# Demonstration of 500 keV beam acceleration on JT-60 negative-ion-based neutral beam injector

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**Abstract**. Hydrogen negative ion beams of 486 keV, 2.8A and 507 keV, 1A have been successfully produced in the JT-60U negative ion source with multi aperture, multi grid accelerator of three stages. This is the first accomplishment of the $H^-$ beam acceleration up to 500 keV at high-current of > 1 A. These successful productions of the high-energy beams at high current have been achieved by overcoming a poor voltage holding of the large negative ion sources with the grids of ~2 $m^2$. To improve voltage holding capability, the breakdown voltage for the large-area grids has been carefully examined by changing the gap lengths. It was found that a vacuum insulation distance for the large-area grids was quantified to be 6-7 times longer than that for the small-area electrodes (0.02 $m^2$) utilized for the vacuum insulation design of the JT-60U negative ion source. From this result, the gap lengths have been tuned to sustain 600 kV with the margin of 20% to the rated value of 490 kV under the condition that the good beam optics is sustained in calculation. This improvement realizes a stable voltage holding and a short conditioning time. In the beam acceleration tests, the stable voltage holding is also confirmed. Moreover, no degradation of the beam optics and stripping loss has been actually confirmed. These results indicate that the high energy multi-stage accelerator with multiple grids is feasible for JT-60SA and ITER by tuning the gap length.

## 1. Introduction

A negative-ion-based neutral beam injector (N-NBI) for JT-60SA is designed to inject 500 keV, 10 MW and 100 s $D^0$ beams with two large negative ion sources, each of which accelerates 500 keV, 22 A negative ion beams [1-2]. The negative ion beams are accelerated through multiple apertures and grids accelerator (MAMuG) with three acceleration stages. The MAMuG type accelerator has been also chosen as the baseline design for the 1 MeV, 40A ITER ion source with five acceleration stages [3] whose dimensions are similar to the JT-60 negative ion source. In both of the accelerators, the large size grids of 2 $m^2$ are designed to produce high current and high energy negative ion beams.

In JT-60U, the negative ion source has been modified to fulfill the rated performance since completion of the JT-60N-NBI in 1996. In the period of 2006-2008, the grid heat load was reduced to an allowable level by tuning the beam steering angles, resulting in achievement of the long pulse injection up to 28.9 s at a $D^0$ injection power of 3 MW as reported in last conference [4-5]. The heat load of the ion source and beamline components is concluded to be removed using existing water cooling capability even for 100 s injections in JT-60SA. In 2008-2010, a significant effort to improve voltage holding capability of the ion source has been made to increase the injection power since the injection power was limited by poor voltage holding capability in the past operation. The achieved beam energy was no more than 416 keV and 80% of the rated value. In the past, the improvement of the voltage holding

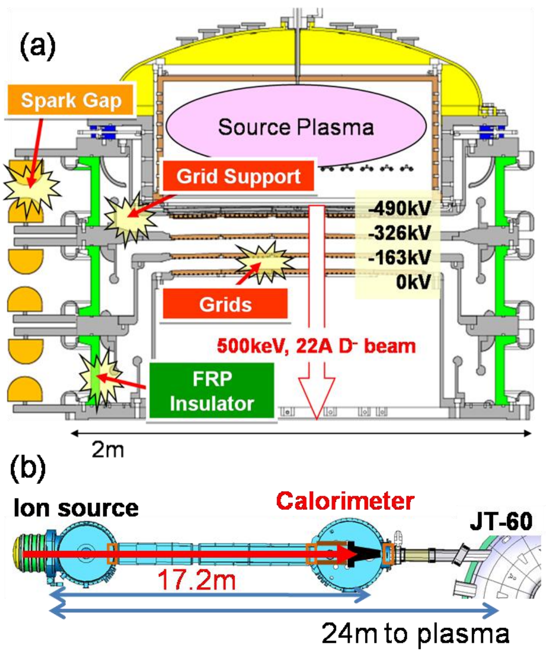


*FIG.1. (a) Negative ion source on JT-60U with three-stage MAMuG accelerator. The diameter is about 2m. The rated acceleration voltage is 490 kV. 163 kV for each stage is required. (b) Schematic view of the beam line for N-NBI.*

capability was tried by installing large stress rings for suppressing surface flashover on the Fiber Reinforced Plastic insulators [6]. However, voltage holding capability has not been improved to the rated voltage [7]. After that, the interior of the ion source during and after high voltage application were carefully observed through CCD camera. This revealed that discharges during high voltage application occurred in a gap between acceleration grids. From the results, the breakdown in a gap between the acceleration gaps was suspected although the gap length between the acceleration grids has been believed to be large enough to sustain high voltage for a long time.

