Status of the Japan Proton Accelerator Research Complex H$^-$ ion source

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A cesium-free H$^-$ ion source driven by a LaB$_6$ filament is being operated for the beam commissioning of the accelerators at Japan Proton Accelerator Research Complex (J-PARC). The beam commissioning started in November 2006. As of June 2008, there have been 17 beam commissioning runs. The duration of each run was approximately 4–5 weeks. In these runs, the ion source has succeeded in providing beam to the J-PARC accelerators for 2720 hours. The interruption time due to the failure of the ion source is only approximately 50 hours. The availability of the ion source is calculated to be 98%. Since the fluctuation of the beam current is small, tuning the beam current once a day is sufficient to maintain the beam current within the error of a few percent. Recently, the ion source succeeded in producing the beam current of 36 mA with a flattop pulse width of 500 μs and a repetition rate of 25 Hz as required for the first stage of J-PARC.

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I. INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a multipurpose facility with a 1 MW class proton beam power [1]. It is located at the Tokai site and is jointly operated by the Japan Atomic Energy Agency (JAEA) and the High Energy Accelerator Research Organization (KEK). The overview of J-PARC is shown in Fig. 1. J-PARC consists of a linac, a 3-GeV rapid cycling synchrotron (RCS), a 50-GeV main ring synchrotron (MR), and experimental facilities such as the Materials and Life science experimental Facility, the Hadron Beam Facility, and a neutrino production facility. In the first stage, a H$^-$ beam with a peak current of 30 mA and a pulse width of 500 μs is accelerated up to 181 MeV by the linac and then injected into the RCS at a repetition rate of 25 Hz.

The beam commissioning of J-PARC linac started in November 2006, and its initial stage was completed in October 2007 [2]. During the commissioning, the linac accelerated the beam of 181 MeV with a peak current of 26 mA. Subsequently, the beam accelerated by the linac was delivered to the RCS in October 2007 [3]. The first neutron and muon beams were produced in May and September 2008, respectively. The neutron beam will be available to users in December 2008. In the beam commissioning of the MR in December 2008, the beam injected from the RCS will be accelerated up to 30 GeV [4]. The 30-GeV beam is planned to be delivered to the Hadron Beam Facility by February 2009, and to the neutrino production facility by June 2009.

The J-PARC ion source has succeeded in providing the required beam during the beam commissioning. In this paper, the detailed structure of the ion source and its performance during the beam commissioning and trial operation are reported.

II. ION SOURCE AND LEBT SYSTEM

Before J-PARC, several types of H$^-$ ion sources were developed at JAEA and KEK independently [5,6]. On the basis of the results of various studies, a cesium-free ion source driven by a lanthanum hexaboride (LaB$_6$) filament was adopted as the ion source for the first stage of J-PARC [7].

A cross-sectional view of the present J-PARC ion source and a low-energy beam transport [LEBT: beam transport line between the ion source and the radio frequency quadruple linac (RFQ)] is shown in Fig. 2. The ion source consists of a cylindrical plasma chamber, a beam extractor, an ejection angle correction (EAC) electromagnet, and a large vacuum chamber with two turbo molecular pumps (TMPs) of 1500 L/s for differential pumping. The LEBT consists of two solenoid magnets, a gate valve, and a diagnostic chamber in which a movable Faraday cup, an emittance monitor, a beam-current transformer, a beam

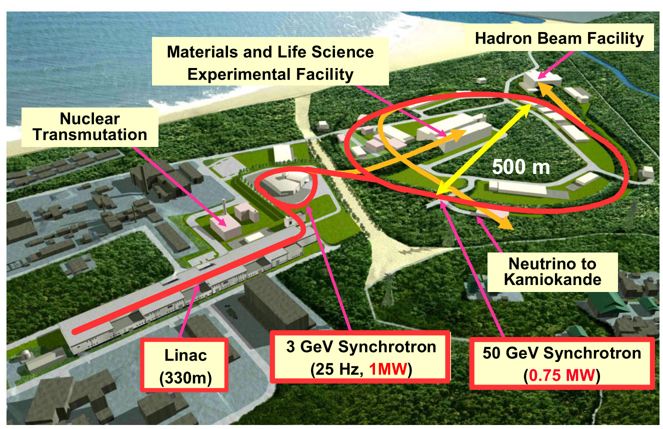

FIG. 1. (Color) Overview of J-PARC.

