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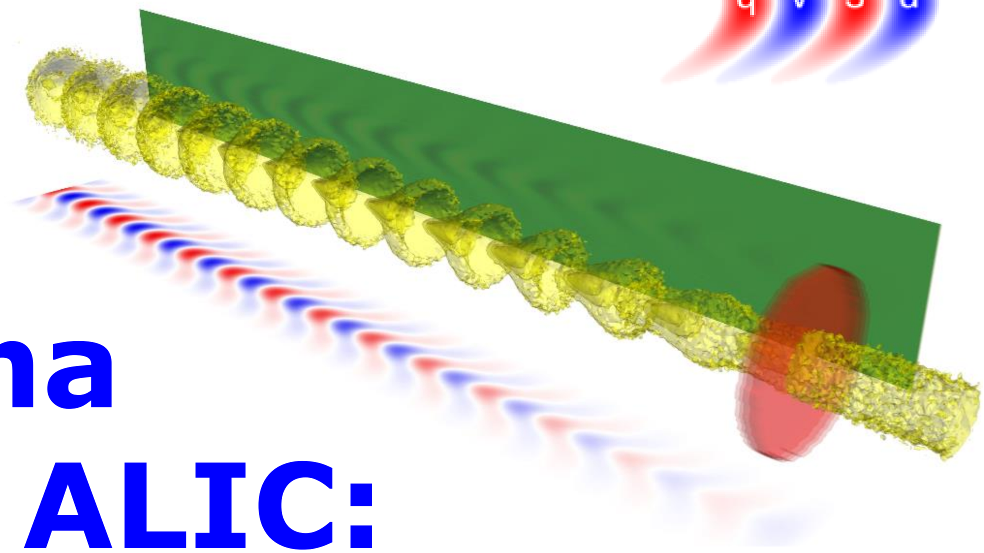
qv3d



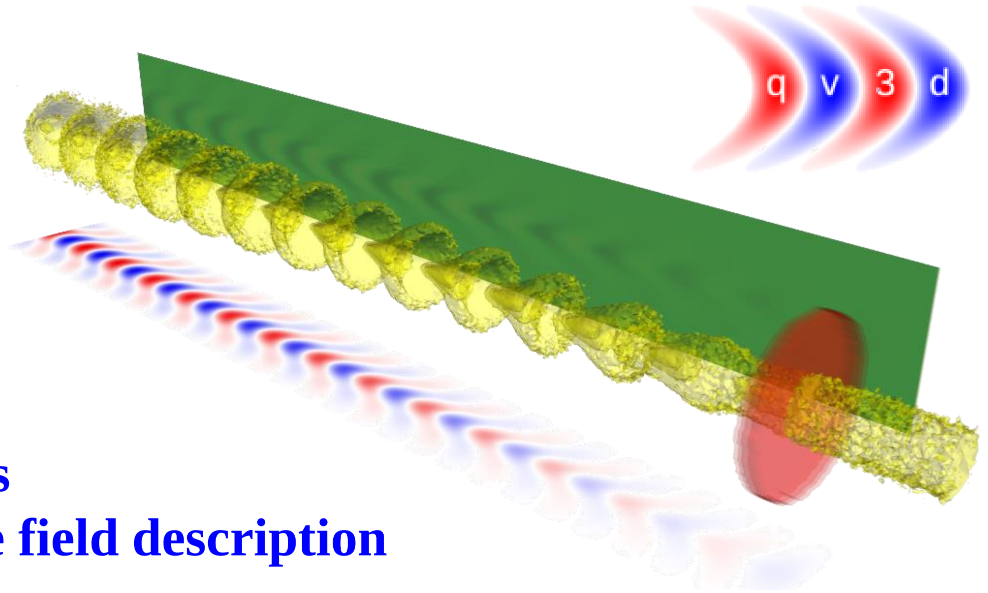
Co-axial hollow plasma channels for ALIC: TeV acceleration

ALEGRO, CERN, 26 March 2019

Outline

- **Hollow plasma channel:**
  control of hosing by a co-axial filament
- **Options to create the plasma structure**
- **TeV acceleration**
  in a hollow plasma channel
  with a hollow on-axis filament

