Simulazione dei primi esperimenti di autoiniezione

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Studies for the SITE

FLAME (Frascati Laser for Acceleration and Multidisciplinary Experiments)

- $P =$0.3 PW, Ti:Sa ($\lambda_0 = 0.8$ μm), $\tau_{fwhm} = 20 \div 30$ fs
- under installation @LNF (commissioning within 2010)
- SITE will be a **relevant part of the commissioning**

SITE $\Rightarrow$ production of GeV-class electron bunches from laser-plasma interaction using a gas-jet of few ($e.g.$ 4) millimeters [no external guiding for the laser] entering directly into the “bubble”($\dagger, \ddagger$) regime **without** significant pulse-evolution

bubble $\Rightarrow$

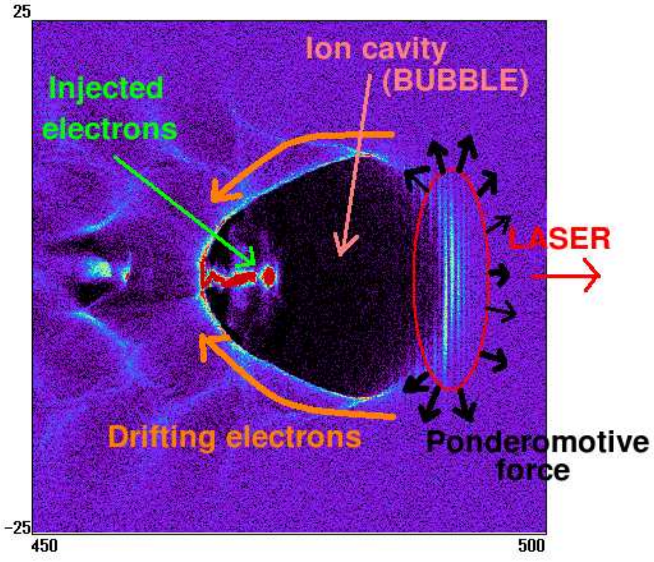
$$\begin{cases} c\tau_{fwhm} < R_{bub} \simeq w_0 \simeq 2\sqrt{a_0}c/\omega_p \; (\sim \lambda_p) \Rightarrow \textbf{short laser pulse!} \\ a_0 \gtrsim 3.5 \div 4 \text{ (injection threshold) } \Rightarrow \textbf{intense laser pulse!} \\ v_{bub} \simeq v_g - v_{etch} \simeq c(1 - 3\omega_p^2/(2\omega_0^2)) < v_{elect} \simeq c \end{cases}$$

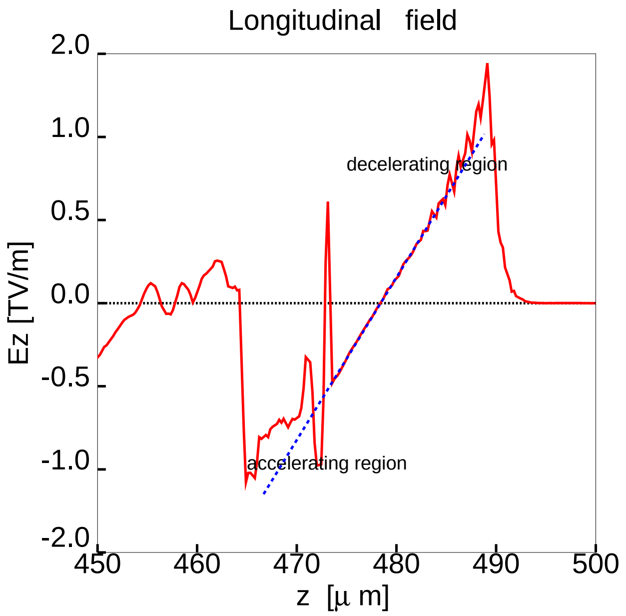
($\dagger$) Pukhov and Meyer-ter-vehn, Appl. Phys. B 74 (2002)

($\ddagger$) Gordienko and Pukhov, Phys. Plas. 12 (2005)

Studies for the SITE

- **Nonlinear 3D regime (bubble)**: phenomenological theory [*W. Lu & al., PRSTAB 10 (2007)*]
  - “stability” of the bubble: $k_p\,R_{bub} \simeq k_p\,w_0 \simeq 2\sqrt{a_0}$
  - dephasing length: $L_{deph} = \frac{2}{3}\frac{\omega_0^2}{\omega_p^2} R_{bub}$
  - pump depletion: $L_{pump\ depl} = \frac{\omega_0^2}{\omega_p^2} c\tau_{fwhm}$
  - $e-$energy (dephasing): $W[\mathrm{GeV}] \simeq 1.7 \times \left(\frac{P[\mathrm{TW}]}{100}\right)^{1/3} \left(\frac{10^{18}}{n_p[\mathrm{cm}^{-3}]}\right)^{2/3} \left(\frac{0.8}{\lambda_0[\mu\mathrm{m}]}\right)^{4/3}$
  - charge injected: $Q[\mathrm{pC}] \simeq 400 \times \left(\frac{\lambda_0[\mu\mathrm{m}]}{0.8}\right) \left(\frac{P[\mathrm{TW}]}{100}\right)^{1/2}$





Studies for the SITE

- **Nonlinear 3D regime (bubble)** for FLAME-like lasers:
We take the waist w_0 (in μm) as a free parameter ($R_{bub} \simeq w_0$), we have

	$P = 150$ TW, $\tau = 24$ fs (I)	$P = 200$ TW, $\tau = 30$ fs (II)
n_p [cm^{-3}]	$7.56 \cdot 10^{21}/w_0^3$	$8.72 \cdot 10^{21}/w_0^3$
L_{deph} [μm]	$0.154 \times w_0^4$	$0.133 \times w_0^4$
$L_{pump\ depl}$ [μm]	$1.662 \times w_0^3$	$1.79 \times w_0^3$
Q [nC]	$\sim$ 0.5	$\sim$ 0.6
$L_{pump\ depl} > L_{deph} = L_{acc}$	$w_0 < 10.8$ ($L_{acc} = 2$ mm)	$w_0 < 13.5$ ($L_{acc} = 4.4$ mm)
$I_0 > 2.6 \cdot 10^{19}$ W/cm^2	$w_0 < 19$ μm	$w_0 < 22$ μm
W_{peak}[MeV] $\simeq$ 5.25$\times w_0^2$	$\sim$ 610	$\sim$ 960

⇒ N.B. beam loading → “monochromatic” bunch even if $L_{acc} < L_{deph}$

Studies for the SITE

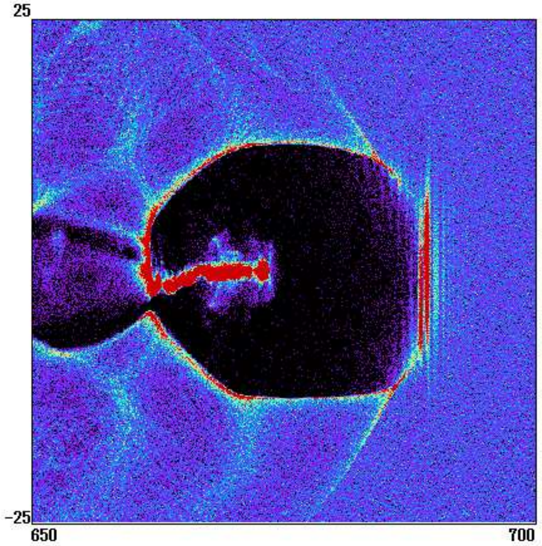
Let's consider some examples:

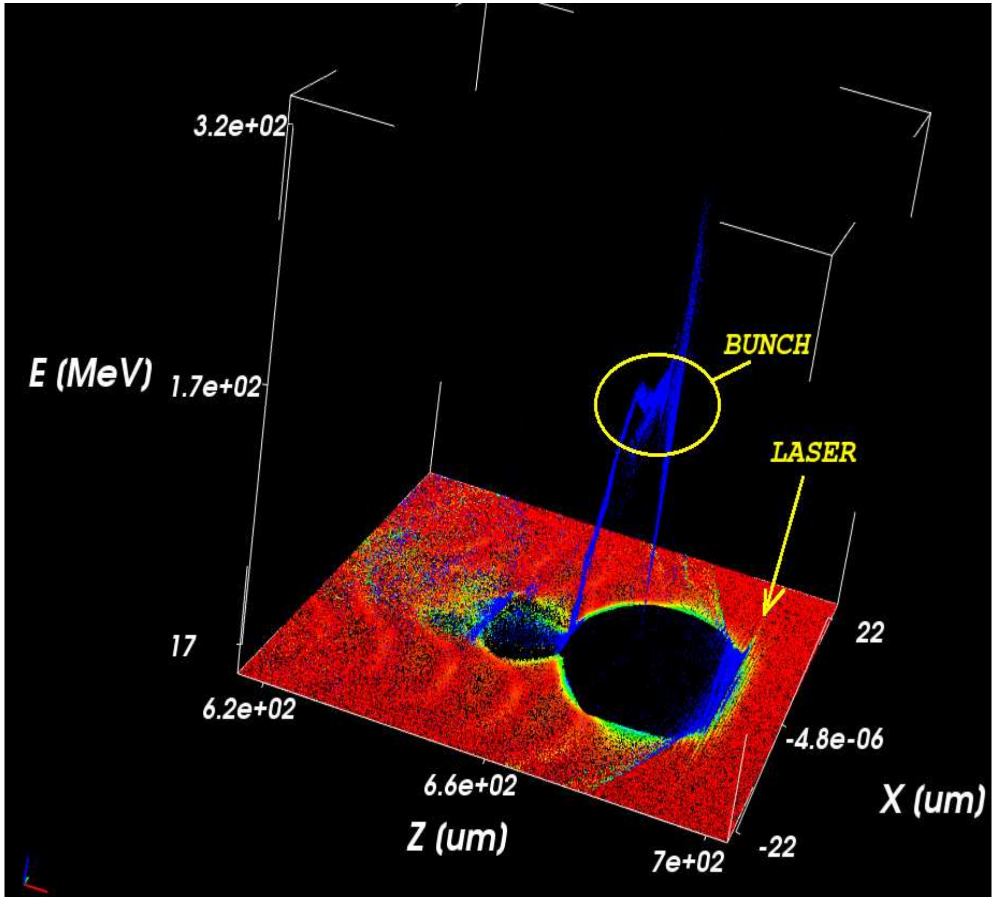
#	L_{gasjet} [mm]	w_0 [μm]	I (a_0) $\left[10^{19}\ \frac{\text{W}}{\text{cm}^2}\right]$	n_p [10^{18} cm^{-3}]	L_{pd} [mm]	W_{peak} [GeV]
1 (I)	1.1	9	12 (7.7)	10	1.2	0.4
2 (II)	4.0	13.2	7.3 (5.8)	3.8	4.1	0.9
3 (II)	13	17.5	4.1 (4.3)	1.6	9.5 (**!!**)	1.6

