Stato simulazioni “self-injection” e “afterburner”

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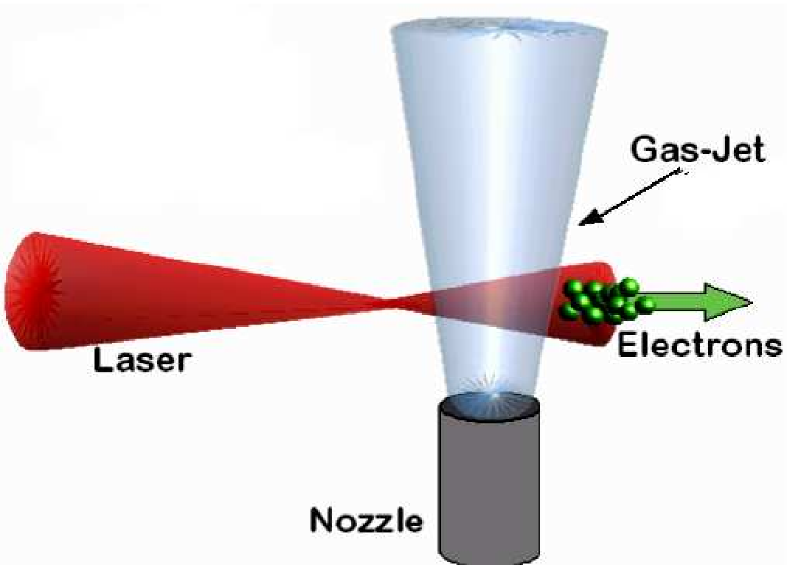
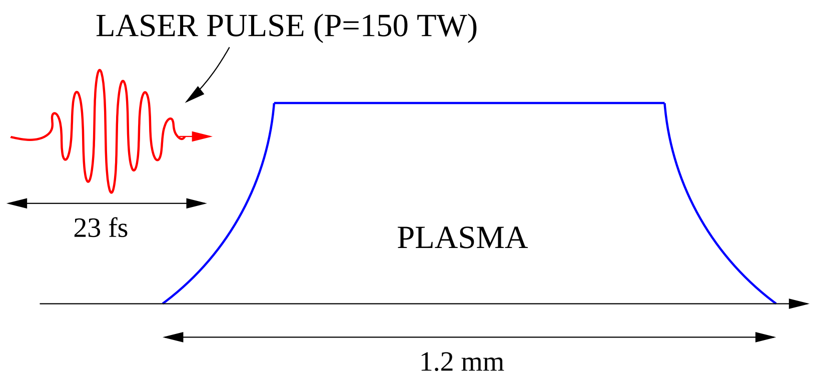
Self-injection experiments with FLAME

- (Half power) FLAME laser
  - P =150 TW, $\tau_{fwhm} = 24$ fs
  - waist: $w_0 = 8 \div 40$ ($1/e^2$ radius of the laser intensity profile, $w_{fwhm} \simeq 1.2\, w_0$)
  - norm. vector potential $a_0 \equiv \frac{eA_{laser}}{mc^2} = 8.5 \cdot 10^{-10} \sqrt{I[\text{W/cm}^2](\lambda[\mu\text{m}])^2} \geq 2$



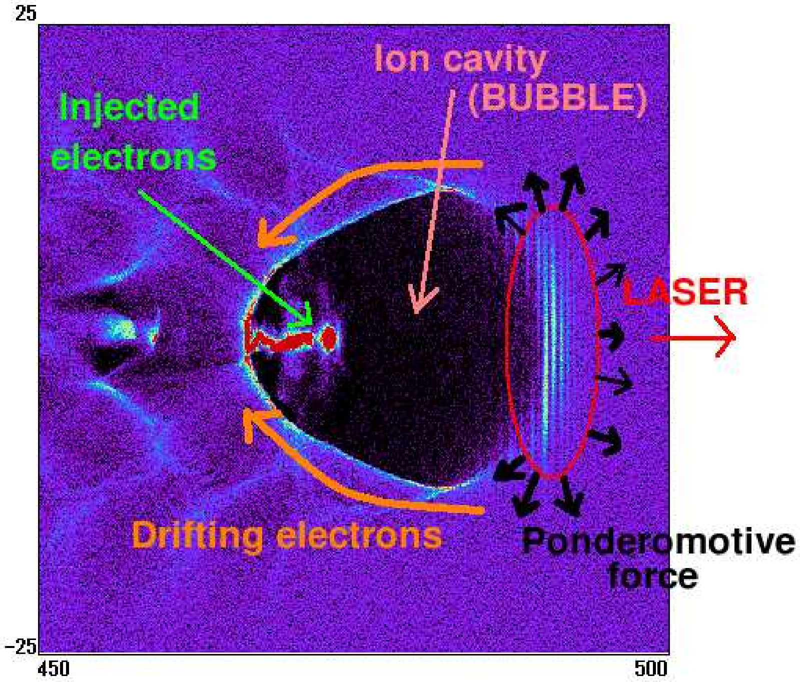


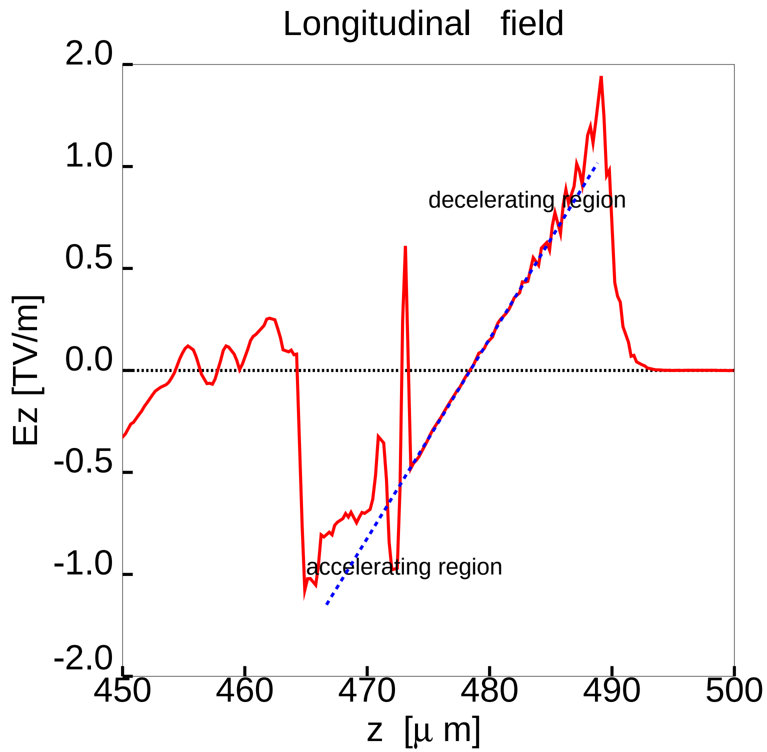
- Two regimes:

1. $w_0 < \lambda_p \Rightarrow$ **Nonlinear 3D regime (bubble)**
2. $w_0 > \lambda_p \Rightarrow$ **Nonlinear "1D-like" regime** (+ properly modulated gas-jet)

Self-injection experiments with FLAME

- **Nonlinear 3D regime (bubble)** [a]





- $R_{bub} \simeq O(\lambda_p)$ $\quad E_z^{(max)} \simeq 100\sqrt{n_0[\mathrm{cm}^{-3}] \times a_0}$ [V/m]
- $\begin{cases} v_{elect} \simeq c \\ v_{bub} \simeq c(1 - 3\omega_p^2/(2\omega_0^2)) < v_{elect} \end{cases}$ $\Rightarrow$ acc. length is finite + monochromaticity

[a] S. Gordienko and A. Pukhov, Phys. Plas. 12 (2005) / W. Lu *et al.* PRSTAB 10 (2007)

Self-injection experiments with FLAME

- **Nonlinear 3D regime (bubble)**: formulae (in general)
  - "stability" of the bubble: $k_p\, R_{bub} \simeq k_p\, w_0 \simeq 2\sqrt{a_0}$
  - dephasing length: $L_d = \frac{2}{3}\frac{\omega_0^2}{\omega_p^2} R_{bub}$
  - pupm depletion: $L_{pd} = \frac{\omega_0^2}{\omega_p^2} c\tau_{fwhm}$, must be L_{pd}> min(L_{gasjet}, L_d)
  - $e-$energy (dephasing): $W[\text{GeV}] \simeq 1.7 \times \left(\frac{P[\text{TW}]}{100}\right)^{1/3} \left(\frac{10^{18}}{n_p[\text{cm}^{-3}]}\right)^{2/3} \left(\frac{0.8}{\lambda_0[\mu\text{m}]}\right)^{4/3}$
  - charge injected: $Q[\text{pC}] \simeq 400 \times \left(\frac{0.8}{\lambda_0[\mu\text{m}]}\right) \left(\frac{P[\text{TW}]}{100}\right)^{1/2}$

