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Innovative Cesiation Deriving Incredible 145 mA Beam from J-PARC Cesiated RF-Driven H^- Ion Source

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Abstract. In NIBS2022, the stable 8 hours operation of the J-PARC cesiated RF-driven H^- ion source (IS) in a test-stand with a 69.9 keV 120 mA beam and a beam duty factor of 4 % (1 ms x 40 Hz) was reported. However, the Cesiation condition was produced after many times and rather large amount of Cs and H_2Os injections. The fluctuation of the H^- ion beam intensity (I_{H^-}) in a pulse and the transverse emittances were rather larger than those for the previous 65 keV 110 mA operation. The plasma electrode temperature (T_{PE}) of 254 ºC much higher than that not only for the usual J-PARC IS (about 70 ºC) but also for the standard cesiated H^- ion sources (180 ~ 200 ºC) suggested the existence of novel H_2O mediated cesiation surviving against the high T_{PE}. In this paper, the J-PARC IS improvements based upon a hypothesis of the best cesiation constituted of sub monolayer H_2O (chemically bound with Mo) mediated cesiation and Cs half monolayer on remaining surface are presented. The innovative cesiation derived a 76.5 keV 145 mA beam stably with the small beam fluctuation and transverse emittances suitable for Radio Frequency Quadrupole LINACs of high energy LINACs. The measured results of the 145 mA / 83 mA beam, extraction electrode current and RF waveforms, parameter trends of an 8 hours 145 mA operation and the transverse emittances are presented. The optimum T_{PE} was increased from 70 ºC to 230 ºC. Furthermore, the beam intensity for the J-PARC IS operation energy of 52.5 keV was increased from 72 mA to 83 mA, which was consistent with the 1.5 power perveance law on the beam energy compared with 145 mA for 76.5 keV.

1. Introduction

The design H^- ion beam intensity (I_{H^-}) at the exit of the Japan Proton Accelerator Research Complex (J-PARC) 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, such as the Spallation Neutron Source (SNS). From Sep. 2018, the LINAC has been steadily operated with the design I_{H^-} [1] by using an internal-RF-antenna developed at the SNS [2]. At each end of 3~6 months J-PARC operation, the IS supplies a 52.5 keV 72 mA beam for the LINAC 60 mA acceleration [3], which is indispensable for the J-PARC Main Ring (MR) and Rapid Cycling Synchrotron (RCS) energy upgrades on 2028 [4, 5]. The IS superior emittances measured in a test-stand were proven by the high Radio Frequency Quadrupole LINAC (RFQ) acceleration efficiency of 94.3 % (I_{H^-RFQ} = 67.9 mA) [3]. The high intensity beam with transverse emittances suitable for the RFQ is produced with several unique measures, such as, slight water molecules addition into hydrogen plasma, the low temperature (about 70 ºC) operation of 45º-tapered 16-mm thick plasma electrode with the precise Cs density control, the impurity elimination in the hydrogen plasma along with the filter-field optimization, the continuous-wave igniter plasma driven with a 42-W 30-MHz RF, and so on [6]. Further improvements of the J-PARC IS, which were attained by a novel cesiation based upon a hypothesis of sub monolayer H_2O (chemically bound with Mo) mediated cesiation in combination with Cs half monolayer on the remaining surface, are presented in this paper.