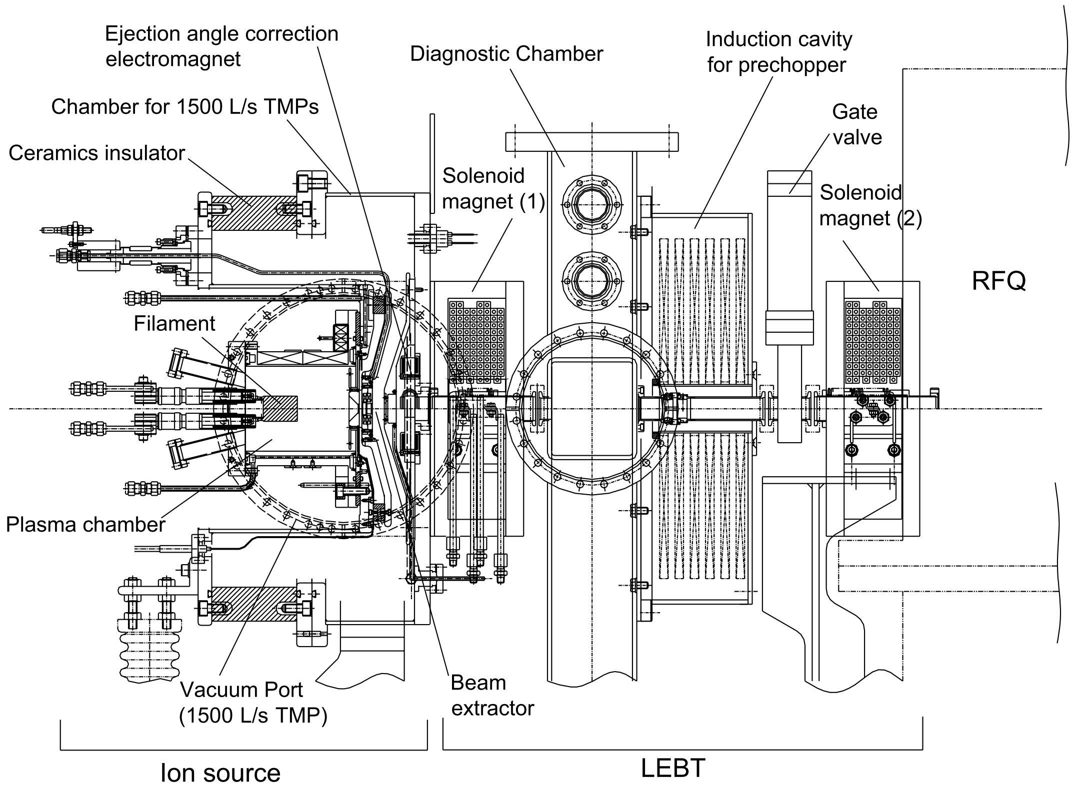

FIG. 2. Cross-sectional view of present J-PARC ion source and the LEBT.

stopper, a vacuum gauge, and two TMPs of 500 L/s are set up. An induction cavity for prechopper installed between the chamber and the solenoid magnet (2) is not used at present.

A. Ion source plasma chamber

Figure 3 shows the detailed layout of the ion source plasma chamber. The plasma chamber is made of oxygen-free copper (OFC). The inner diameter and length of the chamber are 100 and 120 mm, respectively. The source

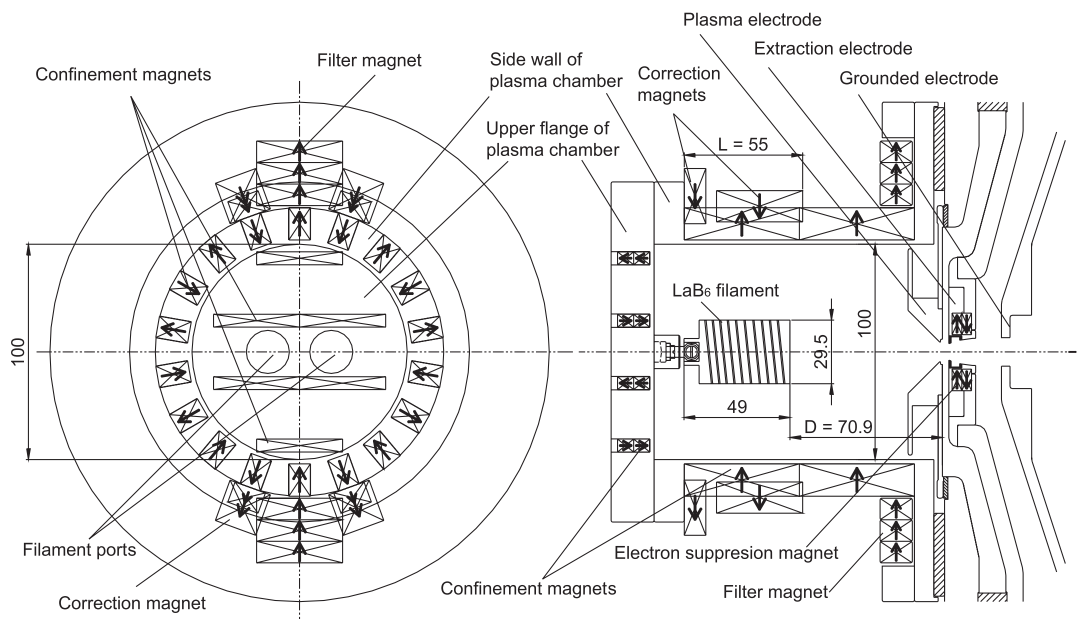

FIG. 3. Detailed layout of ion source plasma chamber.

