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Practical 2.45-GHz microwave-driven Cs-free H^- ion source developed at Peking University

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Chin. Phys. B . 2015, 24(6): 065205. **doi:** 10.1088/1674-1056/24/6/065205

Practical 2.45-GHz microwave-driven Cs-free H^- ion source developed at Peking University*

Tao Zhang(张滔), Shi-Xiang Peng(彭士香)†, Wen-Bin Wu(武文斌), Hai-Tao Ren(任海涛), Jing-Feng Zhang(张景丰), Jia-Mei Wen(温佳美), Teng-Hao Ma(马腾昊), Yao-Xiang Jiang(蒋耀湘), Jiang Sun(孙江), Zhi-Yu Guo(郭之虞), and Jia-Er Chen(陈佳洱)

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A practical 2.45-GHz microwave-driven Cs-free H^- source was improved based on the experimental H^- source at Peking University (PKU). Several structural improvements were implemented to meet the practical requirements of Xi'an Proton Application Facility (XiPaf). Firstly, the plasma chamber size was optimized to enhance the plasma intensity and stability. Secondly, the filter magnetic field and electron deflecting magnetic field were enhanced to reduce co-extracted electrons. Thirdly, a new two-electrode extraction system with farther electrode gap and enhanced water cooling ability to diminish spark and sputter during beam extraction was applied. At last, the direct H^- current measuring method was adopted by the arrangement of a new pair of bending magnets before Faraday cup (FC) to remove residual electrons. With these improvements, electron cyclotron resonance (ECR) magnetic field optimization experiments and operation parameter variation experiments were carried out on the H^- ion source and a maximum 8.5-mA pure H^- beam was extracted at 50 kV with the time structure of 100 Hz/0.3 ms. The root-mean-square (RMS) emittance of the beam is 0.25π·mm·mrad. This improved H^- source and extraction system were maintenance-free for more than 200 hours in operation.

Keywords: electron cyclotron resonance (ECR) ion source, hydrogen plasma, negative ion beam, plasma application

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1. Introduction

Along with the development of high power accelerators[1] and neutral beam injection for fusion[2] in recent years, there has been a sharp increasing demand for high current and high duty factor H^- ion sources. In the past decades, the mainstream H^- ion sources have been operated in low duty factor and the lifetime is limited by frail parts. The 2.45-GHz microwave-driven ion source has unique advantages presented for H^+ production, such as high power efficiency, high duty factor, high reliability, and long lifetime, and it could be a type of high-performance H^- ion source. Recently, an H^- ion source with 5 mA–10 mA H^- current before RFQ is required by Xi'an Proton Application Facility (XiPaf).[3] The H^- source should be maintenance-simple and has a long lifetime.

Therefore, the research on 2.45-GHz microwave-driven H^- ion source has been carried out at Peking University (PKU) ion source group and a prototype of microwave-driven H^- ion source which can produce 40-mA total current had been developed. Unfortunately, as a prototype, the plasma density within the source chamber was limited, and lots of electrons were co-extracted along with H^- ions which led to two problems. On the one hand, the sparks and sputtering during the beam extraction caused by the co-extracted electrons intensified the instability of the system. On the other hand, the current measured in the first Faraday cup (FC) was greater than the real H^- current, and the H^-/e fraction measuring method with weak measuring accuracy was applied to estimate the pure H^- current.[4] Therefore, the prototype source should be further improved.

In order to solve the above problems, a series of modifications were carried out. Firstly, a new plasma chamber was designed to promote microwave feeding; the filter magnetic field and electron deflecting magnetic field were enhanced to reduce the co-extracted electrons. Secondly, a new two-electrode extraction system with enlarged electrode gap and enhanced water cooling capacity was applied to diminish spark and sputtering during the beam extraction. Thirdly, the direct H^- current measuring method was adopted by the arrangement of a new pair of bending magnets before FC to remove residual electrons. Based on these improvements, electron cyclotron resonance (ECR) magnetic field was optimized to enhance ECR resonance efficiency and a series of parameter variation experiments were carried out.

