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Modeling of E-164X Experiment

S. Deng[1], P. Muggli[1], C. D. Barnes[3], C. E.Clayton[2], F. J. Decker[3], R.A. Fonseca[4], C. Huang[2], M. J. Hogan[3], R. Iverson[3], D. K. Johnson[2], C. Joshi[2], T. Katsouleas[1], P. Krejcik[3], W. Lu[2], K. A. Marsh[2], W. B. Mori[2], C. O'Connell[3], E. Oz[1], R. Siemann[3], F. Tsung[2] , D. Walz[3], M. M. Zhou[2]

[1]*University of Southern California, Los Angeles, CA 90089*
[2]*University of California, Los Angeles, CA 90095*
[3]*Stanford Linear Accelerator Center Stanford, CA 94309*
[4]*Instituto Superior Técnico, Lisboa, Portugal*

Abstract In current plasma-based accelerator experiments, very short bunches (100-150μm for E164 [1] and 10-20 μm for E164X [2] experiment at Stanford Linear Accelerator Center (SLAC)) are used to drive plasma wakes and achieve high accelerating gradients, on the order of 10-100GV/m. The self-fields of such intense bunches can tunnel ionize neutral gases and create the plasma [3,4]. This may completely change the physics of plasma wakes. A 3-D object-oriented fully parallel PIC code OSIRIS [5] is used to simulate various gas types, beam parameters, etc. to support the design of the experiments. The simulation results for real experiment parameters are presented.

I. INTRODUCTION

Plasma wakefield accelerators (PWFA) have attracted considerable attention recently because of their high accelerating gradients and the potential to support extremely compact accelerator stages. One realization of this is the energy doubler or plasma afterburner [6] proposed for doubling the energy of a 50 GeV beam in a distance of only several meters. Recent experiments with long bunches (700μm in E157 and E-162 [7]) at SLAC have supported the basic concept of such a plasma wakefield scheme. In current experiments at SLAC, much shorter bunches are used to drive nonlinear (blowout regime [8]) plasma wakes and achieve multi-GeV peak accelerating gradients. In addition, the self-fields of such short beams can easily tunnel ionize neutral gases like Cs or Li and create plasma which supports the wake. Previous work has studied the possibility of creating the plasma by tunnel ionizing neutral gases [3] as well as the optimal gas density for maximizing accelerating field [4]. In this paper we study the ionization effect in more details to support the design and analysis of the SLAC experiments.

II. OSIRIS PIC CODE AND IONIZATION MODELS

OSIRIS is a fully relativistic particle-in-cell (PIC) code with newly implemented ionization package ---2D and 3D impact ionization and tunneling ionization. The impact ionization rate W depends on the gas density n_g, gas cross-section σ, and velocity of the incident particle v_i as [9]:

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$$W[s^{-1}] = n_g \sigma(v_i)|v_i|$$

The Ammosov-Delone-Krainov(ADK) [10] model is used for the tunneling ionization. In this model the ionization rate is given by:

$$W\left[s^{-1}\right] \approx 1.52x10^{15}\frac{4^{n^*}\xi_i[eV]}{n^*\Gamma(2n^*)}\left(20.5\frac{\xi_i^{3/2}[eV]}{E[GV/m]}\right)^{2n^*-1}\exp\left(-6.83\frac{\xi_i^{3/2}[eV]}{E[GV/m]}\right)$$

where E is the amplitude of the local electric field with unit GV/m, ξ_i is the ionization energy, and n* is the effective principal quantum number. For typical SLAC E-164 bunches with $N=2*10^{10}$, $\sigma_r=15\mu m$, $\sigma_z=100\mu m$, the self-fields of the beam are at the threshold for tunnel ionization, while for SLAC E-164X bunches with $N=1*10^{10}$, $\sigma_r=15\mu m$, $\sigma_z=20\mu m$, the self-fields of the beam are far above the tunnel ionization threshold. Gases like Cs, Li have low ionization potentials and can therefore be fully ionized in the region around the beam.

