FLASHForward▸▸ Helmholtz Virtual Institute

Working group 1: Theory and PIC simulations

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LAOLA. collaboration

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Alexander von Humboldt
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Working group 1: Theory and PIC simulations

- **People**

T. Mehrling, J. Grebenyuk, M.J.V. Streeter, A. Aschikhin, A. Martinez de la Ossa, Z. Hu, V. Wacker, J. Osterhoff, A. Knetsch, B. Hidding, J. Vieira, R. Fonseca, C. Benedetti, C.B. Schroeder, R. Robson …

- **Institutes**

Deutsches Elektronen-Synchrotron (DESY),
University Hamburg (UHH),
Instituto Superior Tecnico (IST),
James Cook University (JCU),
Lawrence Berkley National Lab (LBNL).

- **Work**
  - Models and theory on PWFA for FLASHForward.
  - PIC code development: OSIRIS and HiPACE.
  - Start-to-end simulation framework.
  - Post-processing and data visualization: ℙ tools.
  - Physical studies !
- **PIC Codes**
  - OSIRIS, HiPACE, VSIM.
- **Parallel computing centers**
  - IT-HPC (DESY) , JUQUEEN and JUROPA (JSC), HLRN.

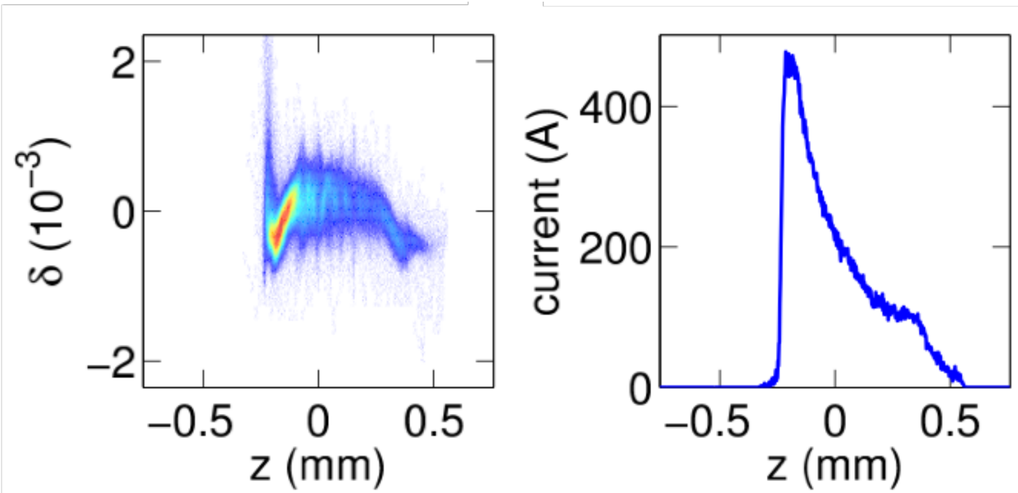
Physical studies:

- Novel controlled injection techniques for FLASHForward
  - Internal injection: Density down-ramp, Laser-Beam-Wakefield induced ionization injection.
- Beam quality preservation
  - External generation of driver/witness pairs.
  - Adiabatic matching with tailored plasma transitions.
- Start-to-end simulations framework
  - Realistic beams from particle tracking codes to PIC codes.

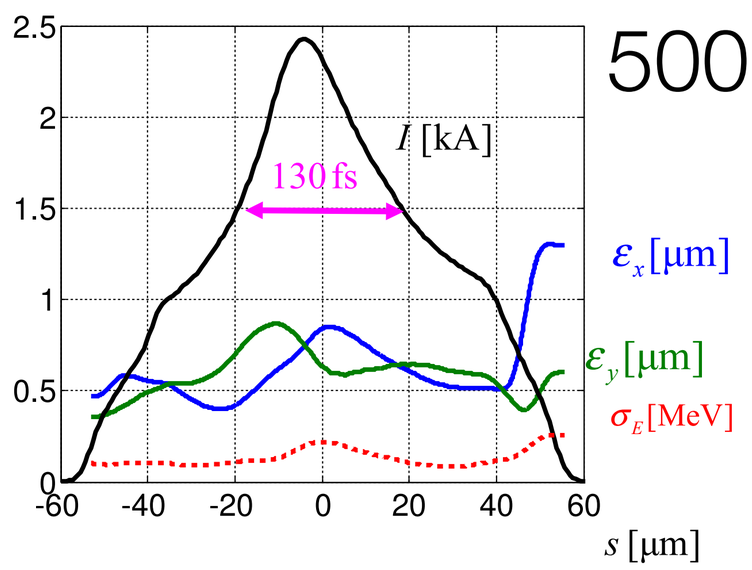
Working group 1: Theory and PIC simulations

- HiPACE: A highly efficient quasi-static code for PWFA with relativistic particle beams.
- Novel controlled injection techniques for FLASHForward.
  - Internal injection: Density down-ramp, Laser-Beam-Wakefield induced ionization injection.
- Beam quality preservation:
  - Considerations for external injection.
  - Adiabatic transitions in and out the plasma for emittance preservation.
  - Phase-space moment-equation model.
- Start-to-end simulations framework:
  - Realistic beams from particle tracking codes to PIC codes in plasma.
  - The hosing effect: Description, models and solutions.
- Near-future plans:
  - Full-study on realistic simulations for beam optimization.
  - PIC codes: Read-in of realistic plasma distributions. Read-in of realistic lasers.

Tailored electron beams in FLASH at 1GeV



P. Piot, et al., Phys.Rev.Lett. 108, 034801 (2012)



500 pC

FLASHForward▸▸

- ★ Average energy:
  - 1 GeV (γ=1957).
  - 0.1% energy spread.
- ★ Variable profiles
  - Peak current : 2 - 10 kA
- ★ Characteristic sizes:
  - Length (rms) : 5 - 25 μm.
  - Spot size (rms) : 5 - 20 μm.
- ★ Norm. emittance: 1 μm.

Linearly ramped beams offer the best transformer ratio

Standard FLASH beams well suited as plasma-wake drivers

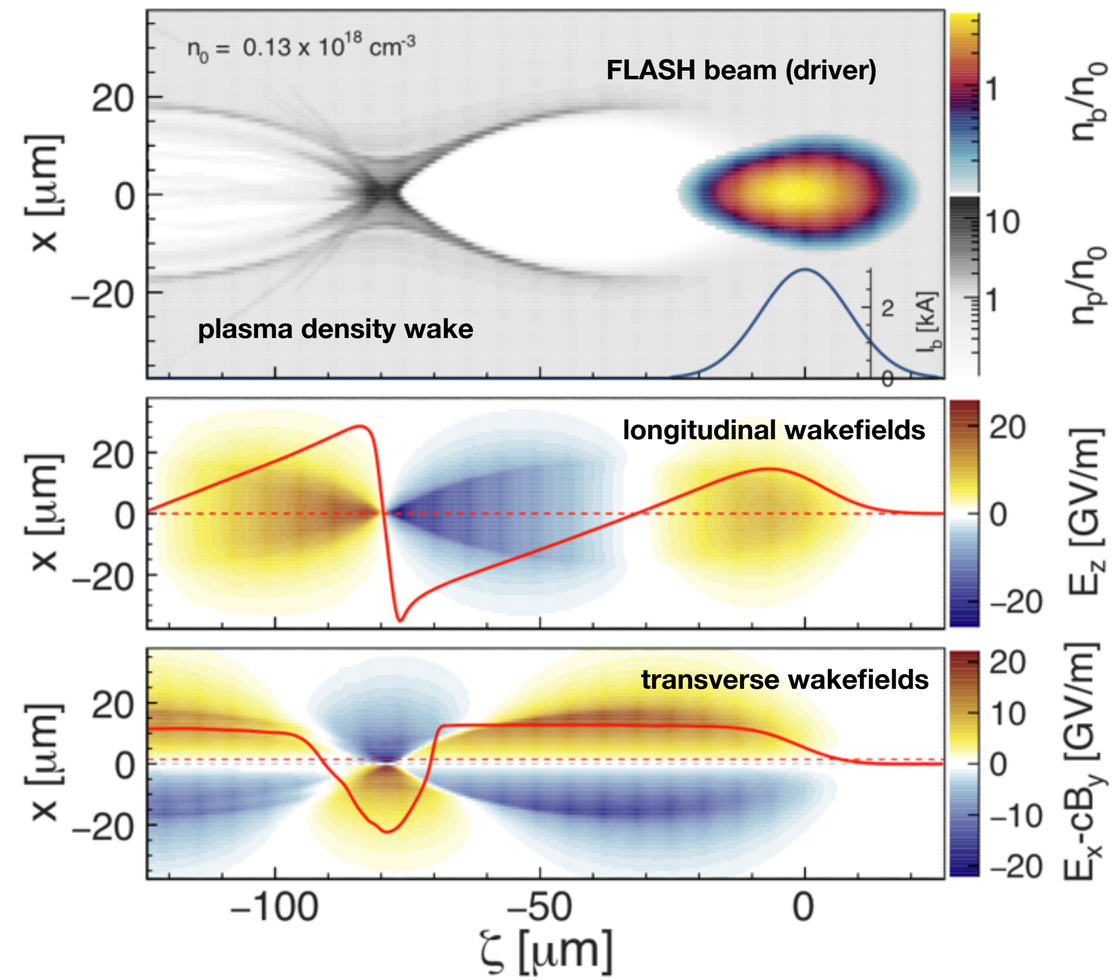
FLASHForward

PWFA in blowout regime

- High-current-density particle beam ~ 2.5 kA.
  - pushes away plasma electrons by space-charge field
  - creates electron-depleted cavity (blowout regime), sets up charge separation
- Strong electrostatic fields pull back plasma electrons
- Electrons oscillate and create co-propagating wakefield

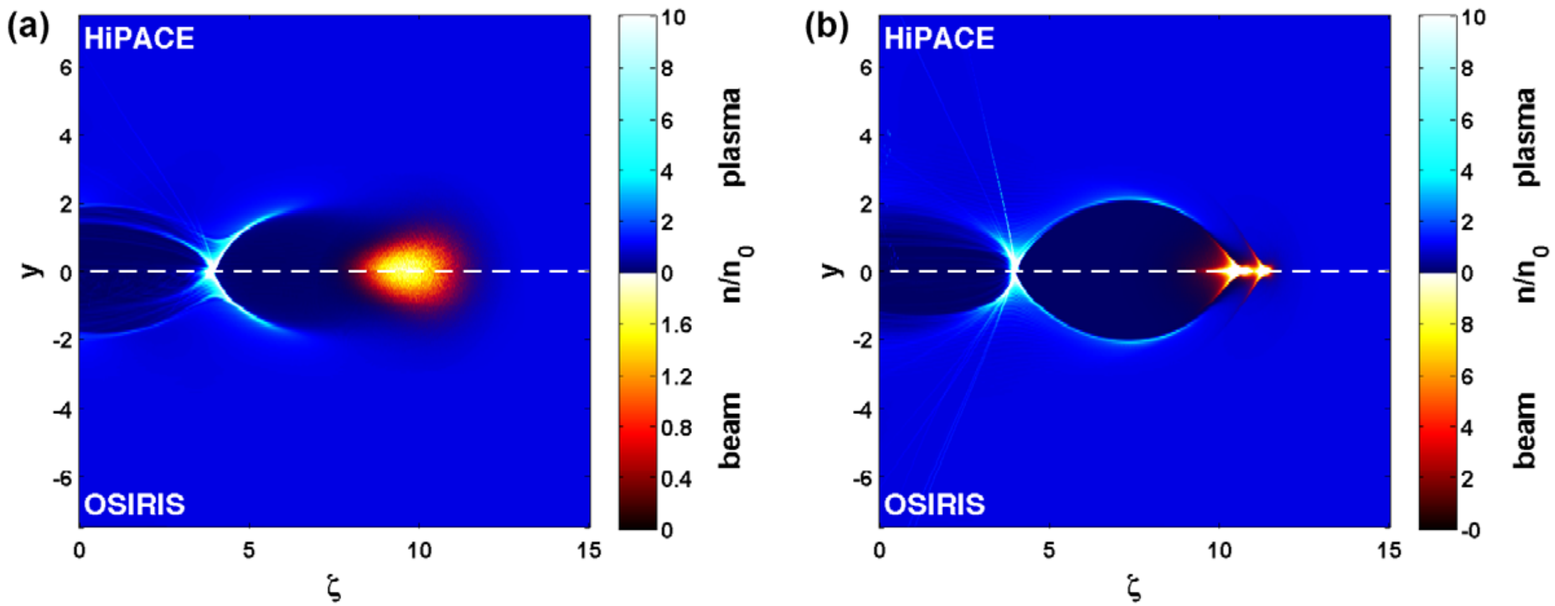
- Strong accelerating fields of >10 GV/m are generated.
- Linear relativistic focusing in the acceleration phase.
- High-transformer ratio: $R \equiv |E_z^{\mathrm{wit}}/E_z^{\mathrm{dri}}|$
- Boost witness electron energy to $\Delta\gamma_{\mathrm{wit}} = R\,\Delta\gamma_{\mathrm{dri}}$ in ~10 cm

3D OSIRIS PIC simulation



Standard FLASH 2 beam: 2.5 kA peak current, 50 fs (rms) long, 5 μm focus size, 1.0 GeV, 0.1% energy spread, 1 μm normalized transverse emittance

Particle-in-cell (PIC) codes: HiPACE



HiPACE

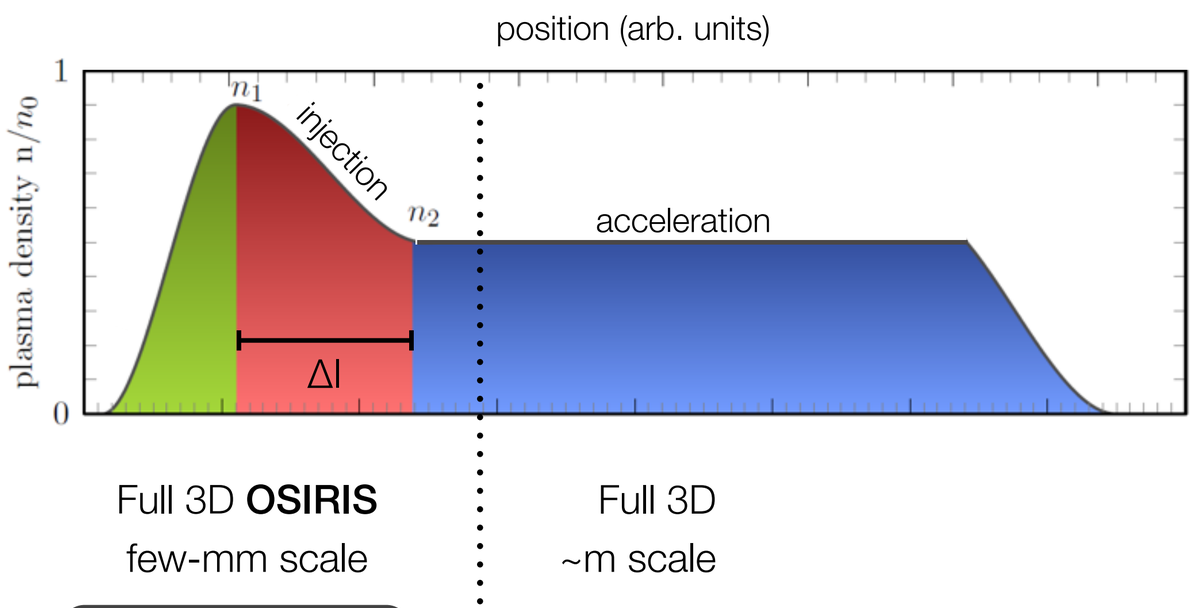
> T. Mehrling *et al.*, Plasma Phys. Control. Fusion 56, 084012 (2014)

developed in collaboration between DESY and LBNL

HiPACE - *a highly efficient plasma accelerator emulation*

- 3D quasi-static particle-in-cell code.
- Dynamic time-step adjustment.
- Fully parallelized and well scalable (tested up to 1024 cores).
- Allows 100x speedup for FLASHForward-type simulations vs. full PIC.
- Interfaces seamlessly with OSIRIS.

Full scale simulations with HiPACE



Computational challenge

- 20 cm-scale acceleration with ~100 nm spatial resolution
- Capture physics of trapping → full PIC required
- Cost: ~M core hours for full PIC 3D simulation.

