Oscillation damper for misaligned witness in plasma wakefield accelerator

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Plasma (laser) wakefield acceleration and problem of witness injection

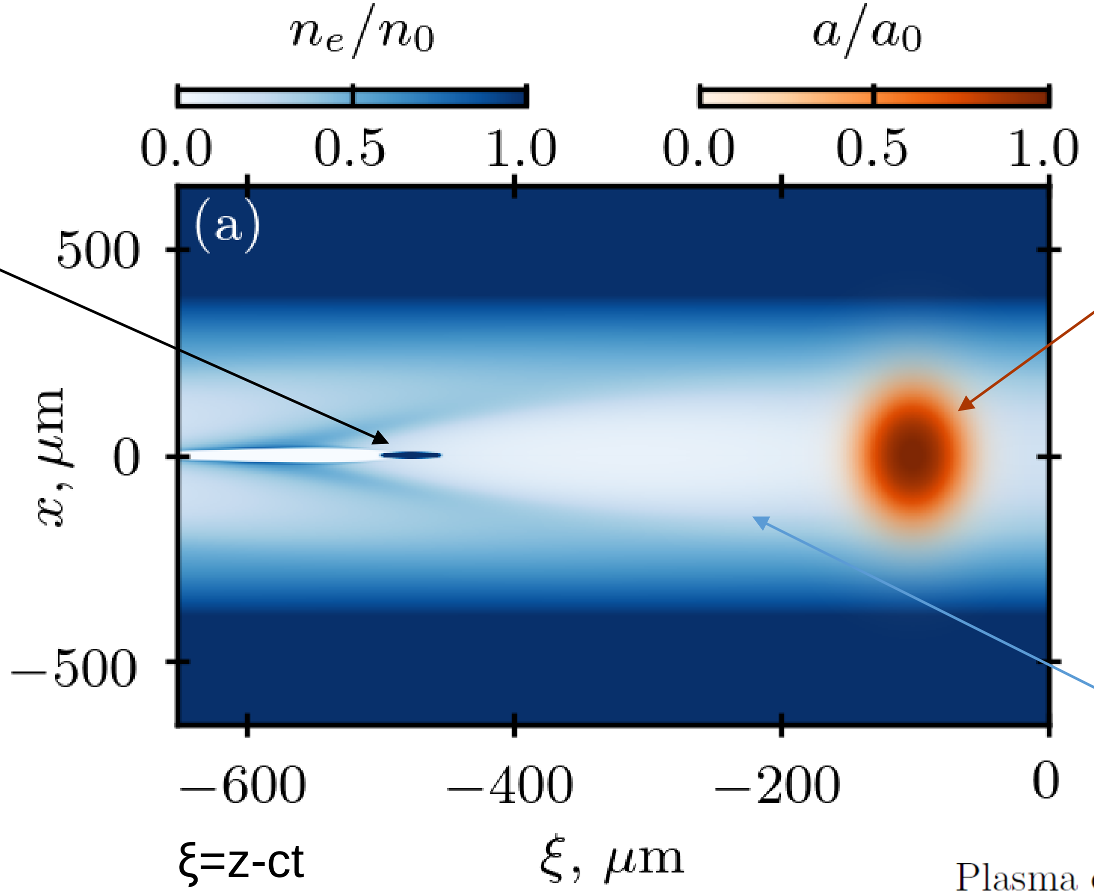
3. The witness (accelerated bunch) : must somehow appear in the right wave phase and have a given shape and small emittance.

How?

Capture and accelerate plasma electrons: the most popular solution, but it doesn't always work, doesn't always have enough degrees of freedom for optimization.
(or)
Produce and pre-accelerate the witness in a conventional RF accelerator and inject it into the plasma:

+ blowout regime not required
+ more freedom to control bunch parameters and shape
- strict time synchronization requirements
- strict requirements for the alignment of witness and driver

AWAKE, SPARC_LAB, DESY, FACET-II, EuPRAXIA



1. The driver: one or several laser pulses or particle bunches, creates the wave

~c/ω_p

2. The wakefield: travelling at the speed of light

4. What if the alignment cannot be ensured?

Plasma density n_0 determines all scales.
Typically n_0 between 10^{14}cm^{-3} and 10^{19}cm^{-3}, numerical examples are for $n_0 = 10^{16}\text{cm}^{-3}$

Times $\sim \omega_p^{-1} = \left(\sqrt{4\pi n_0 e^2/m}\right)^{-1} \to 0.2\,\text{ps}$.

Sizes $\sim c/\omega_p \to 50\,\mu\text{m}$.

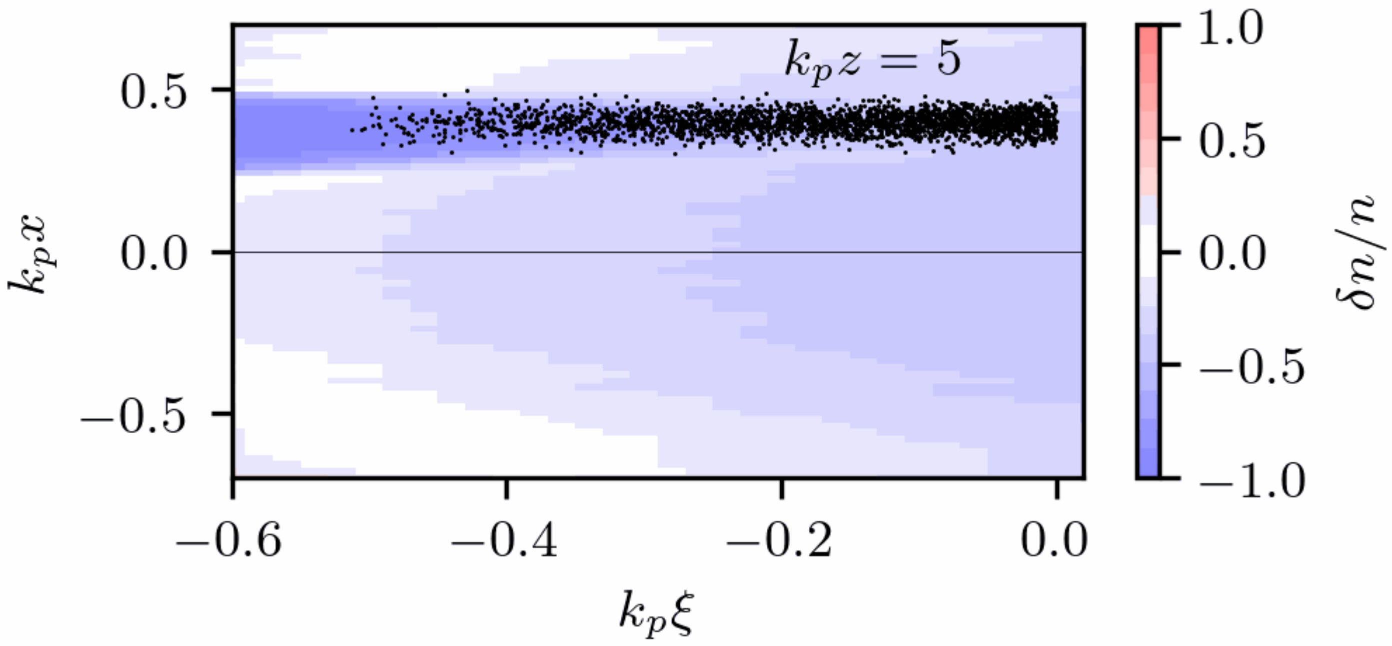
Fields $\sim E_0 = \sqrt{4\pi n_0 mc^2} \to 10\,\text{GV/m}$.

