Cesiated surface H$^-$ ion source: optimization studies

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Abstract

The H$^-$ ion beam intensity required for high-energy and high-intensity proton accelerators is continuously increasing. The required 95%-beam transverse normalized root mean square emittance ($\varepsilon_{95\%nRMSx/y}$) of the beam is around 0.25 $\pi$ mm mrad for all accelerators. The Japan Proton Accelerator Complex (J-PARC) 400 MeV linear accelerator (LINAC) succeeded in accelerating the world’s highest-class H$^-$ ion beam of 50 mA with a cesiated RF-driven H$^-$ ion source. This was achieved by increasing the beam brightness through the following measures:

1. 45°-tapered plasma electrode (PE) with a 16 mm thickness to increase beam intensity by 56%,
2. continuous-wave igniter plasma driven by 50 W 30 MHz RF to reduce hydrogen pressure in the plasma chamber (PCH) by 50% and beam loss in low-energy beam transport by 12%, compared with that by the commonly used 300 W 13.56 MHz RF,
3. axial magnetic-field correction around the PE beam aperture to increase beam intensity by a maximum of 15%,
4. operation at a low PE temperature ($T_{PE}$) of about 70 °C to reduce $\varepsilon_{95\%nRMSx/y}$ by 27%,
5. suitable beam apertures of the plasma and the extraction electrodes to increase beam intensity by a maximum of 7% and to reduce $\varepsilon_{95\%nRMSx/y}$ by more than 4%,
6. argon/nitrogen elimination and 39% filter-field reduction to reduce $\varepsilon_{95\%nRMSx/y}$ by 9% and the required 2 MHz RF power by around 30%,
7. eight-hours conditioning with a 50 kW 2 MHz RF and a 5% (1 ms $\times$ 50 Hz) duty factor to reduce $\varepsilon_{95\%nRMSx/y}$ by 15%, and
8. slight water molecules (H$_2$Os) feeding in hydrogen to avoid $\varepsilon_{95\%nRMSx/y}$ increase by 72% and divergence angle expansion by 50%.

In the studies, we investigated principally the 66 mA H$^-$ ion beams extracted from the source in order to achieve a 50 mA beam at the J-PARC LINAC exit regardless of the beam’s brightness. Consequently, the source can produce the required beam for a 60 mA J-PARC LINAC operation, since the world’s brightest-class beam with the $\varepsilon_{95\%nRMSx/y}$ of 0.23 $\pi$ mm mrad and beam intensity of 66 mA is successfully produced through the above measures.

Nomenclature

- AMF (axial magnetic field)
- AMFC (axial magnetic field correction)
- Cs (cesium)
1. Introduction

The intensity requirements of high-energy and high-intensity proton accelerators for a $H^-$ ion beam are increasing every year. The required 95%-beam transverse normalized root mean square (rms) emittance ($\varepsilon_{95\%nrms/x/y}$) is around 0.25 πmm mrad for all of accelerators. The designed $H^-$ ion beam intensity ($I_{H^-}$) at the exit of the Japan Proton Accelerator Research Complex (J-PARC) [1, 2] 400 MeV linear accelerator (LINAC) was set at the challenging value of 50 mA, which is 20% higher than the values of similar operating LINACs. To achieve the 50 mA value, the J-PARC cesiated RF-driven $H^-$ ion source has been developed to produce an $I_{H^-}$ of 60 mA within normalized emittances of 1.5 πmm mrad both horizontally and vertically. A flat-top beam duty factor of more than 1.25% (500 μs × 25 Hz) and a lifetime longer than one month are also required for the source.
The latter requirements have been satisfied using the superior internal RF-antenna developed at the Spallation Neutron Source (SNS) [3]. Several measures have been implemented to increase the beam brightness [4–16]. Almost all effective measures were found, in persistent experiments, to reproduce the accidentally produced H− ion beam with the record-breaking smallest emittances. These unique measures and the proposed processes are reviewed in this paper.

