PhD activity Report

Stefano Romeo

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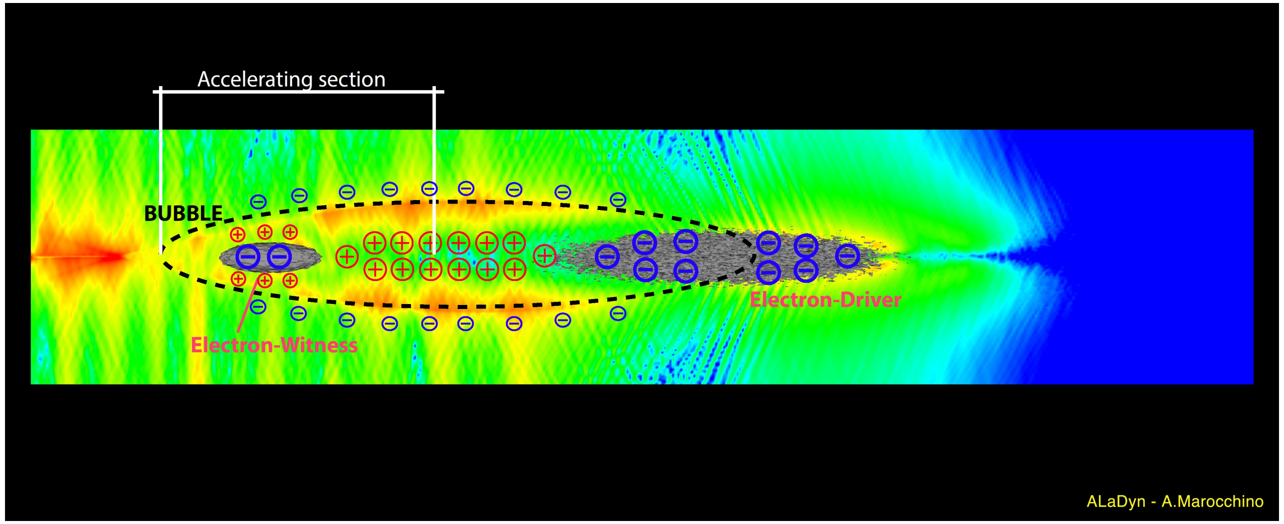
La Sapienza, University of Rome

Plasma Wakefield Acceleration Beam Driven

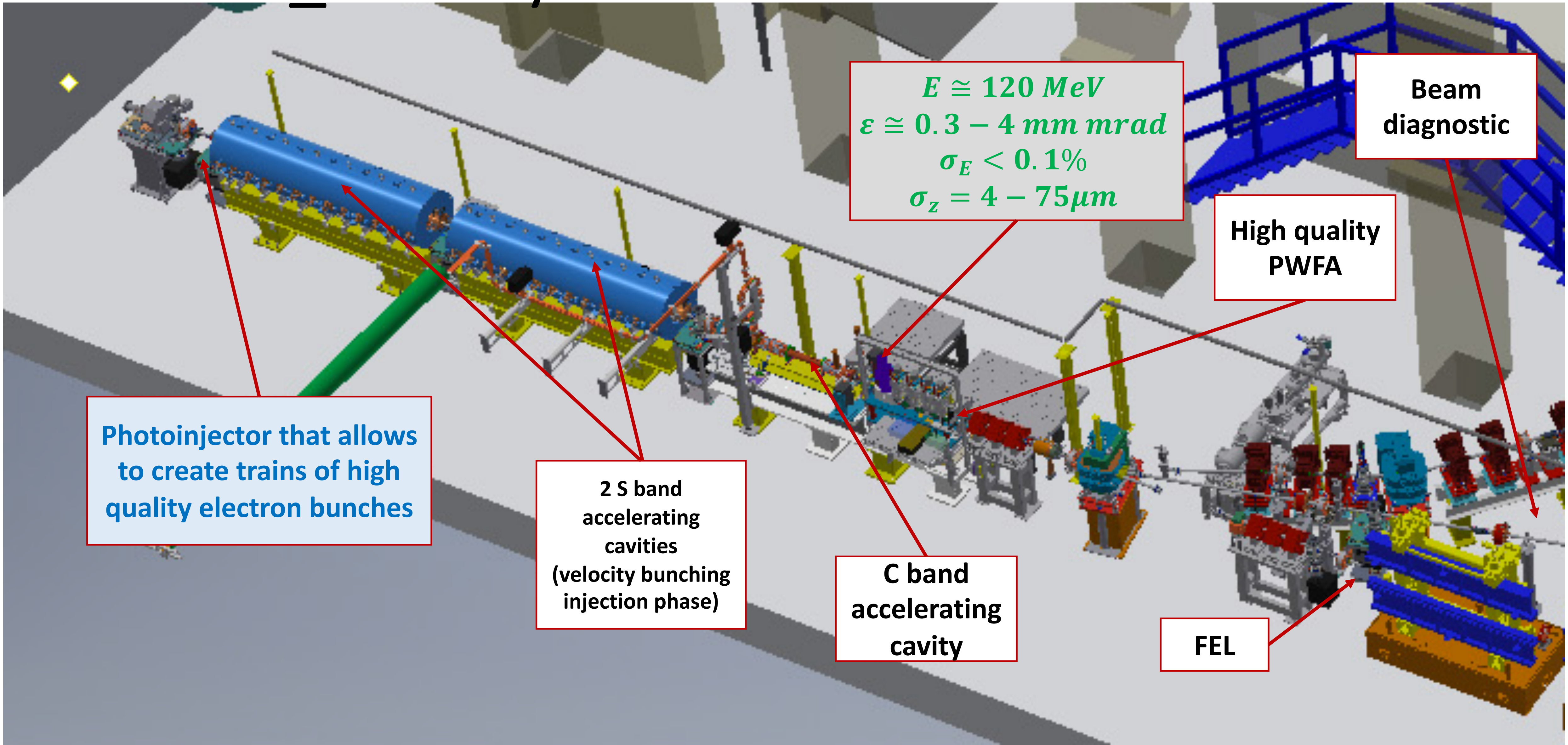


- Plasma Wakefield acceleration is a new kind of device that utilizes the wakefield produced by an electromagnetic pulse inside plasma to accelerate a beam

- In PWFA beam driven the wakefield is generated by the coulombian repulsion of a charged beam

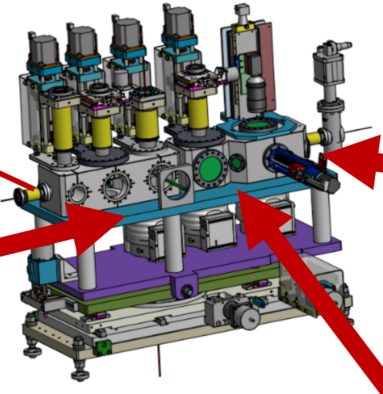
- The beam driven acceleration scheme consist in a driver (or multiple drivers) that looses energy inside plasma and a witness gaining energy

SPARC_LAB Layout



Acceleration experiment @SPARC_LAB

$E \cong 150\ MeV$
$\varepsilon \cong 1 - 2\ mm\ mrad$
$\sigma_E < 1\%$



$\sigma_x < 3\mu m$

Permanent magnets final focus system

Effective accelerating gradient $\cong 1\ GV/m$

Low energy beams

Pre ionized plasma (gas inside a capillary ionized by discharge)