III. SIMULATIONS FOR E-164X EXPERIMENT

A. Lithium gas

To get some basic ideas about the relation between the gas (plasma) density and the accelerating gradient, we simulate four cases with different gas densities in 2-D cylindrical symmetry and compare the peak accelerating field and peak average energy gain by particles. The beam parameters are $N=1*10^{10}$, $\sigma_r=15\mu m$, $\sigma_z=20\mu m$, and E=30 GeV. In the linear theory [11], the density which maximizes the accelerating gradient in a pre-formed plasma is obtained from $\omega_p\sigma_z/c\approx 2^{1/2}$ ($\omega_p=(4\pi ne^2/m)^{1/2}$) and corresponds to $n_0=1.41*10^{17}$ cm^{-3} for the above beam parameters.

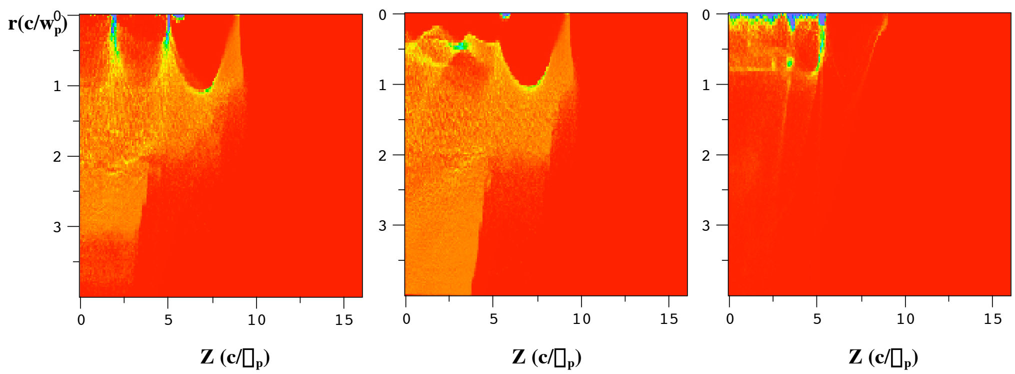
Table 1: Simulation results for beam with $N=1*10^{10}$, $\sigma_r=15\mu m$, $\sigma_z=20\mu m$

	N_{gas} (cm^{-3})	E_{zmax} (GV/m)	Peak average Energy gain (MeV over 3cm)
Case 1	**$7*10^{16}$ cm^{-3}**	73.7	0
Case 2	**$2.1*10^{17}$ cm^{-3}**	123.3	700
Case 3	**$3.5*10^{17}$ cm^{-3}**	**122**	**600**
Case 4	**$5.6*10^{17}$ cm^{-3}**	139.8	400

Table 1 shows that in case 1, the gas density is too low, and the plasma wavelength too long for the bunch length and no energy gain is observed. In case 4, the plasma density is too high, and even though E_{zmax} is the largest, the energy gain is smaller than in cases 2 and 3. In case 2 and 3, accelerating gradients larger than 100 GV/m are achieved. The optimal density for the experiment is therefore in the 2-4*10^{17} cm^{-3} range, larger than that predicted by the linear theory in a pre-formed plasma.

B. Cesium gas

Cesium gas is studied because of its ionization potential ($e\phi$=3.894eV) is lower than that of Li ($e\phi$=5.392eV). It is very easy to obtain a uniform plasma by tunnel ionizing Cs. The concern with Cs is secondary ionization. The Cs^+ ions can be further ionized, and create new electrons which repel the returning plasma electrons (from the first ionization) that support the wake. Fig.1 shows the real space of newly created plasma electrons through ionization of a) Li, b) Cs, c) Cs^+.



(a) Li (b) Cs (c) Cs^+

FIGURE 1. Newly created electrons in real space. The bunch is centered at 8 c/ω_p.

the bunch is 1 c/ω_p in length and .75 c/ω_p in radius. Only the bottom half plane is shown.

