Controlling the compression of an externally injected electron bunch in LWFA accelerators via background density shaping. 1D results.

The PLASMONX group "Laser-Plasma acceleration"

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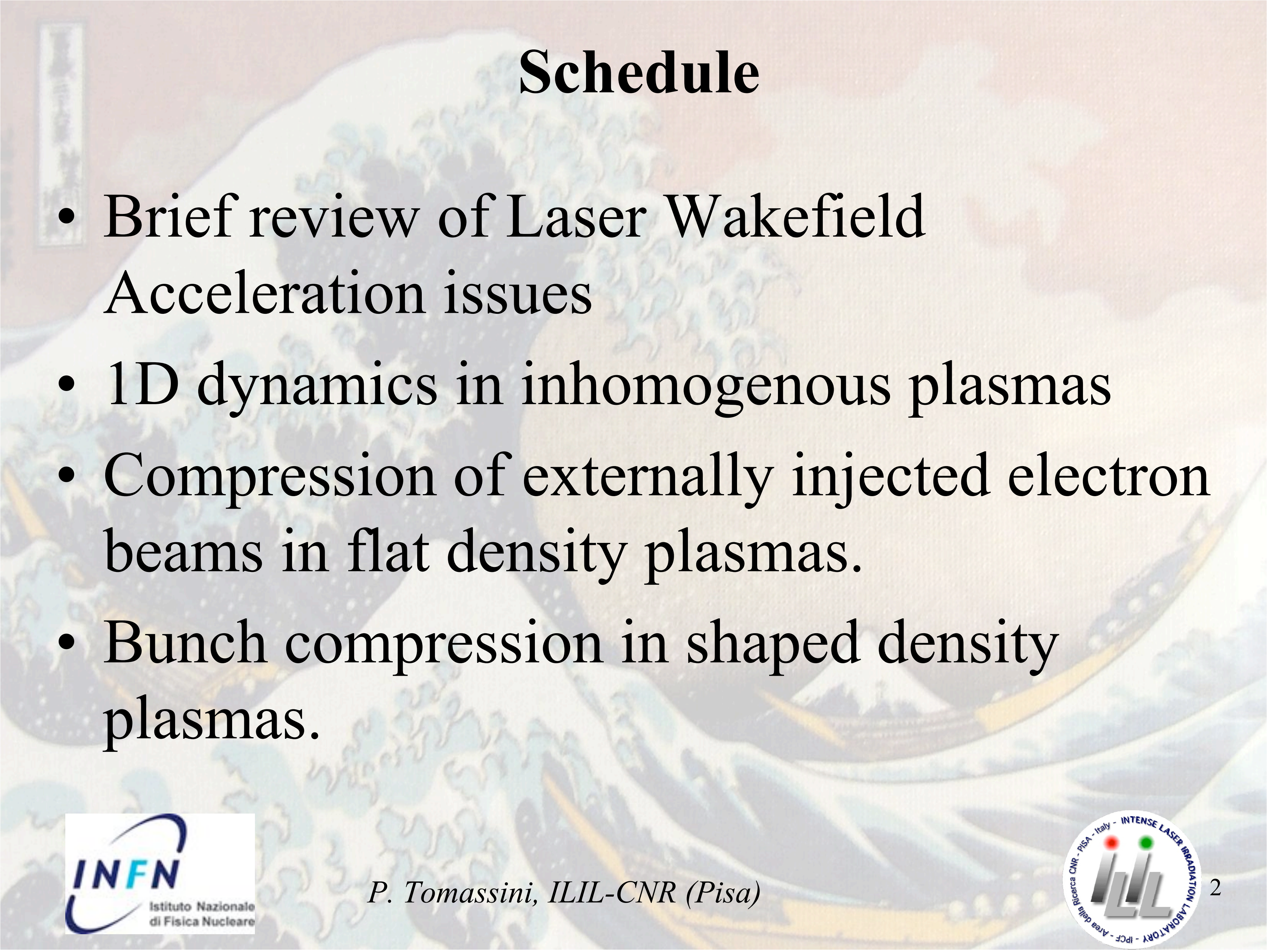


Schedule

- Brief review of Laser Wakefield Acceleration issues
- 1D dynamics in inhomogenous plasmas
- Compression of externally injected electron beams in flat density plasmas.
- Bunch compression in shaped density plasmas.

Brief review of Laser Wakefield Acceleration issues

Brief review of Laser Wakefield Acceleration issues [1]

Consider an underdense plasma with electronic density n_e in the range 10^{15}-10^{19} e/cm^3 .

If an ***intense*** (intensity I>10^{16} W/cm^2) and ***ultrashort*** (duration of few tens of fs for the highest density) laser pulse is focused in the plasma, a (mostly) longitudinal electronic wave behind the pulse (**Langmuir wave**) is excited by the ***ponderomotive forces*** of the pulse.

The longitudinal plasma wave in a cold plasma has negligible group velocity and phase velocity close to that of the pulse.

Brief review of Laser Wakefield Acceleration issues [2]

- The laser pulse group velocity is close to c for a tenuous plasma (1) , the plasma wave wave-length λ_p being linked to the plasma density by the relation (2).
- For a **flat density profile** the phase velocity of the plasma wave v_ϕ equals the group velocity of the driver (the laser pulse), so that the important relation (3) holds.
- The amplitude of the electric field can be roughly estimated as (4)

$$v_g \cong c \cdot \sqrt{1 - \lambda^2 / \lambda_p^2} \qquad (1)$$

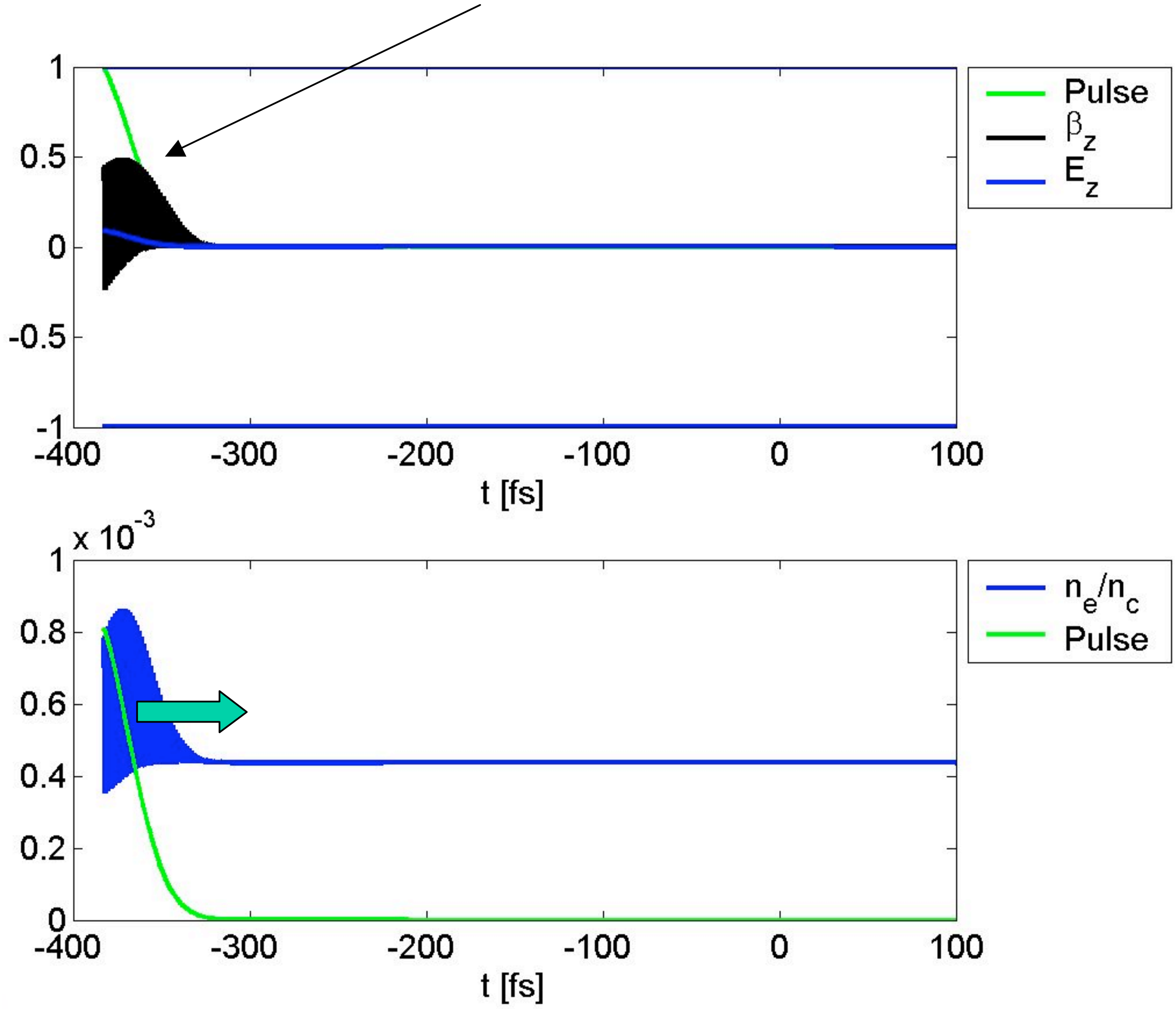
$$\lambda_p = \sqrt{1.1 \cdot 10^{21} / n_0} \qquad (2)$$

$$v_\varphi \cong c \cdot \sqrt{1 - \lambda^2 / \lambda_p^2} = c \cdot \sqrt{1 - n_0 / n_c} \qquad (3)$$

Pulse normalized amplitude

$$E[GV/m] \cong 0.4 \cdot \frac{a_0^2}{\sqrt{1 + a_0^2 / 2}} \sqrt{n_0[10^{16} / cm^3]} \qquad (4)$$

A pulse is propagating inside a cold plasma.
The front ponderomotive forces push the electrons forward.



