EUROPEAN
PLASMA RESEARCH
ACCELERATOR
WITH
EXCELLENCE IN
APPLICATIONS

WP14 - Simulations

Hybrid LWFA-PWFA for a 5 GeV FEL quality beam.

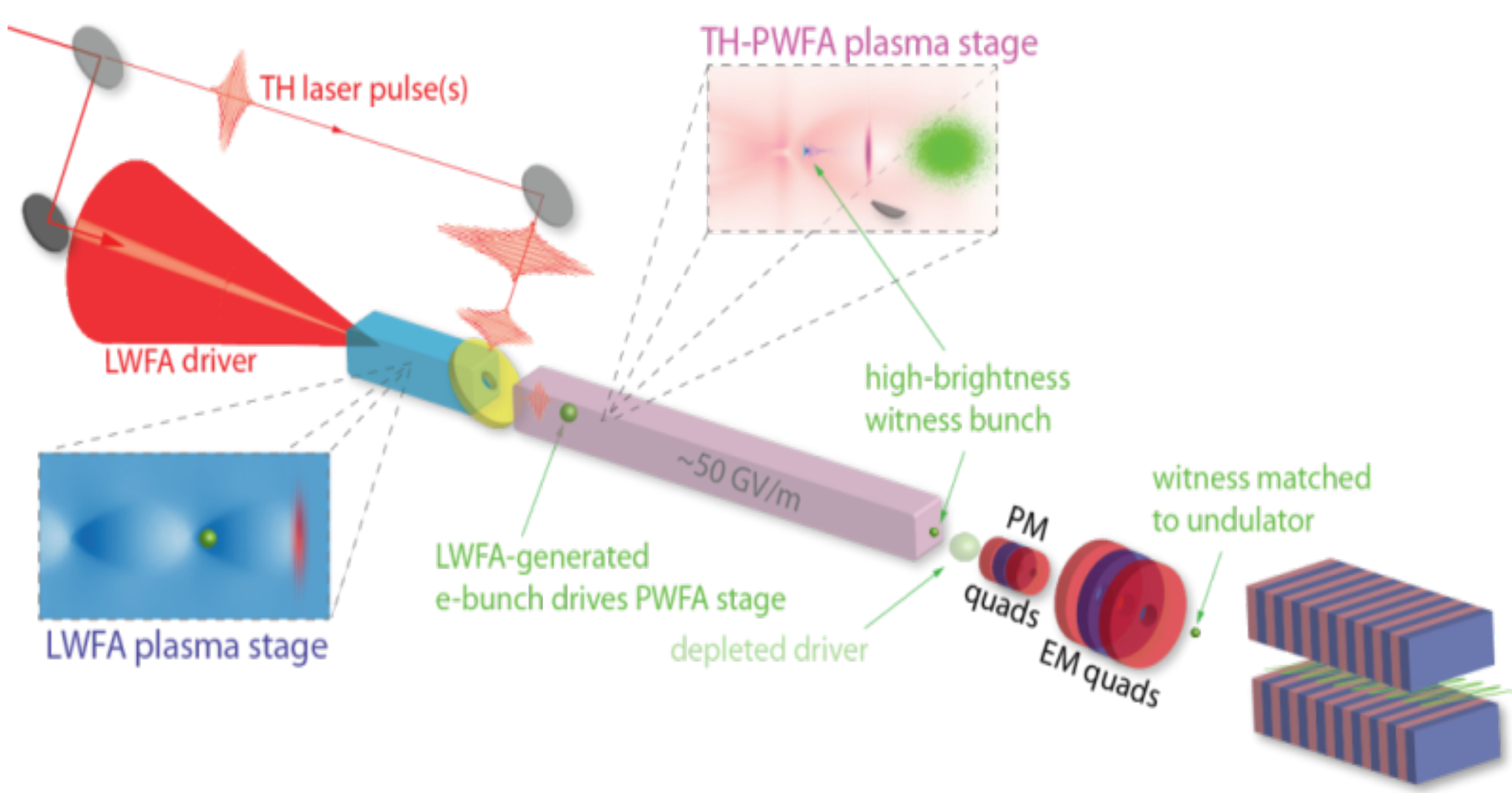
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

LWFA | PWFA

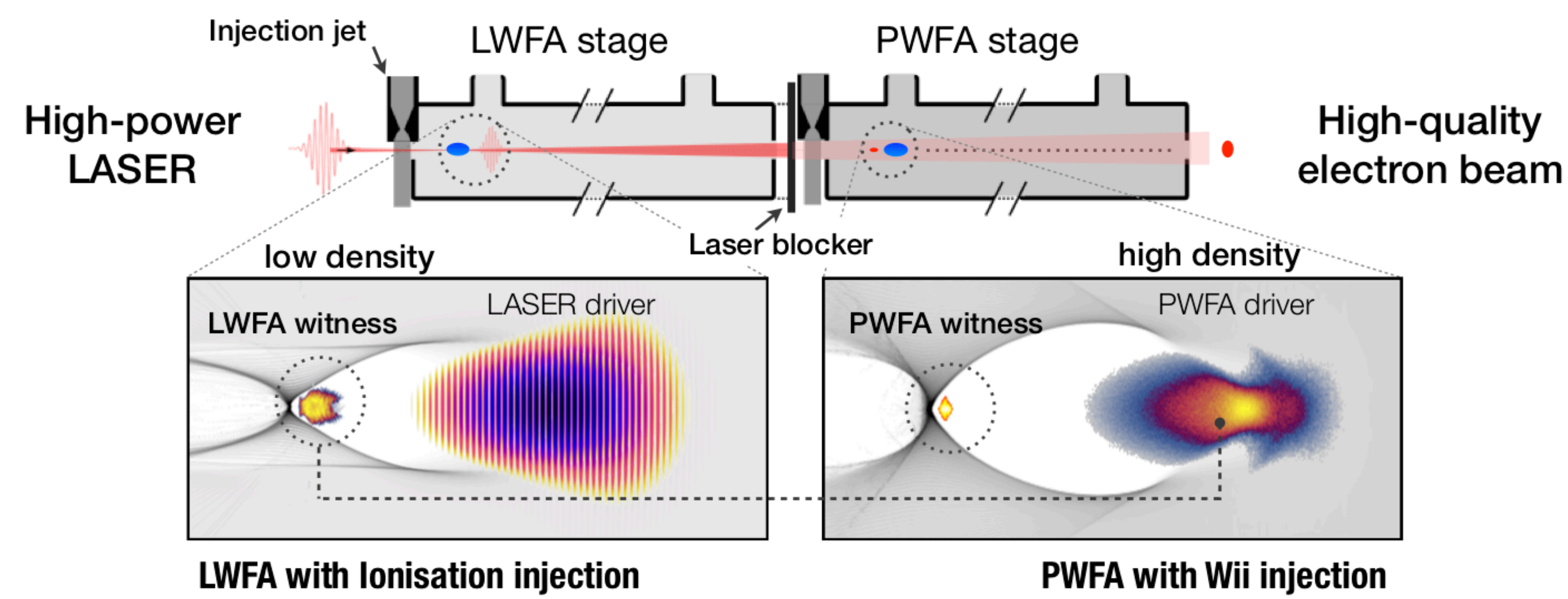
Energy and brightness transformer
for the production of multi-GeV FEL-capable beams

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

Conceptual designs

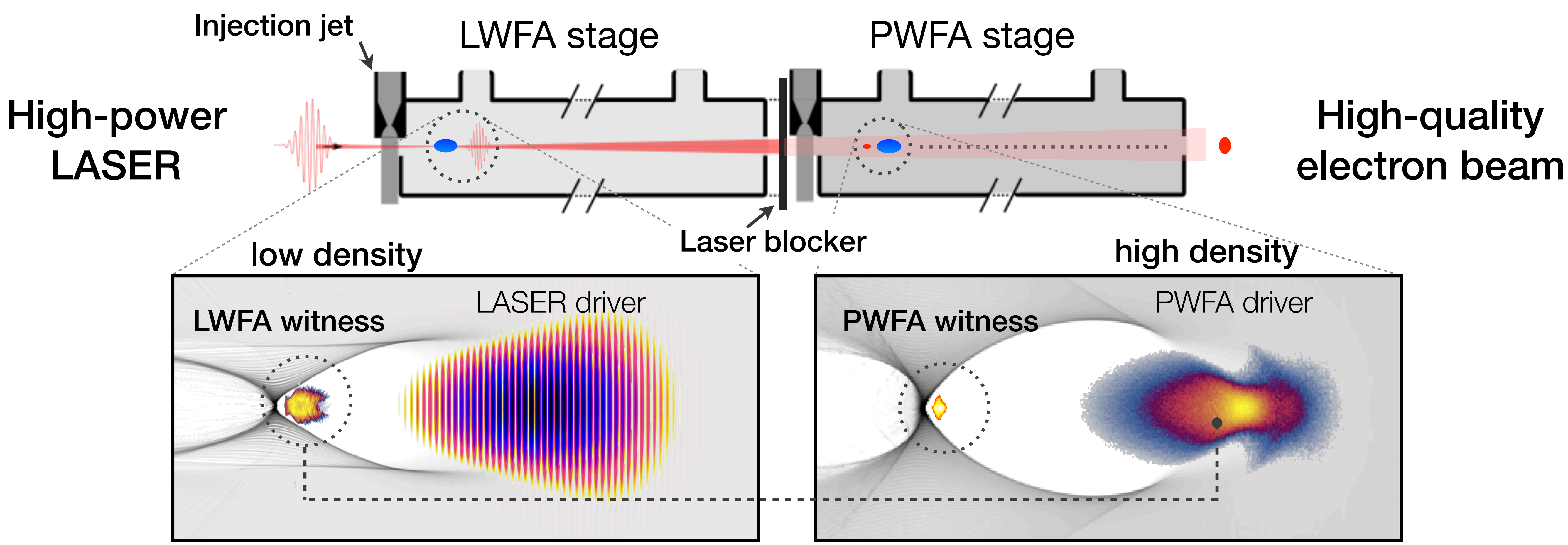


B. Hidding et al., Phys. Rev. Lett. 104, 195002 (2010).
B. Hidding et al., Phys. Rev. Lett. 108, 035001 (2012).



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 gain**: 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

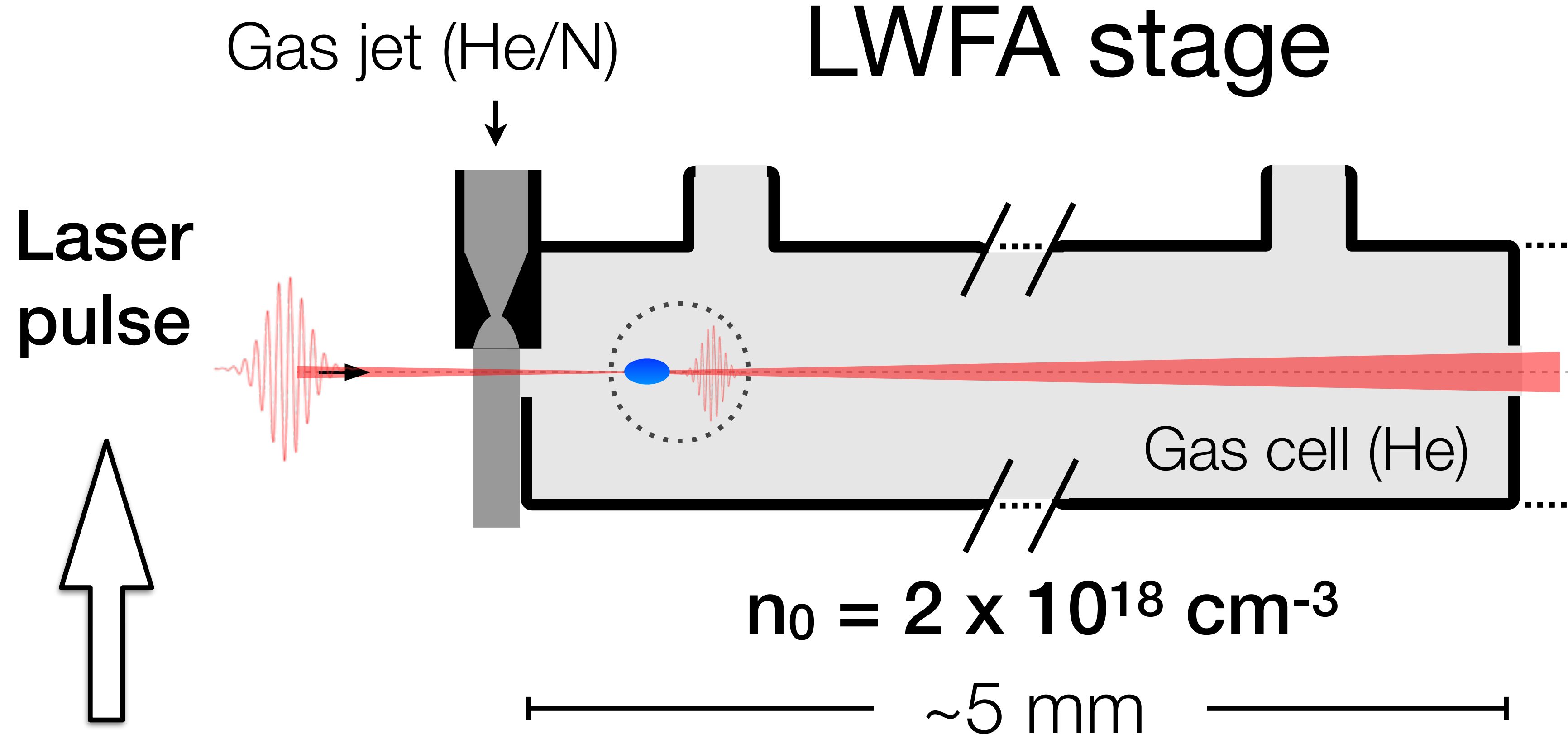
for applications demanding high-quality e.g. FELs.