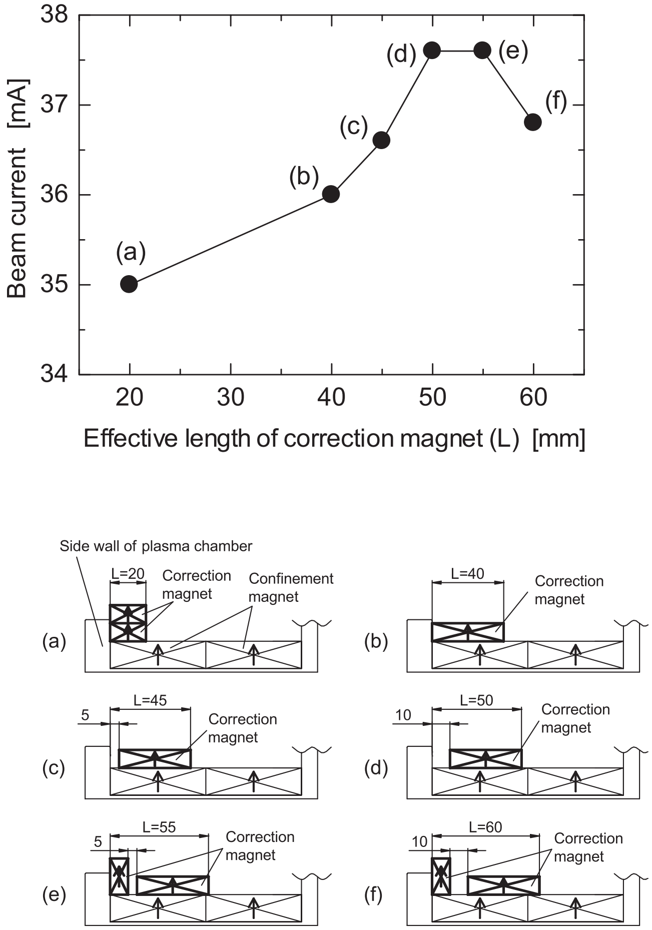

FIG. 4. Dependence of beam current on effective length of correction magnet.

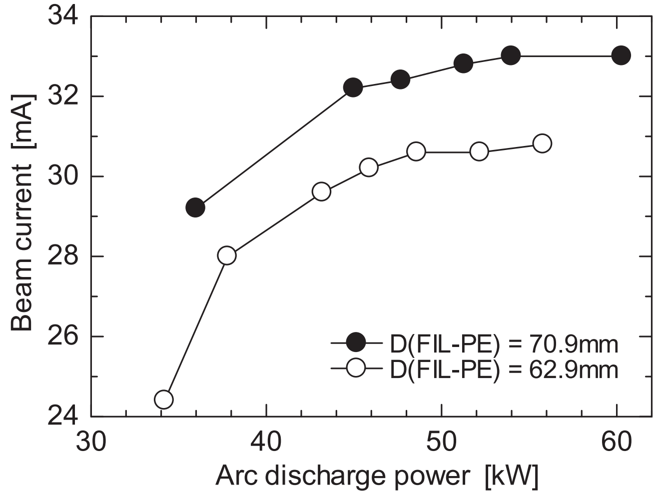

FIG. 5. Dependence of beam current on arc discharge power for different filament positions.

plasma is confined in the chamber by the multicusp magnetic field produced by the 18 rows of Nd-Fe-B magnets and four rows of magnets lining the side wall and the upper flange of the chamber, respectively. Filter magnets, which produce a magnetic filter field, are attached to two of the confinement magnets attached to the side wall near the downstream end. Correction magnets, which produce a field-free region around the filament without changing the magnetic filter field in the extraction region, are attached to four of the confinement magnets attached to the side wall near the upstream end [6,8]. Figure 4 shows that the length of the correction magnets has a significant effect on the beam current; the beam current is maximum when the length of the magnet is around 50 or 55 mm.

The source plasma is produced by an arc discharge using the LaB_6 filament having a cylindrical double-spiral structure (DENKA [9]). The filament was originally developed at KEK and used in the KEK-PS H^- ion source. In order to make high arc power and duty factor operation possible, the diameter, length, and thickness of the filament are gradually increased in the case of three different sources as follows; 15, 42, and 2.25 mm for the KEK-PS source; 20, 45, and 2.50 mm for the JHF source; and 29.5, 49, and 3.25 mm for the J-PARC source, respectively. The distance D between the top of the filament and the beam hole of the plasma electrode (PE) has a significant effect on the beam current. In Fig. 5, the measured beam current is shown as a function of the arc power for two different filament positions. Since the filament supplies high-energy electrons, its position affects not only the density of plasma near the beam hole but also the density of high-energy electrons penetrating the magnetic filter field near the beam hole. Although the plasma density itself is increased and the production rate of H^- ions is also increased by approaching the filament to the beam hole, the simultaneous increase in the density of high-energy electrons leads to an increase in the destruction rate of H^- ions too. There should be the optimum position of the filament. The optimum position of the filament with the present dimensions is at a distance of 70.9 mm from the beam hole of the PE. The longer distance by using a shorter length of filament will be tested in the near future.

B. Ion source beam extractor and LEBT

Figure 6 shows the detailed layout of the beam extractor. The beam extractor consists of three electrodes: a PE, an extraction electrode (EXE), and a grounded electrode (GE). The shapes of the electrodes have been determined by carrying out a two-dimensional beam simulation using BEAMORBT [10]. The 50 keV beam required for the RFQ is produced by applying 10 kV to the extraction gap between the PE and the EXE and 40 kV to the acceleration gap between the EXE and the GE, typically. The H^- ions are extracted from a single aperture with a diameter of 9 mm bored at the center of the PE. The extraction gap length is 3.0 mm. We have optimized the acceleration gap length. Figure 7 shows the relationship between the beam currents measured at the LEBT and at the medium energy