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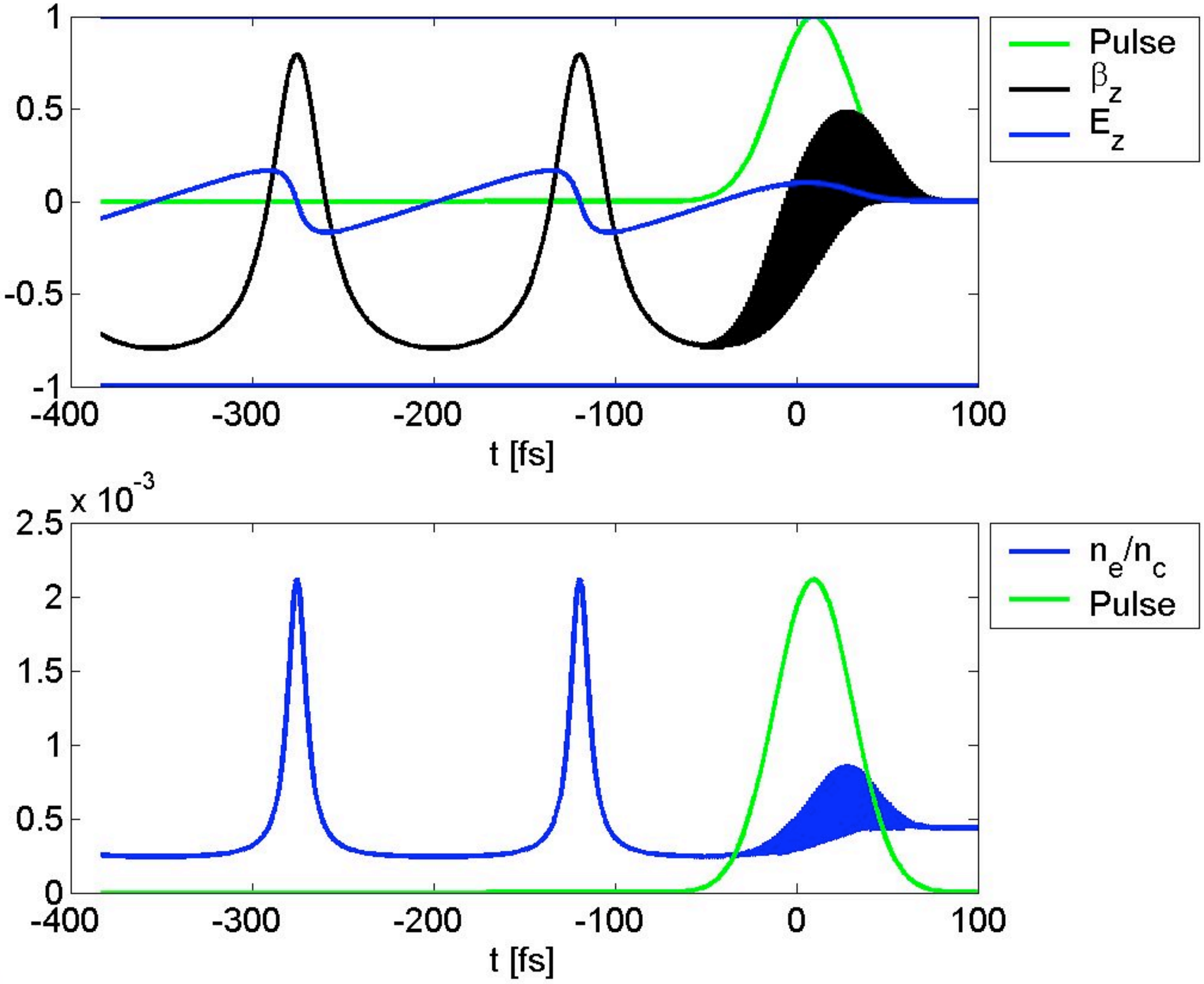
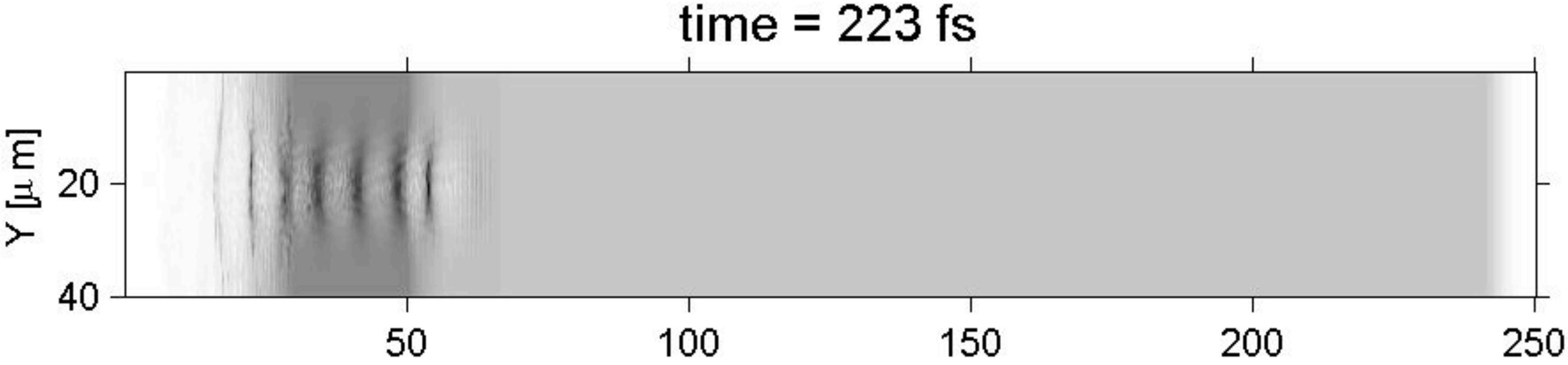
Coulomb forces (immobile neutral ions are considered for these time-scales) do strongly pull-back the electrons, thus exciting a plasma wave.

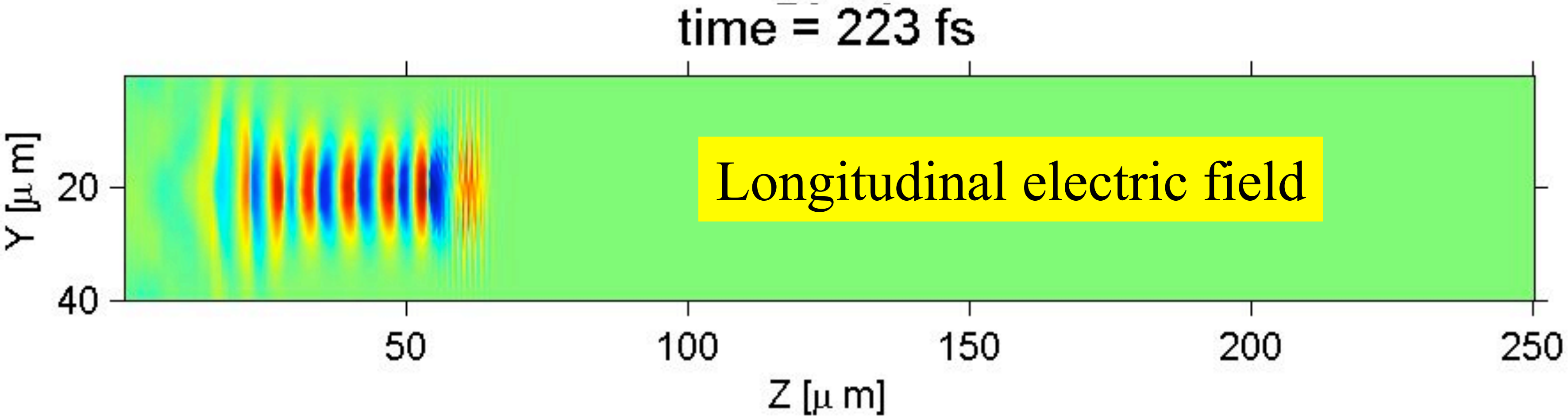


In a full 3D geometry transverse effects should be taken into account.

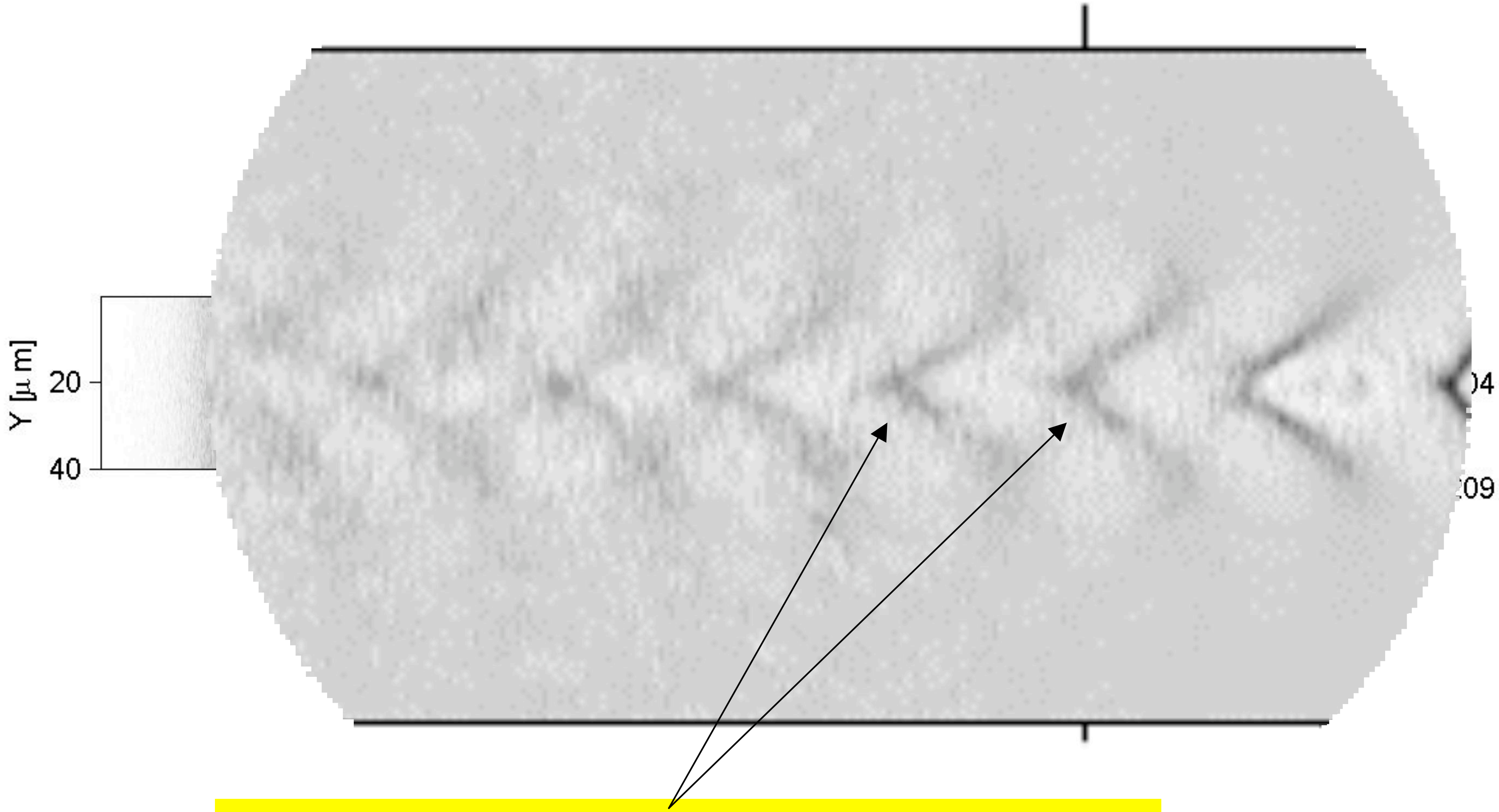
Here we show Particle In Cell simulations of a pulse delivering 1J in 20fs (50TW), focused in a waist of size w_0=20 microns and inpinging onto a plasma of density $n=10^{19}cm^{-3}$.

The density profile presents a sharp downstream transition





Longitudinal electric field



Transverse wave-breaking+ beam loading

Brief review of Laser Wakefield Acceleration issues [3]

- **Pulse evolution**. The laser pulse focused in a gas or a pre-ionized plasma can develop a plethora of instabilities and relativistic effects, as well as a simple diffraction leading to pulse defocusing. The most relevant effects for ultrashort pulses are:
  - Pulse diffraction $Z_R=\pi w_0^2/\lambda$
  - Phase modulation and amplitude depletion
  - Relativistic focusing $P_c\,[\mathrm{TW}]>1.7/(n_0[10^{19}\mathrm{cm}^{-3}]\lambda^2[\mu\mathrm{m}])$
  - Pulse diffraction can be compensated either with relativistic self-focusing (almost unstable method) or **propagation into a preformed plasma channel acting as a positive lens**.

