Detection technique for self-modulation of long electron beams in plasmas

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Abstract

Self-modulation of particle beams in a plasma is considered as a concept enabling plasma wakefield acceleration with long driver beams. An experiment to observe this self-modulation at the Photo Injector Test facility (PITZ) at DESY, Zeuthen site is currently in preparation. In this report the transverse profile analysis of the beam in plasma at PITZ setup, simulated by the particle-in-cell code OSIRIS, is presented. It has been found that the self-modulation of the beam may lead to a different transverse profile in comparison to the case without self-modulation.

Contents

1 Introduction

Plasma wakefield accelerators have gained considerable attention in the last years. It is because of the possibility of achieving large electric potential gradients on a significantly smaller distance than in conventional particle accelerators. When an intense laser pulse (laser-driven acceleration) or an ultra-short bunch (beam-driven acceleration) is focused on a plasma, large wakes are formed behind it. Those wakes can sustain very high accelerating gradients. In 2007, energy doubling of 42 GeV electrons has been demonstrated in a meter-scale plasma wakefield experiment [1]. It is believed that plasma wakefield accelerators may give us the opportunity to reach 1TeV barrier for electrons in the future. However, there is still a number of challenges which have to be addressed. Laser technology has to be improved in terms of power, stability and repetition rate [2]. Another issue is the electron beam-driven wakefield acceleration has the fundamental problem of the transformer ratio limit, which means that the maximum achievable energy gain in one stage is limited by the energy of the particles in the driver beam.

It has been recently proposed by the AWAKE collaboration to use TeV proton beams at CERN to drive plasma waves which are able to transfer energy from the proton beam to the electrons, and accelerate them to TeV regime in a single plasma stage [3]. In order to maximize the size of the acceleration field, the length of the driving bunch must be roughly of the size of the plasma wavelength. It means that a typical beam length should be shorter than 1mm. However, the CERN proton bunches are 12cm long.

When the beam longer than the plasma wavelength is used, self-modulation of the beam occurs. The reason of this effect is the interaction between transverse electric fields in plasma with the beam. Thus, it has been proposed to use this self-modulation instability of the beam propagating through plasma to produce bunch train which will be able to resonantly drive large plasma waves for acceleration [4]. Such a self-modulation has been predicted analytically and in simulations [5][6], but there are very few experimental evidence. In order to observe this phenomenon and analyze it more deeply, experiment at PITZ in DESY is currently in preparation where long electron beams will be used since they are easier to handle and the underlying physics is similar.

One of the way to determine an occurrence of the self-modulation is analysis of the energy spectrum of the beam passing through the plasma cell [7]. The other approach may be the analysis of the transverse profile of the beam. The reason for it is that self-modulation causes beam's transverse profile to evolve. This type of evolution is the subject of analysis in this report.

2 Theory

In a cold plasma (thermal motion can be neglected) behavior of the electrons is simply described by the charge density oscillations at the plasma frequency:

$$\omega_p = \sqrt{\frac{n_0 e^2}{m\varepsilon_0}} \tag{1}$$

where n_0 is the plasma density, e is the elementary charge, m is the electron mass, and ε_0 is the permittivity of free space.

Therefore, plasma wavelength $\lambda_p = 2\pi/k_p = 2\pi c/\omega_p$, where k_p is the plasma wavenumber and c is the speed of light, depends on the density of the plasma in the following way:

$$\lambda_p[\mu m] = \frac{3.3 \times 10^{10}}{\sqrt{n_0[cm^{-3}]}} \tag{2}$$

When the plasma wavelength is smaller than the length of the beam pulse, self-modulation of the beam occurs through coupling of the transverse wakefield with the beam radius. Periodic regions of focusing and defocusing modulate the beam density at λ_p. It leads to the situation of a larger plasma density modulation that further focuses the beam periodically.

The evolution of the self-modulation instability has been derived analytically in [4] under certain approximations or regimes of validity. The growth of the transverse self-modulation instability for a long $k_p L_p \gg (k_p/\sqrt{2\gamma_b})z$, and narrow $k_p\sigma_r \ll 1$, at position $|\zeta| = |z - ct|$ along the bunch with an initial peak density n_{b0} after a propagation distance z and time t in the plasma, is proportional to e^N, where []:

$$N(z,\zeta) = \frac{3\sqrt{3}}{4}\left[\frac{n_{b0}}{n_0}\frac{k_p^3}{\gamma_b}|\zeta| z^2\right] \tag{3}$$

with $\gamma_b = 1/\sqrt{1-(v_b/c)^2}$; where L_b is the length of the particle bunch, σ_r is the RMS beam size, and v_b is the velocity of bunch propagation.