HiPACE

- T. Mehrling *et al.*, Plasma Phys. Control. Fusion 56, 084012 (2014)

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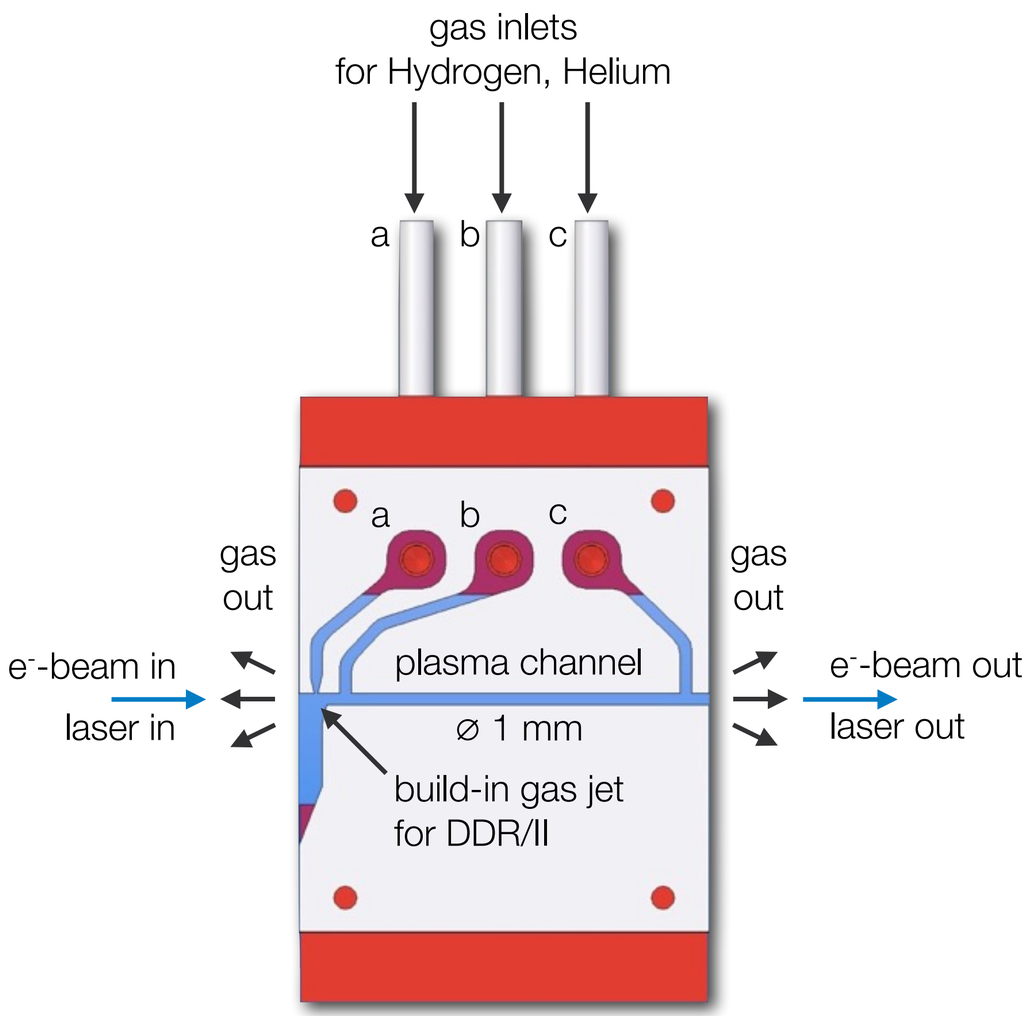
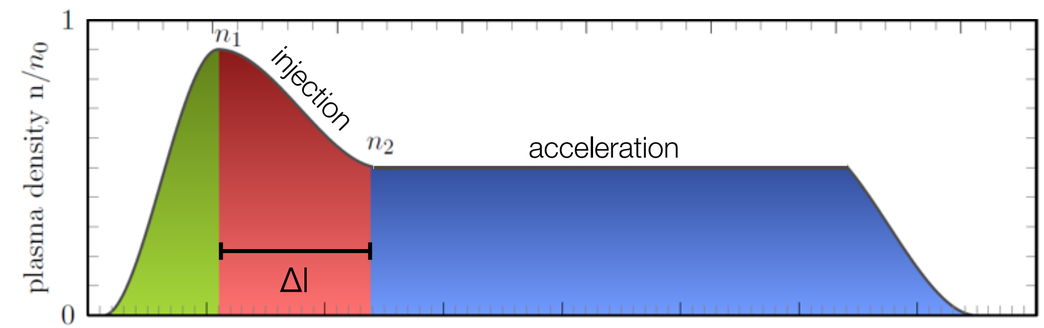
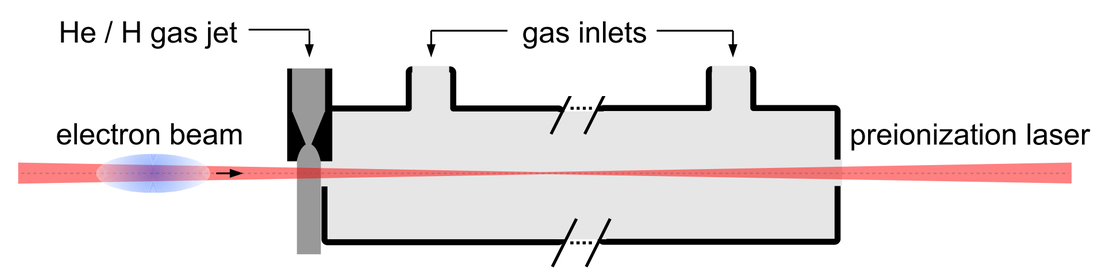
- Allows 100x speedup for FLASHForward-type simulations vs. full PIC.
- Interfaces seamlessly with OSIRIS.

Plasma-cell design supports novel PWFA-injection schemes

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



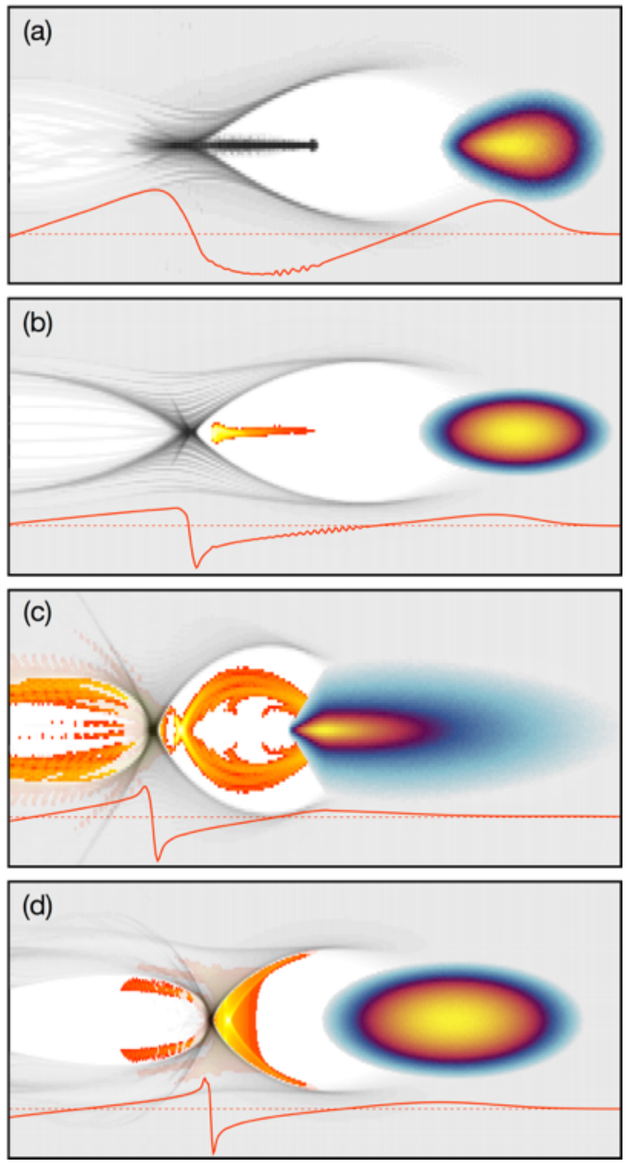




- Preionization laser with an intensity capable to fully ionize a gas with a low ionization threshold (LIT), e.g. Hydrogen.
- Micro-nozzle fed by the same LIT gas doped with a high-ionization threshold (HIT) gas, e.g. Helium.

Novel in-plasma beam-generation techniques

Quality of beams linked to control over initial population of wake-phase space at injection



- **Density down-ramp injection**
  J. Grebenyuk et al., NIM A 740, 246 (2014)
  $I_B \gtrsim 1\ \mathrm{kA}$

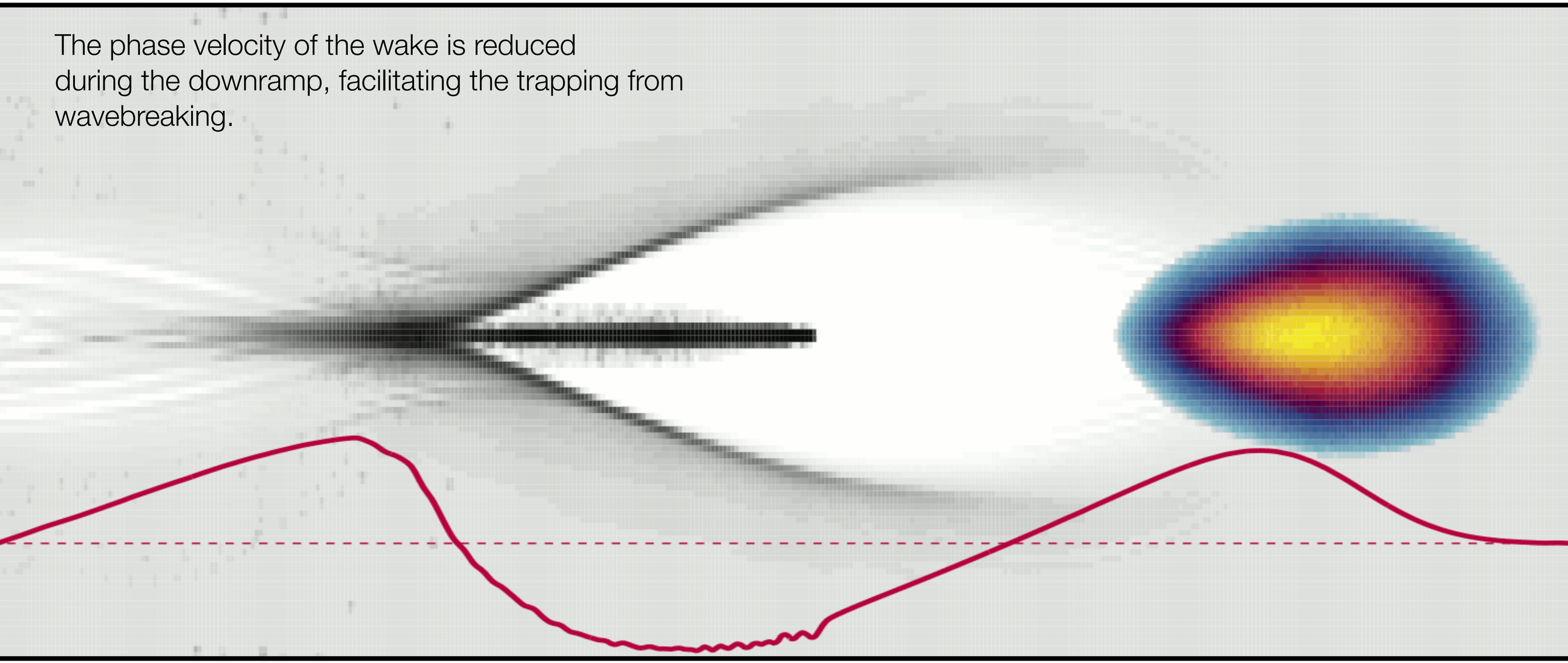
- **Laser-induced ionization injection (Trojan Horse injection)**
  B. Hidding et al., Physical Review Letters 108, 035001 (2012)
  $I_B \gtrsim 5\ \mathrm{kA}$

- **Beam-induced ionization (BII) injection**
  A. Martinez de la Ossa et al., NIM A 740, 231 (2014)
  $I_B \gtrsim 7.5\ \mathrm{kA}$

- **Wakefield-induced ionization (WII) injection**
  A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)
  $I_B \gtrsim 10\ \mathrm{kA}$

Density Down-Ramp Injection

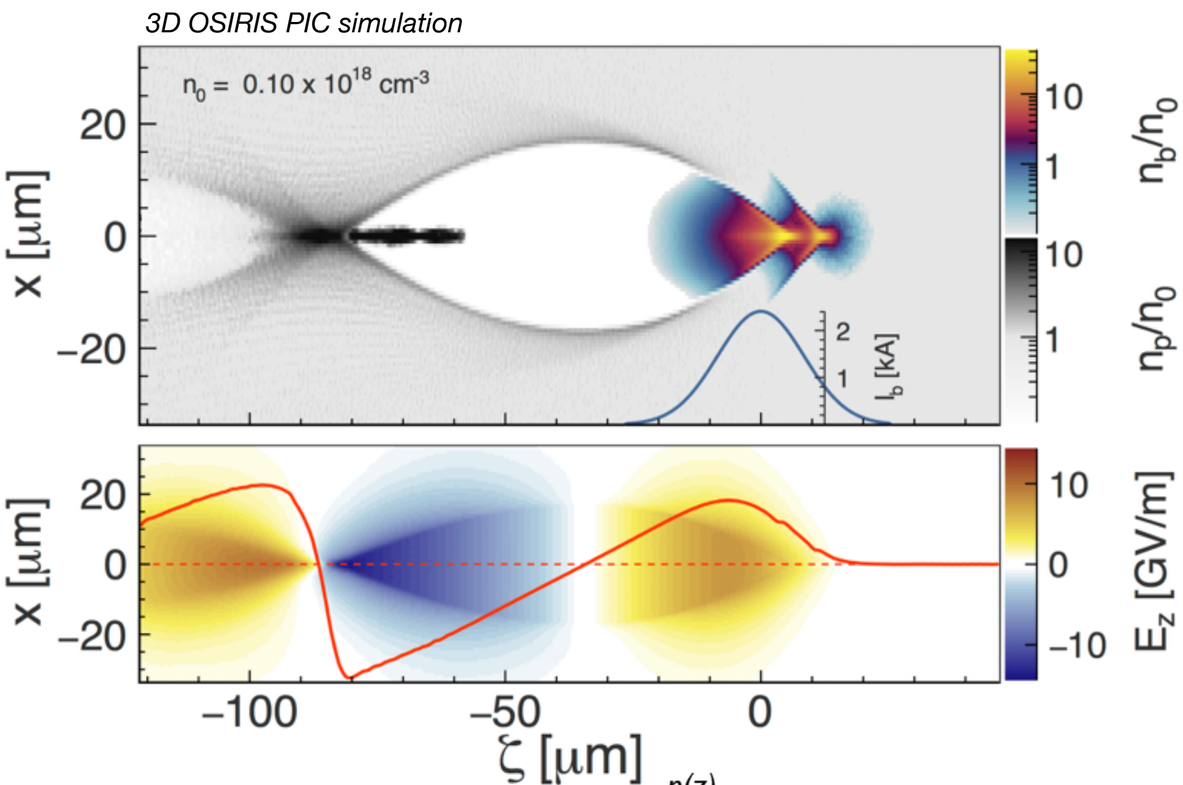
The phase velocity of the wake is reduced during the downramp, facilitating the trapping from wavebreaking.

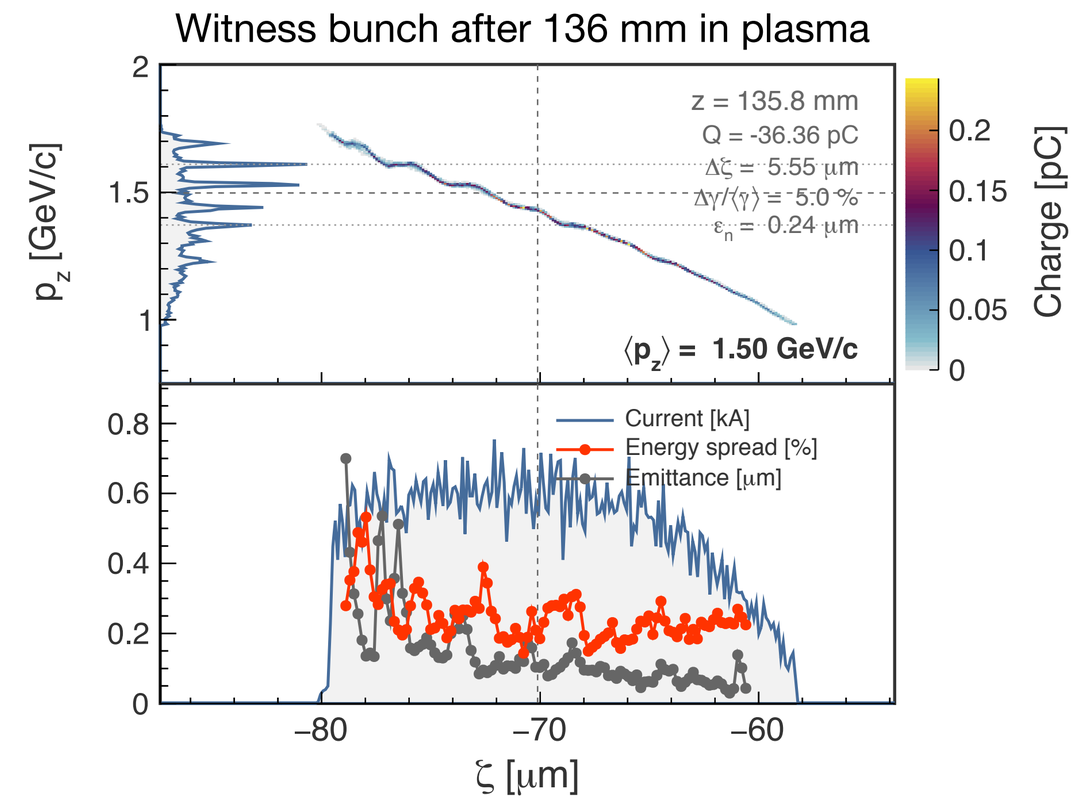


J. Grebenyuk et al. Nucl. Instrum. Meth. A 740, 246-249 (2013)

Density-downramp injection

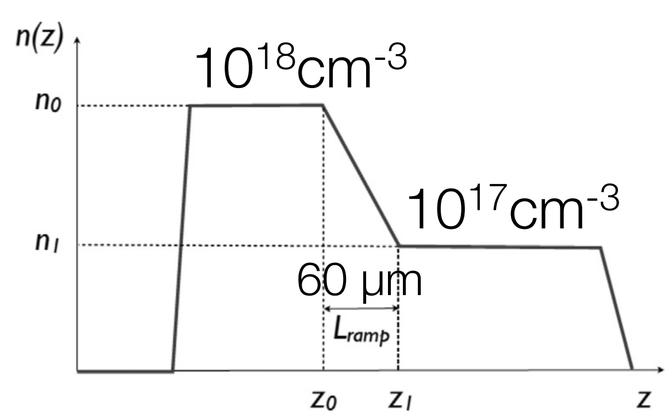
J. Grebenyuk et al., NIM A 740, 246 (2014)





Driver beam ▸▸

Q_b = 180 pC
I_b = **2.5 kA**
E_b = 1 GeV
σ_z = 8.4 μm
σ_x = 5 μm
ε_x = 1 μm



- Duration: **18 fs rms**
- Current: **0.6 kA**
- Normalized emittance: 240 **nm**
- Uncorrelated energy spread: **0.3%**

