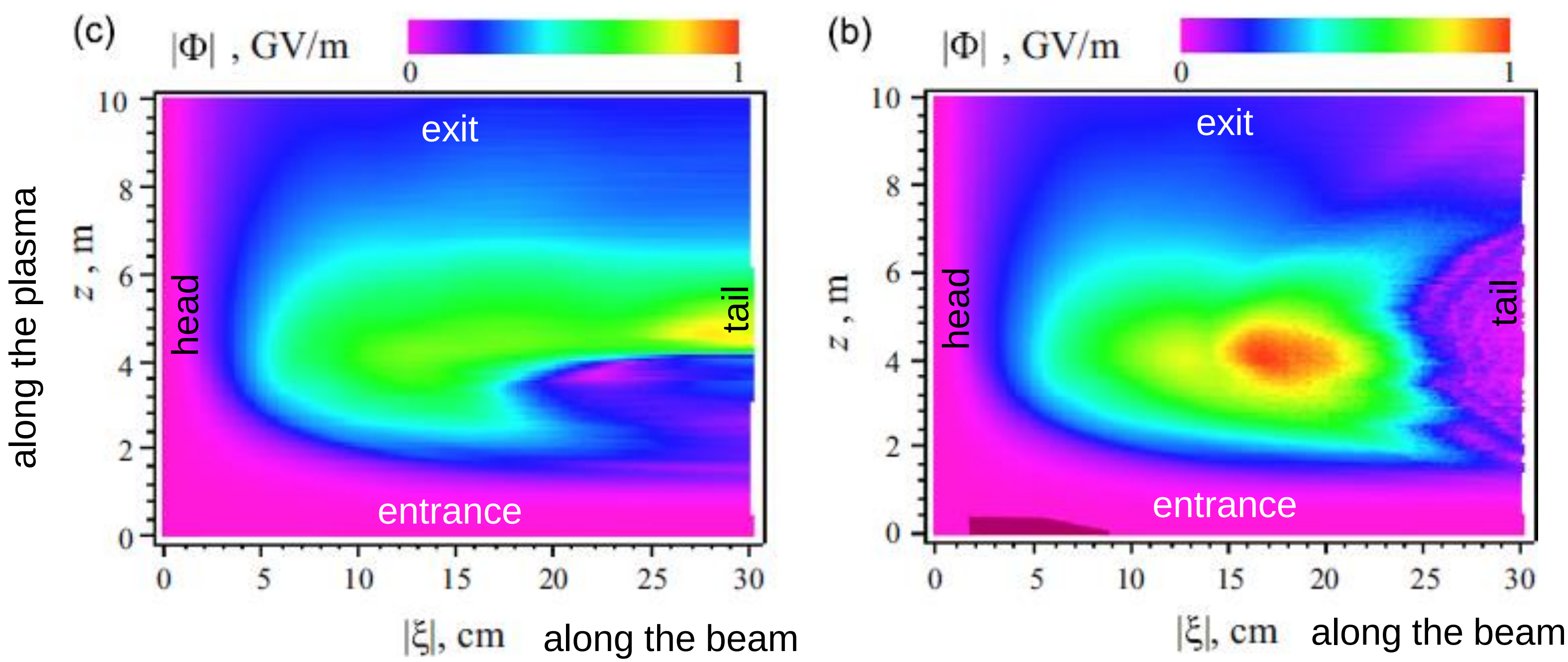
Accelerating field enhancement due to ion motion

Konstantin Lotov, Vladimir Minakov

In old AWAKE simulations, we noticed an unexpected feature:
the peak wakefield is stronger, if ions are allowed to move

