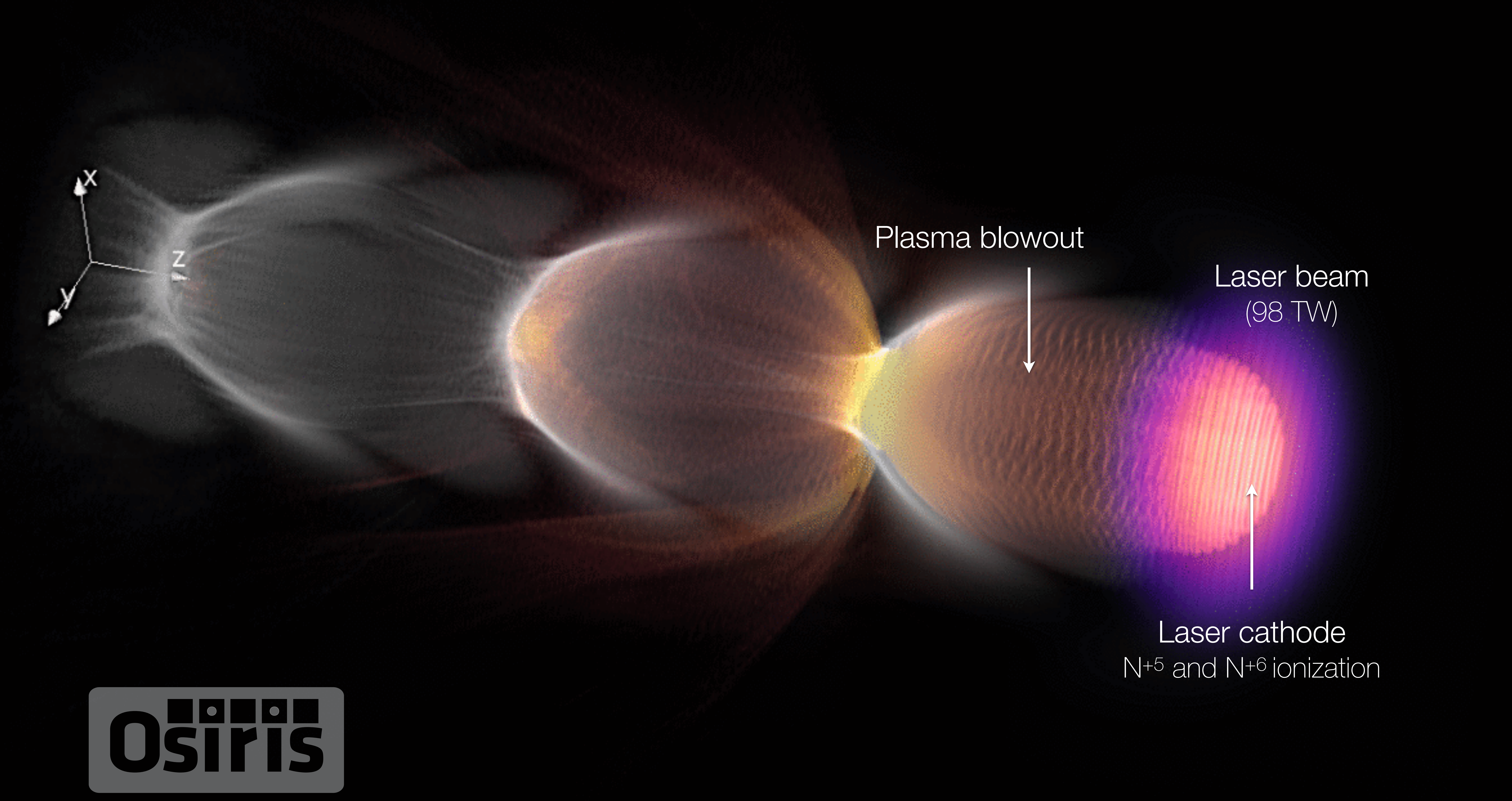
LWFA with Ionisation injection

PIC simulation example

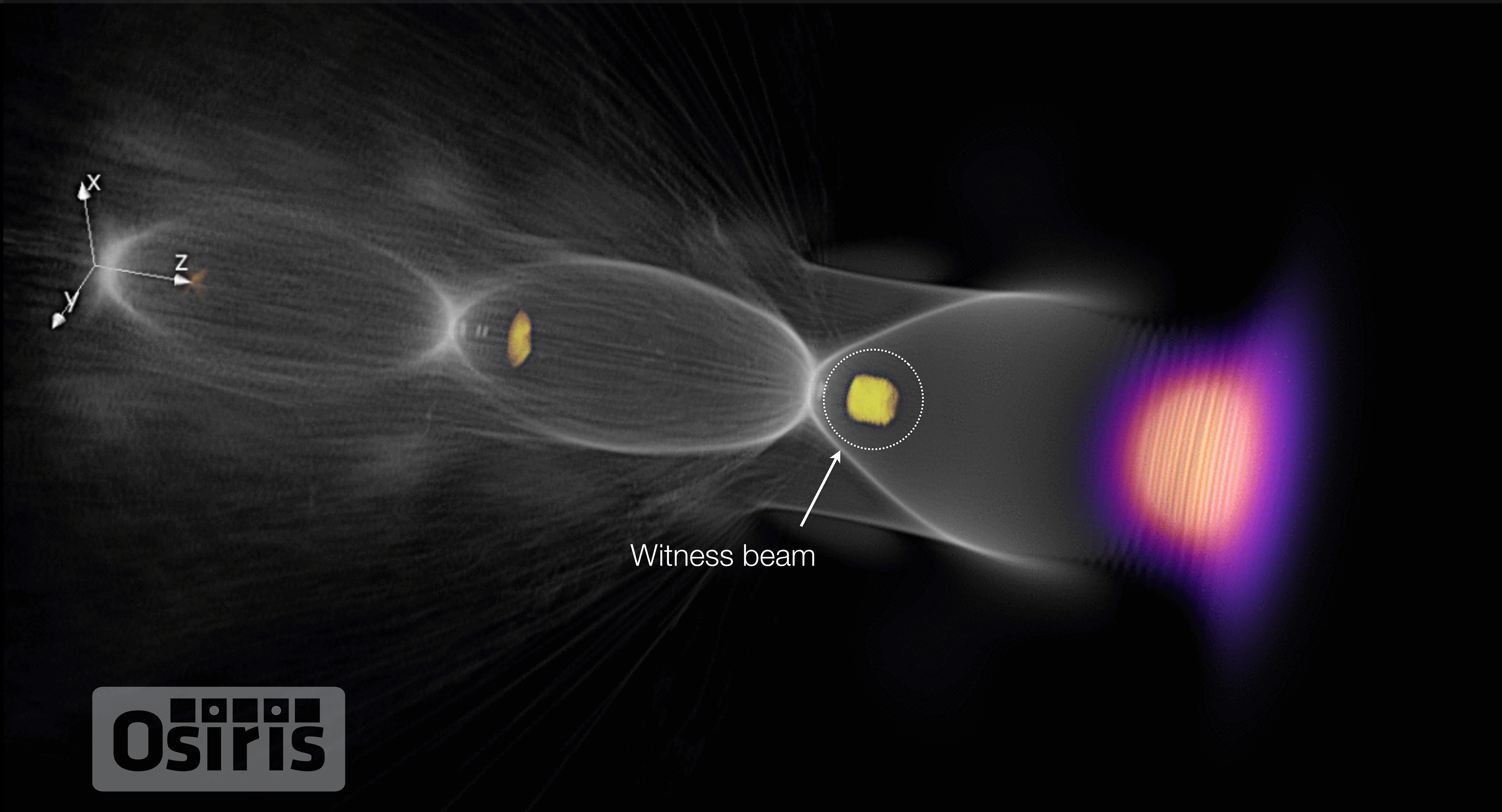


30 kA current beams
from LWFA with ionization injection

Simulation: **LWFA with ionization injection**



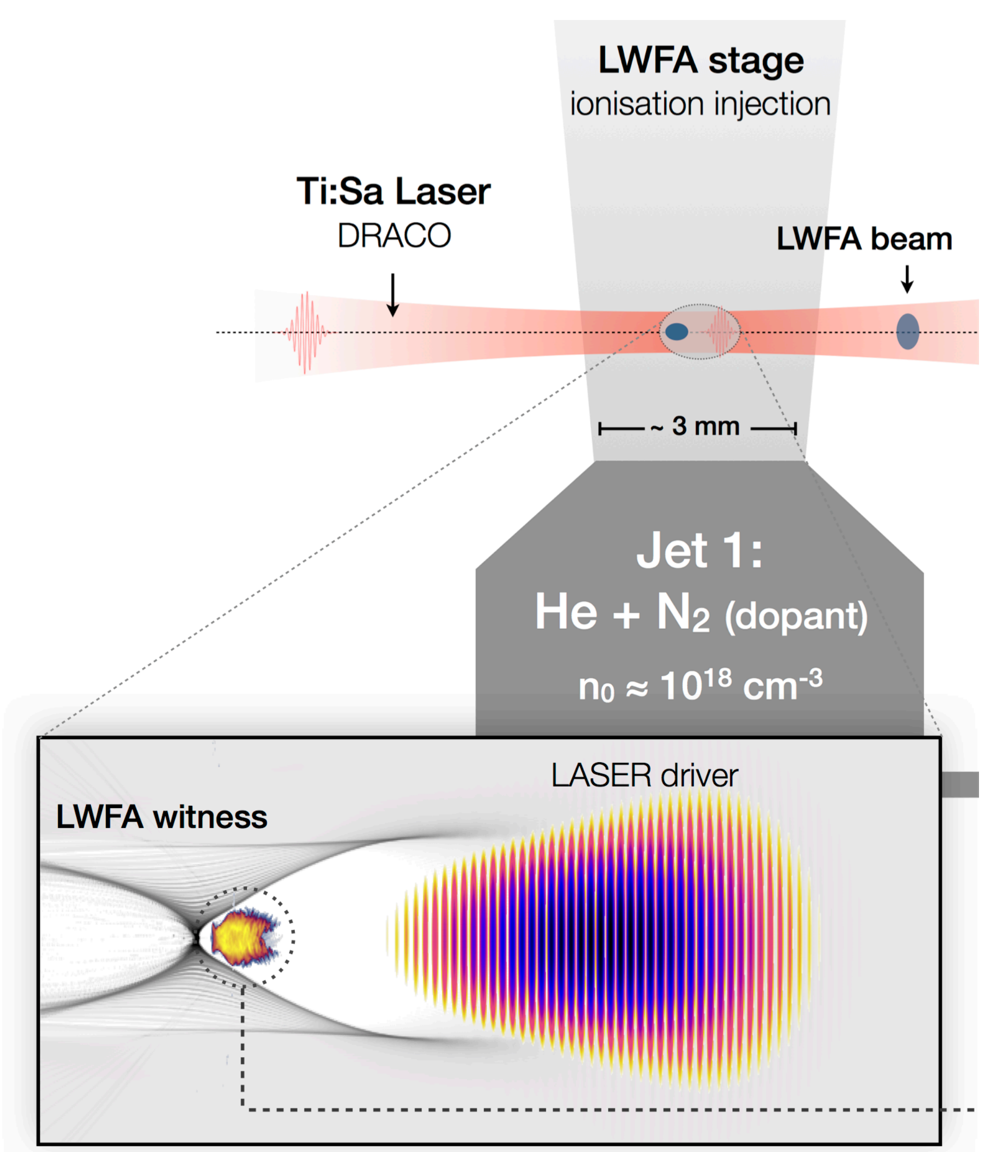
Simulation: **LWFA with ionization injection**



