High Current $H_2^+$ and $H_3^+$ beam Generation by Pulsed 2.45 GHz Electron Cyclotron Resonance Ion Source

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The permanent magnet 2.45 GHz electron cyclotron resonance (ECR) ion source at Peking University (PKU-PMECR) can produce more than 100 mA hydrogen ion beam working at pulsed mode. For the increasing requirements of cluster ions ($H_2^+$ and $H_3^+$), in linac and cyclotron, experimental study was carried out to further understand the hydrogen plasma processes in the ion source for the generation of cluster ions. The constituents of extracted beam have been analyzed varying with the pulsed duration from 0.3 ms to 2.0 ms (repetition frequency 100 Hz) at different operation pressure. The fraction of cluster ions dramatically increased when the pulsed duration was lower than 0.6 ms, and more than 20 mA pure $H_3^+$ ions with fraction 43.2% and 40 mA $H_2^+$ ions with fraction 47.7% were obtained when the operation parameters were adequate. The dependence of extracted ion fraction on microwave power was also measured at different pressure as the energy absorbed by plasma will greatly influence electron temperature and electron density then the plasma processes in the ion source. More details will be presented in this paper.

I. Background

Applications of $H_2^+$ and $H_3^+$

One application for hydrogen clusters is that they can be used as test beams in place of $D^+$ and $T^+$ to eliminate radiation problems in accelerators such as IFMIF, SARAF, Spiral 2 and Beijing ISOL.

Moreover, $H_2^+$ and $H_3^+$ ions also have distinct advantages in ion therapy or in cyclotron by employing the stripping method for the extraction of ultimate proton beam to diminish the space charge effects.

II. Plasma Processes

Production of $H_2^+$, $H_3^+$ and $H^+$

(1) $e + H_2 \rightarrow H_2^+ + 2e \quad E_{th}=15.6 \text{ eV}$
(2) $H_2^+ + H \rightarrow H_2 + H^+ \quad E_{th}=0 \text{ eV}$
(3) $H_2 + e \rightarrow 2H + e \quad E_{th}=9.2 \text{ eV}$
$H + e \rightarrow H^+ + 2e \quad E_{th}=13.6 \text{ eV}$
(4) $H_2^+ + e \rightarrow H_2^+ + e \quad E_{th}=15.6 \text{ eV}$
$H_3^+ + e \rightarrow H^+ + H + e \quad E_{th}=12.1 \text{ eV}$
or $H_2^+ + e \rightarrow 2H^+ + 2e \quad E_{th}=17 \text{ eV}$

During discharge, $H_2^+$ is created by direct ionization process (1) of hydrogen molecule while $H_3^+$ is produced by the dissociative attachment reaction (2) which has a maximum cross-section with lower particle energy. Meanwhile, $H^+$ may be produced mainly by two multiple collision processes (3) and (4) in a 2.45 GHz ECR ion source as the average electron temperature in the volume is about several eV.

With lower electron temperature in plasma, process (3) will predominate the generation of $H^+$: when the temperature increases, the dominant will be process (4).

III. Experiment Setup

The test bench consists of microwave system, ECR ion source, triple-electrode extraction system, Faraday cup, 90° dipole analysis magnet and necessary auxiliaries. The ion source works at 2.45 GHz with inner chamber diameter of 64 mm, and the magnetic mirror confinement is provided all by permanent magnet NdFeB which make the source volume very compact.

IV. Pulsed Duration Study

Experimental evidences show that, after breakdown, there were peaks of $H_2^+$ and $H_3^+$ at about the initial 50 μs on our source, and more time was needed for $H^+$ to reach the plateau.

At different pressure, the average ion fraction of $H^+$, $H_2^+$ and $H_3^+$ are almost invariable when the duration is longer than 0.6 ms; but the cluster ratios increase dramatically when the duration decreases from 0.6 ms to 0.3 ms. The fraction of $H_2^+$ ions reached 45.4% with lower pressure with duration 0.3 ms. Meanwhile, a 20 mA pure $H_2^+$ ion beam with fraction 43.2% was achieved when the pressure was relatively high at $1.5 \times 10^{-3} \text{ Pa}$.

Possible explanation:

- Atomic ion $H^+$ is generated by two-step impact process which needs more time to reach equilibrium.
- The "pre-glow" principle may also contribute to the peaks of clusters for the existence of a transient electron temperature peak at very beginning of plasma breakdown.

V. RF Power

The fraction peaks of $H_2^+$ were measured with 150 W RF power, and there were more than 50% $H_2^+$ ions first reached at $5.5 \times 10^{-4} \text{ Pa}$. Considering the total beam current increases when more rf power is fed into discharge chamber, feeding power was adjusted for high current $H_2^+$; 40 mA $H_2^+$ ion can be finally obtained by 240 W power consumption with ion fraction 47.7%.

The species fraction of $H_2^+$ increases as the RF power decreases because $H_2^+$ ions have a high destruction cross section when they interact with electrons; too much feeding power is disadvantageous for $H_2^+$ generation.

According to above results, lower pressure for $H_2^+$ and higher pressure for $H_3^+$ can be also concluded as the prerequisites for the generation of clusters.

Discussion

High fraction of cluster ions can be obtained with short pulse duration, and this means a high frequency and short pulse working mode may be considered as the possibility for generating high yielding $H_2^+$ and $H_3^+$ ions. 40 mA $H_2^+$ and 20 mA $H_3^+$ ion beam can be achieved by only tuning the operation parameters on identical 2.45 GHz ECR ion source. Several improvements are about to carried out. An ECR ion source with transparent quartz window (Patent Number: ZL 201110026605.4) has been constructed and a spectrometer will be utilized to diagnose the electron characteristics in the plasmas. On the basis of experimental and theoretical study, design of a new ion source is in process for high current $H_2^+$ and $H_3^+$ beam.