2. Experimental setup and methods

The cross-sectional view of the experimental setup of the J-PARC RF-driven H− ion source test stand is shown in figure 1(a). It consists of a stainless-steel (SS) plasma chamber (PCH) unitized from an end flange to a plasma electrode (PE), extraction and ground electrodes (EE and GE), an ejection-angle-correction electromagnet, a vacuum chamber for differential pumping by a 1500 l s−1 turbo-molecular pump (TMP) with a ceramics insulator duct (outer diameter = 500 mm and length = 100 mm for 50 kV insulation), a solenoid magnet (SM) and a vacuum chamber for monitors and a 500 l s−1 TMP. The previously used PCH for the cesium (Cs)-free J-PARC H− ion source [4, 5] driven with a lanthanum hexaboride (LaB6) filament is shown in figure 1(b). This source is called the LaB6-source in this paper. The PCHs for the LaB6-source and the prototype RF-driven source were made of nickel (Ni)-plated oxygen-free copper (OFC) [6], since OFC is normally used for filament sources to remove radiant heat from the filament efficiently. The plasma confinement field is produced with 18 cusp magnets on the outer wall and 4 cusp magnets on the end flange. The filter fields for the LaB6-source and RF-driven sources are produced using external-filter magnets and rod-filter magnets (RFMs), respectively. The RFMs are installed in two rectangular pipes welded inside the PCH and cooled by water flowing through the pipes. An RF-antenna developed at the SNS [3] is installed in the PCH through a port machined on the end flange. A Cs injector is installed on the end flange, and comprised a Cs reservoir, a remotely controlled Cs valve, and a Cs tube, each of which is temperature-controlled using a thermocouple and a heating mantle attached to it. A collimating lens for a JAZ-EL200-XR spectrometer [17] is installed on an end-flange window port looking into the PE beam aperture. The 852 nm spectrum intensity measured with the spectrometer is used to control the Cs density in the plasma. As shown in figure 1(a), a PE temperature (TPE)-control plate made of OFC is attached on the downstream surface of the 45°-tapered PE made of molybdenum (Mo) with a 16 mm thickness. The TPE is controlled by changing the flow rate and the temperature of the air flowing through an SS pipe brazed on the TPE-control plate. The air flow rate is set to 800 or 1800 l h−1 for the TPE lower or higher than 160 °C, respectively. The air temperature is changed by feeding back the air temperature-control heater with power, in order to regulate the temperature measured with a thermocouple attached on the inner surface of the pipe.
The maximum power of the heater is 500 W. An axial magnetic field correction (AMFC) coil, whose maximum current is 13.3 A (1224 AT), is placed around the downstream flange of the PCH [9].

The extraction current (I_{ext}), which is the sum of the I_{H^+} and the co-extracted electron intensity, is 120 ± 40 mA for every measurement producing the 66 mA of I_{H^+} for the RF-source. By finely tuning the RFM arrangement according to the set condition, a superior beam and extraction current ratio (I_{H^+}/I_{ext}) of between 0.82 (66/80) and 0.41 (66/160) are easily attained.

The H^+ ion beam obtained through the extraction voltage (V_{ext}) between the PE and EE is accelerated by the acceleration voltage (V_{acc}) between the EE and GE. V_{ext} and V_{acc} are typically set to 10 kV and 40 kV, respectively. The maximum value of V_{ext} for the test-stand is 10 kV. The 50 keV H^+ beam, which is designed injection energy of the J-PARC radio frequency quadrupole linear accelerator (RFQ), is produced by two-gap acceleration. The electrons extracted simultaneously with the H^+ ion beam are bent to the electron dump attached on the EE by electron-suppression magnets (ESMs) made of Ni-plated NdFeB permanent magnets installed in the EE. The electron dump is made of tungsten. The ejection angle of the H^+ ion beam produced by the rod filter and electron suppression fields is corrected by the ejection angle-correction electromagnet [4]. The ejected H^+ ion beam is focused by the SM into the chamber for the beam monitors and the 500 l s^{-1} TMP. The coil current of the SM is 400 A (56 000 AT) or 450 A (63 000 AT) for the operations presented in this paper.

The horizontal and vertical emittances are measured using two sets of movable slits (S) and movable slits with Faraday-cup (SFC) (S-SFC) emittance monitors. Each slit comprises a pair of tungsten plates with an opening of 0.1 mm. The electric current detected with each SFC is terminated with a 2.5 kΩ terminator, amplified by a factor of 11, and converted to a voltage signal by an operational amplifier. The measured emittance is visualized by plotting dots randomly in each mesh area defined by the moving steps (typically 0.2 mm and 2 mrad) and the positions of the S and SFC. The number of the dots is proportional to the voltage signal measured in each mesh. The total number of dots is normalized to 400 000. The details of the emittance measurements including the structure of the monitors are presented in [11]. The details of the estimation of the emittances are described in [16].

3. Measures for increasing the beam brightness of J-PARC J-PARC source

3.1. 45°-Tapered thick PE for higher beam intensity

The dependence of the PE shapes on the maximum I_{H^+} is studied using the J-PARC Cs-free H^+ ion source driven by direct-current arc discharge with a LaB_6 filament [4, 5]. The LaB_{6c}-source is operated by a LaB_6 filament with a diameter and a length of 20 mm and 35 mm, respectively, and an arc power of 43.5 kw (150 V × 290 A). The LaB_{6c}-source shows excellent reproducibility of the maximum I_{H^+} value, depending only upon the PE shapes due to almost constant H^+ ion formation efficiency of the Mo surface evaporated with La and B exceeding a threshold amount. The results and the half cross-sectional views of the various PE shapes are shown in figure 2. The I_{H^+} improvement by only 1 mA, from 25 mA (figure 2(a)) to 26 mA (figure 2(b)), reflects the effectiveness of the 45°-tapered PE due to reproducibility. Therefore, the thicker 45°-tapered PEs, with thicknesses of 4 mm (figure 2(c)), 6 mm (figure 2(d)), 10 mm (figure 2(e)) and 16 mm (figure 2(f)), are examined. The maximum I_{H^+} values measured are 30.6 mA, 34.4 mA, 38 mA, and 39 mA for each PE shape, respectively. I_{H^+} is enhanced by 56% from 25 to 39 mA. The LaB_{6c}-source with the PE shown in figure 2(f) had been used for the J-PARC operation for about eight years to produce 36 mA H^+ ion beams regularly.

