Emittance of the accelerated electron bunch in two-stage AWAKE scenario

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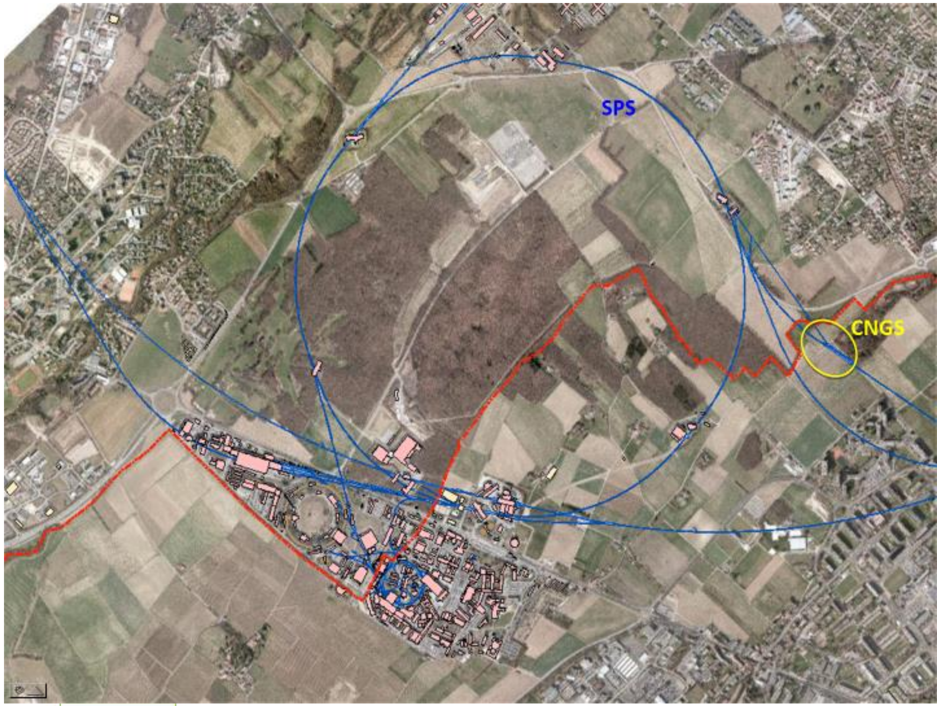
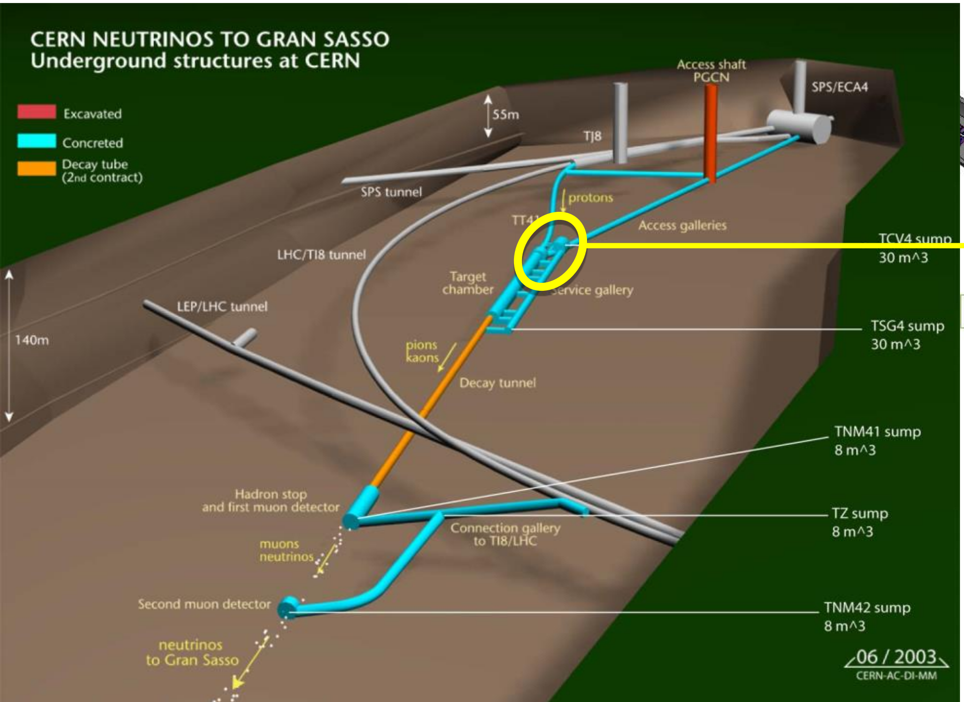
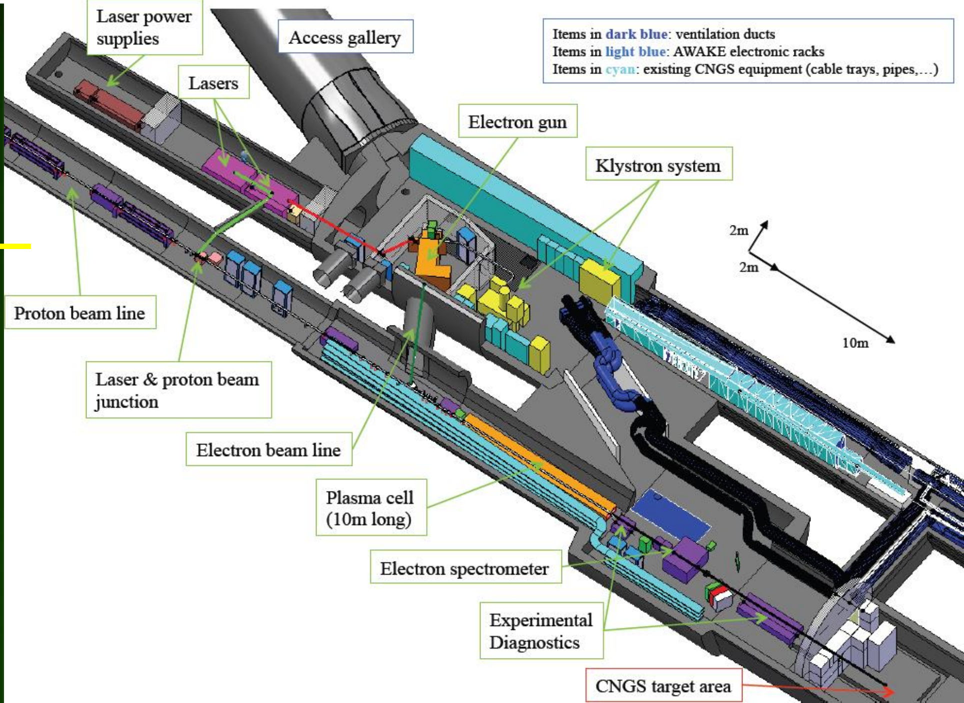
AWAKE Collaboration

