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Title:
Laser-plasma acceleration: A close view on self-injection mechanisms

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Also at INFN, Sezione di Pisa

Event:
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INFN

Outline

- Introduction
- Experimental Results
- PIC Simulation; Jasmine Code
- Conclusion

Introduction: Self-Injection

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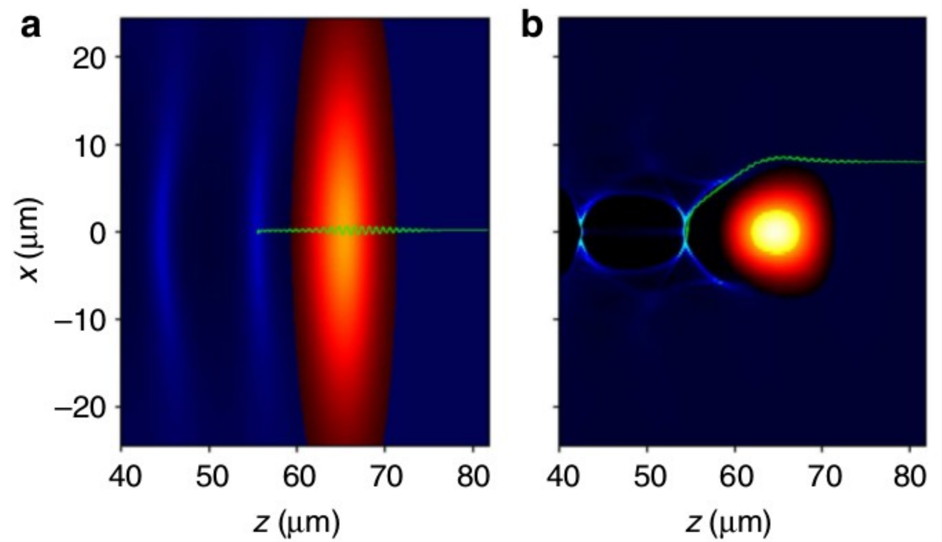
The Self-Injection occurs when the wakefield is strong enough to trap cold plasma electron into the laser wake itself. Two distinct physical mechanism can be distinguished; **longitudinal and transverse self-injection**. These processes are not fully controllable and can lack of shot to shot stability but exist several techniques to improve beam quality.

- **Longitudinal (a):** Trajectrory of injected electrons is mainly longitudinal, with a negligible transverse motion. The trapped electron are those that where initially close to the laser axis where the wakefield amplitude and laser intensity are the highest.
- **Transverse (b):** This mechanism occurs only in the **Bubble Regime** and consist in multi-dimensional effect with longitudinal and transverse motion. In the bubble regime the PM force expels electron and forms an electron-free cavity (a bubble).

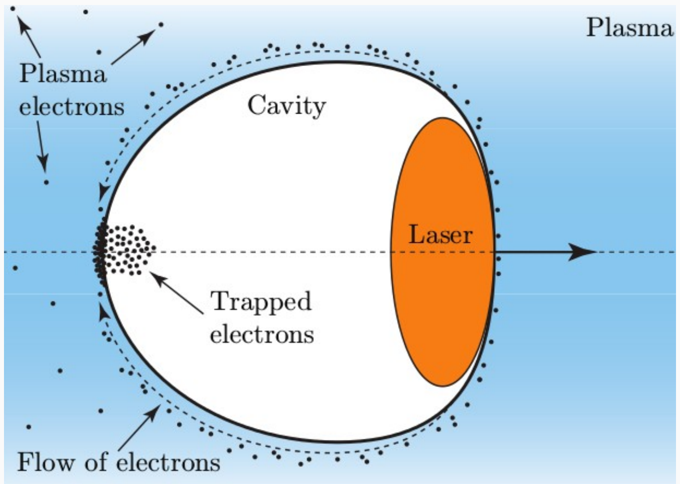


S. Corde et al., Nature Communications 4,1501(2013).

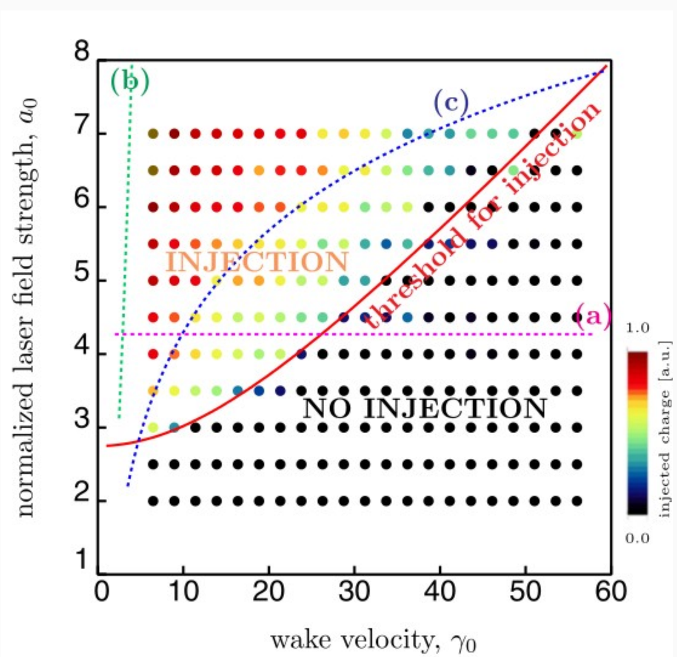
- **Colliding laser pulse:** A first laser pulse is used to excite the wakefield while a second laser pulse, the injection pulse, is used to kick electron in the right position.
- **Density gradient:** A downward density plasma ramp is used to trigger wave breaking in a localized spatial region of plasma. The decrease of the plasma wave phase velocity in the density ramp promote the injection.
- **Ionization:** High-Z gas or gas mixtures have large differences in ionization potential. This is useful because the inner level electrons are ionized later and can be trapped and accelerated.

