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

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The stability and reliability of an ion source and its beam availability are extremely significant for any accelerator, especially for those high current long term CW operation ones like ADS. Although the first high quality 306-hours continuous wave (CW) operating curve at 50 mA@35 keV has been successfully obtained with a standard compact 2.45 GHz ECR ion source at Peking University (PKU), but the uncertainties that caused beam trips before are unacceptable during an accelerator real operation and should be eliminated. Meanwhile, no permission will be given when the beam power is upgraded from 50 mA@35 keV to 50 mA@50 keV. To improve the PKU CW proton source quality, several upgrades were done recently. After those improvements, a new long term CW proton beam experiment at 50 mA@50 keV was carried out in June 2016. The total running time is 300.5 hours, including near 6 hours ion source preparation and 294 hours non-disturb continuous operation. Within the continuous 13 days operation, no beam-off happened, no spark was observed, no beam drop appeared, no interrupting action was needed, and only a few beam fluctuations caused by the air conditional failure occurred. Beam availability and reliability within the 294 hours is 100%. The root-mean-square (RMS) emittance of this 50 mA@50 keV CW proton beam is about 0.186 π.mm.mrad. A careful inspection of the ion source was done after this long term operation and no obvious damage was found. The restart experimental results obtained after the ion source inspection prove the high repeatability of PKU PMECRIS. In addition, a 130-mA H^+ beam was obtained at 50 kV with duty factor of 10% (100 Hz/1 ms) with this source. Details will be presented in this paper.

Keywords: PKU PMECRIS, 50 mA@50 keV CW proton beam, 300-hours continuous operation, no beam-off

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1. Introduction

Interests on high-current high-power CW proton accelerator are increasing with the development of accelerator driven transmutation of nuclear waste[1] and other neutron sources. Elimination of beam trips, improving operational stability and reliability of the accelerators are more important issues than ever, especially for ADS. To meet the requirements of those accelerators, high quality ion sources are extremely important. The 2.45-GHz microwave-driven ECR ion source that has the ability to deliver tens-mA CW proton beam with unique characteristic of high stability, low emittance, operation reliability and longevity, is the best candidate for this kind of facilities.[2] To ensure the safety of the high-current high-power proton accelerators, CW proton source should be carefully qualified at each lab before they were used to deliver beams for accelerators.[3,4] Before 2015, the longest uninterrupted run time period of a CW 2.45-GHz ECR proton source in the world was 103 hours at 95 keV with 75 mA kept by SILHI source at CEA/Saclay France.[3]

As a partner of CIADS project, PKU is undertaking the R & D program on high current CW hydrogen ion source development. A five-year plan (2014–2018) was proposed in the year of 2013. Table 1 is the planned schedule.

PKU compact permanent magnet 2.45-GHz ECR ion sources (PKU PMECRISs) have been demonstrated their reliability to produce hundred mA proton beam in pulsed operation mode with duty factor of 10%.[5] When we first started to produce a 50-mA@35-keV CW proton beam with this kind of ECR ion source, sparks appeared frequently around the source body and on the ion source test bench. Meanwhile, the faraday cup that was developed for pulsed beam measurement in the pass years was melted within 20 minutes. With some improvements described in Refs. [6] and [7], we were succeed to obtain a 306-hours continuous operation curve of 50 mA@35 kV CW proton beam at the beginning of 2015 on PKU ion source test bench. During that 13-days running, neither sparks nor plasma generator failure were observed. Five beam breaks that caused by the failure of the water cooling machines were encountered and some beam current drops and beam current fluctuations appeared. The longest uninterrupted run time was about 122 hours. The beam availability defined as beam-on

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time divided by elapsed time is 99%, and the source reliability is about 100% if there were no cooling water troubles.

Table 1. The plan of CIADS CW H^+ ion source.

Year	Mission
2014	Longevity of RF window > 200 hours. Duration should be longer than 200 hours for 50-mA @ 35-keV CW
2015	H^+ beam continuous operation. Beam off number caused by source instability or spark should be less than five. Duration should be longer than 300 hours for 50 mA @ 35 keV CW
2016	H^+ beam continuous running. Beam off number caused by source instability or spark should be less than five. Duration should be longer than 300 hours for 50 mA @ 50 keV CW
2017	H^+ beam continuous operation. Beam off number caused by source instability or spark should be less than five.
2018	The source has the ability to produce a CW 100 mA@75 keV H^+ beam. Its rms normalized emittance should not be larger than 0.2 π·mm·mrad.

