STUDY OF HIGH TRANSFORMER RATIO PLASMA WAKEFIELD ACCELERATION FOR ACCELERATOR PARAMETERS OF SXFEL FACILITY AT SINAP USING 3D PIC SIMULATIONS*

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Abstract

High transformer ratio (HTR) Plasma Wakefield Accelerator (PWFA) based on shaped electron bunches is an important topic of plasma wakefield acceleration for future light sources and colliders [1]. To explore the possibility of implementing PWFA at SXFEL facility of SINAP, we performed 3D PIC simulations using shaped electron beam parameters obtained by start-to-end beam line simulations [2]. The PIC simulations show that an average transformer ratio around 4 can be maintained for about 10 cm long low density plasma, and the energy gain of the trailing bunch eventually reaches 5.9 GeV. Simulations and analysis are also performed to check the effects of transverse beam size on HTR acceleration. In addition, plasma density downramp injection has also been tested as a possible high brightness injection method for HTR acceleration, and preliminary results will be presented.

INTRODUCTION

In the past decade, research on plasma wakefield acceleration (PWFA) has made great progress. Key milestones such as high gradient high energy acceleration, high efficiency acceleration, positron accelerations etc. have been successfully passed recently [3, 4]. In the future development of PWFA, high transformer ratio acceleration is one key topic that may lead to much reduced accelerator scale, and it will be one key experimental goal for FACE-TII at SLAC [5].

To achieve a high transformer ratio (defined as the ratio of the peak accelerating field within the trailing bunch over the peak decelerating field within the drive bunch, i.e. $R=E^{+}/E$), triangle shaped drive bunches are preferred [6, 1]. Some preliminary techniques for generating such current profiles have been recently demonstrated, typically with limited peak current well below kA [7, 8]. However, to drive ideal wakefields in the nonlinear blowout regime, beam peak current of 5 kA or more are typically needed, and even higher current will be needed for controlled injection based on ionization or density downramp injection methods [9, 10]. One possible way to directly generate such shaped high current bunches is to manipulate the longitudinal phase space of the electron beam by combining the photon-injector with a chicane compressor. To illustrate the feasibility of this method, we performed start-to-end beam line simulations based on the parameters at SXFEL linac. SXFEL is an 840 MeV linac based soft X-ray free electron lasers facility at SINAP, which will be upgraded to 1.5 GeV in near future [11].

Figure 1 shows a possible beam current profile based on the beam line simulations [2]. The beam has a slowly rising triangle like current profile with a sharp termination, and a full pulse duration of 200 fs. The peak current is about 6.3 kA, and the normalized emittance is 2 mm mrad.

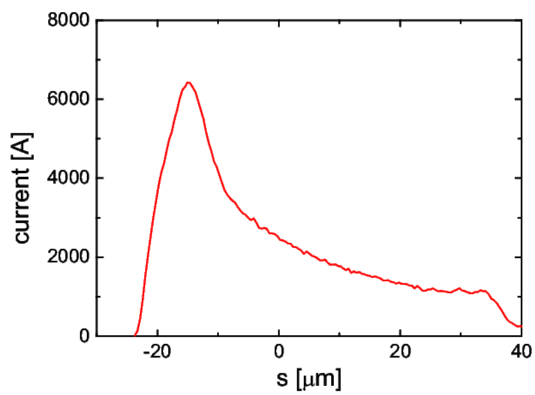

Figure 1: Current profile from beam line simulation.

Based on these beam line simulations, we propose to use SXFEL linac as a possible driver for HTR PWFA in the near future. In the following sections, we present 3D PIC simulation results based on these shaped electron beam parameters above. These simulations suggest that an average high transformer ratio around 4 is possible, and such beam can also lead to high brightness injection using density downramp injection method.

SIMULATION OF HTR PWFA

Based on the beam parameters described above, we performed 3D-PIC simulations using QuickPIC [12] to study HTR PWFA. In Fig. 2 we show the results from a typical simulation, where plasma density is 2.83e17 cm^{-3} and the transverse RMS beam size is 10 um. The first row shows the beam and plasma densities at three different time, and the second row shows the corresponding lineout of the longitudinal field. In this simulation, an average transformer ratio about 6 is obtained. One can notice that the beam density profile developed typical bunching structures due to the lack of transverse matching.

