PLASMA WAKEFIELD ACCELERATORS.

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HELMHOLTZ

DESY.

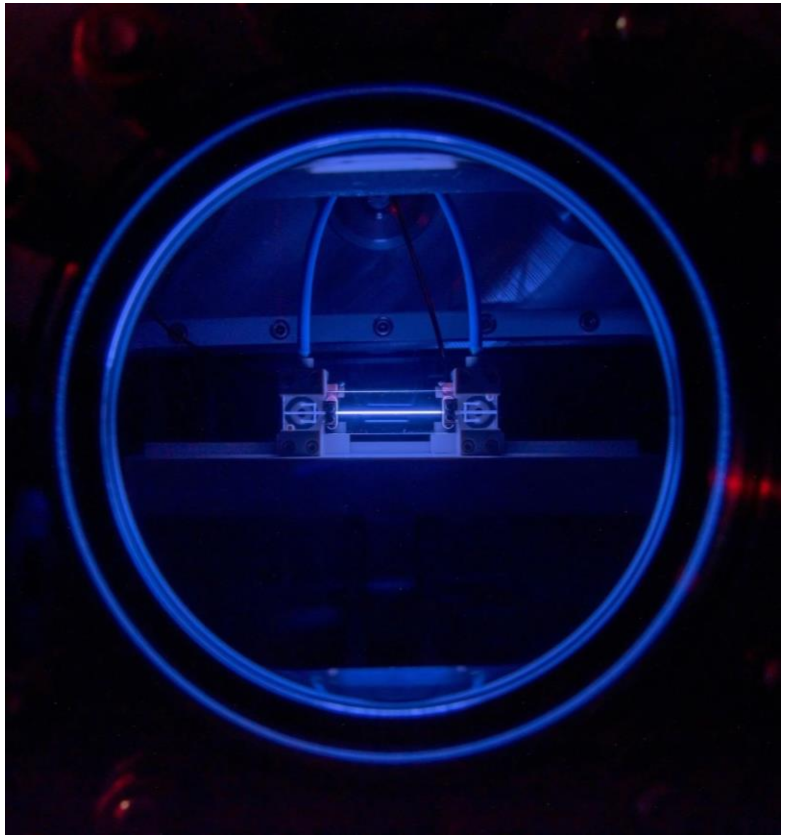
Plasma wakefield accelerators

Why Plasma Accelerators?

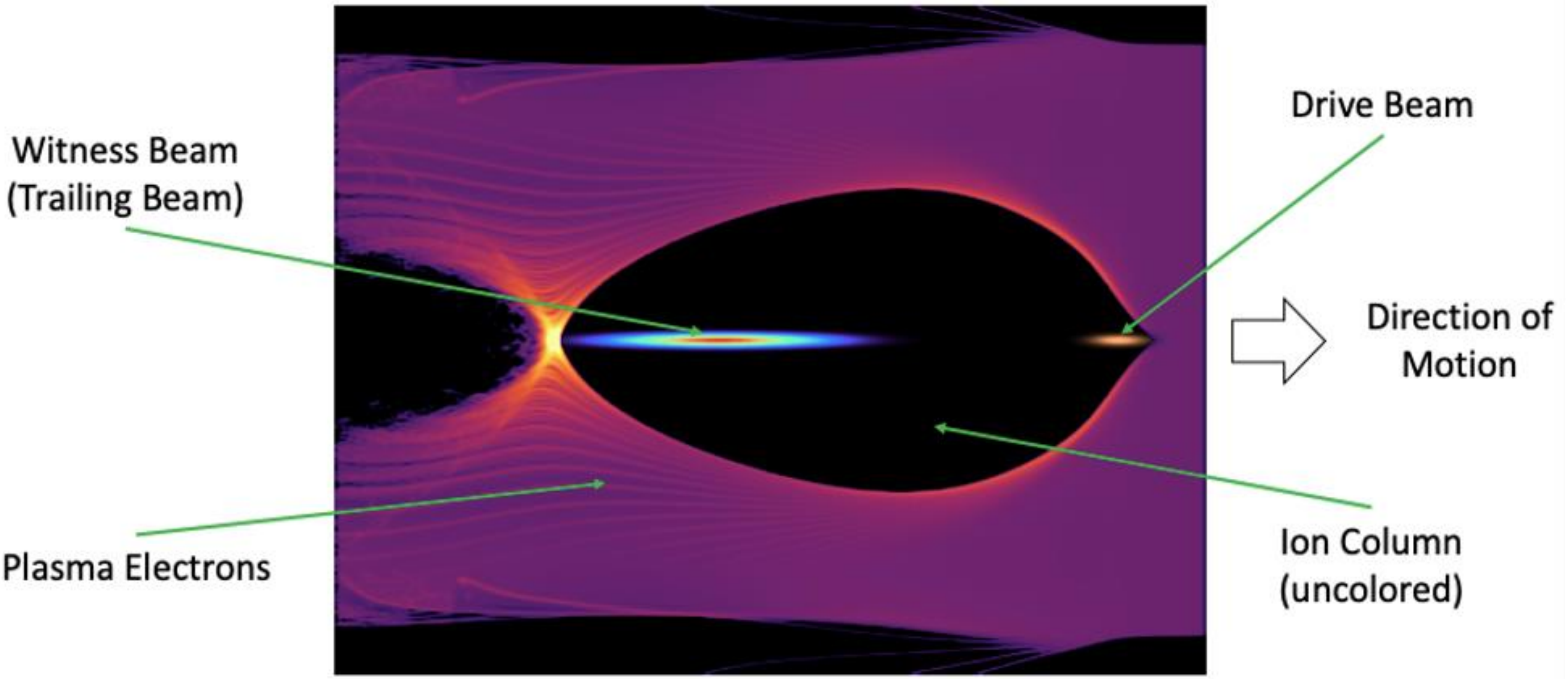
- Compact size
- Millimeter-scale acceleration
- Compact alternative to traditional RF accelerators
- High gradients (100 GeV/m range)

Future Applications

- Next-gen light sources
- Medical accelerators
- Compact electron sources for materials science
- PETRA IV, High-energy physics experiments



