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ABSTRACT

The behavior of the Cesium (Cs) in Cs-seeded negative ion sources has been investigated experimentally under the beam accelerations of up to 0.5 MeV. The pulse length was extended to 100 s to catch the precise variations in the Cs D2 emission, discharge power, negative ion current, and temperatures in the ion source. The variations of the negative ions were estimated by the beam current and the heat loads in the accelerator. This experiment shows that the buildup of temperature in the chamber walls lead to the evaporation of deposited Cs to enter the plasma region and influenced H^- ion production. The H^- ion beams were stably sustained by reducing the temperature rise of the chamber wall below 50 °C. A stable long pulse beam could be achieved through the temperature control of the surfaces inside the source chamber walls.

INTRODUCTION

To achieve high power negative ion beams required for neutral beam injector (NBI) systems of fusion reactors, high density negative ion sources are being developed using Cesium (Cs) to reduce the work function on the plasma grid (PG) and enhance the surface production of negative ions on the PG.[1,2] The layer of Cs deposited on the PG surface has an optimal amount to get higher negative ion current, and the PG temperature has been controlled and kept constant around 200 °C.[3] However, it was observed in previous experiments of negative ion production up to 100 s by using a large negative ion source for JT-60SA that the extracted H^- beam degraded after 60 s although the PG temperature was maintained at 200 °C. Simultaneously, the Cs emission intensity in the plasma region also remarkably increased.[4] The increase in the Cs emission in the plasma region influences negative ion production near the PG. To realize the stability of the H^- ion beam for long pulses, it is necessary to understand the behavior of the Cs neutrals in the large negative ion source as it affects the generated beam current.

The increase in the Cs atoms in the plasma has been observed in several ion sources.[5–7] The pulse length of this experiment was 30 s, and the negative ion current did not degrade in this pulse length. The numerical analysis has also been developed to understand the Cs behavior.[6,7] The analysis includes the measured Cs deposition/evaporation rate from the metal surface according to its temperature. The analytical result showed that most of the Cs is deposited on the walls at room temperature and is evaporated from the wall surface as the temperature increases during discharge. When the wall temperature exceeds over 60 °C, the evaporation of Cs greatly increases and Cs atoms move toward plasma volume depositing on various surfaces including the PG. The change in the Cs layer condition in the PG causes the reduction of negative ion production.

In this paper, considering these processes, the behavior of Cs has been experimentally investigated under long pulse operations toward 100 s. The cause of the increase in the Cs in the plasma region is discussed. To confirm the Cs condition on the PG, the negative ion current and the heat loads on the grid were monitored to estimate the negative ion production condition near the PG. In addition, this experiment was performed with a negative ion acceleration of up to 500 keV by using a multi-aperture and a three-stage electrostatic accelerator. Therefore, precise variation in the negative ion production can be estimated through the measured H^- beam current and the heat loads on the acceleration grids. With the enhancement of the cooling system of the ion source, the variation in the Cs emission line intensity is measured to confirm the conditions in controlling the redistribution of Cs neutrals, which is necessary to achieve the stable operation of the high current H^- beams.

Cs BEHAVIOR IN THE ION SOURCE

The Cs behavior, with the suggestion by Yoshida *et al.*, is summarized in Fig. 1.[8] The Cs is seeded from an oven connected to the ion source, and the injected vapor is deposited on the surfaces of the PG and chamber walls. During the arc discharge, Cs is redistributed and desorbed from the wall surfaces and enters into the plasma region. Thus, the Cs inside the plasma originates from the injected Cs by the oven and the Cs flux from the chamber walls. When the chamber wall temperatures become very high, evaporation of the adsorbed Cs is possible and this can increase the amount of Cs neutrals in the plasma region.

The redistribution of Cs atoms during the arc discharge when operated for long periods causes changes in the surface condition of the Cs layer on the plasma grid. To sustain the low work function condition for the surface production of negative ions, the temperature rise of the chamber walls caused by heat loads during plasma operation should be controlled for suppressing the excessive amount of neutrals entering the plasma volume.