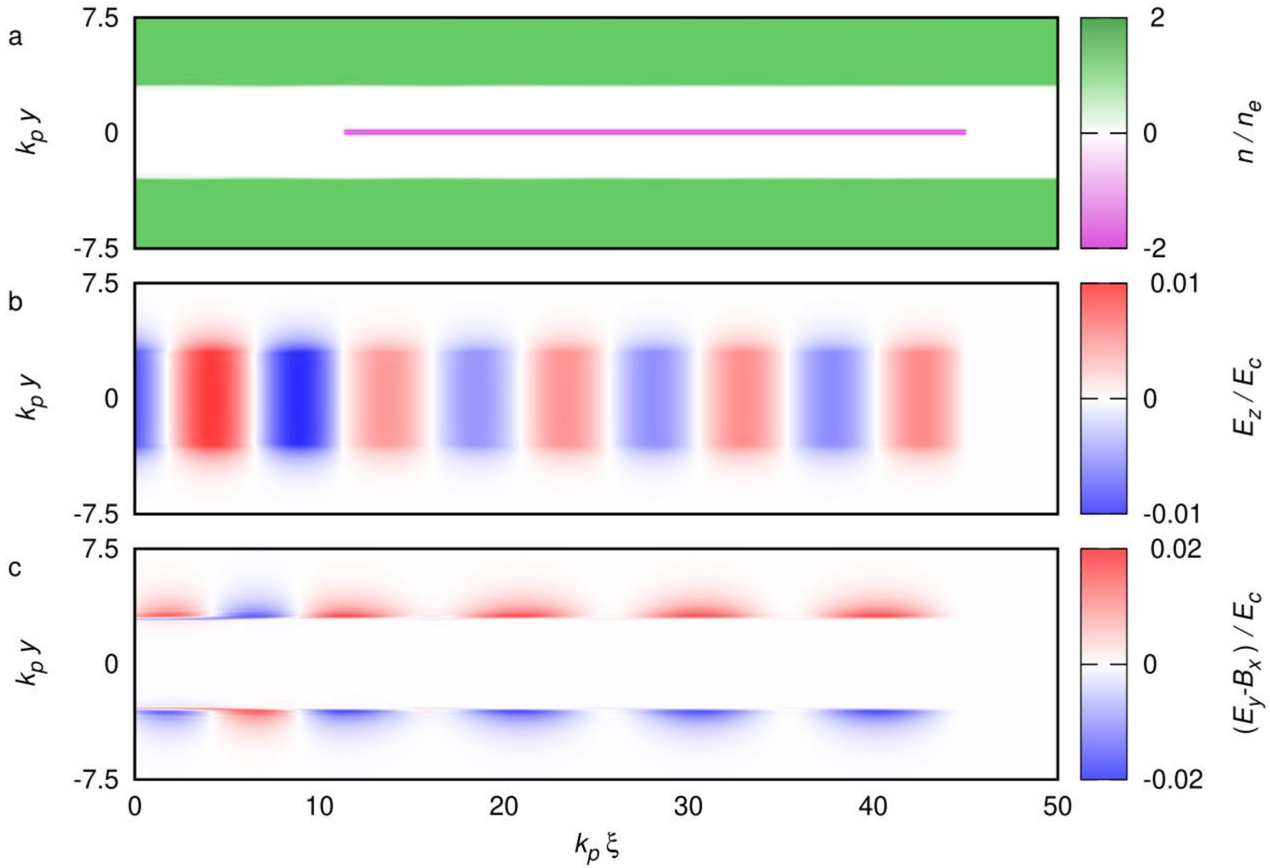
Qausi-static PIC simulations



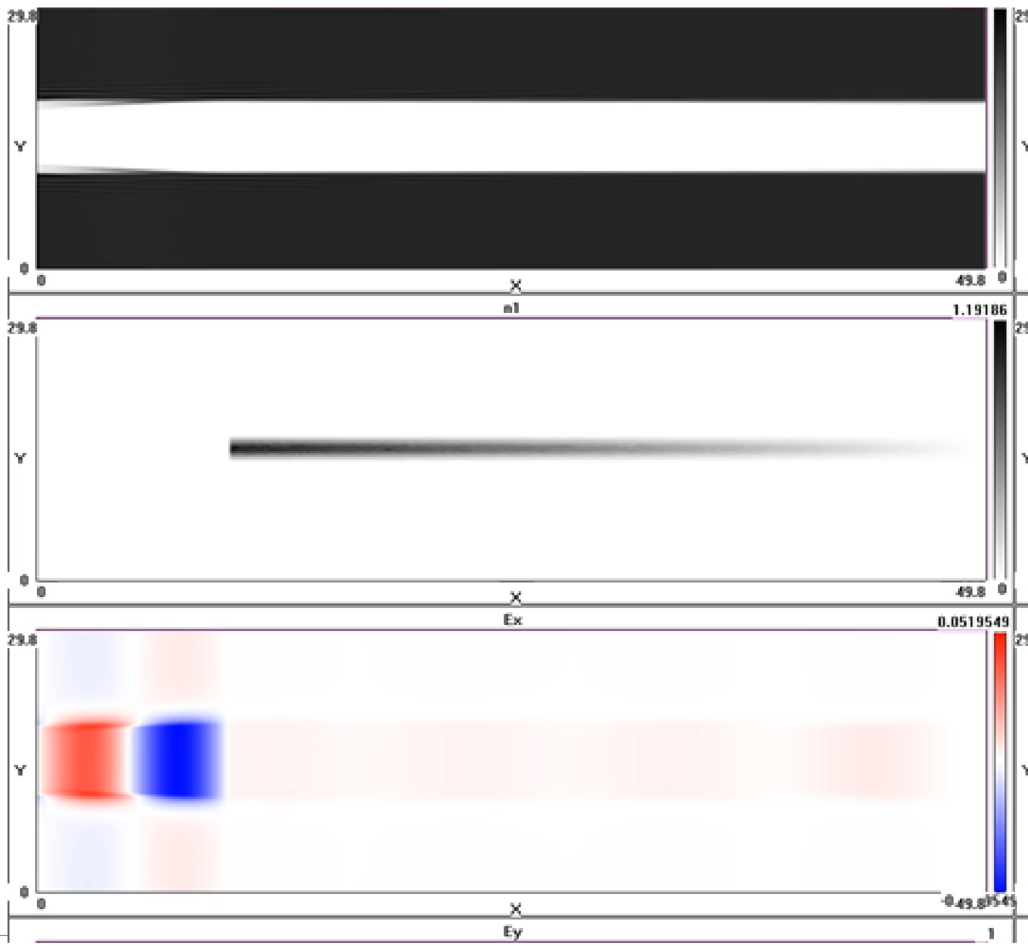
Quasi-static
3D PIC code QV3D

- **Full 3D code, Cartesian coords**
- **High accuracy long term wake field description**
- **Emittance preserved**
- **Envelope laser description**
- **Ionization included**
- **Betatron radiation and radiation losses included**

Perspective approach: Beam-driven wake in a Hollow Plasma Channel



Ramped bunch in a hollow channel: Potentially high transformer ratio Both for e- and e+



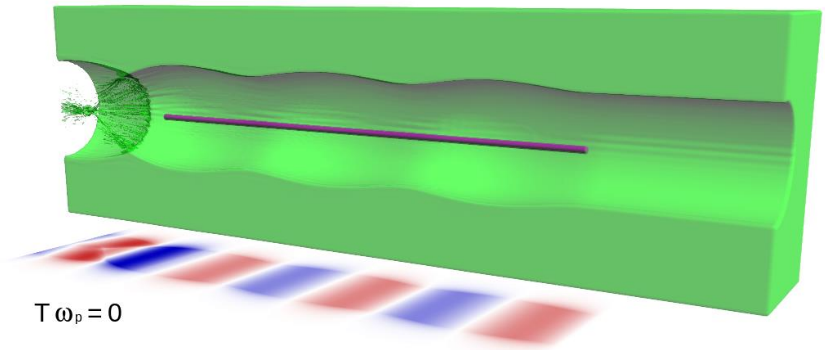
The channel

The driver

The wake

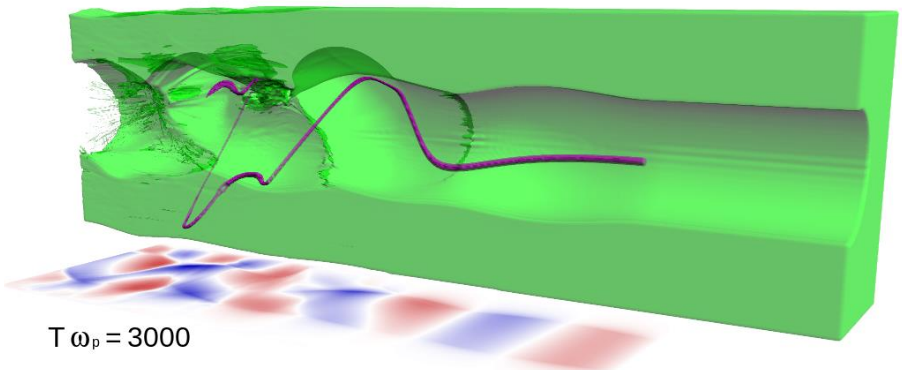
PRL **121**, 264801 (2018)