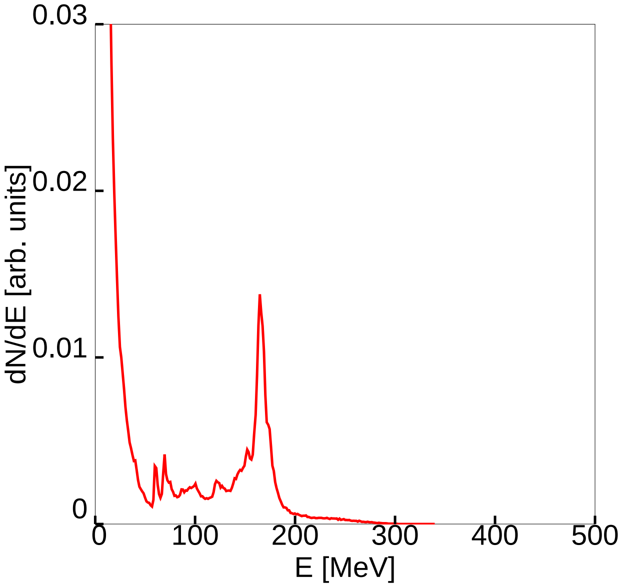
$\Rightarrow$ 3D simulations with the PIC code **ALaDyn** to investigate in detail the acceleration process, in particular:
i. study properties of the accel. structure when $L_{acc} = L_{gasjet} \sim L_{pd}$
ii. study properties of the accelerated bunch
iii. perform the **"fine-tuning"** of analytical models (comp. cost very high)

Studies for the SITE

- Case #1 (I): $L_{gasjet} = 1$ mm, $n_p = 10^{19}$ e/cm^{-3}, $I_0 = 1.2 \cdot 10^{20}$ W/cm^2 (see LIFE/1)







Studies for the SITE

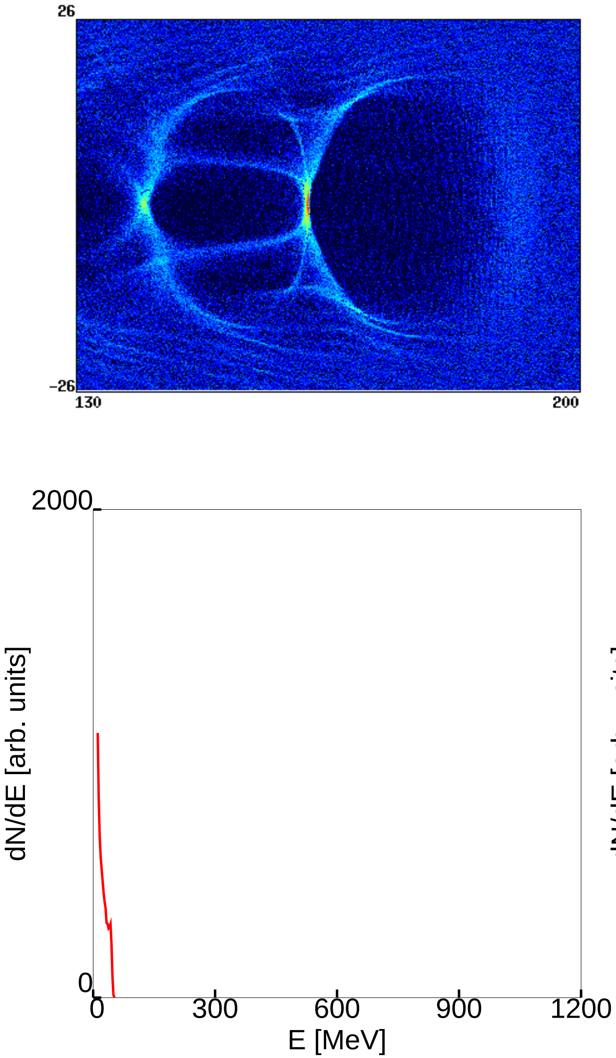
- Case #1 (I): $L_{gasjet} = 1$ mm (see previous LIFE workshop)

case A ($n_p = 10^{19}$ e/cm^3, $I_0 = 1.2 \cdot 10^{20}$ W/cm^2)	case B (not optimal $L_{acc} < L_{deph}$) ($n_p = 6 \cdot 10^{18}$ e/cm^3, $I_0 = 6.4 \cdot 10^{19}$ W/cm^2)
$W_{peak} = 164$ MeV $\Delta W/W \sim 3$ %	$W_{peak} = 420$ MeV $\Delta W/W \sim 8$ %
Considering the particles with $\lvert W - 164 \rvert < 10$ MeV	Considering the particles with $\lvert W - 420 \rvert < 70$ MeV
$\sigma_x \simeq$ 0.7 μm, $\sigma_{x'} \simeq$ 21 mrad $\epsilon_{xn} \simeq$ 4.9 mm mrad	$\sigma_x \simeq$ 0.5 μm, $\sigma_{x'} \simeq$ 5.9 mrad $\epsilon_{xn} \simeq$ 2.3 mm mrad
$\sigma_y \simeq$ 0.6 μm, $\sigma_{y'} \simeq$ 18 mrad $\epsilon_{yn} \simeq$ 3.4 mm mrad	$\sigma_y \simeq$ 0.5 μm, $\sigma_{y'} \simeq$ 5.7 mrad $\epsilon_{yn} \simeq$ 2.4 mm mrad
$Q = 0.8$ nC $\sigma_z \simeq 2$ μm $I_{aver} \simeq 50$ kA	$Q \simeq 0.5$ nC $\sigma_z \simeq 0.94$ μm $I_{aver} \simeq 67$ kA

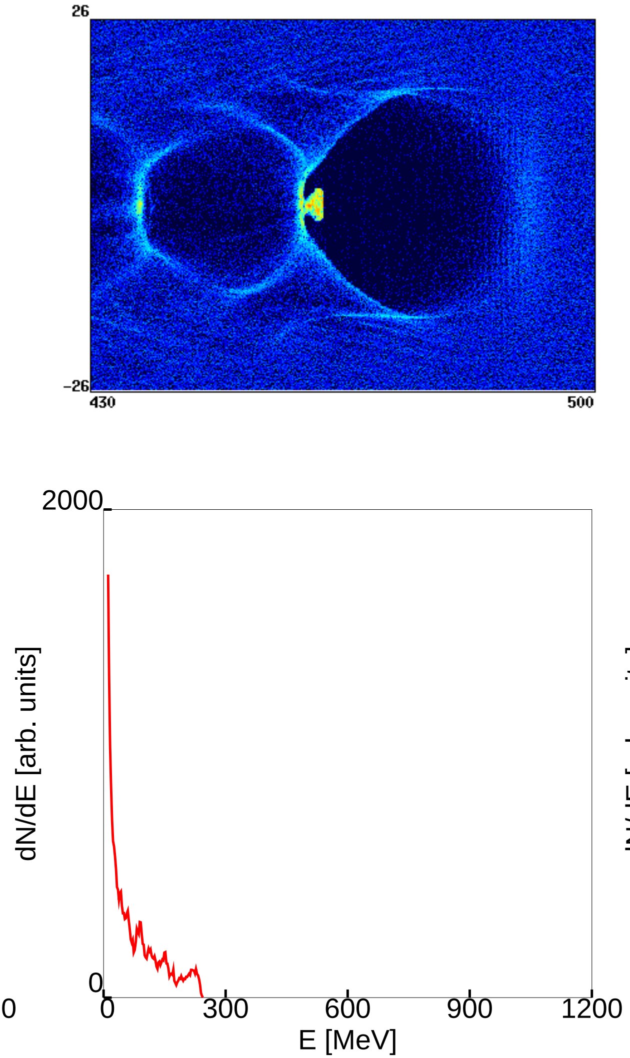
Studies for the SITE

- Case #2* (II): $L_{gasjet} = 4$ mm, $n_p = 3 \cdot 10^{18}$ e/cm^{-3}, $I_0 = 5.3 \cdot 10^{19}$ W/cm^2

