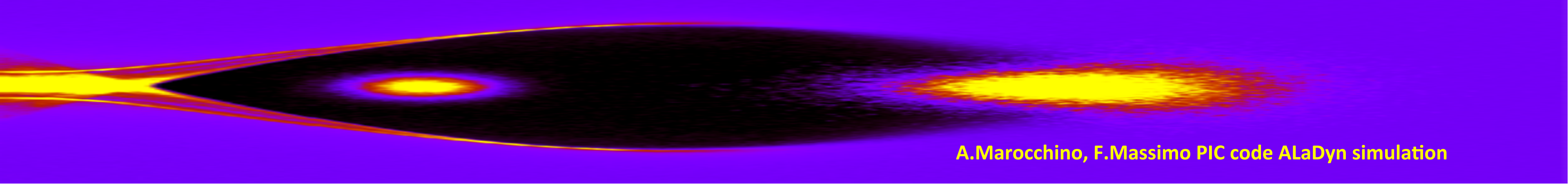


Accelerator Physics Doctoral Course
thesis project advancement report

High quality Wakefield Ionization Injection and acceleration of electron beam in PWFA weakly-nonlinear regime.

Francesco Mira

Supervisors:

Stefano Atzeni Alberto Marocchino

INFN Istituto Nazionale di Fisica Nucleare

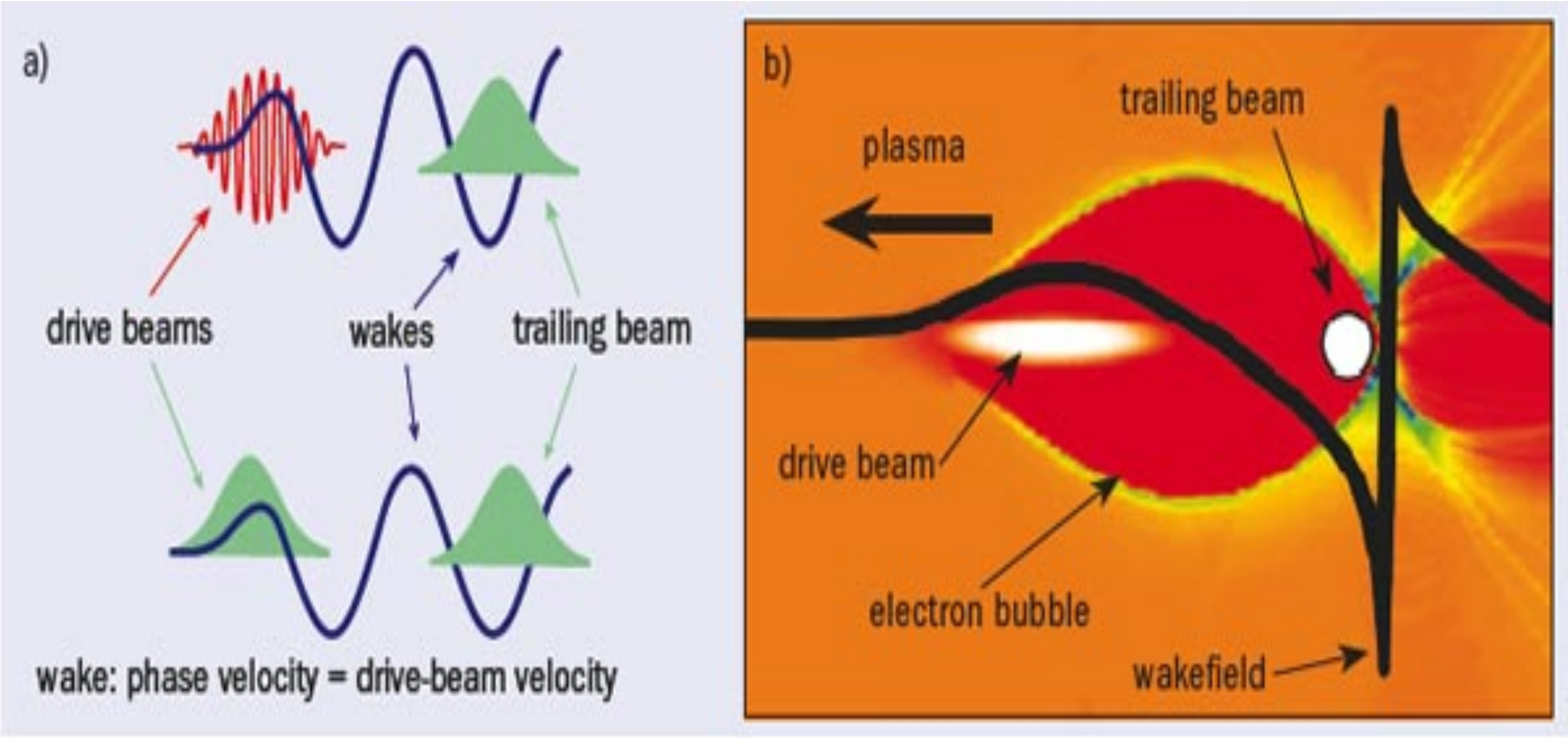
SPARC_LAB

Outline

- What is Plasma Acceleration;
- Third year tasks;
- Numerical tools: the Particle In Cell method;
- Non-linear regime and its features;
- Limits of analytical model;
- Beam loading in non-linear regime;
- Wakefield Ionization Injection;
- Third year working plan.

Plasma Acceleration

A ‘driver’ pushes the plasma electron away from their equilibrium position.
In the wake behind the driver an intense electric field develops.
A ‘witness’ is accelerated and focused if properly injecteded in the wake.



