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SIMULATIONS FOR THE SPACE PLASMA EXPERIMENTS AT THE SAMURAI LAB

P. Manwani*, H. Ancelin, N. Majernik, O. Williams, Y. Sakai, A. Fukasawa, B. Naranjo, G.Andonian, G. Lawler, J. Rosenzweig, UCLA, Los Angeles, CA, USA

Abstract

Plasma wakefield acceleration using the electron linear accelerator test facility, SAMURAI, can be used to study the Jovian electron spectrum due to the high energy spread of the beam after the plasma interaction. The SAMURAI RF facility which is currently being constructed and commissioned at UCLA, will be capable of producing beams with 100s pC of charge with bunch lengths in the 100s of fs range with low transverse emittances in the 3–80 MeV range. Particle-in-cell (PIC) simulations are used to study the beam spectrum that would be generated from plasma interaction. Experimental methods and diagnostics are discussed in this paper.

INTRODUCTION

This study focuses on the generation of broadband electron energy spectra using a beam-driven plasma wakefield accelerator (PWFA) [1], that replicates specific characteristics of the Jovian electron spectrum [2]. The PWFA generated electron spectrum can be beneficial for space research and development as it can serve as a proxy for electron radiation exposure which can cause damage to high-end equipment and electronics used in satellites and flyby operations [3]. PWFA spectra characterization is one of the plasma experiments envisioned using the capabilities of the SAMURAI lab [4, 5], which is a linear accelerator facility currently being constructed on campus at UCLA headed by the Particle Beam Physics Laboratory group. Plasma wakefield accelerators can create high accelerating gradients in the GV/m range, but the magnitude of the accelerating field varies across the length of the blowout cavity that is created by the driving particle beam [6, 7]. A long electron bunch that extends across this blowout cavity interacts with this field, concomitantly imparting a large energy spread on the bunch and leads to the creation of a broadband electron energy spectrum which follows an exponential power law distribution [8]. The electron beam available at the SAMURAI facility is a suitable candidate for the driver of the PWFA and allows us to generate this electron spectrum using a 10 cm long plasma source. Particle-in-cell(PIC) simulations were used to investigate the beam and plasma parameters required to create this spectrum. The plasma and beam evolution are discussed in this paper along with experimental considerations. The simulations were performed using OSIRIS [9], a fully relativistic three dimensional PIC code.

* pkmanwani@gmail.com

Table 1: Parameters for the Space Plasma Simulations

Parameter	Value	Unit
Beam		
Charge, Q	2	nC
Energy, E_b	18	MeV
σ_z	300	µm
$\epsilon_{n,r}$	4	µm rad
Plasma		
Density, n_0	1.25×10^{15}	cm^{-3}
Simulation		
Simulation window (x,y,z)	(3, 3, 16)	k_p^{-1}
Grid	$(150)^2 \times 320$	-
Particles per cell	8	-
Timestep	0.012	ω_p^{-1}
Beam particles	4.07×10^7	-

SIMULATION RESULTS

The simulations were performed using the parameters specified in Table 1. An electron beam having an initial energy of 18 MeV is injected in a plasma having an initial ramp profile with a final density of $n_p = 1.25 \times 10^{15}$, while being externally focused to ensure proper matching conditions. The beam density of the 2 nC beam is sufficient to completely expel the plasma electrons from the beam channel, creating a blowout cavity. The transverse emittance of the beam increases in the initial ramp section as some of the particles of the beam are outside the blowout cavity and are not sufficiently focused by the linear focusing forces of the cavity. The beam evolution and plasma ramp profile are shown in Fig. 1. The beam and plasma electron densities along with the axial longitudinal electric field at$z = 1$ cm are shown in Fig. 2. The beam is long ($k_p\sigma_z = 2$) and extends well into the blowout cavity to ensure that it probes both the decelerating and accelerating fields. The non-uniform profile of the longitudinal electric field creates a large energy spread in the beam, and the spread increases with propagation distance. This is illustrated in Fig. 3, by binning the beam particles in 100 bins according to their energies. The energy of the head of the beam retains its energy as it is unaffected by the plasma wake, and this leads to a spike in the particle count at the initial energy point of the electron spectrum. Some of the particles outside this region are not focused and are lost, while some of them are trapped behind the primary wake and lose energy more rapidly than the rest of the beam. These particles form the outliers that can be seen on the left bottom of the figure, and can be neglected as they can be readily deselected in experimental setups.