Acceleration Mechanism



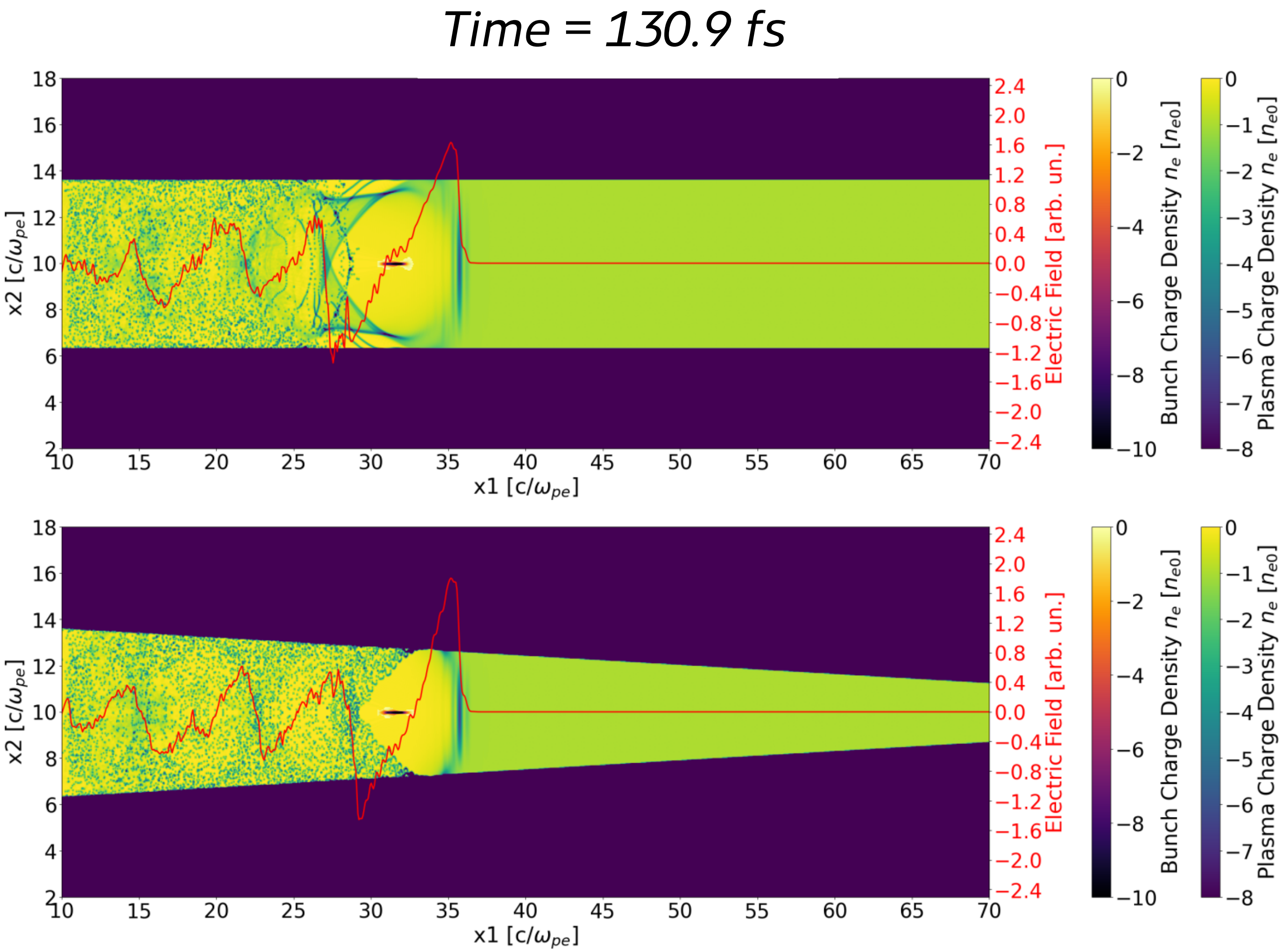
Comparison of conical and cylindrical channels

Cylindrical Channel:

- Bunch trapped in decelerating field
- Self-injected electrons appear

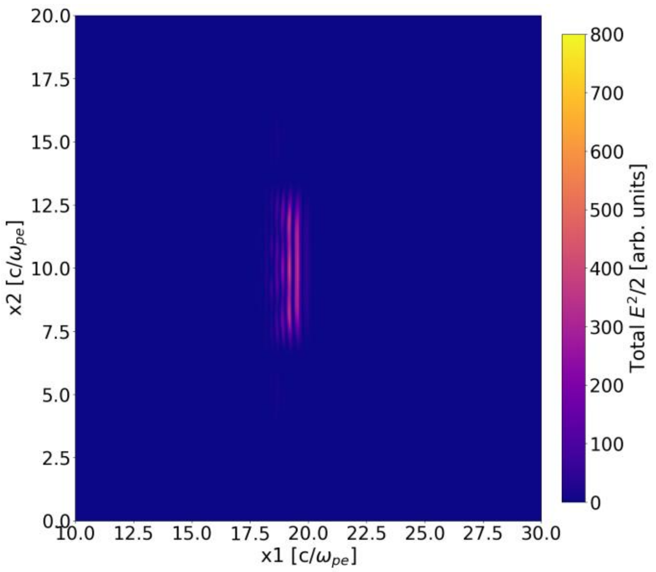
Conical Channel:

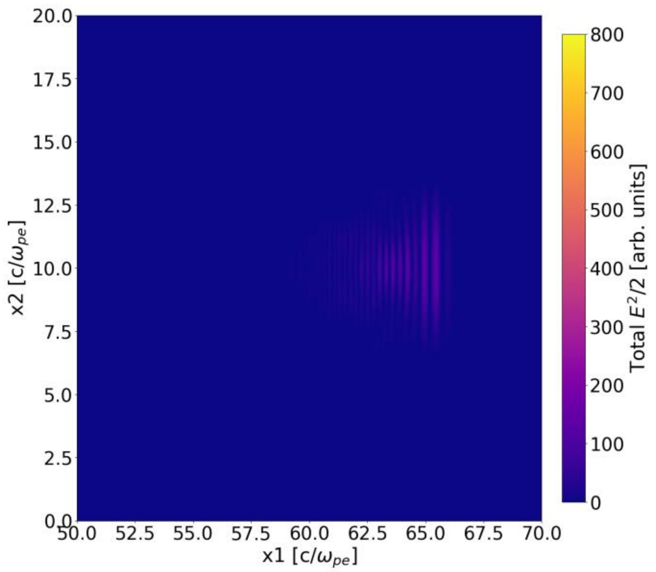
- Bunch stays in accelerating field
- Extends acceleration time

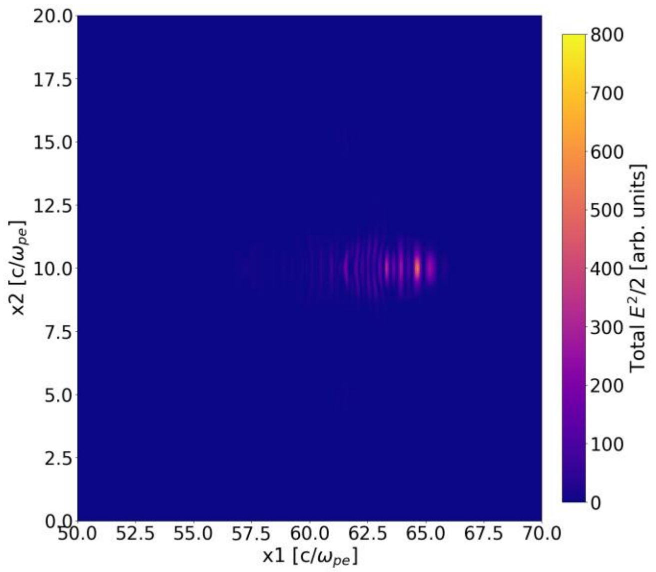


Comparison of conical and cylindrical channels

Laser pulse evolution







Laser field energy:

- laser pulses have similar energy and size in both cases at the beginning of channels

Laser field energy in the cylindrical region:

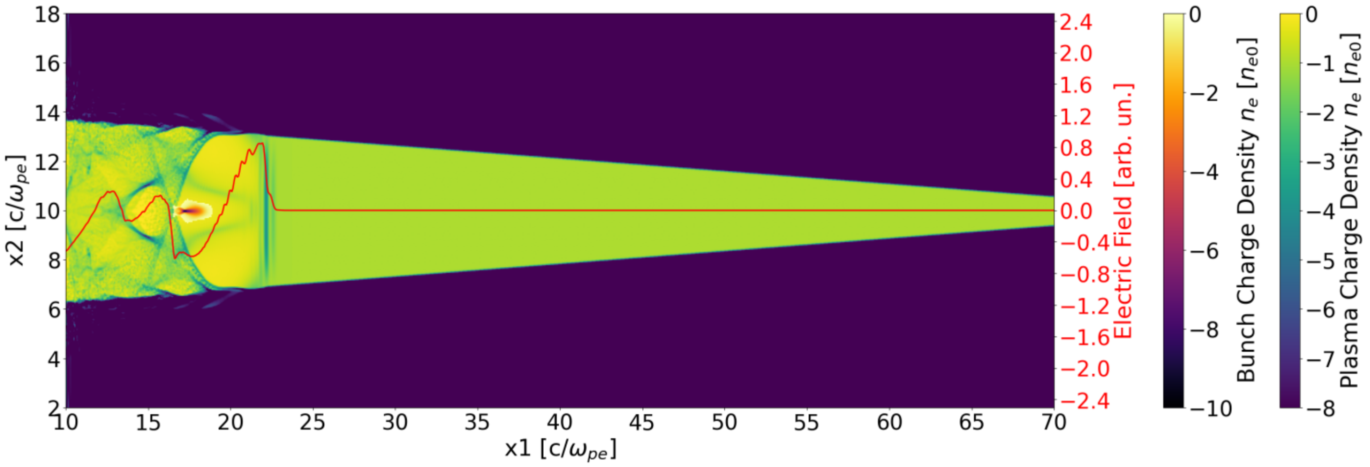
- Faster energy loss during propagation
- Less effective energy transport

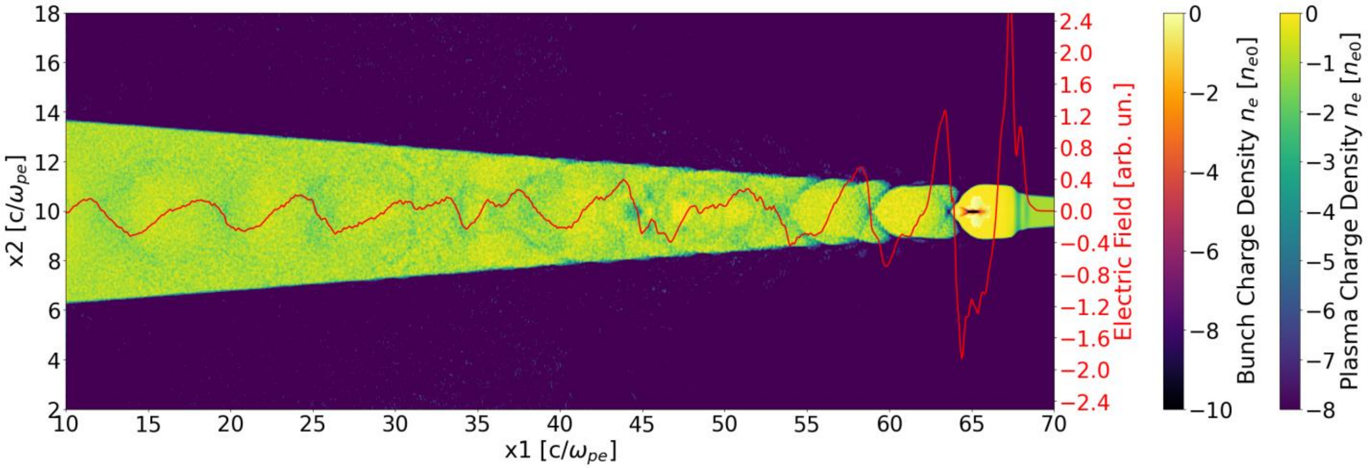
Laser field energy in the conical region:

- Higher energy retained over time
- Supports longer wakefield excitation

Comparison of conical and cylindrical channels

Accelerating gradient and electron bunch energy





Accelerating gradient:

In a conical plasma channel, the bubble compresses, reducing the local plasma wavelength $E_z \sim 1/\lambda(z)$.

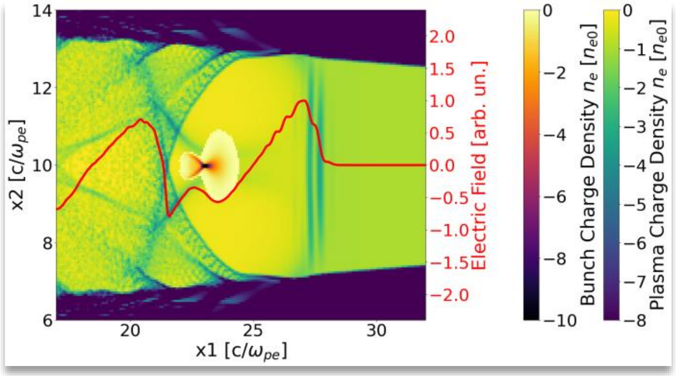
The peak accelerating field increases by a factor of ~3

Electron bunch energy:

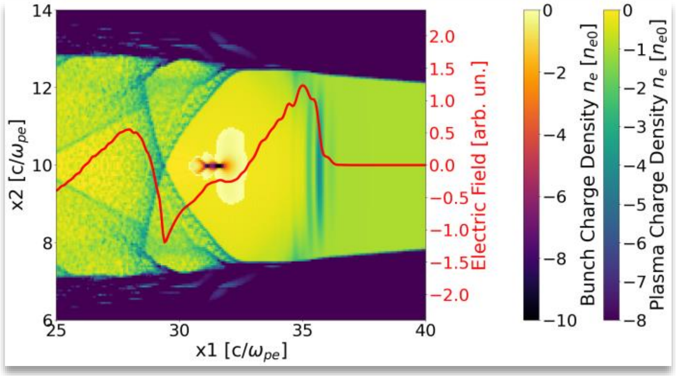
- **Cylindrical channel:** bunch energy increases by a factor of ~1.5
- **Conical channel:** energy increases by a factor of ~4.5

Beam loading effect

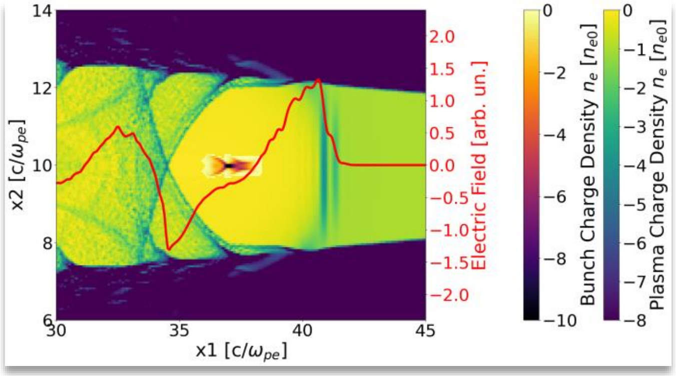
Wakefield spatial distribution caused by beam loading



