

New progress on DC H_2^+ beam generation: Tens of mA output and 70% fraction from a 2.45 GHz microwave driven ion source

Bujian Cui(崔步坚), Shixiang Peng(彭士香), Jianbin Zhu(朱建斌), Yicheng Dong(董宜承), Zhiyu Guo(郭之虞), and Jiaer Chen(陈佳洱)

Citation: Chin. Phys. B, 2025, 34 (**8**): 085203. DOI: 10.1088/1674-1056/adf1ec
http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Power transfer efficiency in an air-breathing radio frequency ion thruster

Gao-Huang Huang(黄高煌), Hong Li(李宏), Fei Gao(高飞), and You-Nian Wang(王友年)
Chin. Phys. B, 2024, 33 (**7**): 075201. DOI: 10.1088/1674-1056/ad426c

Transition from a filamentary mode to a diffuse one with varying distance from needle to stream of an argon plasma jet

Hui-Min Xu(许慧敏), Jing-Ge Gao(高敬格), Peng-Ying Jia(贾鹏英), Jun-Xia Ran(冉俊霞), Jun-Yu Chen(陈俊宇), and Jin-Mao Li(李金懋)
Chin. Phys. B, 2024, 33 (**1**): 015205. DOI: 10.1088/1674-1056/ad0149

Fluid-chemical modeling of the near-cathode sheath formation process in a high current broken in DC air circuit breaker

Shi-Dong Peng(彭世东), Jing Li(李静), Wei Duan(段薇), Yun-Dong Cao(曹云东), Shu-Xin Liu(刘树鑫), and Hao Huang(黄浩)
Chin. Phys. B, 2024, 33 (**1**): 015204. DOI: 10.1088/1674-1056/acd7cb

Surface enhancement of molecular ion H_2^+ yield in a 2.45-GHz electron-cyclotron resonance ion source

Yuan Xu(徐源), Shi-Xiang Peng(彭士香), Hai-Tao Ren(任海涛), Ai-Lin Zhang(张艾霖), Tao Zhang(张滔), Jing-Feng Zhang(张景丰), Jia-Mei Wen(温佳美), Wen-Bin Wu(武文斌), Zhi-Yu Guo(郭之虞), Jia-Er Chen(陈佳洱)
Chin. Phys. B, 2017, 26 (**8**): 085203. DOI: 10.1088/1674-1056/26/8/085203

New progress on beam availability and reliability of PKU high intensity CW proton ECR ion source

Shi-Xiang Peng(彭士香), Ai-Lin Zhang(张艾霖), Hai-Tao Ren(任海涛), Yuan Xu(徐源), Tao Zhang(张滔), Jing-Feng Zhang(张景丰), Jia-Mei Wen(温佳美), Zhi-Yu Guo(郭之虞), Jia-Er Chen(陈佳洱)
Chin. Phys. B, 2017, 26 (**2**): 025206. DOI: 10.1088/1674-1056/26/2/025206

LETTER

New progress on DC H_2^+ beam generation: Tens of mA output and 70% fraction from a 2.45 GHz microwave driven ion source

Bujian Cui(崔步坚), Shixiang Peng(彭士香)†, Jianbin Zhu(朱建斌), Yicheng Dong(董宜承), Zhiyu Guo(郭之虞), and Jiaer Chen(陈佳洱)

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, *China*

(Received 14 July 2025; revised manuscript received 18 July 2025; accepted manuscript online 19 July 2025)

Recently H_2^+ ion beam finds widespread use in many fields, and the demand of high-current H_2^+ ion sources is urgent for numerous applications. However, there are currently almost no reported ion sources capable of generating a direct-current (DC) H_2^+ beam with tens of mA current. In previous work at Peking University (PKU), H_2^+ ion beams with a current of over 40 mA have been obtained in pulse mode, and a current of 16 mA was achieved in DC mode. In this paper, we report the generation of a DC H_2^+ ion beam with a current of 22 mA extracted from an improved miniaturized microwave driven ion source (MMDIS). Beam analysis shows that the H_2^+ fraction in the extracted beam is about 70%. The emittance of the mixed hydrogen beam is about 0.12 $\pi \cdot$ mm $\cdot$ mrad. These results provide references for the applications of H_2^+ beam and the design of H_2^+ ion source.