A. Caldwell et al. / Nuclear Instruments and Methods in Physics Research A 829 (2016) 3–16



immobile ions

mobile ions

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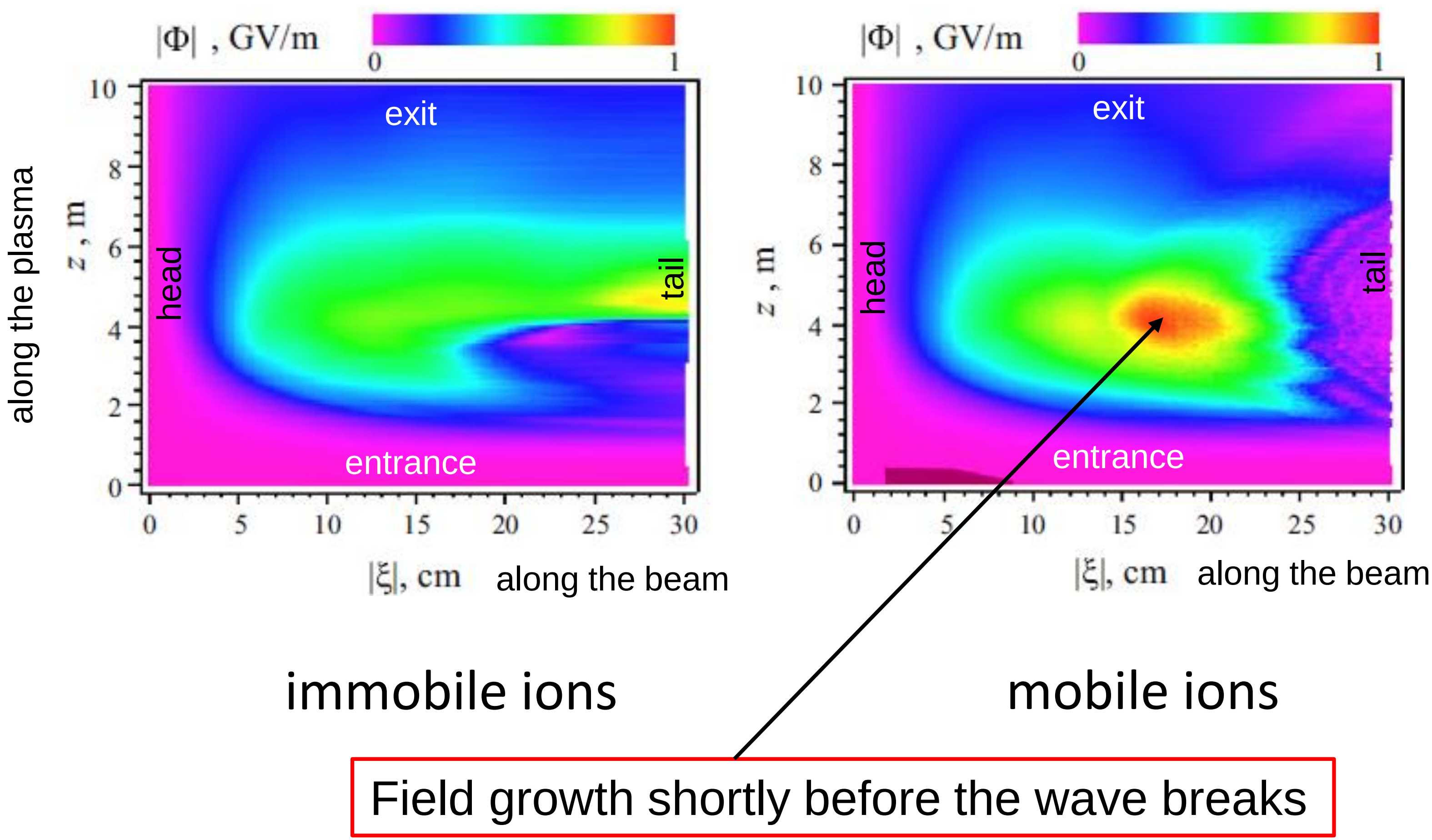
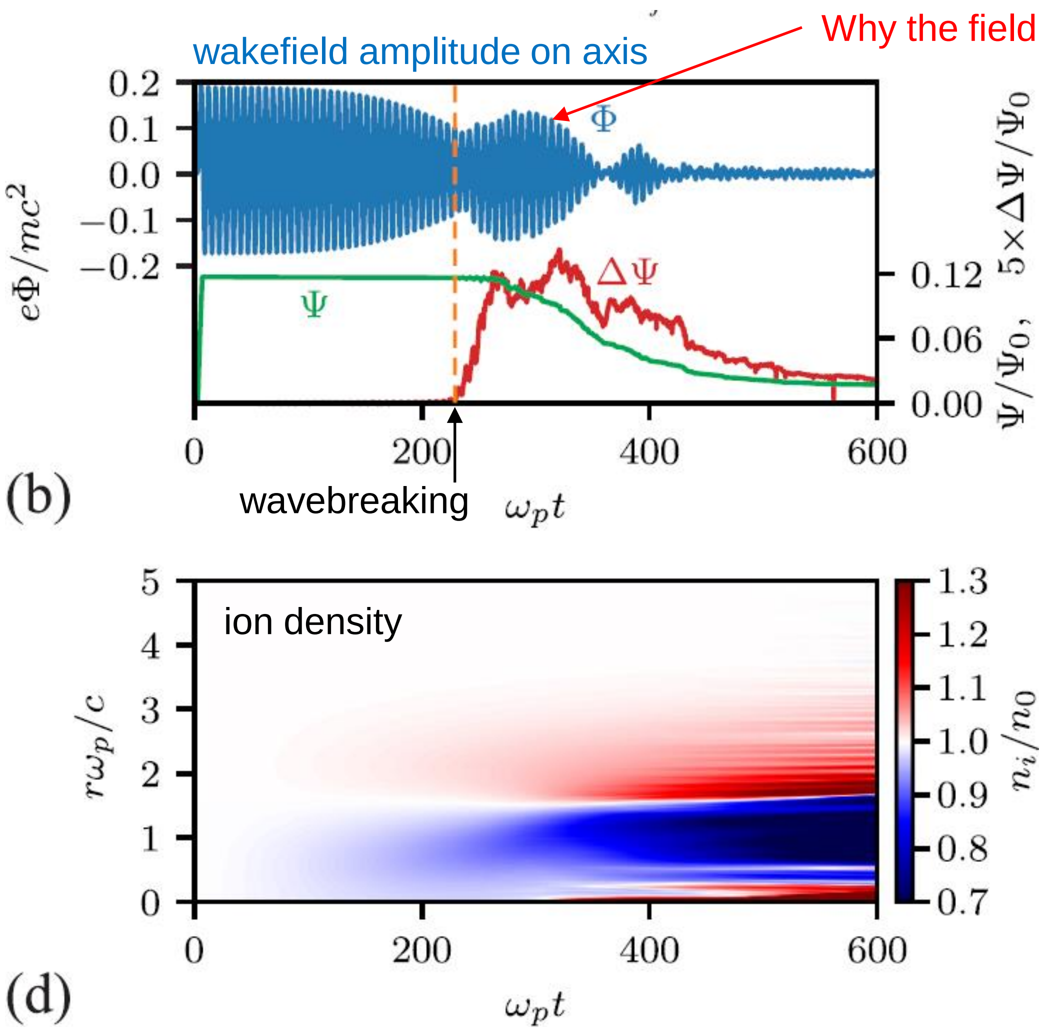