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 2. In this experiment, a semi-cylindrical chamber with 34 cm diameter and 34 cm length was used. Permanent magnets are embedded around the cylindrical chamber to create cusp magnetic fields. The size of this chamber is 1/8 of the chamber of the JT-60SA negative ion source.[9] The thermal

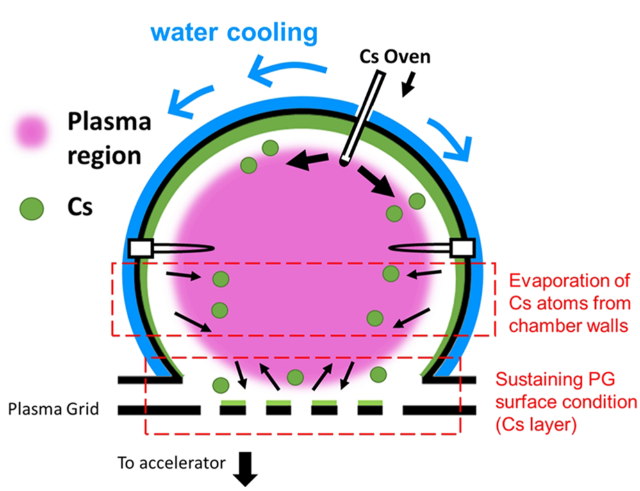

FIG. 1. Illustration of the Cs redistribution in the H^- negative ion source.

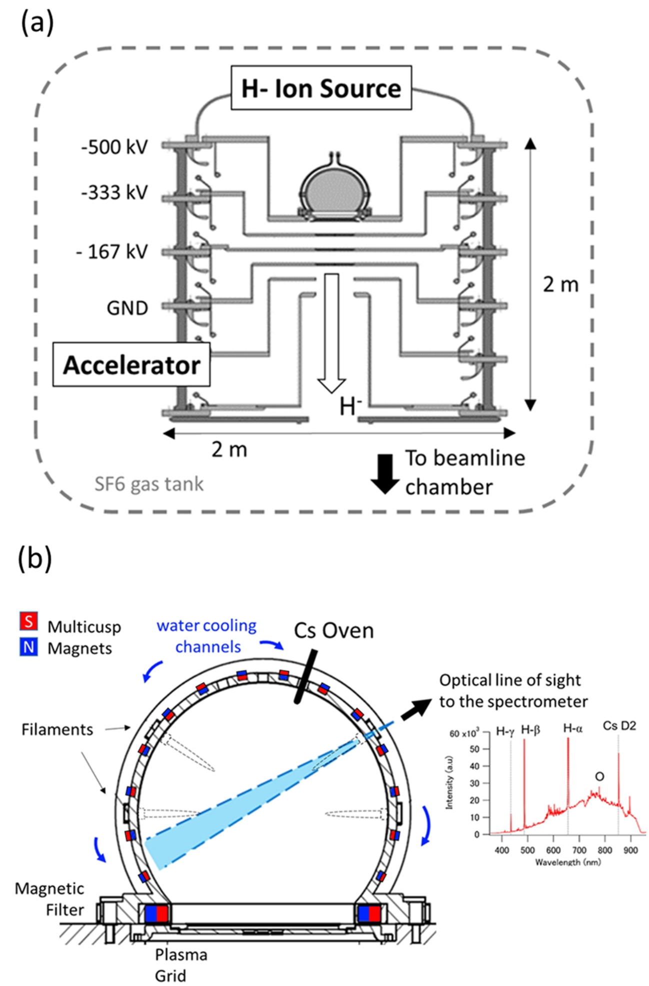

FIG. 2. Experimental setup of the H^- negative ion beam system: (a) schematic diagram of the ion source and accelerator and (b) multi-cusp H^- ion source.

capacity including the cooling capacity between these two chambers is almost identical because of their structural properties: thickness of chamber wall, distances between the multi-cusp magnetic field configuration, and the position of the cooling channels. The similarities of these ion sources allow the comparison of the small-scale chamber to the large chamber for JT-60SA, including the results of the experiment in the viewpoint of temperature dependence.

