Wakefield-induced ionization injection

in beam-driven plasma accelerators and Self-Similar Staging

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La Biodola, Isola d'Elba, Italy

LAOLA. collaboration

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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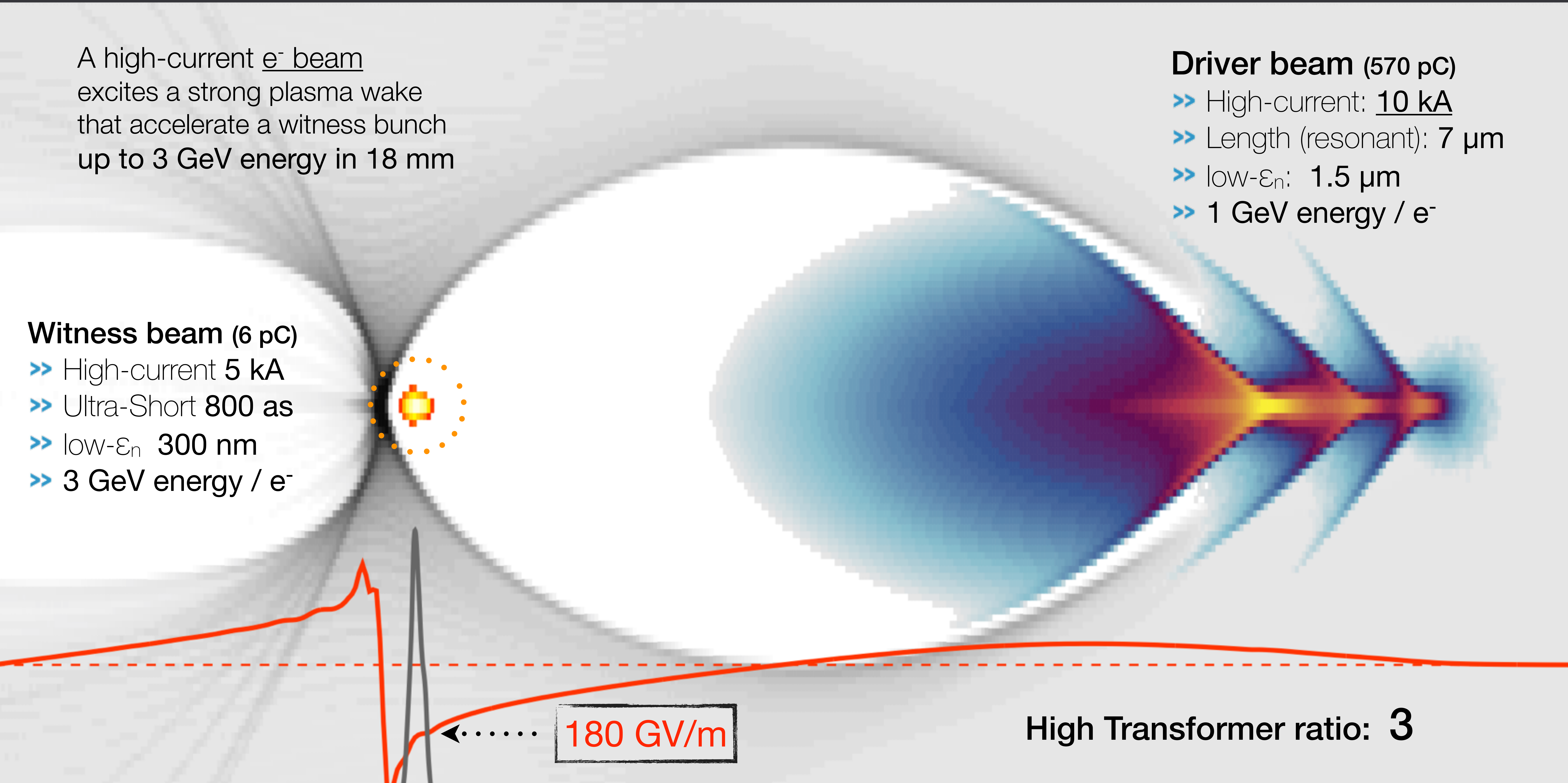
Wakefield-Induced Ionization Injection

in beam-driven plasma accelerators

An **injection technique** for the **beam-driven plasma wakefield accelerator** in the **blowout regime** that **utilizes only the wakefields** **to induce ionization and trapping** of **high-quality electron bunches**.

Beam driven plasma wakefield acceleration (PWFA)

Wakefield-Induced Ionization Injection



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

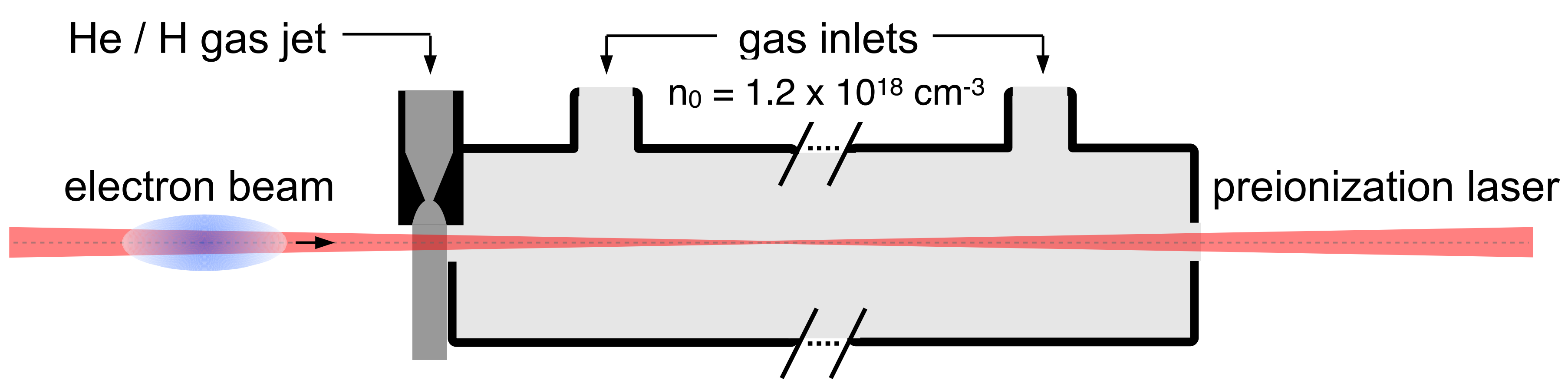
FLASHForward example

FLASHForward

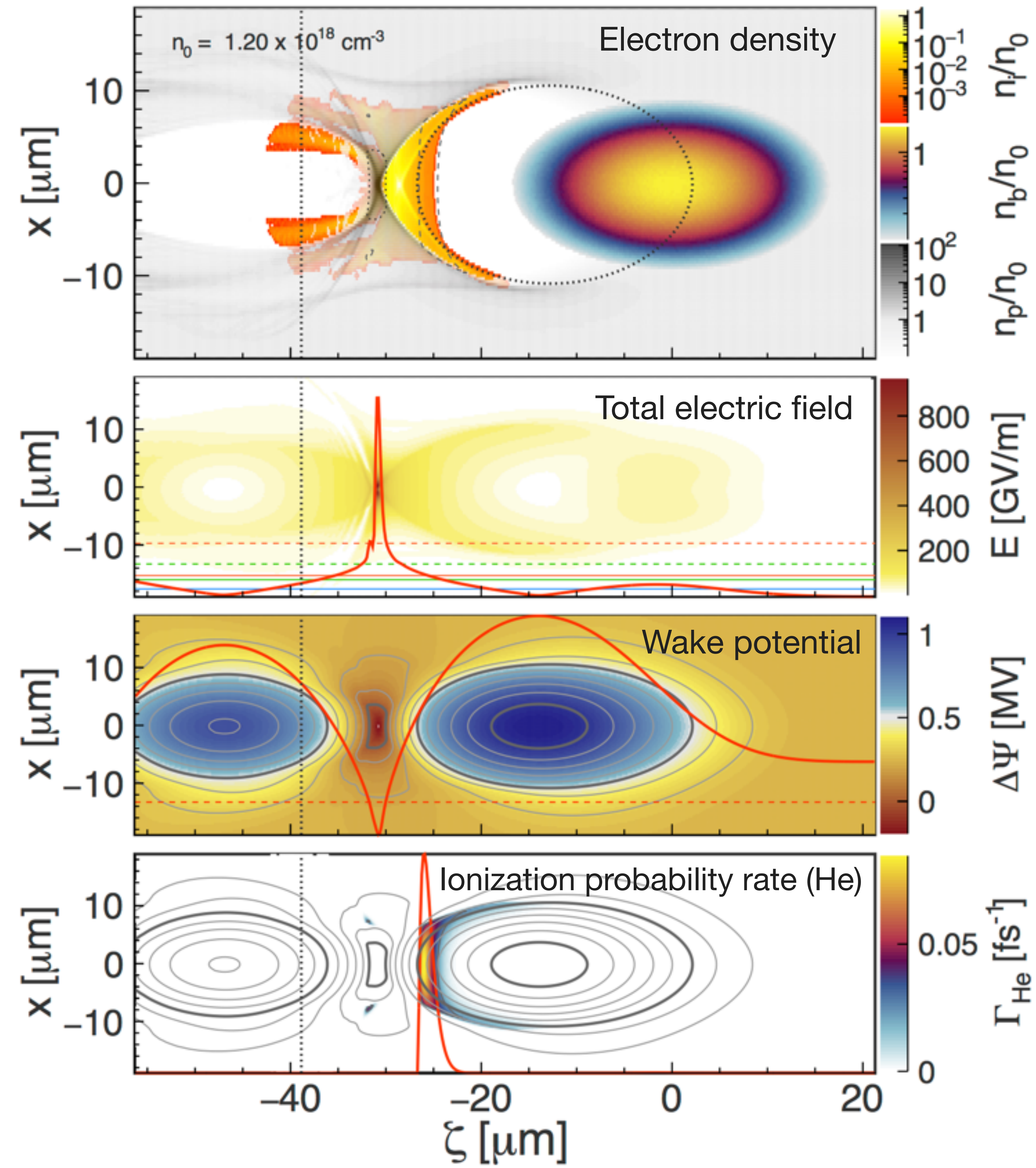
Q_b = 574 pC
I_b = **10 kA**
E_b = 1 GeV
σ_z = **7 µm**
σ_r = 4 µm
ε_n = 1 µm

Wakefield Injection

plasma density
$$n_0 = 12 \times 10^{17}\ \mathrm{cm}^{-3}$$
$k_p\sigma_z$ = 1.41
dopant species: helium



- Preionization laser with an intensity capable to fully ionize a gas with a low ionization threshold (LIT), e.g. Hydrogen.
- Micro-nozzle fed by the same LIT gas doped with a high-ionization threshold (HIT) gas, e.g. Helium.



Electron density

The Blowout regime [1]

High-current, tightly focused e⁻ beams blow out all the plasma electrons from their ions creating a clear ion cavity that propagates at the speed of light.

High-current beams

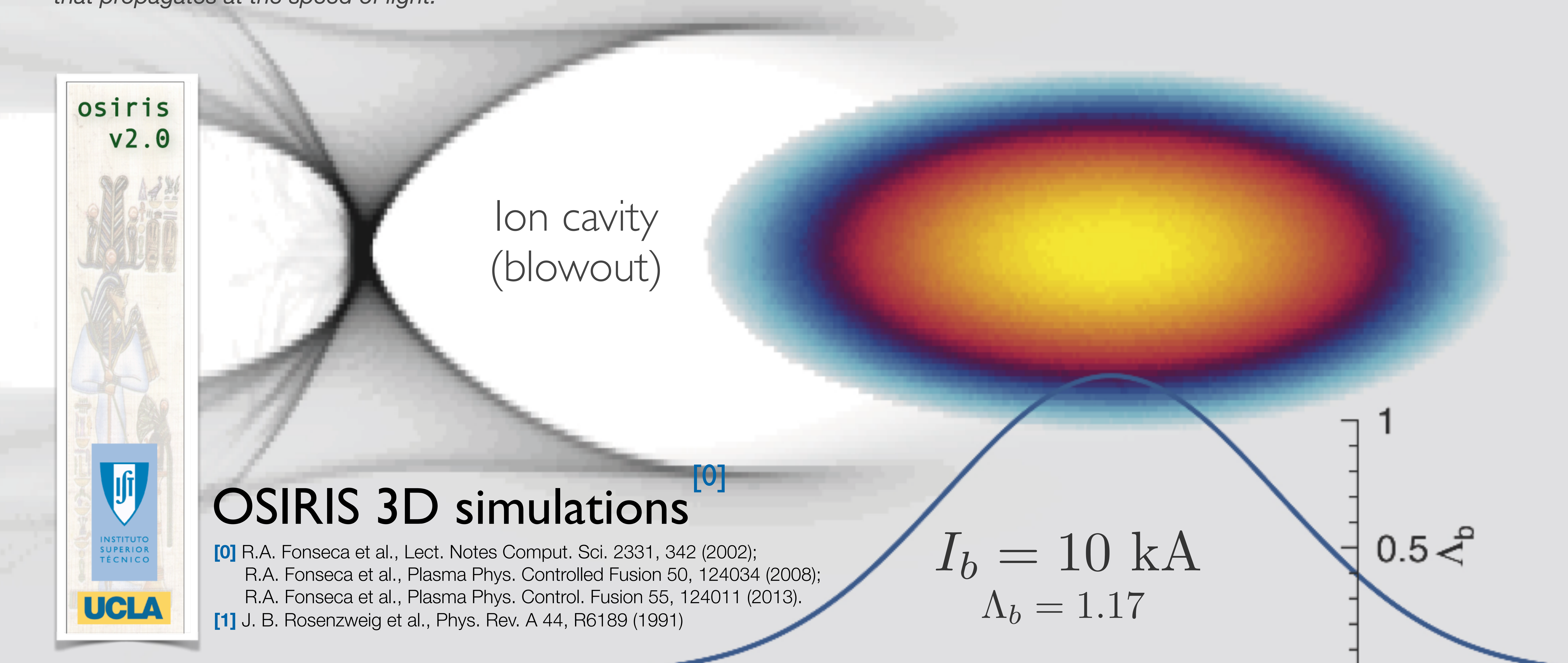
$I_b \gtrsim 1\ \mathrm{kA}$

resonant length

$k_p\sigma_z = \sqrt{2}$

spot size

$k_p\sigma_x = 0.8$



OSIRIS 3D simulations [0]

[0] R.A. Fonseca et al., Lect. Notes Comput. Sci. 2331, 342 (2002);
R.A. Fonseca et al., Plasma Phys. Controlled Fusion 50, 124034 (2008);
R.A. Fonseca et al., Plasma Phys. Control. Fusion 55, 124011 (2013).
[1] J. B. Rosenzweig et al., Phys. Rev. A 44, R6189 (1991)

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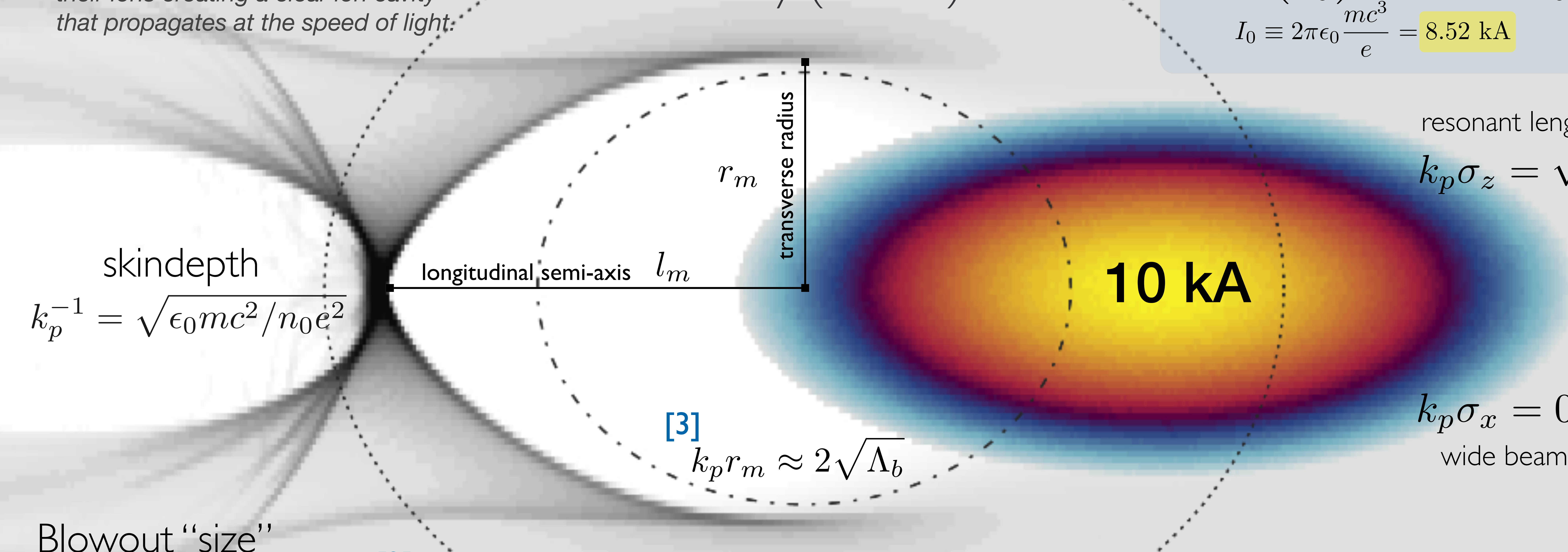