2. Ion source improvements

The schematic diagram of H^- ion source is shown in Fig. 1. This microwave-driven H^- ion source can be briefly

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divided into microwave matching part, source chamber, and beam extraction system. The microwave is fed into the source chamber by dielectric window made of three pieces of Al_2O_3 ceramic and a piece of boron nitride to prevent electron bombardment. An improved two-electrode beam extraction system is applied. The source chamber is made of a water-cooled stainless steel cylinder, which is surrounded by a set of ring shaped Nd–Fe–B permanent magnets to generate ECR magnetic field. The plasma is generated by ECR heating. The source chamber is physically separated into the high temperature discharge chamber (ECR zone) and low temperature H^- formation region by the transversal filter magnetic field created by a pair of filter magnets inside the collar to prevent fast electrons from entering the H^- formation region. The highly vibrationally excited H_2^* are generated via E–V excitation process by collisions of ground state molecules with fast electrons in the discharge chamber[5]

$$H_2 + e(\text{fast}, 20\ \text{eV}) \rightarrow H_2^*(v) + e + h\nu. \tag{1}$$

As H_2^* molecules diffuse into the H^- formation region near the outlet, H^- ions are generated via dissociative attachment process by the collisions of highly vibrationally excited H_2^* with slow electrons

$$H_2^*(v) + e\ (\text{slow}, 1\ \text{eV}) \rightarrow H_2^- \rightarrow H + H^-. \tag{2}$$

The cross section of fast electron colliding with H_2^* to produce H^- is low, while the collision with fast electron is harmful for H^- ion. The filter field is arranged to prevent H^- ions from being destroyed by fast electrons. The experiments carried out by Hall *et al.*[6] showed that a wide spectrum of vibrationally excited molecules is formed by the recombinative desorption process of atomic hydrogen on some metal surfaces. Tungsten and tantalum are among the metals which produce molecules in high vibrational states, up to $v = 9$

$$H^\circ + H^\circ + \text{wall} \rightarrow H_2^*(v) + \text{wall}. \tag{3}$$

Therefore, a tantalum lining with thickness of 0.1 mm was installed inside the whole source chamber to enhance the H_2^* production. A pair of dipole magnets were embedded in the plasma electrode to deflect co-extracted electrons on the ground electrode.

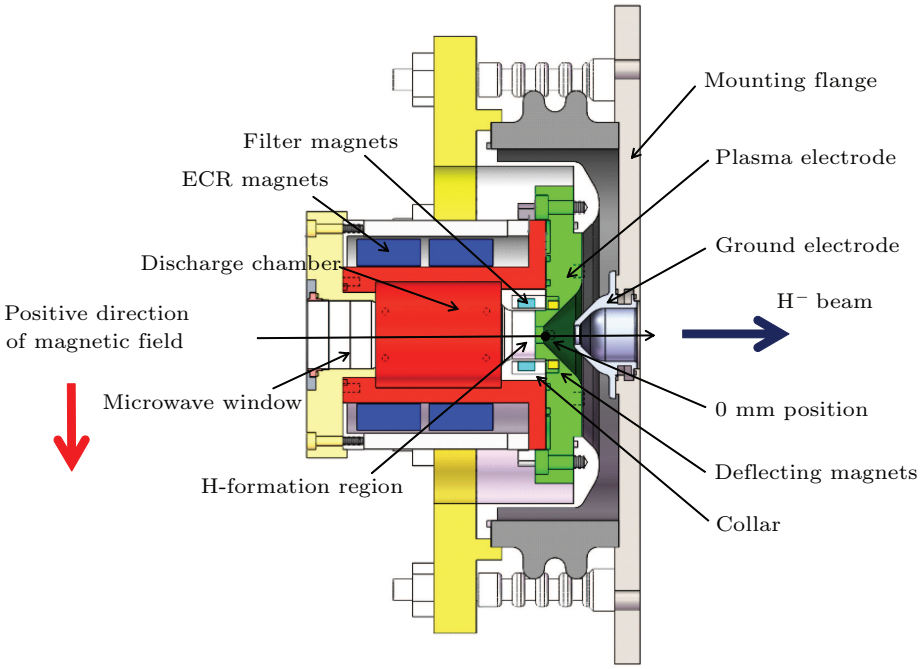


Fig. 1. (color online) Schematic picture of H^- source and the new two electrodes extraction system.

