CATHODE ION BOMBARDMENT IN LCLS AND LCLS-II RF GUN*

L. Wang#, A. Brachmann, F. Decker, Z. Li, T.O. Raubenheimer,
J. Schmerge, F. Zhou, SLAC, Stanford, CA 94309, USA

Abstract

This paper studies the ions bombardment on the cathode in the LCLS and LCLS-II gun. LCLS operates at a low repetition rate of 120 Hz while LCLS-II will operate at 1 MHz rate. Therefore, it is important to estimate the ion bombardment.

A PIC code is used to track arbitrary particles (ions and electron here) in arbitrary 2D/3D electromagnetic field and solenoid field to estimate the possibility of ion bombardment. The LCLS gun has 1.6 cells while the LCLS-II gun is a quarter wave resonator (LBNL APEX gun) so the frequencies of the two guns are quite different. These characteristics make the ion dynamics quite different. In this paper we estimate the bombardment for various ion species.

LCLS GUN

The surface analysis of the first LCLS cathode provides evidence for complex hydrocarbon contamination [1]. The trajectory simulation of ions in LCLS gun shows strong possibility of ion back bombardment [2-3]. Here we do the trajectory simulation with one purpose-written code which can accurately model the ion generation (position and timing) and RF pulse. Both RF field and emittance compensation solenoid field are included. Electrons emitted from the cathode enter the rf cavity and move towards the solenoid region while ions are generated along the electrons' path. The electrons move quickly out of the cavity but the ions move much slower. Ions are tracked until they hit the cathode, hit the cavity surface or exit the cavity.

The on-axis electric field and the solenoid field for the LCLS gun are shown in Fig. 1. The cathode is located at the z=0. The electric field has a peak value at the cathode surface and the center of the full cell with the minimum field located at z=3.34 cm at the iris. Fig. 2 shows the electric fields of the rf gun. When an electron emitted from the cathode surface enters the second cavity, the rf electric field changes direction and the electron continues to accelerate through the second cell. The focusing solenoid is located 20 cm downstream of the cathode with zero field at the cathode. In all simulations, 2D field maps are used for both gun rf and solenoid fields.

The LCLS gun is pulsed at 120 Hz with an rf pulse that has a flat top order of 1 μs duration and decay time approximately 0.5 μs [4]. Electrons are generated at the peak rf pulse and therefore ions are also generated at the peak rf pulse. Since ions move slowly, they see the remaining rf pulse and their dynamics are strongly affected by the decaying pulse. Most ions run away from the cavity regime or hit the cathode before the next rf pulse.

Table 1 lists the main parameters for the LCLS gun and solenoid. For comparison, the parameters for the LCLS-II gun are also listed. The LCLS gun operates pulsed at 2856 MHz, while the LCLS-II gun is continuous-wave (CW) at a much lower frequency of 187 MHz. The LCLS gun has two cells while the LCLS-II gun is comprised of a single cell. Multiple cells make the ion dynamics much more complicated.

In this study we consider only the ions generated by beam gas ionization. Ions are uniformly generated along the electron beam path (z-direction) in the simulation. In reality, the beam ionization cross-section varies with beam energy with a large cross-section for low beam energy ranging from 100*eV* to 1 *MeV*. Ions born at different locations will see different initial rf field as shown in Fig. 3.

Table 1: Main Simulation Parameters

Description	LCLS	LCLS-II
rf frequency (MHz)	2856	187
Peak field (MV/m)	140	22
rf phase (degree)	–60	–8
rf Pulse length (μs)	~3	CW
Repetition rate (kHz)	0.12	1000
Solenoid field (T)	0.24	0.04
Beam energy(MeV)	5.9	0.8

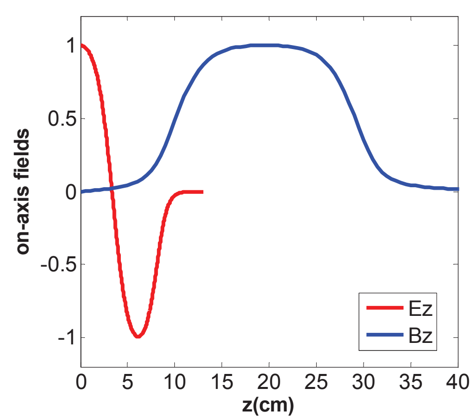

Figure 1: The normalized on-axis gun rf electric field and solenoid field.