Normalized beam current

$$\Lambda_b \equiv \left(\frac{n_b}{n_0}\right)(k_p\sigma_x)^2 = \frac{I_b}{I_0}$$

$$I_0 \equiv 2\pi\epsilon_0 \frac{mc^3}{e} = 8.52\ \mathrm{kA}$$

resonant length

$$k_p\sigma_z = \sqrt{2}$$

$$k_p\sigma_x = 0.8$$

wide beam

skindepth

$$k_p^{-1} = \sqrt{\epsilon_0 mc^2/n_0 e^2}$$

[3]

$$k_p r_m \approx 2\sqrt{\Lambda_b}$$

Blowout "size"

[2]

$$(k_p l_m)^2 \approx \sqrt{32\pi\Lambda_b^0 (k_p\sigma_z)} \longrightarrow k_p l_m \approx 3.77\ (\Lambda_b^0)^{1/4}$$

[2]

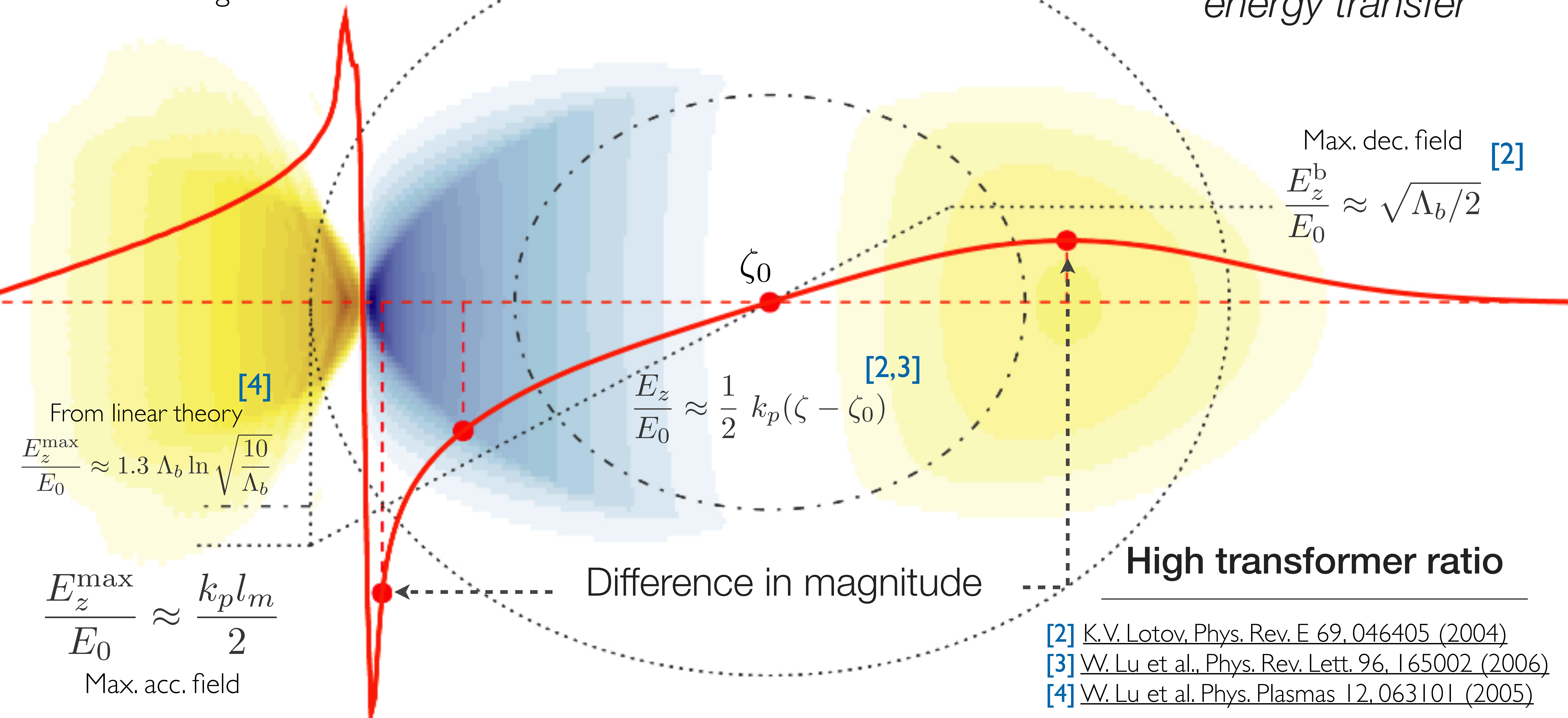
Blowout size scales with drivers current

[1] J. B. Rosenzweig et al., Phys. Rev. A 44, R6189 (1991)
[2] K.V. Lotov, Phys. Rev. E 69, 046405 (2004)
[3] W. Lu et al., Phys. Rev. Lett. 96, 165002 (2006)

Longitudinal Electric field

$E_0 = (mc^2/e)\, k_p$
wavebreaking field

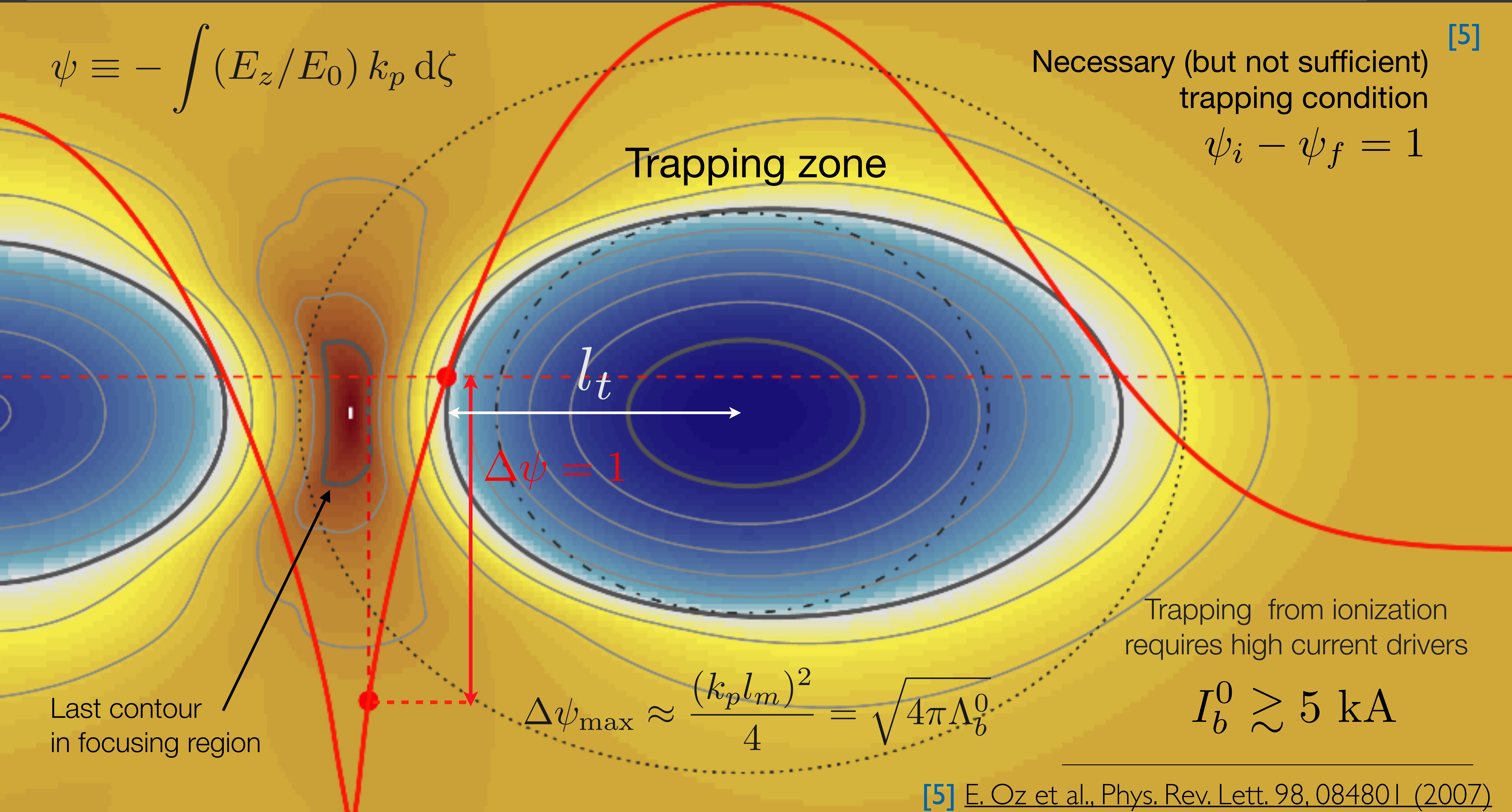
"Most efficient energy transfer" [2]



High transformer ratio

[2] K.V. Lotov, Phys. Rev. E 69, 046405 (2004)
[3] W. Lu et al., Phys. Rev. Lett. 96, 165002 (2006)
[4] W. Lu et al. Phys. Plasmas 12, 063101 (2005)

Wakefield potential



$$\psi \equiv -\int (E_z/E_0)\, k_p \, \mathrm{d}\zeta$$

Necessary (but not sufficient) trapping condition [5]

$$\psi_i - \psi_f = 1$$

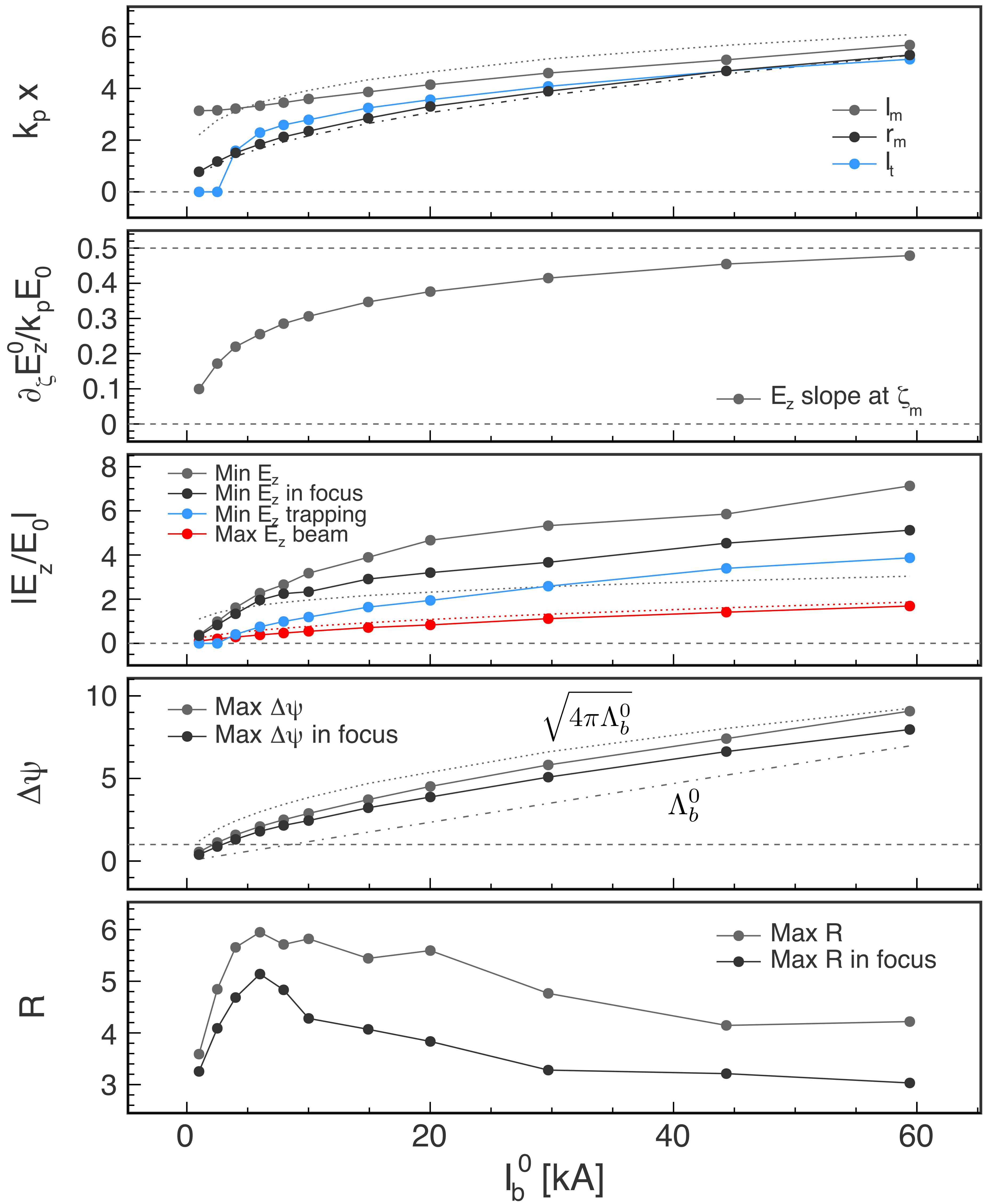
$$\Delta\psi_{\max} \approx \frac{(k_p l_m)^2}{4} = \sqrt{4\pi\Lambda_b^0}$$

Trapping from ionization requires high current drivers

$$I_b^0 \gtrsim 5\ \mathrm{kA}$$

[5] E. Oz et al., Phys. Rev. Lett. 98, 084801 (2007)

Blowout model scalings vs 3D PIC (OSIRIS)



Driver-beam

$k_p\sigma_z = \sqrt{2}$ resonant length

$k_p\sigma_x = 0.1$ narrow beam

$k_p\epsilon_n = (k_p\sigma_x)^2\sqrt{\gamma/2}$ matched emittance

Trapping from Ionization

$$I_b^0 \gtrsim 5\ \mathrm{kA}$$

WII injection

$$I_b^0 \gtrsim 8.5\ \mathrm{kA}$$

Electric field magnitude

The total electric field can induce ionization inside the trapping zone

Beam current

$$I_b = 10 \text{ kA}$$

resonant length

$$k_p \sigma_z = \sqrt{2}$$

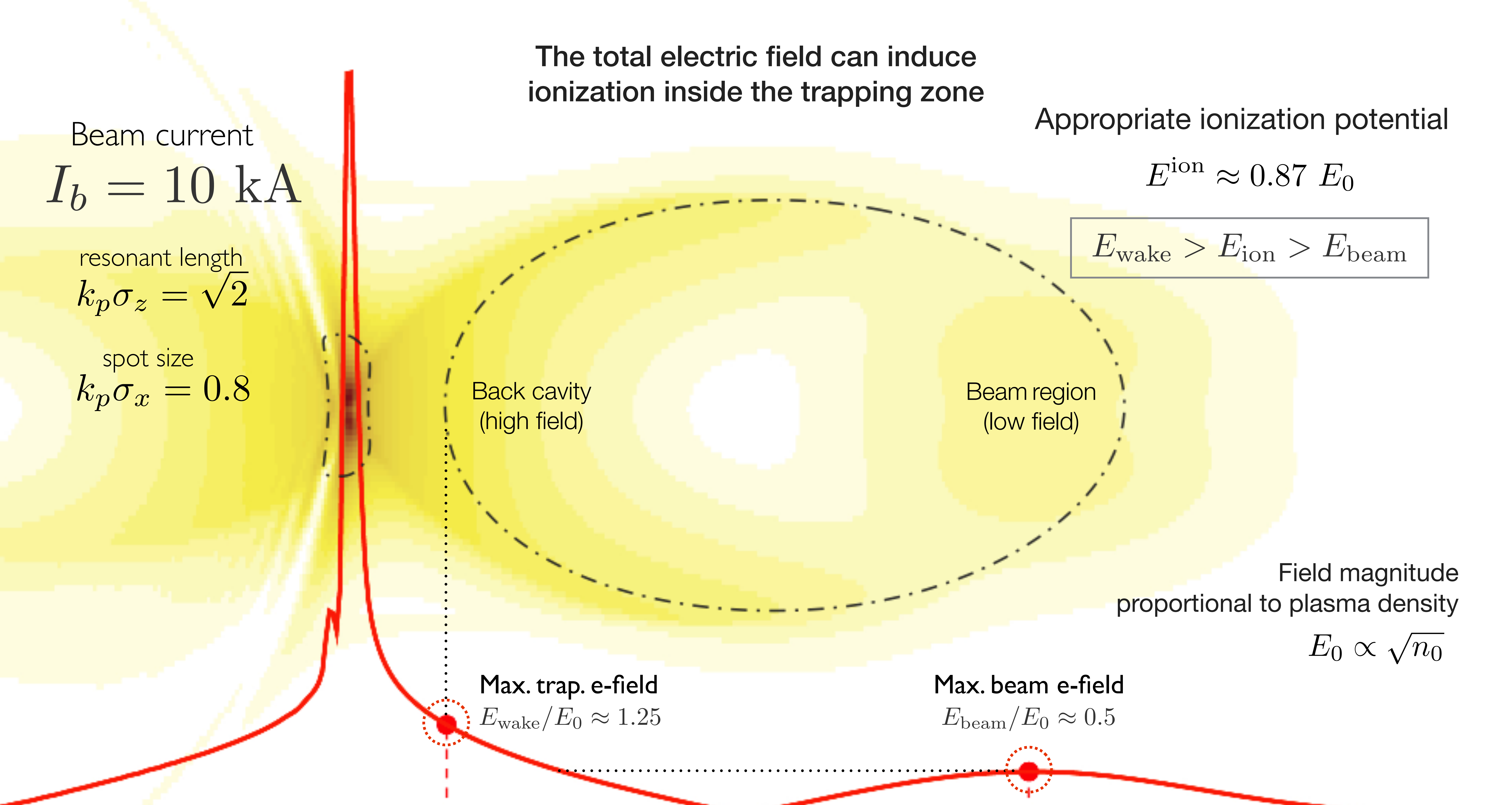
spot size

$$k_p \sigma_x = 0.8$$

Appropriate ionization potential

$$E^{\text{ion}} \approx 0.87\ E_0$$

$$E_{\text{wake}} > E_{\text{ion}} > E_{\text{beam}}$$



Field magnitude proportional to plasma density

$$E_0 \propto \sqrt{n_0}$$

Field Ionization (ADK)

