MITIGATION OF ION MOTION IN FUTURE PLASMA WAKEFIELD ACCELERATORS

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Abstract

Simulation and analysis of the ion motion in a plasma wakefield accelerator is presented for the parameters required for a future ILC afterburner. We show that although ion motion leads to substantial emittance growth for extreme parameters of future colliders in the sub-micron transverse beam size regime, several factors that can mitigate the effect are explored. These include synchrotron radiation damping, plasma density gradients and hot plasmas.

INTRODUCTION

It has been shown in Refs. 1, 2 and 3 that ion motion is an important issue that needs to be taken into account in the design of a plasma wakefield accelerator (PWFA) for a future high-energy e^-/e^+ accelerator. In these accelerators, the electron beam density will be many times larger than the plasma density. As a result, the electron beam will impart a large transverse force to the plasma ions that can not be considered immobile at the time scale of electron plasma oscillations. The nonlinear focusing force created by plasma ions motion, causes emittance growth of the electron beam. It is therefore very important to explore means to suppress or minimize this emittance growth. We showed previously that using plasma with medium ion atomic weight (such as argon) reduces the emittance growth [3] when compared to light ions, such as hydrogen or lithium. Using heavier ions, such as xenon, however, results in too large scattering of the electron beam on the plasma nuclei. In this paper, we briefly investigate other ways to mitigate the emittance growth via a reduced model including witness beam and plasma ions.

REDUCED MODEL

As the witness beam betatron oscillates due to the focusing force created by the ion channel left behind the drive beam, different slices of the beam go through pinching and expanding periods. As the density of the slices varies, the transverse momentum they impart to the plasma ions varies also. The resulting ion motion in turn affects the subsequent transverse focusing of the beam. This results in a complicated system of beam and ion particles transverse motion along the witness beam.

While in principle, numerical tools such as OSIRIS and QuickPIC can be used to study these physics effects, in practice at the nanometer scale of these beams, the cell sizes become so small in the transverse direction that computational time becomes impractically large. We propose to develop a reduced approximation models to speed this research. Since the emittance growth of the drive beam is less important than that of the witness beam, and the witness beam sits typically in a region of electron blowout, it is possible to use a reduced model with beam electrons and plasma ions only. To study the transverse beam dynamics we divide the beam into longitudinal slices and consider the ions' motion in a PIC framework, which is updated in timesteps determined by some fraction of the betatron period in the unperturbed ion column. The plasma electrons are assumed to have blown out and their dynamics and timescale are ignored, resulting in significant computer time saving.

Figure 1 shows a simple simulation result using the beam and plasma parameters of Refs. 2 and 3, witness beam energy of 500GeV (γ=10^6), 35microns in length and 140nm(2.4×10^{-3} c/ω_p) in transverse dimension, carrying 0.5×10^{10} particles going through plasma with the density of 0.9×10^{16}cm^{-3}. The witness beam experiences betatron oscillations traversing Lithium ion channel. Since the head of the beam travels through a uniform ion density, the focusing force is linear along r (fig. 1b left) and there is not any emittance growth. Tail slices of the beam, however, go through severe phase mixing due to nonlinear focusing force resulting from the ion motion triggered by the large density of previous beam slices. Although this does not seem promising, we show in this paper that there are still ways to reduce the effect.

Figure 1b (right) suggests that after large emittance growth through the first ~100 betatron periods, the emittance reaches an approximately constant value. That leads us to believe that emittance convergence proves the existence of an equilibrium state. As a result, one may be able to find the right initial conditions for beam-plasma system (e.g. shaping different slices of the beam, plasma density gradient, etc.) so the system converges slower or to a different lower emittance equilibrium state [4]. This is analogous to the beam matching done to minimize emittance growth in uniform focusing plasma channels [5] but with the added complexity of slice by slice matched radial profiles. We leave this topic for future work and consider other mitigating approaches in the remainder of this paper.

