STATUS OF HYDROGEN ION SOURCES AT PKU*

Yuan Xu, Shixiang Peng#, Haitao Ren, Tao Zhang, Jingfeng Zhang, Jiamei Wen, Wenbin Wu, Zhiyu Guo and Jiaer Chen, SKLNPT & IHIP, School of Physics, Peking University, Beijing 100871, China
Ailin Zhang, School of Physics, UCAS, Beijing 100049, China

Abstract

Cyclotrons are quite often to be used to accelerate different hydrogen ion beams with high intensity for different purposes around the world. At Peking University (PKU), special efforts were paid on developing compact 2.45 GHz microwave driven ion sources with permanent magnets to generate high intensity H^+, H_2^+, H_3^+ and H^- ion beams as well as other ion beams. For the positive ion beam, we can easily produce a 130 mA hydrogen ion beam with H^+ fraction higher than 92% with a PKU standard ϕ100 mm × 100 mm 2.45 GHz ECR ion source. Also we have got 42 mA H_2^+ beam and 20 mA H_3^+ beam with a specifically designed 2.45 GHz ECR ion source under different operation condition. The fractions of H_2^+ and H_3^+ are higher than 50% within the mixed hydrogen ion beams for each case. Recently, a Cs-free volume H^- source based on 2.45 GHz microwave was developed successfully in our lab. It can generate 45 mA H^- beam with duty factor of 10% and a 29 mA beam at CW mode at 35 keV. Its operation duty factor can vary from 1% to 100%. The power efficiency is about 29 mA/kW in CW mode and 21 mA/kW in 10% (100 Hz/1 ms) pulsed mode. A 300 hours 50 keV/50 mA CW proton beam continuous operation with no beam trip demonstrated that PKU 2.45 GHz ECR ion source has high stability and reliability. Details of these sources will be presented in the paper.

INTRODUCTION

Cyclotrons are wildly used in fundamental physics research, medical therapy, radioisotopes production etc. In principle, cyclotrons can accelerate various ions from hydrogen to uranium. Among numerous ions, hydrogen ions (H^+, H^-) are most commonly to be accelerated by cyclotrons. For example, about 10 mA CW H^+ ion beam was injected into the Cockcroft-Walton pre-accelerator of the 590 MeV cyclotron at PSI, which was one of the most powerful cyclotron around the world. [1] Moreover, negative hydrogen ion (H^-) was also very popular as it could be stripped as H^+ at the extraction area of cyclotron so that very high extraction efficiency could be achieved by using charge-exchange extraction method. [2] At TRIUMF, about 15 mA CW H^- ions were needed to inject into a TR30 cyclotron. [3] Otherwise, for some medical cyclotrons, several mA H^- ions extracted from ion source were required for isotope production. [4]

Nowadays, high current high power facility is an important trend for cyclotrons. But accompanying with the increasing of beam current, the space charge effect caused by repulsive force between particles leads to strong beam loss in cyclotron. To solve this problem, it is proposed to accelerate H_2^+ or H_3^+ ions, which have much lower generalized perveance, and then strip them at the export of cyclotron to get H^+. [5] The DAEδALUS project is an example on this idea. [6, 7] DAEδALUS accelerator will produce 800 MeV H^+ with a beam current of 10 mA. This current already exceeds the limitation of present cyclotrons and is unacceptable for the machine. To reduce the space charge effect and achieve the extracted current from the cyclotron, H_2^+ ion beam will be used to take place of H^+.