2. Experimental setup and methods

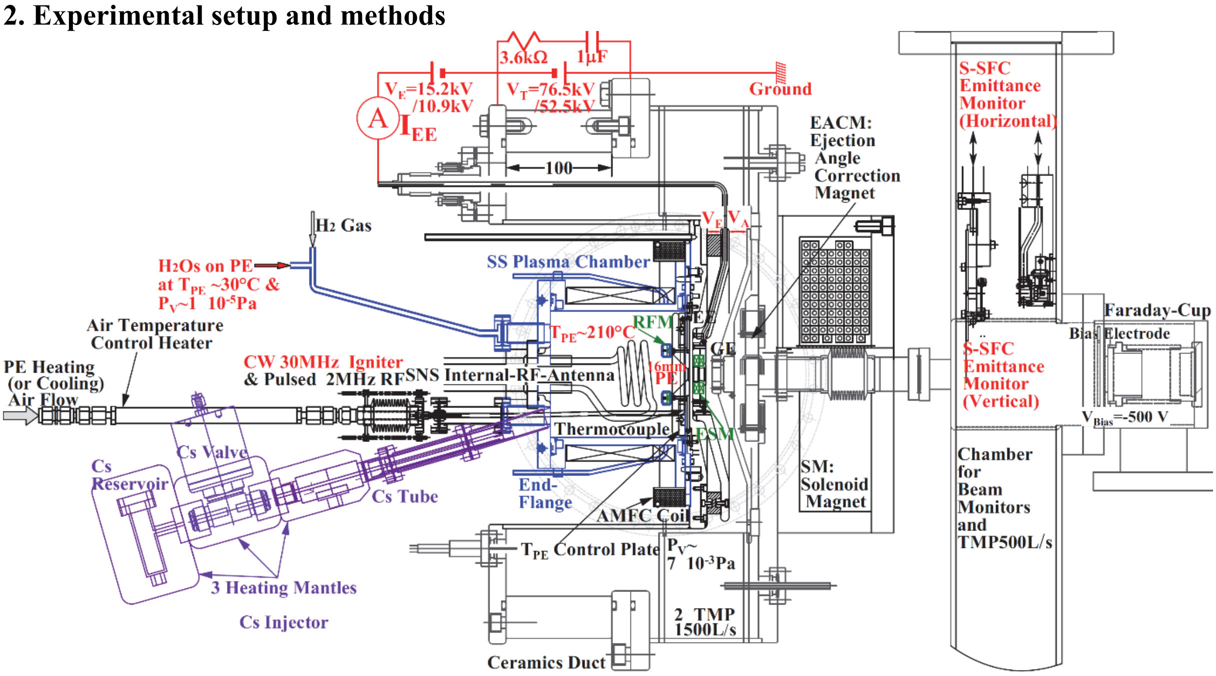

Figure 1. Cross-sectional view of J-PARC RF-driven H^- ion source test-stand.

The cross-sectional view of the experimental setup of the J-PARC IS test-stand, which consists of a stainless-steel (SS) plasma chamber (PCH) unitized from an end-flange to the plasma electrode (PE), extraction and ground electrodes (EE and GE), an ejection angle correction magnet (EACM), a vacuum chamber for differential pumping by two 1500 L/sec turbo-molecular-pumps (TMPs) with a ceramics insulator duct for the terminal voltage (V_T) of 76.5 kV insulation, a solenoid magnet (SM) and a vacuum chamber for beam monitors and a 500 L/sec TMP, is shown in Fig.1. The SS PCH with eighteen plasma confinement permanent magnets for cusp field on the outer-wall has two SS pipes inside to install rod filter magnets (RFMs) cooled by water flowing inside, an end-flange with four plasma confinement permanent magnets for cusp field on the outer-wall, an internal-RF-antenna, a Cs injector composed of a Cs-reservoir, a remotely controlled Cs-valve and a Cs-tube, each of which is temperature controlled by using a thermocouple and a heating mantle attached to it, the PE made of molybdenum, a PE temperature (T_{PE}) control plate made of oxygen free copper (OFC) attached to the PE and an axial magnetic field correction (AMFC) coil with 92 turns located around the downstream flange of the PCH, which is operated with a coil current of -11.9 A for 76.5 keV 145 mA operation or -9.5 A for 52.5 keV 83 mA operation to increase the RF efficiency by several % [6]. The IS was operated with the rather low H_2 flow rate of 17 SCCM for the rather larger PE aperture of 9 mm by using the CW 30-MHz-RF plasma igniter with a 42 W power [6]. At the top of Fig.1, the schematic circuit diagram of the high-voltage power supplies to produce the extraction and terminal voltages (V_E and V_T) and the ampere-meter to measure the extraction electrode current (I_{EE}) directly is shown.
The H^- ion beam extracted by the V_E between the PE and EE is accelerated by the V_A between the EE and GE, which is the difference of the V_T and V_E ($V_A = V_T - V_E$). The electrons co-extracted with the beam are bent to the electron dump made of tungsten (W) brazed on the OFC EE by the four electron suppression magnets (ESMs) installed in the EE [7]. The ejection angle of the H^- ion beam, which is produced by the rod-filter and electron-suppression fields, is corrected with an alignment error of about 50 μm by the EACM [7]. The ejected H^- ion beam is focused by the SM into the chamber for beam monitors. The horizontal and vertical emittances are measured by using two sets of movable slit (S) and movable slit with Faraday-cup (SFC) (S-SFC) emittance monitors installed in the chamber.