Keywords: H_2^+ ion beam, direct-current (DC) operation, 2.45 GHz microwave, high current

PACS: 52.50.Dg, 52.50.Sw, 52.59.–f

DOI: 10.1088/1674-1056/adf1ec **CSTR:** 32038.14.CPB.adf1ec

1. Introduction

H_2^+ ion beams are widely used in many scientific fields such as particle accelerators, medical science, material irradiation modification, astrophysics, and atomic physics. In the 1950s, the H_2^+ ion beam was already being used in cyclotron accelerators.[1] Isotope Decay-At-Rest (IsoDAR) is an early phase of the DAEδALUS project, which aims to test sterile neutrino hypotheses.[2] To supply 10 mA of 60 MeV protons while accounting for cyclotron beam loss and acceleration efficiency, the experiment demands an H_2^+ ion source with an output higher than 25 mA.[3,4] Moreover, since the D^+ accelerator generates intense neutron radiation during operation and commissioning, it poses a threat to the safety of surrounding equipment and personnel. Therefore, H_2^+ ions can be used for commissioning to reduce equipment activation and ensure the safety of accelerator operators.[5–7] In medical science, to reduce costs of expensive heavy-ion cancer therapy accelerators (e.g., for C^{4+}/C^{6+}), reusing them to accelerate cluster ions with identical charge-to-mass ratios is desirable. For example, the Heavy Ion Medical Accelerator in Chiba (Japan) HIMAC, treating cancer with C^{4+} beam, also accelerates H_3^+ beam.[8] Italy's TERA rapid-cycling synchrotron delivers both $^{12}C^{6+}$ for carbon therapy and H_2^+ beam for research.[9] In the field of material science, hydrogen ion beams ($H^+/H_2^+/H_3^+$) are frequently employed for various material irradiation damage studies, with efforts made to explore their equivalence to neutron irradiation.[10] For H_2^+ ions, studies have investigated the effects of H_2^+/He^+ beams on tungsten materials,[11] and the defect evolution within pure iron through triple-beam $H_2^+/He^+/Fe^+$ in fusion reactors.[12] In astrophysics, H_2^+ ions are frequently utilized in research on stellar winds and interstellar matter.[13,14] In the field of atomic physics, the interaction of H_2^+ ions with solid surfaces is widely investigated.[15,16]

To generate H_2^+ ions, one can choose from various types of ion sources, like filament-driven multicusp ion source,[17] volume type ion source,[18] hollow cathode ion source,[19] and electron cyclotron resonance (ECR) ion source.[20] Among these ion beam generators, the filament type ion sources, while effective in many respects, are inherently limited by beam intensity.[21] For example, researchers from the Massachusetts Institute of Technology (MIT) utilized a filament-driven multicusp ion source (MIST-1) to generate an H_2^+ ion beam of approximately 1.3 mA in direct-current (DC) mode, its ion fraction was about 62%.[22] Recently, the MIST-2, an upgraded version of MIST-1, has achieved a total extracted current of 7 mA, and the H_2^+ fraction was estimated to be 60% based on previous experience (information from oral discussion). The volume ion source can achieve a high H_2^+ ion fraction but low beam current. For example, the source at the Goethe University in Germany produced a 2.8 mA H_2^+ ion beam with a 95% ion fraction.[18] The hollow cathode ion sources usually have limited lifespan due to cathode sputtering,[23] and the fraction of H_2^+ ions is low. For instance, the Siberian Branch of the

†Corresponding author. E-mail: sxpeng@pku.edu.cn

© 2025 Chinese Physical Society and IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved.

Russian Academy of Sciences has developed a hollow cathode ion source with an H_2^+ fraction of only 20%, and the maximum H_2^+ current was about 5 mA.[19] ECR ion sources, featuring high beam current, low emittance, simple structure, and long operational lifetime, are highly suitable for generating H_2^+ ions. In 2008, INFN developed an ECR ion source named Versatile Ion Source (VIS) for the DAEδALUS project, which was designed to provide 25 mA of H_2^+ beam with a fraction of 80%. However, limited by the relatively low H_2^+ ion fraction of only 45%, the extracted H_2^+ beam current was 12.2 mA with a beam emittance of 0.4 $\pi \cdot$mm$\cdot$mrad,[24] so this VIS designed for the DAEδALUS project failed to meet the requirements. The China Institute of Atomic Energy (CIAE) has also conducted research on H_2^+ ion sources, aiming to obtain several mA of hydrogen molecular ion beams through a 2.45 GHz ECR ion source for use in cyclotrons.[25] However, no subsequent reports on the ECR source have been published. Peking University (PKU) started to do research on cluster ion generation by ECR ion sources in 2013. Earlier investigations, using a permanent magnet ECR source, have yielded over 40 mA of H_2^+ ion beam in pulse mode.[26,27] Subsequently, a miniaturized microwave driven ion source (MMDIS) was developed to produce a 16.1 mA H_2^+ ion beam in DC mode, demonstrating a very high beam to power efficiency.[28] Recently, modifications were made for this novel miniaturized ion source to improve the performance for H_2^+ production in DC operation.

