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Title:

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

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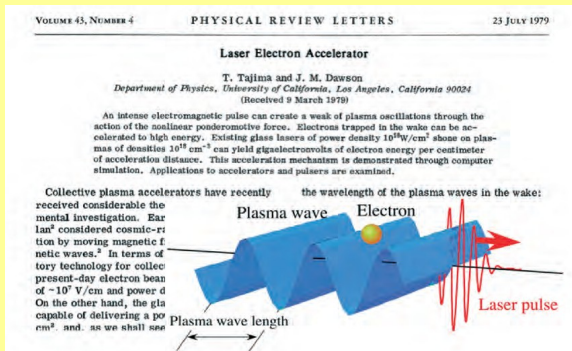
Outline

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



LWFA Mechanism: WakeField

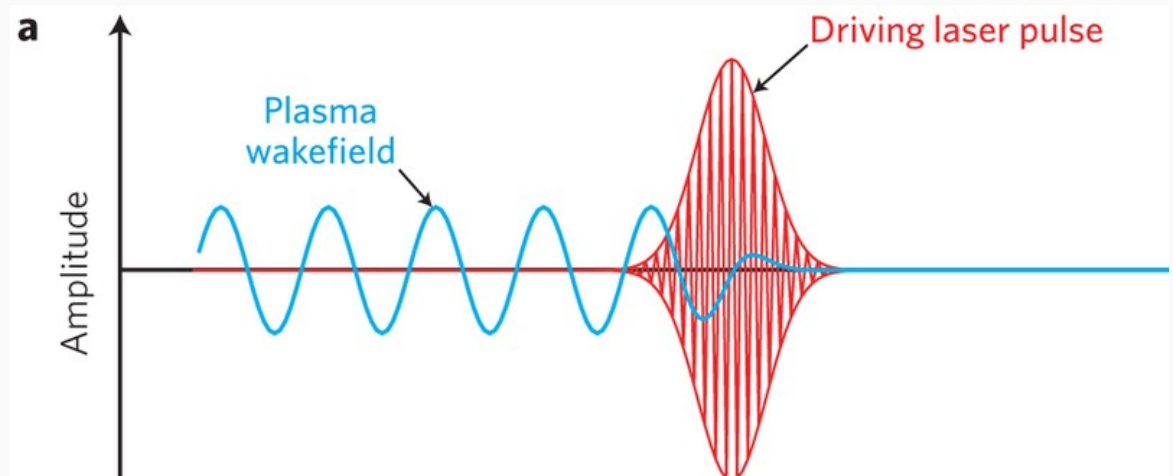
1979: proposal by Tajima&Dawson



A plasma wave can be excited in the wake of an **intense laser pulse** propagating in a plasma due to the **ponderomotive force** (PM). The wavelength and phase velocity of the plasma wave are determined by the way the wave is excited. We can imagine a laser pulse like a traveling (PM) force who generate a wakefield with the same phase velocity of laser pulse.

Ponderomotive force (PF) doesn't depend of particle charges (+-e) but his effect on ions is usually negligible ($m_i \gg m_e$). The main effect of PM force is that electron will be expelled from the region were the electric field is higher.

$$\left\langle m_e \frac{d\vec{v}}{dt} \right\rangle_T = -\frac{e^2}{2m_e \omega^2} \vec{\nabla} \langle E^2 \rangle_T$$





Injection: Injection Main Scheme

The high longitudinal electric field driven by the wakefield becomes completely useless unless we are able to put the electrons with the right speed in the right place at the right time. We can distinguish two type of injection.

- **Self-Injection:** The simplest case from the experimental point of view. The injected electrons came from the background plasma itself. Injection and acceleration process cannot be controlled separately, but there are several techniques to improve the quality of electron beam.
- **External Injection:** The electrons bunch is pre-accelerated and injected from separate external source (usually a conventional rf linear accelerator). Those injected electrons must be with the right phase, with right duration, well synchronized, extremely focused etc.