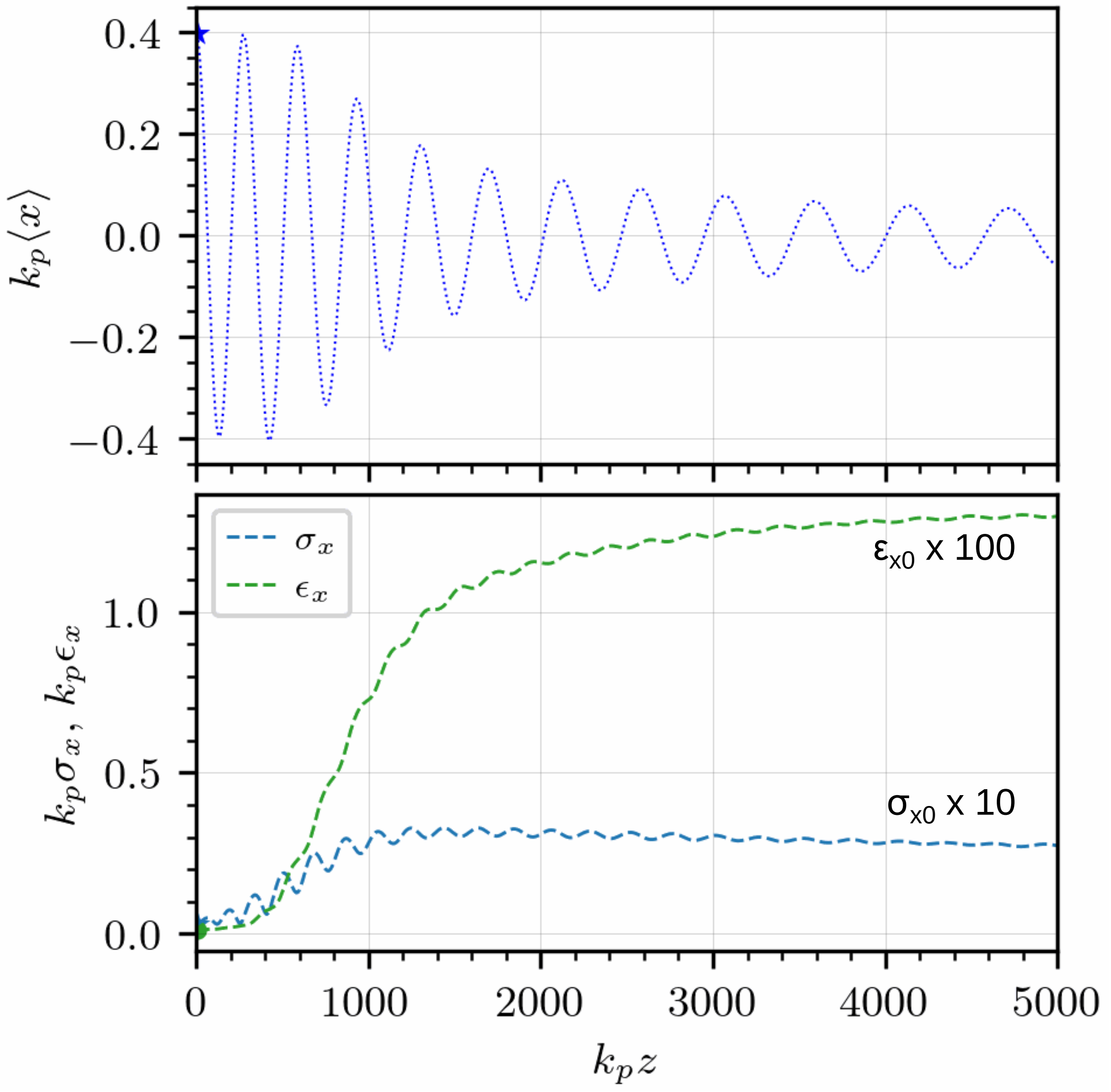
What happens if witness and driver are not aligned?

Different witness slices oscillate at different betatron frequencies, because they are in different focusing fields.

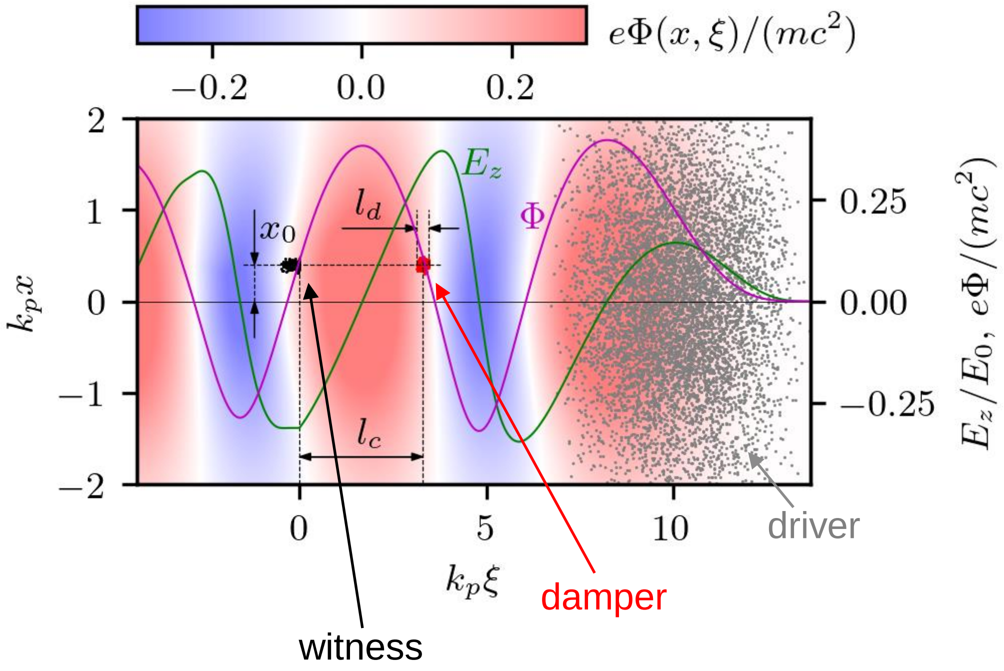
The witness wriggles, its emittance and radius grow, which is bad (quality is lost).