To monitor the negative ion current, the ion source is coupled to the top of the three-stage accelerator. As the produced H^- ions are extracted by a plasma grid with nine apertures with 14 mm diameter, the accelerated beam of up to 0.5 MeV is measured by a beam dump positioned at the downstream region along the beamline. The operational parameters for the ion source are listed in Table I.

In this experiment, Cs vapor is continuously injected into the ion source and the plasma conditions are monitored through optical emission spectroscopy having a 0.2 nm wavelength resolution, a sampling rate of 35 ms, and the line of sight directed to the plasma region. The emission lines of Cs neutrals (852 nm), Cs ions,

TABLE I. Operational parameters for the arc discharge.

Number of filaments	5
H2 gas pressure	0.3 Pa
Arc power	20 kW–30 kW
Cs oven temp	180 °C
Plasma grid temp	200 °C
Acceleration voltage	500 kV

hydrogen Balmer lines, and oxygen were examined as the H^- beam was operated with pulse widths of a few seconds, extending up to more than 60 s. The Cs D2 emission line relates to the Cs neutral density for plasma conditions if the arc power is held constant, and that emission line was measured experimentally during the entire experiment period to understand the behavior of the Cs neutrals during the long pulse beam operation.

OPTICAL EMISSION MEASUREMENT OF Cs NEUTRALS DURING ARC DISCHARGE

The Cs line emissions were monitored from the initial stage of the experimental period with Cs injection into the ion source at constant oven temperatures at around 180 °C. Two pulse schemes were operated: short pulses for beam conditioning that last for less than 5 s and the operation for long pulses that extend up to 100 s. Measurements of the Cs emission line for the two schemes are shown in Fig. 3 where short pulses followed the similar growth in the measured intensities as for long pulses. The Cs D2 emission intensity continued to increase for around 10 s, much longer than the width of the short pulse. The difference in the attained peak intensities between the two pulse schemes is that long pulses continue to rise but eventually saturates. However, the input arc discharge power showed a rapid ramp up within a few seconds and exhibited a stable signal. This suggests that the observed changes in the Cs emission intensities are not due to any changes in the plasma condition.

To understand the variation in the Cs neutral flux to the plasma region for longer pulse lengths, it is important to study the measured Cs emission intensity which can be simply described as

$$I_{Cs} \approx P_{arc}[I_{Cswall}(T_{wall}) + I_{Csoven}(T_{Csoven})], \quad (1)$$

where the emission intensities are contributions from the I_{cswall}, Cs flux from the chamber walls, and I_{csoven}, Cs injected from the oven. Both components are dependent on the temperature conditions of the wall and Cs oven and also on the input arc power in the ion source.

As the arc discharge power input to the source affects the plasma density, the behavior of the Cs emission was examined for the varying arc power conditions with an integrated amount of injected Cs vapor of 1 g. The relation of the Cs emission intensity to the wall temperature is shown in Fig. 4(a). This graph shows that the Cs D2 changes according to the wall temperature.

To analyze further the detected emission signals, the Cs D2 emission was measured under different Cs injection conditions shown in Fig. 4(b). The emission light for both conditions, with and without Cs injection, showed a linear relation to the arc power discharge. The emission signal with Cs injection had stronger intensities, and an offset is observed from the measured signals without Cs injection. Therefore, the observed Cs D2 emissions are dominated by the Cs flux from the chamber wall surfaces, and the Cs from the oven only adds a constant intensity from the baseline of the emission signals.