The BBU (hosing) problem



Long driver in a plasma channel…

… is unstable



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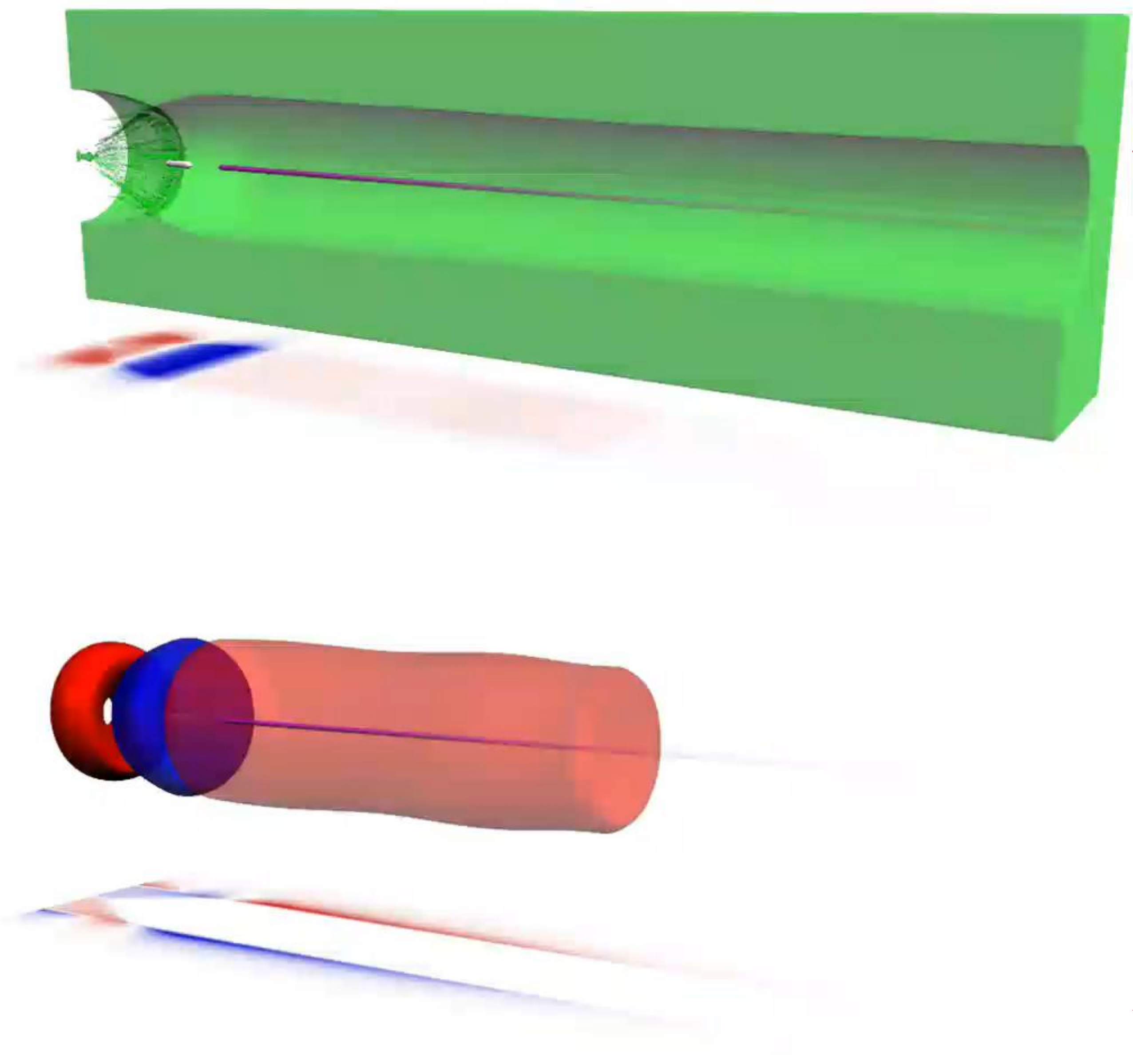
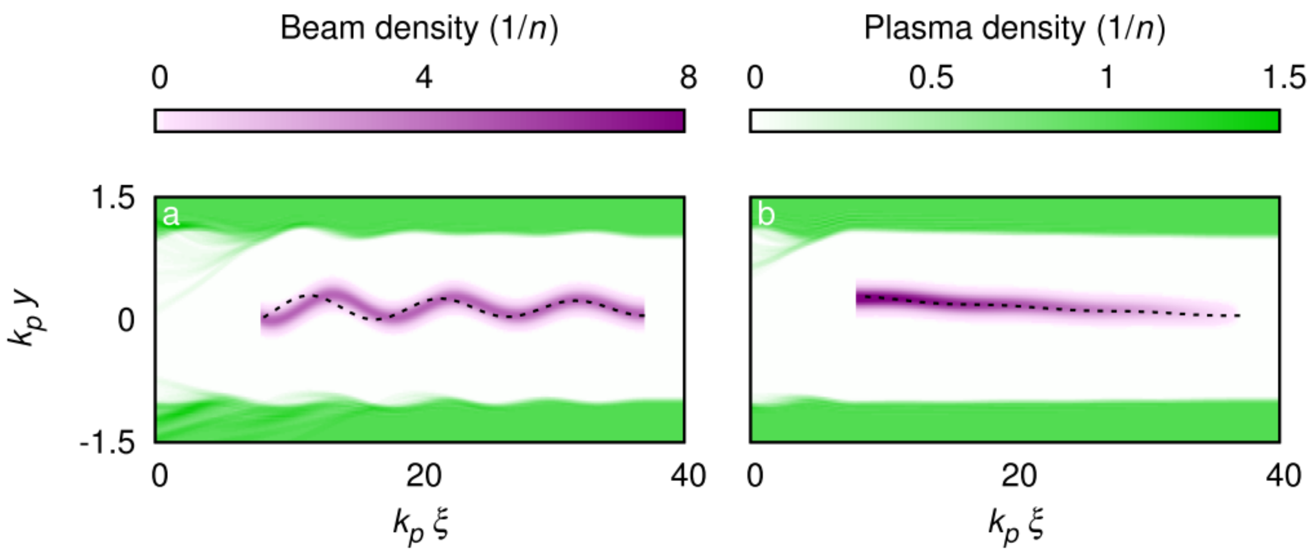


Hollow channel:
BBU
The driver is lost before any useful acceleration

Analytical model from Scroeder *et al.* (1999) for BBU:

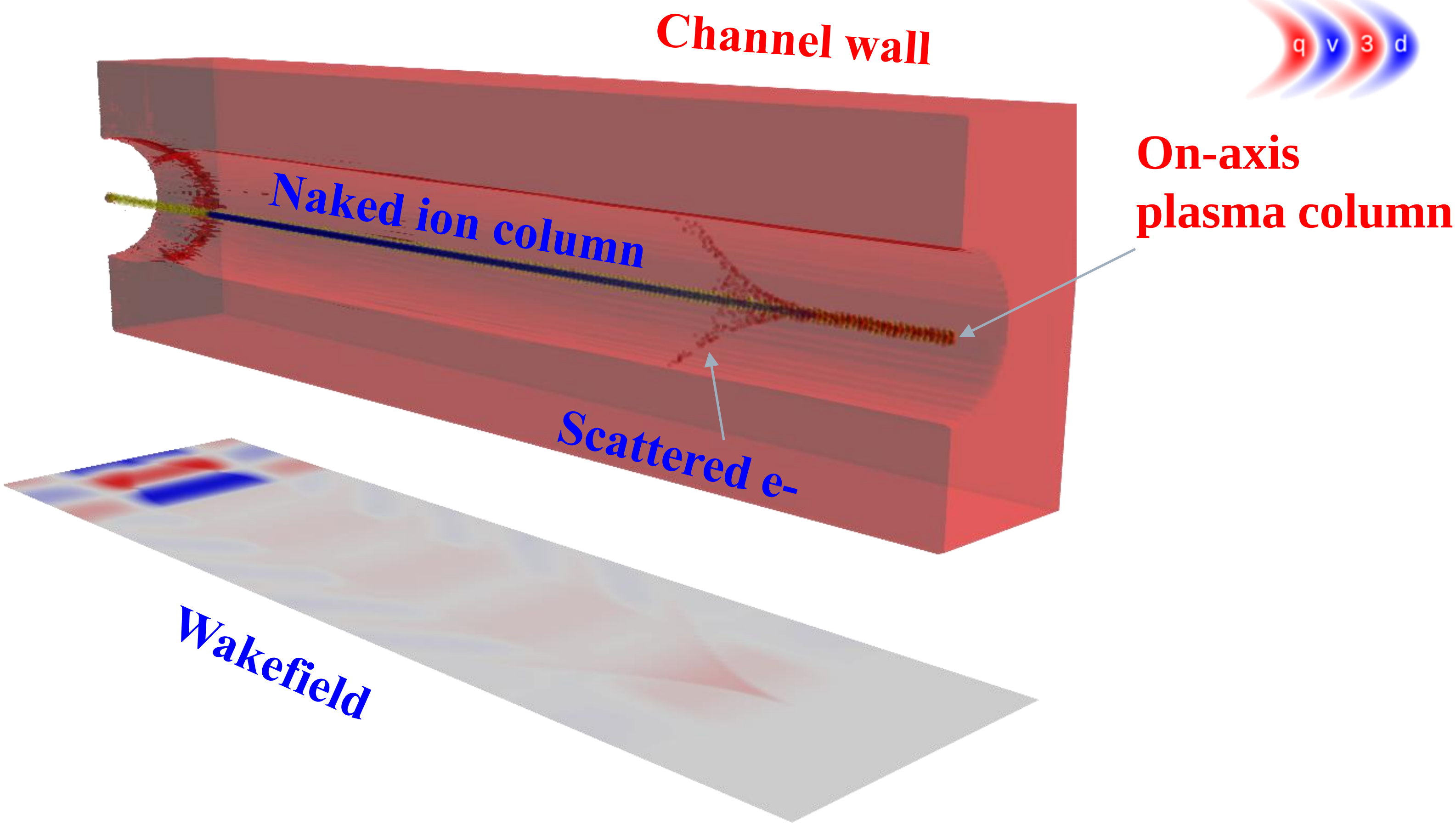
$$\left(\partial_z \gamma(z) \partial_z - \gamma(z) k_\beta^2(z)\right) Y(z,\xi) = \int_\xi^\infty \frac{2\kappa_1 c^2}{\omega_1 r_c^2} \frac{I(\xi')}{I_0} \sin\left(\omega_1 \left(\xi' - \xi\right)\right) Y(z,\xi') \mathrm{d}\xi'$$