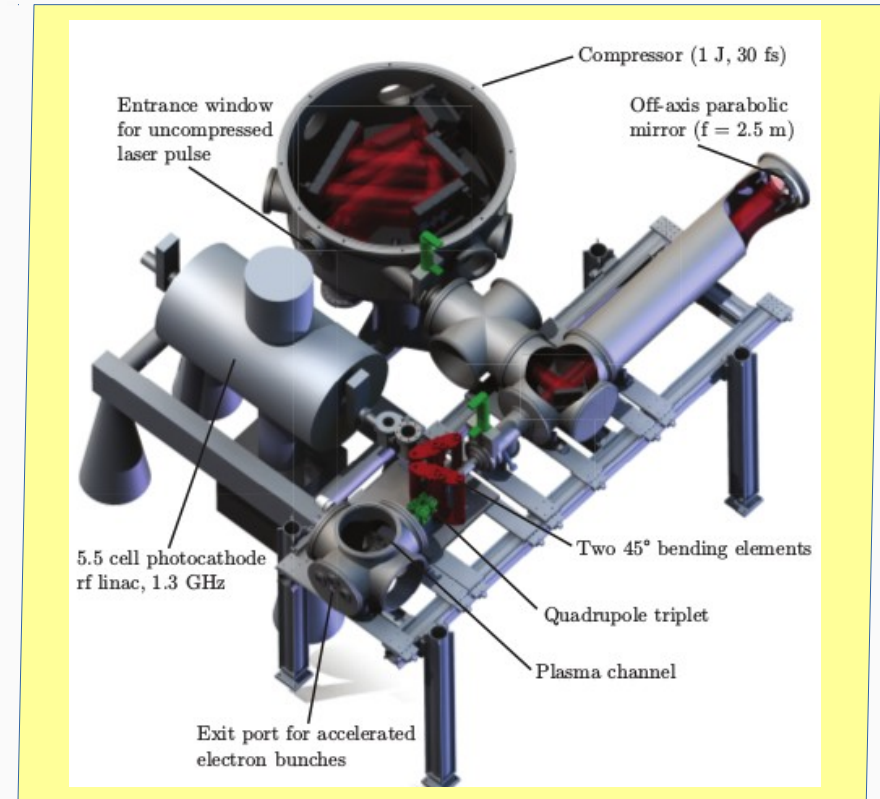


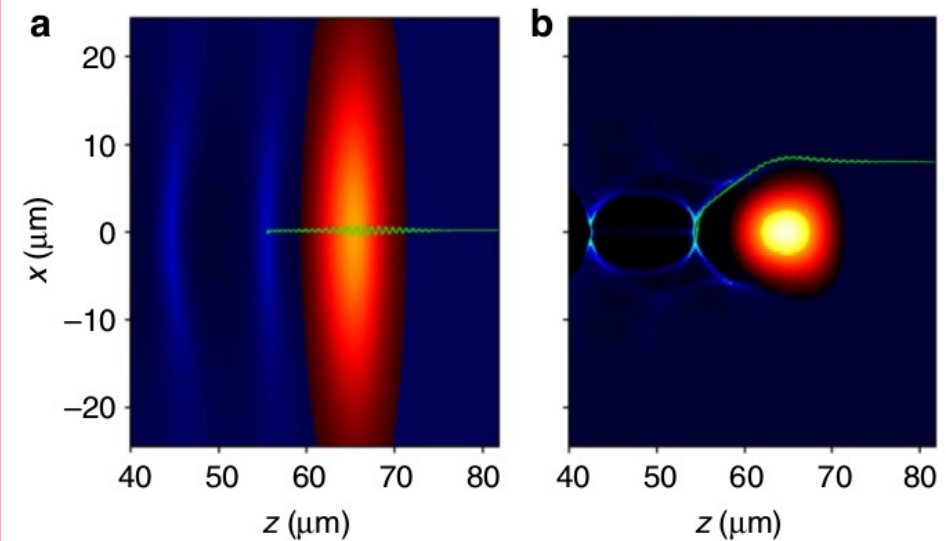
Fig3: The laser wakefield accelerator at the University of Twente; an example of external injection scheme. The bunch, from the photocathode rf linear accelerator, is transported to the channel via a bending section, which consists of two subsequent 45° bending magnets with an intermediate quadrupole magnet, and is focused towards the plasma channel using a focusing section consisting of quadrupole magnets.



Introduction: Self-Injection

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):** Trajectory 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.



The ILIL laboratory: Main parameters

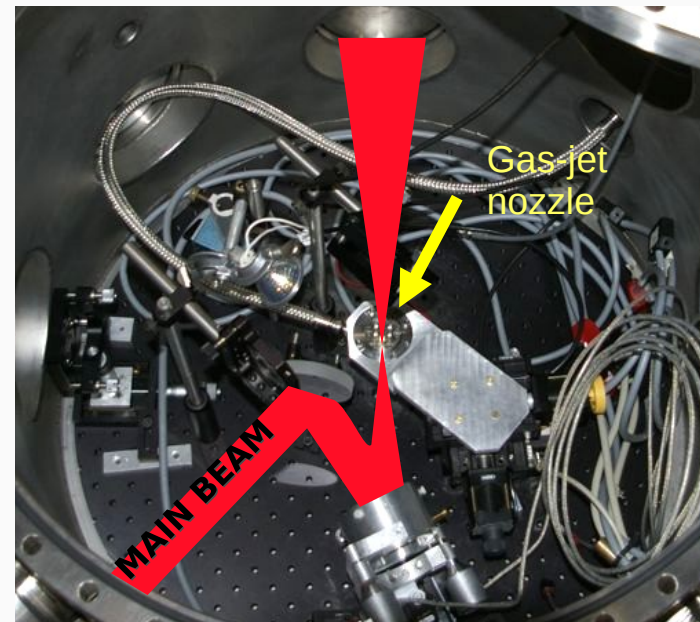


Laser main figures

- energy: up to 450mJ on target
- pulse duration $< 40\text{fs}$
- ASE contrast $> 10^9$
- $M^2 < 1.5$
- wavelength 800 nm