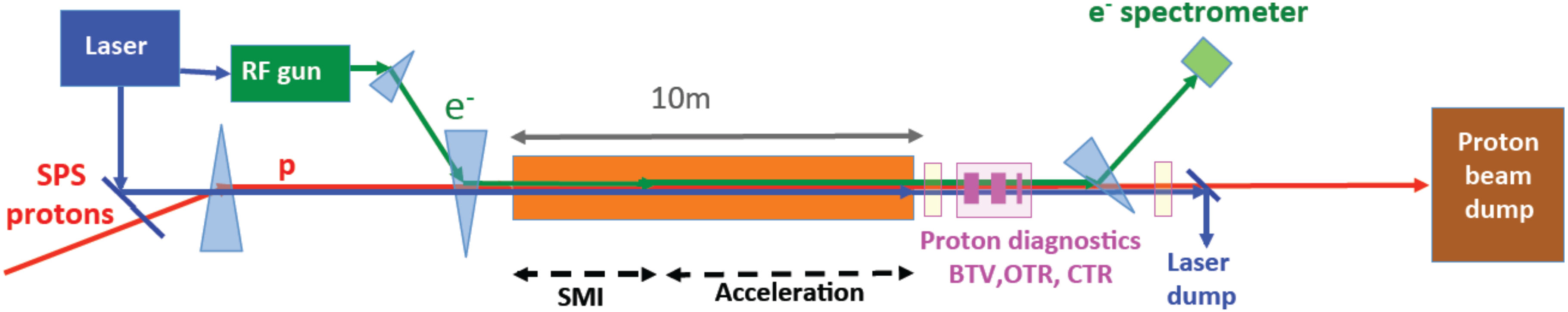
AWAKE experiment



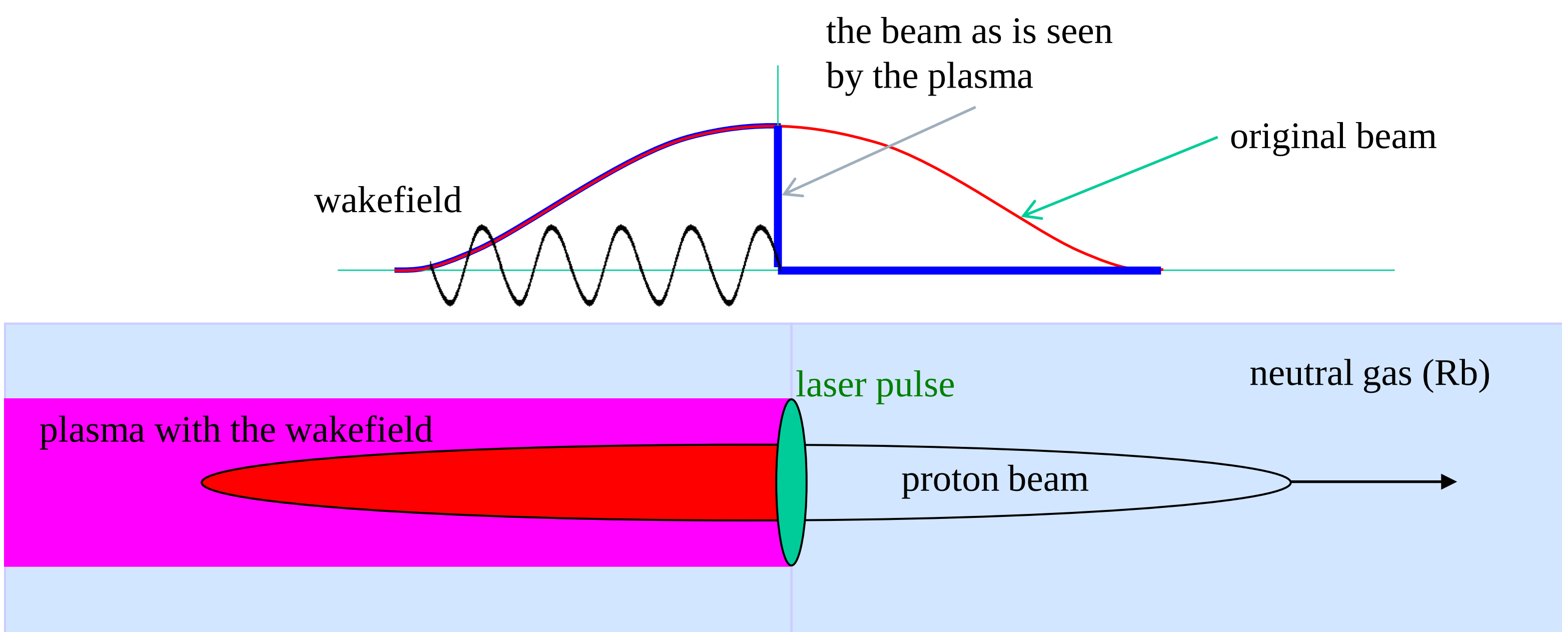




Current scheme of experiment



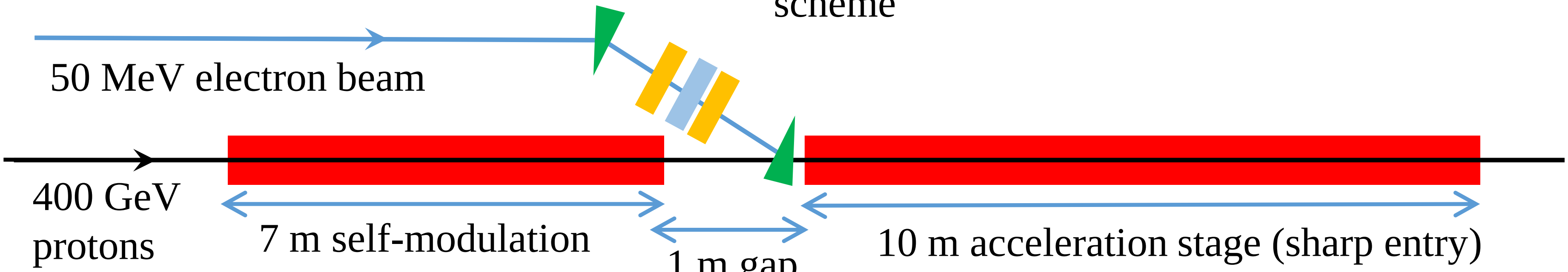
Proton bunch is too long to excite wakefield. That is why we have to synchronize it with the laser beam to seed self-modulation instability, which will cut it into micro bunch train`



The case under study

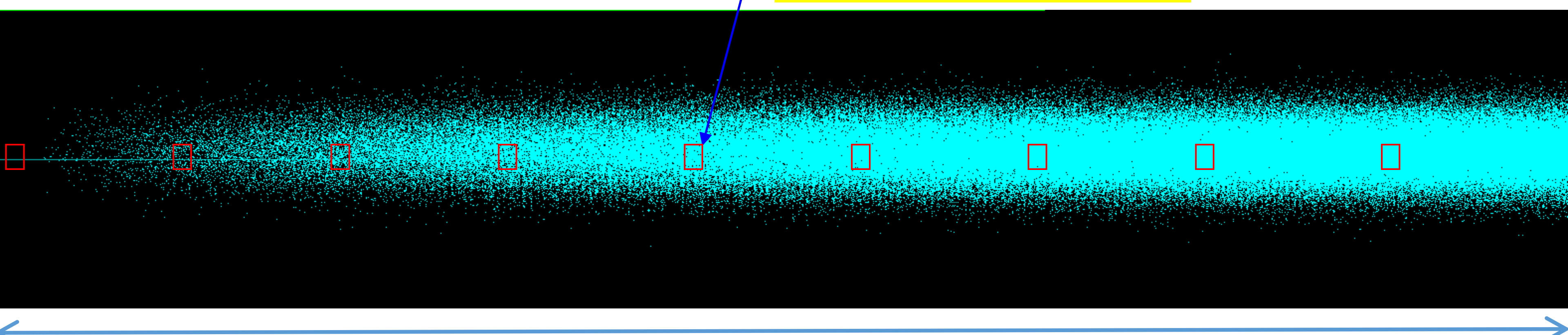
We study emittance of small electron beams, as it shows the minimum emittance possible in this scheme

AWAKE Run II scheme



Electron micro-beams:
$\sigma_r = 0.1\ c/\omega_p = 20\ \mu m$
$\sigma_z = 0.05\ c/\omega_p = 10\ \mu m$
located at various places

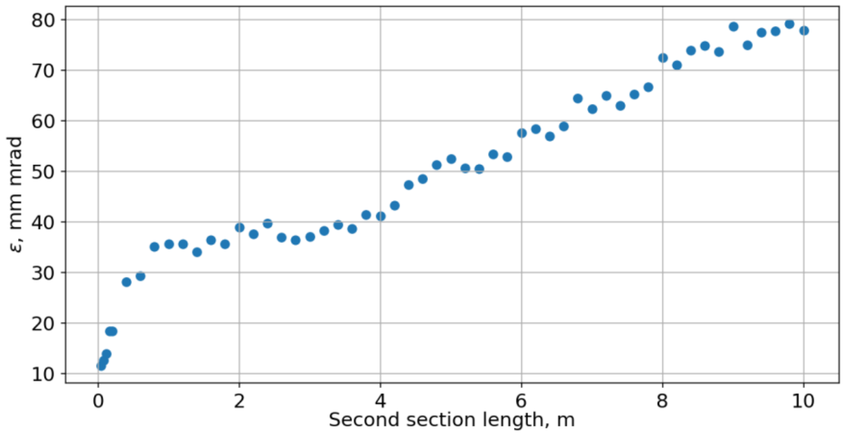
test electrons, zero transverse momentum