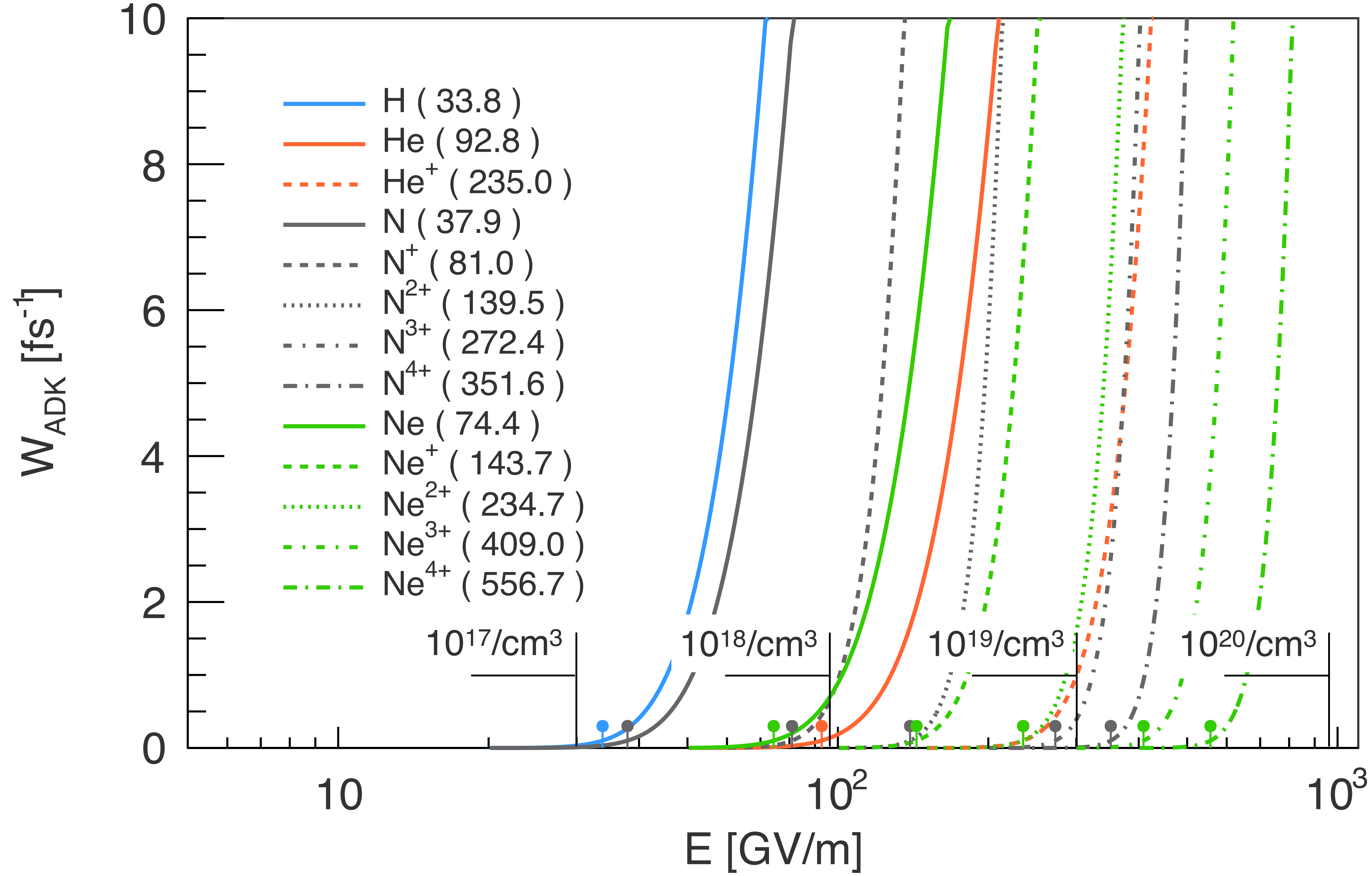
Match the beam to the plasma density

$$k_p \sigma_z \approx \sqrt{2}$$

Select the appropriate dopant species

$$E_0 \propto \sqrt{n_0}$$

ADK ionization probability rate [6]



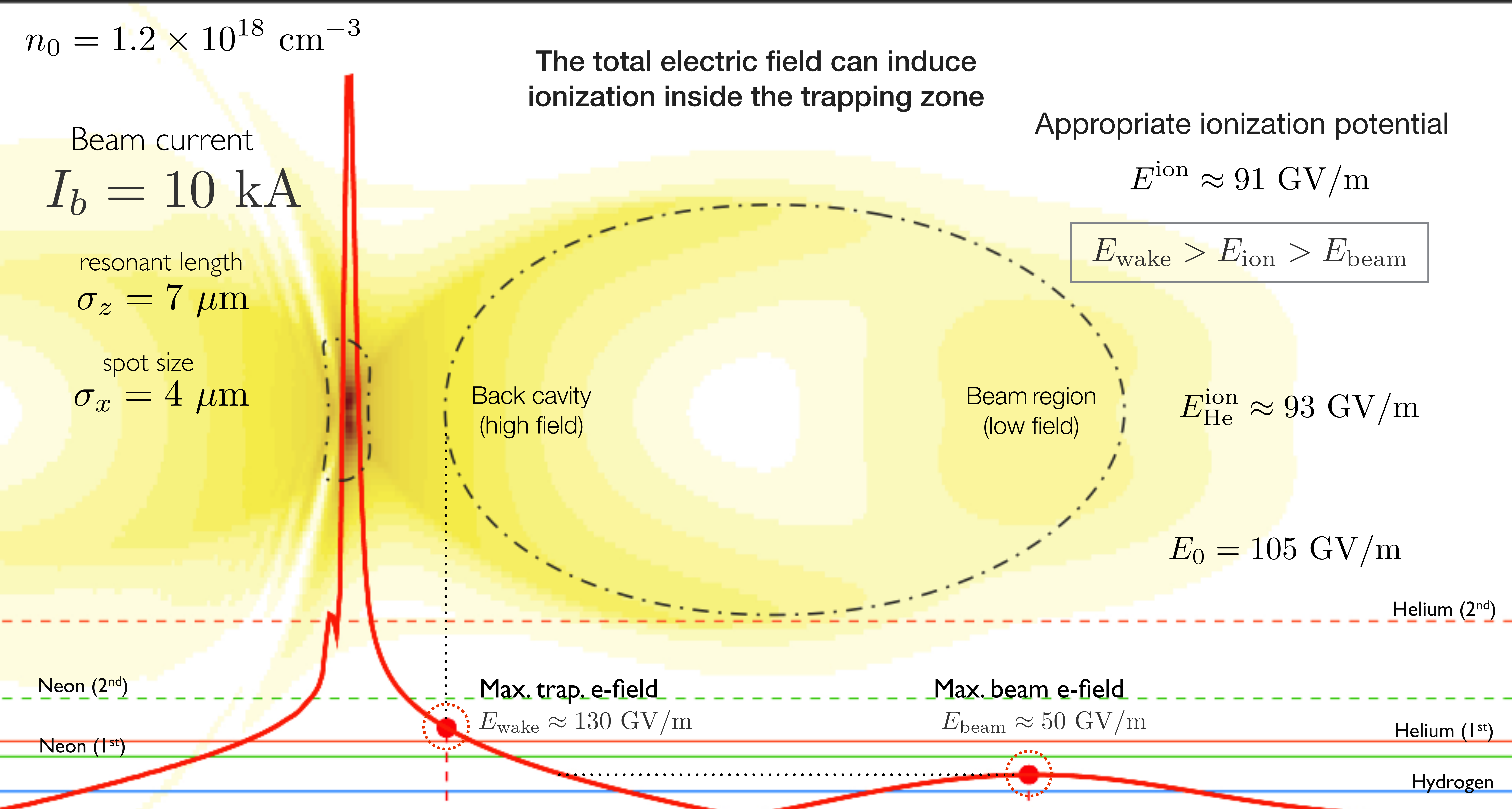
Ionization probability rate [7]

$$W_{\mathrm{ADK}}[\mathrm{fs}^{-1}] \simeq 1.52 \frac{4^{n^*} \xi_i[\mathrm{eV}]}{n^* \Gamma(2n^*)} \left(20.5 \frac{\xi_i^{3/2}[\mathrm{eV}]}{E[\mathrm{GV/m}]} \right)^{2n^*-1} \exp\left(-6.83 \frac{\xi_i^{3/2}[\mathrm{eV}]}{E[\mathrm{GV/m}]} \right).$$

$$n^* \simeq 3.69\ \mathrm{Z}/\xi_i^{1/2}[\mathrm{eV}]$$

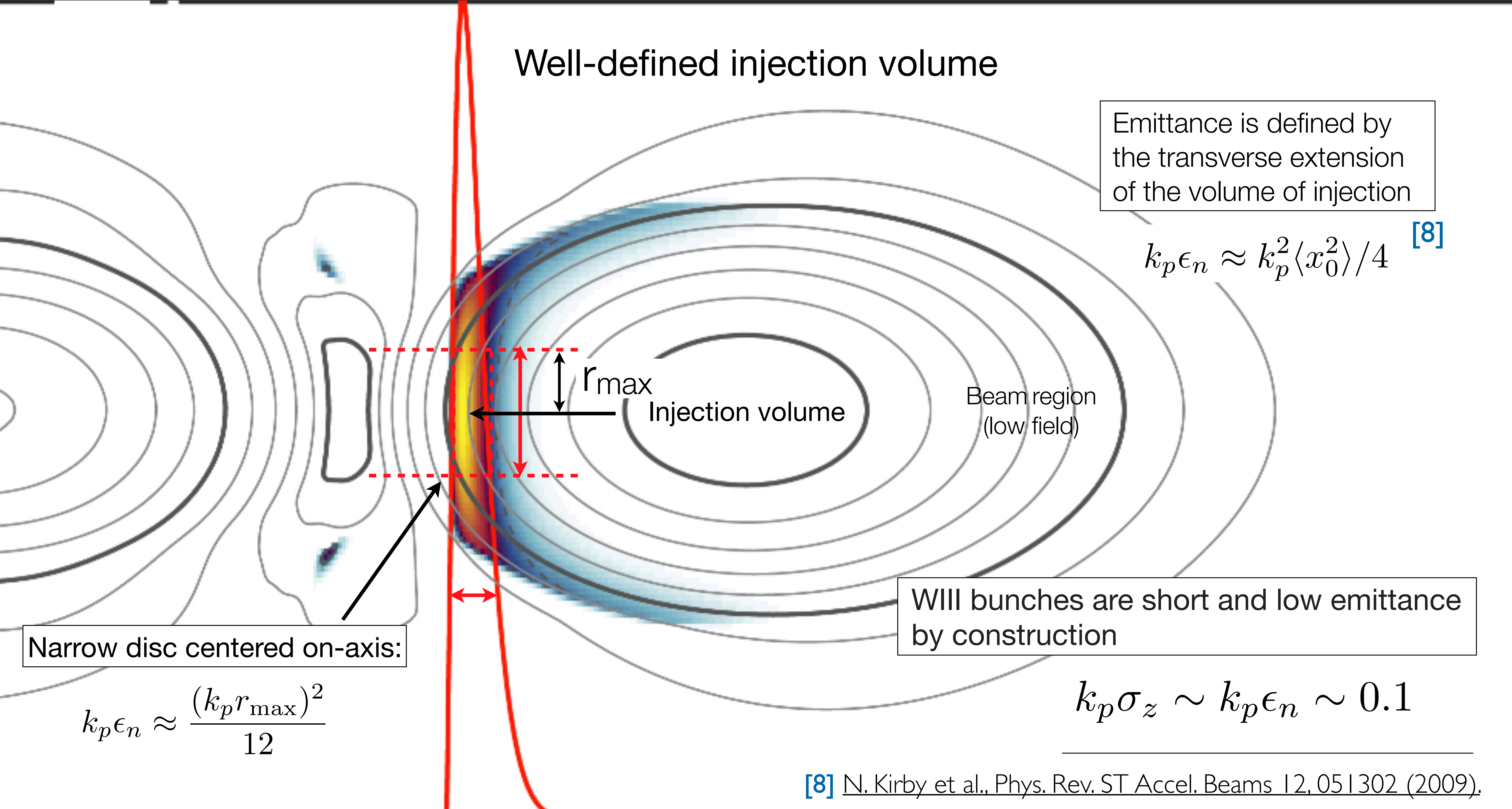
[6] M.V. Ammosov et al, Sov.Phys.JETP 64, 1191 (1986)
[7] D.L. Bruhwiler et al, Phys.Plasmas 10, 5 (2003)

Wakefield Ionization and trapping



Ionization probability rate for He

Well-defined injection volume



Emittance is defined by the transverse extension of the volume of injection

$$k_p \epsilon_n \approx k_p^2 \langle x_0^2 \rangle / 4$$ [8]

Narrow disc centered on-axis:

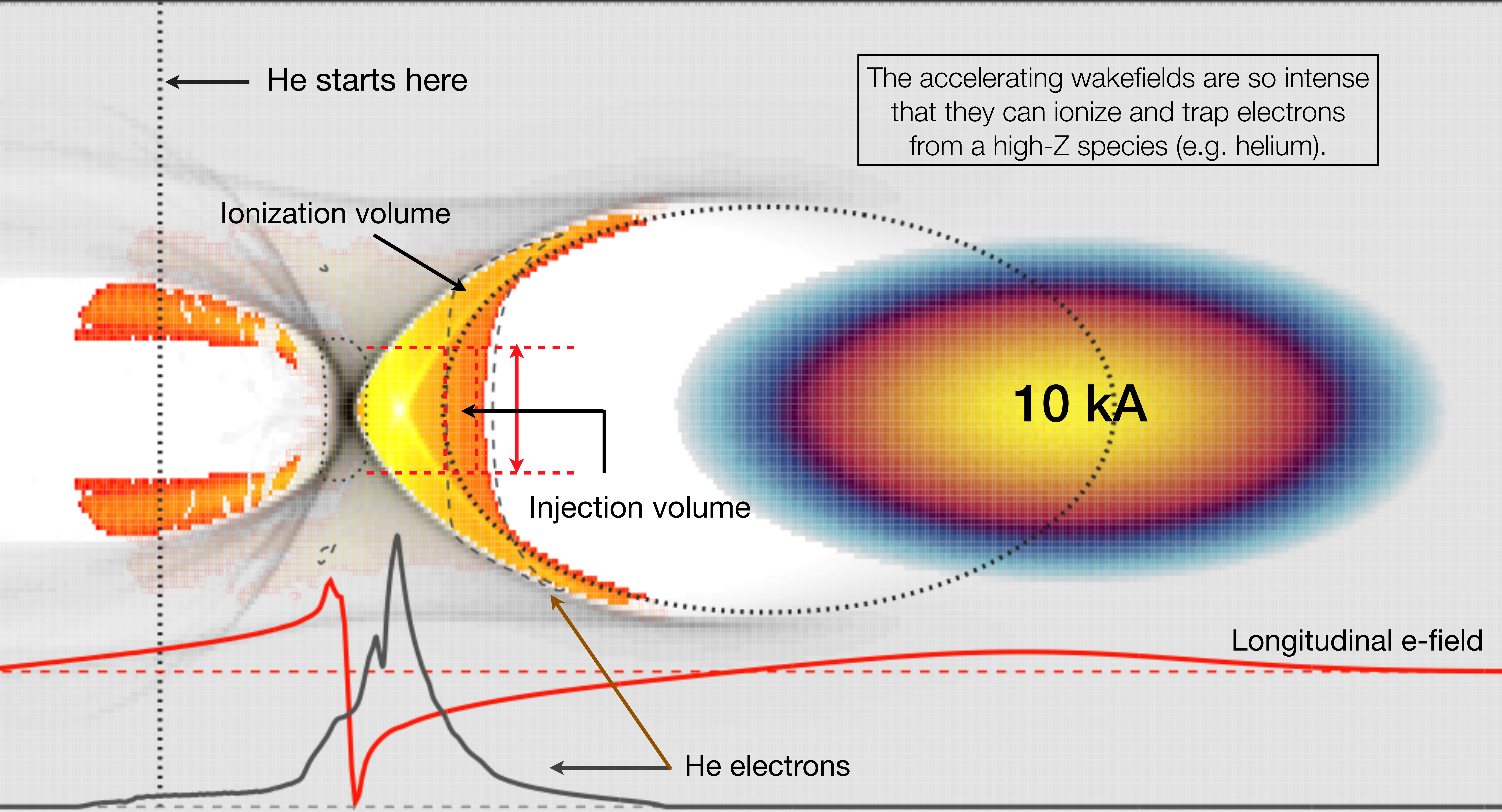
$$k_p \epsilon_n \approx \frac{(k_p r_{\mathrm{max}})^2}{12}$$

