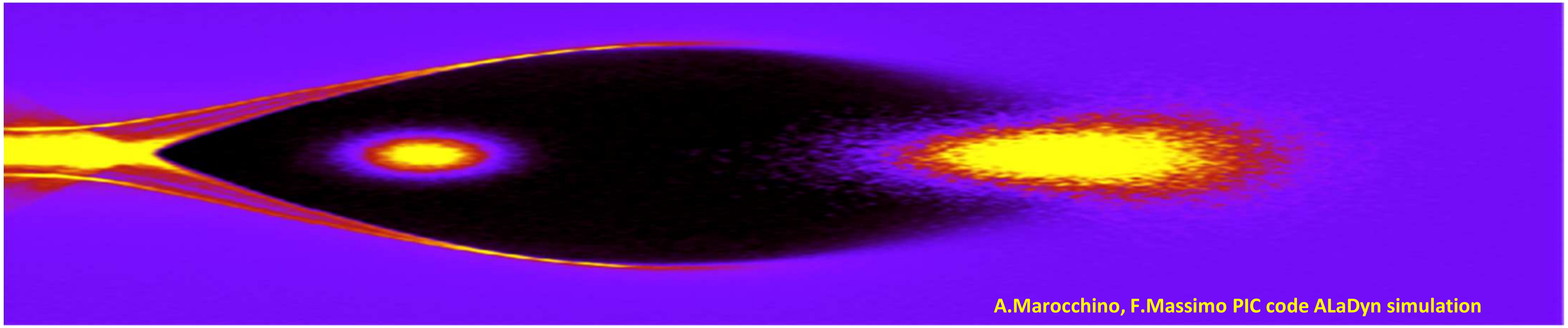

A.Marocchino, F.Massimo PIC code ALaDyn simulation

Accelerator Physics Doctoral Course
Final exam

Characterization of beam driven ionization injection in the blowout regime of Plasma Acceleration

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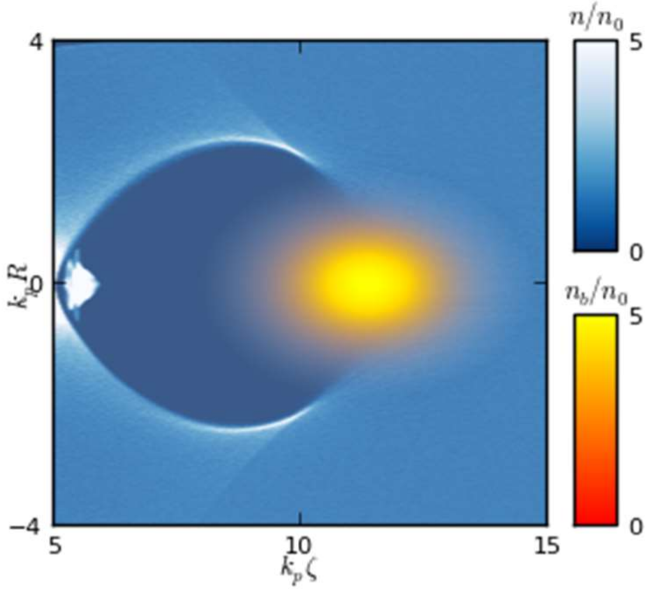
Supervisors:

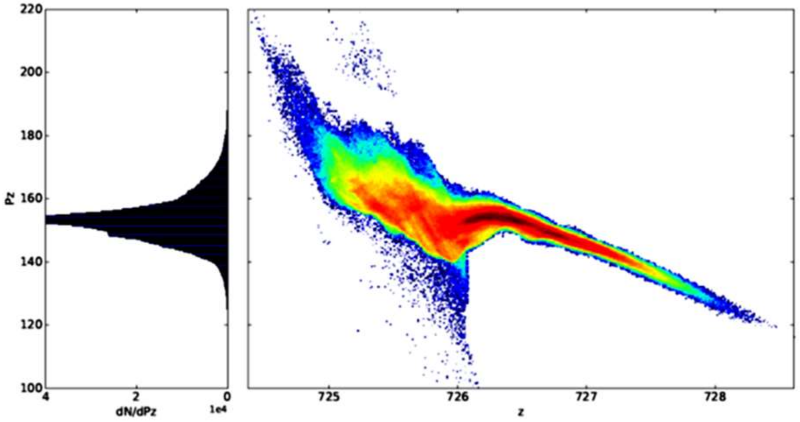
Stefano Atzeni Alberto Marocchino

Istituto Nazionale di Fisica Nucleare

Outline

- ☐ Motivation and Introduction
- ☐ Wakefield Ionization Injection
- ☐ The PIC method and the code ALaDyn
- ☐ Ionization model
- ☐ Particle tracking results
- ☐ PIC Results for various dopant element
- ☐ Conclusions and future work

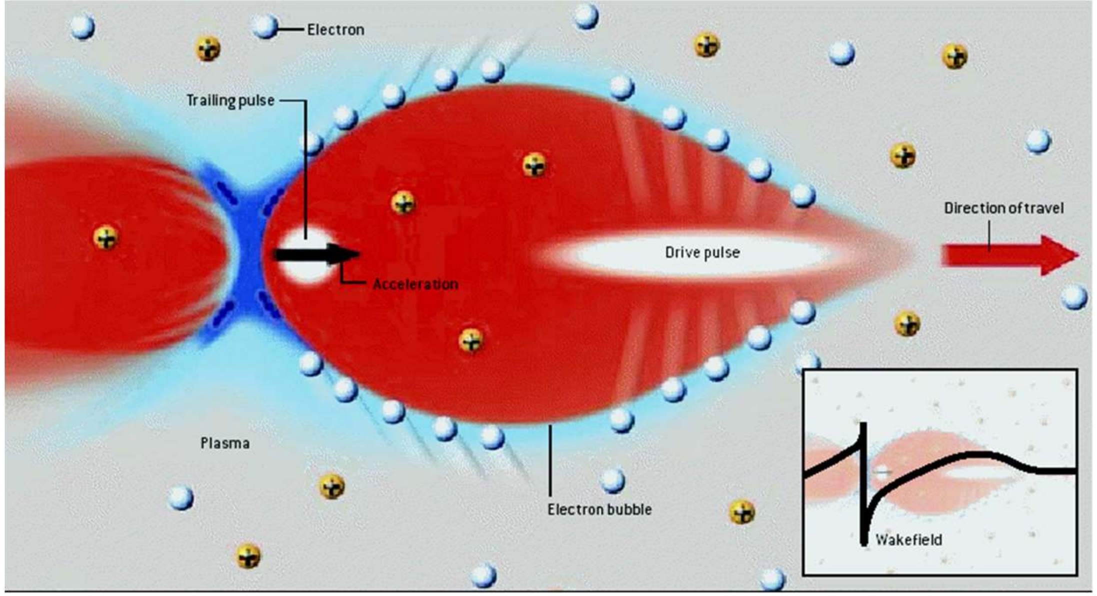




Motivation

- ☐ High brightness electron beam *plasma injector*
  - ☐ $\sim 1\ GeV$ in $1\ cm$ injection+transport
  - ☐ High quality for light source applications
    - ☐ Normalized emittance $\leq 1 \mu m$
    - ☐ Relative energy spread $\sim 0.1\%$
  - ☐ High charge $> 10\ pC$ and high peak current $\sim 10\ kA$
  - ☐ Ultrashort $\sim fs$ and tight focused $\sim 1\ \mu m$
- ☐ Characterization of Wakefield Ionization Injection

Introduction



- A ‘driver’ beam perturbes plasma electron equilirium
- In the wake behind the driver an intense electric field develops.
- ‘Witness’ beam acceleration and focusing if properly injected.

$$E_z\left[\frac{GV}{m}\right] \sim 0.096\times 10^{-9}\sqrt{n_{e0}[m^{-3}]}$$

$$n_{e,o} = 10^{24}m^{-3} \rightarrow E_{z,max}\sim 100\ GV/m$$

Introduction

Driver nature:

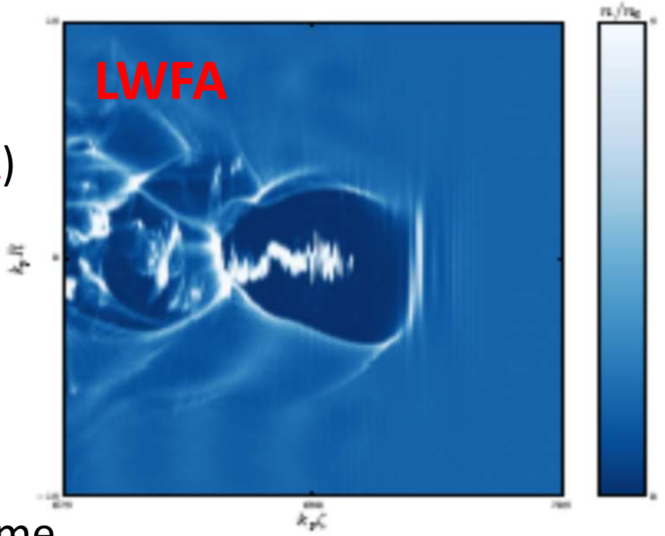
☐ High Power Laser -> Laser Wake-Field Acceleration (**LWFA**)
☐ Relativistic Electron Bunch -> Plasma Wake-Field Acceleration (**PWFA**)

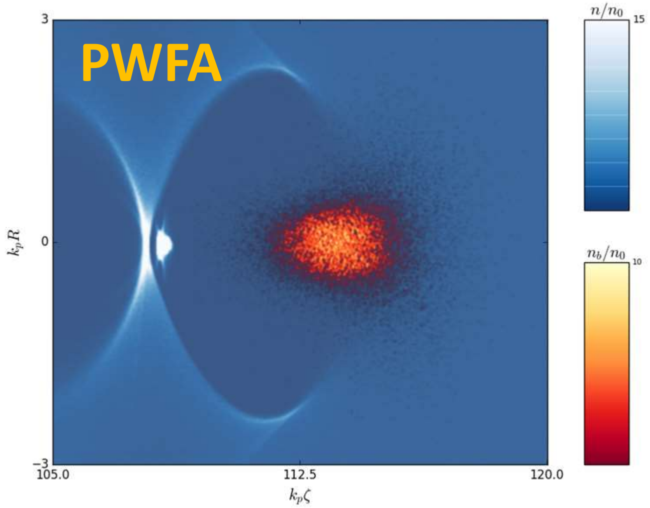
Plasma Perturbation

☐ $\delta n_e / n_{e,0} \ll 1$ -> Linear regime
☐ $\delta n_e / n_{e,0} > 1$ -> Non-Linear regime (NL) or ‘Blowout’ regime
☐ $\delta n_e / n_{e,0} \leq 1$ -> 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;





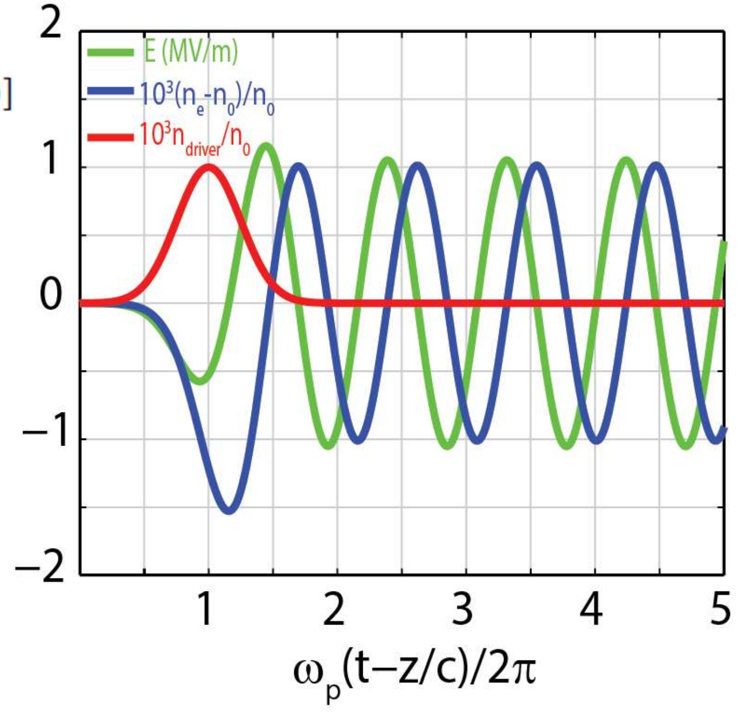
Linear regime

☐ First order expansion of Maxwell equations and plasma 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;
☐ Transformer ratio limitations;
☐ Intrinsecally difficult high quality transport;

Nonlinear Regime

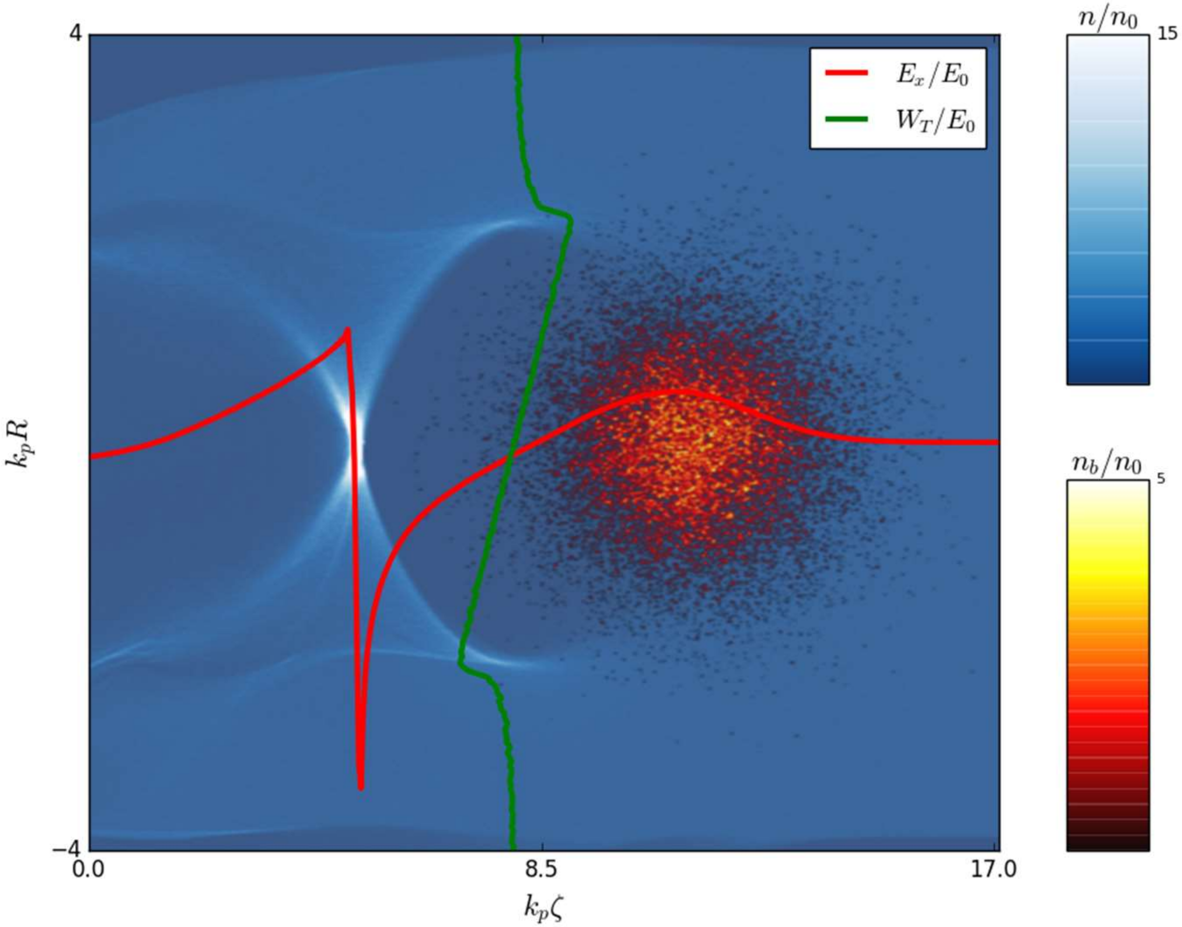
Blowout regime -> high density perturbation in the wake