The ceramics flange is essential for increasing the T_{pe} to around 450 °C, at which the H^+ ion formation efficiency on the Mo surface evaporated with sufficient La and B becomes around half of that for an optimally cesiated Mo surface. The highest-class H^+ ion formation efficiency for un-cesiated surfaces is attributed to the low work function of the La- and B-evaporated Mo surface at a high T_{pe} of around 450 °C. The cesiated LaB_{6c}-source is examined to be operated with a T_{pe} of 200 °C, which is suitable for the H^+ ion formation on the cesiated Mo surface. However, it produces unstable H^+ ion beam with intensity lower than that produced with the un-cesiated LaB_{6c}-source, probably due to the chemical reactions between Cs and La and B [5].

The PE with the shape shown in figure 2(f) is used in all J-PARC cesiated RF-drive H^+ ion sources presented in the following sub-sections. If the cesiated source is used for the J-PARC from the beginning, the 45°-tapered PE will not be devised, since the 1 mA improvement will be concealed by the much larger cesiation condition differences.

3.2. Low-power continuous-wave (CW) igniter plasma driven by 30 MHz RF for lower beam loss

The CW igniter plasma driven by a 13.56 MHz RF is used in the SNS RF-driven H^+ ion source [18] in order to ignite pulsed high-power 2 MHz RF plasma stably. The 13.56 MHz RF matching network is composed of two variable capacitors. The series capacitor is placed between one terminal of the RF-antenna and the center conductor of the coaxial cable connected to the output port of the 13.56 MHz RF power supply. The parallel
capacitor is connected between the connection point of the series capacitor and the center conductor and the other terminal of the RF-antenna. The latter RF-antenna terminal is connected to the outer conductor of the coaxial cable. The smallest hydrogen flow rate \( Q_{H_2} \) and the 13.56 MHz RF power for the stable 2 MHz-RF plasma operation are experimentally confirmed as 27 SCCM and 300 W, respectively.

As shown in figure 3(a), a matching network comprising two COMET CVLI-30 CC/15-BANs \[19\], which are vacuum-variable capacitors with a tunable range between 3 and 30 pF and a peak working voltage of 9 kV, is used for the J-PARC source \[7\]. The RF characteristics of the resonant circuit comprising the network and an RF-antenna are examined with a network analyzer. The highest frequency for stable resonance with the circuit is 30 MHz. RFs higher than 30 MHz are filtered by stray capacitances and not transmitted to the RF-antenna. The CW igniter plasma driven by 30 MHz RF is experimentally examined. The pulsed high-power 2 MHz RF plasma is stably ignited for the smallest \( Q_{H_2} \) of 17 SCCM and 30 MHz RF power of only 50 W.

The beam apertures of the PE for the SNS and J-PARC sources are 7 mm and 9 mm, respectively. The hydrogen differential pumping speeds after the aperture for the SNS and J-PARC sources are 2100 l s\(^{-1}\) and 3000 l s\(^{-1}\), respectively. These are sufficiently high to approximate the hydrogen pressure in the PCHs only by the hydrogen flow rates and the conductance of the apertures. The pressures in the SNS and J-PARC PCHs are estimated as 2.7 and 1 Pa, respectively. In the SNS PCH for an about 10% higher \( Q_{H_2} \) of 30 SCCM, the pressure is measured as 3–3.2 Pa \[20\], which is about 10% higher than the estimated value for the \( Q_{H_2} \) of 27 SCCM.

As shown in figure 3(b), the relation between \( Q_{H_2} \) and \( I_{H_2} \) is measured using the second J-PARC source test stand \[21\] for a constant 2 MHz RF power of 42 kW. The measured data are indicated with red closed circles. A linear polynomial fitted the data is shown as a solid red line. The test stand is composed of the same low-energy beam transport (LEBT) used in the J-PARC operation, a chamber for a Faraday-cup, and a 500 l s\(^{-1}\) TMP. In order to attain the maximum hydrogen pumping speed, three 1500 l s\(^{-1}\) TMPs, two 500 l s\(^{-1}\) TMPs and one 4000 l s\(^{-1}\) cryo-pump are installed in the LEBT. The \( I_{H_2} \) value is inversely proportional to the \( Q_{H_2} \) value with a coefficient of \(-0.71\), since the beam loss due to the electron detachment collision with the residual hydrogen gas.
AMFC coil current is proportional to plated OFC, same as that for the LaB$_6$-source. In this work, the vertical emittance measured for the H$^-$-ion beam produced by the J-PARC LEBT SMs are tuned to match the beam with the acceptance of the J-PARC RFQ condition, in case of an arbitrary coil current. In the normalized 1.5 angular aperture, the AMF of the SM fringe field is 27 G. Notably, only about 36 G difference in the AMF is produced using a Gaussia meter at $-27$ G. The calculated optimal AMF is 29 or 21 G, which is the sum of the fields produced by the SMs (32 or 36 G), the AMFC coil (24 or 12 G) and the RFMs. The axial fields of the RFMs is measured using a Gaussia meter at $-27$ G. Notably, only about 36 G difference in the AMF (13 A difference in the AMFC) produces a rather large difference of about 15% in $I_{H^-}$. Therefore, the AMFC is essential for operating the source under the optimal condition, in case of an arbitrary coil current in the first SM of the J-PARC LEBT. The coil currents of the two J-PARC LEBT SMs are tuned to match the beam with the acceptance of the J-PARC RFQ [21].