This paper proceeds as follows. In Section 2, we introduce the details of the miniaturized microwave driven ion source and discuss the principle of H_2^+ ion generation. Section 3 introduces the experimental setup at PKU. In Section 4, we present new progress of DC H_2^+ ion beam generation from the MMDIS. In the DC mode, a H_2^+ beam over 22 mA was obtained at an energy of 30 keV. In the extracted hydrogen beam, H_2^+ beam was found to be dominant with a fraction of approximately 70%. The RF power consumption was about 150 W. The normalized RMS emittance of the mixed beam was about 0.12 $\pi \cdot$mm$\cdot$mrad. In Section 5, we provide a brief summary and prospect.

2. Miniaturized microwave driven ion source

The miniaturized 2.45 GHz microwave driven ion source at PKU comprises a microwave window, discharge chamber, cooling system, permanent magnets, and an extraction system. Table 1 presents some specific parameters of the source body. And the schematic view of the source is shown in Fig. 1. The microwave window consists of three alumina blocks, the thickness is $\lambda/4$ for each block, and a piece of boron nitride is installed at the end to protect the window against plasma bombardment. The dielectric constants of these components are relatively high, which ensures the transmission of 2.45 GHz microwave. Due to the extremely small size of the ion source, 2.45 GHz microwave with a cut-off size of 72 mm cannot directly propagate inside the discharge chamber. However, when the microwave propagates to the boundary between the boron nitride and the discharge chamber, the surface wave is generated due to the dielectric mismatch. Based on this, a hybrid discharge heating (HDH) model combining surface wave excitation and ECR heating was proposed to explain the ignition issue of the miniaturized ion sources at PKU.[29] Our previous investigation revealed that the surface wave plays a dominant role in the ignition process of the microwave driven ion source and facilitates the continuous progress of the discharge.[30] In addition, the axial magnetic field near the microwave window is approximately 875 Gs, which satisfies the ECR condition, thereby contributing to the maintenance of a high-density plasma. The diagnosis results showed that the electron density in the plasma chamber could reach 10^{19} m^{-3}.[31] Due to the combined effect of surface wave and ECR process in the discharge, the source is called a miniaturized microwave driven ion source (MMDIS). To solve the thermal issues during the DC discharge process, the source cooling system was optimized to provide sufficient cooling capacity for the microwave window and the source body to maintain stability. A bimodal magnetic field distribution was used to produce singly charged ions,[32] and the magnetic field strength is shown in Fig. 2. The maximum and minimum magnetic field strengths on the axis are 880 Gs and 600 Gs, respectively, forming a mirror ratio of about 1.47.

Table 1. Some parameters of the miniaturized microwave driven ion source body.

Parameters	Value
Whole size	Φ60 mm $\times$ 100 mm
Chamber size	Φ24mm $\times$ 50 mm
Weight	2.1 kg
Extraction aperture	Φ6 mm
Magnetic field (axial)	B_{max} = 880 Gs
Mirror ratio (axial)	1.47
Cooling water pressure	2.0 MPa

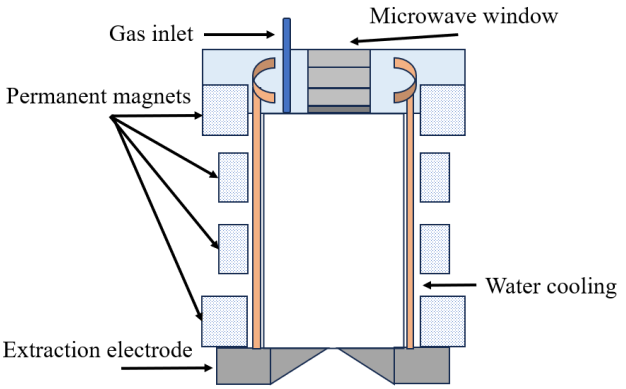


Fig. 1. A schematic view of the miniaturized microwave driven ion source at PKU.

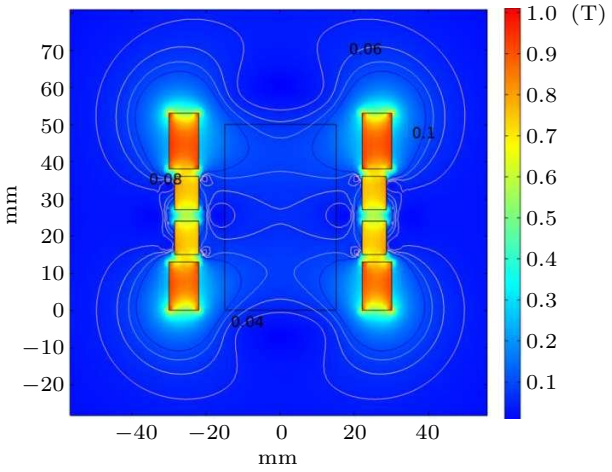


Fig. 2. The magnetic field distribution of the miniaturized microwave driven ion source.

