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Space radiation simulation using blowout plasma wakes at the SAMURAI Lab

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ABSTRACT

We discuss the creation of broadband electron energy spectra using plasma wakefield acceleration at the SAMURAI Lab as part of the UCLA Particle Beam Physics Laboratory group. As the exploration and development of space increases, it will become important to efficiently replicate radiation conditions that exist in low earth orbit and planetary space. Missions such as satellite deployment and exploration of other planets, i.e. the Juno probe launched to explore Jupiter [1], require electronics that are able to withstand the electron radiation spectrum present in these locations. This requires Earth-based testing for development of robust electronics with respect to electron radiation exposure. Conventional accelerators are poorly suited for this purpose because they are designed for monoenergetic electron beams. Current simulation schemes involve the interpolation of discrete exposure tests, with time structures entirely different from space events. This idea poorly captures the radiation damage physics seen in the real world. Conversely, the wakefields produced in the blowout regime of beam plasma wakefield accelerators can be used to create the full spectrum of space radiation including high energy "killer" electrons by injecting a long bunch to excite the plasma blowout. With a long bunch ($k_p\sigma_z \approx 2$) the beam will feel both accelerating and decelerating fields, resulting in an exponential or power law energy spectrum distribution seen in regions outside the Earth and Jupiter. This can be achieved at the new SAMURAI lab at UCLA resulting in broadband energy spectra with maximum energies up to 100 MeV that correctly reflect the radiative conditions of space in low Earth orbit and around Jupiter.

1. Introduction

The future of space travel and development means exposing both high end electronics and humans to the dangerous conditions of space. On top of temperature and vacuum concerns, electron radiation poses significant threat to probes and satellites designed to travel outside of Earth's protective magnetic field. Two cases of particular concern are 1) orbits in the Van Allen Radiation Belts around Earth [2] where many satellites, that provide necessary services to today's society, exist and 2) orbits around Jupiter, which have become increasingly important in the interest of exploring Jupiter's moons [1]. Both of these cases exhibit broadband electron radiation spectra that contains a large number of low energy electrons and a few high energy electrons deemed "killer electrons". This radiation can cause severe damage to electronics that are unprotected. Furthermore, there is evidence to show that there are collective effects to electronics when exposed to concurrent broadband radiation that are not seen when exposed sequentially to different sources of mono-energetic radiation [3]. Currently, sequential exposure is the state of the art in electronics testing here on Earth, but as this method cannot capture the broadband collective effects on electronics a different method would represent a tremendous improvement in terrestrial simulations of space electronics environments for mission preparedness.

A potential solution to this problem is the creation of broadband electron beams through the use of plasma wakefield acceleration (PWFA) techniques [4]. Normally accelerators are poorly suited to create broadband electron beams due to the specifics of standard application design goals aimed at the production of mono energetic beams. However, new techniques for electron acceleration have been developed by using a pre-accelerated driver bunch to excite waves in a plasma. A secondary witness bunch is then injected into the plasma and is accelerated by the field from the wakes driven by the first bunch. Fields experienced by the witness bunch in PWFA are significantly stronger than conventional acceleration methods, having been demonstrated uo to 40 GV/m, or three orders of magnitude higher than those in standard RF techniques. This is especially true with the driver bunch has a higher electron density than the plasma. For many applications, one would like to mimic todays accelerators and produce nearly mono-energetic beams. In this so-called "blowout" regime the plasma electrons are completely ejected from the local area creating a bubble

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region that creates a region with only ions remaining. Witness beams are then placed near the back of the bubble where the highest longitudinal fields are located. Generally, the driver and witness bunches are short with respect to the plasma wavelength, which characterizes the size of the bubble, in order to more uniformly decelerate and accelerate the driver bunch and witness bunch respectively. On the other hand, to create a broadband energy spectrum in a beam we propose using PWFA with a long bunch that extends across the full length of the bubble such that the head of the bunch is decelerated and a small portion of the back of the bunch is accelerated.

2. Simulation results

While the plan is to use PWFA to simulate radiation spectra from around both Earth and Jupiter the focus of this paper is consideration of the radiation from around Earth. Jovian radiation environment simulation requires a higher energy spectrum, and this capability will be reached at UCLA only in in a later phase of experimental work. Here we discuss in detail the plans for lower energy, Earth radiation belt-like environment simulations.

Evaluation of this proposal was done with the Particle-In-Cell (PIC) code OopicPro [5] which can simulate the beam-plasma interaction in an azimuthally symmetric 2D plane. A bi-gaussian electron beam was injected into a uniform plasma of density $n_0 = 3 \times 10^{14}\ \mathrm{cm}^{-3}$. In order to simulate the radiation in the Van Allen Belts, the bunch has an injection energy of 3.5 MeV, $k_p\sigma_z \approx 2$ (to permit broadband spectrum development) and $k_p\sigma_r \approx 0.04$. Finally, to access the blowout regime the bunch has a charge of 2 nC. These parameters were also chosen based on near-future experimental capabilities at UCLA (see Section 3). The results of the simulation are summarized in Fig. 2. The front of the bunch expels the plasma electrons to create the rarefied bubble, shown here as the background. The restoring forces of the ions eventually cause the electrons to collapse back to close the bubble. This effect is mitigated partially by the existence of the beam electrons throughout the length of the bubble which causes a deformation of the bubble shape when compared to short, $k_p\sigma_z < 1$ bunches [6]. The bubble region contains a roughly uniform, ion charge-derived focusing force which keeps the majority of the electron beam from diverging in the plasma channel [7]. This allows centimeter long interactions while maintaining small transverse spot sizes. Due to the long bunch lengths some particles at the front and back of the beam exist outside the bubble region and are not focused, resulting in their eventual loss. This can be seen in Fig. 1 by the particles that exist outside of the phase space trapping region of the bubble. This creates further problems downstream of the interaction which can diminish any signal from measurement..