(There is no such problem in the blowout regime, but in this regime the external witness injection is also not needed since plasma electrons are captured well).

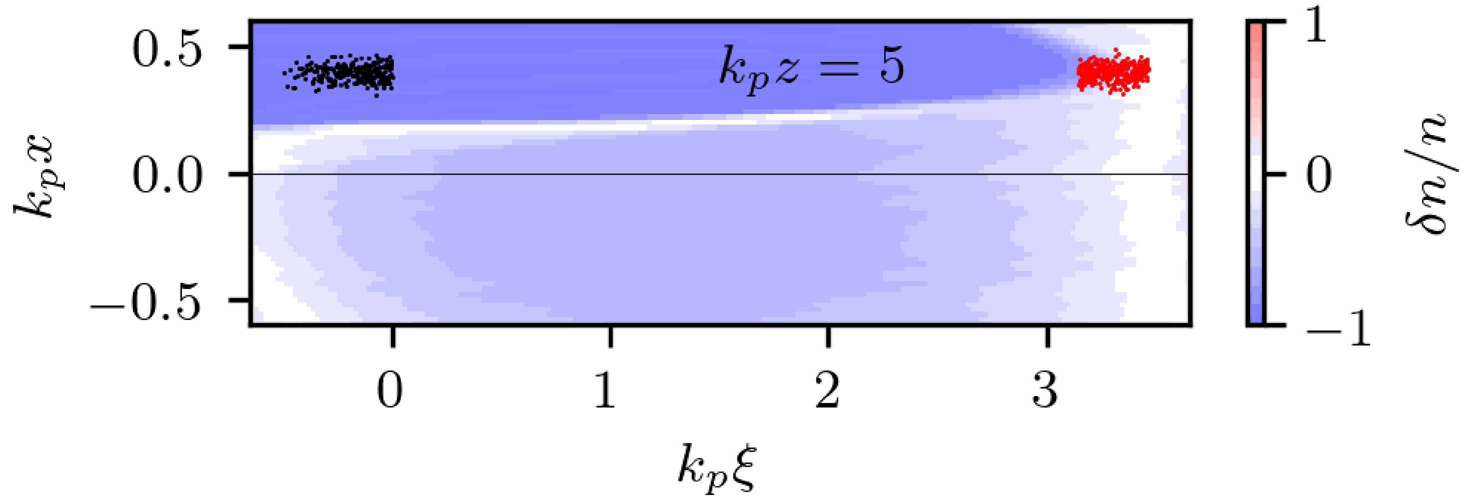


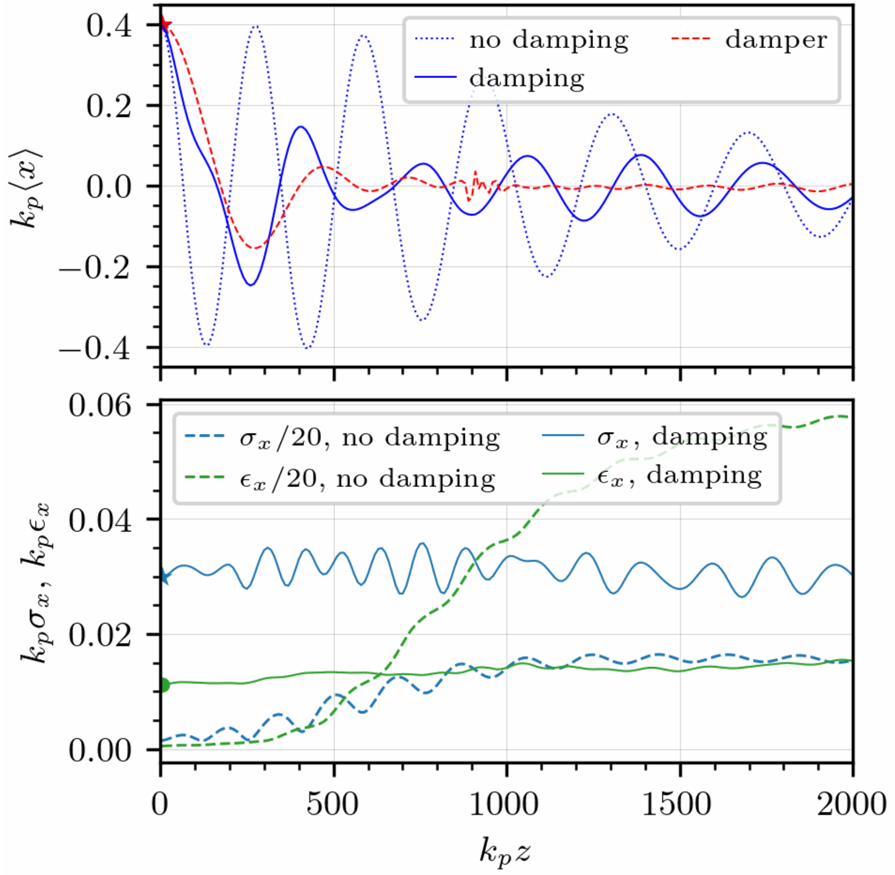


The idea: a short bunch (damper) ahead of the witness



The damper is initially offset in the same way as the witness (they are produced by the same injector).
The damper oscillates and perturbs the plasma wave.
At a certain (close to 1) ratio of oscillation frequencies (witness-to-damper), the witness aligns to the axis without quality loss.