Figure 1c shows that the amount of ionization from Cs^+ in the bunch region is small when compared to the Cs ionization. Most of the Cs^+ is ionized after the beam passes, by the space charge field of the remaining ions (the electrons created from ionization of Cs are blown out, and the ions are left near axis). The ionization of Cs^+ occurs near the axis and the space charge electric filed of the newly born electrons prevents the blown out electrons to return, as can be seen by comparing Fig 1a and b. This causes a lowering of the second and third acceleration peaks. The comparison of longitudinal wakefield for Fig. 1 is given in Fig. 2. As shown in Fig 2, the secondary ionization increases the plasma density and decreases the wake wavelength. The magnitude of the first acceleration peak that accelerates the particles in the back of the bunch also decreases a little bit.

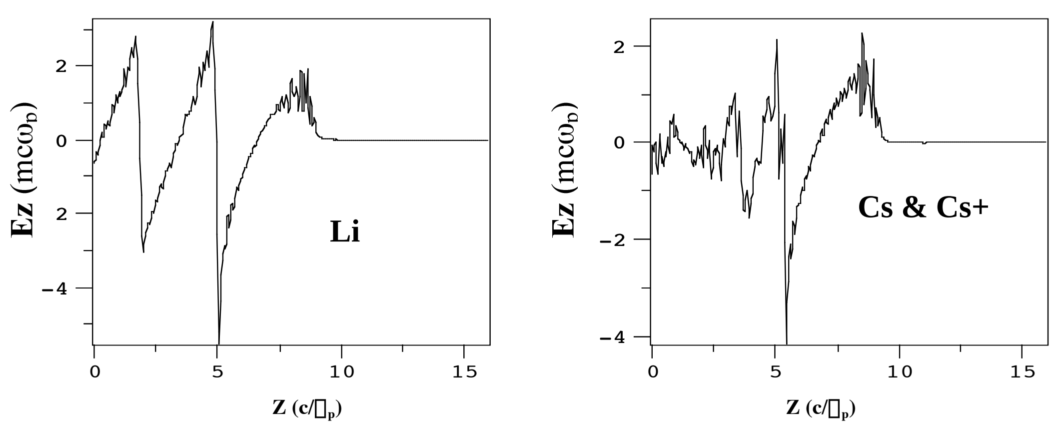


FIGURE 2. Longitudinal electrical field (c/ω_p=20.1μm)

C. Hydrogen gas

Because hydrogen has higher ionization potential ($e\phi$=13.6eV) than Li and Cs, more intense beam is required to tunnel ionize it. When the number of particles in the beam N is increased from $1*10^{10}$ to $1.5*10^{10}$ (for the same σ_r and σ_z), H can be partially ionized, but not ionized enough to form a wake (see Fig. 3a). However, Fig. 3b shows that the wake is recovered when the beam size is reduced to σ_r =10μm, with the same $N=1.5*10^{10}$.