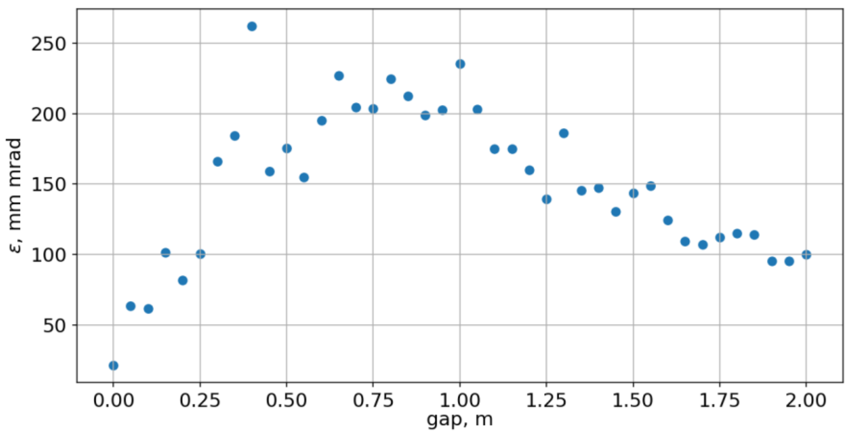
simulation area = 15 cm

$\sigma_z = 6$ cm

Emittance in the second cell rapidly grows:



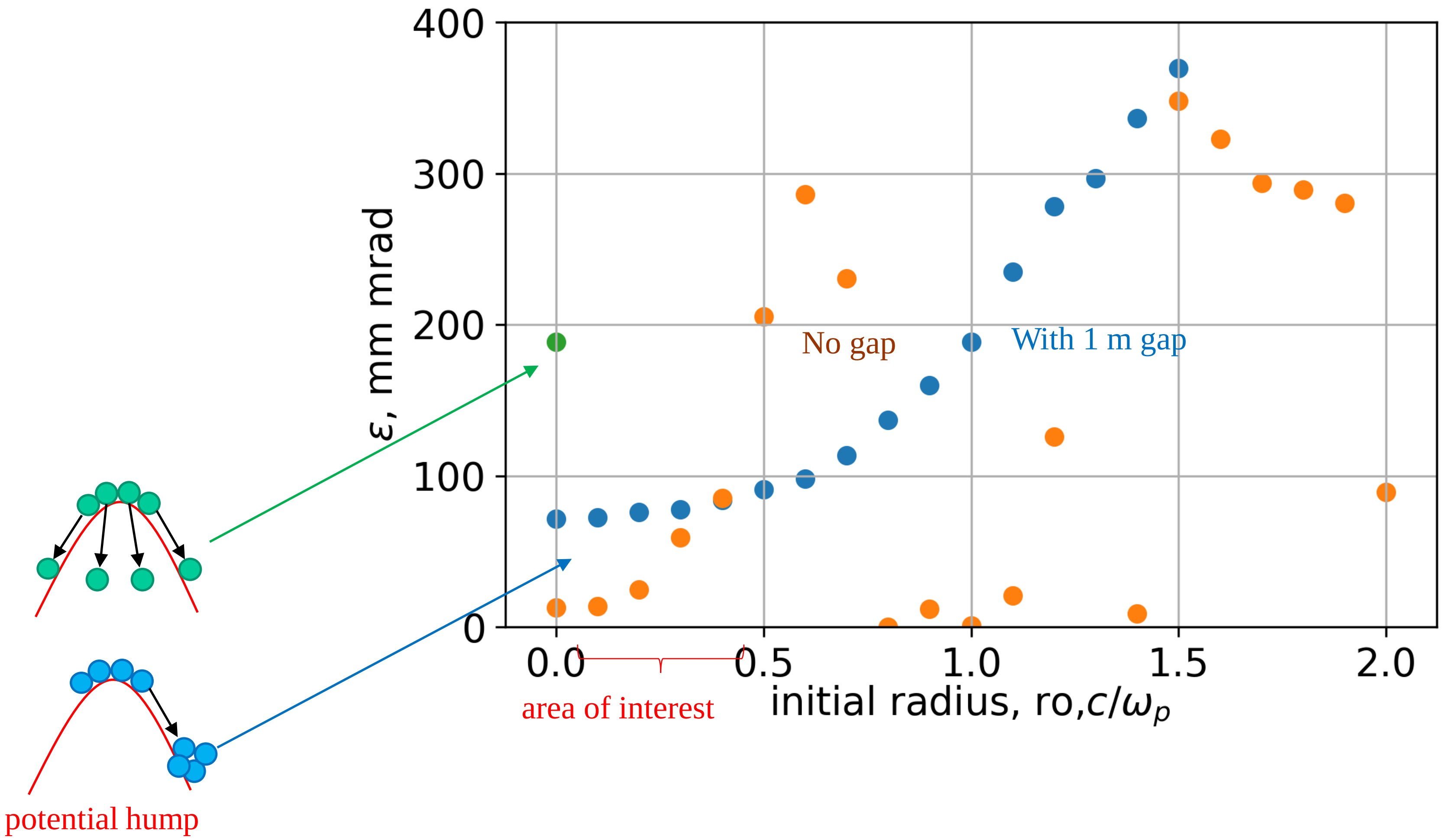
Increase is not instant, but gradual with no saturation



The wider the gap, the faster the growth, the higher the final value (after 10 m in the second cell)

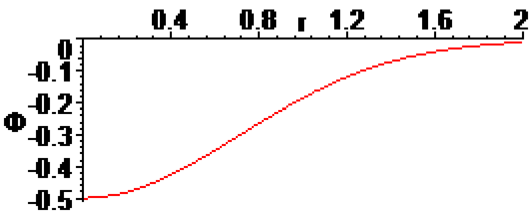
Emittance in the second cell rapidly grows:

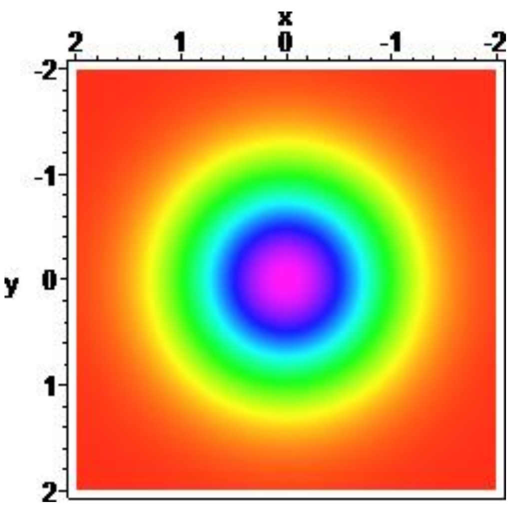
The final value depends on injection offset and assumptions made in 2d simulations



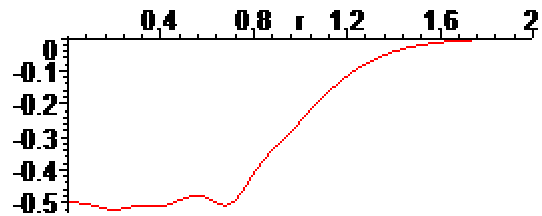
The reason is “flat” potential well with local potential humps

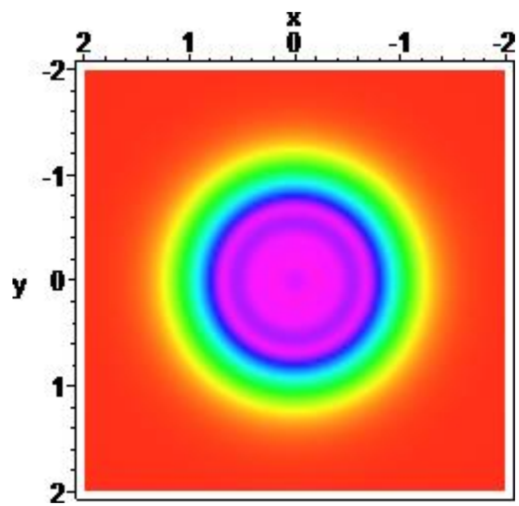
We want the potential well like this:





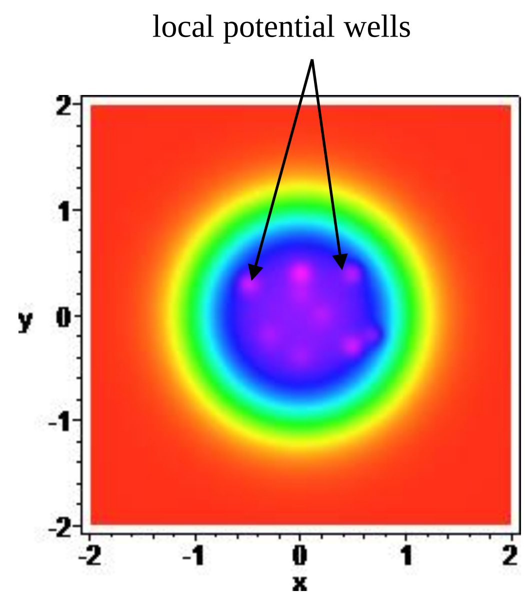
But observe a “swamp” like this:





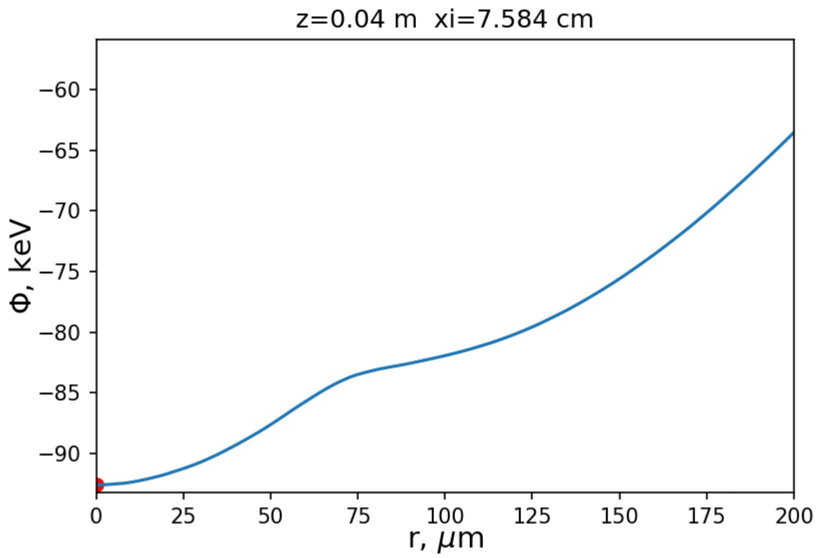
(drawings, not simulation output)

In the non-axisymmetric reality, the “swamp” could look like this:

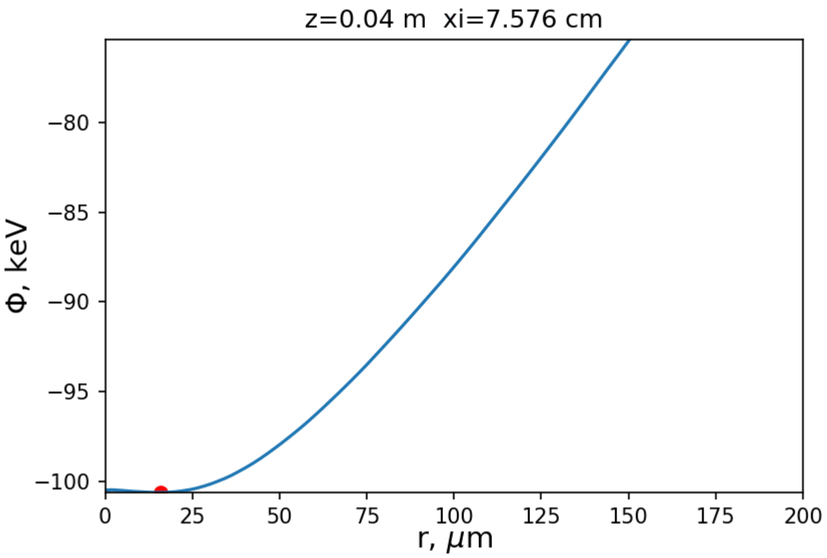


Potential well shape in 2d axisymmetric simulations

No gap

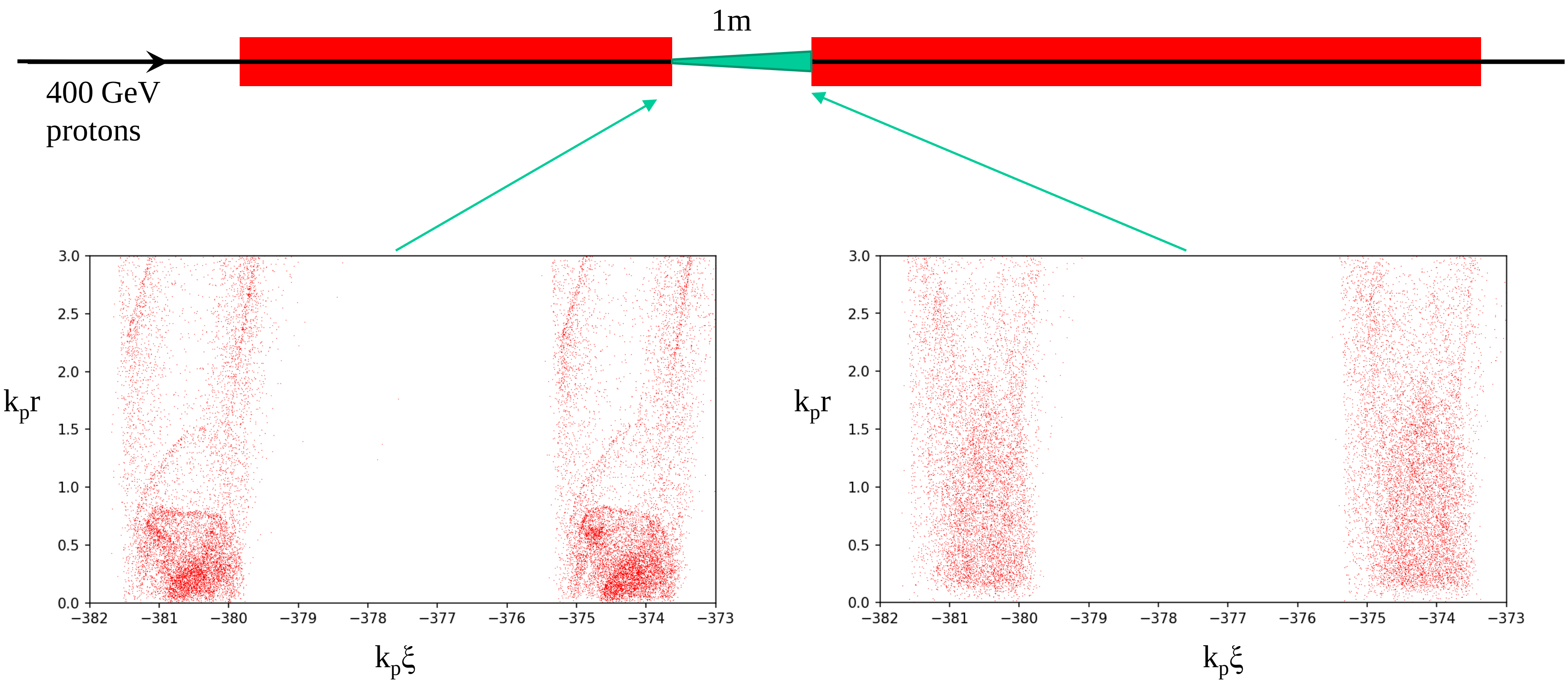


75 cm gap



Why the potential well is like that?