The diameter of the source chamber R has great influence on the microwave transportation and resonance, and a theoretic discussion is demonstrated firstly. When treating the source chamber as a resonance cavity, the electric field intensity E_0 of microwave could be demonstrated as follows:

$$E_0 = \sqrt{\frac{2Q_L P}{0.238\varepsilon\pi R^2 Z_0 \omega_L}}, \tag{4}$$

where P is the fed microwave power, Q is the quality factor of the chamber, ε is the relative permittivity, and Z_0 is the length of the chamber. E_0 is inversely proportional to R according to the formula. When R decreases, E_0 would increase and create higher intensity plasma.

At the same time, we can also treat plasma as dielectric for microwave transportation. The wavelength of electromagnetic wave in plasma can be shown as follows:

$$\lambda = \lambda_0/\sqrt{\varepsilon}, \tag{5}$$

where λ_0 is the wavelength of microwave in the air. When λ is smaller than the resonance cavity cutoff wavelength λ_c, mi-

crowave could transport in the plasma, so the critical condition could be demonstrated as following:

$$\lambda_0/\sqrt{\varepsilon} \leq \pi R. \tag{6}$$

λ_c would decrease as R decreases. When $\lambda = \lambda_c$, the diameter R equals R_{min}. When $R < R_{min}$, the microwave cannot be fed in, and the plasma density would decrease. Based on the above analyses, there is an optimal diameter R for source chamber.

During the previous experiments, the microwave feeding was inefficient, which led to the limitation of plasma intensity and erosion of microwave window by the reflected microwave. The main reason is that the previous ϕ40-mm source chamber was undersized for the rated microwave power of 5400 W, and the H^- current was limited accordingly, thus the diameter R should be enlarged to enhance the plasma stability and intensity. Therefore, a new plasma chamber was designed and installed, the diameter of plasma chamber was increased from 40 mm to 50 mm, and its length from the microwave window to the outlet was increased from 69 mm to 75 mm. Meanwhile, the H^- formation region maintained the same with a diameter of 23 mm and a height of 16 mm, and the outlet aperture diameter was kept as 8 mm. Figure 2 is the photograph of the modified H^- ion source.

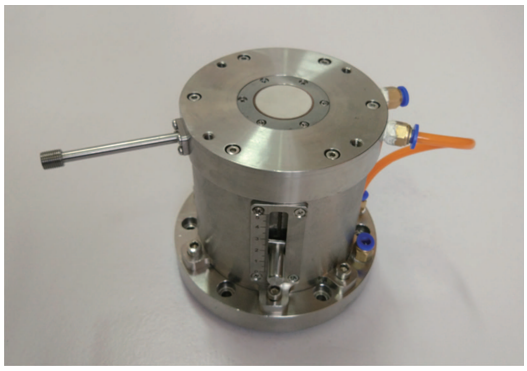


Fig. 2. (color online) Photograph of modified applied H^- source.

At the same time, in order to eliminate the co-extracted electrons, the filter field and deflect field were strengthened carefully, and the expanding experiments of these magnetic fields and theoretical analysis will be given in another article. The configuration of these adjusted magnetic fields on the axis is shown in Fig. 3. The magnetic field between −25 mm and 0 mm which was inside the plasma represents the filter field, the magnetic field between 0 mm and 10 mm which was placed in the extraction system represents the deflect field. The peak filter field on the axis was increased from 350 Gs (1 Gs = 1.0^{-4} T) to 580 Gs to decrease the electron density in H^- formation region by using magnets with stronger magnetic field without the decrease of H^- beam current, and the peak deflect magnetic field was strengthened largely from 150 Gs to 270 Gs by moving deflect magnets from outside of the main source into the plasma electrode until there were almost no electrons entrancing the Faraday cup. For the three-electrode system, the electrode gap between plasma electrode and suppression electrode was 12 mm, the deflected co-extracted electrons would be accelerated and hit the suppression electrode, leading to the sparks of extraction system. To reduce the sparks, several improvements were made for the new succinct two-electrode extraction system. Firstly, for the design of two-electrode extraction, the suppression electrode was removed from the system and the electrode gap between plasma electrode and ground electrode was set as 14.5 mm. Secondly, the sputtering caused by high strength thermal load from electron bombardment on the electrode was taken into account. After the long time running, the sputtering would lead to the electrode rupturing and material deposition on insulation ceramic. Method to solve this problem was to thicken the ground electrode from 1.0 mm to 2.8 mm and expand the cross-sectional area of water tunnel from 11.25 mm^2 to 40.50 mm^2 to strengthen the water cooling capacity of the electrode.

