The Potential Profile and its Influence on the Neutron Yield of Inertial Electrostatic Confinement Fusion Device

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Abstract—We have simulated an IECF (inertial electrostatic confinement fusion) device by developing and using a particle code. Because a virtual anode is built up at large current region, which decelerates ions and reduces neutron yield, suppression of this virtual anode by supply of electrons from an additional electrode inside the cathode has been tried in the simulations. The simulation results show that with increase of electron supply current, potential profile changes drastically and the neutron yield increases at a threshold value. Also the mechanism of the drastic change has been explained well.

Keywords—IECF; neutron generator; particle code

I. INTRODUCTION

An inertial electrostatic confinement fusion (IECF) device is a simple device and is expected to be used as a compact neutron beam generator. This device consists of a spherical grounded anode, which serves as a chamber, and a grid cathode. They are set concentrically as shown in Fig. 1. Ions generated by glow discharge in low pressure deuterium gas (< 2 Pa) are accelerated toward the center by high applied voltage and circulate many times in the chamber. Inside of the cathode, concentrated ions collide with each other and with background neutral gases and this cause fusion reaction [1].

In order to reveal the mechanism of the IECF, we have developed a one-dimensional PIC (particle-in-cell) code and analyzed IECF device. Though it is expected that NPR_{BB} (neutron production rate through beam-beam reaction) increases in proportion to the squared ion-current in low gas pressure discharge assisted by supplying D_{2}+ from an external ion source, our previous result shows less increase than expected [2]. The reason is that a potential structure (“virtual anode”) is built up by concentrated ions in the cathode and decelerates themselves in the center spot as shown in Fig. 2. Therefore it is needed to suppress this virtual anode. We considered that inserting an electrode and emitting electrons (assuming thermal electrons) in the cathode is effective for this purpose. In this study, influence of the electron supply current to the potential profile and to the neutron yield has been investigated.

II. SIMULATION METHOD

In order to analyze the IECF device, we have developed a particle code based on the PDS1 code developed by the Plasma Theory and Simulation Group at the University of California, Berkeley [3]. Since the original PDS1 code was developed to simulate glow discharge between solid (not grid) electrodes with lower voltage and higher pressure than those in the IECF discharge, we made some modifications [4-6]. The potential profile, NPR and its spatial distribution, contribution to the NPR of each species, discharge current and voltage, and so on can be calculated by using this modified code.
In this study, we have improved this code in such a way that low energy electrons are emitted from an additional electrode. The voltage of this electrode can be specified as a constant value or floating. Main simulation parameters used in this study are shown in Table 1. The combination of the gas pressure $P$, the discharge voltage $V$ and the assist (injected ion) current $I_{\text{assist}}$ is fixed where NPR BB becomes almost as same as NPRBN (NPR through beam-neutral reaction) from preliminary calculation and this condition is relatively large current and low pressure compared with usual experimental device. Not only floating voltage but also fixed voltage of $-110\,\text{kV}$ is applied expecting well confinement of electrons inside the cathode by keeping potential slightly higher than the cathode voltage ($-120\,\text{kV}$).

### III. RESULTS AND DISCUSSION

#### A. Dependency of NPR to the electron supply current $I_t$

Figure 3 shows NPR\_BB and NPR\_BN as function of $I_t$ when the applied voltage is floating, fixed to $-110\,\text{kV}$, or electrons are not supplied (indicated as “Normal”). The NPR\_BB is insensitive to $I_t$ in low current region below 4A (in the case $V_t$ is floating) or 2A (in the case $V_t$ is fixed to $-110\,\text{kV}$), but increases drastically at a threshold value (e.g. about 4 times increase when floating voltage is applied). In the current range above 5A ($V_t$: floating) or 3A ($V_t=-110\,\text{kV}$), it hardly increases with increase of $I_t$. NPR\_BN shows same tendency as NPR\_BB, but is not so drastic as NPR\_BB.

In the case $V_t$ is fixed to $-110\,\text{kV}$, NPR\_BB is twice that without thermal electron even though $I_t=0$. The threshold value is smaller, and NPR\_BB and NPR\_BN are larger than the case when floating voltage is applied. These results about neutron yield are strongly related to potential profiles inside the cathode.

#### B. Relationship between potential profiles and spatial distribution of NPR

Potential profiles for different $I_t$ when floating $V_t$ is applied are shown in Fig. 4. The shape of potential profile inside the cathode is flat when $I_t=5\,\text{A}$. At smaller current, the virtual anode exists and its shape does not depend on the current. Therefore, as shown in Fig. 5, when $I_t=5\,\text{A}$, the position where NPR\_BB has peak value shifts to the center and the peak value increases since the beam-beam reaction rate is proportional to squared density of energetic particles, which is in proportional to $1/r^2$. From Fig. 6 which shows spatial distributions of NPR\_BN, it is clarified that spatial distribution of NPR\_BN is responding to