Another phenomenon which needs to be considered during preparation of the plasma acceleration experiment is the scattering through a thin foil. When the particle beam leaves the plasma cell it incidents on exit window. As a result emerging beam is less collimated which leads to emittance growth, as depicted at Fig.1 . The parameter describing this scattering is the standard deviation of an angle between the incident and emerging beams.

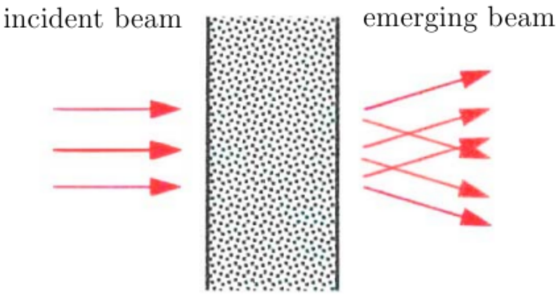

Figure 1: Scattering through a thin foil

3 Experimental setup

Elements of the plasma wakefield experiment at PITZ which are significant for transverse profile analysis of the beam are: photoinjector laser, plasma cell and detecting screen. [8]

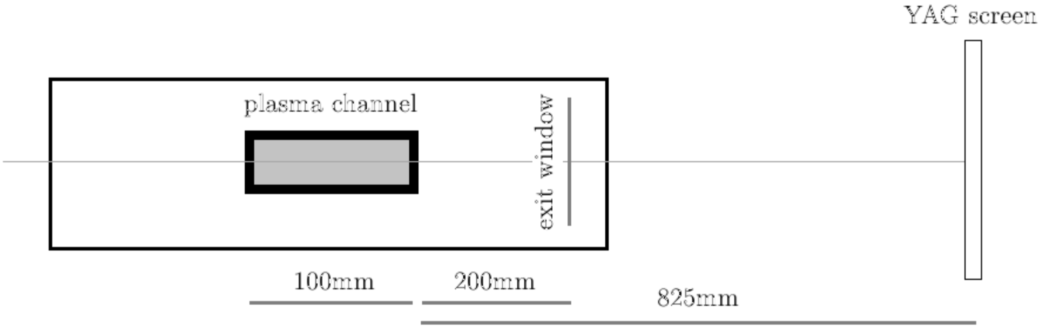

Figure 2: PITZ setup

3.1 Photoinjector laser

The PITZ photoinjector laser generates pulse trains to drive the photo-cathode of the electron linac. Special feature of this laser is the pulse shaper [9], which purpose is to generate a temporal flat top pulse from an incoming Gaussian shaped pulse.

3.2 Plasma cell

In the plasma cell which is 1185 mm long only central bit is the active lithium plasma channel. It is ionized from the side (perpendicularly to the line of beam propagation) which enables very sharp spatial transition from the lithium gas to the active plasma. Moreover, this method allows for an easy length change of the active plasma up to 10 cm. After the plasma channel, 250 mm from the center of the plasma cell, exit window is placed. It is a polymer foil with estimated scattering with an opening angle of 0.2 mrad.

3.3 Drift space

Between plasma cell and the detecting screen magnetic quadrupoles are located. However, in order to simplify complexity of the results, magnetic quadrupoles can be turned off. It means that the distance between the end of the plasma channel and the screen may be considered as a free drift space. Its length is 825 mm for the case of 10 cm plasma length.

3.4 YAG screen

The final part is the YAG detecting screen. Its pixel size is 50 μm , and its usually used to detect beam of the total charge of order nC. However, there are no precise measurements of the charge detection threshold for a single pixel.

4 Particle-in-cell simulation of the PITZ experiment

For the purpose of the transverse profile analysis of the beam at PITZ, data from the particle-in-cell (PIC) 3D simulation of the process are used [10][11]. They are generated using fully relativistic, massively parallel PIC code OSIRIS for the case of homogenous plasma with a density of 10^{15}cm^{-3}. Electron beam parameters in the simulation correspond to the typical parameters used at PITZ and are given in Table 1 [8].

