A High Power Long Pulse RF-driven H\(^-\) Source

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Abstract
We have tested the radio-frequency driven H\(^-\) source and have shown that the H\(^-\) production efficiency and the beam emittance are similar to those obtained from the filament discharge. Typically the numbers are 2.8 mA/cm\(^2\)/kW and 0.017 μmrad-cm (which corresponds to 1.9 eV) respectively. So far we have operated RF pulses of \(\approx 10\) kW for \(\approx 50\) ms with a porcelain-coated antenna and \(\approx 15\) kW for \(\approx 1\) s with additional layers of quartz sleeving. It is necessary to develop better antenna coating material that can withstand the intense plasma heating and sputtering in order to operate at higher power with longer pulse length.

I. INTRODUCTION

In the last Particle Accelerator Conference, Leung et al\(^1\) reported some encouraging results using a radio-frequency driven multicusp source to produce H\(^-\) ions. More than 30 mA of H\(^-\) current was obtained with a 5.4-mm-diam extraction aperture and with an RF input power of 50 kW. As explained by the authors, the RF discharge has many advantages over the filament discharge; these include longer lifetime, ease of operation at high power, fast start-up etc. Similar to filament discharges, the H\(^-\) yield can be enhanced by introducing cesium vapor into the RF-driven discharge. Using the same RF power, Leung et al\(^2\) obtained more than 90 mA of H\(^-\) current in a later experiment which confirms a factor of 3 enhancement by the cesium injection. The above experiments were done with discharge pulses typically less than a couple of ms long. The purpose of our experiment is to test the ion source for a longer pulse length extending up to many seconds at a practical cw power level (e.g. at \(\approx 20\) kW).

II. APPARATUS

A schematic diagram of the ion source is shown in Fig. 1. The source dimension is similar to the one described in reference 1. It has a multicusp chamber 10-cm-diam by 10-cm-deep surrounded by 20 columns of samarium-cobalt magnets. The central field-free region is approximately 6 cm in diameter. Two pairs of filter rods (which have permanent magnets embedded inside) are used to generate the magnetic field in front of the extraction aperture. When needed, cesium can be released into the ion source by SAES dispensers\(^3\) mounted inside the source. The inner surface of the source is covered with molybdenum liners in order to minimize cesium condensation on the cold copper surfaces. Since we are operating at \(\approx 20\) kW instead of 50 kW, the H\(^-\) current density is much lower than that obtained in reference 1 and 2. For this reason, a larger aperture (15 mm in diameter) was selected in order to produce sufficient H\(^-\) beam current. Description of the 100 keV preaccelerator with the electron trap can be found in reference 4.

In the past, the same ion source was driven by two tungsten filaments. In this study, the filament unit has been replaced by an RF antenna. It has the shape of a two-turn induction coil (6 cm in diameter) and is made of 4.7-mm-diam copper tubing coated with a thin layer of hard porcelain material. A small tungsten filament is used as a starter to pre-ionize the hydrogen gas before the RF discharge occurs and it can be turned off after the RF discharge has started.

Apart from the antenna, the ion source itself is designed to

![Fig. 1. Schematic diagram of the ion source with an RF antenna.](image)
handle 36 kW of steady-state input power. During the initial testing, we found that the original RF antenna used in Leung’s experiments began to fail (at the porcelain coating) when the power exceeded 7 kW for pulses over a second long or for 10 kW pulses over a few hundred ms. In our experiment, we found that adding one or two layers of quartz sleeving over the porcelain-coated antenna can improve the antenna’s operating range. However, the quartz sleeving introduces another adverse effect to the production of H- ions. We will discuss this in more detail in the next section.

The RF circuit diagram is shown in Fig. 2. The RF power supply is capable of delivering 100 kW of cw RF power at ~2 MHz. The RF power is transmitted from the power supply via a 50 ohm coaxial cable to a 5-stage 100 kV isolation transformer. The final stage of the transformer is coupled to a LC matching network. As usual, the antenna itself can be represented by a transformer with a single turn secondary while the plasma acts as a resistor in series with an inductor. During operation, the RF frequency is tuned (in the neighborhood of 2 MHz) to obtain resonance in the matching network such that the voltage and the current at the input of the isolation transformer are in phase. The turns ratio of the isolation transformer is adjusted to bring the transformer input impedance (with the plasma load) close to 50 ohms. According to a power balance calibration, the isolation transformer only has a power transmission efficiency of ~70% (probably due to the lossy core material).