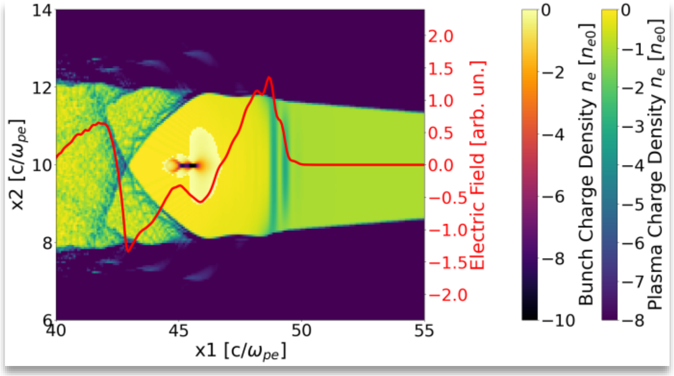
Time: 95.2 fs



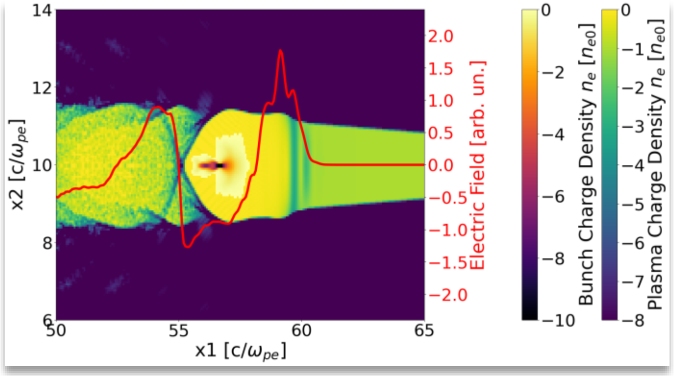
Time: 130.9 fs



Time: 154.7 fs



Time: 190.4 fs



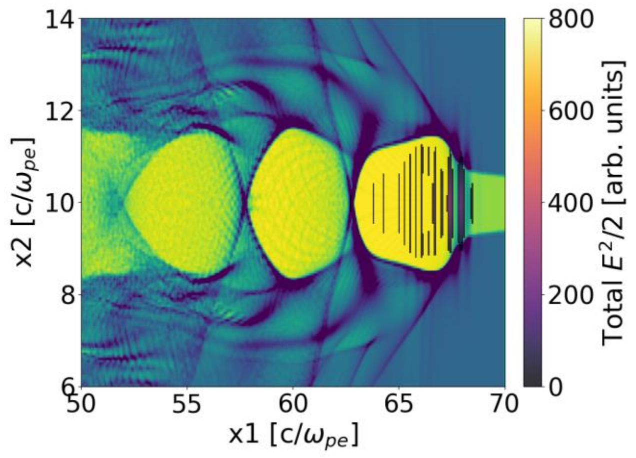
Time: 238 fs

Effect of external plasma density

Laser field energy in the conical region

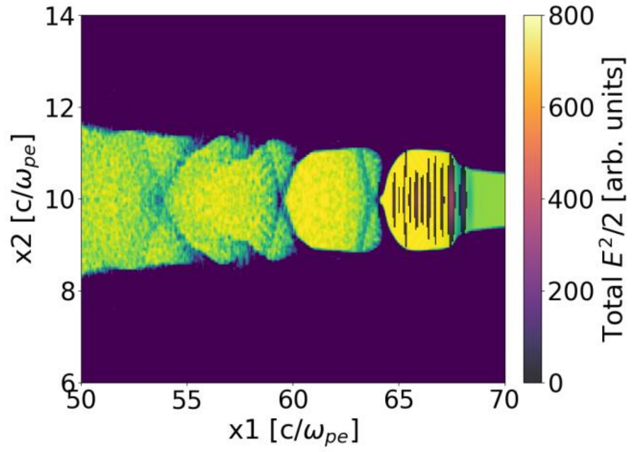
External density 4 n_{e0}:

- Bubble remains too wide, indicating weak confinement.
- Low density contrast limits bubble shaping and laser guiding.
- Even reducing cone radius cannot compensate.



External density 10 n_{e0}:

- Improved bubble confinement within the cone.
- Some lateral expansion still present.



Focusing force

Focusing force for the external plasma density $10n_{e0}$

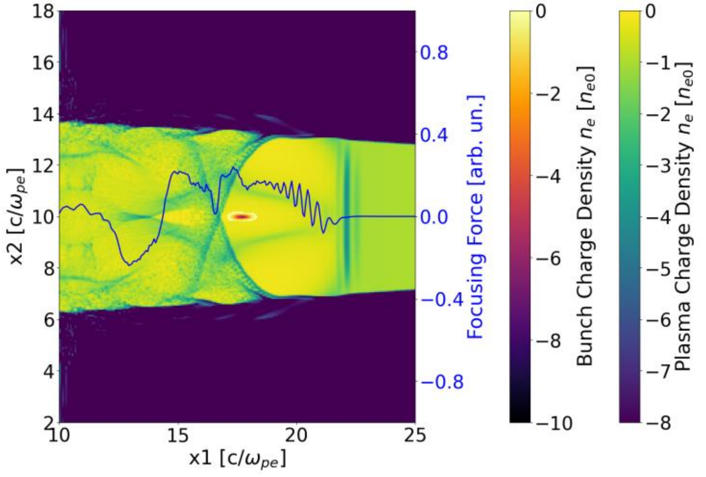
Radial Focusing Force:

- Radial force Fr focuses the electron bunch
- Maximum stability occurs where dFr/dz is largest

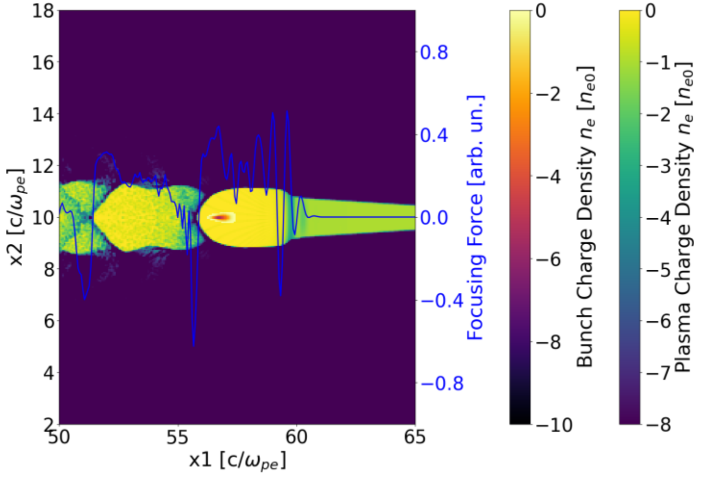
Plasma Electron Behavior:

- Plasma electrons entering the cavity focus toward the axis.
- This has a stabilizing effect on the bunch, improving confinement and structural integrity.

Time: 71.4 fs



Time: 238 fs



Comparison of uniform, non-uniform plasma density

Uniform plasma:

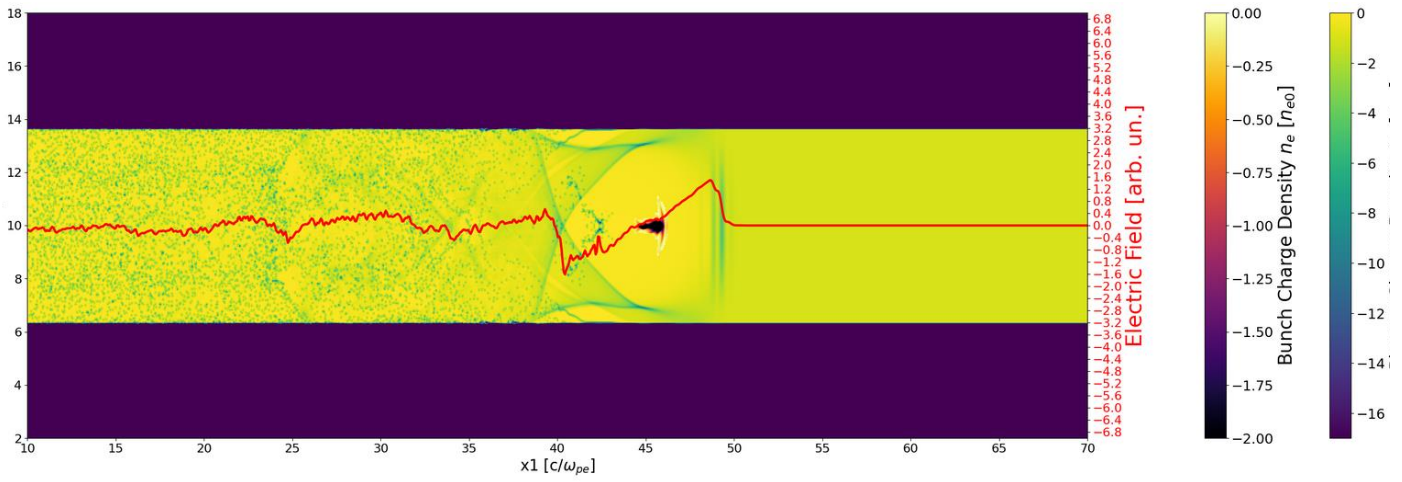
- Bunch enters decelerating region
- Risk of self-injection