Resonant Wakefield Acceleration Scheme

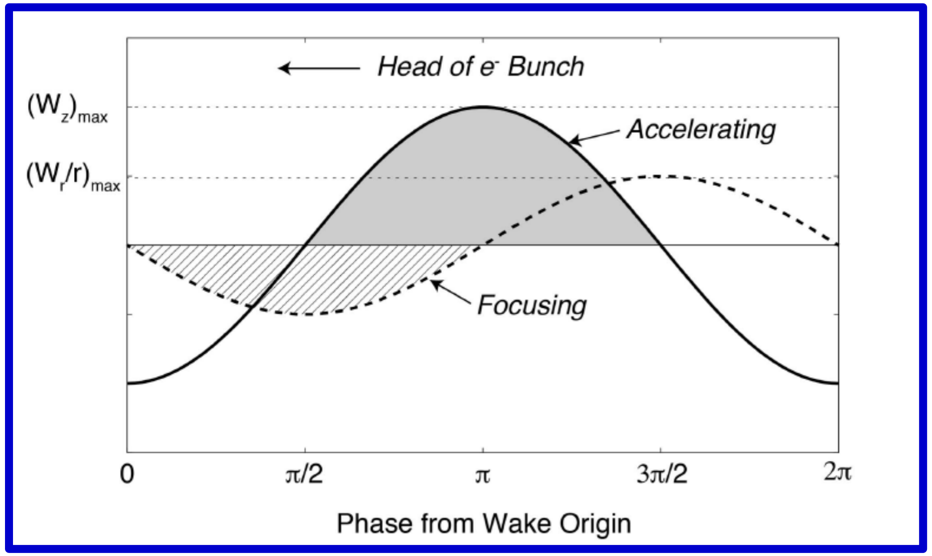
Beam driven acceleration

High quality beams

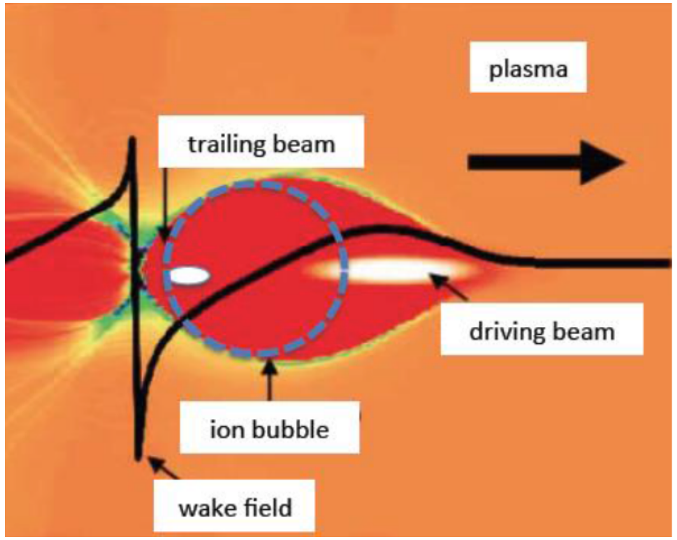
Quasi non linear regime

Linear/Bubble regime

$n_b \ll n_0$



$n_b > n_0$



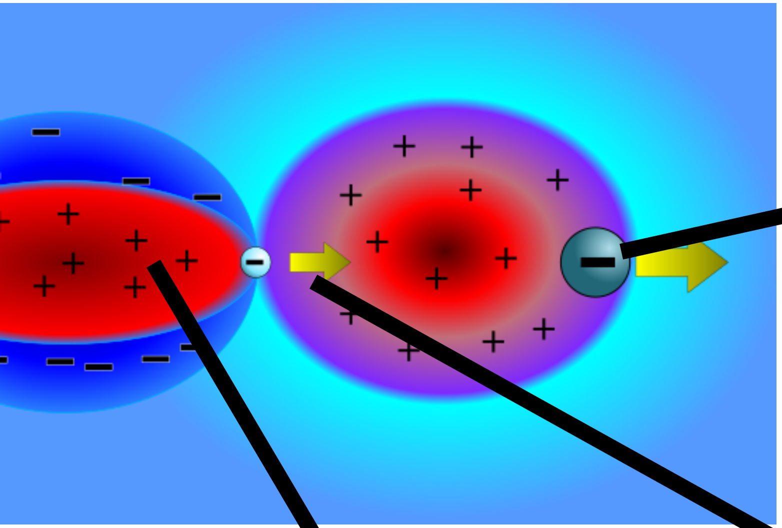
Linear field

- It is possible to inject a beam in the crest region
- Non linear dependency of the focusing
- Accelerating field depends on transverse position
- Lower field

Blow out field

- No crest region -> Spike on field
- Linear dependency of the focusing
- Accelerating field doesn't depend on transverse position
- Higher field