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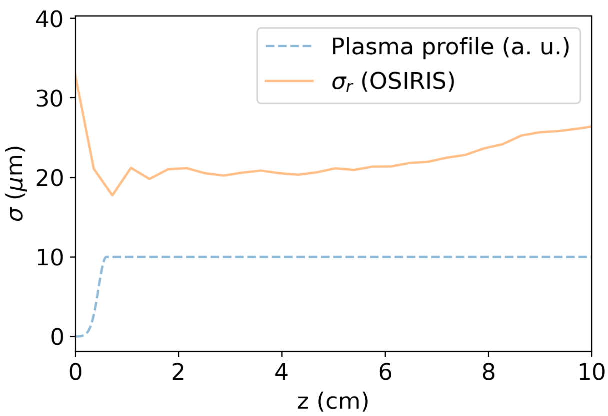

Figure 1: The evolution of the transverse spot size of the beam with the plasma profile.

JOVIAN SPECTRUM

The broadband energy spectra that are created can be used to study space radiation environments as they follow similar power law relationships. The energy range of the created spectra allows for replication of different radiation environments. In this example, we have used a 18 MeV beam which can replicate the radiation on Jupiter, which follows the power law relationship with an exponential cutoff which is given by [2] :

$$j(E)_{jov} \propto \left(\frac{E}{E_0}\right)^{\gamma} e^{\left(\frac{E}{E_{break}}\right)}$$

where $j(E)_{jov}$ is the source function, normalized to E_0= 1 MeV. The equation was suggested by particle acceleration theory and the values of $\gamma = -1.63 \pm 0.07$ and E_{break} = 9.4 MeV were obtained by fitting the electron energy spectra obtained from the Ulysses [10] and Pioneer [11] flyby events. The energy spectrum created by the PWFA after a propagation distance of 6.85 cm can be compared with the Jovian spectrum. The longitudinal phase space of the beam at this distance after removing the low energy outliers is shown in Fig. 4 and the corresponding electron spectrum is shown in Fig. 5. The power factor obtained from the PWFA is 1.69, well within the range of the value of the Jovian spectrum.

EXPERIMENTAL CONSIDERATIONS

The SAMURAI lab is an electron linear accelerator test facility which consists of a compact 3 MeV S-band hybrid gun [5]. This beam can then be accelerated by a 1.5 m band linac. This facility is currently being constructed at UCLA's southwest campus in Westwood and it would be capable of generating beams at various beam energies that can be utilized for space plasma experiments. Beam transport out of the plasma column as well as after the plasma stage would be a challenging aspect of this experiment due to the high energy spread of the beam. The wide spectrum requires a broadband spectrometer which is the focus of further studies.

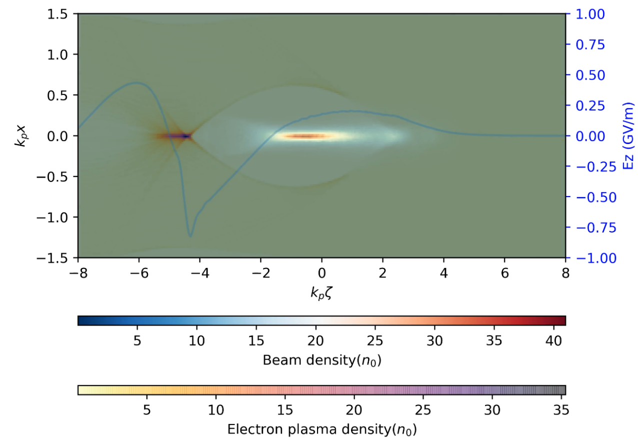

Figure 2: PIC simulation snapshot showing the interaction of the focused beam with the plasma at 1 cm. The shape of the electric field gradient illustrates the creation of a broadband electron spectrum.