The measured emittance is visualized by randomly plotting dots, whose number is proportional to the voltage signal and is normalized to make the total number of 400,000, in each mesh area defined by the moving steps (typically 0.2 mm and 2 mrad) and the positions of the S and the SFC [8,9]. The I_{H^-} is measured with a Faraday-cup attached on the downstream flange of the chamber, whose cup is grounded with a 50 Ω terminator. The I_{H^-} is calculated by converting the voltage on the terminator with a coefficient of 20 mA/V. The coil current of the SM (I_{SM}) was set to 437 A (61180 AT) for 76.5 keV 145 mA operation or 350 A (49000 AT) for 52.5 keV 83 mA operation, to avoid too small beam size causing sputtering problems on the emittance monitor slits and Faraday-cup made of W. The 2 MHz RF duty factor was 3.4 % (1 ms × 34 Hz) for 76.5 keV 145 mA operation, which was lower than the maximum RF power supply duty of 5 %, since the radiation safety permission of the averaged beam intensity (I_{H^-AV}) was 5 mA (145 mA × 3.4 % = 4.93 mA).

3. Hypothesis of H_2O mediated cesiation and procedure to produce the best cesiation

As understood from the J-PARC IS 65 keV 110 mA and 69.9 keV 120 mA operations [10,11], it is necessary to increase not only the W_{H^-} but also the H^- production efficiency (HPE) on the large PE surface for the I_{H^-} higher than 120 mA. In the 69.9keV 120 mA operation, the high HPE was attained after many times and rather large amount of Cs and H_2Os injections. However, the cesiation caused the rather large I_{H^-} fluctuation in a pulse and transverse emittances with the inexplicably high T_{PE} of 254 ºC. From the experimental results, the following four physical descriptions are considered to be correct ; (1) it is difficult to make the Cs half monolayer area on the PE surface sufficient for I_{H^-} higher than 120 mA, (2) the HPE of the H_2O mediated cesiation is almost the same with that for the conventional one, (3) the H_2O mediated cesiation survive against the T_{PE} higher than 254 ºC and high energy plasma bombardments, and (4) the half monolayer of the H_2O mediated cesiaton, which would be the ideal cesiation, is also difficult to be produced uniformly on the PE surface due to its irreversibility.

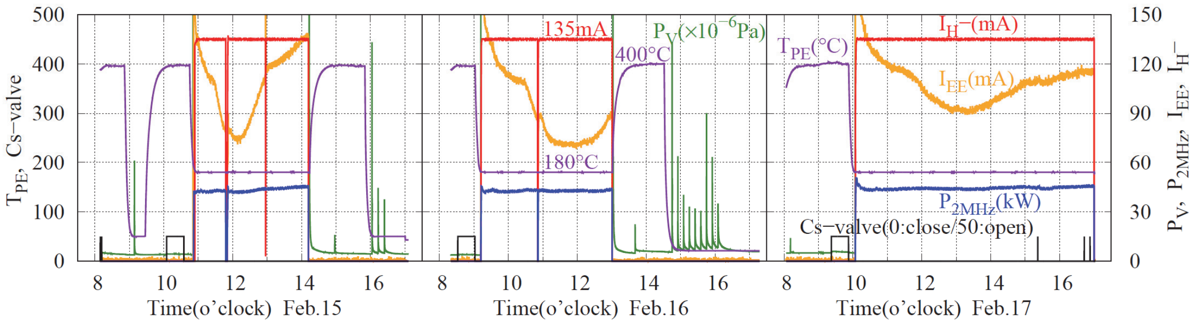

Figure 2. H_2O mediated cesiation procedure : (1) T_{PE} was increased to 400 ºC and keeping it about 1 hour, (2) T_{PE} was decreased to 30~50 ºC, (3) Every 10 min., H_2O injection was introduced 3 or 9 times, (4) Some of H_2O on PE was chemically bound with Mo in 16 hours, (5) after T_{PE} was increased to 400 ºC, Cs valve was opened for 30 min. at the T_{CsR} of 180 ºC (1.7 mg). (6) degree of H_2O mediated cesiation was examined by 72.5 keV 135 mA operation feedbacking P_{2MHz} at T_{PE} of 180 ºC.