II- beam current is measured by a current transformer downstream of a dipole magnet which eliminates all remaining electrons in the beam. The average current density reported here is defined as the beam current measured by the current transformer divided by the area of the source aperture. At a typical source operating gas pressure of 10 mT, our Monte Carlo gas flow computation predicted a 45% stripping loss of H- ions in the preaccelerator.

III. Experimental Results

Our first interest was to compare the H- yield between filament driven and RF driven discharges. Previously, the ion source had been operated to obtain 75 mA of H- beam current from a 14-mm-diam aperture using 17 kW of dc filament discharge. The H- production efficiency in that case was equal to 2.81 mA/cm²/kW. The pulse length was 270 ms. With a slightly reduced power of 14 kW and a smaller aperture (10 mm diameter), we have obtained up to 2.5 s of H- beam; the beam current started at 32 mA, stayed constant for about 1 s and then drooped down to 29 mA at the end of the 2.5 s pulse. We believe that this reduction of H- yield is due to the accumulation of tungsten vapor on the cesiated surfaces during the very long pulse.

We typically accelerate the H- beams to more than 70 keV energy, thus it is necessary to minimize the electrons extracted from the ion source. In order to do this, the plasma electrode must be biased positively with respect to the source anode. Unfortunately, a positive bias has the adverse effect of reducing the H- yield. The electron problem is more severe in the case of RF discharge than the filament discharge and therefore a high positive bias is required which further reduces the H- yield. This situation is different from that in Leung’s experiments, in which a negative bias was applied to the plasma electrode.

Fig. 3 shows the H- yield as a function of RF power with and without cesium injection. The three series of data are labeled as “no cesium”, “some cesium” and “more cesium” because we had no means of quantitatively measuring the amount of cesium vapor in the discharge. Interestingly, the H- output current was proportional to the RF power without showing any sign of saturation at high power. Comparing the performance between “no cesium” and “more cesium”, the H- yield was enhanced by more than a factor of 3. Given that the aperture has an area of 1.77 cm², the H- production efficiency for RF is 2.76 mA/cm²/kW (when there is plenty of cesium vapor in the discharge). This number is very close to the one found for filament discharge mentioned earlier. These beam data were obtained with discharge pulses that were ≥50 ms long.

The pressure in the source was reduced from 15 mT in the case of “no cesium” to <10 mT in the case of “more cesium”. The plasma electrode was typically biased at +10 V for all
cases. The ratio of leakage electron to \( \text{H}^+ \) current varied with discharge power and cesium concentration. For example at 8.5 kW, the ratio was 4:1 in the case of "more cesium" and 8:1 in the case of "no cesium".

Fig. 4 shows an emittance diagram of a 41 mA \( \text{H}^+ \) beam obtained with 8.4 kW of RF input power. The pulse length was equal to 50 ms. The normalized rms emittance was 0.017 \( \text{\pi-mrad-cm} \) which corresponds to an equivalent ion temperature of 1.92 eV at the 15-mm-diam aperture. This ion temperature is certainly within the same range as the ones obtained in our previous experiment using filament dc discharges.

As mentioned earlier, the original antenna design was unable to withstand cw operation exceeding 7 kW of RF power. The first place to show damage was the porcelain coating at the center of the induction coil where the plasma density was expected to be at its maximum. By moving the antenna "return leg" to the outside of the loop, the situation was improved but we are still unable to operate at \( \geq 10 \text{ kW} \) cw. Another approach that we have tried was to add quartz sleeving over the porcelain-coated antenna. Apparently, the quartz sleeving provided enough thermal shielding to the antenna that it could operate at up to \( \approx 15 \text{ kW} \) cw without incurring damage. Unfortunately we found that the quartz sleeving was responsible for depositing a thin layer of insulating material (most likely quartz) all over the inside of the source. For this reason, the cesium enhancement effect was suppressed and subsequently the \( \text{H}^+ \) yield was very low.

IV. DISCUSSION

So far the result in testing the RF-driven multicusp \( \text{H}^+ \) source showed that the \( \text{H}^+ \) production efficiency and the beam emittance are similar to those obtained from the filament discharge; they are typically at 2.8 mA/cm\(^2\)/kW and 0.017 \( \text{\pi-mrad-cm} \) (which corresponds to 1.9 eV) respectively.

The present porcelain coating on the antenna surface works well only for short pulses or for cw low power applications. In order to operate at high power (e.g. \( \geq 15 \text{ kW} \)) with long pulses, it will be necessary to develop better antenna coating material to withstand the intense plasma heating and sputtering.

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VI. REFERENCES

[3] Dispensers were manufactured by SAES GETTERS U.S.A. Inc., Colorado Springs, CO.