- **Transverse plasma and bunch dynamics**. Is excited by nonlinear effects, transverse ponderomotive forces and beam loading.
  - A fluid or PIC code is necessary for taking into account such a issues consistently

Brief review of Laser Wakefield Acceleration issues [4]

Electron beam injection in the plasma wave.

Internal injection

Fast electrons leave the fluid motion being pre-accelerated by some mechanism. Several promising mechanisms are currently under investigation.

☺ **This leads to compact and jitter-free accelerators.**
Very short bunches can be produced.

☹ Results have a poor reproducibility.

External injection

Fast electrons are pre-accelerated with conventional stages and injected into the plasma wave with the proper phase

☺ **The injected beam can be carefully Prepared. Total control of the beam parameters**

☹ Strong limitation from the large beam length. The jitter of the injection phase is critical

Trapping of electrons via wave breaking due to density transition

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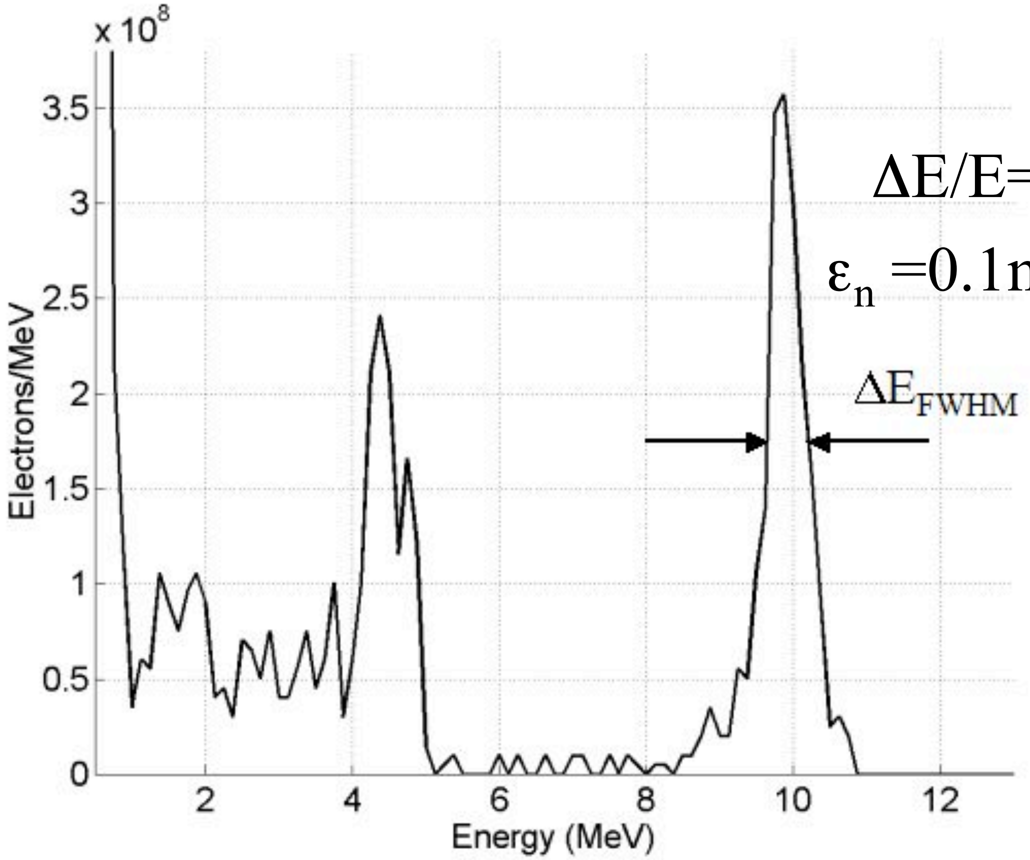
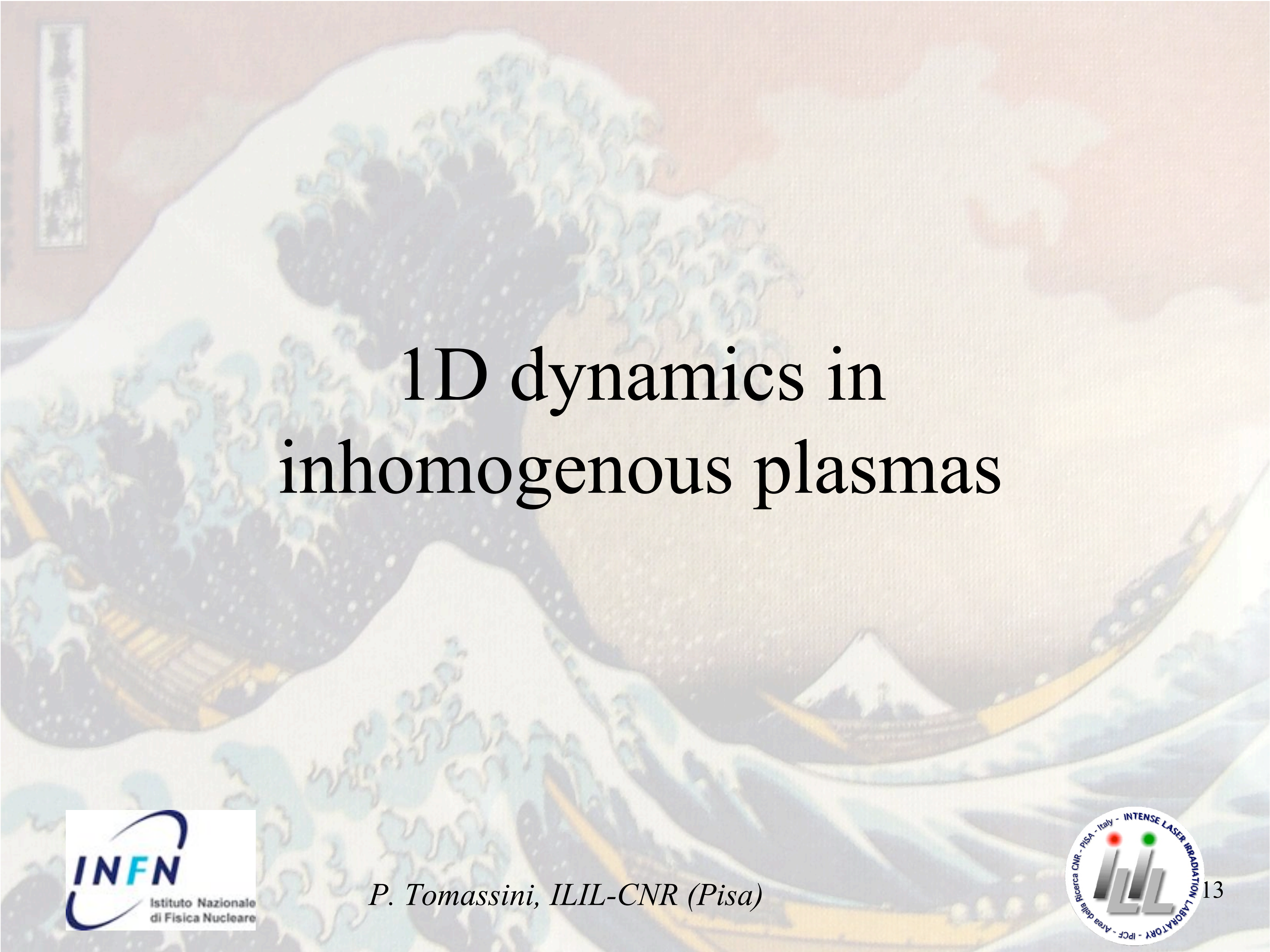
P. Tomassini et al., PRST-AB **6**, 121301 (2003)



$\Delta E/E = 5\%$

$\varepsilon_n = 0.1$ mm mrad



1D dynamics in inhomogenous plasmas

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1D dynamics in inhomogenous plasmas [1]

1D dynamics is the limit of full physics when…

1. The laser pulse (and thus the plasma wave behind that) is much wider than the plasma wave wavelength. ($w_0 >> \lambda_p$).

   This favors relatively high plasma densities: $n_0 >> 1.1 \cdot 10^{21} / w_0^2$.
2. The laser pulse envelope does not experience transverse focusing/defocusing. Either a limitation to longitudinal excursion within one Rayleigh length far away the focusing point or **pulse guiding** is required.
3. The electron beam transverse size σ_r is much smaller than the pulse waist size ($\sigma_r << w_0$).
4. The beam transverse space-charge forces are negligible with respect to longitudinal forces. **Again, this favors high density, i.e. high electric fields**

1D dynamics in inhomogenous plasmas [2]

Self-consistent cold fluid plasma evolution equations

In the Coulomb gauge, normalized units *a=eA/mc²* ; *ψ=eφ/mc²;* *u=p/mc* and by using the conservation of the transverse generalized momentum, the fluid equation of motion of the plasma reads.

$$\gamma = \sqrt{1 + a^2 + u^2}$$

$$\tfrac{1}{c} d_t u = \partial_z \psi - (\tfrac{a}{\gamma}) \partial_z a$$

$$\left(\tfrac{1}{c^2} \partial_t^2 - \partial_z^2\right) a = -\left(\tfrac{2\pi}{\lambda_p}\right)^2 \frac{an}{\gamma n_0(z)}$$

$$\partial_z^2 \psi = \left(\tfrac{2\pi}{\lambda_p}\right)^2 \left[\frac{n + n_b - n_0(z)}{n_0(z)}\right]$$

$$\tfrac{1}{c} \partial_t n + \partial_z (n \cdot u / \gamma) = 0$$

Space-dependent background density

Density of the beam

A strong increase of efficiency in solving the fluid equations is obtained by switching to **comoving variables**

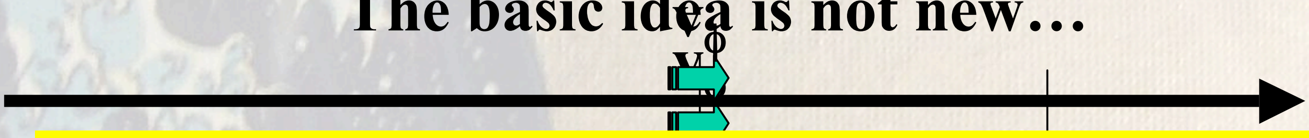
$$\{t, z\} \rightarrow \{\tau = t, \xi = \tfrac{1}{c}(z - z_l)\}, \; z_l = z_0 - \int_0^t dt' v_g(t')$$

1D dynamics in inhomogenous plasmas [3]

What's new with respect to flat density plasmas?

The most interesting new feature seems to be the chance to modify the plasma wave phase velocity by choosing the appropriate density profile.

The basic idea is not new…



S. F P. Sprangle et al., PRE 63, 056405 (2001) 3)

Sudden or quasi-sharp downstream transition: fast and very large reduction of the phase velocity **(v_ϕ<<c)** to trap electrons in the plasma wave

We explore this region, aiming at obtaining an efficient compression of the injected electron bunch

Gentle increase with a known law: Luminal plasma wave motion. It can be use to overcome the problem of *dephasing,* i.e. particle slippage in the de-accelerating region.