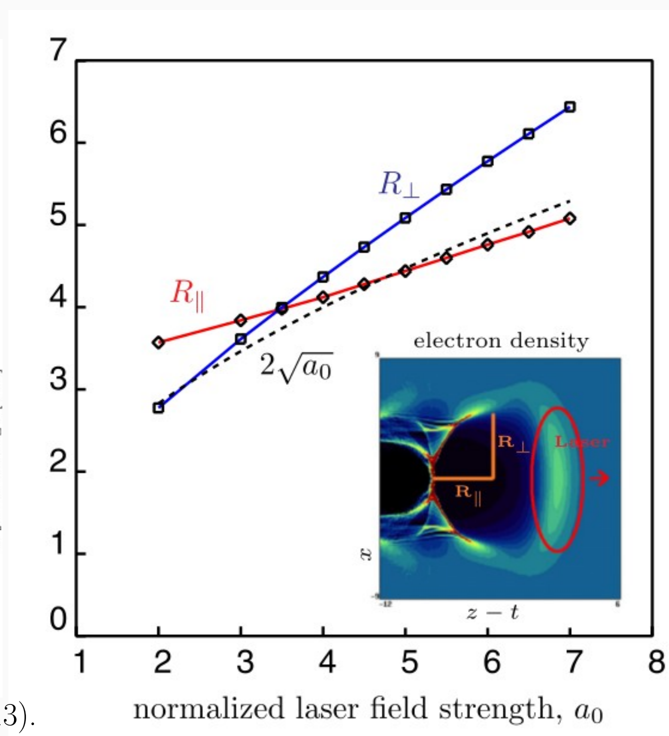
P. Tomassini, at al., Phys. Rev. ST Accel. Beams 6, 121301

Introduction: Bubble Regime Parameter



The bubble shape can be characterized by longitudinal and transverse radius. Basically, the longitudinal radius is the length of accelerating part of the wake. Simulation show that the longitudinal radius is linear in $\mathbf{a}_0$. Threshold for self injection is represented in a (γ_0,$\mathbf{a}_0$) plane, where γ_0 is the wake velocity.





C. Benedetti et al., Phys. Plasmas 20, 103108 (2013).

$$R_{\parallel}(a_0) \approx 2.9 + 0.305 \cdot a_0$$

$$a_0^{thr}(\gamma_p) \approx 2.75\left[1+\left(\frac{\gamma_p}{22}\right)^2\right]^{\frac{1}{2}}$$