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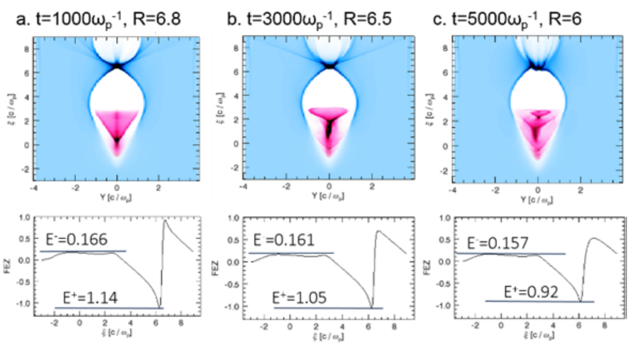

Figure 2: Beam and plasma densities and lineout of E_z at $t=1000\omega_p^{-1}$(a), $3000\omega_p^{-1}$(b) and $5000\omega_p^{-1}$(c), which correspond to distances of 10 mm, 30 mm and 50 mm respectively, since the plasma density n_p=2.83e17 cm^{-3} (k_p^{-1}=10 um). E_z is normalized to $m_e c\omega_p e^{-1}$(51.1 GV/m).

To optimize the transformer ratio and acceleration gradient, we scan the the transverse beam size and plasma density through systematic simulations. In Fig. 3, we show the lineouts of longitudinal field for different beam sizes (from 50um to 1um) after the beam propagates in the plasma for a time of $5000\omega_p^{-1}$. We note that in Fig. 3(a)(b)(c), the plasma density is 2.83e17 cm^{-3} (k_p^{-1}=10 um), while in Fig. 3(d), a higher plasma density (n_p=1.77e^{18} cm^{-3}, k_p^{-1}=4 um) and a larger beam emittance (8 mm mrad) were used to maintain a quasi-matched propagation. In all the cases, transformer ratios more than 3.5 have been achieved. As the beam size reduces, the transformer ratio tends to increases. This may be explained qualitatively based on previous theory on transformer ratio in the blowout regime [1]. The transformer ratio R is proportional to the normalized beam length L_0. When σ_r of the drive beam increases, the beam density drops accordingly, especially at the leading front where the density is low. Equivalently the effective beam length for driving the wake decreases, leading to a smaller R.

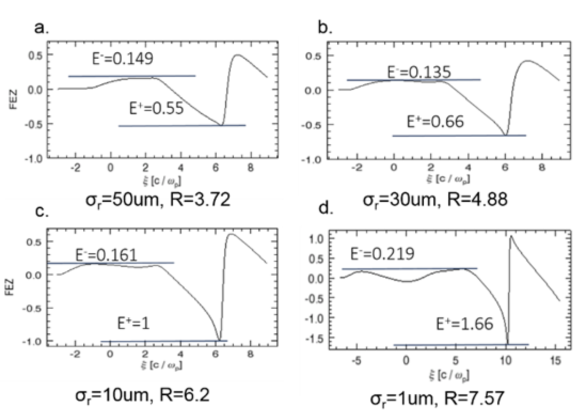

Figure 3: E_z lineout at the time of $5000\omega_p^{-1}$ for different beam sizes in single bunch simulations. The plasma density is 2.83e17 cm-3 corresponding to a skin depth of 10um in the case of (a), (b) and (c), while in (d), the density of plasma is 1.77e18 cm-3(k_p^{-1}=4 um). E_z is normalized to $m_e c\omega_p e^{-1}$(51 GV/m for (a)(b)(c), 128 GV/m for (d)).

As one can see from the single bunch simulations above, the transformer ratio can easily reach 5 or more due to the very high gradient at the tail of the wake. For practical purpose, an effective transformer ratio with a loaded beam is more meaningful. We performed two bunch simulations to get an estimation of the effective transformer ratio. In the two bunch simulations, a bi-Gaussian trailing bunch with a charge of 30 pC and a short pulse duration (10 fs) is used. For the drive bunch, same parameters as those in Fig. 3(c) and (d) were chosen. In Fig. 4, we show the beam and plasma density, and the lineouts of accelerating fields at the time of $1500\omega_p^{-1}$ for both unmatched (left column) and quasi-matched (right column) cases.