3.3. AMFC around PE beam aperture for higher beam intensity

The $I_{H^-}$ of the J-PARC LaB$_6$-source is maximized by eliminating the axial magnetic field (AMF) around the PE beam aperture. The AMF of the SM fringe field is cancelled by the AMFC coil, producing the opposite-direction field. The $I_{H^-}$ is increased by about 5% with the AMFC.

The AMFC coil is also installed in the J-PARC RF-source (figure 1(b)). The measured relations between the AMFC coil current ($I_{AMFC}$) and the $I_{H^-}$ value for two SM coil currents ($I_{SM}$) of 400 and 450 A are shown in figure 4 [9]. The measured data for the $I_{SM}$ of 400 and 450 A are shown with red closed circles and with blue closed circles, respectively.

By using a two-dimensional magnetostatic Poisson code [22], the AFMs at the PE beam aperture produced with the SM and the AMFC coil are analyzed as $0.08 \times I_{SM}$ G and $2.76 \times I_{AMFC}$ G, respectively. For the $I_{SM}$ of 400 or 450 A, the calculated optimal AMF is 29 or 21 G, which is the sum of the fields produced by the SMs (32 or 36 G), the AMFC coil (24 or 12 G) and the RFMs. The axial field of the RFMs is measured using a Gaussia meter at $-27$ G. Notably, only about 36 G difference in the AMF (13 A difference in the AMFC) produces a rather large difference of about 15% in $I_{H^-}$. Therefore, the AMFC is essential for operating the source under the optimal condition, in case of an arbitrary coil current in the first SM of the J-PARC LEBT. The coil currents of the two J-PARC LEBT SMs are tuned to match the beam with the acceptance of the J-PARC RFQ [21].

3.4. Low $T_{PE}$ operation for smaller emittances

The vertical emittance measured for the H$^-$ ion beam with an intensity of 66.4 mA from the prototype PCH with a $T_{PE}$ of 120 °C and a EE beam-aperture ($\Phi_{EE}$) of 7.7 mm is presented in figure 5 [6]. The PCH is made of Ni-plated OFC, same as that for the LaB$_6$-source. In figure 5(a), the H$^-$ ion particle distribution, the fitted normalized 1.5 $\pi$mm r.m.s ellipse, and the normalized 1.5 $\pi$mm r.m.s ellipse backward-traced to the longitudinal position of the GE downstream surface using Trace2D (T2D) [23] are plotted with red dots, a blue line, and a red line, respectively. In figure 5(b), the relation between the vertical normalized emittance ($\epsilon_{ny}$) and the included beam fraction ($f_{in}$) is presented with a blue line.

Although the required $I_{H^-}$ of 60 mA within normalized emittances of 1.5 $\pi$mm r.m.s is possible, it takes more than eight hours to attain sufficient Cs effects after the cesiation process commences. A considerable amount of Cs needs to be injected intermittently, probably due to the Cs aggregation problem on the inner surface of the OFC PCH with a very low temperature. The estimated total Cs consumption for 50 days of operation is about 1 g, even though the very low $T_{PE}$ of 120 °C is used instead of the commonly used temperature of 200 °C–250 °C, at which the maximum H$^-$ ion formation efficiency has been previously reported [24]. Furthermore, it takes about 10 min to recover stable Cs density and $I_{H^-}$ value, after a plasma operation cessation of several minutes, probably due to the additional Cs sputtered by the nonstationary bombardment of the transient plasma on the Cs-aggregated PCH inner surface.
To avoid the Cs aggregation problem at a low inner-surface temperature, all future PCHs should be made of SS. The unified PCH, from the end plate to the PE with a low weight maintainable by hands, is also realized by reducing the thickness of the SS wall, taking advantage of the SS’s higher mechanical strength. The unified PCH is necessary to reduce the online maintenance time of the J-PARC source to about eight hours. Although the required amount of Cs is drastically decreased to around 10 mg, the emittance ($\varepsilon$) of the H$^-$ ion beam with 66 mA intensity from #1 PCH for $T_{PE} = 205$ $^\circ$C is about 25% greater than that ($\varepsilon\sim 0.347 \pi mm mrad$) from the OFC PCH [6]. The RFM difference shown in figures 6(a) and (b) are considered responsible for the emittance difference.