The ILIL laboratory: Main parameters

Laser main figures

-energy: up to 450mJ on target

-pulse duration <40fs

-ASE contrast > 10^9

-M^2 < 1.5

-wavelength 800 nm

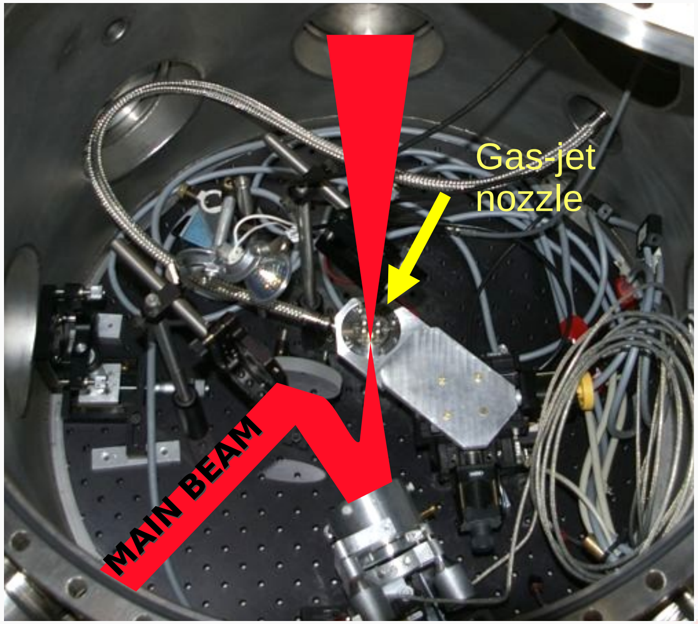
Interaction chamber

Intensity: up to $2x10^{18}$ W/cm^2-

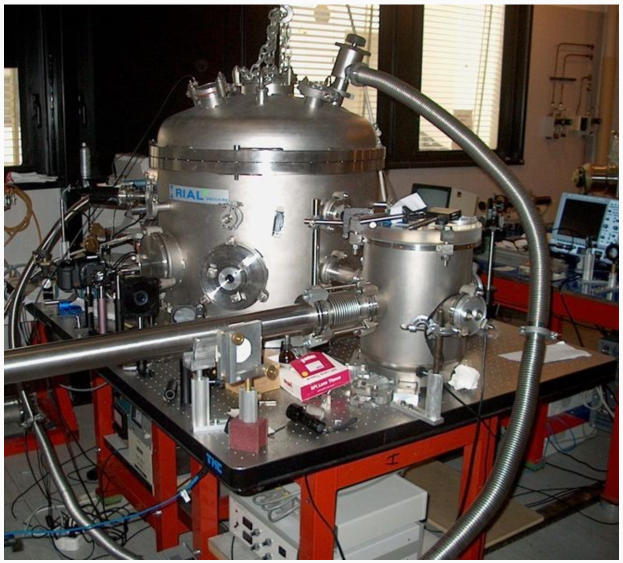
Parabola (OAP) f/10-

Waist (FWHM) 20 µm-

Vector Potential a_0 0,96-

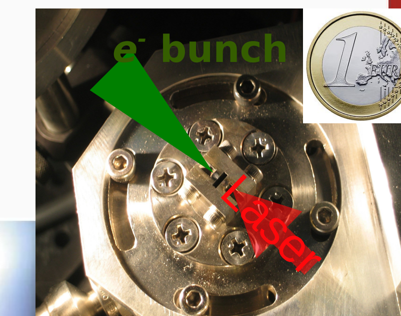


The ILIL laboratory: Chamber Configuration



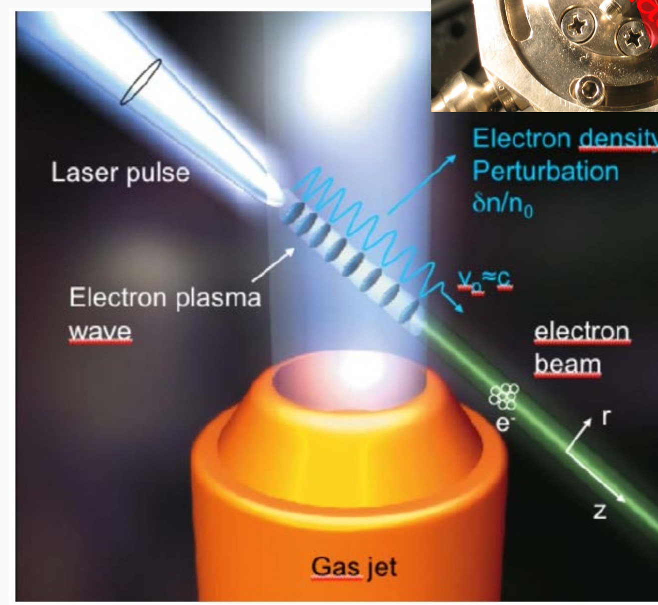
Target area equipment

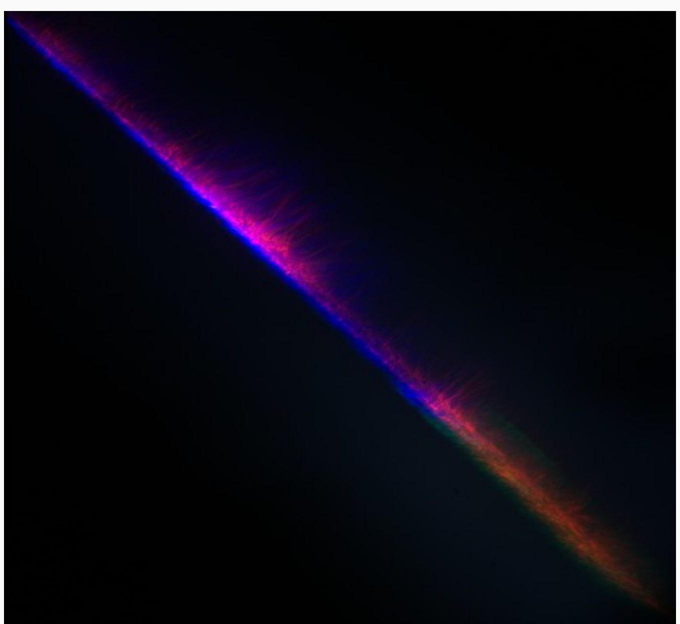
-2 "dedicated" vacuum chambers ("gas-jet" and "solid" targets)
-optical and X-ray diagnostics
-electron diagnostics
-integrated environment for diagnostic data automatic collection



Basic arrangement

Supersonic nozzle with a size of 4x1.2 mm^2 (laser propagating along the shortest size)





The laser pulse is focused in the proximity of the entrance edge of the gas-jetgas used are He, N_2, Ar and mixture of He-N_2 and Ar-He

The laser-gas interaction is monitored using Thomson scattering imaging, shadowgraphic and interferometric techniques. The electrons beam is monitored using a LANEX scintillator screen and a magnetic spectrometer.

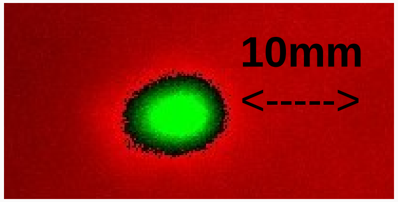
The ILIL laboratory: Main objectives of beam control

Beam Whishlist ⟷ **Tools (Fixed Laser Conf.)**

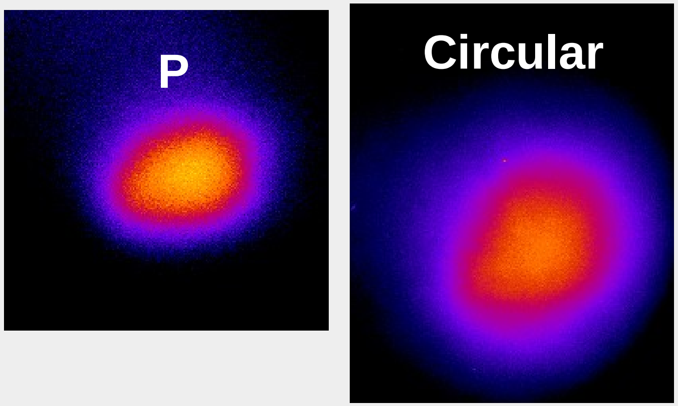
- **Energy**: Maximum energy as possible and a easy way to reduce it if necessary
- **Energy spread**: Minimum spread as possible and a way to control it independently from energy peak
- **Collimation:** Minimum solid angle as possible and a easy way to increase
- **Charge**: Best as possible
- **Shot to shot reproducibility:** Best as possible

- **Move/change Gas jet**: Change focus position, density profile etc
- **Change Gas**: ionizing injection "control", change density etc
- **Change gas pressure**; plasma density control
- **Change parabola**: Change laser intensity, Rayleigh length, etc. It requires a complete chamber reconfiguration!
- **Laser Polarization**: Thomson emission, transverse dynamics