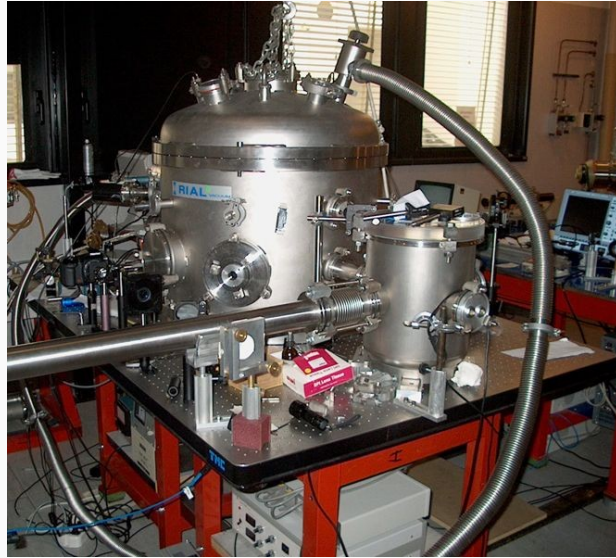
Interaction chamber

Intensity: up to $2 \times 10^{18} \text{ W/cm}^2$
Parabola (OAP) f/10-
Waist (FWHM) $20 \mu\text{m}$
Vector Potential a_0 0,96-





The ILIL laboratory: Chamber Configuration



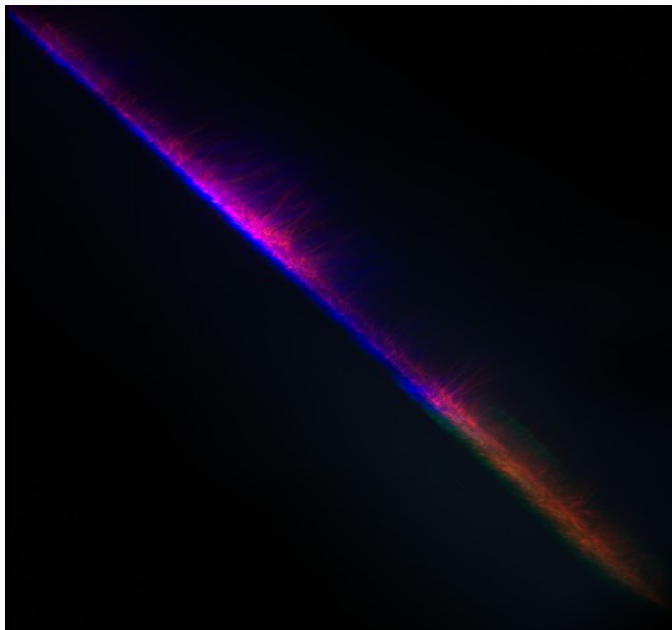
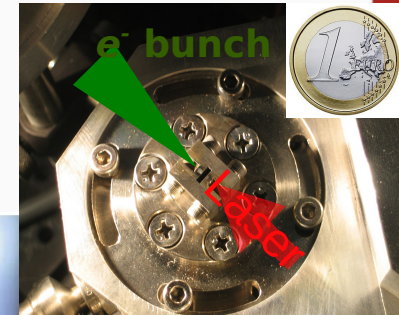
Target area equipment

- 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 $4 \times 1.2 \text{ mm}^2$ (laser propagating along the shortest size)

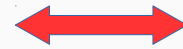
The laser pulse is focused in the proximity of the entrance edge of the gas-jet gas used are He, N_2 , Ar and mixture of He- N_2 and Ar-He



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.



Beam Whishlist



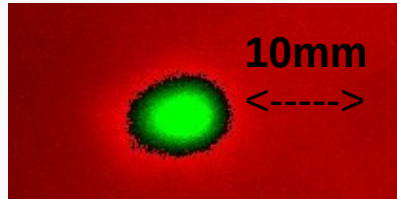
Tools (Fixed Laser Conf.)

- **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

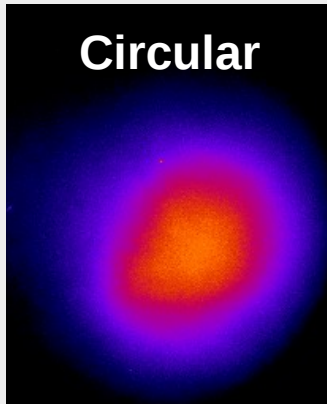
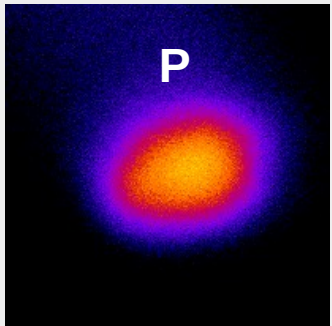
- **Move/change Gas jet:** Change focus position, density profile etc
- **Change Gas:** ionizing injection “control”, change density etc
- **Change gas pressure;** plasma density control
- **Change parabola:** Change laser intensity, Rayleigh length, etc. It requires a complete chamber reconfiguration!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