The ultimate reason is, of course, divergence of proton bunches:

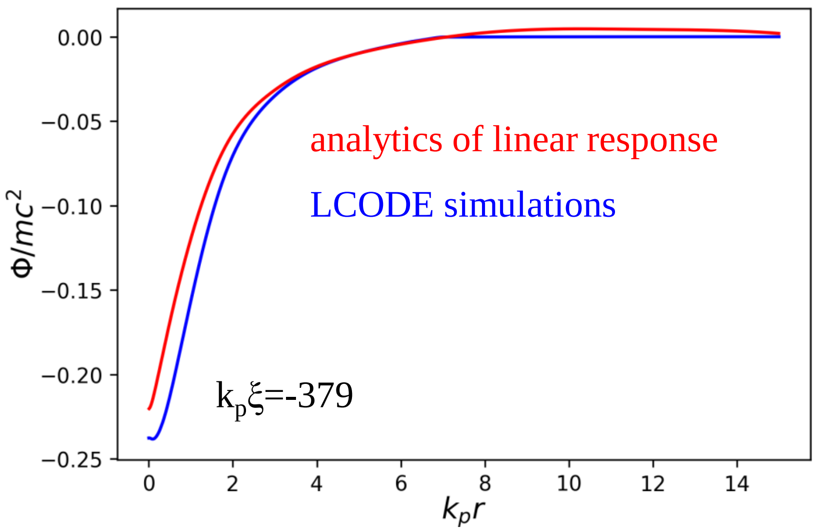


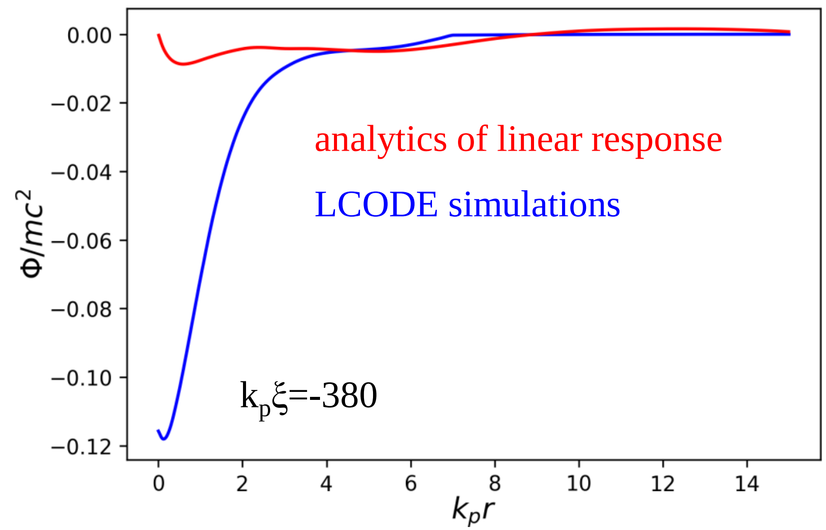
... but being wider is not sufficient by itself for creating an off-axis or flat-bottom potential well.
So why the off-axis well?

Why the potential well is like that?

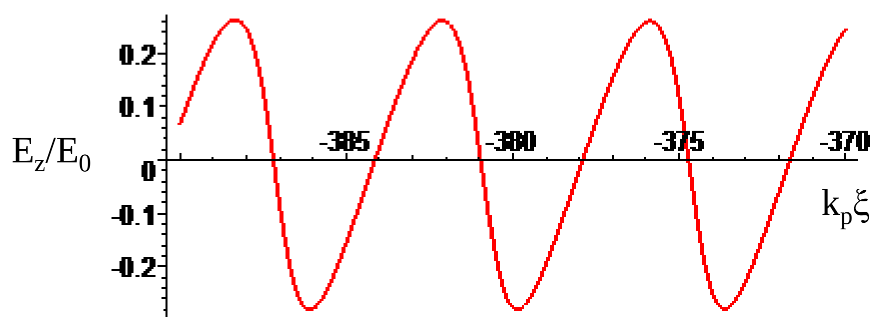
According to the linear theory, these bunches must not create off-axis potential wells. Only donut-shaped can (not observed).

Non-linearity of the plasma response is important:





A paradox: fields are sinusoidal and far below the wavebreaking limit, but the potential shape is affected by nonlinear effects



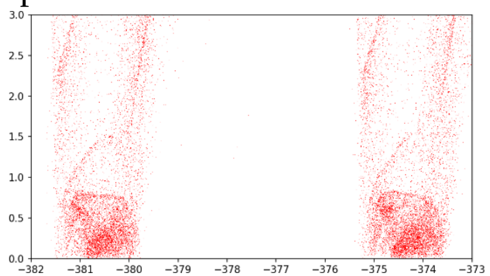
Why the potential well is like that?   Our hypothesis:

Nonlinear effects are responsible for the flat bottom of the potential well

Beam density fluctuations creates small potential wells and humps near the axis

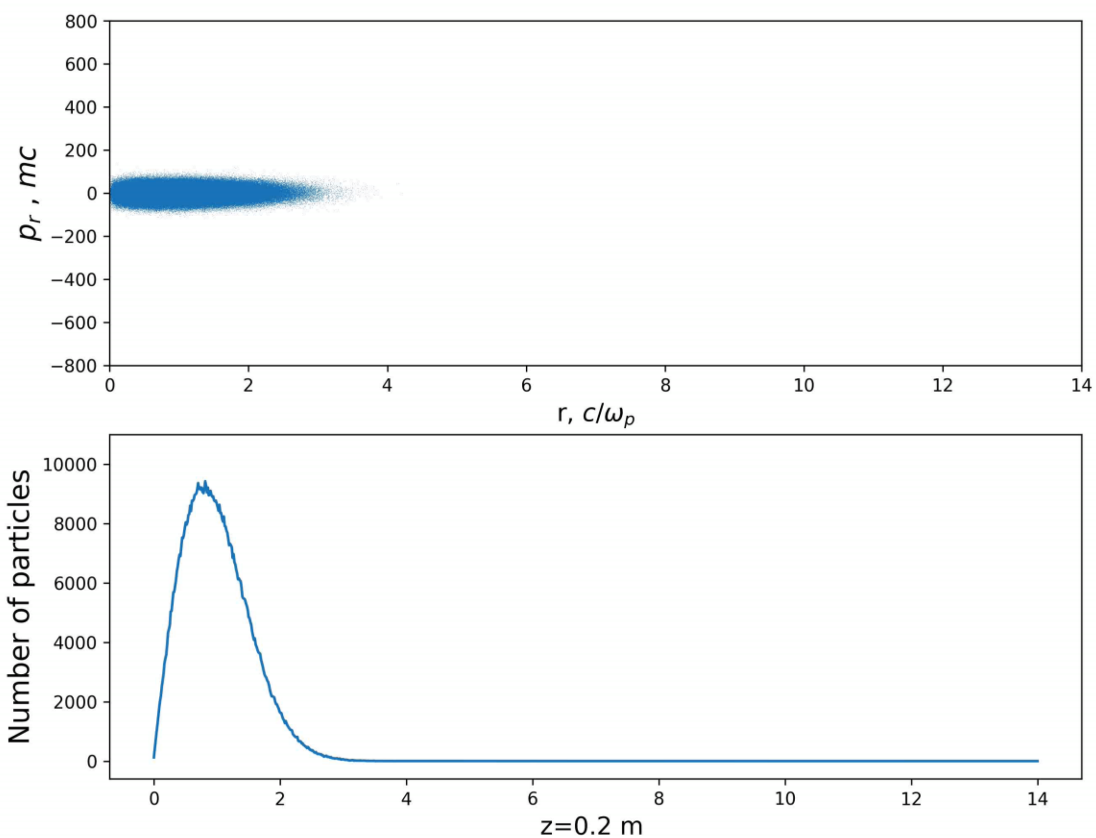
Phase portraits of a proton bunch slice at different propagation distances in the plasma with no gap.