- **Nonlinear 3D regime (bubble)**: formulae (for $\frac{1}{2}$FLAME)

Taking w_0 as a free parameter we have

- n_p [cm^{-3}]=$7.56 \cdot 10^{21}/(w_0[\mu\text{m}])^3$
- $L_d[\mu\text{m}] = 0.154 \times (w_0[\mu\text{m}])^4$
- $L_{pd}[\mu\text{m}] = 1.66 \times (w_0[\mu\text{m}])^3$
- $\boxed{W[\text{MeV}] \simeq 68.3 \times \frac{L_{gasjet}[\mu\text{m}]}{(w_0[\mu\text{m}])^2}\left(1 - \frac{3.25\times(L_{gasjet}[\mu\text{m}])}{(w_0[\mu\text{m}])^4}\right)}$ (for $L_d \geq L_{gasjet}/2$)
- $Q \simeq 0.5$ nC

Self-injection experiments with FLAME

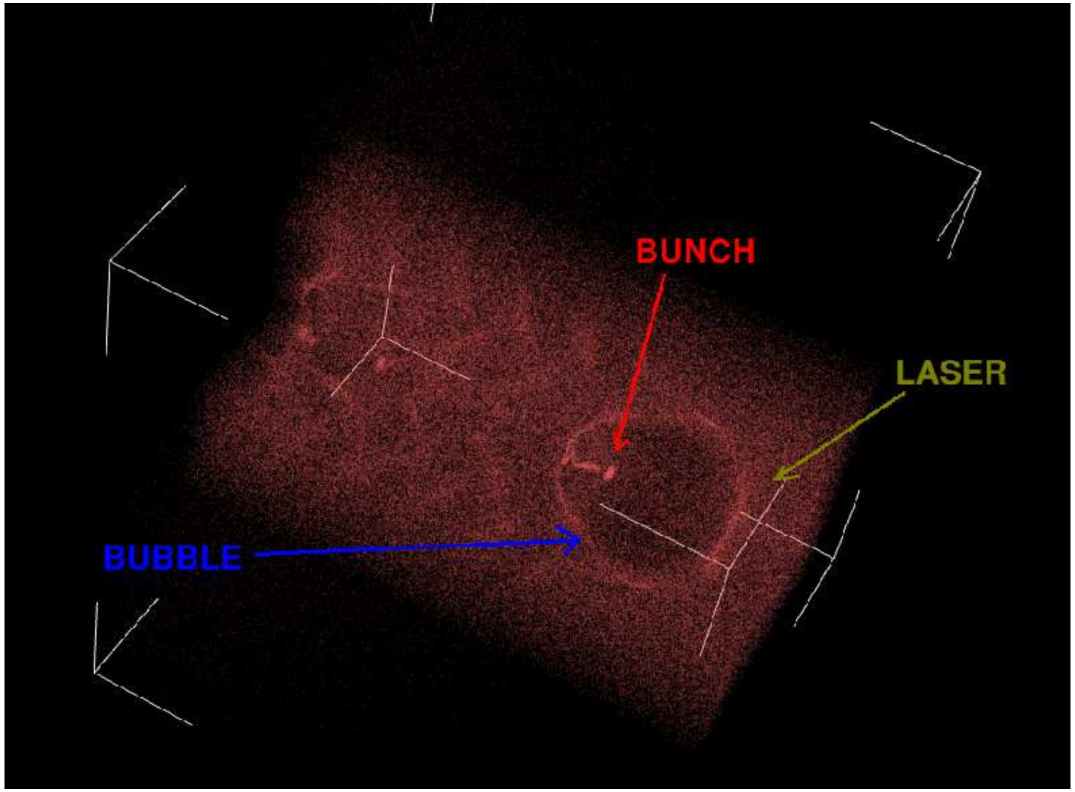
- Let's consider some examples:

1. "best" (in terms of monochromaticity) bunch: $L_d \equiv L_{gasjet} \simeq 0.9 \div 1$ mm
   $w_0 \simeq R_{bub} \simeq 9\ \mu$m, $I \simeq 1.2 \cdot 10^{20}$ W/cm^2, $a_0 = 7.4$
   $L_{pd} \simeq 1.2$ mm > L_{gasjet}, L_d
   $n_p \simeq 1 \cdot 10^{19}$ cm^{-3}
   $W \simeq 400$ MeV
2. highest energy for a given L_{gasjet} ($\simeq$ 1 mm): $\frac{\partial E}{\partial w_0}\Big|_{L_{gasjet}} = 0$
   $w_0 \simeq R_{bub} \simeq 10\ \mu$m, $I \simeq 9.7 \cdot 10^{19}$ W/cm^2, $a_0 = 6.7$
   $L_d \simeq 1.5$ mm > L_{gasjet}, $L_{pd} \simeq 1.7$ mm > L_{gasjet}
   $n_p \simeq 7.7 \cdot 10^{18}$ cm^{-3}
   $W \simeq 450$ MeV (monochromaticity ???)
3. $W = 1$ GeV monochromatic electron beam (with gas jet):
   $w_0 \simeq R_{bub} \simeq 14\ \mu$m, $I \simeq 5 \cdot 10^{19}$ W/cm^2, $a_0 = 4.8$
   $L_d \equiv L_{gasjet} \simeq$5.6 mm, $L_{pd} \simeq 4.4$ mm < L_{gasjet} (!!!)
   $n_p \simeq 3 \cdot 10^{18}$ cm^{-3}
4. Out of "bubble" regime: $a_0 \lesssim 3.5$
   $w_0 \gtrsim 19\ \mu$m, $I < 2.6 \cdot 10^{19}$ W/cm^2