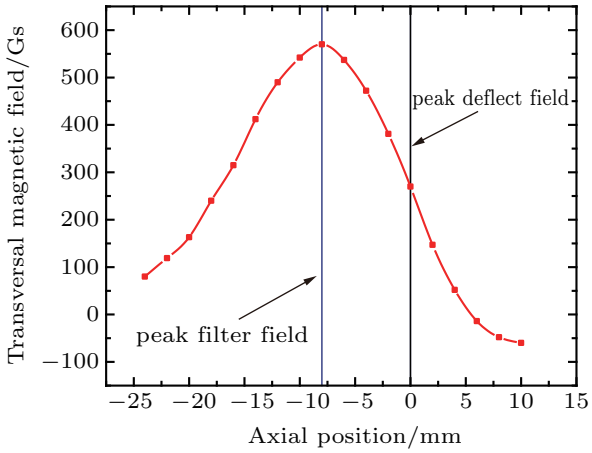


Fig. 3. (color online) The transversal magnetic field at axis of Φ50 mm H^- ion source (0 mm position represents the outer edge of the plasma electrode extraction hole which is labeled in Fig. 1, and the arrow of the axis in Fig. 1 points in the positive direction.)

Although most of the co-extracted electrons were diminishing by the strengthened filter field and deflect magnetic field as discussed above, there would still be little residual electrons in the extracted H^- beam. After the H^- beam was extracted, a pair of bending magnets with 50-Gs transverse magnetic field on the axis was implemented at two sides of the main vacuum chamber to diminish the residual electrons. So a direct H^- current measuring method with the FC was applied, and the structure details of the Faraday cup could be seen in Ref. [7]. With these improvements, this practical 2.45-GHz microwave-driven Cs-free H^- ion source was tested on the ion source (IS) test bench of PKU.[4] The IS test bench consists of an H^- ion source with its microwave system and extraction system, a vacuum chamber containing an FC to measure H^- beam, and a multi-slit single-wire (MSSW) beam emittance monitor. Figure 4 shows the layout of the IS test bench at PKU.

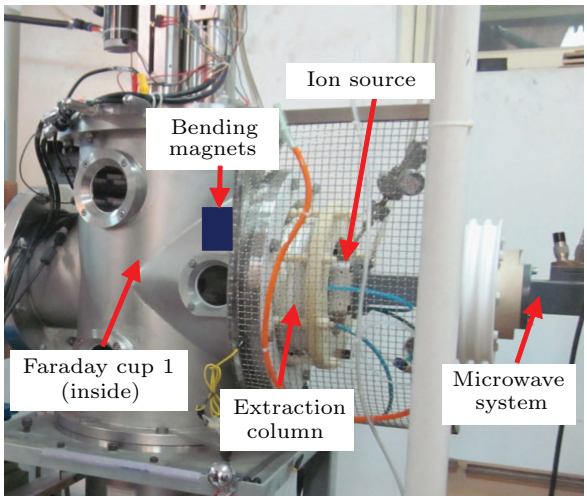


Fig. 4. (color online) Ion source test bench of PKU.

To ensure the measurement accuracy of the H^- beam current, a validation experiment of the practical H^- ion source with helium discharge was carried out. With a microwave power of 2200 W (repetition frequency: 100 Hz, pulse width: 0.3 ms), a gas pressure of 1×10^{-3} Pa, and an extraction voltage of 50 kV, almost zero electron current was measured in the FC, and the oscillograph of the current is shown in Fig. 5.