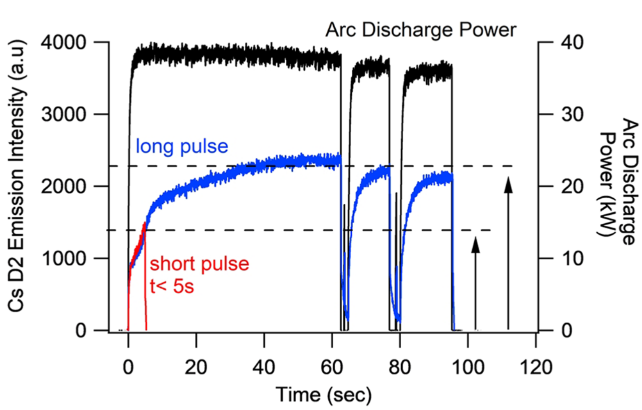

FIG. 3. Cs D2 emission intensities for long and short pulse schemes with arc power at 28 kW and an integrated amount of injected Cs vapor at 0.7 g.

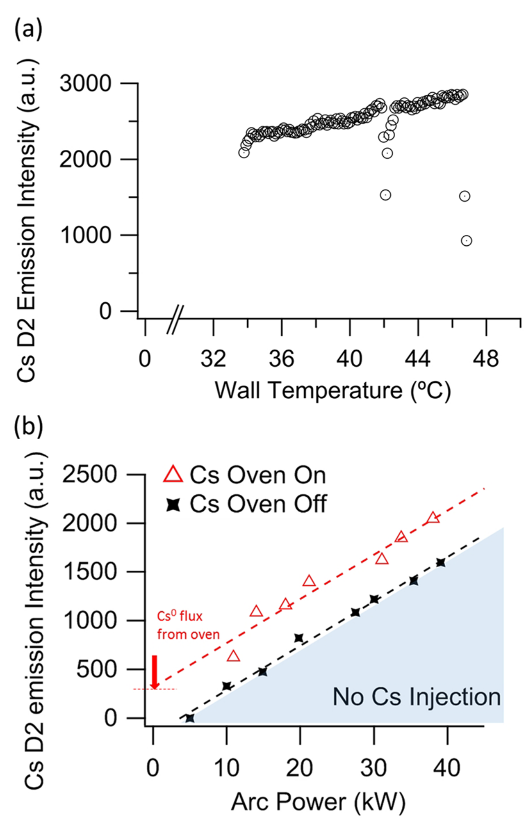

FIG. 4. Cs D2 emission intensities with varying input arc power at a Cs amount of 1 g with (a) chamber wall temperature and (b) different Cs injection conditions.

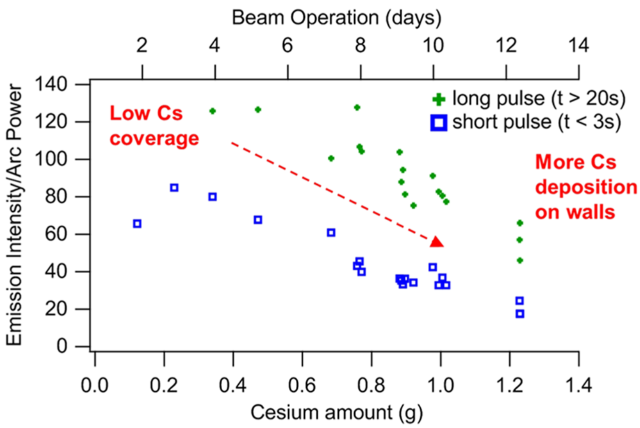

FIG. 5. Progression of the Cs D2 emission intensities with continuous Cs injection for the duration of beam operation.