PIC simulation (with ALaDyn) of the case #1

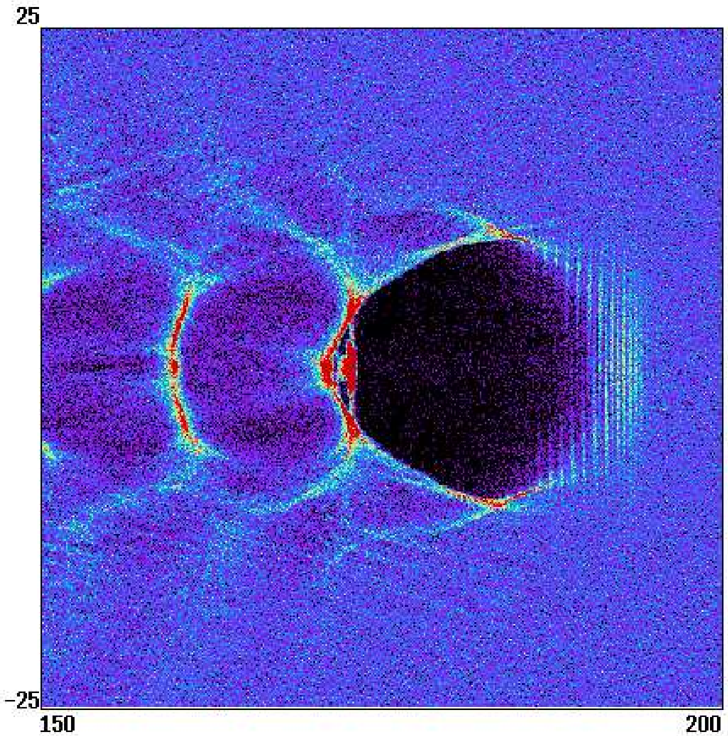
Self-injection experiments with FLAME

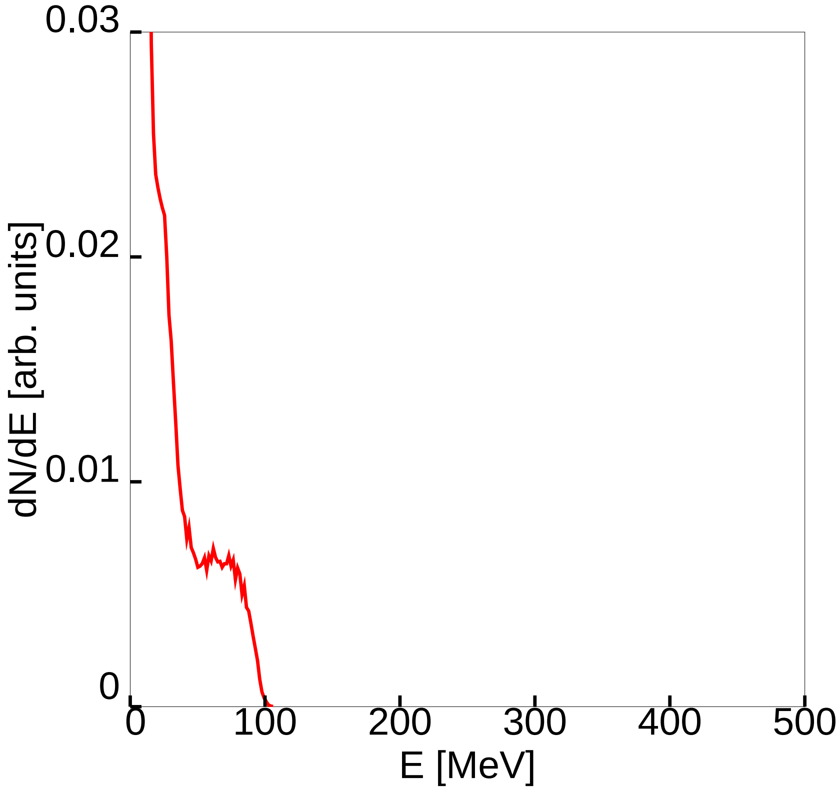
- **3D ALaDyn PIC simulation @ CINECA** ($\sim$ 14000 CPUh = 7 days on 80 CPUs)
  - domain: (80$\times$80$\times$80) μm^3
  - grid: 1439$\times$131$\times$131 $\Rightarrow$ res. in the center: 18 points/μm long., 3 points/μm trasv.
  - 25 $\times 10^6$ numerical particles
  - $\sim$ 20000 time steps



Self-injection experiments with FLAME

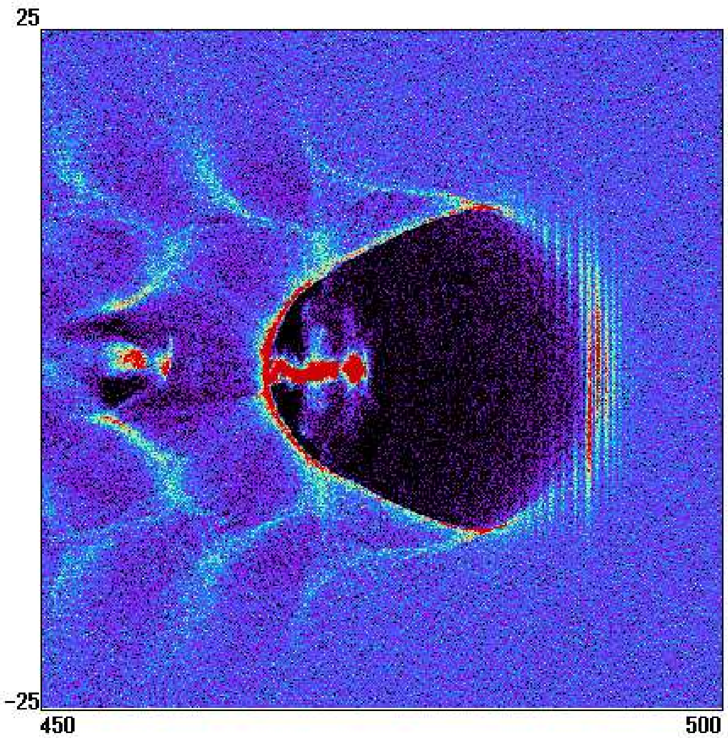
- 3D simulation of the case #1: $c\,t = 200\ \mu$m (injection)

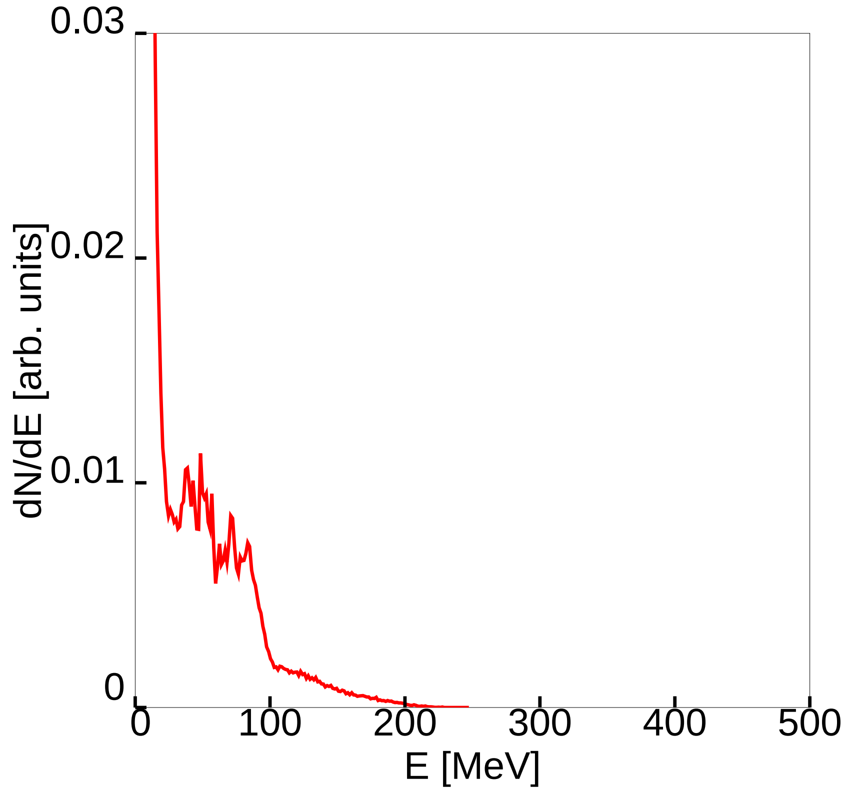




Self-injection experiments with FLAME

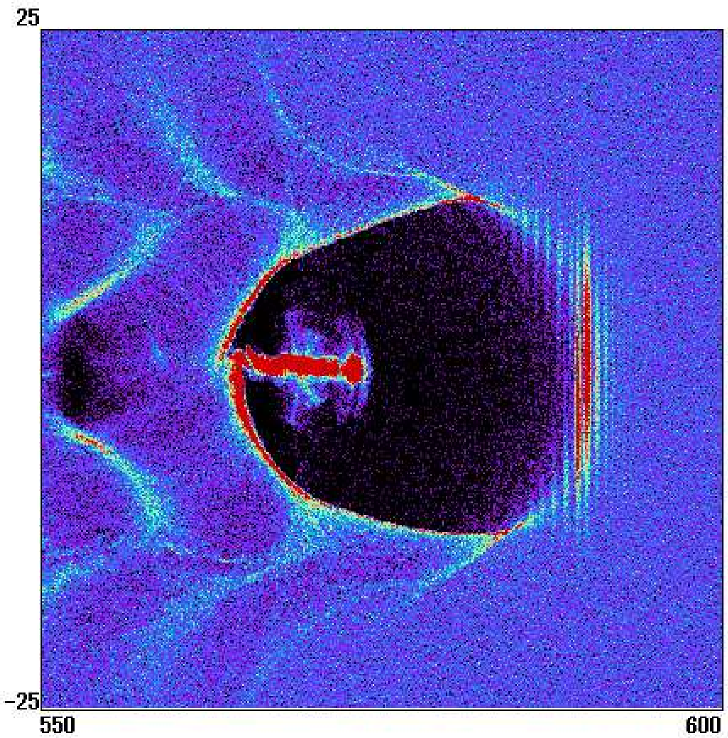
- 3D simulation of the case #1: $c\,t = 500\ \mu$m