1D dynamics in inhomogenous plasmas [4]

The relation between the plasma wave phase velocity v_ϕ, the driver (the laser pulse) group velocity v_g and the plasma density profile

[in the linear regime, i.e. when $(n-n_0)/n \ll 1$]

is:

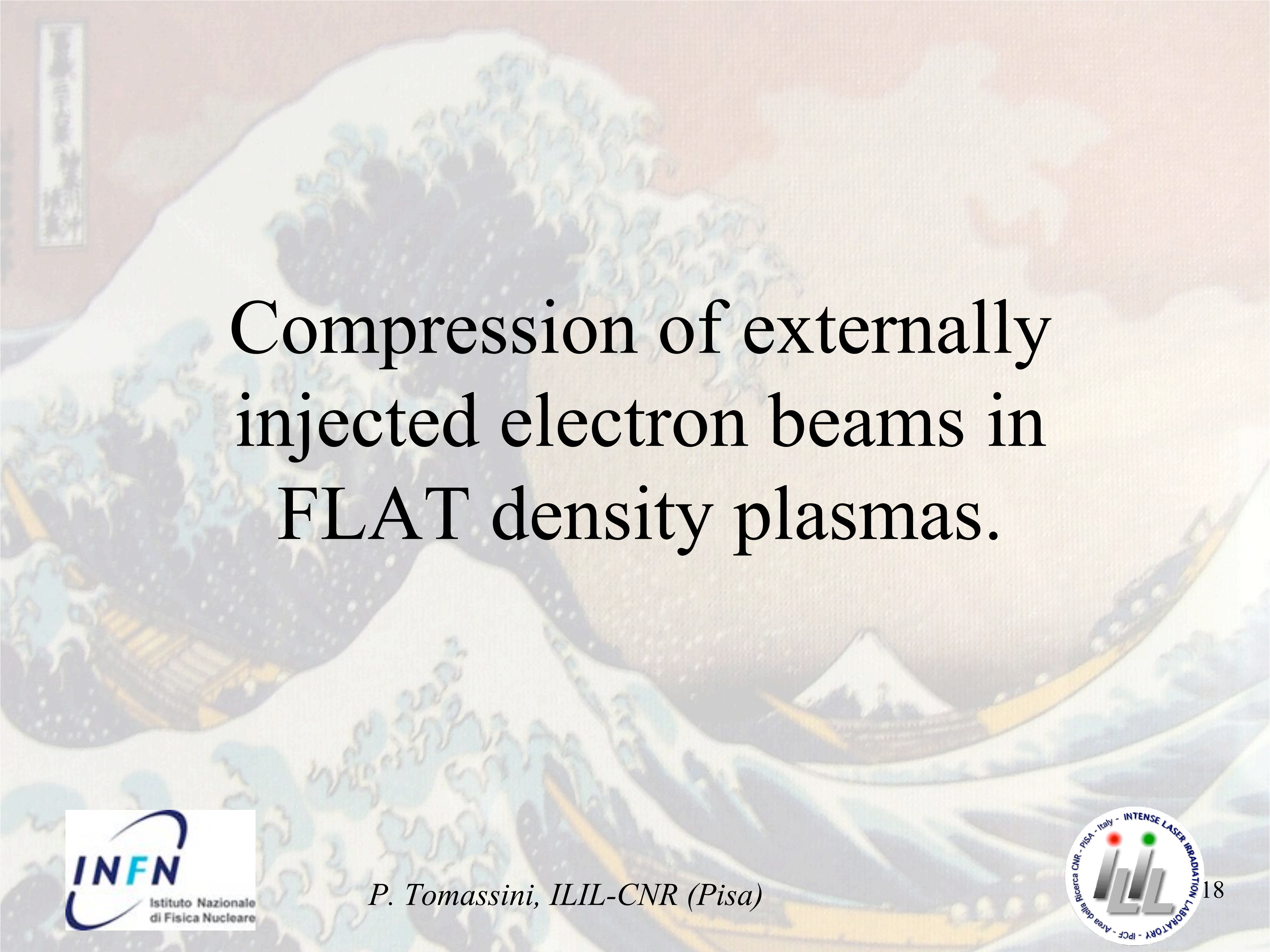
$$\boxed{v_\varphi = v_g \frac{1}{1 - c\xi\partial_z \log(\lambda_p)}}$$

$$\lambda_p(z) = \sqrt{1.1 \cdot 10^{21} / n_0(z)}$$

where cξ is the distance from the laser pulse.

Having fixed a required phase speed v_{fixed} at a given variable distance cξ , the background density profile that realizes that accomplishes this is found by solving the equation for λ_p

$$\frac{\lambda^2}{\lambda_p^2} - \frac{2c\xi}{\lambda_p}\partial_z \lambda_p = \frac{1}{\gamma_f^2} \longrightarrow n_0(z) = 1.1 \cdot 10^{21} / \lambda_p^2(z)$$



Compression of externally injected electron beams in FLAT density plasmas.

Bunch compression in FLAT density plasmas [1]

- The idea of bunch compression in LWFA can be attributed to two independent groups in 2000
  - Andreev, Kuznetzov and Pogorelsky [PRST-AB **3**, 021301]
  - Ferrario, Katsouleas, Serafini and Ben Zvi [IEEE Trans. on Plasma Science , **28**, p.1152]
- The electron bunch has a length L **much smaller than the plasma wavelength** and a **speed lower than the phase speed of the wave.** It is injected close to the node of the plasma wave where the transverse forces are focusing. The gradient of the longitudinal force induces a longitudinal bunch compression. **Particles do accumulate close to the trapping point**

  (i.e. the where the particle get enough energy to move as fast as the wave)

Bunch compression in FLAT density plasmas [2]

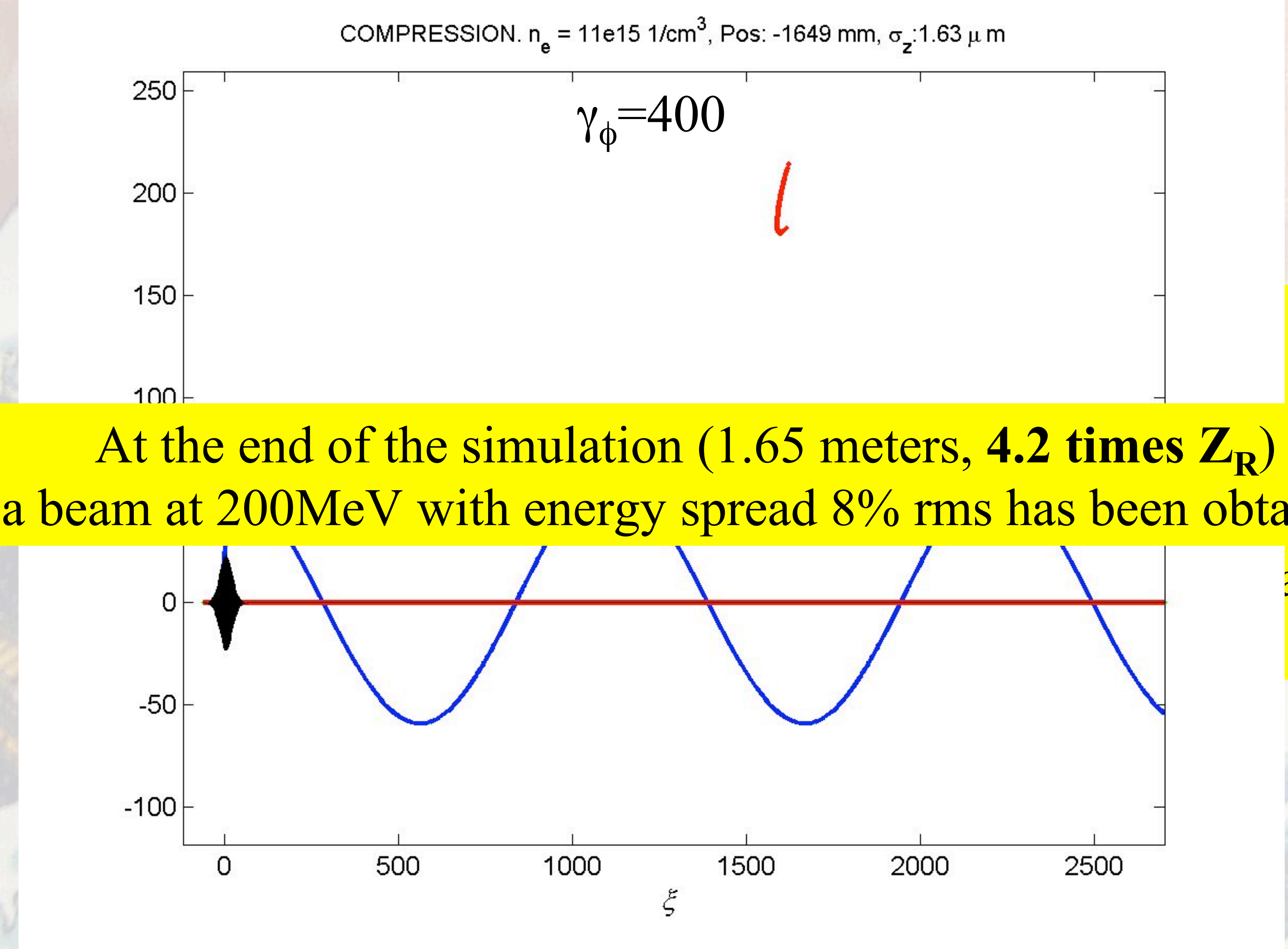
Example #1.

FLAT density background and **NO SPACE CHARGE**.

Bunch:
Quasi monochromatic at **25 MeV** with energy spread 0.1% rms, transverse emittance 1mm mrad, rms length $\sigma_l = 10.5\ \mu m$ and rms transverse size $\sigma_r = 33\ \mu m$

Laser pulse:
Delivers 3J in 30 fs, it has wavelength 0.8 μm it is focused on $w_0=100\ \mu m$ ($w0>>\sigma_r$ should be satisfied)

Plasma:
Flat profile with $n_0=1.1\cdot10^{16}\ cm^{-3}$. The plasma wavelength is $\lambda_p=330\ \mu m$ and the maximum accelerating field is E=0.6GV/m



At the end of the simulation (1.65 meters, **4.2 times Z_R**)
a beam at 200MeV with energy spread 8% rms has been obtained

as

Bunch compression in FLAT density plasmas [3]

Example #2.

FLAT density background **WITH SPACE CHARGE**.