WIII bunches are short and low emittance by construction

$$k_p \sigma_z \sim k_p \epsilon_n \sim 0.1$$

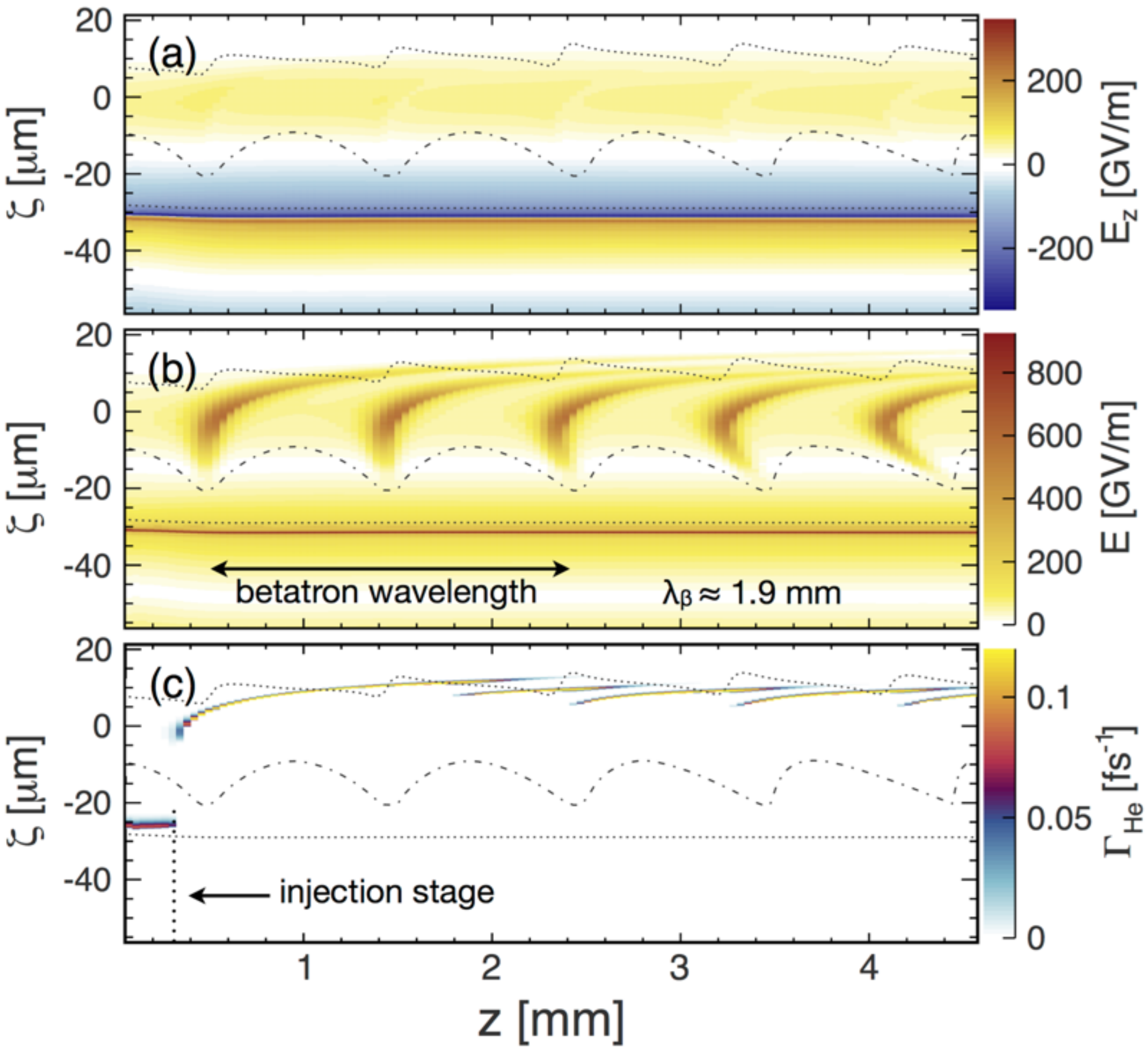
[8] N. Kirby et al., Phys. Rev. ST Accel. Beams 12, 051302 (2009).

Injection Volume



The accelerating wakefields are so intense that they can ionize and trap electrons from a high-Z species (e.g. helium).

Betatron oscillations and beam focusing



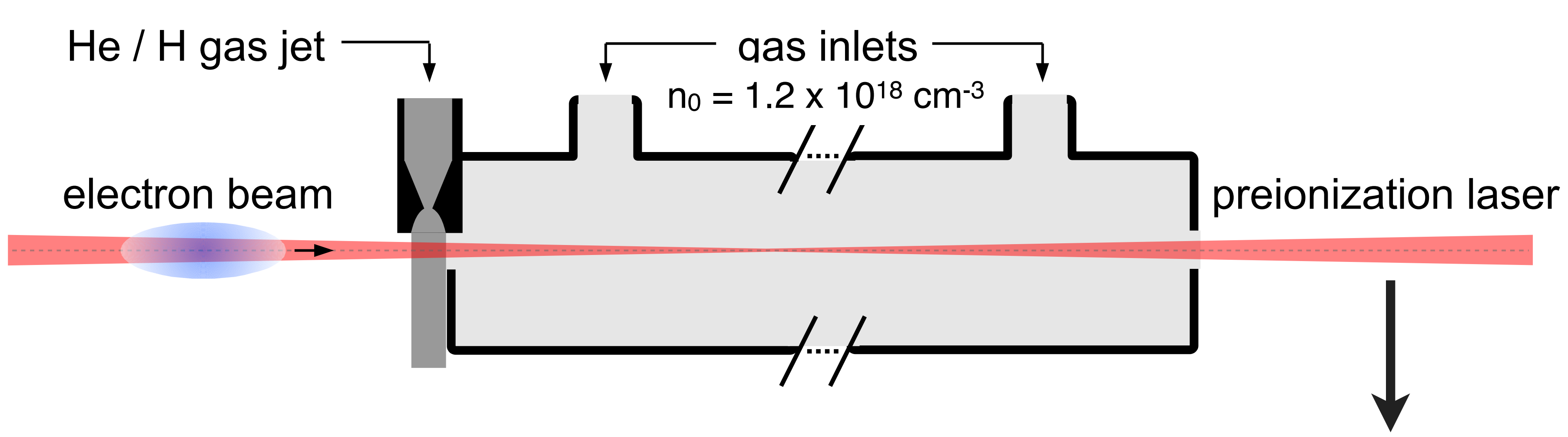
Betatron wavelength $\lambda_\beta = \sqrt{2\gamma}\,\lambda_p$

$$E_x^{\max}/E_0 \approx 0.45\ \Lambda_b/k_p\sigma_x$$

Ionization by the radial electric fields of the beam strongly depends on the beams radius, which undergoes betatron oscillations.

[9]

The dopant high-Z species is confined in a narrow jet at the beginning of the plasma cell

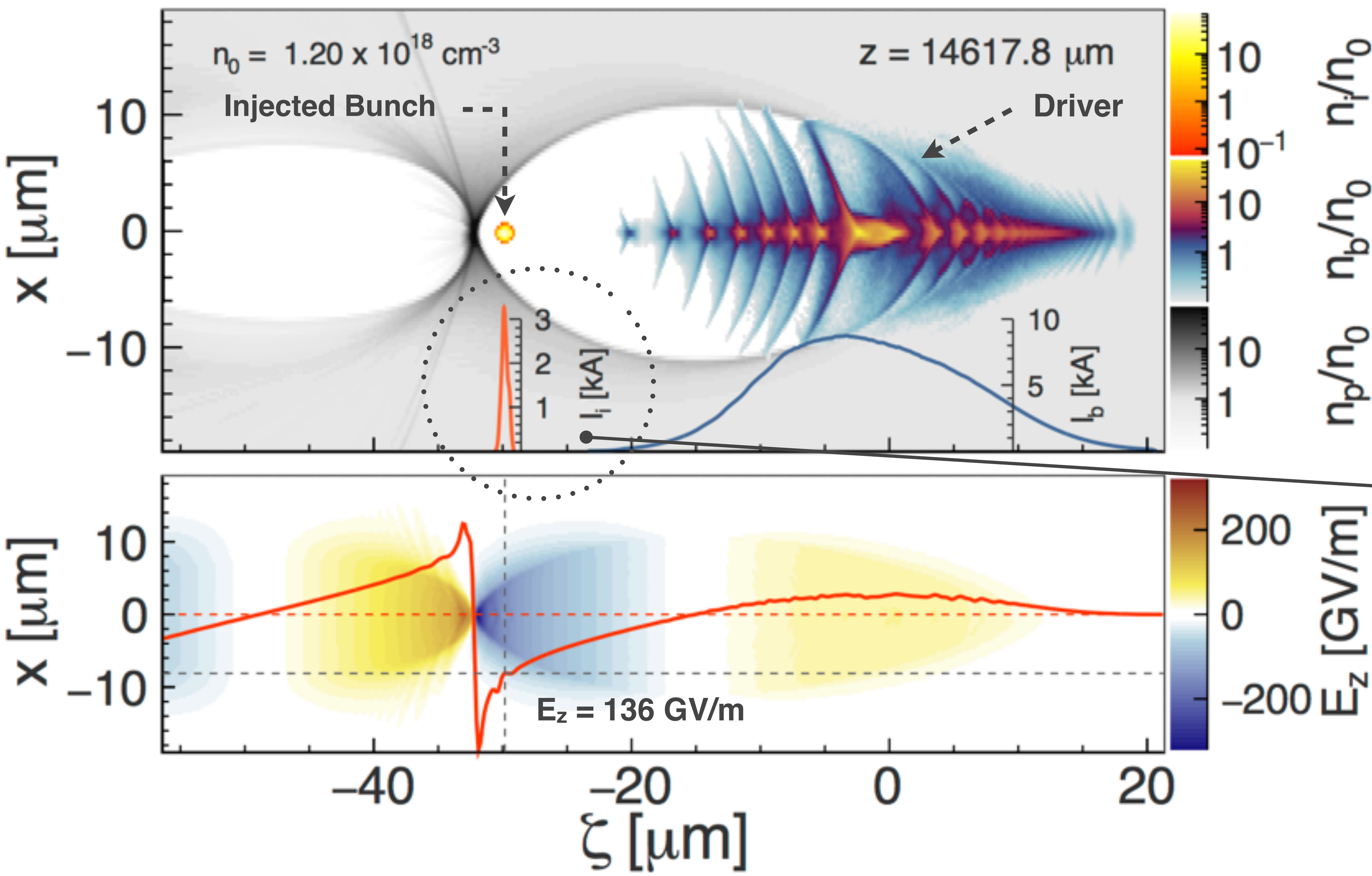


It may not be necessary

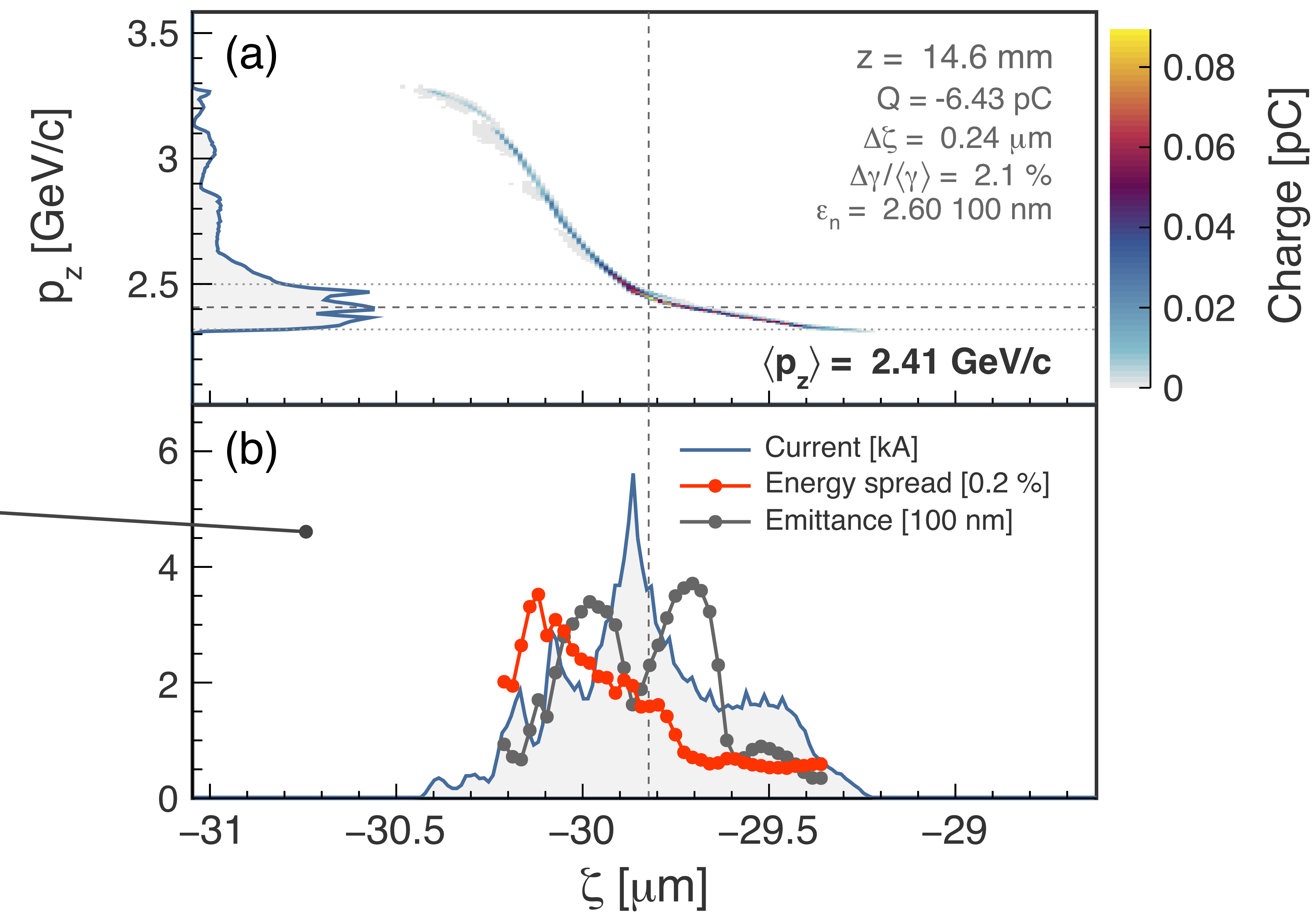
[9] L. Schaper et al., Nucl. Instrum. Meth. A740 208-211 (2014)

Injected bunch properties

Driver and witness bunch after 14.6 mm



Witness properties after 14.6 mm



Transformer ratio

$$R \equiv |E_z^{\mathrm{witness}} / E_z^{\mathrm{driver}}| \approx 3$$

Up to 3 GeV/e⁻ in 2 cm

- High-current (tunable): **5 kA**
- Ultra-short bunches: **770 as**
- Low emittance: **300 nm**.
- Low uncorrelated energy spread ~ **1%**

FACET example

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

FACET [10,11]

Q_b = 2.7 nC
I_b = **22 kA**
E_b = 23 GeV
σ_z = **14 µm**
σ_x = 10 µm
ε_x = 50 µm
ε_y = 5 µm

