Optimization of cathode settings in a low-energy electron gun to develop a diagnostic tool for H^- ion source plasmas

Yoshikatsu Matsumoto[1], Haruhisa Nakano[2,3], Masashi Kisaki[4], Katsuhiro Shinto[5], Mamiko Sasao[6] and Motoi Wada[6]

[1]Tokushima Bunri Univeristy, Nishihama, Tokushima 770-8514, Japan
[2]National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan
[3]SOKENDAI (The Graduate University for Advanced Studies), 322-6 Oroshi-cho, Toki, 509-5292 Japan
[4]National Institutes for Quantum and Radiological Science and Technology, 801-1 Mukoyama, Naka-shi, Ibaraki 311-0193 Japan
[5]Japan Atomic Energy Agency, J-PARC center, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan
[6]Doshisha University, Kyotanabe, Kyoto 610-0394, Japan
Corresponding Author:Yoshikatsu Matsumoto, e-mail address: ymatsumoto@tokushima.bunri-u.ac.jp

1. Introduction

We need a very low energy electron gun to research electron behavior (transport) in H- source plasmas.

- Low energy electron behaviour in H^- source plasmas is one of essential information to improve performances of H^- sources.
- To research the electron behaviour (especially transport), we decided to introduce a new experimental idea in an ion source plasma.
- Like Fig.1, we inject additional electrons into an ion source plasma from a position which is very close to or the inside of the plasma. The energy of the injected electrons from the source is adjusted to the similar level of bulk electrons in the plasma, which we expect from 1 to 20 eV.
- The injected electrons are expected to diffuse from the injection point following a transport manner as same as that of the bulk electrons in the plasma. It means that understanding of transport manner of the injected electrons is almost equivalent to learning the manner for low-energy bulk electrons.
- Observation of the injected electrons in the plasmas is probably possible from a spatial distribution of electron density. Injected electrons locally elevate the electron density around the injection point. The local elevation gradually decreases as an observation point goes away from the injection point. The tendency of the density slope is expected to be feedback of the transport of the injected electrons in the plasma.

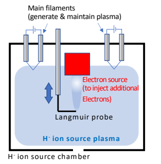

Fig. 1 Image of electron transport study using additional electron source.

- Analysis of the experimental results about the injected electrons with a Particle-In-Cell (PIC) simulation will give us understanding of the low-energy electron transport.
- To research electron transport in H^- source plasma, we need a low-energy electron gun to inject electrons into an ion source plasma.

Requirement of the low-energy electron gun for our purpose

- The gun must provide low energy electrons which have similar energies to bulk electrons in the ion source plasma. The energy range we expect is 1 ～20 eV.
- Beam current density we want to obtain is 1 mA/cm^2 in case of 1 eV beam energy.
- A low beam energy means "easy to spread". Therefore, we have to inject the low energy electron beam from a position which is very close to or inside the H^- source plasma like Fig. 1.

The electron gun is requested to be able to work inside the ion source chamber even under the influence of the ion source plasma. And it also has to be small size to be installed in an H^- source chamber.

The current issue we have to overcome & contents we show here …

- Now we are under development phase through improvement of a prototype electron gun. It obtained 0.04 mA/cm^2 at 1 eV beam energy as a maximum beam current in a vacuum, which we showed in ICIS2019.
- Our prototype gun has not achieved the requirement in the beam current density, yet. We have to enhance the beam current density.

To obtain basic knowledge for improvement of the beam current density, we analyze electron behavior, especially transport, inside the gun with PIC simulation. We show the results here, focusing on size and voltage settings of a filament(cathode) .

2. Experimental setup

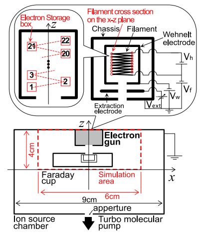

Fig.2 Experimental apparatus and simulation domain.

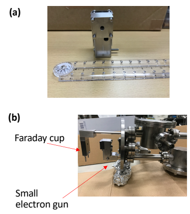

Fig.3 Photos of the electron gun
(a) Confirmation of the size of the electron gun
(b) Overall view of the system to test the electron gun.