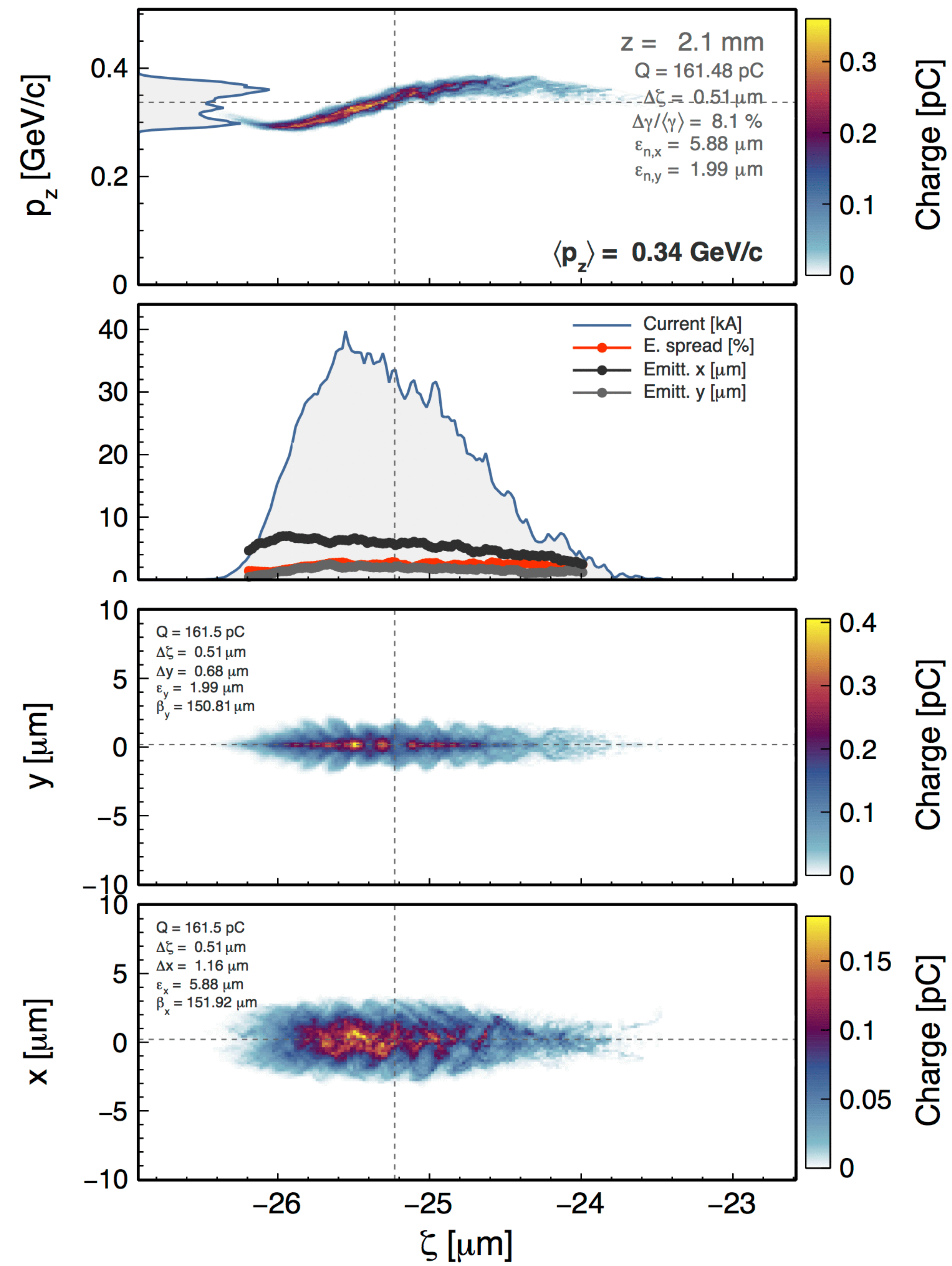
Simulation: **LWFA with ionization injection**

DRACO laser

$$P_0 = 98\ \mathrm{TW}$$
$$\lambda_0 = 800\ \mathrm{nm}$$
$$w_0 = 17\ \mu\mathrm{m}$$
$$a_0 = 3.18$$
$$\mathcal{E} = 2.8\ \mathrm{J}$$
$$\tau = 27\ \mathrm{fs}$$



LWFA with Ionisation injection



LWFA beam (after 2 mm)

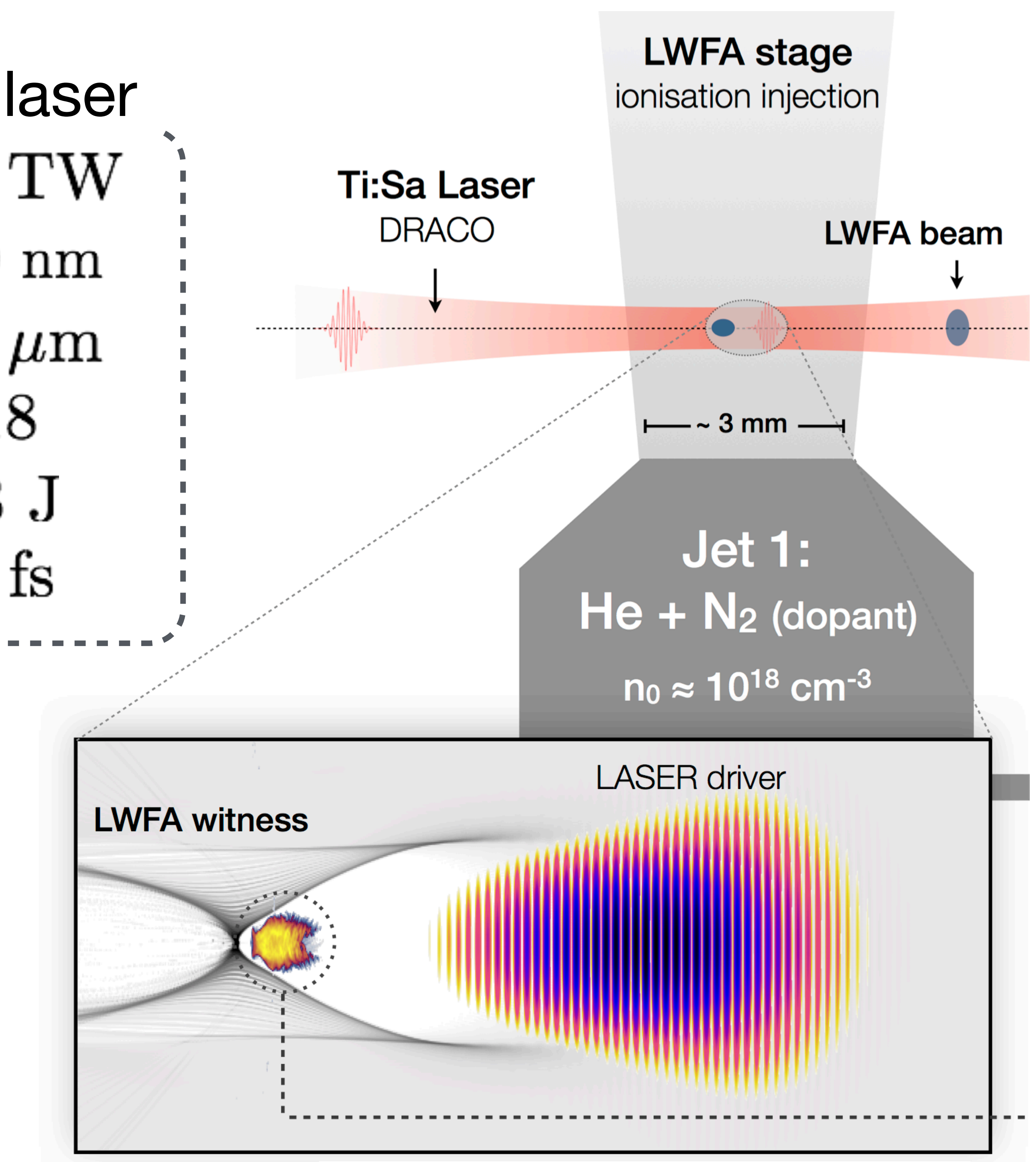
- Energy: **340 MeV**
- Energy spread: **8%**
- Charge: **162 pC**
- Current: **35 kA**
- Duration (fwhm): **4 fs**
- Norm. emittance: **6 μm**

Experiment: **LWFA with ionization injection**

First jet: LWFA with DRACO laser

DRACO laser

$$P_0 = 98\ \mathrm{TW}$$
$$\lambda_0 = 800\ \mathrm{nm}$$
$$w_0 = 17\ \mu\mathrm{m}$$
$$a_0 = 3.18$$
$$\mathcal{E} = 2.8\ \mathrm{J}$$
$$\tau = 27\ \mathrm{fs}$$