New concept: Linear/non Linear



The driver generates a linear field

The witness can be injected in the zone of maximum field

Minimum energy spread
Maximum gradient

The focusing is guaranteed by a beam loading effect

Increased witness stability

The field generated by the witness is non linear

Simple matching

Hollow driver scheme

- **Short witness** → Witness compression by velocity bunching

Velocity bunching → Witness emittance growth

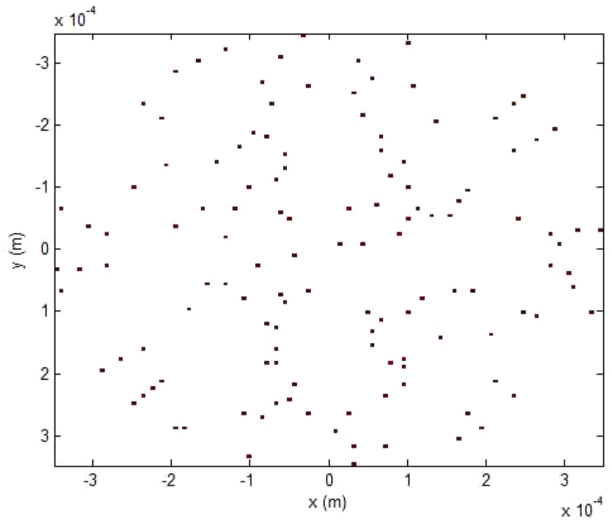
Lower compression

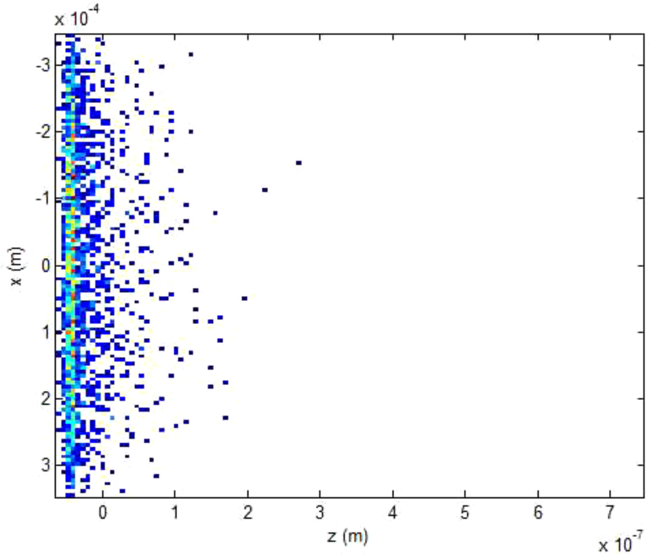
Hollow Driver

↓

Very short and low emittance witness

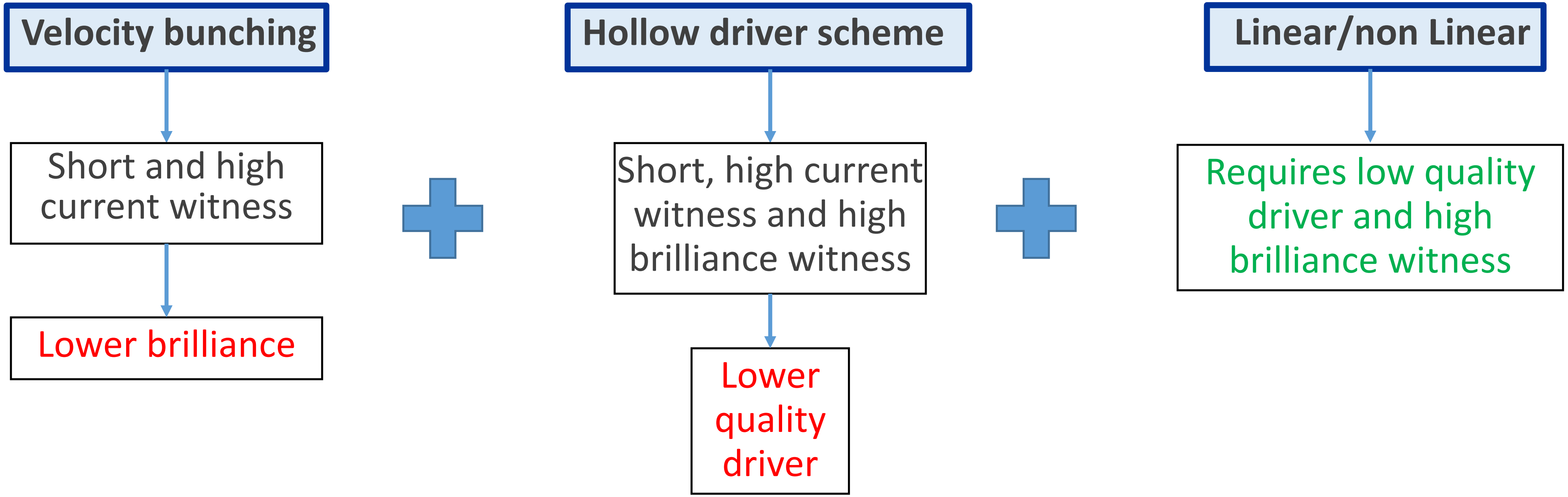
High emittance driver





Courtesy of R. Pompili

Proposal:
Hollow driver scheme+Linear/non Linear



High quality witness requirements: Driver

A driver that follows the matching conditions guarantee a field that varies slowly (with a frequency very lower than the betatron frequency of witness)

- **Driver transverse matching**
  - Ion column (non linear) $\sigma_x = \sqrt[4]{\frac{2}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}$ → $\beta_x = \frac{\sqrt{2\gamma}}{k_p}$
  - 1D-linear theory (linear) $\sigma_x = \sqrt[4]{\frac{2}{\alpha\gamma\mathcal{Z}(0)}}\sqrt{\frac{\varepsilon_n}{k_p}}$ → $\beta_x = \frac{1}{k_p}\sqrt{\frac{2\gamma}{\alpha\mathcal{Z}(0)}}$

$$\mathcal{Z}(\xi) = \sqrt{\frac{\pi}{2}}k_p\sigma_z e^{k_p^2\sigma_z^2/2} Im\left[e^{ik_p\xi} erfc\left(\frac{\xi}{\sqrt{2}\sigma_z} + i\frac{k_p\sigma_z}{\sqrt{2}}\right)\right]$$

High quality witness requirements: Driver

Matched beams

- **Non linear driver treshold** $\ell = \frac{Q}{e}\frac{k_p}{(2\pi)^{3/2}\sigma_z\varepsilon_n n_0}\sqrt{\frac{\gamma}{2}}$

$\ell \gg 1$ non linear field

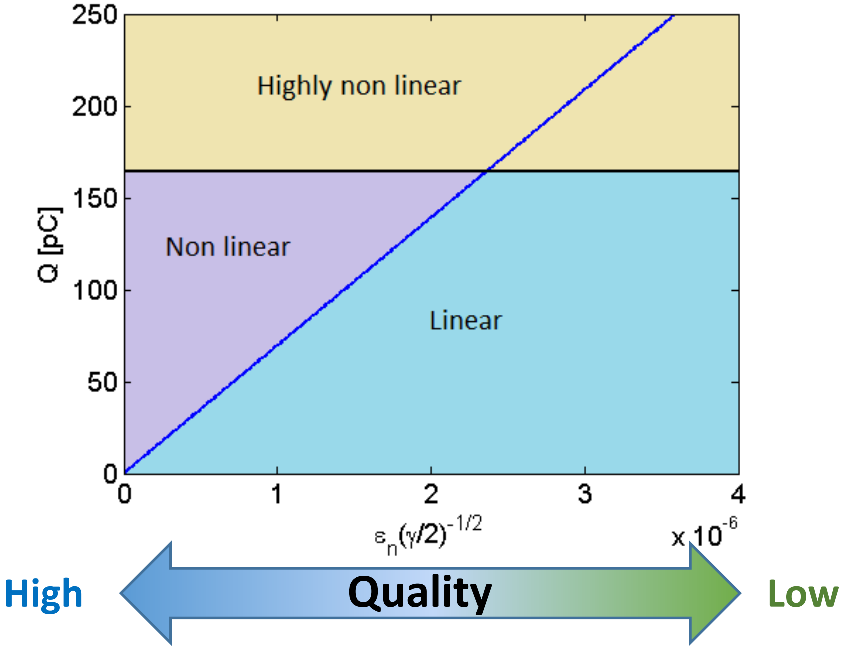
$\ell \ll 1$ linear field

Within the acceleration $\frac{\sqrt{\gamma}}{\varepsilon_n}$ decreases for:

- **Deceleration**
- **Beam depletion**
- **Head erosion**

QNL treshold $\frac{Q}{e}\frac{k_p^3}{n_0} < 1$

Within acceleration the bubble can be destroyed by driver erosion

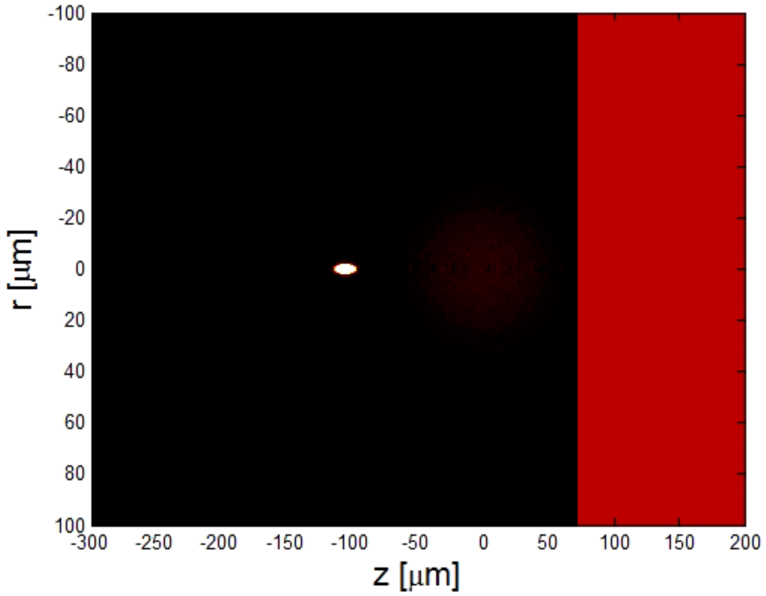


High quality witness requirements: Driver outside of matching

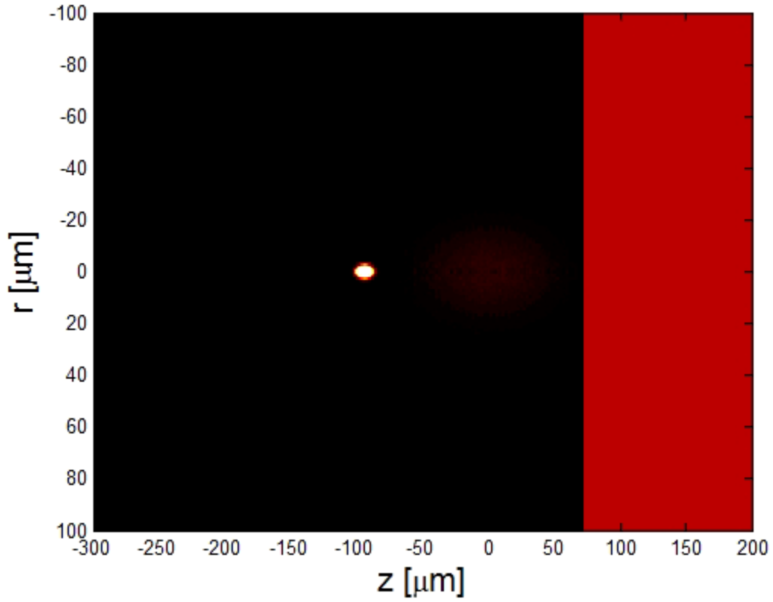
- **It is difficult to inject both the driver and the witness at the matching conditions**

Driver is usually injected with a spot size that is higher than the matching condition

$\ell \gg 1$



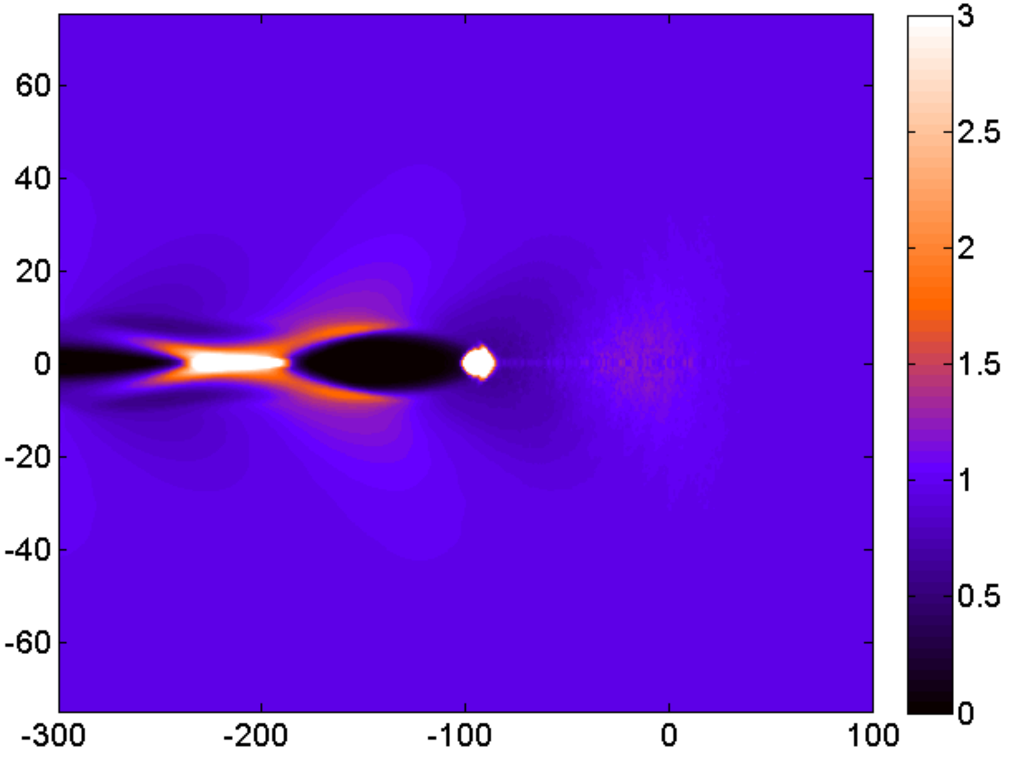
$\ell \ll 1$



High quality witness requirements: Driver outside of matching

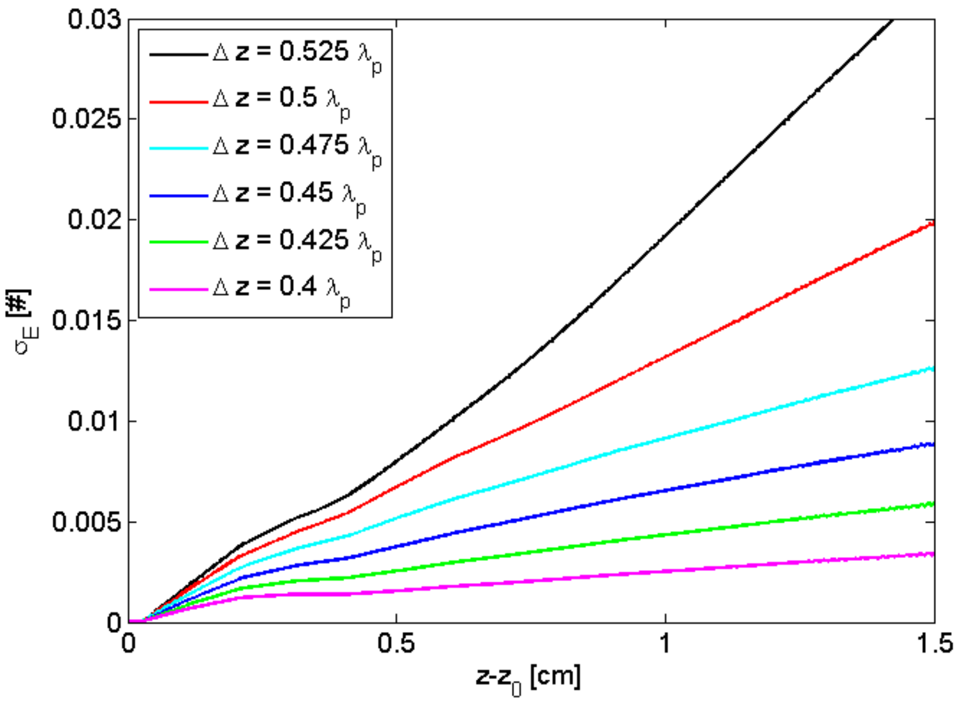
- **Linear field crest zone:**
- Guarantees the maximum accelerating field
- Has a local electron plasma density that is independent from bunch density
- Has a negligible focusing field
- Enhanced witness beam loading creates a focusing field such that matching condition is