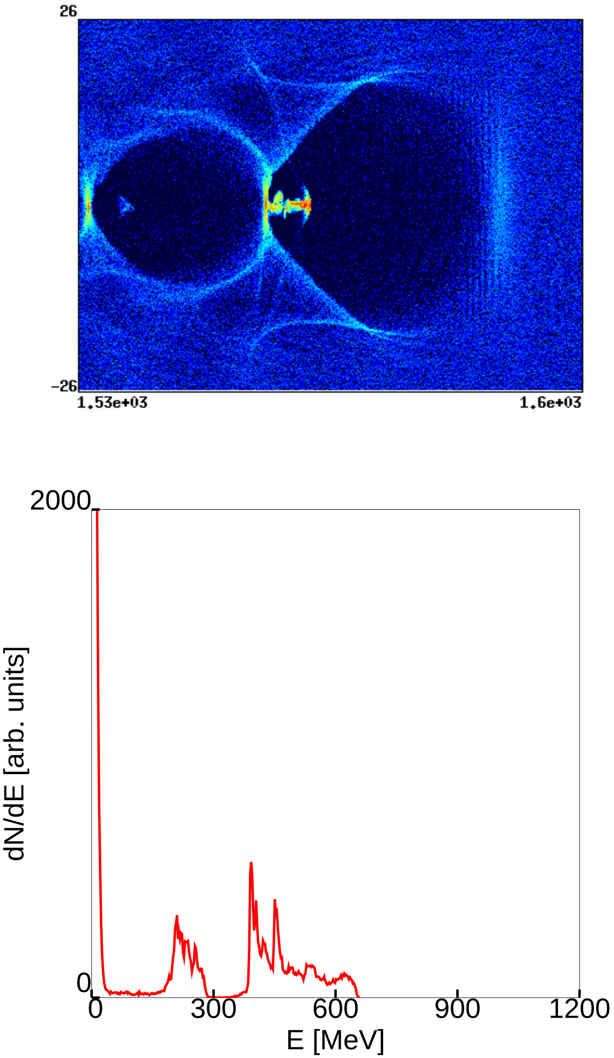
$ct = 200\ \mu$m



$ct = 500\ \mu$m



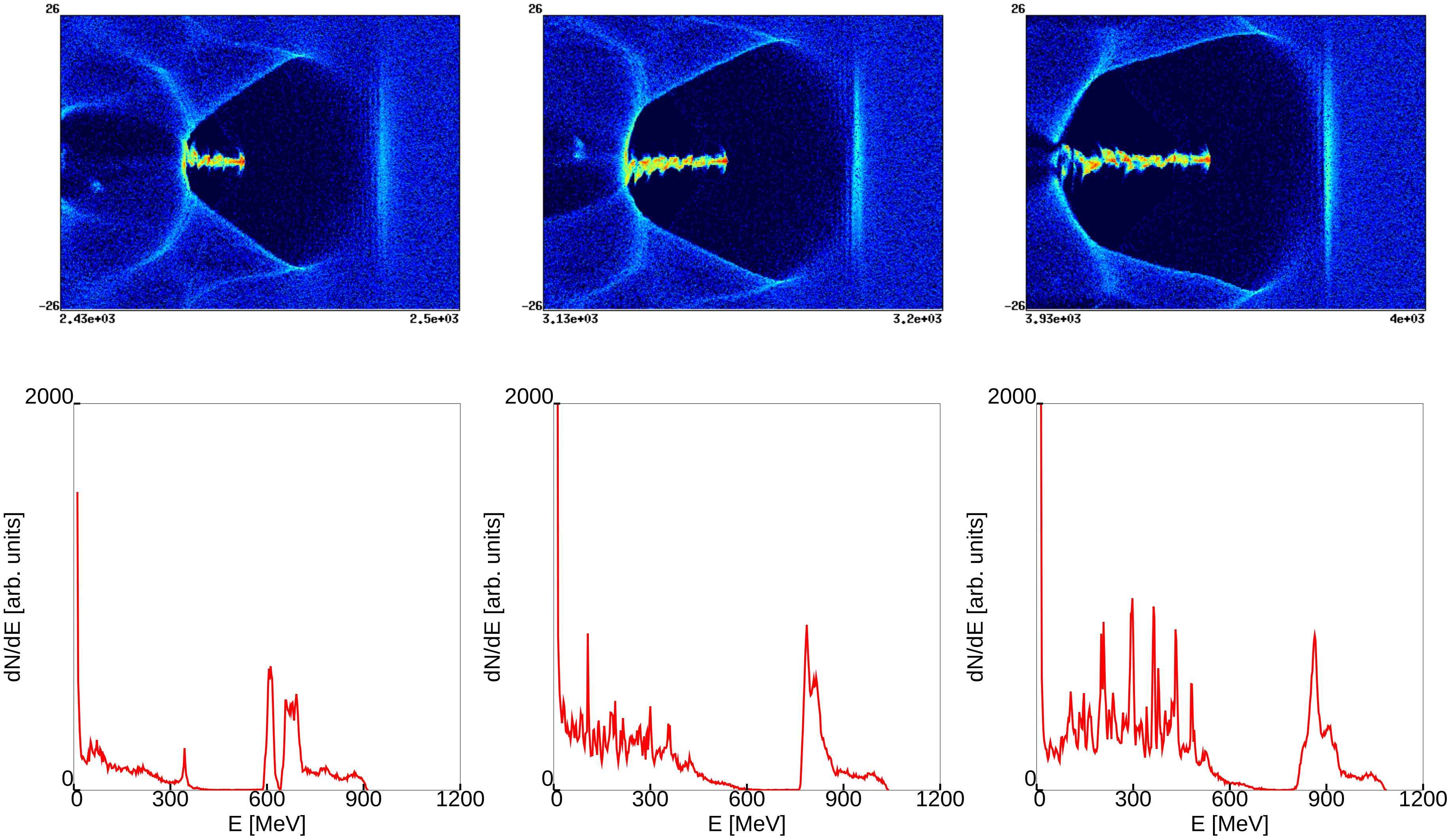
$ct = 1600\ \mu$m



Studies for the SITE

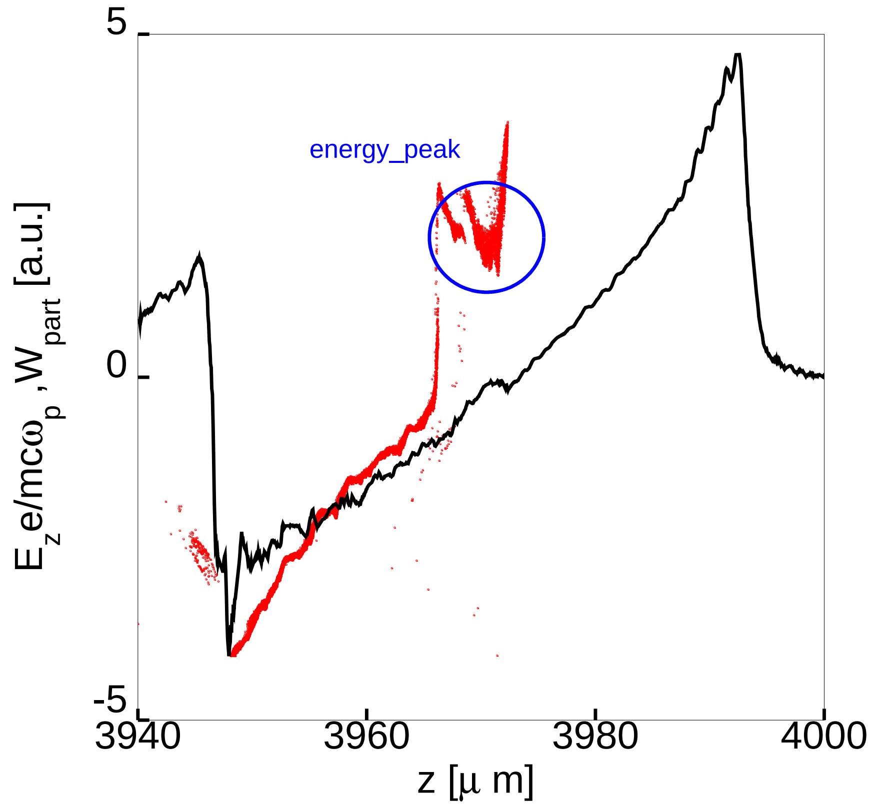
- Case #2* (II): $L_{gasjet} = 4$ mm, $n_p = 3 \cdot 10^{18}$ e/cm^{-3}, $I_0 = 5.3 \cdot 10^{19}$ W/cm^2

$ct = 2500$ μm $ct = 3200$ μm $ct = 4000$ μm



Studies for the SITE

- Case #2* (II): $L_{gasjet} = 4$ mm $\Rightarrow$ final parameters of the **bunch** (@ $c\,t = 4000\ \mu$m)



$W_{peak} \simeq 900$ MeV
$\Delta W/W = 3.3$ %

Considering the particles with $|W - 900| < 90$ MeV

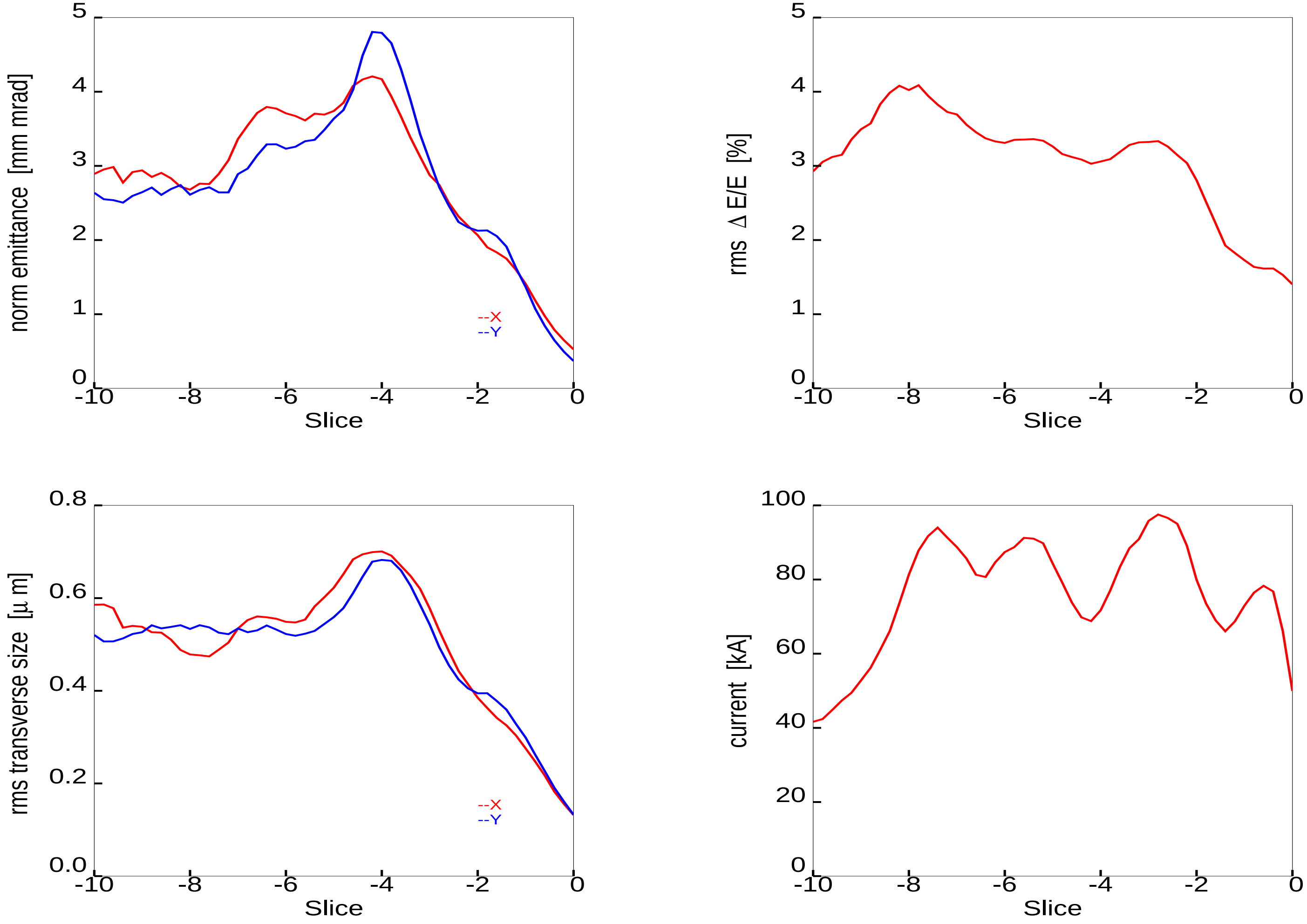
$\sigma_x \simeq 0.5\ \mu$m
$\sigma_{x'} \simeq 2.8$ mrad
$\epsilon_{xn} \simeq 2.3$ mm mrad

$\sigma_y \simeq 0.6\ \mu$m
$\sigma_{y'} \simeq 2.8$ mrad
$\epsilon_{yn} \simeq 2.8$ mm mrad

$Q = 0.62$ nC
$\sigma_z \simeq 1.8\ \mu$m
$I_{aver} \simeq 44$ kA

Studies for the SITE

- Case #2* (II): slice analysis (for FEL-like applications: $\lambda_w = 2$ cm, $a_w = 2$, $\lambda_{FEL} \sim 10$ nm, $\rho_{FEL} \sim 5 \cdot 10^{-3} \Rightarrow L_{slice} \simeq L_c \simeq 0.1$ μm, ϵ_n <1.2 mm mrad, $(\Delta W/W) < 0.5$ %)