Since the peak intensity of the Cs D2 emission line continue to rise depending on the accumulated chamber headload and chamber wall temperature, the cooling capacity was increased to sustain low temperatures on the chamber wall surfaces. The progression of the Cs emission intensity in the plasma region with respect to the amount of Cs injected into the source during the experiment period is shown in Fig. 5. The emission intensities for short and long pulse schemes were examined as cesium was continuously injected into the system and both pulse schemes were measured under the same arc conditions. The two beams with short and long pulse schemes were operated consecutively to keep the discharge conditions as similar as possible. The difference in the emission intensity of the two pulse schemes shows the increase in Cs neutral density in the plasma region during the attempt of the long beam pulse operation. In the beginning of the experiment with a small amount of injected Cs vapor, the measurement in the plasma region shows strong emissions and the peak emission intensities eventually decreased as beam operation continued with up to 1.2 g of the accumulated Cs amount. With Cs being injected into the source at a constant rate, the decrease in the Cs emission indicates the possibility of Cs transport to other parts inside the source such as the cold surface spots, supporting structures, plasma grid, extractor, and even the accelerator. The strong Cs emission intensity is also a possible tendency of Cs behavior during the operation of H^- beams for long pulses as the pulse widths exceed 100 s since the Cs dynamics have not been completely clarified. However, with the lower temperatures of the chamber wall caused by the improvement of the chamber cooling system, there is likely the accumulation of Cs deposited on the wall surfaces inside the chamber as more Cs vapor is injected into the source. The behavior of Cs during the operation of long pulse beams should be carefully analyzed, and a more detailed investigation on long pulse schemes will be performed to clarify this phenomenon.

LONG PULSE H^- BEAM OPERATION

In previous experiments for the beam production of 100 s, a large semi-cylindrical magnetic multi-cusp ion source with 68 cm diameter and 110 cm length was operated with the injection of Cs.[3] It was reported that beam current degradation started at around 60 s and was reduced by 30% for 100 s. The variation with time corresponded to a large increase in the Cs line emission. During the H^- operation with long arc discharges, chamber wall temperatures reached up to 90 °C as the Cs emission intensity greatly increased. This suggests that the Cs is redistributing inside the ion source and a large amount is moving toward plasma region since the temperature rise of the chamber walls can lead to the evaporation of Cs deposited from the surface. If this speculation is correct, temperature control is necessary to manage the Cs evaporation from the surface and the stable Cs on the PG during long pulse operation.

By enhancing the cooling capability of the ion source chamber walls, suppression of the excessive evaporation of Cs neutrals to the plasma is possible. Improvements on the water-cooling system of the ion source were applied to the chamber walls, and the time-evolution of the Cs D2 emission signals during the pulse with the corresponding wall temperature is shown in Fig. 6.

The Cs neutral emission continued to increase and then saturated after 40 s of the discharge operation. The modification of the chamber cooling system allowed the wall temperature to remain below 50 °C even for long operation of arc discharges of up to 100 s. The Cs neutral emission intensity was observed to produce more steady signals. The flux of Cs neutrals was conserved as the Cs emission became constant. The redistribution of Cs in the source chamber could be managed during the long discharge as the suppression of the wall temperature rise was sufficient to limit the movement of Cs neutrals toward the plasma region.

With the Cs neutrals in the plasma volume showing a stable signal during long discharges, the response of the H^- beam current was analyzed with the Cs neutral emission during the beam operation with high current densities. One of the results of the 100 s class beam acceleration at 0.5 MeV is shown in Fig. 7(a) where the time evolution of the Cs D2 emission line almost saturated at around 60 s. The corresponding generated beam current density was measured in the acceleration power supply where the major part of the

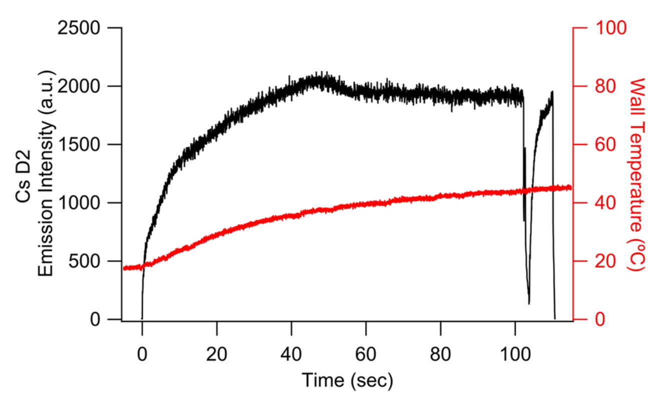

FIG. 6. Measurements of the chamber wall temperature and Cs D2 emission during a long pulse operation with the improvement of the cooling system.