2.45 GHz microwave driven ion source has the reputation for its high current, low emmitance, long lifetime and high stability. [8] It can operate in pulsed and CW mode. At PKU, high current ion sources driven by 2.45 GHz microwave has been developed for several decades. [9] Single charged ions such as H^+, O^+, N^+, Ar^+, D^+ etc. can already be generated by the ion source. In addition, H_2^+, H_3^+ and H^- ions were also extracted from this kind of ion source by modifying the structure and adjusting operation parameters. [10, 11] Up to now, the 2.45 GHz microwave ion source at PKU has been utilized by the Separated Function Radio Frequency Quadrupole (SFRFQ) project, [12] the Peking University Neutron Imaging FaciliTY (PKUNIFTY) project, [13] Coupled RFQ & SFRFQ, [14] Dialectical Wall Accelerator(DWA) [15] and the Xi'an Proton Application Facility (XiPAF) [16]. During the operation of these facilities, the ion sources developed at PKU have already shown very good performance and stability. More details of hydrogen ion sources at PKU will be reported in this paper.

PROTON ION SOURCE

The standard structure of the microwave ion source at PKU is shown Fig. 1. [13] It is a very compact ion source with an outer diameter of 10 cm and a length of 10 cm, and its weight is lower than 5 kg. The magnetic field is generated by three NdFeB permanent magnetic rings. Microwave generated by magnetron is injected into the ion source through a circulator, a three-stub tuner, a directional coupler, a dc-break waveguide and a standard BJ26 rectangular waveguide. A three-layer Al_2O_3 microwave window is used here to couple the microwave with plasma chamber, and a protective BN disc is mounted to prevent the bombardments of electrons. The extraction system is composed of three electrodes: plasma electrode, screening electrode and ground electrode. The diameter of the beam emission aperture is ϕ6 mm.

Many efforts were carried out to improve the beam current, beam quality, proton fraction as well as source stability and reliability. Up to now, a 130 mA H^+ beam with proton fraction of 92% was extracted at 50 kV from

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#sxpeng@pku.edu.cn

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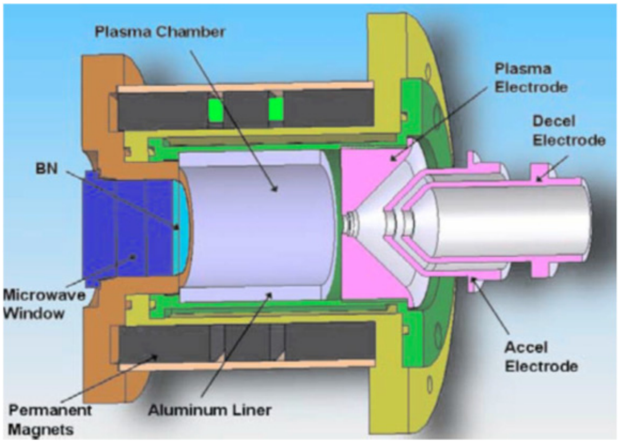

Figure 1: The schematic diagram of ECR ion source at PKU [13].

the ion source in pulsed mode with duty factor of 10% (100 Hz/1 ms). The peak RF power was about 2 kW and H_2 gas consumption was 2 sccm. The rms emmitance of the beam is 0.16 π.mm.mrad. The waveform of the total current is shown in Fig.2. In CW mode, the source could also work very well. Around 100 mA ion beam was extracted after improving the water-cooling and operation parameters. [17] To characterize the lifetime and stability of the ion source at PKU, a long time experiment was done in June 2016. [18] A 50 mA CW H^+ beam was continuous extracted with energy of 50 keV for 300 hours, and the input power was around 500 W. A screenshot of the monitor computer at the end of longevity test is shown in Fig.3. During 300 hours' test, no beam-off or beam drop happened during the 294 hours' duration, and the ion beam availability was 100%.

