Energy-chirp compensation in plasma

ATF proposal

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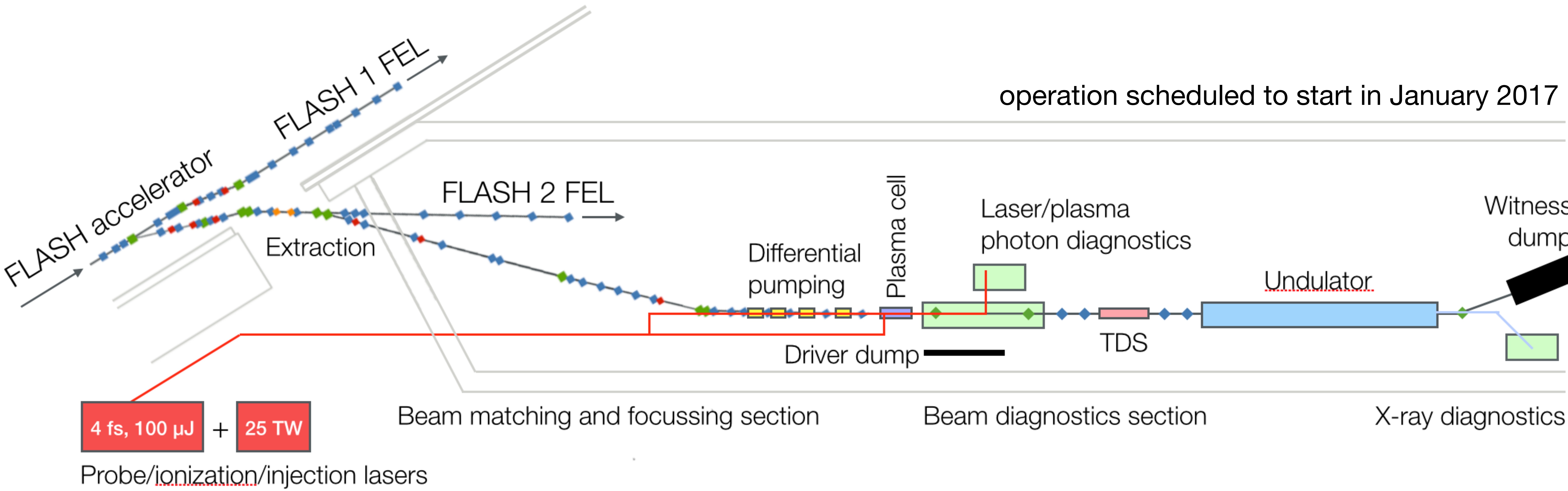
a 1 GeV beam-driven plasma wakefield accelerator facility

> **Main goal:** generate beams from a plasma wakefield accelerator of sufficient quality to show FEL gain at few nm



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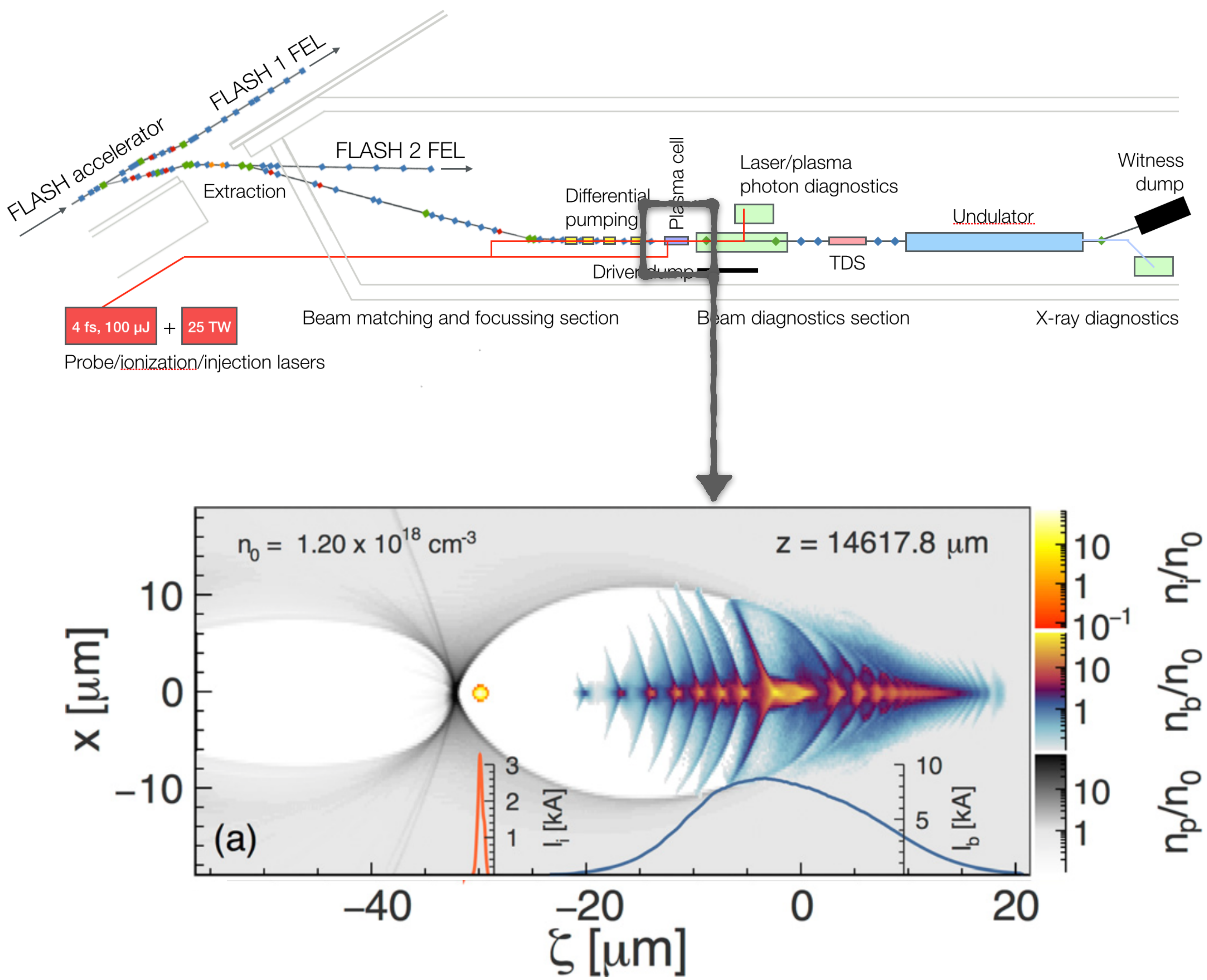
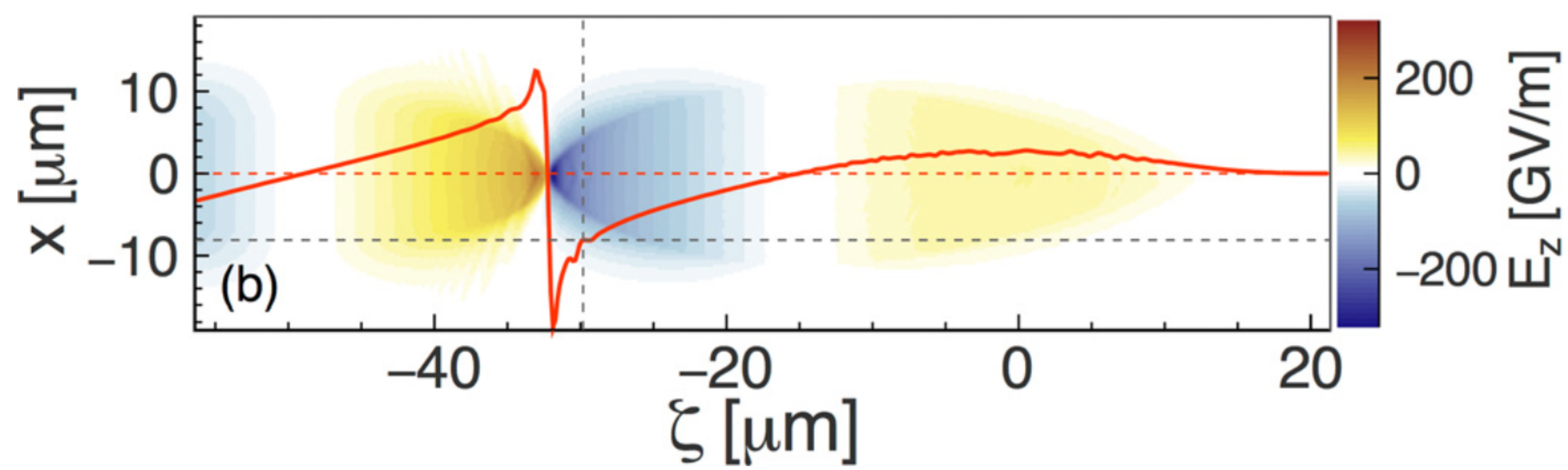
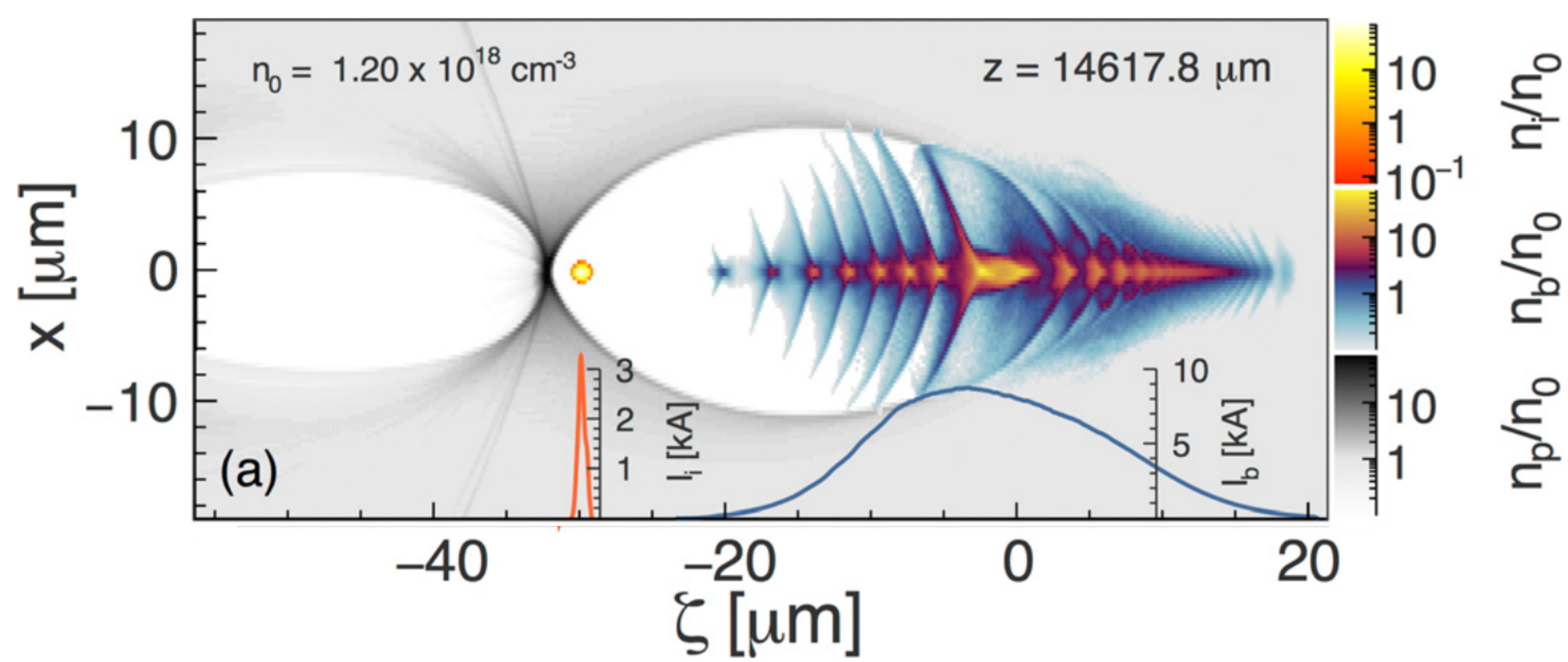