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

First Stage: LWFA with ionization injection

Osiris 3.0

LWFA stage



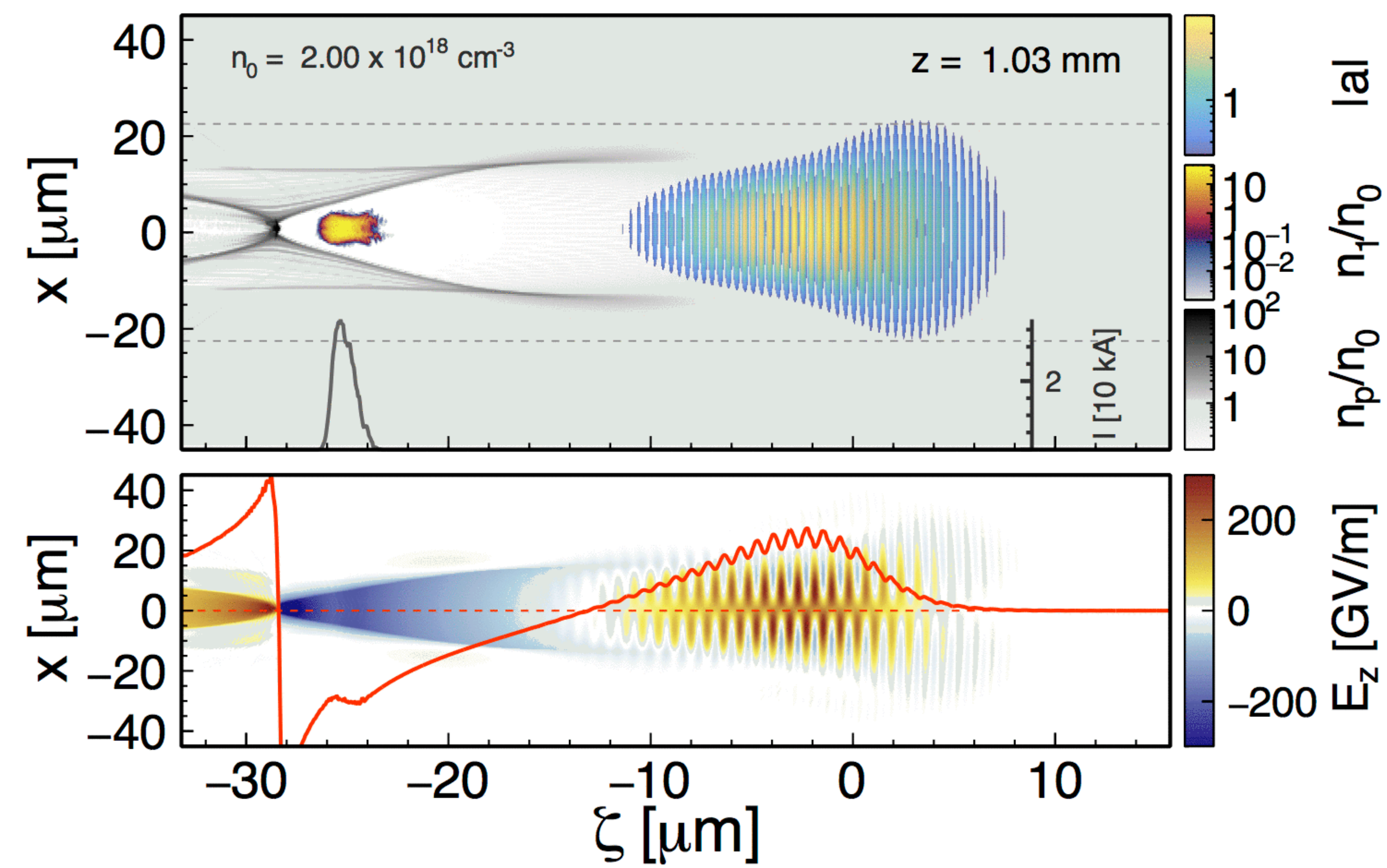
Laser parameters

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

e.g. DRACO laser

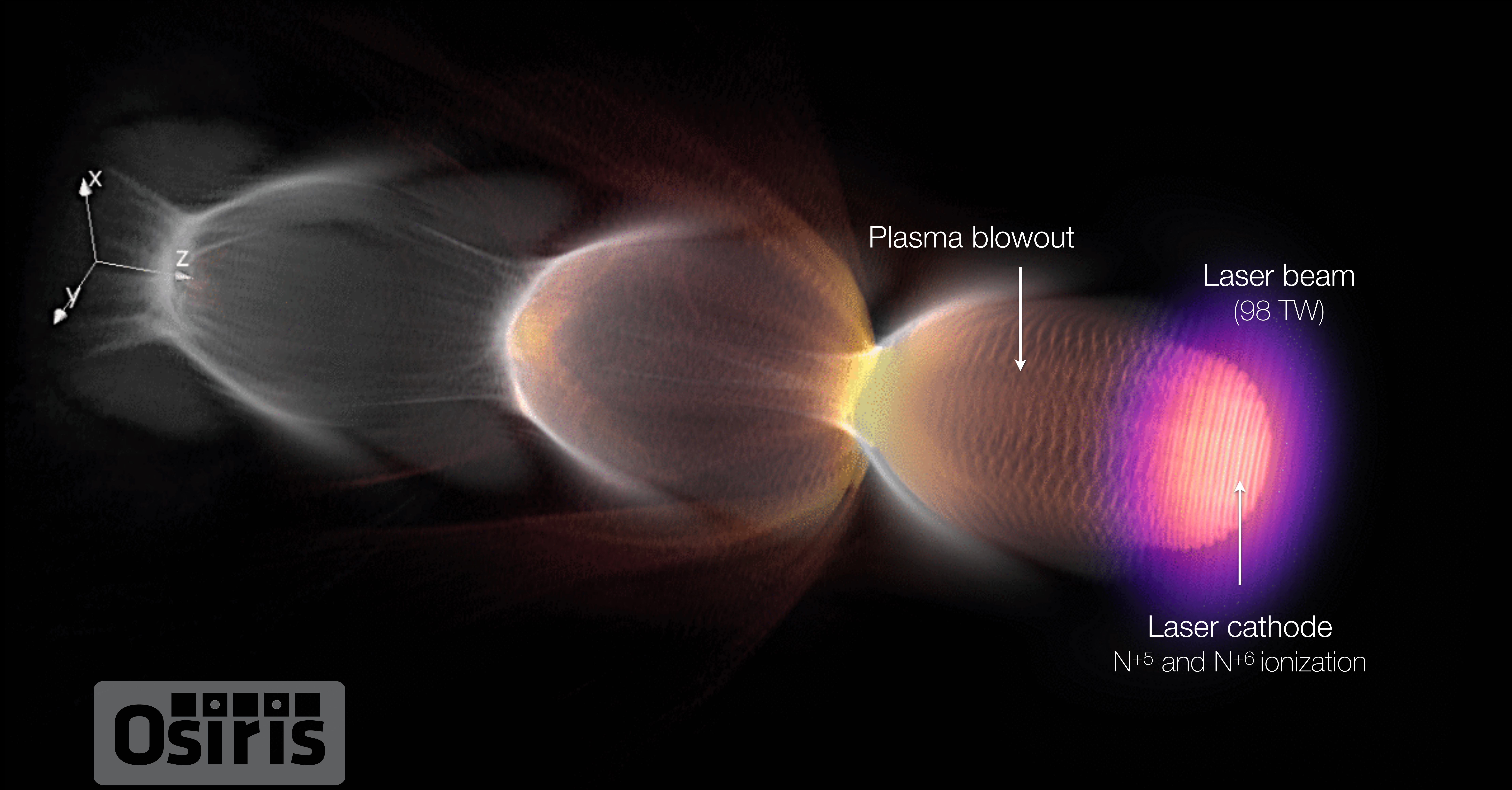
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