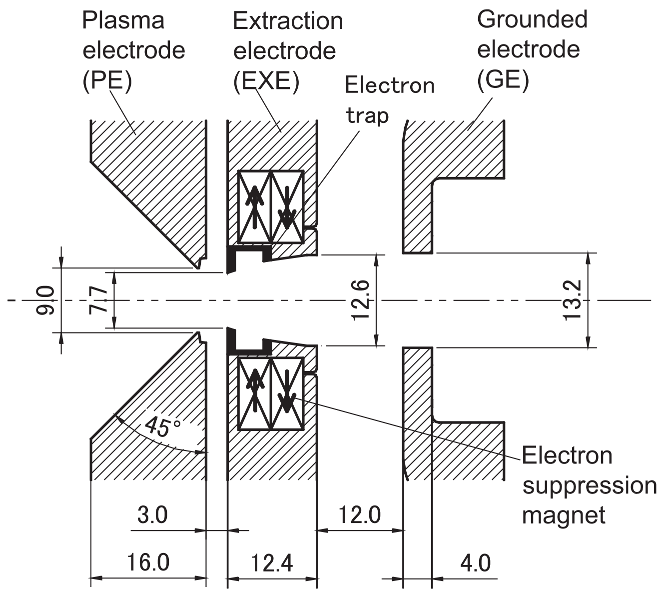

FIG. 6. Detailed layout of ion source beam extractor.

beam transport (MEBT; beam transport line between the RFQ and the drift tube linac) for different acceleration gap lengths. The blue squares, red circles, and green triangles indicate the results for the acceleration gap length equal to 10, 12, and 14 mm, respectively. The dashed lines indicate the beam transmission rate (Trans) through the RFQ, which is defined as the ratio of the beam current at the MEBT to that at the LEBT. From these results, we set the acceleration gap length to 12 mm at which the beam transmission rate through the RFQ is the highest; 90% approximately. The PE is fabricated by boring a 45 degree tapered hole with a diameter of 9 mm on a molybdenum plate with a thickness of 16 mm. The taper angle is optimized in order to produce the highest beam current [6]. The EXE is an OFC plate with a thickness of 12.4 mm. A copper pipe is

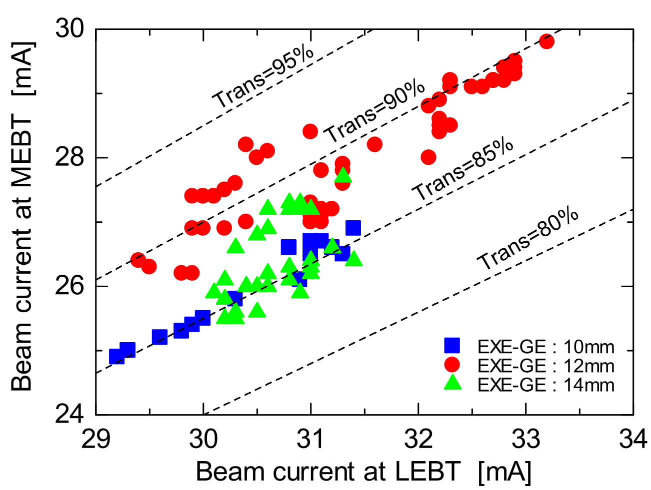

FIG. 7. (Color) Relationship between beam current at MEBT and LEBT for different acceleration gap lengths.

brazed on the EXE and is used as a water cooling channel. Since the beam simulation result shows that the beam divergence angle at the exit of the ion source decreases with the diameter of the beam hole of EXE, we set the hole diameter to 7.7 mm, which is approximately 10% larger than the simulated beam diameter at the EXE surface. Two pairs of Nd-Fe-B permanent magnets are mounted inside the EXE in order to produce a dipole magnetic field which deflects the electrons extracted along with the H^- beam. These magnets are called electron suppression magnets. The deflected electrons are dumped on the electron trap made of molybdenum, which is brazed on the EXE. The GE is fabricated by boring a hole with a diameter of 13.2 mm on a molybdenum plate with a thickness of 4 mm (for 12 mm acceleration gap). A copper pipe is brazed on the base of the GE and is used as a water cooling channel. The base of the GE is made of stainless steel. The ejection angle error mainly produced by the electron suppression magnets is corrected by an EAC electromagnet, which is located just behind the GE. This electromagnet has four poles to deflect the beam both horizontally and vertically [6].

The length of the LEBT is approximately 650 mm. The minimum bore size of the beam duct at the LEBT is 25 mm in diameter. A magnetic focusing transport system that consists of two short and strong solenoid magnets (SM1 and SM2) are adopted for the LEBT because this type of system has been confirmed to be superior for the injection system of the RFQ used to accelerate H^- beams [11]. The solenoid magnets can produce a magnetic flux of 1.1 T. The beam current extracted from the ion source is measured by the Faraday cup or current transformer installed into the diagnostic chamber in the LEBT.

C. Ion source timing sequence

Figure 8 shows the schematic diagram of the ion source power supply system along with the typical operation parameters and timing chart [12]. The source plasma is produced by a pulsed arc power supply. The acceleration voltage is produced by two different types of power supplies; a constant-voltage power supply and a modulation voltage (pulsed) power supply. The former is always turned on during the beam being ready to be extracted. Since the extraction voltage power supply has two field-effect transistor switching circuits, it is capable of pulsed operation. It is usually switched on during the beam being ready to be extracted. In the timing chart of the ion source operation, the turn-on time of the arc voltage is set as the origin (0 μs). The time interval from 0 to 250 μs is the prebeam extraction duration during which the beam energy is less than 40 keV; at this energy level no beam acceleration takes place in the RFQ. The prebeam extraction duration is necessary for the source plasma rise time in the plasma chamber and the rise time of space charge neutralization effect, which is produced by beam plasma formed with