Later, in simulations of laser-driven wakefields, we observed non-monotonous field decay due to wave-breaking:



and again, that was on disturbed ion background

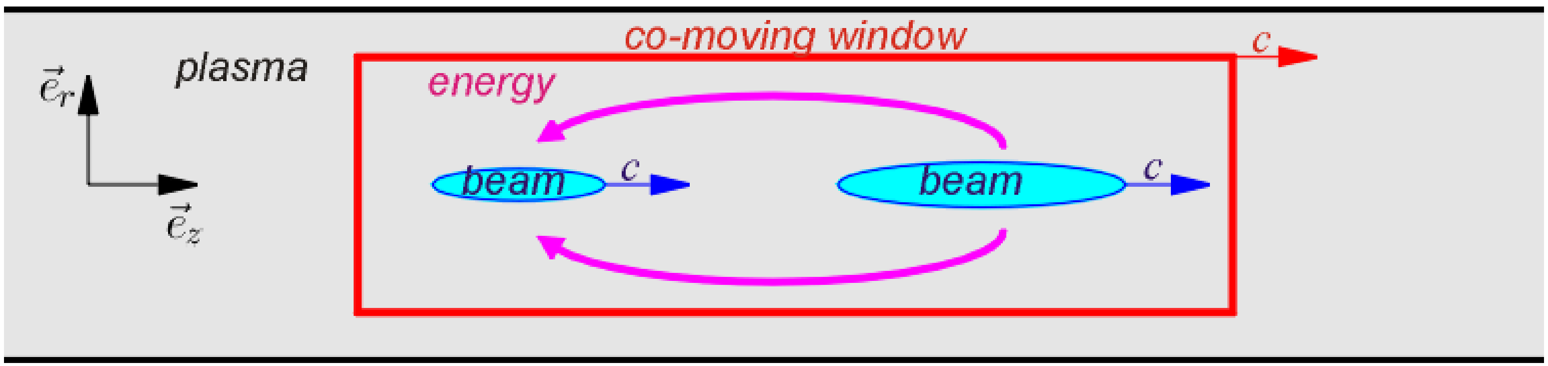
Why ion non-uniformity causes wakefield enhancement?

We simulated various drivers exciting wakefields on various non-uniform density backgrounds, and the key to the answer was …

R.Spitsyn et al., Phys. Plasmas 25, 103103 (2018)

Energy flux in the co-moving window

The wakefield acceleration is the process of energy transfer from one beam to another:



We can visualize this energy flux:

unperturbed field (if any) — kinetic energy of separate electrons

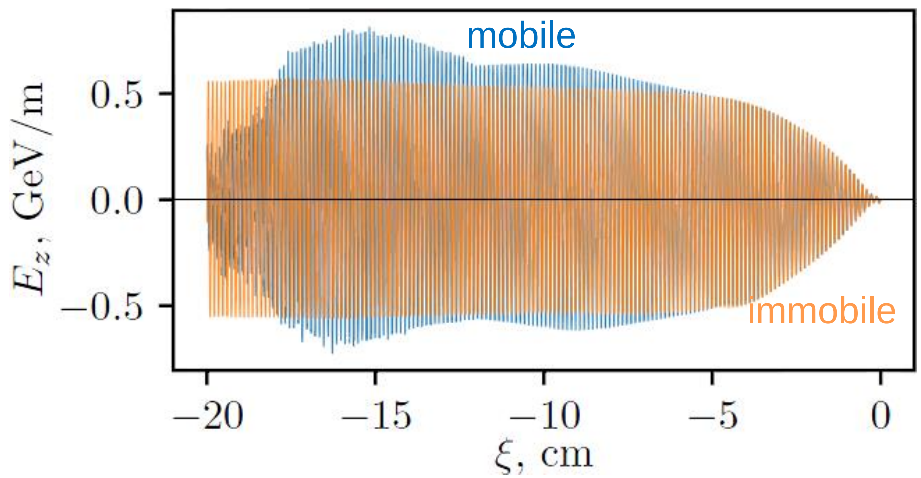
Energy flux density: $$\vec{S} = -c\,\vec{e}_z \frac{E^2 + B^2 - B_0^2}{8\pi} + \frac{c}{4\pi}\left[\vec{E} \times \vec{B}\right] + \sum_{\text{unit volume}} (\gamma - 1) m c^2 (\vec{v} - c\,\vec{e}_z)$$