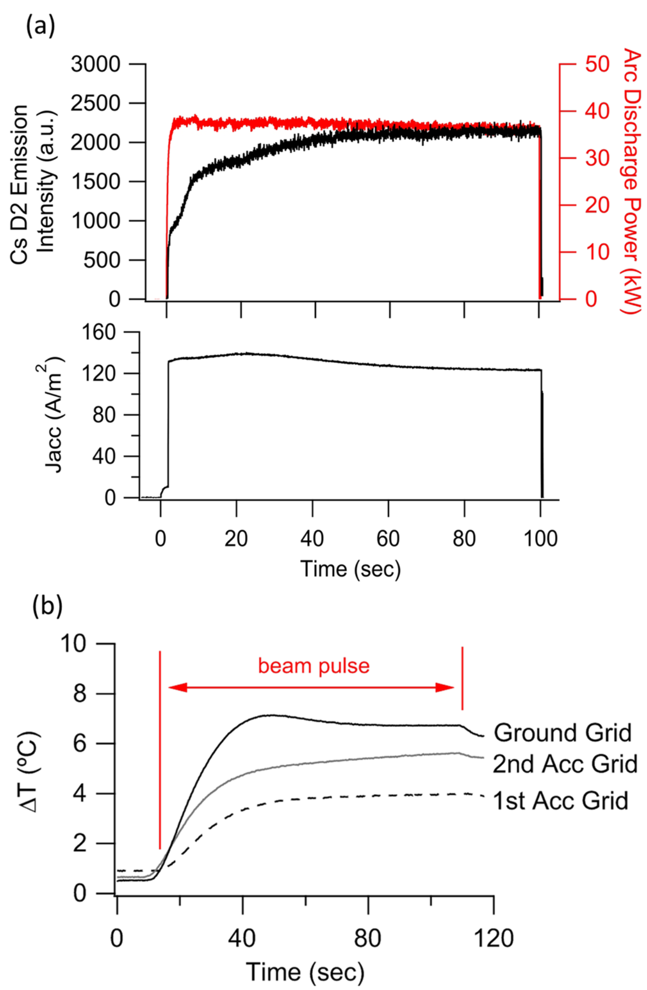

FIG. 7. Long beam pulse operation for 118 s with a high current density of 154 A/m^2 and the measurements of (a) the Cs D2 emission line and the arc discharge power and (b) the heat loads on the accelerator and ground grids.

current is due to the current of the extracted H^- beam. The current density was slightly decreased within the allowable value of 10% because the PG temperature increased from 200 °C to 300 °C during the 100 s beam. The beam current almost saturated and did not degrade drastically as observed in the previous experiment. To confirm the condition of the negative ion production, the heat loads on the grids by water calorimetry were also measured in Fig. 7(c). The calorimetric signals on the acceleration and ground grids were almost saturated, and the variation during 100 s was also less than 10%. These results showed that the negative ion production was successfully kept constant within the variation of 10%, which satisfy the design requirement. Finally, for the long pulse operation, the generated beam demonstrated a stable current density of 154 A/m^2, extending to more than 100 s. The current density variation during the beam production remained lower than 5% and is within the acceptable requirement.

During the experiment where the emission signals were monitored during beam production, the large variation in the Cs flux toward the plasma region and the fluctuations in the beam current were reduced as long pulse beams with high current densities were achieved. Controlling the source wall temperatures to remain below 50 °C resulted in the suppression of the Cs flux in the plasma region as observed in the Cs D2 emission signal during the long beam pulse operation. This suggests the influence of the temperature control in the ion source, and optimizing the cooling system will manage the amount of Cs neutrals in the plasma to achieve stable beam current operation especially for longer periods even greater than 100 s.

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