Pukhov and Farmer, PRL (2018)

PRL **121**, 264801 (2018)

The stabilization idea:
Co-axial plasma channel



Stable acceleration in a co-axial plasma channel

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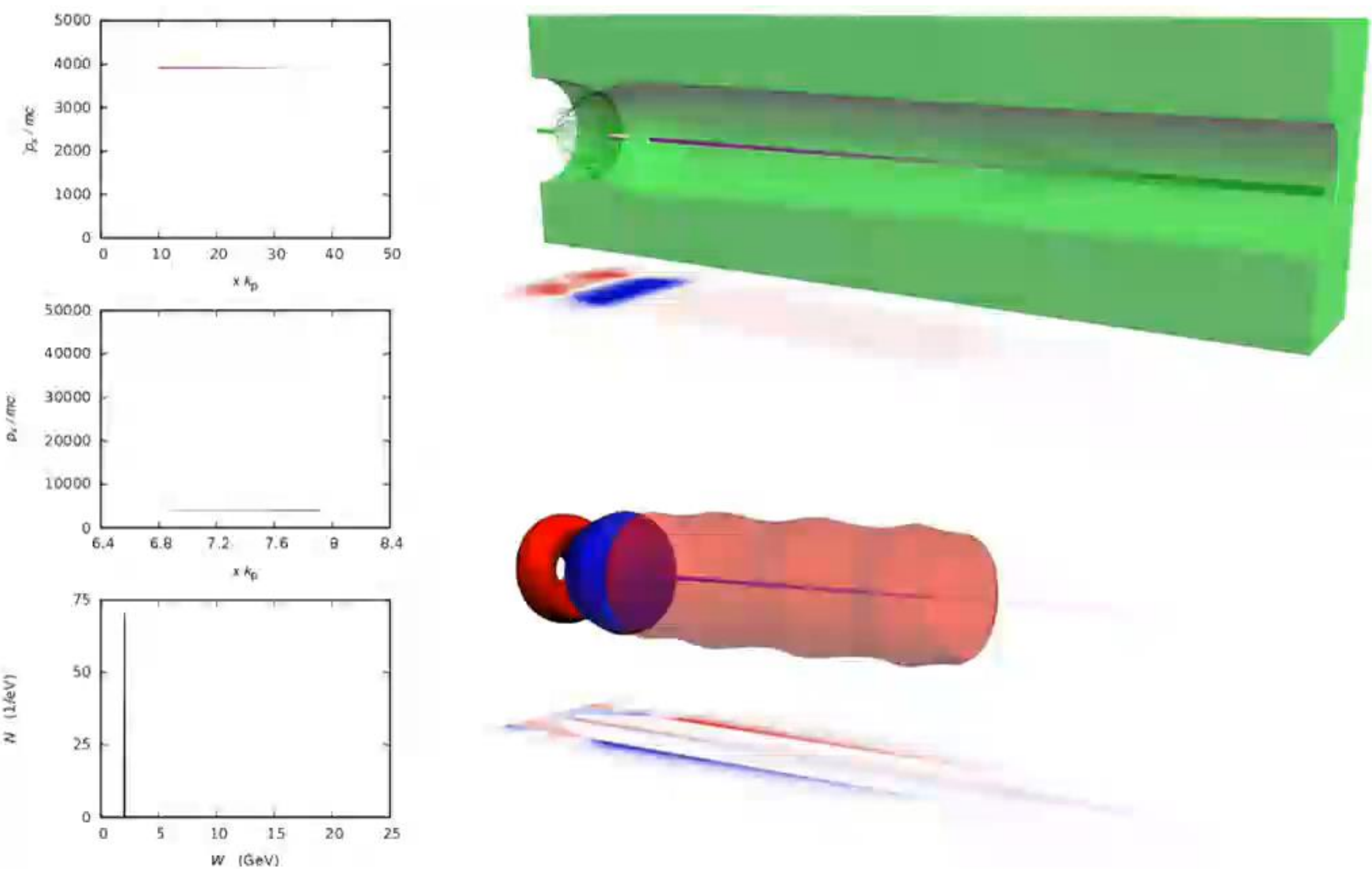

The simulation parameters

- 2 GeV electron bunch driver, 2 GeV witness bunch
- ramped driver current zero to 10 kA over 530 μm
- Plasma density n=5.7x10^{16} 1/cc
- Channel radius $k_p r_c$=3
- Central filament radius $k_p r_f$=0.2
- Witness final energy 21 GeV
  Final energy spread 0.2% r.m.s.
  Final emittance 1.5 μm (what causes it?)
- Accelerating gradient 2 GV/m
- Loaded transformer ratio is R=10.5
- 44% driver-to-witness energy efficiency

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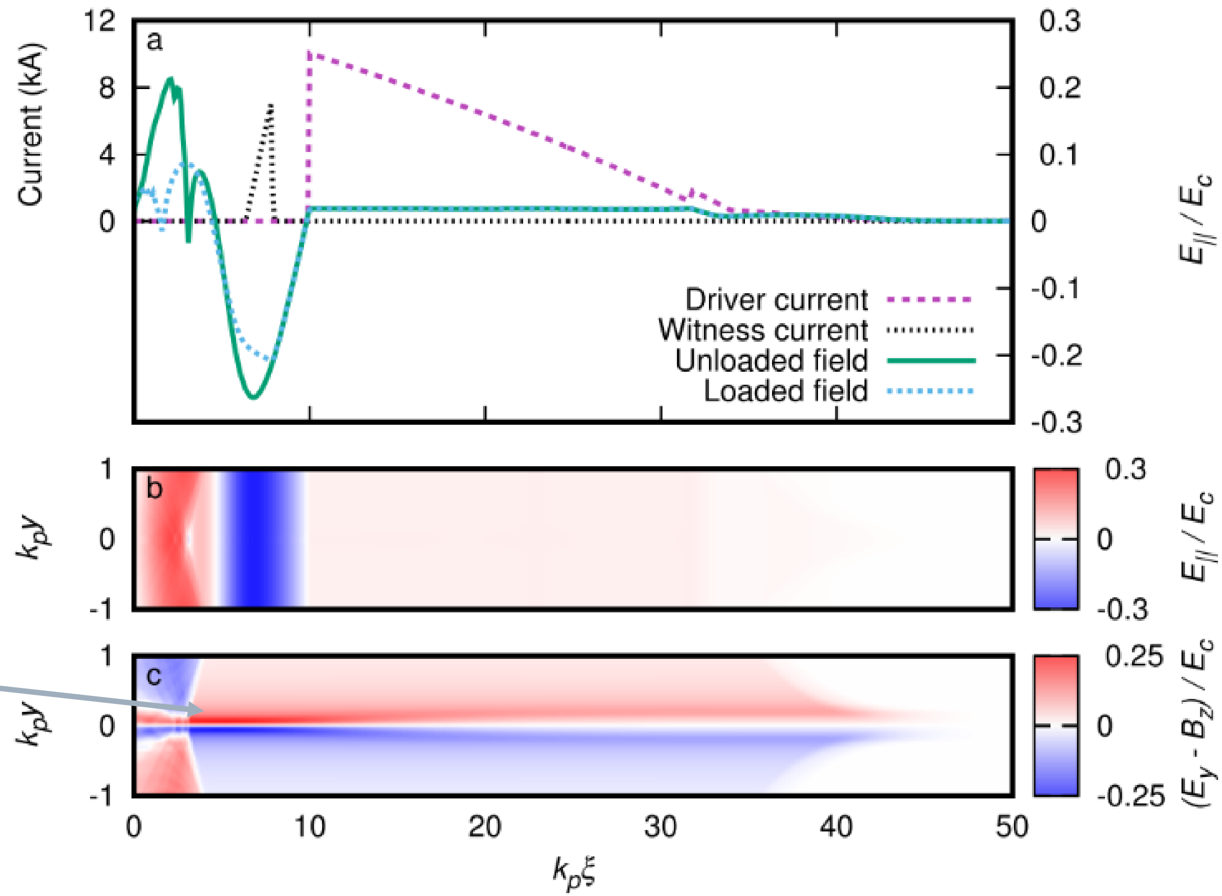
The simulation details

