COMPUTER SIMULATIONS OF IMPEDANCE CHARACTERISTICS FOR MAGNETICALLY INSULATED DIODES

Xiang Wei, Zhao Weijiang, Han Baoxi, Peking University, Beijing 100871, China.
Zeng Baoqing, Yang Zhonghai, UESTC, Chengdu, Sichuan 610054, China

Abstract

Impedance characteristic is one of the most important parameters for a magnetically insulated diode (MID) used to produce intense pulsed ion beams. Based on explosive emission model, the time-dependent characteristics of the MID have been simulated by using the self-consistent, 2-1/2 dimensionally electromagnetic particle-in-cell code MAGIC. The results of numerical calculations are presented at a diode voltage from 200 kV to 500 kV with 40 ns pulse duration and an externally insulating magnetic field in the range of $4B_{crit}$. The effects of the externally insulating magnetic field and the diode voltage on impedance characteristics of diodes are also discussed.

1 INTRODUCTION

Intense pulsed ion beam (IPIB) technique has been developed over the last two decades primarily for nuclear fusion and high energy density physics research[1,2]. As a unique pulsed energy source, IPIB source has also demonstrated to be a very promising for the industrial applications of the surface modification of materials due to flash heat processing and pulsed ion implantation[3,4].

Usually, the IPIB is generated by a magnetically insulated diode (MID) because only the MID can operate over hundreds shots without maintenance to the anode[1,2]. In order to effectively deliver the electronic energy of pulsed power generator into the ion beam energy, it is necessary to understand the impedance characteristics of the MID. However, the previous diode models[5,6], based on simple geometries and the physical assumption, did not successfully explain the MID impedance behaviour. The impedance control of the MID has been unsatisfactory and the diodes have frequently operated at impedance well below that expected on the basis of earlier theories. Desjarlais's model[7], which is based upon a self-consistent calculation of the diamagnetic effect on the electron sheath, further increased our understanding of phenomenon of impedance collapse, but his assumptions of the uniform electron density profile in the sheath and of about 100% ion current efficiency are not generally applicable when the insulating magnetic field is not sufficiently strong.

In this paper, we investigate the time-dependent impedance behaviour of a planar MID by using numerical simulation on basis of plasma explosive emission model. The effects of the externally insulating magnetic field and the diode voltage on impedance characteristics of diodes are also discussed.

2 SIMULATION METHOD

Simulations were performed using the MAGIC code[8]. MAGIC is a 2-1/2 demensional, finite difference time-domain and electromagnetic particle-in-cell code, which self-consistently incorporates the interaction between charged particles and the electromagnetic field. The full set of Maxwell equations together with Lorentz particle motion equation are utilized and space charge effects are automatically treated.

Actual plasma formation is a complicated process. In present work, the plasma formation is based upon the explosive emission model. Plasma surface emission is assumed to occur once the local electric field exceeds a specified threshold for surface breakdown. The resulting plasma surface can be considered as a metal with zero work function. Both electron and ion may be "emitted" under the influence of the ambient electric field. The particle emission itself abides by Child-Langmuir Law. The created particles per unit area is calculated from[8]

$$\frac{dq}{dA} = \varepsilon_0 f(t - t_b)(E_c - E_r) - \rho dx \qquad (1)$$

where ε_0 is the permittivity of a vacuum, f is the plasma formation function, t_b is the time of cell breakdown, E_c is the threshold for surface electric field, E_r is the residual electric field strength, ρ is the existing charge density at the surface, and dx is the cell height. In calculations, the E_c and t_b selected as 2.3×10^7 V/m and 5 ns, respectively.

Figure 1 is a schematic of a planar MID with a 200 mm wide, an 8 mm anode-cathode(AC) gap and a 190 mm flashboard. The flashboard is used to form surface anode plasma. The cathode is also employed to be a single turn coil to provide the externally insulating magnetic field whose direction is perpendicular to the electric field. In calculations, a uniform magnetic filed in the range of $4B_{crit}$ is introduced, where B_{crit} is the minimum field for insulation of electrons given by the condition that the electron gyro-radius equals the AC gap. For a planar diode, the B_{crit} can be represented as[2],

$$B_{crit} = \frac{1}{d}\sqrt{\frac{2m_eV}{e}}\left(1 + \frac{eV}{2m_ec^2}\right)^{1/2} \qquad (2)$$

where d is the AC gap, V is diode voltage, m_e is the electron rest mass, e is the electron electric-charge, and c is the velocity of light in vacuum, e.g., for d=8 mm, V=300 kV, we have B_{crit}=0.26 T.