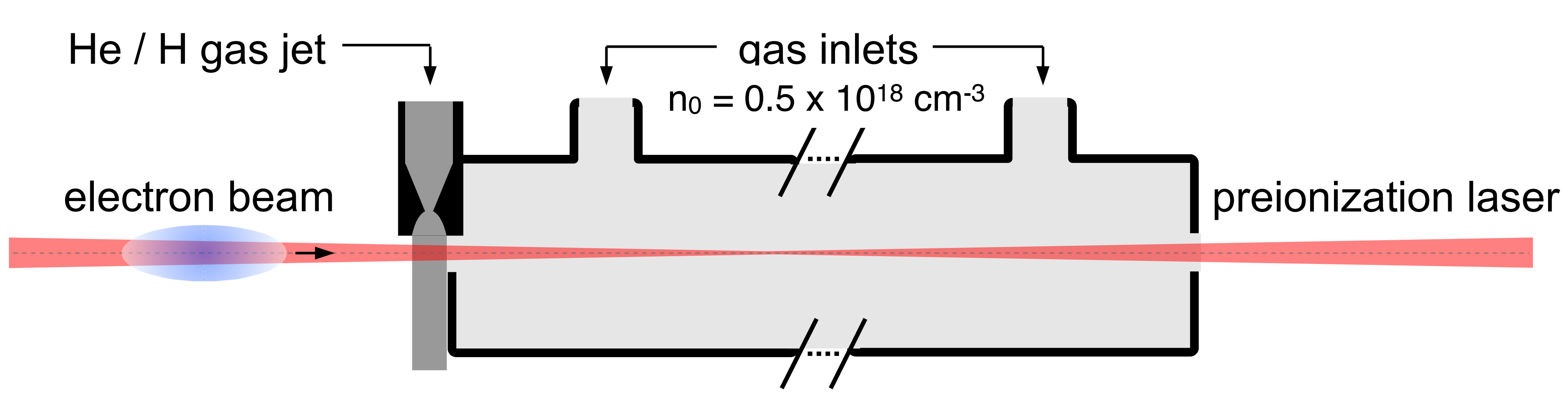
Wakefield Injection

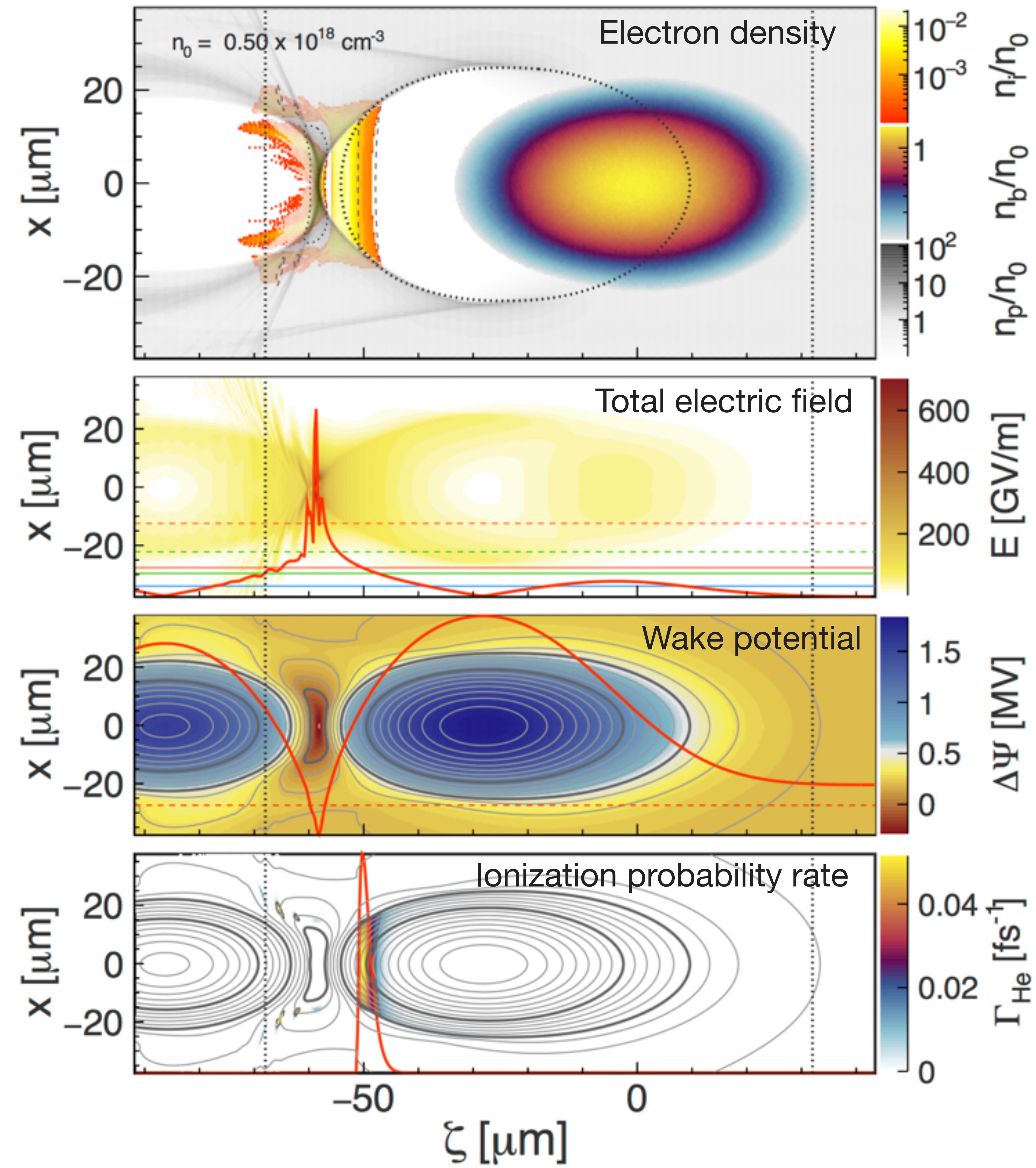
plasma density

$n_0 = 5 \times 10^{17}\ \mathrm{cm}^{-3}$

$k_p\sigma_z$ = 1.86

dopant species: helium



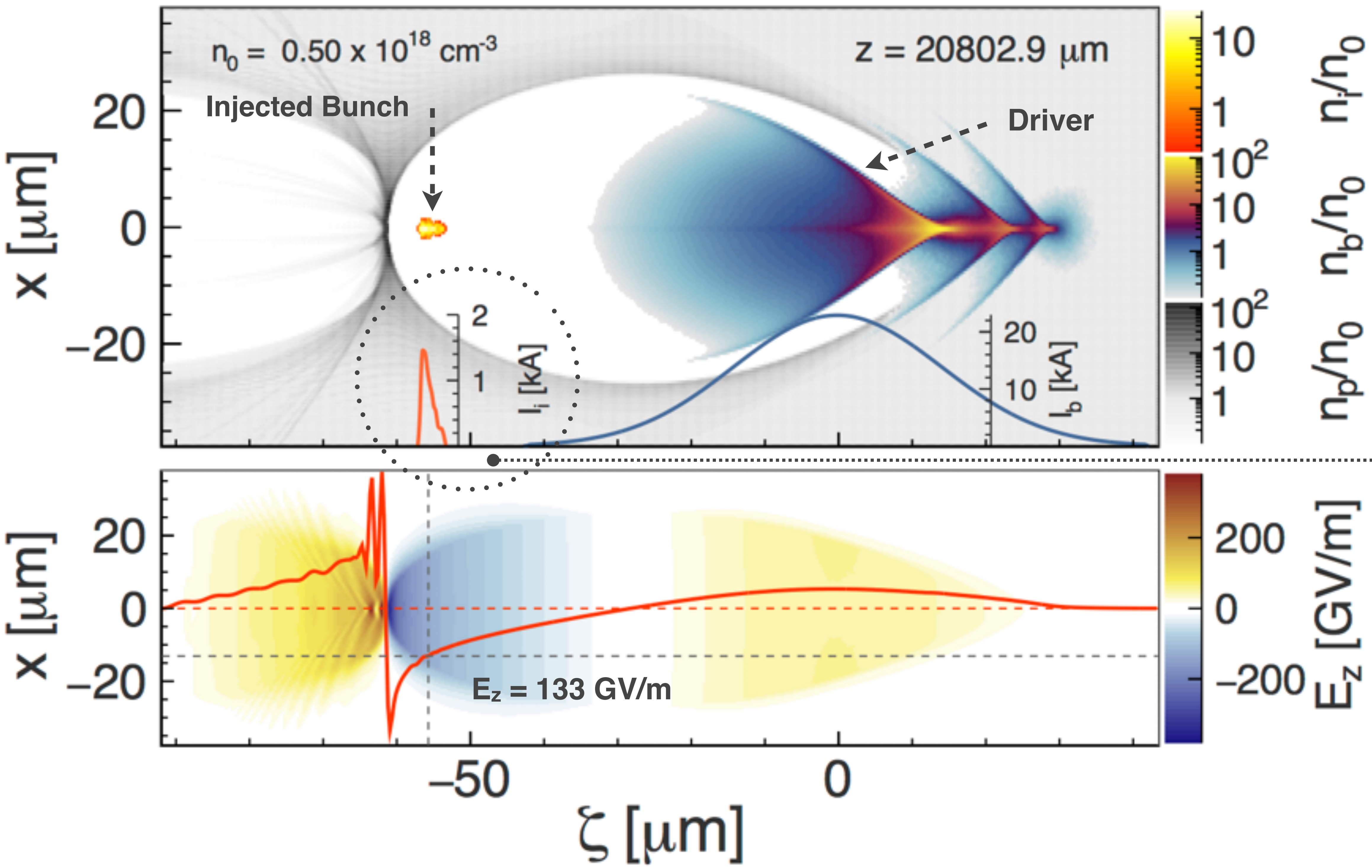


[10]. S. Z. Li and M. J. Hogan, SLAC-PUB-14412.
[11]. M.J. Hogan et al, New J.Phys. 12 (2010) 055030.

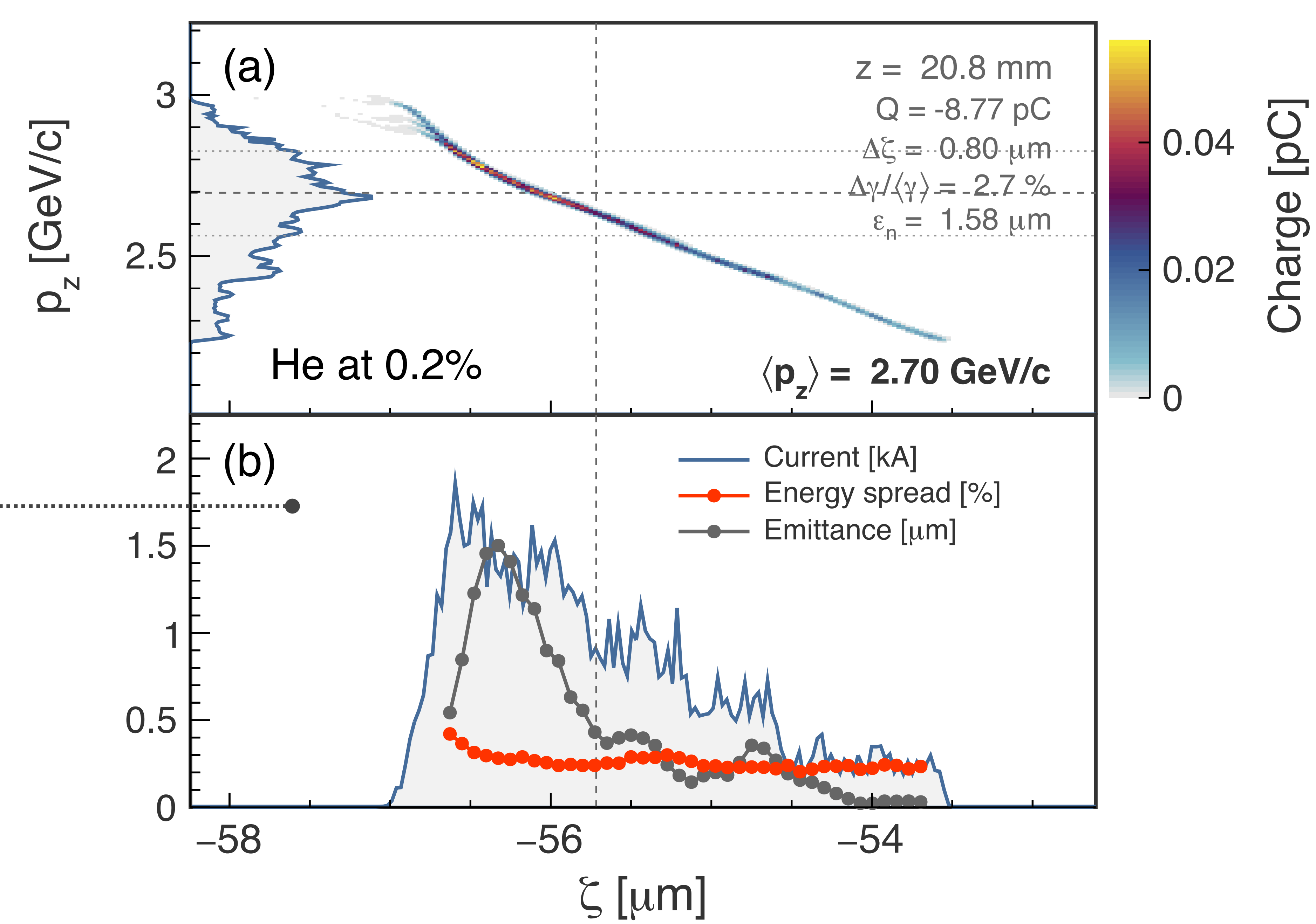
Injected bunch properties

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

Driver and witness bunch after 20.8 mm



Witness properties after 20.8 mm



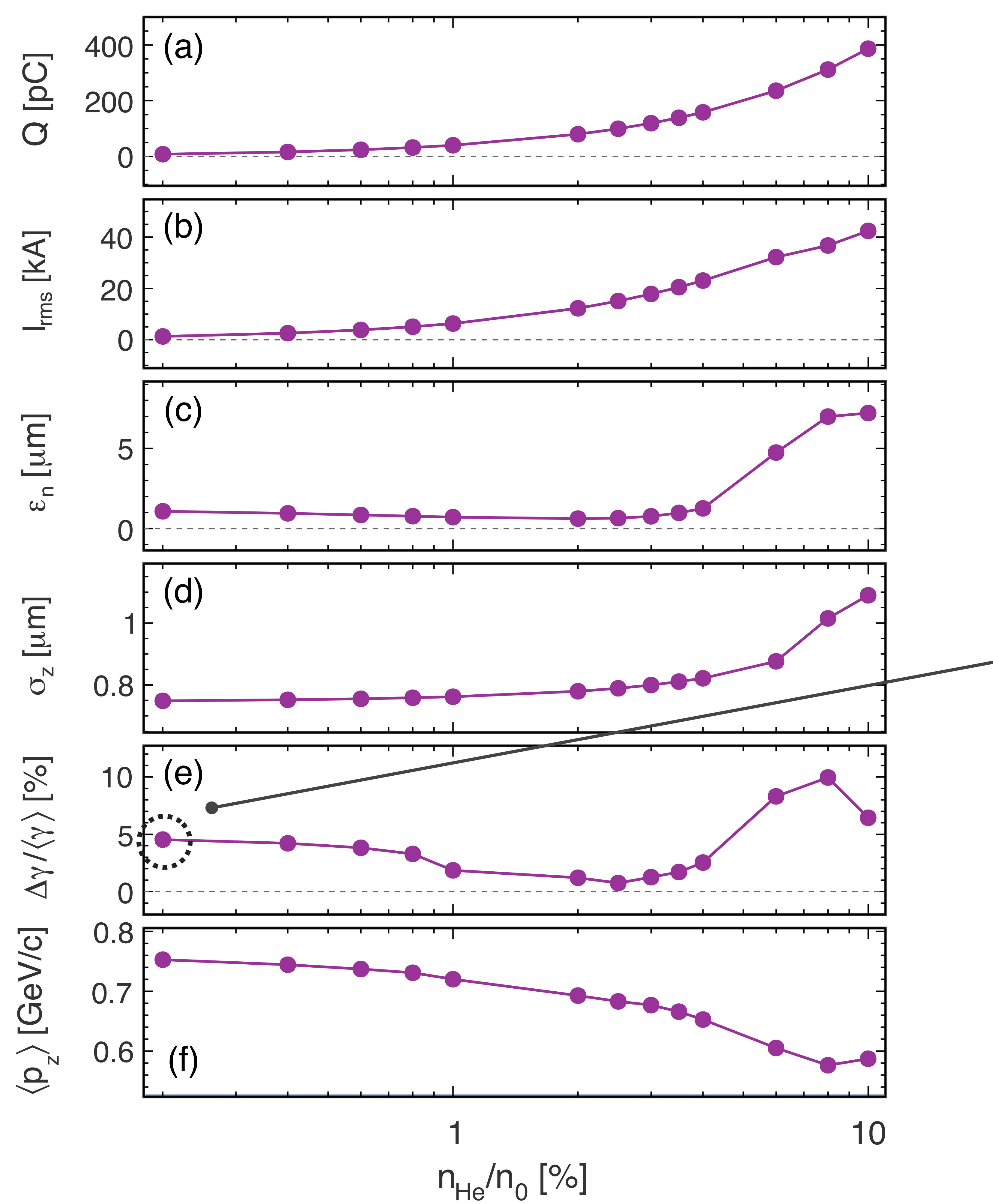
Transformer ratio

$$R \equiv |E_z^{\mathrm{witness}} / E_z^{\mathrm{driver}}| \approx 2$$

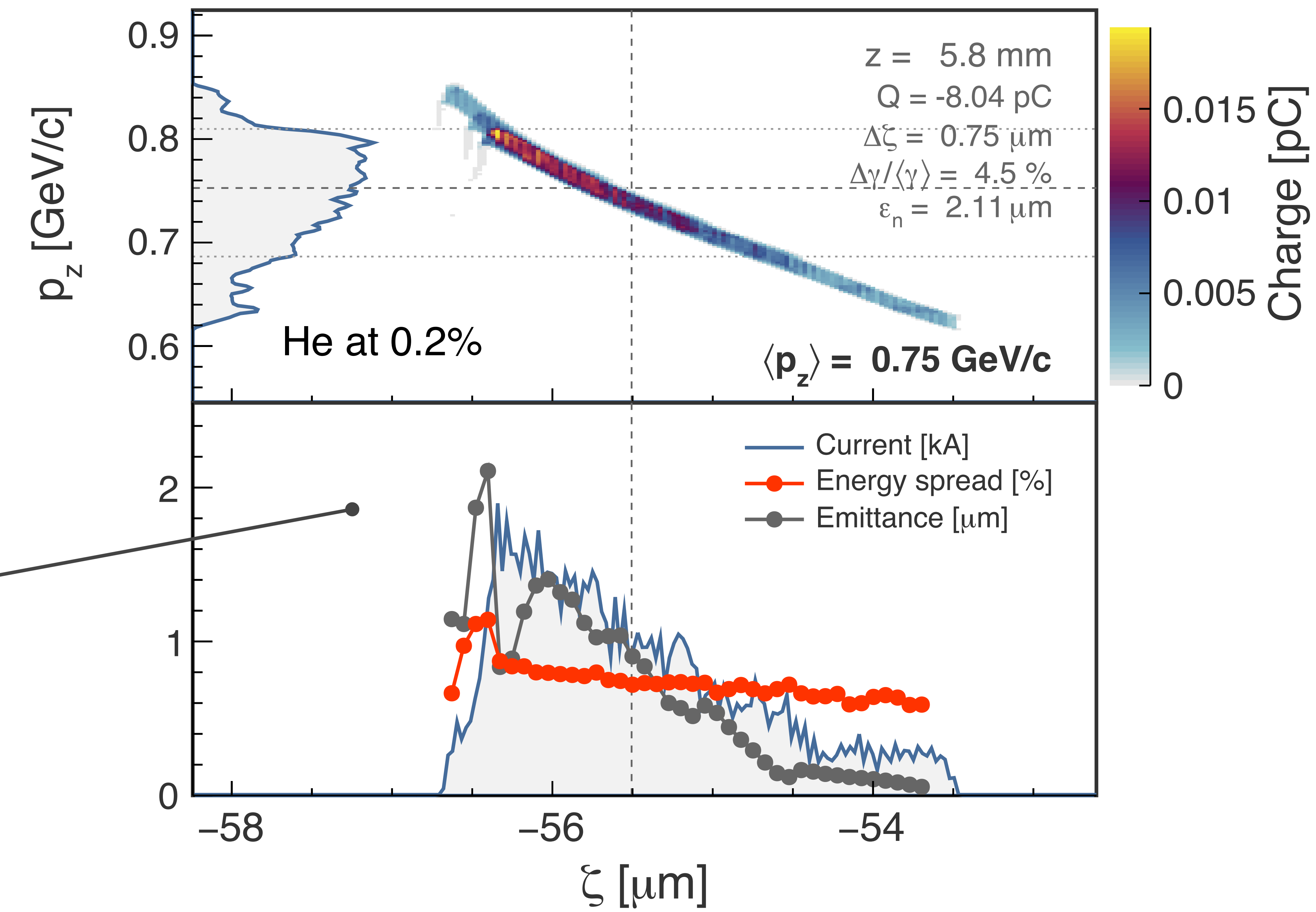
Up to 46 GeV in ~50 cm

- High-current (tunable): **~2 kA**
- Ultra-short bunches: **2.7 fs**
- Low emittance: **1.5 μm**.
- Low uncorrelated energy spread **~0.3%**