Head-to-tail chirp
in the focusing strength
=
betatron frequency chirp
due to the ion motion



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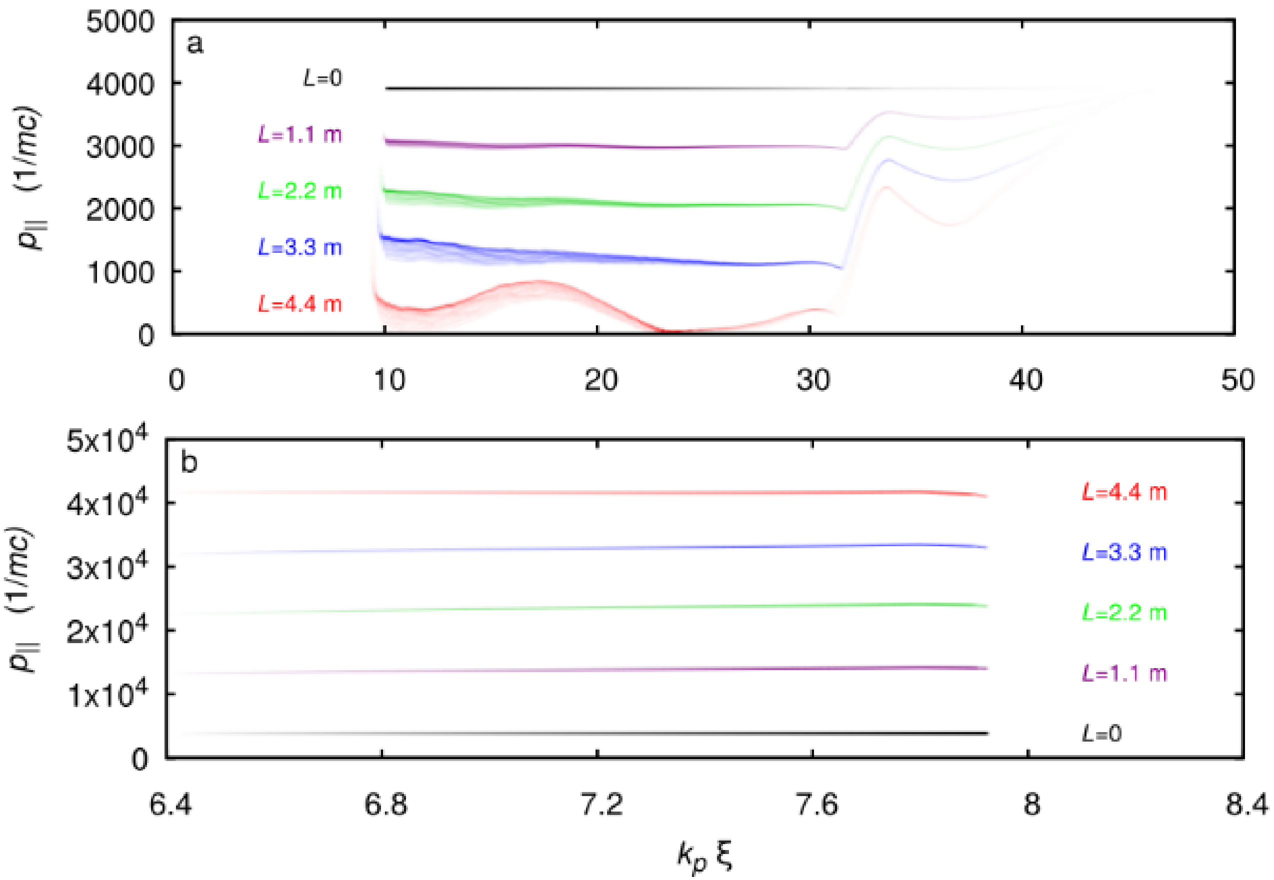
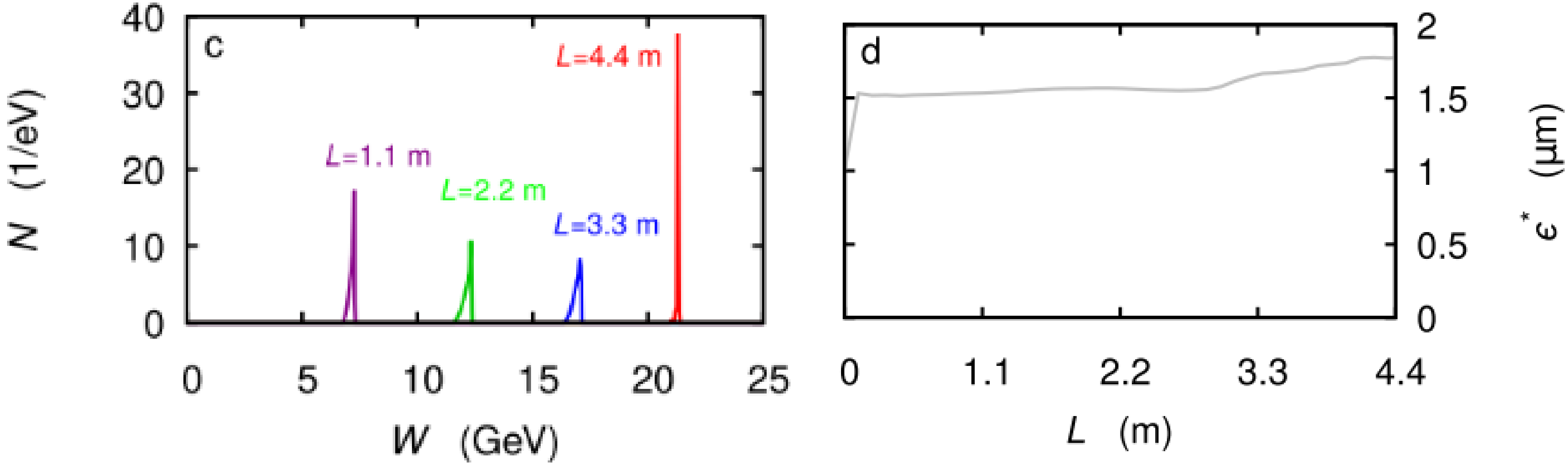
The phase space evolution