Bunch portraits:



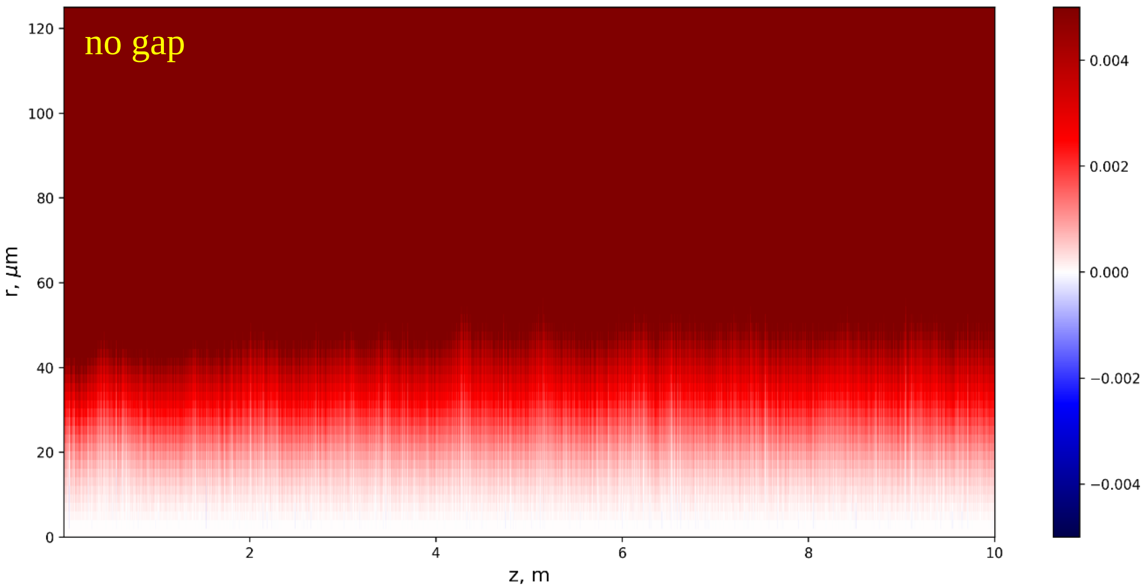
Corresponding radial distributions of bunch particles.

As the bunch evolves, local humps appear at various radii (at different propagation distances for different bunches).

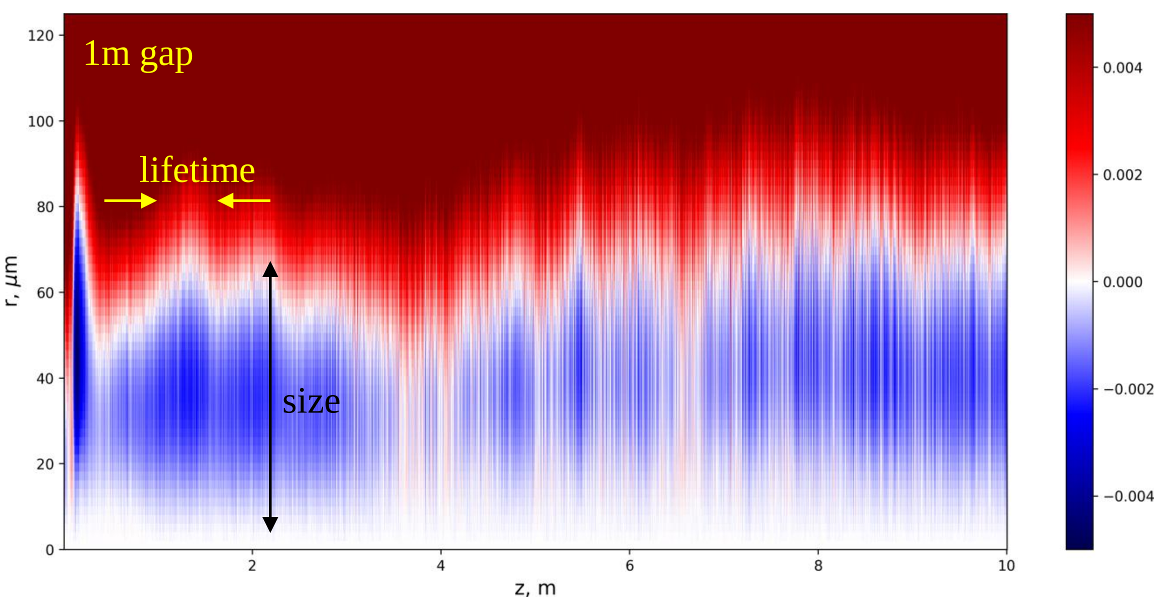


Chaotically appearing small potential wells cause the gradual emittance growth.

Temporal behavior of the potential near the axis

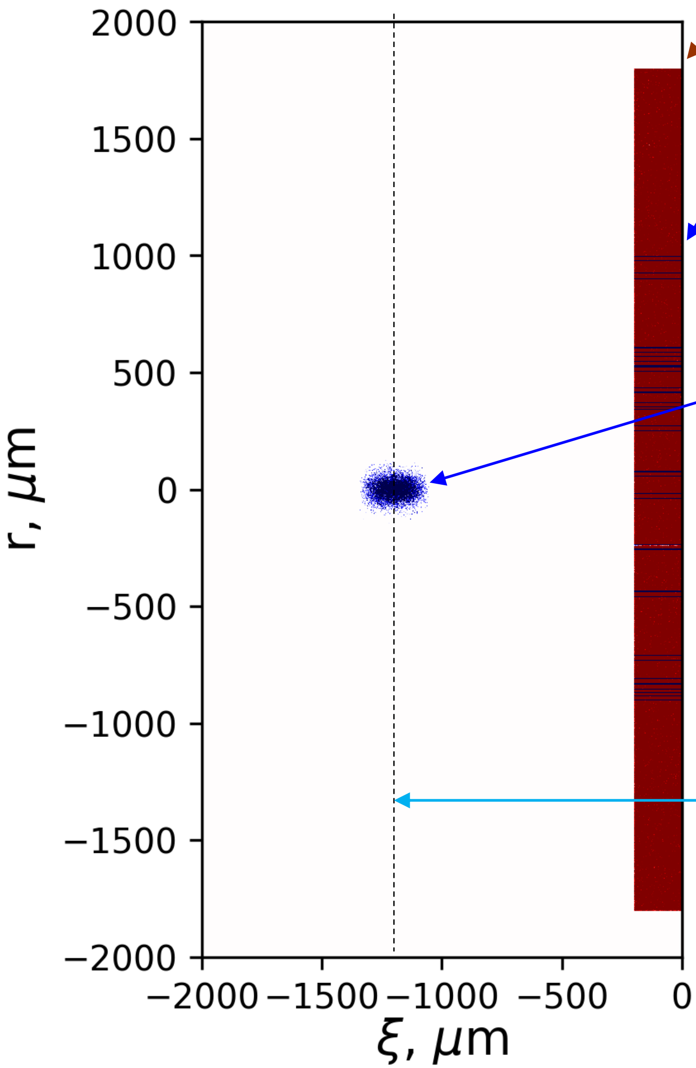


$\Phi(r,z)-\Phi(0,z)$ for ξ=const



We may expect even more chaotic behavior in 3d
We cannot simulate 3d witness beam dynamics in these potential wells,
so we mimic this time-varying potential structure in 2d plane geometry and study witness dynamics there

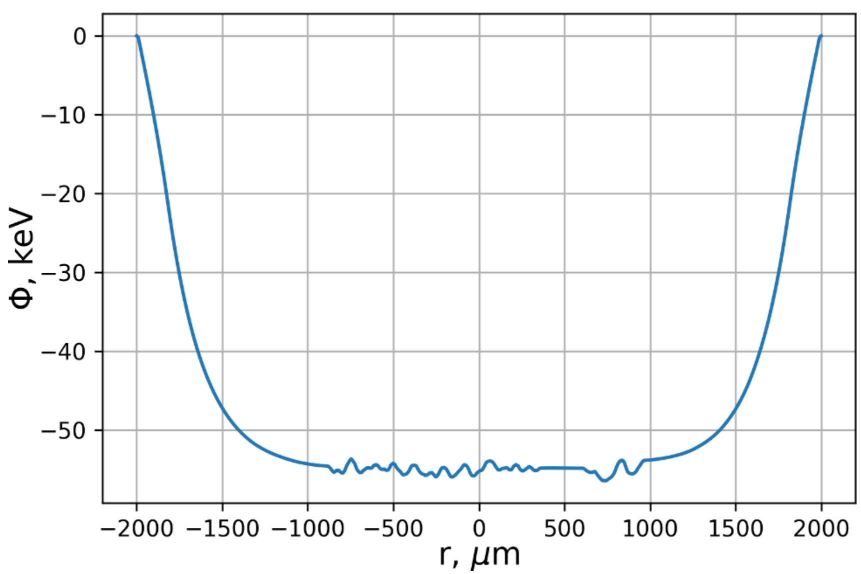
Two-dimensional test problem (plane geometry)