Plasma accelerators operate off-crest, produce chirped beams





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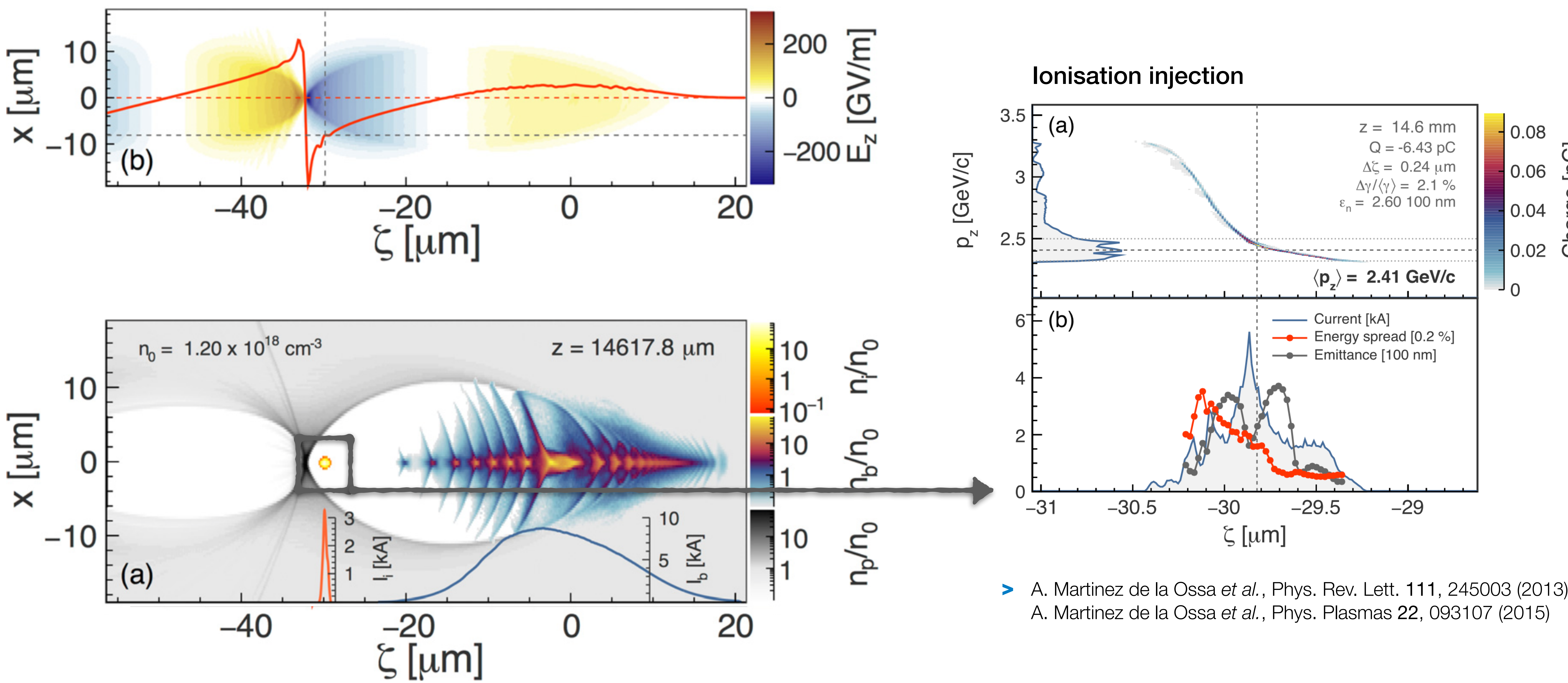
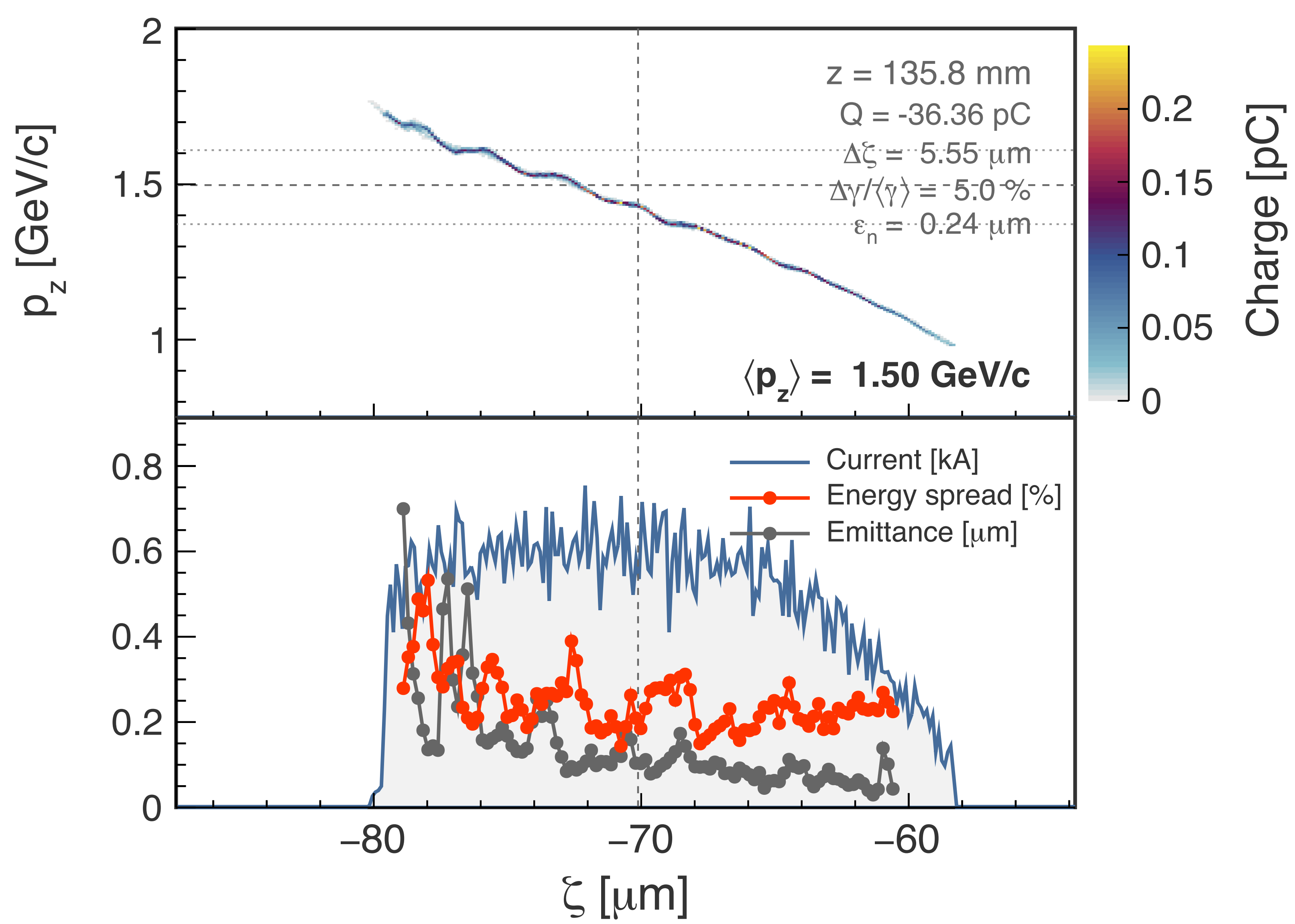


- A. Martinez de la Ossa *et al.*, Phys. Rev. Lett. **111**, 245003 (2013)
  A. Martinez de la Ossa *et al.*, Phys. Plasmas **22**, 093107 (2015)

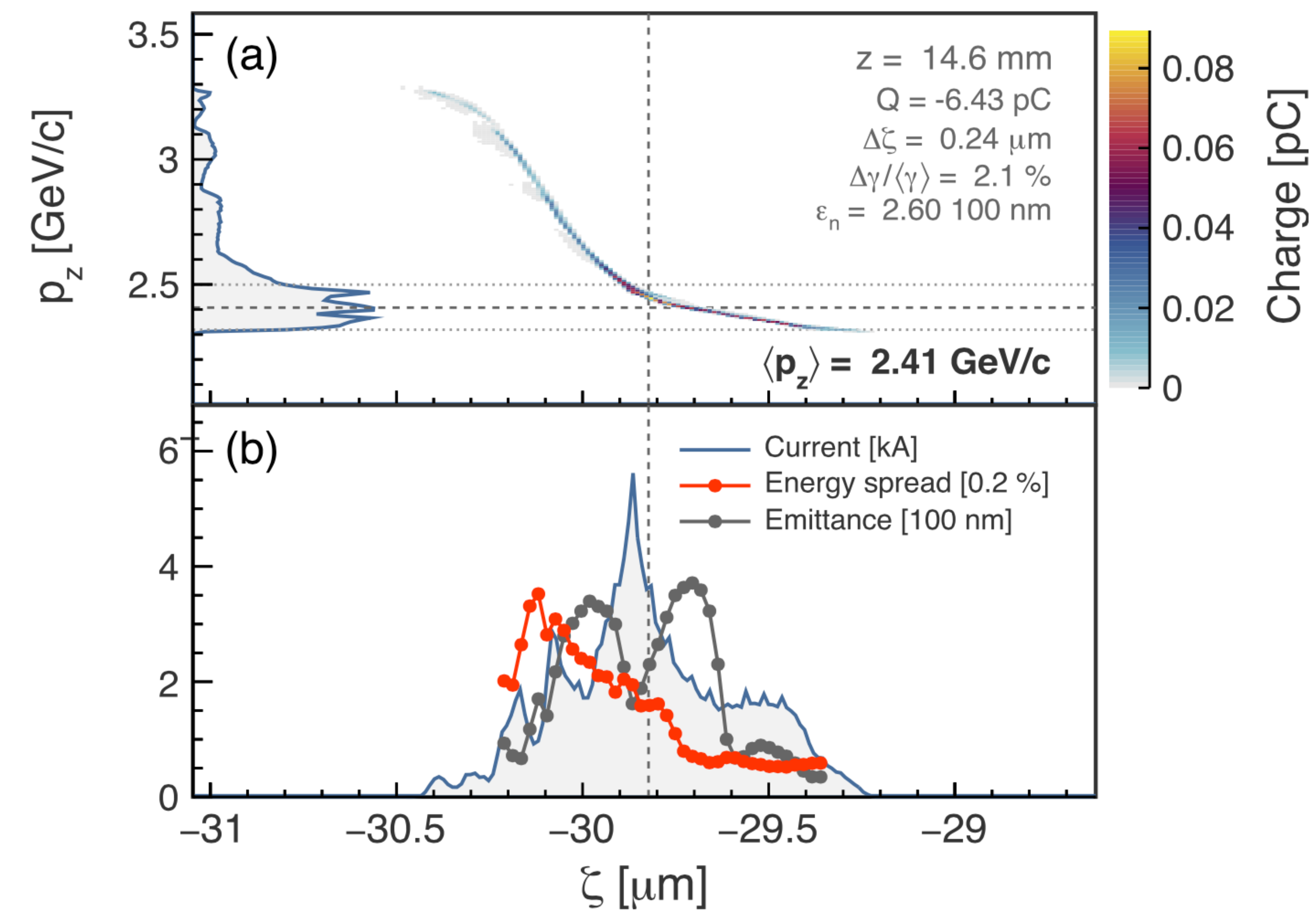
Plasma accelerators operate off-crest, produce chirped beams

- Negative chirps are characteristic for unloaded beam-driven wakefield accelerators

Density downramp injection



Ionisation injection



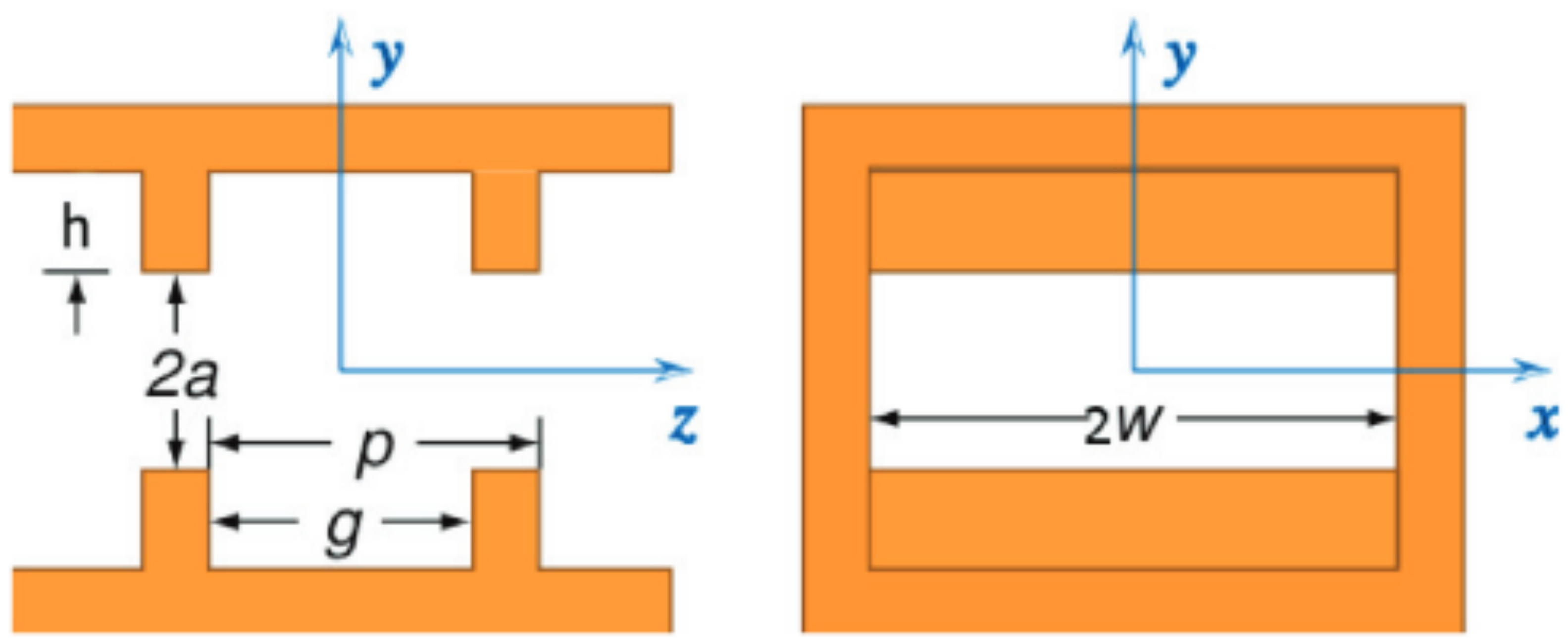
> Beam loading may be difficult to control + influence other beam properties, e.g. slice energy spread, transverse emittance