Driver

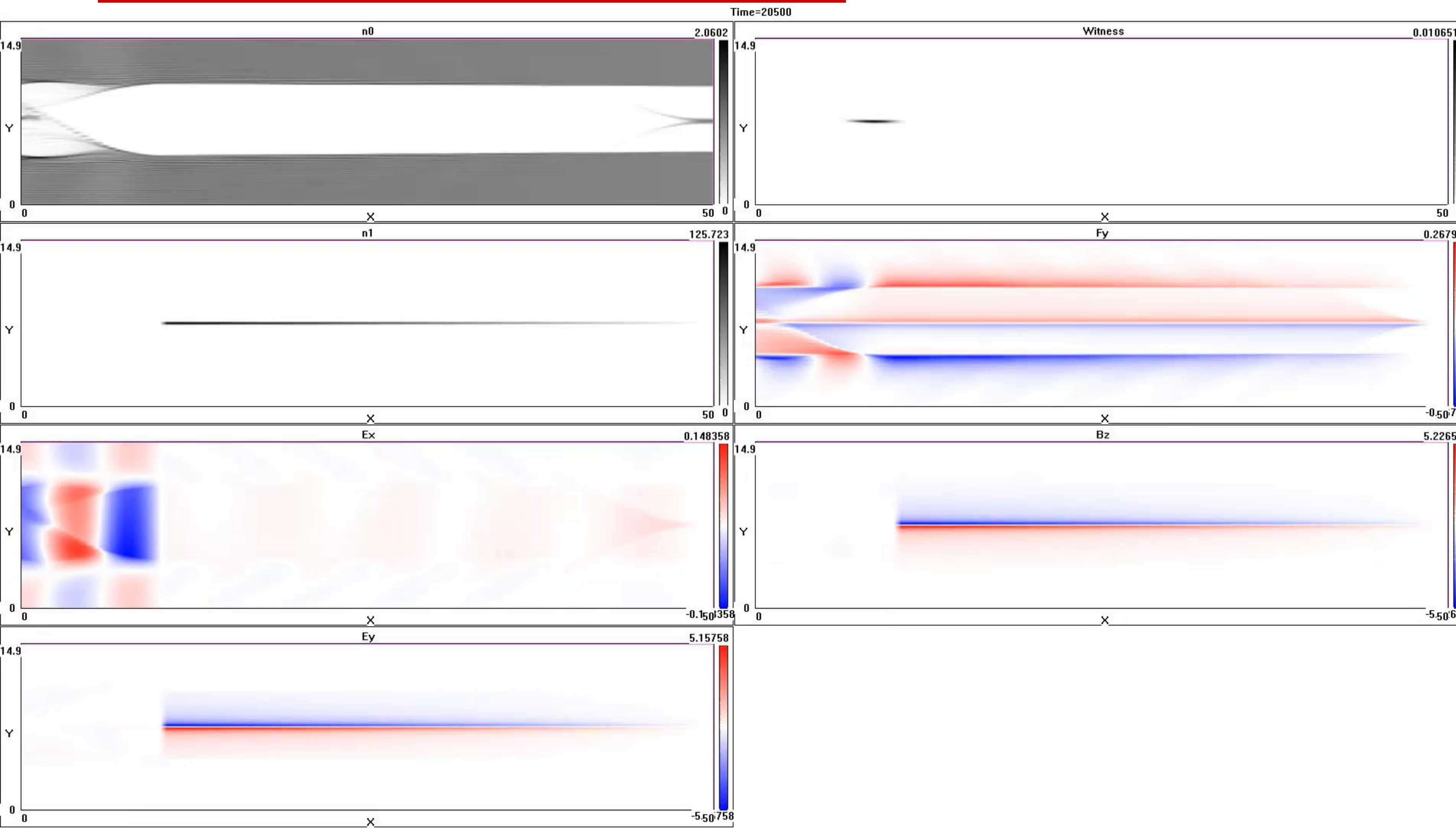
Witness

The acceleration quality



Witness energy spectrum and emittance

Stabilization in a co-axial plasma channel 7% off-axis misalignment

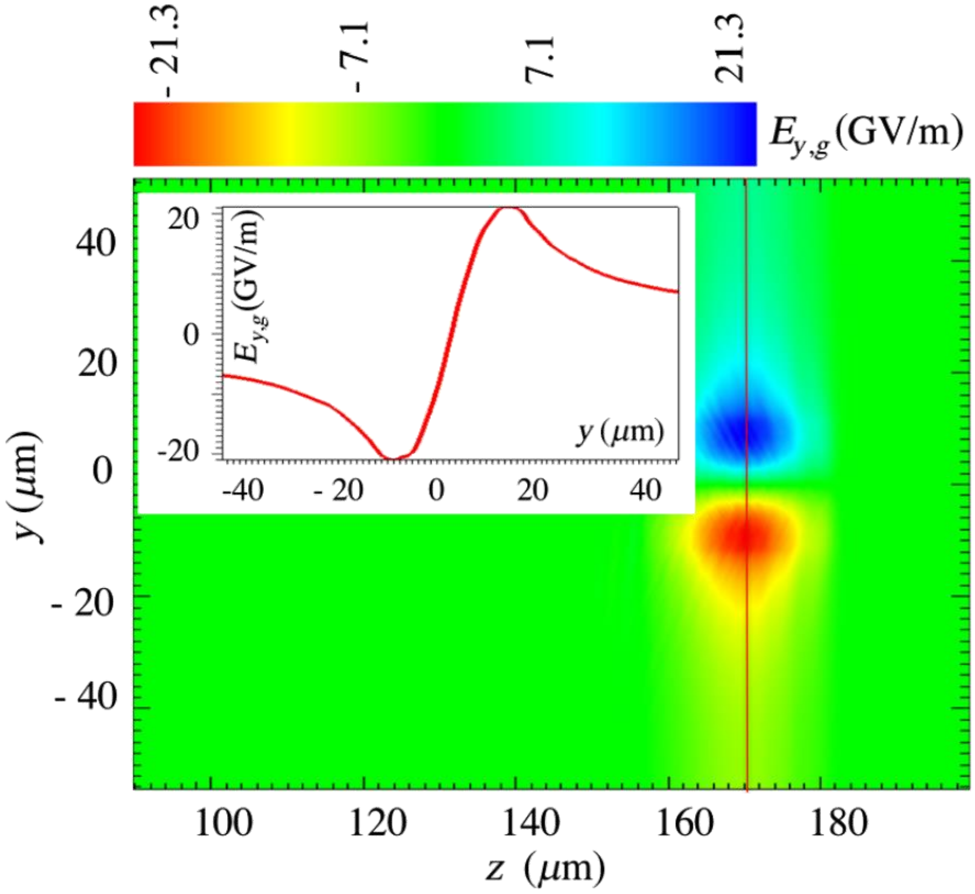


Options:
how to create the plasma channel with a co-axial filament?

- **3d laser printing of plasma in gas**
  pointing stability?
  laser Rayleigh length is too short

- **Gas ionization by a charged particle bunch**
  the bunch can be externally guided over long distances
  high current bunch is required
  ultra-short duration to avoid plasma self-action

Transverse bunch field



Bunch parameters required for ionization

Ionizing field E_{crit} [GV/m] ~ $0.17(I_p\,[\text{eV}])^2$

Bunch field E_{max} [GV/m] ~ $30\, I_b$ [kA]/a[μm]