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#wanglf@SLAC.stanford.edu

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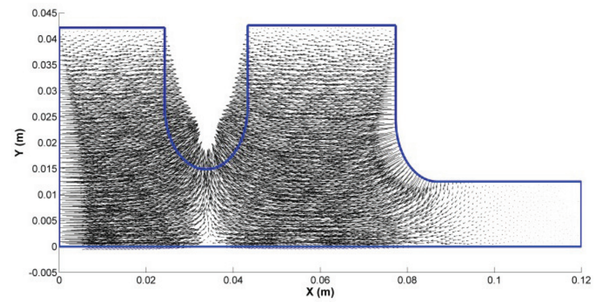

Figure 2: Geometry and electric field of the LCLS rf gun. The blue line shows the boundary (2D approximation).

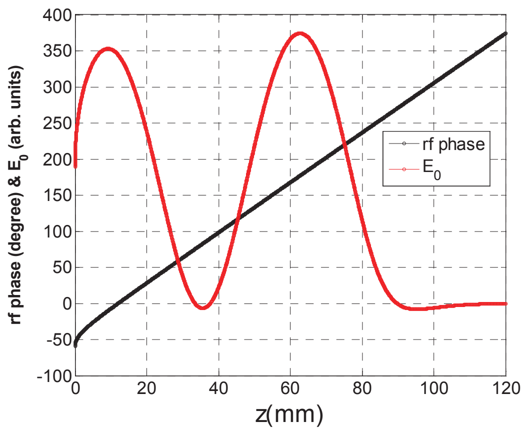

Figure 3: The initial rf phase (black line) and electric field (red line) seen by ions born at different location in the cavity.

H_2^+ ion

The hydrogen ion has small mass and moves fast. In most cases for the LCLS gun, hydrogen ions either hit the cathode or exit the gun during the rf pulse. Figure 4 shows the dependence of the ions striking the cathode and exiting the gun on their starting location. There are several narrow regions between 2 and 6 cm where ions strike the cathode (red line). The dynamics in this region is complicated by the decay of the rf pulse, rf phase and the variation of field amplitude shown in Fig. 1. The ions born near the cathode always hit the cathode because the rf phase is negative when the ions are generated and the ions are accelerated towards the cathode.

About 39% of the total ions reach the cathode surface; while 58% exit the gun longitudinally. The remaining ions move significantly off axis and eventually hit the cavity surface. No secondary particles are generated in the simulation. If the energy dependence of the cross-section is included, 44% ions hit the cathode and 53% exit the gun.

It is very useful to look at detail of individual ions born at different longitudinal location along the cavity. Figure 5 shows the final energy at the cathode or at the gun exit for ions born at different location. Each dot represents one ion particle used in the simulation. The red and black dots are for ions reaching the cathode and exiting the gun respectively. The ions born near the cathode (z<1cm) hit the cathode with energy up to 3500eV with random energy distribution even they are born at the same longitudinal cavity position. The ions are born at different radial positions and hit the cathode at slightly different times with very different energies. The ions are initially born with the same radial distribution as the electron beam, which is assumed to be Gaussian with a *rms* beam size of order of mm. Besides the ions near the cathode, a large number of ions born at the first part of the 2nd cell impact on the cathode as shown in Fig. 5. The multiple regions where ions impacting on the cathode as shown in Figs. 4-5 is one important feature of multiple cell guns. There are similar results in another study [5].

On the other hand, the ions exiting the gun (black dots), have very similar energy regardless of initial radius.

Note that the peak energy of ion hitting the cathode has strong dependence on the rf frequency, ion mass and rf field. It can be approximated as

$$T_{max} \approx \frac{2q^2 E_{Z=0}^2}{A m_p \omega_{rf}^2} \; . \tag{1}$$

Where $E_{z=0}$ is the amplitude of the rf field at the cathode, ω_{rf} is the angular frequency of the rf gun, A is the ion mass number and m_p is the proton mass.