From this result, the gap extension was decided to improve the voltage holding capability. However, an excess gap extension over-reduces the acceleration electric field, which results in the beam expansion due to space charge of the ion beam. In addition, the longer gap gives the higher stripping losses of the negative ions by collisions with residual gas molecules in the accelerator. Therefore, the gap lengths should be optimized to satisfy these requirements. The shortest gap length between the acceleration grids in the JT-60U ion source was originally designed to be 55 mm from the results of quasi-Rogowski electrodes with small area (0.02 $m^2$) where 400kV is applicable in a 55 mm gap [8]. However, the actual grids in the JT-60U ion source are two orders of magnitude larger than the small-area electrode and also have a local electric field concentration. The vacuum gap insulation is not well understood, and hence no databases are applicable to the design of the JT-60U negative ion source. Then, the vacuum gap insulation has been investigated by changing the gap length in the JT-60U ion source, and the ion source was modified to improve the voltage holding capability. After the modification of the ion source, voltage holding capabilities with and without beam acceleration were examined, and then the beam acceleration was tested. In this paper, the latest experimental results on the development of the JT-60SA negative ion source are

| | **JT-60U achievement** | **JT-60SA requirement** |
|---|---|---|
| Beam Energy | 416 keV(0.48 s) before 2008<br>500 keV(0.8 s) in 2010 | 500 keV |
| Beam Current<br>Current density | 17.4 A<br>120 A/$m^2$ | 22 A<br>130 A/$m^2$ |
| Pulse Length | 28.9 s (345 keV) | 100 s |

*TABLE I. Achievements on JT-60U negative ion source and requirements for JT-60SA negative ion source.*

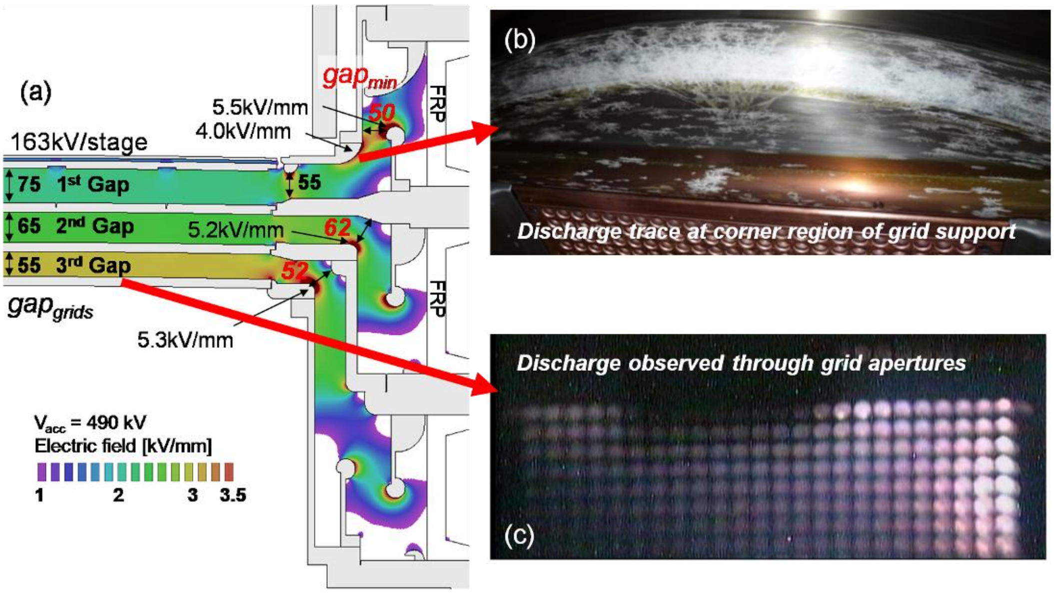


*FIG.2. (a) Result of electric field analsis in the original configuration at acceleration voltage of 490 kV. $gap_{grid}$ of $1^{st}/2^{nd}/3^{rd}$ gaps is 75/65/55 and $gap_{min}$ is 50/62/52. Trak/ESTAT@Field precision is used for this analysis. (b) Photograph of the discharge mark at the corner region of the grid support in $1^{st}$ gap cathode at which electric field is 4 kV/mm. (c) Photograph of the discharge between the acceleration grids at the breakdown.*

reported.