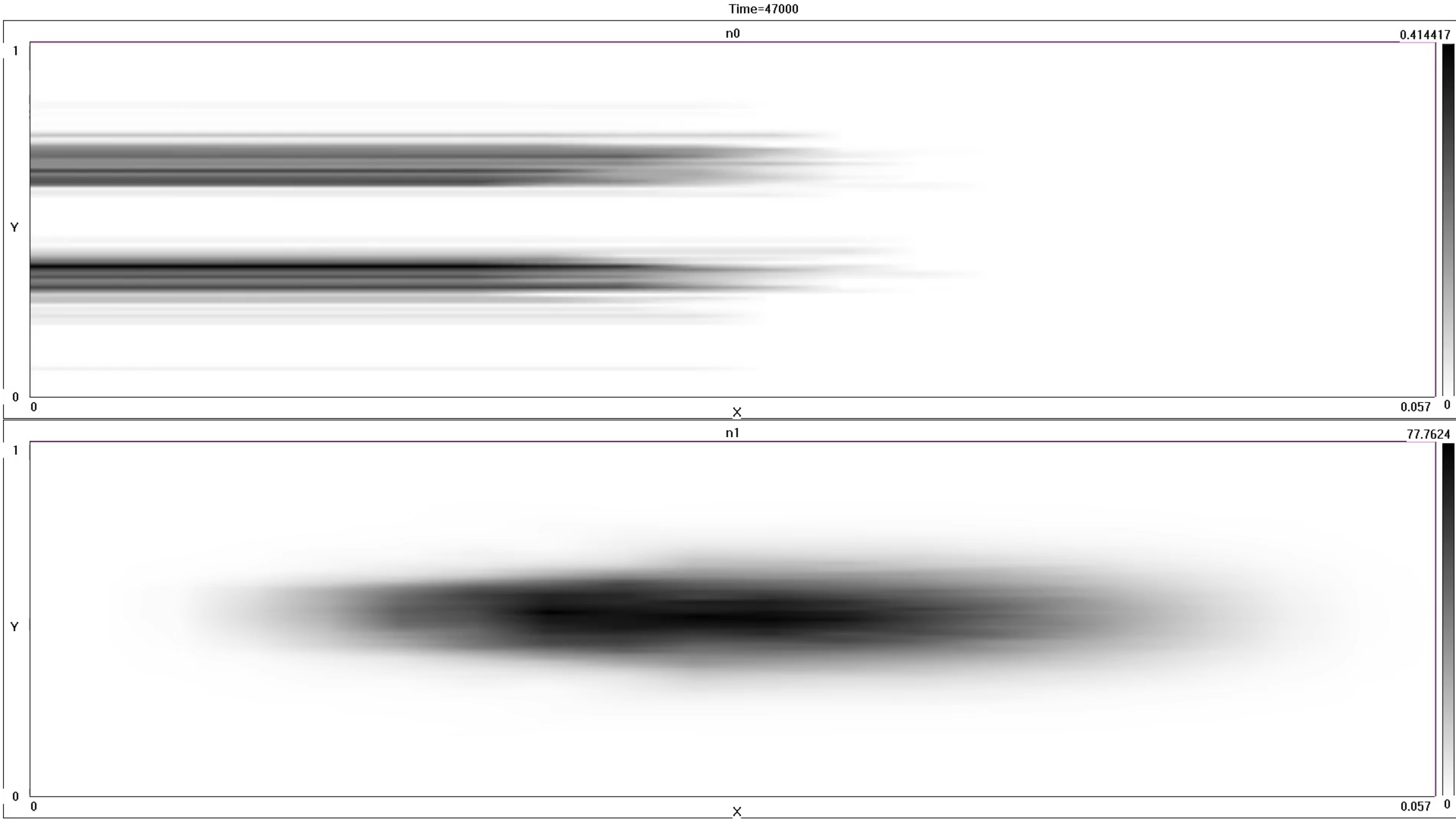
For central plasma filament radius a=1.5 μm:

H: I_b ~ 10 kA, duration 1 fs, charge 10 pC
He: I_b ~ 40 kA, duration 1 fs, charge 40 pC
Li: I_b ~ 1 kA, duration 1 fs, charge 1 pC

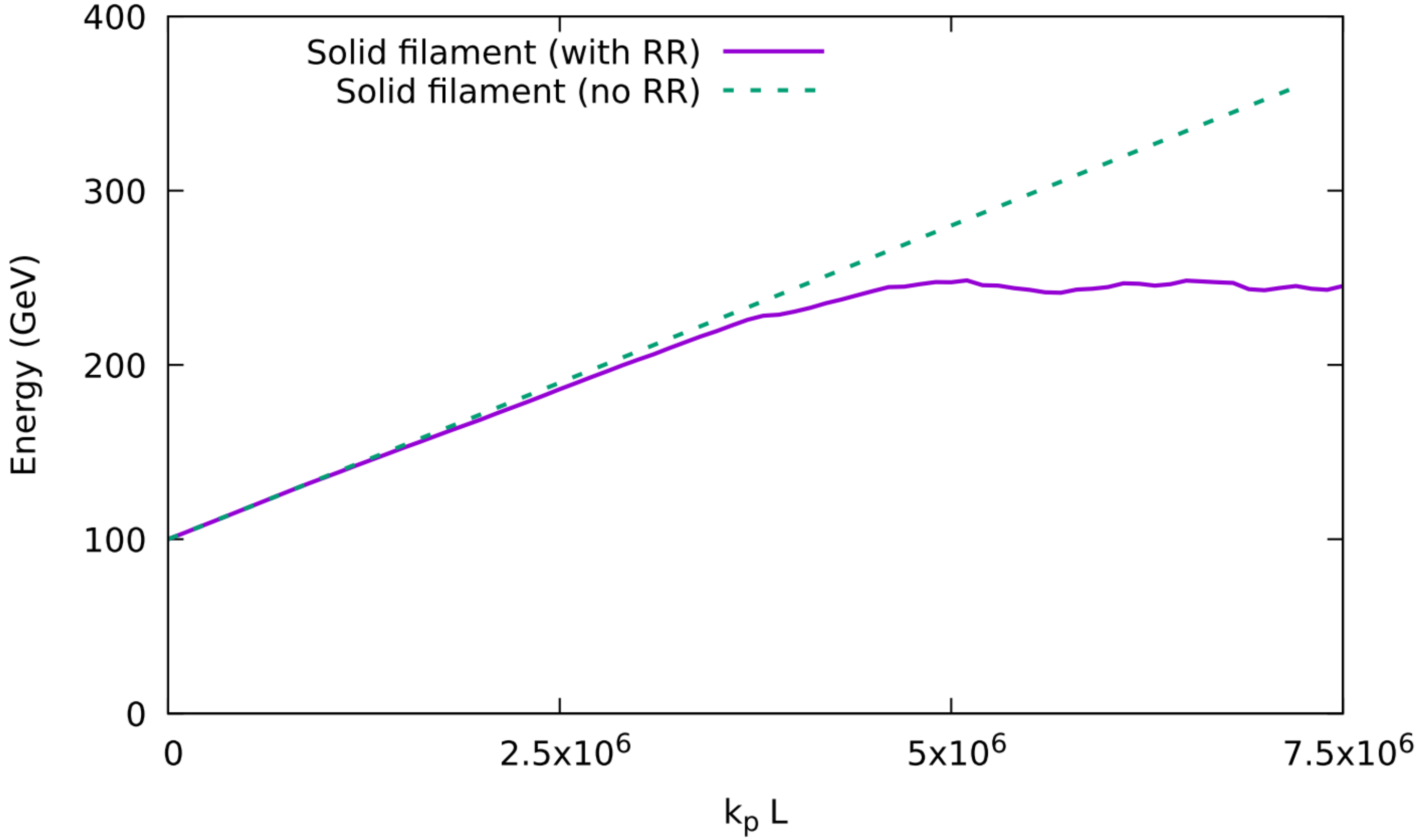
Assuming plasma density ~ $1\text{x}10^{17}$ $1/\text{cm}^3$