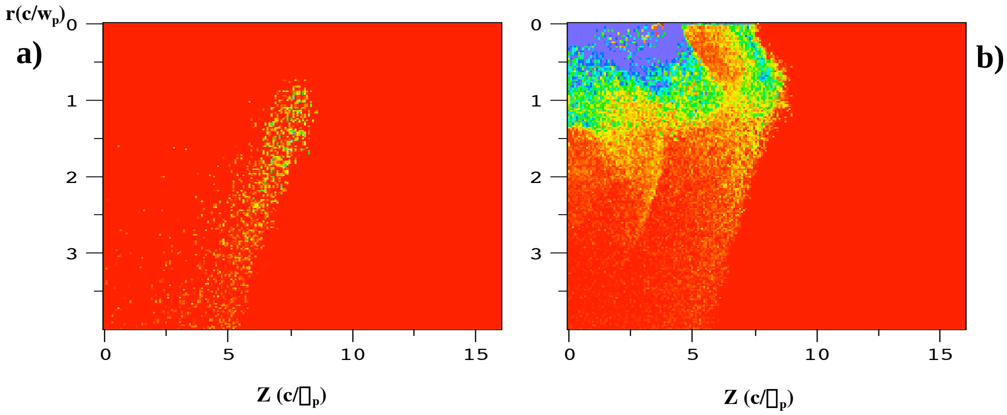


FIGURE 3. Newly created electrons in real space

a) σ_r=15μm and $N=1.5*10^{10}$, no wake is formed b) σ_r=10μm and $N=1.5*10^{10}$, a wake is formed

Considering the difficulty of controlling the secondary ionization of Cs and making beam with short bunch length and high density to ionize H, Li is a better option for current experiment.

D. Tilted beam

With the 3D feature of PIC code OSIRIS, we can study the effect of beam tilt. Note that in the previous sections the beam has no tilt. The result is shown in Fig. 4. The tilt slope is $.3\sigma_z / 1\sigma_z$. With such a tilt, the maximum average energy gain decreases to 1/3 the value of that in non-tilt case. The reason for the decrease is that the later part of the tilted beam is off axis where the longitudinal acceleration field is much smaller than that near axis.

E. Non-Gaussian beam and oven gas profile

In the first run of E-164X experiment, the preliminary results showed larger energy loss than that predicated by simulations. A possible reason for this difference is the simple gas density profile we considered in our simulations --- we only considered a Li gas with uniform density. In the experiment, low temperature helium gas is used as buffer on both side of the hot region of the oven to prevent the lithium gas from running away. Both gas pressure profiles are not uniform and have a sharp drop in the transition region. To simulate the real oven profile more realistically, piecewise linear functions for the gas profiles measured in experiment are used as the input for simulations (See Fig. 5a). Also, in the experiment the longitudinal bunch profile is not Gaussian, and a more realistic beam is modeled by taking the output beam profile from Litrack [12] simulation. Litrack tracks the electron beam 2-D longitudinal phase space through several accelerator sections including bunch compression and the longitudinal wakefield of the accelerating structures before the beam enters plasma. Fig. 5b shows the beam density profile used in simulations. The simulation results are given in Fig. 6. We find that Li^{+} is ionized to be Li^{++} and some of the newly created electrons from secondary ionization are trapped in the wake (Fig. 6a). The helium buffer gas is also ionized and the electrons created are trapped also (Fig. 6b). Those trapped particles may contribute to the higher energy loss in the experiment. As in the case of Cs and Cs^{+} studied above, the electrons newly created through ionization of He prevent the returning of the electrons created from Li ionization, which leads to the decrease of the peak accelerating field. The maximum average beam energy gain is around 2.8GeV and the energy loss is about 2.5GeV after propagating 16 cm. This agrees very well with the experiment results.

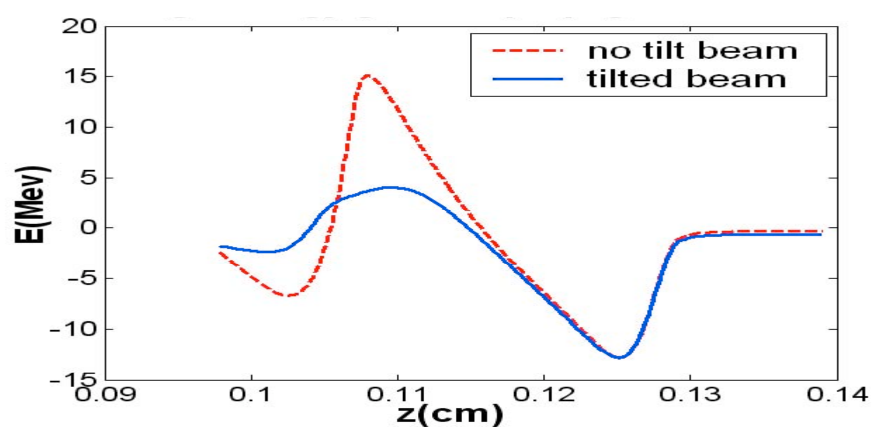
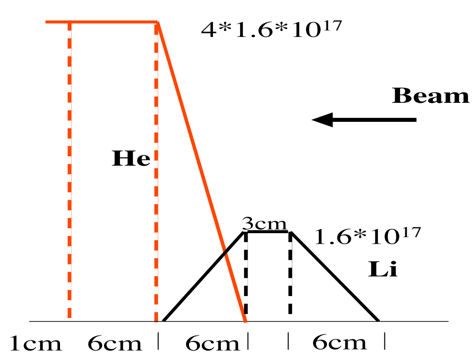