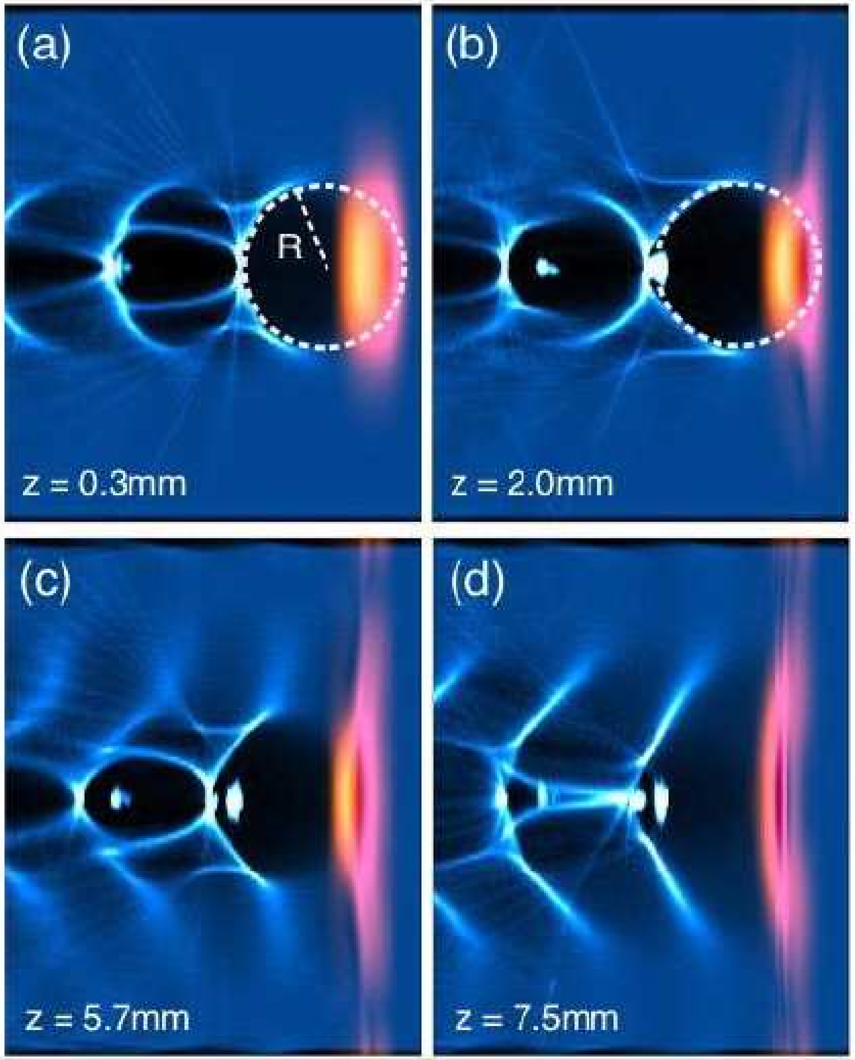


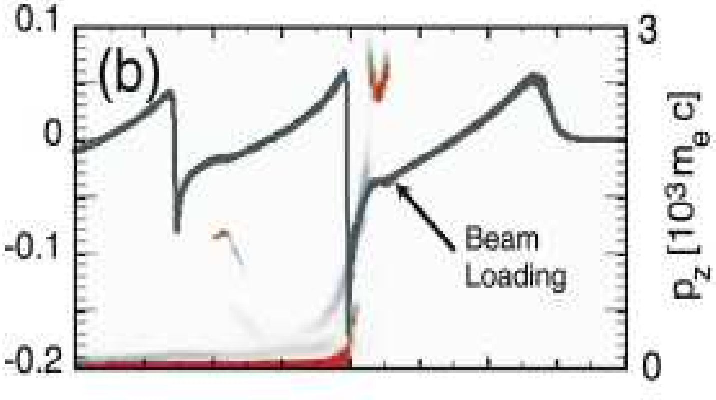
$\Rightarrow$ **(to date)** slice parameters **not suitable** to drive a FEL ($\Delta E/E$, ϵ_n too large !)

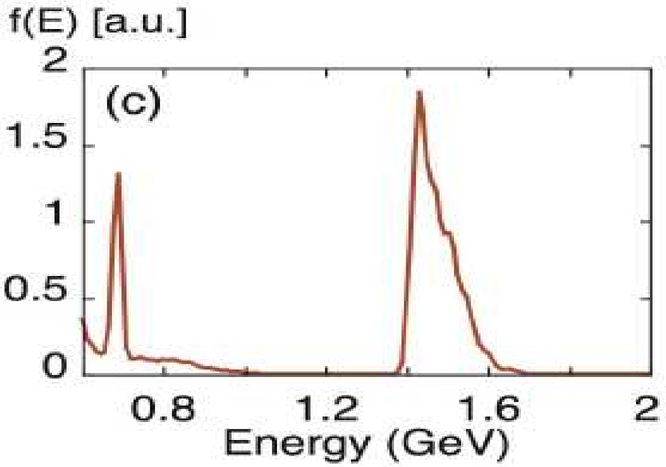
$\Rightarrow$ all the issues related to the **extraction from the plasma** and **matching** have been neglected

Studies for the SITE

- Case #3* (II): $n_p = 1.5 \cdot 10^{18}$ e/cm^{-3}, $I_0 = 3.6 \cdot 10^{19}$ W/cm^2 [*W. Lu et al., PRSTAB*] :
$L_{acc} < L_{pd} \simeq$ 1 cm < $L_{deph} \simeq$ 1.3 cm



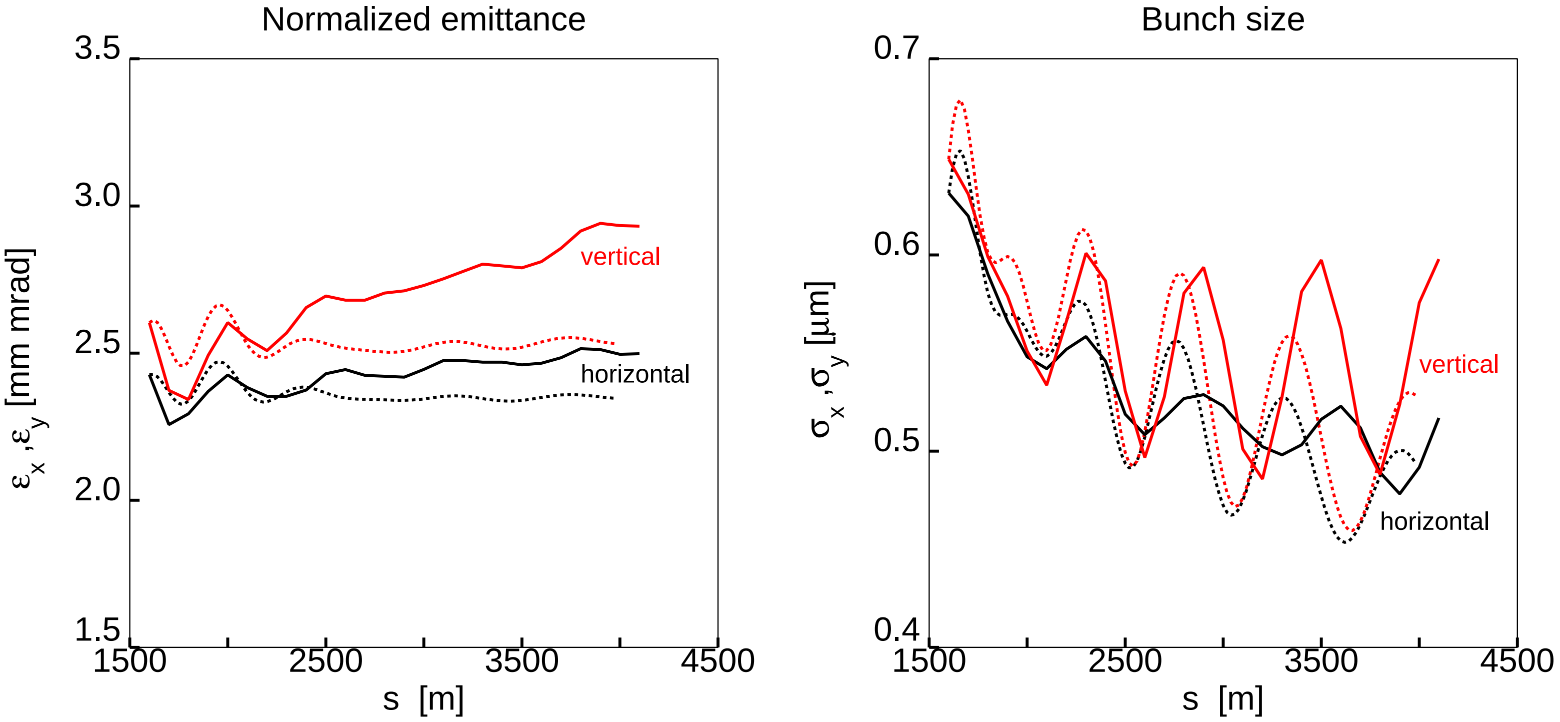




$W_{peak} \simeq 1.6$ GeV – $\Delta W/W \sim 3.8$ %
$\sigma_x \sim 2$ μm, $\sigma_{x'} \sim 5$ mrad
$\epsilon_n \sim 30$ mm mrad (?), $Q \sim 0.3$ nC

Studies for the SITE

- Acceleration inside the bubble (for simulation # 2): the dynamic of the bunch can be described by a simplified phenomenological model (**dashed lines**) where all the forces are linear

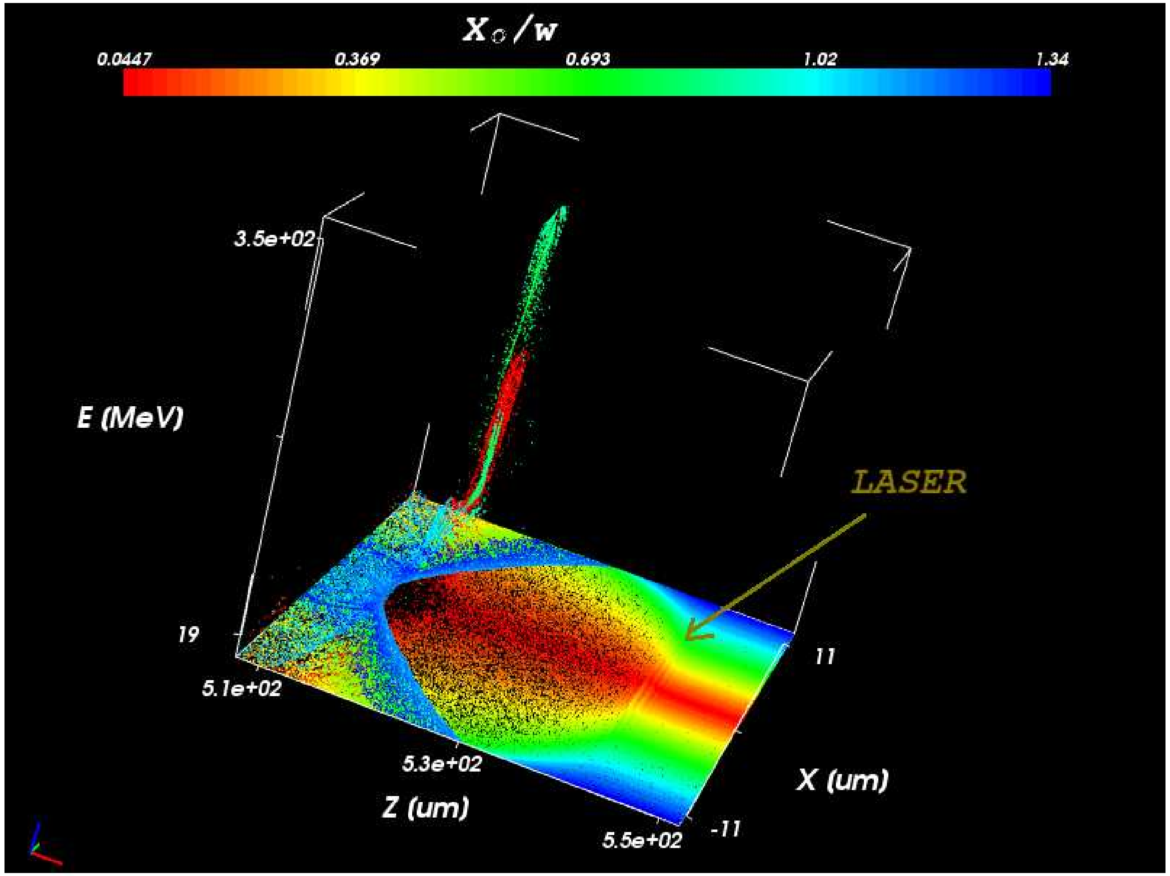


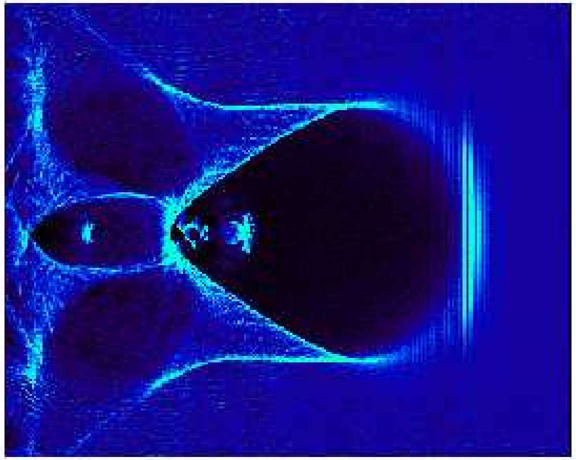
⇒ **no significant emittance degradation** during acceleration (less than 15% increase)

⇒ **the emittance is “high” at the injection**

Studies for the SITE

- Injection into the bubble: where do accelerated particles came from?