> Independent way of beam dechirping would be desirable

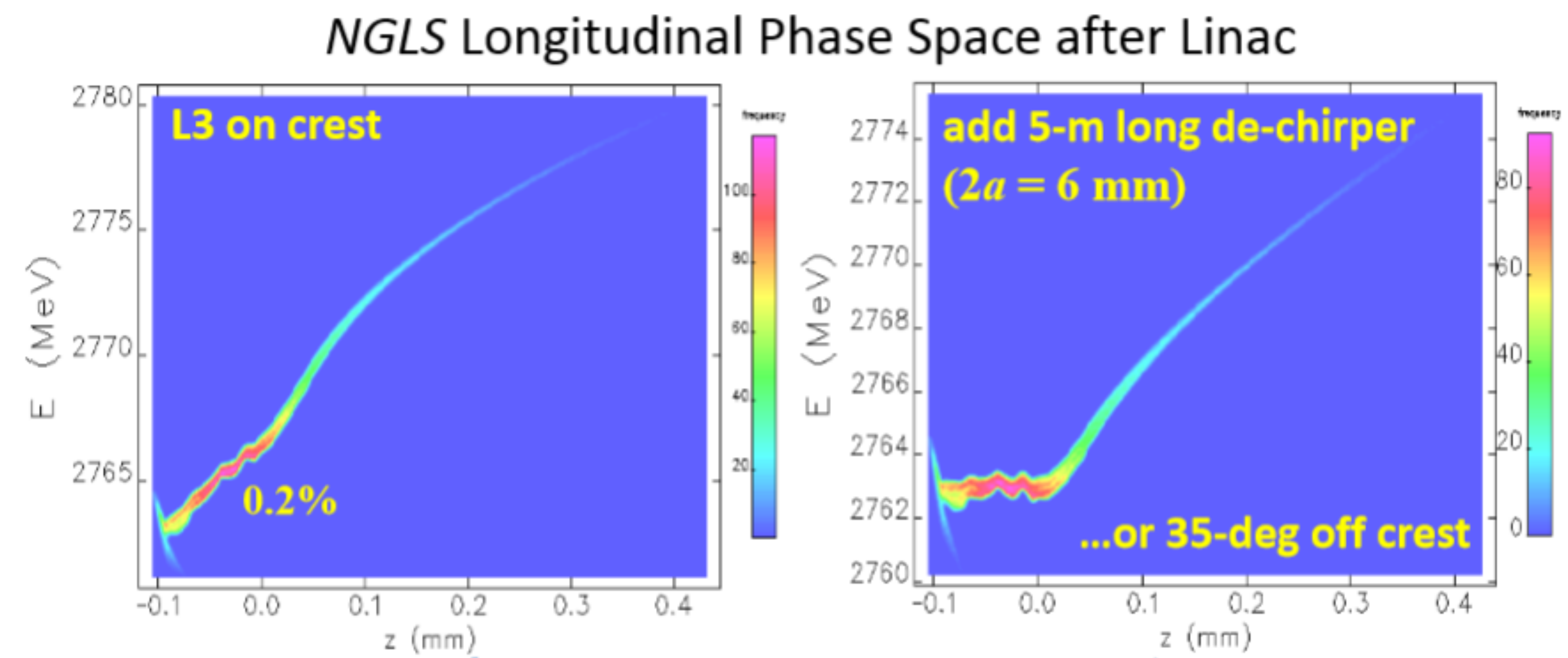
> A. Martinez de la Ossa *et al.*, Phys. Rev. Lett. **111**, 245003 (2013)
A. Martinez de la Ossa *et al.*, Phys. Plasmas **22**, 093107 (2015)

Wakefield-based beam dechirper techniques have been proposed and demonstrated

- **Corrugated pipe beam dechirper** - K.L.F. Bane, G. Stupakov, NIM A 690, 106 (2012)

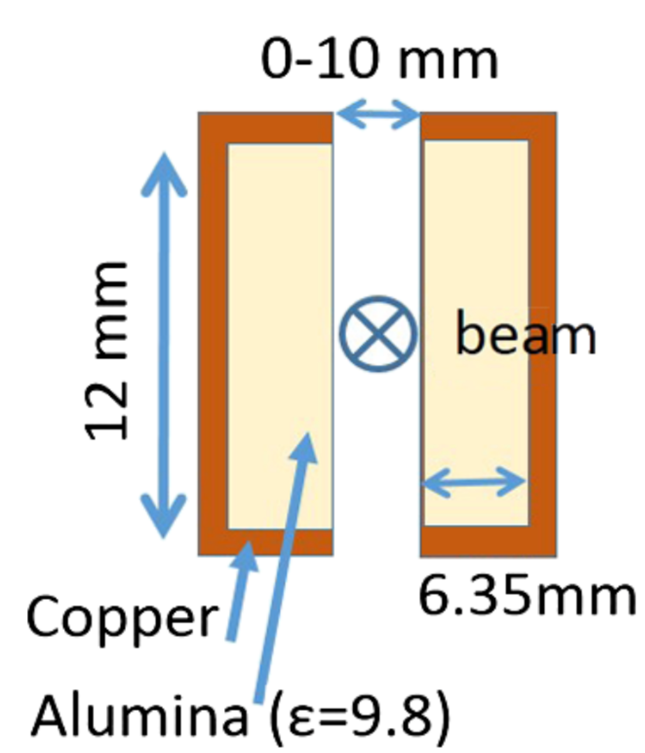


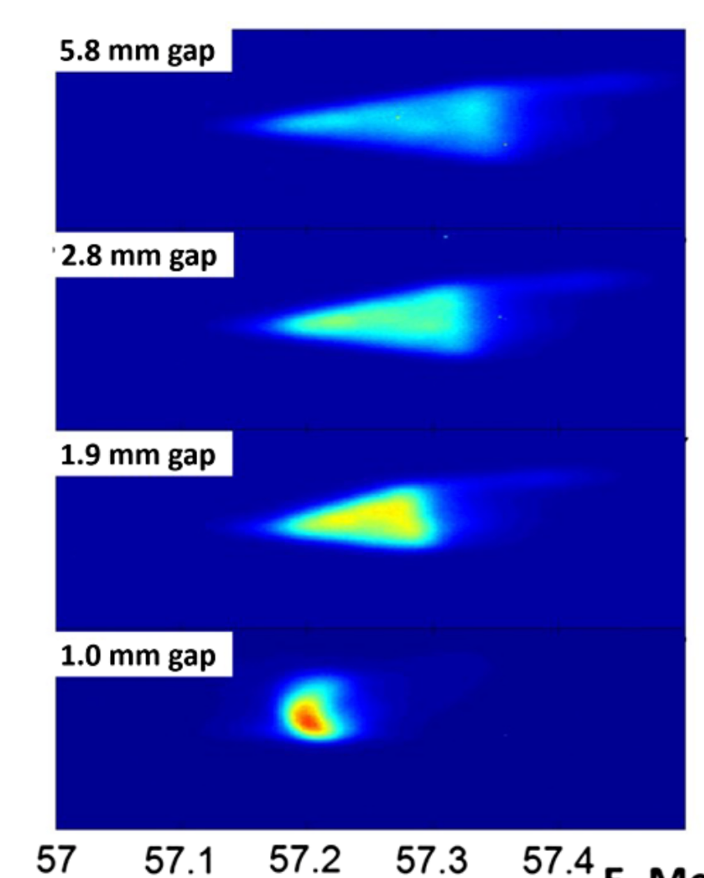
beam wakefields in the pipe are dechipripg

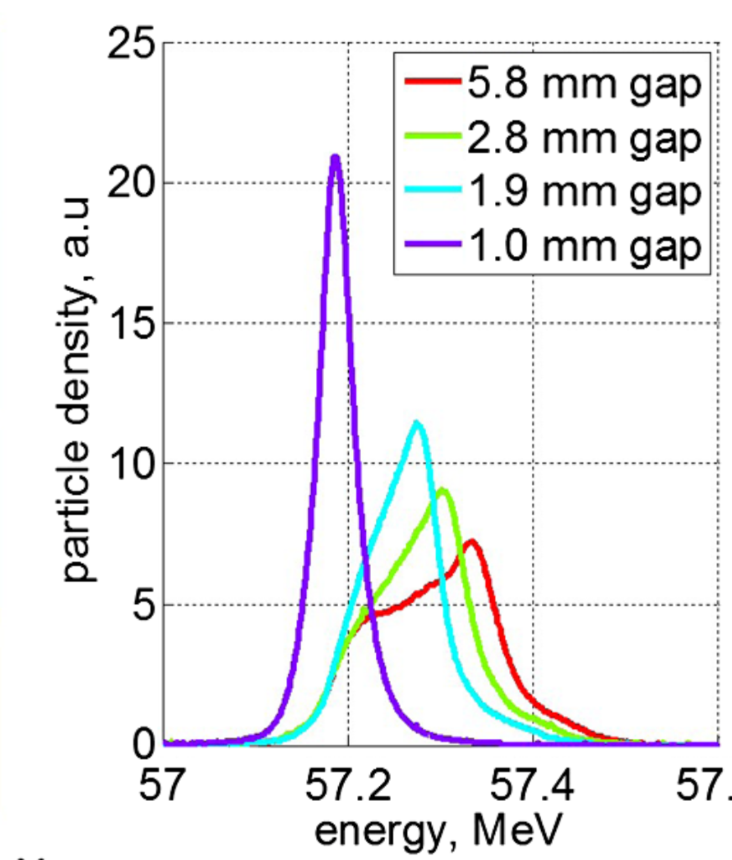


simulations by P. Emma

- **Chirp compensation by dielectric-based slab structure** - S. Antipov *et al.*, Phys. Rev. Lett. 112, 114801 (2014)







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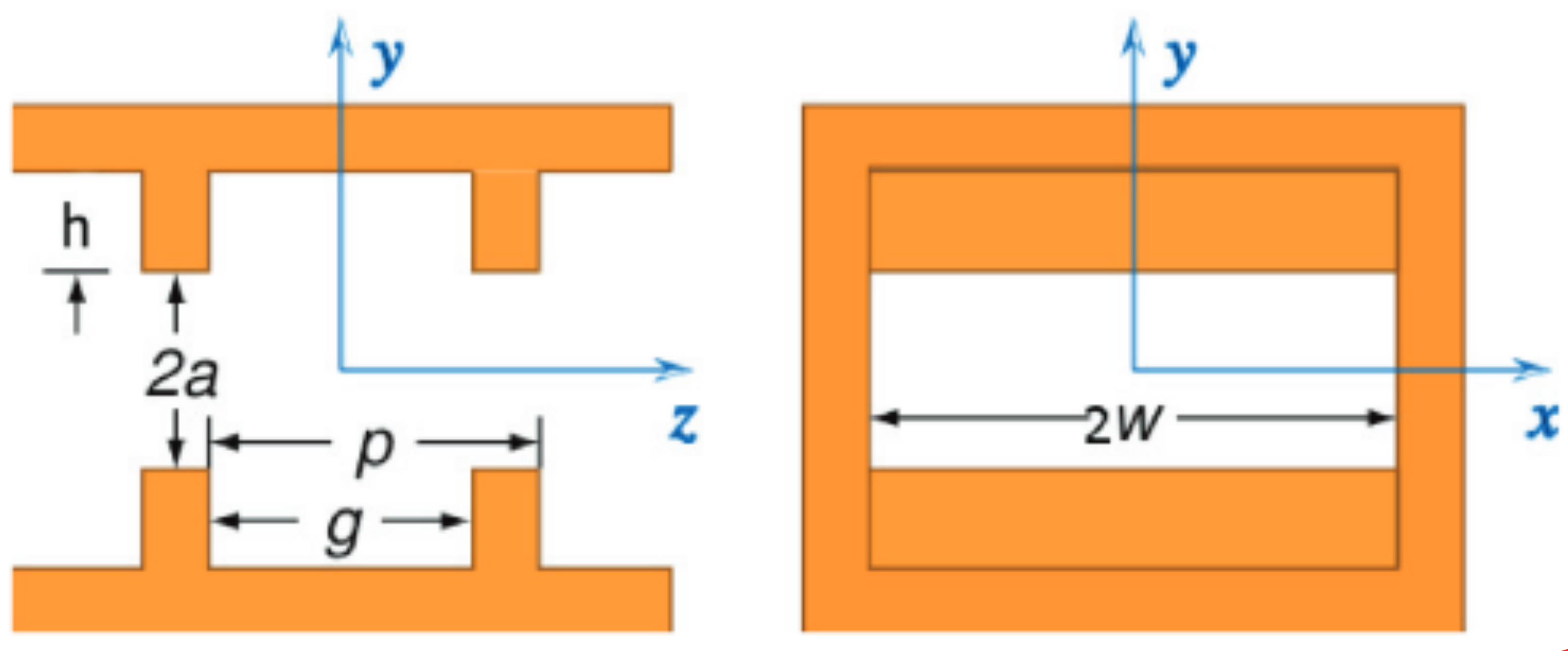