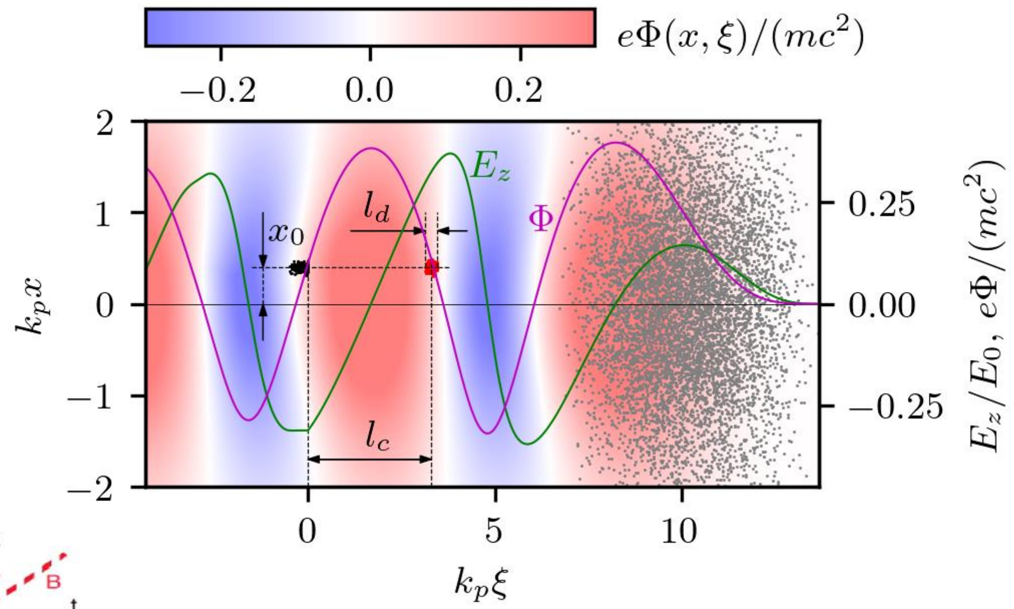


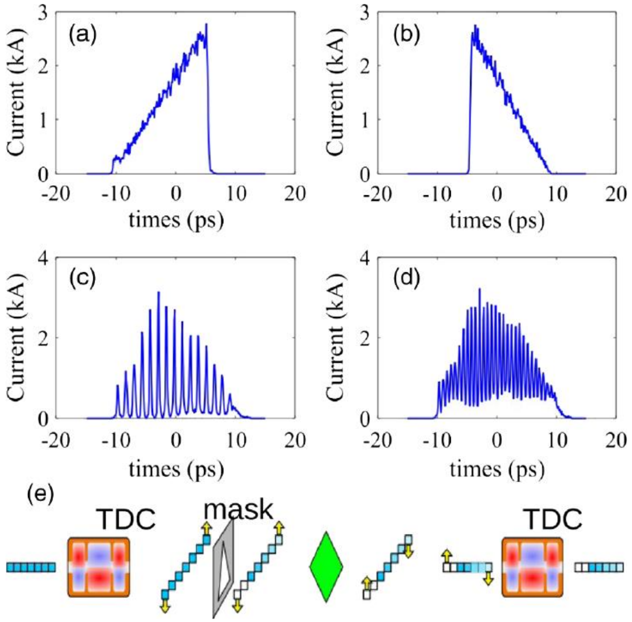


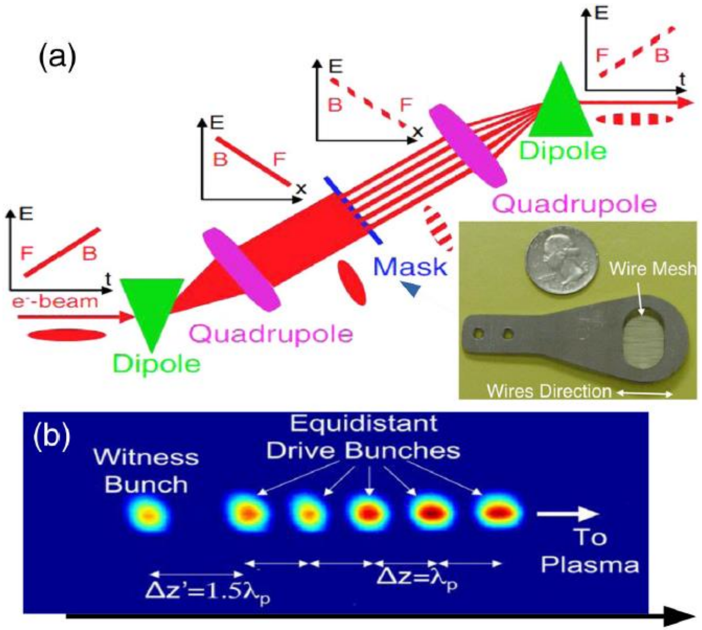
The damping method relies on several physical principles and technological advances

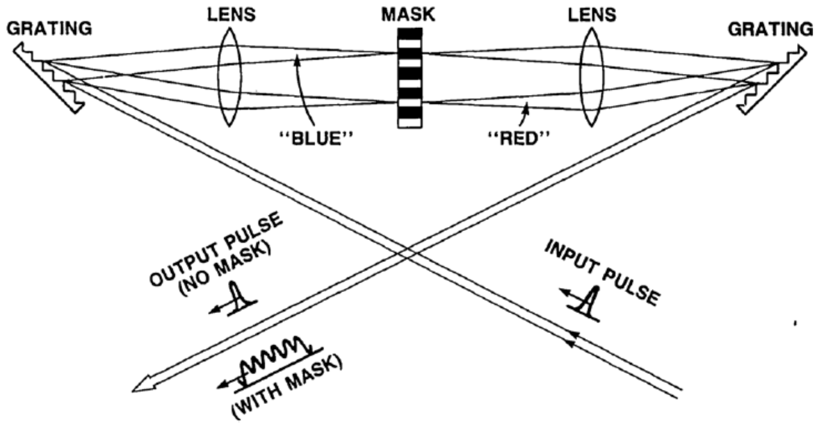
1. In the wave, there is always a cross-section in which the frequency of damper oscillations equals that of the witness head, but the longitudinal field is decelerating (because $\vec{F} = -q\nabla\Phi$). This cross section is about half a wavelength ahead of the witness.

2. The technique of generating electron bunch trains or bunches of a given shape is now rapidly developing. The damper could have a different energy, larger emittance, or larger radius than the witness, and it would still work well.









