POSSIBILITY OF CONFIRMING SMI THROUGH ENERGY SPECTRUM WITH THE $1\ nC$ ATF ELECTRON BUNCH

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Abstract

In this paper, we demonstrate numerically the possibility of measuring the energy gain/loss experimentally to confirm the self-modulation instability (SMI) development with electron bunch parameter available at Accelerator Test Facility (ATF) of Brookhaven National Laboratory (BNL). The results also show that due to plasma wakefield dephasing during the SMI development, the actual energy gain/loss by drive bunch particles is lower than deduced from maximum accelerating fields. All the simulations are performed with the 2D-cylindrically symmetric partilcle-in-cell code OSIRIS [1].

INTRODUCTION

We have successfully demonstrated the excitation of multiple-periods plasma wakefields by a 50 pC bunch with square current profile available at the Accelerator Test Facility of Brookhaven National Laboratory (BNL-ATF) [2]. These wakefields act as the seed for self-modulation instability (SMI). The experimental data is in excellent agreement with the linear theory and OSIRIS-2D [1] simulation results. With this low 50 pC charge, the SMI does not grow within the 2 cm propagation distance in the plasma density range available in the experiment (10^{15}-10^{17} cm^{-3}), and therefore periodic energy modulation measurements were possible. However, simulations have shown that the SMI of the 1 nC bunch grows significantly and reaches saturation over the 2 cm propagation distance (see Fig. 1 *b*)). Note that for 1 nC bunch, the beam-plasma interaction is still in the linear regime of the PWFA for the plasma density range as indicated above, i.e., n_b/n_p <0.06. According to linear theory, the initial wakefield amplitude is 20 times higher for 1 nC bunch than that of 50 pC bunch, and this has been confirmed by previous simulations [3]. We here further analyze the simulation results of 1 nC bunch to examine the possibility of measuring the energy spectrum experimentally to confirm the development of SMI. As an example, we take the plasma density of $n_e = 4.85 \times 10^{15}$ cm^{-3} such that $L_{\text{beam}}/\lambda_{pe} = 2$. It has been demonstrated that during the development of SMI, the plasma wave phase velocity becomes smaller than the beam velocity, resulting in dephasing between the bunch particles and the wakefields [4, 5]. The following results show that due to such dephasing, the actual energy gain/loss by drive bunch particles is $\approx$ 25% lower than deduced from maximum accelerating field plots, i.e. assuming the wakefield on the particles do not dephase. However, the resulting energy gain is approximately 2.4 times larger than the case without SMI development. It is therefore still possible to confirm the SMI development through the measurement of resulting energy spectrum in the experiment.

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ENERGY GAIN/LOSS

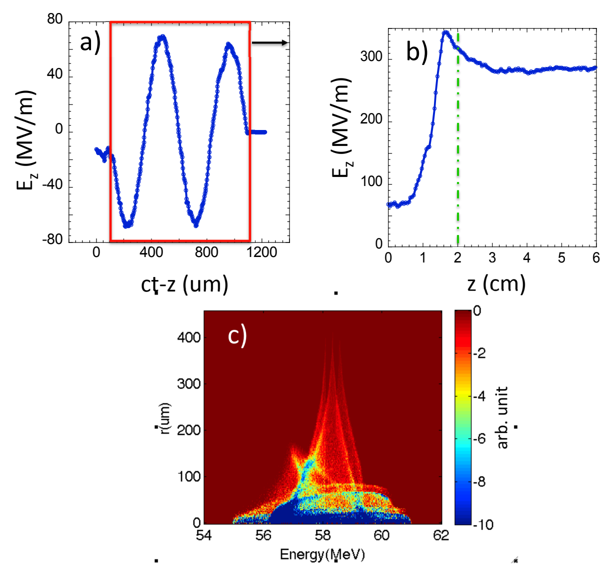

Figure 1: *a*) The longitudinal wakefield E_z on the axis ($r = 0$) at plasma entrance ($z = 0$) within the bunch. The red rectangle indicates position of the electron bunch. *b*) The evolution of maximum E_z on the axis ($r = 0$) along the propagation distance. The green line indicates the plasma length in the experiment. *c*) Electron bunch density in the r, E space, showing the energy spectrum of the beam at plasma exit ($z = 2$ cm). Results are obtained from OSIRIS 2D.