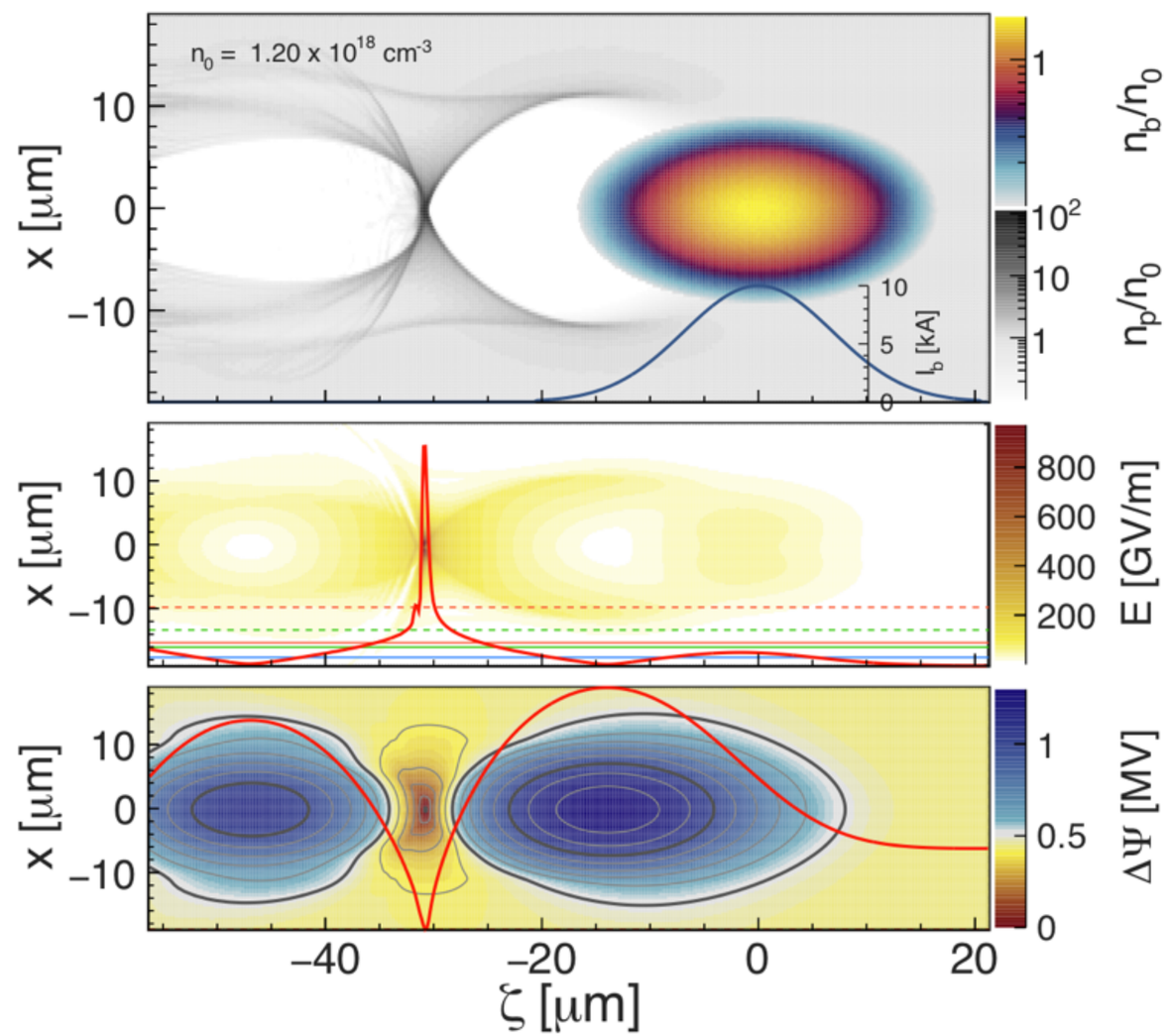
Ionization-based injection:
Ionizing and trapping electrons into the wake

- Field ionization thresholds:
  - H = 33.8 GV/m (13.6 eV)
  - He = **92.8 GV/m** (24.6 eV)
- The wakefields in blowout regime can be high enough to trigger from He.
- The space charge fields of the beam too.
- An assistive laser can be used to control ionization.
- To trap electrons from ionization they need to gain enough kinetic energy to co-propagate with the wake:

$$\Delta\Psi = -\frac{mc^2}{e} \approx -0.511 \text{ MV}$$

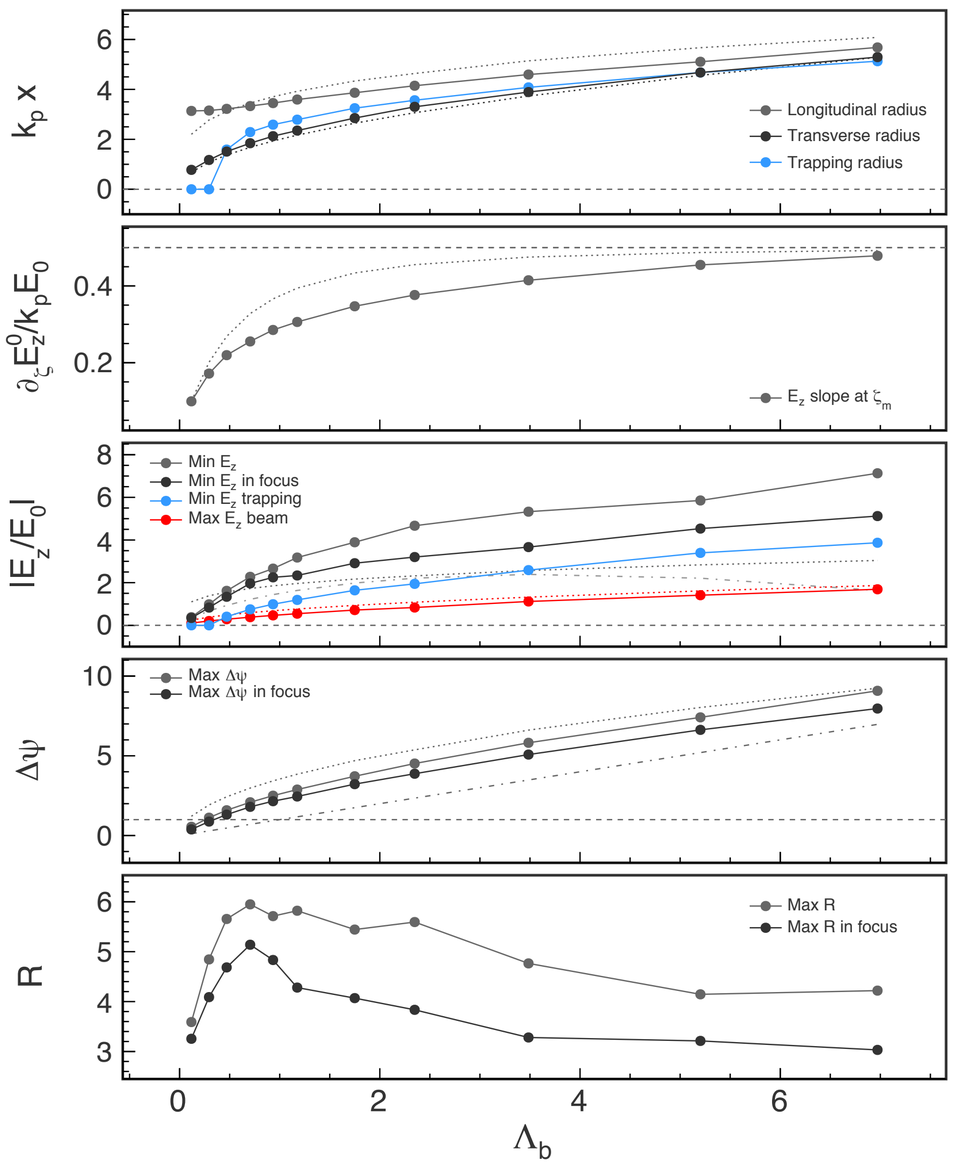
- The maximum difference in wake potential depends mainly on the drivers current:

$$\Delta\Psi_{\max} \propto \sqrt{I_b/I_0}$$



Trapping electrons into the wake (from ionization)

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



- Scalings of blowout parameters (3D-PIC vs Model).

Gaussian beams

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

$k_p\sigma_x = 0.1$ narrow beam

$k_p\epsilon_{x,n}^{\mathrm{match}} = (k_p\sigma_x)^2\sqrt{\gamma/2}$ matched emittance

Trapping from Ionization

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

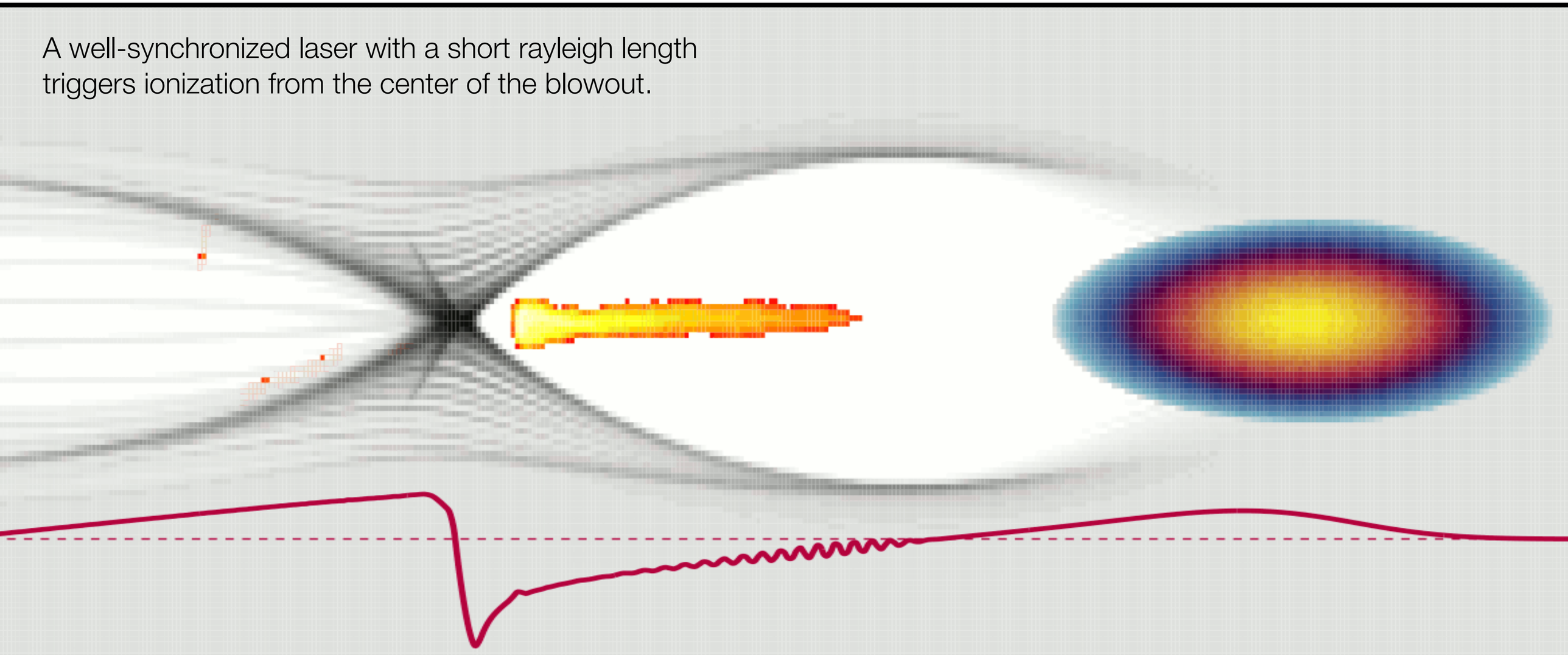
FLASHForward▸▸

Tunable R_{56} in extraction dogleg
for optimized peak current (up to 10 kA)

$$\Lambda_b = I_b/I_0$$

$$I_0 = 8.52\ \mathrm{kA}$$

Laser-assisted Ionization Injection



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

Laser-assisted Ionization Injection

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

Driver beam

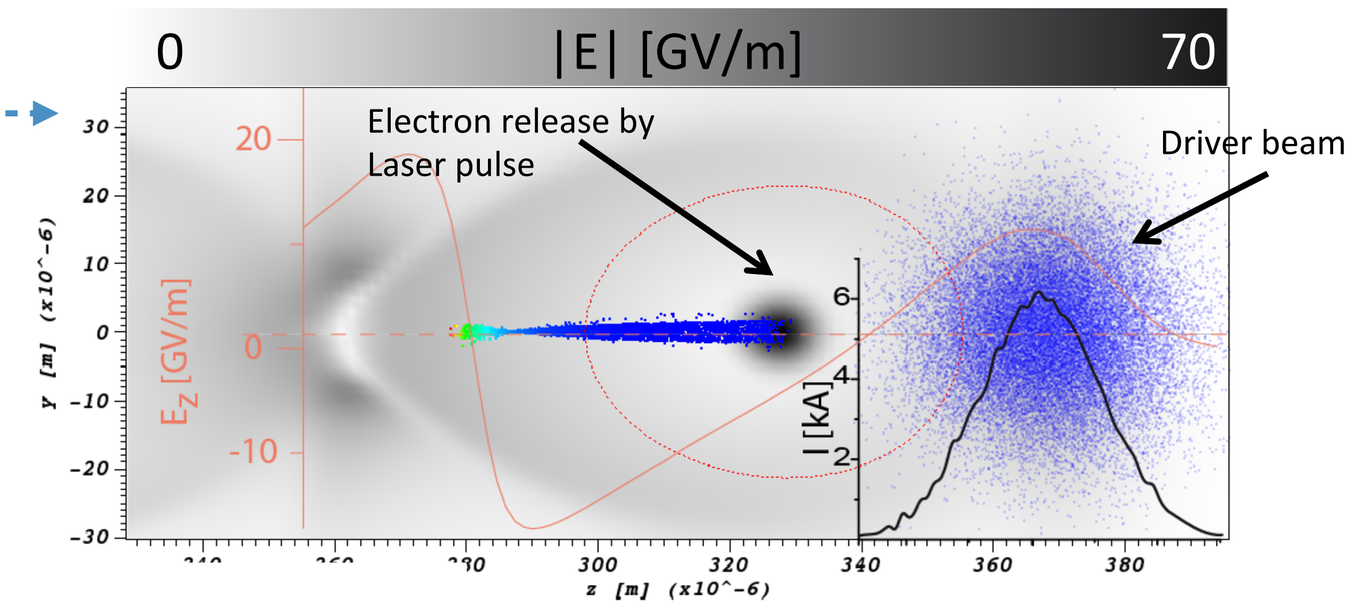
Q_b = 500 pC
I_b = **6 kA**
E_b = 1 GeV
σ_z = **10 µm**
σ_x = 9 µm
ε_x = 2 µm