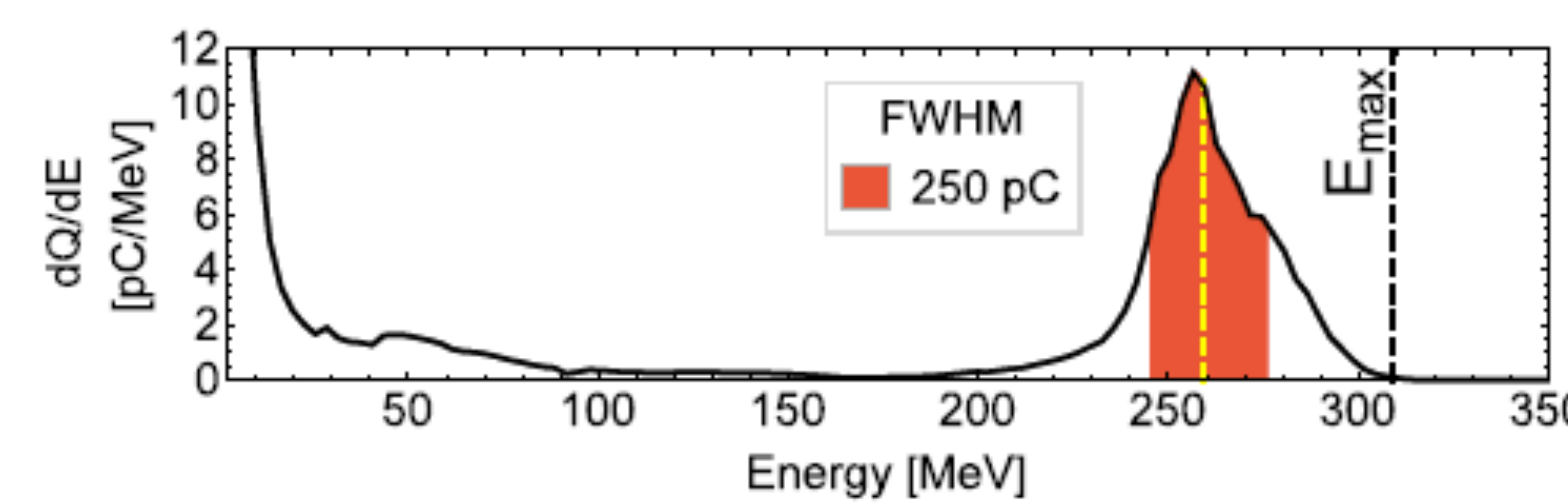


LWFA with Ionisation injection

Beam parameters from experiment

HZDR LWFA beam

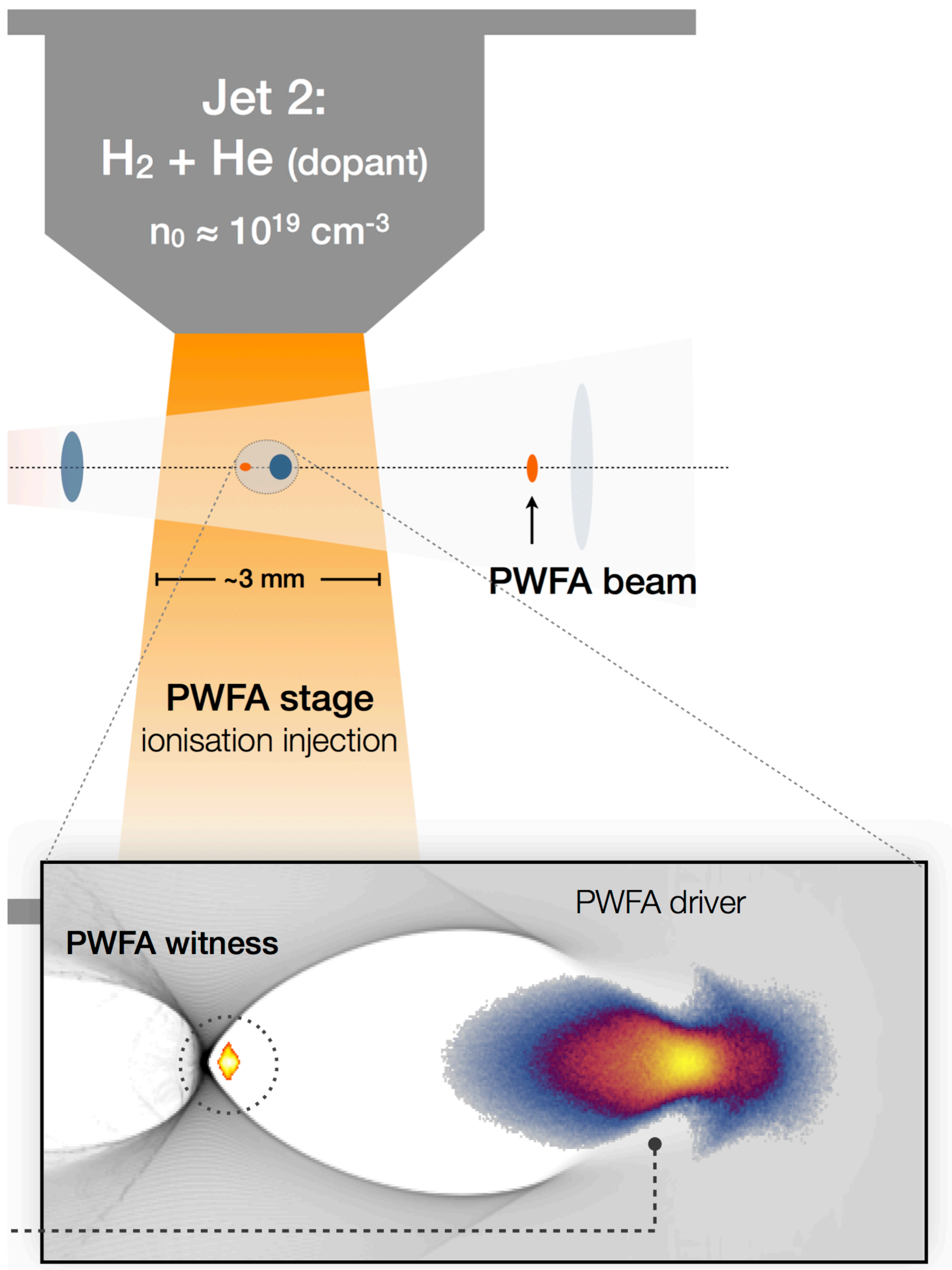
- Mean peak energy: **E = 252 MeV**
- Energy width (fwhm): ΔE=36.4 MeV
- Charge ($1/e^2$): **Q = 292 pC**
- Divergence: **θ = 6.8 mrad**
- Emittance: $\boldsymbol{\varepsilon_n = 5\ \mu m}$
- Duration: **τ = 10 fs** (fwhm).
- Peak current: $\boldsymbol{I_0 = 30\ kA}$ (assuming Gaussian shape).



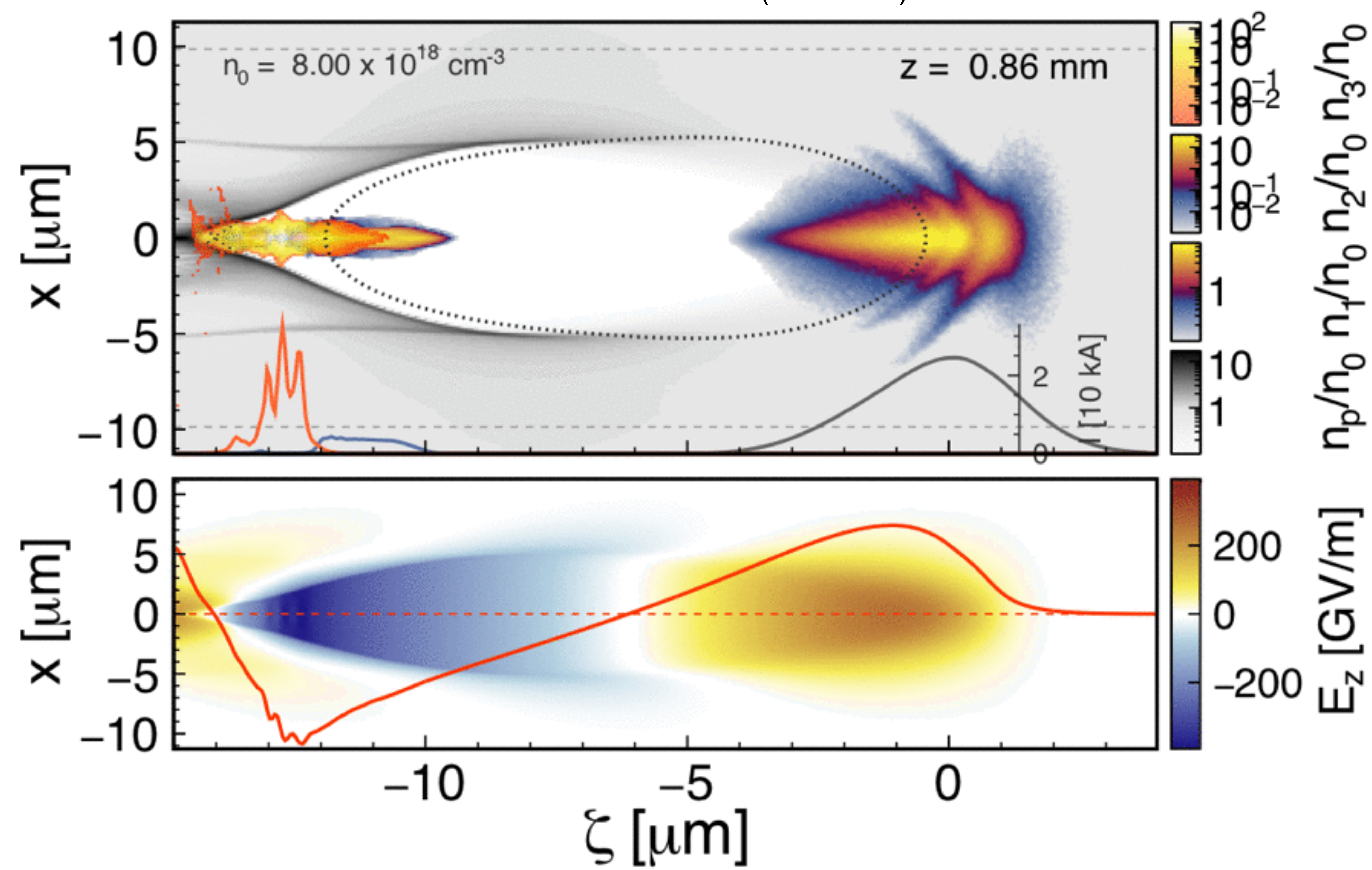
J. Couperus et al., Nature Comm. 8, 487 (2017)