Bunch:

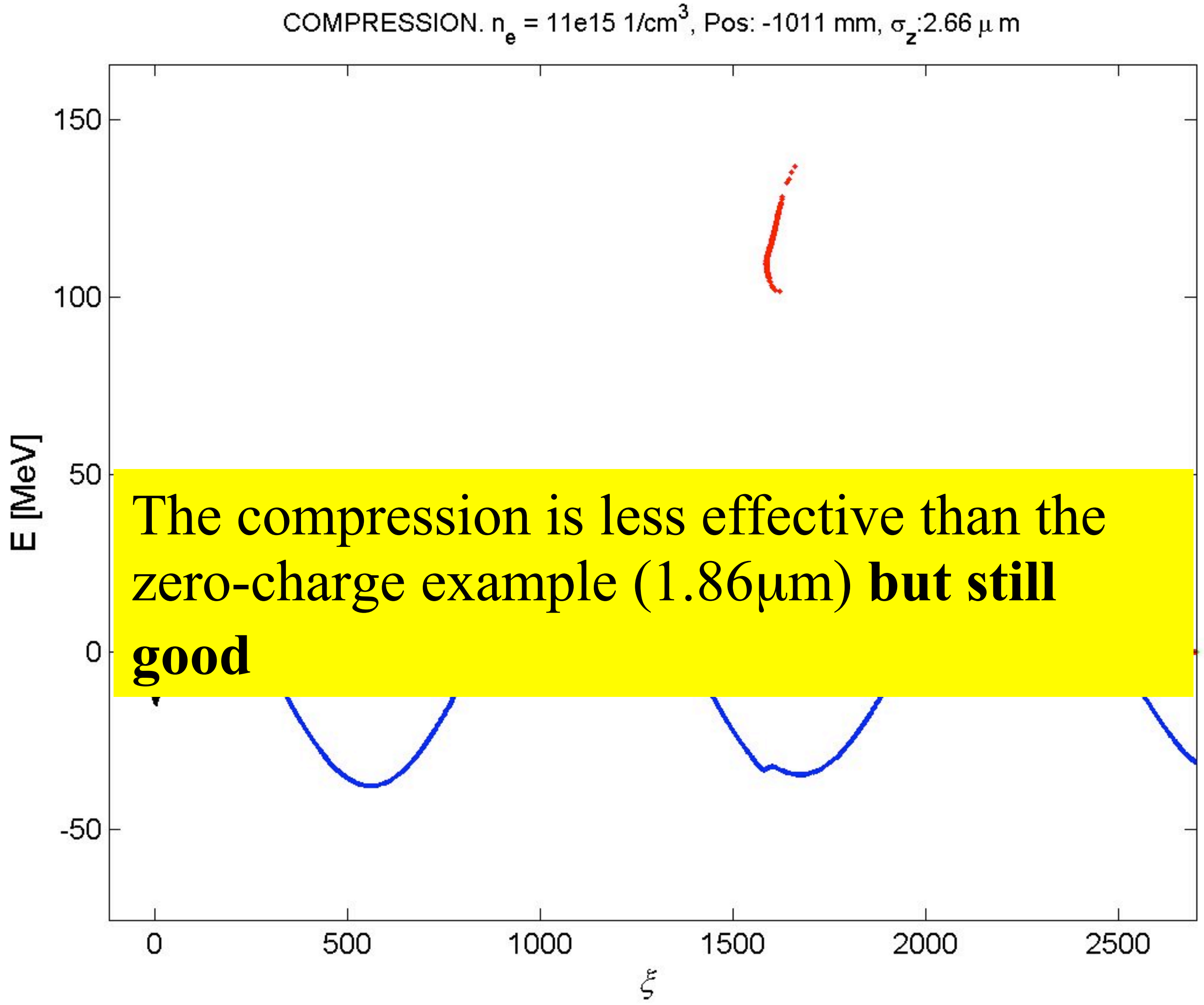
The same of the previous example but with charge 1pC. Quasi monochromatic at 25MeV with energy spread 0.1% rms,transverse emittance 1mm mrad, rms length $\sigma_l = 10.5\ \mu\text{m}$ and rms transverse size $\sigma_r = 33$ mm

Laser pulse:

The same of the previous example It Delivers 3J in 30fs, it has wavelength 0.8 μm and it is focused on w_0=100 mm ($w0 >> \sigma_r$ should be satisfied)

Plasma:

The same of the previous example. Flat profile with $n_0 = 1.1 \cdot 10^{16}\ \text{cm}^{-3}$.
The plasma wavelength is λ_p=330 μm and the maximum accelerating field is E=0.6GV/m



The compression is less effective than the zero-charge example (1.86μm) **but still good**

Bunch compression in FLAT density plasmas [4]

Example #3.

FLAT density background **WITH SPACE CHARGE**.

Injection in the node

Bunch:

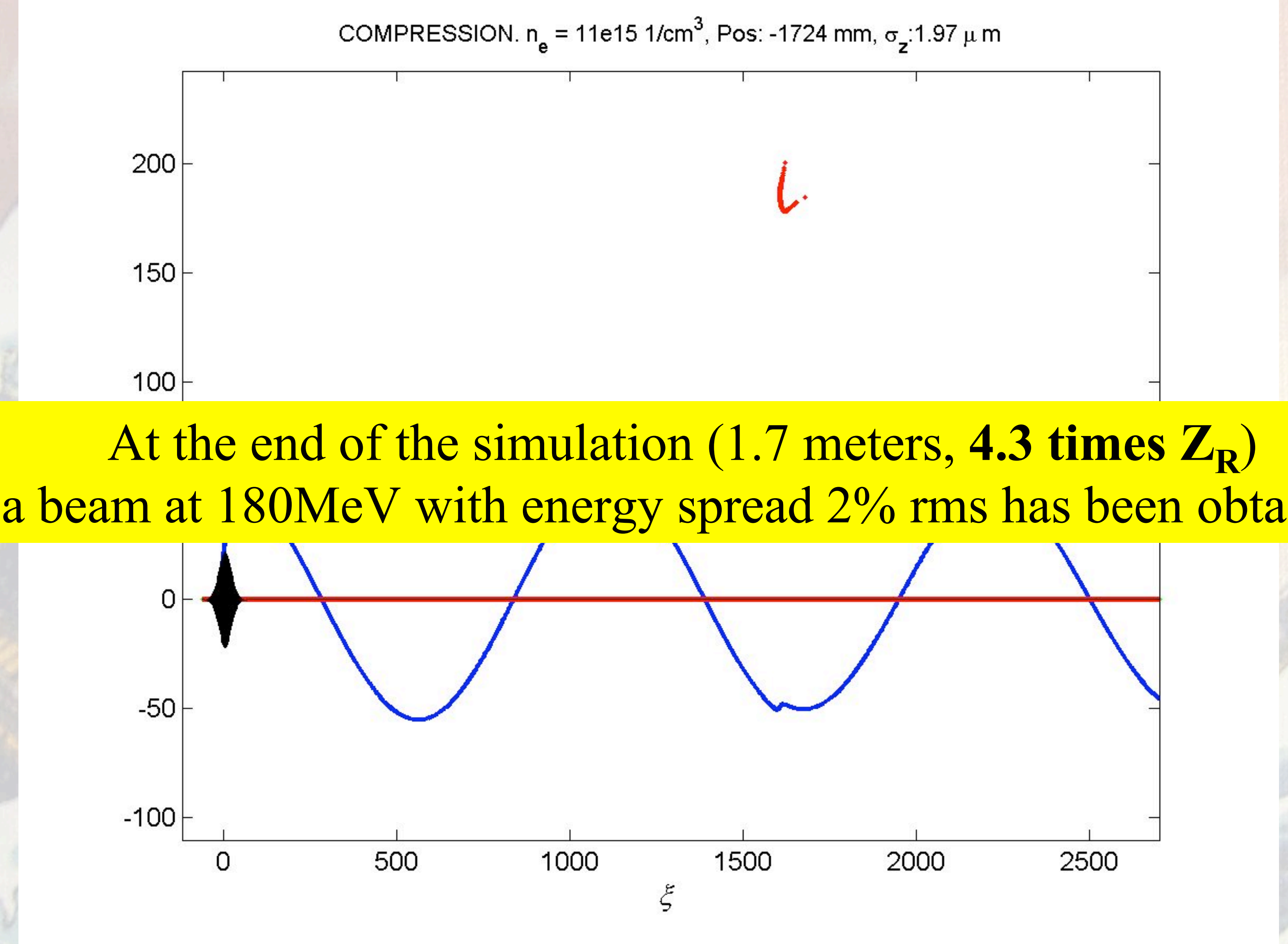
The same of the previous example but the injection phase is in the node of the wave. Quasi monochromatic at 25MeV with energy spread 0.1% rms,transverse emittance 1mm mrad, rms length $\sigma_l = 10.5$ μm and rms transverse size $\sigma_r = 33$ mm

Laser pulse:

The same of the previous example It Delivers 3J in 30fs, it has wavelength 0.8 μm and it is focused on w_0=100 mm (w0>>σ_r should be satisfied)

Plasma:

The same of the previous example. Flat profile with $n_0=1.1\cdot10^{16}$ cm^{-3} .
The plasma wavelength is λ_p=330 μm and the maximum accelerating field is E=0.6GV/m



At the end of the simulation (1.7 meters, **4.3 times Z_R**)
a beam at 180MeV with energy spread 2% rms has been obtained

Bunch compression in FLAT density plasmas [5]

Example #4. **COMPACT Accelerators**

FLAT density background **WITH SPACE CHARGE**.

Low-energy beam with injection in the node

Bunch:

Quasi monochromatic at **2.5MeV** with energy spread 0.1% rms,transverse emittance 1mm mrad, rms length $\sigma_l = 10.5$ μm and rms transverse size $\sigma_r = 33$ mm

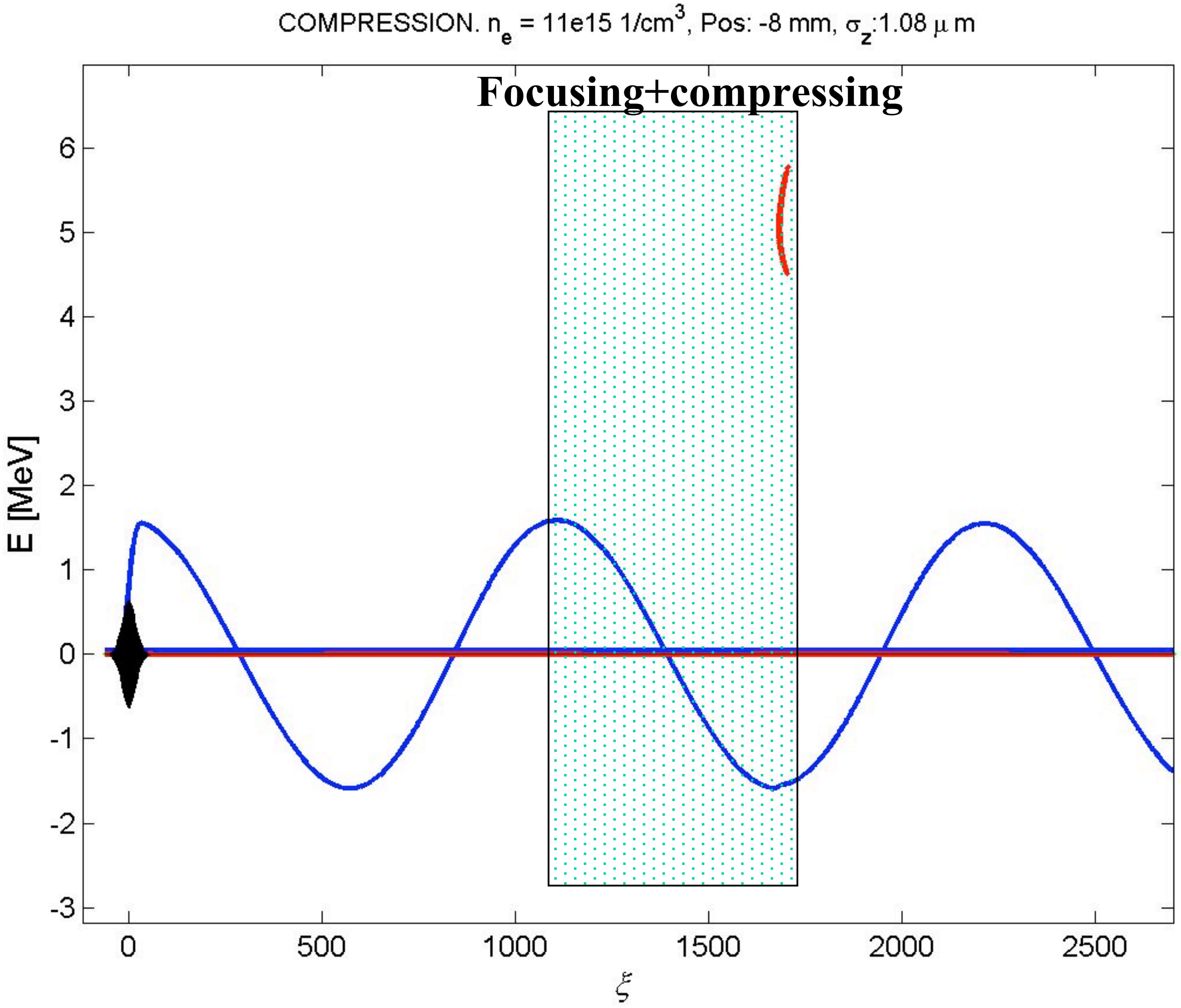
Laser pulse:

The same of the previous example It Delivers **12J in 30fs,** it has wavelength 0.8 μm and it is focused on w_0=100 mm (w0>>σ_r should be satisfied)

Plasma:

The same of the previous example. Flat profile with $n_0=1.1 \cdot 10^{16}$ cm^{-3} .