Therefore, we attempt to operate #2 PCH, where RFMs with the same cross-section as that used in the OFC PCH are installed, with $T_{PE} = 120$ $^\circ$C. However, the operation is unrealistic due to the too long time constant (a few hours) of the cesiation effects probably caused by the very strong filter field. By using the RFMs shown in figure 6(c), which have a cross-section slightly smaller (4.75 mm \times 10 mm) than that for OFC PCH (5 mm \times 10 mm) and rather large triple gaps (2 mm) between the separated RFMs, #2 PCH is successfully operated with $T_{PE} = 70$ $^\circ$C. The lowest $T_{PE}$ attained with 0.7 MPa compressed air to cool the PE is 70 $^\circ$C. The vertical emittance measured with #2 PCH is shown in figure 7. The emittance ($\varepsilon\sim 0.317 \pi mm mrad$) of #2 PCH for $T_{PE} = 70$ $^\circ$C is improved by about 10% from that of OFC PCH for $T_{PE} = 120$ $^\circ$C [10]. The dependence of the emittances on $T_{PE}$, which has not been assumed so far, is proven here. The appropriate sputtering of Cs from the PE surface caused by the slightly weakened filter field, instead of the Cs thermal detachments by the $T_{PE}$ higher than 200 $^\circ$C is thought to produce the controllable equilibrium condition of the optimal Cs density on the PE surface. Although the measured magnetic fields on the beam axis present no observable difference [12, 14], the gaps between the separated RFMs have unpredictably large effects on the controllability of Cs density. The local magnetic fields around the gaps are thought to cause the leakage of some energetic particles to the PE surface area.

3.5. Beam apertures of PE and EE for higher beam intensity and smaller emittances

As reported previously [8], the measured emittance of $\varepsilon_{95\%nrms/\pi} \sim 0.396 \pi mm mrad$ for the PE of 8 mm is about 15% larger than that for the original PE for 9 mm ($\varepsilon_{95\%nrms/\pi} \sim 0.345 \pi mm mrad$) contrary to our expectation. A PE larger than 9 mm is un-adoptable since a higher QH is required and a larger beam loss is caused, as described in section 3.1. In order to optimize the extraction condition, the $\Phi_{PE}$ of 7.1 and 8.3 mm are compared with the original PE of 7.7 mm. PE and EEs drawings are shown in figure 8. By using the #4 PCH with $T_{PE} = 70$ $^\circ$C, the relations between $\Phi_{EE}$ (7.1, 7.7, 8.3 mm) and the emittances for several $I_{H}$ (33, 46, 66 mA, and the maximum value) are measured (figure 9). For each $I_{H}$, the smallest emittances are observed for the smallest $\Phi_{EE}$ of 7.1 mm. This phenomenon is attributed to the collimation of filamentation components by the smallest $\Phi_{EE}$. On the other hand, the highest $I_{H}$ is also produced with the smallest $\Phi_{EE}$ of 7.1 mm. This is attributed to the sufficient focusing force against the space-charge force with $\Phi_{EE}$ of 7.1 mm and the insufficient focusing force with $\Phi_{EE}$ of 7.7 or 8.3 mm.

The smallest vertical emittance for $I_{H} = 66$ mA ($\varepsilon_{95\%nrms/\pi} \sim 0.295 \pi mm mrad$) is measured with $\Phi_{EE} = 7.1$ mm (figure 10). The divergence angles of the backward-traced ellipse indicated with a red line in figure 10(a) are $\pm 60 mrad$ ($\sim 50 \sim +70 mrad$). These are significantly smaller than $\pm 100 mrad$, which are the simulated values obtained using the two-dimensional ion beam extraction simulation code BEAMORBT [4, 25].

![Figure 5](image_url)
The plasma meniscus is estimated with self-consistent field calculations including co-extracted electrons by BEAMORBT. The experimentally revealed cause for the discrepancy between the experiment and the simulation is presented in section 3.8. The J-PARC LEBT is designed to accept only beams with divergence angles of $\pm 100$ mrad. The beam extracted with a $V_{\text{ext}}$ higher than 10 kV is easily accepted with the LEBT due to the significantly reduced divergence angles. The RF-source operations with higher $V_{\text{ext}}$ up to 14 kV will be examined by using the second J-PARC test stand in the near future. Both of the beam emittances and the maximum beam intensity are expected to be improved by these operations, since the above results indicate that the space-charge limited current for $V_{\text{ext}} = 10$ kV is about 80 mA.