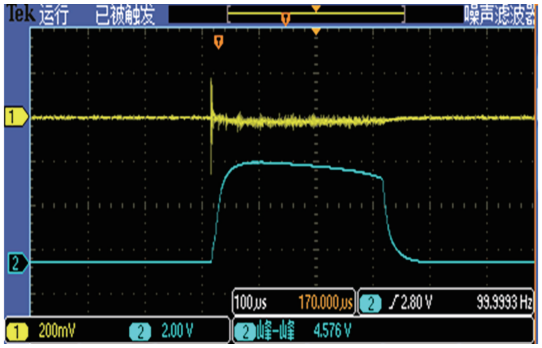


Fig. 5. (color online) Zero electron current of H^- source under helium discharge (No. 2 signal represents the fed microwave intensity; No. 1 signal represents the voltage measured in the Faraday cup).

After the commissioning of the ϕ50 mm H^- ion source, an H^- beam extraction experiment was carried out, and the experimental conditions are shown as following:

(i) microwave power: 5400 W (100 Hz/0.3 ms);

(ii) pressure: 6.7×10^{-3} Pa;

(iii) extraction voltage: −35 kV.

At this condition, a 4.8-mA pure H^- current was measured in the Faraday cup.

3. Results and discussion

After the ϕ50 mm H^- ion source was completed and the H^- current measuring method was verified, a series of experiments were carried out to explore the performance of the H^- ion source. Firstly, for the non-optimized ECR magnetic field, the microwave power absorbed in the plasma chamber would be inefficient which led to the low microwave coupling efficiency and plasma instability, and then a series of experiments were carried out on the ϕ50 mm H^- ion source to find the optimum magnetic field near the microwave window and ECR resonance region. Secondly, to test the performance of the improved H^- source, a series of experiments were carried out by changing the source operation parameters, including gas pressure and duty factor of microwave. Thirdly, to validate the stability of the H^- source and extraction system, the beam extraction experiments had been carried out on the source system for more than 200 hours.

The experiments to find the optimum magnetic field near the microwave window and ECR resonance region on the ϕ50 mm H^- ion source include

i) the H^- current varies with the magnetic field intensity in the ECR resonance region by adding pure iron layer(s) of 0.3 mm at the periphery of the ECR magnet rings, and the comparisons of different magnetic field intensities are shown in Fig. 6;

ii) the H^- current varies with the magnetic field intensity near the microwave window by moving ECR magnet rings in the axial direction.

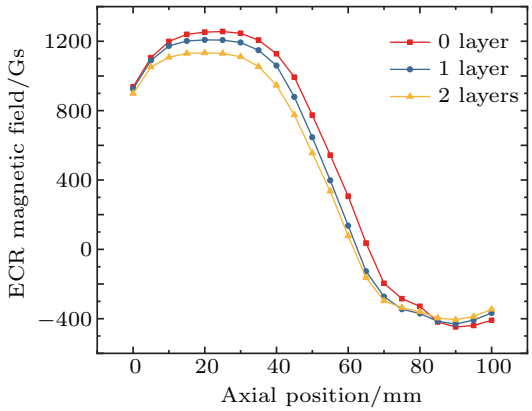


Fig. 6. (color online) Different ECR magnetic field intensities by adding layer(s) of 0.3-mm pure iron (0 position is the microwave window; the magnetic field was measured by means of gaussmeter).

The experimental conditions are shown below.

(I) microwave power: 5400 W (100 Hz/0.3 ms);

(II) pressure: 5×10^{-3} Pa;

(III) extraction voltage: −35 kV.

The experiment results of the H^- current as a function of the ECR magnetic field intensity are shown in Table 1. At the condition of one layer of pure iron with a magnetic field intensity of 1185 Gs, the H^- current reaches the maximum of 6.5 mA.

The wave vector of microwave of a pure ECR model must be vertical to the magnetic field, but the off-resonance model

just requires the wave vector to keep an angle θ with the magnetic field through the model transition in the plasma, which relaxes the restriction to resonance.[8] When the magnetic field intensity within the resonance region was optimized to about 1200 Gs, the best effect of off-resonance wave plasma interaction was achieved.

Table 1. Experiment results of H^- current as a function of the ECR magnetic field intensity.