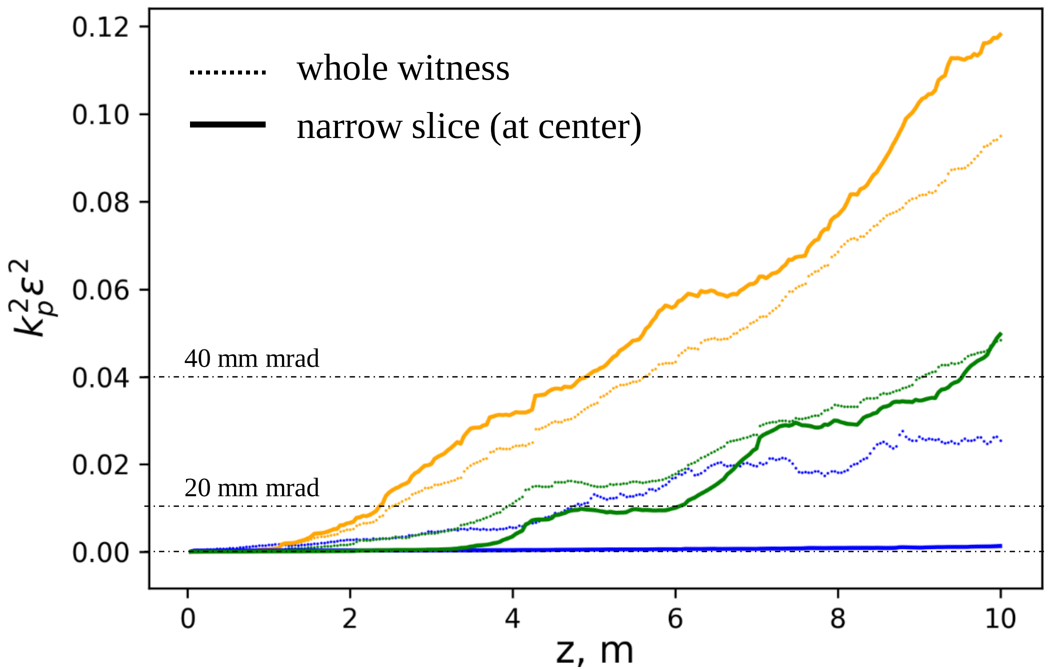
Wide non-evolving bunch with flat-top density distribution:
- creates flat-bottom potential well,
- produces the same accelerating field as in cylindrical case

Time-evolving beam density fluctuations:
- same lifetime and well width as in cylindrical case
- amplitudes adjusted to produce the same emittance growth rate for test electrons

Electron witness beam:
- same size and peak density as in Run II “short-bunch” case
- optionally test particles



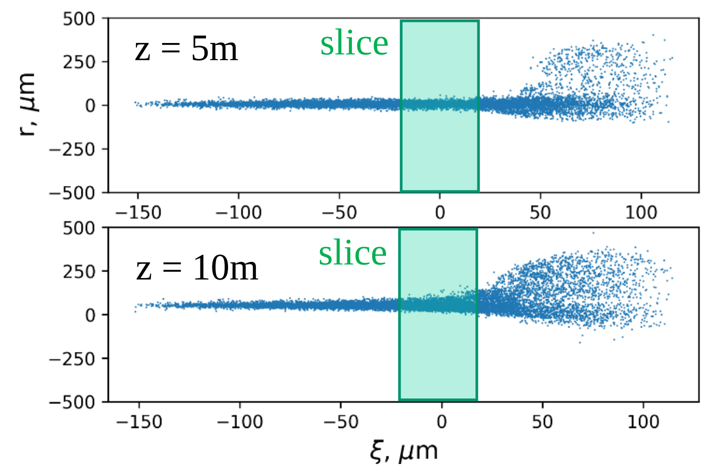
Two-dimensional test problem: results and consequences



test particles

10% charge

full charge (200 pC):



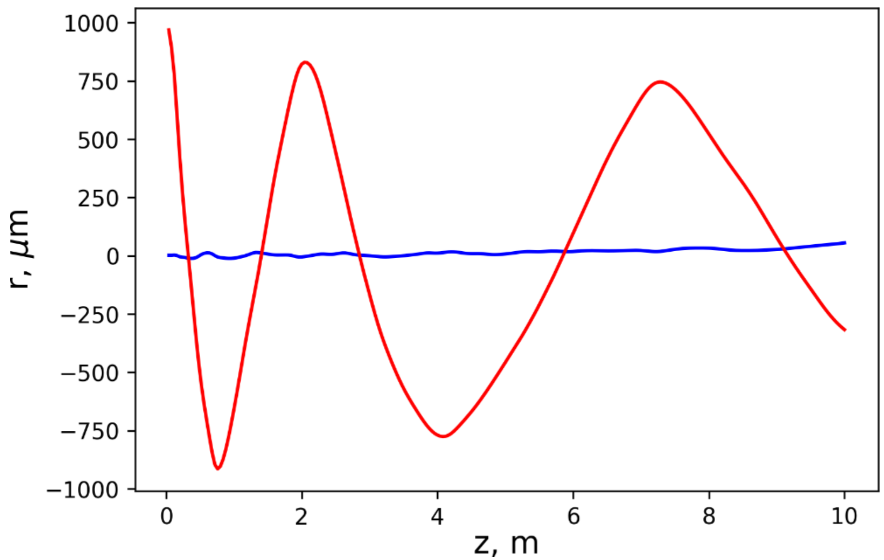
Emittance squared grows linearly, but at different rates.

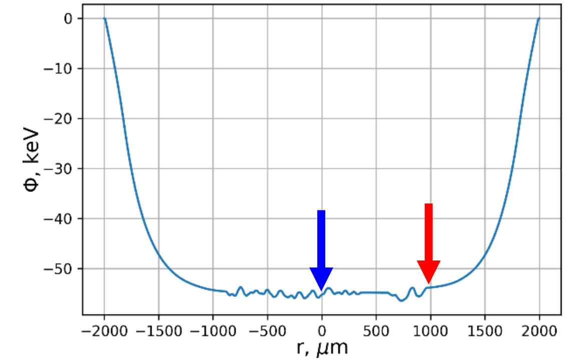
Strong beam loading favors emittance preservation.

The witness head suffers from potential fluctuations, while the tail does not.

A good-quality part of the witness reduces with propagation distance.

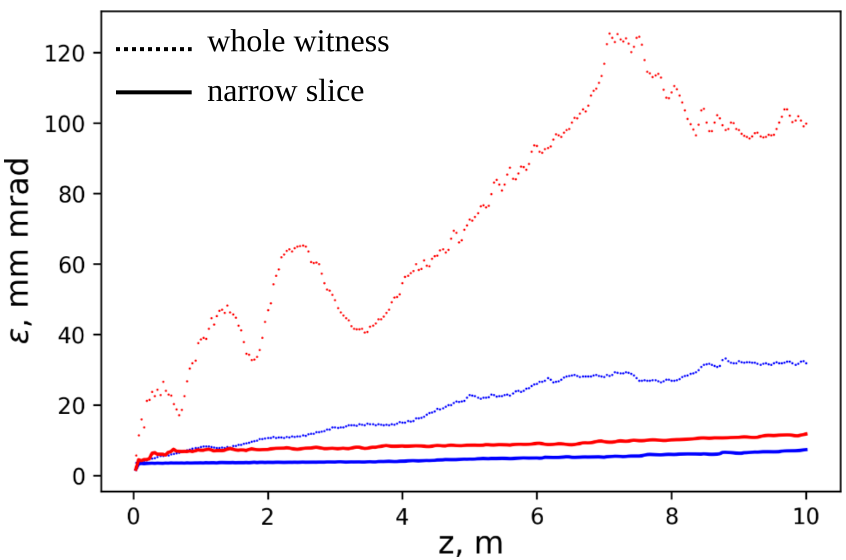
Two-dimensional test problem: misaligned injection