Field scaling in plasma:

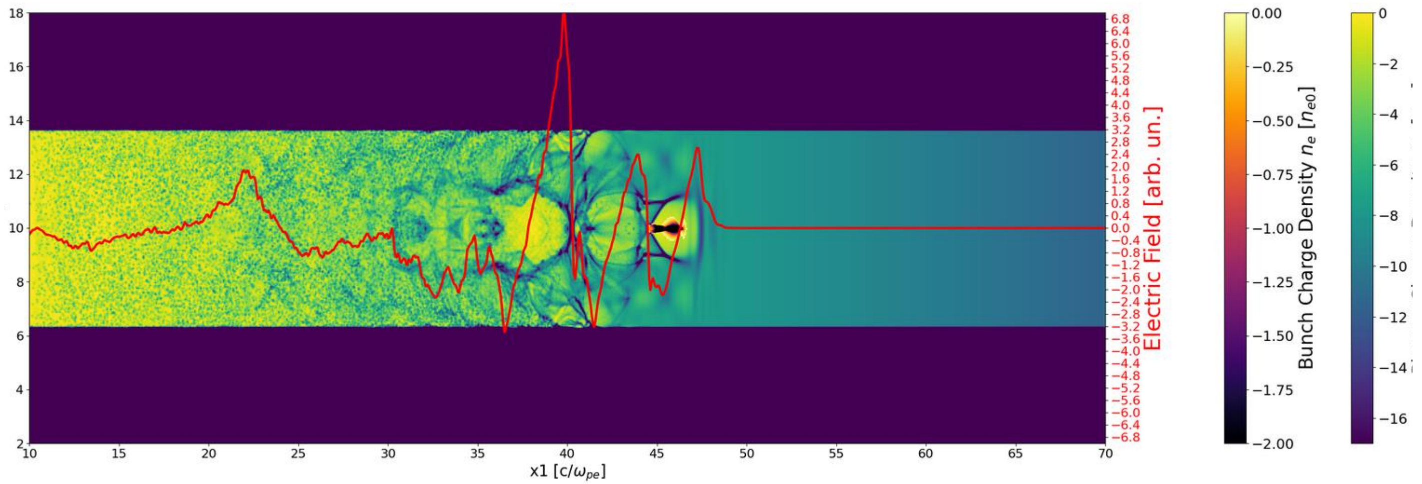
$Ez = \nabla\varphi = k\varphi \sim 1/\lambda(z) \sim \sqrt{n_0}$

Non-uniform plasma:

- Accelerating field (~0.874 TV)
- Bunch stays in accelerating field
- Gradient suppresses self-injection and improves control



Time = 190.4 fs



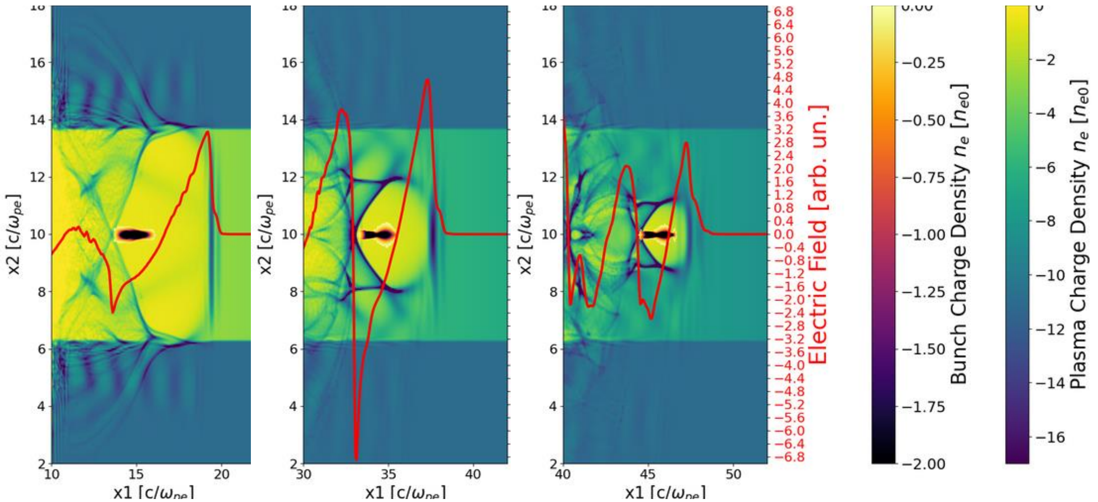
More real density outside

Uniform plasma(11 n_0):

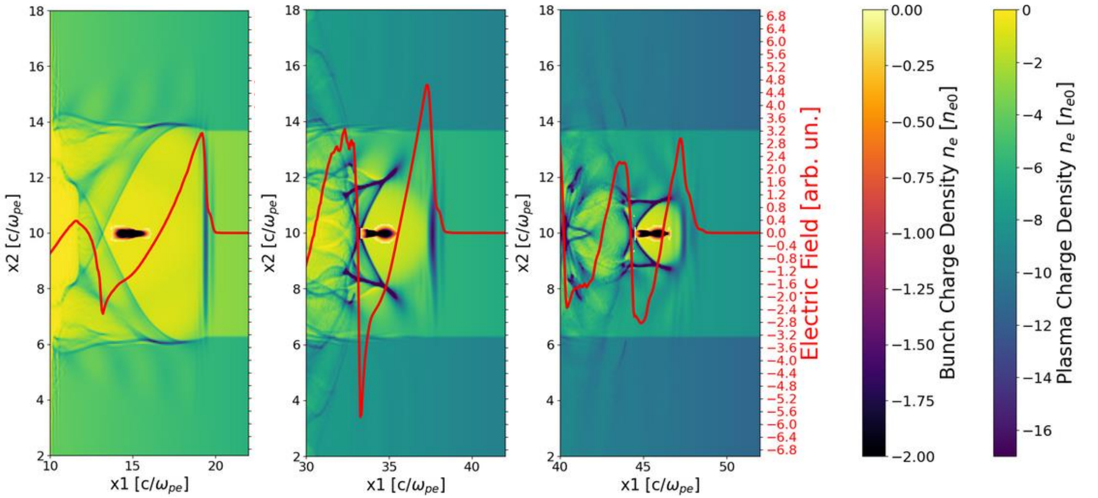
- Higher initial density.
- Stronger fields, faster bubble formation (full wall at t = 142.8 fs).