Table 1: PITZ beam parameters used for simulations

Parameter	Value
Total charge (pC)	100
Horizontal RMS beam size (μm)	42.0
Vertical RMS beam size (μm)	42.0
Bunch length in FWHM (mm)	5.93
Average kinetic energy (MeV)	32.5
Peak slice current (A)	5.0
Horizontal RMS emittance (mm mrad)	0.372
Vertical RMS emittance (mm mrad)	0.372
Peak beam density (10^{13}e/cm^3)	0.9

5 Results

The first step of the project was analysis of the radial size along the propagating beam. Different stages of the propagation were captured, referring to different times of propagation in plasma. Fig. 3 represent RMS of the beam charge distribution ($\hat{r} = \sqrt{< r^2 >}$) as a function of ζ. It is difficult to describe the envelope of these modulations by eq.(3) since the conditions for validity of this equations are not perfectly fulfilled. Especially, for a beam travelling long distance in a plasma since this quantity is growing with z, and equality $k_p L_p = (k_p/\sqrt{2\gamma_b})z$ is achieved for 55 mm ($\gamma_b = 43.08$), which means, that the beam is too short. Beam width is is also relatively broad before entering the plasma channel $k_p \sigma_r = 0.25$. We can also see that in [12], where self-modulation of a long electron beams in plasma at PITZ in 2D is investigated, radial width evolution follows the e^N pattern. It tells us about the difference between 2D and 3D simulations of the plasma behaviour.

The next part of the project was investigation of the transverse profile seen on the YAG screen. Strong focusing of the beam is observed in its first 24 mm propagation in plasma. After that time some electrons start moving away from the center of the beam leading to effect observed in Fig. 4 at 67 mm. Obtained profiles can be compared to the case when the beam is not going through the active plasma channel, it drifts with a transverse profile simillar to a Gaussian and it remains well collimated. Detection in PITZ experiment may be very strightforward method for observing self-modulation in plasma. The problem connected with the detection of this phenomenon is the width of the beam with respect to the pixel size in YAG screen. If the screen was placed right after the plasma channel the resolution of the beam would be smaller than 10 by10 pixels. However, when the beam propagates through the plasma, electrons gain transverse momentum with respect to the axis of initial propagation, i.e. the beam exits plasma with large divergence. Therefore, when the beam propagates through the drift space between the plasma channel and the detecting screen its rms beam size grows. At the point when the electrons reach the screen, beam's width may be of the order of 1cm. As a result, it gives the resolution of about 400 by 400 pixels, which would allow to observe beam transverse profile with a good precision. On the other hand, the problem connected with such a large group of pixels is a relatively small charge absorption by each of them. There are no precise studies defining the minimal charge detectable by the YAG screen used at the PITZ experiment. However, for the case of beam's total charge 100 pC, charge absorbed by one pixel may be smaller than 0.1 pC. Hence, using quadrupole magnets in order to focus the beam could be helpful in order to acheve higher charge absorption by a pixel. Fig. 5 presents the 2D image of the transverse profile of the beam after travelling 67 mm is plasma and 1m in a drift space.

During self-modulation in the plasma energy profile along the beam attains oscillatory shape [12]. At the length scale of the plasma cell this fact doesn't cause any visible changes in the longitudianl profile of the beam. It is because the beam's speed is close to the speed of light and variations in kinetic energy are of order 1%. However, after drifting about 1m, these differances become noticable. They lead to oscillatory variations in a longitudinal beam's profile as shown at Fig. 6.

The important aspect which needs to be considered is the scattering on the exit window. For the cases when the beam has travelled at least several milimeters in plasma this scattering has a marginal effect on the way beam propagates in a drift space. For example, for plasma channel of length 40 mm the average angle of deviation from the beam line is 3.4 mrad, and small scattering angle such as 0.2 mrad causes no effect leaving the average angle equal about 3.4 mrad. That's why effects conected with a scattering through the thin foil may be neglected in analysis pf the transverse profiles.

Finally, the parameters which qualitatively describe evolution of the transverse profile of the beam are: intensity at centre of the beam (height of the peaks in Fig. 4), standard deviation of electrons from the center of the beam, and full width at half maximum. Fig. 7 presents these quantities right after the beam leaves the plasma channel (before the free drift) for different lenghts of the active plasma. Fig. 8 depicts the same quantities, but after additional 1m of the free drift.