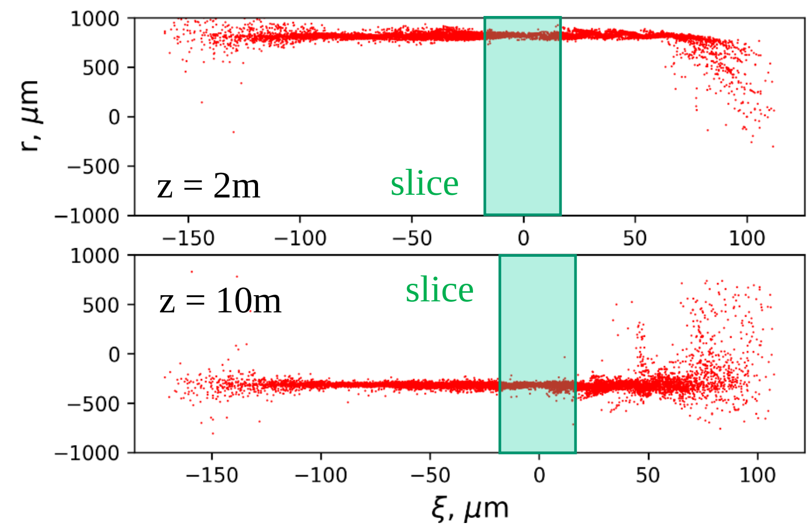




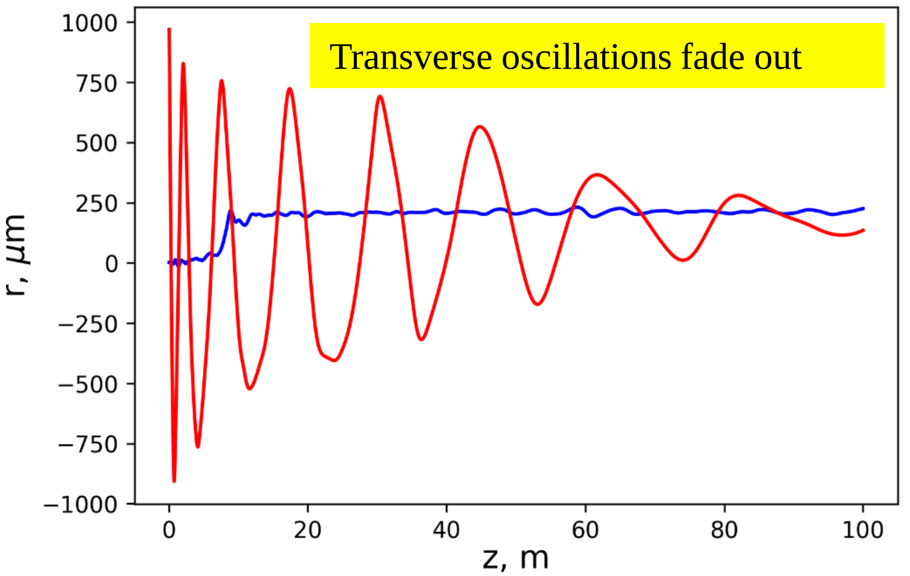
Transverse oscillations of witness as a whole

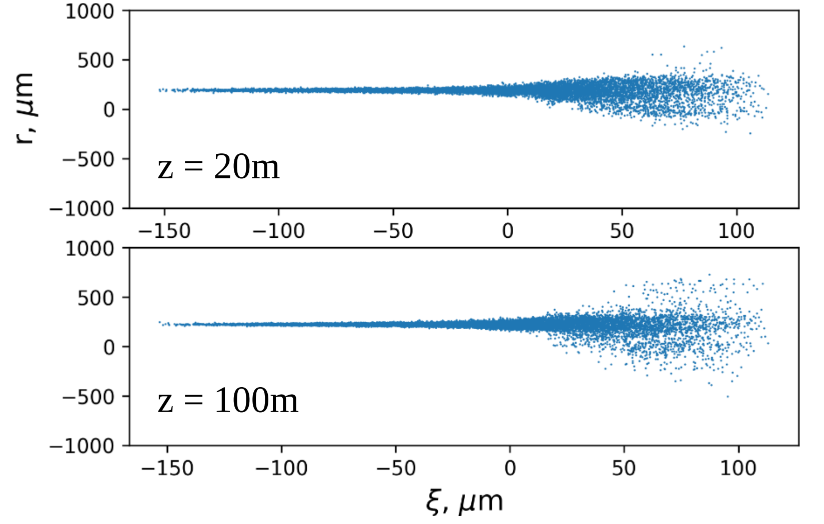
Witness body preserves low emittance

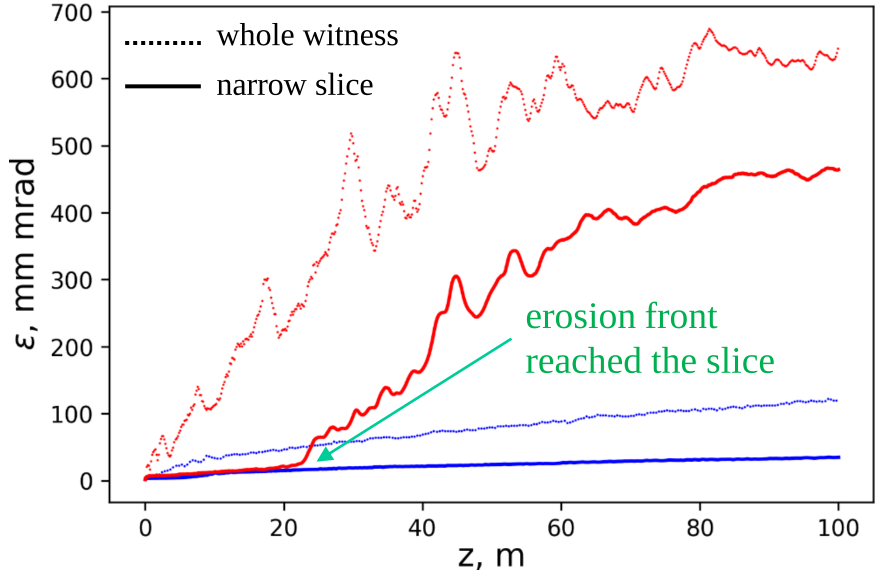




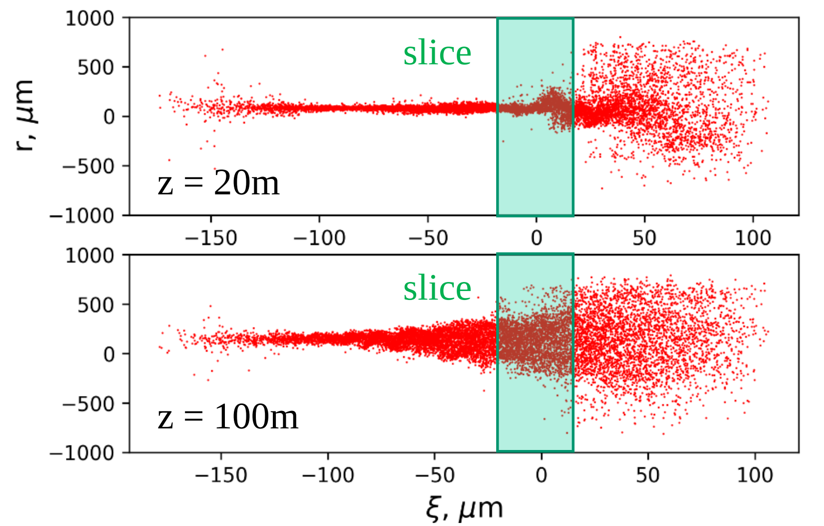
Long-term evolution of misaligned injected beam







Faster erosion of misaligned bunch



Summary

Vacuum gap between plasma cells takes the driver out of radial equilibrium and results in appearance of flat-bottom potential wells with time-varying potential “noise” on it.

“Noisy” potential results in linear (with time) growth of witness emittance squared.

Beam loading reduces the emittance growth rate.

Witness head gradually erodes, as sees no effect of beam loading.

In case of off-axis injection, the witness first transversely oscillates as a whole, then oscillations decay (maybe this can relax alignment tolerances).