Plasma Acceleration

Driver nature:

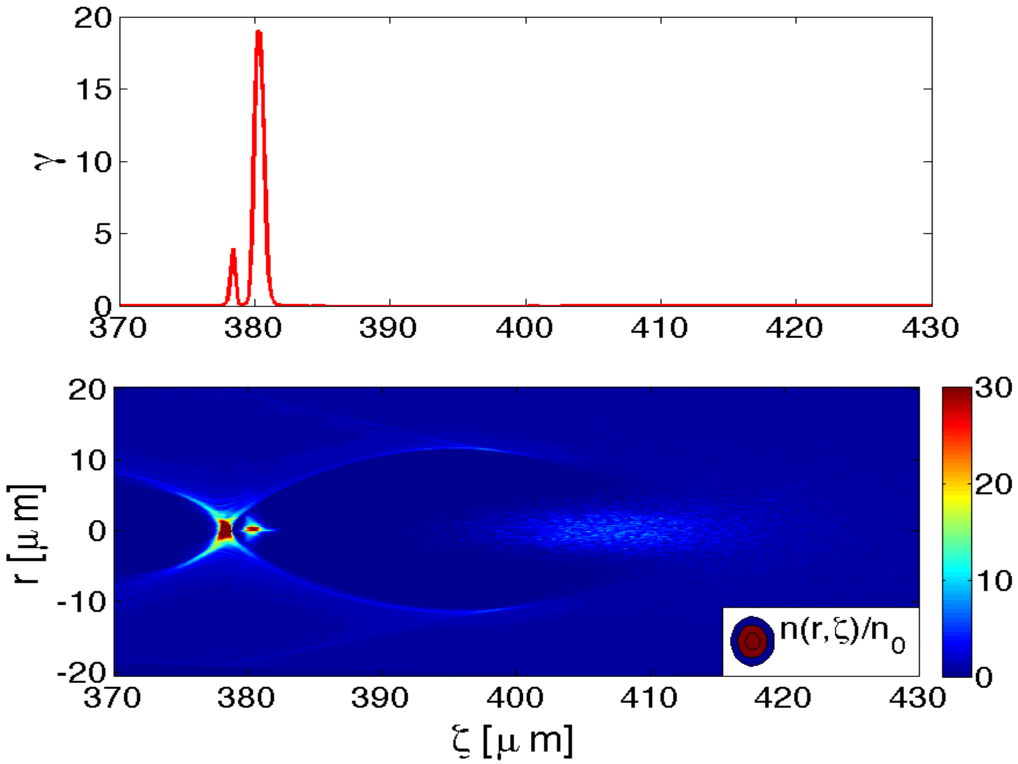
- High Power Laser -> Laser Wake-Field Acceleration (LWFA);
- Relativistic Electron Bunch -> Plasma Wake-Field Acceleration (PWFA);
  - $n_b << n_0$ -> Linear regime;
  - $n_b > n_0$ -> Non-Linear regime (NL);
  - $n_b > n_0$ and $\tilde{Q} < 1$ -> Weakly Non-Linear regime (WNL).

Injection scheme :

- External injection;
- Self injection:
  - Wakefield Ionization Injection (WII)
  - Laser driven self-injection;
  - Downramp beam driven self-injection;
  - Trojan Horse self-injection;

Working project

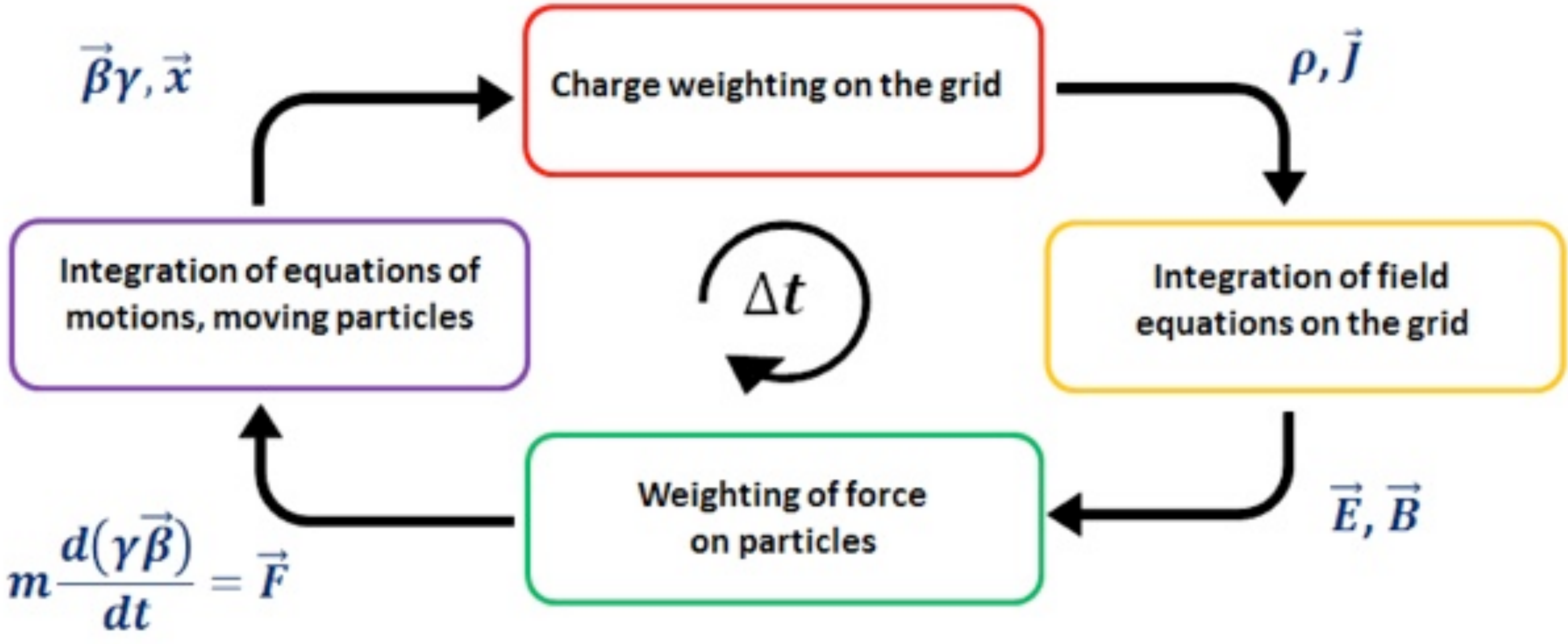
- Analytical and numerical studies of the WII scheme in the NL regime;
- Analytical and numerical studies of the WII in the WNL regime;
- Analysis of the feasibility of triggering the WII with a multi-driver scheme in the WNL regime .



Produced beams are intrinsecally synchronised, low-emittance and strongly accelerated!