Beam loading for energy spread reduction

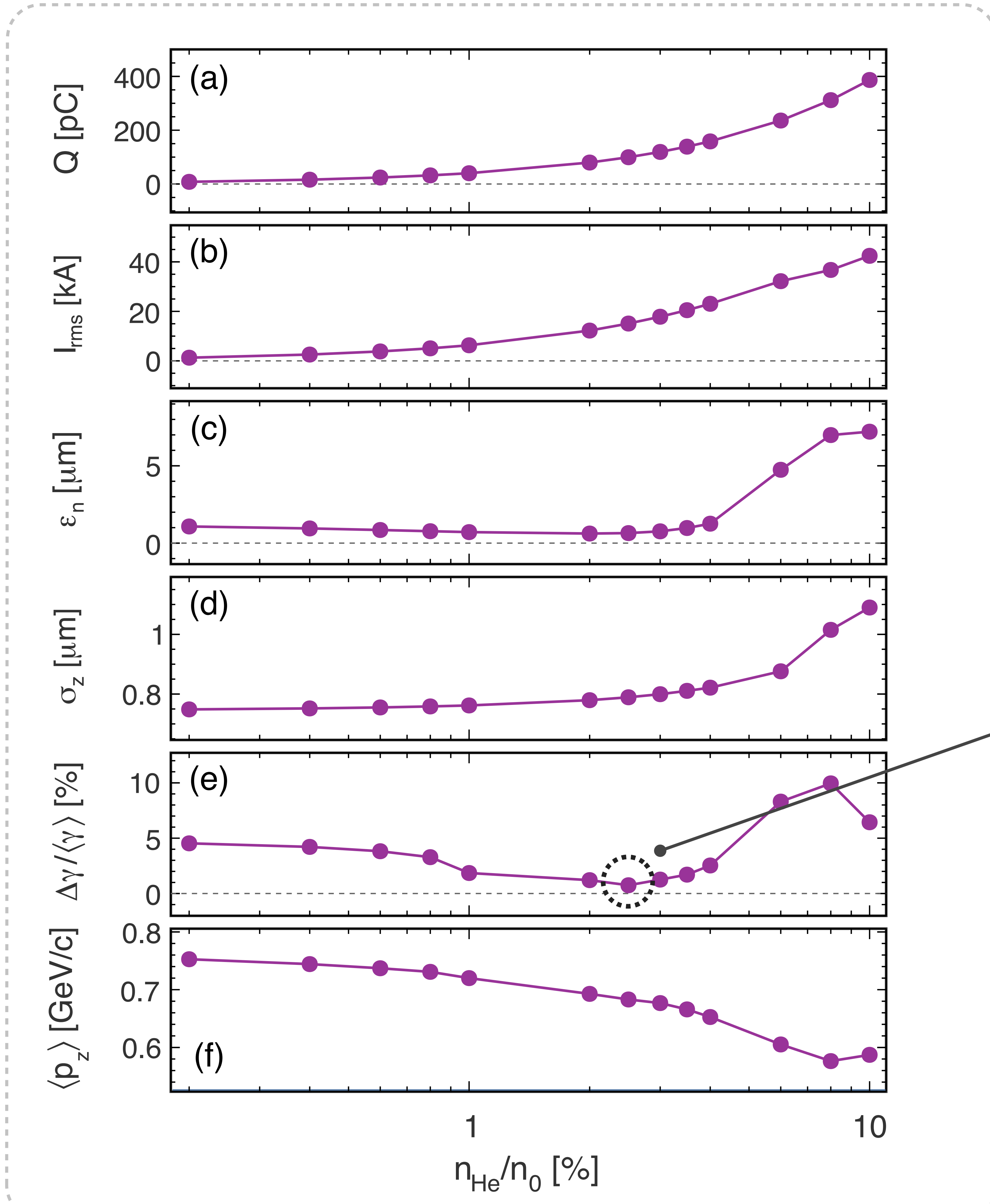


Improved energy spread + higher current

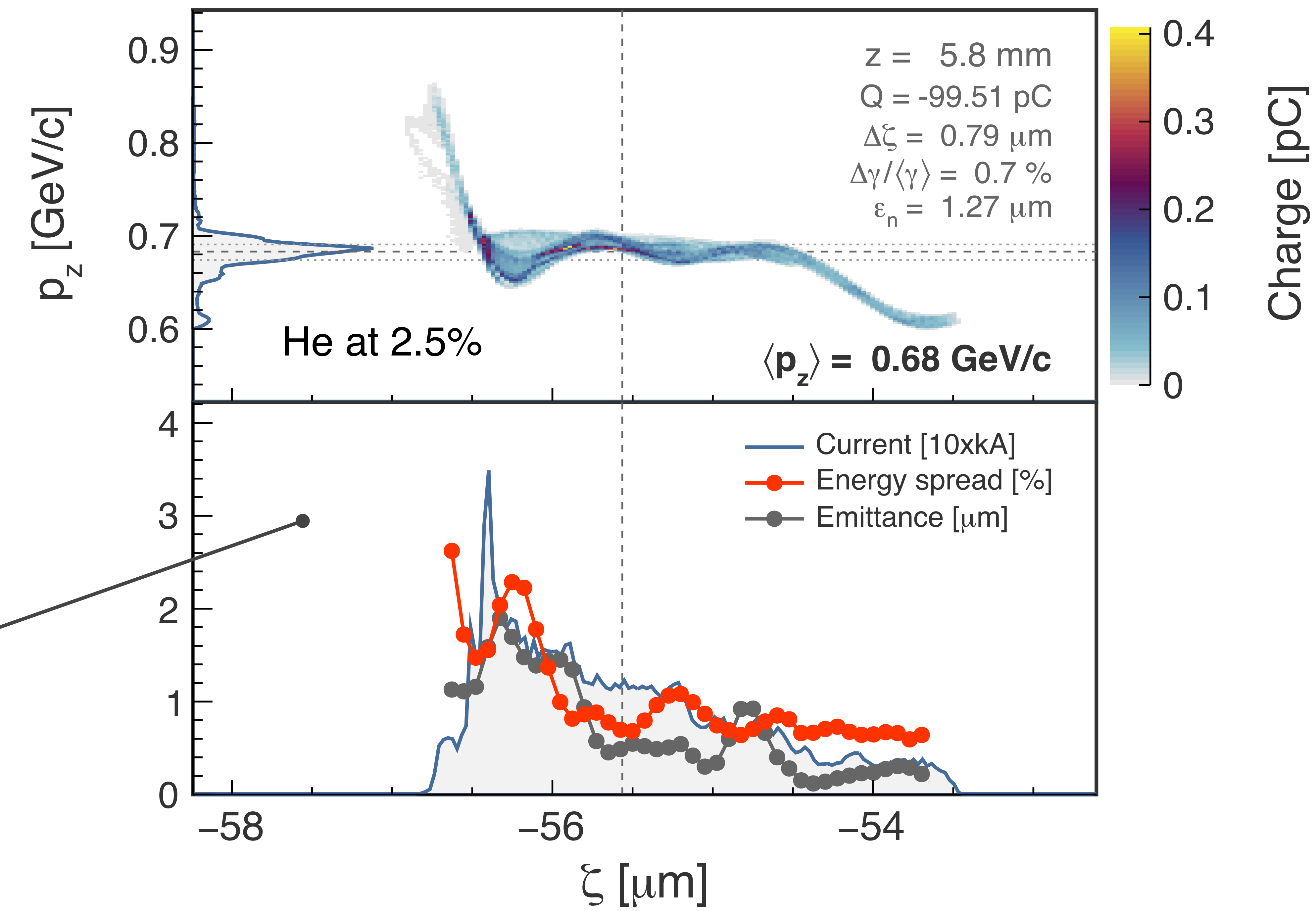


Short (~**µm**), low-current (~**2kA**)
low-emittance (~**µm**) and
linearly chirped
GeV-electron beams

Beam loading for energy spread reduction

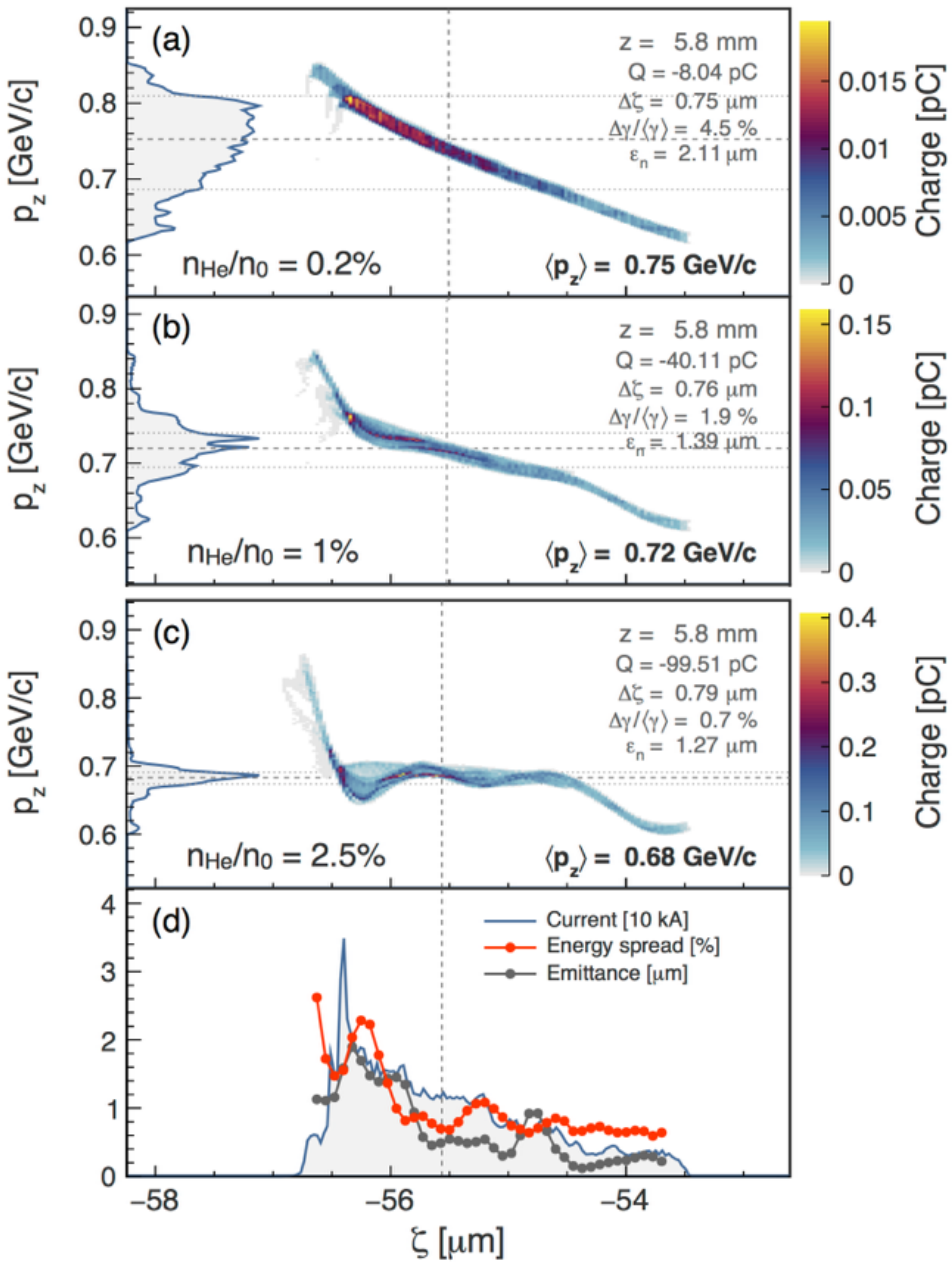


Improved energy spread + higher current



Short (~**µm**), high-current (~**20kA**) low-emittance (~**µm**) and quasi-mono-energetic **GeV**-electron beams

Beam loading for energy spread reduction



[10]

Witness bunch profile for perfect beam loading

$$\Lambda_w = \sqrt{\left[\frac{E_z^w}{E_0}\right]^4 + \left[\frac{k_p r_m}{2}\right]^4} - \frac{E_z^w}{E_0} k_p(\zeta - \zeta_w) .$$

Witness/driver current ratio

$$\frac{\Lambda_w}{\Lambda_d} \approx \sqrt{\left(\frac{R_w}{\sqrt{2}}\right)^4 + 1}$$

for reduced energy spread

→

High-current (~**20kA**)
low-emittance (~**μm**)
quasi-mono-energetic
GeV-electron beams

High-brightness for applications $B \propto \frac{I_b}{\epsilon_n^2}$

[10] M.Tzoufras et al., Phys. Rev. Lett.101.145002 (2008)

Features and requirements

Requirements

- **High-current drivers** ($I_b^0 > 8.5$ kA) to operate a strong blowout regime.

$$k_p\sigma_z \simeq \sqrt{2}$$
Resonant length

$$k_p\sigma_x \simeq 1$$
Moderate spot size

$$k_p\epsilon_n < (k_p\sigma_x)^2\sqrt{\gamma/2}$$
Low emittance

- A jet with dopant species with **appropriate ionization threshold**.

$$E_{\mathrm{wake}} > E_{\mathrm{ion}} > E_{\mathrm{beam}}$$

- Plasma cell technology for the experimental setup.

Features

- Ultra-short, high-quality bunches.
  Injected beams are short and low-emittance

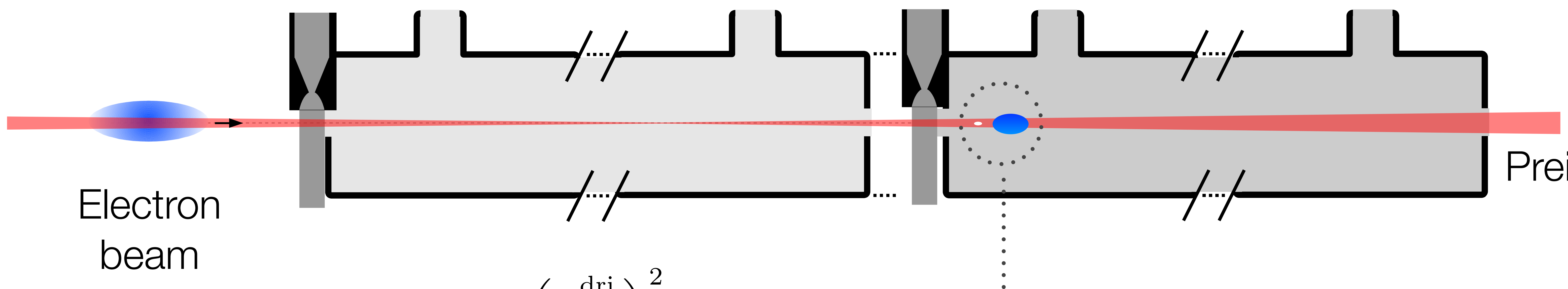
$$k_p\sigma_z \approx k_p\sigma_r \approx k_p\epsilon_n \approx 0.1$$

- **High-current**, low-energy spread
  by controlled beam loading
- Energy doubling/tripling:
  Transformer ratio ≥ 2

WII bunches can do WII injection
in higher plasma densities !!