Layer of pure iron	Length/mm	Magnetic field/Gs	H^- current/mA
0	66	1250	6.2
1	66	1185	6.5
2	66	1130	5.6

Figure 7 represents the experiment results of the H^- current as a function of the axial position of the ECR magnet rings with one layer of pure iron. The 0 position denotes the initial position, and the magnetic field intensity near the microwave window $B_{\rm fed}$ is about 875 Gs. The positive value means the magnet rings moving to the microwave window, and $B_{\rm fed}$ is higher than 875 Gs; the negative value means the magnet rings moving to the extraction system position, and $B_{\rm fed}$ is lower than 875 Gs. The H^- current achieves a maximum of 6.5 mA at the initial position, and the best $B_{\rm fed}$ is about 875 Gs.

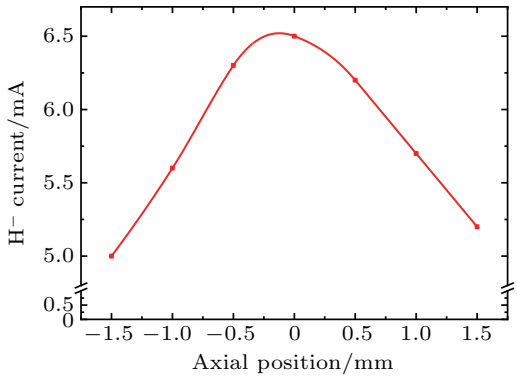


Fig. 7. (color online) The H^- current varies with the ECR ring axial position of the Φ50 mm H^- ion source.

Because the microwave window is at the edge of the plasma, the microwave near the window is hard to go through model transformation to achieve off-resonance ECR model when $B_{\rm fed}$ is higher than 875 Gs. When $B_{\rm fed}$ is about 875 Gs, the microwave near the microwave window would be absorbed sufficiently by classical ECR resonance.

To test the performance of the improved H^- source, the operation parameter variation experiments are shown as following. A series of experiments were carried out under different pressures from 4.0×10^{-3} Pa to 7.0×10^{-3} Pa at a fixed microwave power of 5400 W. The pulse width was 1 ms with a frequency of 100 Hz. Another series of experiments were also done under different duty factors from 1% to 10% at a repetition frequency of 100 Hz with a fixed microwave power of 2800 W and a gas pressure of 7.0×10^{-3} Pa.

The experiment results of the variation of pulsed H^- current under different pressures at a fixed microwave power of 5400 W are displayed in Fig. 8. There was an optimal pressure for the H^- current under each extraction voltage. For instance, at the extraction voltage of 50 kV, the H^- current was 6.6 mA at a pressure of 4×10^{-3} Pa. As pressure increased up to 5.5×10^{-3} Pa, the H^- current was increased to the highest value of 8.5 mA, as shown in Fig. 9. Its normalized root-mean-square (RMS) beam emittance was 0.25π·mm·mrad, as shown in Fig. 10. When the pressure increased to 7.0×10^{-3} Pa, the H^- current decreased to 7.6 mA. In other words, the H^- current would reach the maximum at a certain pressure.

This non-monotonic trend can be explained as following. When the gas pressure increases in the 2.45-GHz microwave driven source, the temperature of the vibrationally excited hydrogen molecules increases as well,[9] which leads to the enhance of the H^- current. The collision with hydrogen atoms is the key factor for the destruction of H^- ion.[5] When the pressure continues to increase, the density of hydrogen atoms would increase as well,[10] and the H^- ion would be severely destroyed during its transportation from the H^- formation region to the outlet. The H^- current would decrease accordingly.

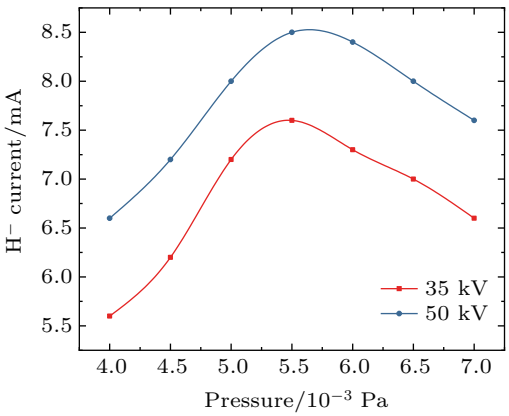


Fig. 8. (color online) The H^- current under different pressures with a fixed microwave power at the extraction voltages of 35 kV and 50 kV. The background pressure is 5×10^{-5} Pa.