electromagnetic energy — Poynting vector — relativistic factor

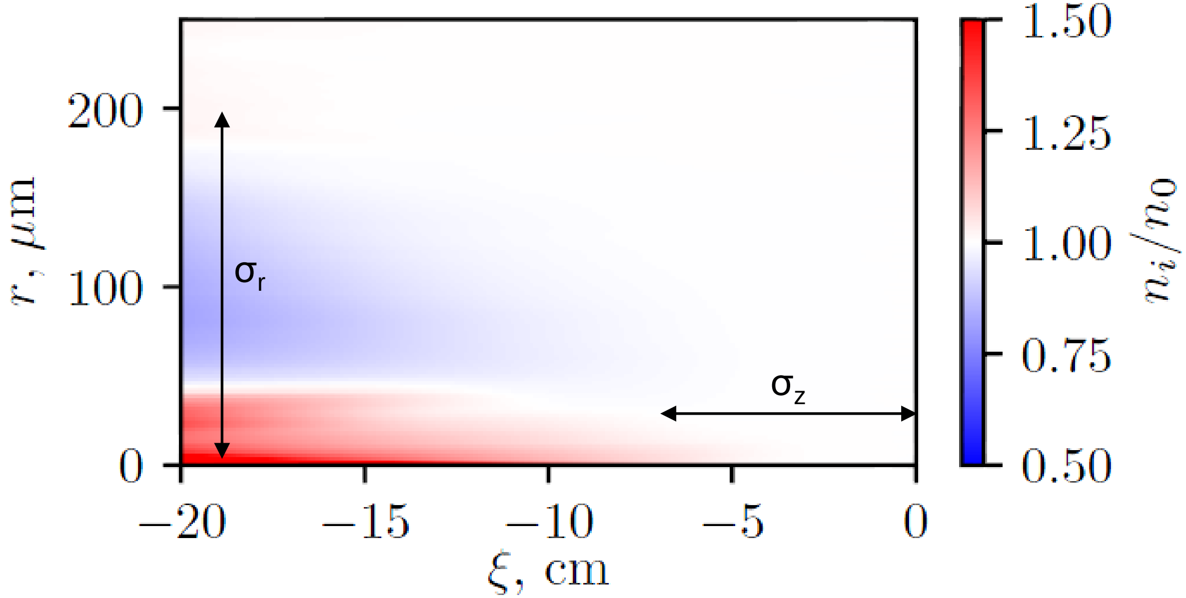
Electromagnetic energy flux density, $\vec{S}_{em}$

PHYSICAL REVIEW E **69**, 046405 (2004)