According to the planned listed in Table 1, next step we should start is to launch a 50-mA@50-keV CW proton study. Although the results of 50-mA@35-kV CW proton beam operation is very impressing, but no permission can be given if this system is used to generate a higher energy CW proton beam for hundreds hours. Therefore, before starting next long term test, the accidents that forced us to stop ion source operation during previous experimental period should be eliminated, and some other uncertainties that may cause unforeseen events in a higher beam power long term CW proton operation should be minimized.

In Section 2, we will list the improvements done since last long term CW operation. In Section 3, a new prosperous results of the continuous 300-hours 50-mA@50-keV CW proton beam experiment, its rms emittance and the relationship of room temperature and beam stability will be presented. A conclusion will follow at the end of this paper.

2. Improvements for 50-mA@50-kV CW H^+ beam

In last long period 50-mA@35-keV CW proton running, the failures of water cooling machines caused five beam-offs, room-temperature variation during each day induced some beam current fluctuations and several beam current drops, and the inadequate gas in gas reservoir during later operation days affected the beam stability. To eliminate those unexpected accidents encountered before, and to avoid the unforeseen cases that may occur in the coming experiment, new improvements on PKU ion source test bench have been carried out since 2015.

First, the high voltage cooling water machine (HVCW) safety was improved. It was done in two steps. First, we enlarged the water cooling efficiency by replacing the original 1-kW water machine to a new 2-kW one. Second, an optoelectronic isolator (Fig. 1) was installed between the isolation transformer and the ground to protect the HVCW electronic control and display system.

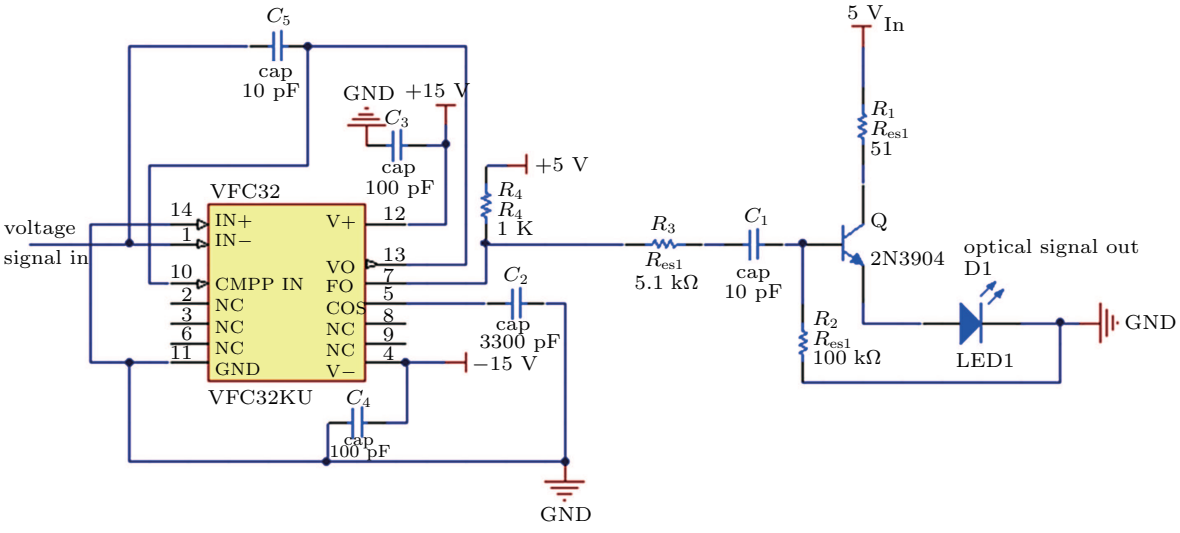


Fig. 1. (color online) The configuration of the optoelectronic isolator used for HVCW protection.

Second, an adequate gas source has been prepared. To avoid beam instability caused by the pressure drop inside the H_2 gas vessel that came up at the end of last long term running, a new 4-liter volume vessel with gas pressure of 100 atm (1 atom = 1.1325×10^5 Pa). was installed for this new term operation.

Third, the room temperature and the humidity of the lab have been strictly controlled. To limit beam current fluctuations and current drops phenomenon occurred again in the new long term operation, an air conditioner has been used. The room temperature is kept at around 20 °C and the humidity is around 40%.