- The electron gun was installed on the end plate of H^- source chamber.
- The length, width and height of the electron gun were 2.6cm, 2.2cm and 6 cm, respectively.
- The electron gun used the spring-shape tungsten filament whose diameter was φ0.2mm. The heater voltage V_h, which was approximately 10 V, was applied to the filament to generate thermal electrons in our experiment.
- The filament was surrounded by the Wehnelt electrode to confine emitted electrons. It had a negative potential lower than that of the filament.
- The electrons inside the Wehnelt electrode were extracted by an beam extraction field induced by the voltage V_{ext} at the extraction electrode.
- The extracted electron beams were decelerated with electric field between the extraction electrode and chassis of the electron gun. The chassis also worked as Faraday shield.
- Extracted electron beams were measured by the a Faraday cup which was located on the z axis at 3 mm away from the extraction aperture of the electron gun.
- The cylindrical small ion source chamber, in which the electron gun was installed, has 9 cm-diameter and 11 cm-height.
- We were focusing on enhancement of the beam current. Thus, discharges and hydrogen gas loadings were not conducted here. We also didn't use a filter magnetic field in the H^- source.

3. Simulation settings

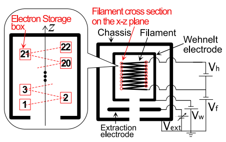

Fig.4 settings of the electron gun in the simulation.

3.1 Basic information of this simulation

- The experimental data was analyzed with 2D3V Particle-In-Cell simulation (2D3V-PIC).
- The simulation domain was shown in Fig. 2 with a red broken line whose size was 6cm in x and 4cm in z, respectively. The area was divided into 600 x 400 grids in the simulation.
- The size and configuration of electrodes of the electron gun were assumed in the PIC code as well as the real one.
- Collisions among particles were not considered in the simulation, because our experiment was conducted in a vacuum.

3.2 Treatment of spring-shape filament in this simulation

We more carefully treated the filament spatial structure than that of our previous work. It enabled us to discuss electron behaviour around the filament more precisely. We explain the detail here using Fig. 4.

Electron storage box

We used "electron storage boxes" to simulate filament. It worked as special electrodes with the definitions as follows.

- It could store electrons in the inside like the real filament. The electrons inside the box could move without feeling any forces by electric fields, magnetic fields and collisions among particles. When the electrons reached a boundary of the box in their transports, they could get out and leave the box like real emission events.
- For electrons after emission events, the box worked as a normal electrode. The motions of the electrons were affected by the electric potential of the box. When electrons reached the boundary of the box, they could collide and vanish like in real collision events on a metal wall.

Treatment of filament structure with the electron storage box

- The cross section of the real spring-shape filament on the x-z plane seems to be seen like Fig. 4. Some small circle-shape electrodes, whose sizes are determined by the tungsten wire diameter, are in the two rows along and both side of the z axis.
- We shrunk the electron storage box into the same size of the wire diameter. In addition, we increased the number of the storage boxes placing them onto same positions of the wire footprints on the x-z plane in Fig. 4.

Procedure to give electrostatic potential to the filament in the simulation

- The real filament was driven by the heater voltage, V_h, in Fig. 4 It was applied between both edges of the filament. The voltage gave a spatial potential distribution to the filament.
- The potential distribution was decided depending on a distance from the one of edges to an observation point on the filament.
  → To simulate the potential distribution, we gave a unique potential to each box as a function of the distances from the edge. The distances were calculated with a procedure that neighboured two boxes were connected with a straight line in the order shown in Fig. 4. In this treatment, the potential of the series of boxes gradually changes from one of edges to another.

4. Filament size effect

How does the filament size affect a beam current density?

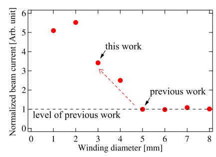

Fig. 5 Dependence of the electron beam current on winding diameter of the filament in PIC simulation. The beam currents were normalized based on the current in the previous work whose winding diameter was 5 mm.

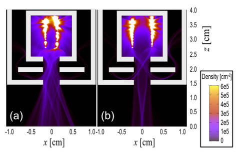

Fig. 6 Contour plots of electron density in the electron gun by PIC simulation. The winding diameters of the filaments are (a) 3 mm, (b) 5 mm. Electrodes were hand-drawn to guide positions roughly.

- We change the winding diameter (width) of the filament size from 5 mm to 3 mm in our experiment.

Beam current was enhanced from 0.04 mA/cm^2 to at least 0.1~0.2 mA/cm^2. Ratio of the enhancement was around 3.

- Why? → PIC simulation was conducted.

The simulation said that the shrinkage of the filament from 5 mm to 3 mm is expected to realize about 3 times larger beam current (Fig. 5).
→ It was good agreement with the experiment.