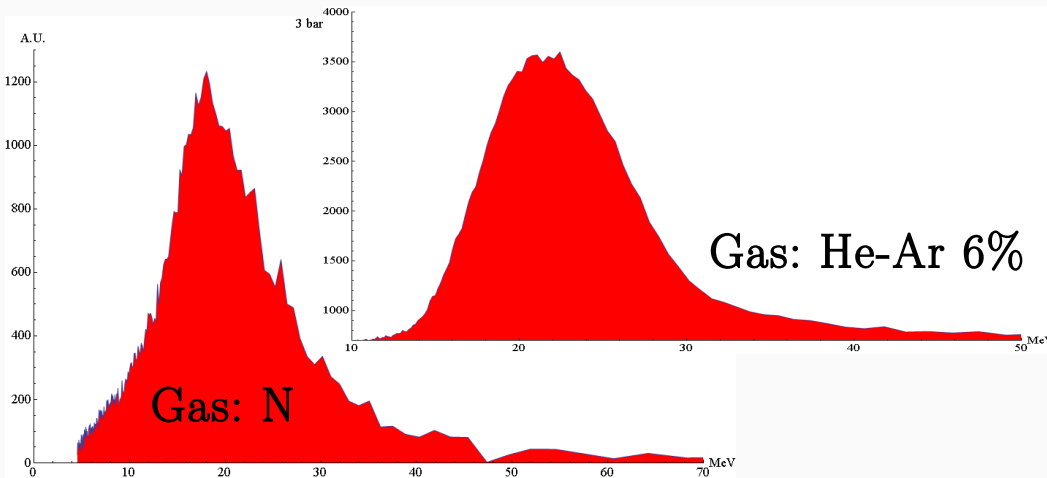
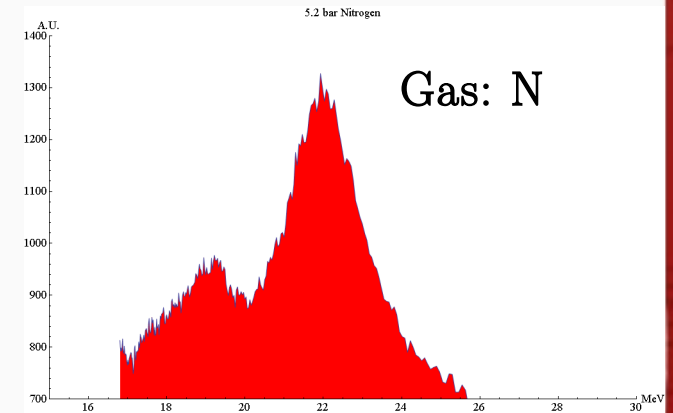
The ILIL laboratory: Some experimental results



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 1.9×10^{18} N/Cm³ 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 20-25 MeV 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-consistent 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 .

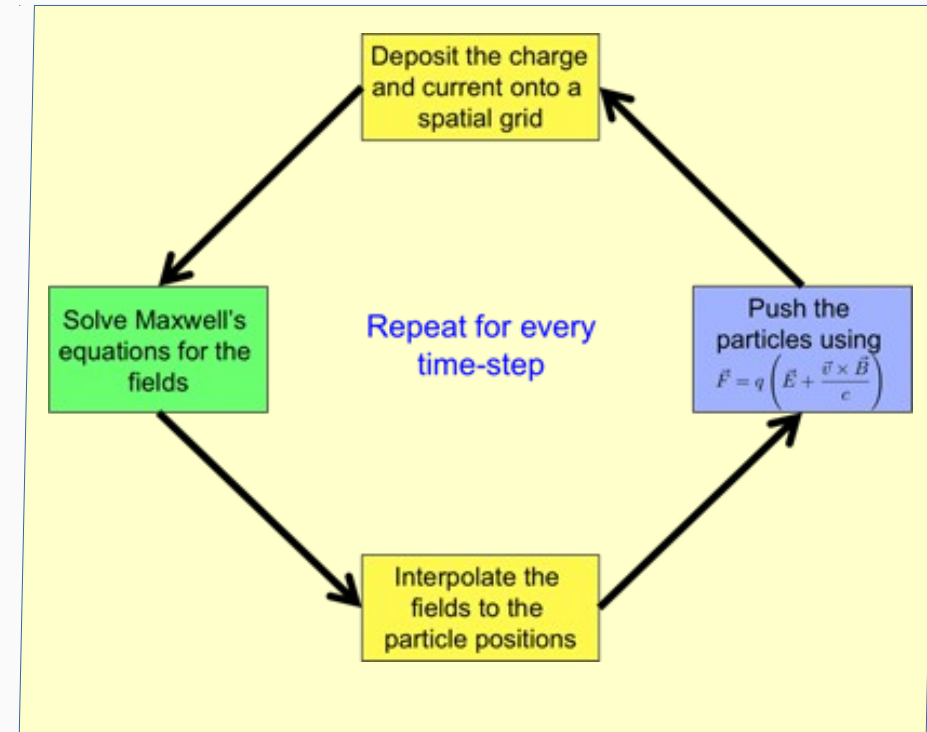
Parameters used in the 2-D simulation:

$$n_{\text{nitrogen}} = (1.6 - 16) \times 10^{18} \text{ cm}^{-3} \quad (\text{This correspond to nitrogen at 4-40 bar backing pressure})$$

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

Acceleration set-up for acceleration at ILIL laboratory.