Besides, water cooling efficiency of the source as well as the faraday cup were improved. To strengthen the source cooling efficiency, a new water cooling channels was embedded into the connecting flange between the source body and the extraction system to better cool the source. Meanwhile, the cooling water pressure of both the HVCW and the ground level for faraday cup cooling were increased from 2.5 atm to 6 atm. In addition, pollution of the ceramic within the extraction system during a long term high power beam operation has also been careful treated. During a source running, sputtering contamination from electrodes will accumulate on the inner surface of the ceramic rings. This will descend the insulation capacity and raise spark risk. This risk is increasing with the increasing of running time. What we did is shielding the ceramic termination with the metal electrode. As a result, the electrode metallic supports is integrated with such a ceramic shielding. Moreover, a remote network monitoring system based on EASYSEE was established so that the operation parameters can be visited on cell phone or pc through internet from anywhere at any time. The room-temperature and humidity are monitored by a mobile communication depended system which can send alarm messages to experimenter.

3. Experimental results and analysis

3.1. The 300-hours continuous running results and its emittance

Experiment was completed with the same source on the same test bench in Ref. [6]. A standard compact PKU PMECRIS with a water-cooled three-electrode extraction system is used for CW H^+ ion beam generation. A self-made high voltage breakup microwave guide will be installed to limit the high voltage region and all other radio frequency (RF) components are located on ground level. A 1-m long PE pipe is used between the micro-valve that connected with source body located on high voltage platform and the gas vessel on ground level. The beam operation mode from CW to pulse is selected through changing the RF power operating mode. The improved Faraday cup locates 280-mm downstream the ion emission aperture.

The experiment was performed during the period from June 6–18, 2016. The beam extraction voltage increased from 35 kV to 50 kV and the current is kept above 50 mA for this test. The extraction voltage is 50 kV and the suppressing voltage is −2.5 kV. The RF power from the microwave generator was set at 500 W. Vacuum inside the diagnostic chamber with beam on was 2.2×10^{-3} Pa. During this experiment, the room temperature was set at 20 °C and the humidity was kept around 40%. No parameter adjustment was allowed during the continuous operation except the air conditioner. For safety reasons, operators on duty were present on site along all this thirteen-day long-term duration. Still no current feedback loop for RF tuner matching, and no gas-flow controller feedback loop was used for this running. Figure 2 shows the beam record captured from the control PC panel at the end of the long term operation. The total continuous running time of the source is 300.5 hours.

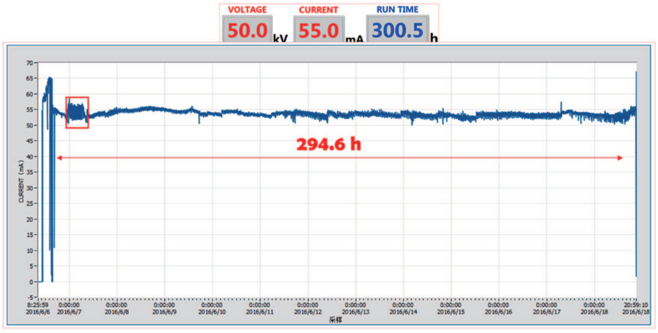


Fig. 2. (color online) Screenshot of the monitor computer at the end of longevity test. Top: extraction voltage, instantaneous current, and counting hours. Bottom: beam current versus elapsed time.

As shown in Fig. 2, the very beginning 6 hours on 6th June was used for the ion source optimization for this longevity test. Following that was a 294-hours continuous operation. During those 294 hours, no beam break came up, no beam current drop appeared, no spark was observed. The uninterrupted continuous run time is about 294 hours. The average current is about 53.8 mA. Beam availability reaches up to 100% under this operation condition. The source stability and reliability is about 100%. All the above data are much better than that of 50 mA@35 keV. This results become a milestone of PKU PMECRIS.

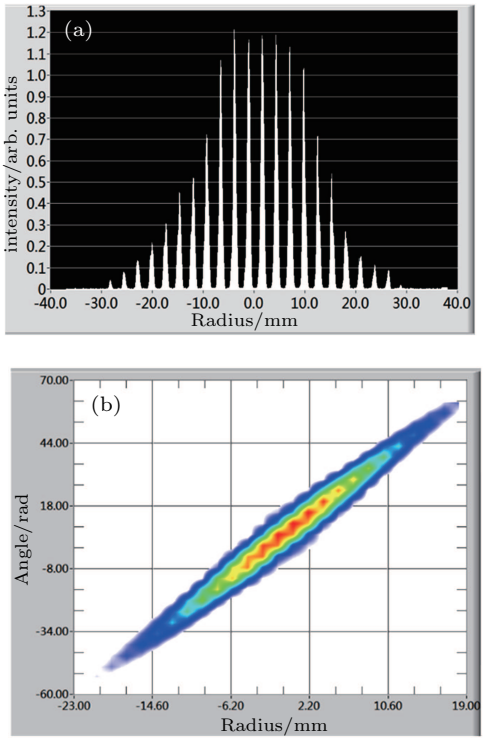


Fig. 3. (color online) Beam distribution (a) and its rms emittance (b) of a CW 50-mA@50-keV H^+ beam.