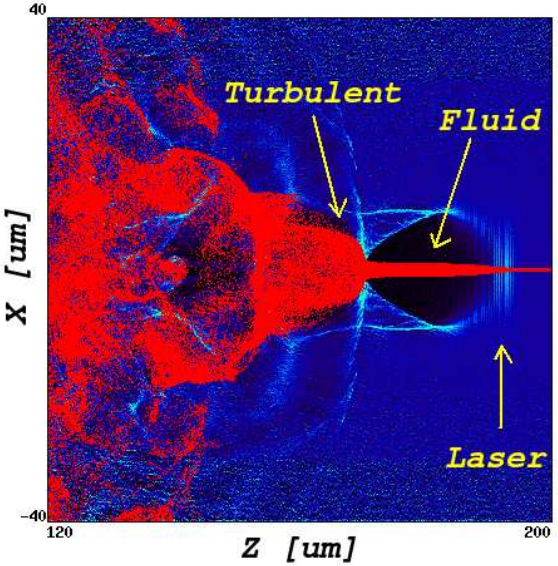




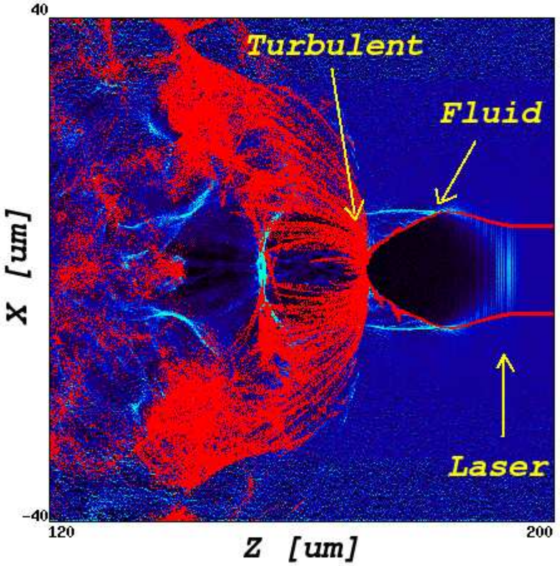
Studies for the SITE

- Injection into the bubble: where do accelerated particles came from?

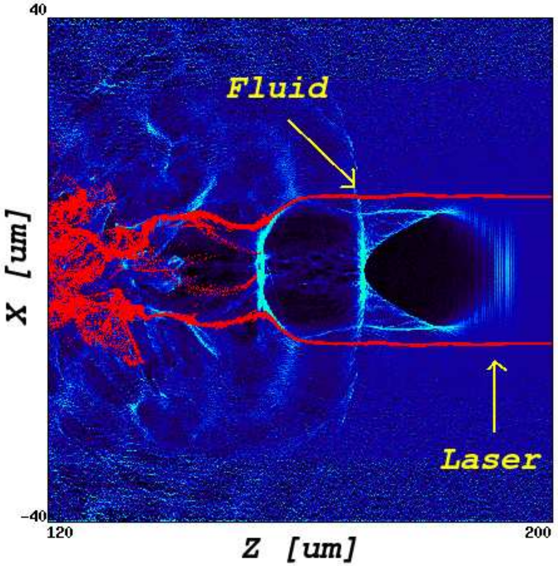
$x_0/w \simeq 0$



$x_0/w \simeq 0.8$



$x_0/w \simeq 1.3$

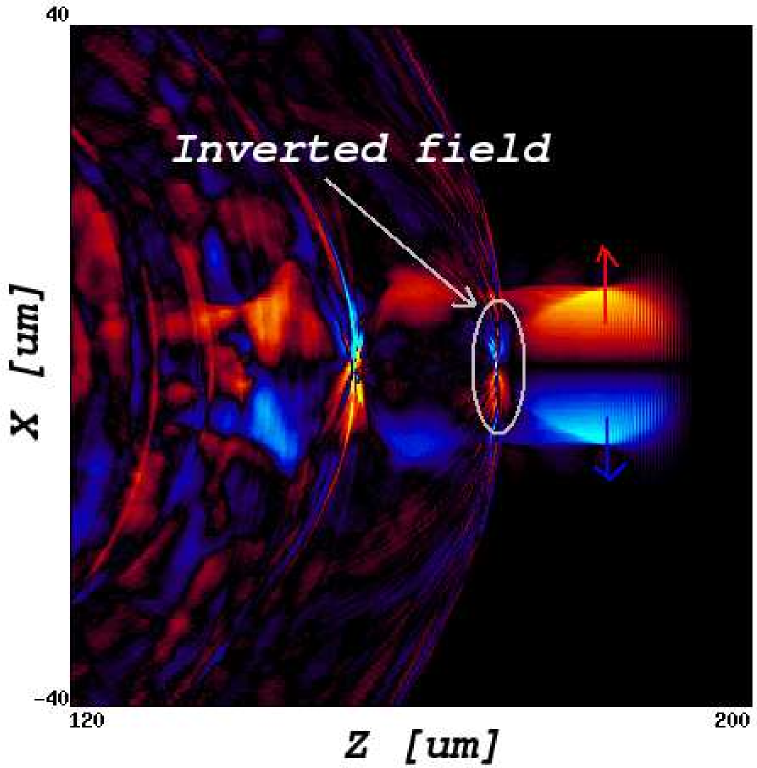


$\Rightarrow$ the motion **becomes turbulent** when the electron sheet reaches the back of the bubble

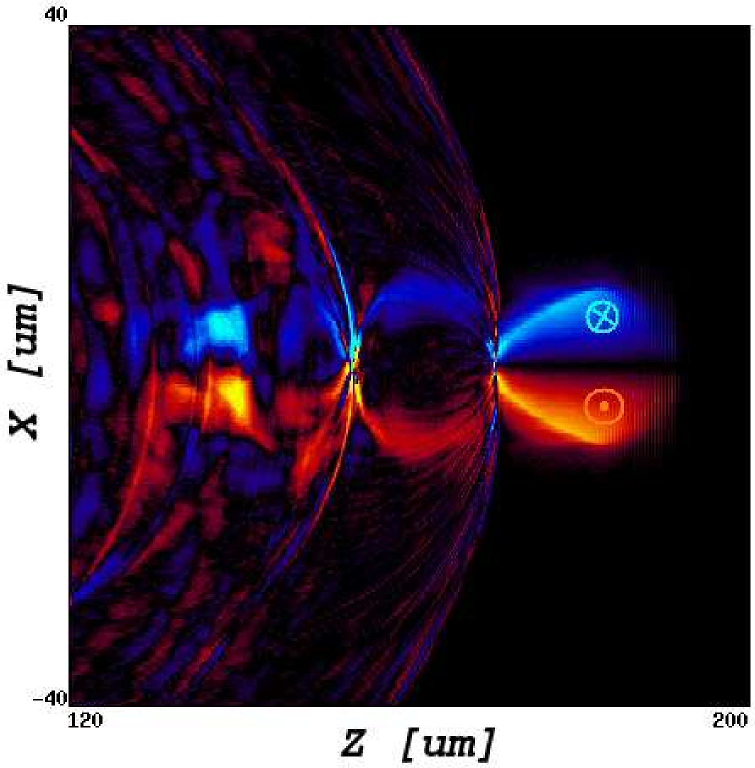
Studies for the SITE

- Structure of the wakefield (transverse fields)