Trojan horse

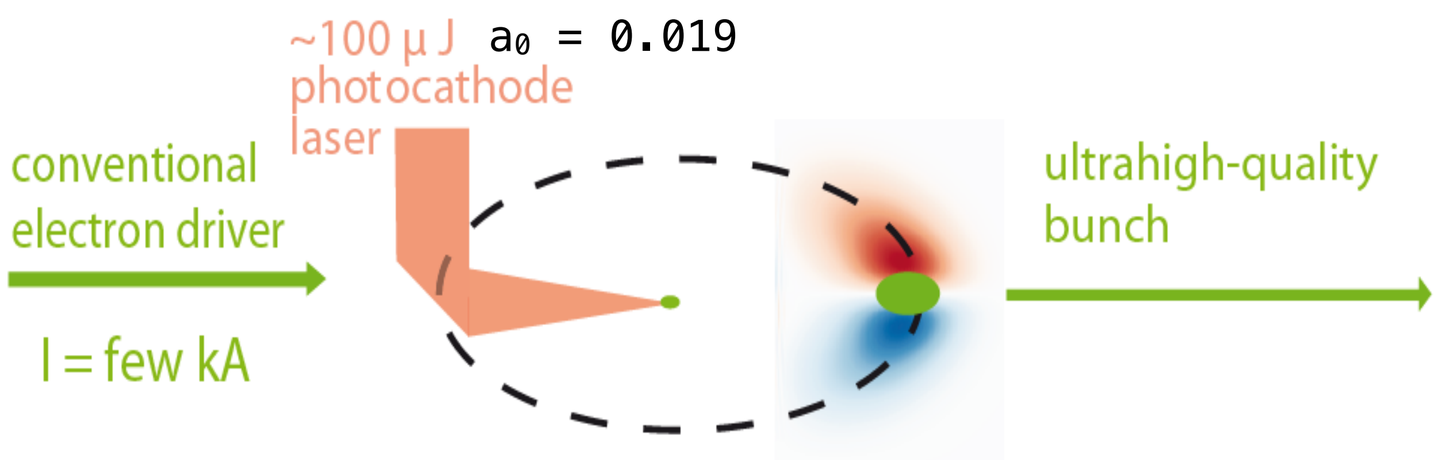
plasma density

$n_0 = 8 \times 10^{16}\ cm^{-3}$

dopant species: helium



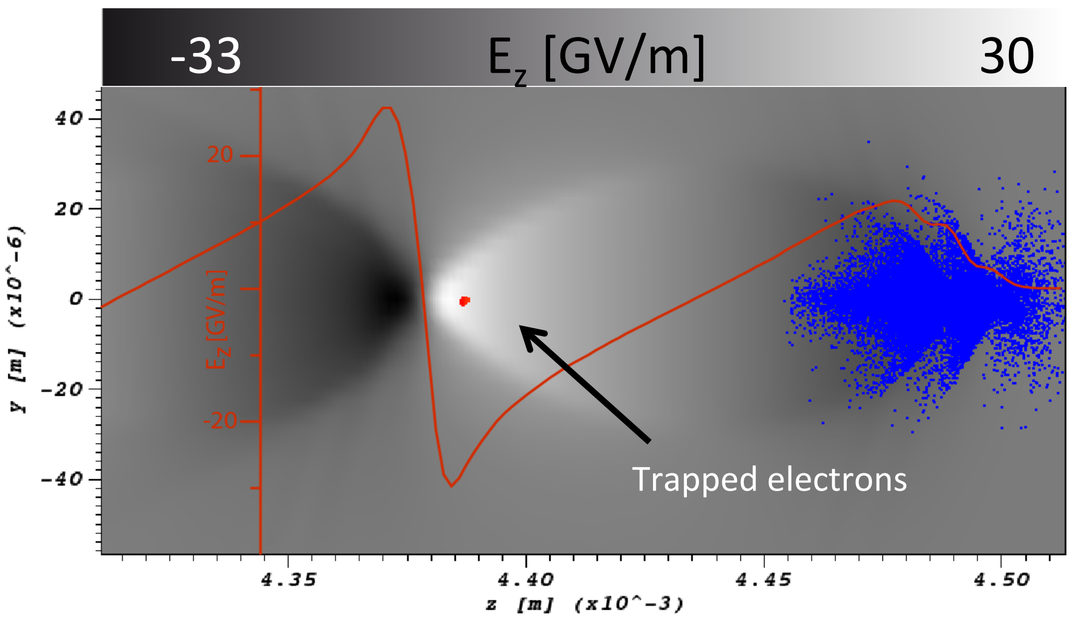
simulation by A. Knetsch with VSIM

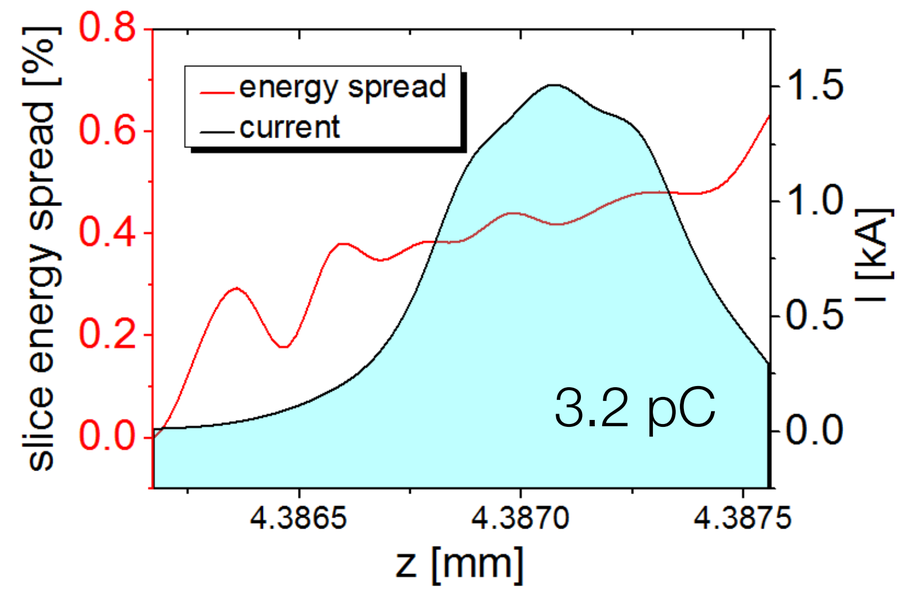


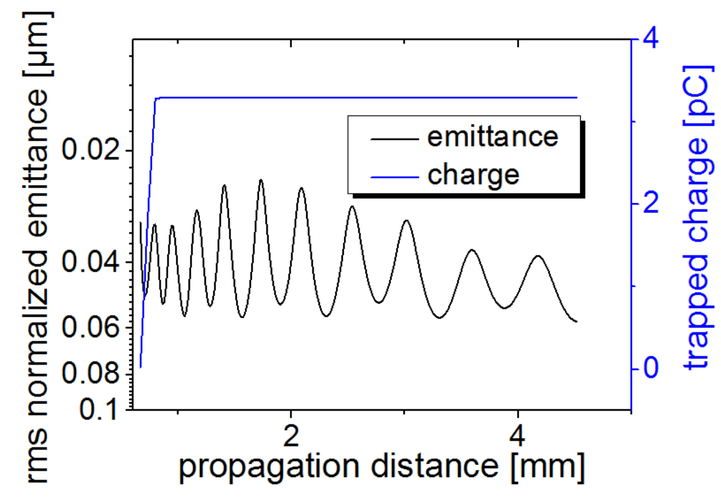
Laser-assisted Ionization Injection

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

After 4 mm of propagation





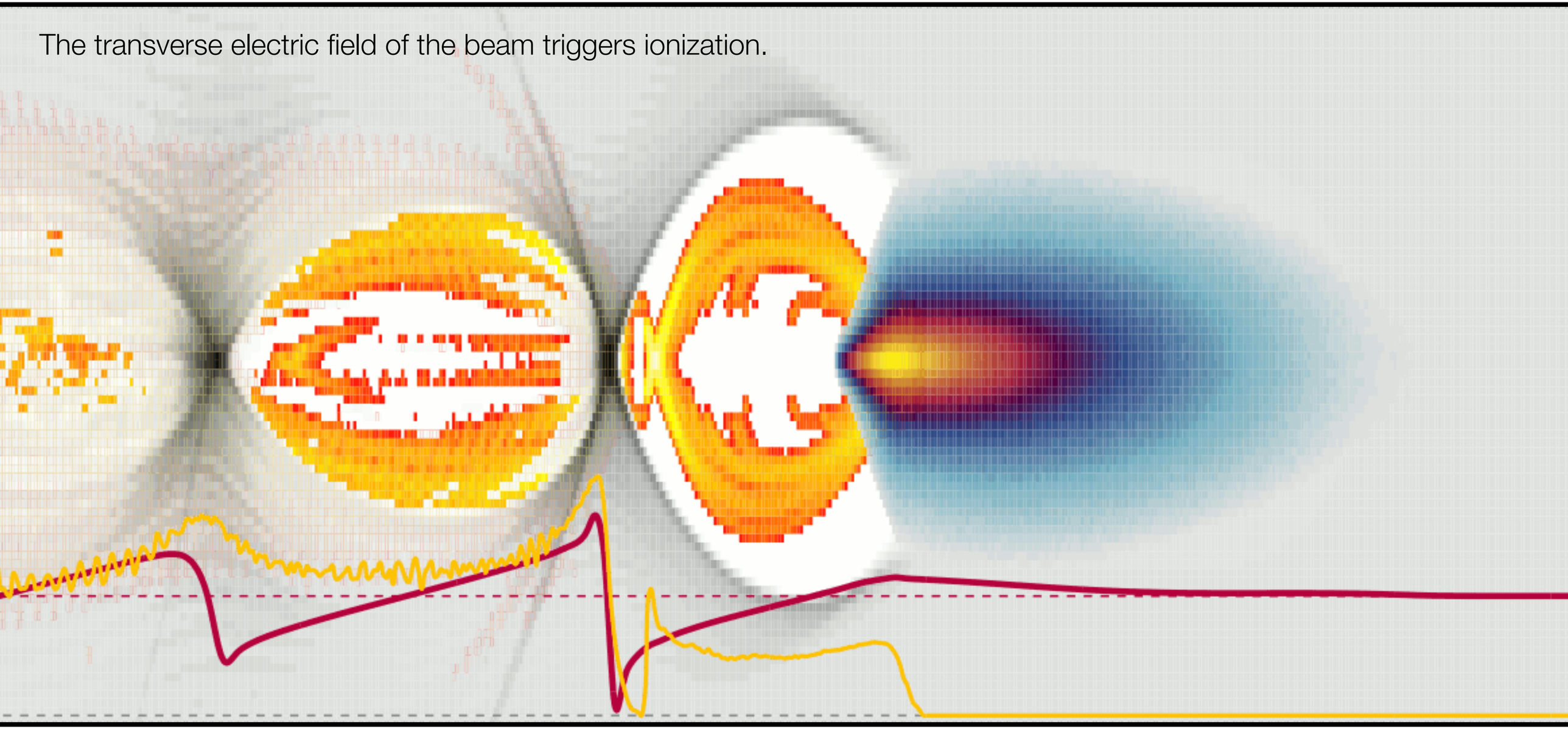


Witness-beam parameters after 4 mm of propagation

- Duration: ~1 fs rms
- Current: 1.5 kA
- Normalized emittance: 40 nm
- Uncorrelated energy spread: < 1%

Beam-Induced Ionization Injection

The transverse electric field of the beam triggers ionization.



A. M. de la Ossa et al. Nucl. Instrum. Meth. A 740, 231-235 (2013)

Beam-Induced Ionization (BII) Injection

A. M. de la Ossa et al. Nucl. Instrum. Meth. A 740, 231-235 (2013)

Driver beam

Q_b = 690 pC
I_b = **7.5 kA**
E_b = 1 GeV
σ_z = 11.5 μm
σ_x = 7 μm
ε_x = 1 μm

BII Injection

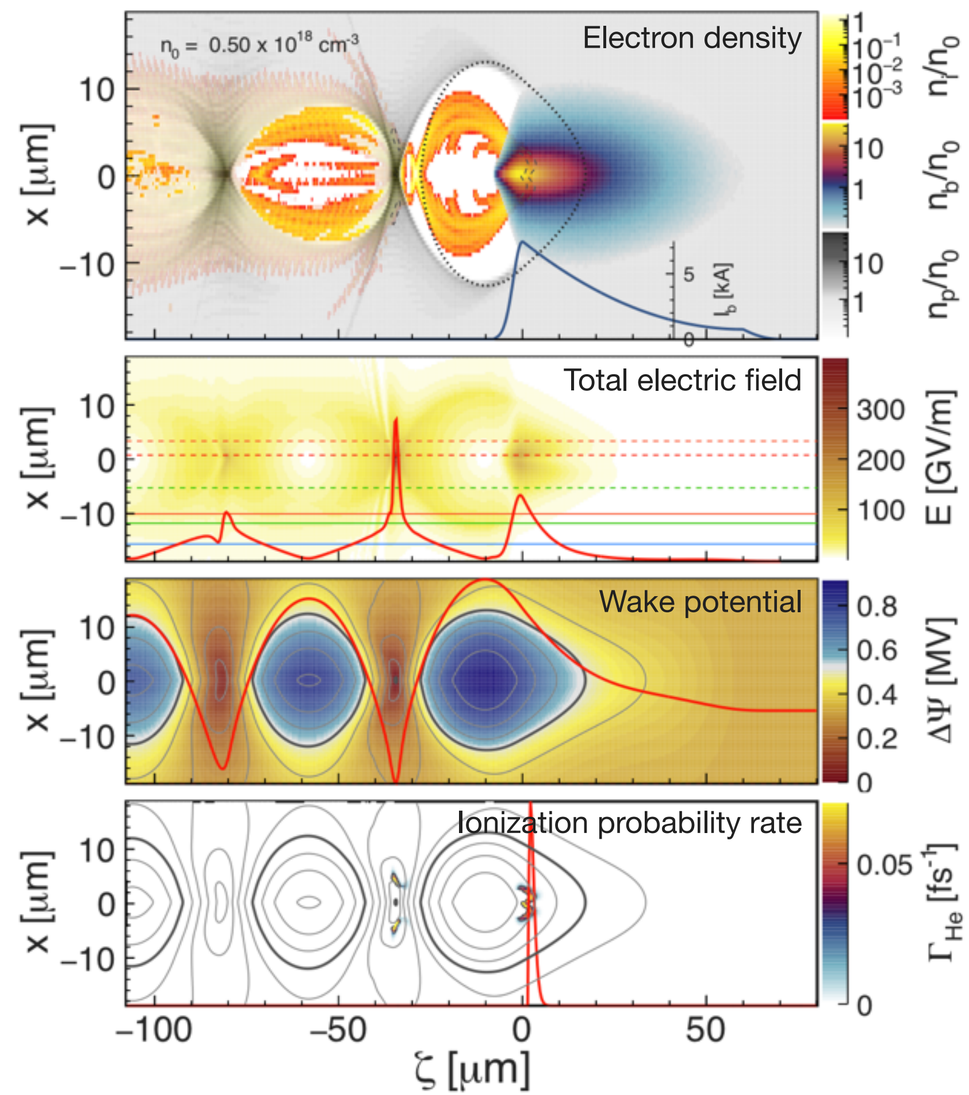
plasma density

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

(resonant)

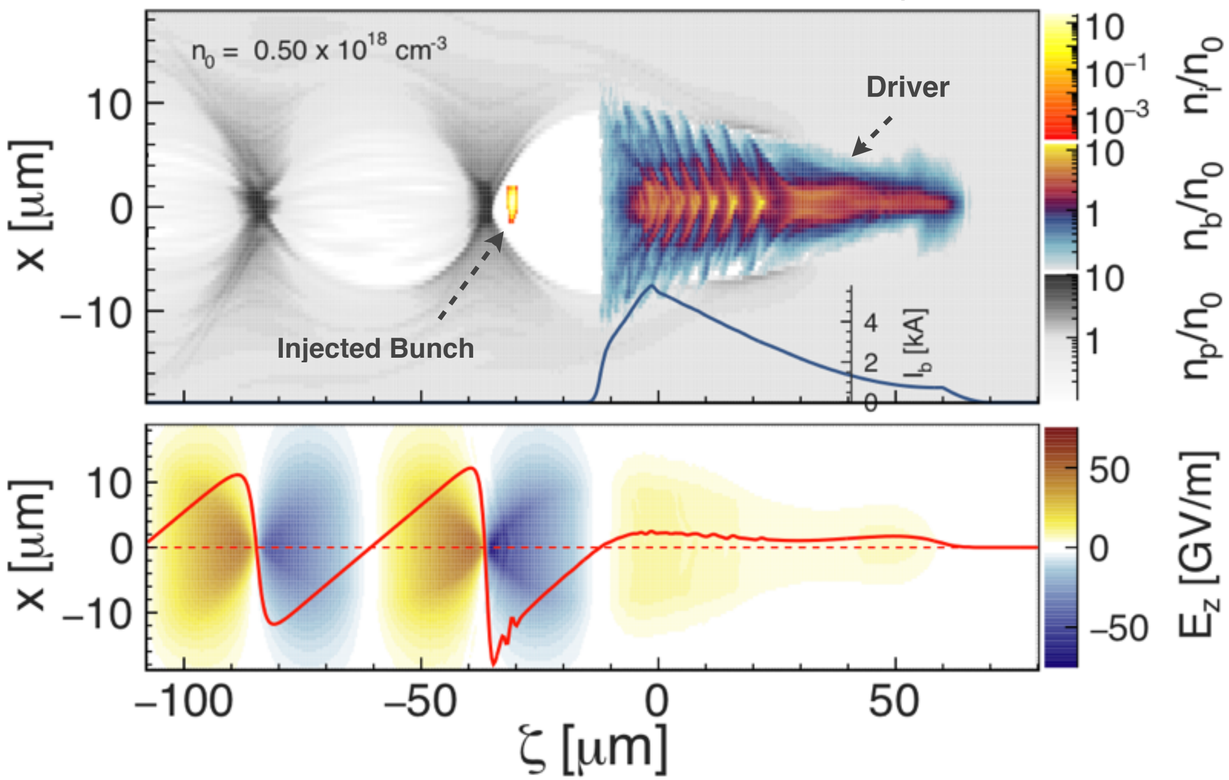
dopant species: helium

- Ionization induced by the beam's field when focused.
- Sensitive to the beam's microstructure and betatron oscillations.
- Triangularly ramped drivers facilitate injection from an appropriate phase and provide high transformer ratio.

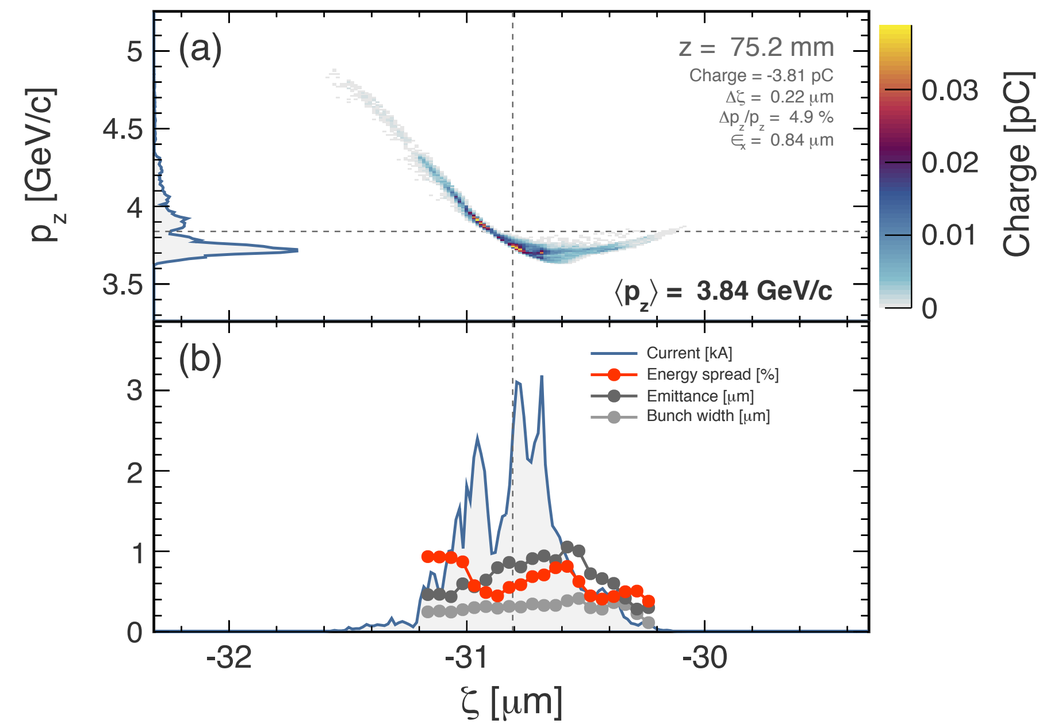


Beam-Induced Ionization (BII) Injection

Driver and witness bunch after 75 mm in plasma



A. M. de la Ossa et al. Nucl. Instrum. Meth. A 740, 231-235 (2013)

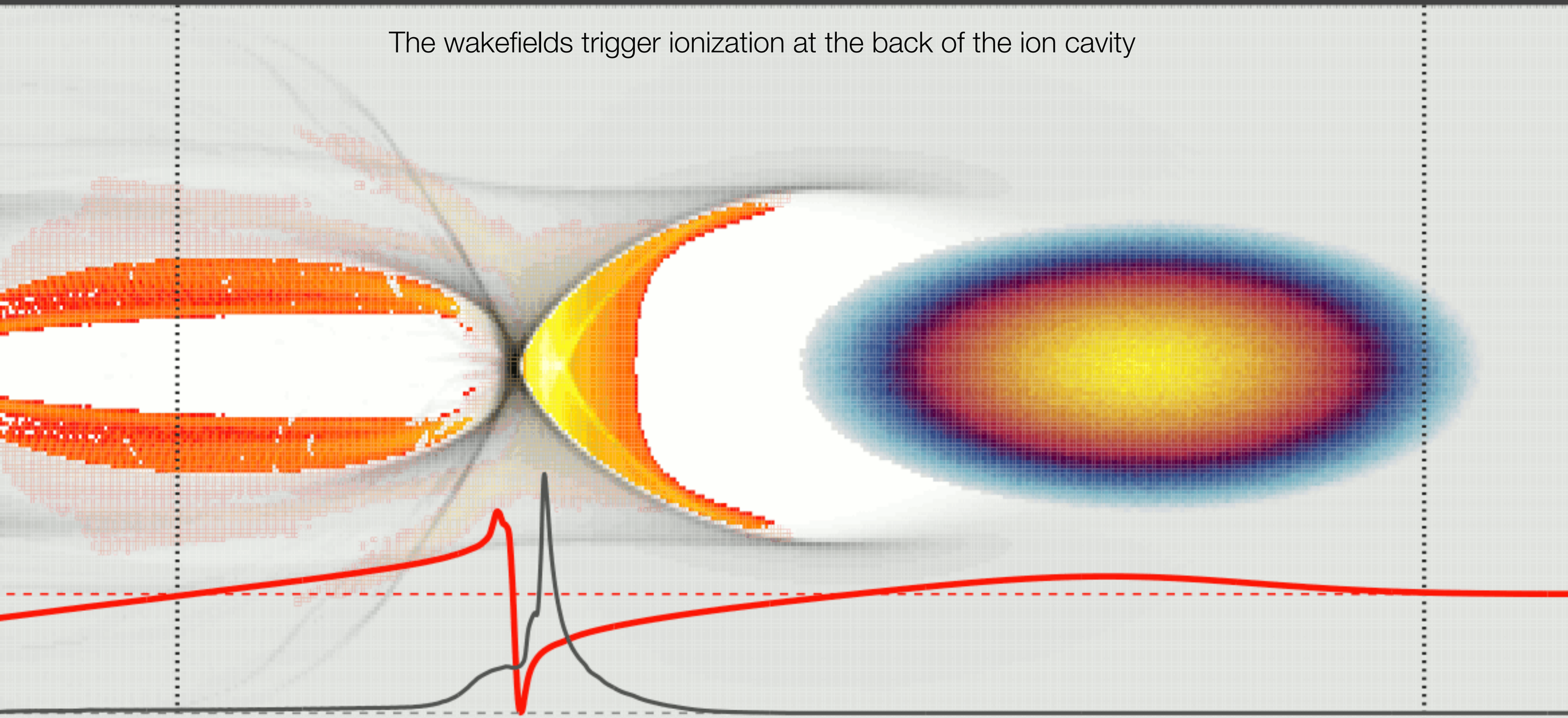


The driver beam here is close to depletion. The witness beam has been accelerated up to **3.8 GeV** in around 7.5 cm.