### 3.6. Argon/nitrogen elimination and low rod-filter-field (RFF) for smaller emittances

During vacuum pumping of the sufficiently cesiated #6 PCH, from atmospheric pressure after argon filing during maintenance, bursty fluctuations in the vacuum pressure are occasionally observed [14]. The fluctuated...
Figure 8. Drawing of PE and EE magnified around beam apertures. 'Reproduced from (2016 Rev. Sci. Instrum. 87 02B130), with the permission of AIP Publishing.'

Figure 9. Relations between $I_{H^{-}}$ and $\varepsilon_{y_{95\%nrms}}$ and $\varepsilon_{x_{95\%nrms}}$ measured with #4 PCH for $\Phi_{EE}$ of 8.3 (blue open and closed squares), 7.7 (green open and closed triangles), and 7.1 (red open and closed circles) mm.

Figure 10. (a) H$^{-}$ ion particle distribution in vertical phase-plane (red dots), fitted normalized 1.5 mm mrad ellipse (blue line) and ellipse backward-traced to longitudinal position of GE downstream surface by using T2D (red line) and (b) relation between $\varepsilon_{y_{95\%}}$ and $f_{ny}$ measured with #4 PCH for $T_{PE}$ of 70 °C and $\Phi_{EE}$ of 7.1 mm.
elements are specified as argon and nitrogen through mass spectroscopy. Since each bursty fluctuation lasts longer than 24 h, the argon and nitrogen are thought to be confined in pocks with rather large volumes. The most probable candidates for these pockets are corner triangle areas between O-rings and grooves. Therefore, two ventilation pathways are machined for all three O-ring grooves (figure 11). The #6 PCH with the ventilation pathways is renamed #6’ PCH in order to clarify the difference. Other PCHs named #n’ also include the ventilation pathways. Bursty fluctuations in the vacuum pressure are not observed in #6’ PCH.

However, it is impossible to stably produce a H\(^-\) ion beam of 66 mA by using #6’ PCH with \(T_{PE} = 70^\circ\)C, since the cesiation of the PE easily becomes an excessive condition and can create the proper condition only by increasing \(T_{PE}\) to more than 200 °C. The optimal strength of RFF for \(T_{PE} = 70^\circ\)C is thought to decrease by eliminating the argon/nitrogen. A strong RFF is necessary for #6 PCH without ventilation pathways in order to reduce the bombardments of argon/nitrogen ions on the PE surface, which decrease the Cs density on the PE by sputtering.

The RFMs shown in figure 6(d) are installed in a brand-new #7’ PCH, which is the first PCH initially designed with ventilation pathways for O-ring grooves. The RFF is decreased by replacing central two RFMs, which have a cross-section of 4.75 \(\times\) 10 mm\(^2\) and a length of 20 mm (figure 6(c)), with an RFM having a cross-section of 5 \(\times\) 5 mm\(^2\) and a length of 50 mm. The gaps between RFMs are set to 0 mm. The measured transverse magnetic field on the beam axis produced by the newly arranged RFMs and the ESMs for #7’ PCH is shown with a red line in figure 12 as a function of the longitudinal position from the downstream surface of the PE. As references, we show in figure 12 the measured transverse magnetic fields on the beam axis produced by the RFMs in OFC PCH (figure 6(a)) and ESMs (blue line) and by the EFMs used for LaB\(_6\)-source and old ESMs with smaller cross-sections (green line). The RFF for #7’ PCH is approximately half that for OFC PCH with respect to the cross-section ratio of the replaced RFMs. Since averaged values of the red and green lines between and 40 mm are almost the same, it is possible to produce the optimal filter field for #7’ PCH by EFMs.

The vertical emittance measured with #7’ PCH is presented in figure 13. The measured emittance of \(\varepsilon_{95\%_{rms}}/\gamma \sim 0.265\pi\) mm mmrad is improved by about 10% from that of \(\varepsilon_{95\%_{rms}}/\gamma \sim 0.295\pi\) mm mmrad, as shown in figure 10, through the argon/nitrogen elimination. Furthermore, the weaker RFF decreases the necessary 2 MHz RF power by more than 10%, from 34–43 to 26–30 kW, probably by increasing the positive hydrogen ion flux reaching the PE surface. The positive hydrogen ions are the seeds of H\(^-\) ions.

**3.7. High-power and high-duty conditioning with cesium-abundant plasma for smaller emittances**

During the commissioning of a brand-new PCH, several RF-antennas are inevitably broken, probably due to the impurity elements sputtered from the PCH inner surface. The preconditioning procedure [13] has been applied to each RF-antenna. After failure of three RF-antennas, #7’ PCH with ventilation pathways for O-ring grooves successfully produces the 66 mA beam with the superior emittance shown in figure 13. However, the intensity of the spectra with wavelengths between 250 and 400 nm measured with the spectrometer JAZ-EL200-XR [17] is about twice compared with other PCHs. In other PCHs, the intensity of the spectra decreases during operation.
with the highest power of 50 kW, the highest duty factor of 5% (1 ms \times 50 Hz), the high $T_{PE}$ of around 300 °C, and the excessive Cs of about 100 mg. In order to reduce the risks of antenna failures during the J-PARC operations, the above high-power and high-duty conditioning is executed for eight hours with #7′ PCH. After the conditioning, the intensity of the spectra is only slightly decreased for the usual operation with a duty factor of 2.5% (1 ms \times 25 Hz). Since the antenna survives under much severer condition than those of the J-PARC operations, the impurity elements producing the spectra will cause no risk on antenna failures.