As the bunch travels through the plasma, different regions of the bunch may gain or lose energy. During a majority of the interaction the electrons are ultra-relativistic so they remain in nearly the same longitudinal position with respect to the speed of light frame. This means that different parts of the beam are exposed to an unchanging electric field profile created by the blowout. Thus, it is appropriate to qualitatively predict the evolution of the energy distribution of the full bunch by observing each section of the bunch independently once the plasma response is steady state. The beam and electric field profiles are plotted in Fig. 3 after traveling a distance of 15 mm into the plasma.

This causes the spectrum to increase in width, shown as the green line in Fig. 2 as the majority of the beam is decelerated while few particles are accelerated above the injection energy. Near the end of the interaction, the majority of the beam is no longer ultra-relativistic so it de-phases with respect to the speed of light frame. This causes a significant change in the shape of the bubble and thus results in a different field profile experienced by the beam electrons. The high energy electrons, which still travel ultra-relativistically, now drift forward with respect to the electric field from an accelerating to a decelerating region and tend to lose energy. This is illustrated in the final distribution plotted in Fig. 2.

Comparison of the resulting electron spectrum from the simulation and what is measured in the Van Allen Belts around Earth show a significant difference in slope. Here the flux of particles at a given energy, range between 10 pC/s at low energies to 10 fC/s at the maximum energy level (operating at 1 Hz repetition rate) while the measured spectrum at GPS satellite distances from Earth varies between 1 pC/s at low energy to 1 aC/s at the highest energy levels. This difference can be overcome by using a beam with an optimized profile, to provide more uniform defocusing in the beam body, and a longer tail to enhance the upper end of the energy distribution. It should also be noted that space radiation environments may also take on an inverse power law form. This spectral shape can be obtained by simply choosing a slightly longer (in terms of k_p^{-1}) beam.

Producing a Jovian-like radiation spectrum is to happen after the experimentation that is discussed here, so likewise, simulation of this case is still preliminary. Fig. 4 shows a electron spectrum from this case.

3. Experiment at SAMURAI Lab

The proposed experiment is to take place at the new SAMURAI Lab, located in UCLA Southwest Campus. Currently under construction, the facility will produce up to 60 MeV electron bunches to be delivered to an array of potential experiments including microscale free electron lasers [8], inverse compton scattering [9] and beam-plasma interactions. The new facility is ideally suited for this experiment because if the S-band hybrid photoinjector gun [10]. The hybrid gun is able to produce 3.5 MeV electron beams with a few micron normalized emittance. The hybrid is comprised of a standing wave section starting at the photocathode for acceleration and a subsequent traveling wave section that can provide strong velocity bunching. The main advantage of this gun is thus the ability to easily compress and control the longitudinal bunch length by changing the relative phase between the standing wave section and the traveling wave section. Transverse focusing is accomplished through the use of strong solenoids that controls beam size in the hybrid, and eventually focuses the beam to the required spot size in the plasma channel.

A challenging aspect of this experiment is the design of a wide bandwidth spectrometer to measure the resulting spectrum of the beam coming out of the plasma. Unlike in most experiments, the energy spread is on the order of the central beam energy; typically the energy spread is at maximum on the order of a few percent. This

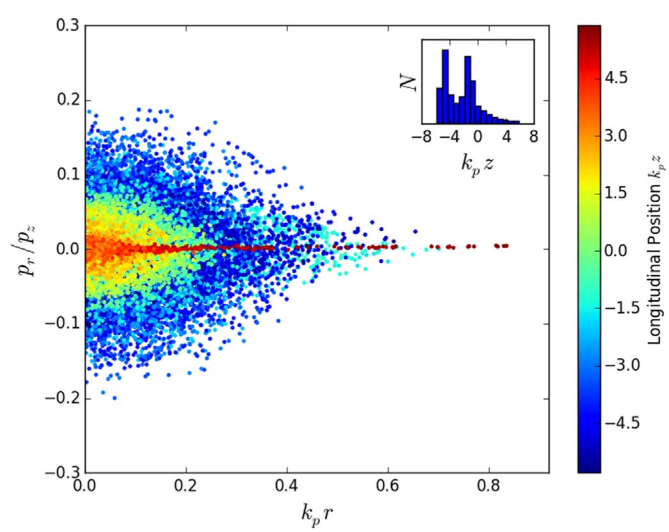

Fig. 1. Plot of the transverse phase space of the electron beam after 74 mm interaction length. Colors correspond to the relative longitudinal position of each macro-particle. Inset: Longitudinal bunch profile.