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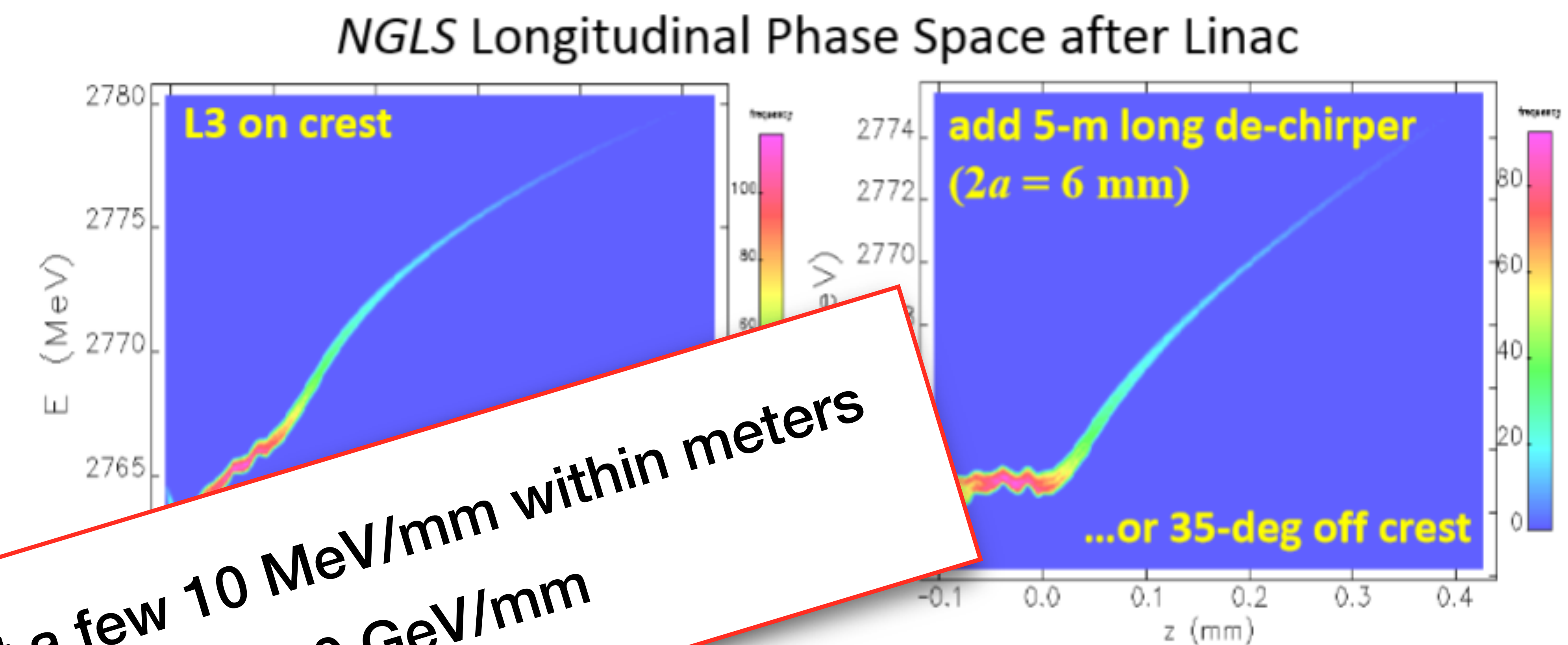
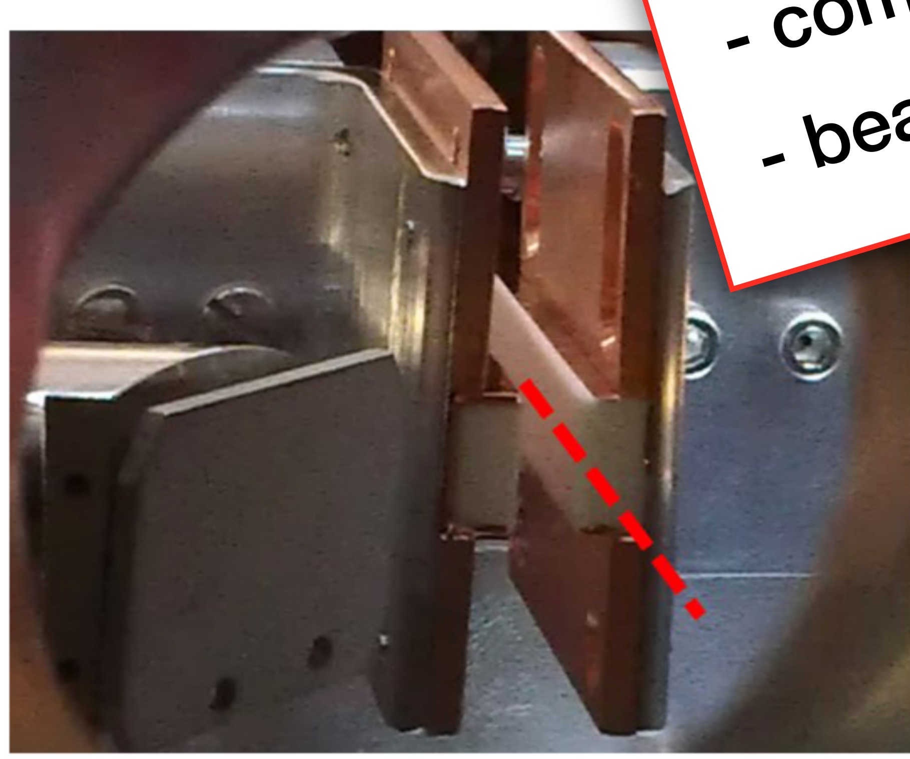
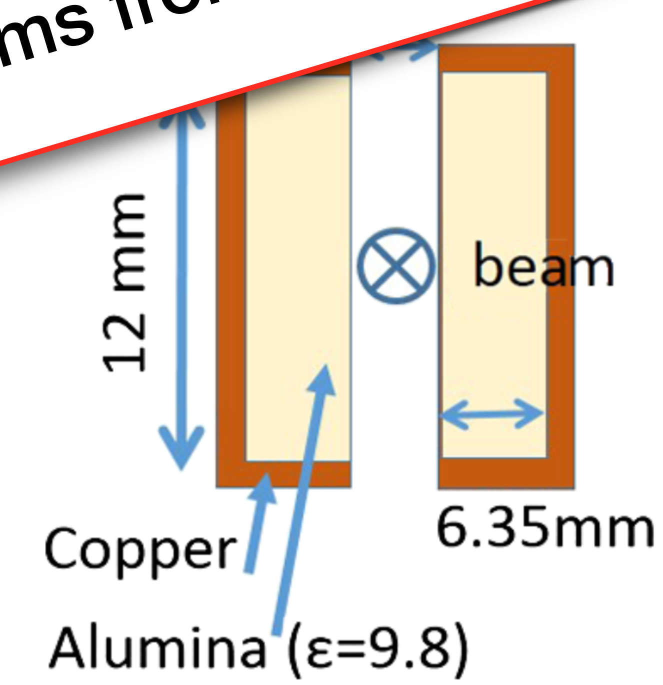


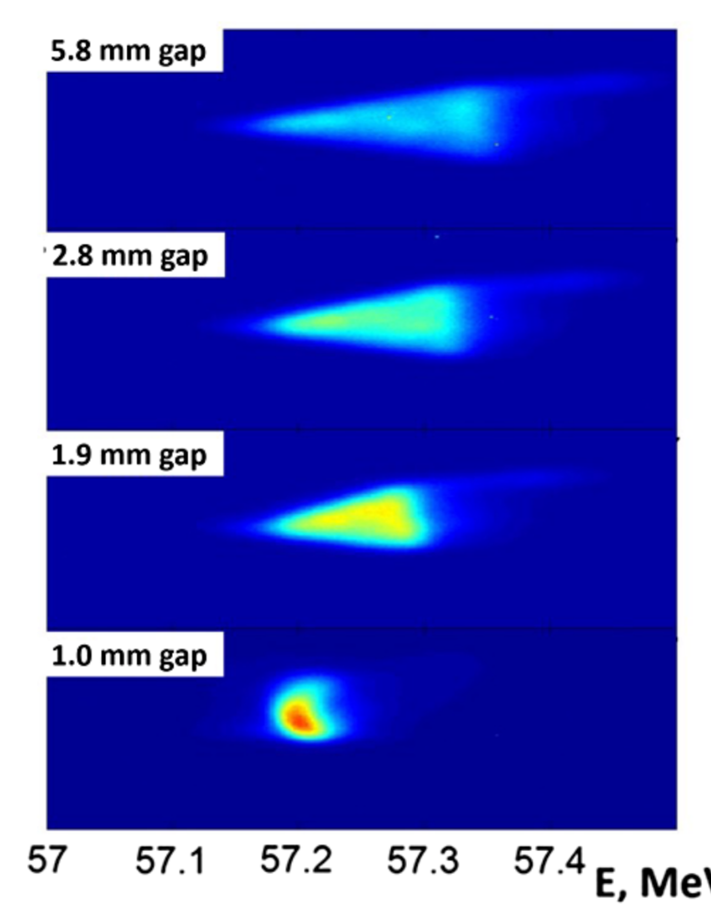
simulations by P. Emma

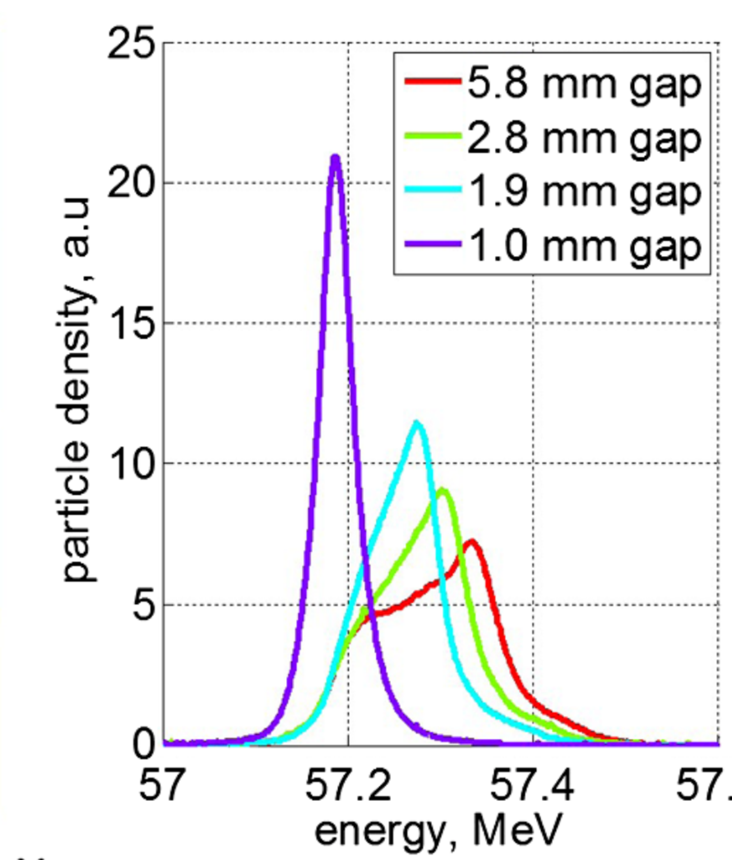
> **Chirp compensation by** ... pov *et al.*, Phys. Rev. Lett. 112, 114801 (2014)

- compensate energy chirps at a few 10 MeV/mm within meters
- beams from plasmas feature chirps of 10 GeV/mm