Emittance Damping due to Synchrotron Radiation

As one might expect, beam particles emit strong synchrotron radiation as they oscillate in the ion column. The power radiated is [6]:

$$P_s = \frac{2}{3}(\frac{d\beta}{dt})^2 \frac{e^2\gamma^4}{c} \approx \frac{2e^2\gamma^2}{3m^2c^3} F^2{}_{focusing} \quad (1)$$

Modeling the effect of synchrotron on the beam particles by a so called drag force F_{drag} that acts as a

1-4244-0917-9/07/$25.00

friction force in the opposite direction of particle motion, equation of motion for beam particle becomes [7]:

$$\gamma mc^2\ddot{x} = F_{focusing}(x) - \frac{\dot{x}}{c}F_{drag}(x) \quad (2)$$

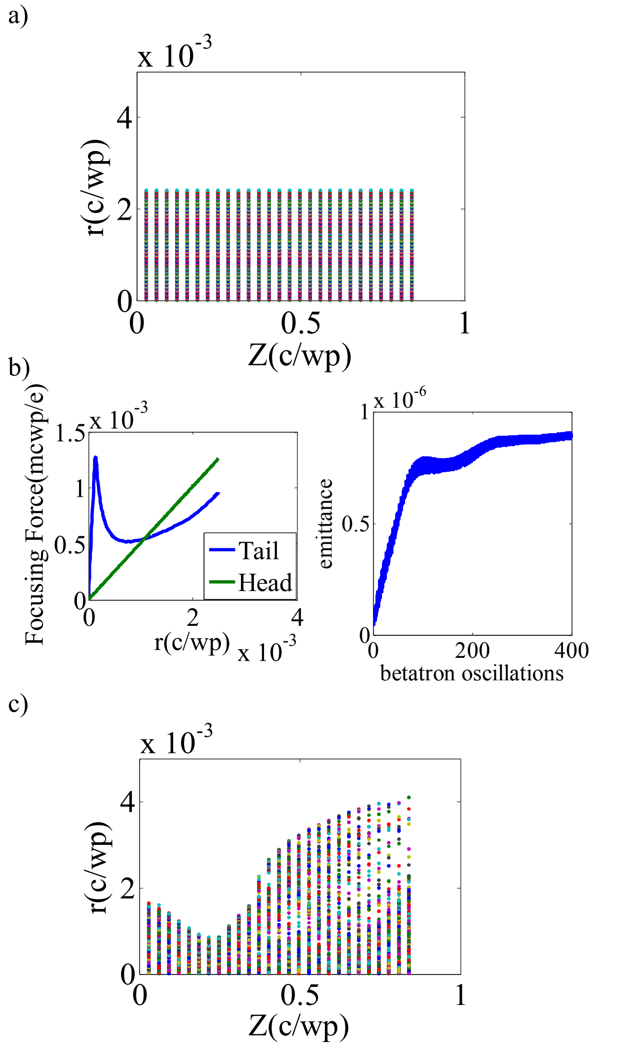


Figure 1: a) Initial real space of the beam with square shaped profile, moving to the left b) Focusing force due to the ion column evaluated in the head and tail of the witness bunch right after beam enters plasma (left). The right figure shows the resulting emittance growth for the whole witness bunch.c) Real space of the witness bunch after 200 betatron oscillations

Using the approximation in eq. (1),

$$\gamma mc^2\ddot{x} = F_{focusing}(x) - \Gamma\dot{x}F^2_{focusing}(x) \quad (3)$$

in which Γ is a constant. The drag force will damp down x and x' thus the emittance. The perturbation force (second term on the right hand side of eq. (3) is proportional to γ^4, which is small for low energy particles, but becomes significant for energies above 1TeV.

Figure (2) shows a simulation result for the emittance growth of 500GeV and 10TeV electron beams over 200 betatron oscillations with synchrotron radiation included. This simulation only studies the effect of synchrotron damping due to the drag force and does not take into account the change in energy gain which is discussed in Ref. 5.

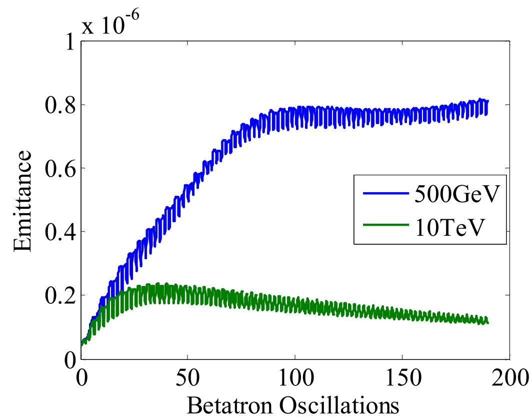


Figure 2: Emittance growth of 500GeV and 10TeV electron beams with synchrotron radiation included. The damping effect is significant in the high-energy case.