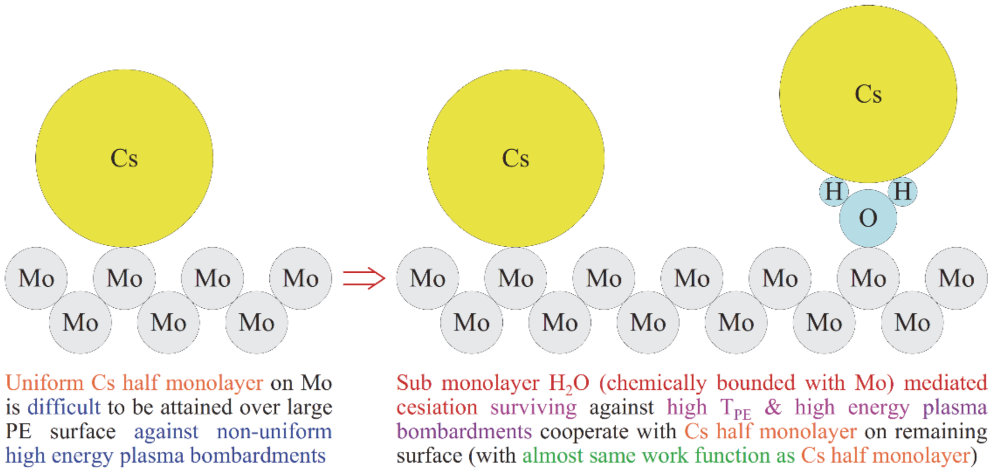

Figure 3. Hypothesis of the best cesiation constituted of H_2O (chemically bound with Mo) mediated cesiation and conventional one.

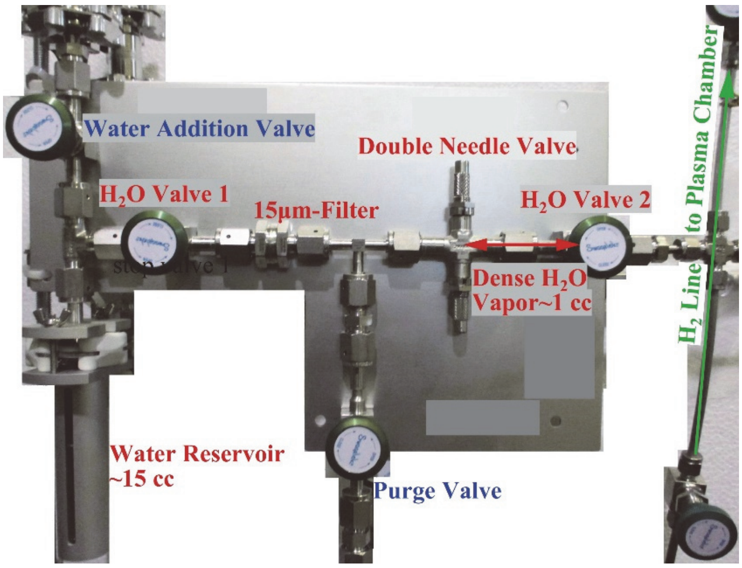

Figure 4. Photo of H_2O injector. One H_2O injection was defined as opening of H_2O valve 2 for 5 min. and ejecting about 1 cc dense H_2O vapor in the pipe between the double needle valve and valve 2. The dense H_2O vapor is created by opening valve 1 and the double needle valve for 5 min with closed valve 2. The 15µm-filter is used to avoid the double needle valve blockage. The variation of the H_2O quantity for one injection might be produced by the uncontrolled pipe temperature and so on.

Therefore, the following cesiation procedure (shown in Fig. 2) based upon a hypothesis of the best cesiation constituted of sub monolayer H_2O mediated cesiation and Cs half monolayer on remaining as shown in Fig. 3 was examined, after confirming the difficulty of the stable 72.5 keV 135 mA operations with no H_2O injection for about 30 days (240 hours). On 15-Feb-2023, at first, the T_{PE} was kept at about 400 ºC for 1 hour to reduce conventional cesiation. Secondary, one H_2O injection, which was produced by opening H_2O valve 2 for 5 min. shown in Fig.4 and ejecting dense H_2O vapour in the pipe with about 1 cc between the double needle valve and it stored by opening H_2O valve 1 and double needle valve for 5 min., was introduced on the PE surface after the T_{PE} decreased to less than 40 ºC. In the third, the Cs valve was opened for 30 min. at the Cs reservoir temperature (T_{CsR}) of 180 ºC (estimated injected Cs~1.7 mg) after the T_{PE} was increased to about 400 ºC. Finally, the degree of the H_2O mediated cesiation was examined by the 72.5 keV 135 mA operation feedbacking 2 MHz RF power (P_{2MHz}) at the T_{PE} of 180 ºC. As predicted from the short duration of about 30 min. after the H_2O injection before increasing the T_{PE} from 40 to 400 ºC, almost no H_2O mediated cesiation was formed due to the insufficient chemical reaction time between the H_2O and Mo. Therefore, the P_{2MHz} and I_{EE}