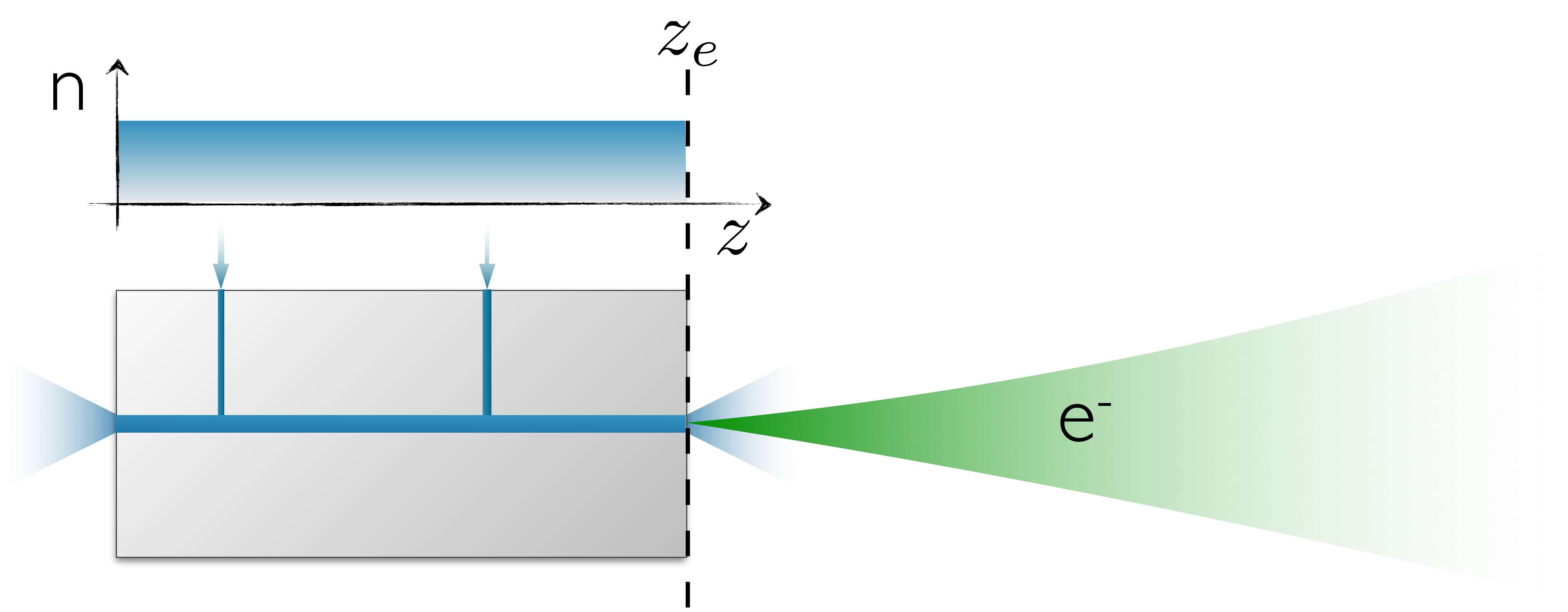


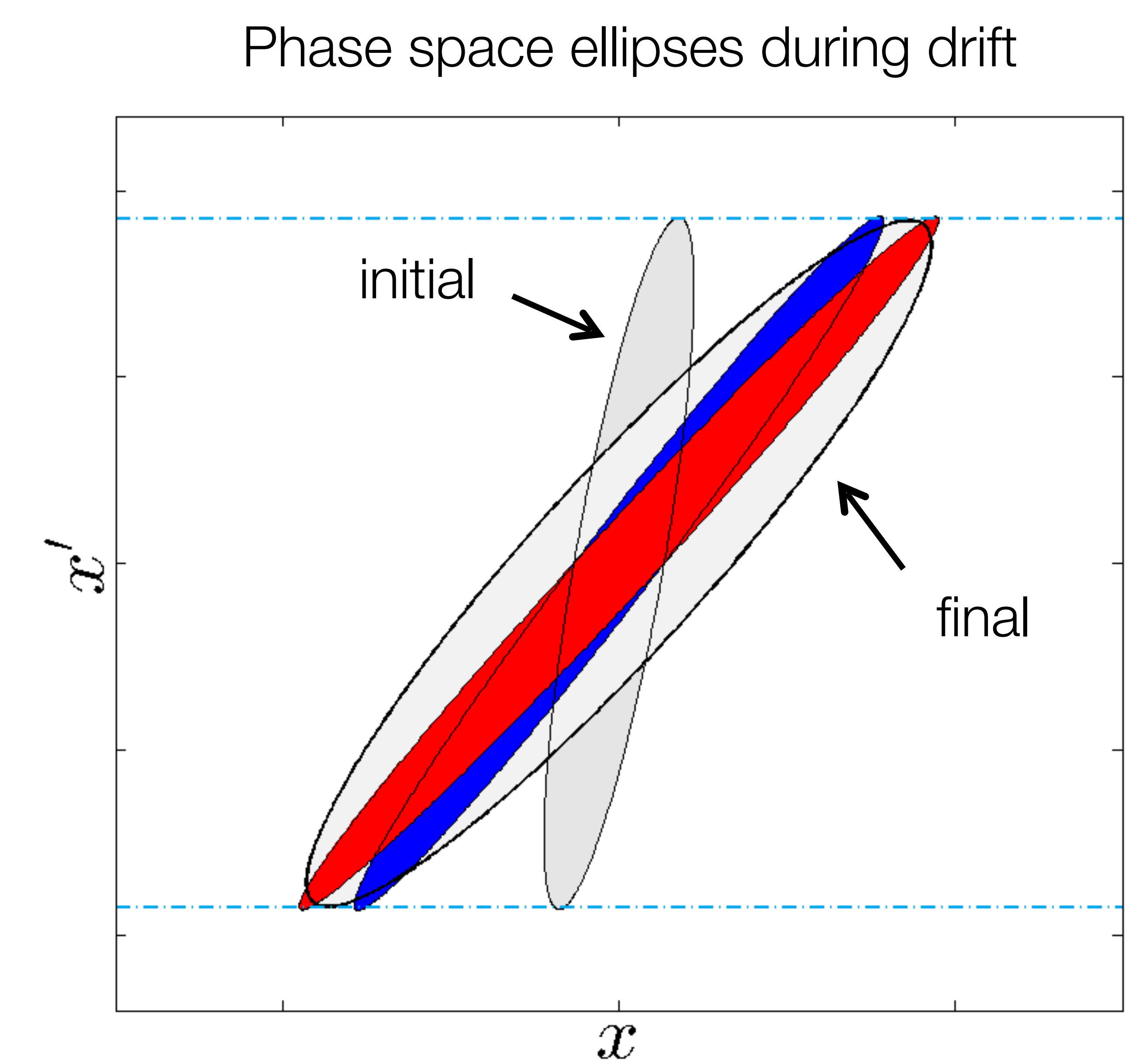






Chirp complicates beam transport and applications





- beams at plasma exit:
  - ~% level energy spread
  - small beta function, mrad divergence
- leads to transverse emittance growth in free drift

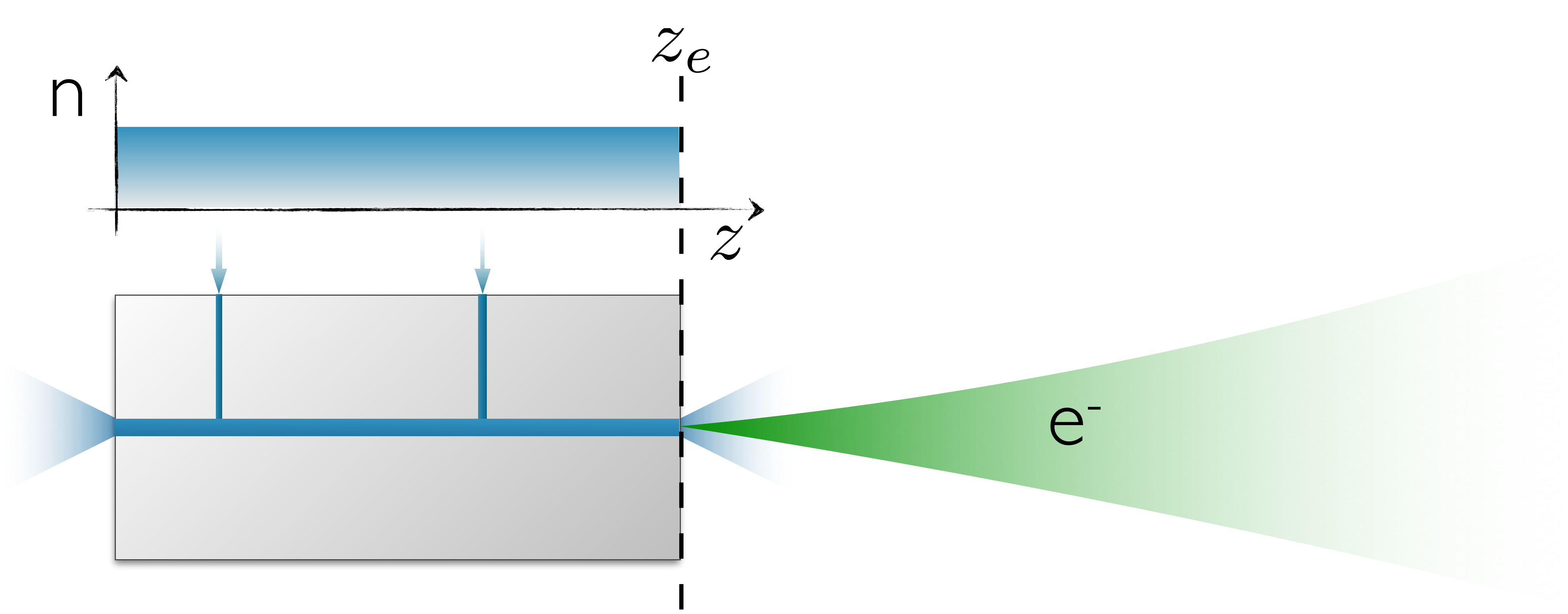
  → K. Floettmann, Phys. Rev. STAB 6, 034202 (2003)

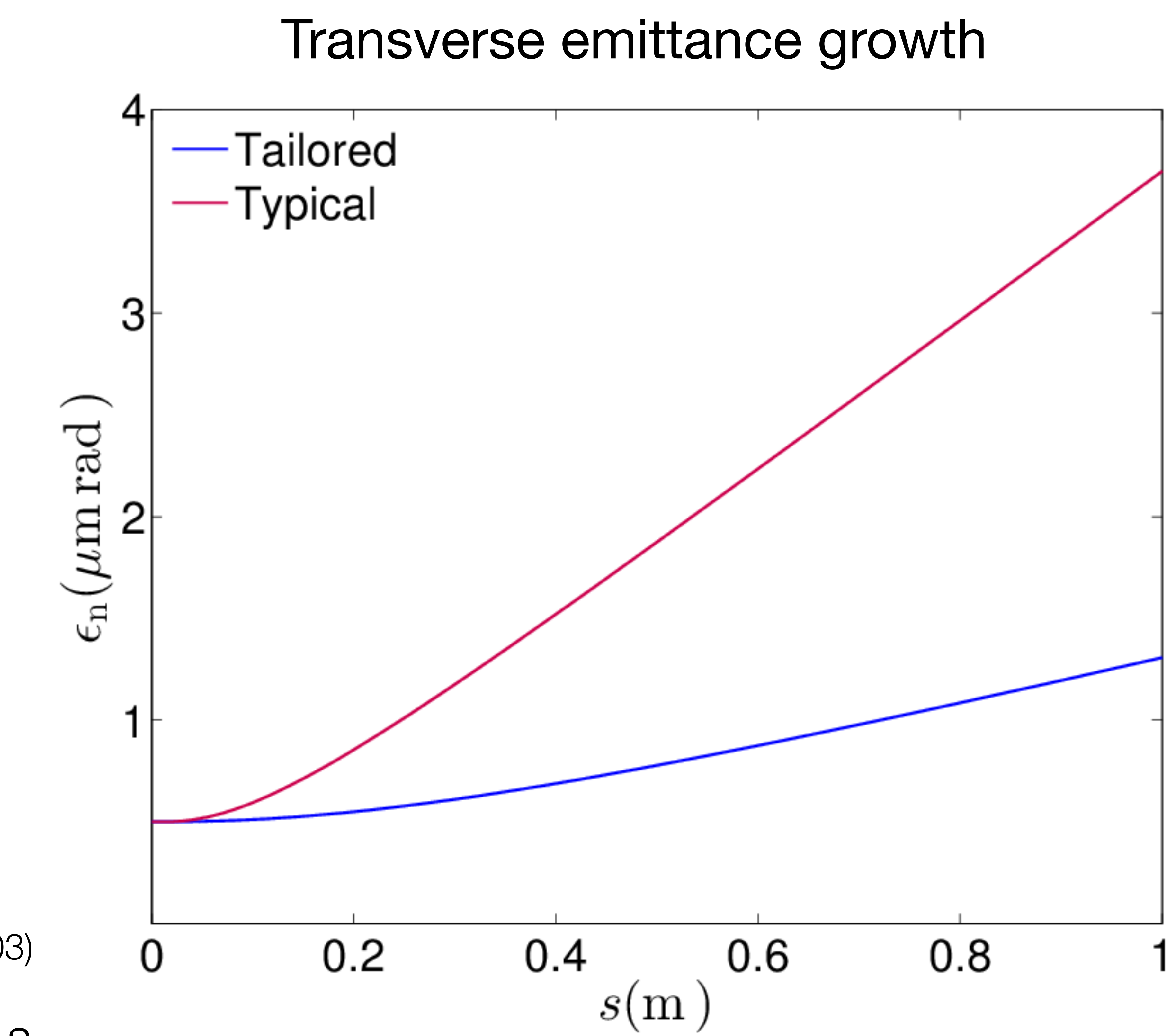
$$\varepsilon_n{}^2 \cong \langle\gamma\rangle^2 \cdot (\sigma_E{}^2 \sigma_{x'}{}^4 s^2 + \varepsilon^2)$$

+ chirp may degrade performance in applications, e.g. FELs

- in-plasma energy chirp compensation is desirable

Chirp complicates beam transport and applications





E = 1.5 GeV, σ_E = 1%, $\epsilon_{n,0}$ = 0.5 µm rad

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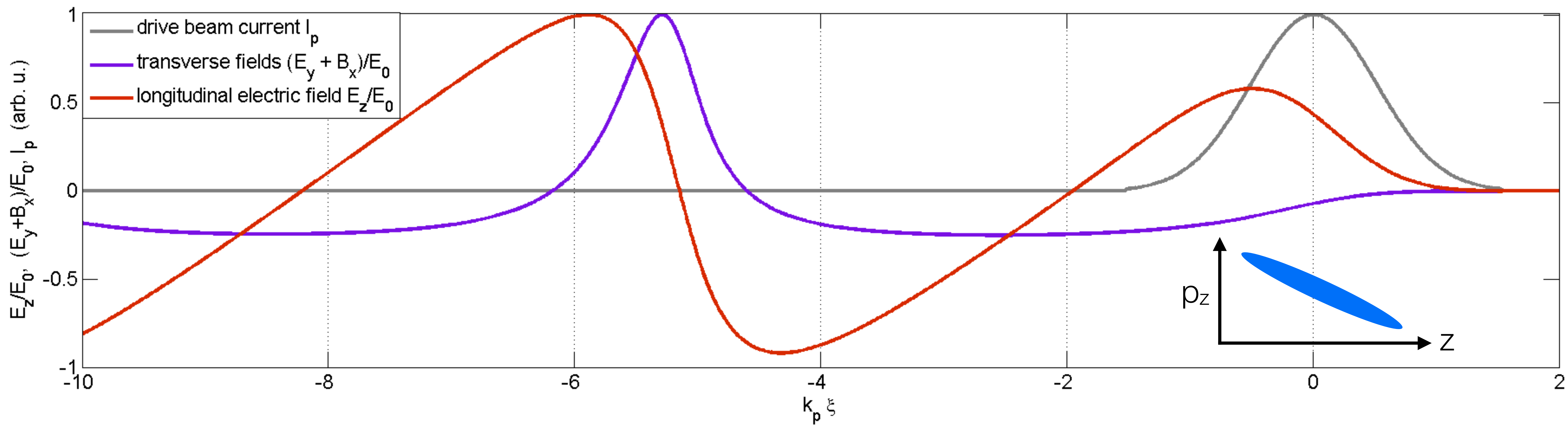
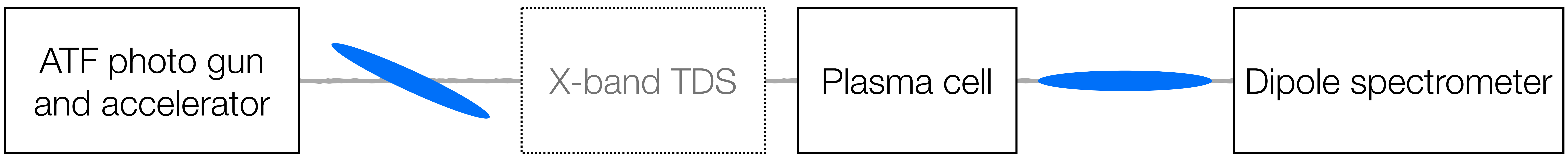
Proposal: a plasma-based dechirper