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

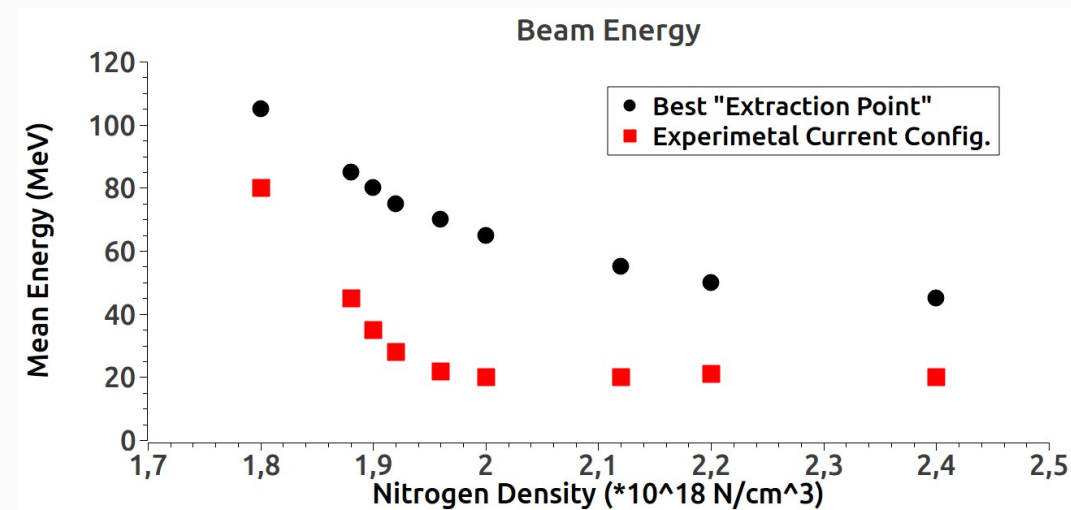
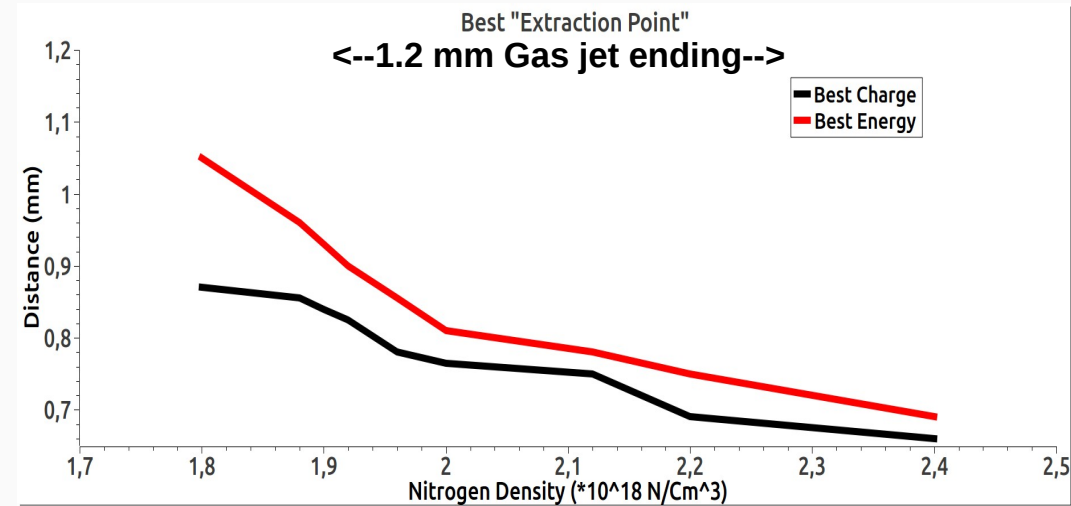




PIC Simulation: Injection and energy evolution ($1.8-2.5 \times 10^{18} \text{ n/Cm}^3$)