changed rapidly as shown in Fig. 2 left graph. The first H_2O mediated cesiation procedure was started form 14:14 of 15-Feb-2023 as follows. (1) The T_{PE} was increased to 400 ºC and keeping it about 1 hour. (2) The T_{PE} was decreased to 50 ºC. (3) Every 10 min., the H_2O injection was introduced 3 times. (4) Some of the H_2O on the PE was chemically bound with Mo in 16 hours. (5) At the start of 16-Feb-2023, after the T_{PE} was increased to 400 ºC, the Cs valve was opened for 30 min. at the T_{CsR} of 180 ºC. (6) The degree of the H_2O mediated cesiation was examined by the 72.5 keV 135 mA operation feedbacking 2 MHz RF power (P_{2MHz}) at the T_{PE} of 180 ºC. Although the time constants of the P_{2MHz} and I_{EE} changes shown in Fig. 2 centre graph were increased compared with those in Fig. 2 left graph, further increases of them were expected with another H_2O mediated cesiation procedure. The last H_2O mediated cesiation procedure was started from 13:01 of 16-Feb-2023 with 9 H_2O injections. Although the longer time constants of the P_{2MHz} and I_{EE} changes in the 72.5 keV 135 mA operation on 17-Feb-2023 were attained as shown in Fig. 2 right graph, the slightly excessive H_2O mediated cesiation was suggested by the increased minimum I_{EE} of 90 mA at 13:20 compared with that of 71 mA at 12:00 of Fig. 3 centre graph. After 6 days (48 hours) 72.5 keV 135 mA operations, the 76.5 keV 145 mA operations with the V_E of 15.1 kV were succeeded by increasing the highest V_E from 14.3 kV to about 16 kV.

4. 145 mA 8 hours operation and transverse emittance measurements

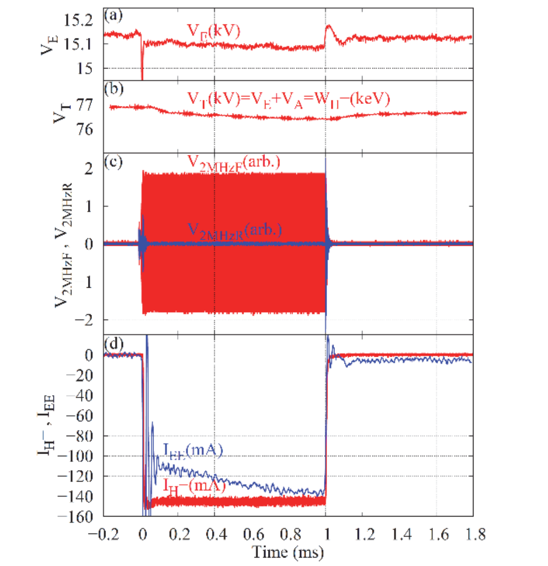

Figure 5. Measured waveforms of V_E (a), V_T (b), V_{2MHzF} and V_{2MHzR} (c) and I_{H^-} and I_{EE} (d) of one beam pulse.

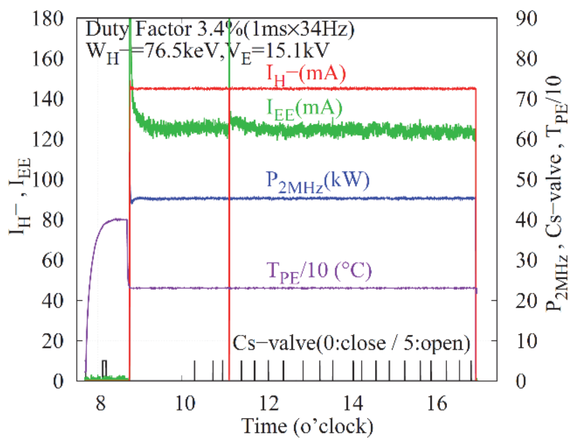

Figure 6. Trend graph of I_{H^-}, I_{EE}, P_{2MHz} and Cs-valve close/open during 8 hours operation of well-conditioned J-PARC-IS, in which I_{H^-}, was feedbacked to 145 ±1 mA by P_{2MHz}, for W_{H^-} and V_E of 76.5 keV and 15.1 kV, respectively.