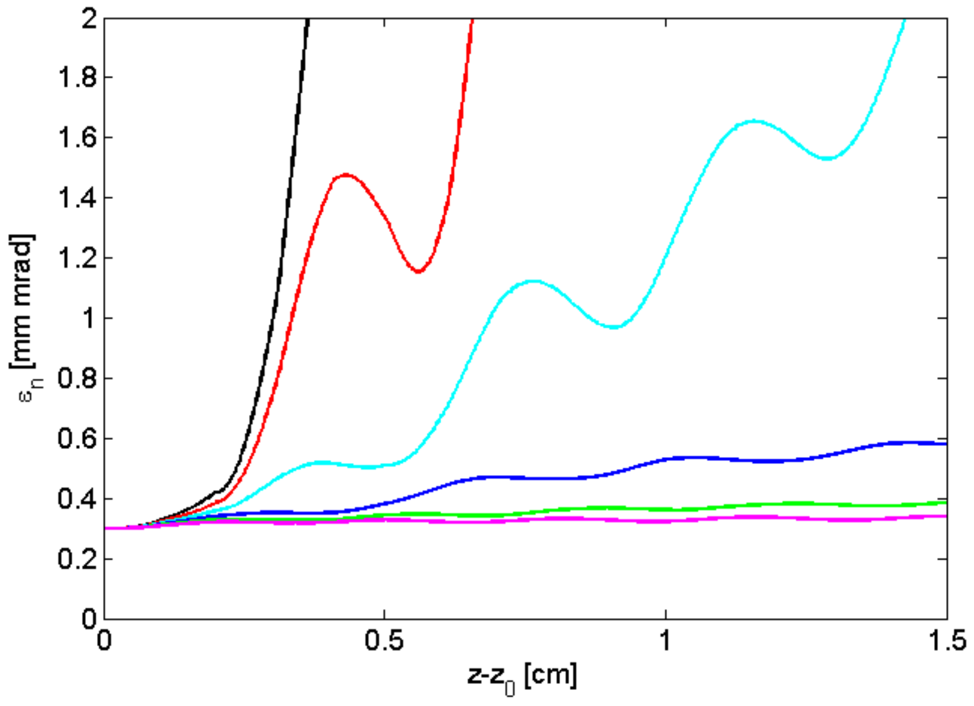
$$\sigma_x = \sqrt[4]{\frac{1}{\gamma}}\sqrt{\frac{2\varepsilon_n}{k_p}} \longrightarrow \beta_x = \frac{2\sqrt{\gamma}}{k_p}$$



High quality witness requirements: Witness matching

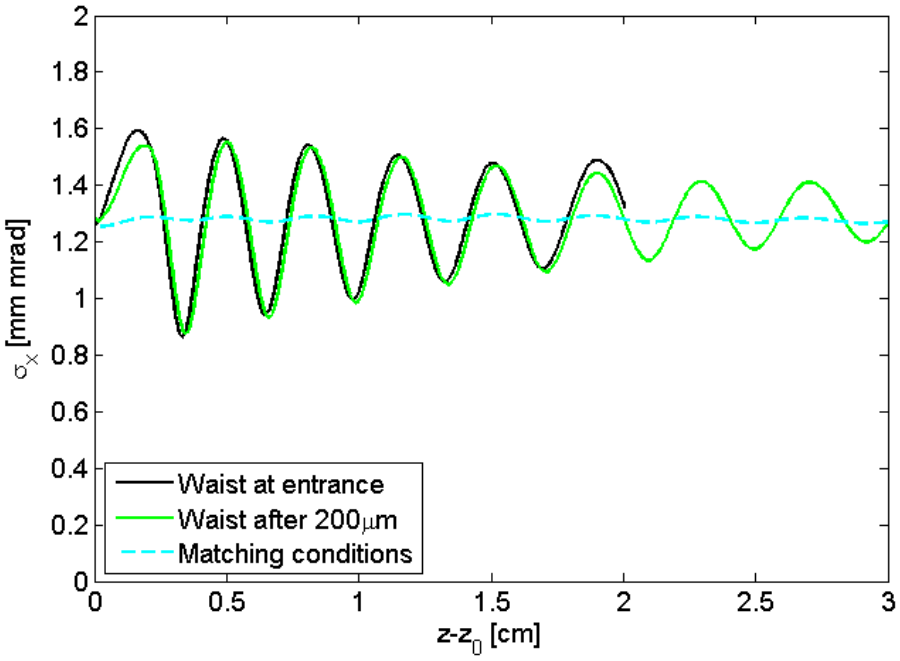
- **2 required scans:**
- Injection phase optimizes energy spread and emittance (rough