Figure 6 shows radius distribution of ions impacting on the cathode. Most ions hit the cathode with $r < 10\ mm$.

Figure 7 shows the energy distribution for the ions hitting the cathode. The high energy ions (> $2keV$) are from the ions born near the cathode as shown by Fig. 5.

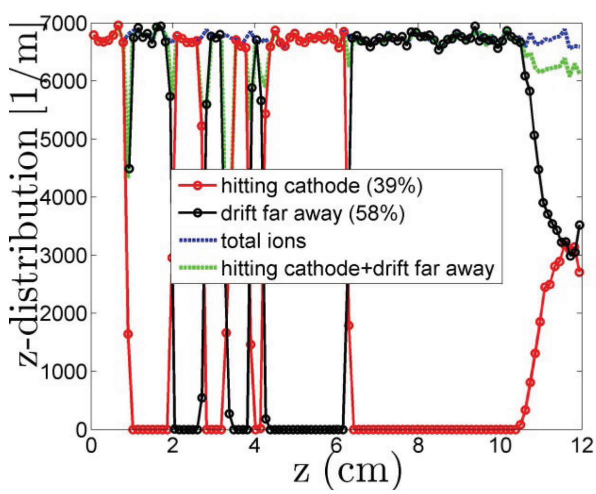

Figure 4: The dependence of the H2 ions striking the cathode and exiting the gun based on their initial position along the cavity. The red and black lines represent ions reaching the cathode and exiting the gun, respectively.

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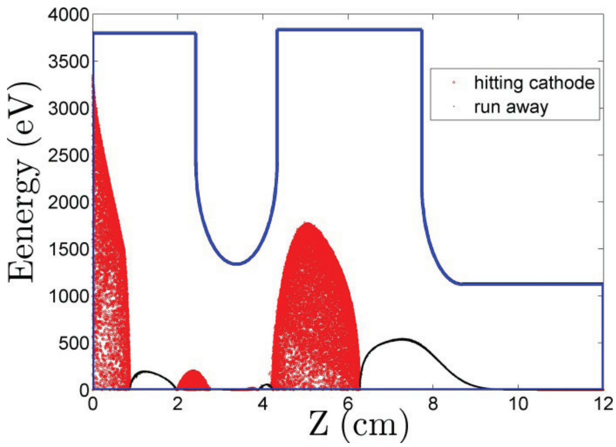

Figure 5: The final H_2+ ion energy for ions born at different position along the cavity. The red and black dots represent ions reaching the cathode and exiting the gun, respectively. The blue line shows the geometry of the gun cavity.

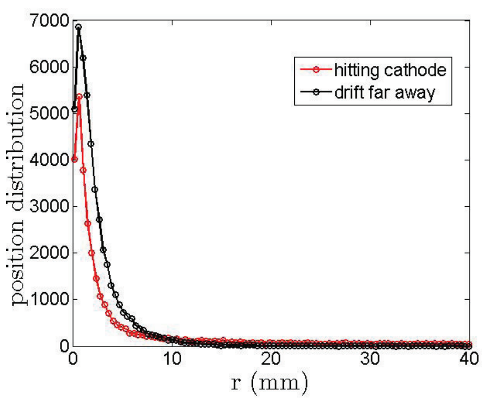

Figure 6: Radius distribution of the H2 ions hitting the cathode (red line).

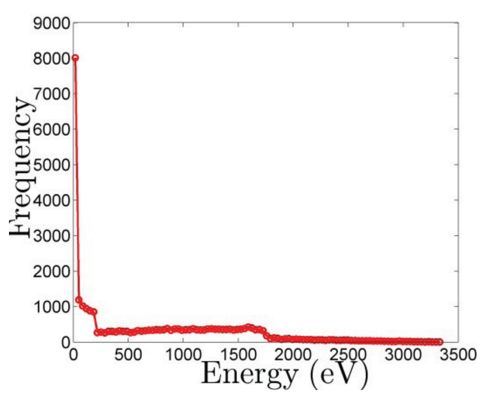

Figure 7: Energy distribution of the H2 ions hitting the cathode.