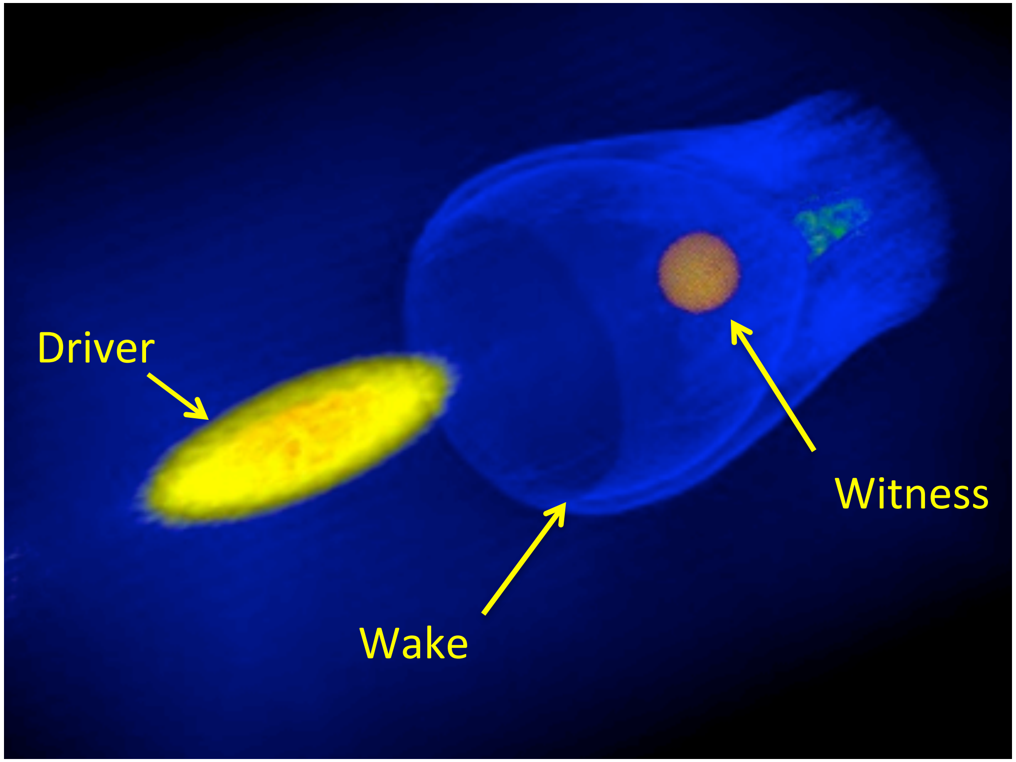
How to do it

- Analytical simplified models;
- Computer simulations: Particle In Cell method.



PIC code ALaDyn

- Fully Relativistic three dimensional;
- 3D (2D-1D) High Order in Space and time;
- Charge preserving high order scheme;
- Ionization module;
- 3D output -> Visit;
- Used on both Tier-0 class and small clusters.



Pic Codes are very time consuming

~ Weeks on a 100-cores cluster

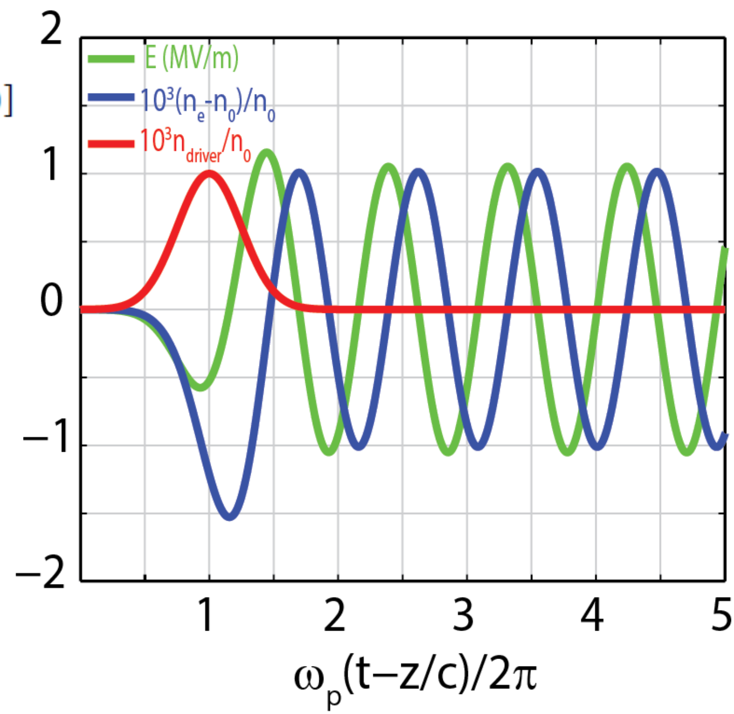
Linear regime

Small density perturbation → first order expansion of Maxwell equations and plasma continuity and momentum equations in cylindrical symmetry and quasi-static approximation (QSA).

$$E_z(r,\xi) = \frac{k_p{}^2}{\varepsilon_0}\int_0^r dr' r' I_0(k_p r'_<) K_0(k_p r'_>) \int_\xi^{+\infty} d\xi' \rho_b(r',\xi') \cos[k_p(\xi-\xi')]$$

$$E_r(r,\xi) = -\frac{k_p}{\varepsilon_0}\int_0^r dr' r' I_1(k_p r'_<) K_1(k_p r'_>) \int_\xi^{+\infty} d\xi' \frac{\partial}{\partial r'} \rho_b(r',\xi') \sin[k_p(\xi-\xi')]$$

$$B_\varphi(r,\xi) = -\frac{\beta}{\varepsilon_0 c}\int_0^r dr' r' I_1(k_p r'_<) K_1(k_p r'_>) \frac{\partial}{\partial r'} \rho_b(r',\xi)$$