- Duration: **730 as rms**
- Current: **3 kA** (tunable)
- Normalized emittance: **840 nm**
- Uncorrelated energy spread: < 1%

Wakefield-Induced Ionization Injection

The wakefields trigger ionization at the back of the ion cavity



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

Wakefield-induced ionization injection

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

Driver beam

Q_b = 574 pC
I_b = **10 kA**
E_b = 1 GeV
σ_z = **7 µm**
σ_x = 4 µm
ε_x = 1 µm

WII Injection

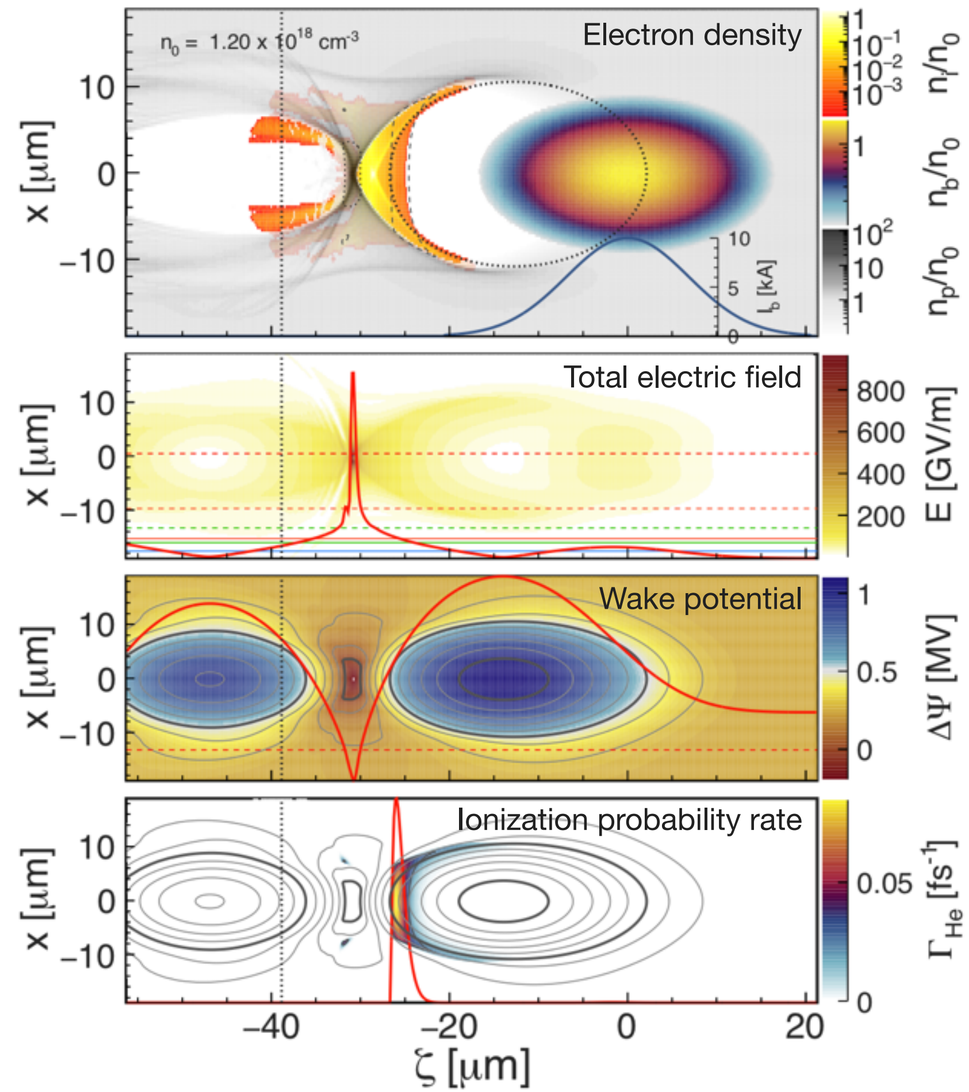
plasma density

$$n_0 = 12 \times 10^{17}\ \mathrm{cm}^{-3}$$

(resonant)

dopant species: helium

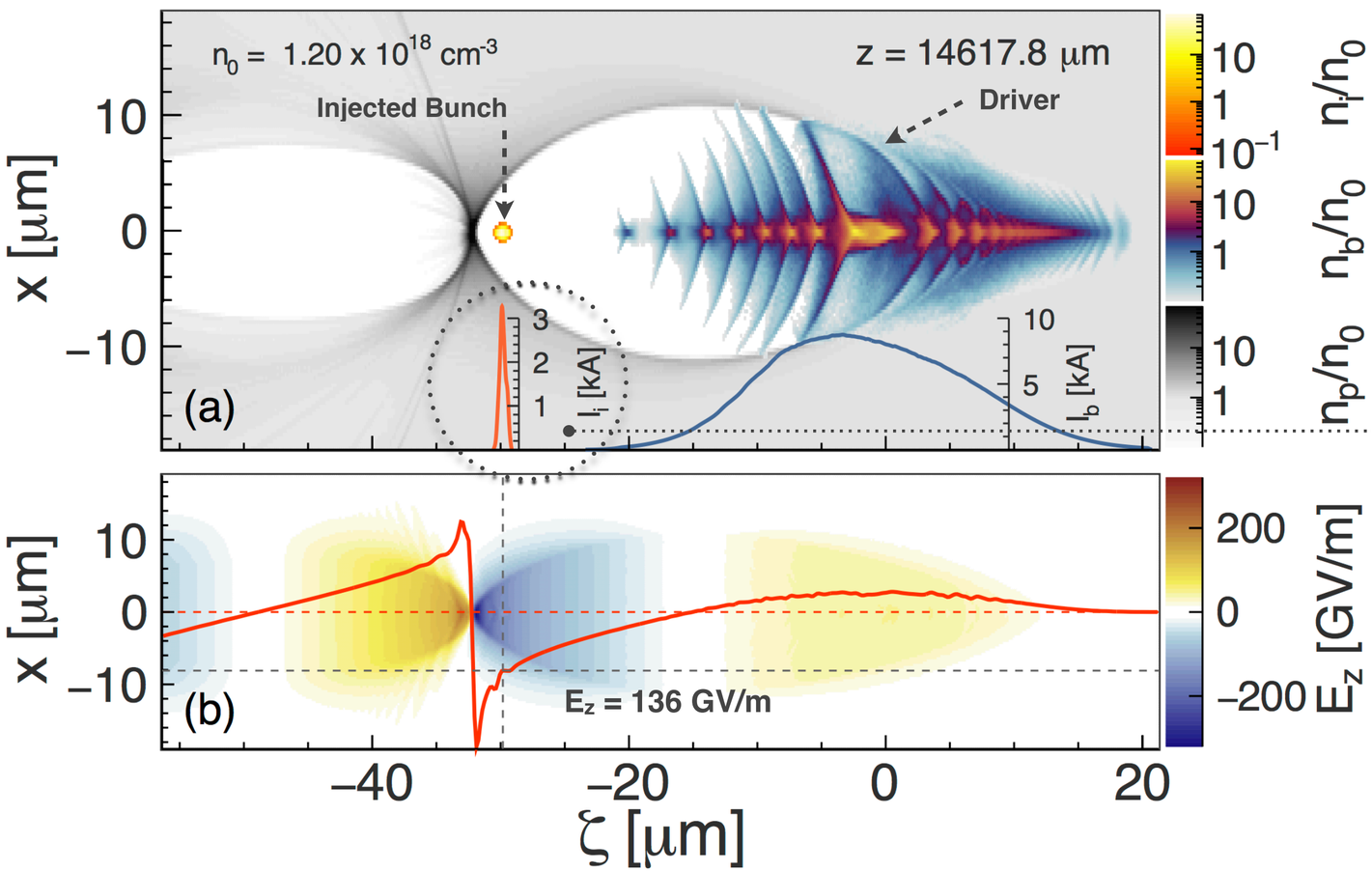
- Ionization is induced by the accelerating wakefields at the rear of the ion cavity.
- A stable and constrained volume of injection leads naturally to compact high-quality witness.
- High-transformer ratio (by construction).

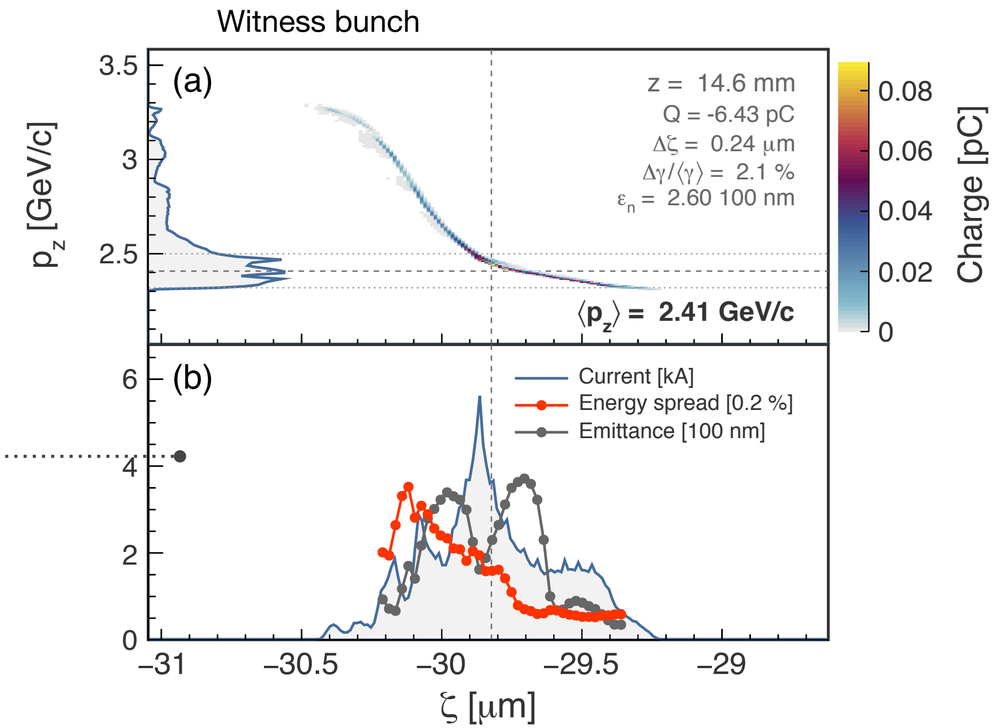


Wakefield-induced ionization injection

Driver and witness bunch after 14.6 mm in plasma

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





Transformer ratio ~ 3

Up to 3 GeV in 2 cm

- Duration: **770 as rms**
- Current: **5 kA** (tunable)
- Normalized emittance: **300 nm**
- Uncorrelated energy spread: **0.2%**

External beam injection: a challenge to preserve beam emittance

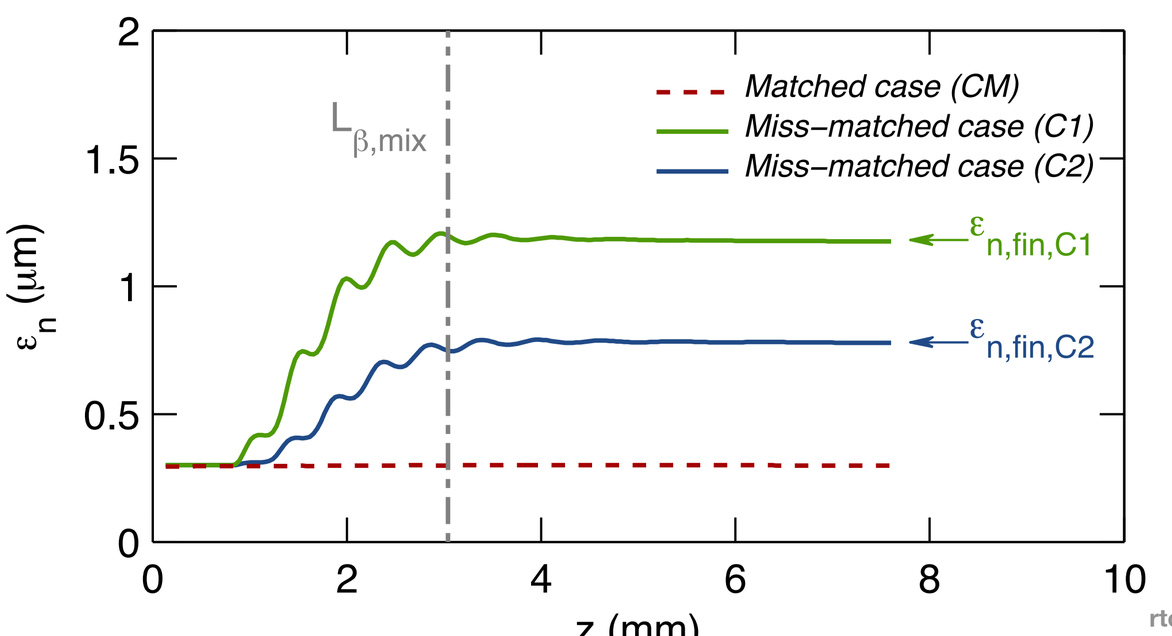
T. Mehrling *et al.*, Phys. Rev. STAB 15, 111303 (2012)

Beam envelope equation

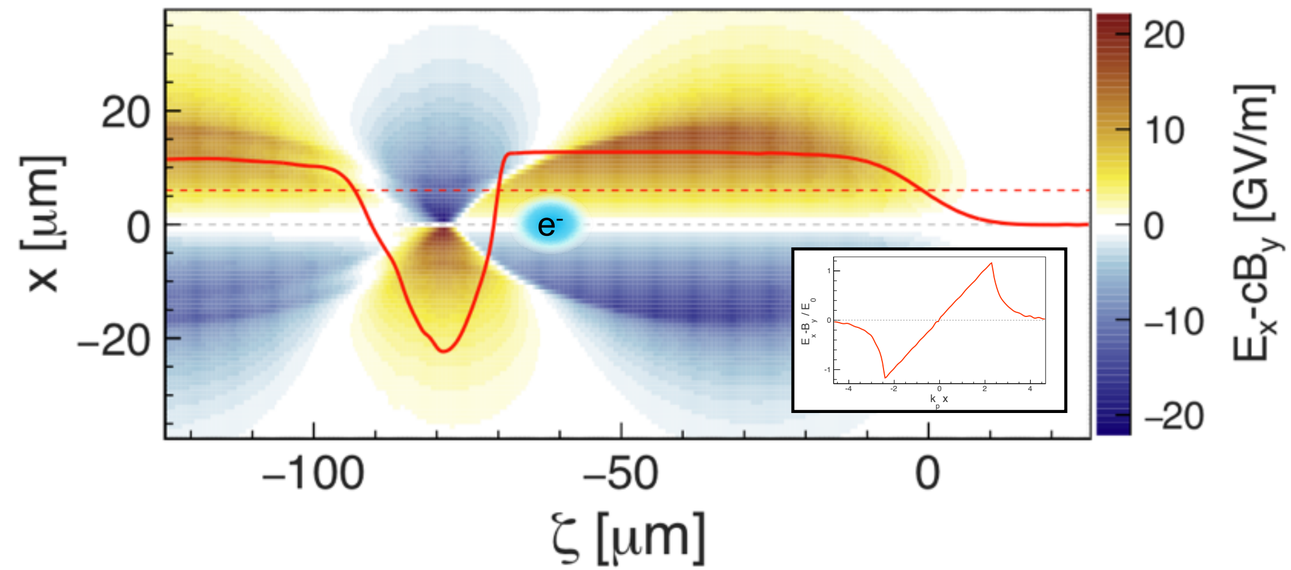
$$\sigma_x''(z) + \left[k_\beta^2(z) - \frac{1}{\hat{\beta}^2(z)}\right]\sigma_x(z) = 0$$