CO^+ ion

The CO ion moves slowly compared to the H2 ion. Therefore it takes longer time to reach the cathode. Except the ions born near the cathode surface, other ions reaching the cathode see much lower rf field due to the decay of the rf pulse. Figure 8 shows the ion distribution along its initial position in the cavity for both ions impacting on the cathode and exiting the gun. The distribution of ions hitting the cathode is simple compared to the H2 ion case. The CO ions born in two regions hit the cathode surface: near the cathode and 1st part of the 2nd cell with z ranging from 3.8 cm to 6 cm. About 36% of CO ions hit the cathode.

The final energy of individual ion particles is shown in Fig. 9. Four regions are clearly shown from the plot. The energy of the CO ion is smaller compared to that of H2 ion due to its large mass as described by Eq(1). Figure 10 shows the final energy distribution for ions hitting the cathode. The distribution can be explained by results shown in Fig. 9.

Figure 11 shows the radial distribution of ions impacting on the cathode. Similar to H2 ions, most CO ions hit the cathode with r <10 mm.

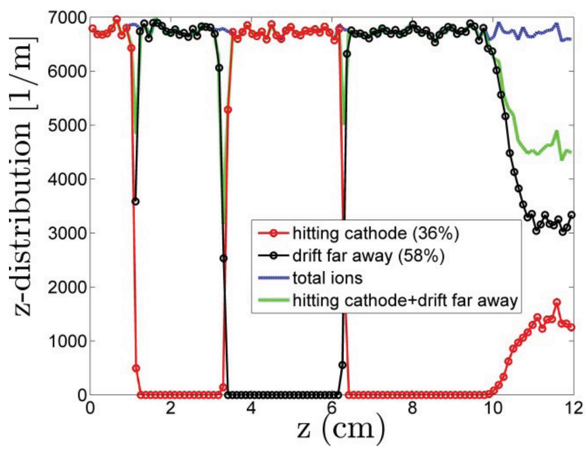

Figure 8: The dependence of the CO ions reaching the cathode and exiting the gun based on their initial position along the cavity.

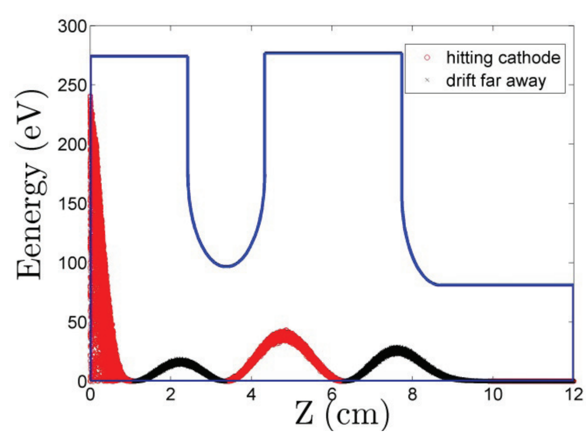

Figure 9: The final CO+ energy for ions born at different position along the cavity. The red and black dots represent ions reaching the cathode and exiting the gun respectively.

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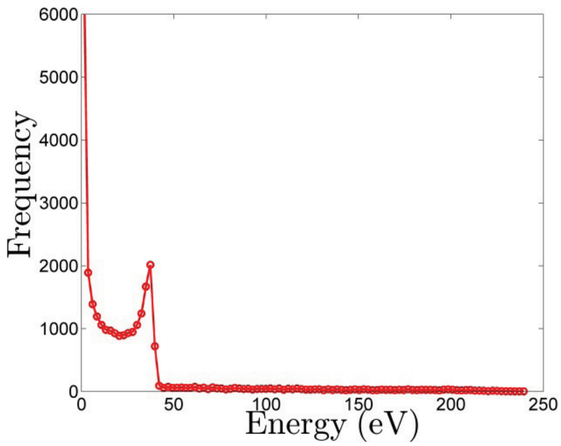

Figure 10: Energy distribution of the CO ions hitting the cathode.