In order to optimize this ion source to produce H_2^+ ions with a high fraction, it is vital to understand the principles of H_2^+ formation and loss processes. Hydrogen plasma contains electrons, photons, atoms, molecules, ions, and their metastable, vibrational and rotational states. Therefore, the interaction processes within the plasma chamber are highly complex, encompassing collision, ionization, attachment, recombination, charge exchange, and interactions with the chamber walls. The main reactions inside a hydrogen plasma are listed in Table 2.[33,34] In general, H_2^+ ions are produced by electron collision ionization of hydrogen molecules and lost via dissociation processes. As presented in Table 2, the cross section of the direct ionization of H_2 reaches a maximum at 70 eV and then gradually decreases as the electron energy increases. Research shows that the average electron temperature of 2.45 GHz hydrogen plasma is usually lower than 20 eV and drops sharply with the increase in gas pressure.[35] Therefore, to generate more H_2^+ ions, the operating pressure inside the plasma chamber needs to be kept low. On the other hand, reducing the gas pressure also helps to increase the mean free path of H_2^+ ions, which is favorable for reducing H_2^+ losses since the probability of colliding with neutral particles is decreased. Additionally, the dissociation process of H_2^+ ions colliding with electrons will lead to the loss of H_2^+ ions. Theoretical studies have shown that the power of the ion source correlates positively with electron density.[36] In other words, if the power continues to increase, an excessively high electron density inhibits the generation of H_2^+. That is to say, in order to produce more H_2^+ ions, an appropriate input power is needed. In conclusion, based on these analyses, more meticulous adjustments are required in the experiment to maintain the gas pressure and input power within a reasonable range, which is favorable for the generation of H_2^+ ions.

Table 2. Reactions and characteristic parameters within hydrogen plasma.[33,34]

Description	Reaction equation	Threshod energy (eV)	Optimal energy (eV)
Ionization	$H_2 + e \rightarrow H_2^+ + 2e$	15.4	70
Dissociative recombination	$H_2^+ + e \rightarrow 2H$	thermal	~ 0
Dissociative ionization	$H_2 + e \rightarrow H^+ + H + 2e$	40	125
Dissociative ionization	$H_2^+ + e \rightarrow 2H^+ + 2e$	17	105
Dissociative excitation	$H_2^+ + e \rightarrow H^+ + H + e$	12.4	~ 24
H_2 dissociation	$H_2 + e \rightarrow H + H + e$	8.8	17
H ionization	$H + e \rightarrow H^+ + 2e$	13.6	64
H_3^+ formation	$H_2^+ + H_2 \rightarrow H_3^+ + H$	thermal	~ 0
Dissociative recombination	$H_3^+ + e \rightarrow 3H$	thermal	~ 0
Dissociative excitation	$H_3^+ + e \rightarrow H^+ + 2H + e$	15	17
Dissociative excitation	$H_3^+ + e \rightarrow H_2^+ + 2H + e$	12.4	24
Wall recombination	$H_3^+ + e + \text{wall} \rightarrow H_2 + H + e$	–	–
Wall recombination	$H_2^+ + e + \text{wall} \rightarrow H_2$	–	–
Wall recombination	$H^+ + e + \text{wall} \rightarrow H$	–	–

3. Experimental setup

To characterize the 2.45 GHz microwave driven ion source, an experimental test bench, which is commonly used for miniaturized ion sources, was constructed for efficient plasma generation and beam control at PKU.[37] The schematic diagram of the test bench is shown in Fig. 3. A photograph of the miniaturized ion source mounted on the test bench is presented in Fig. 4. The experimental setup primarily consists of a microwave power supply, a miniaturized microwave driven ion source, a front Faraday cup, an emittance meter, a solenoid, a dipole magnet, an end Faraday cup, a water-cooling system, a vacuum system, etc. A very compact 200 W DC solid-state power supply made by Beijing Yingqi Electronic Technology Co., Ltd. was used to deliver 2.45 GHz microwave for this test (Fig. 4). To make the RF system compact and efficient, a coaxial to BJ32 waveguide transition was utilized. The microwave coupling is adjusted by tuning the microwave frequency through software. In this experiment, pure hydrogen is filled into the chamber for discharge. And the gas pressure is measured at a vacuum vessel that follows the extraction system of the ion source. The ion source employs a three-electrode extraction system, operating at 30 kV to ex-