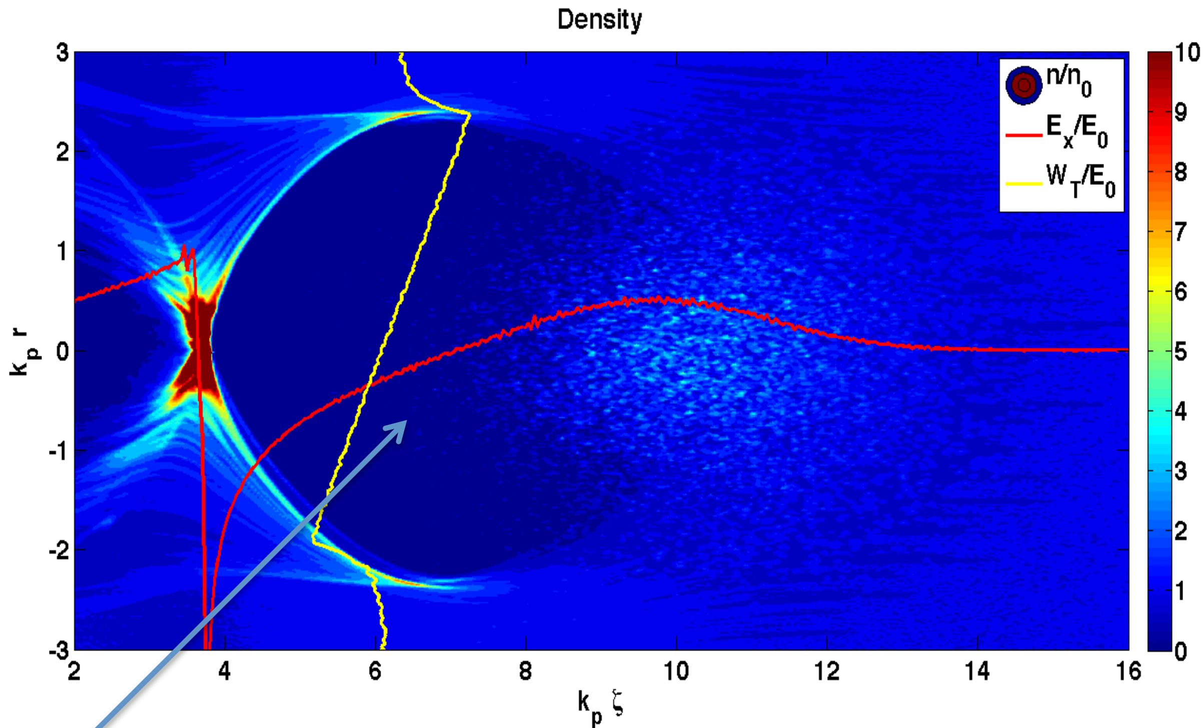


- Existence of general analytical solutions;
- Low current driver;
- Accelerating fields lower than 1GV/m;
- Intrinsecally difficult high quality transport;

Non-Linear regime

- High density perturbation;
- Fields higher than 100 GV/m;
- Correlated longitudinal energy spread;
- Emittance conservation;

… no general analytic solution!



All the electrons are expelled from the wake: ‘bubble’ or ‘blowout’ regime.

Analytical models

Different assumptions required for simplified models:

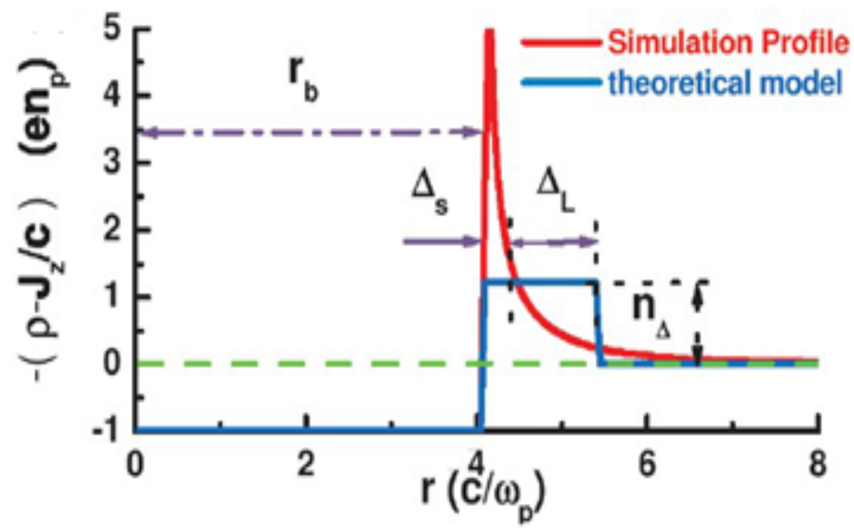
- The bubble is spherical and positive;
- The electrons accumulate in a narrow layer at the border of the bubble with constant density;
- Cylindrical symmetry and QSA.

The **trajectory of the innermost electron**, the longitudinal field and the transverse force are derived

$$A(r_b)\frac{d^2 r_b}{d\xi^2} + B(r_b) r_b \left(\frac{dr_b}{d\xi}\right)^2 + C(r_b) r_b = \frac{\lambda(\xi)}{r_b},$$

$$E_z(r,\xi) = \frac{d}{d\xi}\left[\frac{1}{4} {r_b}^2 \big(1+\beta(\xi)\big)\right],$$

$$F_r(r,\xi) = -e\left(E_r + v_e B_\varphi\right) = -e^2 n_p \frac{r}{2\varepsilon_0},$$



Analytical models

Different assumptions required for simplified models:

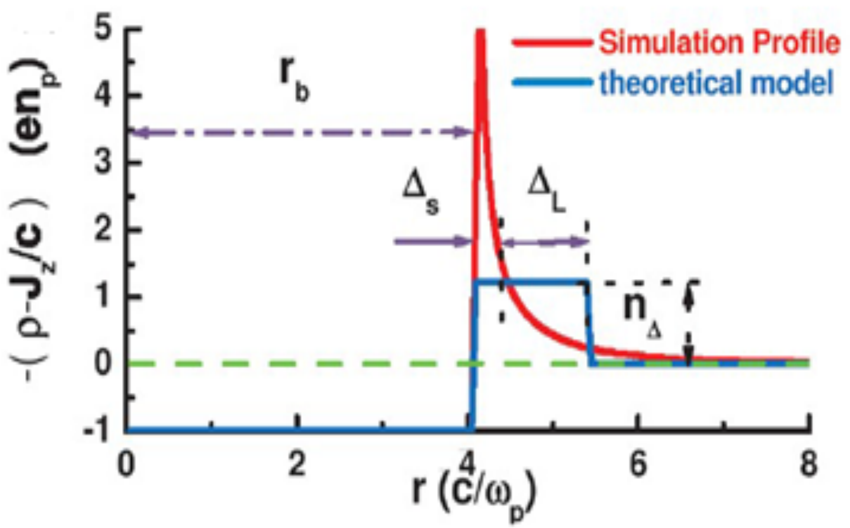
- The bubble is spherical and positive;
- The electrons accumulate in a narrow layer at the border of the bubble with constant density;
- Cylindrical symmetry and QSA.