Simulations: **LPWFA with ionization injection**

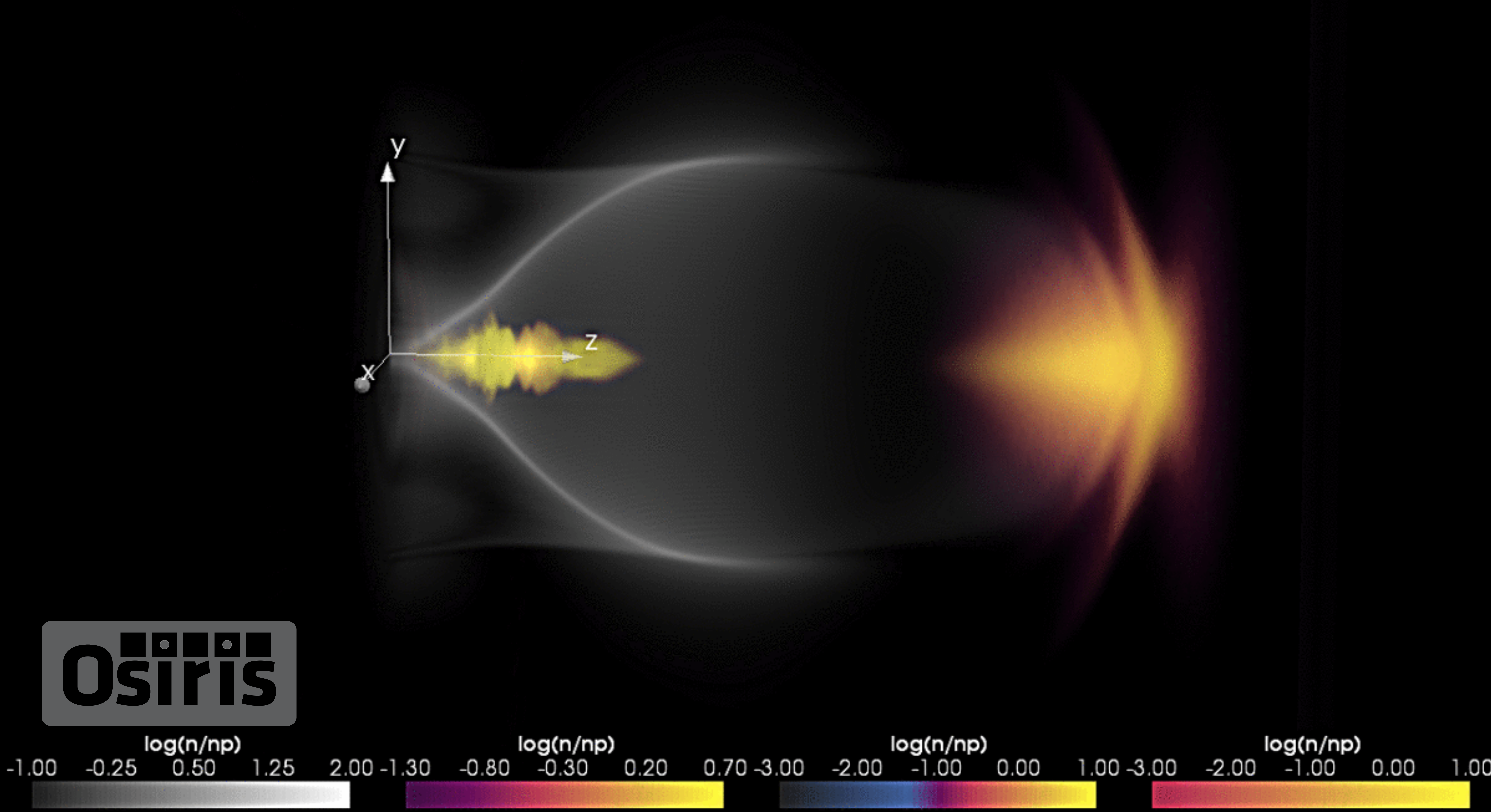
Second jet: PWFA with LWFA beam



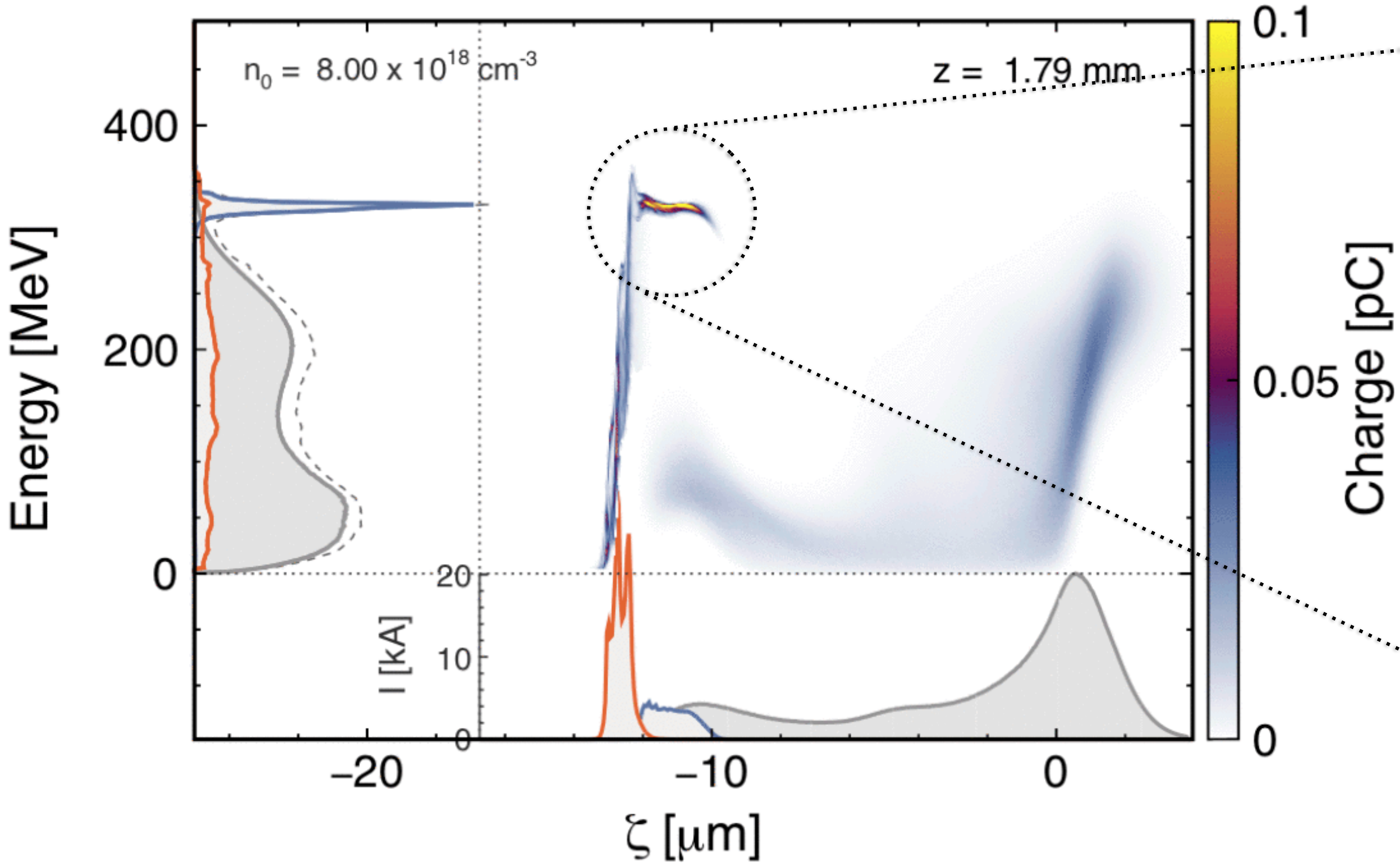
3D PIC simulation (OSIRIS)