tract an H_2^+ ion beam. After extracting the hydrogen beam, an electrical load is generated on the high voltage power supply, which is consistent with the current measured by the Faraday cup. The extraction voltage is combined with the beam optics design,[38] which achieves a 30 kV beam transmission efficiency of 75%–80% along the beamline. Due to the DC operation of the ion source, the water-cooling system is also optimized with an upgraded internal water circuit maintaining a water pressure of 2.0 MPa, which ensures thermal stability during discharge periods. The experimental setup is capable of conducting a complete measurement of the hydrogen beam. When the front Faraday cup is online, it measures the total beam current in real time. When the front Faraday cup is offline, the slit-wire type High Intensity Beam Emittance Measurement Units (HIBEMUs) developed by PKU can measure the emittance of the total ion beam.[39] When both the front Faraday cup and the emittance meter are offline, the 90° bending magnet performs beam composition analysis by sweeping the spectrum distribution to determine the fractions of $H^+/H_2^+/H_3^+$.

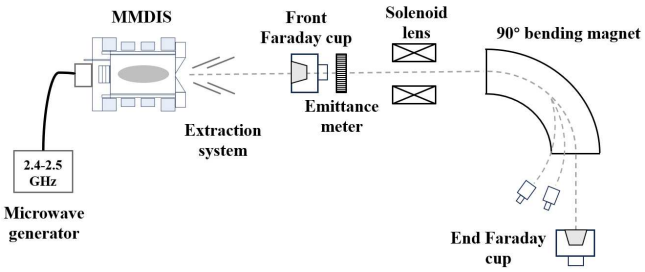


Fig. 3. A schematic diagram of the test bench at PKU.

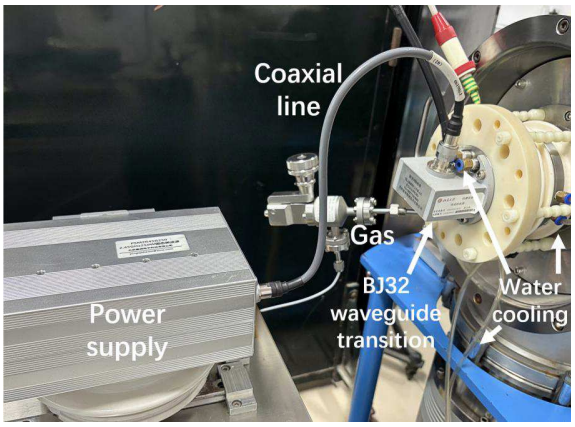


Fig. 4. A photo of the microwave driven ion source on the test bench.

4. Results and discussion

Based on the discussion before, it is necessary to determine the appropriate working pressure and input power to facilitate the generation of H_2^+ ions. Firstly, the load current and reflected microwave power were measured under different gas pressures. At a fixed input power of 180 W in DC mode, the results are presented in Fig. 5. It can be observed that although a low pressure theoretically facilitates the production of H_2^+, excessively low pressure leads to a decrease in total hydrogen beam current. The discharge of the ion source exhibits an optimal pressure range, beyond which the current of the hydrogen beam decreases significantly. Furthermore, it was also found that when the gas pressure exceeds the optimal range, the reflected power increases rapidly, which means that more microwave power will be converted into heat deposition, thereby imposing a burden on the system. From the perspective of microwave coupling, the plasma can be regarded as a load of the microwave transmission line. The impedance matching between the power supply and the plasma depends on the equivalent electrical conductivity of the plasma. When the plasma density drops, the electrical conductivity decreases accordingly. This means that the impedance matching will be imbalanced, thereby causing the reflected power to increase rapidly. Consequently, considering the principle that the minimum gas pressure promotes the generation of H_2^+ ions, the optimal gas pressure is determined to be 1.0×10^{-3} Pa. Under these conditions, the reflected power is only a few Watts (3.5 W@180 W), exhibiting a high power-coupling efficiency.

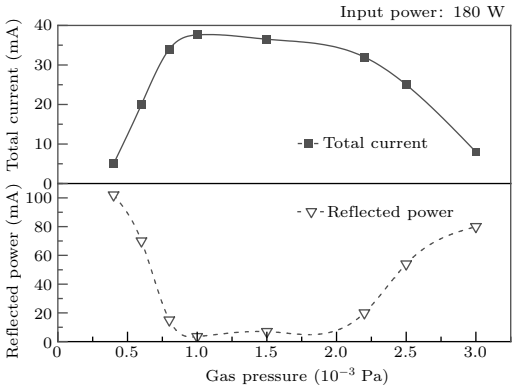


Fig. 5. The parameters under different gas pressures.