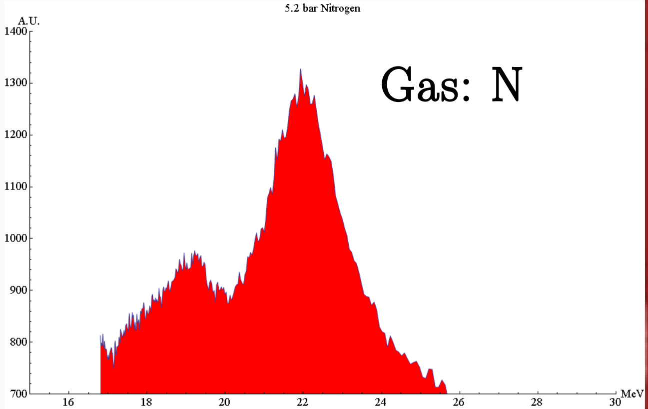
The ILIL laboratory: Some experimental results

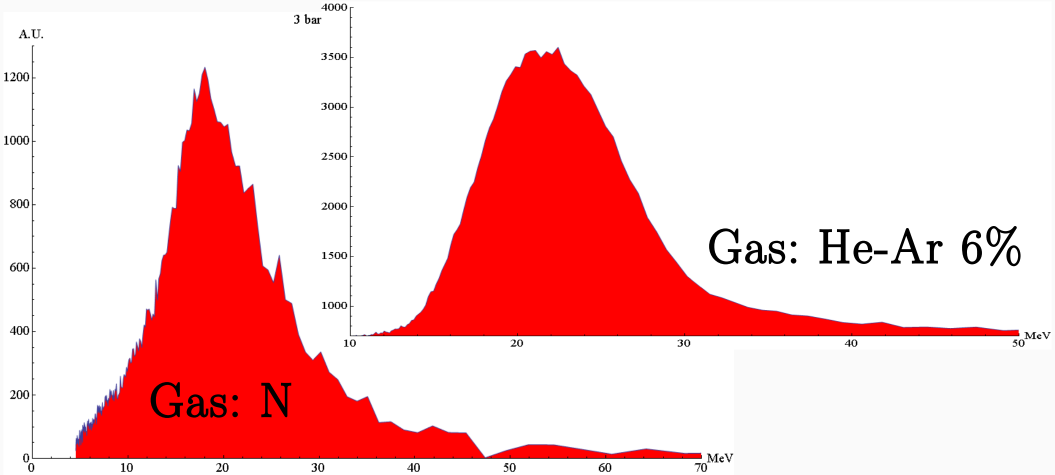


In some stable configuration ~**15 mrad** circular electron beam has been observed. On the left a lanex picture (false color) **550 mm** far from the gas-jet. Those result are obtained using **nitrogen** with backing pressure 4 bar which means **$1.9\text{x}10^{18}$ N/Cm^3** density at gas-jet



Two different electron spot in identical condition except laser polarization; **p** on left pictures and **circular** on the right one. Polarization have effect on beam geometry

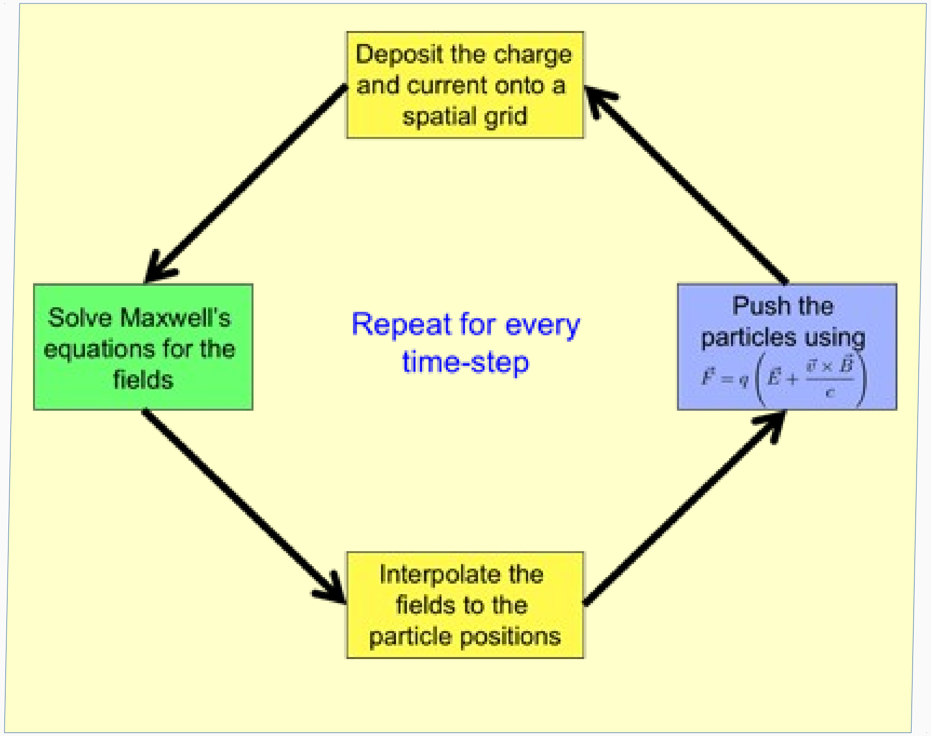




Most of shot show electron with a peak energy around **20-25MeV** and maximum energy **up to 40 MeV**.
Due to "ionizing-injection" some energy spectrum obtained with mixures show a remarkable monocromaticity (**10 MeV FWHM**)

PIC Simulation: Jasmine Code[1]

In the particle in cell (PIC) method, individual particles in a Lagrangian frame are tracked in continuous phase space, whereas moments of the distribution such as densities and currents are computed simultaneously on Eulerian (stationary) mesh points.
The **Jasmine code** is an example of Fully self-consisted 3-D (also 2-D) Particle-in-cell Method code based on **Maxwell-Vlasov equation**. This code it may also take account of the **ionization of gas** (or gas mixtures) and provides to simulate a realistic structure of wakefield .