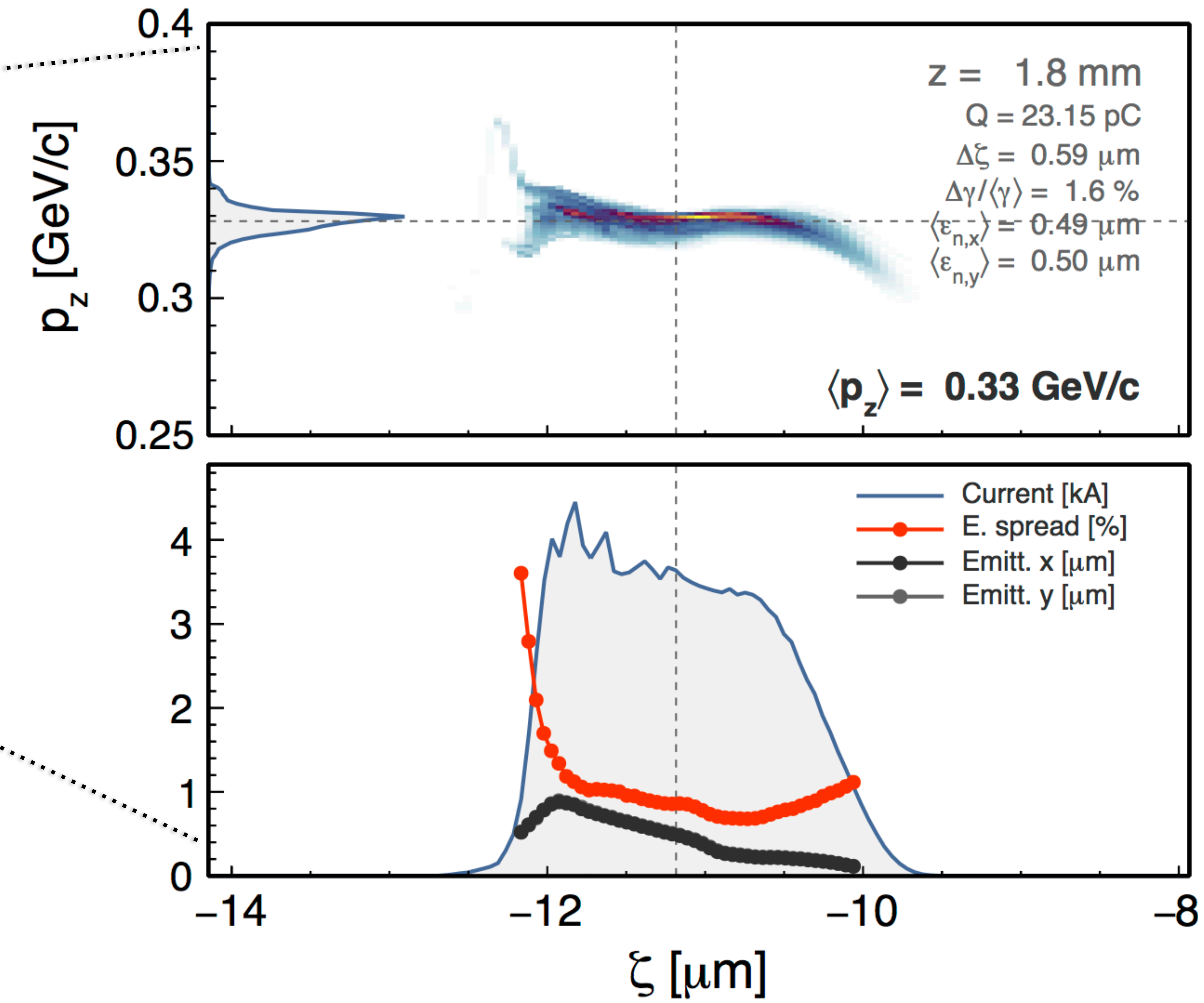


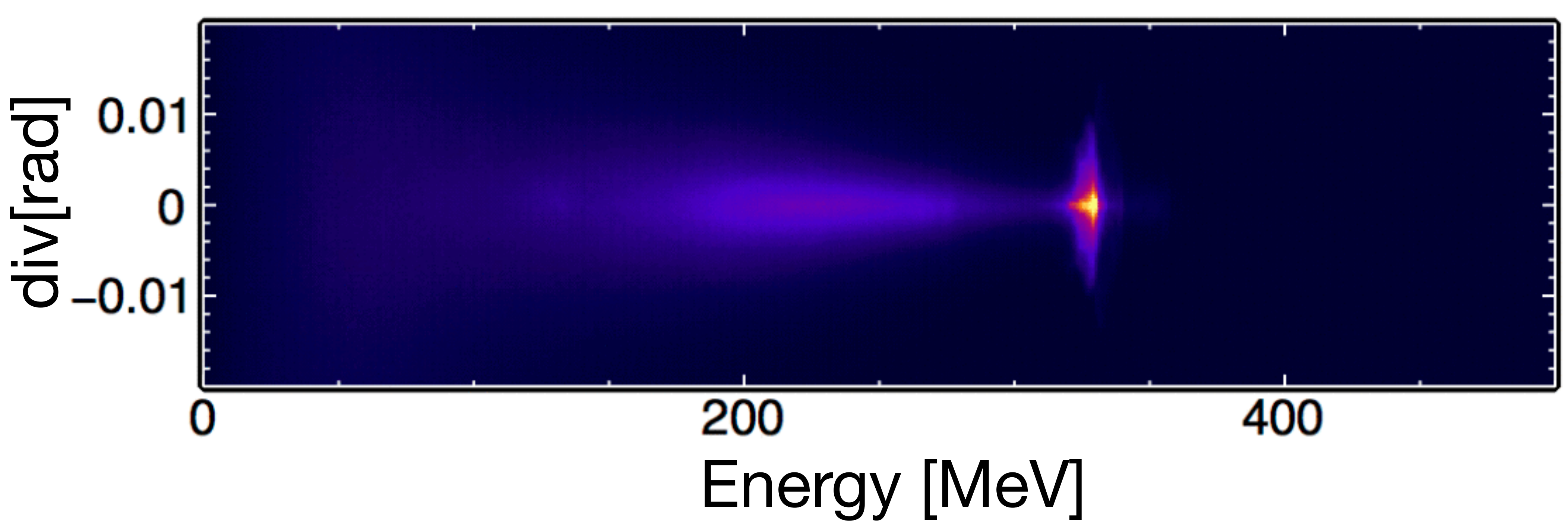
Second jet: PWFA with Ionisation injection (LWFA-driver)



Simulations: **LPWFA with ionization injection**





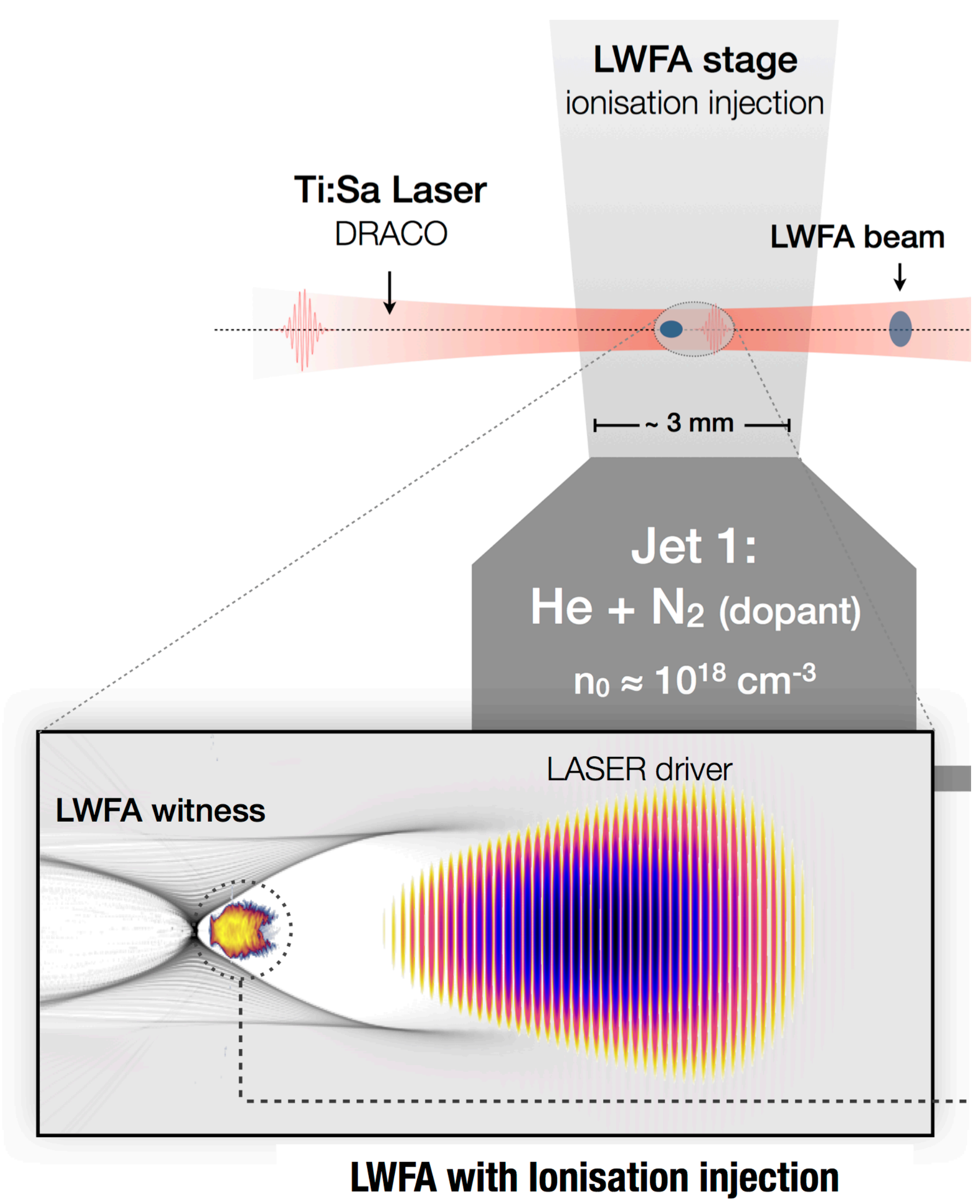


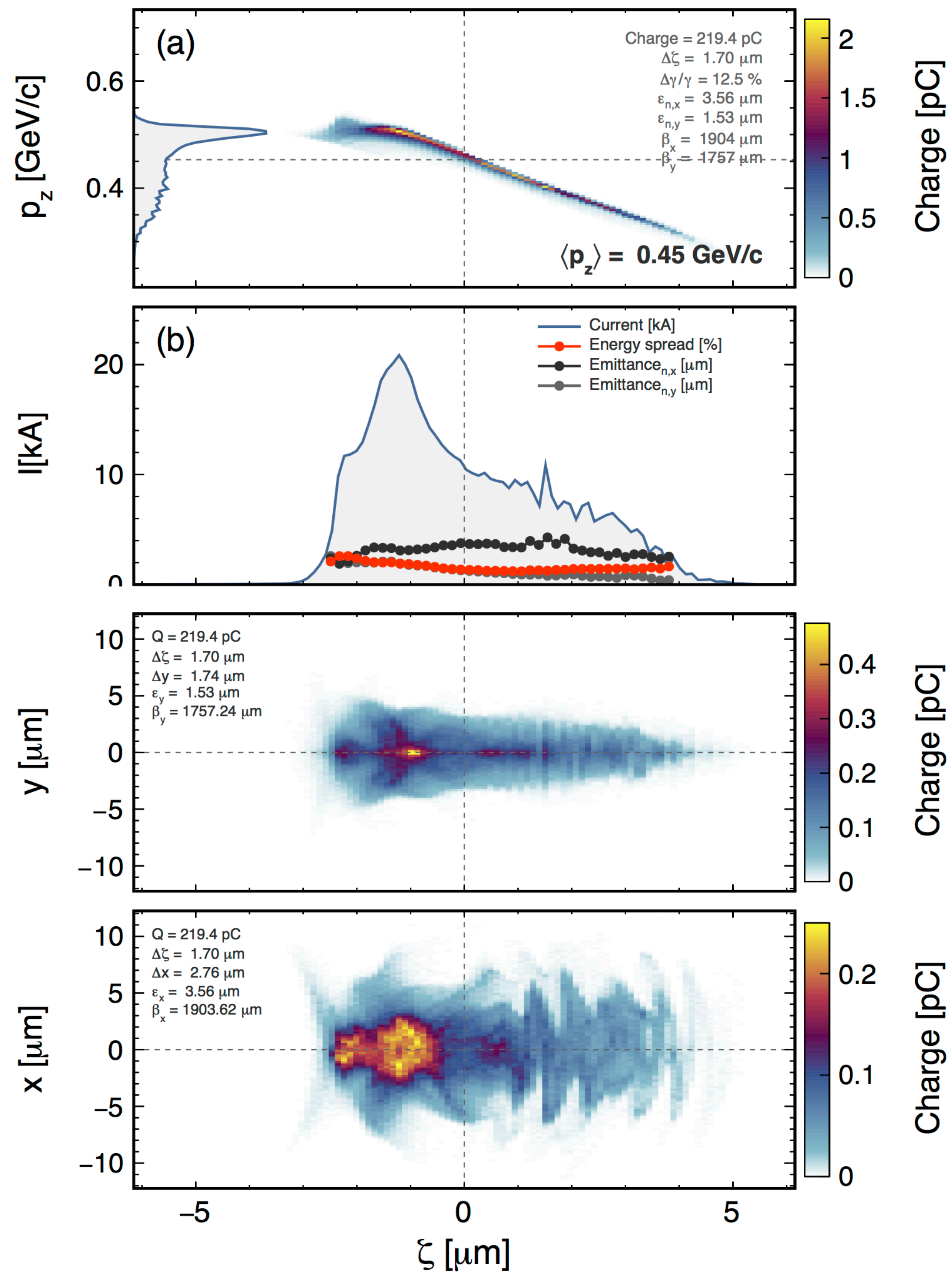
New witness from PWFA largely improves the one from LWFA

Simulation: **LWFA with ionization injection**

DRACO laser

$$P_0 = 98\ \mathrm{TW}$$
$$\lambda_0 = 800\ \mathrm{nm}$$
$$w_0 = 17\ \mu m$$
$$a_0 = 3.18$$
$$\mathcal{E} = 2.8\ \mathrm{J}$$
$$\tau = 27\ \mathrm{fs}$$