At the optimal gas pressure, the load current of the hydrogen beam and the fraction of H_2^+ beam under different microwave powers in DC mode are presented in Fig. 6. It can be observed that as the input power increases, the fraction of H_2^+ beam first increases and then decreases, reaching the optimal value at 150 W. This is in accordance with the three-phase diagram we previously proposed, which describes the main conditions for the dominance of different hydrogen ions.[40] These results show that, when the microwave power is reduced, the energy acquired by electrons from the microwave field decreases, leading to a reduced H_2^+ ion yield. Conversely, excessively high power enhances the probability of H_2^+ dissociation processes. Therefore, a moderate microwave power is essential to optimize the H_2^+ ion fraction. For the total current, it increases with the higher input power, which is reasonable since the plasma density has increased. However, for this miniaturized ion source, the total current increases at a

decreasing rate as the power increases. When the input power exceeds 180 W, it reaches a maximum value of approximately 38 mA. This might be due to the small size of the ion source chamber. As the power continues to increase, the Q factor decreases, which limits the further increase in extracted beam current.

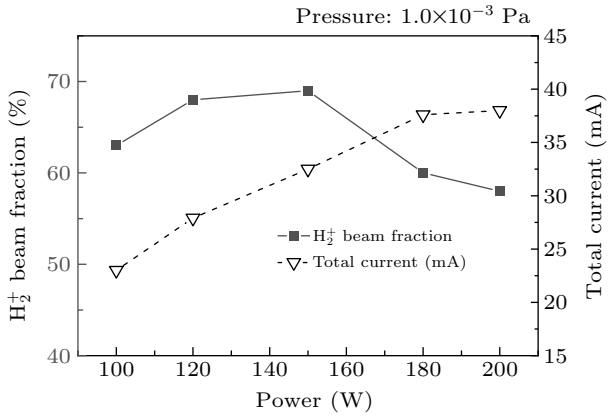


Fig. 6. The hydrogen beam current and H_2^+ fraction under different microwave powers.

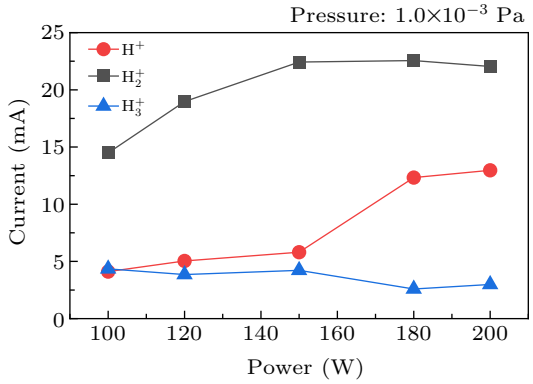


Fig. 7. The currents of $H^+/H_2^+/H_3^+$ ion beam under different microwave powers.

The currents of $H^+/H_2^+/H_3^+$ ion beams are shown in Fig. 7. It can be found that the H_2^+ beam current first increases and then slightly decreases with the increase in microwave power, while the current of H^+ beam continues to rise consistently. On the contrary, as the input power increases, the H_3^+ beam current shows a decreasing trend. The trend of the $H^+/H_2^+/H_3^+$ currents with respect to the input power is consistent with the theoretical analysis presented earlier (three-phase diagram). That is to say, the generation of H_2^+ requires an appropriate power level. As the power continues to increase, the dissociation processes of H_2^+ and H_3^+ become more favorable, resulting in an increase in the proportion of H^+ and a decrease in the proportion of H_3^+. These results show that at the optimal input power of 150 W and gas pressure of 1.0×10^{-3} Pa, the microwave driven ion source can generate a DC H_2^+ beam with a current of about 22 mA@30 keV. In the total hydrogen beam, the fraction of H_2^+ is approximately 70%. The spectrum distribution of the hydrogen beam is shown in Fig. 8. Figure 9 shows the phase space distribution of the mixed beam under these conditions. The normalized RMS emittance of the mixed beam is about $0.12\ \pi \cdot \text{mm} \cdot \text{mrad}$.

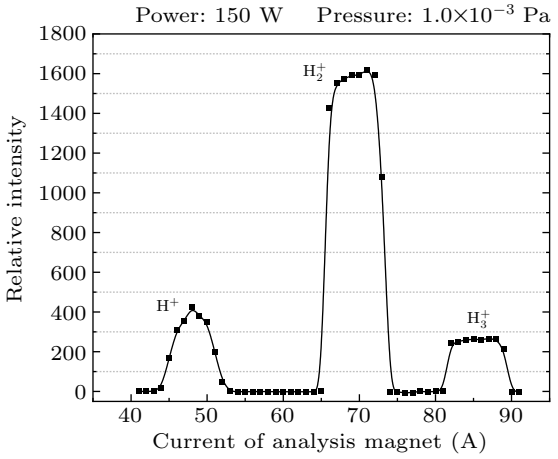


Fig. 8. Spectrum of the extracted hydrogen ion beam.