Parameters used in the 2-D simulation:

$$n_{nitrogen} = (1.6 - 16) \times 10^{18} \quad cm^{-3}$$

(This correspond to nitrogen at 4-40 bar backing pressure)

$$\tau_l = 40\, fs \quad \lambda = 800\, nm \quad a_o = \frac{e E_{laser}}{m_e \omega_e c} = 0.96 \quad w = 20\, \mu m$$

Acceleration set-up for acceleration at **ILIL** laboratory.

[1] F. Rossi et al., AIP Conference Proceedings 1507, 184 (2012).

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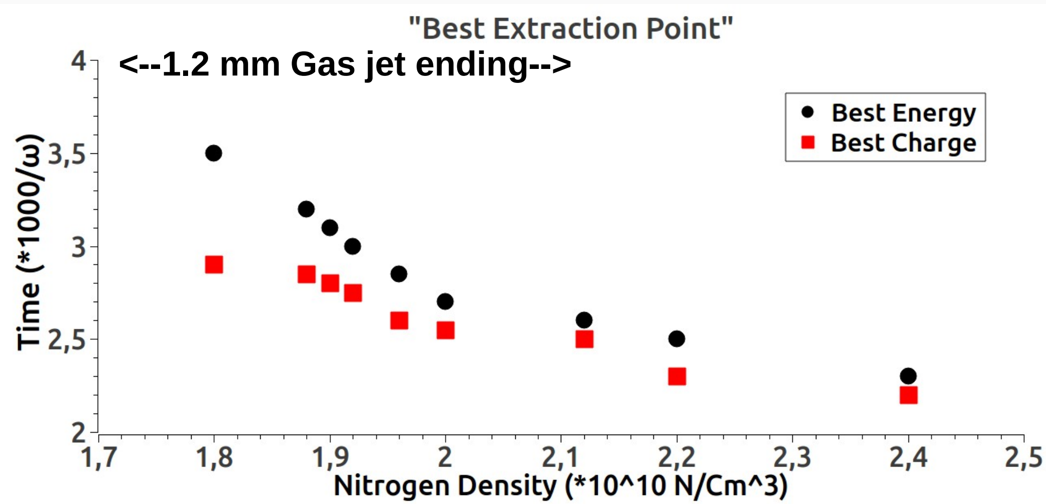
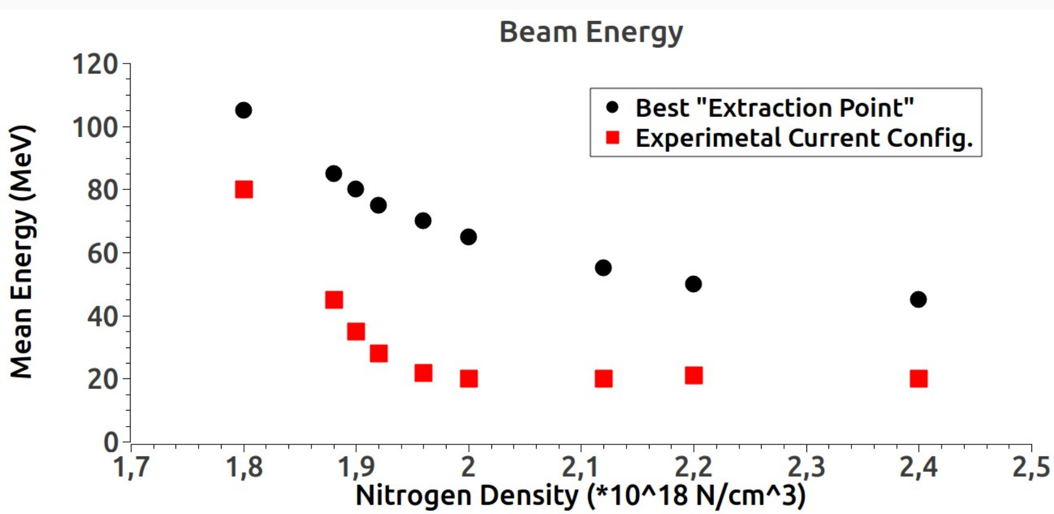
PIC Simulation: Injection and energy evolution (1.8-2.5X10^{18} n/Cm^3)