The trajectory of the innermost electron, the **longitudinal field** and the transverse force are derived

$$A(r_b)\frac{d^2 r_b}{d\xi^2} + B(r_b) r_b \left(\frac{d r_b}{d\xi}\right)^2 + C(r_b) r_b = \frac{\lambda(\xi)}{r_b},$$

$$E_z(r,\xi) = \frac{d}{d\xi}\left[\frac{1}{4} {r_b}^2 \left(1+\beta(\xi)\right)\right],$$

$$F_r(r,\xi) = -e\left(E_r + v_e B_\varphi\right) = -e^2 n_p \frac{r}{2\varepsilon_0},$$



Analytical models

Different assumptions required for simplified models:

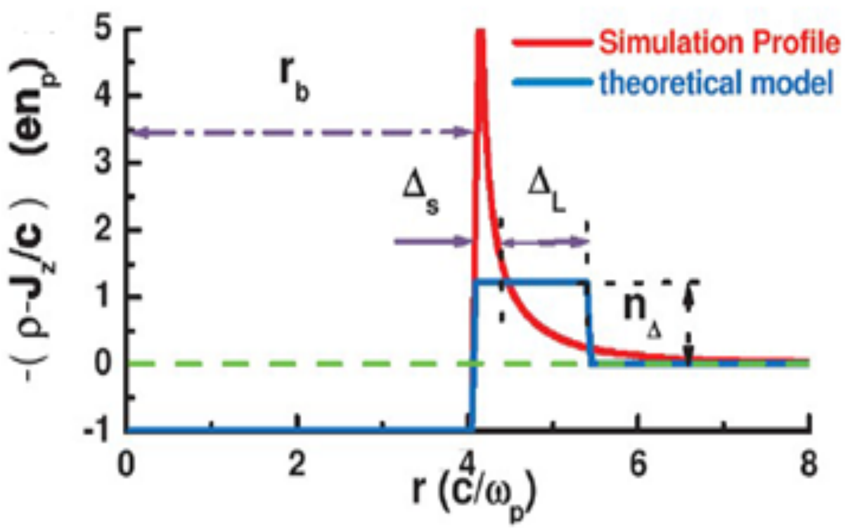
- The bubble is spherical and positive;
- The electrons accumulate in a narrow layer at the border of the bubble with constant density;
- Cylindrical symmetry and QSA.

The trajectory of the innermost electron, the longitudinal field and the **transverse force** are derived

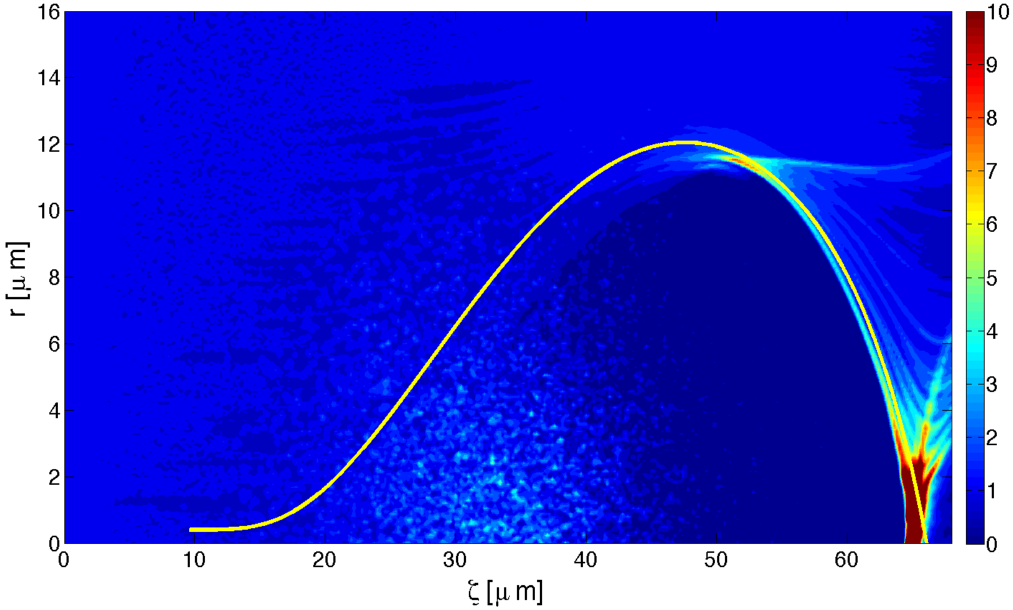
$$A(r_b)\frac{d^2r_b}{d\xi^2} + B(r_b)r_b\left(\frac{dr_b}{d\xi}\right)^2 + C(r_b)r_b = \frac{\lambda(\xi)}{r_b},$$

$$E_z(r,\xi) = \frac{d}{d\xi}\left[\frac{1}{4}r_b{}^2\big(1+\beta(\xi)\big)\right],$$

$$F_r(r,\xi) = -e\left(E_r + v_e B_\varphi\right) = -e^2 n_p \frac{r}{2\varepsilon_0},$$

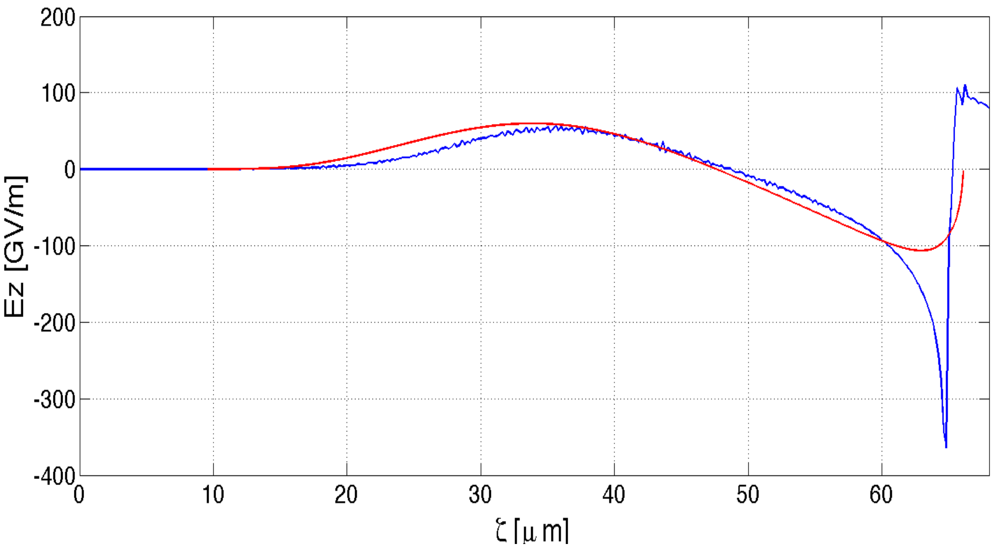


Analytic model and PIC comparison



- Good agreement with the profile of the bubble

- The longitudinal field profile is well reproduced everywhere but at the head and the tail of the bubble!