## 2. Voltage holding capability of large-area grids

FIG. 1 shows the schematic diagram of the JT-60 negative ion source. The negative ions are produced in KAMABOKO source [9] and then accelerated in multi-stage accelerator. Large stress rings are installed to suppress electric field at triple junction of vacuum, metal, Fiber Reinforced Plastic insulator. There are three acceleration stages, in which the shortest gap length between the acceleration grids is originally designed to be 55 mm and the minimum gap length $gap_{min}$ is located at the corner region as shown in FIG. 2(a). The discharges was observed in the strong electric field area as shown in FIG. 2(b)(c).

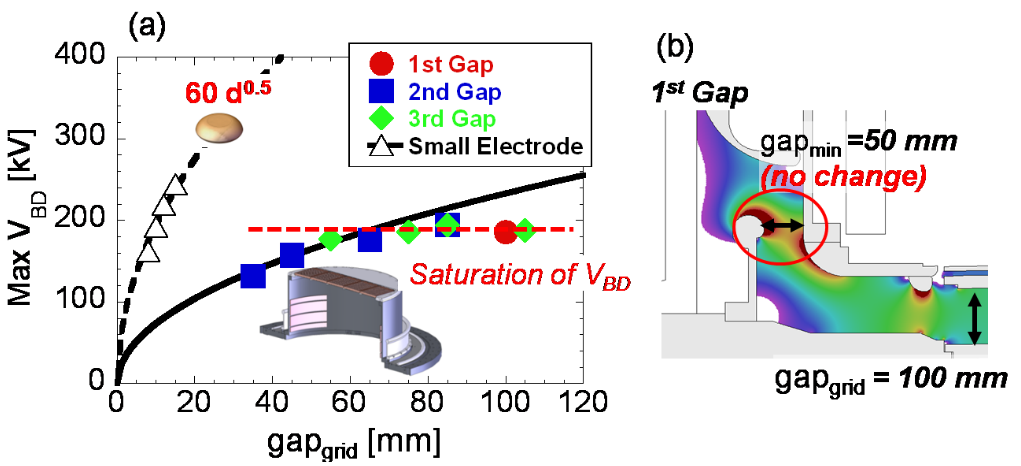


*FIG.3. (a) Relation between $gap_{grid}$ and highest $V_{BD}$ for the small-area grid and the each acceleration stage of the large-area grids at the pressure of $1\times10^{-4}$ Pa. (b) Electric field analysis of the corner region of $1^{st}$ gap with $gap_{grid}$ of 100 mm. $gap_{min}$ of 50 mm does not vary even if the gapgrid is extended.*

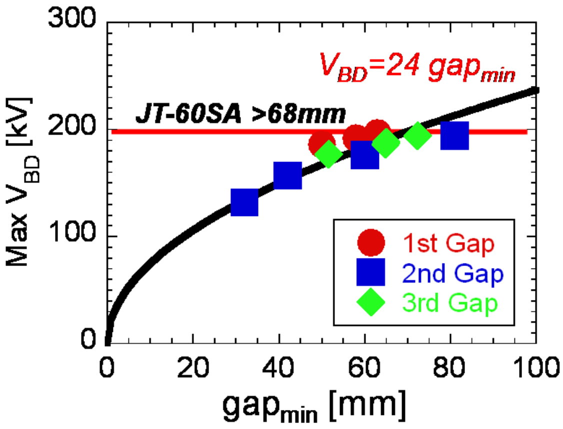


*FIG.4. Relation between $gap_{min}$ and highest $V_{BD}$ for each acceleration stage of large-area grids at the pressure of $1\times10^{-4}$ Pa.*