PIC simulation example

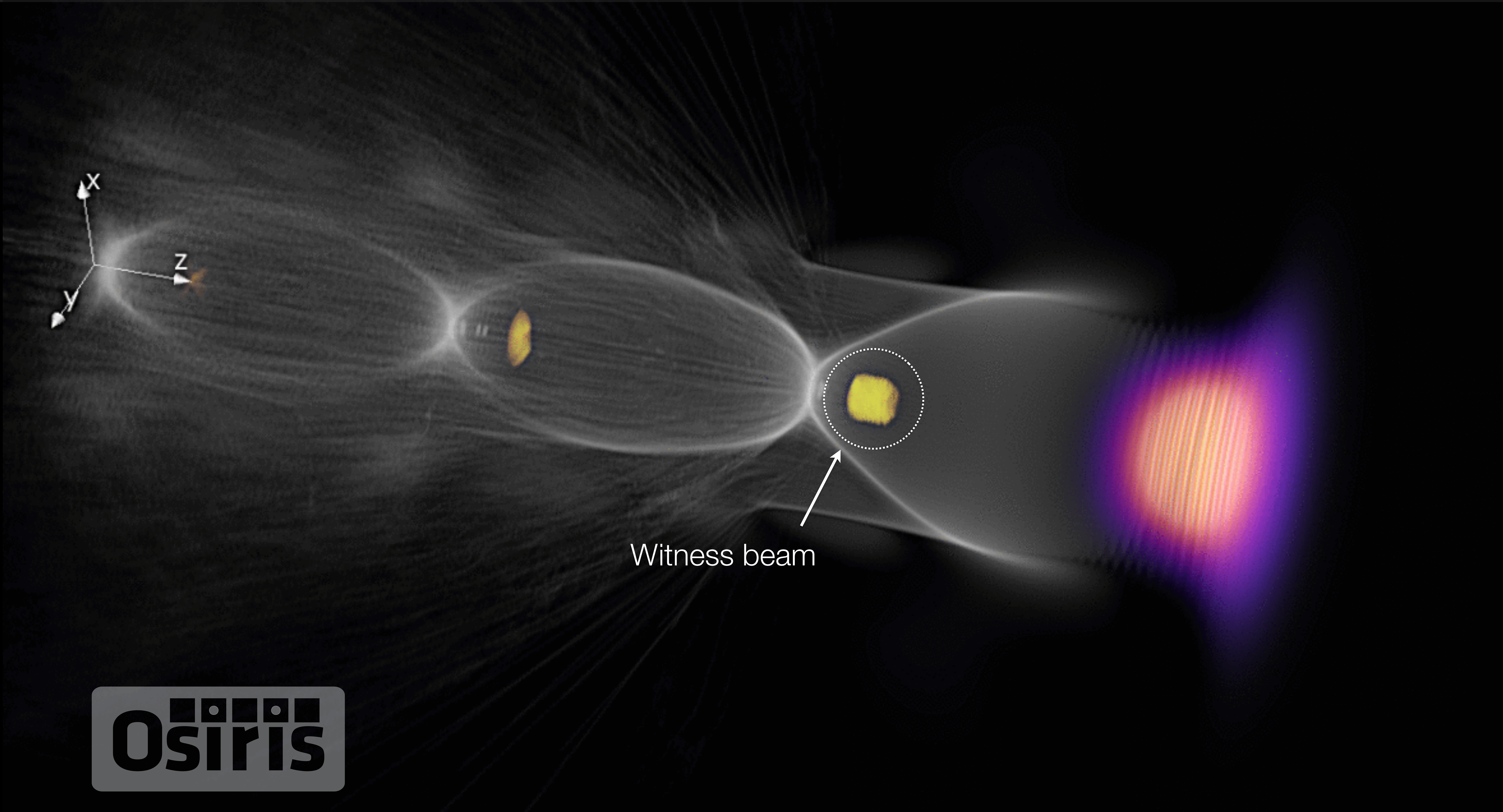


A. Pak et al., Phys. Rev. Lett. 104, 025003 (2010).
J. Couperus et al., Nature Comm. 8, 487 (2017).

Simulation: **LWFA with ionization injection**

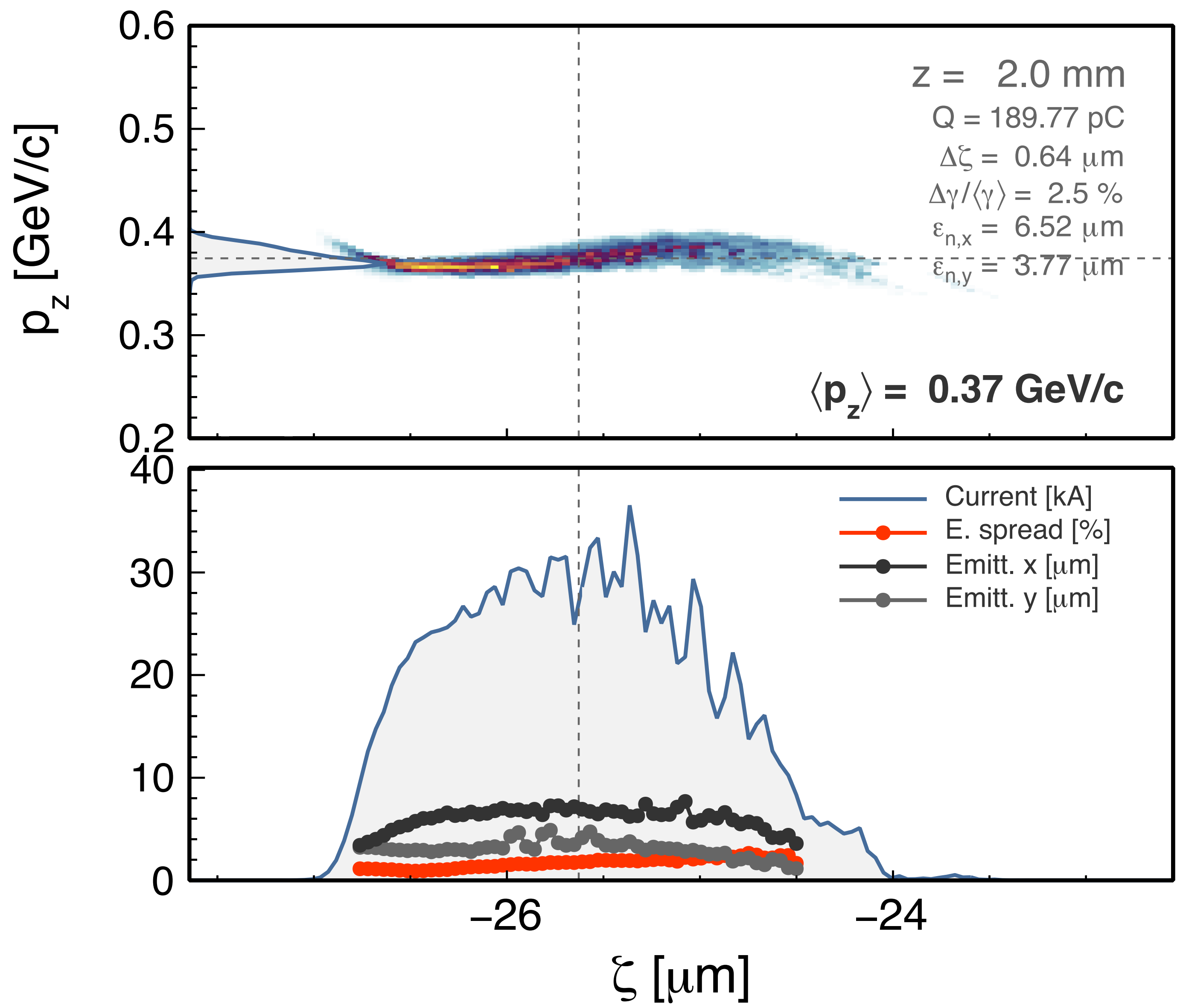


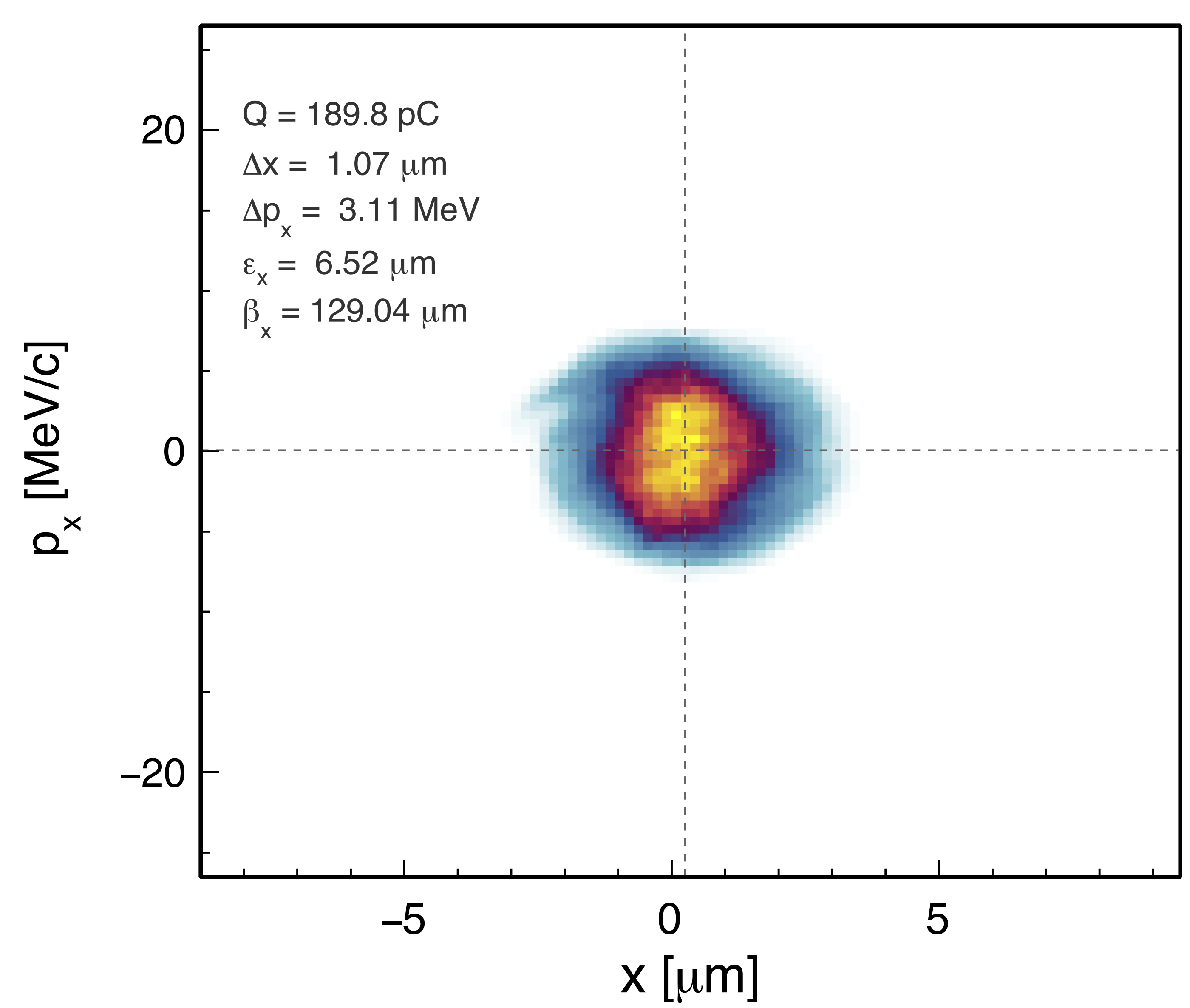
Simulation: **LWFA with ionization injection**



Simulation: **LWFA with ionization injection**

Witness beam from LWFA with ionization injection





OSIRIS 3.0

LWFA beam (after 2 mm)

- Energy: **340 MeV**
- Energy spread: **2.5%**
- Charge: **190 pC**
- Current: **30 kA**
- Duration (fwhm): **6 fs**
- Norm. emittance: **~5 µm**

Average acc. field

$$\langle E_z \rangle \simeq 180\ \mathrm{GV/m}$$

$$L_{dp} = (\lambda_p/\lambda_0)^2\,(\omega_p\tau)\,k_p^{-1} \simeq 7\ \mathrm{mm}$$

$$\Delta E \approx (\lambda_p/\lambda_0)^2\,(\omega_p\tau)\,\sqrt{a_0}\,mc^2/2 \simeq 0.85\ \mathrm{GeV}$$

Further acceleration is possible…

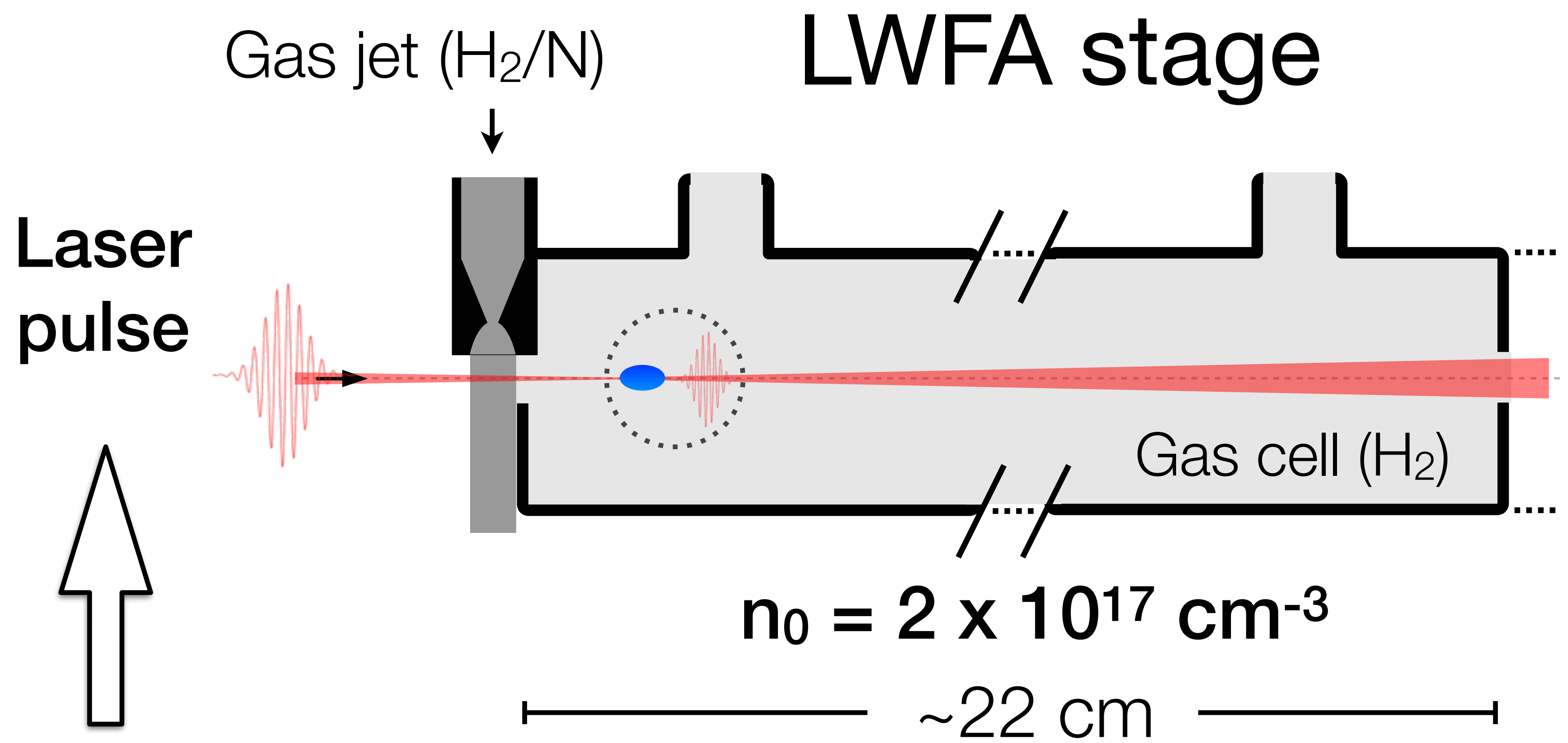
W. Lu et al., Phys. Rev. ST Accel. Beams 10, 061301 (2007).

Simulation: **LWFA with ionization injection**

Witness beam parameters until laser pump depletion length

LASER/plasma parameters			3D simulation (after 2 mm)	Extrapolation (after 7 mm)
P_0	98 TW	Average energy	370 MeV	~800 MeV
τ	27 fs	Energy spread	2.5%	~2%
w_0	17 µm	Energy spread (sliced)	1-2 %	~1%
a_0	3.18	Norm. emittance	~5 µm	~5 µm
Energy	2.8 J	Charge	190 pC	190 pC
Plasma density	2×10^{18} cm^{-3}	Duration (fwhm)	6 fs	6 fs
Acc. distance	2 - 7 mm	Peak current	30 kA	30 kA
Injection length	0.2 mm	Brightness	1.2 kA/µm^2	1.2 kA/µm^2

Scaling to EuPRAXIA laser operating a 10 times less dense plasma



Laser parameters

$$P_0 = 1 \text{ PW}$$
$$\lambda_0 = 800 \text{ nm}$$
$$w_0 = 54\ \mu\text{m}$$
$$\tau = 85 \text{ fs}$$
$$a_0 = 3.18$$
$$\mathscr{E} = 88 \text{ J}$$

Fix 'normalized' laser parameters

$$a_0 = 3.18 \quad k_p\tau = 2.15 \quad k_p w_0 = 4.5$$

$P_0 \propto n_p^{-1}$ peak power

$\mathscr{E} \simeq P_0\tau \propto n_p^{-3/2}$ laser energy

$\bar{E} \propto n_p^{-1}$ energy gain

$L_{\text{acc}} \propto n_p^{-3/2}$ acc. distance

Witness beam properties

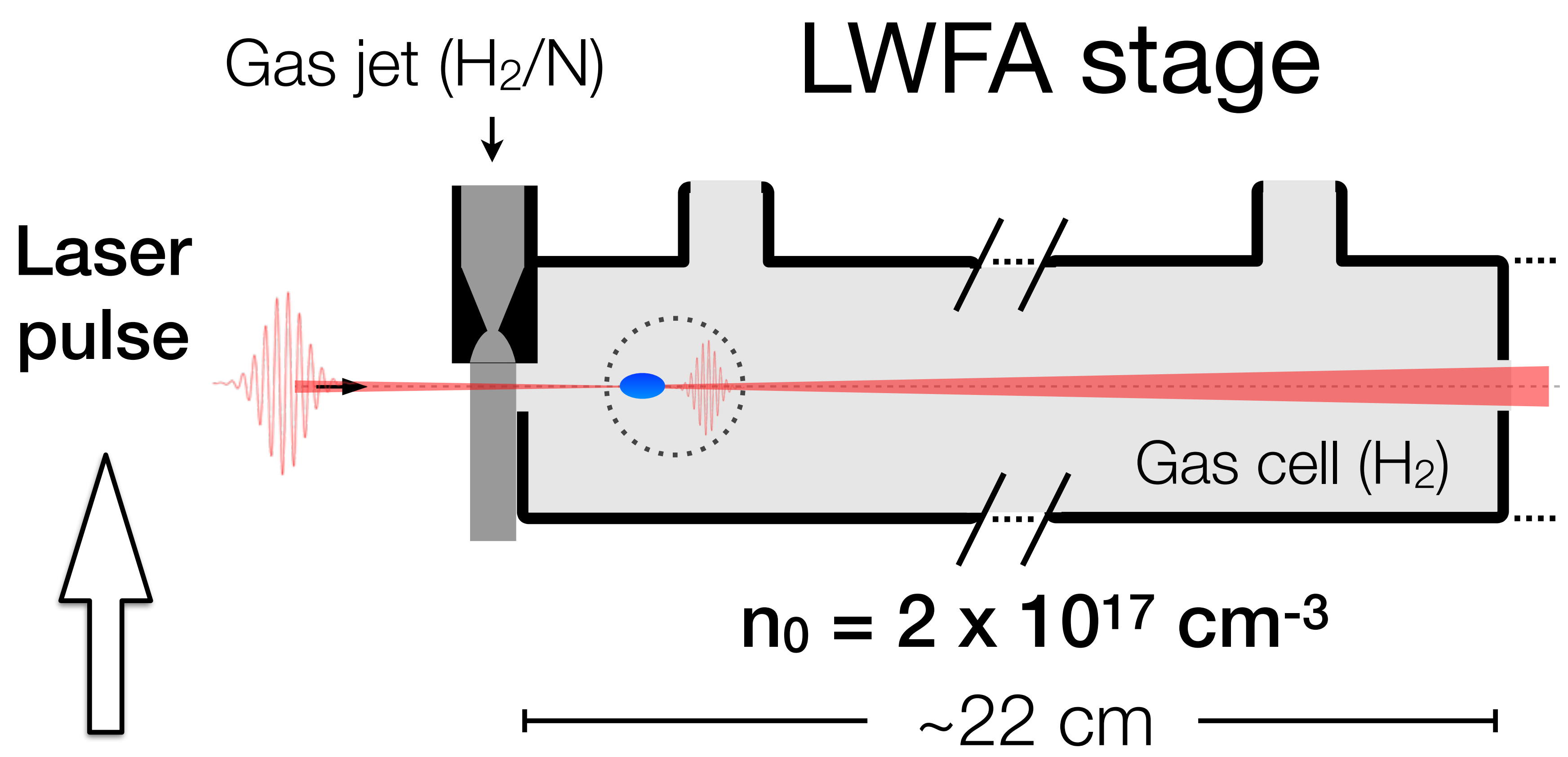
- Same current for beam loading
- Length and emittance scale as $k_p^{-1} \propto n_p^{-1/2}$
- Charge follows same scaling