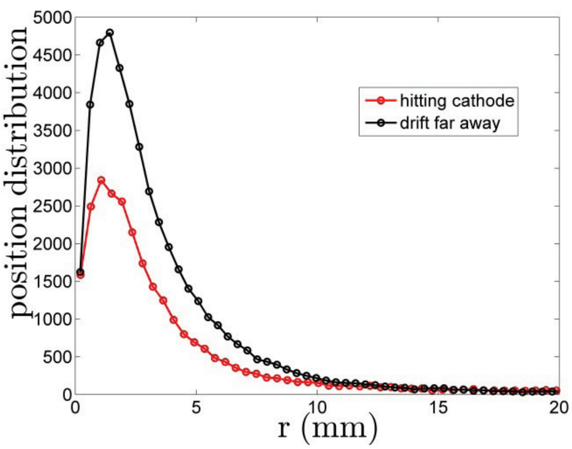

Figure 11: Impact radius distribution of the CO ions hitting the cathode (red line).

LCLS-II GUN

The LCLS-II gun operates at 187 MHz. Figure 12 shows the geometry of the LCLS-II gun with the cathode centre located at (z, r)=(0,0). The low frequency makes the ion dynamics different from the LCLS gun. There is a peak electric field at the cathode and the electric field decays monotonically along the beam direction as shown in Fig. 13 where both the on-axis rf electric field and the focusing solenoid field are shown. The solenoid field inside the cavity is very weak and its effect on the ions is negligible.

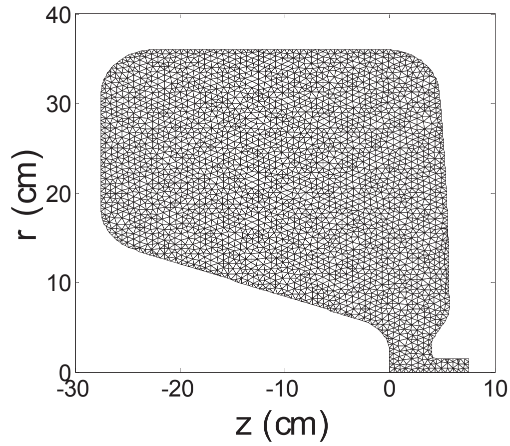

Figure 12: LCLS-II gun. The cathode is located at z=0 cm. Electron beam moves from left to the right.

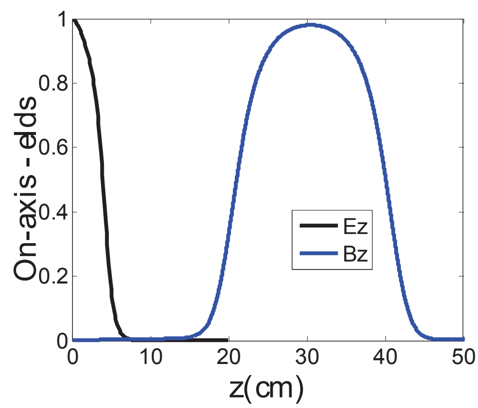

Figure 13: The normalized on-axis LCLS-II gun rf electric field (black line) and solenoid field (blue line).

H_2^+ ion

Figure 14 shows the simulation results for H2 ions: only 7% of the H2 ions reach the cathode. Those ions are generated near the cathode with z<0.5 *cm*. A large number of H2 ions (91%) exit the gun. Most H2 ions born at *z* between 5 *mm* and 7 *mm* move off axis and eventually hit the cavity surface. When the energy dependent cross-section is included, the percentage of ions hitting the cathode increases to 37% due to the large cross-section at low energy. The number of ions lost on the cavity surface also increase to 22%.

Figure 15 shows the typical trajectories of H2 ions: One ion hits the cathode and the second exits the gun. The oscillation due to rf fields are clearly shown for both cases.

Figure 16 shows the final energy when H2 ions hit the cathode (black dots) or run away from the cathode (red dots). Again there is a strong correlation between the final energy and their initial position. For the ions born at the same z-position, the energy of ions impacting on the cathode has large spread because the ion's energy at the cathode largely depends on the rf phase at that moment.

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On the other hand, the energy of ions exiting the gun has much smaller energy spread.