Hollow channel generation in He by charged particle bunchest

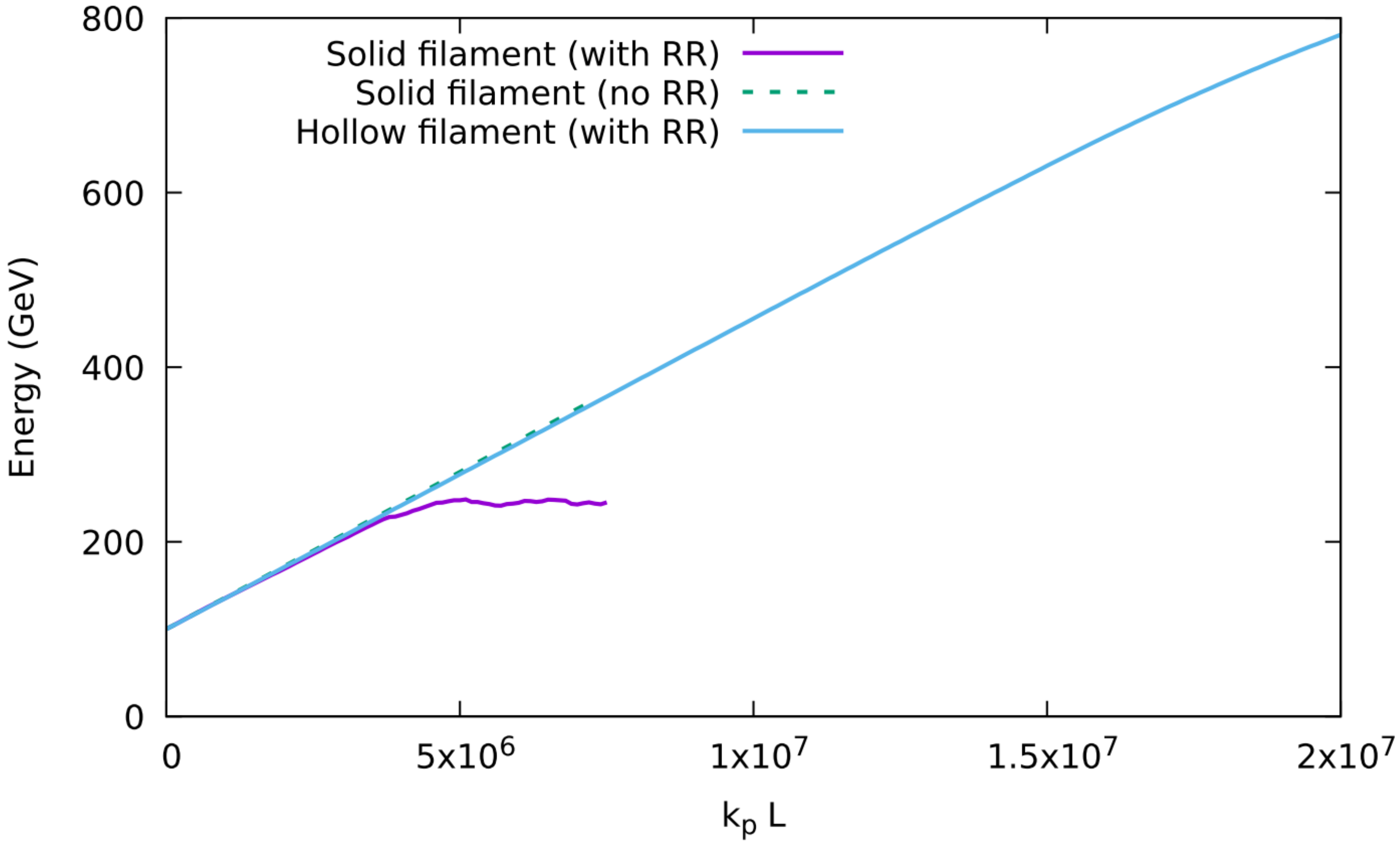
I=40 kA, τ=1 fs, σ=1.5 mm, *W*=10 GeV, *B*: 0.5 T/mm



Electron acceleration in solid filament



Electron acceleration in hollow filament

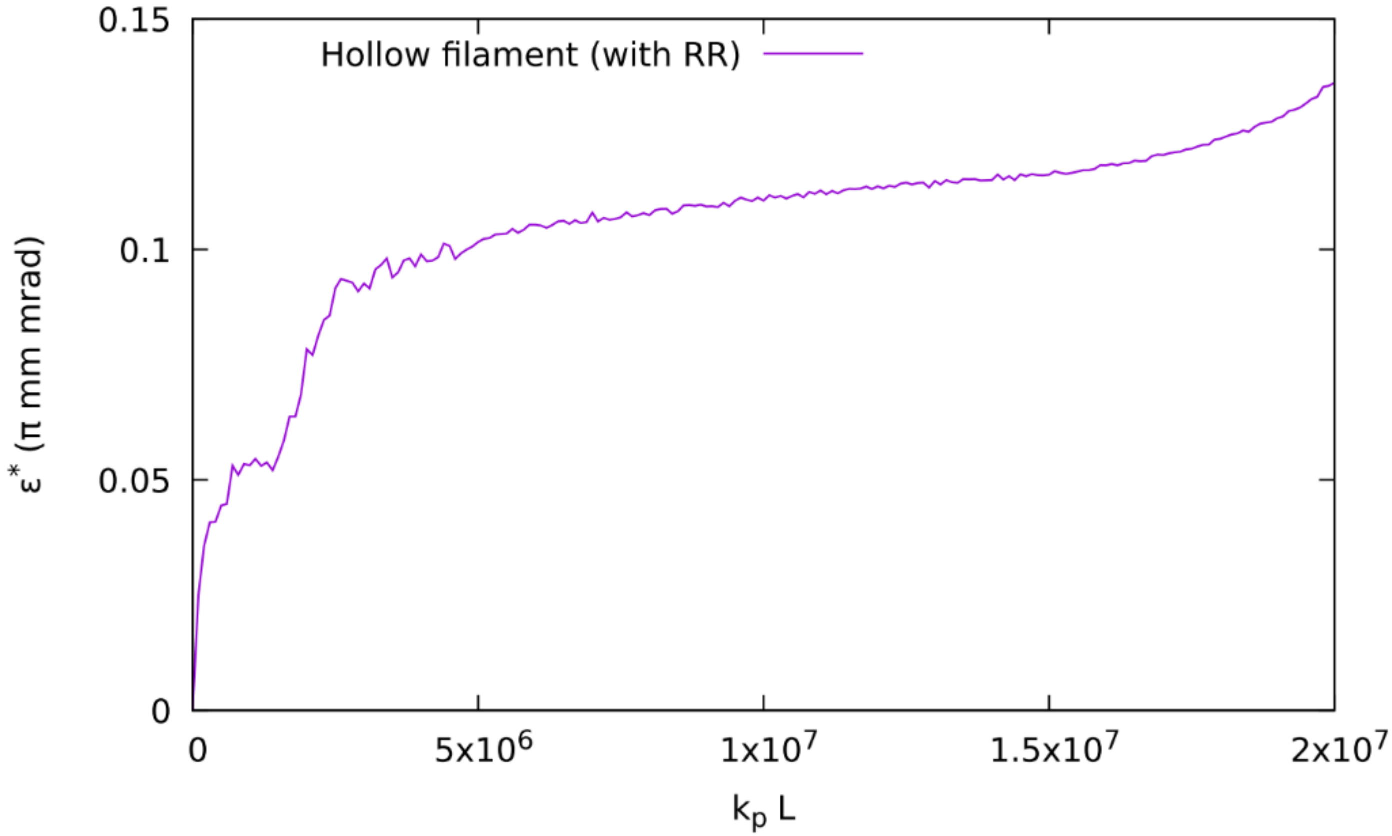


The TeV simulation parameters (nothing optimized at all)

- 100 GeV electron bunch driver, 100 GeV witness bunch
- 1.7 nC driver
- ramped driver current zero to 14 kA over 300 μm (1 ps)
- Plasma density n=1.1x10^{17} 1/cc
- Channel radius $k_p r_c$=2
- Central filament radius $k_p r_f$=0.15
- Witness final energy ~0.8 TeV

  Final emittance ~0.1 μm (unmatched bunches!)

Electron acceleration in solid filament



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Outlook

- **Hollow/solid plasma channels can be created by high current ultra-short particle bunches**

- **TeV acceleration in hollow plasma channels with hollow on-axis filaments is feasible**

- **Further studies towards matched bunches, final emittance reduction and positron acceleration are needed**