- Energy spread $\sigma_E \simeq -eE_z L_{\text{jet}} \propto n_p^{1/2}$, $\sigma_E/\bar{E} \propto n_p^{3/2}$

$Q_w\bar{E} \propto n_p^{-3/2}$ - Total energy in witness

Simulation: **LWFA with ionization injection**

Scaling to EuPRAXIA laser operating a 10 times less dense plasma



Laser parameters

$$P_0 = 1\ \mathrm{PW}$$
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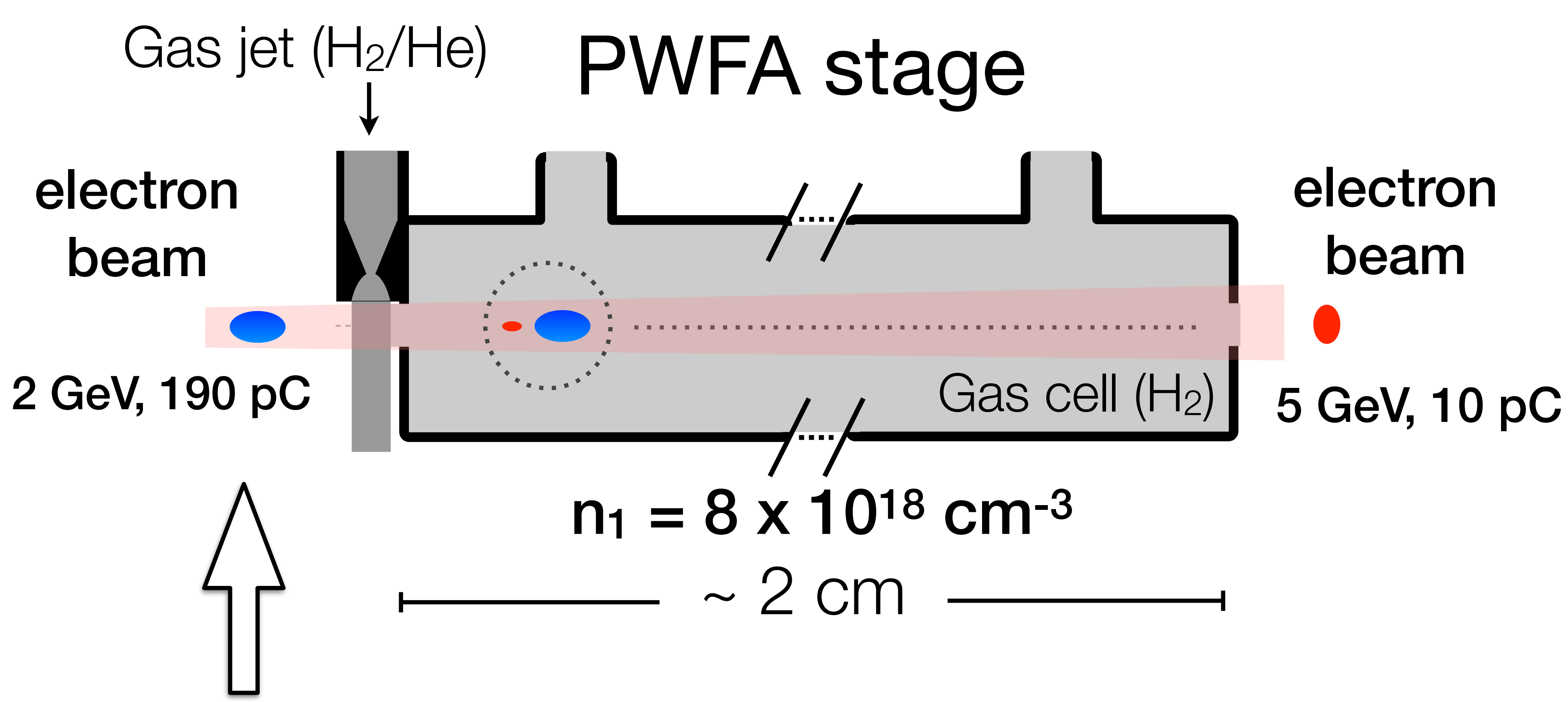
$$w_0 = 54\ \mu\mathrm{m}$$
$$\tau = 85\ \mathrm{fs}$$
$$a_0 = 3.18$$
$$\mathscr{E} = 88\ \mathrm{J}$$

LASER/plasma parameters		**Witness beam (via ionization injection)**	
P_0	980 TW	**Average energy**	1 - 5 GeV
τ	85 fs	**Energy spread**	~2 %
w_0	54 μm	**Energy spread (sliced)**	0.5 - 0.1 %
a_0	3.18	**Norm. emittance**	~15 μm
Energy	88 J	**Charge**	600 pC
Plasma density	2 x 10^{17} cm^{-3}	**Duration (fwhm)**	19 fs
Acc. distance	4 - 20 cm	**Peak current**	30 kA
Injection length	0.6 mm	**Brightness**	0.12 kA/μm^2

LWFA with II for the production of nC multi-GeV beams.

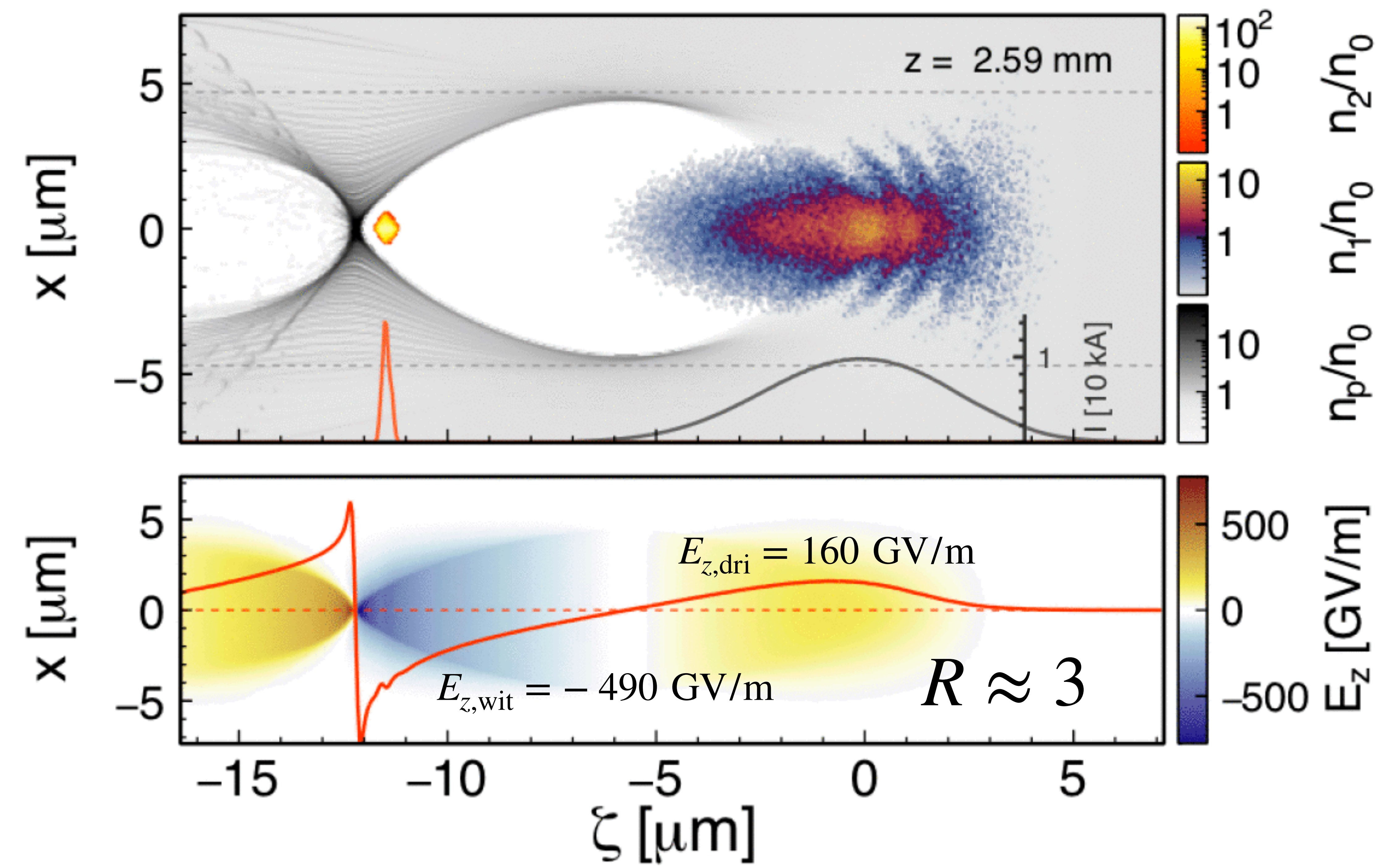
Second Stage: PWFA with wakefield-induced ionization injection

Osiris 3.0



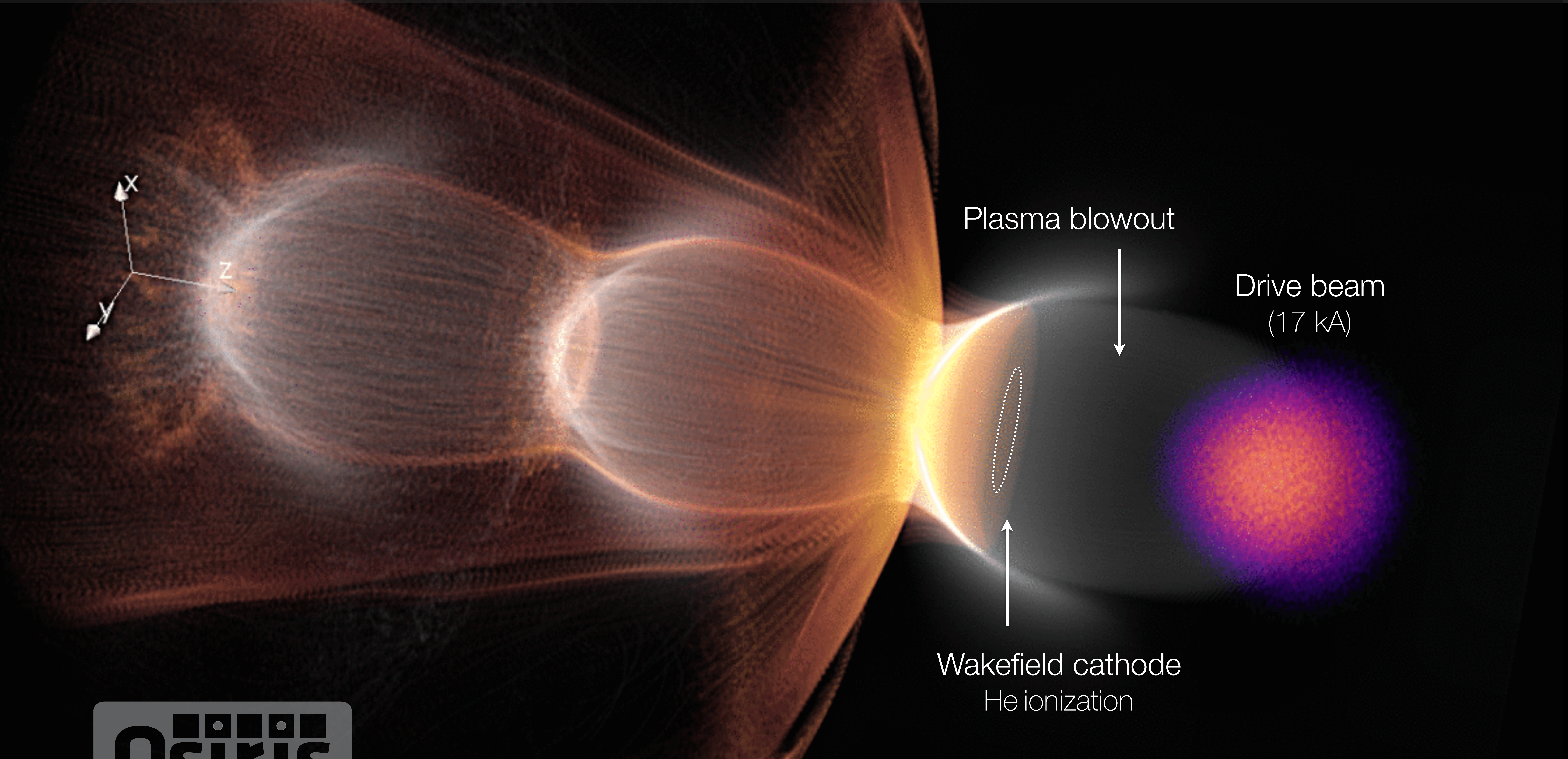
Drive beam from LWFA	
Average energy	2 GeV
Energy spread	3 %
Energy spread (sliced)	3 %
Norm. emittance	10 µm
Charge	190 pC
Duration (fwhm)	19 fs
Peak current	10 kA
Brightness	0.1 kA/µm^2

