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Characterization of oxygen ion beams emitted from plasma focus

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ABSTRACT

The Lee model is modified to include oxygen in addition to other gases. It is then applied to characterize the ion beams emitted from the low energy plasma focus PF 1 kJ device operated with oxygen gas. The numerical experiments give the following results: ion fluence- 3×10^{18} ions m^{-2}, ion flux- 2.4×10^{26} ions m^{-2} s^{-1}, ion energy- 261 keV, ion number- 3.5×10^{13}, ion current- 3.5 kA, and damage factor- 1.12×10^{9} Wm^{-2} $s^{0.5}$. Numerical experiments are systematically carried out on other plasma focus devices of various energies. Scaling trends are suggested for oxygen ion beam characteristics. These results provide much needed benchmark reference values and scaling trends for ion beams of a plasma focus operated in oxygen gas.

1. Introduction

The plasma focus produces copious amounts of neutrons, highly energetic ions, relativistic electrons and X-rays. Energetic ions from the focus are used for processing thin films irradiated at different distances from the focus pinch [1]. The generated ion beams are of short time duration with continued and wide range of energies (few keV up to MeV). Ion implantation is a powerful technique used in research and industry for doping and modification of the surface of materials. The exposure of a material to such plasma environment leads to different effects and process such as amorphization, melting, fast cooling, and interaction with highly reactive plasma ions, sputtering, and deposition and so on. Although many works presented the observation of different topographic changes on plasma focus-treated surfaces, these topographic changes need more attention in order to understand the involved processes by correlating plasma focus parameters to different surface modifications [2–6]. On the other hand, the different properties of the deposited films are attributed to ion energy flux generated by plasma focus. Thus, ion energy flux and other ion beam characteristics play a key role to deposit smooth and uniform films of diverse properties [7–9]. Rico et al. studied the effects of oxygen incorporation, by ion implanting, on the crystallization behavior of Strontium Bismuth Tantalate (SBT) thin films using a small plasma focus device with oxygen filling gas, and found that the incorporation of oxygen into the intermediate fluorite phase produces a better crystallization of the SBT perovskite phase, increasing the driving force for the fluorite-perovskite transformation. These preliminary results indicate that the implantation of oxygen by a plasma focus is a promising technique to lower the processing temperature of SBT thin films [10]. Rico et al. also reported the results of crystallization of amorphous zirconium thin films using ion beams generated by oxygen plasma focus. The oxygen-irradiated films showed a delayed and less extensive cubic nucleation, but a more ordered structure and well-defined grains [11]. We note that research on oxygen plasma focus concentrated on the treated surface modifications, but no results have been reported about the ion beam properties emitted from plasma focus leading to these changes. The correlation between the plasma focus parameters and produced ion beam properties could be of help to understand the plasma surface interactions and to find the optimum conditions for desired material science applications. The Lee model code [12,13] had been extended, based on the virtual plasma diode mechanism proposed by Gribkov et al. [14,15], for studying of ion beams from plasma focus [16,17]. In this work, we apply the code version RADPF5.15FIB, further extended to oxygen, to characterize the ion beams emitted from oxygen plasma focus at various conditions. We discuss in some detail the results of many numerical

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experiments carried out using this modified code on different plasma focus devices.

2. Calculations of ion beam properties produced by plasma focus

S. Lee and Saw [17] derived the equation for the flux of the ion beam; linked to the Lee model code and hence computed the ion beam properties of the plasma focus for various gases. They proposed that since the ion beam exits the focus pinch as a narrow beam with little divergence, the exit beam is best characterized by the ion number per unit cross-section which we term the fluence. Following Lee and Saw we use the following equations:

$$\mathrm{Flux}(\text{ions m}^{-2}\text{s}^{-1}) = J_b = 2.75\times10^{15}\left(f_e/\left[M\,Z_{\mathrm{eff}}\right]^{1/2}\right)\times\left\{(\ln[b/r_p])/\left(r_p^2\right)\right\}\left(I_{\mathrm{pinch}}^2\right)/U^{1/2} \quad (1)$$

$$\mathrm{Fluence}\left(\text{ions m}^{-2}\right) = 2.75\times10^{15}\tau\left(f_e\Big/\left[M\,Z_{\mathrm{eff}}\right]^{1/2}\right)\times\left\{(\ln[b/r_p])/\left(r_p^2\right)\right\}\left(I_{\mathrm{pinch}}^2\right)\Big/U^{1/2} \quad (2)$$

where $M = 16$ for oxygen, cathode radius b; and $f_e = 0.14$ (the fraction of energy converted from pinch inductive energy PIE into beam kinetic energy BKE) is equivalent to ion beam energy of 3%–6% E_0 for cases when the PIE holds 20%–40% of E_0 as observed for low inductance PF. The diode voltage U is $U = 3V_{\max}$ taken from data fitting in extensive earlier numerical experiments [16,17], where $V_{\max}$ is the maximum induced voltage of the pre-pinch radial phase. The code is configured with the parameters of the experiment. The value of the ion flux is deduced by computing the values of effective charge Z_{eff}, pinch radius r_p, pinch duration τ, pinch current I_{pinch} and U. Once the flux is determined, the following quantities are also computed: power density flow (energy flux) (Wm^{-2}), current density (Am^{-2}), current (A), ions per sec (ions s^{-1}), fluence (ions m^{-2}), number of ions in beam (ions), energy in beam (J), damage Factor (is defined as energy flux × (pulse duration)$^{0.5}$) ($\mathrm{Wm}^{-2}\ \mathrm{s}^{0.5}$), and energy of fast plasma stream (J).