The distributions of impact energy and radial position at the cathode surface are shown in Figs. 17 and 18 respectively. The peak energy is about 9 *keV*, which is larger than that of the LCLS gun although the LCLS-II gun has lower peak field. The lower rf frequency makes the impacting energy larger as shown in Eq.(1). Most H2 ions hit the cathode within 5.0 *mm* radius. It is interesting that the peak in the distribution is located at 1.5 *mm*, instead of the center of the cathode (r=0 *mm*).

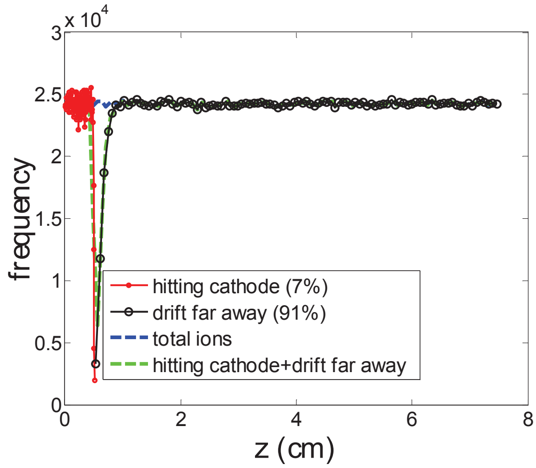

Figure 14: The dependence of the H2 ions reaching the cathode and exiting the gun on their initial position along the cavity.

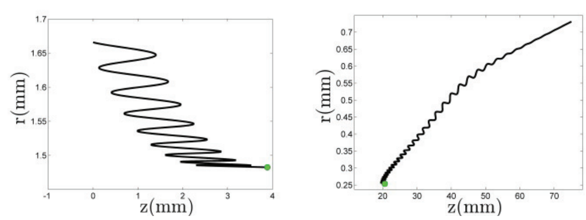

Figure 15: Trajectories of H2 ions born at different cavity positions. One ion hits the cathode (left) and one ion exits the gun (right).

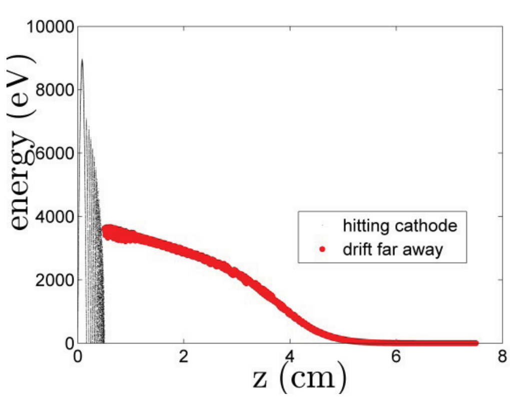

Figure 16: The final H_2+ ion energy for ions born at different position along the cavity. The black and red dots represent ions finally reaching the cathode and exiting the gun respectively.

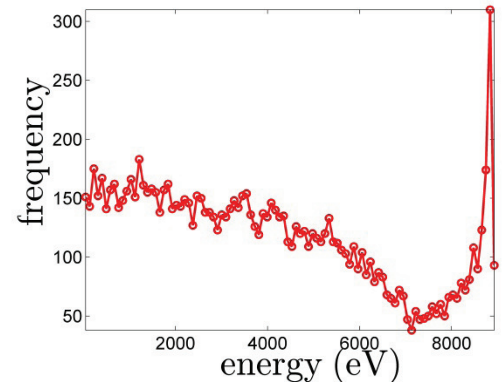

Figure 17: Energy distribution of the H2 ions hitting the cathode.

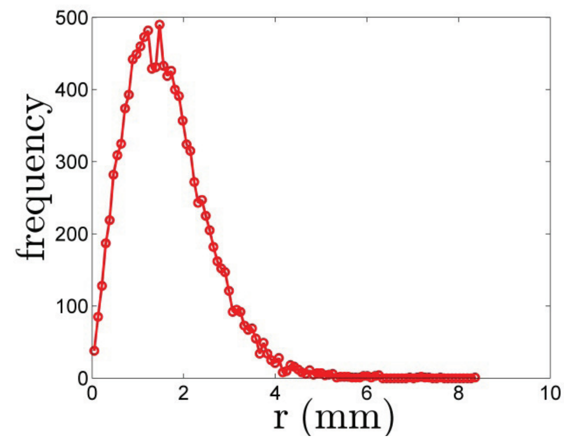

Figure 18: Impact radius distribution of the H2 ions hitting the cathode.