PIC simulation example



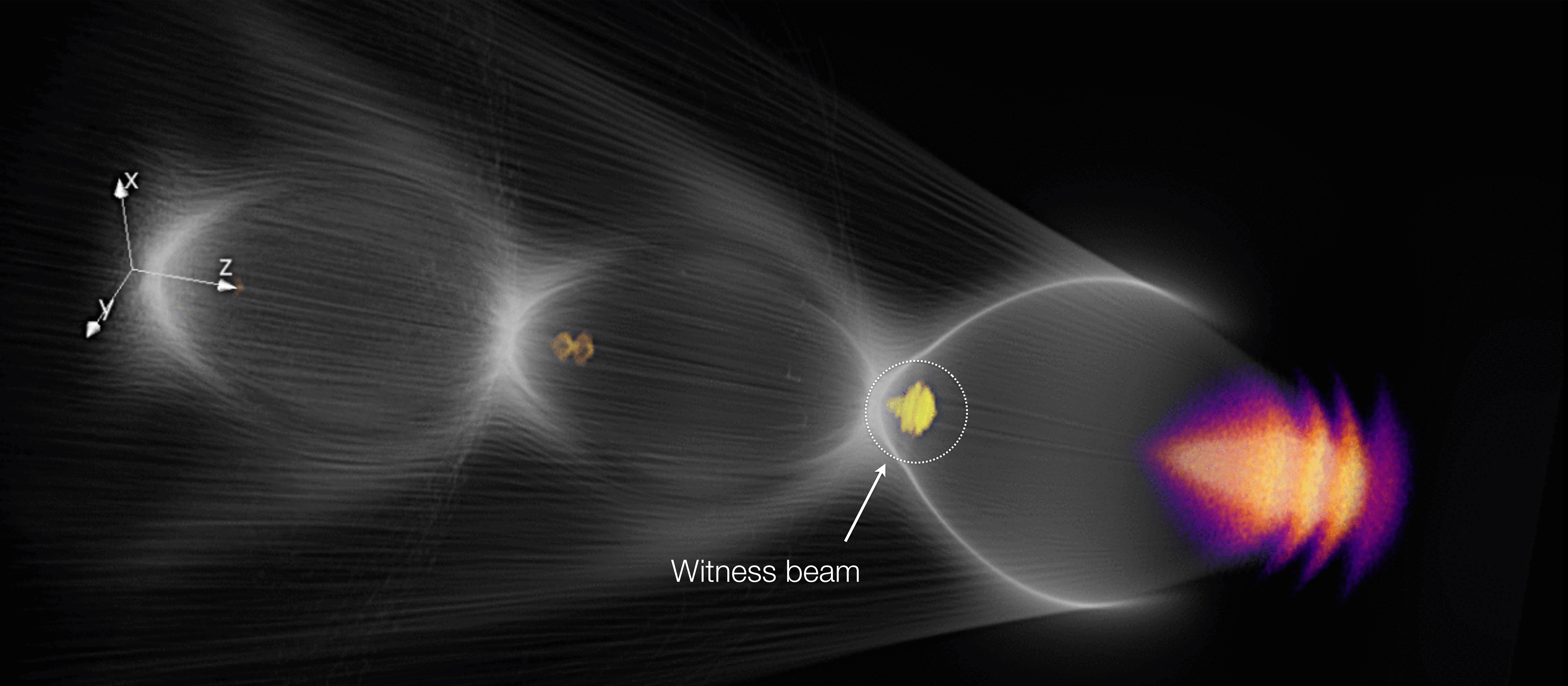
A. Martinez de la Ossa et al., Phys. Rev. Lett. 111, 245003 (2013).
A. Martinez de la Ossa et al., Phys. Plasmas 22, 093107 (2015).

Simulation: **PWFA stage with Wii injection**



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

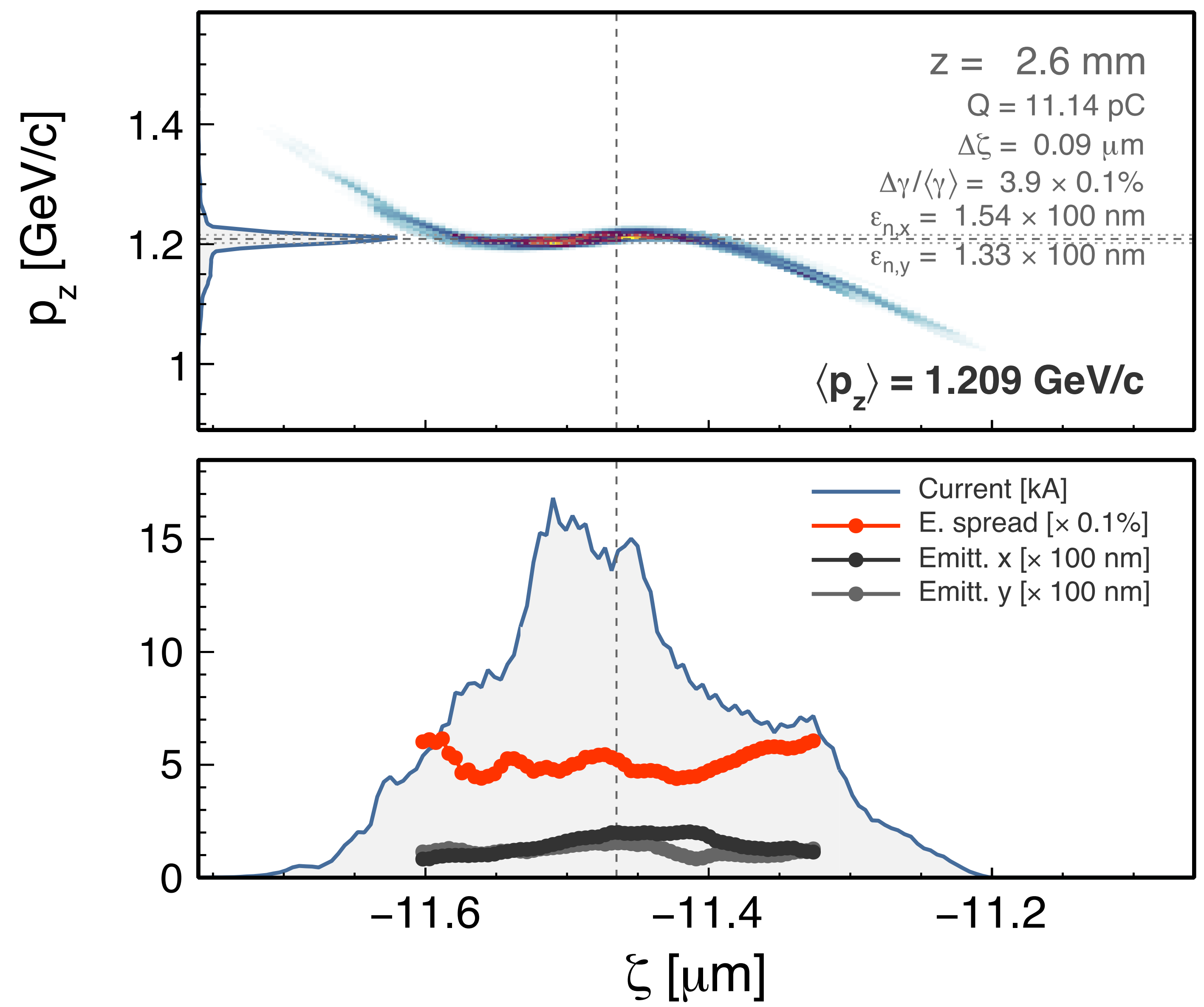
Simulation: **PWFA stage with Wii injection**

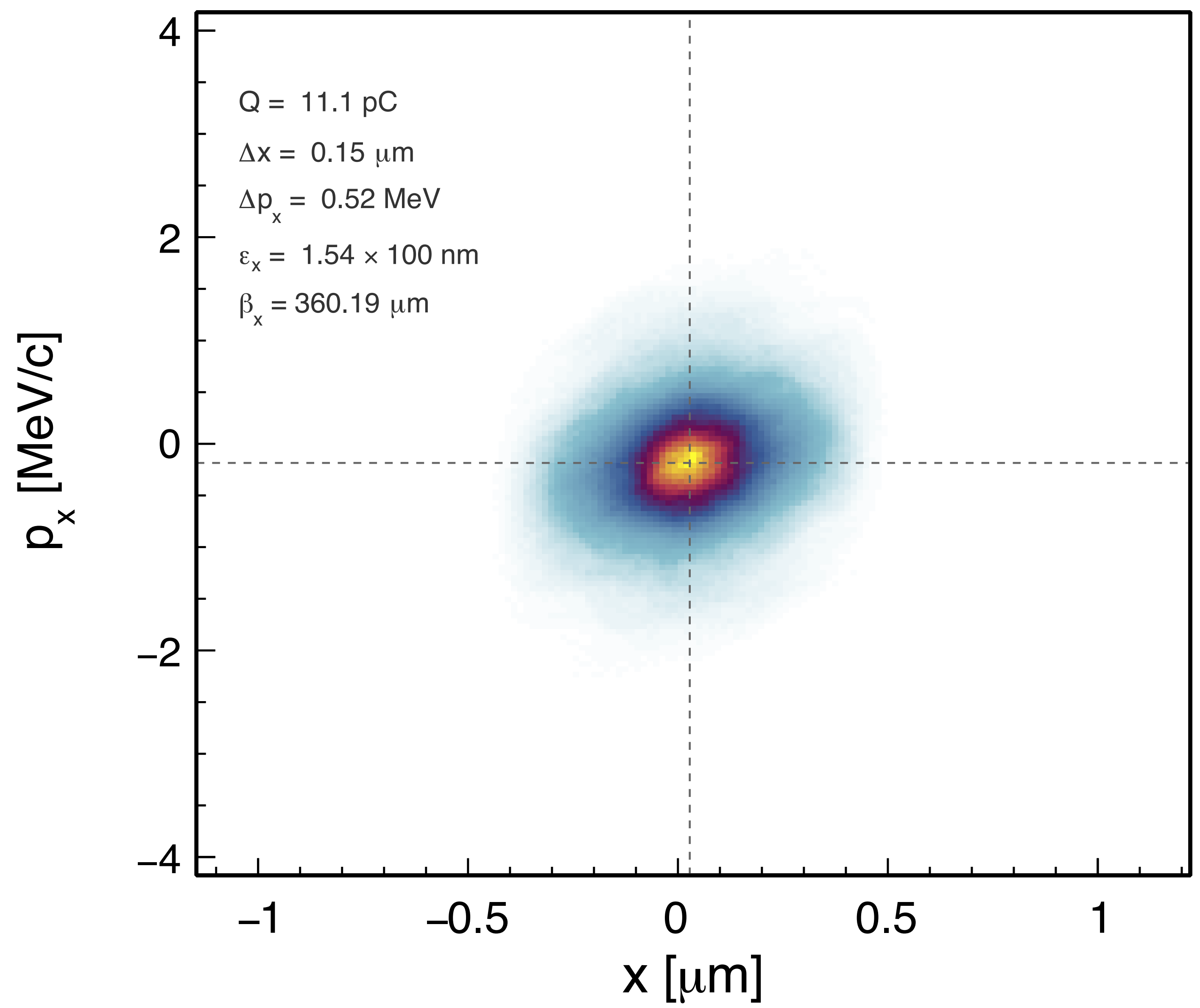


A. M. de la Ossa et al., PRL 111, 245003 (2013)

Simulation: **LWFA with ionization injection**

Witness beam from PWFA with Wii injection





Osiris 3.0

PWFA beam (after 2.6 mm)

- Energy: **1.2 GeV**
- Energy spread: **0.5%**
- Charge: **11 pC**
- Current: **15 kA**
- Duration (fwhm): **1 fs**
- Norm. emittance: **~100 nm**