Figure 2 shows the typically simulated diode voltage waveforms, which are similar to the TEMP source of Nuclear Physics Institute in Tomsk, Russia[3].

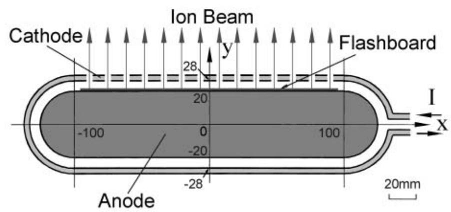


Figure 1: Schematic of a planar MID.

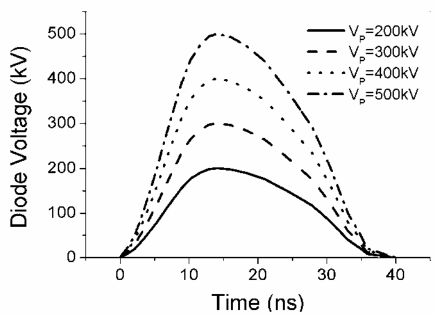


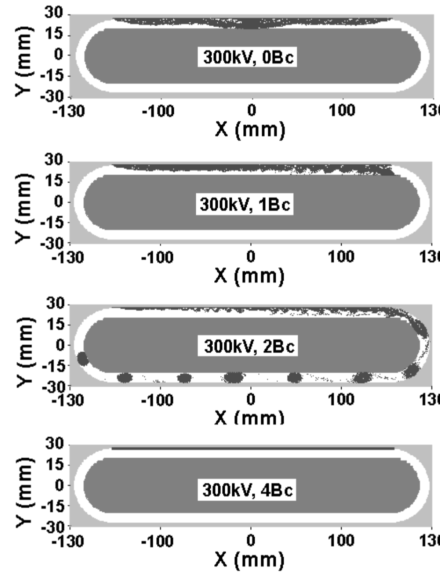
Figure 2: Waveforms of diode voltage for simulations.

3 RESULTS AND DISUSSION

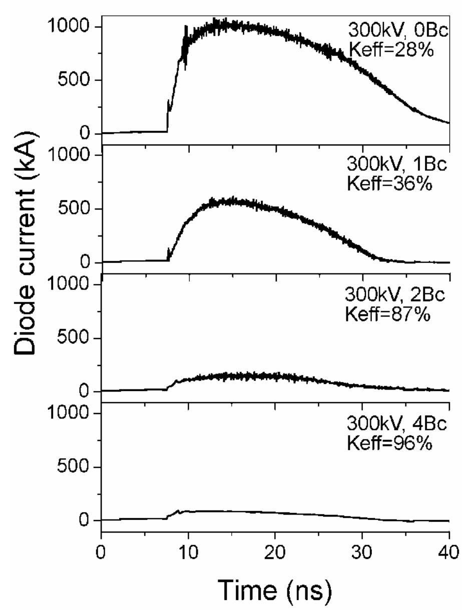
Figure 3 shows snapshots of the simulation electrons at 15 ns. Figure 4 and Figure 5 show the time-dependent results of the diode current and the corresponding diode impedance histories with respect to the externally magnetic field, respectively. Under the assumption of the 100% cathode transparency for ions, Figure 4 also presents the results of the diode efficiency K_{eff} ($K_{eff} = I_i/I_d$, where I_i and I_d are the total ion current at the extracted surface and the total diode current, respectively).

We clearly note that, as the magnetic field rises from 0 to $4B_{crit}$, the electron emission is more effectively confined; the thickness of electron sheath becomes thinner and more uniform in AC gap; the peak diode current decreases rapidly; while the diode impedance at the peak of the diode voltage and the K_{eff} increase. The increase of the K_{eff} from 28% to 96% implies that more electron loss to the flashboard at lower magnetic field. Because irradiation of electrons on the flashboard surface causes the enhancement of electronic field at the flashboard surface, thus results in the rapid enhancement of ion emission. Namely, with the increase of the magnetic field, diode current may reduce, and the diode impedance is increased.

Generally, the diode impedance at the peak of the diode voltage is as low as several Ohm. At B=0, the peak diode current as high as 1000 kA. Clearly, such intense diode current creates the strong enough self-magnetic field to pinch the electrons in the AC gap. Actually, the electrons shift along the $\mathbf{E}\times\mathbf{B}$ direction. At $B=2B_{crit}$, there exists electron bunches due to the electromagnetic focusing.