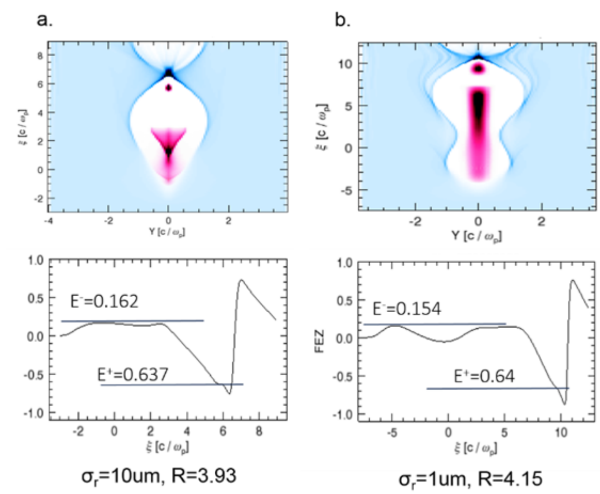

Figure 4: Beam and plasma densities and lineout of E_z at the time of $1500\omega_p^{-1}$. (a) unmatched case, σ_r=10um, k_p^{-1}=10um, ε_n=2mm mrad (b) quasi-matched case, σ_r=1um, k_p^{-1}=4um, ε_n=8mm mrad.

It is found that the transformer ratio decreases slowly in both cases (from around 4 to 3) as the driver propagating through the long plasma. In the quasi-matched case, this decline of R mainly occurs near the end of the simulation, where the drive bunch loses most energy and starts to change shape. At the end of simulation of quasi-matched case (10 cm plasma), the trailing beam has gain an energy of 5.9 GeV (7.4 GeV for total), with an average transformer ratio of 4. For the unmatched case with lower plasma density (n_p=2.83e17 cm^{-3}) and larger beam size (σ_r=10 um), an average transformer ratio of 3.7 has been maintained for 23 cm, with an energy gain about 5.5 GeV.

SIMULATION OF HIGH BRIGHTNESS DOWNRAMP INJECTION

To experimentally test the two bunch scenario of HTR PWFA, a second bunch is needed to sample the wake. This can be implemented using various methods. One method is directly using the photo-injector to produce two bunches. The second bunch can also be generated directly in the plasma by utilizing proper controlled injection methods, such as ionization based and density ramp based injection methods. Here we explored the density down-

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ramp injection as an example. Recently the work by X.L. Xu, F. Li et al. shows that such method can potentially produce extremely high quality beams under proper condition [10].

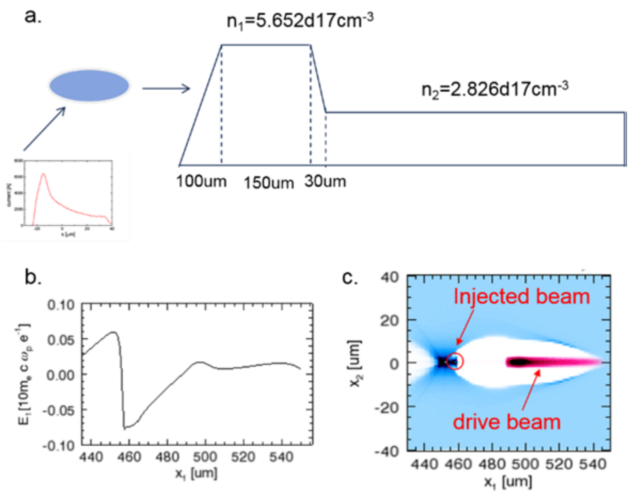

Figure 5: (a) schematic of the simulation. (b) lineout of E_z, which is normalized to $10 m_e c\omega_p e^{-1}$ (511 GV/m). (c) beam and plasma densities.

We performed full 3D PIC simulations with OSIRIS [13] to explore the performance of HTR PWFA with density down-ramp injection. Some preliminary results are presented here. In Fig. 5 we show a sample simulation with the same drive bunch as Fig. 3(d) (σ_r=1 um). In this simulation, an electron bunch with a charge of 31 pC has been directly injected into the plasma wake, and a loaded transformer ratio of 4.3 has been obtained. The injected beam has a peak brightness about 1.66e18 A/rad^2/m^2 (1.53 kA current and 43 nm rad normalized emittance). More simulations will be performed to further optimize the beam quality.

SUMMARY

In this paper, we have explored the possibility of HTR PWFA at SXFEL by performing 3D PIC simulations using shaped electron beam parameters obtained by start-to-end beam line simulations. The PIC simulations show that an average transformer ratio around 4 can be maintained for about 10 cm long low density plasma, and the energy gain of the trailing bunch eventually reaches 5.9 GeV. Simulations and analysis are also performed to check the effects of transverse beam size on HTR acceleration. In addition, plasma density downramp injection has also been tested as a possible high brightness injection method for HTR acceleration, and preliminary results were presented.

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