Plasma Density Gradient

Since ion motion results in ion density increase on axis, which is what creates the nonlinear focusing force [3], one might try to compensate for this effect by starting with a non-uniform ion density, i.e. lower density on axis. In fact simulation results (fig. 3) show that this indeed results in lower emittance growth.

Figure3 (top) shows a parabolic density profile, with an on axis density of 10% of the background plasma. The density is constant for $r>\sigma_r$ the transverse size of the witness beam, so that it does not affect the wakefield. Density gradients are achievable for example in capillary discharges [8] although they are created in larger radial scales than sub micron. It is also worth mentioning that a density gradient is an interesting compromise between a flat density (strong but highly nonlinear focusing force) and hollow plasma (no ion density and no focusing force). Hollow plasmas can in principle circumvent the ion motion problem entirely but may be more difficult to create.

Hot Plasma

As plasma temperature increases, plasma ions will have more pressure to resist the extremely large electric field of the witness beam. Assuming the ions will behave like a perfect gas, we can write:

$$PV = NRT$$
$$PV^{\gamma} = const. \quad (4)$$

where γ= (f+2)/f and f is the number of degrees of freedom. For rapid radial compression we expect f=2 [9] Therefore,

$$V^{\gamma-1} \approx V = \frac{cst.}{T} \quad (5)$$

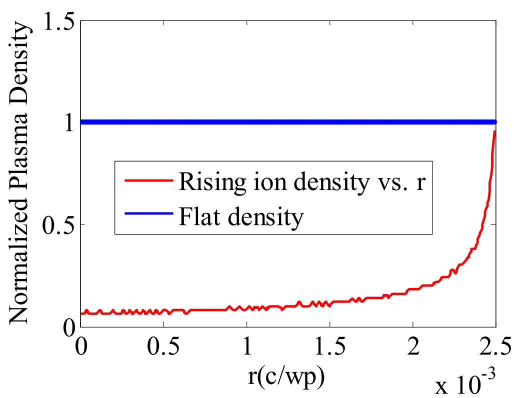
On the other hand, V is proportional to σ^2 where σ is the radius enclosing the volume, so

$$\sigma^2 T = \sigma_0{}^2 T_0 = cst. \quad (6)$$

And eq.(4) becomes

$$P = \frac{cst.}{\sigma^4} \quad (7)$$

Eq. (7) shows that the plasma ion pressure increases quickly as ions collapse. This can limit the ion collapse. Preliminary results show that with a temperature of the order of a few hundred eV, when the ions collapse by half their initial radius, the pressure rise is enough that the ion motion is significantly reduced.That results in a more linear focusing force and less emittance growth. Work on this topic is still in progress.



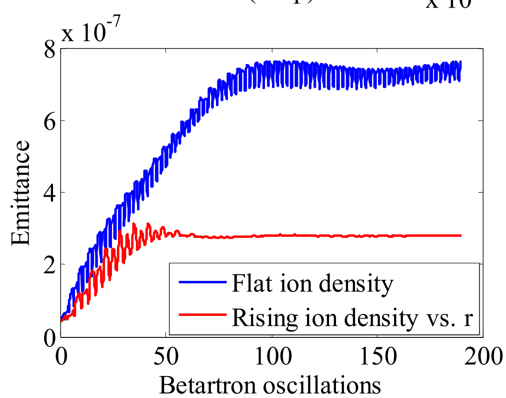


Figure 3: (top) Plasma ions density gradient. (Bottom) Emittance growth of witness beam in uniform and parabolic ion density.

CONCLUSIONS

Ion motion and emittance growth due to the resulting nonlinear focusing are important issues that must be included in the designs for future high energy plasma wakefield accelerators and in designing a plasma afterburner. In this paper, we have introduced a reduced model that saves significant computation time when studying this issue numerically. We have also used it to analyze some possible methods, such as synchrotron radiation damping, plasma density gradients and plasma temperature, to compensate for the ion motion and mitigate the effect of ion motion.

ACKNOWLEDGEMENT

The authors would like to acknowledge super computing time and support from the USC HPCC (High Performance Computing & Communications center). This work was supported by Department of Energy Contract No. DE-FG02-92ER40745.

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