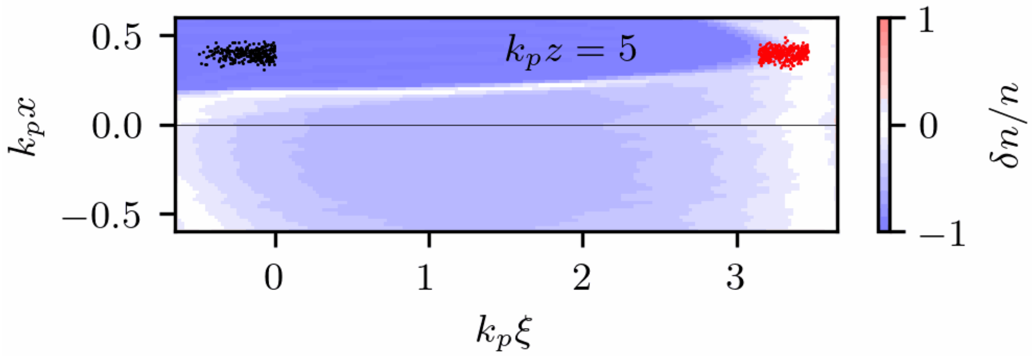
Figures from G. Ha et al., Rev. Mod. Phys. 94, 025006 (2022).

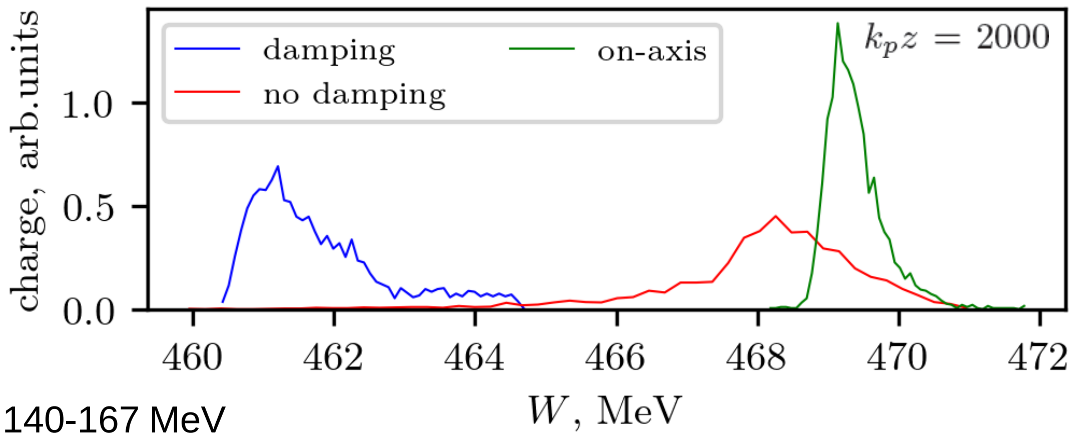
The damping method relies on several physical principles and technological advances

3. There are plasma electrons around the damper (because the blowout is not reached). The damper locally perturbs the wave, and this perturbation is transferred by the wave exactly to the witness position.

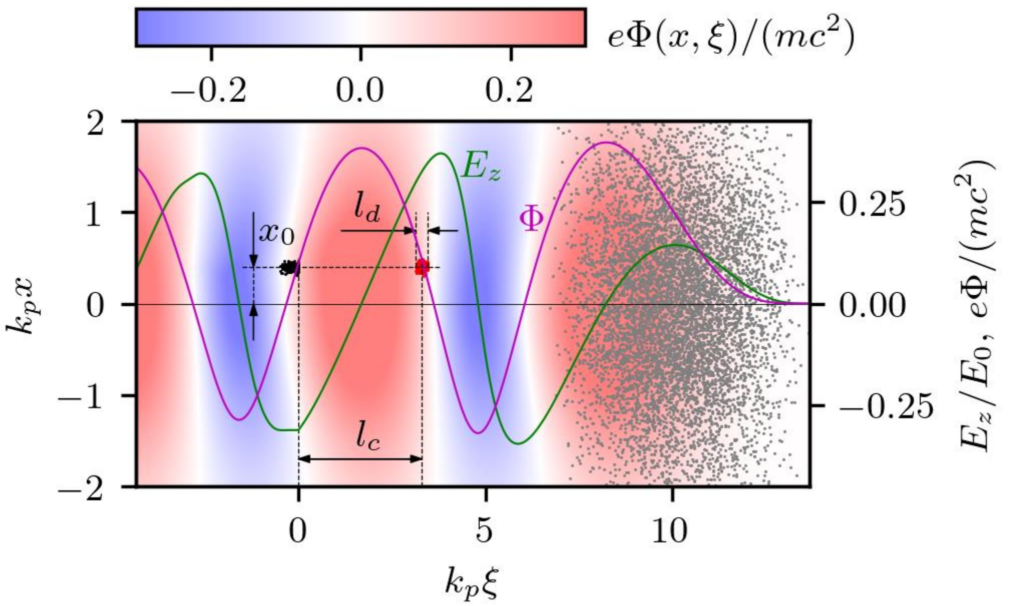
4. Damper's effect on the witness is time-limited, because of
   - damper deceleration,
   - phase mixing of damper oscillations.

5. The damper gains a lower energy than the witness and can subsequently be separated in energy. The energy difference is about twice the initial damper energy, as the witness gains energy while the damper slows down by a field of the same amplitude. The damper loads the wave and must be taken into account when matching the witness and the wave.