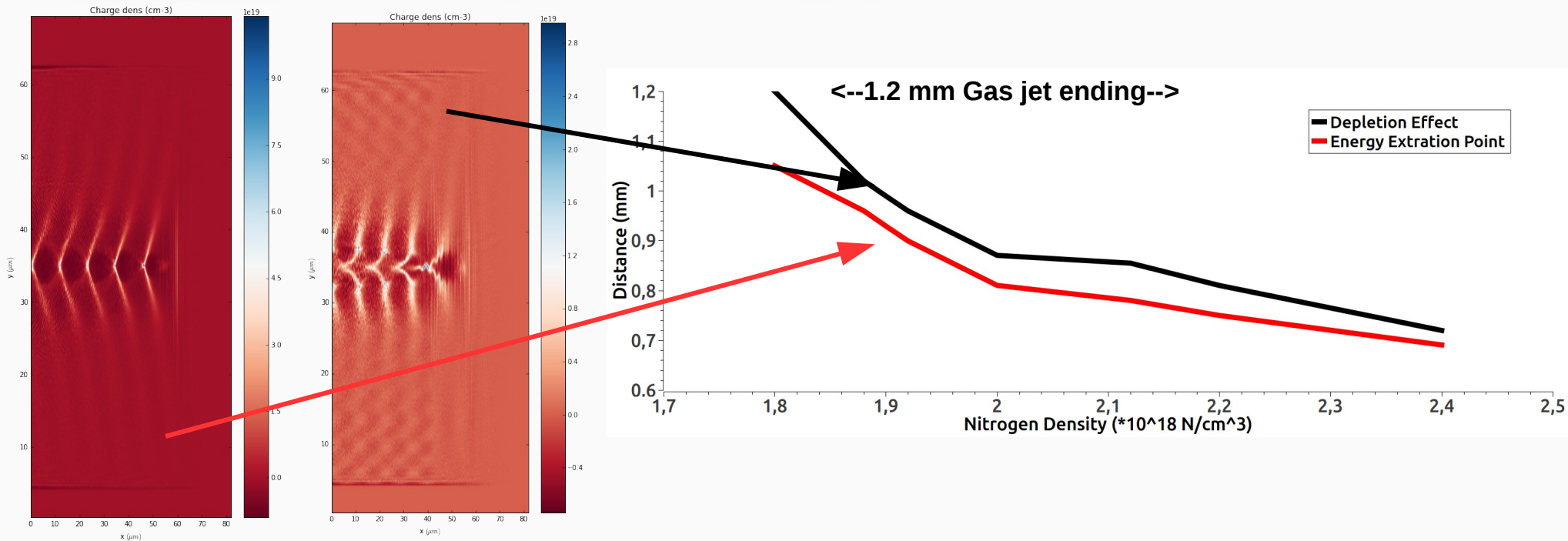
Observation

- “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** $\sim 1.8 \times 10^{18} \text{ N/Cm}^3$
- It's not possible obtain maximum of energy and beam charge at same time; especially at lower density
- **Injection threshold** is close to $1.7 \times 10^{18} \text{ N/Cm}^3$
- With current 1.2 mm gas jet the mean energy (for some density) can be **only 25%** of maximum possible





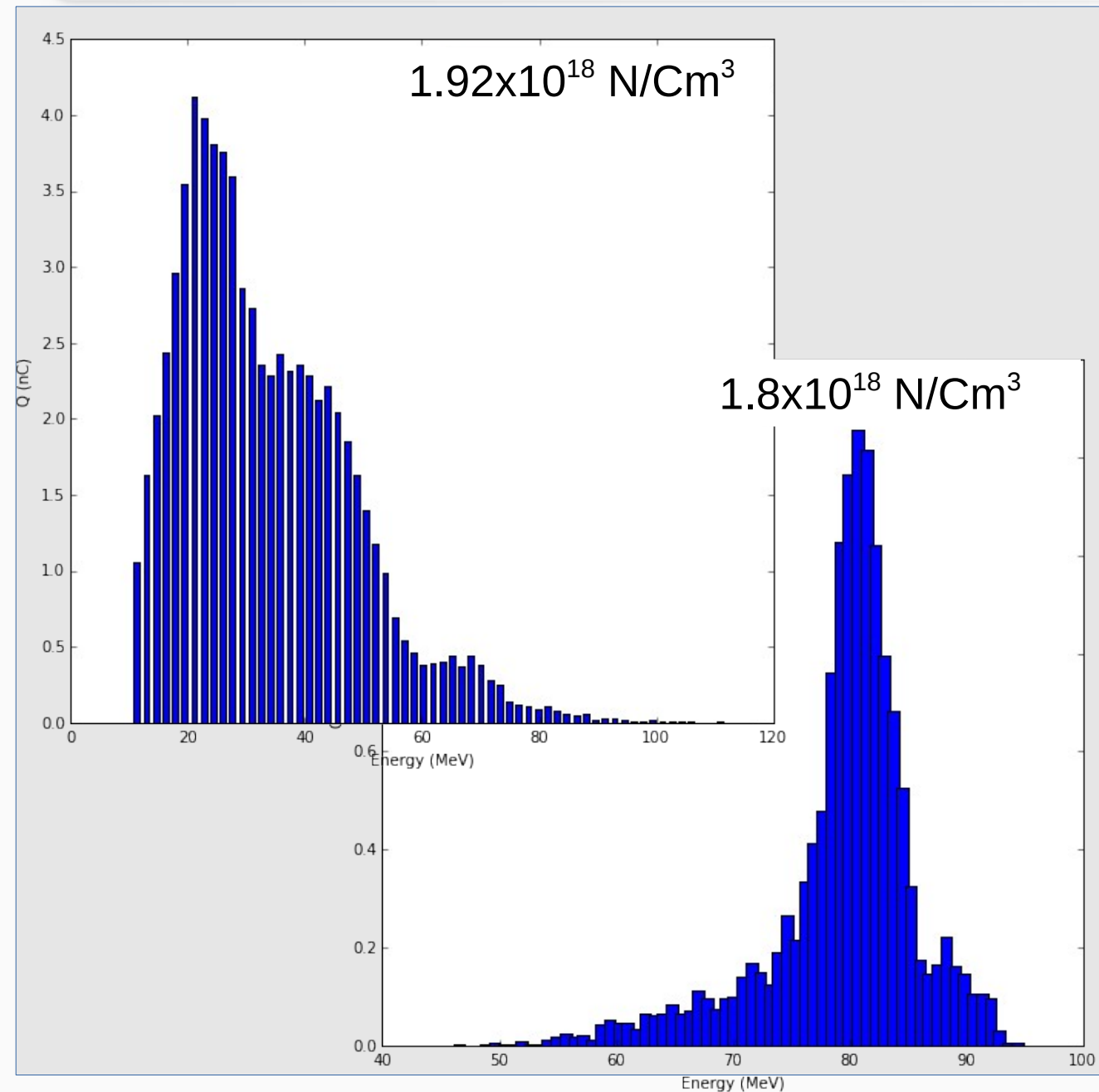
PIC Simulation: Depletion effect (1/3) ($1.8-2.5 \times 10^{18}$ N/Cm³)