- Contour plots of electron density in Fig. 6 explained the reason. The small size filament was useful to improve in front of electron density inside the electron gun. It seemed to link to the beam enhancement in our experiment.

A smaller filament will be better to enhance an electron beam current.

5. Role of extraction and heater voltages for beam extraction

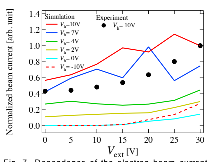

Fig. 7 Dependence of the electron beam current on Vext in experiment and simulation. Several V_h conditions were used. V_f = 1 V, V_w=2.4 V, respectively.

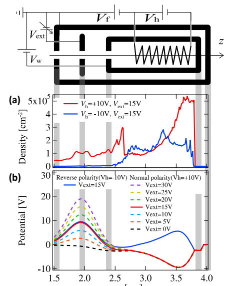

Fig. 8 Spatial distributions on the z axis of (a) electron density, (b) space potential in PIC simulation. The results were calculated changing V_{ext} and V_h. V_f and V_w were same to Fig. 7. The gray transparent bars roughly show positions of electrodes.

We discuss roles of the extraction voltage V_{ext} and the heater voltage V_h in the Fig. 8 for electron transports and extractions inside the electron gun.

To discuss it, we conduct an experiment shown in Fig. 7. It was an experimental beam current dependence on V_{ext}, using a constant V_h values which were +10 V. Here, the beam currents are normalized by the highest beam current obtained in V_{ext} = 30 V, V_h = +10 V case, for convenience in comparison with simulation results later.

This is a main figure which we often use to discuss, here.

5.1 Role of extraction voltage (V_{ext})

- The beam current showed a growing trend with increment of V_{ext}. The reason is found in Fig. 8, which are spatial profiles of electron density and space potential in the Wehnelt electrode on the z axis by PIC simulation.
- The result in Fig. 8(b) shows that the increment of V_{ext} elevates the potential in vicinity of the extraction hole. It connected to the enhancement of the simulated beam current with V_h = +10 V in Fig. 7.
- However, the influence of V_{ext} was limited electrons near the extraction hole.
  → Were electrons at inner region in the Wehnelt electrode (far from the extraction hole) independent on the beam current?
  → The answer is "No", thanks to the work of the heater voltage V_h.

5.2 Role of heater voltage (V_h)

- Despite under no extraction electric field condition promised by V_{ext} = 0 V, the beam current was not zero. The result indicates an existence of electron extractions which was independent of the extraction field induced by V_{ext}.
- In Fig. 8(b) with V_h = +10 V and V_{ext} = 15 V case, V_h formed a potential structure which accelerated electrons at a region from z = 2.5 to 3.5 cm, along the z axis toward the hole. These accelerated electrons were expected to reach the extraction hole, even without a support by the extraction electric field induced by V_{ext}.
- There is another example to confirm the work of V_h. The beam currents at V_{ext} = 0 V among several V_h settings showed a clear dependence on V_h.
- Besides, when V_h was set to a reversed polarity value, -10V, the electron beam current was largely decreased in Fig. 7 even applying high V_{ext} values. In this case, the potential distribution shown in Fig. 8(b) was formed to confine electrons inside the Wehnelt electrode, whose example is in Fig. 8(a). As a result, the beam current became small. We have already confirmed this beam current tendency in an experiment with a similar voltage setting, which were V_h = -10 V, V_{ext} = 35 V, V_w = 3.6 V and V_f = 1 V.

The heater voltage V_h has a large impact to a beam current, and the support of V_h is indispensable to obtain an intense beam.

6. Conclusion

We analyzed electron behavior in the spring-shape electron gun with PIC simulation. It gave us indication to improve a beam current density telling the electron extraction mechanism from an electron gun.

- A smaller filament size should be chosen. It is favorable to improve electron density in front of the extraction hole. It is expected to connect to higher extracted beam current.
- An beam extraction voltage, which induces beam extraction electric field near the extraction hole, directly attracts electrons toward the hole. However, the influence by the field is limited in the vicinity of the hole.
- A heater voltage to drive a filament for thermal electron emissions has a significant role for efficient electron extraction from a electron gun. It forms a potential structure which guides electrons, especially far from an beam extraction hole, toward the hole.

There are two kinds of electron extraction functions provided by the extraction voltage and the heater voltage. Combination of them is very important to obtain low-energy, intense electron beams.