Damper: 140-167 MeV

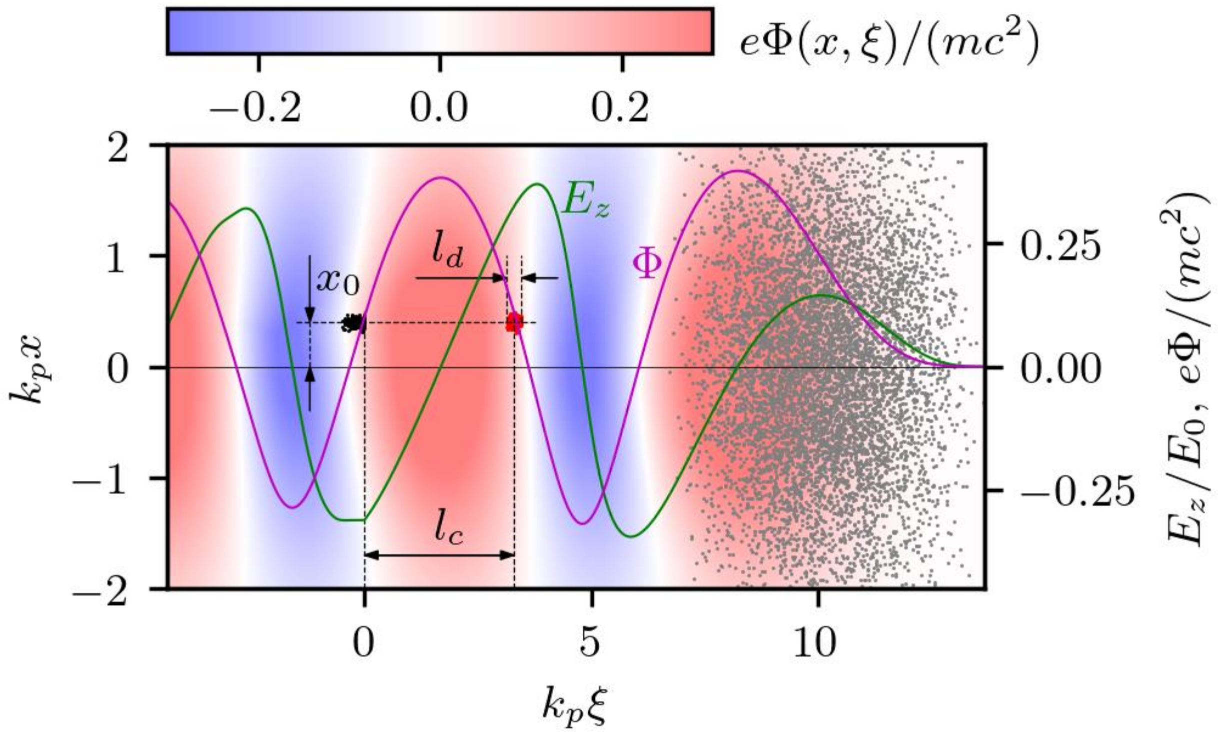


The damping method relies on several physical principles and technological advances

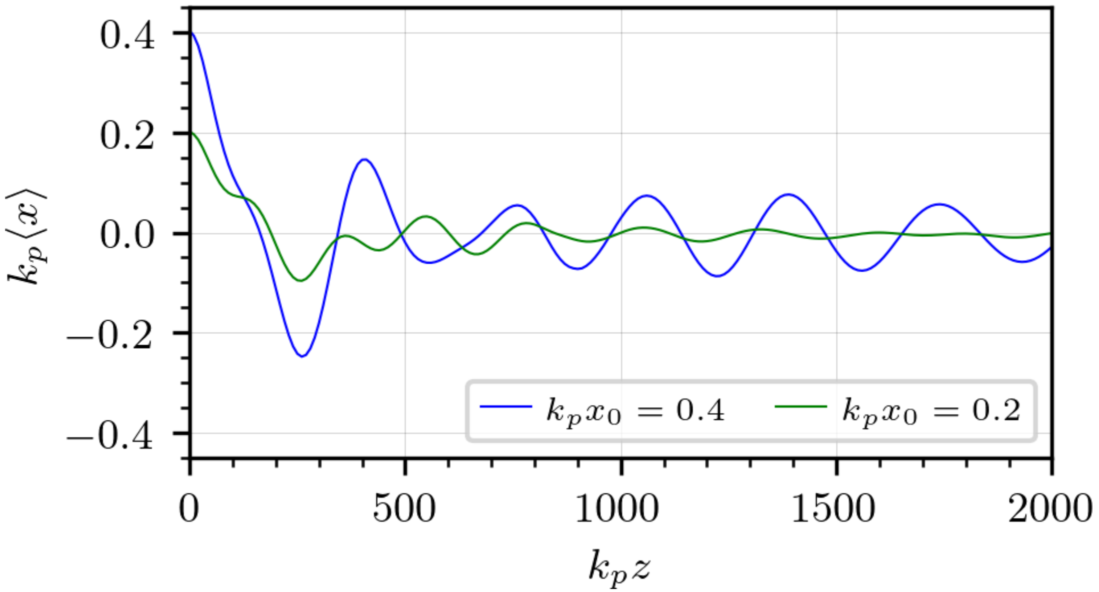
6. In a moderately nonlinear axially symmetric plasma wave, small transverse oscillations of beam particles are harmonic. The oscillation frequency does not depend on the magnitude and direction of the offset.

   Oscillations are small if their amplitude << k_p^{-1}

   The “golden ratio” of oscillation frequencies (damper-to-witness) at which the witness goes exactly on the axis, found for some initial offset x_0, is the same for any other offset.



In reality, things are not so perfect, but the method works



Let us numerically demonstrate the damper operation at parameters close to those at which the external injection could be used:

TABLE I. Parameters of the illustrative variant

Parameter, notation	Value
Driver radius, σ_{rd}	k_p^{-1}
Driver length, σ_{zd}	$1.05 k_p^{-1}$
Peak driver density, n_d	$0.4n$
Witness and damper radius, σ_r	$0.03 k_p^{-1}$
Witness and damper peak current, I_w	$0.0268 mc^3/e$
Witness and damper normalized emittance	$0.01 k_p^{-1}$
Witness length, l_w	$0.52 k_p^{-1}$
Damper length, l_d	$0.32 k_p^{-1}$
Witness-to-damper distance, l_c	$0.36 k_p^{-1}$
Witness and damper energy, W_0	150 MeV
Witness and damper offset, x_0	$0.4 k_p^{-1}$
Grid steps in x, y, ξ	$0.02 k_p^{-1}$
Step in z for updating plasma state	$5 k_p^{-1}$
Number of electrons per cell	9
Simulation window width in x and y	$8 k_p^{-1}$

Most figures in this presentation are for this parameter set

Wave amplitude $E_m \approx 0.35 E_0$ (moderately nonlinear)

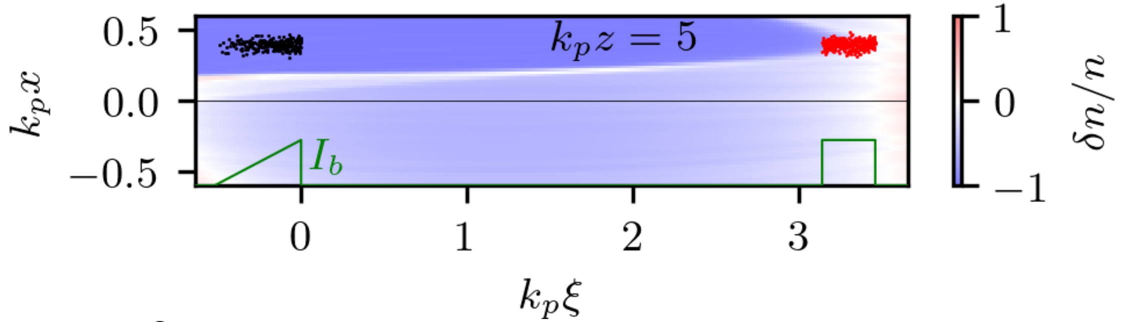
Witness current profile (triangular) and position are matched to the wave:

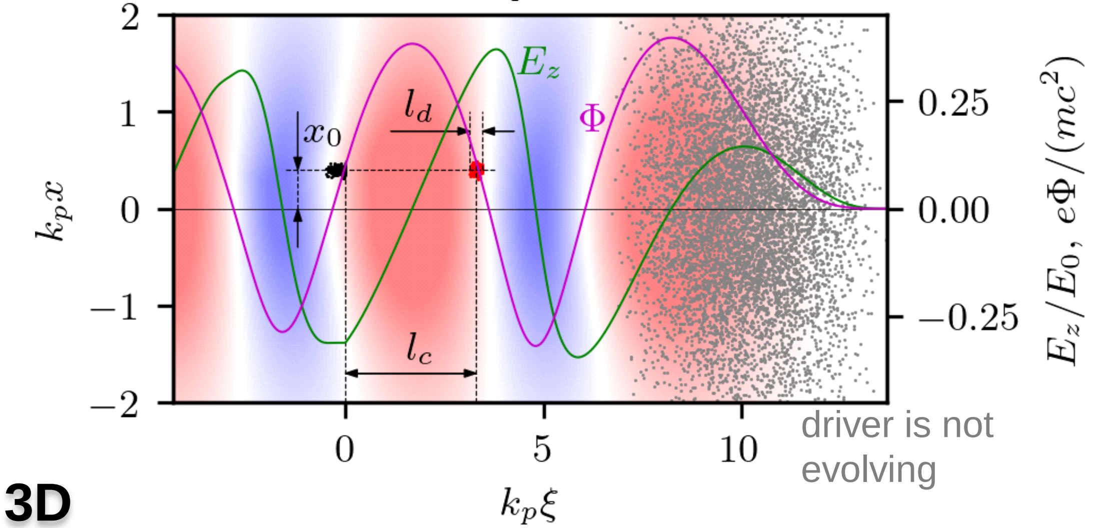
$$E_{\text{acc}} \approx 0.9 E_m \approx 0.311 E_0$$

Witness radius and emittance are matched to the ion focusing force

Damper: radius, emittance, peak current are the same

Damper charge is controlled by the length





driver is not evolving

LCODE 3D

… at parameters close to those at which the external injection could be used

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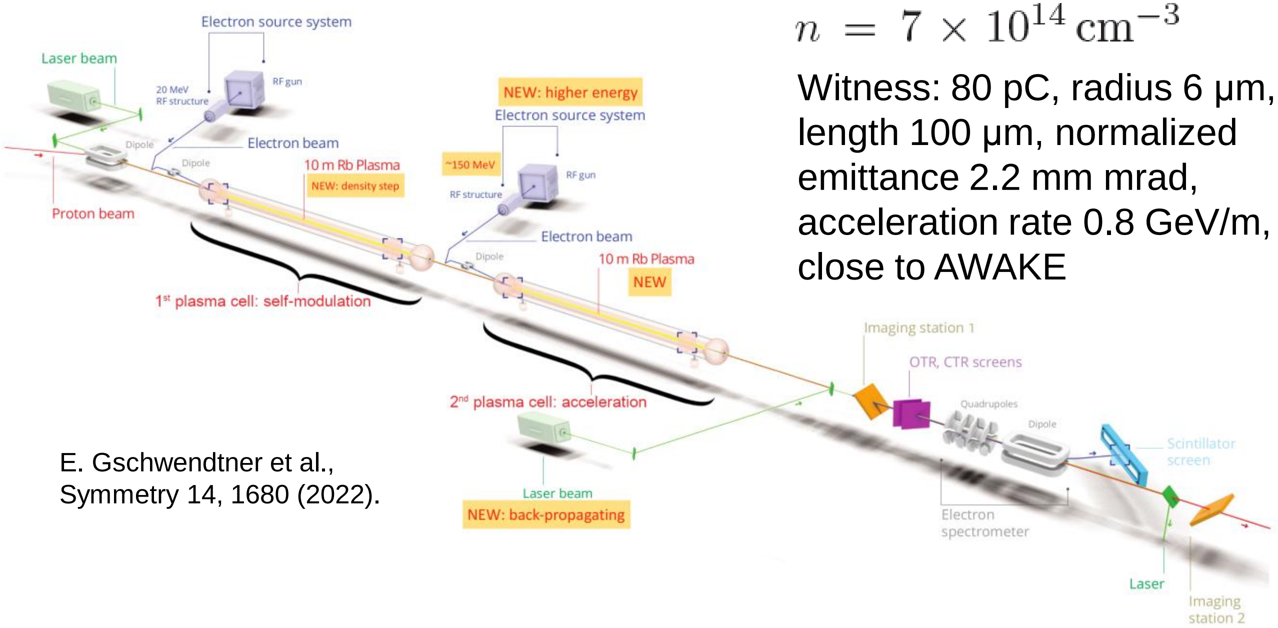
$E_m \approx 0.35E_0$ $\qquad$ $E_{acc} \approx 0.9E_m \approx 0.311E_0$



E. Gschwendtner et al., Symmetry 14, 1680 (2022).

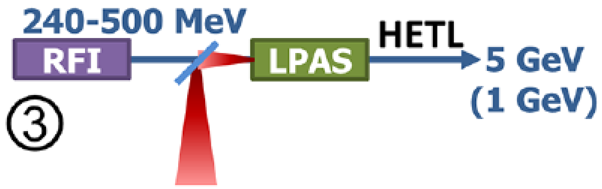
$n = 7 \times 10^{14}\,\text{cm}^{-3}$

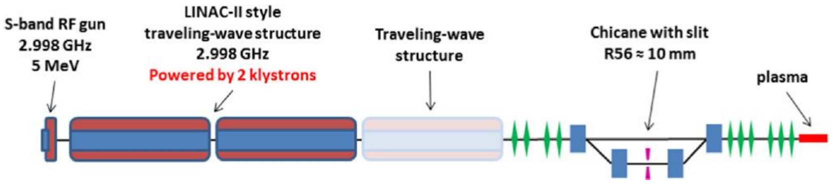
Witness: 80 pC, radius 6 μm, length 100 μm, normalized emittance 2.2 mm mrad, acceleration rate 0.8 GeV/m, close to AWAKE

$n = 10^{17}\,\text{cm}^{-3}$

Witness: 7 pC, radius 0.5 μm, length 9 μm, normalized emittance 0.18 mm mrad, acceleration rate 9 GeV/m, between SPARC_LAB, SINBAD (DESY) and EuPRAXIA

P.A.P. Nghiem et al., PRAB 23, 031301 (2020).