Average acc. field

$$\langle E_z \rangle \simeq 465\ \mathrm{GV/m}$$

Further acceleration is possible…

$$\Delta E_{\mathrm{wit}} = R E_{\mathrm{dri},0} \simeq 6\ \mathrm{GeV}$$

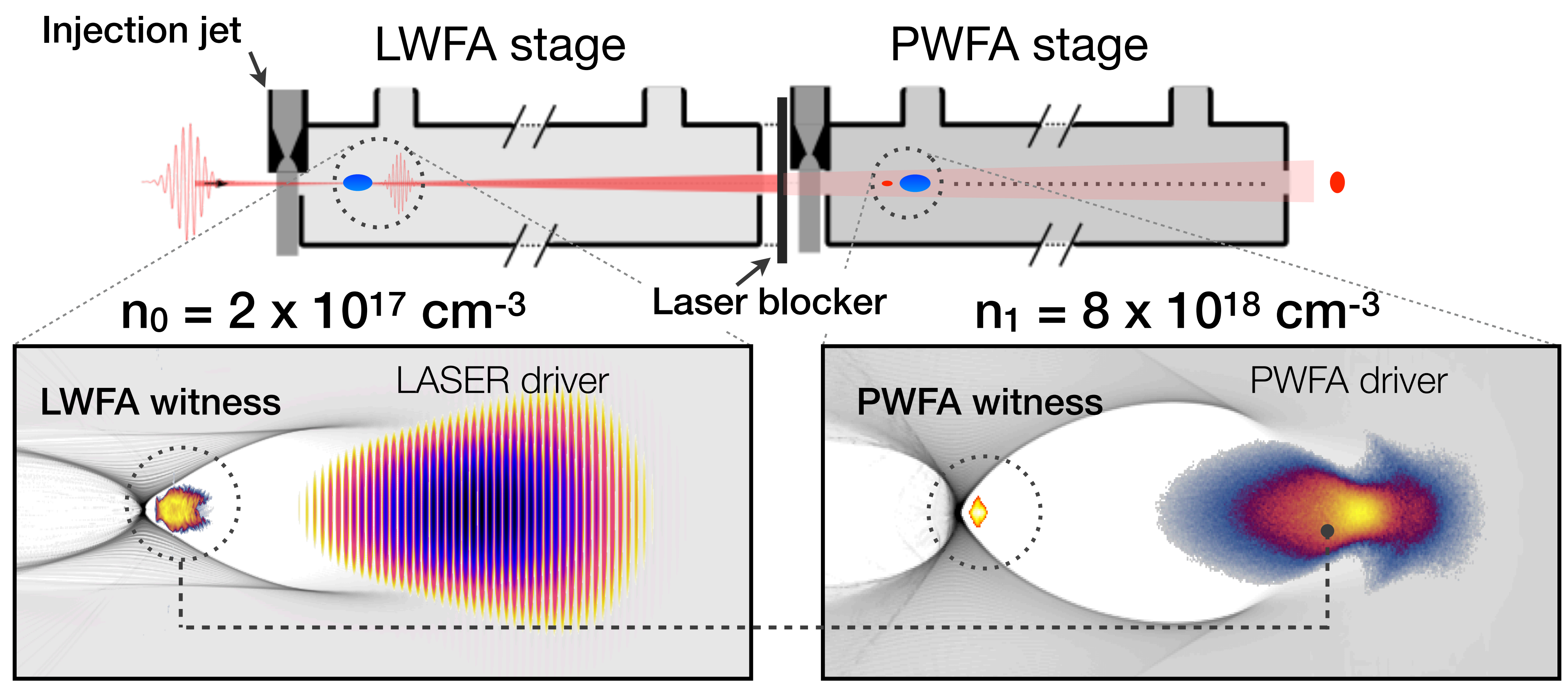
↑ transformer ratio

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

LPWFA design with ionization injection: EuPRAXIA example

Laser beam

$P_0 = 1000$ TW
$\lambda_0 = 800$ nm
$w_0 = 54$ µm
$a_0 = 3.18$
$\tau = 85$ fs
Energy = 88 J

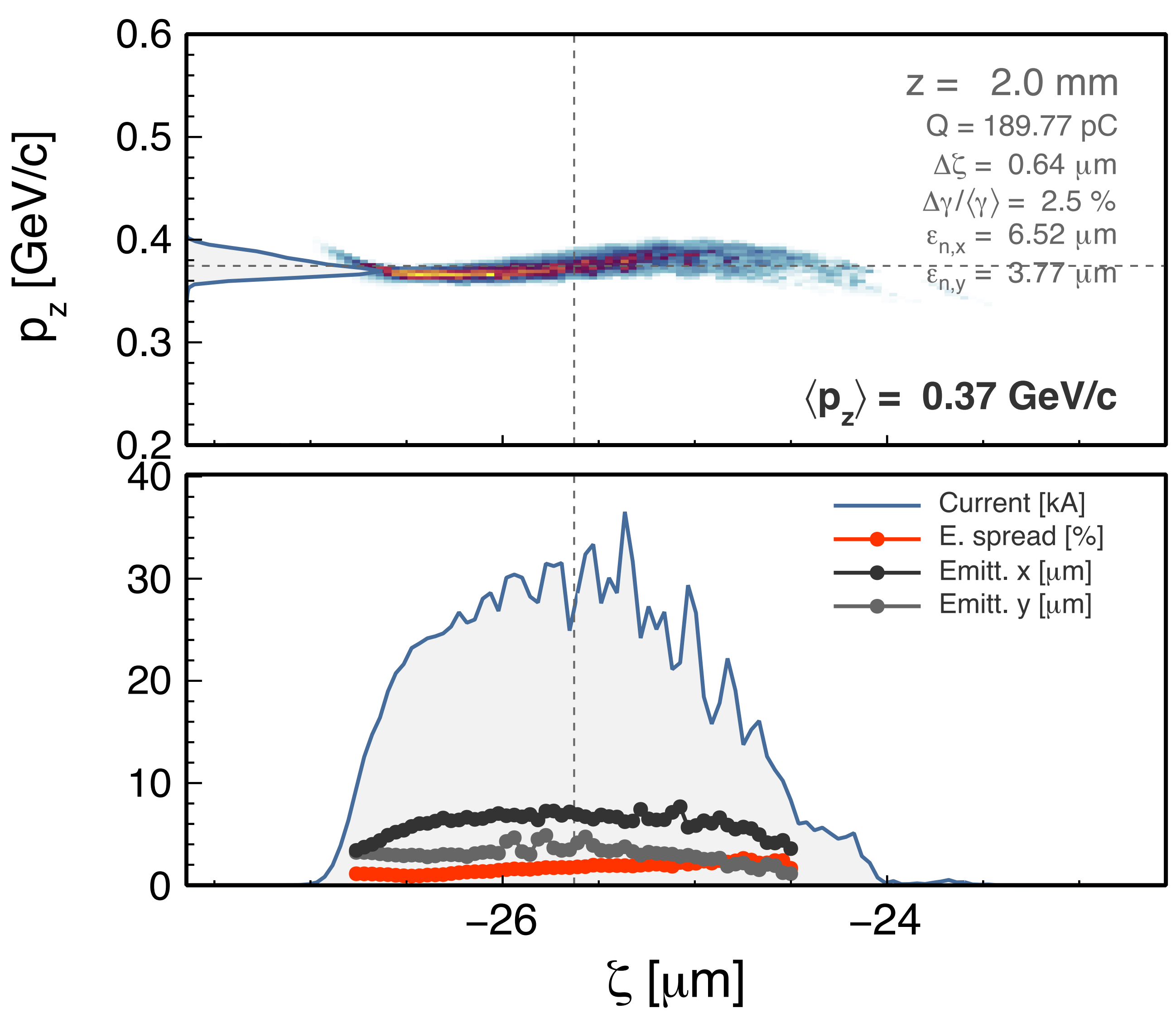


LWFA with Ionisation injection

PWFA with Wii injection

Electron beam

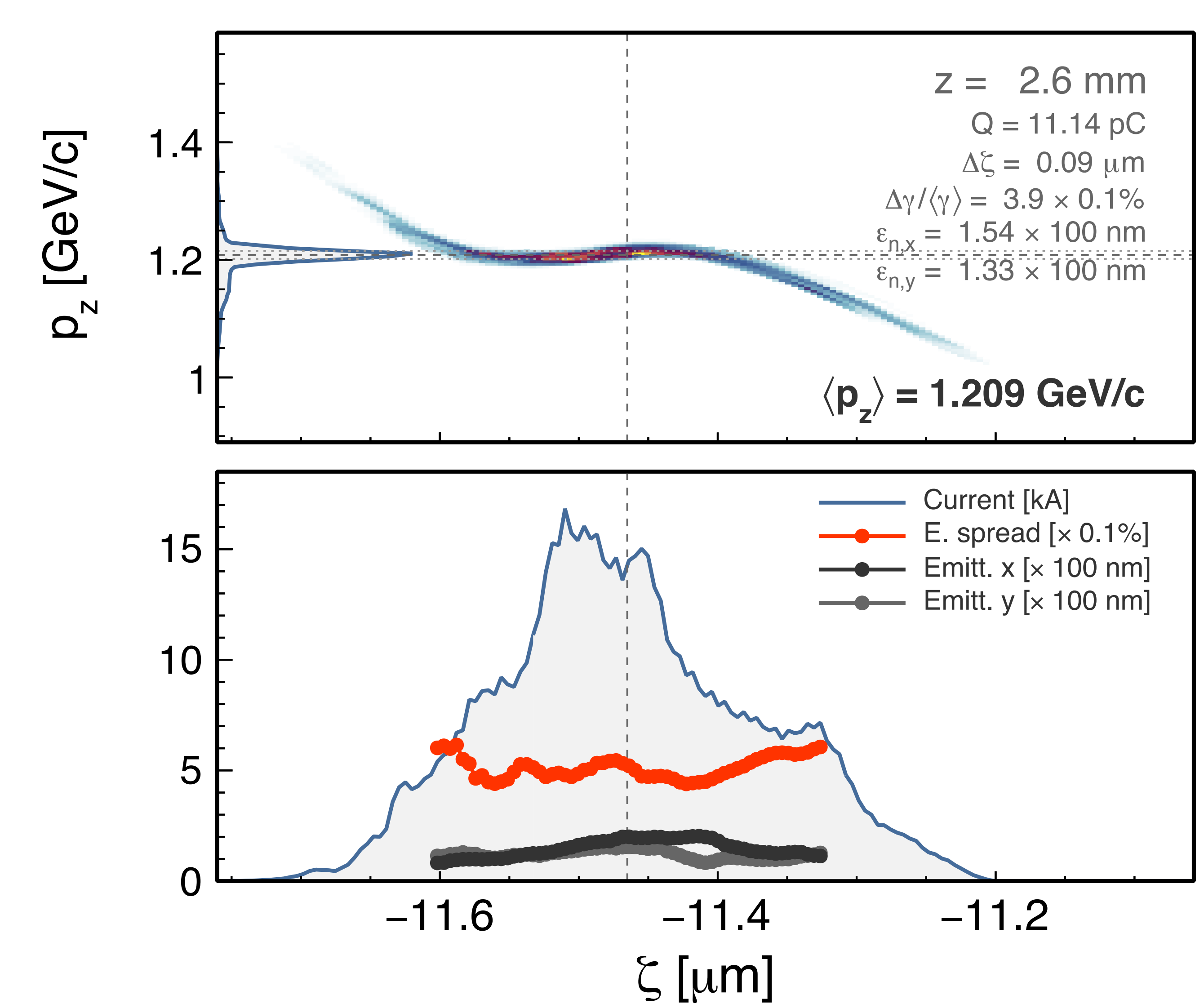
$I_0 = 15$ kA
$\epsilon_n = 130$ nm
$\tau = 700$ as
$\gamma mc^2 = 5$ GeV
$\Delta\gamma/\gamma = 0.2$ %
Charge = 11 pC



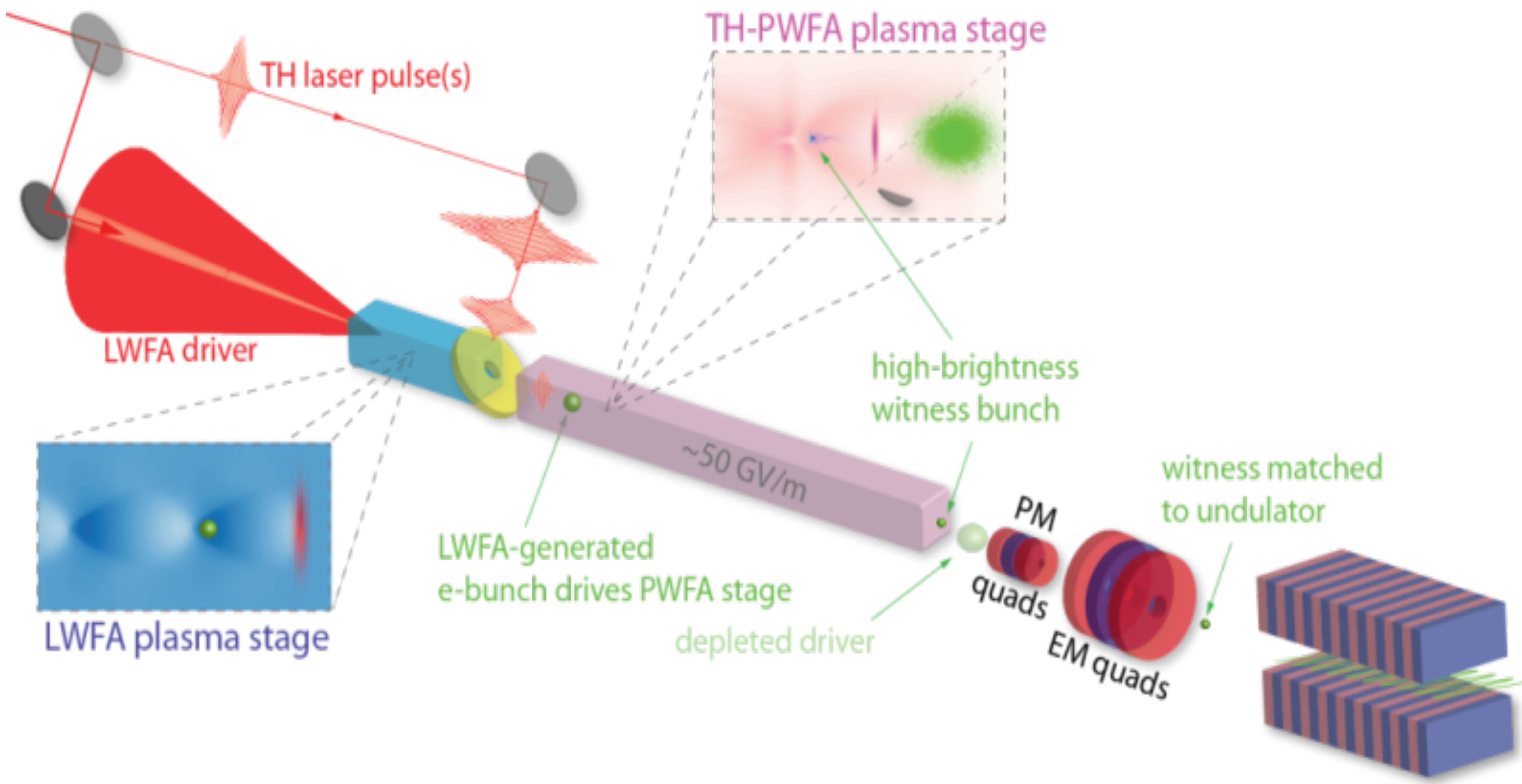
'Energy doubling' $\Delta\gamma_w = R\,\gamma_d$