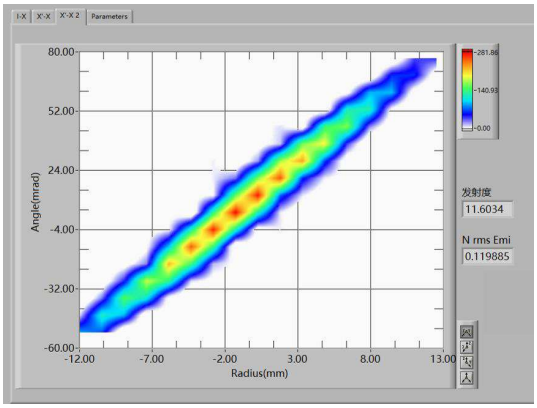


Fig. 9. The phase space distribution of the mixed hydrogen ion beam.

5. Summary and prospect

H_2^+ ion beam has attracted extensive attention in numerous fields, while a high-performance H_2^+ ion source is of great significance. In this work, more than 20 mA H_2^+ ion beam with a fraction of 70% was generated in the DC mode by a miniaturized permanent magnet 2.45 GHz microwave driven ion source. The source operated at a low input power of 150 W and a gas pressure of 1.0×10^{-3} Pa. In addition, the effects of gas pressure and microwave power on the generation of H_2^+ were also investigated. The experimental results were consistent with the theoretical analysis of the three-phase diagram, indicating that a moderate input power and low gas pressure are conducive to the generation of H_2^+ ions. In the future, the possibility of generating higher current H_2^+ beam will be discussed, and more rigorous theoretical analysis will be carried out to quantitatively predict and interpret the experimental findings.

Acknowledgments

Project supported by the National Natural Science Foundation of China (Grant No. 11975036). We appreciate the sup-

port from the State Key Laboratory of Nuclear Physics and Technology at PKU.

References

[1] Damodaran K K and Moon P B 1997 *Proc. Roy. Soc. Lond. Ser. A. Math. Phys. Sci.* **239** 382

[2] Alonso J, Axani S, Calabretta L, Campo D, Celona L, Conrad J M, Day A, Castro G, Labrecque F and Winklehner D 2015 *J. Instrum.* **10** T10003

[3] Axani S, Winklehner D, Alonso J and Conrad J M 2015 *Rev. Sci. Instrum.* **87** 02B704

[4] Wagner W, Seidel M, Morenzoni E, Groeschel F, Wohlmuther M and Daum M 2009 *Nucl. Instrum. Methods Phys. Res., Sect. A* **600** 5

[5] Peng S X, Zhu F, Wang Z, Gao Y and Guo Z Y 2016 *Nucl. Instrum. Methods Phys. Res., Sect. B* **376** 420

[6] Farhoodi K, Setayeshi S and Feghhi S A 2021 *J. Instrum.* **16** T11002

[7] Simakov S P, Bém P, Burjan V, Fischer U, Forrest R A, Götz M, Honusek M, Klein H, Kroha V, Novák J, Sauer A, Šimečková E and Tiede R 2008 *Fusion Eng. Des.* **83** 1543

[8] Tinschert K, Iannucci R and Lang R 2008 *Rev. Sci. Instrum.* **79** 02C505

[9] Garonna A, Amaldi U, Bonomi R, Campo D, Degiovanni A, Garlasché M, Mondino I, Rizzoglio V and Andrés S V 2010 *J. Instrum.* **5** C09004

[10] Was G S, Jiao Z, Getto E, Sun K, Monterrosa A M, Maloy S A, Anderoglu O, Sencer B H and Hackett M 2014 *Scr. Mater.* **88** 33

[11] Zhou Q, Togari A, Nakata M, Zhao M, Sun F, Yajima M, Tokitani M, Masuzaki S, Yoshida N, Hara M, Hatano Y and Oya Y 2020 *Int. J. Hydrogen Energy* **45** 9959

[12] Cao Z, Li C, Ding Y, Cui D, Zhong Q and Ran G 2024 *Materialia* **38** 102227

[13] Shull J M and Beckwith S 1982 *Annu. Rev. Astron. Astrophys.* **20** 163

[14] Werbowy S and Pranszke B 2011 *Astronomy & Astrophysics* **535** A51

[15] Juodkazis K, Juodkazytė J, Grigucevičienė A and Juodkazis S 2011 *Appl. Surf. Sci.* **258** 743