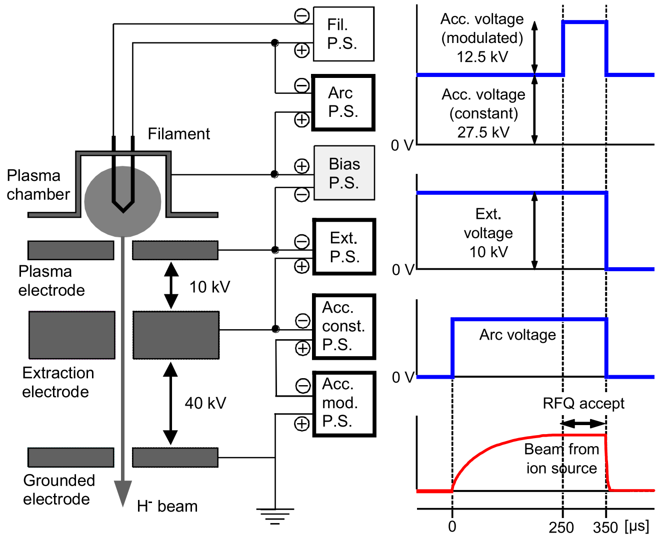

FIG. 8. (Color) Typical schematic drawing of time sequence of ion source power supply.

ionized residual gas in the LEBT. The effect seems to become constant within less than 100 μs [13]. In order to minimize the beam loss in the linac, especially in the high-energy section, the peak current of the beam should be maintained constant for making a matched beam with constant space charge effect. During the prebeam extraction, the beam from the ion source is dumped in the RFQ since the RFQ cannot accelerate such a low-energy beam. We assume that the dumped beam does not damage the RFQ remarkably because the heat load corresponding to the intensity of this beam is only approximately 8 W, even when the ion source is operated at full specifications. After the space charge neutralization effect becomes constant, the acceleration modulation voltage is turned on (at 250 μs in this case). Then, the beam is given the full energy of 50 keV and accelerated by the RFQ. All power supplies

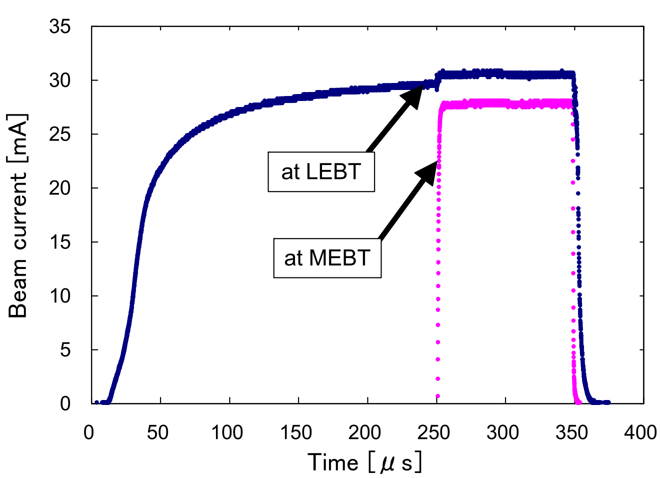

FIG. 9. (Color) Waveforms of beam current measured at LEBT and MEBT.

except for the constant-voltage acceleration power supply are turned off at 350 μs, after which the beam extraction from the ion source is stopped. Figure 9 shows the waveforms of beam current measured at the LEBT and MEBT when the ion source is operated as described above.

D. Ion source system layout

The layout of the J-PARC ion source system is shown in Fig. 10. The ion source and LEBT are placed in a metal shielded room located at the upstream end of the accelerator tunnel, in order to spatially isolate the high-voltage component of the ion source system from the linac area and to confine the switching and rf noises produced by the power supplies of the ion source and LEBT. No one is allowed to enter the tunnel during the operation of the accelerator because of the presence of highly radioactive air in the tunnel. Moreover, entry into the tunnel is allowed only after the radiation level in the tunnel is reduced to a safe level. In order to minimize the downtime of the ion source system, the ion source power supply is placed in a room adjoining the accelerator tunnel. High-voltage cable ducts are laid through the concrete wall between the tunnel and the room. These cable ducts consist of an inner cylindrical pipe with a diameter of 150 mm and made of aluminum and an outer square pipe with sides of length of 600 mm and made of stainless steel. Approximately 30 cables can pass through the inner pipe. In order to apply a high voltage of -50 kV between the inner pipe and the outer one, the inner pipe, located at the center of the outer one, is isolated by using supports made of fiber reinforced plastics (FRP). In order to prevent the leakage of radioactive air into the power supply room, two FRP plates are

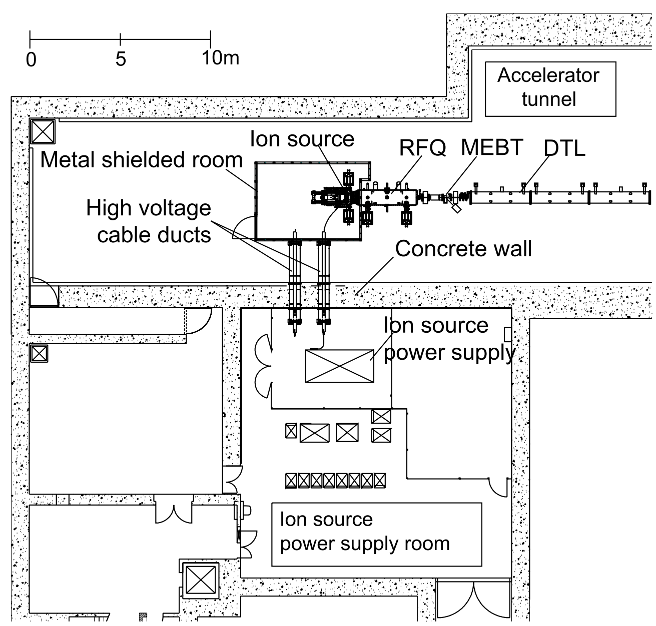

FIG. 10. Layout of J-PARC ion source system.