The beam distribution 300-mm downstream the emission aperture of the plasma electrode and the beam RMS emittance obtained with slit-grid emittance device were displayed in Fig. 3. Its RMS emittance is about 0.186 π·mm·mrad.

3.2. Beam fluctuation analysis

An obvious fluctuation region (the red rectangle) appeared during the evening time of 6 June in Fig. 2. Curve in Fig. 4 is a broadening one of this region. According to the on spot record, the room temperature during that period was oscillated between 25 °C and 30 °C. This was caused by the failure of the air-condition machine in the lab. This phenomenon disappeared after the air conditioner problem solved in the next day.

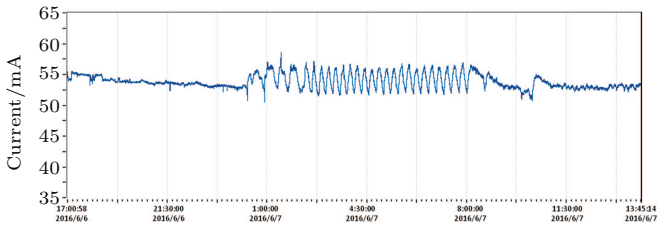


Fig. 4. (color online) A broadening display of the red rectangle section in Fig. 2.

The phenomenon displayed in Fig. 4 can be explained in the following. According to the thematic theory, the pressure inside the PE pipe can be expressed as the following formula,

$$P = nk_{\mathrm{B}}T.$$

Here P is pressure, n is the gas molecular density, and T is the temperature. During the whole experiment, the pressure P inside the vacuum chamber was constant. When the room temperature T changes, it will affect the gas flow n that passing through the 1-m long PE pipe into the plasma chamber. And this gas density changing will impact the plasma stability unless RF matching is adjusted correspondingly. Here we used a manual RF turner and no interference action was allowed during the long term test getting start.

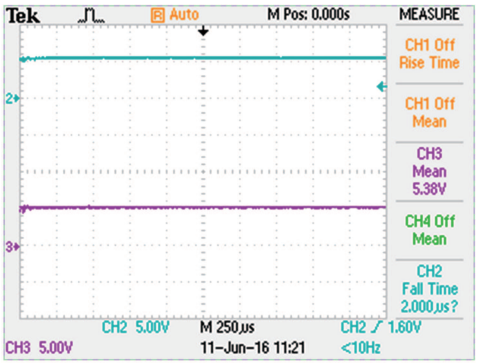


Fig. 5. (color online) Instant beam current displayed on oscilloscope at every moment.

Although an obvious fluctuation region can be found in Fig. 4, at each moment the beam current displayed on the oscilloscope is quite stability. Figure 5 is an example of the beam current at one moment captured from the oscilloscope.

After completion of the thirteen days run, the ion source was inspected for wear or imminent component failure. No obvious signs of wear were found, and it is unknown how long the source would have run before failing. After inspection, the source was re-installed and an onsite test was carried out. The running parameters as well as the beam current were repeated quite well with that obtained by ourselves before. Beside, a 130 mA H^+ beam was obtained at 50 kV with duty factor of 10% (100 Hz/1 ms).

4. Conclusion and outlook

With the help of all improvements done on the source and on the test bench, a 294-hours CW proton curve of 50 mA@50 keV with none beam trip was succeed obtained with a PKU PMECRIS. Its RMS emittance is about 0.186 π·mm·mrad. The CW proton beam availability, its stability and reliability are getting 100%. Results have been improved as we expected and are much better than that of 50 mA@35 keV. This is a milestone of PKU permanent magnet 2.45-GHz CW proton source. The re-visit results indicate that it is in a good condition after this long term operation. It is predictable that our present PMECRIS has the ability deliver a stable 50-mA@50-keV CW proton beam for an accelerator for more than 300 hours with beam availability of 100%.

A new fully water cooled four-electrode extraction system and a new higher voltage breakup microwave guide have been developed. Testing on producing 100-mA CW proton at 75 kV will be arranged in the near future. Results will be presented then.

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