- High transformer ratio
- Linear focusing forces
- No analytic solution

↓

Assumptions required for simplified fluid models:

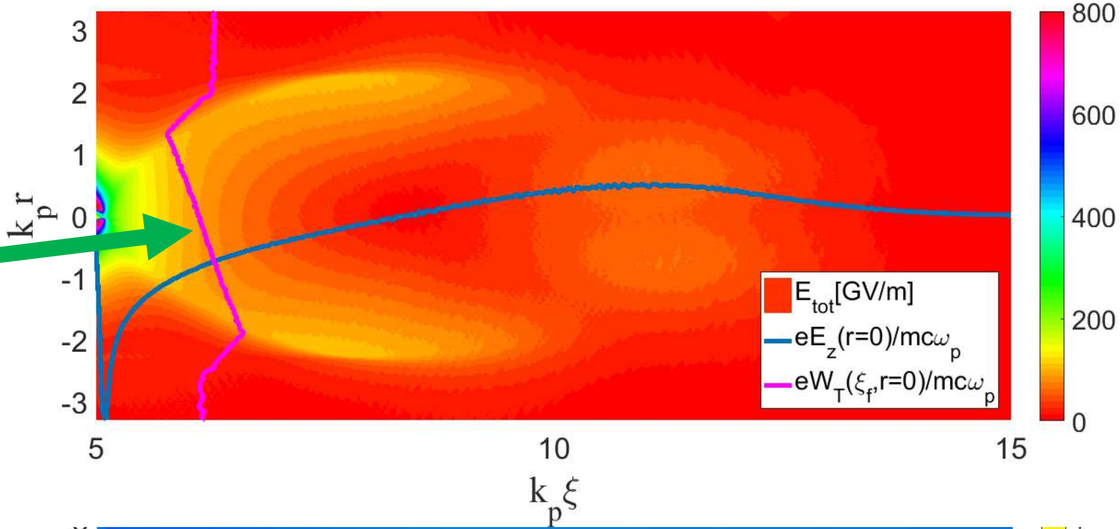
- W.Lu et al. Phys. Plasmas, 2006;
- I.Kostyukov et al. Physics of Plasmas **11**, 5256 (2004)
- K.V.Lotov Phys.Rev.E, 2004

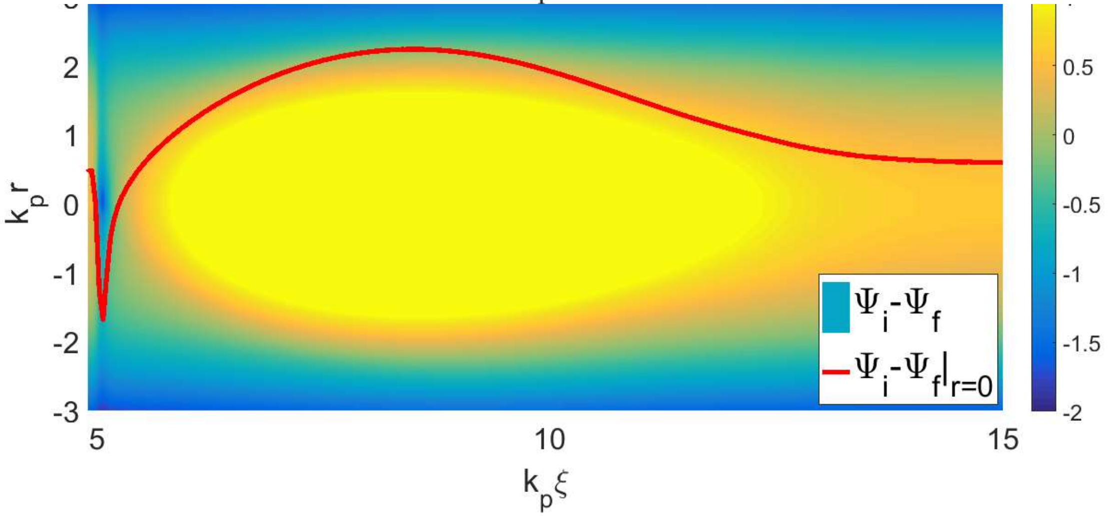


- Uneasy external injection: two electron bunches with $\sim fs$ separation

→ **Wakefield Ionization Injection**

Wakefield Ionization Injection





- ☐ Ionization in the focusing and accelerating phase ζ_i.

- ☐ **The beam field does not contribute to ionization.**

- ☐ Electrons are trapped if :

$$\Psi(\zeta_i) - \Psi(\zeta_F) = 1$$

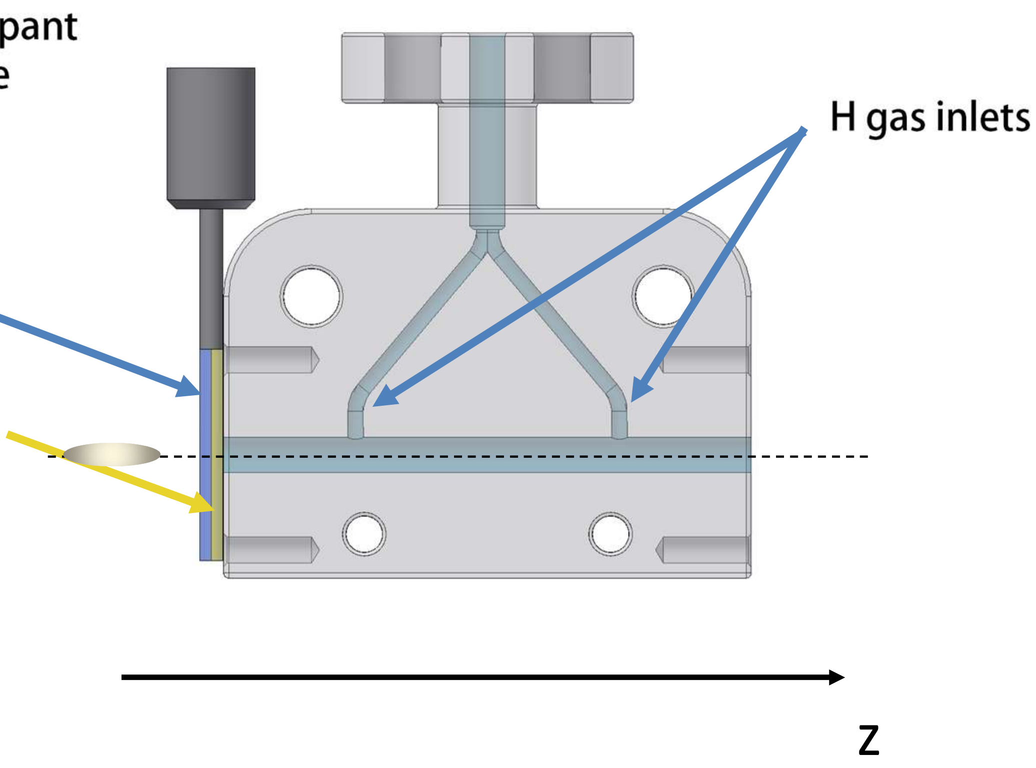
where $\zeta_F \sim 2R_b$.

- $\Psi(\zeta_i) - \Psi(\zeta_F) \sim k_p R_b$
- $R_b \sim 2\sqrt{\Lambda_b}$
- $\Lambda_b = 2\frac{I_b}{I_A} = \frac{n_b}{n_0}\sigma_r^2$

We need peak driver beam current $\boldsymbol{I_b > 5kA}$!