E_x



B_y

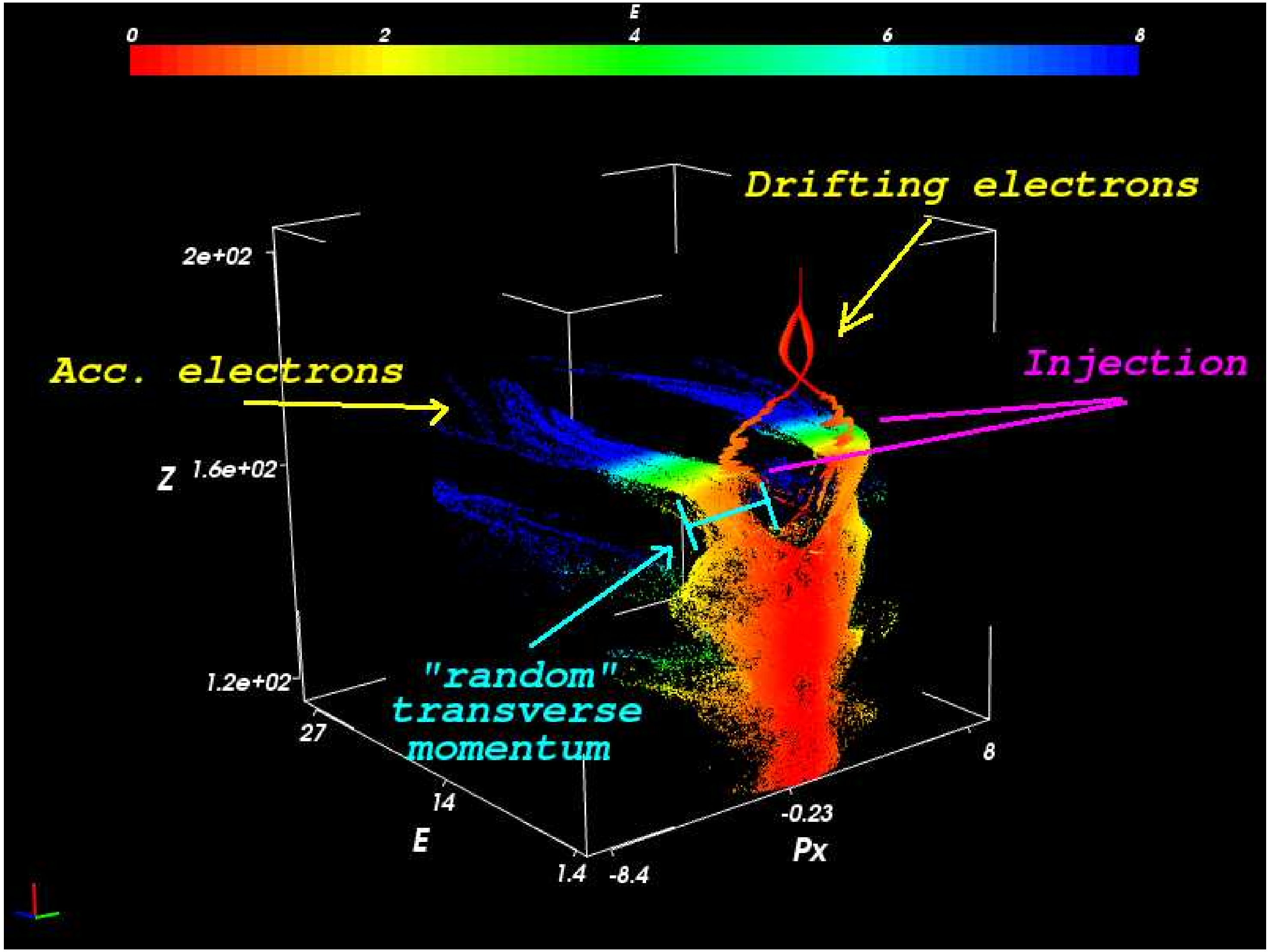


$\Rightarrow E_x^{max} \sim 5 \cdot 10^{11}$ V/m

$\Rightarrow B_y^{max} \sim 1.7 \cdot 10^{3}$ T

Studies for the SITE

- Focus on the injection mechanism

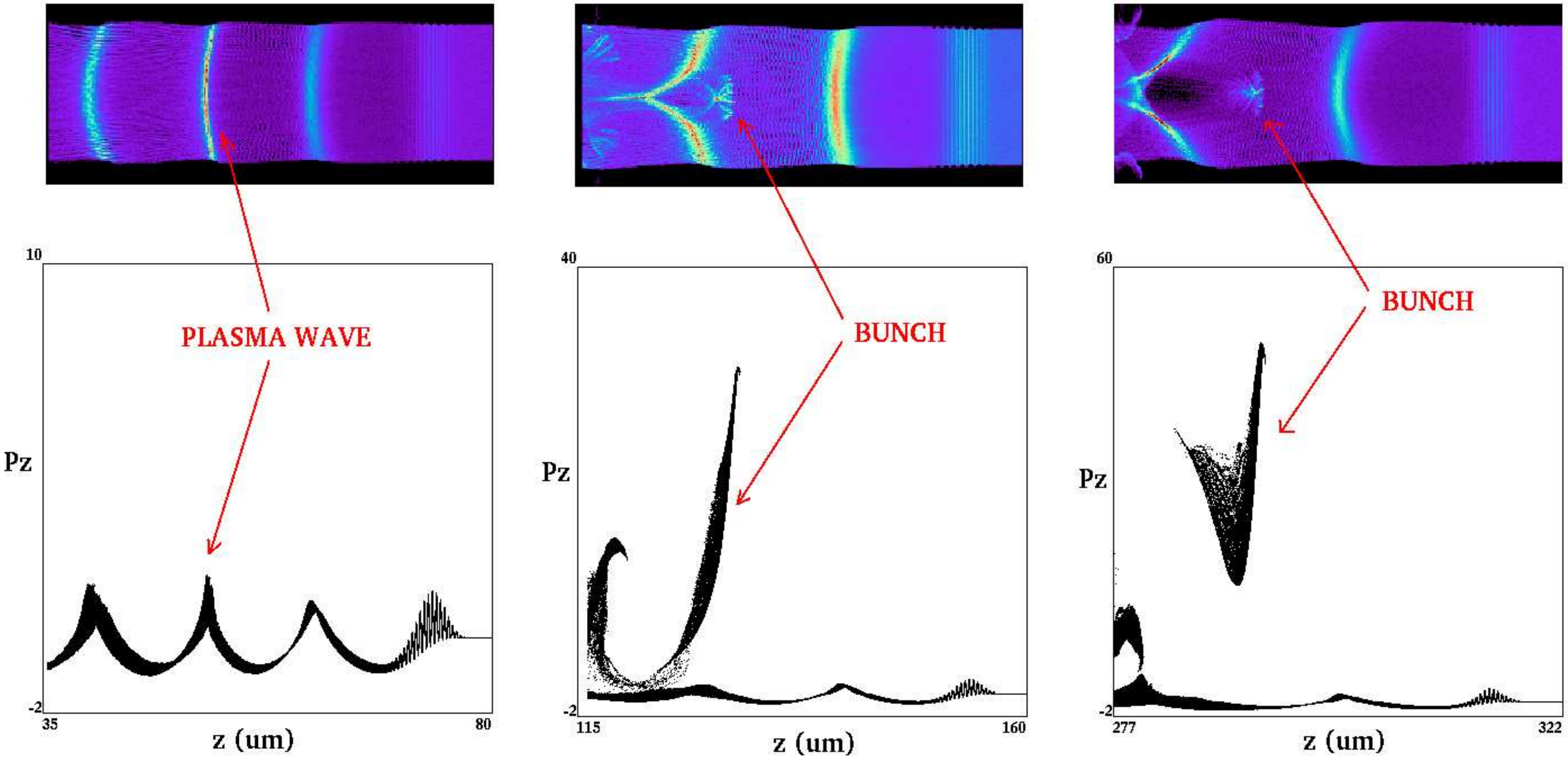


Studies for the SITE

- Ongoing activities:
  - Start-to-end simulation: bunch generation in the plasma + extraction [with Milano]
  - Injection at density downramp: better beam quality (emittance, momentum spread) [with Milano]
  - External injection in a laser-driven plasma wave (see previous LIFE workshop): $L_{acc} \sim 10$ cm, $\Delta E \sim 2$ GeV, $\Delta E/E < 3$ %, $\epsilon_n <$ 1.5 mm mrad $\Rightarrow$ self consistent evolution of the laser pump has been included [P. Tomassini]

Injection at density downramp

- **Nonlinear “1D-like” regime**: generation of a **high current** e^- bunch containing slices with **low emittance** and **low momentum spread** (see AOFEL [a])
  ⇒ a properly modulated gas-jet is required (injection after density downramp [b])



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[a] V. Petrillo *et al.*, PRSTAB 11, 070703 (2008)

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

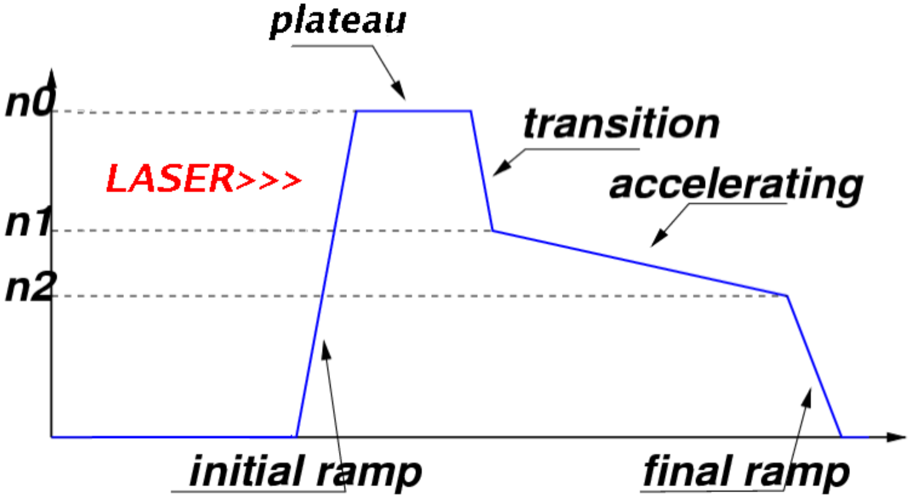
Injection at density downramp

- **Laser parameters:**

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

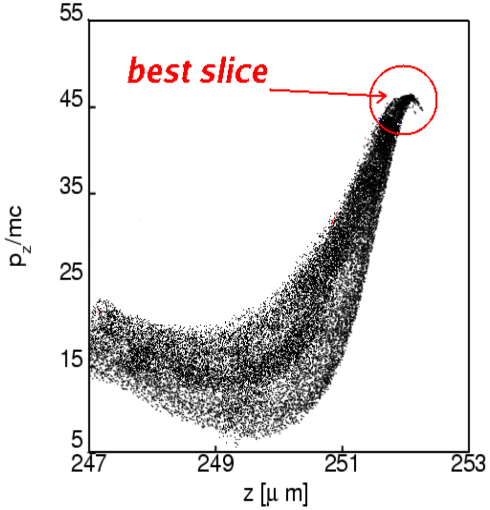
- **Plasma profile:**

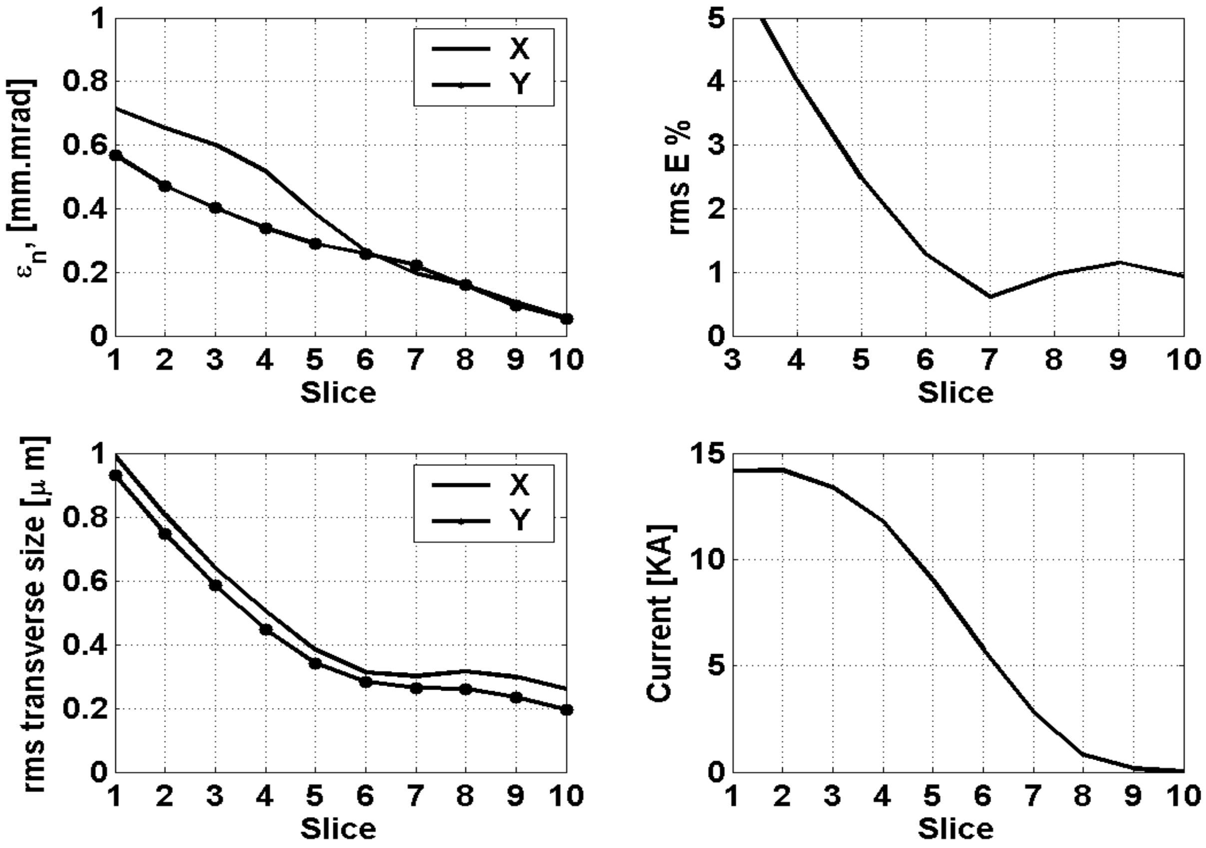
n_0 [$\times\ 10^{19}$cm^{-3}]	ℓ_{trans} [μ m]	n_1 [$\times\ 10^{19}$ cm^{-3}]	L_{acc} [μ m]	n_2 [$\times\ 10^{19}$ cm^{-3}]
1.0	10	0.75	330	0.4