FIGURE 4. Comparison of average energy gain between non-tilted beam and tilted beam



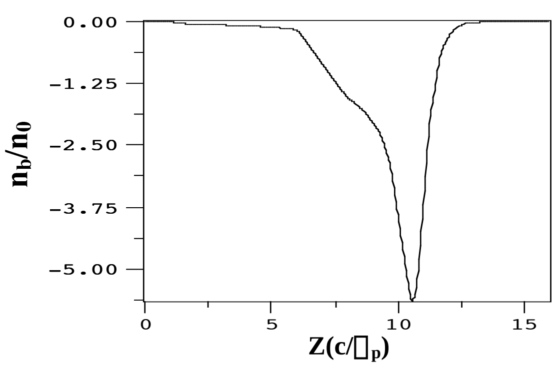


FIGURE 5 a). Oven gas profile **b).** Non-Gaussian beam profile from Litrack [12]

IV. CONCLUSION

In the E-164X experiment, tunneling ionization of a neutral gas is used as new source of plasma. Lithium has proved to be a good option for E-164X beam parameters. The He and Li^+ can be further tunnel ionized, some of the newly created electrons can be trapped and cause more energy loss. Work is still ongoing on the trapped particles and their effects on the plasma wake.

V. ACKNOWLEDGMENTS

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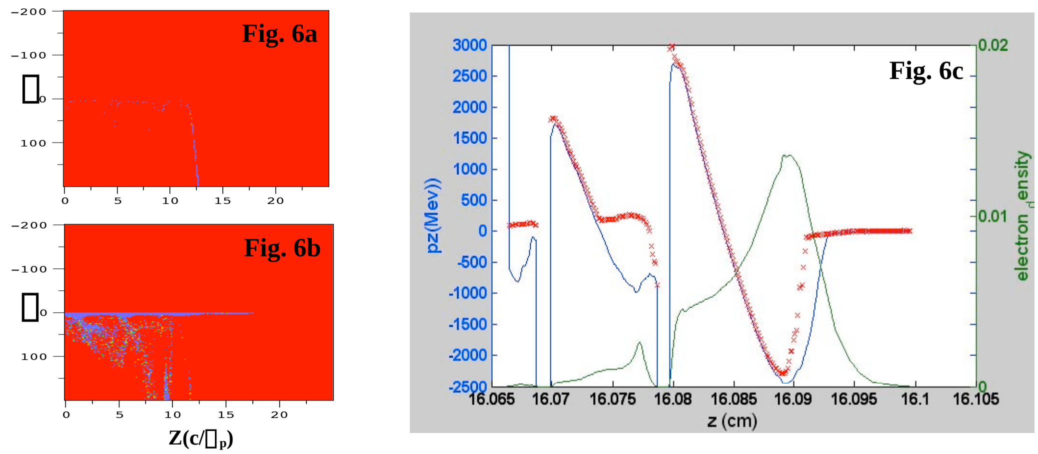

FIGURE 6. a) Phase space of electrons from ionization of Li^+ b) Phase space of electrons from ionziation of He c) Beam energy gain (solid line---average energy gain, 'x' line ---- maximum energy gain, dotted line ---beam density profile

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