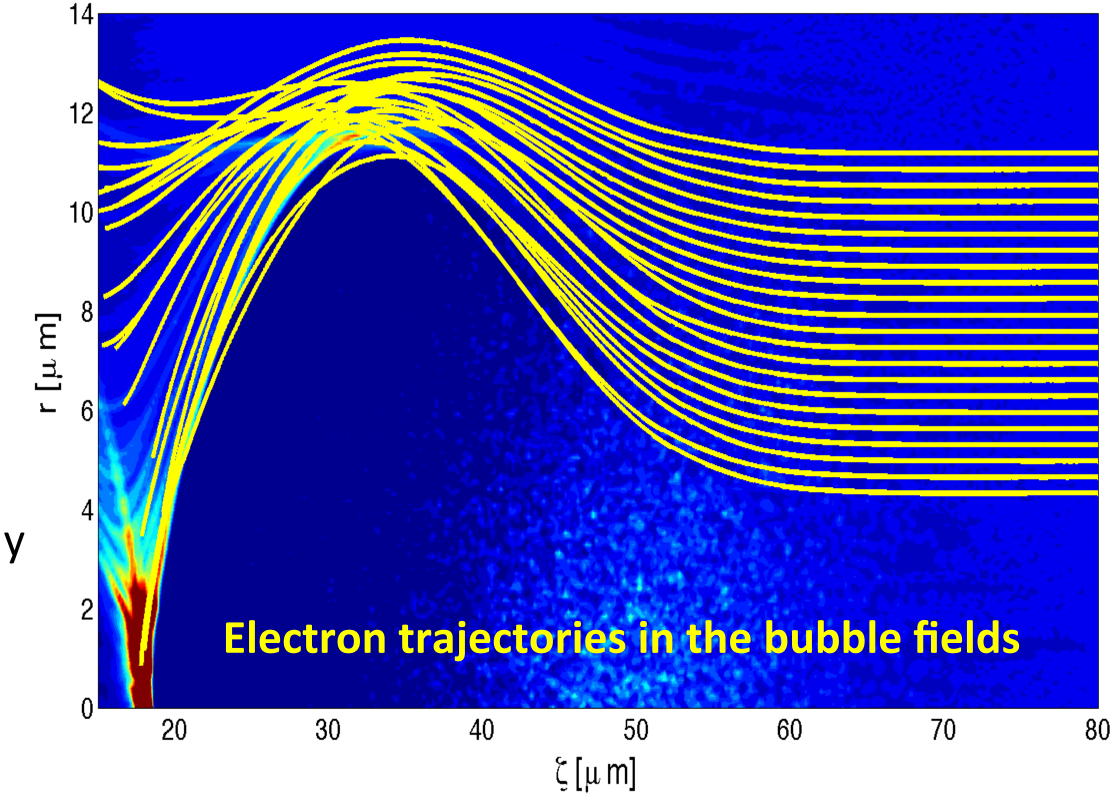


Limits of the analytical model

The analytical model does not reproduce:

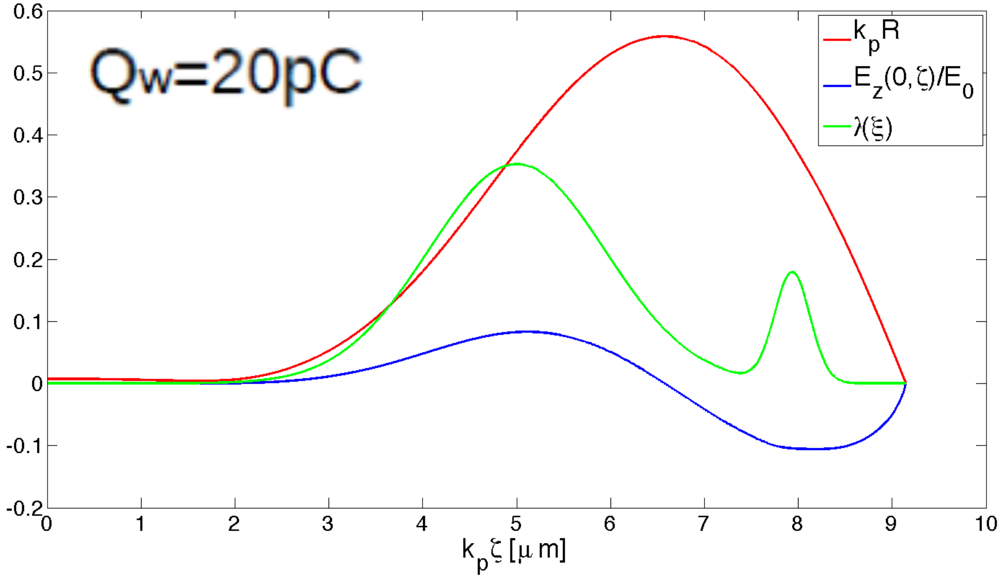
- The density spike at the back of the bubble;
- The transition region at the beginning of the bubble.

The dynamics of the electrons in these regions is currently subject of studies with a particle tracking code I developed.



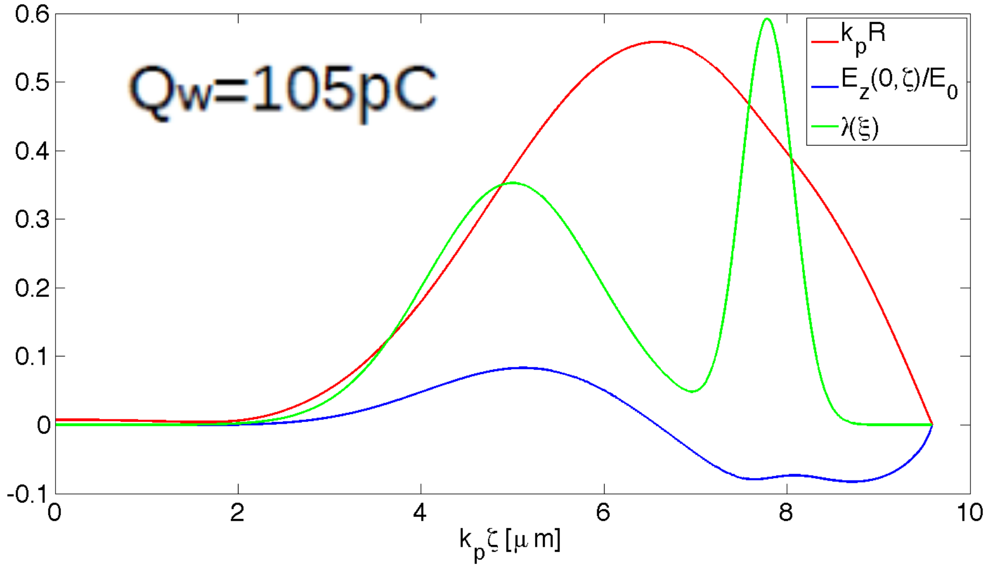
Application of the analytical model: beam loading in the external injection scheme for gaussian bunches