The case for in-depth study: AWAKE



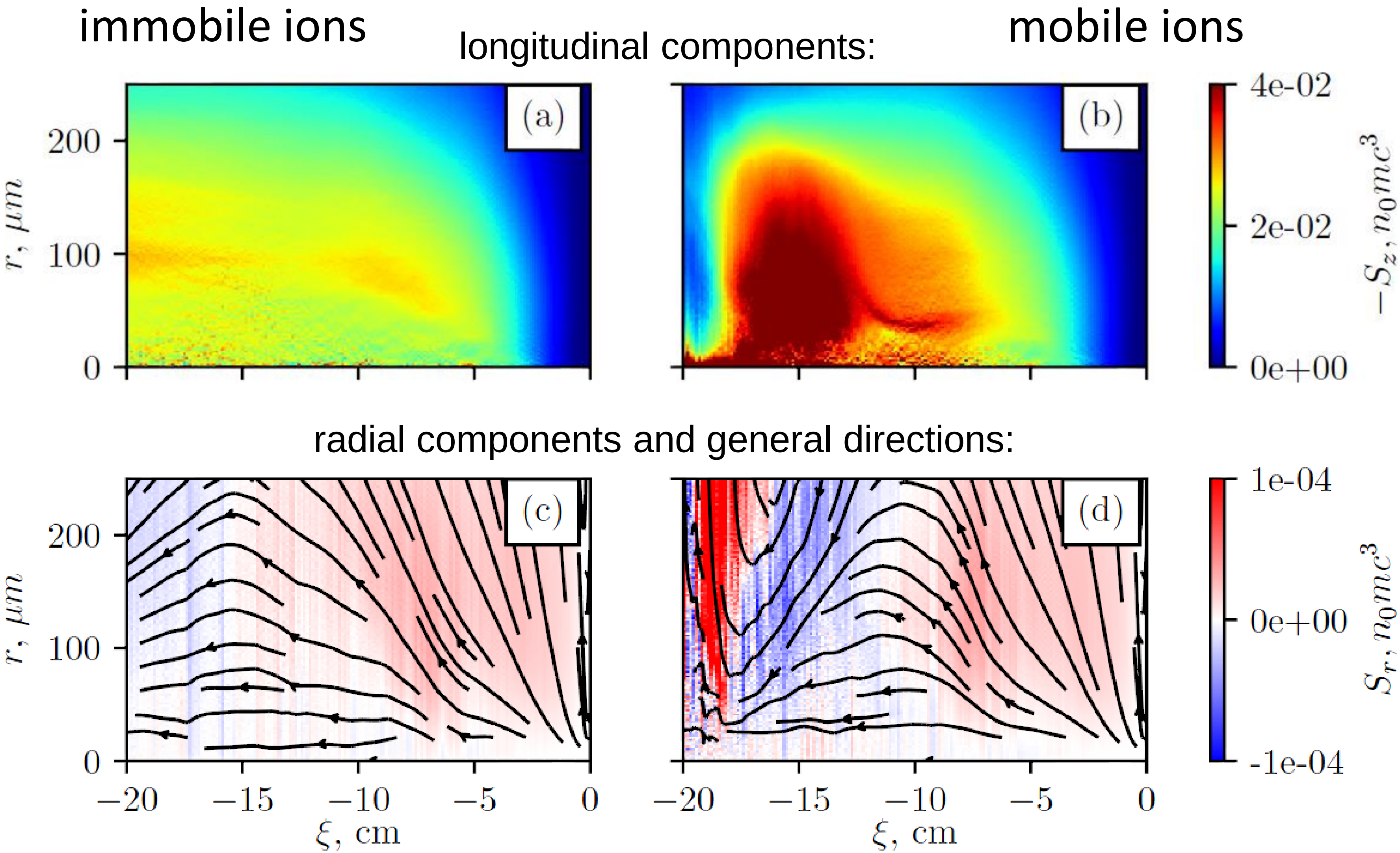
Parameter & notation	Value
Plasma density, n_0	$7 \times 10^{14}\,\mathrm{cm}^{-3}$
Distance to observation point, z_0	5 m
Plasma ion-to-electron mass ratio	157 000
Maximum beam density, n_{b0}	$6.9 \times 10^{12}\,\mathrm{cm}^{-3}$
Beam half-length, σ_{zb}	7 cm
Beam radius, σ_{rb}	0.2 mm
Beam energy, W_b	400 GeV
Beam energy spread, δW_b	0.35%
Beam normalized emittance, ϵ_{bn},	3 mm mrad