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

x 10000



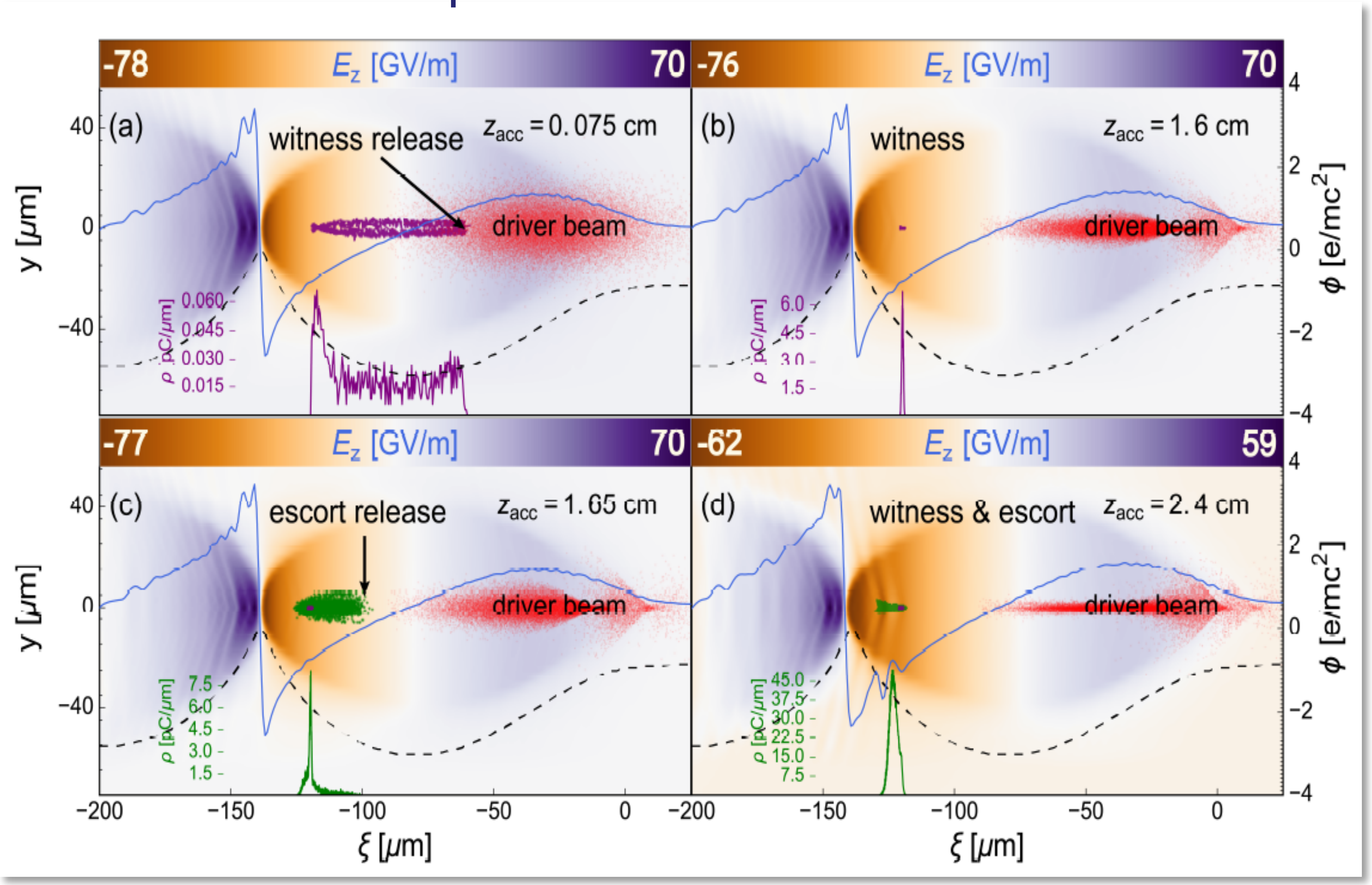
Hybrid LWFA | PWFA design with Trojan horse



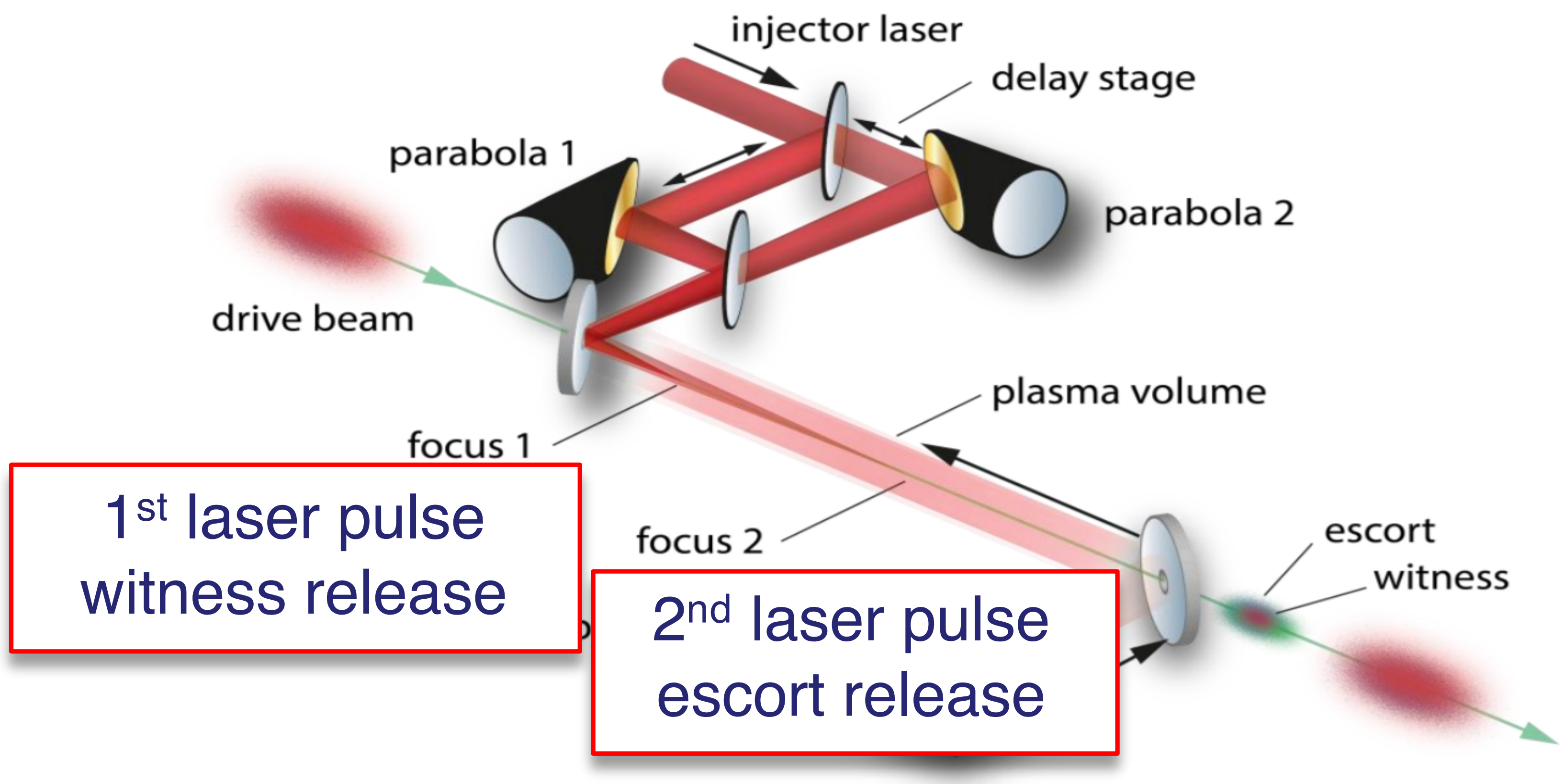
B. Hidding et al., Phys. Rev. Lett. 104, 195002 (2010).
B. Hidding et al., Phys. Rev. Lett. 108, 035001 (2012).

Energy chirp compensation in a single TH-PWFA stage

Proof-of-concept 3D Particle-In-Cell simulation



1. Ultrahigh 5D brightness witness beam release
2. Witness beam is accelerated to high energy
3. Second high charge escort beam release using plasma photocathode laser
4. **Escort beam** is trapped and the wakefield is reversed locally