Blowout regime (linear focusing) $k_\beta = \frac{k_p}{\sqrt{2\gamma}} = \hat{\beta}_m^{-1}$

The beta function $\hat{\beta} \equiv \gamma \frac{\sigma_x^2}{\epsilon_{n,x}}$



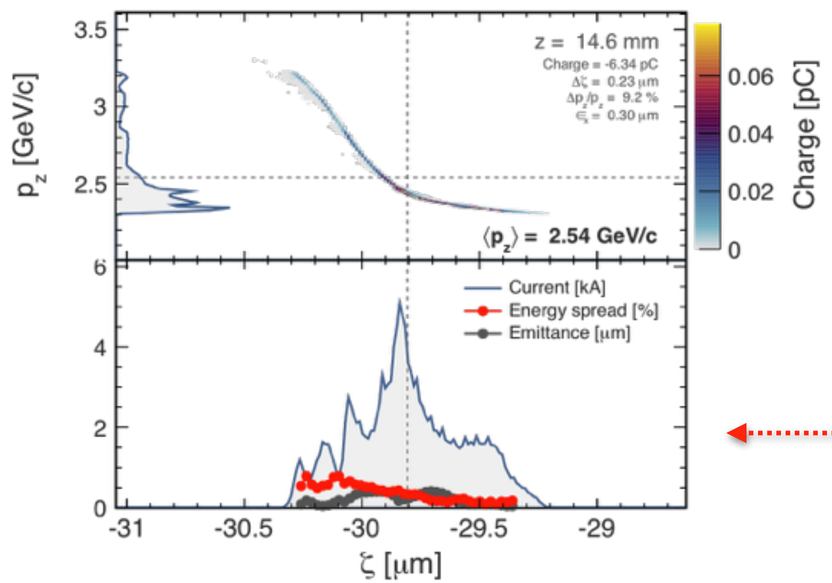
Transverse wakefields

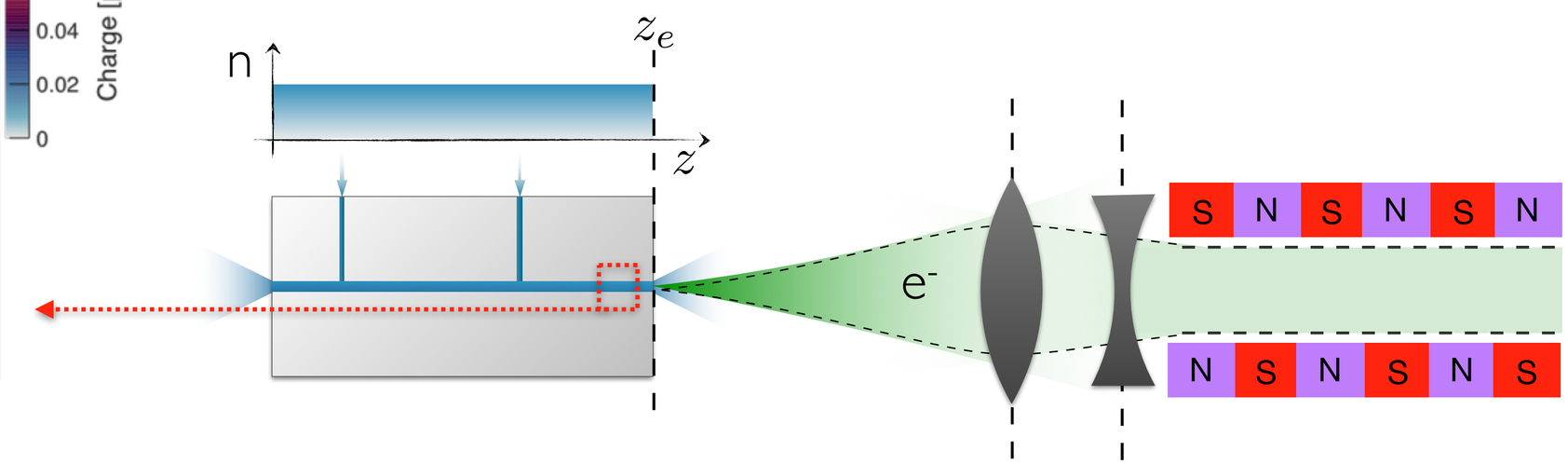


Final emittance $\epsilon_{n,f} = \frac{\epsilon_n}{2}\left(\frac{1+\hat{\alpha}^2}{\hat{\beta}/\hat{\beta}_m} + \hat{\beta}/\hat{\beta}_m\right)$

- Matched beta for 1 GeV beams in 10^{17} cm^{-3} plasmas = 1 mm
- FLASH beams β ~100 mm at waist.

Beam extraction: Also needs for matching





Witness beam in plasma

- Parameters:
  Energy ~2.5 GeV
  Peak current 5 kA
  Bunch duration 770 as
  Transverse emittance ~300 nm
  Uncorrelated energy spread < 1%
- Correlated energy spread 9 %
- Beta function ~1 mm

Extraction from plasma

- Main scientific challenge:
  How to preserve beam properties in plasma-to-vacuum transition?
- Small beta function, large energy spread:
  - (a) emittance growth[1]
  - (b) bunch lengthening

Application in FEL

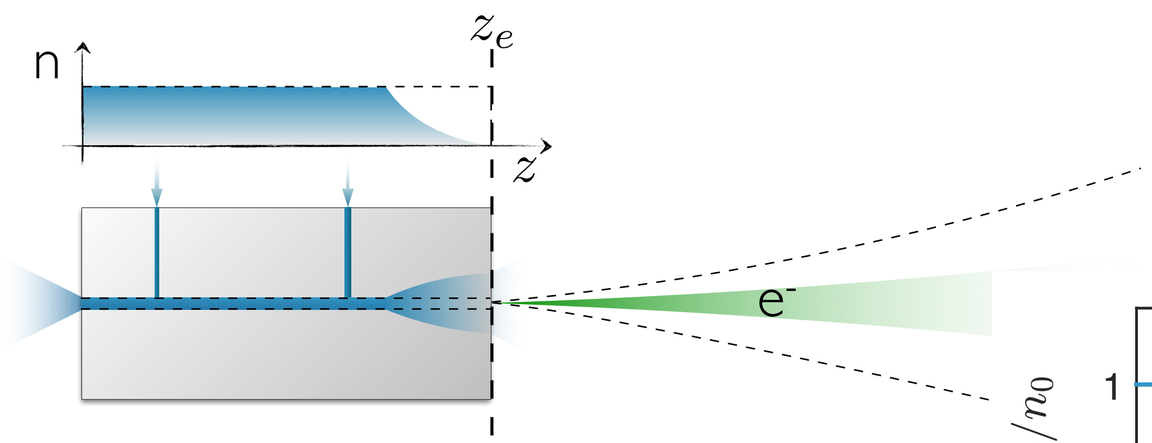
- Goal: demonstration of gain
- Requires excellent properties, low emittance, high current, low energy spread

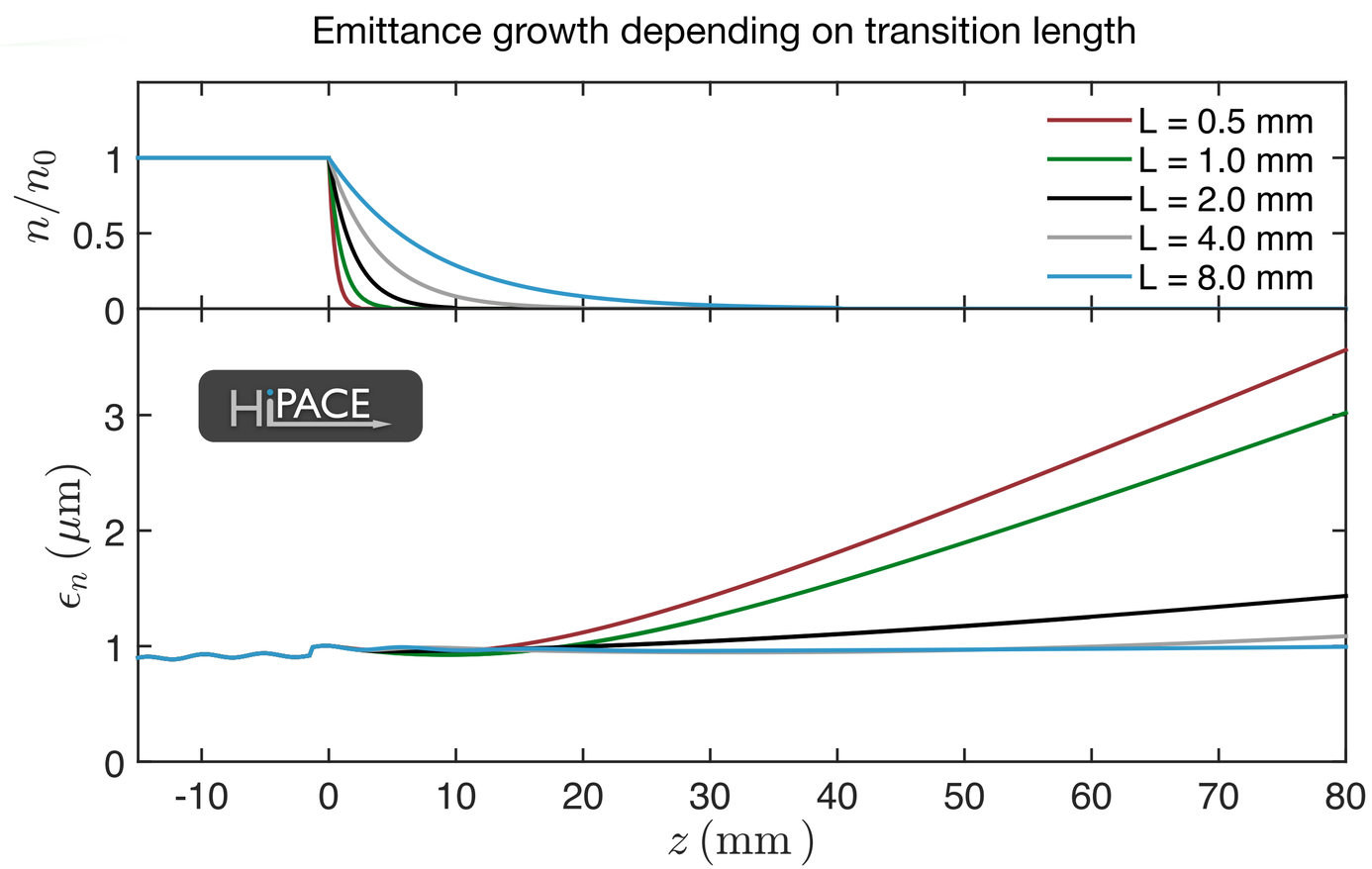
Scientific challenge

[1] K. Floettmann, Phys. Rev. ST Accel. Beams 6, 034202 (2003)

Beam extraction:
Adiabatic transitions to minimize emittance growth

> Mehrling, PhD Thesis, Universität Hamburg (2014).



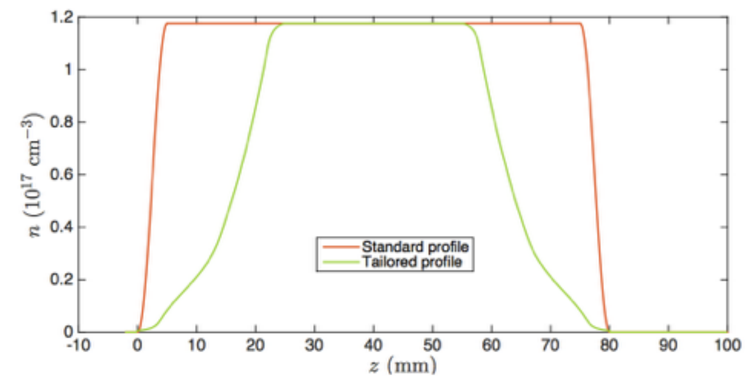


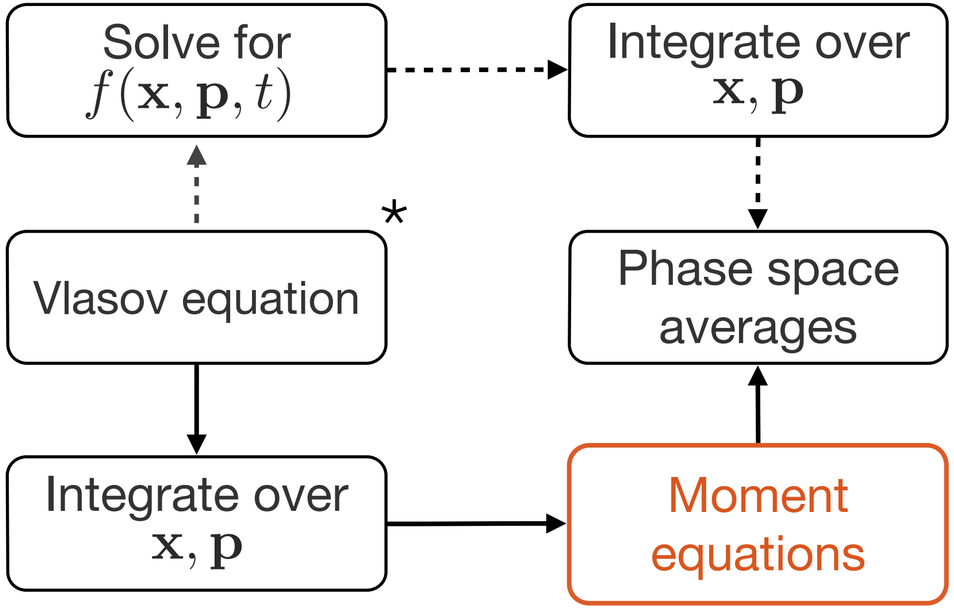
- **Quality preserving extraction** challenging due to small betatron function and sizeable energy spread.
- Simulations with HiPACE show: **Tapered plasma density extraction** enables quality-preserving beam extraction

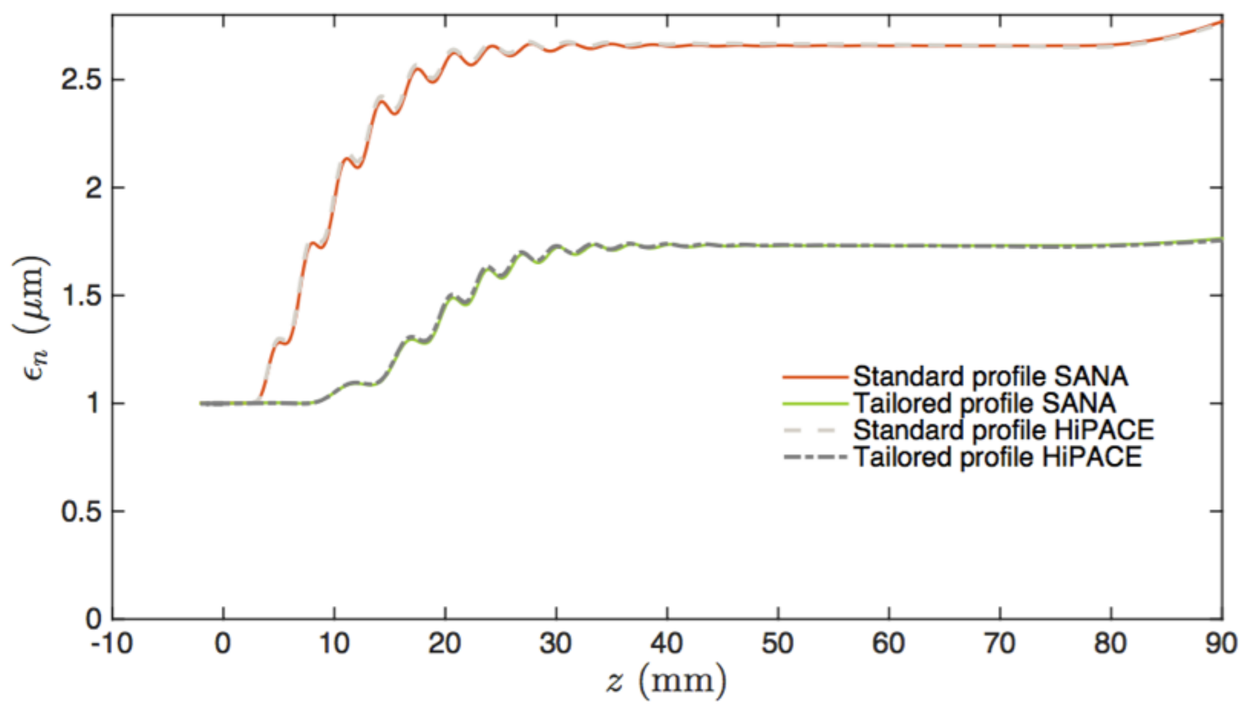
Quality preservation: Analytic model for emittance growth

> R.E. Robson et al., Annals of Physics 356 (2015) 306–319

- New Analytical approach based on moment equations
- Calculated phase space averages and emittance analytically
- Allows for fast probing of tailored plasma entries and exits.
- Results agree well with results from HiPACE simulation.