CO^+ ion

Because CO ion has large mass, the energy of CO ion is relatively low compared to the H2 ion. Other than the energy, the dynamics of CO ion is very similar to the H2 ion for the LCLS-II gun. Figures 19 to 21 shows the main results from simulation.

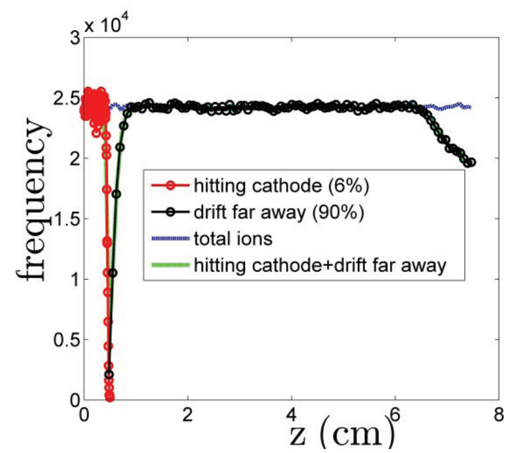

Figure 19: The dependence of the CO ions reaching the cathode and exiting the gun on their initial position along the cavity.

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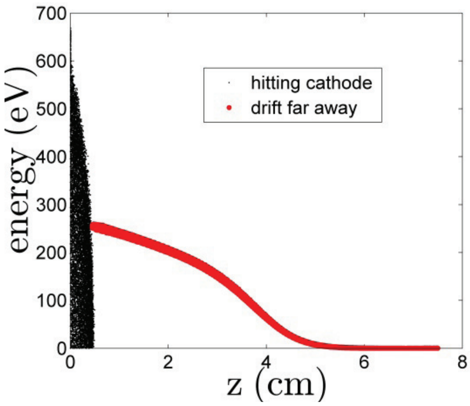

Figure 20: The final CO ion energy for ions born at different positions along the cavity. The black and red dots represent ions reaching the cathode and exiting the gun respectively.

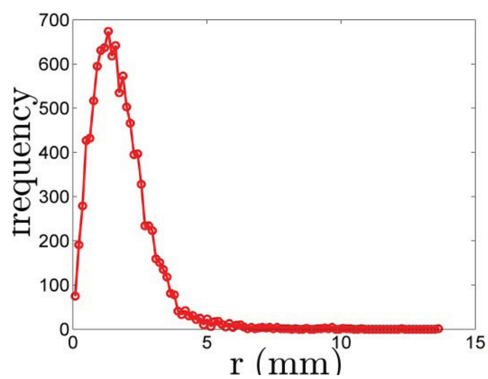

Figure 21: Impact radius distribution of the CO ions hitting the cathode.

SUMMARY AND DISCUSSION

A PIC code has been developed to simulate the dynamics of electron and ion particles in the rf gun. Arbitrary electric and magnetic fields can be modelled. Beside rf fields, the focusing solenoid is also included in the simulation although it has a small effect on the ions hitting the cathode surface.

The studies show very strong effects of the rf frequency, field variation along the cavity in beam direction and the rf phase. The ion dynamics for LCLS gun is complicated by its multiple-cell structure and pulsed rf.

We demonstrate that there are large potential ion back bombardment in the LCLS and LCLS-II rf guns. About 44% and 37% H_2 ions can hit the cathode surface for the LCLS and LCLS-II guns respectively. There is a similar number for CO ions. The chance of ions impacting on the cathode has strong dependence on the rf phase. A large negative rf phase, such as the LCLS gun, increases the probability of hitting the cathode. For example if the LCLS gun phase is -24^{o}, then only 15% H2 ions can impact on the cathode.

The impacting energy on the cathode is larger for low rf frequency guns, such as LCLS-II. The spot size of ions impacting on the cathode is on the order of 10 *mm* and 5 *mm* for the LCLS gun and LCLS-II gun respectively.

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