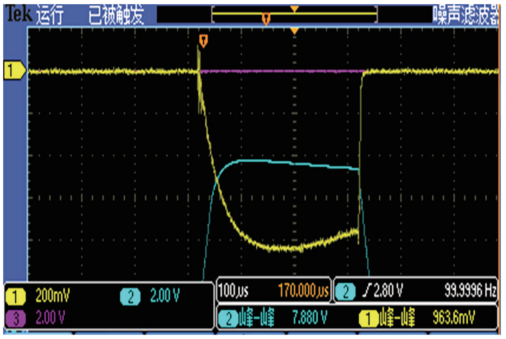


Fig. 9. (color online) The peak H^- current of 8.5 mA (No. 2 signal represents the fed microwave intensity; No. 1 signal represents the voltage measured in the Faraday cup).

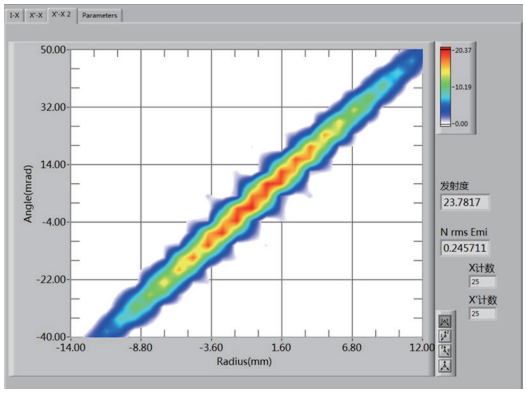


Fig. 10. (color online) The RMS beam emittance of the 8.5-mA H^- beam.

The experiment results of the variation of H^- current under different duty factors are displayed in Fig. 11. Under the extraction voltage of 50 kV, the H^- current was increased from 2.5 mA at 1% to a peak value of 5.2 mA at 4%, and then the H^- current would almost keep constant and was slightly decreased to 4.9 mA at 10%. The trend of H^- current under the extraction voltage of 35 kV was similar to that of 50 kV.

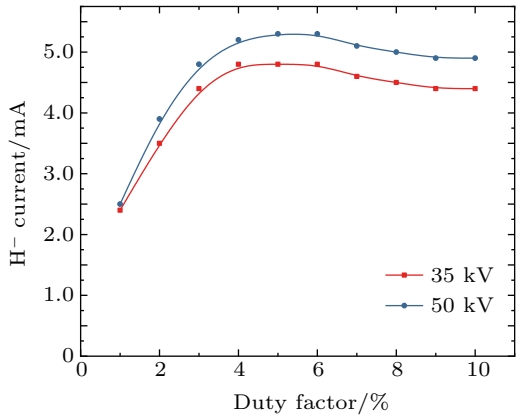


Fig. 11. (color online) The H^- current under different duty factors with a fixed microwave power and pressure at extraction voltages of 35 kV and 50 kV. The background pressure is 7.0×10^{-3} Pa.

As the duty factor of the microwave power is lower than 4%, the pulse width is also lower than 0.4 ms, which is not enough to ignite and maintain stable plasma. The oscillogram with a pulse width of 0.1 ms is shown in Fig. 12(a); the waveform had a slow rising edge and the H^- current did not reach the steady state, which decreased the H^- average value of the pulse. As the pulse width increased, the discharge would be more sufficient, and the H^- current would increase as well. As the pulse width reached 0.4 ms, the discharge became stable, and the H^- current reached the maximum of 5.2 mA. The oscillogram with a pulse width of 0.4 ms is shown in Fig. 12(b) and the waveform is stable. As the pulse width continued to increase, the H^- current would almost keep constant. The oscillogram with a pulse width of 0.7 ms is shown in Fig. 12(c); as the discharge continued in the pulse, the H^- current just decreased a little, so the H^- current mean value almost kept constant.