placed between the inner pipe and the outer pipe. The space between the inner pipe and the plate and that between the outer duct and the plate are sealed using airtight gaskets.

III. ION SOURCE PERFORMANCE

A. Operation history

The operation of the J-PARC ion source started in September 2006. Before June 2008, 17 of the accelerator beam commissioning runs were accomplished. The commissioning was performed during 4–5 week cycles, which consisted of a 3–4 weeks beam commissioning run and a 1–2 week down-period interval. The beam commissioning was usually carried out during the daytime hours (from 9:00 to 21:00). In order to maintain the good condition of the plasma chamber surface, the filament current was turned on and sometimes the beam extraction was carried out during the nighttime hours. During the down-period intervals, we performed maintenance or ion source studies. Total operational time of the ion source was 3350 hours (2720 hours for the beam commissioning and 630 hours for the ion source studies) as of June 2008. Figure 11 shows the operation history of the ion source. The red and blue bars denote the typical beam current during the commissioning and ion source studies, respectively. Since the commissioning tasks did not always require a high peak beam current, the ion source has been operated either at a low current of approximately 5 mA or at a high current of approximately 30 mA.

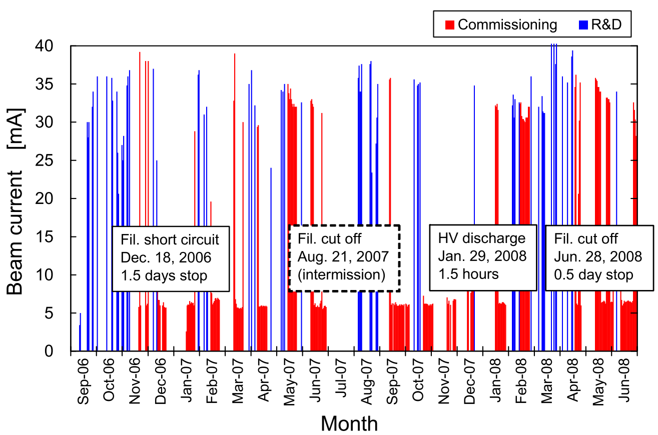

FIG. 11. (Color) Operation history of J-PARC ion source.

B. Operation performance

Table I lists the typical operation parameters of the ion source and LEBT during the beam commissioning in the high current mode. Since the commissioning tasks required a highly stable beam, the ion source was operated at a beam current of 30–33 mA, which is approximately 15% lower than the achieved maximum current of 38 mA [7]. The beam repetition rate was changed frequently during the day depending on the commissioning tasks. To keep the condition of the ion source constant, the repetition rate of the arc discharge was kept constant at 25 Hz, although the beam repetition rate was changed. If beam was not required, the arc discharge was delayed with respect to the time when the extraction voltage was turned off.

The ion source interrupted the beam commissioning 3 times as of June 2008. The first interruption was caused by the filament failure in which the filament shorted. It took 1.5 days to restart the commissioning. The second one was caused by the frequent occurrence of high-voltage dis-

TABLE I. Typical operation parameters of ion source and LEBT during beam commissioning in high current mode.

Parameter	Value
Beam current	32 mA
Beam pulse length/repetition rate	100 μs/1–25 Hz
Arc pulse length/repetition rate	350 μs/25 Hz
Filament heating voltage/current	10.2 V/120 A
Arc voltage/current	147 V/326 A
Arc power	48 kW
Bias voltage/current	8.9 V/41 A
H_2 gas flow rate	17.9 SCCM (SCCM denotes standard cc/ min)
Extraction voltage/current	10 kV/880 mA
Acceleration voltage (constant)	29.7 kV
Acceleration voltage (modulation)	12.5 kV
Ejection angle correction electromagnet (V) voltage/current	1.8 V/ − 6.0 A
Ejection angle correction electromagnet (H) voltage/current	2.1 V/7.0 A
Solenoid magnet (1) voltage/current	11.6 V/511 A
Solenoid magnet (2) voltage/current	13.5 V/592 A
Vacuum pressure in ion source 1500 L/s TMPs chamber	5.9×10^{-3} Pa
Vacuum pressure in LEBT diagnostic chamber	1.1×10^{-3} Pa

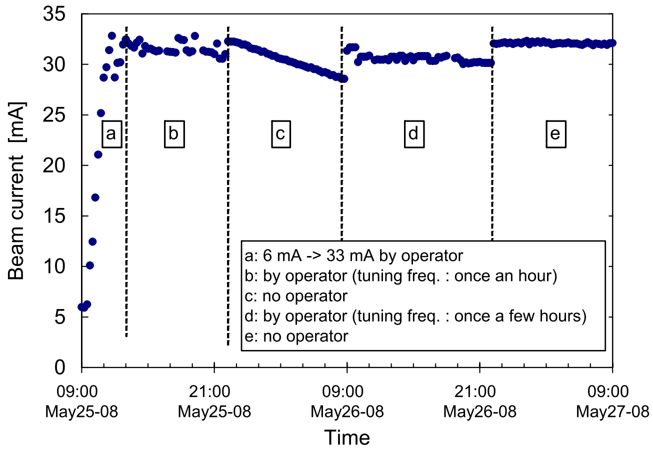

FIG. 12. (Color) Example of change in beam current when mode is changed from low to high mode.