Self-Similar Staging (new concept)

Experimental setup



$$\frac{n_1}{n_0} \approx \left(\frac{\sigma_z^{\mathrm{dri}}}{\sigma_z^{\mathrm{wit}}}\right)^2 \approx 100$$

WII bunches can do WII injection in 10^2 times higher plasma densities !!

Witness in the second PWFA stage

- >> 10 times shorter and lower emittance.
- >> Higher current.
- >> **10^2 times brighter!**
- >> "Redoubles" the energy per electron.

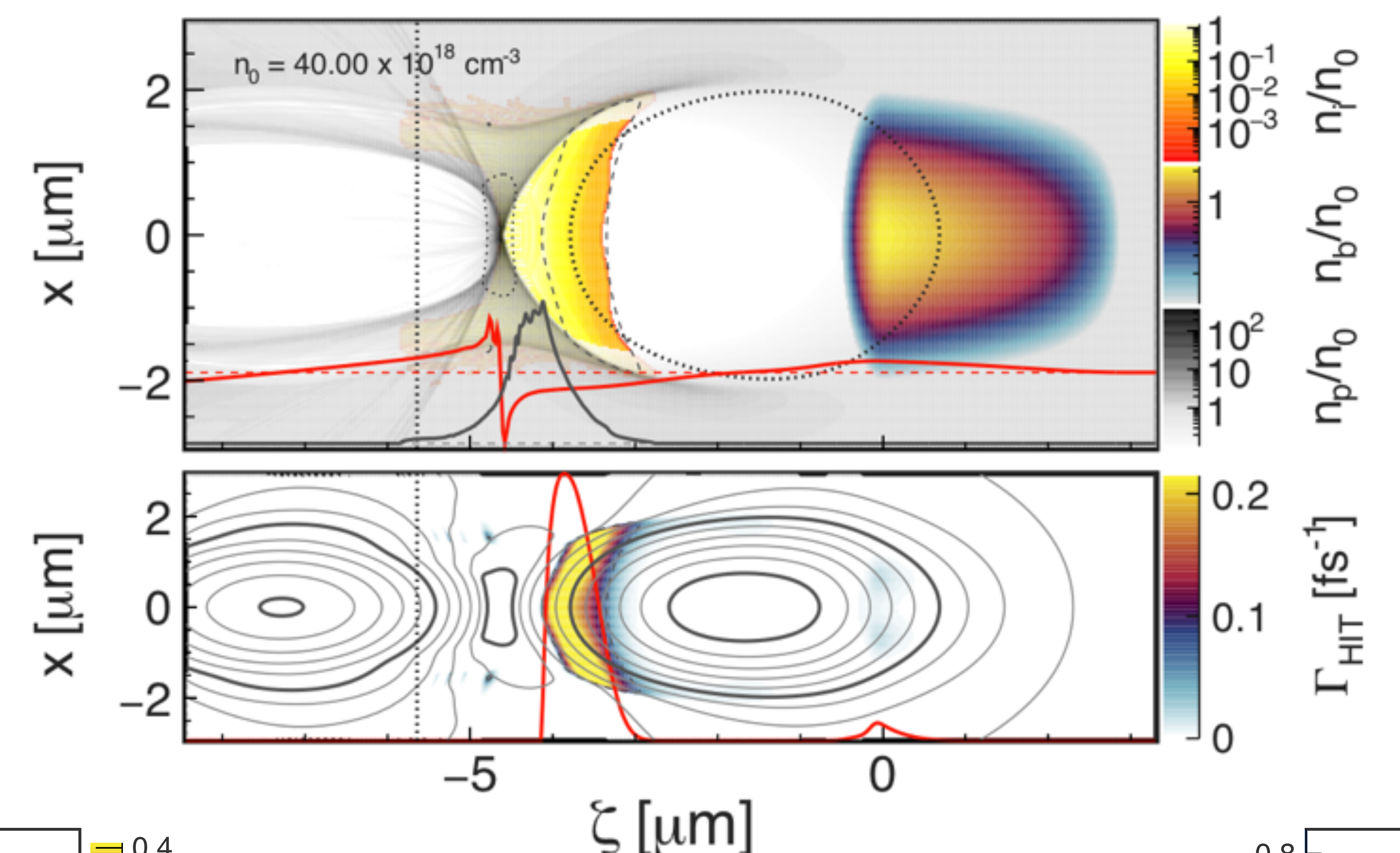
Self-Similar Staging: First simulations

$n_0 = 4 \times 10^{19}$ cm^{-3}

Ionization threshold 90 eV

N^{5+} (IP 98 eV)

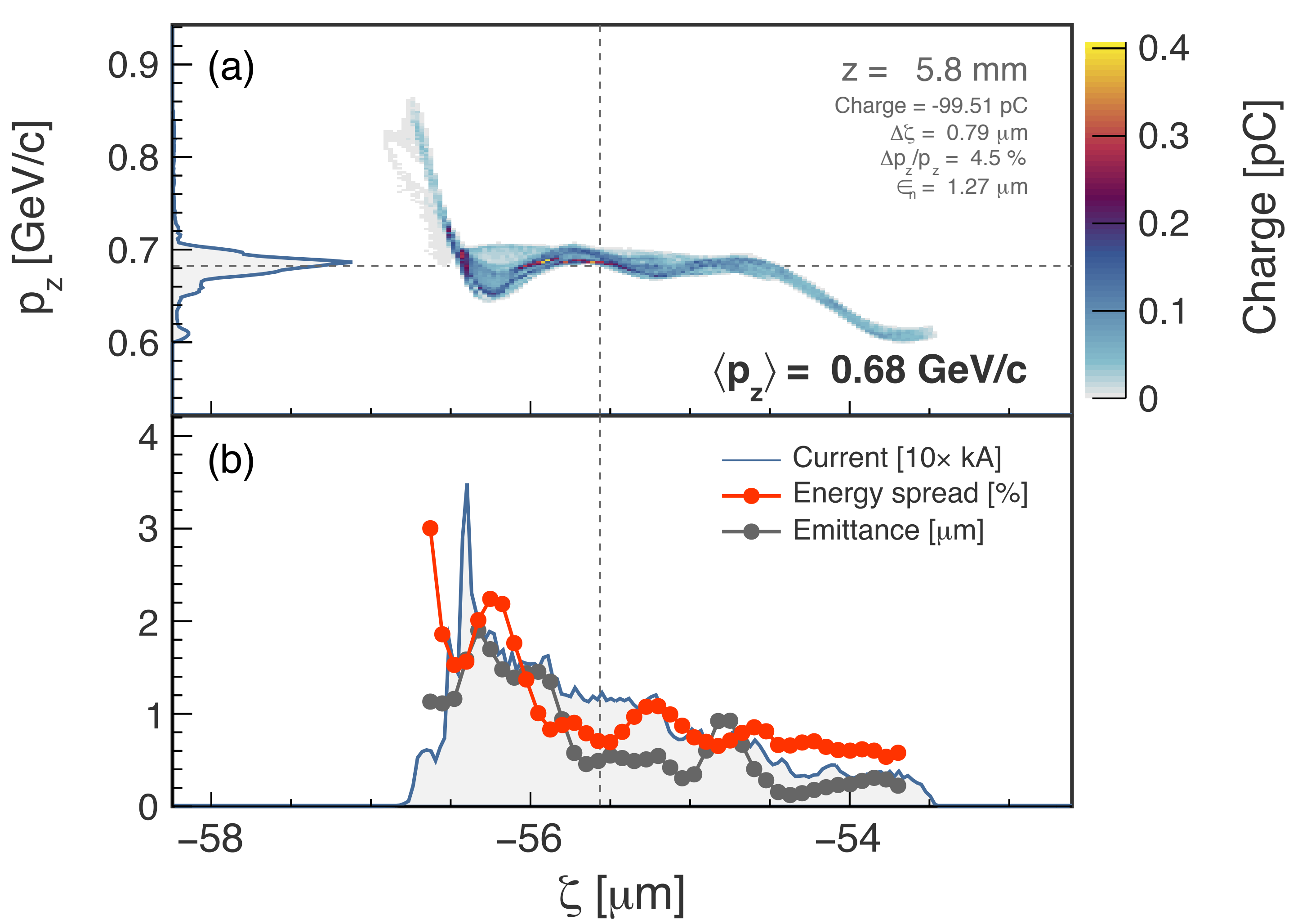
The witness bunch is now the driver

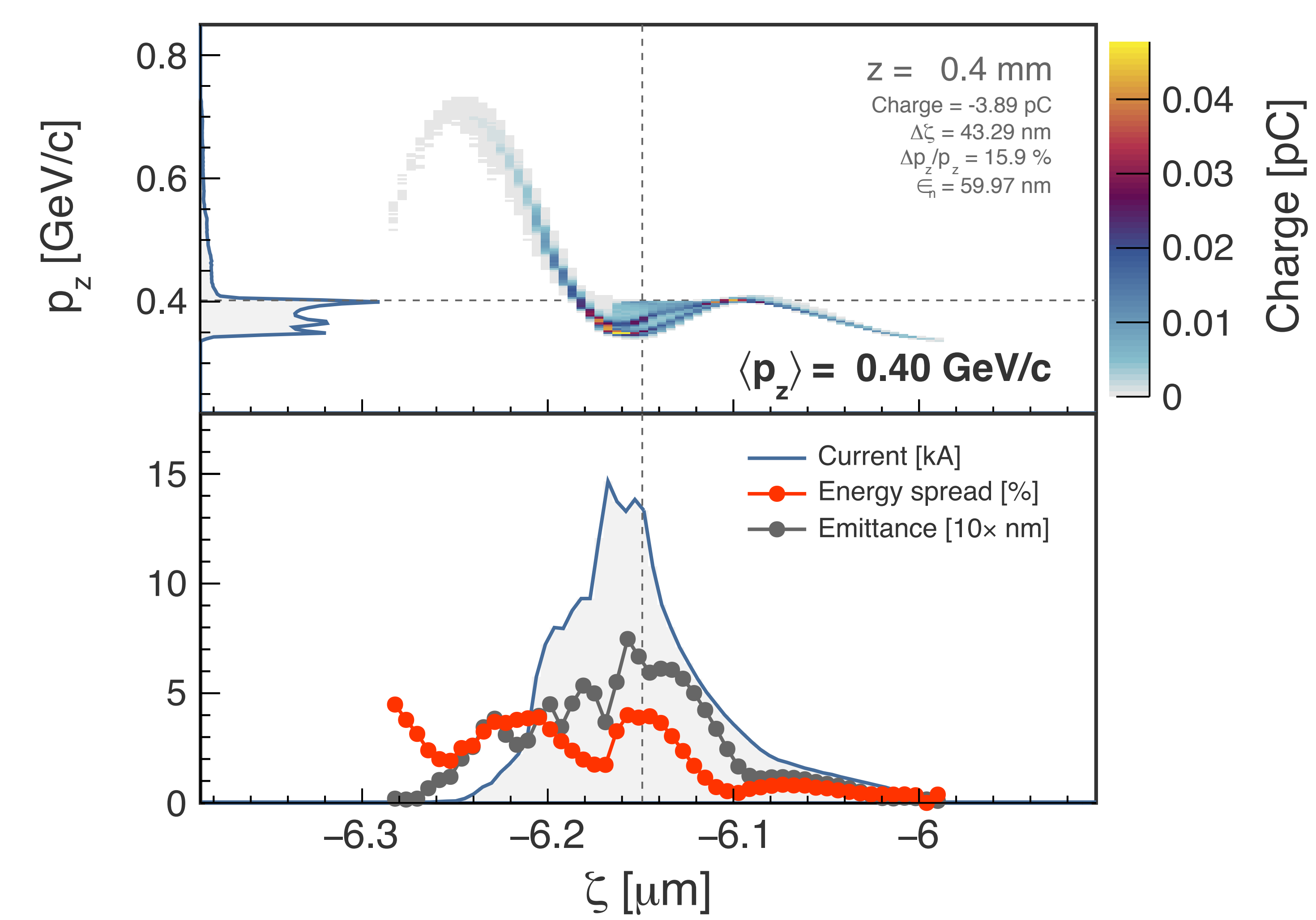


$E_z^{\mathrm{wit}} \approx 1\ \mathrm{TV/m}$

Up to 92 GeV in ~9 cm

Second witness



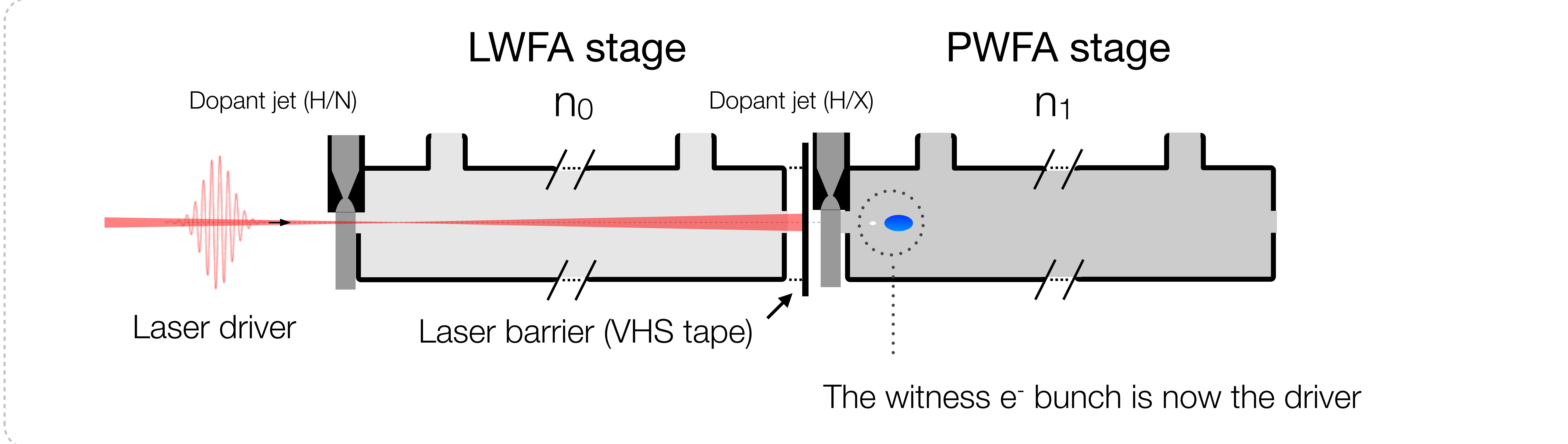


Properties

- >> High-current **15 kA.**
- >> Ultra-short **140 as.**
- >> Ultra-low emitt. **60 nm.**
- >> Transformer ratio ~**2.**

Staging from a LWFA accelerator

Experimental setup



Electrons beams **from LWFA can do WII injection!**

if they have enough current ~10kA

Witness in the PWFA stage

- **>>** 10 times shorter and lower emittance.
- **>> Higher current.**
- **>> 10^2 times brighter!**
- **>>** “Doubles” the energy per electron.

Boost the energy and the quality of electron beams produced in LWFA accelerators to the next level

Staging from a LWFA accelerator

Laser driver

$$\lambda_0 = 800 \text{ nm}$$
$$P_0 = 24.4 \text{ TW}$$
$$\tau = 25 \text{ fs}$$
(FWHM on intensity)

Energy in the pulse: 640 mJ

Matched conditions

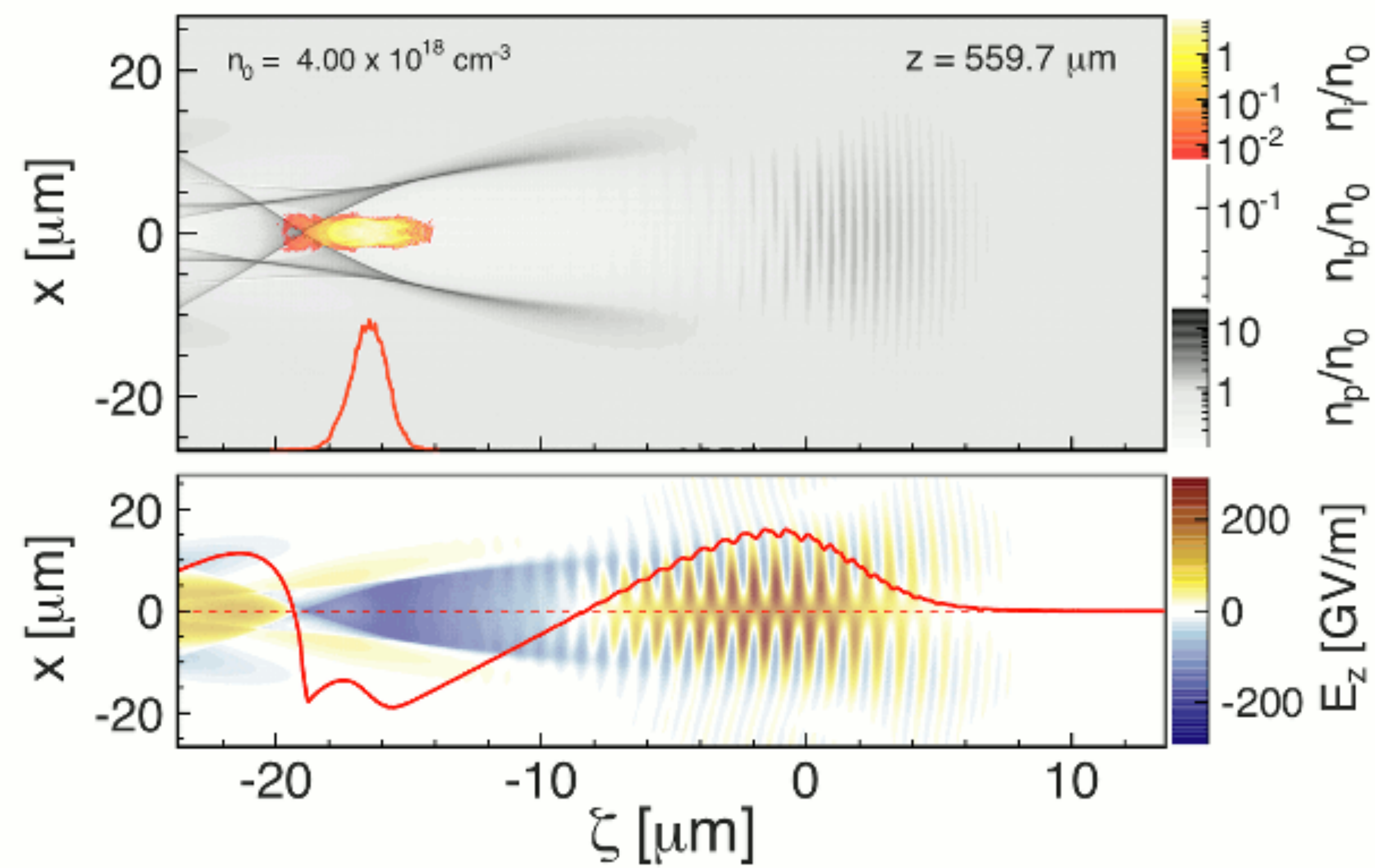
$$k_p R_b \simeq k_p w_0 = 2\sqrt{a_0}$$

$n_0 = 5 \times 10^{18}\ \text{cm}^{-3}$ → $a_0 = 3.1$

High current witness from LWFA (experiments)

- O. Lundh et al., Nat. Phys 7, 219 (2011).
- S. M. Wiggins et al., Plasma Phys. Controlled Fusion 52, 124032 (2010).