In Fig. 5, the measured waveforms of the V_E (a), V_T (b), forward and reflected 2 MHz RF voltages (V_{2MHzF} and V_{2MHzR}) detected with -60 dB directional couplers (c) and I_{H^-} and I_{EE} (d) of one beam pulse are shown. By tilting up the 2 MHz RF Power (P_{2MHz}) by 0.9 % (from 45.9 to 46.3 kW) during the beam pulse, the flat I_{H^-} pulse of 145 mA was produced as shown in Fig. 5(d) for the T_{PE} of 230 ºC which is rather higher than the world standard of 180~200 ºC. The RF power efficiency is calculated as 3.15 mA/kW {145 mA / ((45.9+46.3)/2) kW}.

In Fig. 6, the trend graph of one working time (8 hours) operation with the (W_{H^-}, I_{H^-}) of (76.5 keV, 145 mA) and the beam duty factor of 3.4 % (1 ms × 34 Hz) are shown. The I_{H^-}, I_{EE}, P_{2MHz}, T_{PE}, and Cs-valve close/open (0/5) are shown with red, green, blue, violet, and black lines, respectively. The T_{PE}

was kept at 400 ºC for about 1 hour before the operation to remove the excess Cs on the PE surface attached at the plasma lights-out of the previous day operation end. Since the IS was well cesiated, the I_{H^-} of 145 mA was produced with P_{2MHz} of about 46 kW immediately and it was feedbacked within ±1 mA by the P_{2MHz}. The Cs feedback, which was the control sequence to open the Cs-valve automatically for 5 s when the P_{2MHz} was increased higher than 46 kW, was also started. For this operation, the T_{CsR} was set to 180 ºC. The injected Cs amount is estimated with the coefficient of 0.97 μg/sec derived from previous measurement. For the stationary state, the Cs injection rate was 14 μg/hour (totally 95 s Cs-valve open for 6.59 hours) which was about one third of that for the previous 69.9 keV 120 mA operation with the T_{PE} of 254 ºC. However, there was one high voltage sparking at about 11 o'clock, probably around the 2 MHz RF matching circuit.