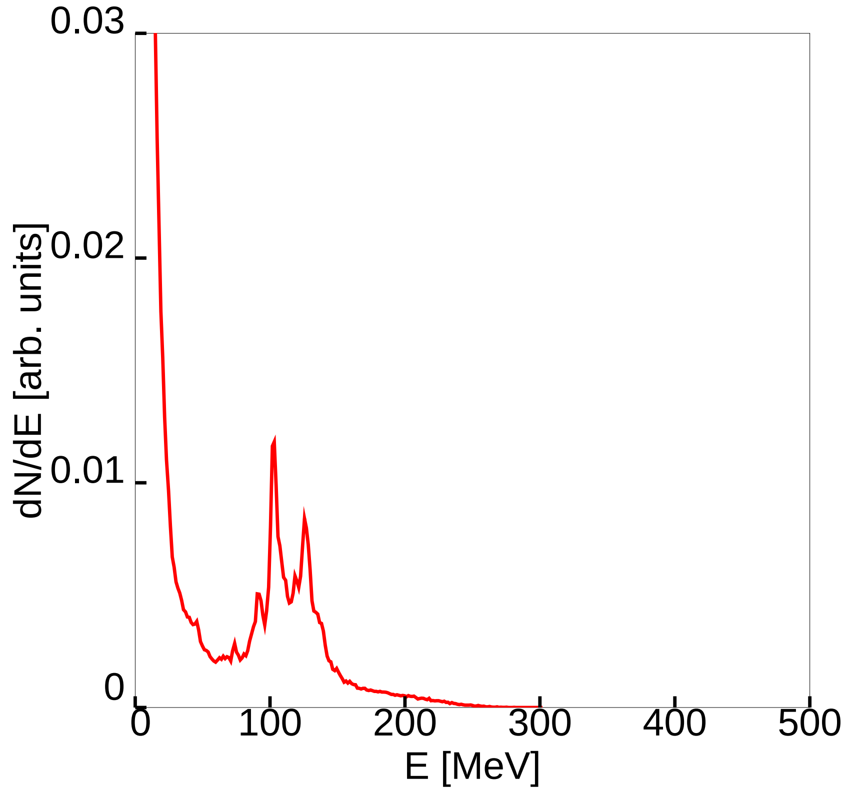




Self-injection experiments with FLAME

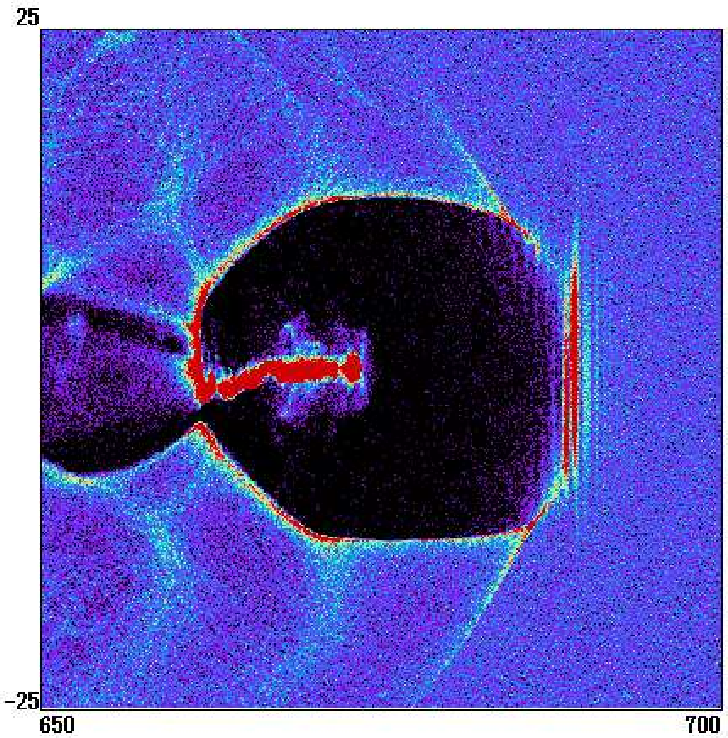
- 3D simulation of the case #1: $c\,t = 600\ \mu$m

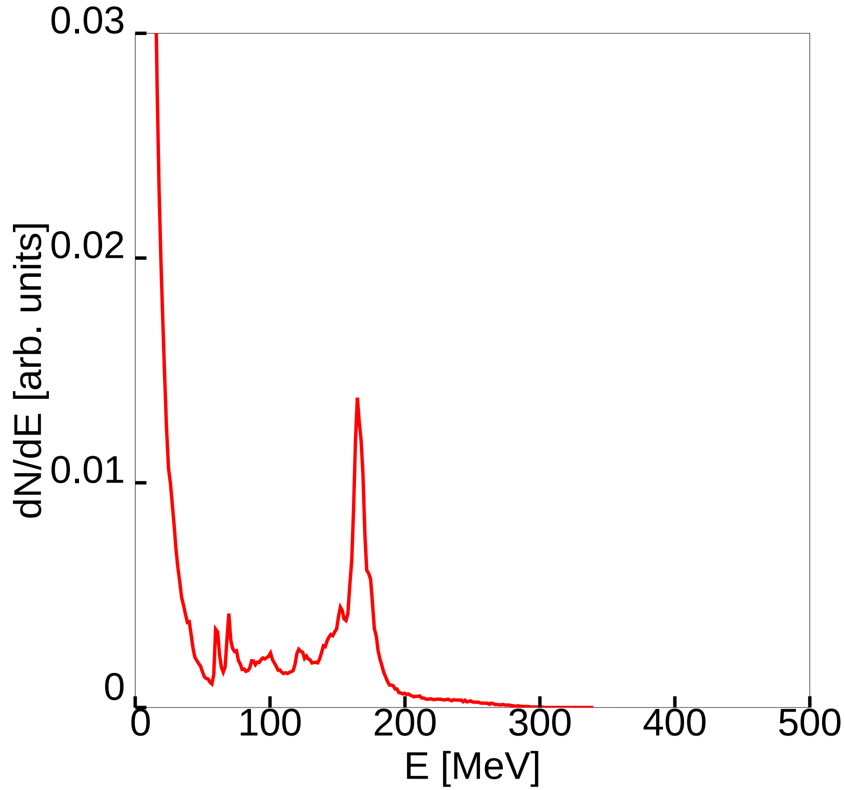




Self-injection experiments with FLAME

- 3D simulation of the case #1: $c\,t = 700\ \mu$m

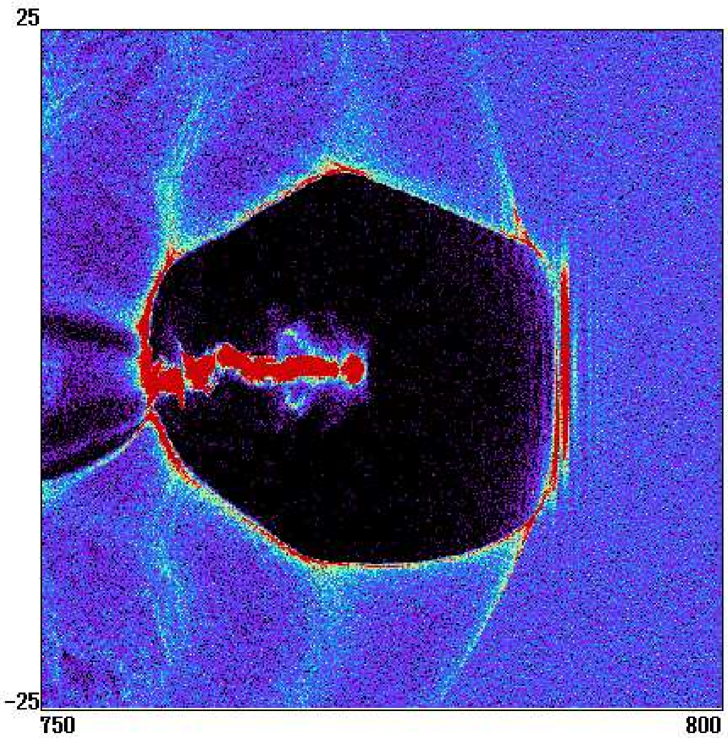


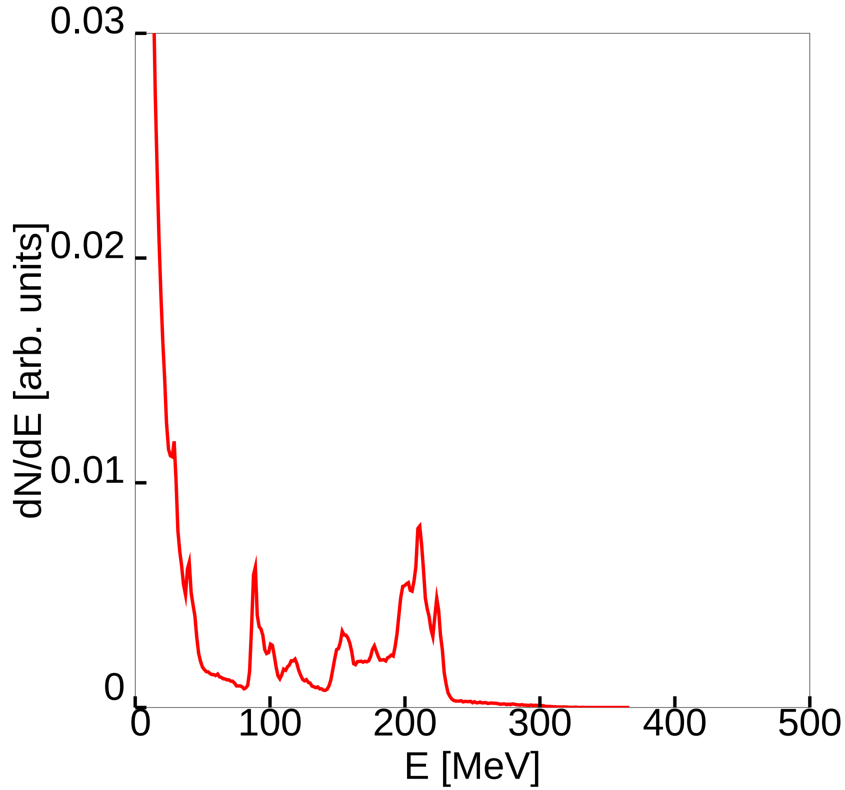


⇒**monochromatic peak!!** $W = (160 \pm 5)$ MeV, $Q = 0.45$ nC (FWHM)

