# Optical Emission Spectroscopy for Plasma Diagnosis of 2.45 GHz ECR Ion Source at Peking University


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**Abstract:** A quartz-chamber 2.45 GHz Electron Cyclotron Resonance Ion Source (ECRIS) was designed for diagnostic purpose at Peking University [Patent Number: ZL 201110026605.4]. It can produce a maximum of 84 mA hydrogen ion beam at 50 kV with duty factor of 10%. The root-mean-square (RMS) emittance of the beam is smaller than 0.12 $\pi$ mm·mrad. For the comprehension of plasma behavior inside the discharge chamber, a spectrum measurement platform has been set up with this quartz-chamber ion source and experiments were carried out recently. Electron temperature and electron density inside the ECR plasma chamber have been measured with the method of line intensity ratio of noble gas. And dissociation degree of hydrogen is measured with the line ratio of hydrogen. Moreover, hydrogen plasma processes and dependence of species fraction of the hydrogen ion beam on plasma parameters are discussed based on these results. Details will be presented in this paper.


## DIAGNOSTIC PLATFORM

Figure 1 is a schematic illustration of the experimental set-up for plasma diagnosing at PKU. The test platform is composed of ECR ion source, gas control system and diagnostic system. In order to simplify the calculation of spectra, mixed He and Ar are used as diagnostic gases from one gas cylinder with He and Ar mixed at the ratio of 1:1. Therefore, a two channels gas control system with calibrated flow meters is needed to mix the noble gases and hydrogen at specified fractions (He/Ar : H2 =1:5) .The diagnostic system consists of optic fiber, a high resolution spectrometer (AvaSpec-USL3648) in the spectral range of 410 nm to 920 nm and a computer for data analysis.

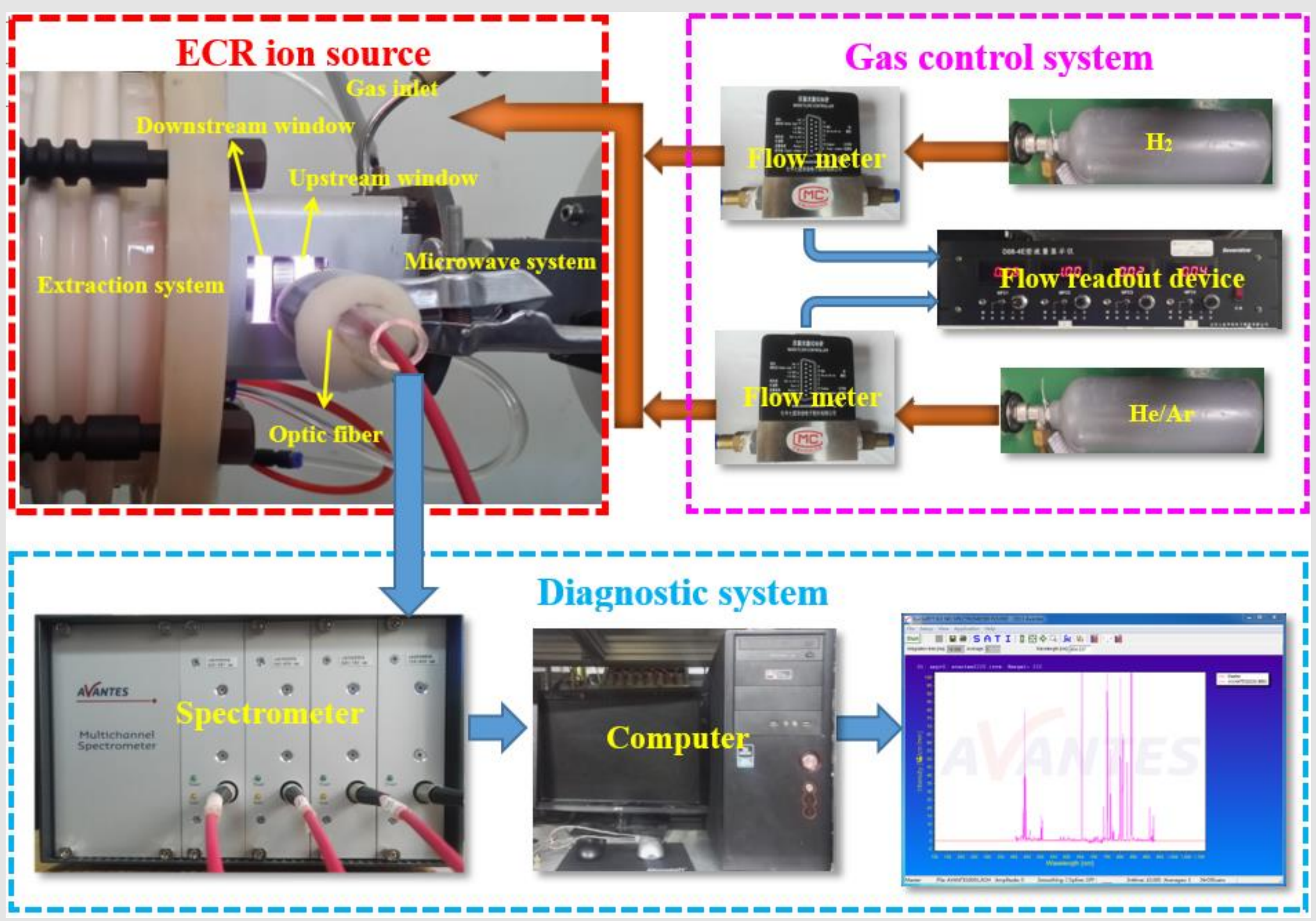



Fig. 1. Schematic illustration of the experimental set-up.