[16] Shen Q, Ran G, Zhou W, Ye C, Feng Q and Li N 2018 *Materials* **11** 282

[17] Winklehner D, Axani S, Bedard P, Conrad J, Corona J, Hartwell F, Smolsky J, Tripathee A, Waites L, Weigel P, Wester T and Yampolskaya M 2018 *AIP Conf. Proc.* **2011** 030002

[18] Joshi N, Droba M, Meusel O and Ratzinger U 2009 *Nucl. Instrum. Methods Phys. Res., Sect. A* **606** 310

[19] Oks E M, Shandrikov M V and Vizir A V 2015 *Rev. Sci. Instrum.* **87** 02B703

[20] Castro G, Torrisi G, Celona L, Mascali D, Neri L, Sorbello G, Leonardi O, Patti G, Castorina G and Gammino S 2016 *Rev. Sci. Instrum.* **87** 083303

[21] Bahng J, Kim Y, Lee Y W, Yu J, Nam S H, Choi B H and Jeon Y 2024 *J. Phys. Conf. Ser.* **2743** 012054

[22] Winklehner D, Conrad J M, Smolsky J and Waites L H 2021 *Rev. Sci. Instrum.* **92** 123301

[23] Bosi F, Guarducci F and Gabriel S 2021 *J. Propul. Power* **37** 509

[24] Alonso J R, Calabretta L, Campo D, Celona L, Conrad J, Martinez R G, Johnson R, Labrecque F, Toups M H, Winklehner D and Winslow L 2014 *Rev. Sci. Instrum.* **85** 02A742

[25] Jia X, Zhang T, Luo S, Wang C, Zheng X, Yin Z, Zhong J, Wu L and Qin J 2010 *Rev. Sci. Instrum.* **81** 02A321

[26] Wu W, Peng S, Ma T, Ren H, Zhang J, Zhang T, Jiang Y, Li K, Xu Y, Zhang A, Wen J, Guo Z and Chen J 2019 *Rev. Sci. Instrum.* **90** 101501

[27] Xu Y, Peng S, Ren H, Zhao J, Chen J, Zhang A, Zhang T, Guo Z and Chen J E 2013 *Rev. Sci. Instrum.* **85** 02A943

[28] Peng S, Ma T, Cui B, Wu W, Jiang Y, Guo Z and Chen J 2024 *J. Phys. Conf. Ser.* **2743** 012056

[29] Wu W, Peng S, Zhang A, Ma T, Jiang Y, Li K, Cui B, Guo Z and Chen J 2022 *J. Appl. Phys.* **132**

[30] Peng S X, Ma T H, Wu W B, Cui B J, Zhang A L, Jiang Y X, Guo Z Y and Chen J E 2023 *Radiat. Detect. Technol. Methods*

[31] Wu W B, Peng S X, Ren H T, Xu Y, Wen J M, Zhang A L, Zhang T, Zhang J F, Sun J, Guo Z Y and Chen J E 2018 *AIP Conf. Proc.* **2011** 020004

[32] Peng S X, Xu R, Zhao J, Yuan Z X, Zhang M, Song Z Z, Yu J X, Lu Y R and Guo Z Y 2008 *Rev. Sci. Instrum.* **79** 02A310

[33] King R F, Surrey E and Holmes A J T 2008 *Fusion Eng. Des.* **83** 1553

[34] Wu W, Zhang A, Peng S, Ma T, Jiang Y, Li K, Zhang J, Zhang T, Wen J, Xu Y, Guo Z and Chen J 2020 *Vacuum* **182**

[35] Asadi Aghbolaghi M, Abbasi Davani F, Yarmohammadi Satri M, Riazi Mobaraki Z and Ghasemi F 2024 *J. Theor. Appl. Phys.* **18**

[36] Cui B, Peng S, Wu W, Ma T, Jiang Y, Li K, Zhang A, Sun J, Zhang J, Guo Z and Chen J 2021 *Contrib. Plasma Phys.* **61** e202100048

[37] Cui B, Peng S, Wu W, Ma T, Jiang Y, Guo Z and Chen J 2023 *J. Instrum.* **18** P10038

[38] Wu W B, Peng S X, Ma T H, Jiang Y X, Ren H T, Li K, Zhang J F, Xu Y, Zhang A L, Zhang T, Wen J M, Sun J, Guo Z Y and Chen J E 2020 J 2020 *J. Instrum.* **15** P03028

[39] Lv P, Peng S, Guo Z, Yuan Z, Ren H, Zhao J, Zhang M, Chen J and Lu Y 2011 *Sci. China Phys., Mech. Astron.* **54** 287

[40] Wu W, Ren H, Peng S, Xu Y, Wen J, Zhang T, Zhang J, Zhang A, Sun J, Guo Z and Chen J 2018 *Sci. China Phys., Mech. Astron.* **61** 045211