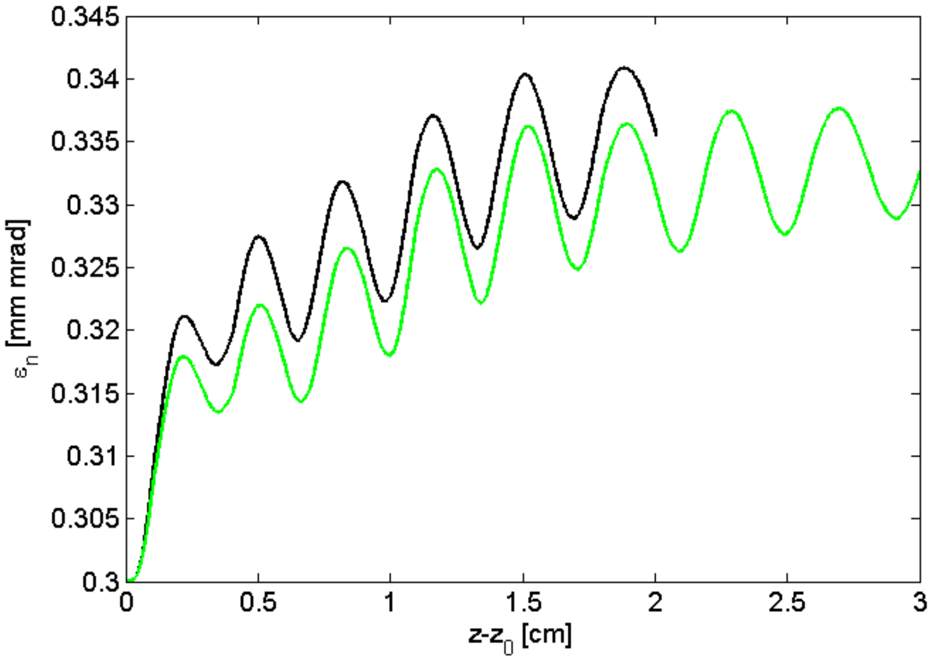




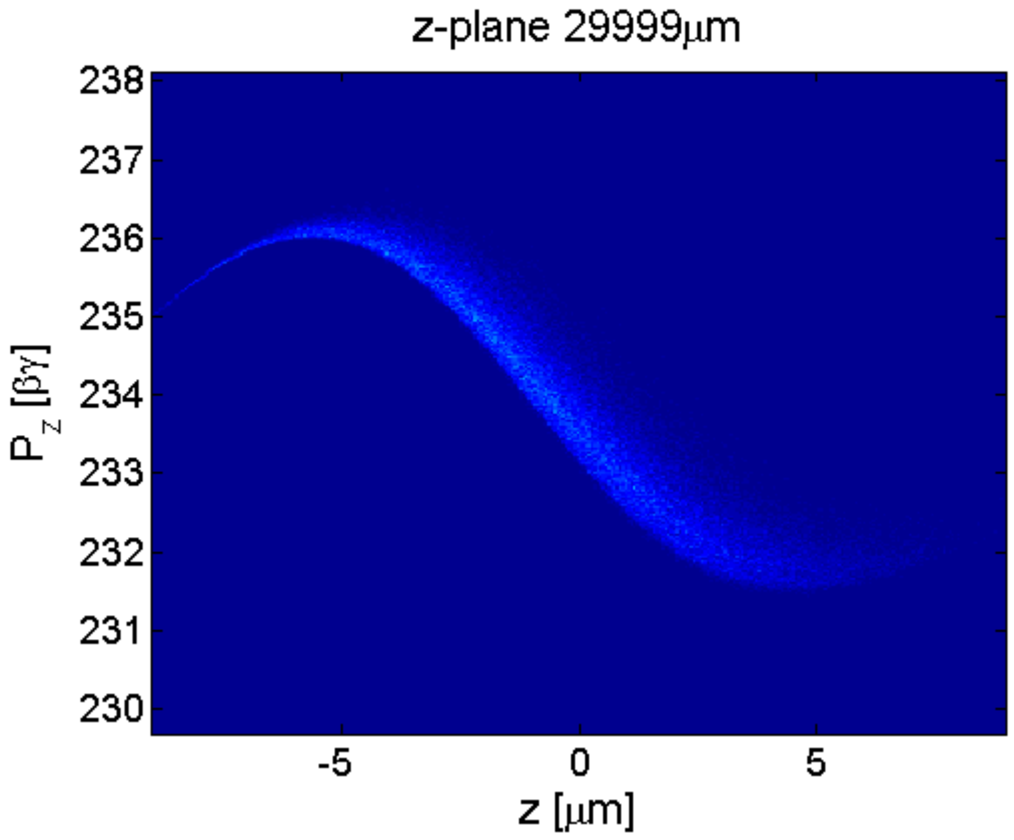
High quality witness requirements: Witness matching

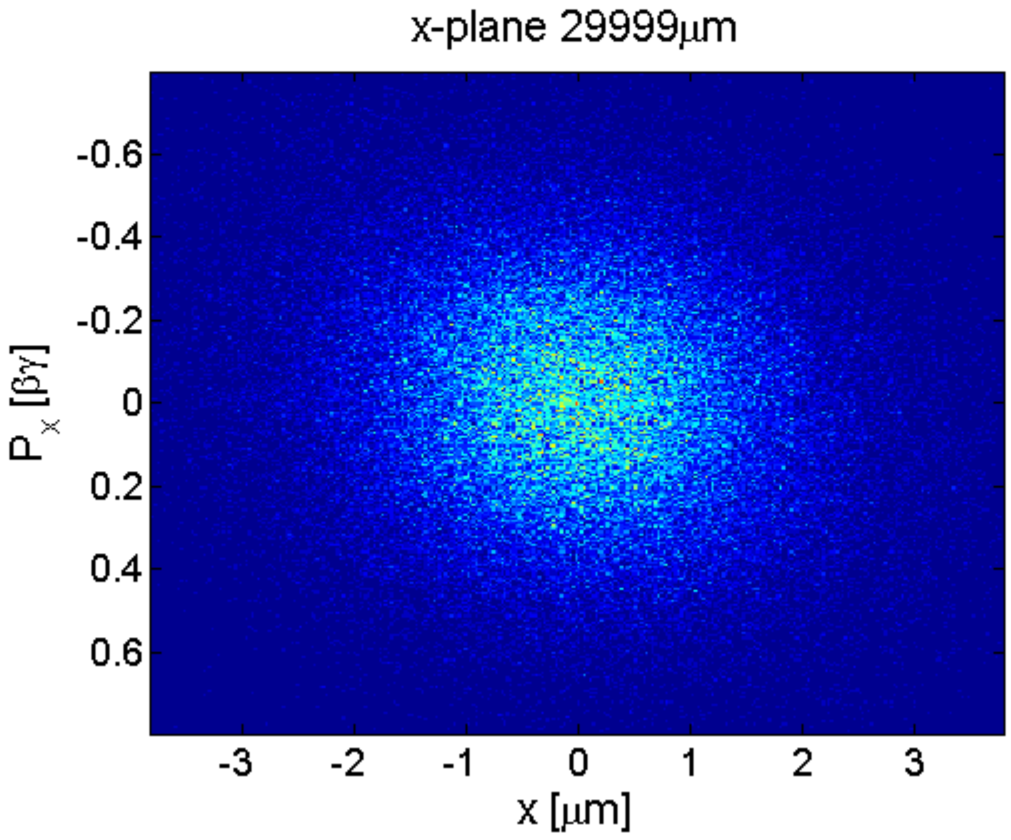
- Witness waist position optimizes emittance (fine tune)





Witness phase space after acceleration





- **Accelerating gradient: 600 MV/m**

1 GV/m working point

Driver

$Q = 200pC$

$$\sigma = \begin{pmatrix} 13 & 0 & 0 \\ 0 & 13 & 0 \\ 0 & 0 & 38 \end{pmatrix} \mu m$$

$$\varepsilon = \begin{pmatrix} 20 & 0 \\ 0 & 20 \end{pmatrix} \text{mm mrad}$$

$\gamma = 200$

$\sigma_E = 0.1\%$

Witness

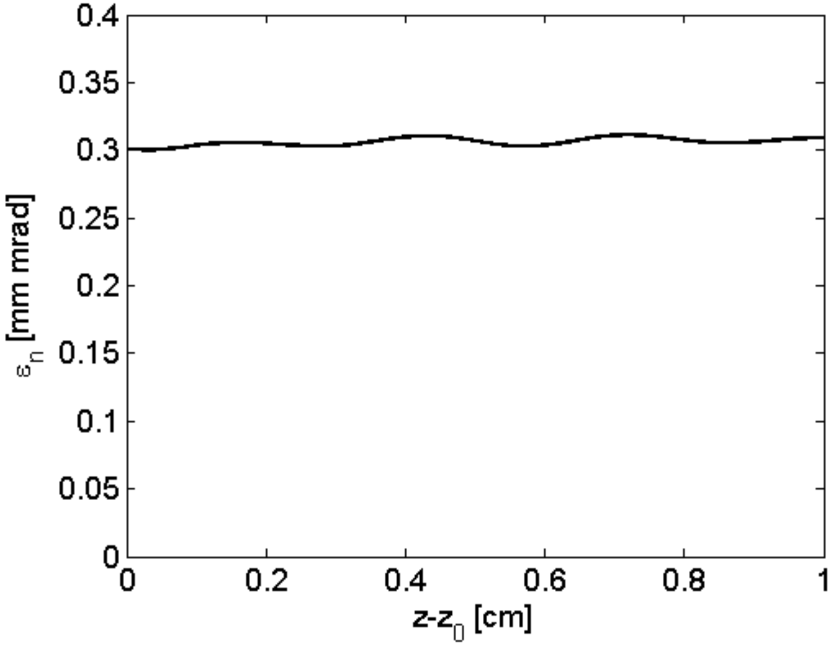
$Q = 15pC$

$$\sigma = \begin{pmatrix} 1.25 & 0 & 0 \\ 0 & 1.25 & 0 \\ 0 & 0 & 5.3 \end{pmatrix} \mu m$$

$$\varepsilon = \begin{pmatrix} 0.3 & 0 \\ 0 & 0.3 \end{pmatrix} \text{mm mrad}$$