We first assume that there is no SMI growth during the 2 cm propagation for the 1 nC bunch, and therefore the energy gain/loss at the plasma exit can be estimated by multiplying the initial E_z amplitude (at $z = 0$) with 2 cm. Figure 1 *a*) shows the initial longitudinal wakefield E_z on the axis ($r = 0$) at the plasma entrance ($z = 0$) obtained from simulation, with an acceleration amplitude $E_{z0} \approx 67$ MV/m, which is within $\%5$ difference with the estimation of linear theory ($\approx$ 64 MV/m). Therefore, assuming no SMI growth and hence no E_z amplitude evolution, the energy

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gain/loss at the plasma entrance would be $\Delta E_{\mathrm{no-growth}} = E_{z0} \times 2$ cm≈ 1.33 MeV. Figure 1 b) shows the evolution of maximum longitudinal field on the axis E_{zmax} along the propagation distance. The exponential growth and saturation of E_{zmax} indicate the development of SMI with the 1 n bunch. Since the SMI is a convective instability, the maximum E_z is expected to be at the back of the bunch, e.g. at the acceleration peak of the second wakefield bucket in this case. Assuming no dephasing of the plasma wave with respect to the square bunch during the propagation, the maximum energy gain can be estimated as the integral of E_{zmax} over the propagation distance, resulting in $\Delta E_{\mathrm{growth-integration}} \approx 3.52$ MeV. Figure 1 c) shows the energy spectrum of the electron bunch particles at the plasma exit, obtained from the OSIRIS-2D simulation. With the mean incoming energy of 58.35 MeV, the maximum energy gain is estimated as $\Delta E_{\mathrm{growth-spectrum}} \approx 60.98 - 58.35 = 2.63$ MeV, more than 2 times larger than the value obtained assuming no SMI growth. We hence conclude that it is experimentally possible to confirm the development of SMI through the measuring of the energy gain/loss at the plasma exit. It is also worth noting that the particles' actual maximum energy gain/loss $\Delta E_{\mathrm{growth-spectrum}}$ is 25% smaller than the integration of the maximum E_z result $\Delta E_{\mathrm{growth-integration}}$. This clearly indicates the occurrence of dephasing during the development of SMI, which will be further examined in the following section. Note that the conclusion also applies to energy loss, although the figures are not shown here.

DEPHASING OF THE WAKEFIELD

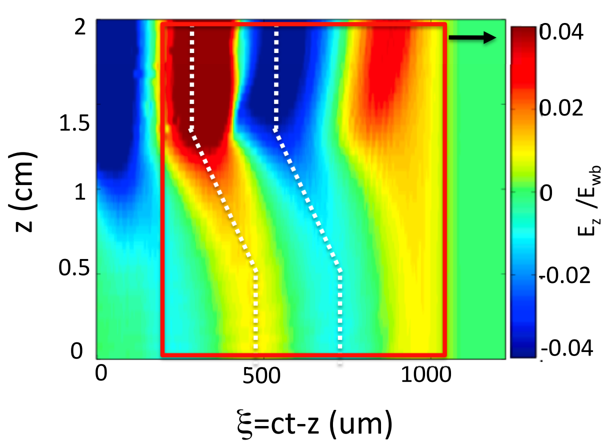

Figure 2: Evolution of the accelerating wakefield structure E_z within the bunch(es) along the propagation distance z. The red rectangle shows the longitudinal position of the bunch and the white dotted lines show the "trajectory" of the peak accelerating and decelerating field in the $z - \xi$ plane, respectively.

To confirm the dephasing of the plasma wave with respect to the electron bunch during the propagation, Fig. 2 shows the evolution of accelerating wakefield structure E_z. The phase velocity of the longitudinal plasma wave v_ϕ can be deduced from the slope of maximum E_z in the z and $\xi(= ct - z)$ plane (as shown schematically by the dotted line in Fig. 2), yielding $v_\phi = c \times (1 + \frac{1}{\delta z/\delta \xi})$ [6]. Consequently, a smaller negative slope ($\delta z/\delta \xi$) means a smaller phase velocity. Figure 3 d) shows the fitting to obtain the phase velocity. During the first 0.5 cm propagation, there is no significant growth of SMI (as can be observed in Fig. 1 b)) , and therefore the wakefield phase velocity is close to the beam velocity $v_b(\approx c)$. Between $z = 0.5 - 1.5$ cm, the beam density becomes modulated due to the periodic focusing/defocusing field and hence SMI develops, resulting in a lower wakfield phase velocity v_ϕ. Its value is estimated as 0.986 c according to Fig. 3 d). For $z = 1.5 - 2.0$ cm, the SMI saturates and the wake phase velocity almost reaches c again.