Self-injection experiments with FLAME

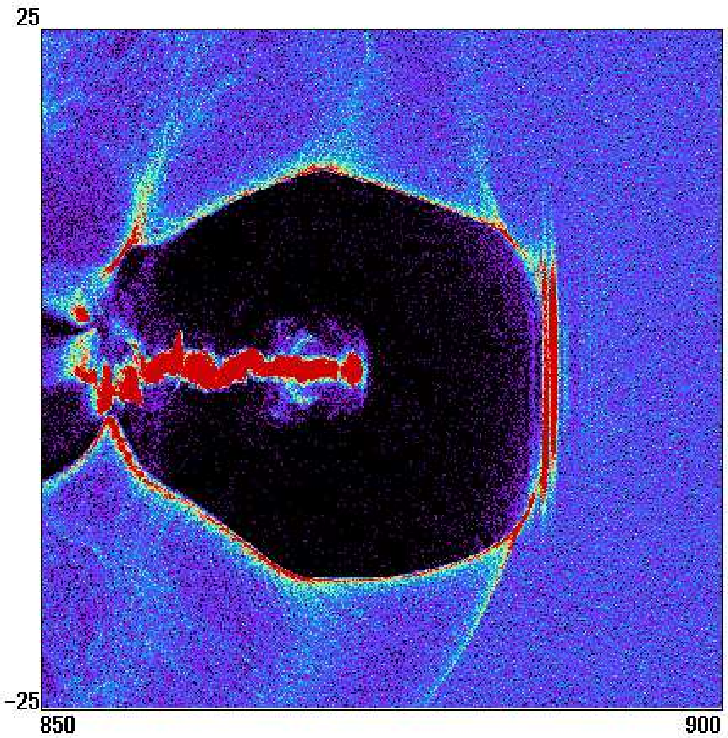
- 3D simulation of the case #1: $c\,t = 800\ \mu$m

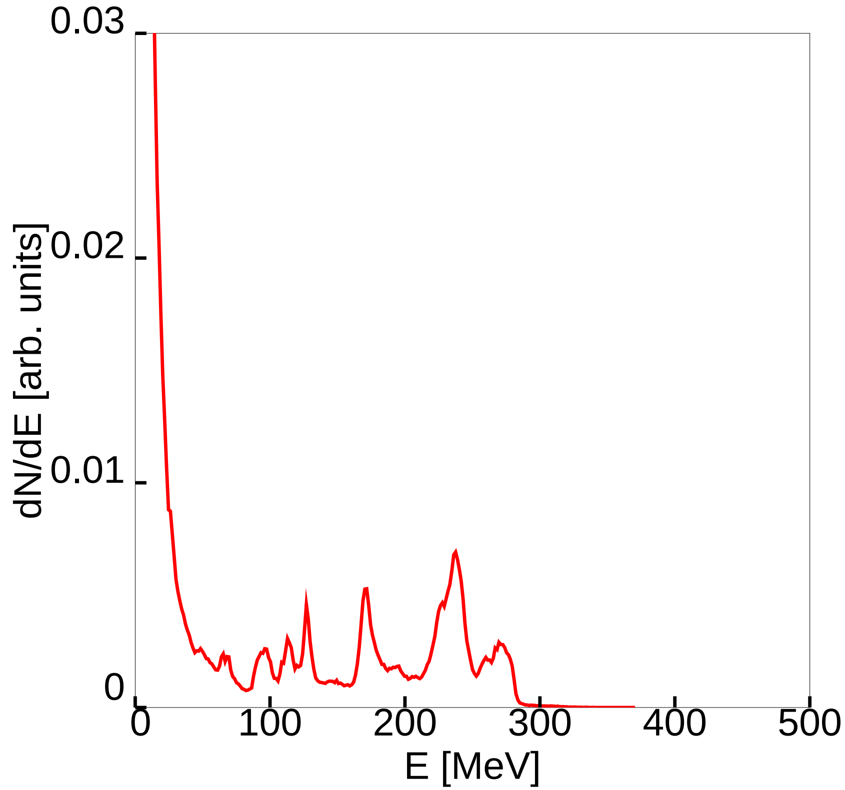




Self-injection experiments with FLAME

- 3D simulation of the case #1: $c\,t = 900\ \mu$m





⇒ Several peaks (post-dephasing pattern) !!

$W_1 = (236 \pm 9)$ MeV, $Q = 0.8$ nC (FWHM)

$W_2 = (170 \pm 5)$ MeV, $Q = 0.35$ nC (FWHM)

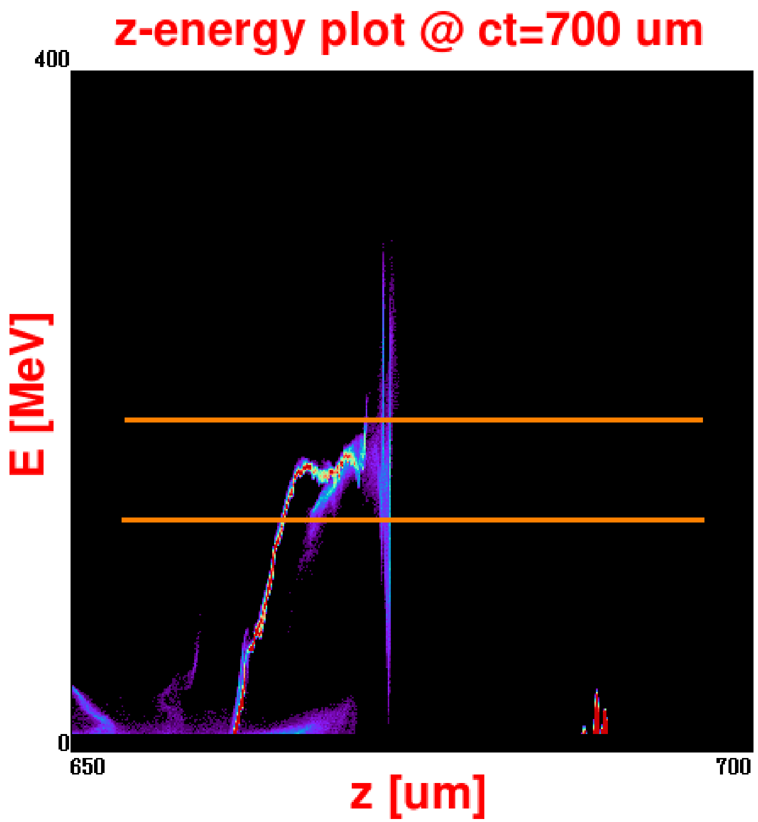
$W_3 = \cdots$

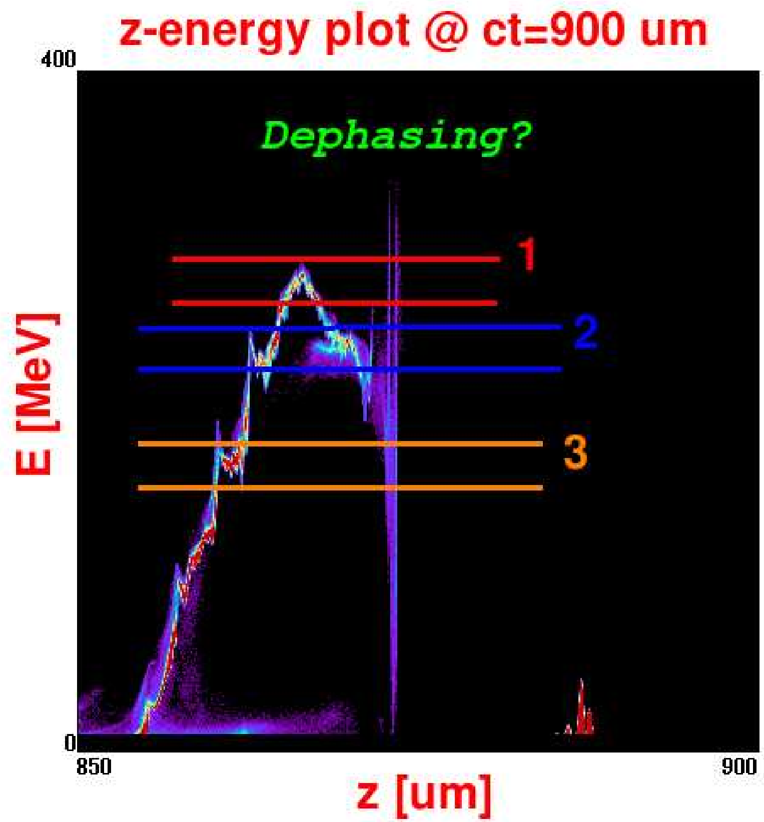
Self-injection experiments with FLAME

- The simulated energy ($\sim$ 200 MeV) is **LOWER** than the theoretical value ($\sim$ 400 MeV):