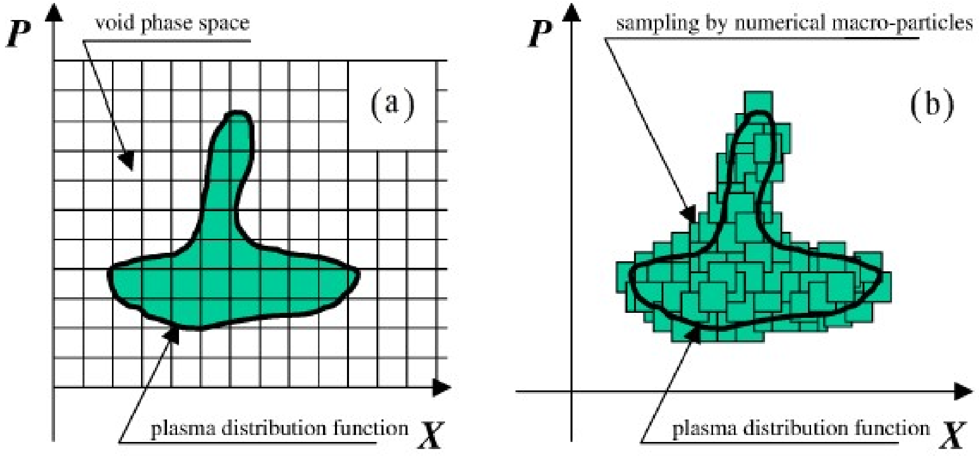
Wakefield Ionization Injection Layout

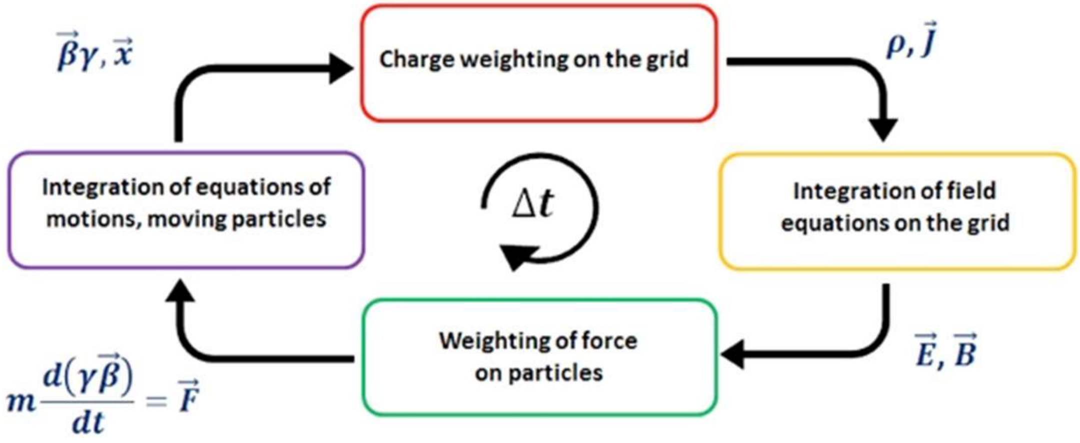
- **Hydrogen gas jet**
- **Hydrogen+Dopant gas jet**



High degree of control of dopant Density distribution!

The Particle In Cell method




$\vec{\beta}\gamma, \vec{x}$

Charge weighting on the grid

$\rho, \vec{J}$

Integration of equations of motions, moving particles

Δt

Integration of field equations on the grid

$m\frac{d(\gamma\vec{\beta})}{dt} = \vec{F}$

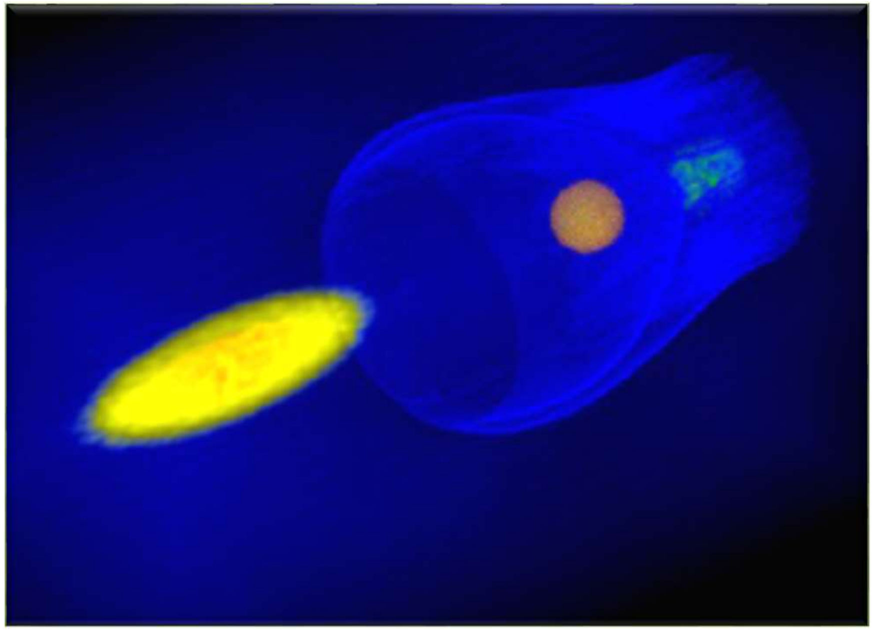
Weighting of force on particles

$\vec{E}, \vec{B}$

- ~~Continuos distribution function~~
- Discrete ensamble of computational macroparticles
- Electromagnetic fields on a computational grid in space and time
- Discrete integration of the equation of motion

The PIC-Code ALaDyn

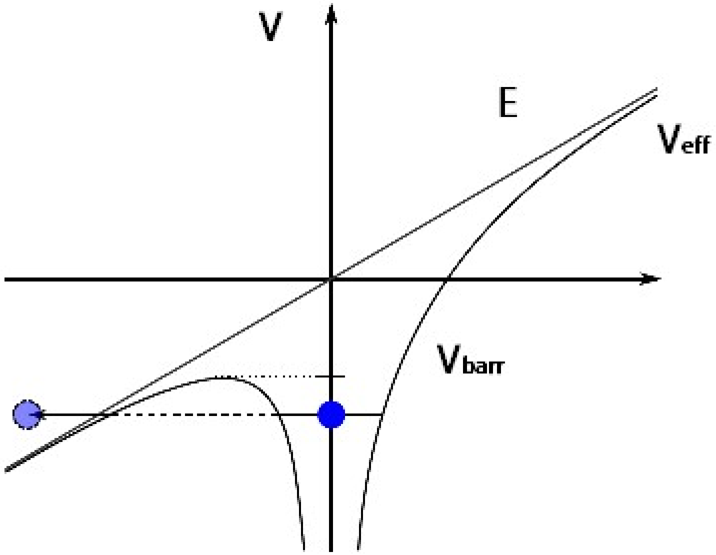
- ☐ PIC Code ALaDyn
  - ☐ Fully Relativistic
  - ☐ Full 3D (2D-1D fashion)
  - ☐ High order in space and time
  - ☐ Charge preserving high order scheme
  - ☐ Field Ionization module -> ADK, BSI
  - ☐ 3D-ouput -> Visit
  - ☐ Python online diagnostic routines