H_2^+ & H_3^+ ION SOURCE

H_2^+ and H_3^+ exist inevitably in the mixed ion beam from hydrogen ion source. Generally, H_2^+ ion is generated by direct ionization of molecular hydrogen H_2 which is a pilot process for proton generation, and H_3^+ is created by

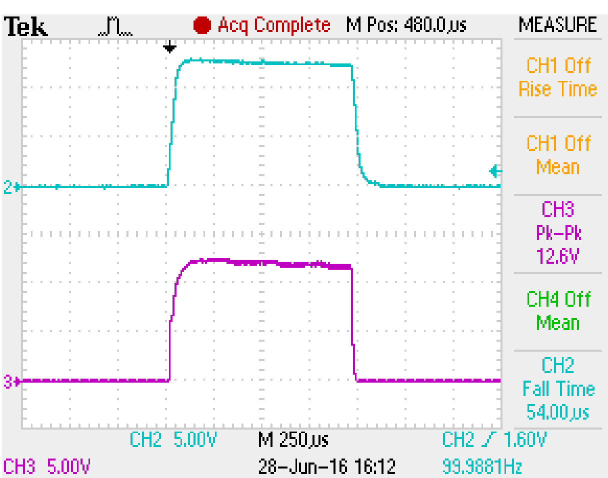

Figure 2: The waveform of 130 mA proton beam in pulsed mode.

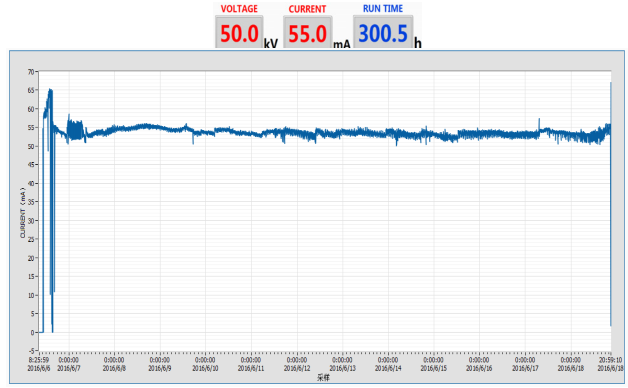

Figure 3: Screenshot of the monitor computer at the end of longevity test. (Top: extraction voltage, instantaneous current, and counting hours. Bottom: beam current versus elapsed time) [18].

dissociative attachment process. The structure of ion source for hydrogen molecular ions was similar to that of proton source. The most differences were the diameter and the material of the plasma chamber. [19] For H_2^+ generation, a 64 mm diameter chamber, which was larger than normal proton source, was preferred. Moreover, materials with high recombination coefficient such as stainless steel should be used to enhance the yield of H_2^+.

After modifying the ion source and optimizing the operation parameters, high current H_2^+ and H_3^+ beam were extracted with identical ion source. With operation pressure 6.5×10^{-4} Pa (the pressure was measured in the vacuum chamber after the extraction system) and rf power 1400 W, pure 42 mA H_2^+ ion beam with ion fraction of 54% was extracted at 45 kV in pulsed mode. It is shown in Fig.4 that the fraction of H_2^+ is obviously higher than H^+. By increasing the pressure to 2×10^{-3} Pa and decreasing the rf power to 1000 W, 20 mA H_3^+ with fraction of 55% was got also in pulsed mode (Fig.5). Actually, if sacrificing the current, the fraction of H_3^+ could reach nearly 70% by further reducing the input power.

In general, the operation parameters should be adjusted thoroughly as molecular ions are easily destructed. For H_2^+ ion generation, a lower operation pressure and moderate rf power are needed. However, for H_3^+ ions, the pressure should be increased and the rf power should be decreased to some extent.

NEGATIVE HYDROGEN ION SOURCE

PKU ion source group has developed the 2.45 GHz microwave driven Cesium-free volume negative ion source for several years, and formal upgraded sources named as No. 1, No. 2, No. 3 and No. 4 H^- source were manufactured. [10] After theoretical and experimental study, tens of mA H^- beam both in pulsed mode and CW mode were obtained. [20] The duty factor of these four sources was variable from 1% to 100% by adjusting the rf power supply.