1. beam loading effect (perturbation of Ez in the bunch region) [small effect]

2. Anticipate dephasing $\Downarrow$

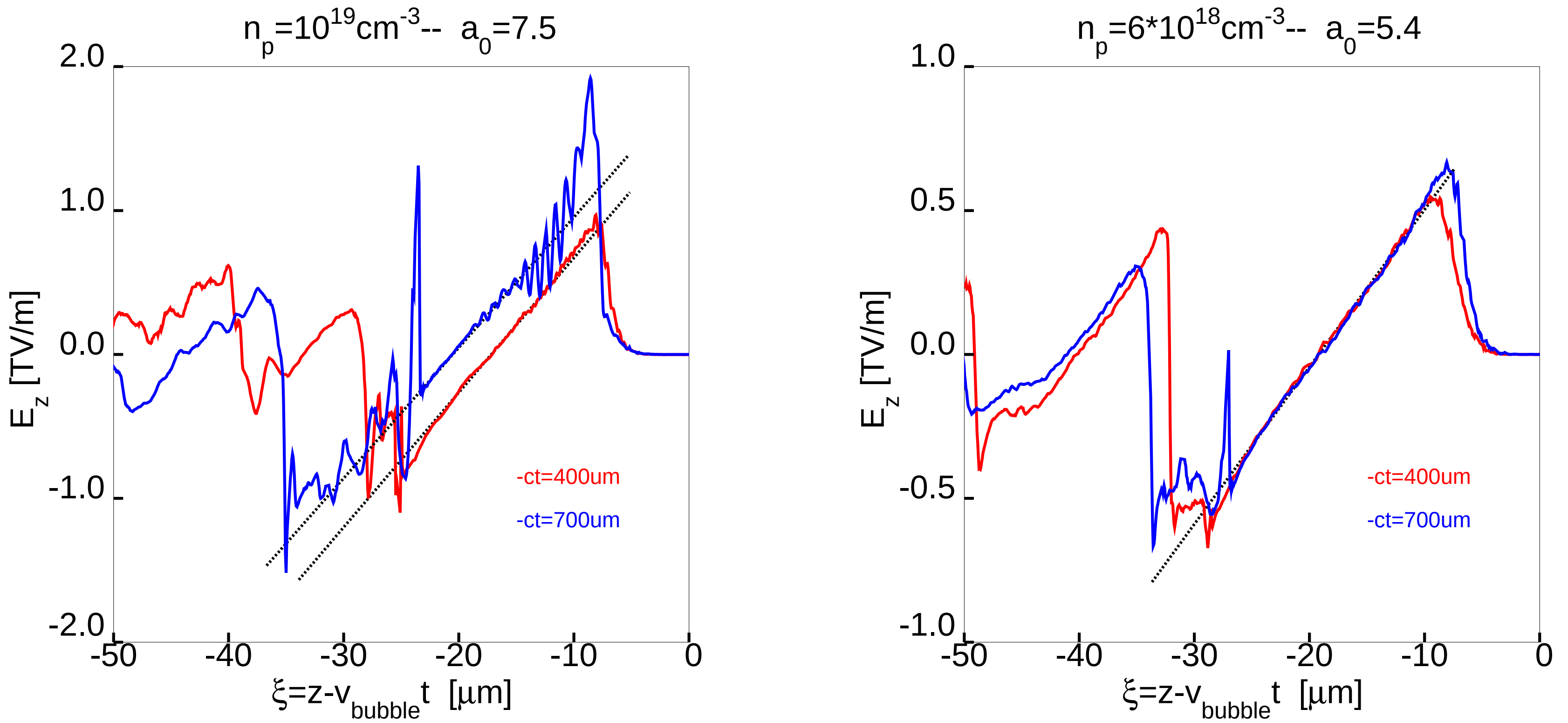




$\Rightarrow$ Why do we have an almost complete dephasing already at $c\,t \sim 700\ \mu$m instead of $c\,t \sim 1000 - 1100\ \mu$m as expected?

Self-injection experiments with FLAME

• The **anticipate dephasing** is due to a **coherent "upshift"** of the accelerating field E_z which occurs for high densities and high laser intensities



⇒ The field "upshift" (largely) **reduces** the energy gain: even a fictitious particle which moves at the bubble velocity would see a *decreasing accelerating field*

Self-injection experiments with FLAME

- A (very) simple phenomenological model:
  - we model the longitudinal (accelerating) field in the following way

$$E_z(\xi,t) = E_0(t) + \frac{1}{2}\frac{m\omega_p^2}{e}\xi$$

    where $\xi = z - v_{bubble}\, t$ and $E_0(t) = \alpha t$ is the uniform longitudinal field.
  - for the energy gain we obtain the following expression

$$W_{corrected} = \frac{W_0}{1 + \frac{4}{3}\frac{\omega_0^2 \alpha e}{m\omega_p^4}}$$

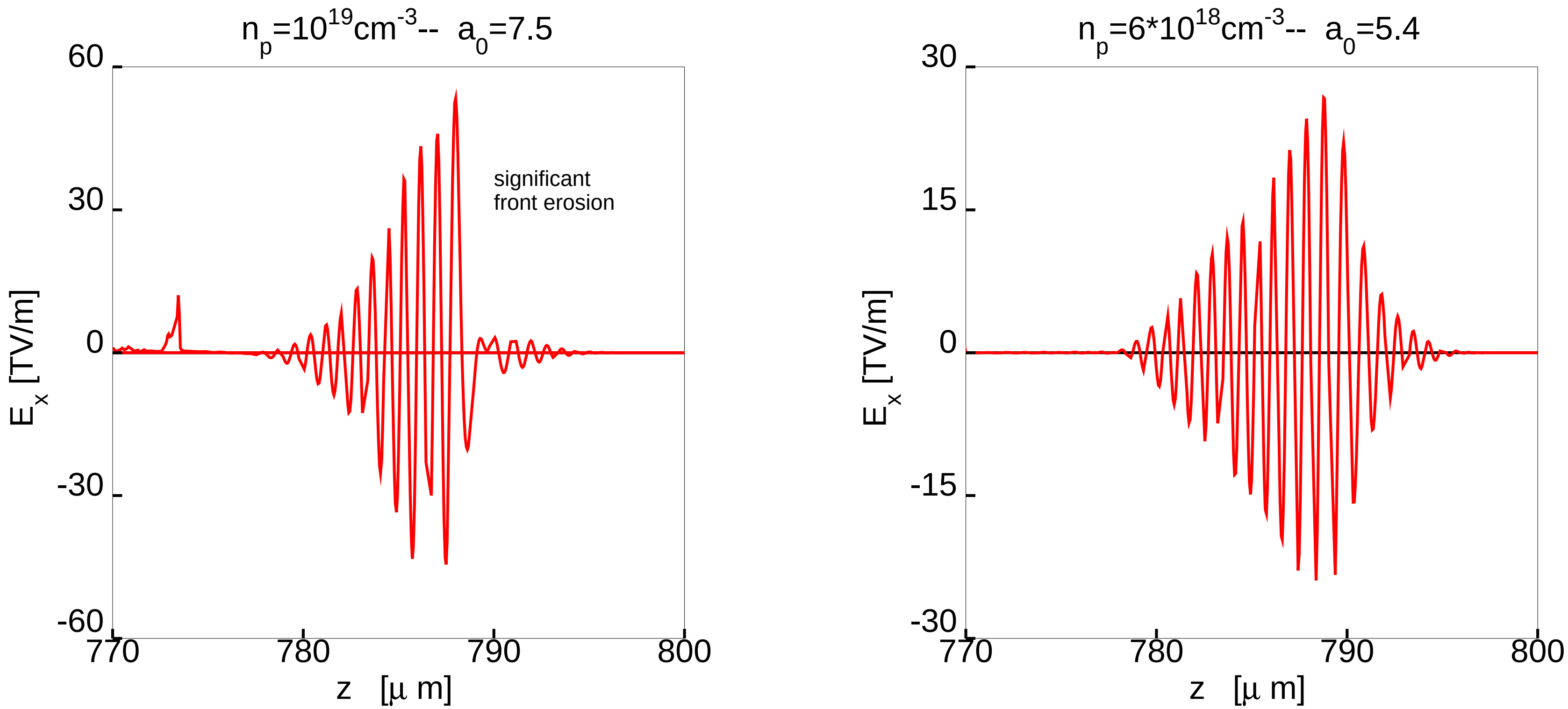
  - we measure the “upshifting rate” α directly form the simulation and we get