- 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^o, 3^o and 4^o 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



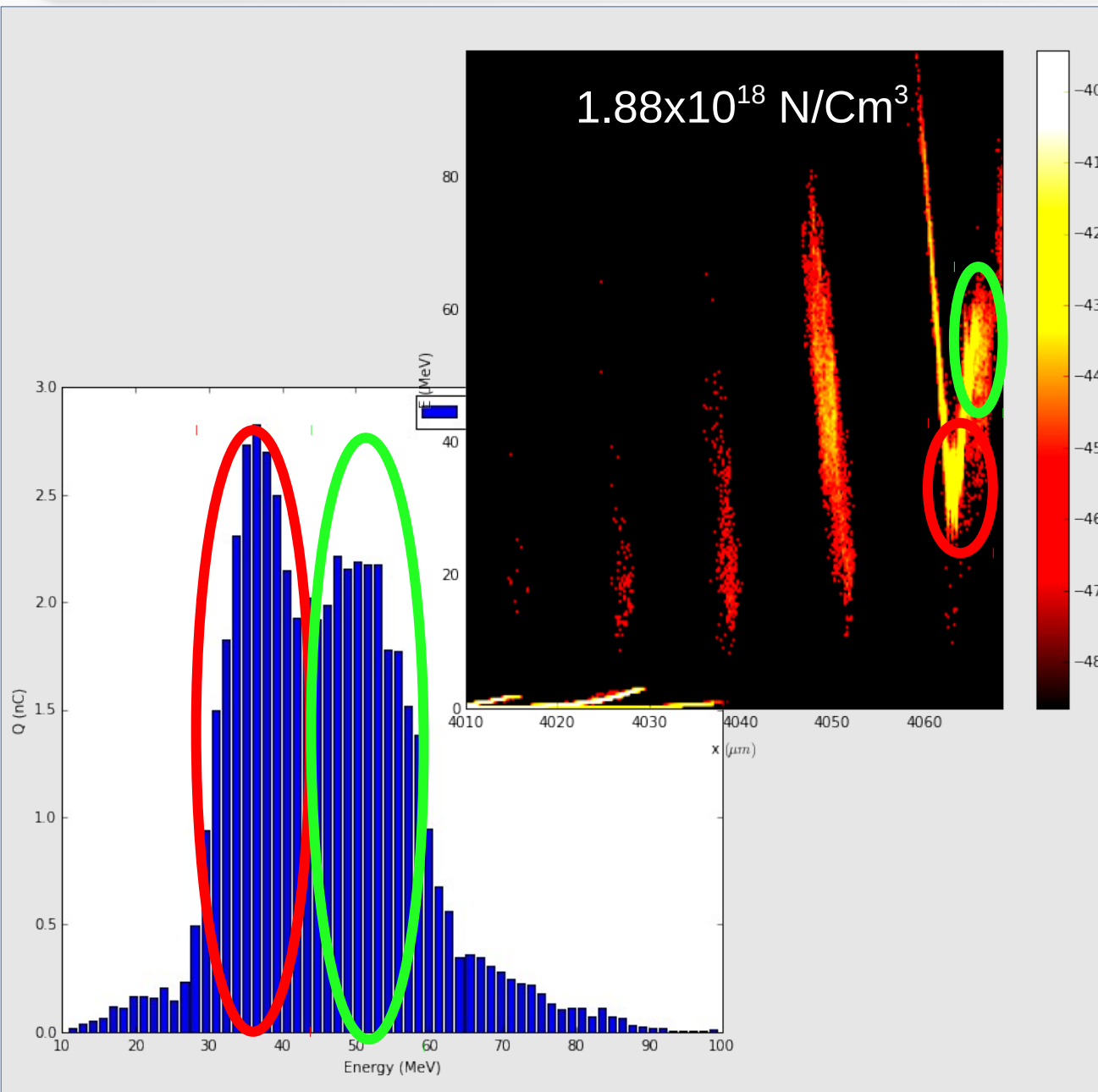
PIC Simulation: Depletion effect (2/3) ($1.8\text{-}2.5 \times 10^{18}$ N/Cm³)