The plasma wavelength is λ_p=330 μm and the maximum accelerating field is E=2.4GV/m (**lower than the minimum field for obtaining trapping of the particles**)


COMPRESSION. n_e = 11e15 1/cm^3, Pos: -8 mm, σ_z:1.08 μm
Focusing+compressing
E [MeV]
6
5
4
3
2
1
0
-1
-2
-3
0
500
1000
1500
2000
2500
ξ

Bunch compression in FLAT density plasmas [6]

Observations…..

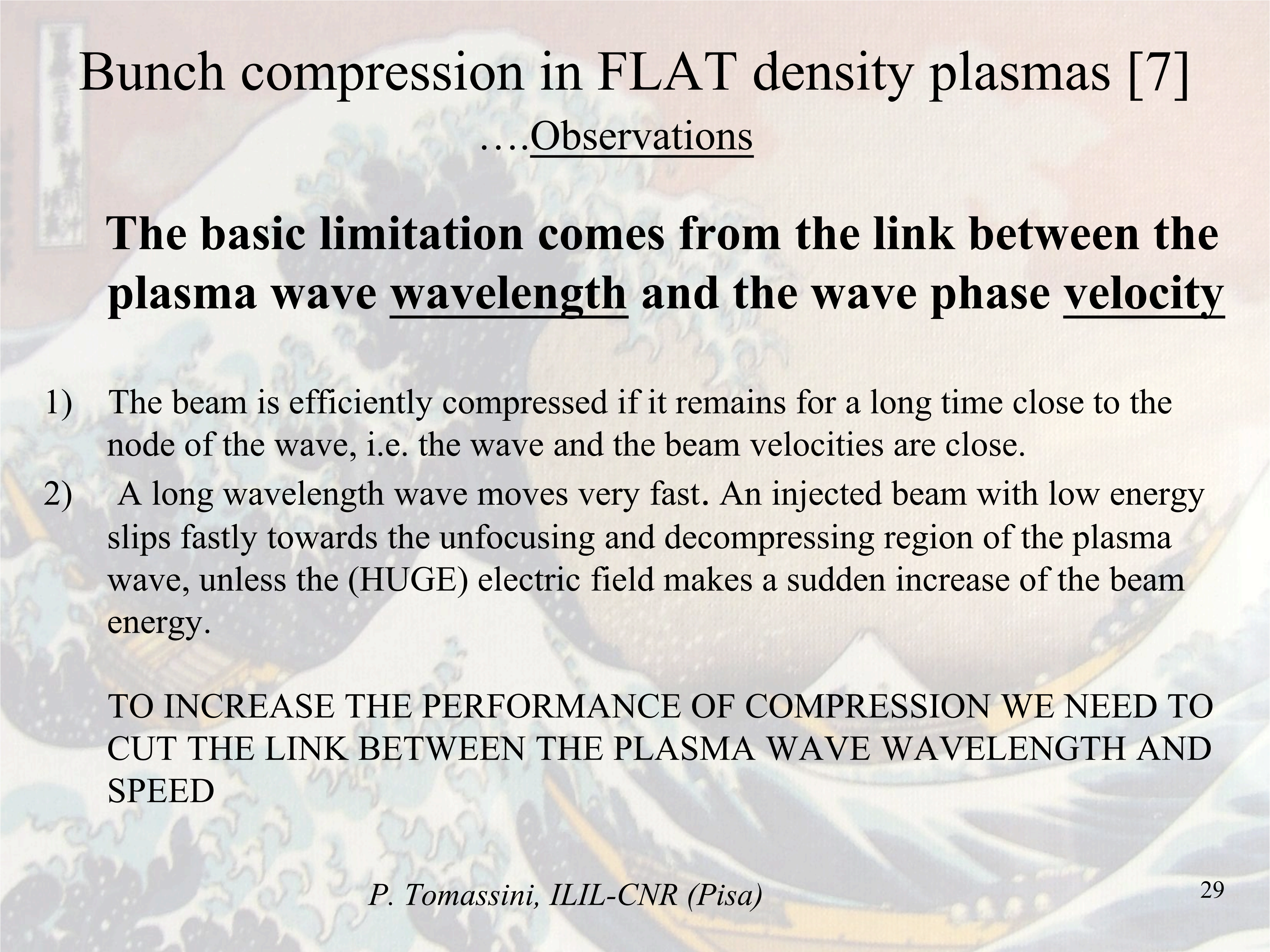
1) Longitudinal space-charge effects may be poorly invasive, provided that the bunch charge is low enough and the beam is not strongly focused (1pC and 33 micron for the previous examples, respectively).

   However, other simulations (not shown here) demonstrate that the plasma electric field should not be reduced significantly, otherwise the beam opposes to compression.

   This imposes the use of a very energetic pulse (2.5-3J)

2) The injection of the beam with the center of mass close to the wave node strongly increases the compression performance.

4) The compression of low energy electron bunches is a critical issue.



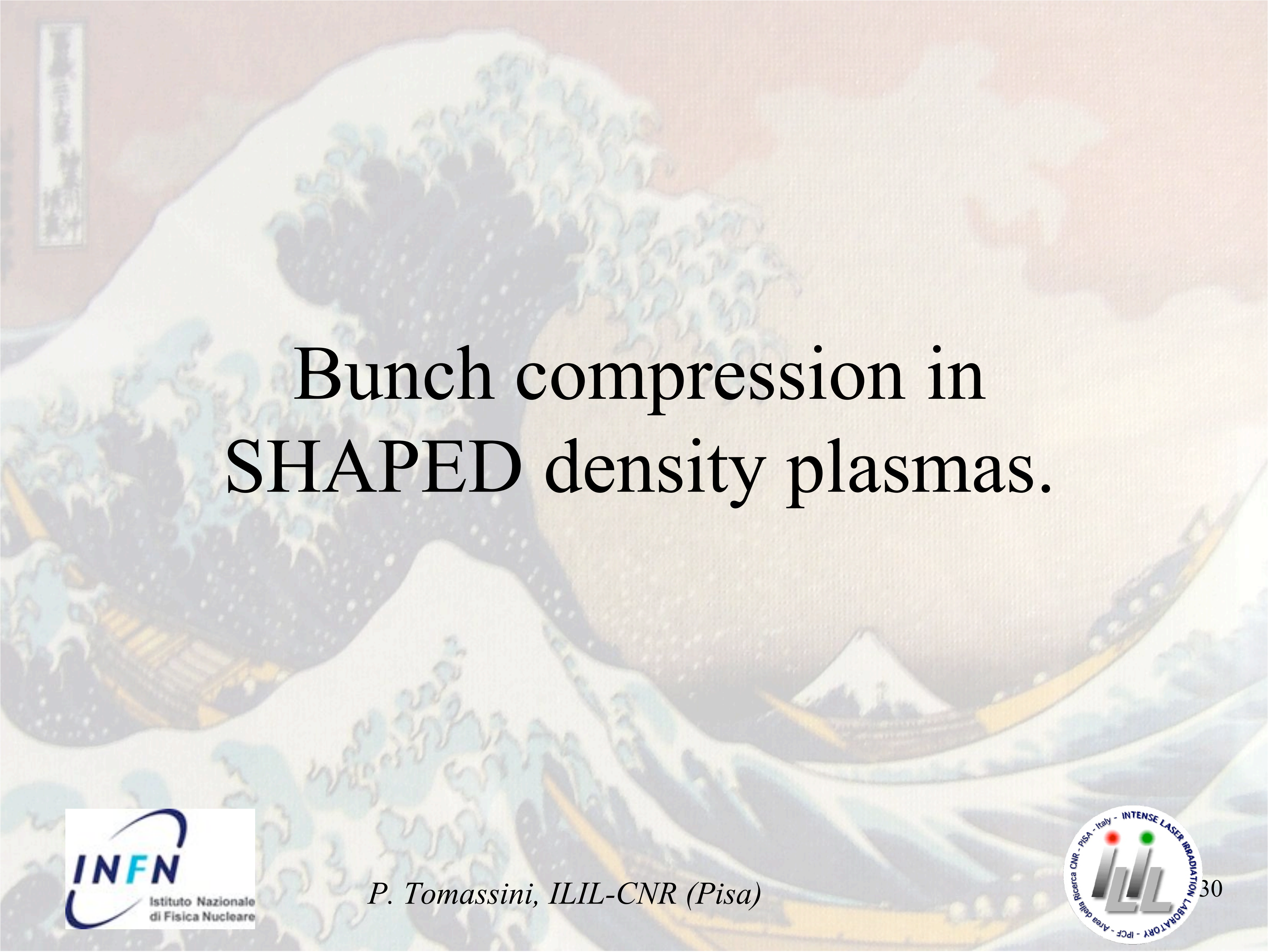
Bunch compression in FLAT density plasmas [7]

….Observations

The basic limitation comes from the link between the plasma wave wavelength and the wave phase velocity

1) The beam is efficiently compressed if it remains for a long time close to the node of the wave, i.e. the wave and the beam velocities are close.
2) A long wavelength wave moves very fast. An injected beam with low energy slips fastly towards the unfocusing and decompressing region of the plasma wave, unless the (HUGE) electric field makes a sudden increase of the beam energy.

TO INCREASE THE PERFORMANCE OF COMPRESSION WE NEED TO CUT THE LINK BETWEEN THE PLASMA WAVE WAVELENGTH AND SPEED



Bunch compression in SHAPED density plasmas.

Bunch compression of SHAPED density plasmas [1].

- In shaped density plasmas the link $\lambda_p \leftrightarrow v_\phi$ **is broken.**

  <u>We are now free to chose the best phase speed and wavelength for a given injected bunch.</u>

The phase velocity of the wave is chosen be close (a bit higher) to that of the bunch.

In this way the electrons do not slip too fast in the bad region of the wave and very weak electric fields could be employed

Bunch compression of SHAPED density plasmas [2].