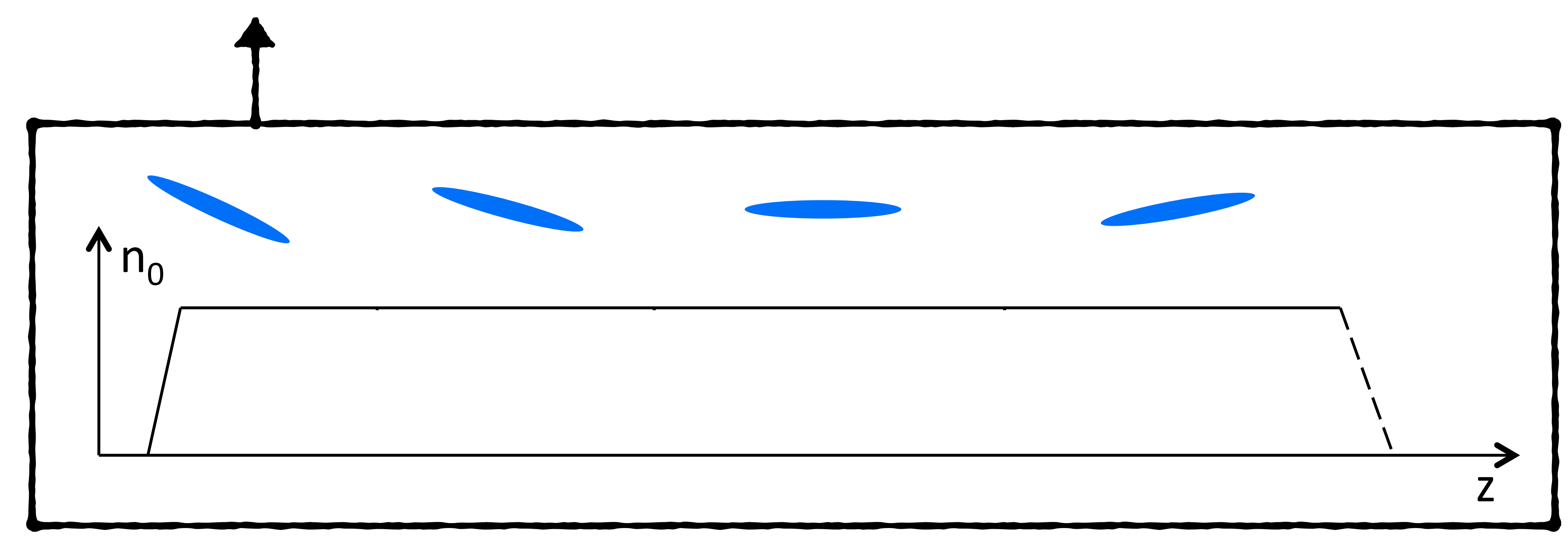


- utilize wakefield slope and and focussing properties generated by beam itself driving a plasma wake
- for energy chirp compensation: $6 \cdot \sigma_z \lesssim \frac{\lambda_p}{4}$

Step 1: demonstrate the basic idea of plasma dechirping

Proposed experiment at the ATF: utilise chirped electron beam to self-dechirp in a plasma wakefield





Electron beam requirements

- monotonically changing, increasing energy from head to tail
- an energy bandwidth of ≥ 1% rms
- sufficient current density to drive a wakefield

> measure energy spread as a function of bunch charge and plasma density

PIC simulations show feasibility - Case A

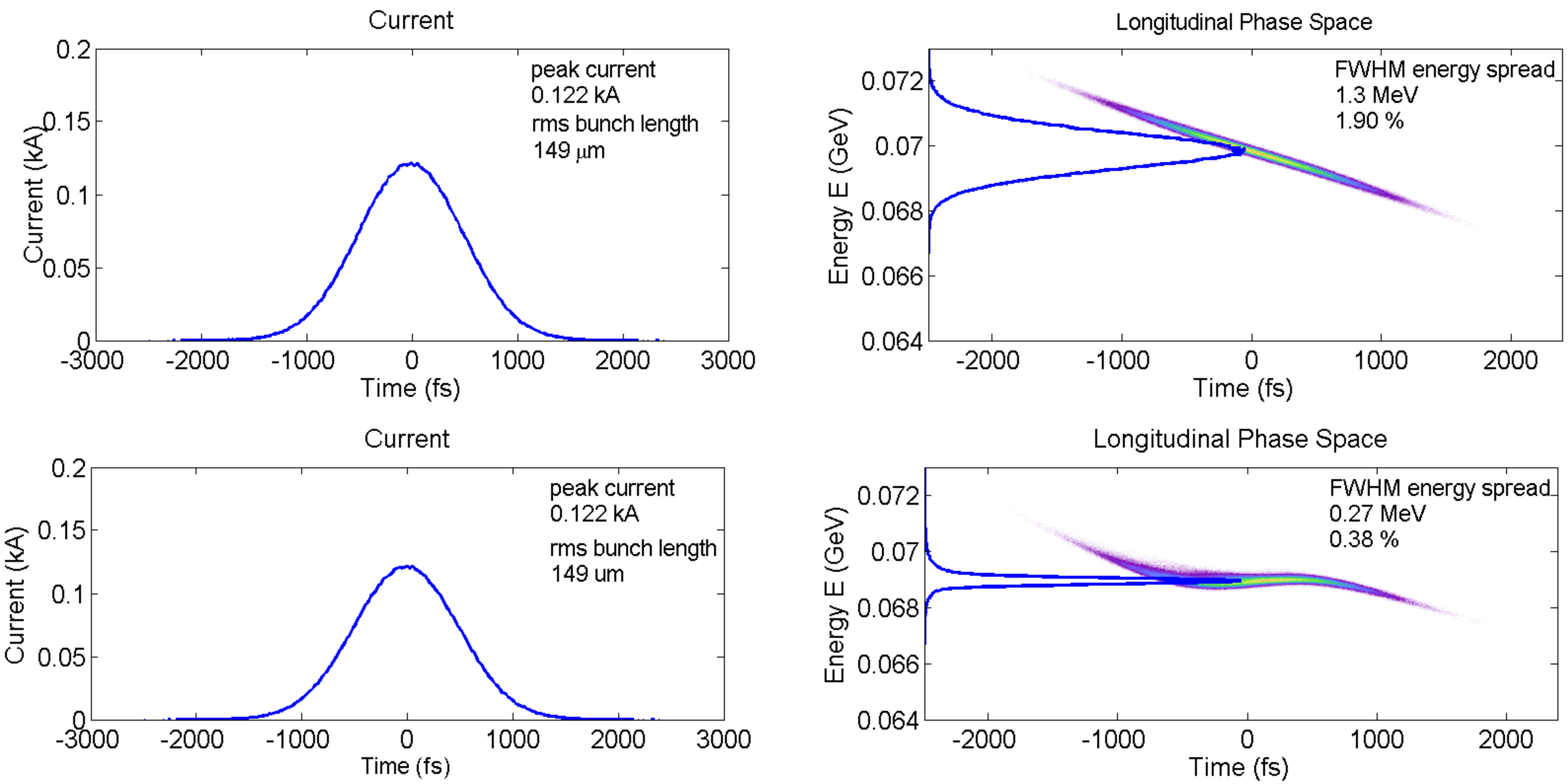
T. Mehrling *et al.*, Plasma Phys Control Fusion **56**, 084012 (2014)

Beam parameters

- $E = 70$ MeV
- $\Delta E = 2.35\%$ FWHM
- $\sigma_{x,y} = 50$ µm
- $\sigma_z = 150$ µm
- $I = 122$ A
- $\varepsilon_{x,y} = 1$ µm
- $Q = 150$ pC

Plasma parameters

- $n_0 = 1\times10^{14}$ cm^{-3}
- $d = 99$ mm
- box-profile



- **conservative ATF parameters**
- projected FWHM energy spread reduced from 2.35% to 0.38%, reduced by factor of ~6
- length of plasma exceeds current capabilities of ATF plasma cell (~20 mm)

PIC simulations show feasibility - Case B

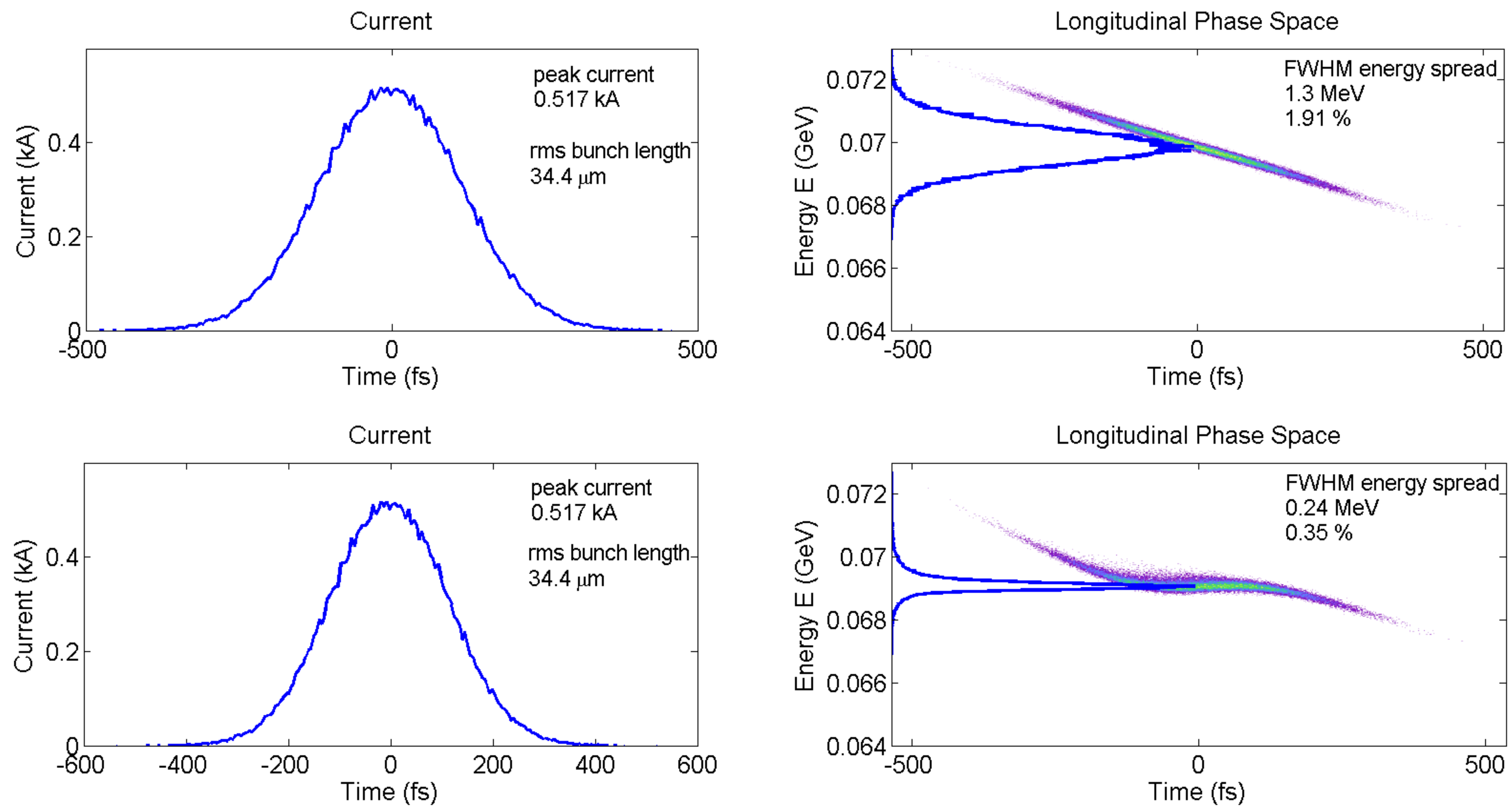
T. Mehrling *et al.*, Plasma Phys Control Fusion **56**, 084012 (2014)

Beam parameters

- E = 70 MeV
- ΔE = 2.35% FWHM
- $\sigma_{x,y}$ = 50 μm
- σ_z = **34 μm**
- I = **517 A**
- $\varepsilon_{x,y}$ = 1 μm
- Q = 150 pC

Plasma parameters

- $n_0 = 2\times10^{15}$ cm^{-3}
- d = 5 mm
- box-profile



- **optimistic (realistic?) ATF parameters**
- projected FWHM energy spread reduced from 2.35% to 0.35%, reduced by factor of ~6
- length of plasma compatible with current ATF plasma cell