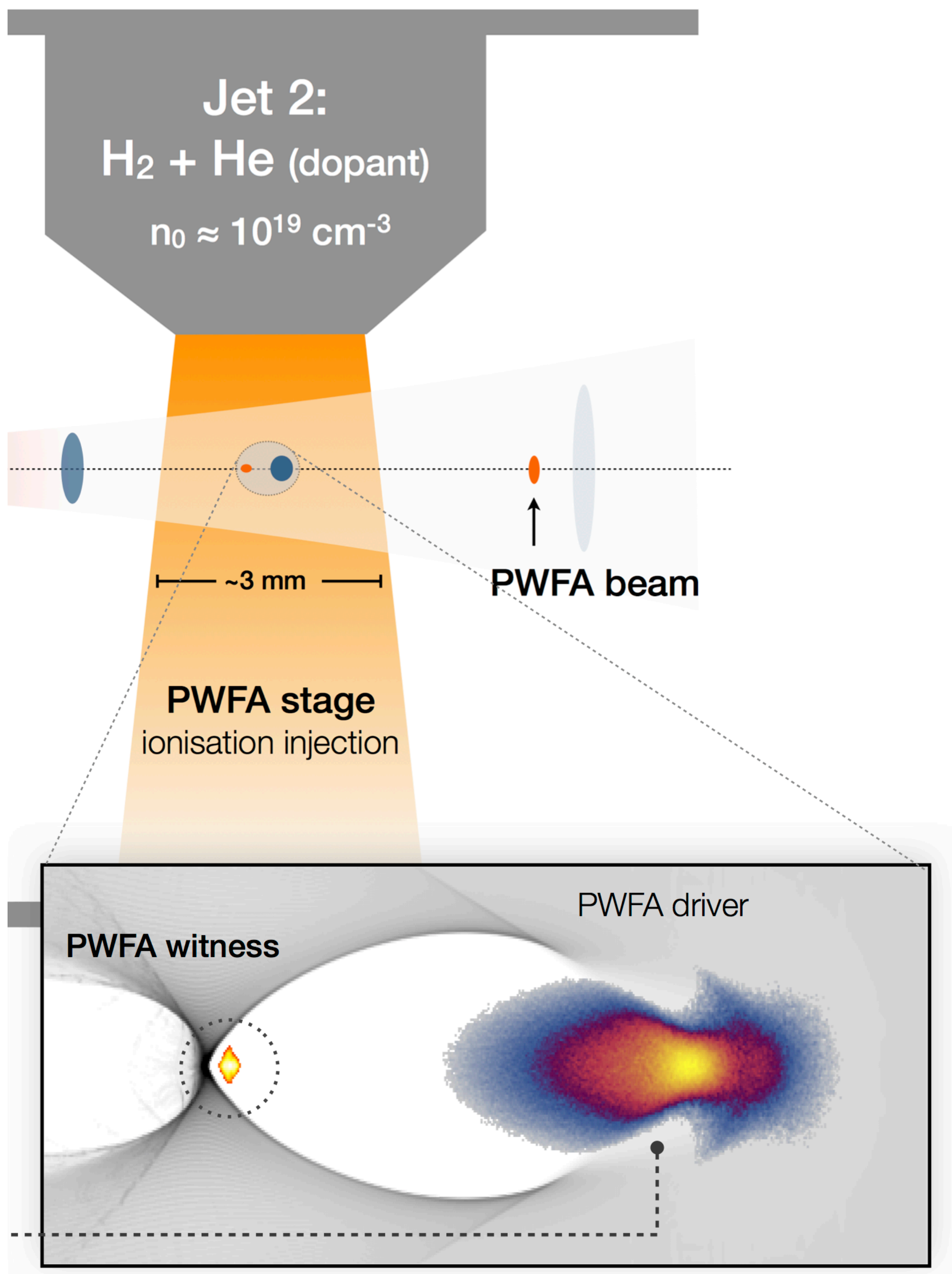


Witness bunch LWFA

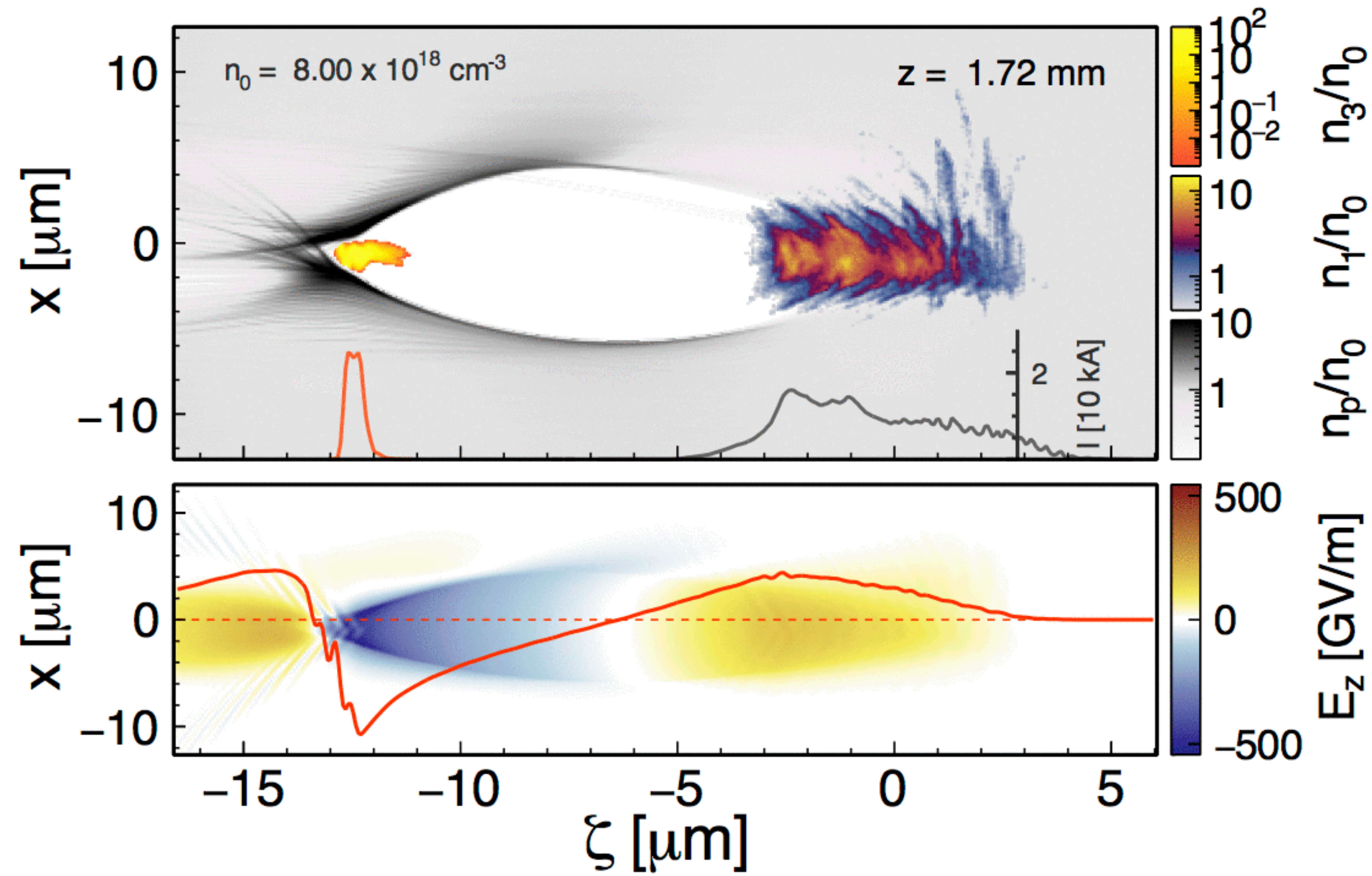
- Energy: **450 MeV**
- Energy spread: **12%**
- Charge: **220 pC**
- Current: **22 kA**
- Duration (fwhm): **13 fs**
- Norm. emittance: **3.6 µm**

S2E simulation: **L**PWFA with ionization injection

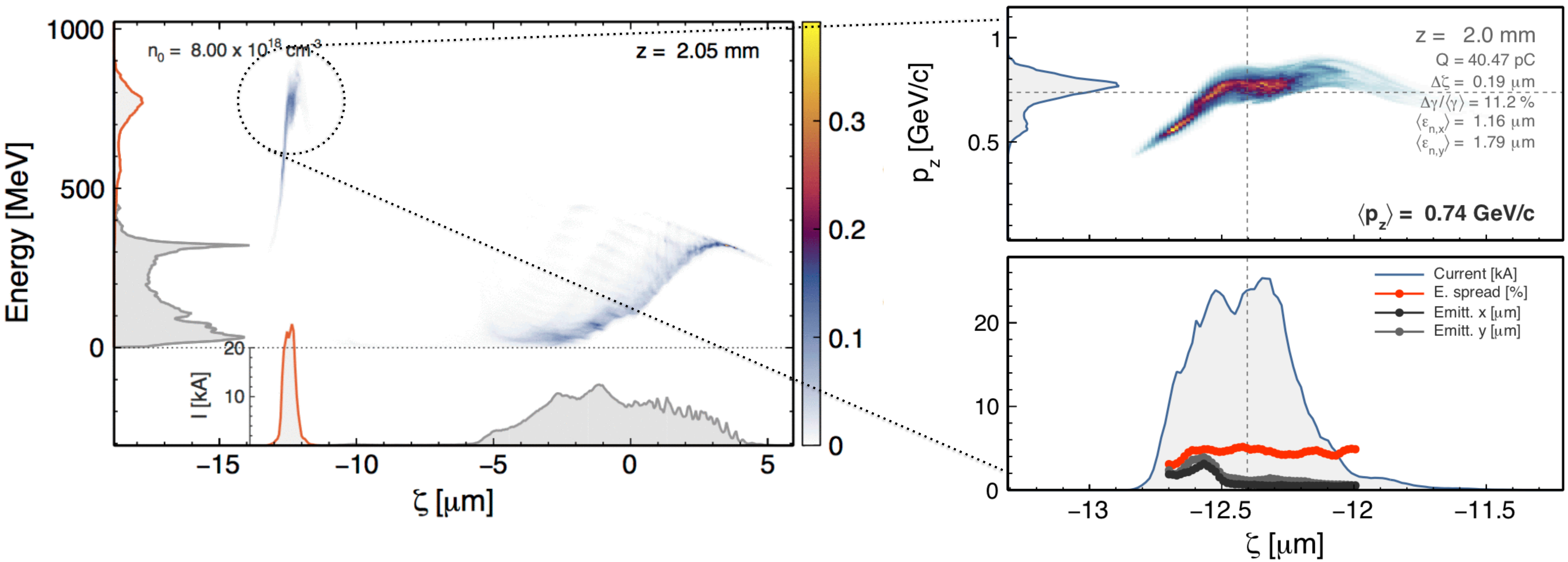
Second jet: PWFA with LWFA beam from PIConGPU.