- 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**



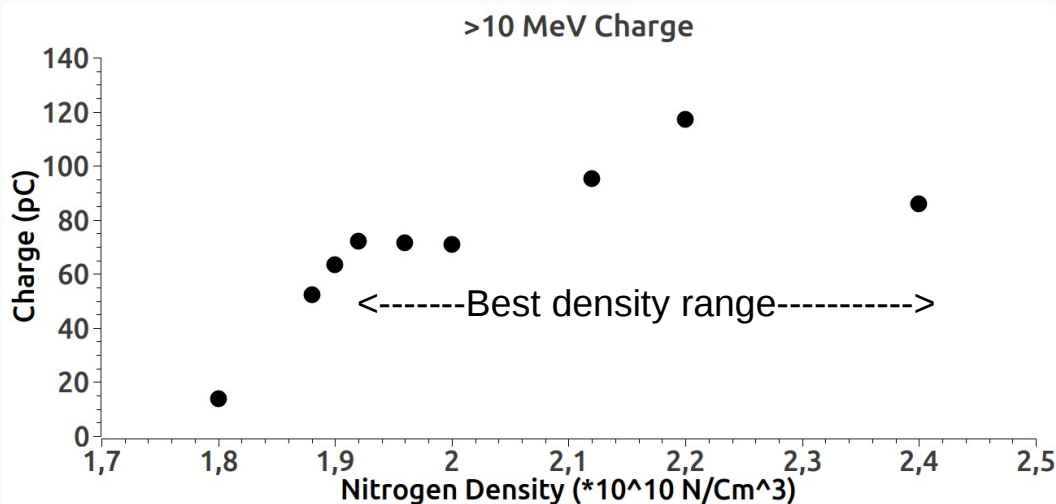
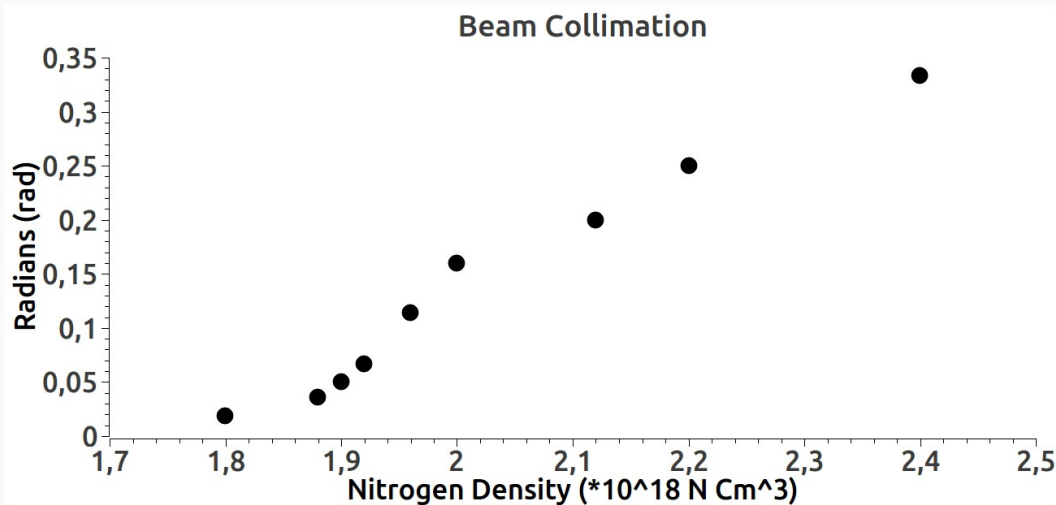
PIC Simulation: Depletion effect (3/3) ($1.8\text{-}2.5 \times 10^{18}$ N/Cm³)



- 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 spikes energy spectrum**



PIC Simulation: Charge and Beam Divergence ($1.8-2.5 \times 10^{18}$ N/Cm³)



- 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 2×10^{18} N/Cm³ density
- Beam charge graph show a maximum around 2.2×10^{18} N/Cm³ and a quickly decrease down to 1.9×10^{18} N/Cm³ density
- Beam charge and collimation can be optimezied around 1.9×10^{18} N/Cm³



Conclusion

- PIC simulation are in **good agreement** with experimental result
- The **useful density range** to obtain $\sim 1\text{nC}$ high energy beam is $1.9\text{-}2,4 \times 10^{18} \text{ N/Cm}^3$
- We can not have simultaneously the best result in terms of **energy** and **charge** at fixed plasma density; especially close to threshold injection ($1.7 \times 10^{18} \text{ N/Cm}^3$)
- Gas jet optimization may enable to obtain up to **4 time more energy** in the **useful density range** (10-80MeV Vs 10-25meV)
- Beam collimation improve decreasing the pressure; **15-100 mrad** tunable beam is possible
- **Two spikes energy spectrum** can explain in terms of laser depletion; if laser depletion effect occurs near gas jet exit, two spikes energy spectrum are possible

The background features a series of curved, overlapping light trails in shades of blue, red, and green, creating a sense of motion and depth against a dark, almost black, background. The trails are most prominent in the lower right quadrant and fade towards the top left.

Thanks for your attention!