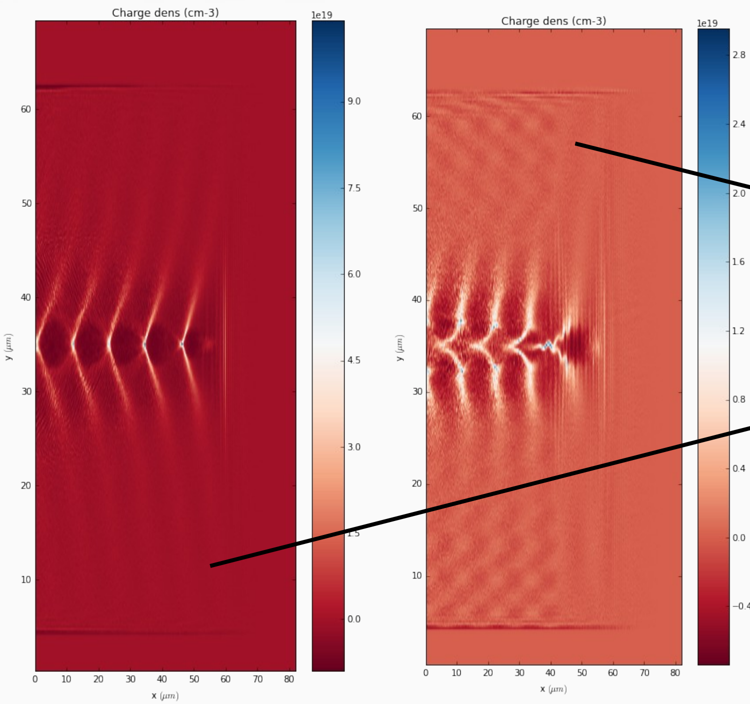


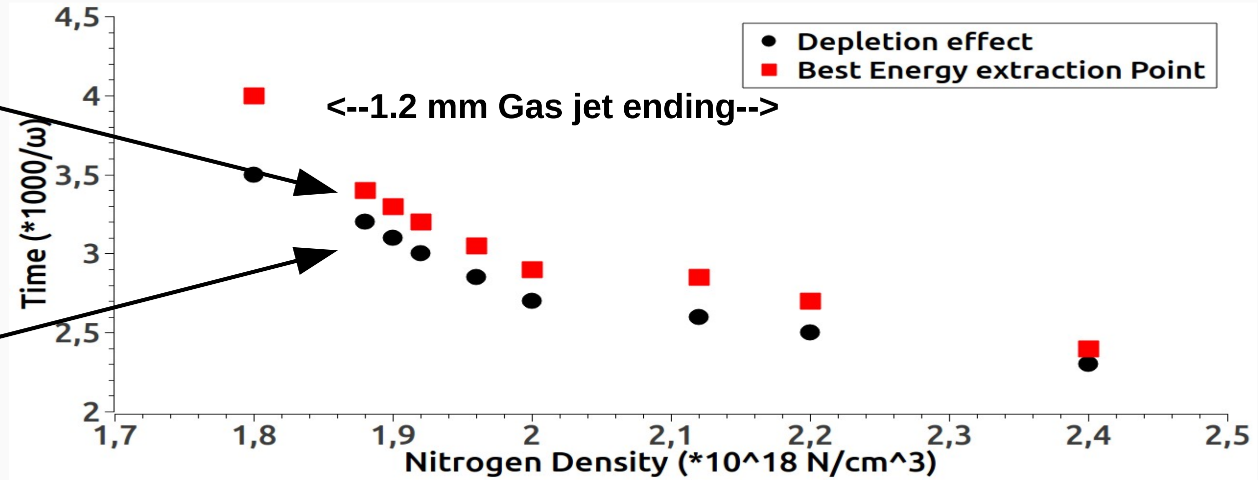


Observation

- "Extraction point" is nothing but the **ending of gas jet** (ideal or not)
- Best energy extraction point represent the **best compromise** between maximum mean energy and best "monochromaticity"
- For 1.2 mm gas-jet currently used best result can be obtained with **lower density** ~1.8x10^{18} N/Cm^3
- It's not possible obtain maximum of energy and beam charge at same time; especially at lower density
- **Injection threshold** is close to 1.7x10^{18} N/Cm^3
- With current 1.2 mm gas jet the mean energy (for some density) can be **only 25%** of maximum possible

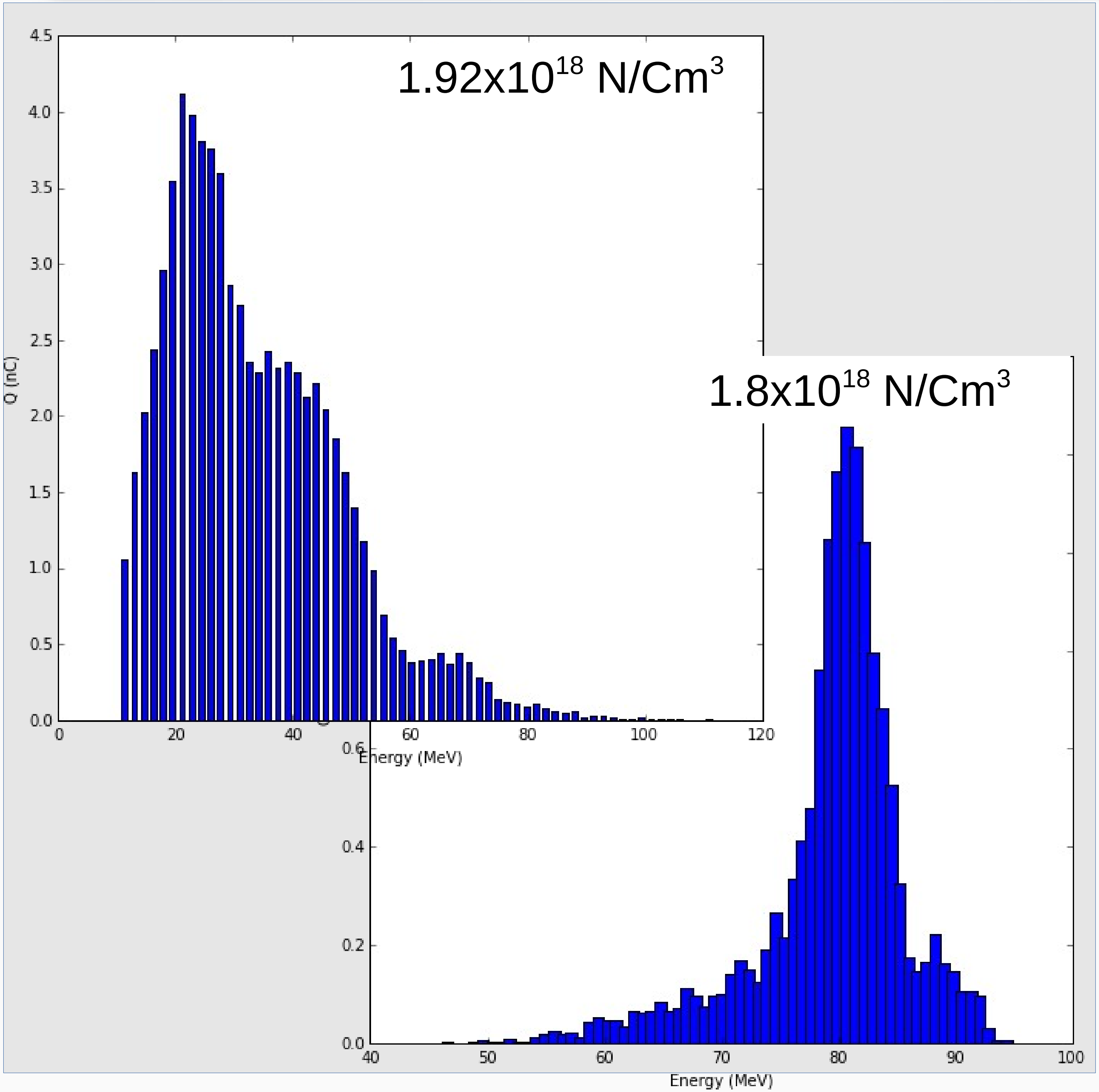
PIC Simulation: Depletion effect (1/3) (1.8-2.5X10^{18} N/Cm^3)