Non-uniform plasma:

- Smooth density gradient.
- Bubble not fully formed at t = 142.8 fs.
- Bunch remains longer in the accelerating phase.



t = 59.5 fs t = 142.8 fs t = 190.4 fs



Density of the bunch

$2\ n_0$:

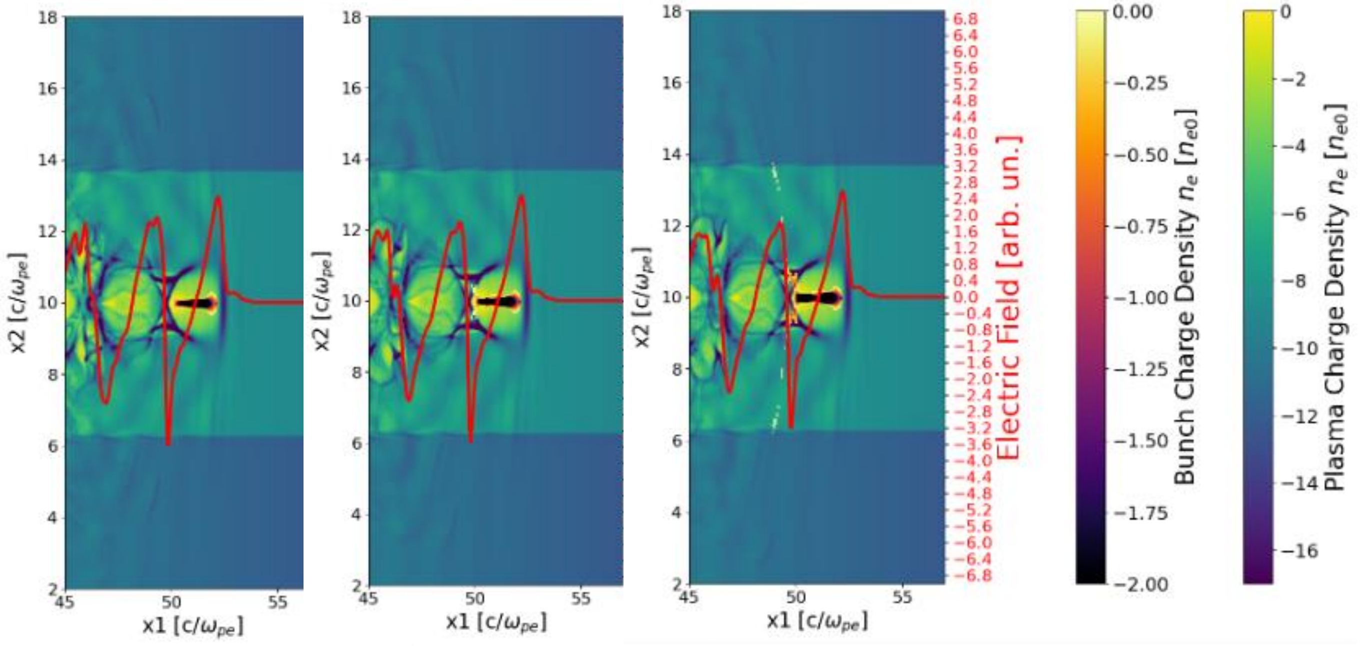
- Effective gradient ≈ 6.75 GeV/cm
- Stable

$2.5\ n_0$:

- Lower effective gradient ≈ 6.36 GeV/cm
- Higher instability risk

$3\ n_0$:

- Bunch breakup at t = 214.2 fs (unstable)



$2\ n_0$ $2.5\ n_0$ $3\ n_0$

Bunch Optimization

Stability:

- At 3 n_0 reducing bunch length to 0.314 c/ωpe ensured stability at t = 214.2 fs.

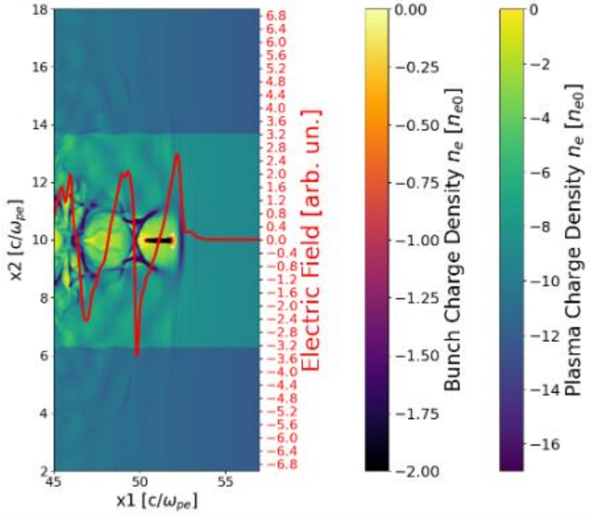
Length effect:

- A long bunch overlaps with near-zero accelerating field → inefficient.

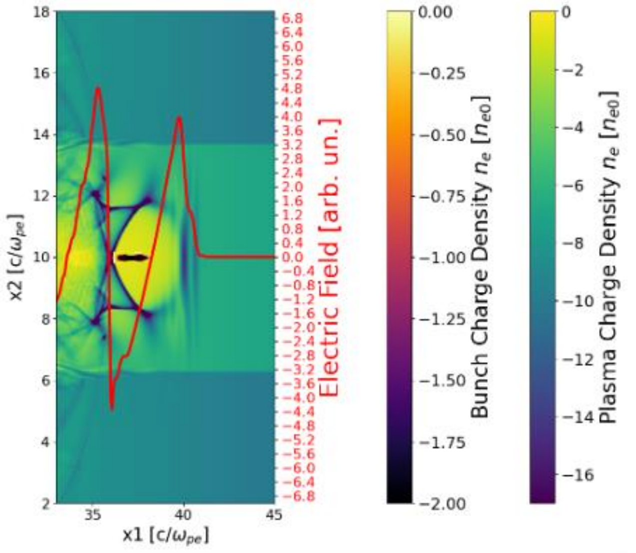
Improvement:

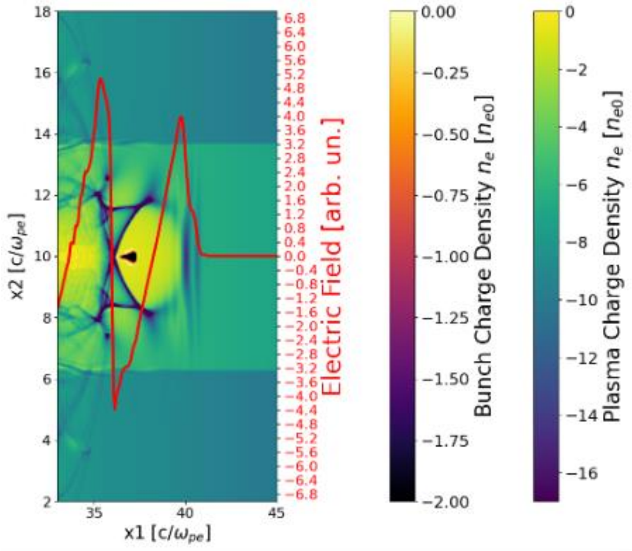
- Shortening the range 2.279 → 1.079 c/ωpe led to
- Reduced energy spread: ΔE = 45.6 → 26.1 norm.
- Effective gradient ≈ 9.6 GeV/cm