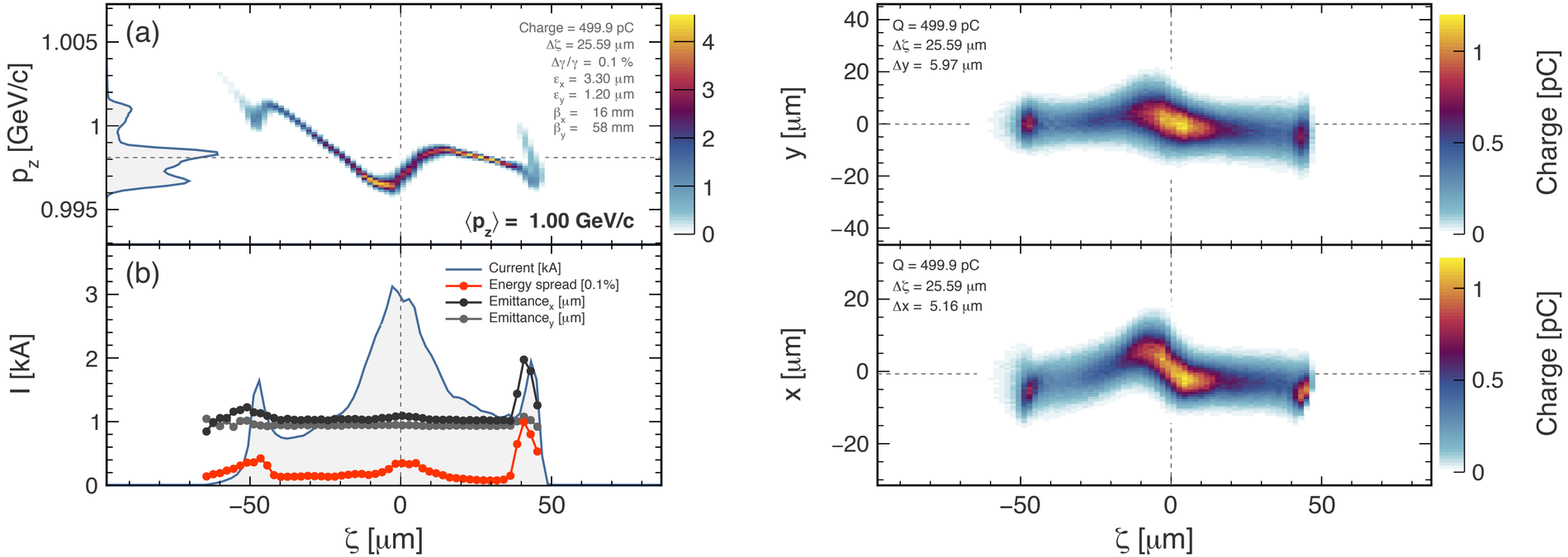


$$* \quad (\partial_t + \mathbf{v} \cdot \nabla + \partial_{\mathbf{p}} \cdot \mathbf{F}) f(\mathbf{x}, \mathbf{p}, t) = 0$$

Start-to-end simulations:
Simulating realistic drivers in plasma

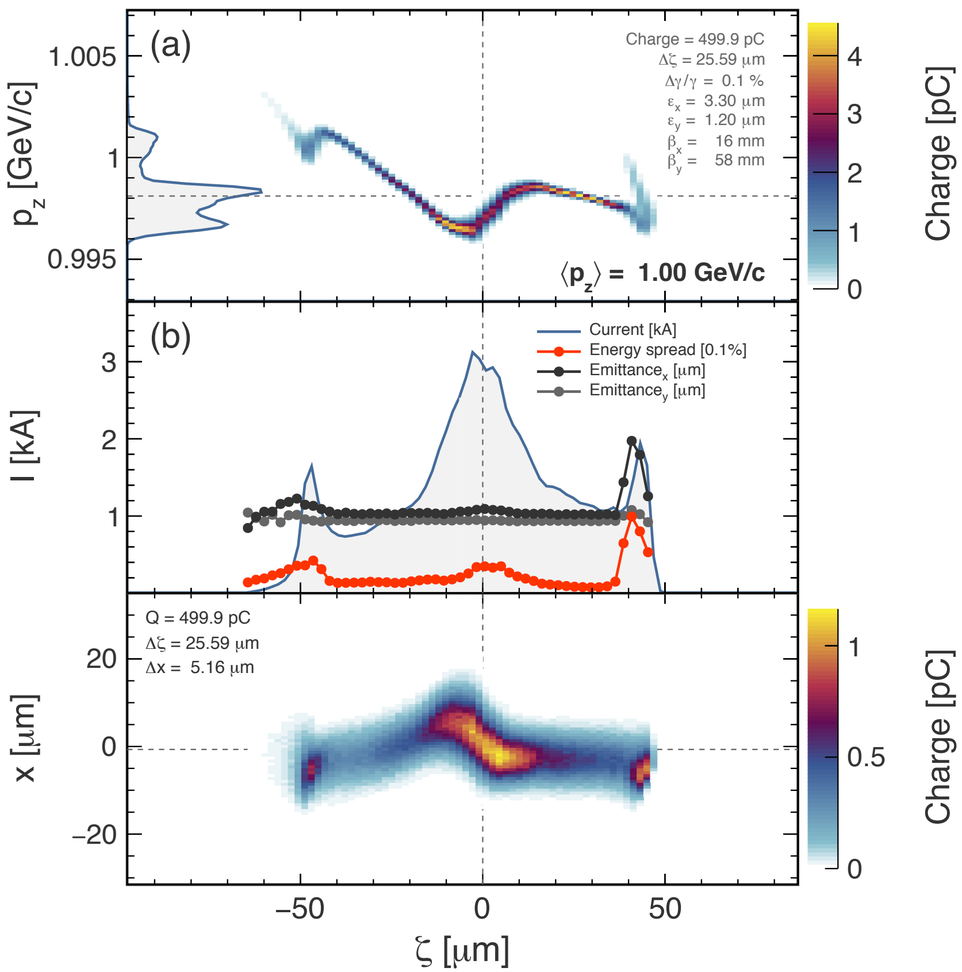
- HiPACE is ready for 6D phase-space beam initialization.
- OSIRIS can do it as well (since early 2015).
- ELEGANT simulations of FLASH beams up to plasma target are operative:

Beam: 500 pC R56 max

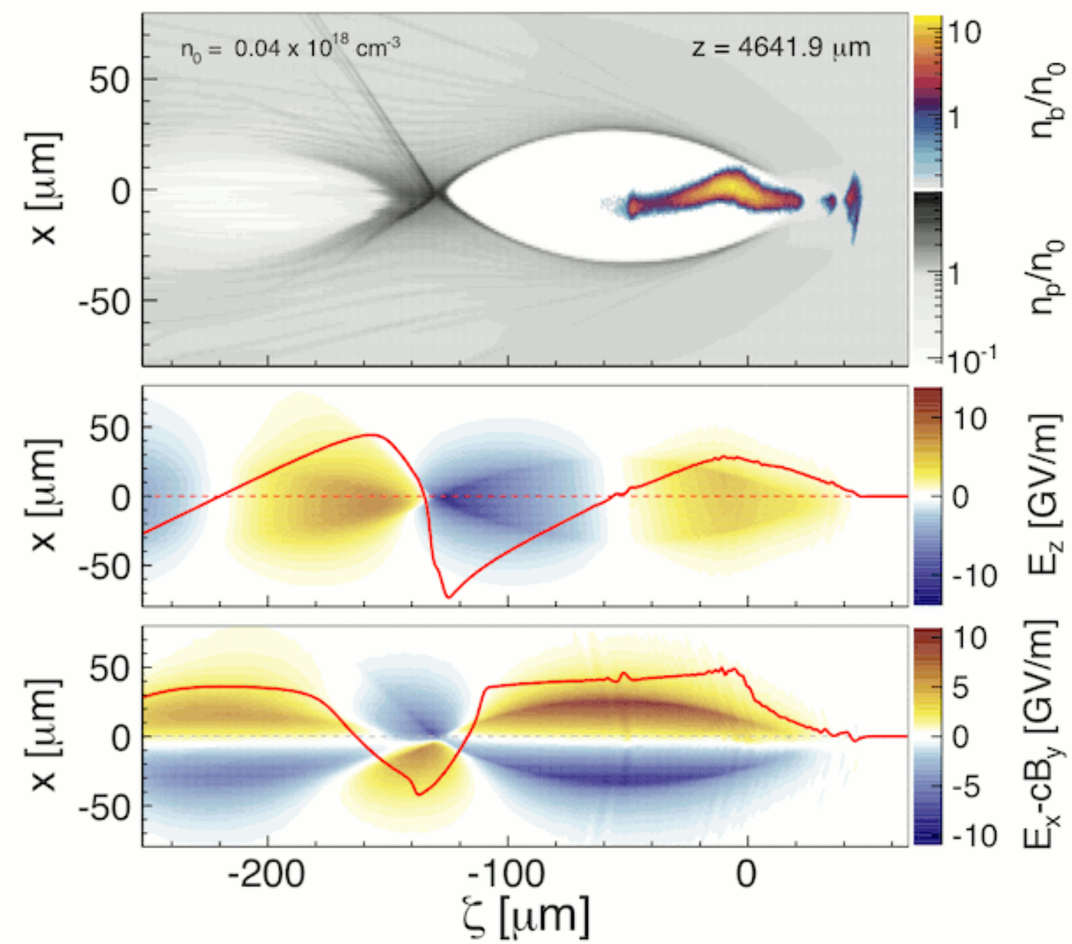


Start-to-end simulations:
Simulating realistic drivers in plasma

Beam: 500 pC R56 max



OSIRIS-3D simulation with realistic FLASH beam



Start-to-end simulations: A model for the hosing

Hosing seed parameter:

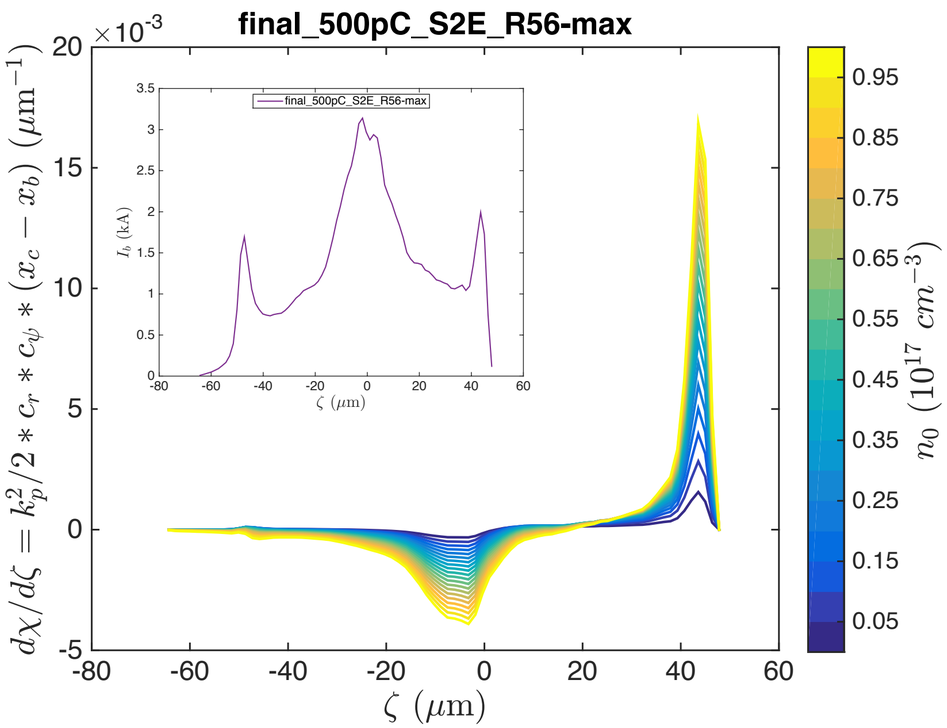
$$\chi = \int \frac{c_r c_\psi k_p^2}{2}(x_b - x_c)d\xi$$

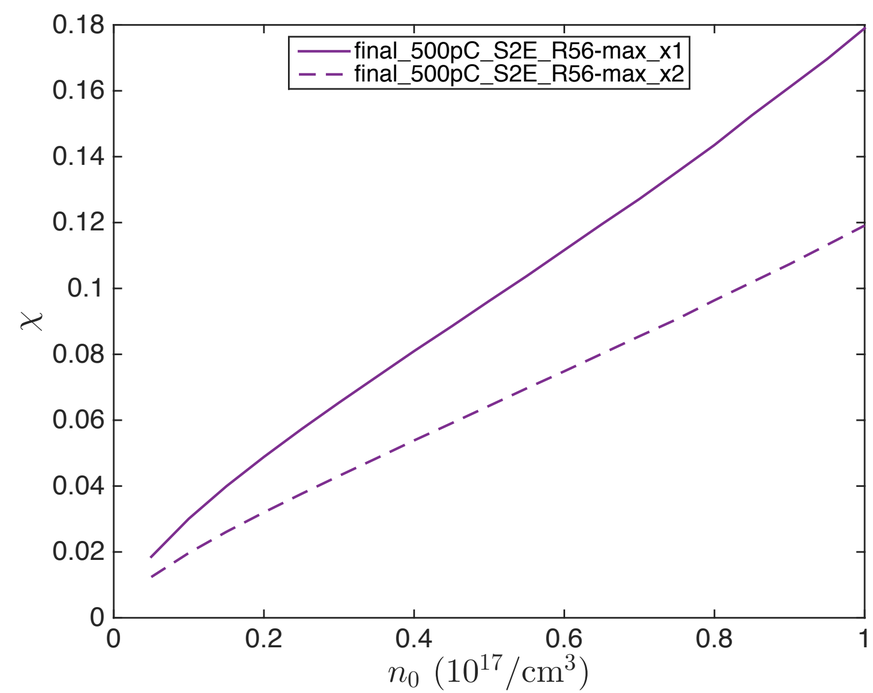
$$\partial_s^2 x_b = -k_\beta^2(x_b - x_c)$$

$$\partial_\xi^2 x_c = \frac{c_r c_\psi k_p^2}{2}(x_b - x_c)$$

Differential equations, describing centroid dynamics.

Huang et al. *Phys. Rev. Lett.* **99**, 255001 (2007)





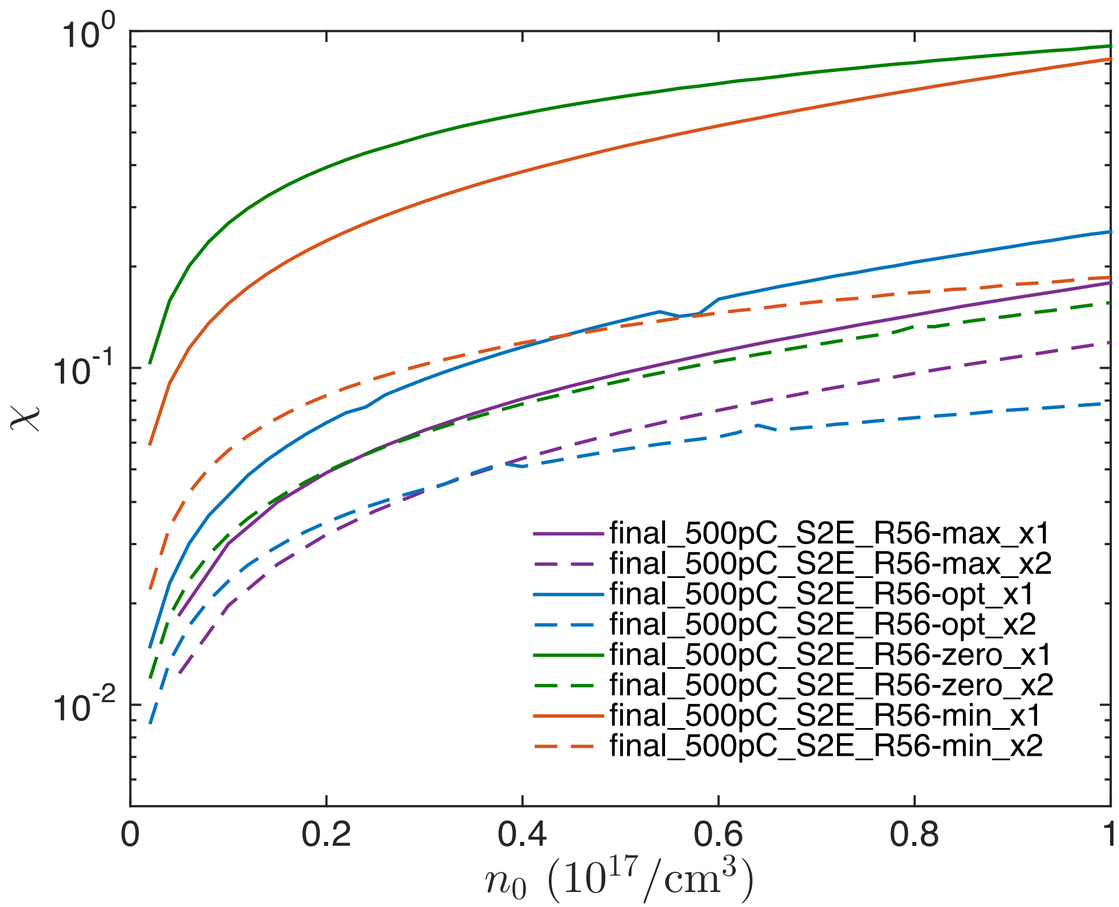
$$c_\psi = \frac{1}{1+\psi_0}$$

$$c_r = \frac{\Lambda}{(k_p r_b)^2}$$

$$\Lambda = \frac{4I_b}{I_A}$$

Start-to-end simulations:
Allows for numerical beam evaluation and optimization

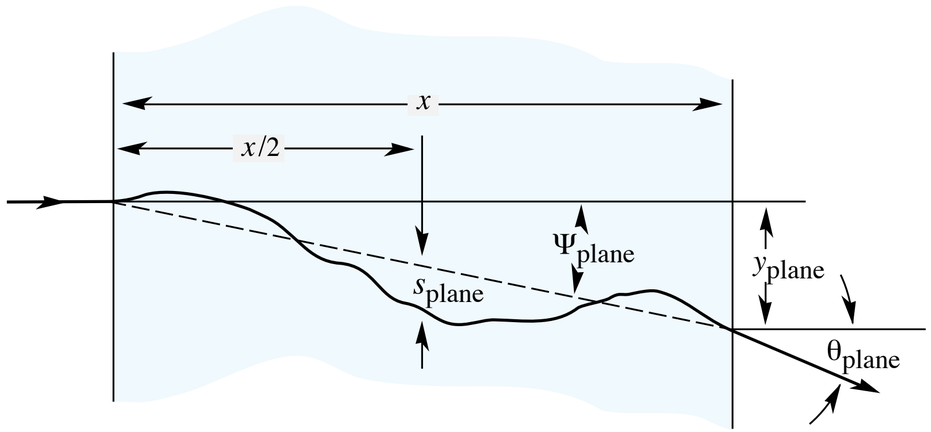
Hosing seed parameter:



- Simulated beams at the plasma entrance have varying properties.
- The model allows for quick numerical beam evaluation and optimization.
- Rule of thumb: High-current part in the tail.
- Only first order effects.
  - Emittance is not taken into account for the dynamics of transverse phase space.
  - Requires more accurate modeling.
- Studies with full PIC simulations still needed.
  - For beam optimization prior to the plasma cell.
  - HiPACE for improved performance.