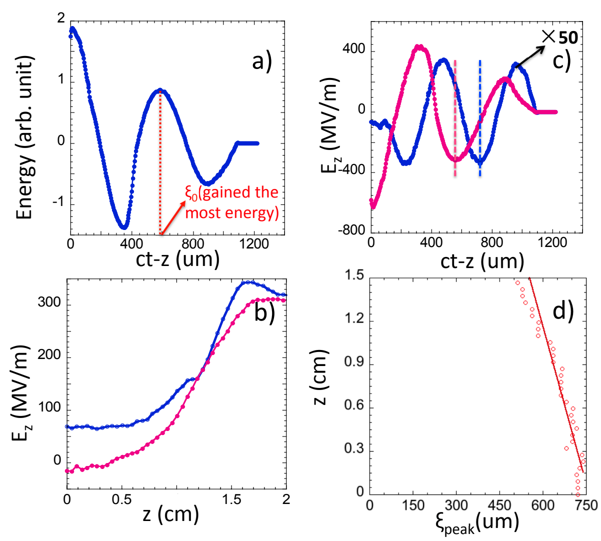

Figure 3: a) Energy gain/loss by particles along the bunch (ξ) after 2 cm plasma, obtained by integrating the acceleration field (as shown in Fig. 2 c)) over the propagation distance z. ξ_0 indicates the position in the bunch where particles gain the most energy; b) the accelerating field on the axis at position ξ_0 of the bunch ($E_z(\xi_0, r = 0)$) along the propagation distance z (red line) and the maximum E_z field on the axis along z (blue line); c) Longitudinal wakfield E_z on axis ($r = 0$) at plasma entrance $z = 0$ (blue line) and plasma exit $z = 2$ cm (red line). Note that E_z at $z = 0$ (blue line) is multiplied by 50 in order to make it visible on the same scale. The dotted lines show the accelerating peaks of the respective fields, and the distance between the two dotted lines directly shows the wakefield dephasing; d) the shifting of the position ξ of the peak accelerating field along the propagation distance z, and the fitted line is given as: $z(\mathrm{cm}) = 5.5467 - 0.0072932 \times \xi(\mathrm{cm})$, yielding $v_\phi = c \times (1 + \frac{1}{\delta z/\delta \xi}) \approx 0.986c$.

Figure 3 a) shows the energy gain of the beam particles along ξ, obtained by integrating the acceleration field in Fig. 2 over the propagation distance z, yielding the ap-

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proximate energy gain/loss of the bunch particles during the 2 cm propagation ($\int E_z dz \approx \sum E_z \Delta z$). We can therefore identify the ξ_0 position where the bunch particles gain the most energy. This is indicated by the dotted line in the Fig. 3 a). Figure 3 b) shows the evolution of the accelerating wakefield experienced by the the particles at ξ_0 (red curve), compared to the maximum accelerating wakefield (blue curve) along the bunch. The fact that the former amplitude is smaller than the later one explains the energy difference between the integration from maximum E_z and the actual energy spectrum of the particles at the plasma exit, as mentioned above. Fig. 3 c) shows the longitudinal field E_z on the axis along ξ at the plasma entrance $z = 0$ (blue line, $\times 50$) and at the plasma exit $z = 2$ cm (red line). The shift of the peak accelerating field between $z = 0$ and $z = 2$ cm clearly confirms the dephasing. It is worth noting that the dephasing occurs mostly over the first plasma period.

CONCLUSION

In conclusion, simulation results presented here demonstrated that the SMI grows significantly over the 2 cm propagation distance for 1 nC bunch at ATF with a plasma density such that $L_{beam} = 2\lambda_{pe}$. Due to dephasing between the bunch particles and the plasma wakefield, the actual energy gain is $\approx 25\%$ smaller than the integration of the maximum E_z over the propagation distance. However, the resulting energy gain is still approximately 2 times larger than the case without SMI development. It is therefore possible to confirm the SMI development through the measurement of resulting energy spectrum in the experiment.

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