sigma 0.314 c/ωpe t = 214.2 fs



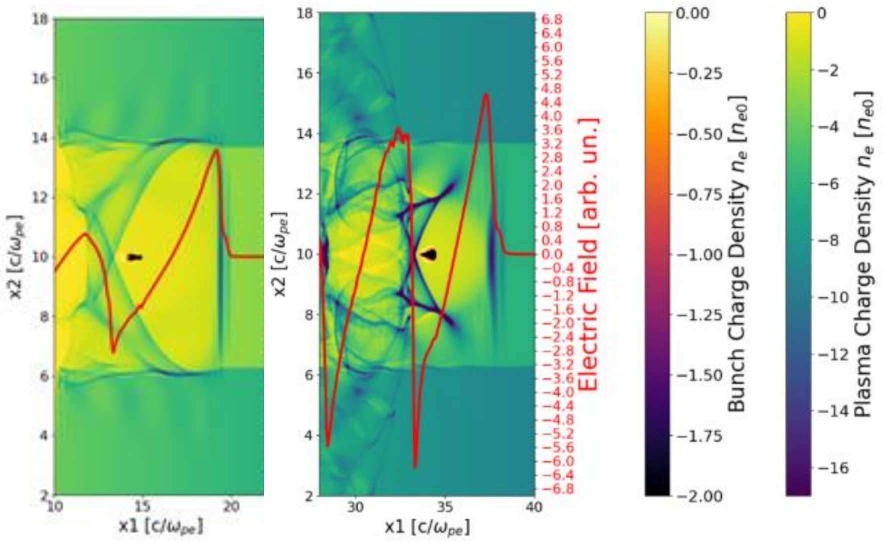
t = 154.7 fs





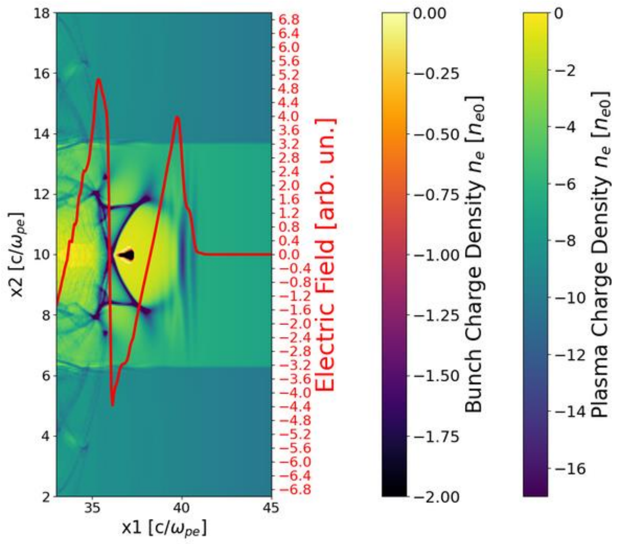
Evolution of Accelerating Field (Ez)