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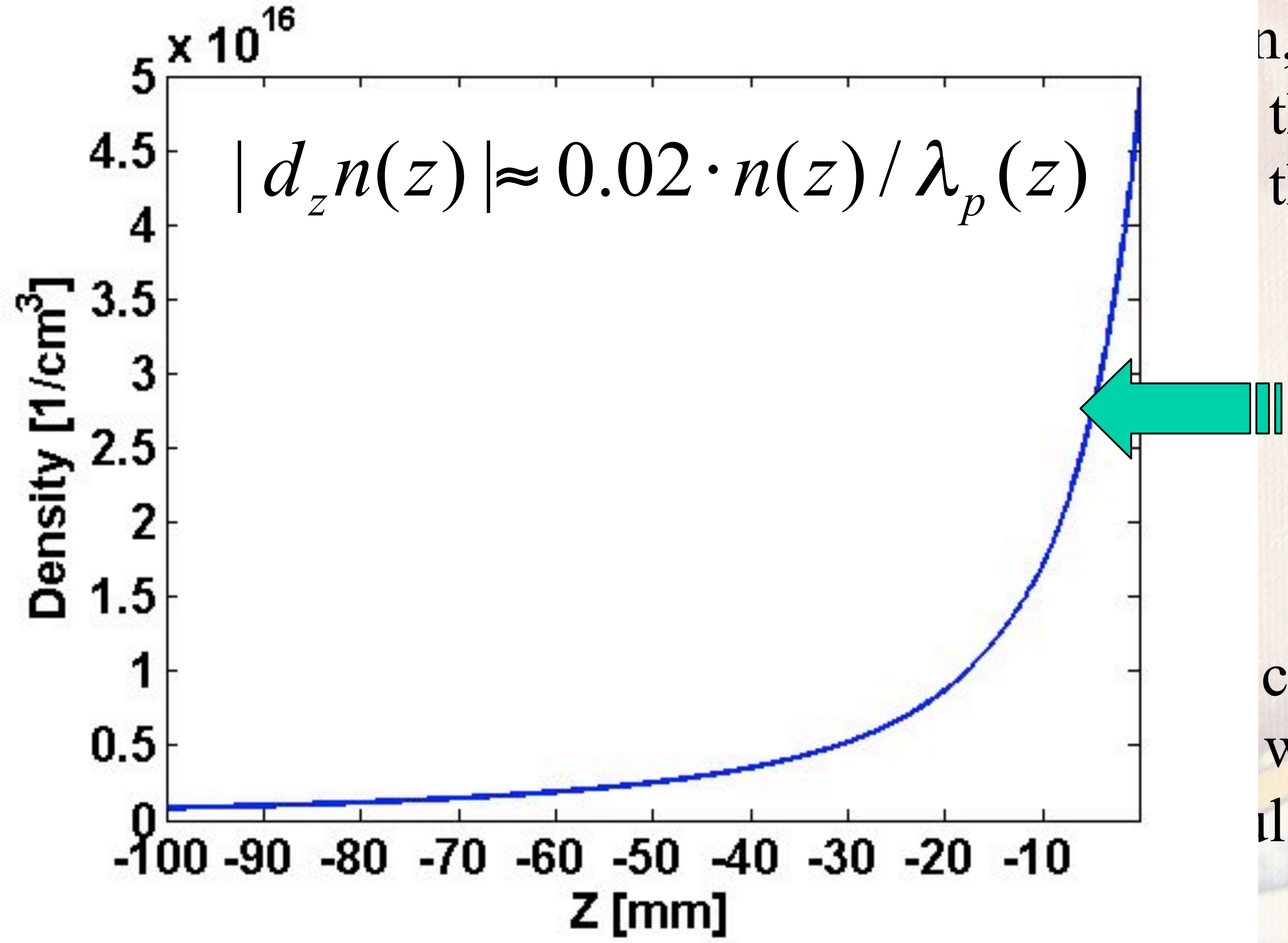


$$| d_z n(z) | \approx 0.02 \cdot n(z) / \lambda_p(z)$$

Bunch compression in SHAPED density plasmas [3]

Example #5.

SHAPED density background **WITH SPACE CHARGE**.

Injection in the node

Bunch:

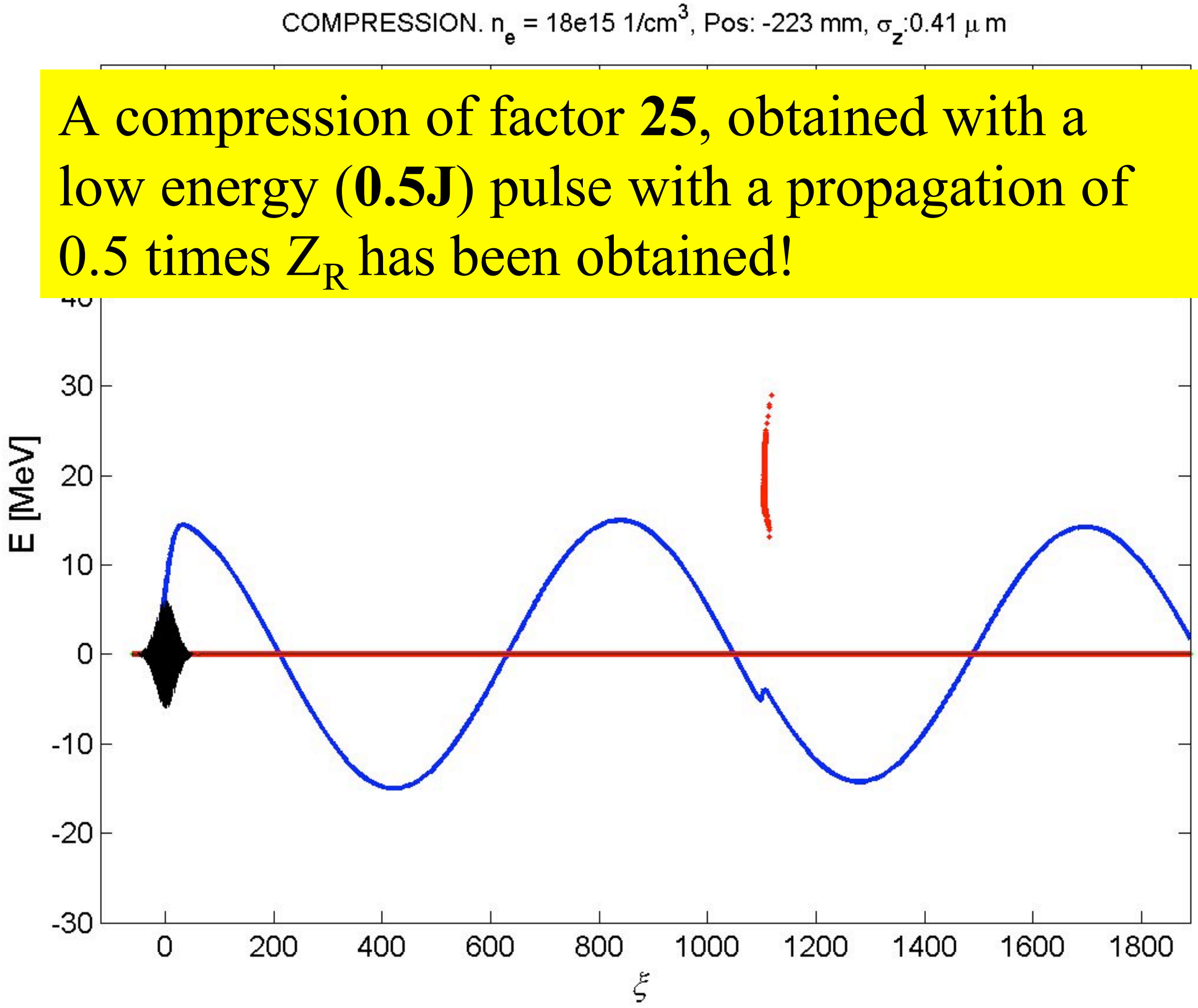
Quasi monochromatic at **25MeV** with energy spread 0.1% rms,transverse emittance 1mm mrad, rms length $\sigma_l = 10.5\ \mu m$ and rms transverse size $\sigma_r = 33$ mm

Laser pulse:

It Delivers **0.5J in 30fs**, it has wavelength 0.8 μm and it is focused on $w_0=100$ mm ($w0 >> \sigma_r$ should be satisfied)

Plasma:

Shaped density plasma with plasma wave velocity tuned at $\gamma_\phi = 70$ with initial density $n_0=2 \cdot 10^{16}$ cm^{-3} . The maximum accelerating field is E=0.2 GV/m



A compression of factor **25**, obtained with a low energy (**0.5J**) pulse with a propagation of 0.5 times Z_R has been obtained!

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Bunch compression in SHAPED density plasmas [4]

Example #6.

SHAPED density background **WITH SPACE CHARGE**.

Low energy bunch

Bunch:

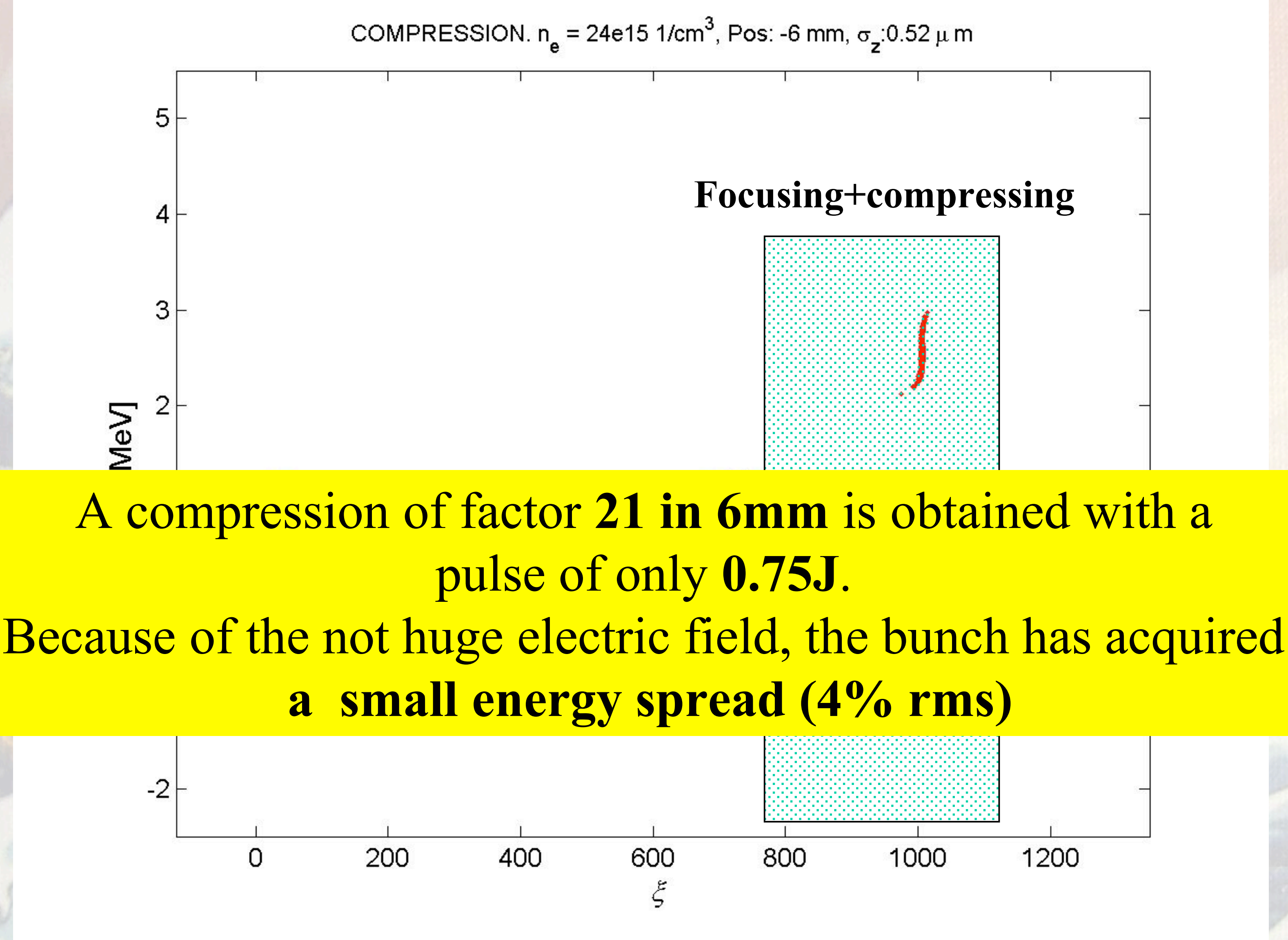
Quasi monochromatic at **2.5MeV** with energy spread 0.1% rms,transverse emittance 1mm mrad, rms length $\sigma_l = 10.5\ \mu m$ and rms transverse size $\sigma_r = 33$ mm

Laser pulse:

It Delivers **0.75 in 30fsJ**, it has wavelength 0.8 μm and it is focused on w_0=100 mm ($w0 >> \sigma_r$ should be satisfied)

Plasma:

Shaped density plasma with plasma wave velocity tuned at $\gamma_\phi = 6$ with initial density $n_0 = 5 \cdot 10^{16}$ cm^{-3} . The maximum accelerating field is E=0.75 GV/m



A compression of factor **21 in 6mm** is obtained with a pulse of only **0.75J**.