Field Ionization Models

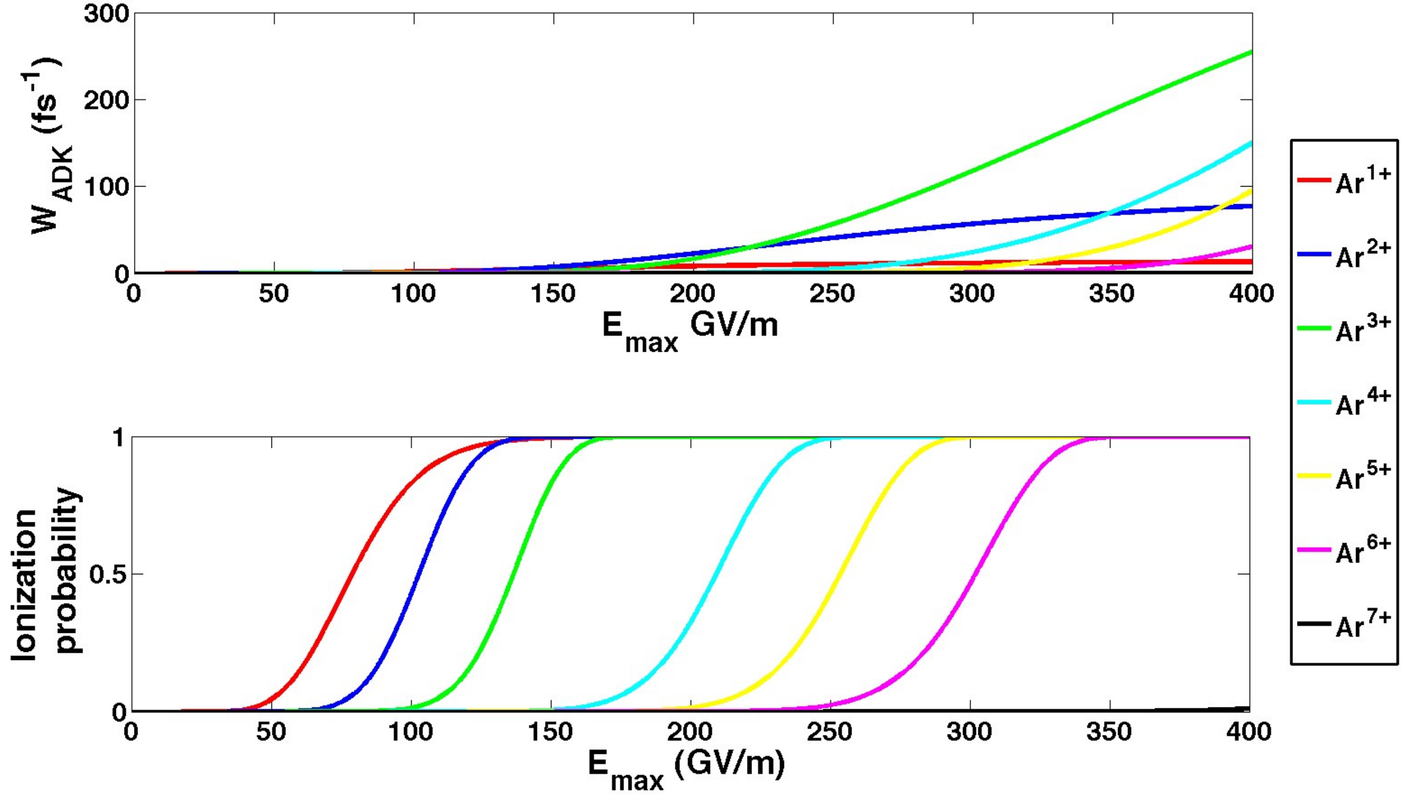
- Landau and Lifshitz formula (hydrogen-like atoms)
- Keldysh formula
- **ADK formula**

$$W_{ADK}[\mathrm{fs}^{-1}] \approx 1.52\,\frac{4^{n^*}\,\xi_i[\mathrm{eV}]}{n^*\,\Gamma(2n^*)}\left(20.5\,\frac{\xi_i^{3/2}[\mathrm{eV}]}{E[\mathrm{GV/m}]}\right)^{2n^*-1} \times \exp\left(-6.83\,\frac{\xi_i^{3/2}[\mathrm{eV}]}{E[\mathrm{GV/m}]}\right),$$



- ξ_i → ionization potential of the i-th atomic level;
- $n^* = Z\sqrt{\frac{13.6[eV]}{\xi_i}}$ → effective principal quantum number;
- $E = \sqrt{E_x^2 + E_y^2 + E_z^2}$ → magnitude of electric field on the atom.

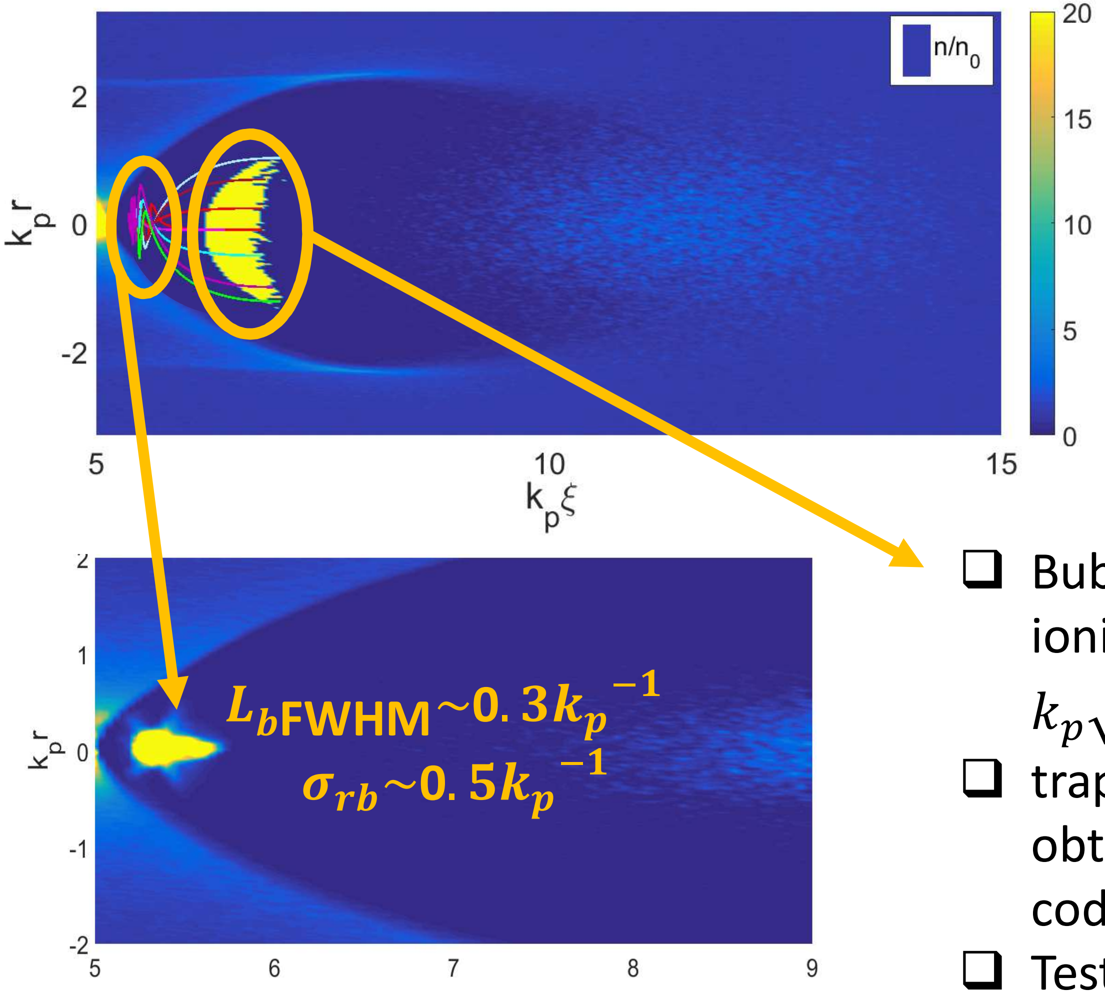
Ionization rate and probability (ADK)



$$P(t) = 1 - \exp(-\int_0^t W_{ADK}[E(t')]dt')$$

→ e.g. field close to $200GV/m$ is enough to ionize Ar up to Ar^{3+}

ParticleTracking Analysis



$L_{b\text{FWHM}}\sim 0.3{k_p}^{-1}$

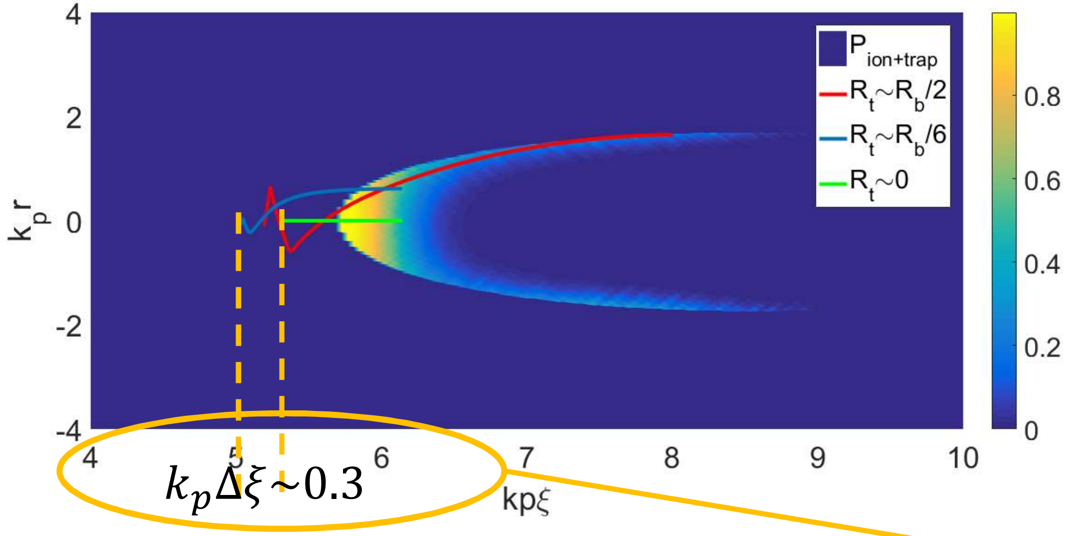
$\sigma_{rb}\sim 0.5{k_p}^{-1}$

☐ Bubble volume where both ionization and trapping occur $k_p\sqrt{\langle {r_i}^2\rangle}\sim 1.2$, $k_pL_{injection}\sim 0.6$