OSIRIS 2D simulation



Injection-jet: H doped with N

L_{jet} = 100 μm n_N/n_H = 1%

Staging from a LWFA accelerator

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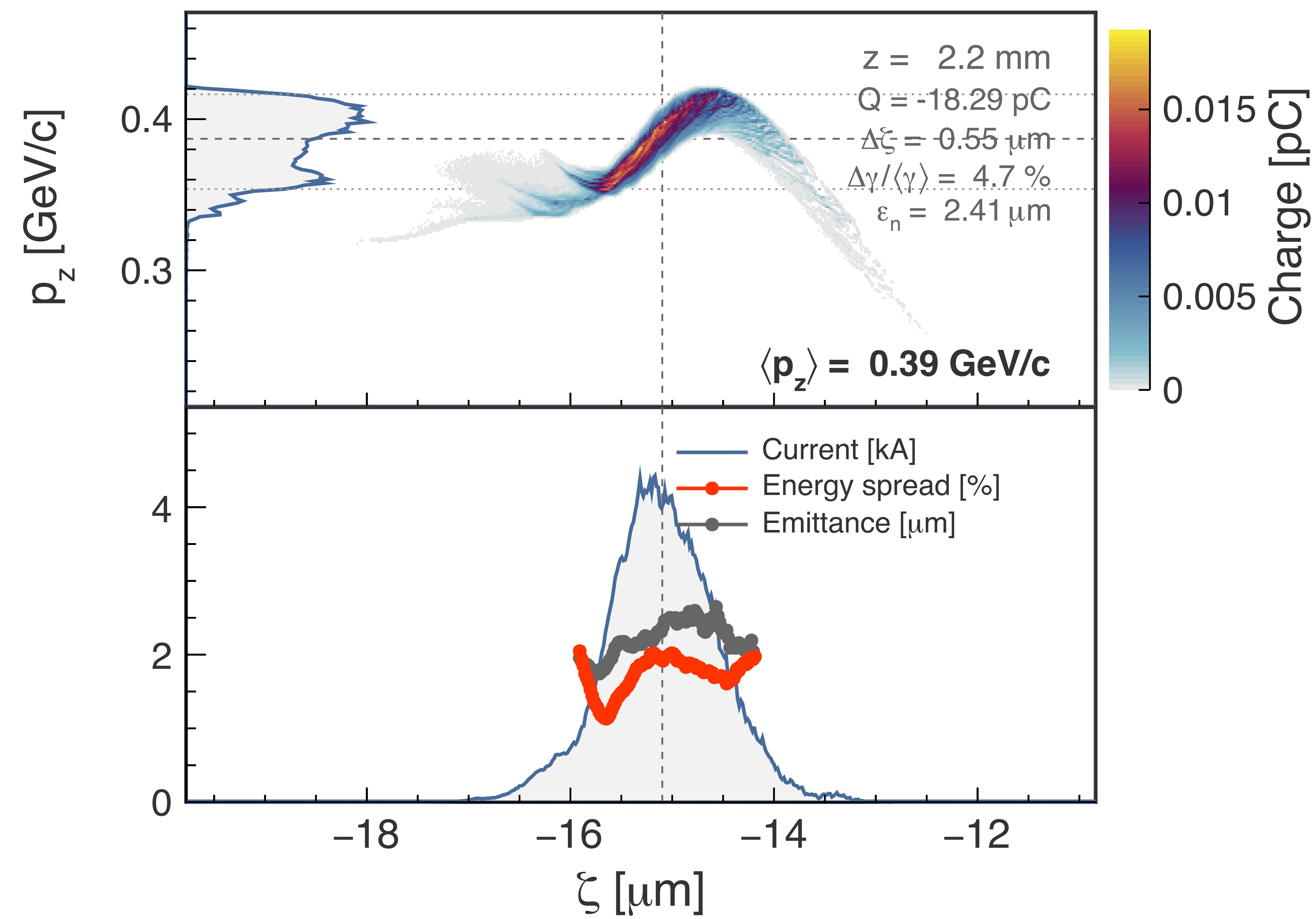

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- O. Lundh et al., Nat. Phys 7, 219 (2011).
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Injection-jet: H doped with N

$\mathbf{L_{jet} = 100\ \mu m}$ $\mathbf{n_N/n_H = 1\%}$

Wakefield-Induced Ionization Injection

Needs

- >> High-current electron drivers (I_b > 8 kA) to operate a strong blowout regime.
- >> A dopant species $E_{\mathrm{wake}} > E_{\mathrm{ion}} > E_{\mathrm{beam}}$ with appropriate ionization threshold.
- >> Plasma cell technology for the experimental setup.

Features

- >> Controlled ionization-based injection. Injects from a narrow and well-defined region
- >> Simple experimental setup. No need for extra devices
- >> Stable operation. Not very sensitive to driver fluctuations

Produces

- >> Ultra-short, high-quality bunches. Naturally, Injected beams are short and low-emittance

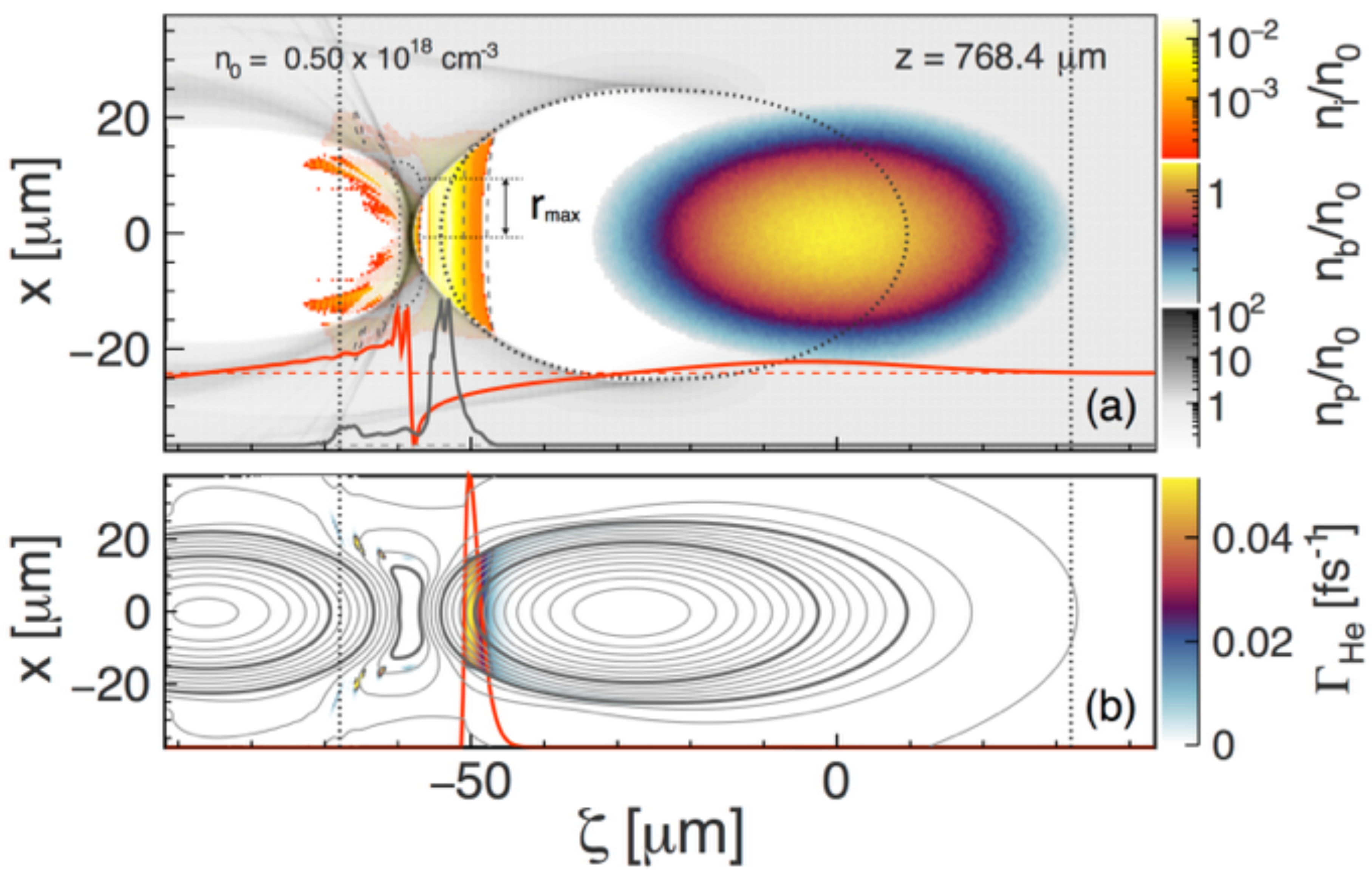
$$k_p \sigma_z \sim k_p \epsilon_n \sim 0.1$$

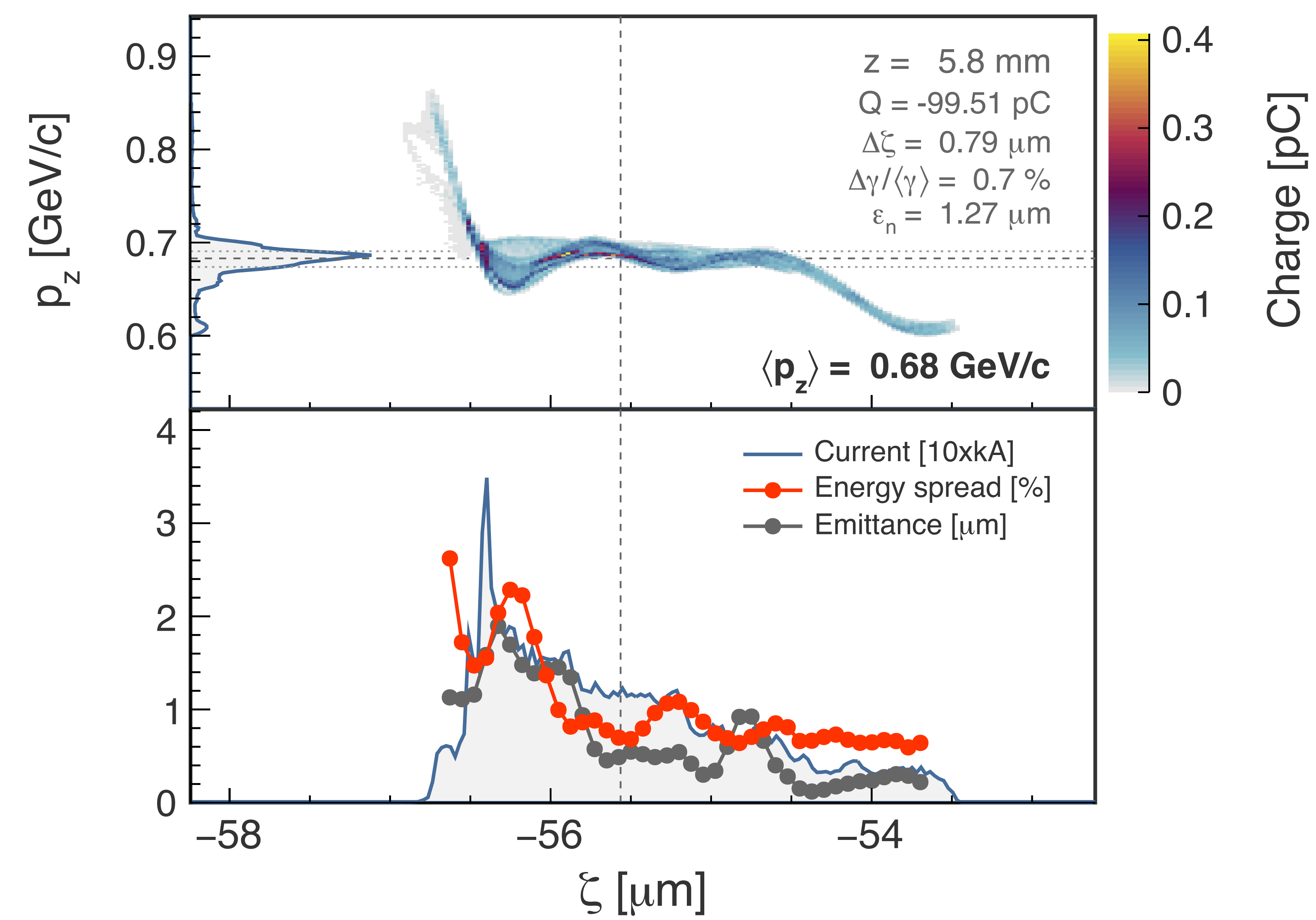
- >> High-current, quasi-mono-energetic electron-beams. by controlled beam loading
- >> Energy doubling: Transformer ratio ≥ 2

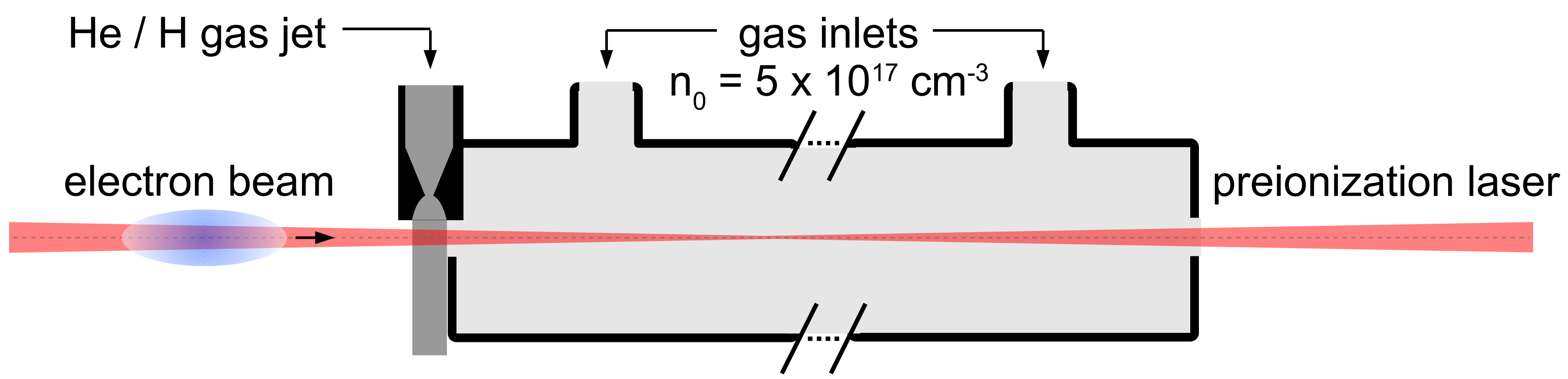
Self-Similar Staging

- >> The produced bunches could do WII injection at 10^2 times higher plasma density.
- >> Short and high-current electron beams from LWFA could do it as well.
- >> To produce 10 times reduction in emittance and length with double the energy per electron.
- >> **10^2 times brightness enhancement.**

Summary slide







- Preionization laser with an intensity capable to fully ionize a gas with a low ionization threshold (LIT), e.g. Hydrogen.
- Micro-nozzle fed by the same LIT gas doped with a high-ionization threshold (HIT) gas, e.g. Helium.

Short (~**μm**), high-current (~**20kA**) low-emittance (~**μm**) and quasi-mono-energetic **GeV**-electron beams

WII bunches can do WII injection in 10^2 times higher plasma densities for the production of 10^2 times higher brightness e^- beams