3. Numerical experiments: results and discussions

3.1. Ion beam properties of PF 1 kJ operated with oxygen gas

The PF 1 kJ plasma focus device [10,11] operated with oxygen filling gas has been used for ion beam implantation and irradiation of different materials. In this work, we use the modified Lee model code, to get some information about the ion beams emitted from PF 1 kJ. To start the calculations, the modified Lee model code is configured to operate as the PF 1 kJ starting with the bank, tube and fitted parameters shown in Table 2 [18].

Then, for studying the effect of pressure on the ion beam characteristics, more numerical experiments were carried out; but varying oxygen gas pressure from 11 Pa to 120 Pa (see Table 1).

Table 1 shows that the ion energy decreases with increasing gas pressure from 307 keV to 55 keV, due to the induced voltage reduction in the radial phase with higher pressures. It can be noticed that the ion flux initially increases with the increase in gas pressure and reaches a maximum (3.1×10^{26} ions $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$) at a pressure of 67 Pa. The fluence has the same trend with pressure, and the peak value of the fluence is 6.2×10^{18} ions m^{-2} at oxygen gas of 93 Pa. The beam ion number increases with the increase in gas pressure until the plasma pinch becomes very weak. The beam ion number range from 2×10^{13} to 7.6×10^{13} for PF 1 kJ. Plasma focus devices have three typical regimes of influence of ion and plasma beams upon a target material placed downstream of the pinch [15,19,20]: (i) "implantation mode" of irradiation when power flow density of the streams is (10^{9}–10^{11} Wm^{-2}) (ii) screening of the surface by a secondary plasma cloud in the so-called "detachment mode" ($\approx10^{11}$–10^{12} Wm^{-2}) (iii) strong damage with the absence of implantation in the "explosive destruction mode" ($\approx10^{12}$–10^{14} Wm^{-2}). The numerical experiments show that maximum power flow density reaches 1×10^{13} Wm^{-2} at a pressure of 40 Pa, and decreases with higher pressures. So, based on the obtained power flow densities, it can be said that the explosive destruction mode is dominant for the PF 1 kJ operation. The damage factor is defined as power flow density multiplied by (pulse duration)$^{0.5}$. It is shown that, the damage factor reaches almost 1.2×10^{9} $\mathrm{Wm}^{-2}\mathrm{s}^{0.5}$ for PF 1 kJ at a pressure of 40 Pa.

3.2. Ion beam characteristics for plasma focus devices with a range of energies

Numerical experiments were carried out systematically on plasma focus devices operated with oxygen (see Table 2). For each of these devices, model parameters were fitted and then used for the computation at various pressures. For each run the dynamics is computed by the code which also computes the ion beam properties (beam ion number, ion beam energy, flux, fluence, current, power flow density and damage factor).

In the same way as described for the PF 1 kJ we carried out numerical experiments for the range of different plasma devices (see Table 2) to obtain the trends across the range of plasma focus operated with oxygen filling gas. The results are shown in Table 3.

From Table 3, we see: (1) the I_{peak} and I_{pinch} typically decrease as E_0 is reduced; except for NX2, NX3 and PF1000 which produces higher performance in I_{peak} and I_{pinch} because of their unusually low L_0. The values of I_{peak} and I_{pinch} for the other studied devices are relatively low due to larger L_0. There is no evident trend with E_0. (2)

Table 1
Variation of oxygen ion beam properties emitted from PF 1 kJ.

p_0 (Pa)	Ion fluence ($\times10^{18}$ m^{-2})	Ion flux ($\times10^{26}$ $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$)	Ion energy (keV)	Ion number ($\times10^{13}$)	Ion current (kA)	Power flow density ($\times10^{12}$ Wm^{-2})	Damage factor ($\times10^{9}$ $\mathrm{Wm}^{-2}\ \mathrm{s}^{0.5}$)
11	1.5	1.5	307	2.0	2.7	7.6	0.75
13	1.8	1.7	300	2.3	2.9	8.3	0.84
27	3.0	2.4	261	3.5	3.5	10	1.12
40	4.2	2.8	224	4.4	3.7	10	1.2
67	5.8	3.1	158	5.9	3.6	7.7	1.1
93	6.2	2.5	104	7.0	3.1	4.2	0.66
107	5.6	1.9	78	7.3	2.7	2.4	0.41
120	4.2	1.2	55	7.6	2.2	1.1	0.2