To quantify the required vacuum insulation distance, the gap length in each of acceleration stage was varied within the structure restriction of the accelerator. High voltages were applied to each acceleration stage at pressure of $1\times10^{-4}$ Pa. After a sufficient conditioning of the ion source, the relations between the highest breakdown voltage ($V_{BD}$) and $gap_{grid}$ have been measured as shown in Fig. 3(a), where voltage holding of small-area electrode is also indicated for reference. Both voltage holding capabilities of the JT-60U ion source and small-area electrode increases with $gap_{grid}^{0.5}$. This shows that voltage holding capability obeys Clump theory [10]. However, the voltage holding capability of the JT-60U ion source was twice lower than the small-area electrode, for which the large-area grid required much longer distance to sustain the same voltage as the small-area electrode. In addition, $V_{BD}$ of the JT-60U ion source was saturated in the range of $gap_{grid}$ > 70-80 mm. The voltage holding capability in this range was determined by the $gap_{min}$ at the corner region of the grid supports which was kept to be 50 mm even for the longer $gap_{grid}$ as shown in FIG. 3(b). This result suggests that $gap_{min}$ is a dominant factor to sustain high voltage especially for the JT-60U ion source.

From these understanding, $V_{BD}$ is plotted as a function of $gap_{min}$ in order to estimate the required $gap_{min}$ for the stable sustainment of the rated voltage per single stage as shown in FIG. 4. Based on this relation, $gap_{grid}$ has been redesigned so as to insure that $gap_{min}$ within the grid support is adequate to hold high voltage > 200 kV for each acceleration stage as shown in FIG. 5. A safety factor of 1.2 for stable holding of 490 kV is taken because the voltage holding capability with the beam acceleration are experienced to be 90% of that without beam acceleration in the past operation. All $gap_{grid}$ of 85 mm has been tentatively chosen to examine the beam acceleration with the longer gaps without the significant modifications of the existing accelerator structure. These tentative $gap_{grid}$ extensions have been also confirmed not to affect the beam optics and stripping loss from the results of the beam calculations because the extension of 1st $gap_{grid}$ is no more than 10 mm which is almost negligible for those issues.

After tuning gap lengths, voltage holding of the JT-60U ion source has been dramatically improved and stabilized. Without beam acceleration, each acceleration stage has sustained 200 kV which is higher than the rated voltage per single stage on the JT-60U ion source and comparable to that for the ITER ion

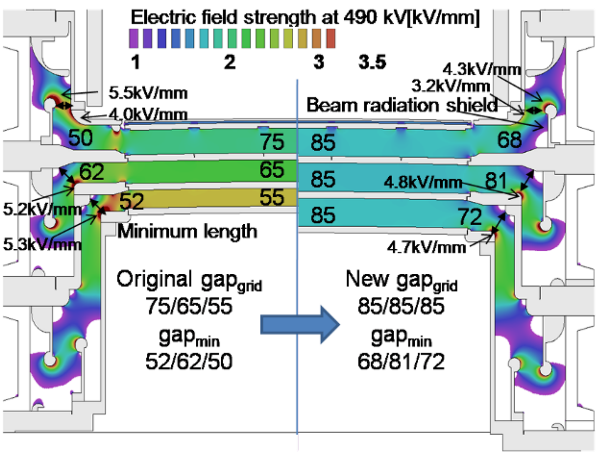


*FIG.5. Result of electric field analysis before and after the modification. $gap_{grid}$ is adjusted from 75/65/55 to 85/85/85 in order to ensure the modification of $gap_{min}$ from 50/62/52 to 68/81/72. The new beam radiation shield was installed at 1st gap.*