+40% field enhancement

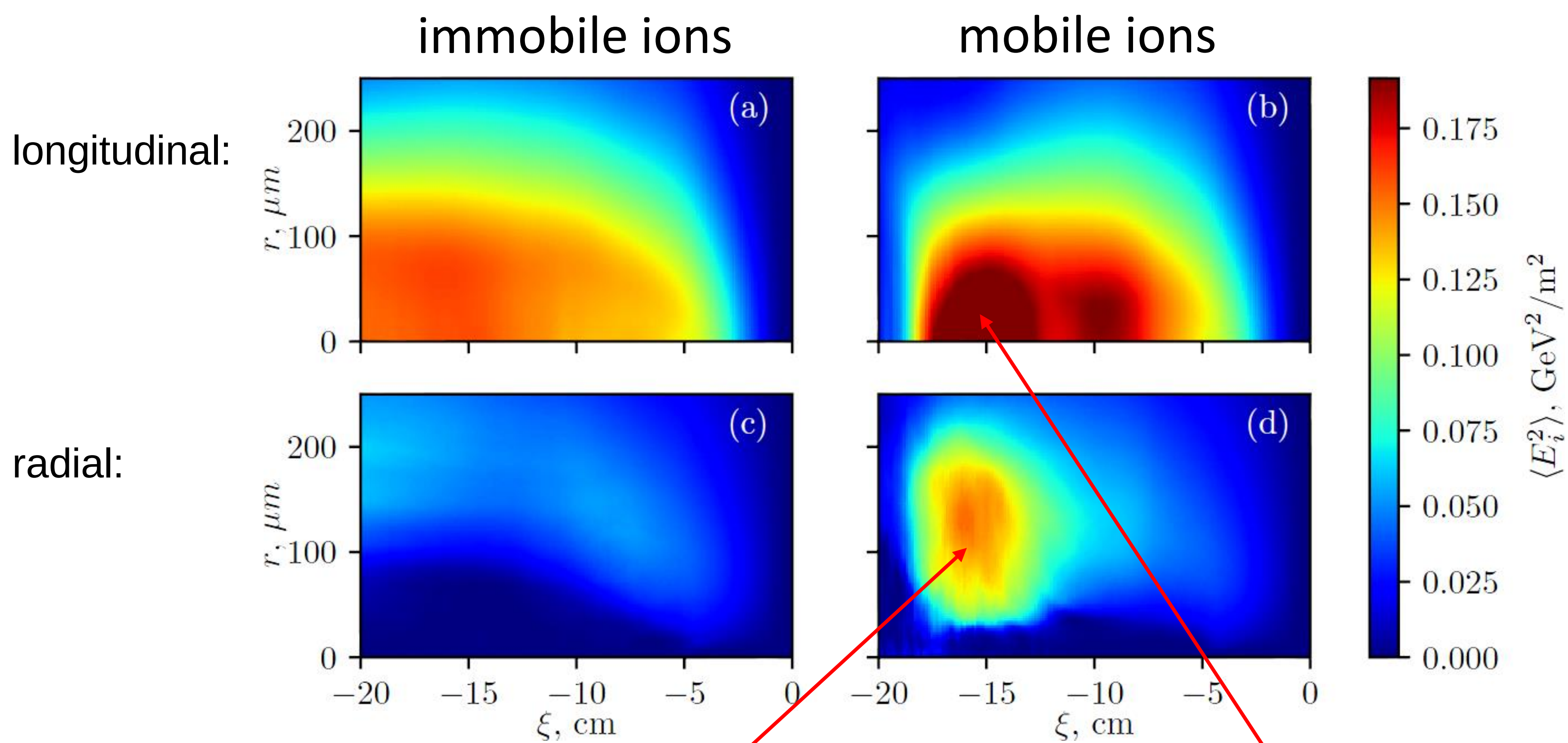
Field grows after the beam passage

Energy flows



Ion non-uniformity causes concentration of the wave energy near the axis

What happens with electric fields?



Ion non-uniformity causes wave-breaking, wavebreaking causes energy re-distribution from longitudinal to transverse fields

However, energy inflow from outer regions dominates, so the longitudinal wakefield grows

Summary

We discovered a novel effect: Ion motion in a plasma wakefield accelerator can cause temporal increase of the longitudinal electric field shortly before the wave breaks.

The increase is caused by re-distribution of the wave energy in transverse direction. Energy comes from large radii to the axis.

The field enhancement occurs after the beam passage, so the transformer ratio also increases proportionally.

The effect may be important for correct interpretation of experimental results and acceleration of high-quality beams.

and yes, we tried to optimize it in search of a high transformer ratio, but +40% is currently our best result (by chance, it is for AWAKE beam),

and yes, we tried to understand why the energy behaves like this, but have no ideas yet.

Thank you