Driver: $\sigma_z = 50\ \mu m, \sigma_r = 4 \mu m$, Q = 200 pC
Witness: $\sigma_z = 10\ \mu m$, $15\ \mu m$
Plasma Density: $n_0 = 10^{16}\ cm^{-3}$
Distance: $L = 3\ cm$



Low charge witness:

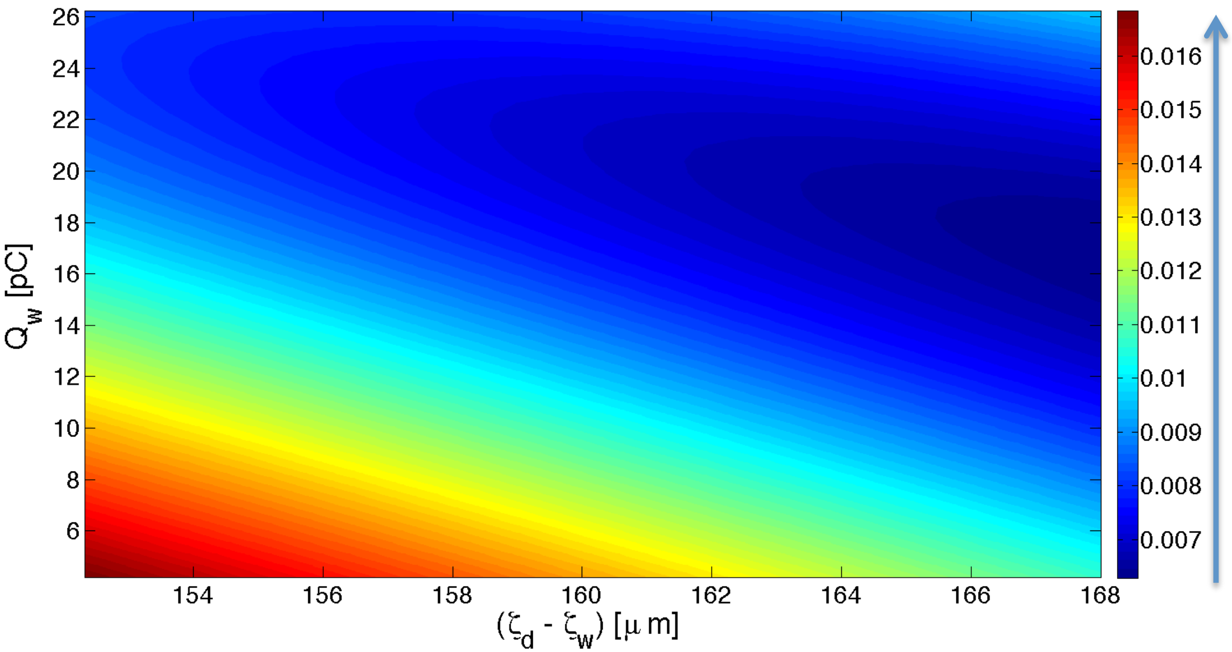
- Weak field distortion;
- Positioning on the crest of the wake;
- **ΔE/E < 1%.**



High charge witness:

- Strong field distortion;
- Positioning on the rising side of the wake;
- **ΔE/E ≈ 3%.**

Application of the analytical model: beam loading in the external injection scheme for gaussian bunches



ΔE/E

Optimization analysis of witness charge and position in the wake: the higher the charge the less the sensitivity. Very narrow region with energy spread < 1%.

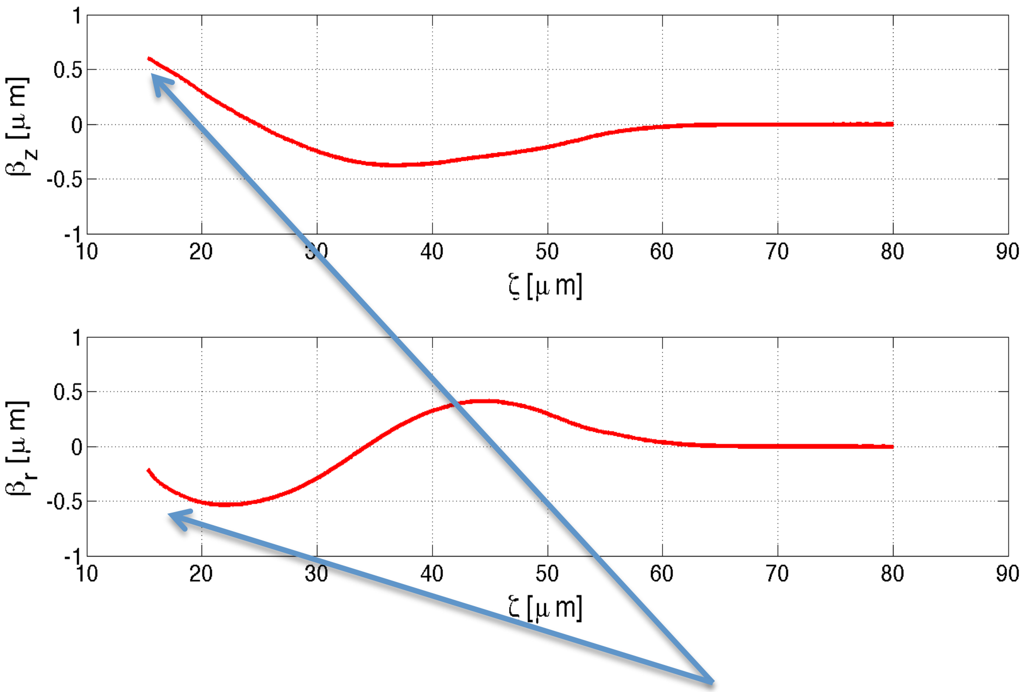
External injection limits:

- High charge → difficult to handle at low energy. Higher energy spread induced;
- Low charge → extremely sensitive to positioning.