Injection at density downramp

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



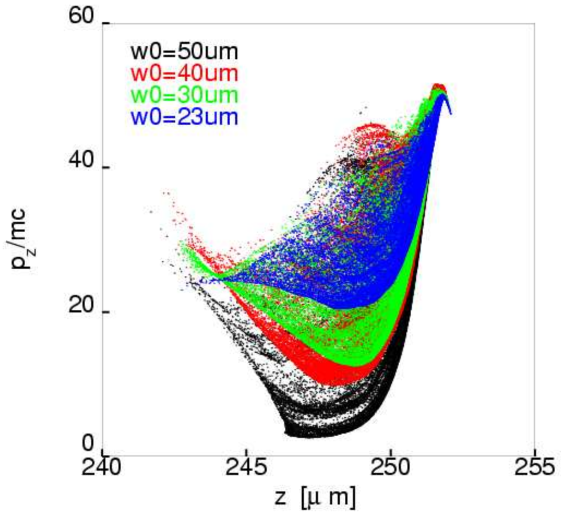


γ	σ_z [μm]	Q [pC]	$(\delta\gamma/\gamma)^s$ [%]	ϵ_n^s [mm mrad]	$\sigma_{x,y}^s$ [μm]	I^s [kA]
45	1.7	160	0.55	0.2	0.3	4-5

Injection at density downramp

We can further optimize the properties of the accelerated bunch increasing the current*

1. the most practical way is to **increase** w_0 to **collect more charge** during the wave breaking $\Rightarrow Q \propto w_0^2$
2. σ_z of the bunch is determined **only** by ℓ_{trans} (doesn't depend on w_0) $\Rightarrow \boxed{I \propto w_0^2}$
3. the dynamics is $\sim$ 1D (small transverse effects): the r.m.s. parameters of the best slices (the ones in the front part of the bunch) are not affected by the increase in w_0



w_0 [μm]	σ_z [μm]	Q_{bunch} [nC]	I^s [kA]	I^s/w_0^2
23	1.50	0.2/0.25	5-7	0.011
30	1.55	0.3/0.4	9-12	0.012
40	1.46	0.6/0.8	20-24	0.014
50	1.56	1.0/1.2	30-32	0.012

$\Rightarrow$ in all the (2D) sim. changing w_0 we obtained $(\delta\gamma/\gamma)^s \sim 0.3/0.5\%$, $\epsilon_n^s \sim 0.1/0.2$ mm mrad

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* C. Benedetti *et al.*, *"PIC simulations of the production ⋯ "*, NIM-A (2009)

Studies for the external injection

- Proposed by Paolo Tomassini (LIFE workshop, Frascati, 19-20/02/09): **preliminary study**!

⇒ we consider the injection of a high quality bunch (*e.g.* from SPARC) into the plasma wave generated by FLAME

Advantages	Limits
1. good quality for the beam and high energy (> 2 GeV in $\sim$ 10 cm) 2. flexibility in the choice of the final energy	1. bunch length: must be $\ll$ of λ_p 2. jitter in the injection phase potentially detrimental 3. the plasma profile must be accurately designed

- **Bunch:** $Q =$ 25 pC, $E =$150 MeV, $\delta E/E = 0.2$%, $\epsilon_n = 0.8$ mm mrad, $\sigma_x =$ 5 μm, $\sigma_z =$ 2.5 μm, $I \simeq 1$ kA
- **Plasma:** channel for the **guiding** of the laser up to 20Z_R and “tailoring” of the longitudinal density profile to **control the dephasing** (energy spread): $n_p = (1.5 \rightarrow 2.5) \cdot 10^{17}$ e/cm^3, $L_p = 10$ cm
- **Laser:** E_l=7 J, τ= 30 fs, $w_0 = 32.5$ μm (minimum)

⇒ injection in the second bucket of the nonlinear plasma wave

Studies for the external injection

Goals:

- best compromise between beam quality and high energy
- final energy above 2 GeV
- global energy spread **below** 4 %
- normalized emittance **below** 1.5 mm mrad
- good beam slice properties

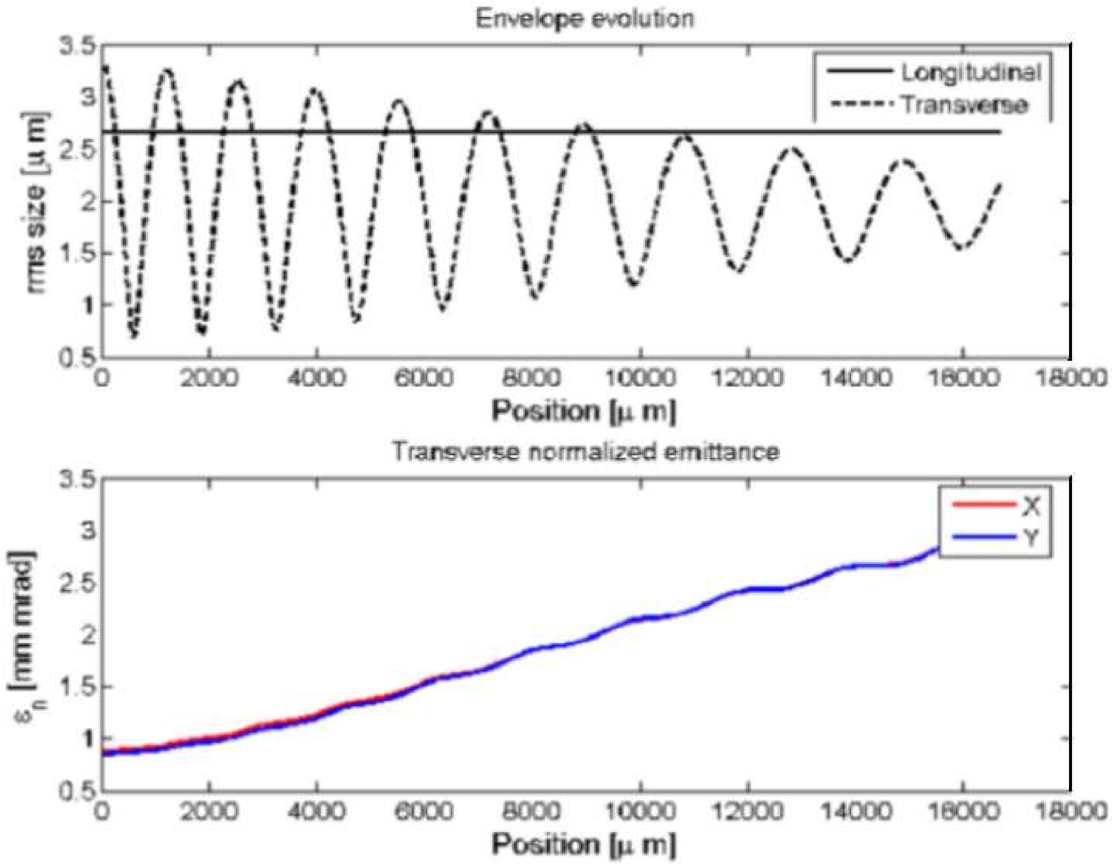
Simulations:

- performed with **Q-fluid** (by Paolo Tomassini) 2D cylindrical, fluid with frozen laser-pump + 1D PIC (only for the laser) to have a first estimate of the laser depletion (~ 15 % in 10 cm)
- 2D PIC simulations (only for the laser) are quite demanding but **necessary** and **planned** to study self-focusing since $P_l > P_c$
- 3D PIC are not feasible ($Lacc \sim 10$ cm)
- QSA model for the laser pulse evolution under implementation NOW + merging with ALaDyn

Studies for the external injection

Key feature of this schema: **adiabatic (transverse) compression of the bunch during injection** provided by the focusing of the laser pulse ($w_0 = 130 \rightarrow 32.5$ μm) $\Rightarrow$ matching of the bunch in order to **minimize spot oscillations and emittance growth** ($\sigma_{matched} \simeq 1$ μm $< \sigma_x$= 5 μm)