☐ trapped electron trajectories obtained with a Particle Tracking code

☐ Test particles -> no beam loading and space charge

Particle Tracking Analysis



$k_p\Delta\xi\sim0.3$

- ☐ Beam length -> difference between trapping longitudinal positions $\Delta\xi$

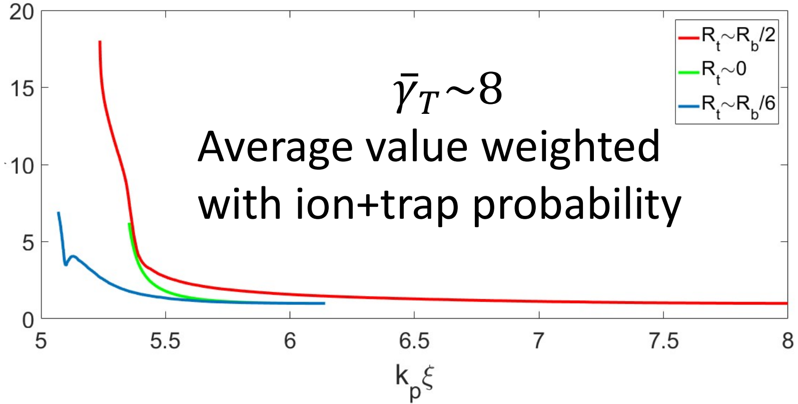
$$L_b = f(\langle {r_i}^2\rangle)$$

- ☐ Beam spot size

$$k_p\,\bar{r_T} = \frac{1}{2}k_p\bar{r_i}\left(\frac{1}{\bar{\gamma}_T}\right)^{1/4}\sim0.09 \ll \sigma_{rb}$$

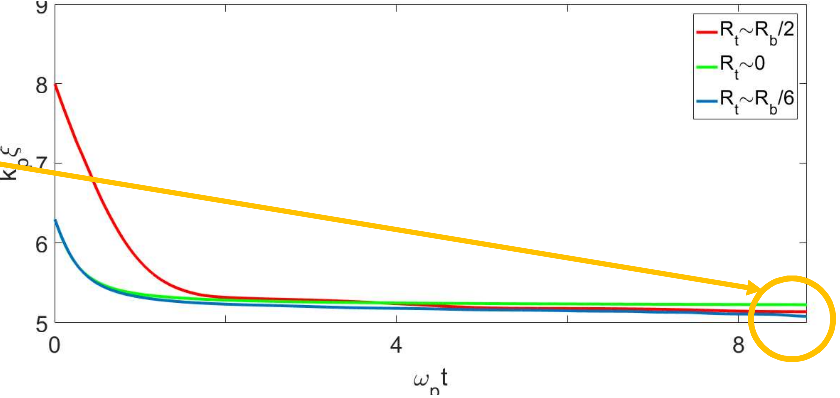
  - ☐ Space charge effects during transient

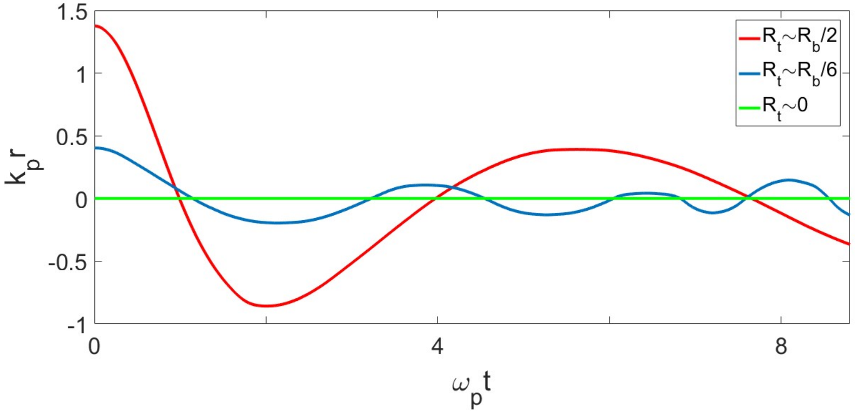
$$\sigma_{rb}\sim f(\langle {r_i}^2\rangle,\gamma,Q)$$



$\bar{\gamma}_T\sim8$

Average value weighted with ion+trap probability





Numerical experiment via ALaDyn

Plasma Background:

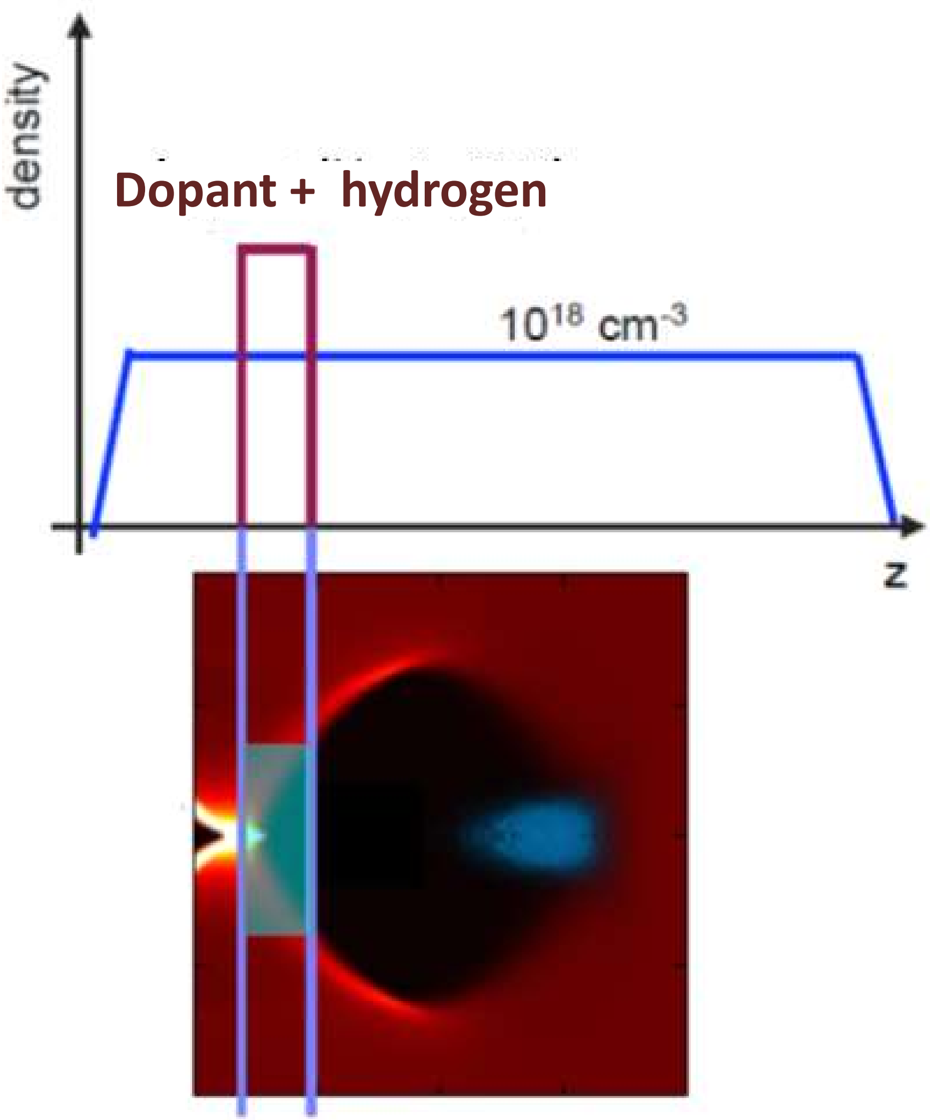
- *Hydrogen density*: $1.2 \times 10^{18} cm^{-3}$;
- *Dopant density*: $8\% \, n_H$;
- *Initial ionization degree*
    - H^{1+}
    - Z^{1+}
- *dopant layer length*: $15 \, \mu m$;
- *Totall distance: 600 μm*