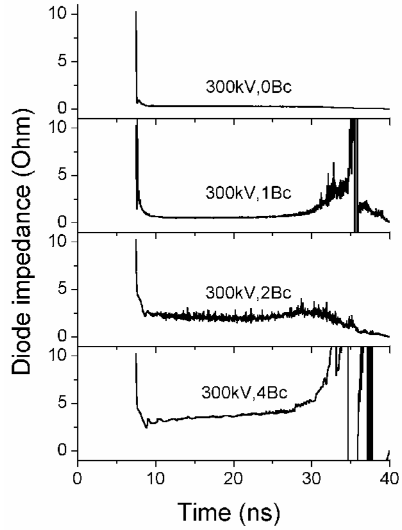


Figue 3: Snapshots of simulated electrons at 15ns.



Figue 4: The time-dependent diode current at various externally magnetic fields.

Figure 5 also shown the impedance generally starts out very high because no current flow across the AC gap at this moment. This is in agreement with a number of experimental results[9]. As the cathode and anode plasma formation and expanding, the diode impedance falls dramatically because the space charge causes the time-dependent rapid enhancement of ion emission. Furthermore, Figure 5 shows that the fast turn-on can achieve at the lower magnetic field. This phenomenon implies that electron irradiation is necessary at the beginning of main pulse to achieve fast turn-on because irradiation of electrons on the flashboard surface plays a very important role in the production of anode plasma.



Figue 5: The diode impedance histories at various externally magnetic fields.

Figure 6 and Figure 7 show the time-dependent results of the diode current and diode impedance histories at various diode voltages, respectively. We clearly note that the magnetic field has more significant influence on diode impedance than the diode voltage. With the increase of the diode voltage, the peak diode current increases; and the impedance histories and the K_{eff} are almost identical. These results indicate that the diode impedance characteristics depend on the relationship between the magnetic field supplied to the MID and the diode voltage. When they satisfy equation (2), the diode impedance are same, namely, the diode current is proportion to the diode voltage and does not satisfy the Child-Langmuir 3/2 law.

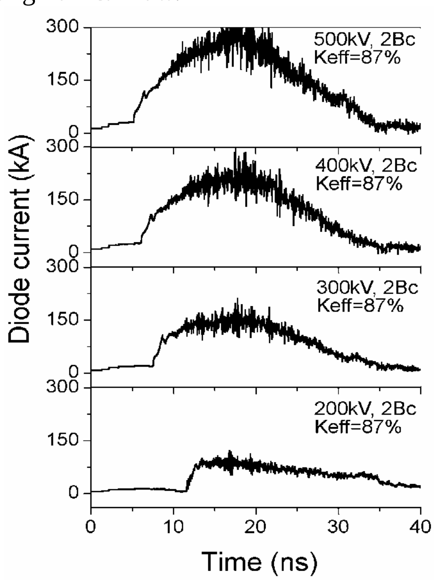


Figure 6: The time-dependent diode current at various diode voltages.

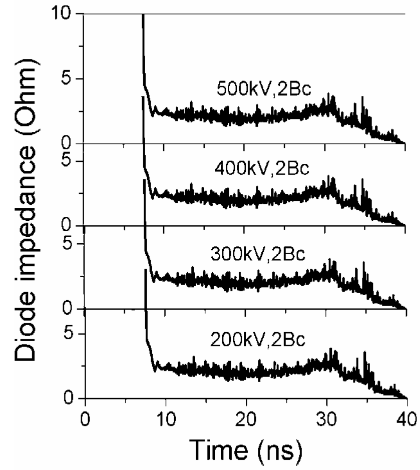


Figure 7: The diode impedance histories at various diode voltages.

4 CONCLUSIONS

The effects of the magnetic field and the diode voltage on the impedance characteristics of a planar MID have been simulated. The magnetic field has a more significant effect on the diode impedance behaviour than the diode voltage. The diode impedance at the peak of the diode voltage is normally several Ohm. With the increase of magnetic field in the range of $4B_{crit}$, the diode current are dramatically reduced; while the diode impedance and diode efficiency are increased. With the increase of the diode voltage, the diode current increases; and the diode impedance and diode efficiency are identical.

5 ACKNOWLEDGEMENTS

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