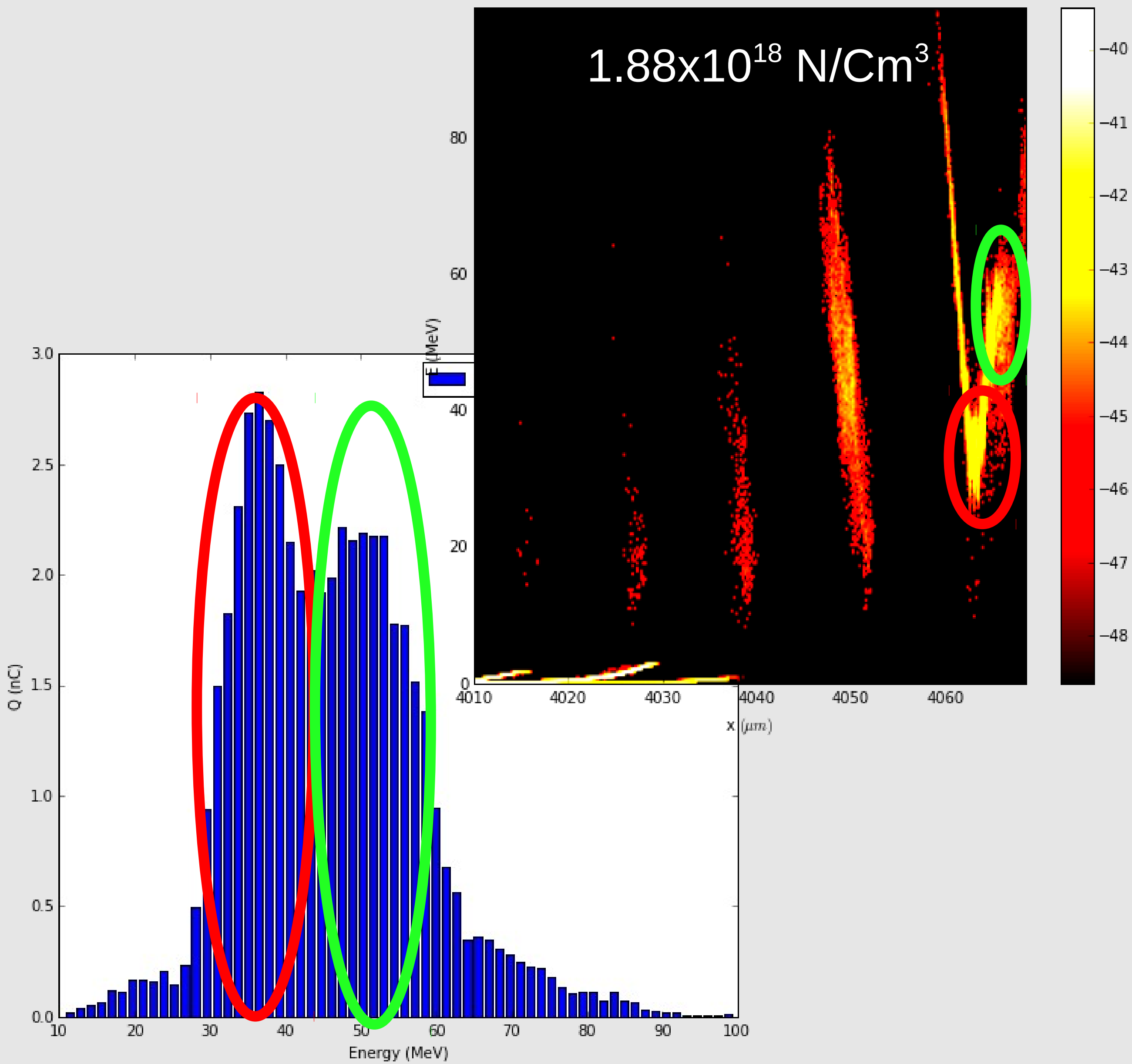
- Laser depletion can quickly compromise the regular structure of wakefield
- Main effect of depletion on injection is the **increase of energy spread** due to delocalization of injected charge. Main injection point became wider and the contribution of the 2°, 3° and 4° wave bucket increasing significantly
- If depletion occurs shortly before beam extractions its effects can be **visible** on energy spectrum
- For 1.2 mm gas jet depletion effect are already present