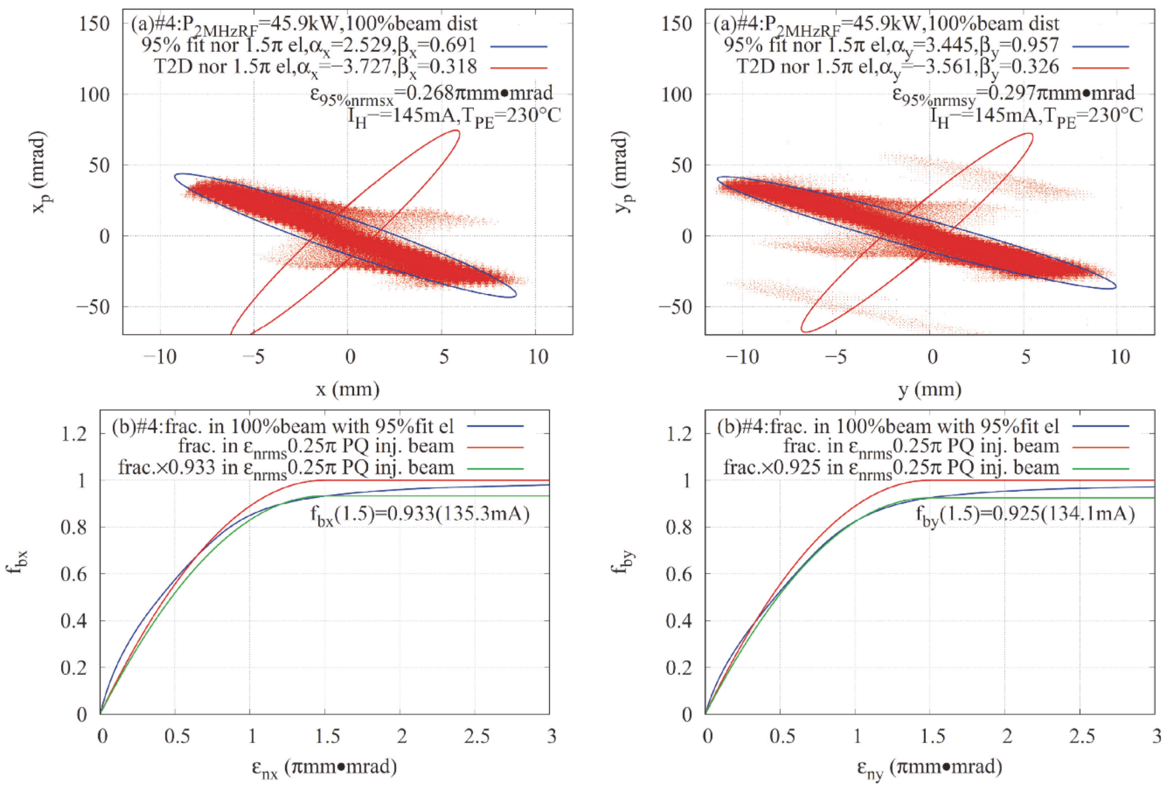

Figure 7. 100 % beam H⁻ ion distributions (red dots), fitted normalized 1.5 πmm·mrad ellipses fitting 95% beam (blue lines) and ellipses backward-traced to GE downstream surface with TRACE2D (T2D) (red lines) are plotted in horizontal (a) and vertical (b) phase-planes. For horizontal (c) and vertical (d) beam distributions, relationships between ε_{nx} and included f_{bx}, and ε_{ny} and included f_{by} in 100 % beams with ellipses fitting 95 % beams (blue lines), ε_{nx} and included f_{bx} in common PARMTEQ (PQ) injection beam with ε_{nxrms} of 0.25 πmm·mrad and ε_{nx} and included f_{bx} × 0.925 in PQ beam (b) for W_{H^-}, I_{H^-} and V_E of 76.4 keV, 145 mA and 15.1 kV, respectively.

The measured 100 % beam distributions in horizontal and vertical phase-planes for the (W_{H^-}, I_{H^-}, V_E) of (76.5 keV, 145 mA, 15.1 kV) are shown with red dots in Figs 7(a) and 7(c), respectively. The 1.5π mm•mrad ellipses fitting 95 % beam and backward traced to the GE downstream surface with Trace2D (T2D) [12] are also shown with blue and red lines in Figs 7(a) and 7(c), respectively. The 95 % beam horizontal and vertical normalized rms emittances ($\varepsilon_{95\%nrmsx}$ and $\varepsilon_{95\%nrmsy}$) are evaluated as 0.268 and 0.297π mm·mrad, respectively. The measured relationships between the horizontal and vertical normalized emittances (ε_{nx} and ε_{ny}) and beam fractions (f_{bx} and f_{by}) included in the ellipses fitting the 95 % beam are shown with blue lines in Figs. 7(b) and 7(d), respectively. The f_{bx} and f_{by} included in the injection beam distribution with the normalized rms emittances of 0.25π mm•mrad commonly used in the PARMTEQ (PQ) simulation [12] are plotted with red dashed lines as the

functions of ε_{nx} and ε_{ny} in Figs. 7(b) and 7(d), respectively. The 100 % beam normalized emittances of the PARMTEQ injection beam are 1.5π mm•mrad. The beam fractions for the PQ injection beam multiplied by the measured beam fractions in 1.5π mm•mrad {f_{bx}(PQ) × 0.941 and f_{by}(PQ) × 0.932} are also plotted with green lines as the functions of ε_{nx} and ε_{ny} in Figs. 7(b) and 7(d), respectively. By comparing the blue and green lines in Figs. 7(b) and 7(d), it is comprehended that the normalized rms emittances of the beam inside 1.5π mm•mrad (135.3 and 134.1 mA for horizontal and vertical phase planes, respectively) are smaller than those of the PARMTEQ injection beam. Therefore, the 134.1 mA of the measured beam is expected to be accelerated with the acceleration efficiency similar to that of the PARMTEQ simulation. The parameters of the J-PARC IS and test-stand for the 145 mA / 83 mA operation are listed in Table 1.
Just after the emittances measurements of the 76.5 keV 145 mA beam, the waveforms of V_E, V_T, P_{2MHzF}, P_{2MHzR}, I_{H}- and I_{EE} were also measured for the W_{H}- of 52.5 keV (V_E + V_A = 10.9 + 41.6 kV) being used for the J-PARC operation. By tilting down the P_{2MHz} by 2.9 % (from 31.3 to 30.4 kW) during the beam pulse, the flat I_{H}- pulse of 83 mA was produced, which was 11 mA higher than the highest I_{H}- of the J-PARC IS operations so far. The RF power efficiency is calculated as 2.69 mA/kW {83 mA / ((31.3+30.4)/2) kW}. The beam distributions in horizontal and vertical phase-planes were also measured and $\varepsilon_{95\%nrmsx}$ and $\varepsilon_{95\%nrmsy}$ were evaluated as 0.239 and 0.272π mm•mrad, respectively. Since the I_{H}-(52.5 keV) of 83 mA is consistent with the 1.5 power perveance law {145*(52.5/76.5)1.5~83}, the I_{H}-s were the space charge limited currents. If the design I_{H}- equal to or lower than 145 mA with an appropriate tolerance was determined, the optimum W_{H}- can be calculated by W_{H}- = 76.5 × (I_{H}- / 145)$^{2/3}$.