The principle of the H^- ion source is shown in Fig. 6. The source body of the PKU 2.45 GHz microwave-driven

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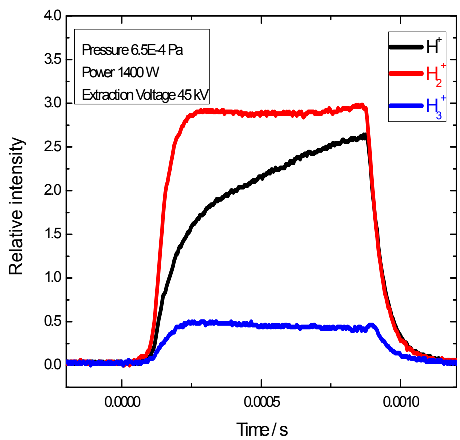

Figure 4: Profiles of H^+, H_2^+ and H_3^+ beam pulse. (6.5×10^{-4} Pa, 1400 W).

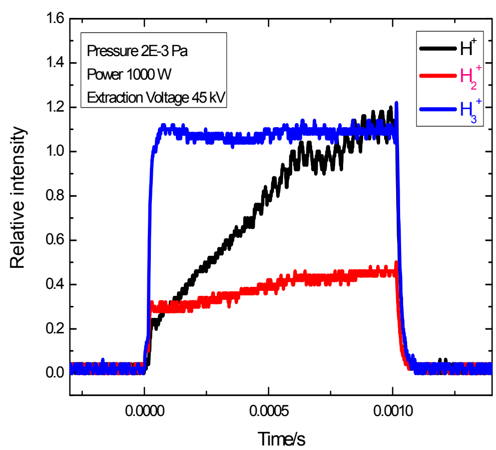

Figure 5: Profiles of H^+, H_2^+ and H_3^+ beam pulse. (2×10^{-3} Pa, 1000 W).

H^- source is consisted of a microwave matching part (microwave window), a plasma chamber, and a connection flange for the source body installation. Just like the 2.45 GHz positive ion source, the ECR filed, the filter magnetic field and e-dump filed are all generated by permanent magnets. The discharge chamber is physically

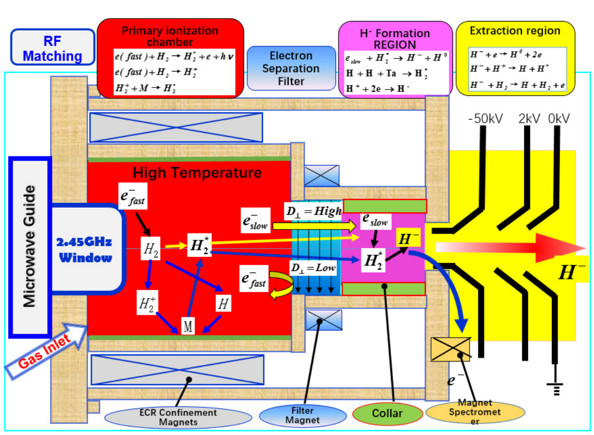

Figure 6: The principle of PKU No.4 H^- ion source [10].

separated into three sections: the primary ionization chamber (ECR-zone) where high temperature electrons interact with hydrogen molecules to generate excited H_2^*, the filter region acting as electron energy filter which only has a high diffusion coefficient for lower energy electron (<1 eV), and the H^- formation region where H_2^* interacts with low energy electrons. Most of electrons near the outlet could be dumped inside the plasma chamber by transverse magnetic field so that they will not be co-extracted with H^- ions. Tantalum liners are placed in both primary ionization chamber and H^- formation region to increase the population of excited hydrogen molecule the population of excited hydrogen molecule by surface effect. In the design of this H^- ion source, no Cesium (Cs) is used which makes the operation of the source more easily and safely.

A 45 mA pure H^- current in pulsed mode with 100 Hz/1 ms was extracted in 35 keV with 2100 W RF power from No. 4 H^- Source, and a 29 mA H^- current was extracted in CW mode with RF power of 1000 W, the detailed parameters of the conditions could be found in Table 1. [21] As shown in Table 1, the power efficiency of this kind of ion source can be as high as 29 mA/kW in CW mode and 21 mA/kW in pulsed mode which is much higher than that of typical RF-driven H^- ion source with or without Cs.