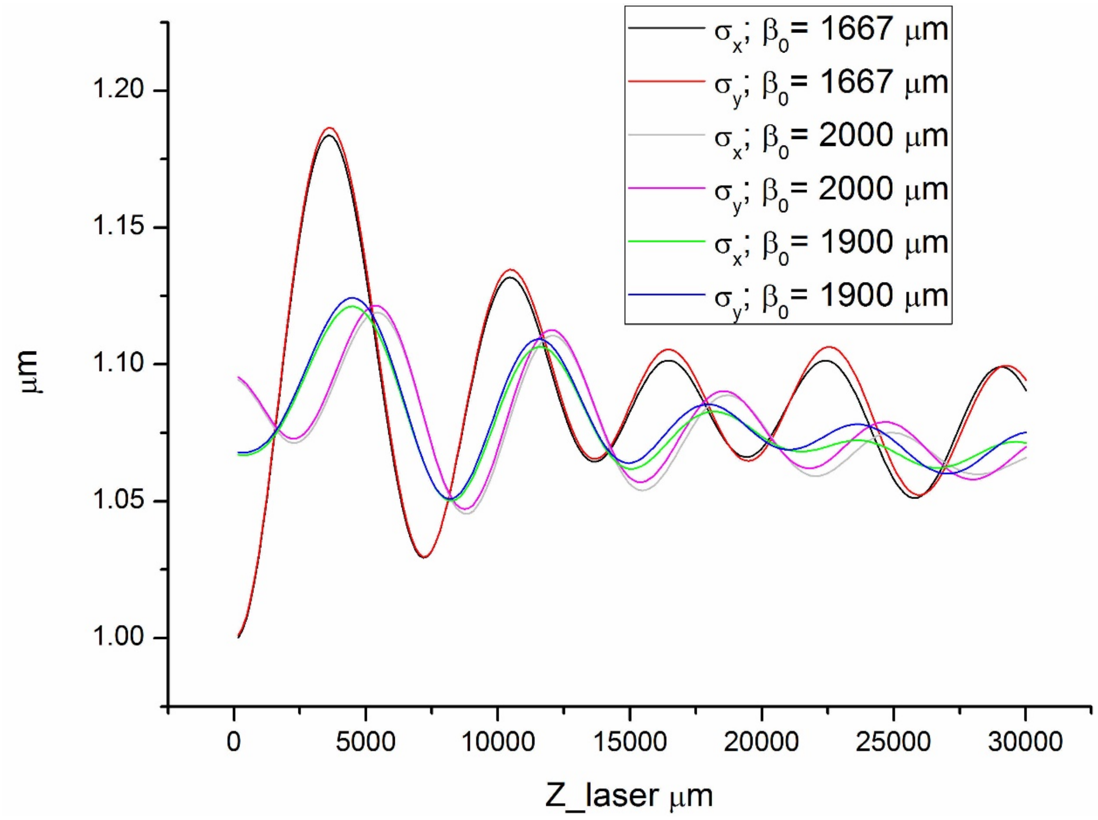
$\gamma = 200$

$\sigma_E = 0\%$

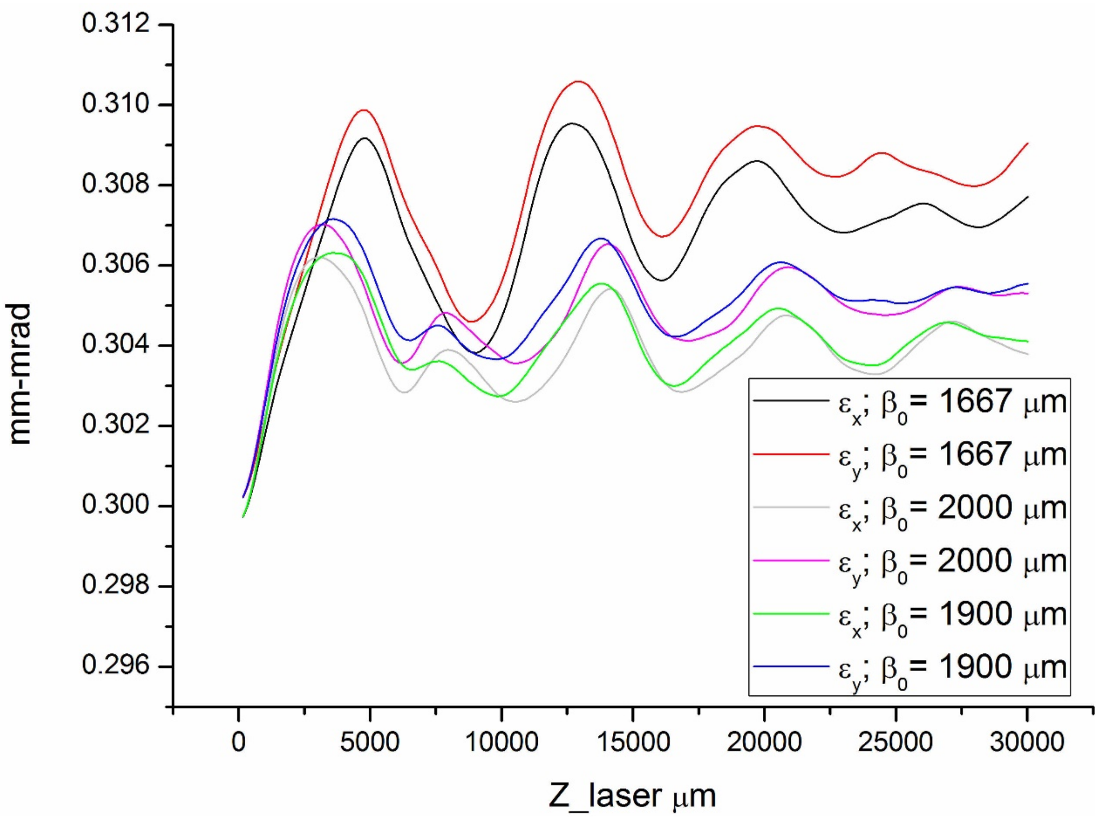


- **Accelerating gradient: 1 GV/m**

LWFA ExIn

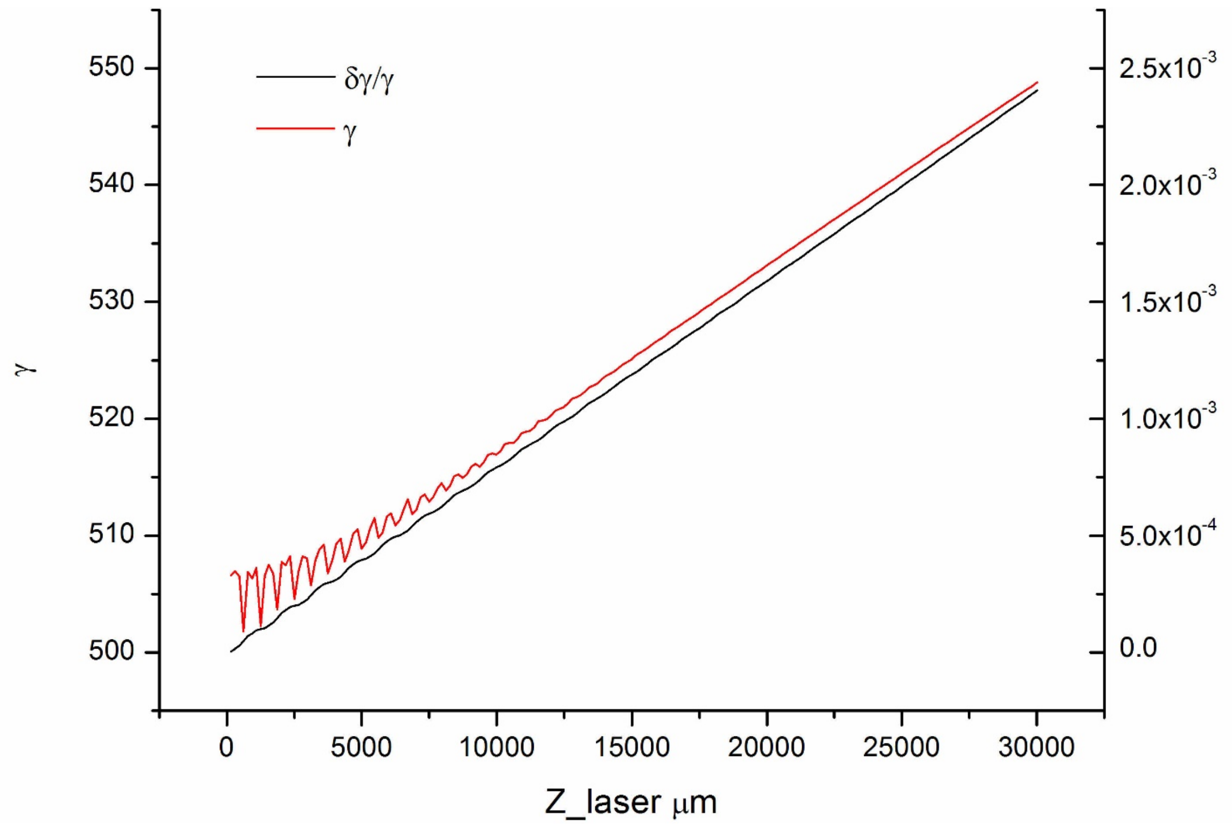


σx; β0= 1667 μm
σy; β0= 1667 μm
σx; β0= 2000 μm
σy; β0= 2000 μm
σx; β0= 1900 μm
σy; β0= 1900 μm
μm
1.00
1.05
1.10
1.15
1.20
0
5000
10000
15000
20000
25000
30000
Z_laser μm

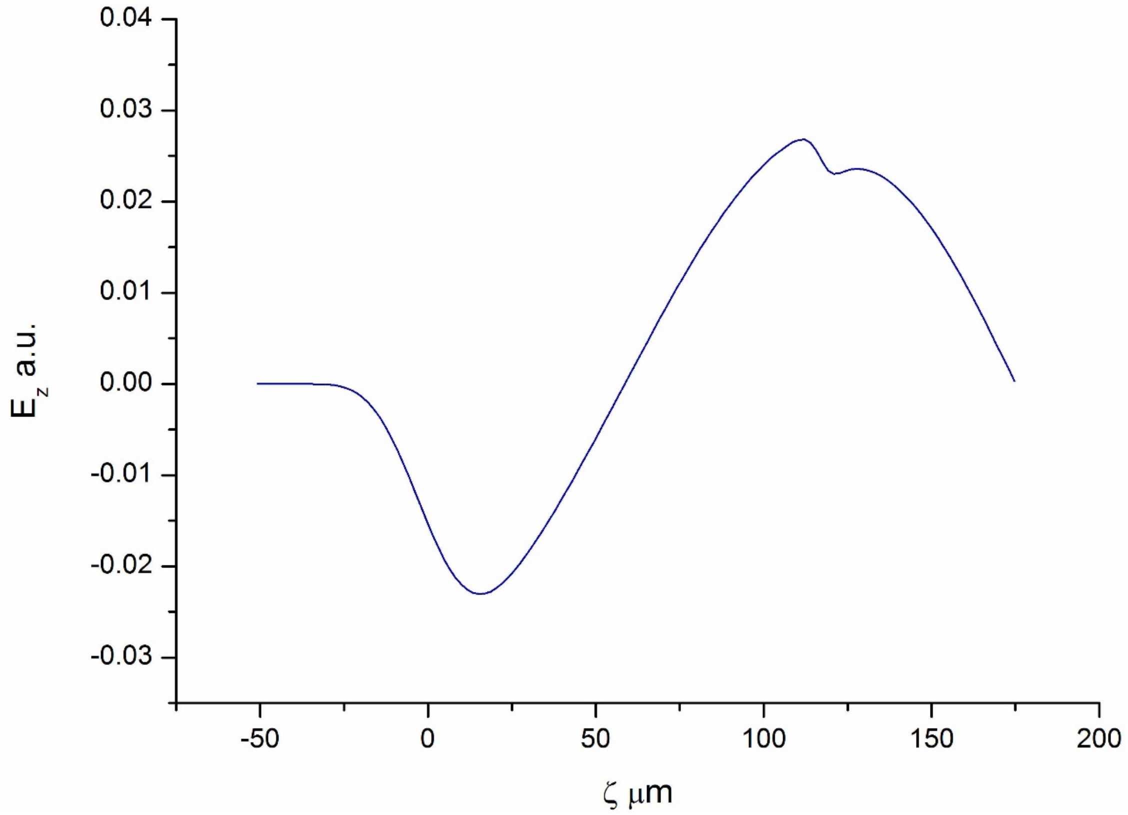


εx; β0= 1667 μm
εy; β0= 1667 μm
εx; β0= 2000 μm
εy; β0= 2000 μm
εx; β0= 1900 μm
εy; β0= 1900 μm
mm-mrad
0.296
0.298
0.300
0.302
0.304
0.306
0.308
0.310
0.312
0
5000
10000
15000
20000
25000
30000
Z_laser μm

LWFA ExIn



δγ/γ
γ
550
540
530
520
510
500
γ
2.5x10^-3
2.0x10^-3
1.5x10^-3
1.0x10^-3
5.0x10^-4
0.0
δγ/γ
0
5000
10000
15000
20000
25000
30000
Z_laser μm



0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
E_z a.u.
-50
0
50
100
150
200
ζ μm

Conclusions

- During my PhD work I focused on beam dynamics inside plasma in order to obtain high quality witness at the exit
- The study of beam dynamics required to develope scaling laws for PWFA
- Using the scaling laws I was able to find a way to create a new kind of PWFA scheme