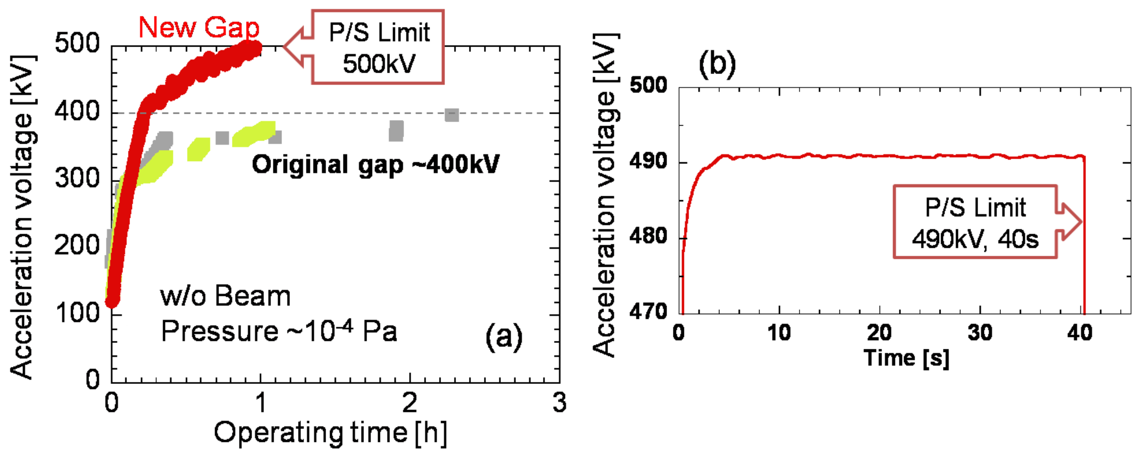


*FIG.6. (a) Result of voltage conditioning with three-stage for the new gap and the original gap, where conditioning time denotes the integration of the operation of the acceleration power supply. Conditioning was carried out without beam acceleration and at pressure of about $1\times10^{-4}$ Pa. (b) Waveform of long pulse sustainment of the rated acceleration voltage of 490 kV for 40 s. The pulse length was limited by the temperature increase of the breeder resistor in the acceleration power supply.*

source. The acceleration voltage of the JT-60U ion source in vacuum has been improved from 400 kV to > 500 kV which is limited by the acceleration power supply as shown in FIG. 6(a). This modification has also reduced conditioning time. In addition, the rated voltage of 490 kV has been sustained for 40 s which is limited by the acceleration power supply as shown in FIG. 6(b). As for the voltage holding without beam acceleration, the extension of the pulse length is feasible, because no degradation of the voltage holding capability due to the pulse extension has been observed [10].

Since the overall design of the ITER megavolt accelerator is conceptually similar to that of JT-60, obtained results suggest that the gap tuning overcomes the critical issues of the vacuum insulation in JT-60SA and ITER ion sources.

## 3. 500 keV beam acceleration with the N-NBI

After the improvement of the voltage holding capability, the acceleration of $H^-$ ion beams have been tested through 216 apertures corresponding to 20 % of total 1080 apertures for 0.8 s. The reduction of the extracting apertures and short pulse length were due to the electricity limits on the test facility because JT-60U was already shutdown. The beam current through 20% of the ion extraction area was expected to be 4.4 A corresponding to the rated beam current density of 130 $A/m^2$. After the sufficient conditioning of the acceleration voltage and production of arc plasmas for 1.3 hour, 500 keV, 1 A beams have been obtained stably without the cesium seeding as shown in FIG. 7(a). After seeding cesium to enhance the negative ion production, the $H^-$ ion current has been increased up to 2.8 A without any degradation of the voltage holding capability. In this beam acceleration test, the extracted current has been unfortunately limited by a trouble of the ceramic feed-through for the extraction voltage. The highest beam energy of 507 keV at beam current of 1 A and highest beam current of 2.8 A at beam energy of 486 keV have been achieved as shown in FIG. 8. These results are the first achievements of the beam acceleration over 1 A up to beam energy of 500 keV. The beam current has been measured with the calorimeter as shown in FIG. 7(b) which is installed at 17.2 m downstream from the ion source as shown in FIG. 1(b). From the