$$W_{corrected} \simeq \frac{W_0}{2.27} \simeq 175 \text{ MeV}$$

$\Rightarrow$ **in agreement with simulations for $c\,t$=700 μm**

Self-injection experiments with FLAME

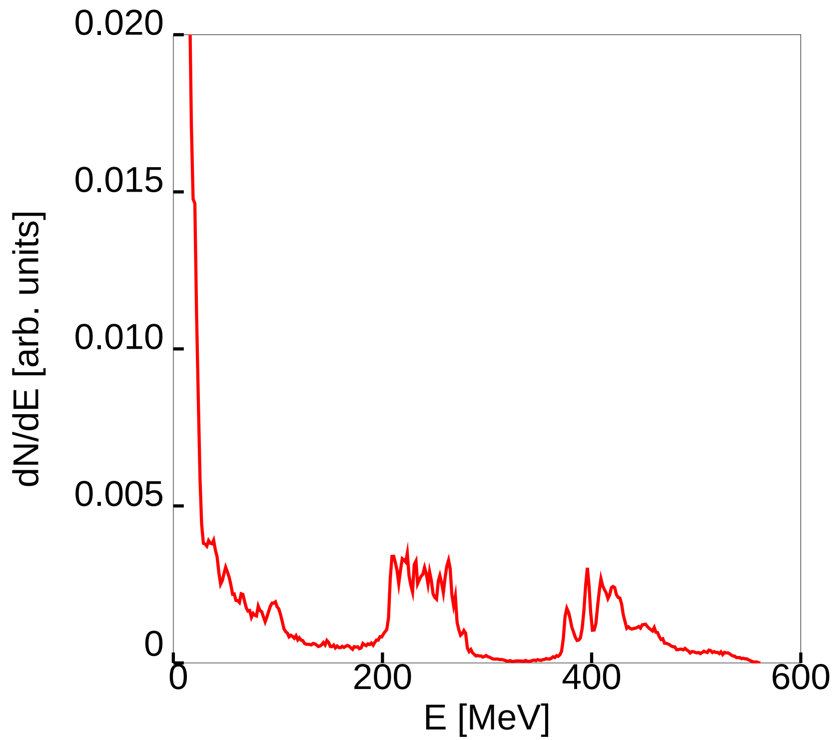
• The field upshift is probably related to the gathering of charge in front of the laser. The laser pulse undergoes a significant **front erosion**: the intensity profile becomes more and more steep yelding an **increase in the (longitudinal) ponderomotive force**



⇒ **The effect is important only at high densities and intensities (see left plot).**

Self-injection experiments with FLAME

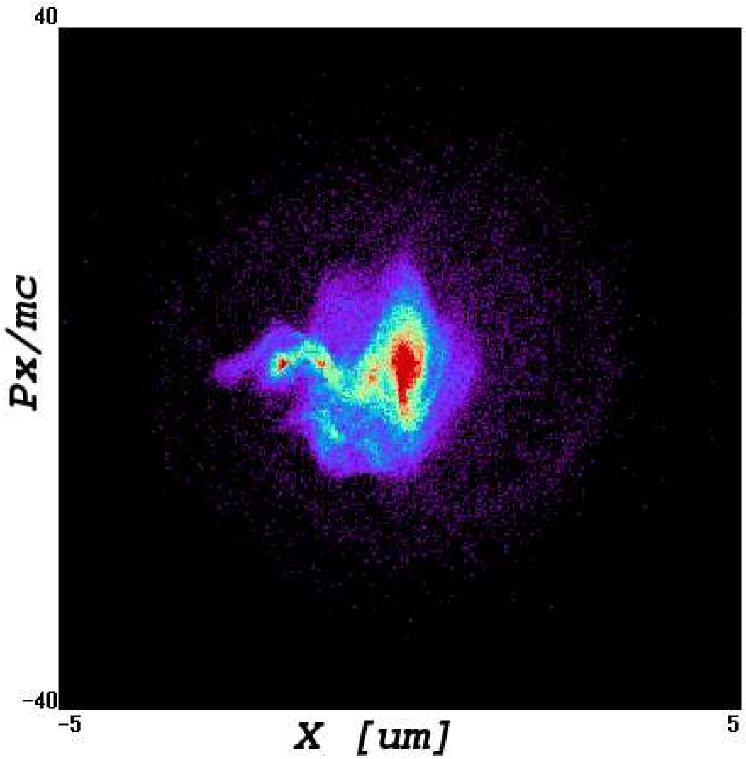
• Simulation at lower density ($n = 6 \cdot 10^{18}$ cm^{-3}) and intensity ($a_0 = 5.4$) $\Rightarrow$ NO field upshift observed $\Rightarrow$ we expect an energy of $W_{theo} \simeq 440$ MeV according to W. Lu theory



$\Rightarrow W_{sim} \simeq (420 \pm 40)$ MeV, $Q = 0.4$ nC (FWHM)

Self-injection experiments with FLAME

- Parameters for the **best bunch** in sim. #1 (@ $c\,t = 700\ \mu$m)



$W_{peak} = 160 \pm 5$ MeV (FWHM)

Considering the particles with $|W - 160| < 10$:

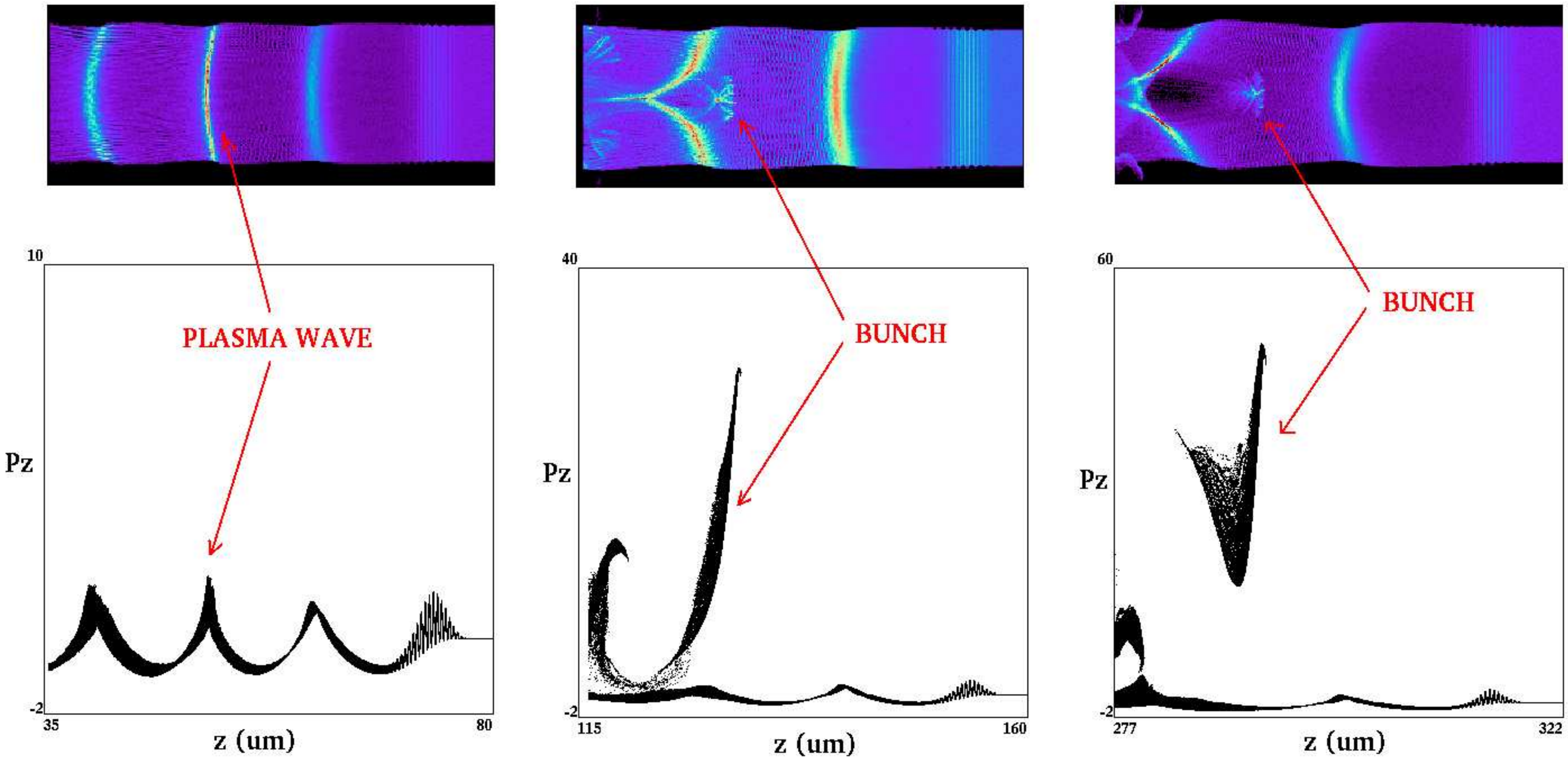
$\sigma_x \simeq$ 0.8 μm
$\epsilon_{xn} \simeq$ 5.5 mm mrad