6 Conclusions

Self-modulation of long beams in the plasma acceleration leads to the evolution of beam's transverse profile. Differences in transverse profiles measured for the beams passing through plasma or without plasma can be used as technique to detect the self-modulation. Additionally, such analysis may allow to gain qualitative and quantitative understanding of the underlying physics processes. The self-modulation instability is a phenomena with complex non-linear nature, which may be difficult to describe analytically. Therefore full understanding of the transverse profiles behaviour would require further analysis. Except pure analysis of the simulation data, two experimental conditions were considered: scattering thorugh a thin foil, and a free drift of the beam after plasma. The free drift, is a significant factor determining the shape of the beam profile. It was found that the detection of the self-modulation at PITZ using YAG screen may be possible, but mostly for the central part of the bunch because of relatively small intensity of the beam. Hence, using quadrupole magnets to focus the beam could be useful.

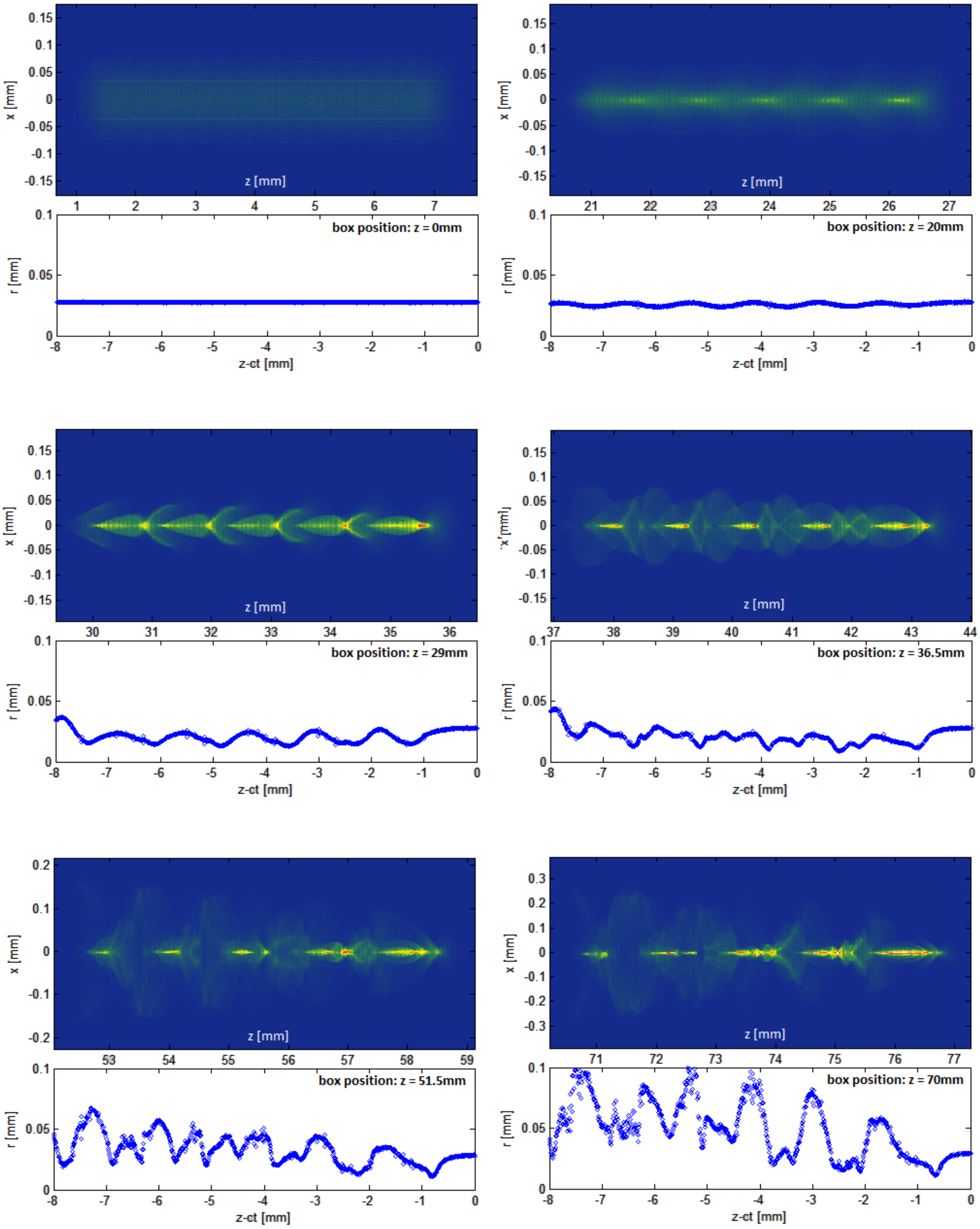

Figure 3: Radial evolution of the beam

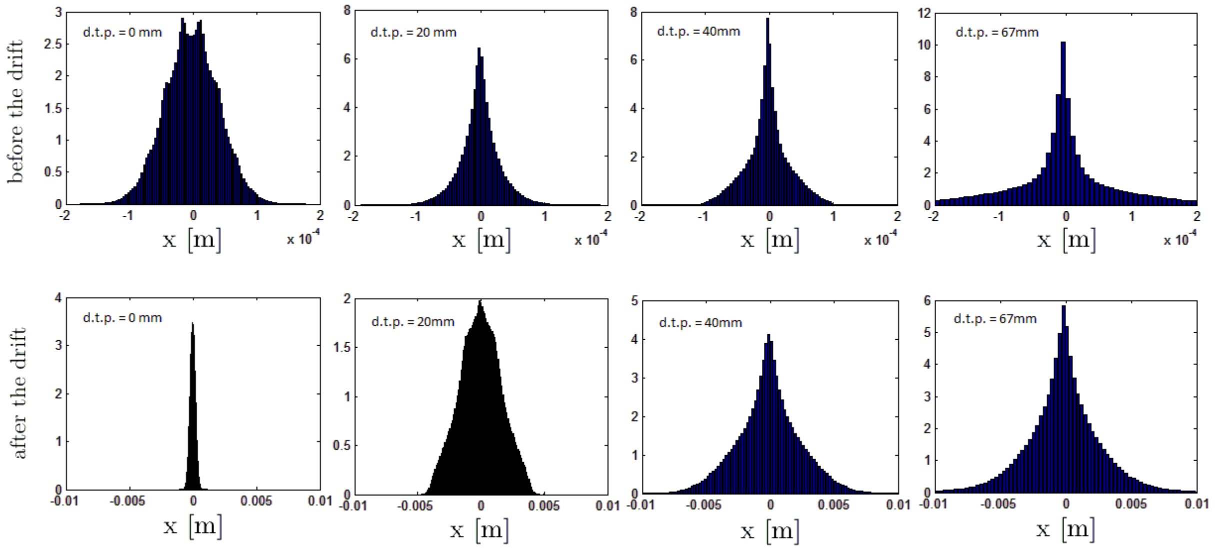

Figure 4: 1D transverse profiles of the beam. d.t.p. denotes the distance travelled in plasma. Top row shows the profiles right after leaving plasma channel. Bottom row shows the shape of the transverse profile of the beam after travelling in the plasma (d.t.p.) and in a drift space (1m). Vertical scale represents just the relative charge distribution presenting the shape of the profile.

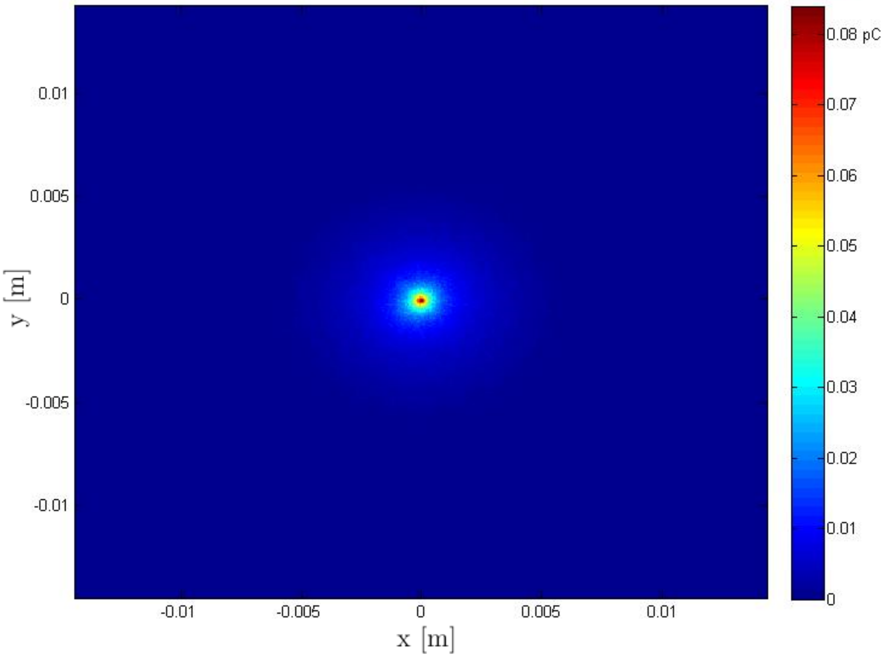

Figure 5: 2D transverse profile of the beam after travelling 67mm in plasma and 1m in a drift space. Colormap represents a charge absorbed by a single pixel.