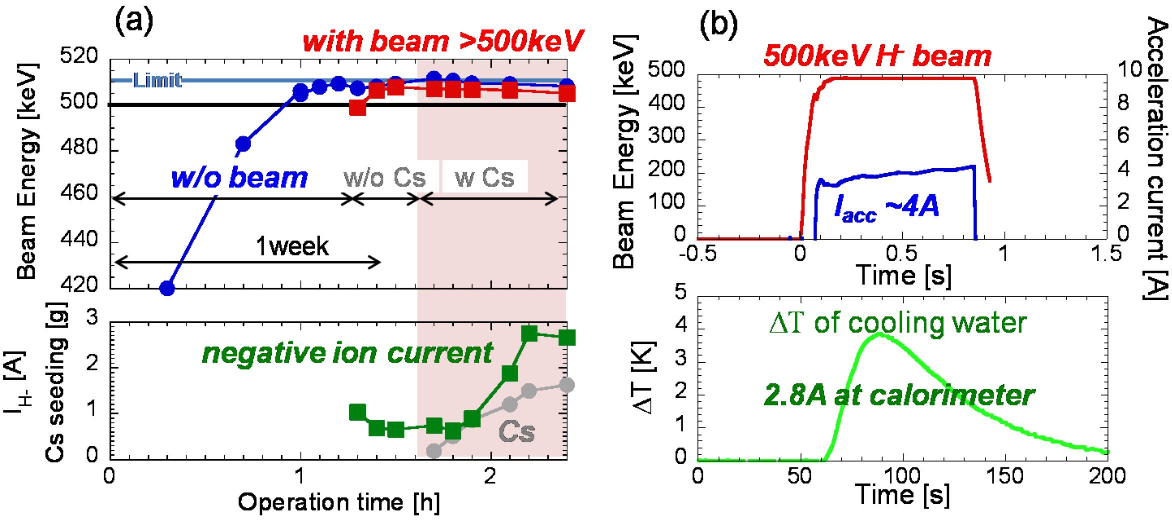


*FIG.7. (a) Results of the conditioning for the beam acceleration. At first, the acceleration voltage was increased without beam and then, arc plasmas were produced without cesium seeding. Finally, the high energy beams were produced with enhancement by seeding cesium. The beam acceleration was carried out by using the extraction area of 20% due to the electricity limitation. (b) Waveform of the 500keV, 2.8A beam acceleration where $I_{acc}$ denotes the acceleration current. $H^-$ current was estimated from the temperature increase of the cooling water for the calorimeter which was installed at 18 m downstream from the ion source (see Fig. 1(b)).*

acceleration efficiency of 70%, the produced beams are confirmed to have as small beam divergence angle as before the modification.

The issues for the gap extension, i.e, the beam optics and the stripping losses of the negative ions have been quantified. The degradation of the beam optics due to the gap extension might enhance the direct interception of the negative ions with the intermediate grids. The increase of the stripped electrons from the negative ions due to the gap extension increase with the gap length. These degradations result in higher heat load. In order to investigate these issues, the grid heat load after the gap extension was measured by changing the pressure in the arc chamber, and compared with that before the gap extension. FIG. 9(a) shows the heat load of the grounded grid as a function of the source pressure. The grid heat load is normalized by acceleration beam power. The grid heat loads before and after the gap extension increases linearly with the source pressure. There is no significant difference between the grid heat loads before and after gap extension. From this result, increases of both the direct interception and stripping loss of $H^-$ beams were found to be negligible in the longer gap as confirmed with both the experiments and calculations. As a result, it was found that adequate gap tunings

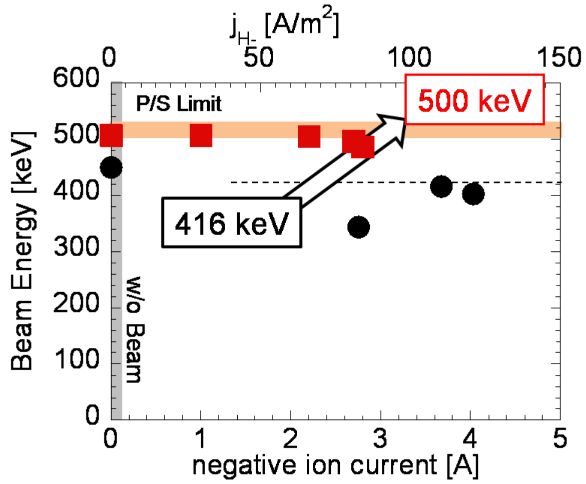


*FIG.8. The progress of the beam acceleration toward the JT-60SA ion source. The beam energy has increased from 416 keV to 507 keV at which the acceleration and extraction power supplies are marginal.*