PIC simulations show feasibility - Case B

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Beam parameters

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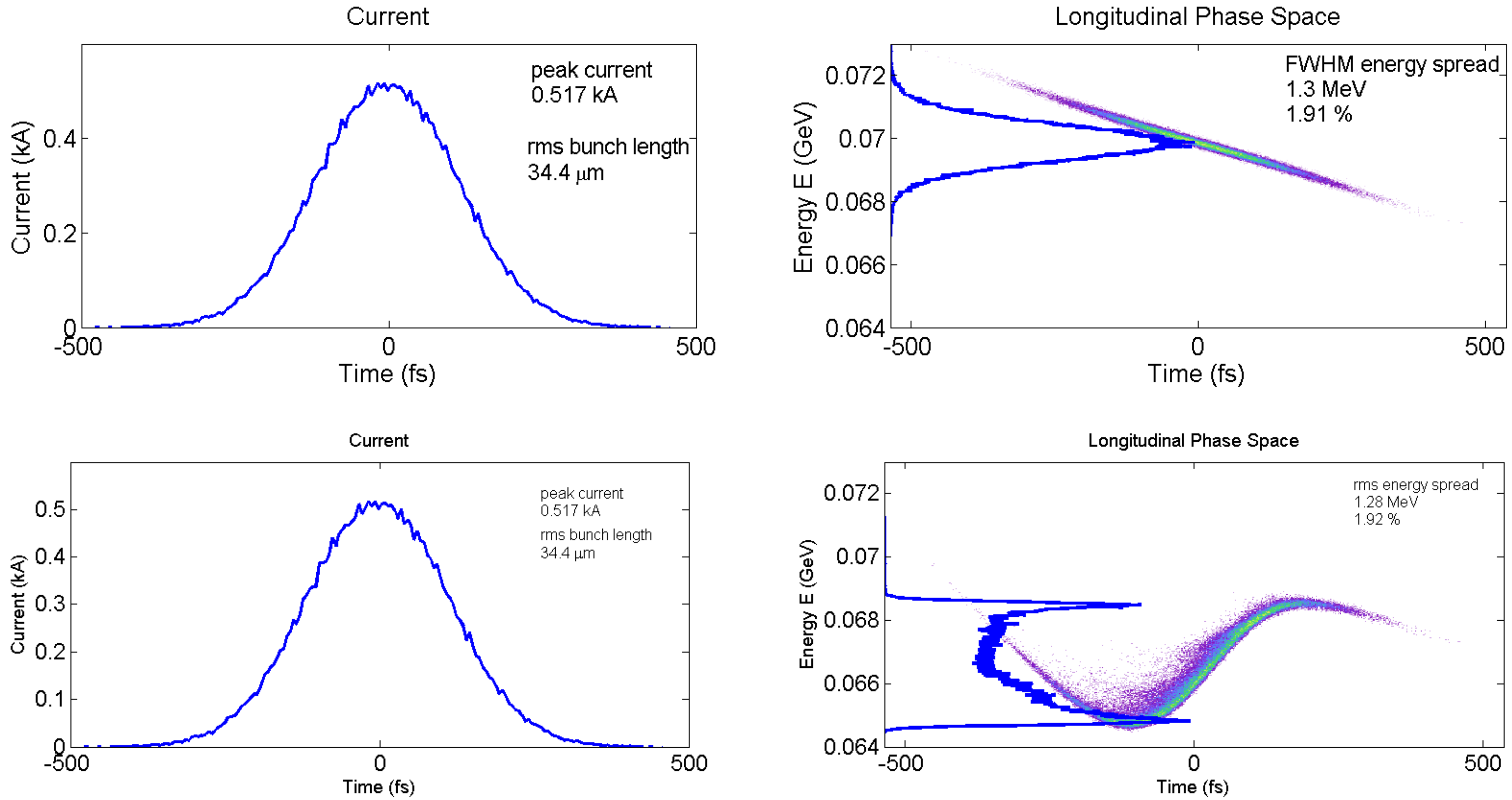
$\sigma_z =$ **34 µm**
$I =$ **517 A**
$\varepsilon_{x,y} = 1$ µm
$Q = 150$ pC

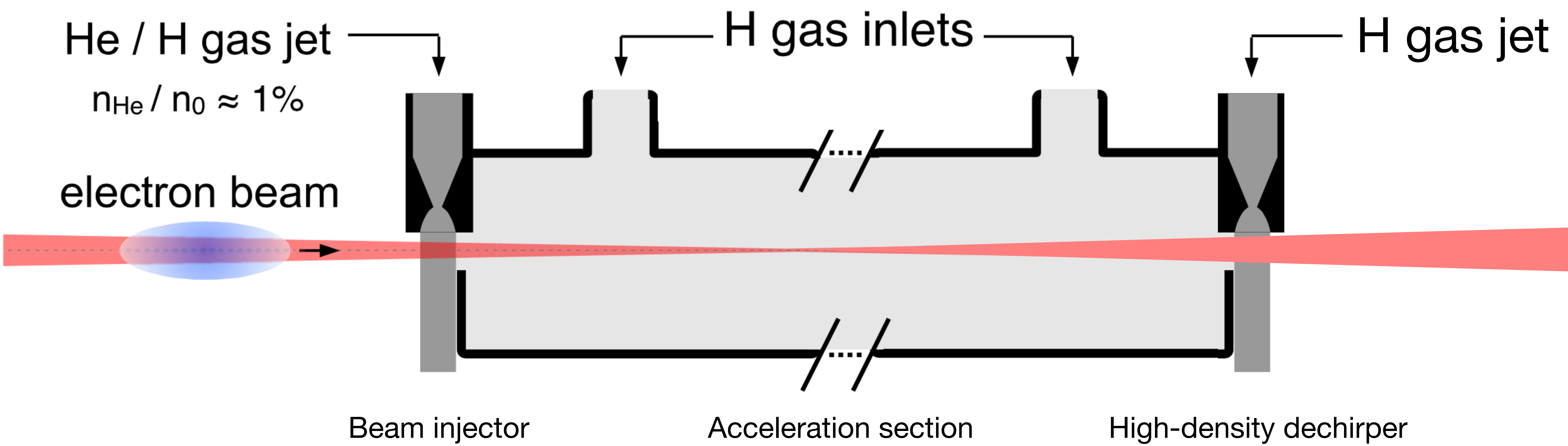
Plasma parameters

$n_0 = 2\times10^{15}$ cm^{-3}
$d = 20$ mm
box-profile



- **optimistic (realistic?) ATF parameters**
- projected FWHM energy spread reduced from 2.35% to 0.35%, reduced by factor of ~6
- length of plasma compatible with current ATF plasma cell

Outlook and step 2: integrate dechirper into plasma accelerator (at future facilities ATF II, FACET II, FLASHForward, …)



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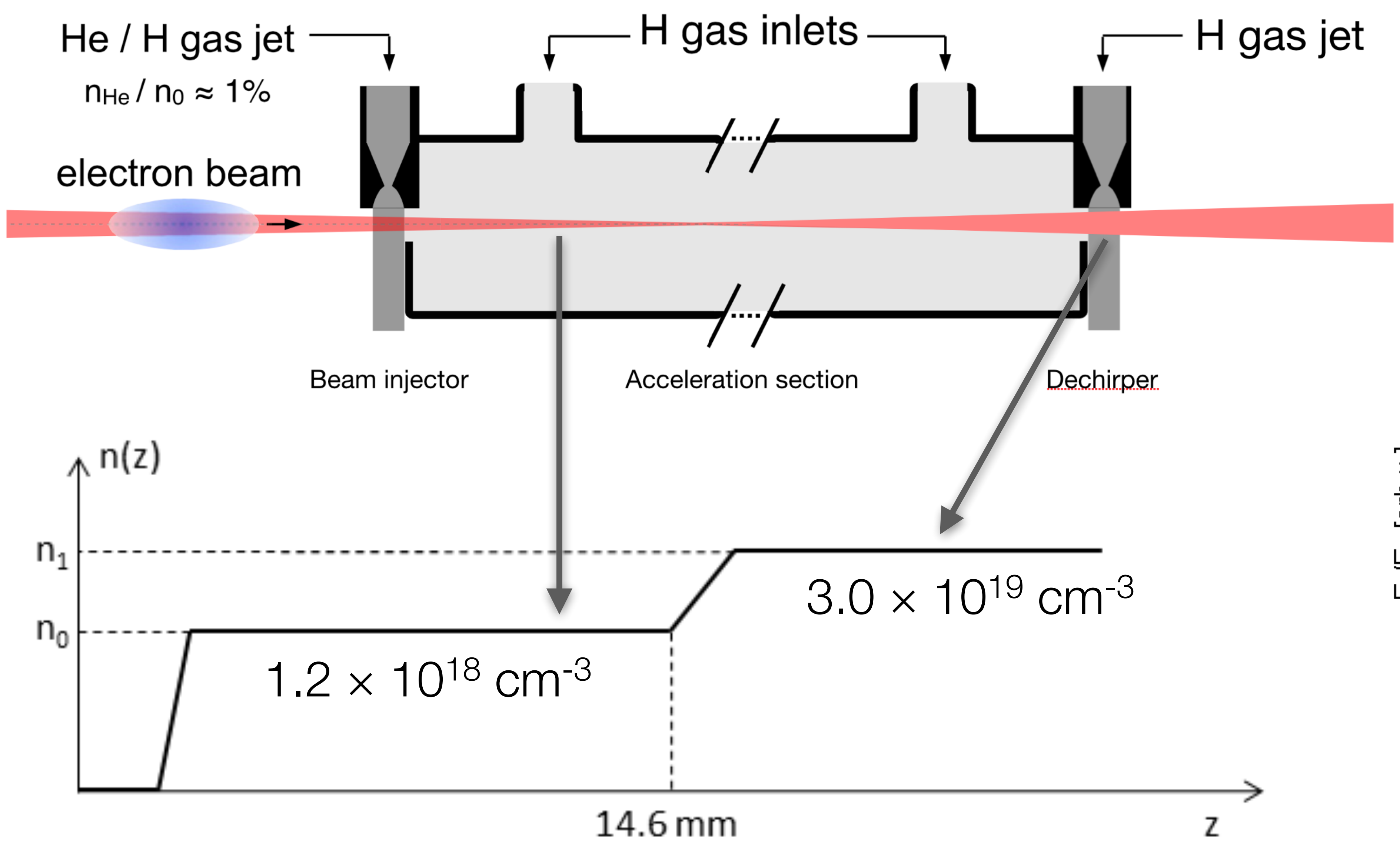