Table 1: Optimal Operation Parameters with PKU Cs-Free 2.45 GHz Microwave-Driven H^- Ion Source.

Operation mode	Pulse	CW
Gas pressure (Pa)	4.0×10^{-3}	4.5×10^{-3}
RF Power (W)	2100	1000
Duty factor	10%	100%
Extraction voltage (kV)	35	35
Current (mA)	45	29
Power efficiency (mA/kW)	21.4	29

CONCLUSION

2.45 GHz microwave driven ion sources have been developed at PKU for several decades. After improvements, the ion sources can already produce high current H^+, H_2^+, H_3^+ and H^- ions to fulfil the requirements of cyclotrons. For positive hydrogen ions, 130 mA H^+, 42 mA H_2^+, and 20 mA H_3^+ ion beam could be extracted in pulsed mode. Moreover, result of the long-time continuous test with 50 mA CW H^+ beam demonstrates that the stability and reliability of the ion source are very promising. For negative hydrogen ion source, 29 mA CW H^- beam and 45 mA pulsed beam can be generated with very high power efficiency. In conclusion, it is promising to use 2.45 GHz microwave driven ion source in cyclotrons as it has very high reliability to generate both CW and pulsed beam.

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REFERENCES

[1] P. A. Schmelzbach *et al.*, in *Proc. Cyclotrons'07*, Giardini, Italy, 2007, pp. 292.
[2] H. Etoh *et al., Rev. Sci. Instrum*. **87**, 02B135, 2016.
[3] T. Kuo *et al.*, *Rev. Sci. Instrum*. **67**, 1314, 1996.
[4] P. W. Schmor, *in Proc. Cyclotrons'10,* Lanzhou, China, 2010, paper FRM2CIO01, pp. 419.
[5] L. Calabretta *et al.*, in *Proc. Cyclotrons'10,* Lanzhou, China, 2010, paper TUA1CIO0, pp. 298.
[6] Jose R. Alonso *et al., Rev. Sci. Instrum*. **85**, 02A742, 2014.
[7] S. Axani *et al., Rev. Sci. Instrum*. **87**, 02B704 (2016).
[8] R. Gobin *et al., Rev. Sci. Instrum.* **83**, 02A345 (2012).
[9] S. X. Peng *et al., in Proc. ECRIS'10*, Grenoble, France, 2010, paper TUCOCK02, pp. 102.
[10] S. X. Peng *et al., AIP Conf. Proc*., **1655**, 070005, (2015).
[11] Y. Xu *et al.*, in *Proc. IPAC'13*, Shanghai, China, paper MOPFI035, 2013, pp. 363–365.
[12] S. X. Peng *et al., Rev. Sci. Instrum.*, vol. **79**, 02B706, 2008.
[13] H. T. Ren *et al., Rev. Sci. Instrum.,* vol. **81**, 02B714, 2010.
[14] S. X. Peng *et al.*, *Rev. Sci. Instrum.*, vol **85**, 02A712, 2014.
[15] S. X. Peng *et al., Nucl. Instr. and Meth. A*, **763,** 120, 2014.
[16] S. X. Zheng *et al.,* in *Proc. HB'16,* Malmö, Sweden, 2016, paper MOPR006, pp. 56.
[17] H. T. Ren, S. X. Peng *et al., Rev. Sci. Instrum.,* **83,** 02B905, 2012.
[18] Shi-Xiang Peng *et al.*, "Significant breakthrough on stability and reliability of PKU high intensity CW 2.45 GHz ECR proton source", *Chinese Physics B,* Summited (2016/8).
[19] Yuan Xu *et al.*, *Rev. Sci. Instrum.*, **85**, 02A943, 2014.
[20] S. X. Peng, *et al*., *Rev. Sci. Instrum.,* **87**, 02B125, 2016.
[21] T. Zhang, S. X. Peng *et al., in Proc. NIBS2016,* Oxford, UK, 2016, paperTueO7.