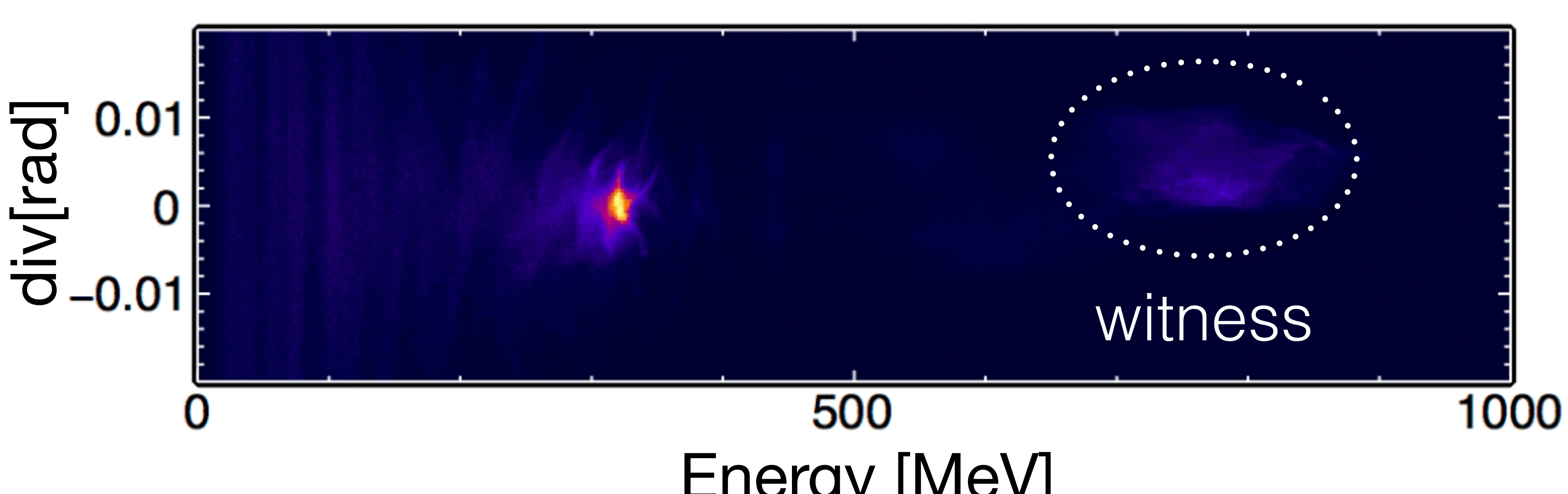


PWFA with WII injection



S2E simulation: **L**PWFA with ionization injection



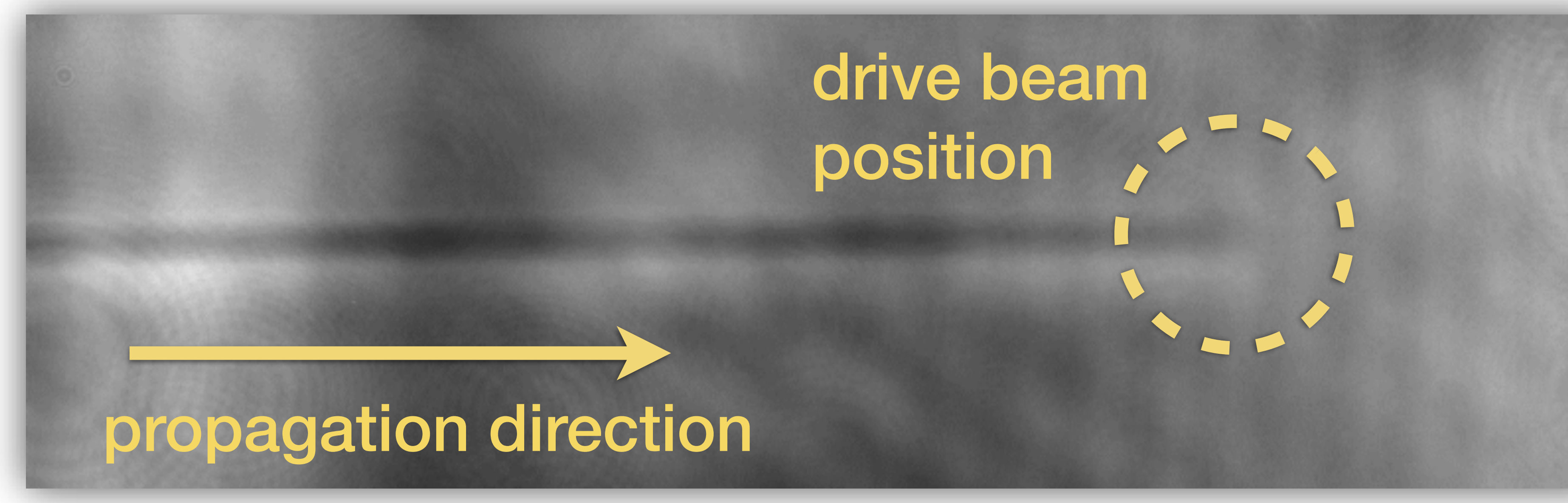


Energy doubling with sub-μm emittance beams from PWFA stage.

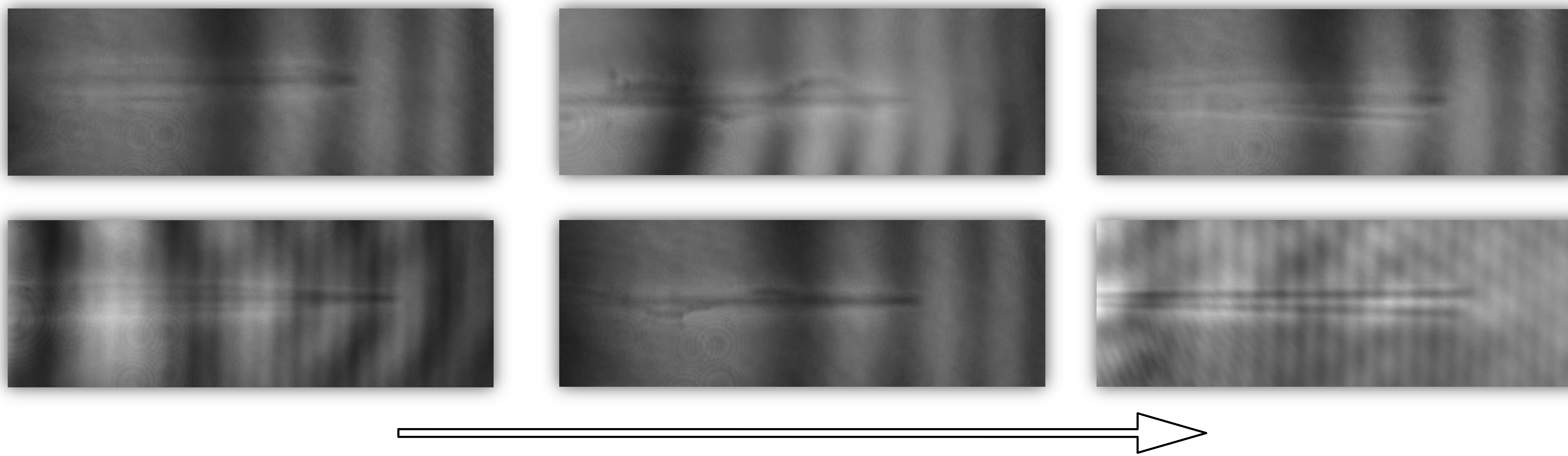
Experiments: **LPWFA. Beam dynamics.**

Experiment

- ➤ Transverse probe shadowgraphy.
- ➤ Self-ionized plasma filament.
- ➤ Explore beam dynamics and stability.
- ➤ PWFA physics!



Beam focusing? **Hose instability?** **beam breakup?**



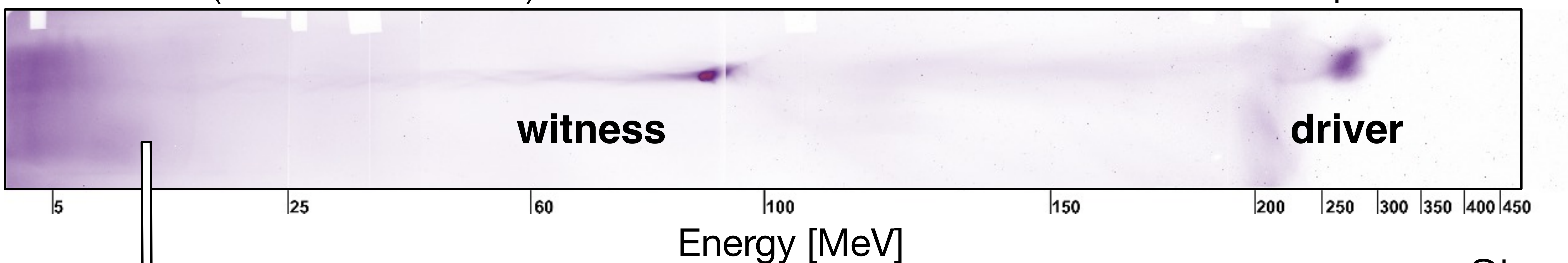
Higher gas pressure

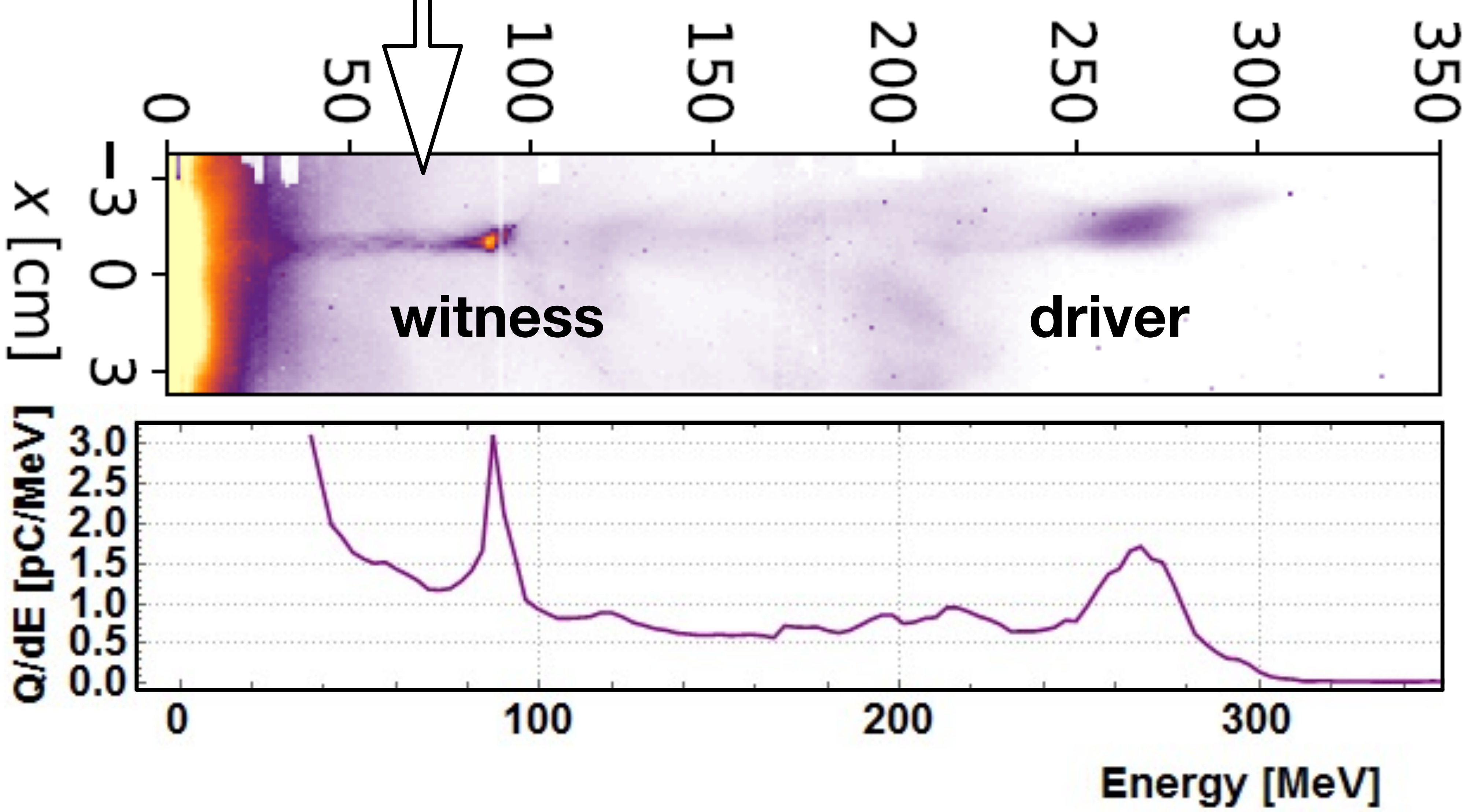
Experiments: **LPWFA. Injection and acceleration.**