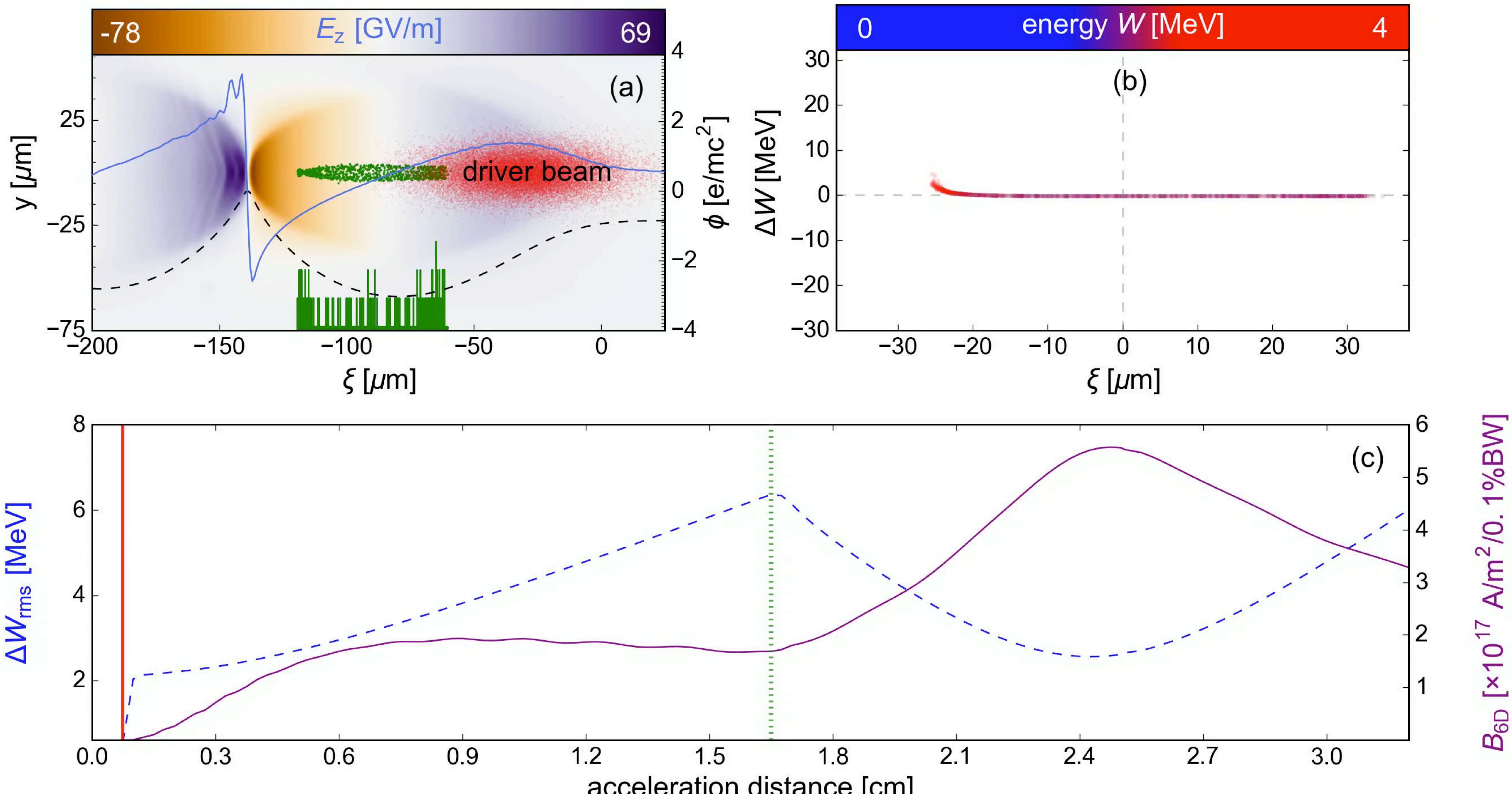


No additional complexity compared to Trojan Horse injection

VSim

G. G. Manahan, et.al., Nat. Commun. 8, 15705 (2017).

Energy chirp compensation in a single TH-PWFA stage



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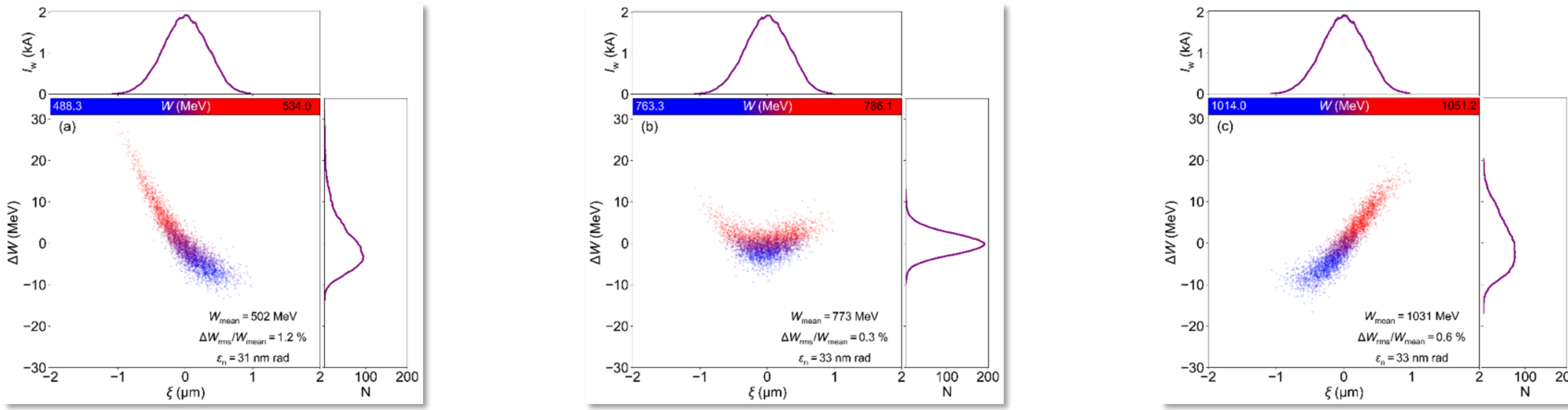
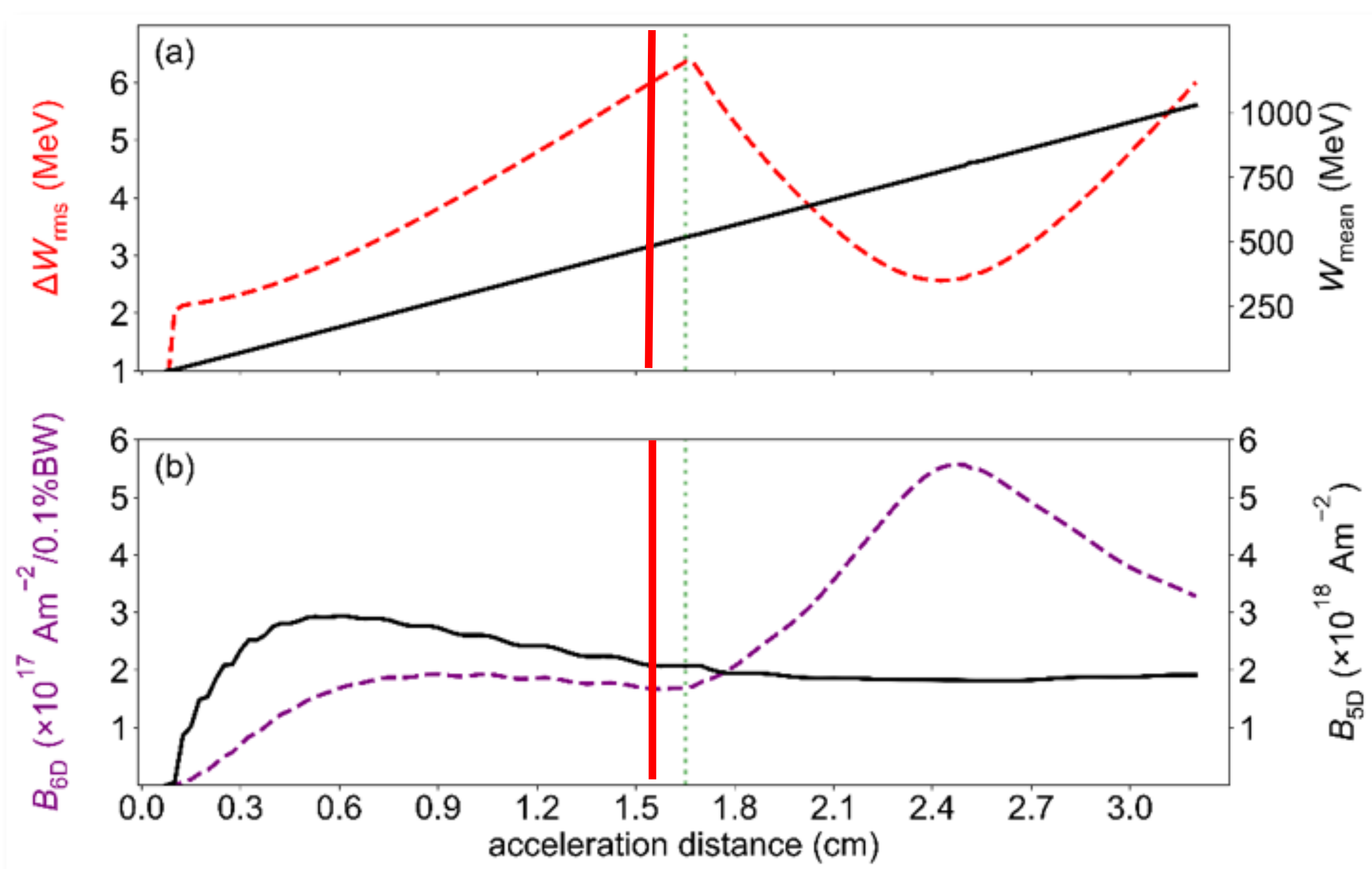
Energy chirp compensation in a single TH-PWFA stage





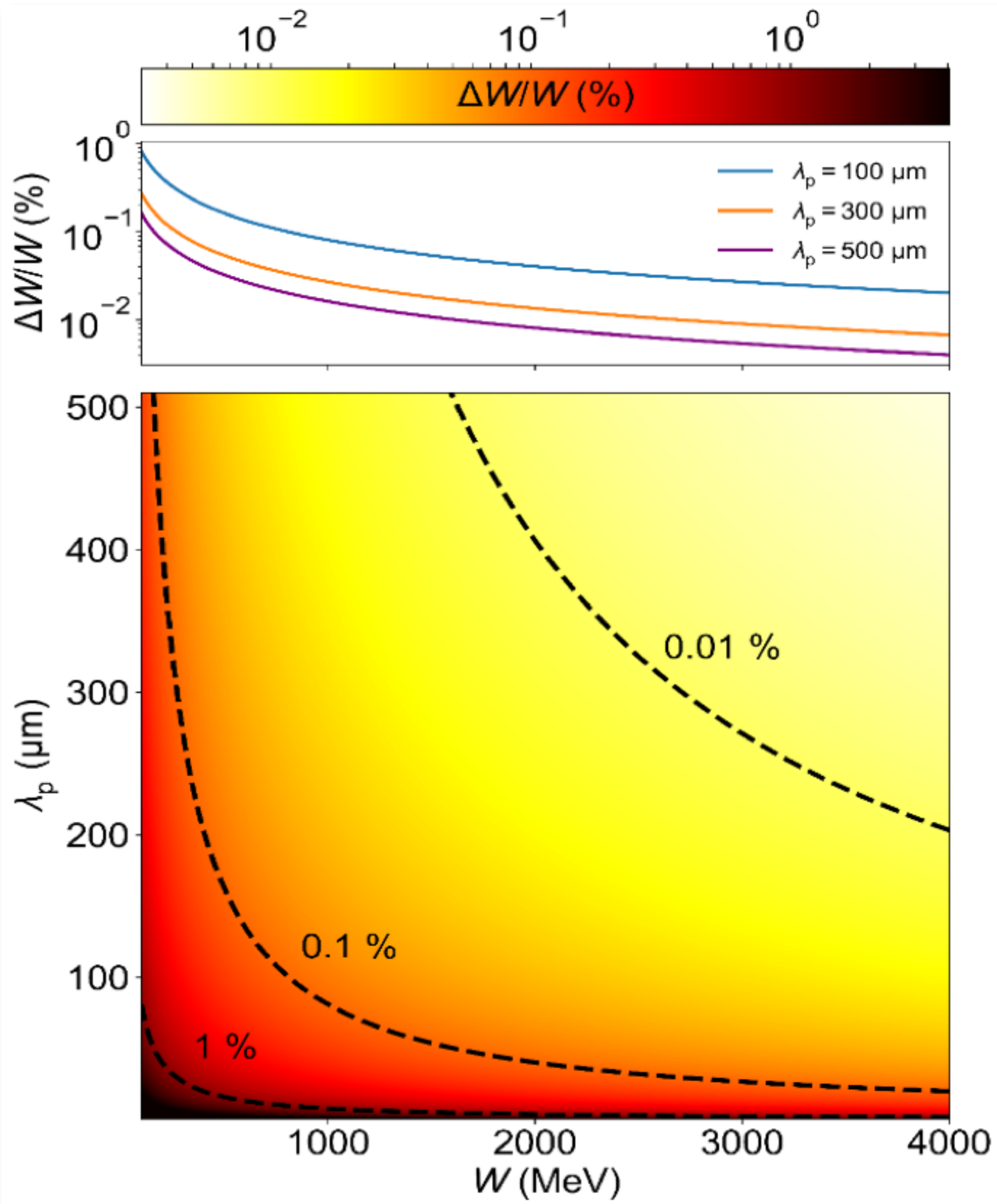
- ❑ Normalized emittance still at nm rad level
- ❑ Residual energy spread $\Delta W = 2.56$ MeV
- ❑ Relative energy spread of $\Delta W / W = 0.3$ %

Unprecedented ultrahigh 6D Brightness
$B_{6D} \approx 5.5\times10^{17}$ A/m^2 rad^2/0.1%BW

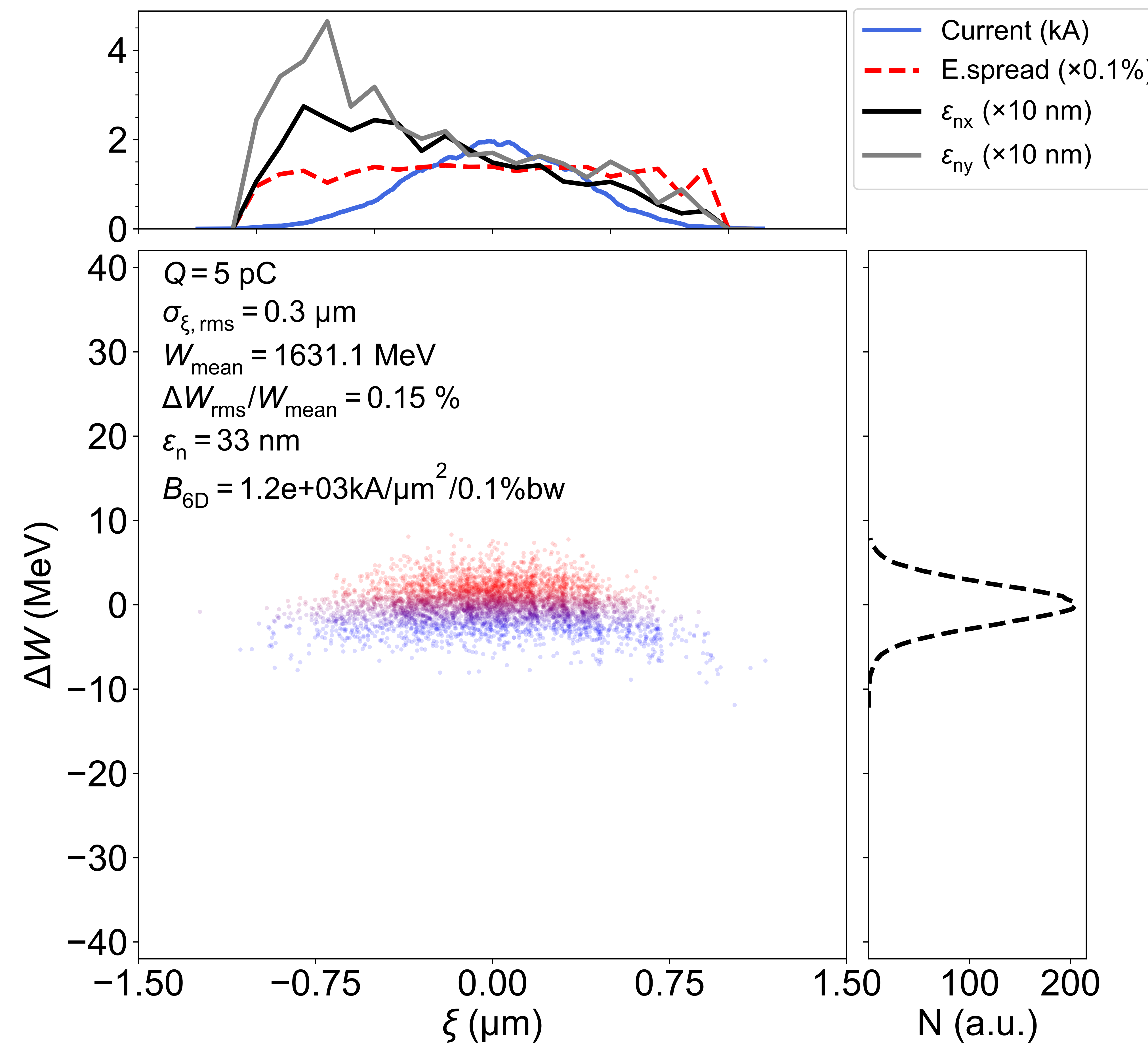
G. G. Manahan, et.al., Nat. Commun. 8, 15705 (2017).

Energy chirp compensation in a single TH-PWFA stage

Relative energy spread scaling



High-energy example



G. G. Manahan, et.al., Nat. Commun. 8, 15705 (2017).

Hybrid LWFA | PWFA: **Summary**

Conceptual designs for hybrid LWFA - PWFA
for the production of **multi-GeV, superior quality beams**.

Hybrid LWFA/PWFA with Wii injection:
Energy and brightness transformer: 2 x energy, 10000 x brightness.
Stable beam loading conditions for low energy spread: ~0.1% at 5 GeV energy.
Simple setup.

Hybrid LWFA/PWFA with TH and the Escort dechirping technique:
The beam loading process is decoupled from witness beam production.
Keeps the ultra-low emittance of the witness beam.