On the other hand, the 66 mA beam with the smallest vertical emittance of $\epsilon_{95\%nrms}x/\epsilon_{95\%nrms}y \sim 0.224 \pi$ mm mrad is unexpectedly produced with $T_{PE} = 70$ °C and the 2 MHz RF power = 29 kW (figure 14). The brightest beam is thought to be produced by eliminating the unspecifiable impurity elements, which are gradually sputtered from the inner surfaces of the PCH in the usual operation with the 2 MHz RF power of around 30 kW, by bombardments of the high-temperature hydrogen plasma produce with the 2 MHz RF power of 50 kW.

3.8. Slight water-fed hydrogen for lower beam-divergence angles and smaller emittances

The drastically degraded emittances are measured for a 66 mA H− ion beam produced using #6′ PCH with ventilation pathways for O-ring grooves (figure 15). The measured emittance of $\epsilon_{95\%nrmax}/\epsilon_{95\%nrmin} \sim 0.387$ π mm mrad is about 46% larger than that of $\epsilon_{95\%nrmax}/\epsilon_{95\%nrmin} \sim 0.265$ π mm mrad produced using #7′ PCH (figure 13). The measured divergence angles of ±80 mrad are about 60% larger than those of ±50 mrad (−45 ∼ +55 mrad) produced using #7′ PCH (figure 13). Similar emittances were measured two times for 66 mA beams produced using #2 PCH without ventilation pathways. All three degraded beams were produced after the preconditioning procedure [13], in which $T_{PE}$ was kept at the high value of 300 °C for eight hours in the initial stage of the procedure, and a 24 h usual beam operation. The elimination of impurity elements with the high $T_{PE}$ is essential.
to reproduce the beams with similar emittances. Any drastic degradation of emittance is never observed if $T_{PE}$ is not maintained at 300 °C, even though the usual beam operation lasted for more than five days. Since the most probable candidate for an impurity element causing drastic degradation is water molecules ($H_2O_s$), an $H_2O_s$ feeder [15], comprising a water reservoir with a 1.6 cc capacity, an SS-4FW-15 Swagelok in-line filter [26] and an SS-SS2-D Swagelok metering valve [27] is installed in the hydrogen line. One port of SS-SS2-D is connected perpendicularly to the hydrogen line, and the other is connected to SS-4FW-15, which is, in turn, connected to the water reservoir. The two needle valves of SS-SS2-D are used with fully opened states. After the installation of the $H_2O_s$ feeder, no drastic emittance degradation is observed.

4. Summary

The following diverse unique measures used in the J-PARC cesiated RF-driven $H^-$ ion source were reviewed. The measured $\varepsilon_{95\%nrms/x/y}$ for each operation condition is summarized in figure 17. The source successfully produced the world’s brightest-class beam with $\varepsilon_{95\%nrms/x} = 0.23 \, \pi \, \text{mm mrad}$ and beam intensity of 66 mA.

![Figure 14](image1.png)

**Figure 14.** (a) $H^-$ ion particle distribution in vertical phase plane (red dots), fitted normalized 1.5 \( \pi \) mm mrad ellipse (blue line) and ellipse backward-traced to the longitudinal position of GE downstream surface using T2D (red line) and (b) relation between $\varepsilon_{ny}$ and $f_{ny}$ measured with the argon/nitrogen-eliminated #7′ PCH for $T_{PE} = 70 \, ^\circ\text{C}$ and $\Phi_{EE} = 7.1 \, \text{mm}$ after eight hours high-power conditioning.

![Figure 15](image2.png)

**Figure 15.** (a) $H^-$ ion particle distribution in vertical phase plane (red dots), fitted normalized 1.5 \( \pi \) mm mrad ellipse (blue line) and ellipse backward-traced to the longitudinal position of GE downstream surface using T2D (red line) and (b) relation between $\varepsilon_{ny}$ and $f_{ny}$ measured with argon/nitrogen-eliminated #7′ PCH at $T_{PE} = 70 \, ^\circ\text{C}$ and $\Phi_{EE} = 7.1 \, \text{mm}$ after 24 h beam operation.
Therefore, it could prepare a beam for 60 mA J-PARC LINAC operation. The following measures were implemented:

1. $45^\circ$-tapered PE with 16 mm thickness to increase the beam intensity by 56%,
2. CW igniter plasma driven by 50 W 30 MHz RF to reduce hydrogen pressure in PCH by 50% and beam loss in LEBT by 12%, compared with those by commonly used 300 W 13.56 MHz RF,
3. AMFC around PE beam aperture to increase the beam intensity by maximum 15%,
4. operation with a low $T_{PE}$ of 70 °C to reduce $\varepsilon_{95\%\text{rms}}/x$ by 27%,
5. suitable beam apertures of PE and EE to increase beam intensity by a maximum of 7% and reduce $\varepsilon_{95\%\text{rms/}y}$ by more than 4%,
6. argon/nitrogen elimination and 39% filter field reduction to reduce $\varepsilon_{95\%\text{rms/}y}$ by 9% and the required 2 MHz RF power by around 30%,

Figure 16. $H^-$ ion beam emittance at the longitudinal position of GE downstream surface simulated with BEAMORBT. ‘Reproduced from (2004 Rev. Sci. Instrum. 75 1714), with the permission of AIP Publishing’.

Figure 17. Relation between operational conditions and measured $\varepsilon_{95\%\text{rmsmax}}$ and $\varepsilon_{95\%\text{rmsy}}$. 

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Table 1. Performances of SNS and J-PARC RF-driven H\(^-\) ion source representing performance differences.

|                       | SNS RF-driven H\(^-\) ion source | J-PARC RF-driven H\(^-\) ion source |
|-----------------------|-----------------------------------|-----------------------------------|
| Hydrogen gas flow rate| 27 SCCM                           | 17 SCCM                           |
| RF power efficiency  | ~1 mA kW\(^-1\) at source exit (~55 mA/55 kW) | ~2.2 mA kW\(^-1\) at Source Exit (~44 mA/20 kW, ~66 mA/30 kW) |
| H\(^-\) ion beam intensity | 0.7–0.9 mA kW\(^-1\) at LINAC exit \(^*\) due to Degraded RFQ Transmission | ~2 mA kW\(^-1\) at LINAC Exit (~40 mA/20 kW, ~50 mA/25 kW) |
| H\(^-\) ion beam intensity fluctuation at LINAC exit | ± ~2 mA | ±0.4 mA by RF power & Cs feedbacks |

(7) eight-hours conditioning with a 50 kW 2 MHz RF and a 5% (1 ms \times 50 Hz) duty factor to reduce \(\varepsilon_{95\%}^{\text{nrmx/y}}\) by 15%, and

(8) slight H\(_2\)Os feeding in hydrogen to avoid \(\varepsilon_{95\%}^{\text{nrmx/y}}\) growth by 72% and divergence angle expansion by 50%.

The beam intensity enhancement by the tapered thick PE (1) devised for the J-PARC source fourteen years ago has started being used in several H\(^-\) ion sources [e.g. 28] for not only accelerators but also negative beam injectors in fusion experiments. The H\(^-\) ion density enhancement mechanism around the PE beam aperture by the H\(^-\) ions produced on the PE surface has been elucidated in several plasma simulations [e.g. 29]. The H\(^-\) ion beam intensities are enhanced by several 10% in the simulations.

The CW 30 MHz RF plasma (2), whose frequency is rather higher than the commonly used 13.56 MHz [18], is the easiest measure to increase beam intensity and reduce the hydrogen loading to the following RFQ. In addition, 30 MHz is the optimum frequency, since it is the highest one stably transmitted inside the PCH, and higher frequency is preferable to ignite plasma. Frequency higher than 30 MHz is easily shielded by stray capacitances.

The beam intensity enhancement by the AMFC (3) was unexpected. Plasma simulations are expected to elucidate the AMFC mechanism. It will provide novel knowledge on not only the H\(^-\) ion beam extraction mechanism but also the optimum AMFC field.

The impurity elements in hydrogen plasma also unexpectedly influenced \(\varepsilon_{95\%}^{\text{nrmx/y}}\) as shown by (4), (6), (7) and (8). The impurity elements causing (4), (6), and (8) were Cs, argon/nitrogen, and H\(_2\)Os, respectively. The impurity element causing (7) seems to be the argon/nitrogen adsorbed on the inner surface of the PCH, since the conditioning of (7) is required for the pre-conditioned and offline-preserved PCHs. The elucidation of the causes of impurity effects by plasma simulations is also expected. It reveals the novel knowledge on the meniscus formation mechanism and the transverse emittance origin. Furthermore, the optimum shapes of the PE and EE can be simulated.

Finally, the recent performances of the SNS [30, 31] and J-PARC [15] sources are compared in table 1, in order to clarify the improvements by the measures presented in this paper. The 37%-lower \(Q_{\text{fl}}\) not only reduces the required 2 MHz RF power but also contributes to the stable operation of the RFQ. The 2 MHz RF power efficiency of the J-PARC source to produce H\(^-\) ion beam intensity is improved by more than twice compared with that of the SNS source. The J-PARC strict requirement on the H\(^-\) ion beam intensity fluctuation of ±0.2 mA is also satisfied by feeding back the 2 MHz RF power and Cs injection. Furthermore, the small tilt in a H\(^-\) ion beam pulse of less than 1 mA is also attained with the J-PARC source.

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