Start-to-end simulations: Emittance spoilers

Multiple scattering through small angles



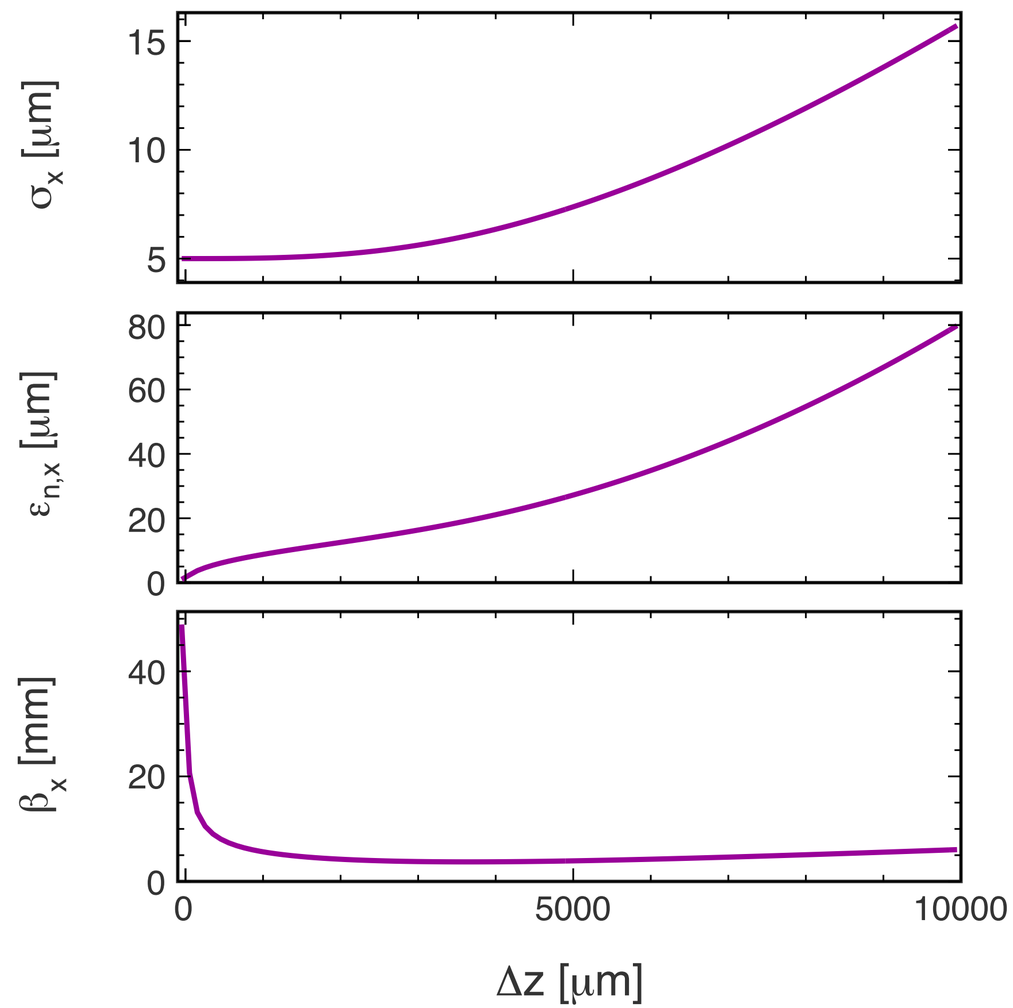
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right] .$$

$$y^{\,\mathrm{rms}}_{\,\mathrm{plane}} = \frac{1}{\sqrt{3}}\, x\, \theta^{\,\mathrm{rms}}_{\,\mathrm{plane}} = \frac{1}{\sqrt{3}}\, x\, \theta_0 \ ,$$

Material	X_0 (cm)
Be	35,28
Al	8,897

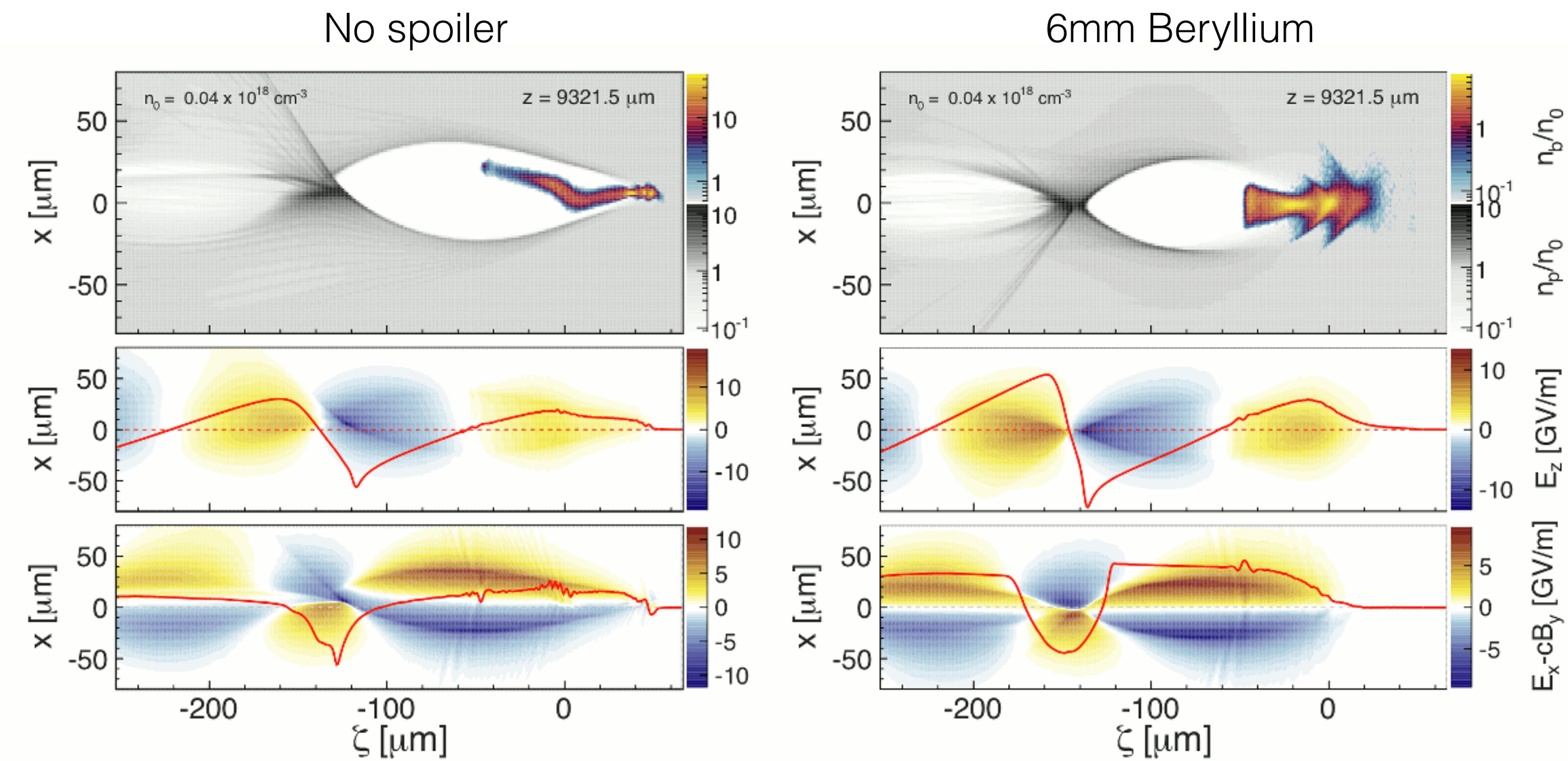
matched beta

$$\beta_m \simeq 1.051\ \mathrm{mm}\ \sqrt{\frac{10^{17}\ \mathrm{cm}^{-3}}{n_0}}$$



http://pdg.lbl.gov/2013/reviews/rpp2012-rev-passage-particles-matter.pdf
http://pdg.lbl.gov/2014/AtomicNuclearProperties/

Start-to-end simulations: Emittance spoilers



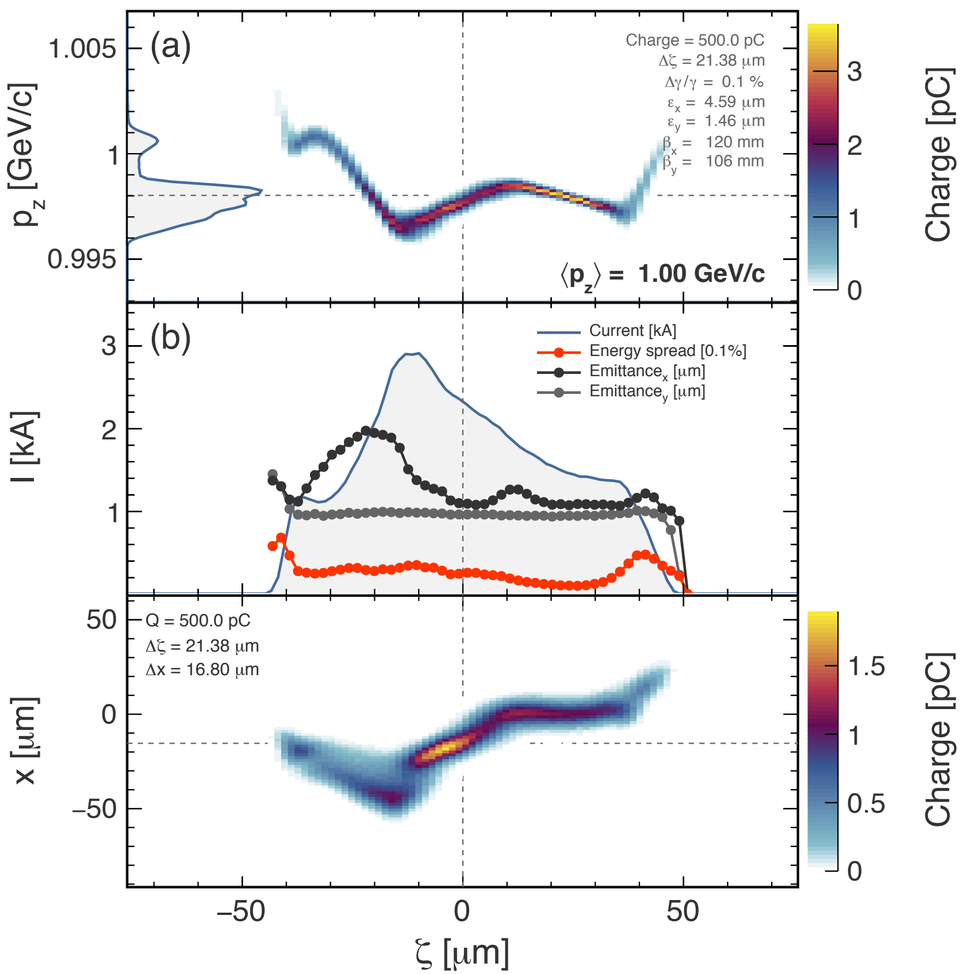
Summary and conclusions

- WG1 simulations develops theoretical understanding on PWFA for applications.
- PIC codes: OSIRIS and HiPACE (for better performance in PWFA).
- Novel internal injection mechanism.
  - High-quality bunches for FEL application.
- External injection and beam extraction studies:
  - Beams need to be matched for emittance preservation.
  - Tailored plasma-vacuum transitions for adiabatic matching.
- Start-to-end simulations framework ready for realistic studies in FLASHForward:
  - Reading of 6D particle beams implemented in OSIRIS and HiPACE.
  - Hose instability may severely affect quality and stability of accelerated beams
  - Analysis and mitigation of hose-instability crucial for FLASHForward:
    - Theoretical models for hosing and beam assesment.
    - Solutions: Beam optimization, emittance spoilers, etc.
  - PIC simulations with realistic plasma distributions, and laser profiles.

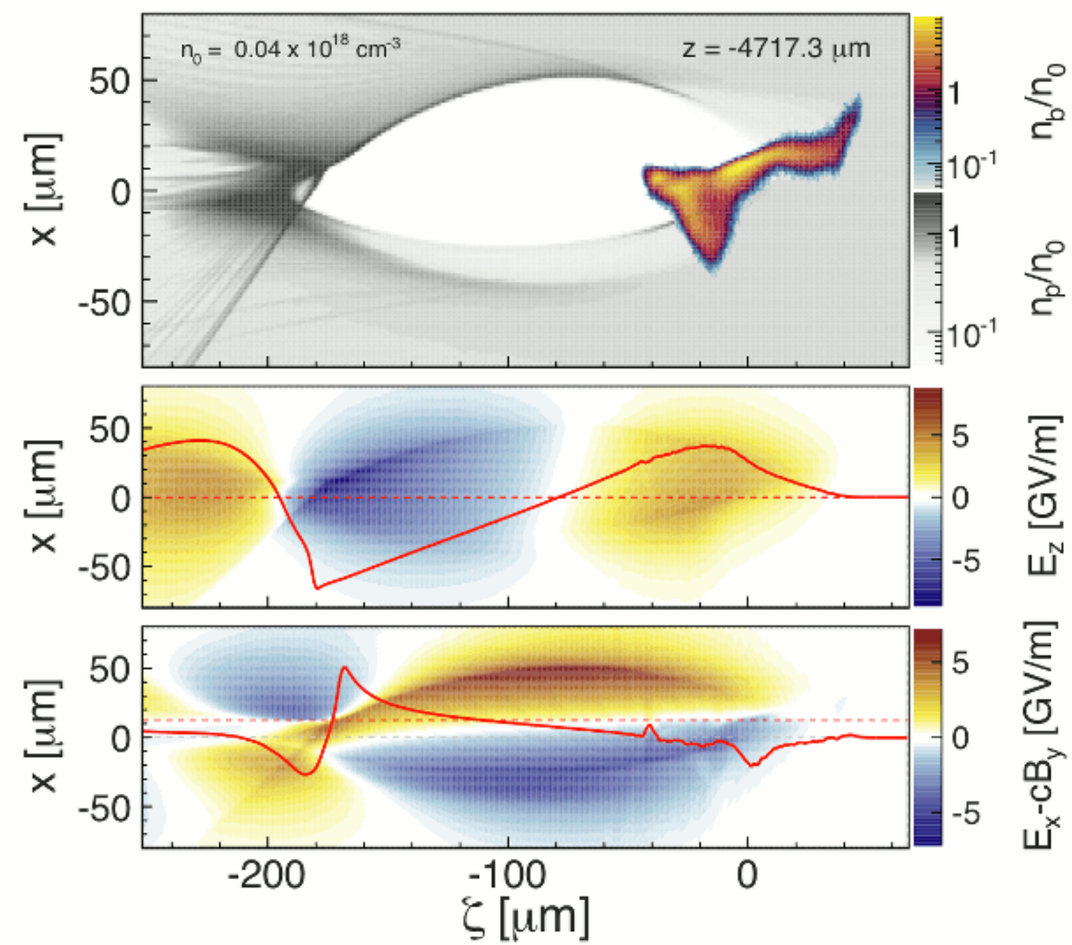
Backups

Start-to-end simulations:
Simulating realistic drivers in plasma

Beam: 500 pC R56 zero

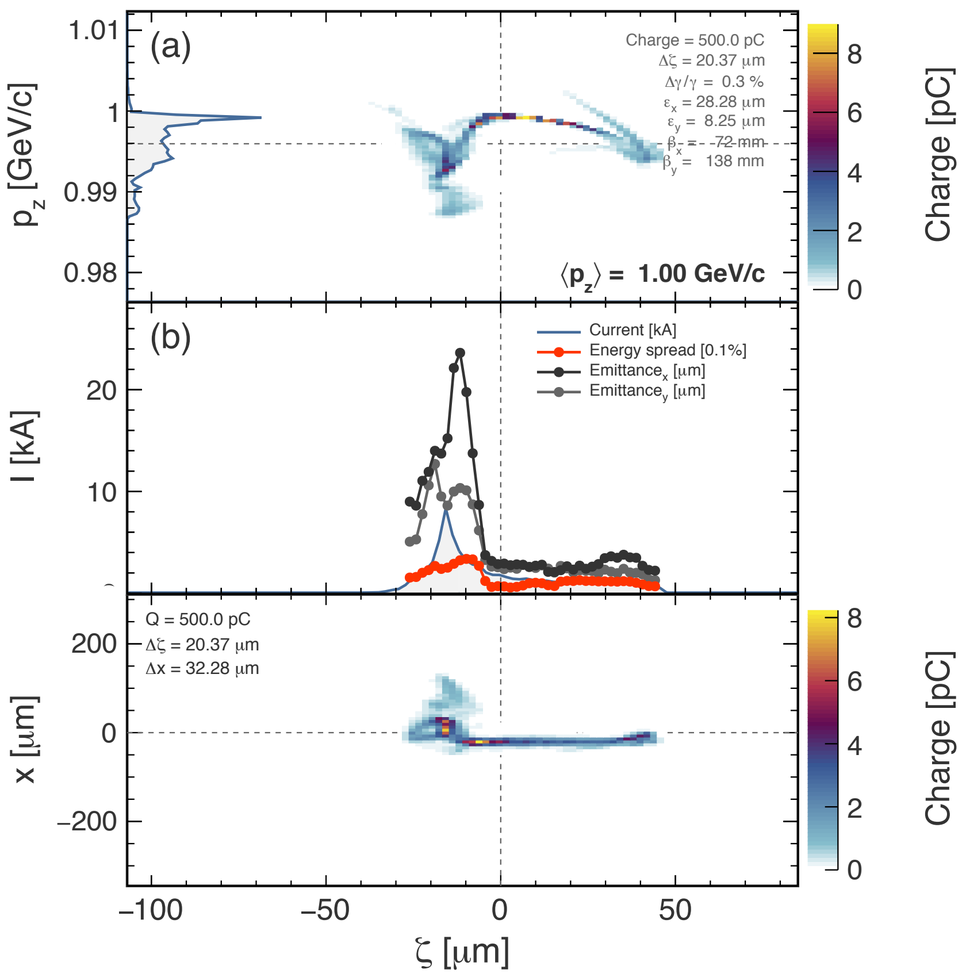


OSIRIS-3D simulation with realistic FLASH beam



Start-to-end simulations:
Simulating realistic drivers in plasma

FLFP_Ip9kA



OSIRIS-3D simulation with realistic FLASH beam