charge at the ceramics insulator of the ion source. The discharge could be stopped by wiping off the dust from the insulator surface. It took 1.5 hours to restart the commissioning. To avoid the same trouble we installed a ventilation system having the HEPA filter in the metal shielded room for the purpose of keeping the air in the room clean. The third one was also caused by a filament failure, but in open circuit. It took 12 hours to restart. Therefore the total interruption time of the commissioning due to the ion source stop was approximately 50 hours; it corresponds to an ion source availability of 98%. The availability is so high in spite of the early operation period. The details of the filament failures are described later.

The high or low beam-current operation mode is alternated once or twice during the beam commissioning runs. Figure 12 shows an example of the change in the beam current when the mode is changed from low- to high-current mode. The mode change started at 9:00 on May 25, 2008, and the beam current increased gradually (region a). At 13:00, the beam current reached 33 mA; however, the variation of the current was large (region b). In order to keep the beam variation within the permitted level, the ion source operator tuned the source parameters such as the filament heating current, the gas flow rate, the bias voltage, and so on, approximately once an hour. The beam commissioning was over at 22:00, after which the ion source was left untouched during the night (region c). The beam current decreased linearly from 32 to 28 mA until the commissioning was resumed at 9:00 on May 26. On the next commissioning day, the variation level became smaller than that on the previous day. As a result, the tuning frequency was reduced to once every few hours (region d). From 22:00 May 26 to 9:00 May 27, the beam current remained almost constant without tuning (region e). Then, the tuning frequency was reduced to once a day.

After each commissioning run, the ion source is overhauled, cleaned, and inspected for any damage to its internal elements. After a long-term operation, the surface of the filament darkened partially. The discolored section is refurbished using a hand grinder since the section cannot emit the electron effectively. The surface of the plasma chamber and the plasma electrode are also polished by using alumina powder. After the ion source elements are reassembled, the ion source is evacuated for approximately 24 hours to allow degassing of the filament. The filament heating current is increased at the rate of approximately 5 A in 10 minutes. When the current reaches the operation level of approximately 130 A, the current is kept constant until the decrease in the vacuum pressure is saturated (which takes approximately one hour). A total time of approximately 6 hours is necessary to accomplish the degassing process. If the filament is brand new or left under the atmosphere for a long time, it has to be prebaked by using a baking stand before mounting it in the ion source. The beam operation is started after the degassing process is over. At the beginning of the operation, the bias voltage, which is the voltage between the PE and the plasma chamber, is usually too high and cannot be set to the optimum value, probably due to the surface oxidation of the PE. Therefore, the surface of the PE is conditioned by applying the maximum bias voltage of 40 V for a few hours. During this process, the PE surface gets cleaned due to positive ion bombardment. Then, the bias voltage is adjusted to the optimum value in order to obtain the beam current required for the beam commissioning.

C. LaB_6 filament issue

The lifetime of the filament is one of the main restrictions for the maintenance cycle of the ion source. Since the maintenance cycle of the ion source is directly related to the operation time of the overall J-PARC facilities, a study has been conducted to lengthen the filament lifetime. As mentioned above, filament failure occurred twice during the beam commissioning as of June 2008. In addition, another failure occurred during the ion source study.

On December 18, 2006, a short circuit between the adjacent turns of the filament led to its failure. The failure was caused by filament deformation due to arc power heating. In order to prevent such failures, the gap between the turns of the filament was increased from 0.3 to 0.6 mm. We have not encountered similar problems since then. On August 21, 2007 (during the ion source study), there was an open circuit filament failure. We assumed that the filament was broken because of the strong mechanical stress due to its inappropriate connection to the support because the filament showed no signs of remarkable consumption. The filament was replaced with a new one with utmost care. This new filament was successfully used in nine commissioning runs until another open circuit failure occurred on June 28, 2008.

Figure 13 shows an image of the broken filament after the open circuit failure on June 28, 2008. The circle in the

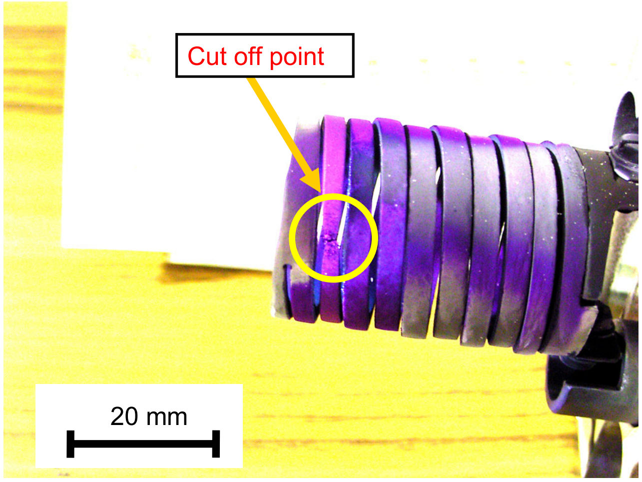

FIG. 13. (Color) Image of broken filament.

figure shows the damaged region. The coil necked gradually toward the cutoff point. In order to understand the mechanism of the cutoff process, we examined the damaged region in detail. Figure 14 shows an image of fracture surface of the broken filament obtained by using a secondary electron microscope (SEM). An increase in the size of crystals is observed at the surface, especially at the right-hand side of the image. This result indicates that the temperature at the damaged region increased remarkably. We suppose that the cutoff was induced by the evaporation due to the local heating by spotted arc discharge.