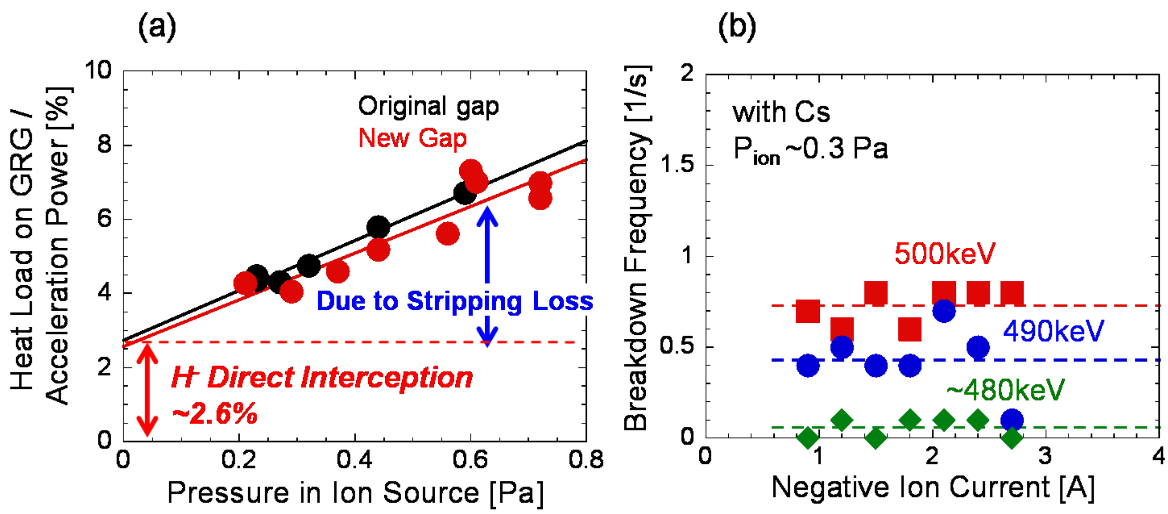


*FIG.9. (a) Relation between the heat load on the grounded grid and the pressure of the arc chamber. By extrapolating the relation to zero pressure, the crosspoint denotes the direct interception of $H^-$ beams. Typical operational pressure is 0.3 Pa. (b) Breakdown frequency from 480 keV to 500 keV obtained at the pressure of 0.3 Pa with seeding cesium.*

enabled the improvement o the voltage holding without any degradation of the beam performance. From the viewpoint of both the voltage holding capability and beam performance, the extension of $gap_{grid}$ in a range up to 85 mm is applicable to the JT-60SA ion source.

The feasibility of the stable acceleration was investigated by measuring the breakdown frequency of high energy beam under the different $H^-$ current and beam energy as shown FIG. 9(b). The breakdown frequency is defined as the number of the breakdowns per the actual beam pulses. The variation of the $H^-$ current corresponds to the change of the heat load on the grids. Although the $H^-$ current was limited up to 3 A, the breakdown frequency did not depend on $H^-$ current in the range of 3 A. These results suggest that voltage holding during beam accelerations has been also improved. In the lower energy than 480 keV, much stable beam acceleration has been achieved even in cesium seeding. Because the achieved voltage is limited by the voltage limit of the acceleration power supply, these breakdown probabilities are expected to be reduced by the conditioning with higher voltage.

## 4. Summary

Based on the results of the recent voltage holding tests, the voltage holding capability of the JT-60U ion source has been improved by tuning the gap lengths. Thus, 500 keV, 3 A class $H^-$ beams have been produced stably without any degradation of the beam performances. In summary, it was found that,

- The voltage holding of the large-area grids (~2m$^2$) is much smaller than the small-area electrodes (~0.02m$^2$).
- By employing the new vacuum insulation scaling with the larg-area grids on JT-60 ion source, appropriate gap tuning is obtained without any degradation of the beam performance.
- Breakdown frequency with beam acceleration does not depend on the beam current up to 3 A. This result indicates that stable beam acceleration is obtained once a stable voltage holding in vacuum is achieved.

The latest results indicate that 500 keV acceleration of the high current negative ion beam is feasible for JT-60SA although the pulse length should be increased from achieved value of 30s to 100s.

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