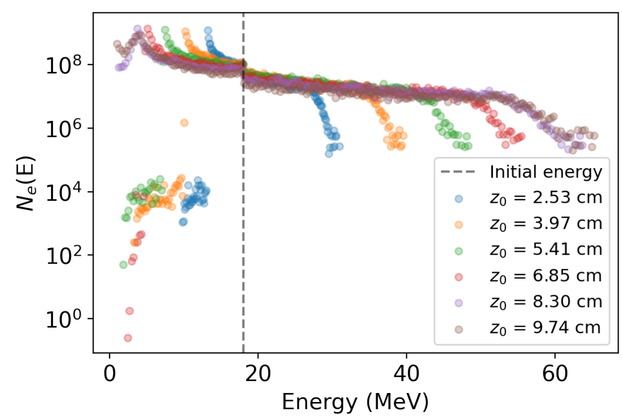

Figure 3: Broadband electron energy spectrum created by the PWFA at different positions in the plasma with N_e and z_0 representing the electron count and beam location respectively.

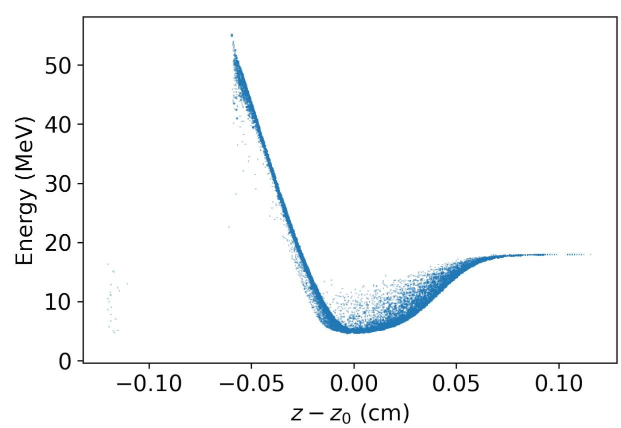

Figure 4: Longitudinal phase space of the beam at 6.85 cm with z_0 representing the beam location.

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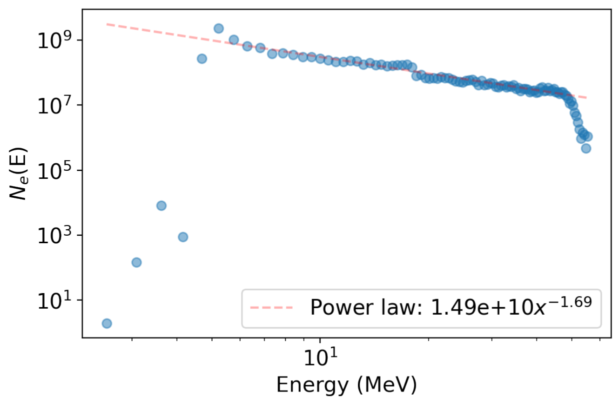

Figure 5: The broadband electron spectrum of the beam at the distance z_0 = 6.85 cm follows the power law relationship similar to the Jovian spectrum, with N_e representing the particle count.

CONCLUSION

We have presented a path to create broadband electron energy spectra that follow the exponential or power law relationship similar to the Jovian electron spectrum. Lower energy beams having energies around 3.5 MeV can also be used to the produce electron spectrum seen in the Van Allen Belts [8]. This spectra can be utilized for modeling the effects of radiation exposure on space equipment due to planetary radiation belts. Here we have discussed how to obtain an electron spectrum similar to these radiation belts but to create space radiation environments for equipment testing, particle fluxes are also important which depend on the repitition rate of the experiments. Further studies and experiments will be performed in the future at the SAMURAI lab to verify the creation of this broadband electron energy spectrum.

ACKNOWLEDGMENTS

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