t = 59.5 fs t = 142.8 fs



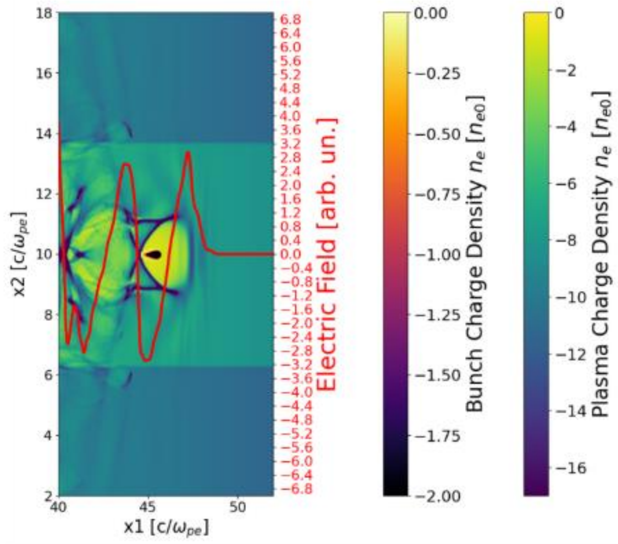
Ez rises from 0.82 → 2.03 TV/m

t = 154.7 fs



Ez decreases to 1.55 TV/m

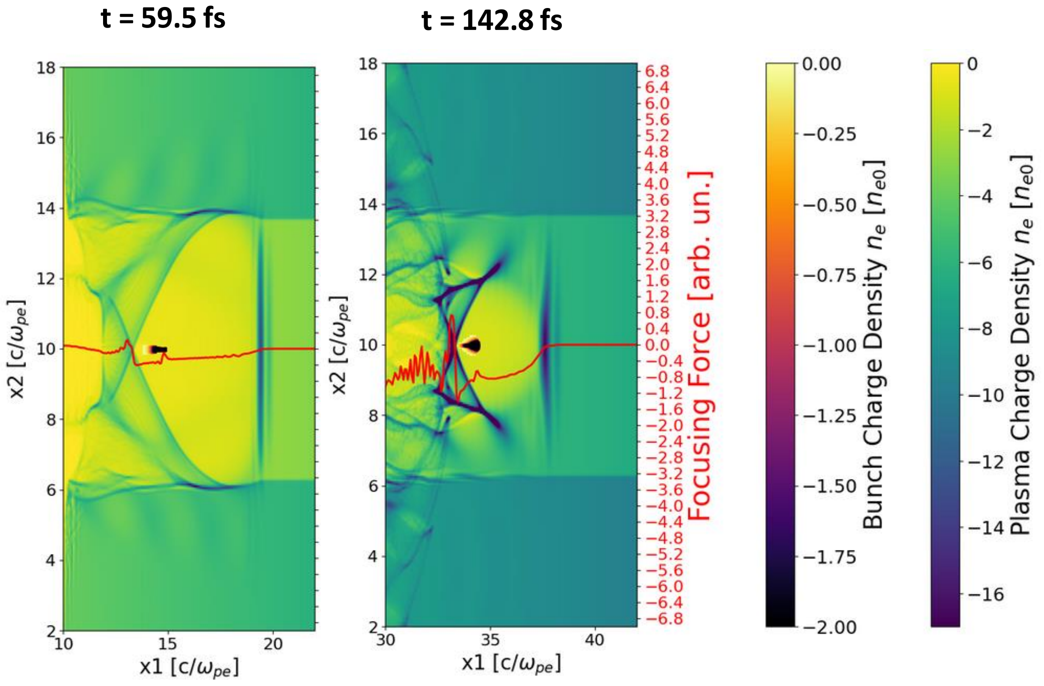
t = 190.4 fs



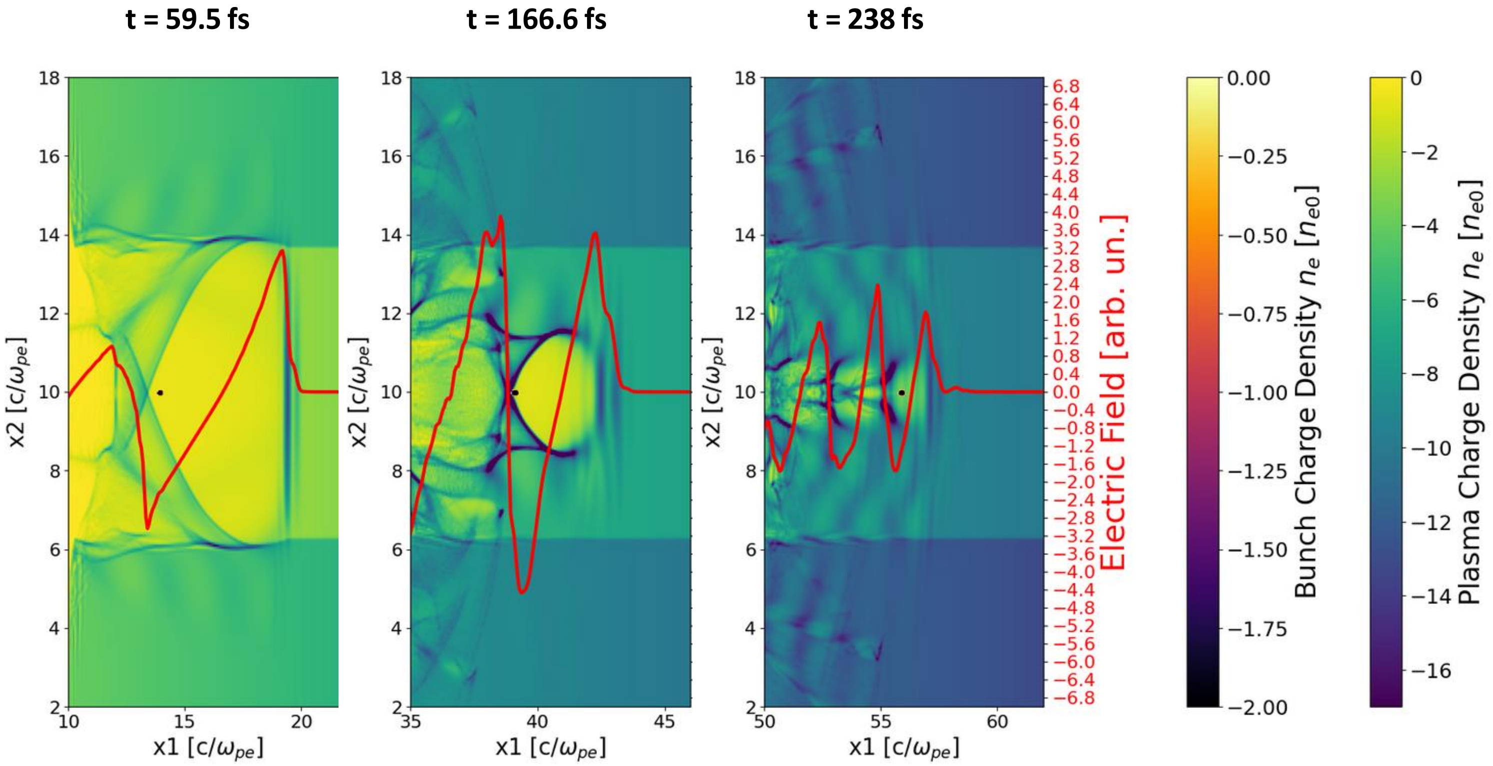
Bunch energy spread decreases

Focusing Force (F⊥)

- F⊥~Ez — bubble contraction strengthens focusing, ensuring transverse compression of the witness.
- Witness remains in the most stable region throughout acceleration.
- Force becomes stronger over time.



Point-like Bunch



- Almost uniform accelerating field.
- Minimal energy spread, strong field maintained longer – very few particles (low charge)
- Gradient ≈ 16.5 GeV/cm. Very small spread: 0.4%

Summary

Demonstrated:

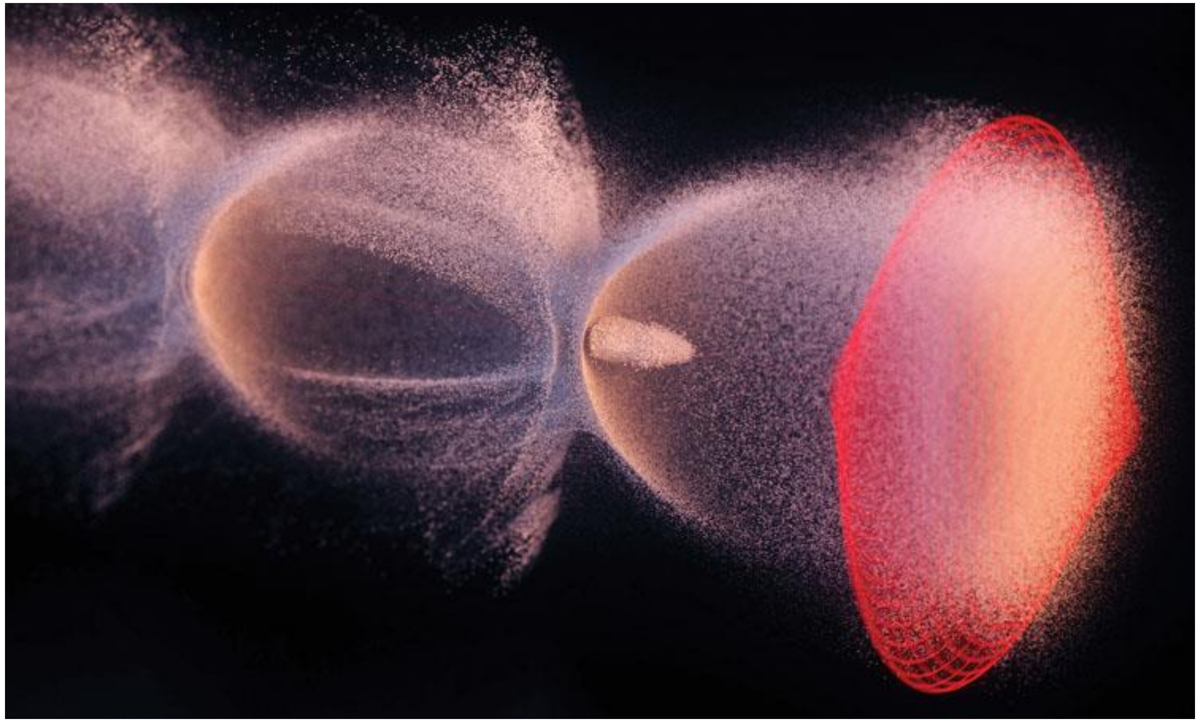
- High energy gain of the witness bunch in plasma wakefield acceleration.

Separately studied:

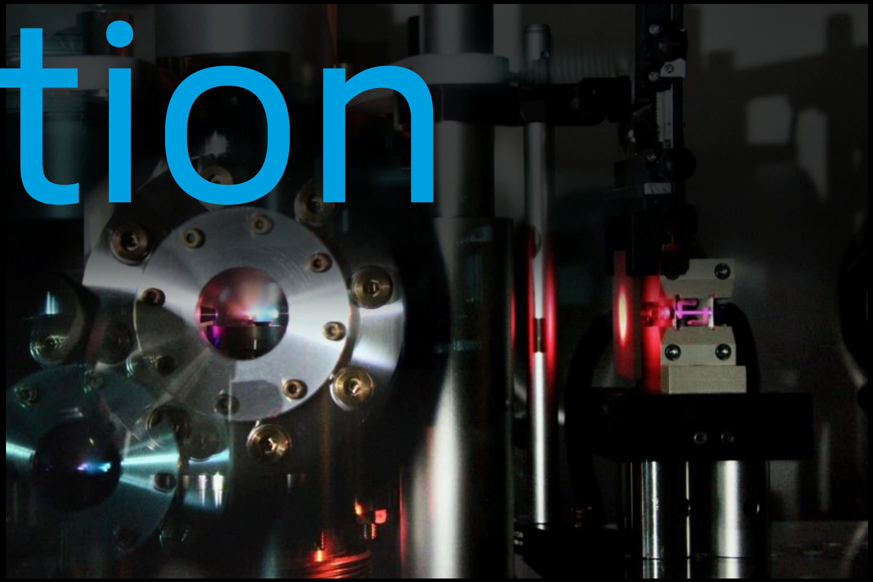
- Non-uniform plasma density.
- Plasma channel shaping (conical form)

Future step:

- Combine density tailoring with channel shaping for optimized acceleration.
- Higher final energies
- Reduced energy spread




Thank you for your attention

Units of Measurement

- **$1/\omega_{pe}$** = 4.25 fs
- **c/ω_{pe}** = 1.27 μm
- **Laser wavelength**: λ = 800 nm
- **Reference plasma density**: $n_{e0} = 1.74 \times 10^{19}\ cm^{-3}$
- **Electric field unit:** multiply by 0.401 TV/m
- **Energy:** multiply by 0.511 MeV