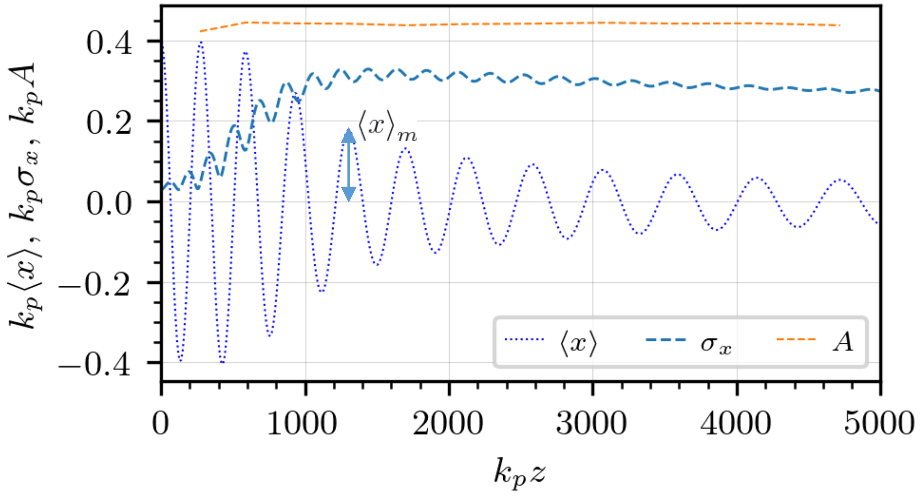
J. Zhu et al., NIMA 829, 229 (2016).

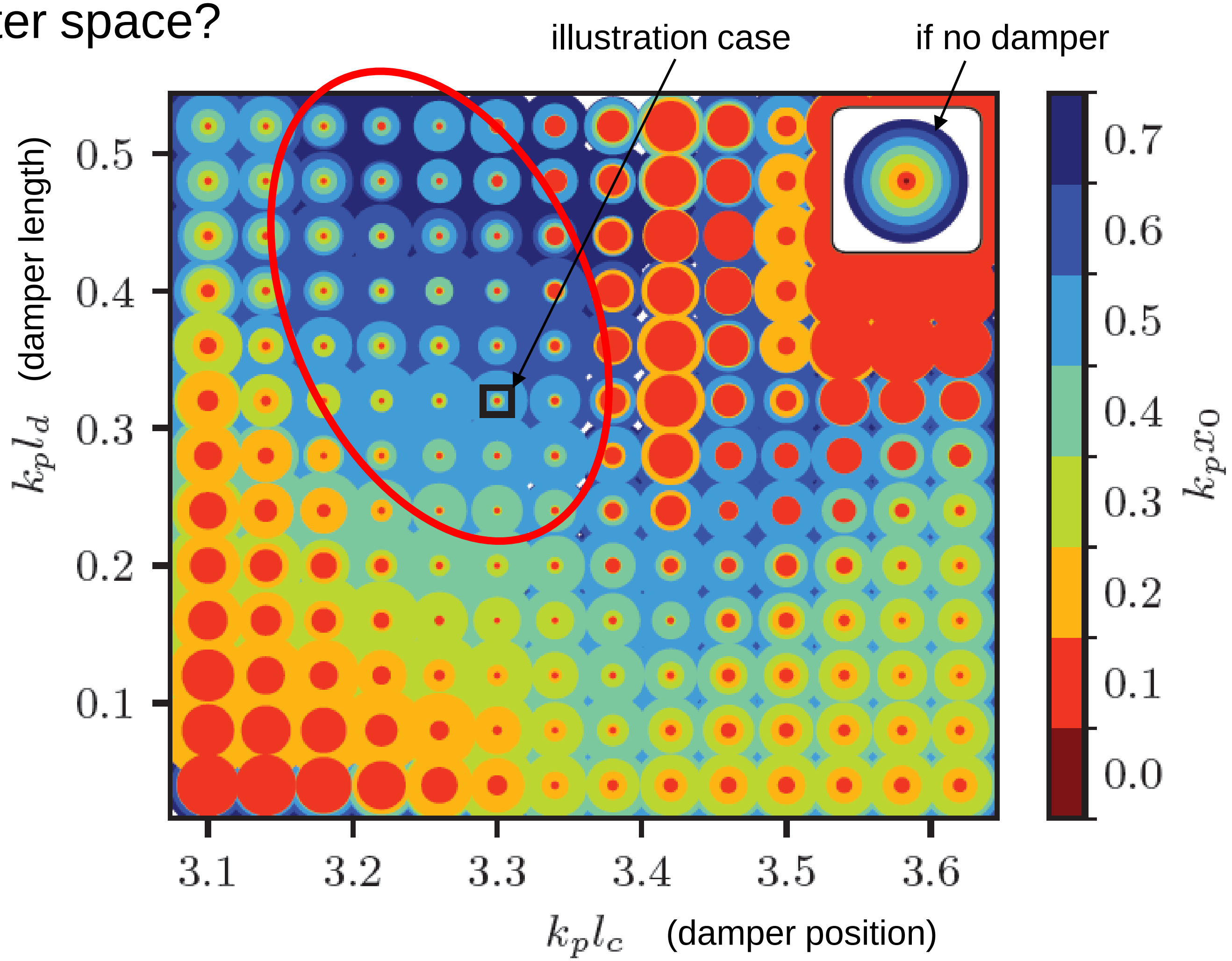
How wide the damping regime is in the parameter space?

We need some target function to compare the variants: effective witness size:

$$A = k_p \sqrt{\langle x \rangle_m^2 + \sigma_x^2} \left(\frac{\langle p_z \rangle}{p_{z0}} \right)^{1/4}$$

This function is convenient in that it quickly approaches a constant and does not change further as the witness accelerates (we can «measure» it any time, at $k_p z = 2000$ for definiteness):





Damping efficiency is a points in the four-dimensional space (l_c, l_d, x_0, A)

We plot circles of radius A on the plane (l_c, l_d)

Color shows the initial offset x_0, smaller offsets over larger ones. If a circle is smaller than the circle of the same color on the inset, then the damper reduces witness oscillations.

The dominant background color is the maximum offset up to which the damping works efficiently.

The required accuracy:

$\sim 0.2 k_p^{-1}$ of damper positioning,

±20% of damper charge.

Not stricter than needed for %-level energy spread

Message:

If we can put a bunch of comparable charge at a distance $\sim(\pi\pm0.1)k_p^{-1}$ ahead of the witness, then the tolerable aiming parameter with which a quality witness should hit the wakefield axis increases by an order of magnitude, from $\sim0.05k_p^{-1}$ to $\sim0.5k_p^{-1}$
(and the cross-section increases by two orders of magnitude).

https://arxiv.org/abs/2409.12041

Thank you!