Spectrometer data: **Observation of electron trapping and acceleration**

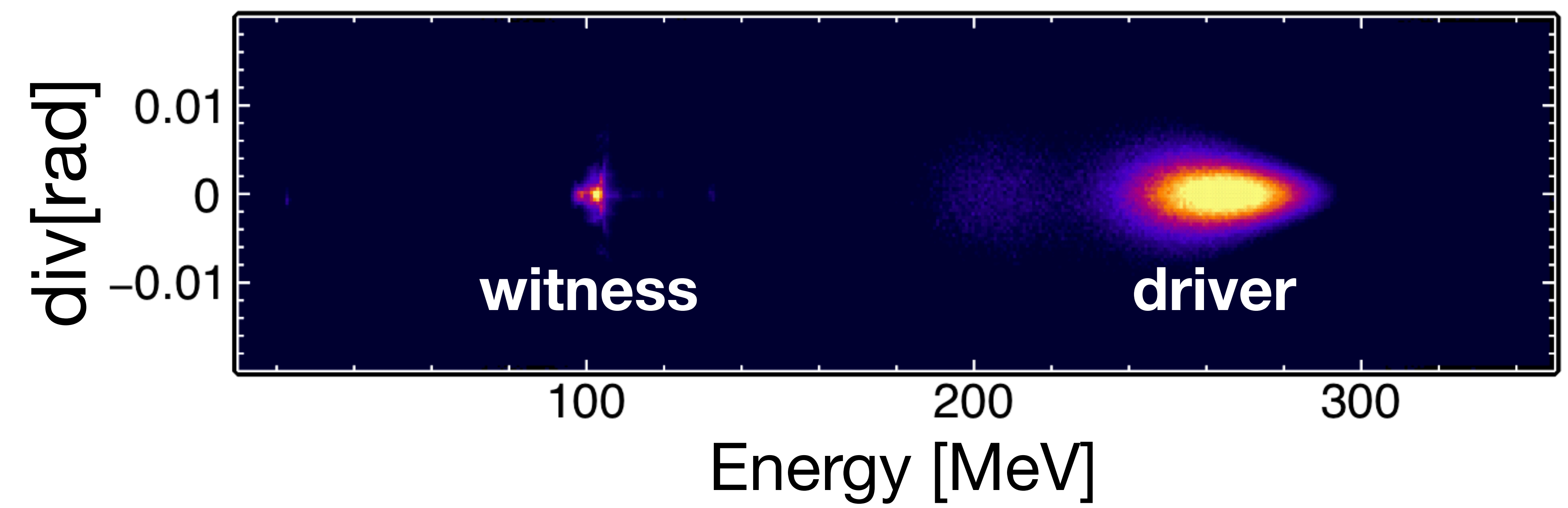
Shot #196 (November 2017)

Experiment





Simulation

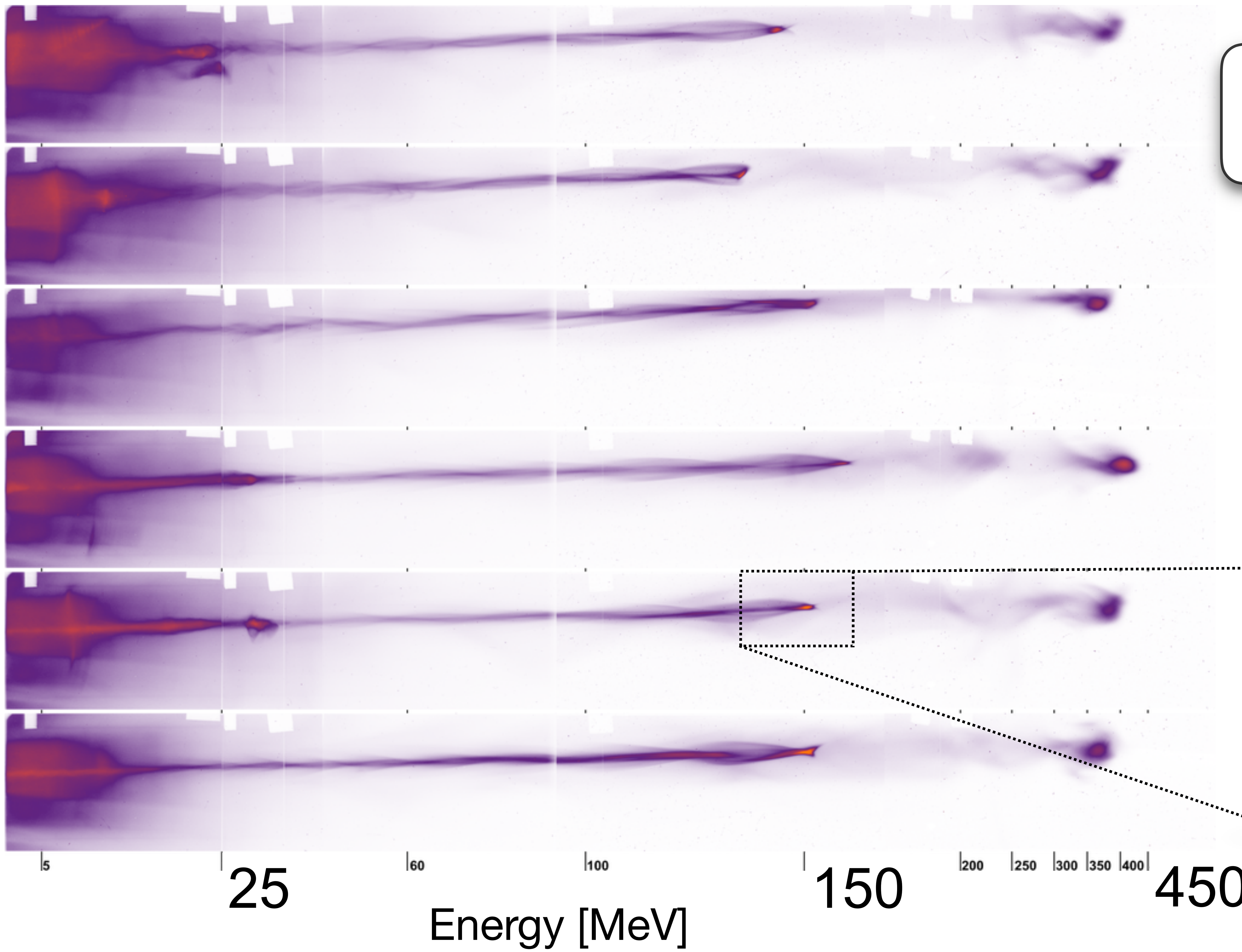


Higher quality witness beam!

Narrower energy spread
and smaller divergence

Experiments: **L**PWFA. **Injection and acceleration.**

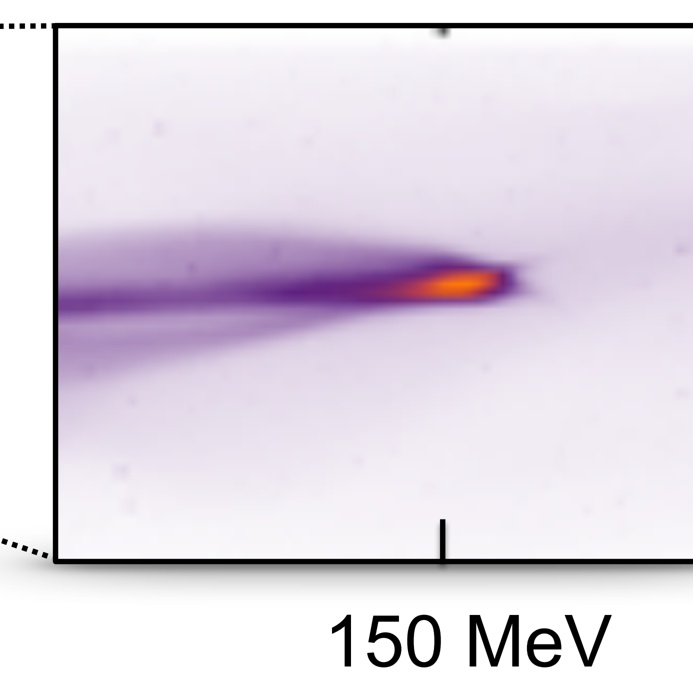
Spectrometer data: **Consecutive shots!**



Stable injection and acceleration
in a PWFA stage driven by a LWFA beam.

Preliminary results…

- Data analysis going on.
- Improving setup and diagnostics.
- Next goal: Energy boost.



Low divergence
LPWFA witness

to be continued…

Hybrid LWFA | PWFA staging: **Summary**

Conceptual design for a LWFA-driven PWFA (LPWFA):
For the production of multi-GeV, superior quality beams.

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

Preliminary start-to-end simulations for the LPWFA experiment at HZDR:
Energy doubling of low-emittance beams in the PWFA stage.

Proof-of-concept experiment at HZDR (LPWFA experiment):
- Observation of PWFA physics in a Laser-lab:
  Beam self-ionization, focusing, hosing, beam breakup/filamentation.
- First observation of stable injection and acceleration in a **L**PWFA