Driving beam:

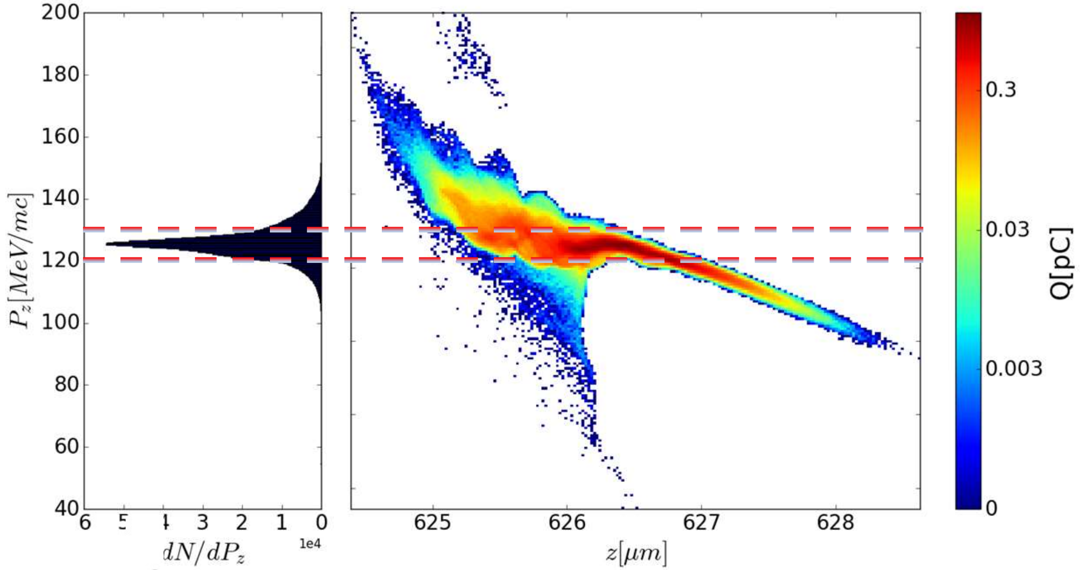
- *longitudinal dimension*: $7 \, \mu m$;
- *transverse dimension*: $4 \, \mu m$;
- *peak current*: $10 \, kA$;
- $\gamma = 2000$

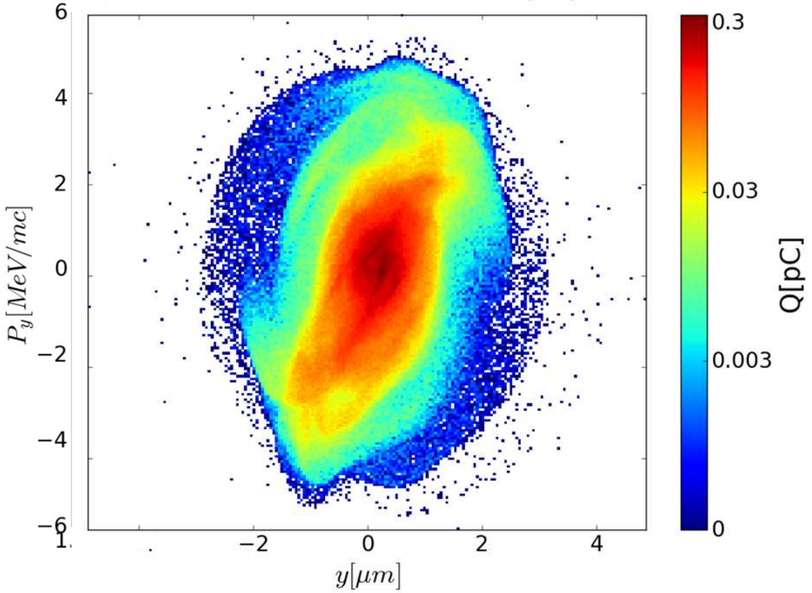
Simulation setup

- *416x520x520 3D grid;*
- $\Delta_z = 0.2 \, \mu m, \Delta_x = \Delta_y = 0.08 \, \mu m$;
- *8 electrons per cell,;*
- *1 ion per cell;*



Example result: N^{1+}

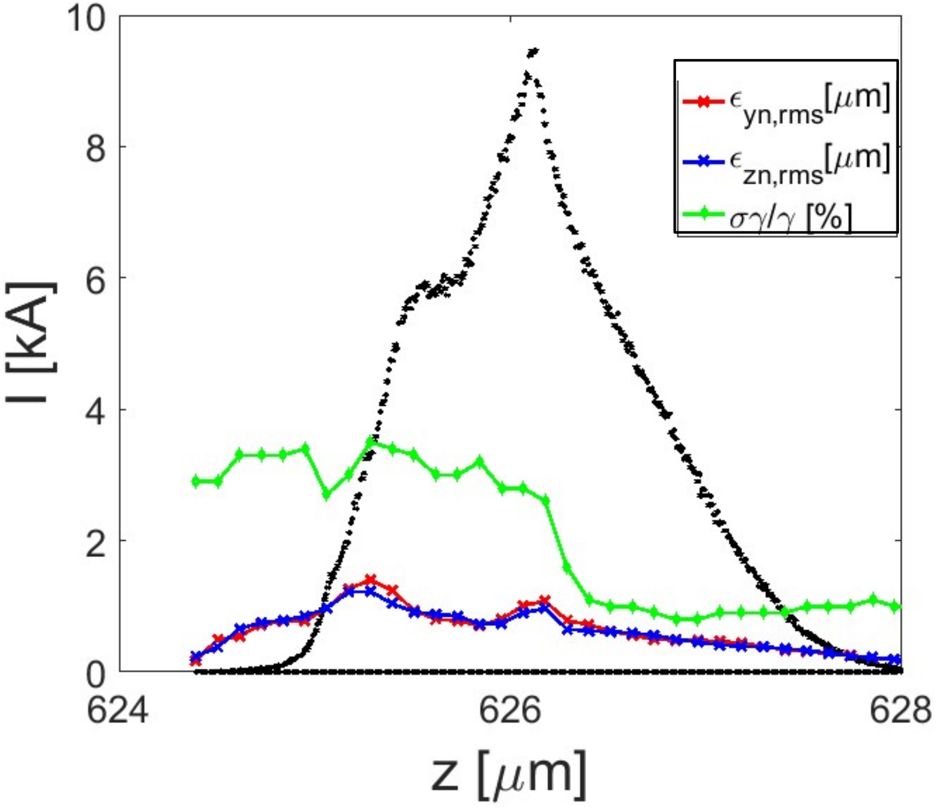




- ☐ Curved chirped profile along the longitudinal phase space
- ☐ 75% of the charge confined in the central region $\sim 1.5\mu m$
- ☐ Similar profiles for both Ar^{1+}, Ne^0