without matching



Studies for the external injection

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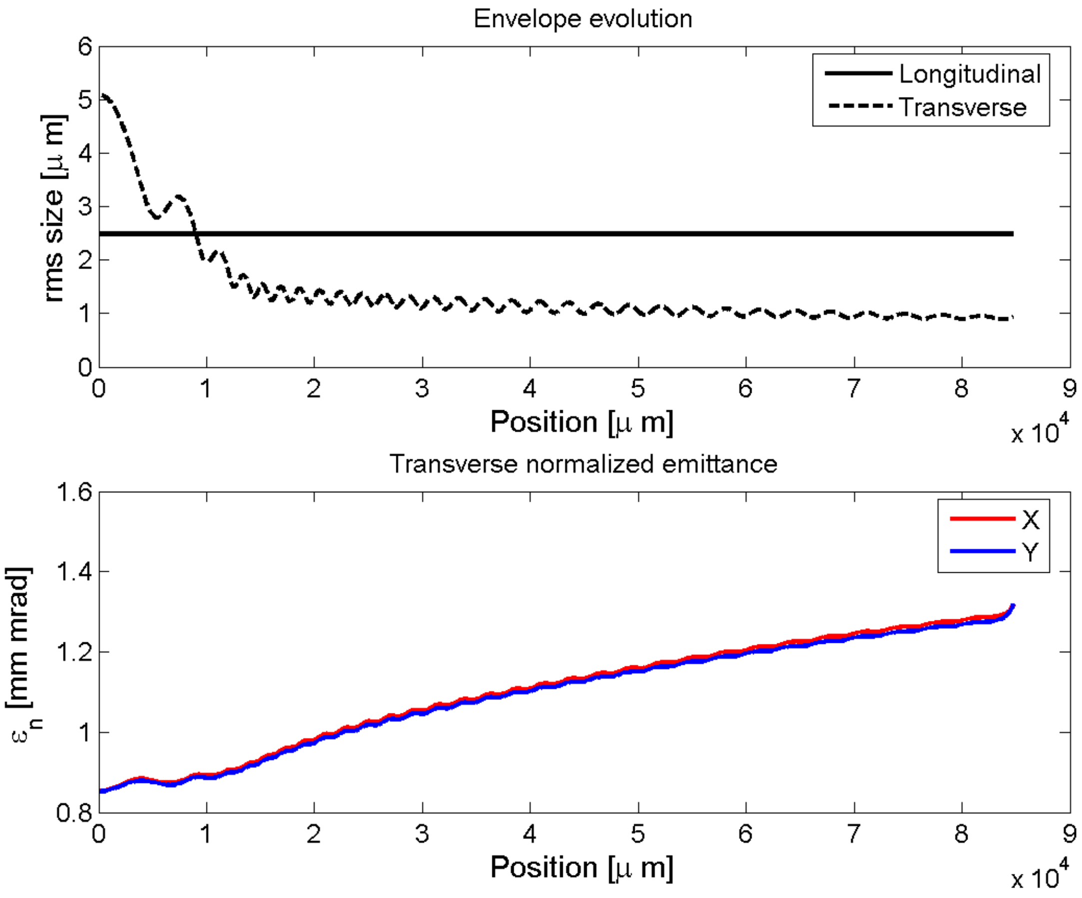
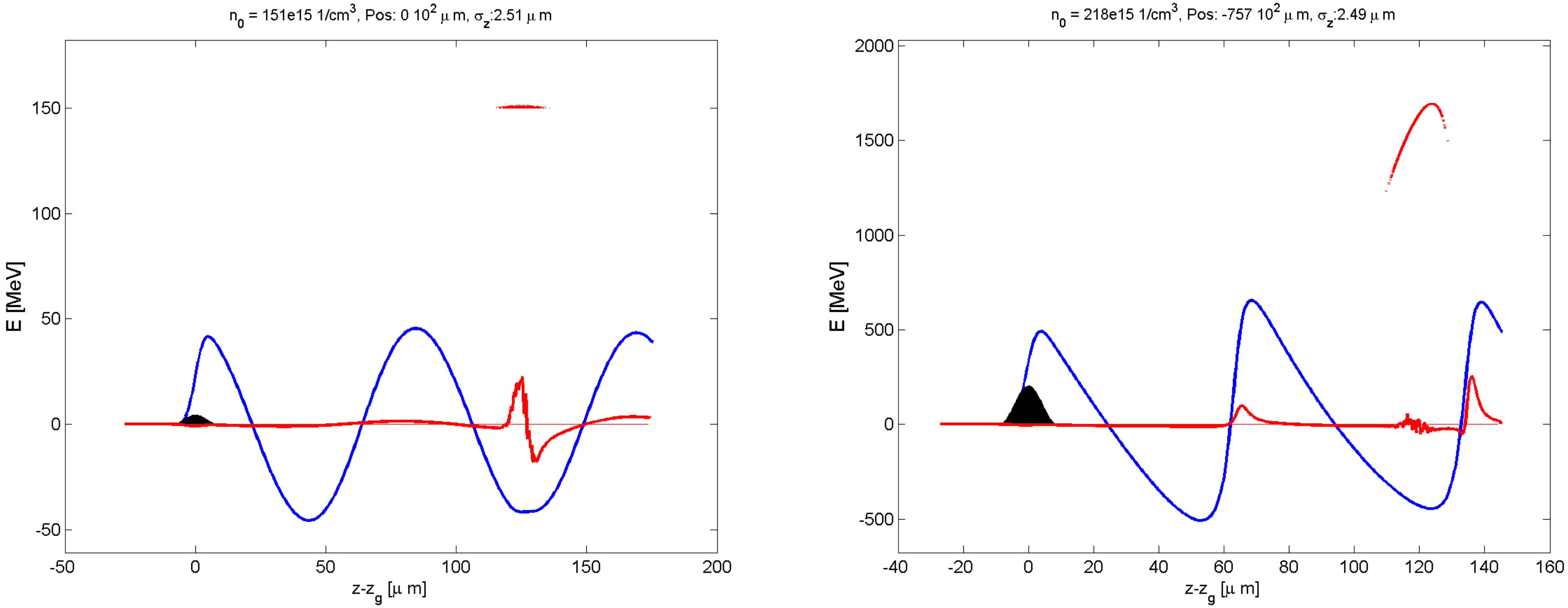
with matching



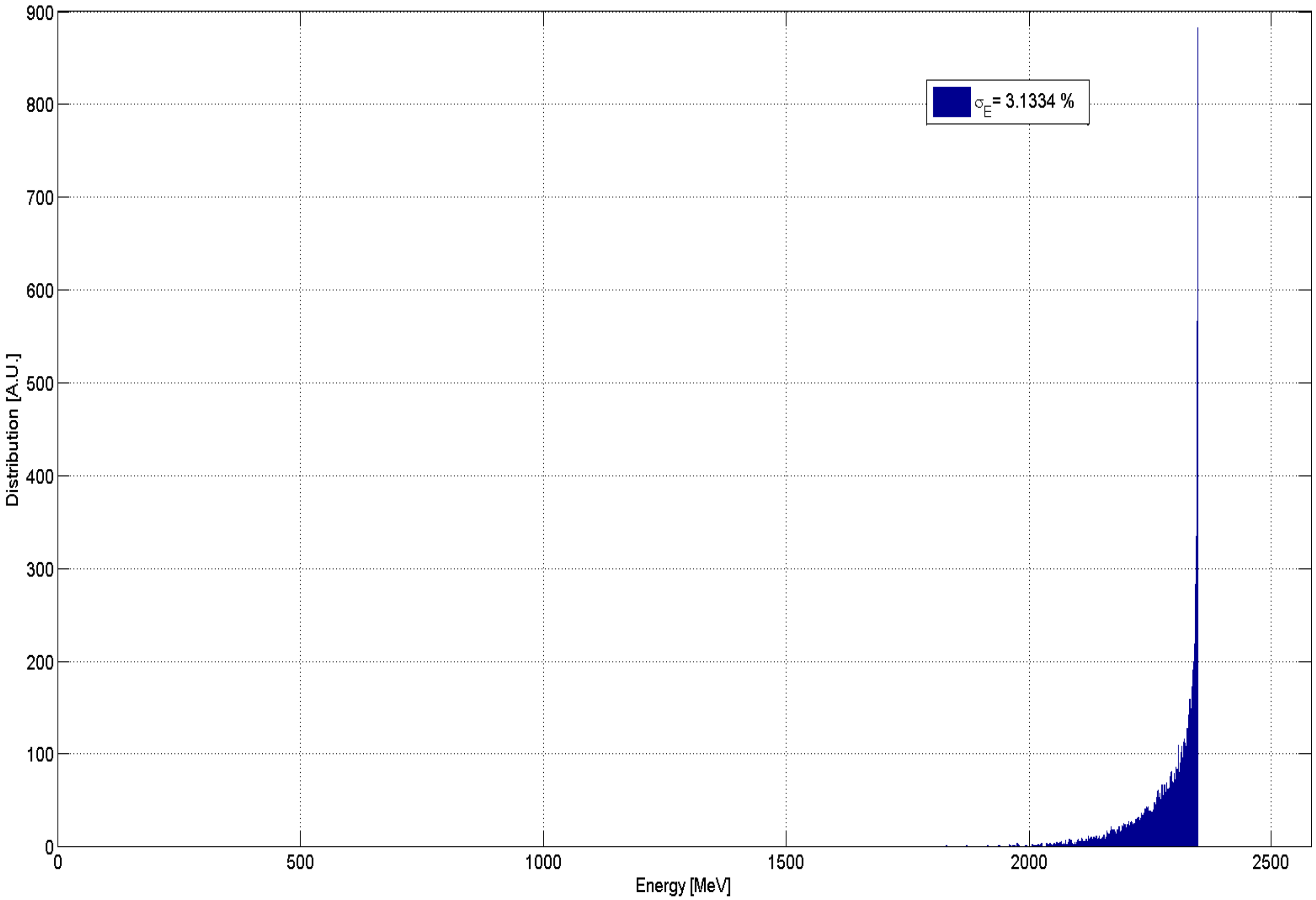
Studies for the external injection

Lineout of the density/fields and longitudinal phase space at two different simulation times



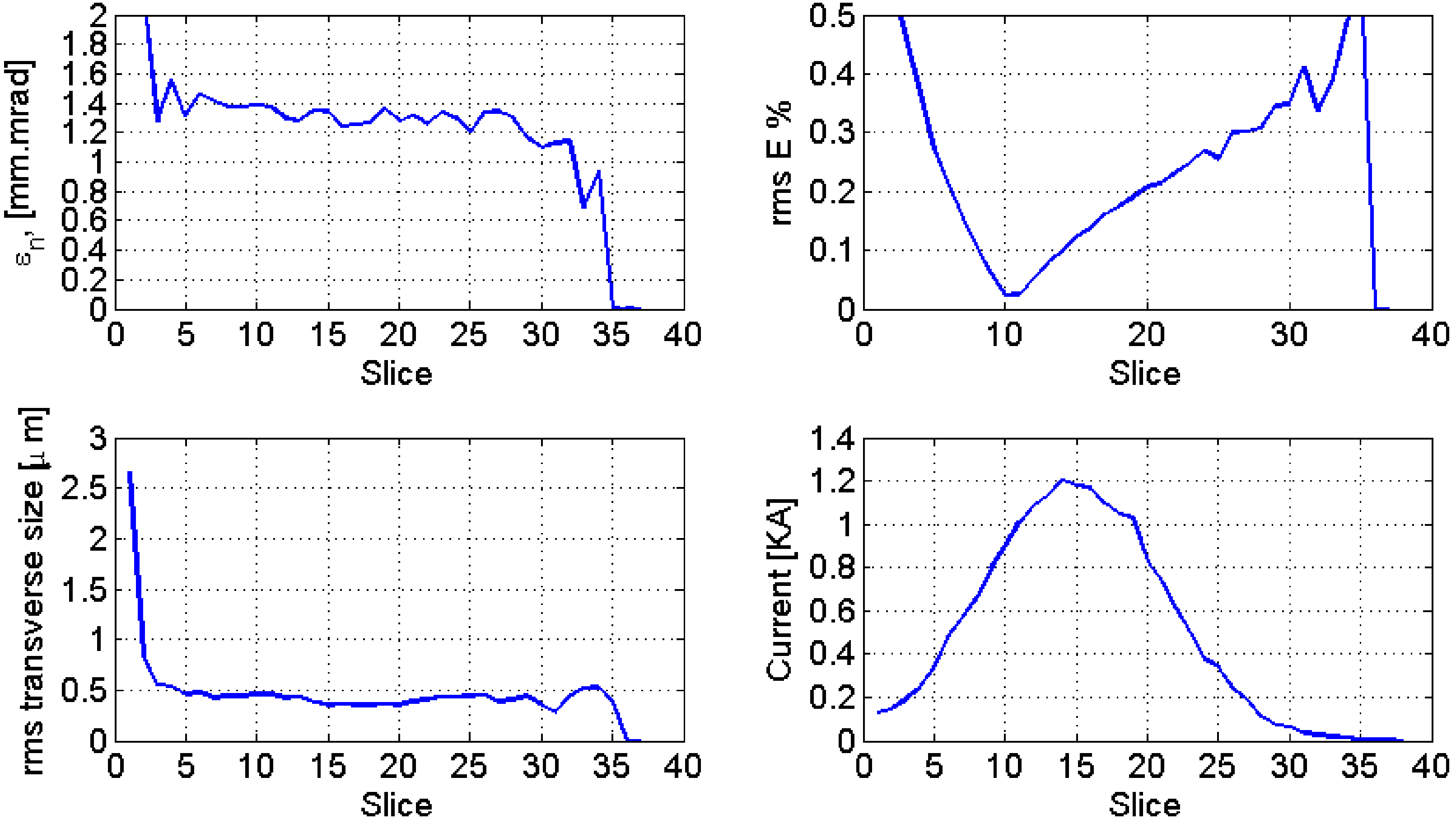
Studies for the external injection

$E_{peak} = 2.2$ GeV after 10 cm $\delta E/E \simeq 3$ %



Studies for the external injection

Slice analysis ($L_{slice} = 0.2\ \mu$m)



⇒ good slice emittance/mom spread (slices 5-20) [potentially interesting for XFEL applications]

Studies for the external injection

Jitter in the injection phase