PIC Simulation: Depletion effect (2/3) (1.8-2.5X10^{18} N/Cm^3)



- Energy spectrum are taken at the end of 1.2 mm gas-jet
- A little difference in plasma density can produce a **large variation in electrons energy spectrum**. From **80 to 20** Mev in 10% of density variation
- FWHM of energy spectrum also strongly depend of plasma density; 3 times bigger (again in 10% of density variation)
- The first effect of weak laser depletion regard the "stretching" of main injection point with the result of **two spike energy spectrum**

PIC Simulation: Depletion effect (3/3) ($1.8-2.5X10^{18}$ N/Cm^3)



- Energy spectrum are taken at the end of 1.2 mm gas-jet
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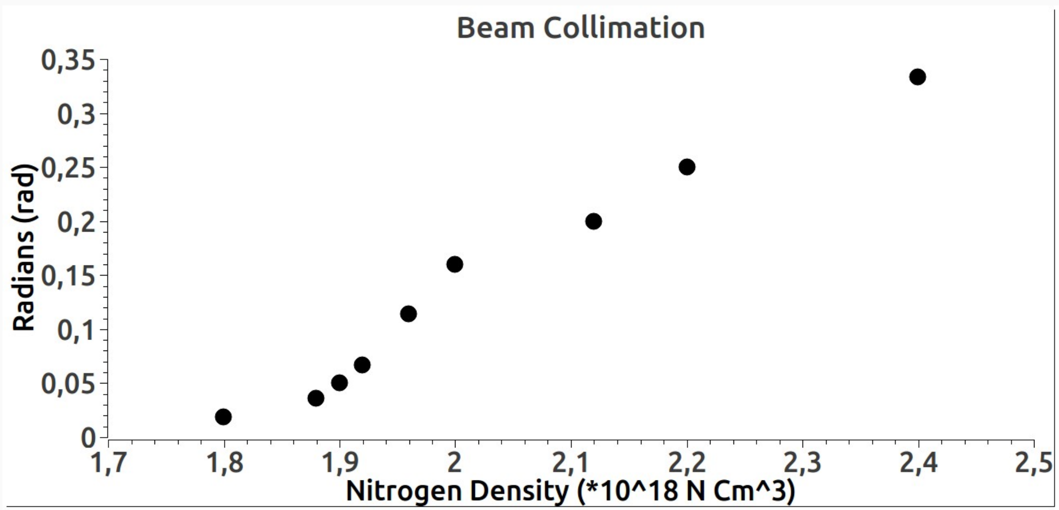
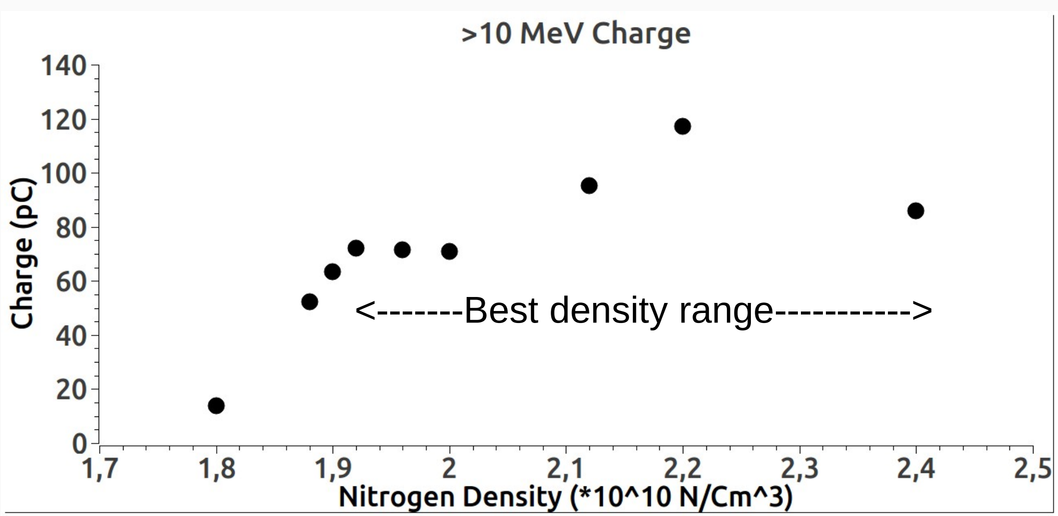
- FWHM of energy spectrum also strongly depend of plasma density; 3 times bigger (again in 10% of density variation)
- The first effect of weak laser depletion regard the "stretching" of main injection point with the result of **two spikes energy spectrum**

PIC Simulation: Charge and Beam Divergence (1.8-2.5X10^{18} N/Cm^3)





- Beam charge take account only of high energy particle
- Beam with <20 mrad collimation beam can be obtained at lower density
- Beam divergence increase linearly from 2x10^{18} N/Cm^3 density
- Beam charge graph show a maximum around 2.2x10^{18} N/Cm^3 and a quickly decrease down to 1.9x10^{18} N/Cm^3 density
- Beam charge and collimation can be optimezied around 1.9x10^{18} N/Cm^3

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Conclusion

- PIC simulation are in **good agreement** with experimental result
- The **useful density range** to obtain ~1nC high energy beam is 1.9-2,4x10^{18} N/Cm^3
- We can can not have simultaneously the best result in terms of **energy** and **charge** at fixed plasma density; especially close to threshold injection (1.7x10^{18} N/Cm^3)
- Gas jet optimization enable to obtain up to **4 time more energy** in the **useful density range**
- Beam collimation improve decreasing the pressure
- **Two spikes energy spectrum** can explain in terms of laser deplation; if laser depletion effect occurs near gas jet exit, two spikes energy spectrum are possible

Thanks for your attention!