Table 1. Parameters of J-PARC RF-driven H⁻ ion source test-stand in 145 mA / 83 mA operation.

H_2 gas flow rate	17 SCCM
CW 30 MHz RF igniter power	43 W
2 MHz RF duty factor ~ Beam duty factor *Limited by radi. safety permis :I_{H-av}=5mA	3.4%(1ms×34 Hz) / 5%(1ms×50 Hz) *145 mA × 3.4 % = 4.93 mA
2 MHz RF power (P_{2MHz}) *Tilting during pulse for flat beam pulse	45.9~46.3kW / 31.3~30.4kW
RF power efficiency (I_{H}- / P_{2MHz})	145/46.1=3.15mA/kW / 83/30.9=2.69mA/kW
H^- ion density at PE (ϕ_{PE} = 9mm)	2279A/m^2 / 1305A/m^2
Plasma electrode temperature (T_{PE})	230˚C
Stationary state Cs injection rate *Mainly attached on low temp. part	14 / - μg/hour *Mainly not ejected
H^- ion beam energy (W_{H}-) = (V_E + V_A)	76.5(15.1+61.4)keV / 52.5(10.9+41.6)keV
1st sec. vacu. pumps & vacu. pressure	1500 L/s TMP×2 & 7×10^{-3} Pa
2nd section vacuum pump	500 L/s TMP
Solenoid magnet current	437A(61180AT) / 350A(4900AT)
Trans. emittances : $\varepsilon_{95\%nrmsx}$ & $\varepsilon_{95\%nrmsy}$	0.268&0.297πmm•mrad / 0.239&0.272πmm•mrad *0.268/0.239=1.12~βγ(76.5keV)/βγ(52.5keV)=1.21

5. Conclusions
With the novel cesiation based upon the hypothesis of H_2O (chemically bound with Mo) mediated cesiation, the J-PARC IS successfully produced I_{H}-(76.5 keV / 52.5 keV) of 145 mA / 83 mA. It was operated with (I_{H}-, W_{H}-, V_E, T_{PE}, duty factor) of (145 mA, 76.5 keV, 15.1 kV, 230 ºC, 3.4 %) for one working time (8 hours) with only one high voltage sparking probably around the 2 MHz RF matching circuit. For the stationary state, the I_{H}- was feedbacked to 145 ±1 mA by the P_{2MHz} and the Cs feedback,

in which the Cs injection rate was 14 μg/hour. The flat I_{H^-} of 145 mA / 83 mA beam pulse was produced by 0.9 % / -3 % tilting P_{2MHz} during the pulse. The superior $\varepsilon_{95\%nrmsx/y}(I_{H^-}, W_{H^-})$ of 0.268 / 0.297 (145mA, 76.5keV) π mm•mrad and 0.239 / 0.272 (83mA, 52.5keV) π mm•mrad were attained. The 134.1 mA (76.5keV) / 78.0 mA (52.5keV) of the beam is inside of PARMTEQ injection beam emittances. Therefore, the 134.1 mA (76.5keV) / 78.0 mA (52.5keV) of the measured beam is expected to be accelerated with the acceleration efficiency simulated with the PARMTEQ. Although the lower T_{PE} (down to 50 ˚C) produced the beam with the smaller $\varepsilon_{95\%nrmsx/y}$ in the J-PARC IS operation with the previous slight H_2Os injected cesiation, in the operation with the novel cesiation, the T_{PE} of 230 ˚C rather higher than the world standard of 180 ~ 200 ˚C produced the highest HPE without any $\varepsilon_{95\%nrmsx/y}$ enlargement.
In the next step, the optimized procedure to reproduce the optimum H_2O mediated cesiation should be established. Since there are so many parameters, such as the T_{PE} variations, how to inject H_2O and so on, it will take rather long time. The real physical state of the H_2O mediated cesiation is expected to be revealed from the procedure.

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