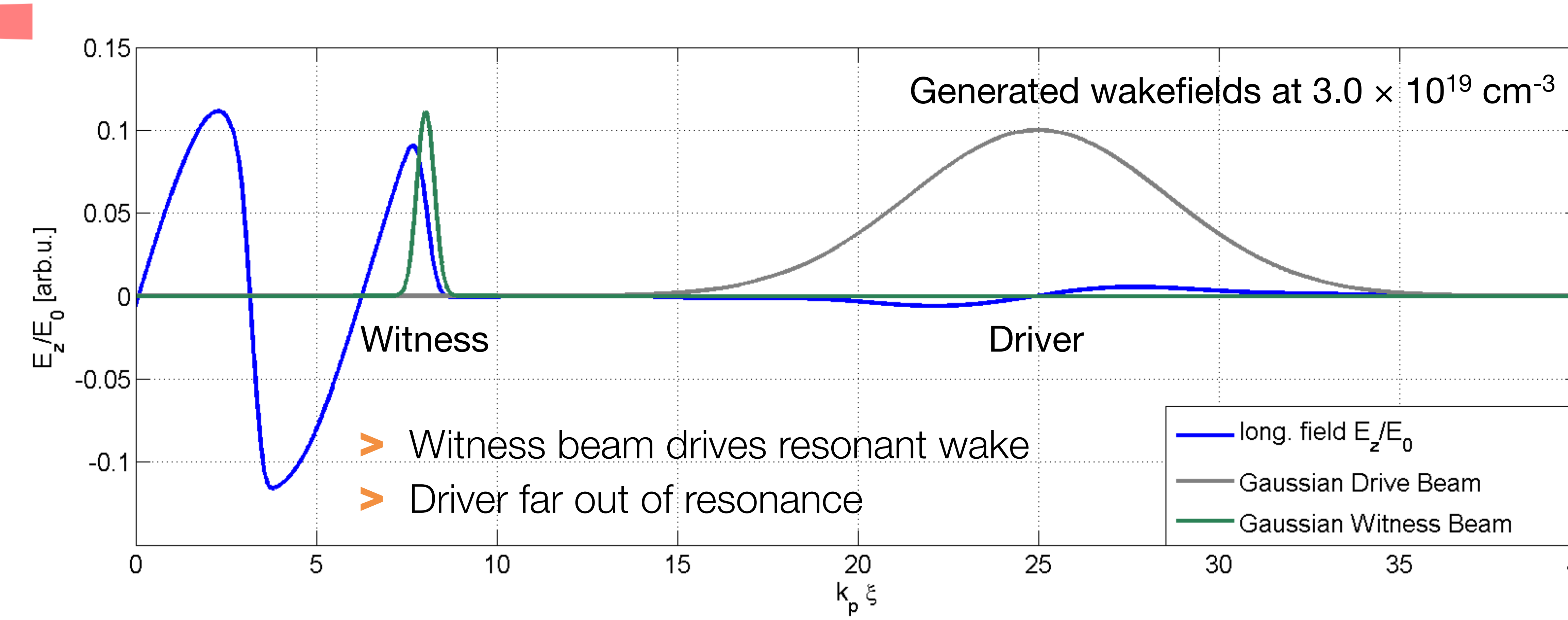

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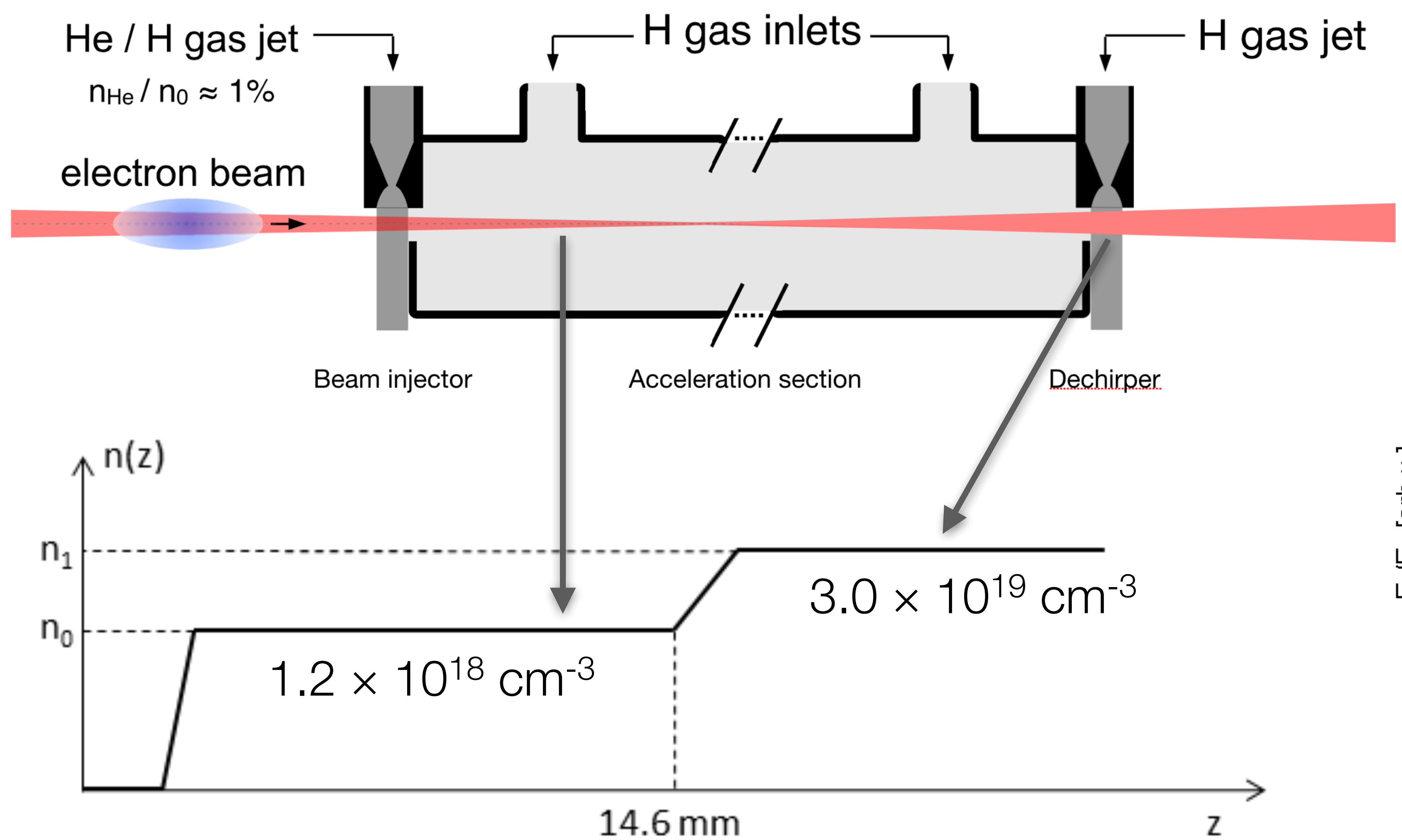

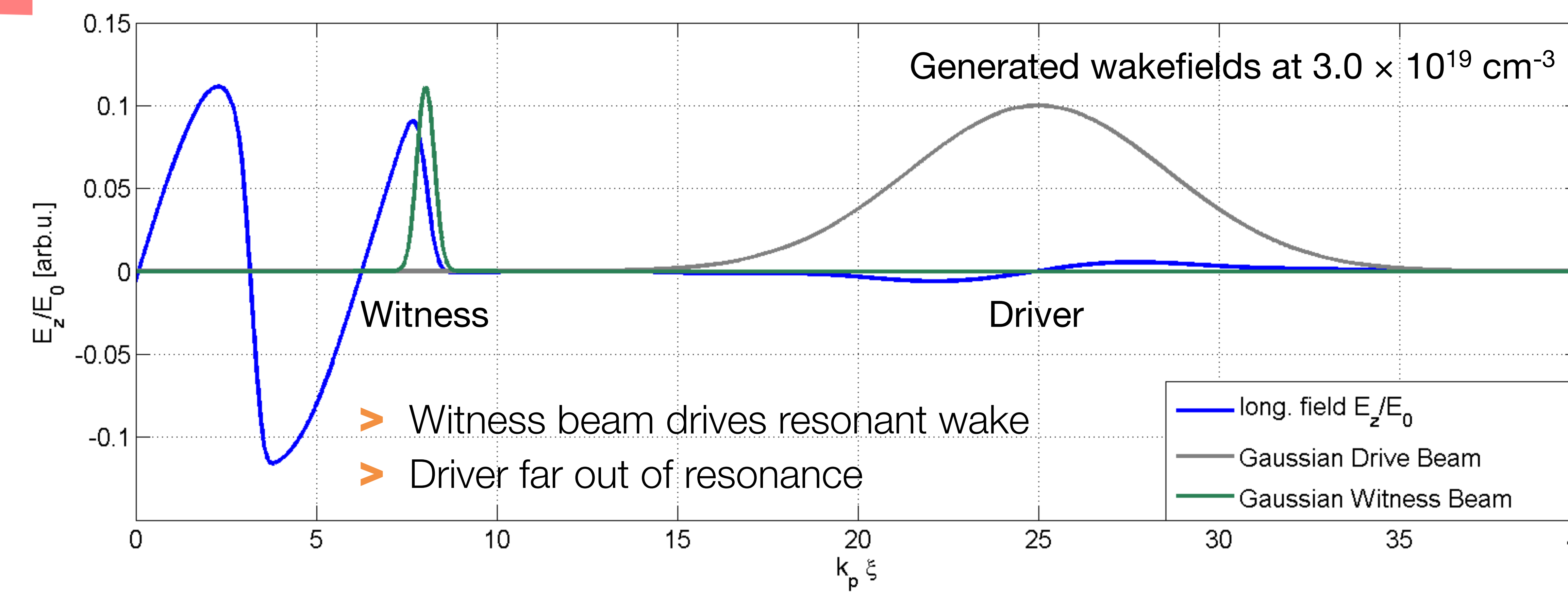

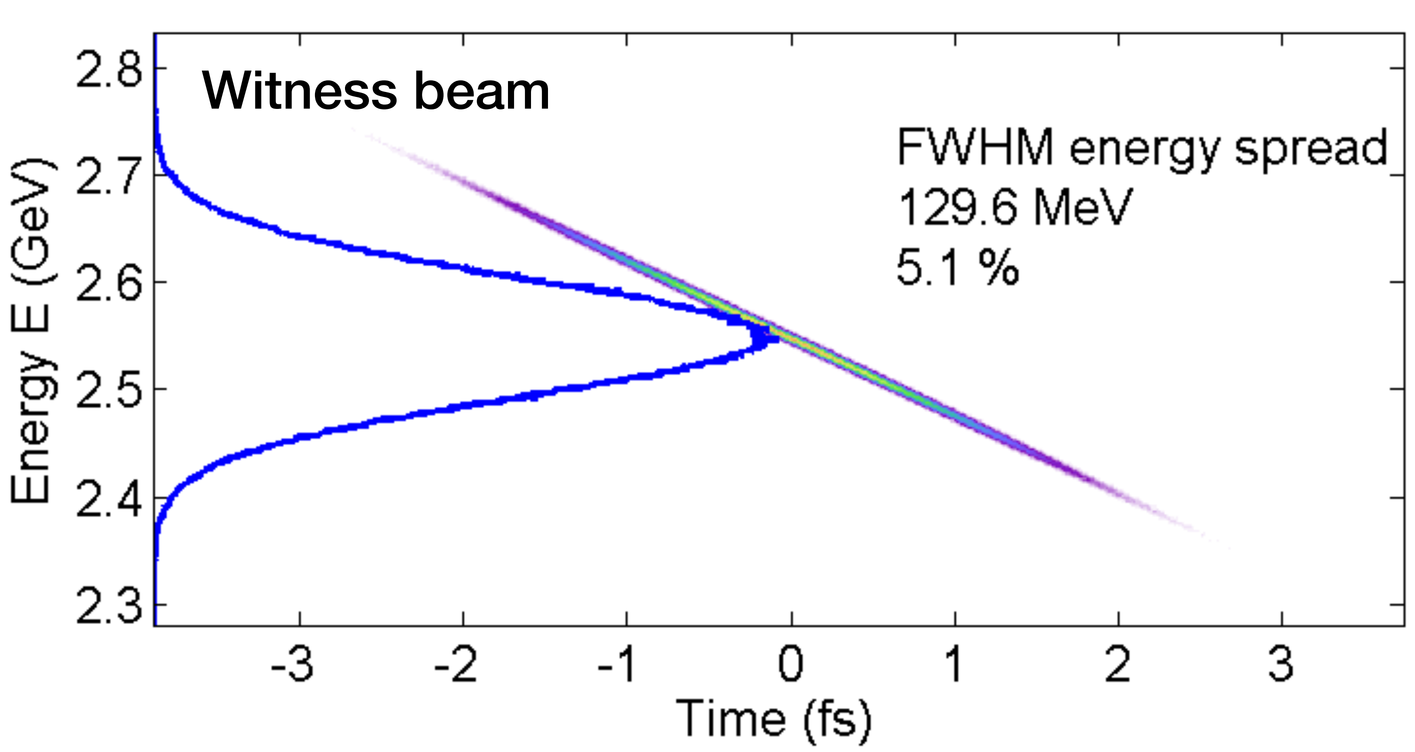

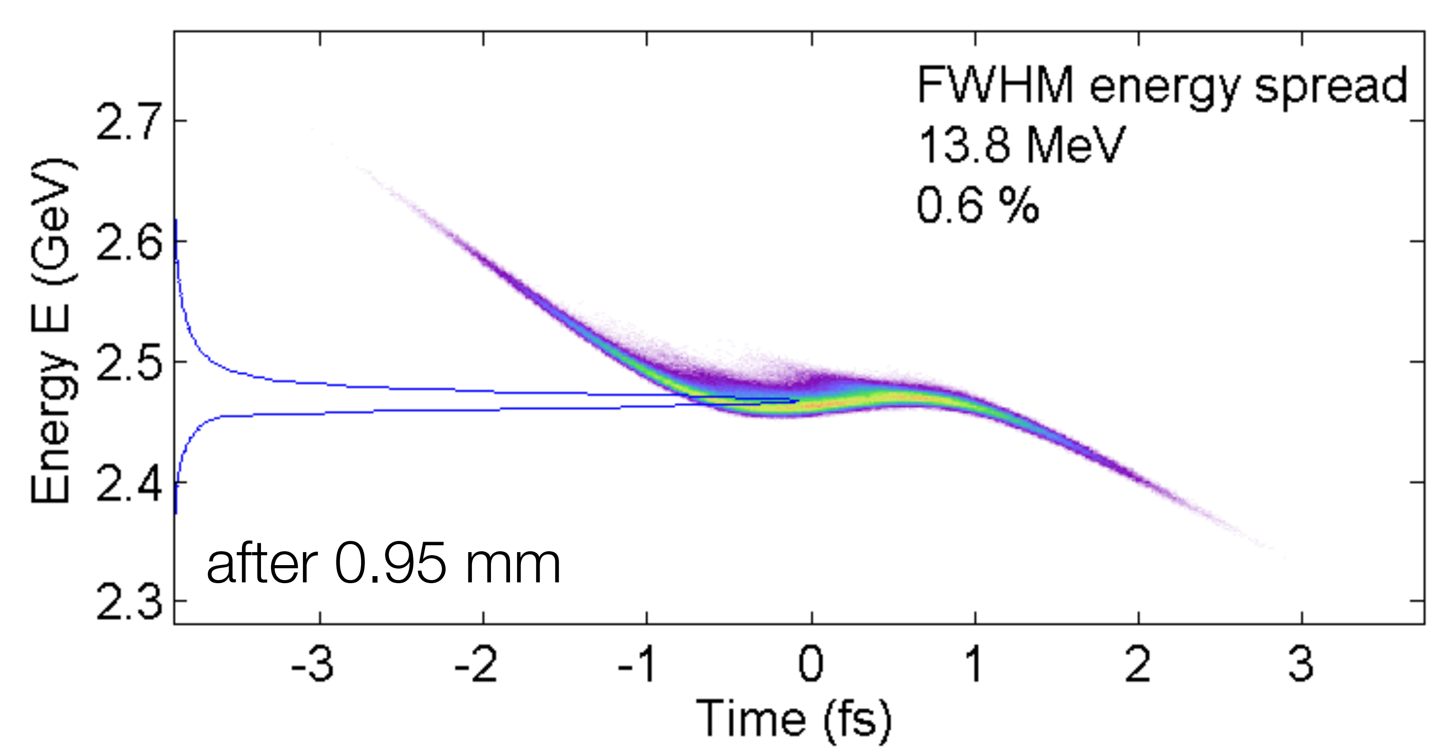

- Drive beam
  $\sigma_z = 7$ μm, $\varepsilon_{x,y} = 1$ μm, $I_B = 10$ kA,
  Q = 574 pC, E = 1 GeV
- Witness beam
  $\sigma_z = 0.23$ μm, $\varepsilon_{x,y} = 10.3$ μm, $I_B = 5$ kA,
  Q = 32 pC, E = 2.5 GeV

Summary

- Large energy spread complicates emittance preservation of beams from plasma wakefield accelerators during transport
- Chirp needs to be minimized before beam leaves plasma, classical dechirping schemes do not help
- Proposal: utilize self-generated wakefields in plasma for beam dechirping
  - *Step 1: demonstrate proof-of-principle in existing ATF setup*
  - *Step 2: integrate dechirper section into plasma-wakefield accelerator at ATF II, FACET II, FLASHForward*
- Experiment at ATF
  - *Generate and characterize linearly chirped beams, X-band TDS would be of great benefit*
  - *Make beams drive wakes in plasma, scan charge and plasma density, measure beam spectrum after plasma*
  - *Should work with existing ATF equipment, asked for 100 hours of beam time*
- Minimizing the energy spread is a key challenge for applications