Because of the not huge electric field, the bunch has acquired **a small energy spread (4% rms)**

Bunch compression in SHAPED density plasmas [4]

Example #7.

SHAPED density background **WITH SPACE CHARGE**.

Low energy bunch

Bunch:

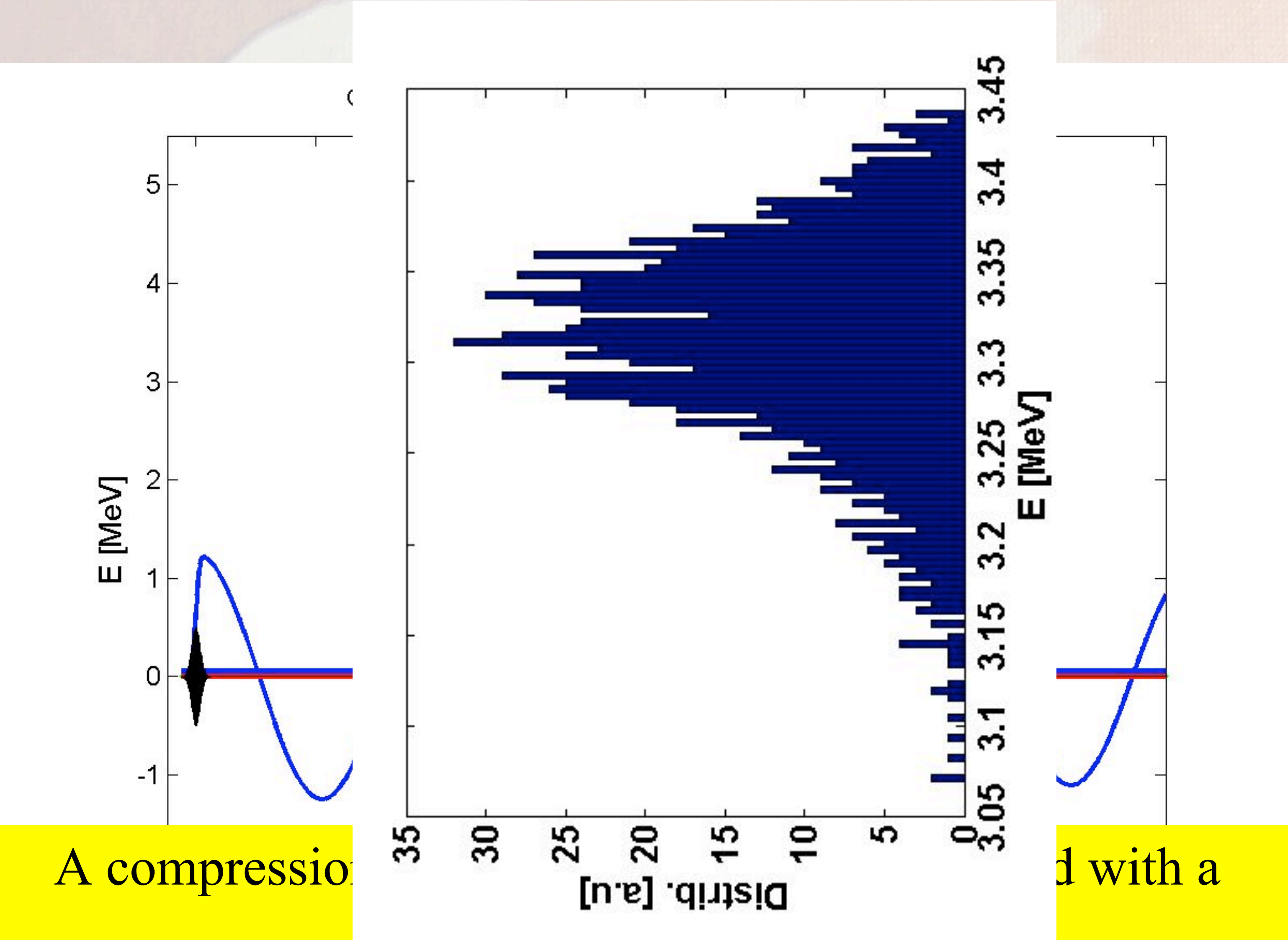
Quasi monochromatic at **2.5MeV** with energy spread 0.1% rms,transverse emittance 1mm mrad, rms length $\sigma_l = 10.5\ \mu m$ and rms transverse size $\sigma_r = 33$ mm

Laser pulse:

It Delivers **1J in 30fs**, it has wavelength 0.8 μm and it is focused on w_0=100 mm (w0>>σ_r should be satisfied)

Plasma:

Shaped density plasma with plasma wave velocity tuned at $\gamma_\phi = 8$ with initial density $n_0=1.5 \cdot 10^{16}\ cm^{-3}$. The maximum accelerating field is E=0.3 GV/m



A compressio … d with a pulse of only [illegible].

Because of the not huge electric field, the bunch has acquired **a small energy spread (3% rms)**

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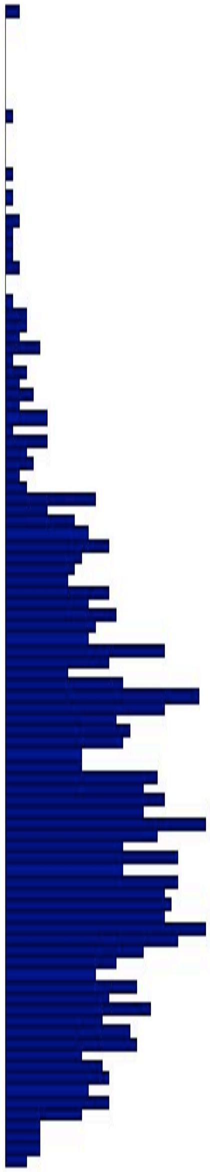

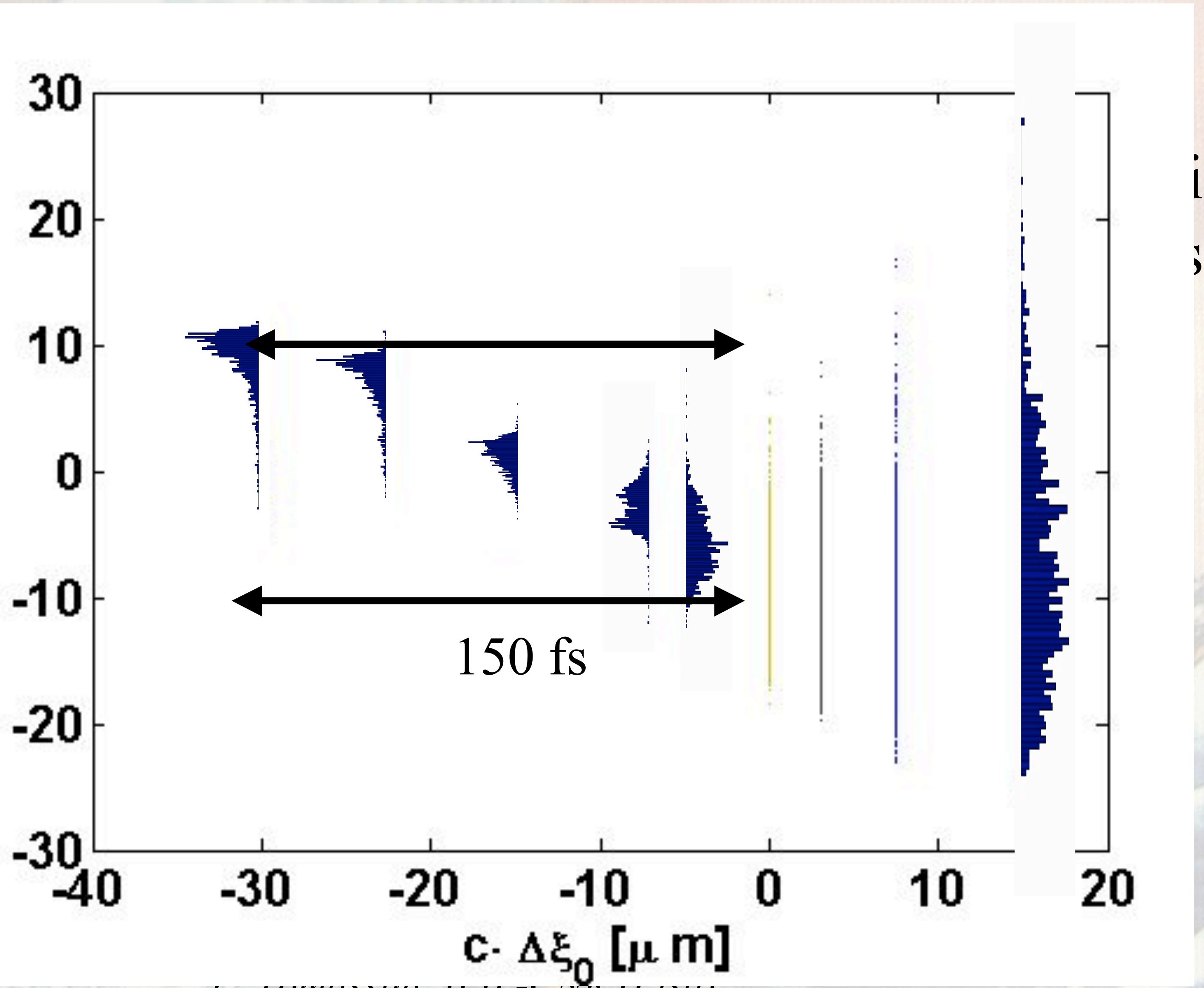

Comments

- By cutting the link between the phase speed and wavelength of the plasma wave we have strongly increased the compression efficiency of the mechanism,
- The new method allows us to compress very low energy electron bunches as well with not so big laser pulses.
- We have analyzed only 1D effects, 3D effects must be taken into account if either more focused pulses/beams or highly charged should be faced. 3D effects analysis is running…
- The production of the properly shaped plasma density is a challenging issue.