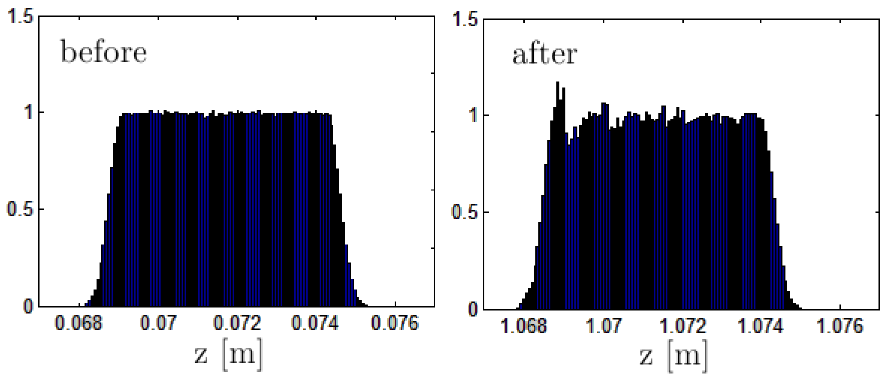

Figure 6: 1D longitudinal profile, before and after 1m of the free drift. Vertical scale represents the relative charge distribution.

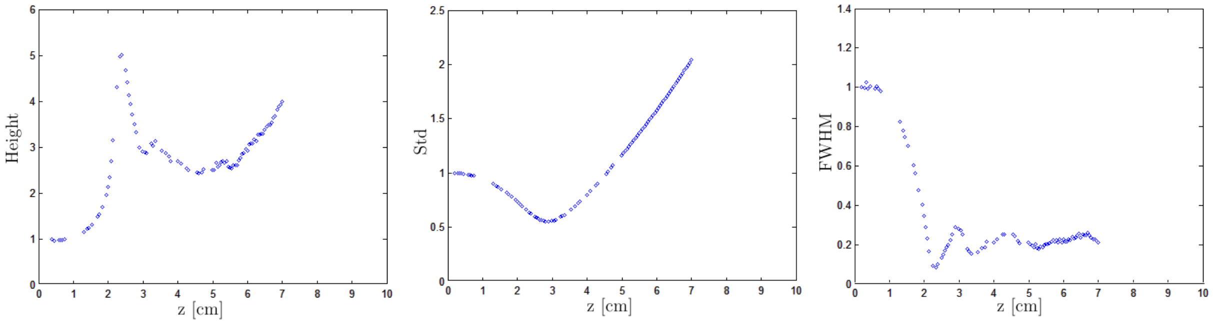

Figure 7: Maximum in the transverse intensity profile, standard deviation from the centre of the beam and it's full width at half maximum before the free drift. The vertical scale is choosen to present relative change with respect to the initial conditions.

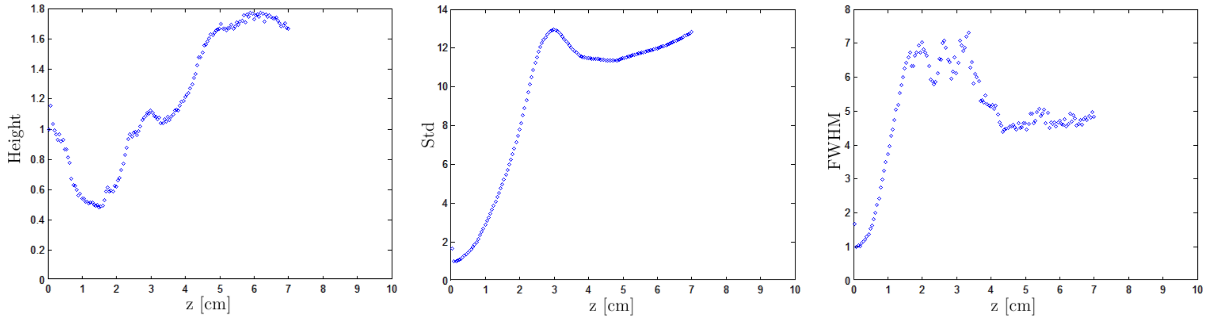

Figure 8: Maximum in the transverse intensity profile, standard deviation from the centre of the beam and it's full width at half maximum after 1m of the free drift. The vertical scale is choosen to present relative change with respect to the initial conditions.

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