At present, the lifetime of the filament is 2030 hours, which includes 780 hours in the high current mode and 1250 hours in the low current mode. It is a point notice that this result does not always guarantee the filament to operate 2000 hours continuously because we cleaned up the filament surface at the interval of the beam commissioning, as described above.

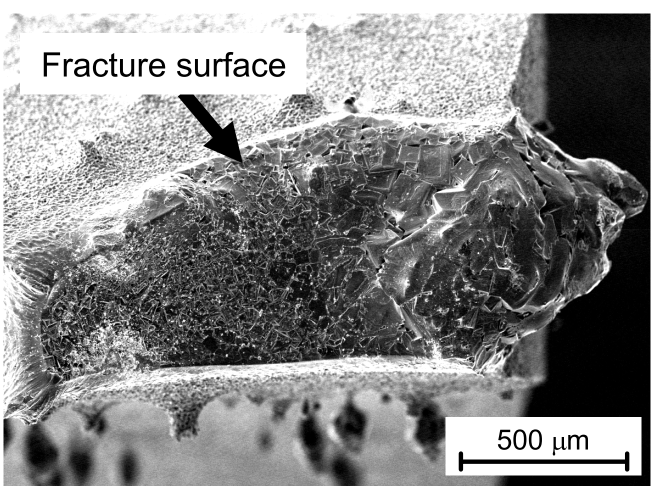

FIG. 14. SEM image of fracture surface at cutoff point.

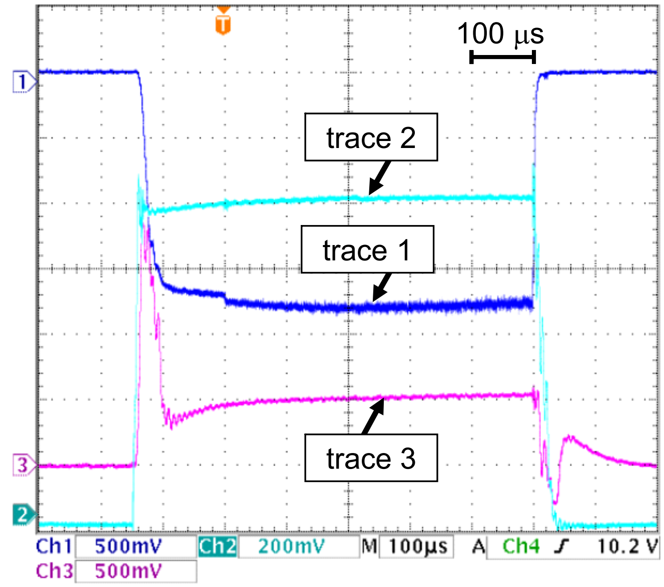

FIG. 15. (Color) Waveforms of beam current (trace 1: 10 mA/div), arc current (trace 2: 80 A/div), and arc voltage (trace 3: 150 V/div).

D. Demonstration of long pulse and high power operation

At present, the ion source produces a 30–33 mA beam with the maximum pulse width of only 100 μs as required for the beam commissioning tasks. In the recent ion source study carried out during the interval between the commissioning runs, we have tried to operate the ion source with long pulse at a beam repetition rate of 25 Hz. Figure 15 shows the result of the trial operation. The waveforms in Fig. 15 denote the beam current (trace 1), arc current (trace 2), and arc voltage (trace 3). The time scale of the horizontal axis is 100 μs/div. The result indicates that the ion source can produce a beam current of 36 mA with a flattop pulse width of 500 μs at an arc power of 63.6 kW (arc current and arc voltage are 400 A and 159 V, respectively). This result shows the ion source meets the specifications of the ion source required for the first stage of the J-PARC ion source beam specification. The trial operation lasted for approximately 5 hours without any failures and instabilities.

IV. SUMMARY

The operation of the J-PARC ion source started in September 2006 after which 17 beam commissioning runs each of 4–5 weeks have been carried out in approximately 2 years. Some of the operational parameters of the ion source were determined by the result of the ion source study. During the commissioning runs, the ion source successfully delivered the beam to the J-PARC accelerator for 2720 hours without any serious failures beyond the two filament issues previously described. After establishing a beam-current operating mode, the variation of the beam current could be reduced, and the tuning frequency was reduced to approximately once a day. The achieved lifetime of the filament was 2030 hours, which included 780 hours in the high current mode and 1250 hours in the low current mode. We do not have sufficient data regarding the lifetime of the filament, but we are confident that a LaB_6 filament can be used at least for a few weeks. In the recent ion source study carried out during the down-period interval of the commissioning runs, we have demonstrated that the ion source can produce a beam current of 36 mA with a flattop pulse width of 500 μs and a repetition rate of 25 Hz. This result shows that the ion source meets the specifications of the ion source required for the first stage of the J-PARC ion source beam specification.

ACKNOWLEDGMENTS

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