Self injection scheme

How do we overcome the limit of external injection?

In the LWFA we can use the electrons of the plasma background!



Average longitudinal and transverse β of the background electrons at the back of the bubble.

The electrons at the back of the bubble feel a strong accelerating field and can be trapped into the wake.

In the PWFA the wake propagates at the speed of light.

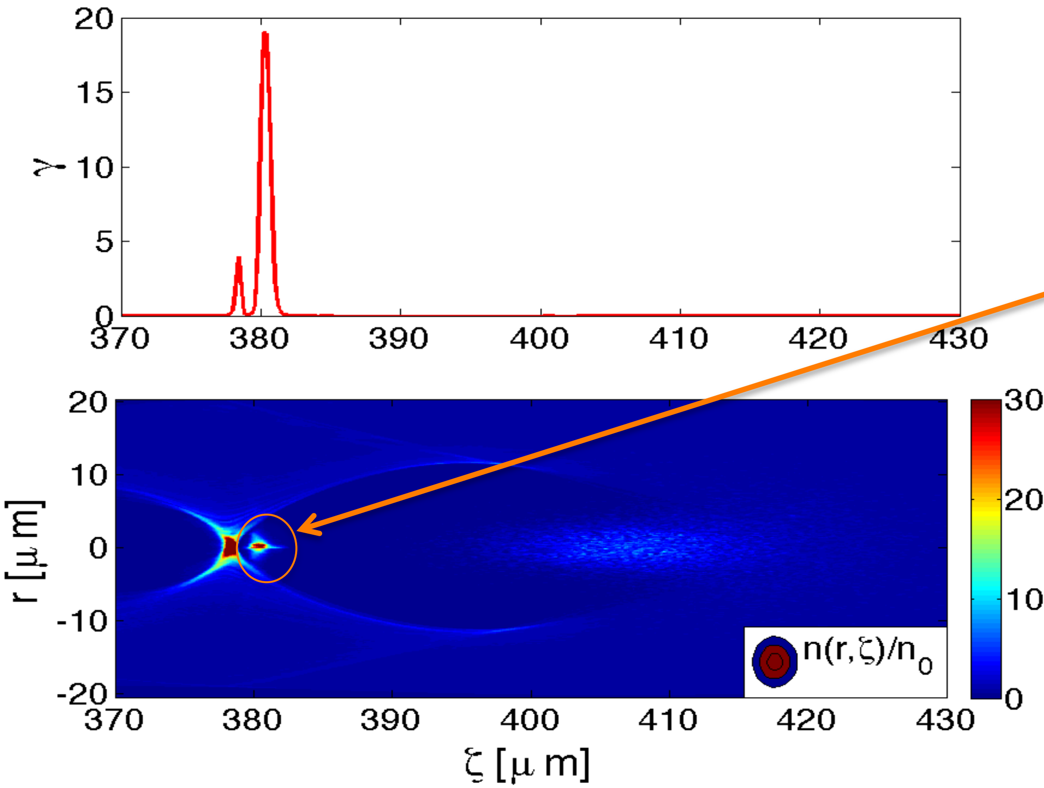
The electrons accumulates at the back of the bubble but no trapping occurs.

Wakefield Ionization Injection

The electrons are injected directly in the back of the bubble via ionization of a dopant element (He, Ar) confined in a thin layer at the entrance of a capillary.

Preliminary results of WII for a H+Ar plasma (no layer):

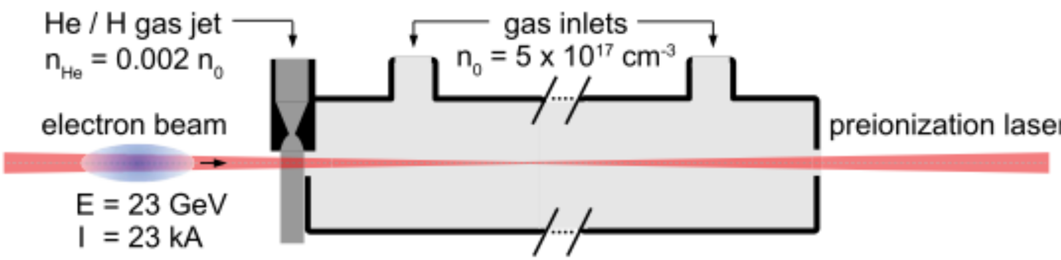
- Average accelerating field > 30GV/m;
- Self injected beam energy ≈ 10MeV gained in ≈ 400 μm;
- Energy spread < 5%;
- Injected charge > 10 pC.



Main limitations:

- Driver current required >10 kA;
- High degree of control of the dopant distribution.

Aim of the thesis project



- Emittance, energy spread, spot size and energy measurement in a realistic PIC simulation with the dopant layer;
- Studies of the beam quality and acceleration varying the dopant density distribution in the capillary;
- Studies of the effect of different gases (Ar, He, Ne, N …);
- Studies of the feasibility of triggering the WII with a multi-driver scheme in the weakly non-linear regime;
- Studies on an extension of the analytical model of the non linear regime to the regions of the head and the back of the bubble.

References

- R. Keinigs, M. E. Jones, *Two-dimensional dynamics of the plasma wakefield Accelerator*, Phys. Fluids, 1987;
- W. Lu, C. Huang, M. Zhou, et al. A *nonlinear theory for multidimensional relativistic plasma Wakefields*, Phys. Plasmas, 2006;
- K.V.Lotov, *Blowout regimes of plasma wakefield acceleration*, Phys.Rev.E, 2004;
- A.M. de la Ossa et al. *High-Quality Electron Beams from Beam-Driven Plasma Accelerators by Wakefield-Induced Ionization Injection,* Phys.Rev.Lett 2013;
- N Barov, J B Rosenzweig,et al. *Energy loss of a high-charge bunched electron beam in plasma: Analysis*. Phys. Rev. ST Accel. Beams, 2004;
- C. Benedetti et al., *ALaDyn: A High-Accuracy PIC code for the Maxwell-Vlasov Equations*, IEEE Transactions on Plasma Science, 2008;
- P. Londrillo et al. *Charge preserving high order PIC schemes*, Nucl. Instrum. Meth. A, 2010;
- P. Londrillo et al. *Numerical investigation of beam-driven PWFA in quasi-nonlinear regime*, Nucl. Instrum. Meth. A, 2014.