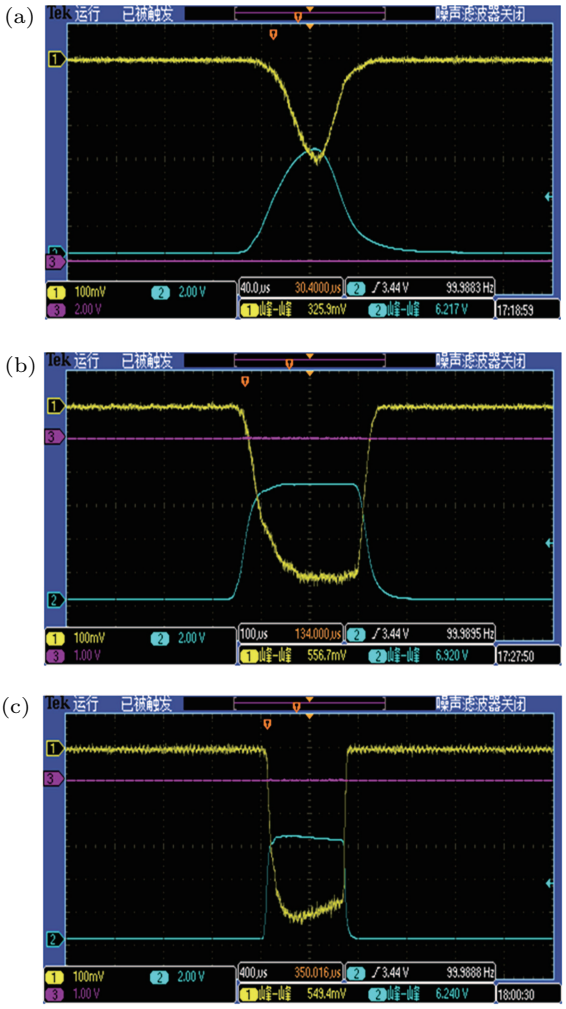


Fig. 12. (color online) At the condition of 50 kV extraction voltage and 7×10^{-3} Pa pressure. (a) The oscillogram at Faraday cup of pulse width of 0.1 ms; (b) the oscillogram at Faraday cup of pulse width of 0.3 ms; (c) the oscillogram at Faraday cup of pulse width of 0.7 ms (No. 2 signal represents the fed microwave intensity, and No. 1 signal represents the voltage measured in the Faraday cup).

To validate the stability of the H^- source and extraction system, the beam extraction experiments had been carried out on the source system for more than 200 hours. Figure 13 shows the condition of the upgraded high voltage extraction system after more than 200 hours running under a microwave power of 2800 W–5400 W in the pulsed model with a repetition frequency of 100 Hz and a pulse width of 0.3 ms at 35 kV–50 kV extraction voltage. The ground electrode in Fig. 14 was intact and kept smooth, and there was no deposit in the ceramic after more than 200 hours' experiments. It indicates that the optimized electrode can hold the electron heat deposit and no sputtering occurred. Both the H^- source and the extraction system are in good condition during the extracted H^- beam for a longtime. The extraction system and source body have a long lifetime and their maintenance is easy.

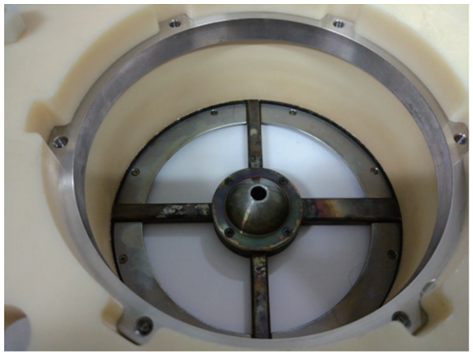


Fig. 13. (color online) The upgraded high voltage extraction system after more than 200 hours' experiments.

4. Conclusion

In conclusion, the ion source can produce several milliampere H^- current under a duty factor of 3%10% and the peak H^- current could reach 8.5 mA with normalized RMS beam emittance of 0.25 mm·mrad. This H^- source is intact and the extraction system has no spark or sputtering during the long time experiments. It basically meets the demand of the application of XiPaf project. As the first applied microwave-driven H^- ion source, this ion source has its unique advantages of high power efficiency, Cs-free, and long lifetime. By continually increasing the microwave power fed in and conducting further improvement, it has the potential for the long demand for scientific and application fields.

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