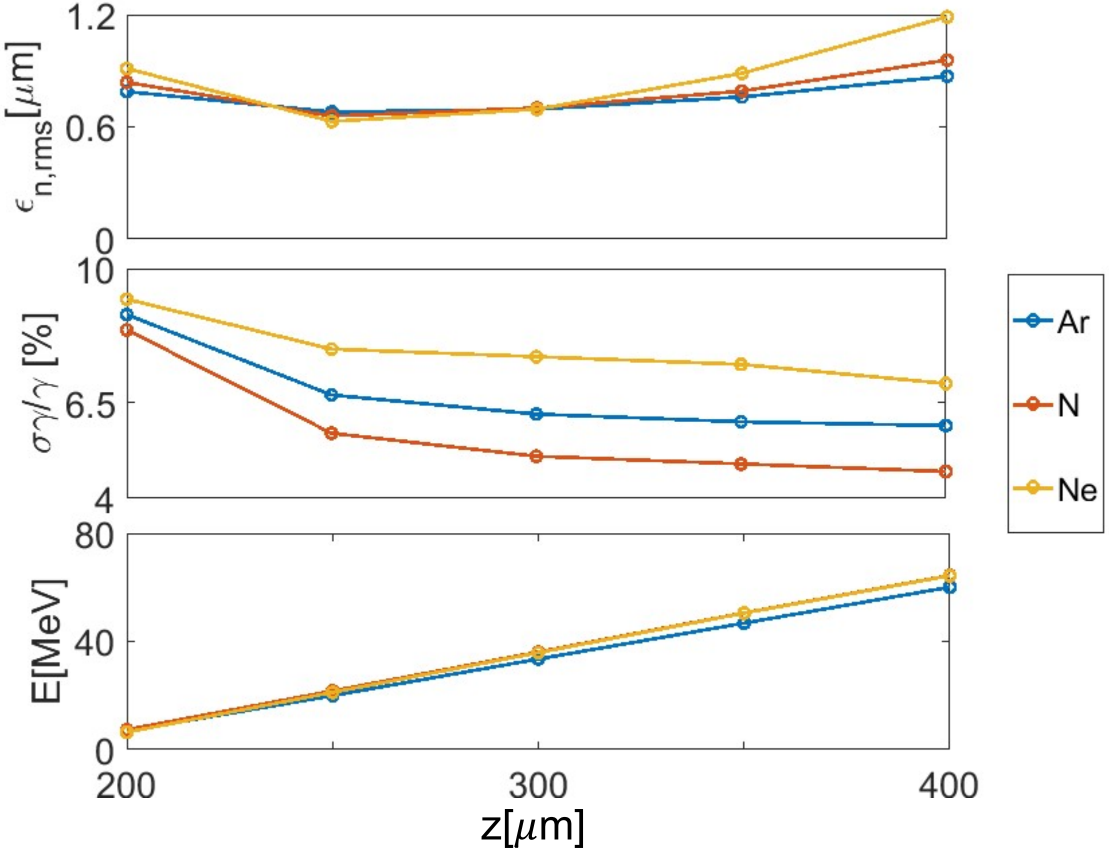
600 μm **propagation**	$Q[pC]$	**FWHM** $\frac{\sigma_\gamma}{\gamma}$ $[\%]$	$\varepsilon_{n,rms}$ $[\mu m]$
N^{1+}	22.2	2.9	0.96
Ar^{1+}	26.7	3.3	0.87
Ne	22.5	3.9	1.2

Slice analysis



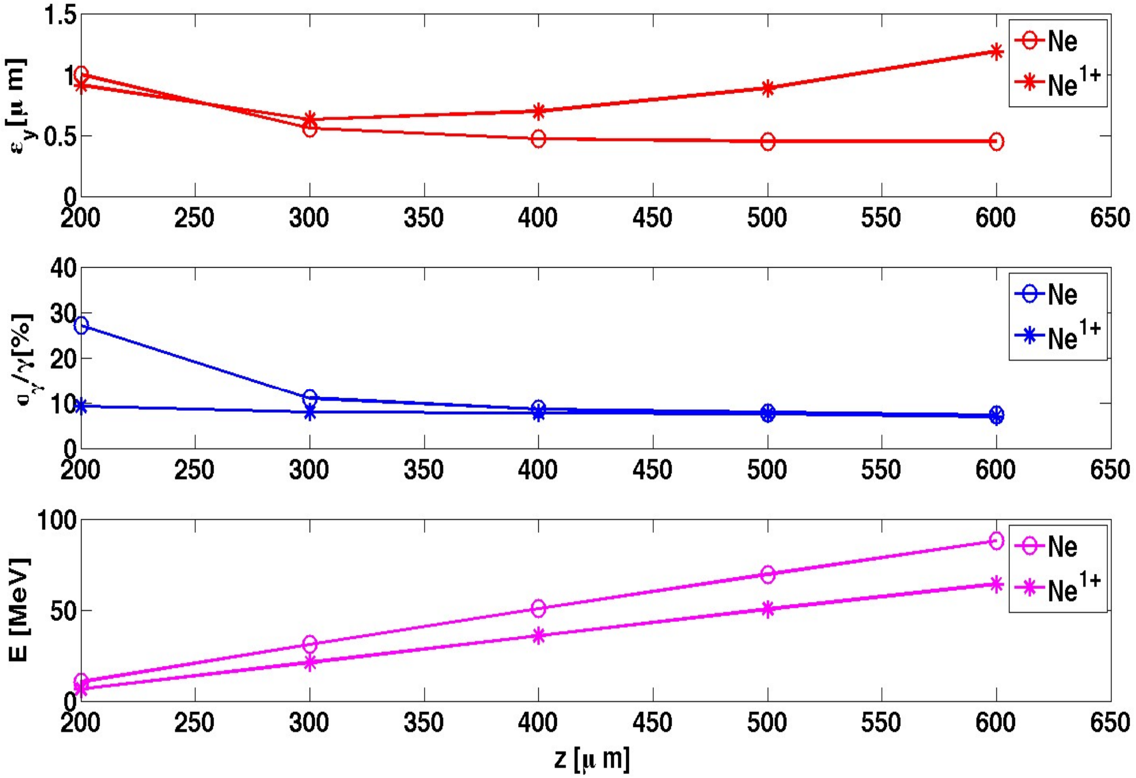
- ☐ Peak current of $\sim 10kA$
- ☐ Symmetric sliced normalized emittance $\varepsilon_{n,rms} k_p{}^3 \frac{\langle r_i \rangle^2}{4} \sim 1\mu m$ for $k_p r_i \sim 0.8$
- ☐ Slice energy spread from 1% to 4% in highly nonlinear region -> higher resolution + Cherenkov radiation mitigation algorithm needed

Beam quality transport



- ❑ Normalized emittance increasing due to numerical Cherenkov
- ❑ Energy spread decreasing down to a asymptotic value $f\left(V_{injection}, L_{dopant}, Q_{injected}\right)$
- ❑ Linear energy growth $\sim 150 GeV/m$

Comparison Ne / Ne^{1+}



- ☐ $\frac{\sigma_\gamma}{\gamma} Ne \sim \frac{\sigma_\gamma}{\gamma} Ne^{1+}$ -> beam loading effects compensate smaller ionization volume
- ☐ $\varepsilon_{n,rms} Ne > \varepsilon_{n,rms} Ne^{1+}$-> ionization volume for Ne is larger thanNe^{1+} ($V_1 = 21.5eV < V_2 = 41eV$)
- ☐ $Q_{Ne} \sim 20pC \sim 50\ Q_{Ne^{1+}}$-> $E_{Ne} < E_{Ne^{1+}}$ due strong beam loading effects

Conclusions

- ☐ High brightness electron beam *plasma injector*
  - ☐ $\sim 1\ GeV$ in $1\ cm$ injection+transport ✓
  - ☐ High quality for light source applications
    - ☐ Normalized emittance $\leq 1 \mu m$ Work in Progress
    - ☐ Relative energy spread $\sim 0.1\%$ 🚫
  - ☐ High charge $> 10\ pC$ and high peak current $\sim 10\ kA$ ✓
  - ☐ Ultrashort $\sim fs$ and tight focused $\sim 1\ \mu m$ ✓
- ☐ Characterization of Wakefield Ionization Injection Work in Progress

Future work

- ☐ Space charge effects on beam properties via online Particle Tracking implemented in ALaDyn
- ☐ Higher resolution simulations needed on both longitudinal and transverse dimension ($10\ nm$) and Cherenkov mitigation algorithm
- ☐ Gas dynamic simulations required for realistic density profiles of the gas mixture
- ☐ Studies on experimental feasibility at FLAME for kA driver beam generation via LWFA self injection
- ☐ Studies on a solid dopant layer

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