$\sigma_y \simeq$ 0.7 μm
$\epsilon_{yn} \simeq$ 4.2 mm mrad

$Q = 0.75$ nC
$\sigma_z \simeq 2.2\ \mu$m
$I \simeq 40$ kA

Self-injection experiments with FLAME

• **Nonlinear "1D-like" regime**: generation of a **high current** e^{-} bunch containing slices with **low emittance** and **low momentum spread**
$\Rightarrow$ a properly modulated gas-jet is required (injection after density downramp [a])



[a] S. Bulanov *et al.*, PRE **58/5**, R5257 (1998) / P. Tomassini *et al.*, PRSTAB **6**, 121301 (2003)

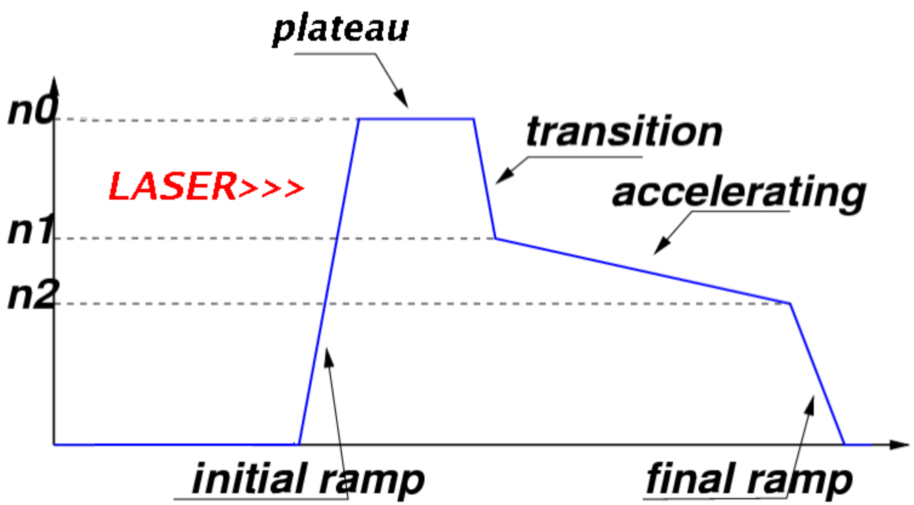
Self-injection experiments with FLAME

- **Laser parameters:**

λ_0 [μm]	I [W/cm^2]	τ_{FWHM} [fs]	waist [μm]
0.8	8.5×10^{18}	20	23

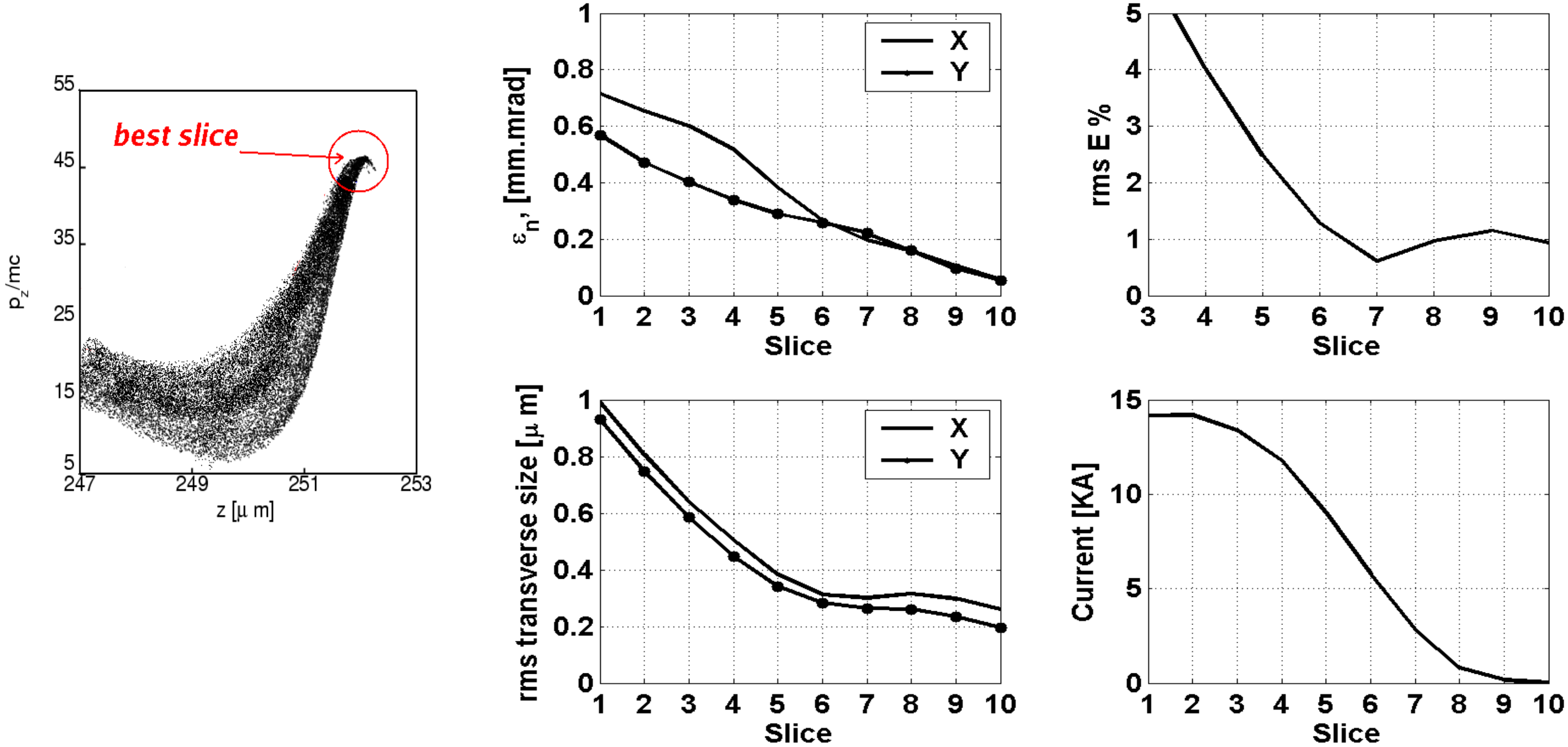
- **Plasma profile:**

n_0 [$\times$ 10^{19}cm^{-3}]	ℓ_{trans} [μ m]	n_1 [$\times$ 10^{19} cm^{-3}]	L_{acc} [μ m]	n_2 [$\times$ 10^{19} cm^{-3}]
1.0	10	0.75	330	0.4



Self-injection experiments with FLAME

- Slice analysis of the accelerated bunch (3D simulation)



γ	σ_z [μm]	Q [pC]	$(\delta\gamma/\gamma)^s$ [%]	ϵ_n^s [mm mrad]	$\sigma_{x,y}^s$ [μm]	I^s [kA]
45	1.7	160	0.55	0.2	0.3	4-5

$\Rightarrow$ The current can be **raised increasing** w_0: $I \propto w_0^2$ [for instance $I(w_0 = 40) > 30$ kA]