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Value</th>
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<tbody>
<tr>
<td>$r_a$</td>
<td>Anode radius</td>
<td>10cm</td>
</tr>
<tr>
<td>$r_c$</td>
<td>Cathode radius</td>
<td>3cm</td>
</tr>
<tr>
<td>$r_i$</td>
<td>Electron emitting electrode radius</td>
<td>1.5cm</td>
</tr>
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<td>$P$</td>
<td>Background gas pressure</td>
<td>0.067mPa</td>
</tr>
<tr>
<td>$V$</td>
<td>Discharge voltage</td>
<td>-120kV</td>
</tr>
<tr>
<td>$V_t$</td>
<td>Voltage of electron emitting electrode</td>
<td>Float or $-110,\text{kV}$</td>
</tr>
<tr>
<td>$I_{\text{DisC}}$</td>
<td>Discharge current</td>
<td>Calculated</td>
</tr>
<tr>
<td>$I_{\text{inj}}$</td>
<td>Injected ion current</td>
<td>200mA</td>
</tr>
<tr>
<td>$I_t$</td>
<td>Electron supply current</td>
<td>0-10A</td>
</tr>
</tbody>
</table>

[Figure 3](#). Neutron production rate through beam-beam reaction (NPR\_BB) and through beam-background neutral reaction (NPR\_BN) as function of electron supply current $I_t$.

[Figure 4](#). Potential profiles for various electron supply current $I_t$ when the potential of electron emitting electrode is floating.

[Figure 5](#). Spatial distributions of NPR\_BB for various $I_t$ when the potential of electron emitting electrode is floating. Notice that radius range drawn in this figure is 0-5cm, half of the device size.
the potential profile, not decreasing with approaching to the center when $I_t=5A$.

Figure 7 shows potential profiles for different $I_t$ when $V_t$ is fixed to $-110kV$. The tendency that the potential profile changes drastically when $I_t$ crosses certain value is similar to the case applied floating voltage, but the width of the virtual anode becomes narrow and the potential profile between the cathode and the additional electrode becomes flat even when the electrons are not supplied ($I_t=0$). Therefore both NPR$_{BB}$ and NPR$_{BN}$ increase compared with normal condition.

By narrowing or canceling the virtual anode, concentration of energetic ions more close to the center increases NPR$_{BB}$ and the expansion of the range where ions keep high energy increases NPR$_{BN}$.

C. Confinement of electron inside the cathode

Though it has been clarified that electron supply inside the cathode changes the potential profile and this affects the neutron yield, the electron supply current needed to cancel the virtual anode seems to be too large considering that the injected ion current is 200mA. And the mechanism of drastic change of NPR at the threshold value has not been clarified.

Considering about confinement of electrons, the problem is that it is more disadvantageous than ions because; a) electrons which escape from the center region never return to inside the cathode while ions continue to circulate until they collide with background neutrals or the cathode, b) since the potential structure inside the cathode is unstable as shown in Fig. 8, electrons can easily gain energy and escape from center region. The following consideration clarifies this in detail.

The required condition to cancel the virtual anode is that the density of electron $N_e$ equals to that of ion $N_i$. The density $N$ is calculated as

$$N = \frac{ni}{S\nu}$$

(1),

where $n$ is the number of circulation, $i$ is the current, $S$ is cross section at a radius and $\nu$ is the velocity. Since the velocity is expressed as

$$\nu = \sqrt{\frac{2E}{m}}$$

(2),

the required electron current $i_e$ which satisfies $N_i=N_e$ is solved as

$$i_e = \frac{n_i}{n_e} \sqrt{\frac{E_e}{E_i}} \frac{m}{m_i} - i_i$$

(3),

where subscription “e” and “i” means electron and ion, respectively. By assuming that $n_i=n_e$ and $E_e/E_i=1/10$, required electron current is calculated as about $27i_i=5.4A$ because $m_i/m_e<7300$ and $i_i=I_{assist}=200mA$. This value is almost the same as the threshold value evaluated from simulations.

By applying (3), the reason why the potential profile changes drastically when $I_t$ crosses the threshold is explained as follows. When $I_t$ is smaller, requirement (3) cannot be satisfied and the virtual anode still exists. Whereas, $I_t$ becomes large
enough to satisfy the requirement, the virtual anode is canceled, and $E_e$ becomes small because electrons are not accelerated by the virtual anode. Therefore the required $I_e$ becomes small and this may seem to be over-supply of electron. However, when it happens, the potential inside the cathode becomes lower than the cathode voltage and electrons run away toward outside, this results in small $n_e$ and balance.

IV. CONCLUSIONS

In this work simulation of an IECF device added an electrode which supplies electrons inside the cathode in order to cancel the virtual anode has been done by using a particle code, and the potential profile and its influence to the neutron yield has been investigated. It has been clarified that a) the neutron yield increases as the virtual anode is suppressed by increasing electron supply current, b) the neutron yield increases drastically at certain electron supply current, not linearly, c) when fixed voltage is applied to the additional electrode, the neutron yield increases even if the electrons are not supplied. From the consideration about relationship between the electron supply current and the potential profile, drastic change of potential profile at the threshold value has been explained.

Though the required electron current is considered to be too large and it is important to improve confinement of electrons inside the cathode, it is shown that supplying electrons inside the cathode at large current is effective to increase the neutron yield by suppressing the virtual anode.

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REFERENCES