## PERFORMANCE OF QUARTZ-CHAMBER SOURCE

This quartz chamber ion source can produce a maximum of 84 mA hydrogen ion beam working at 50 kV with a peak RF power of 2300 W (10% duty factor) as shown in Fig. 2. And the RMS emittance of the beam is only 0.116 $\pi$· mm ·mrad as shown in Fig. 3.

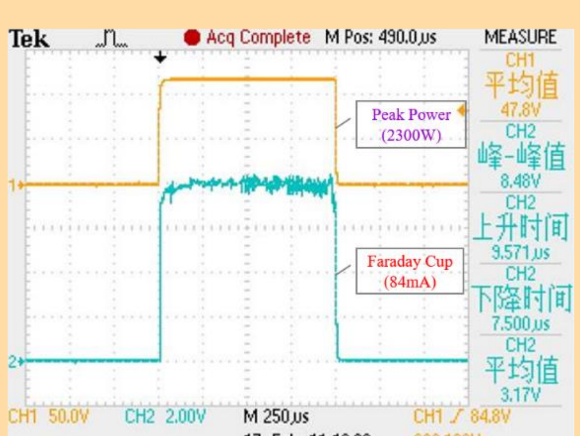



Fig. 2. Beam current of the quartz-chamber ion source.

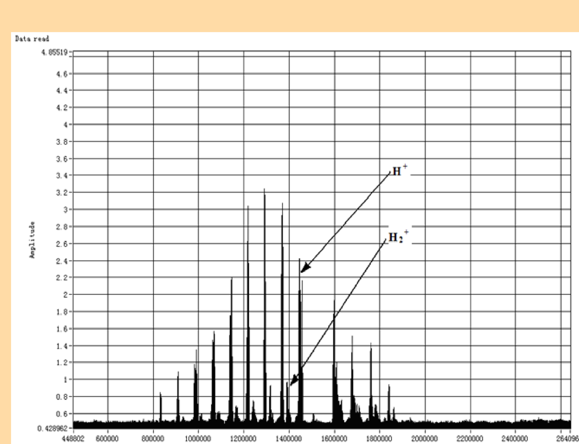


Fig. 3. Beam profile of the quartz-chamber ion source.

## SPECTRA MEASUREMENT

TABLE 1. Discharge of pure hydrogen and gas mixture at different RF power with gas pressure of $1.0\times10^{-3}$ Pa.

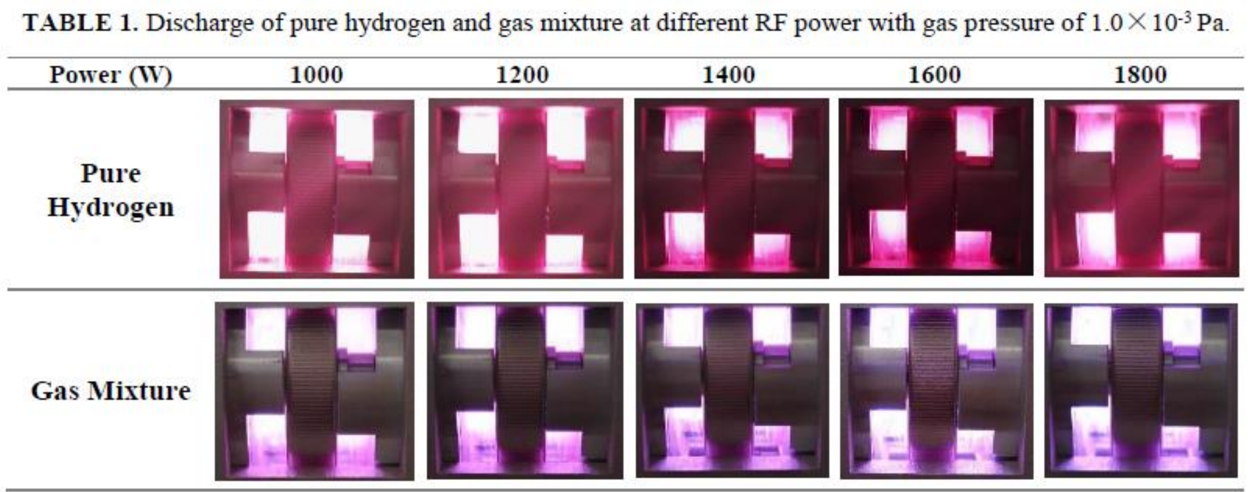
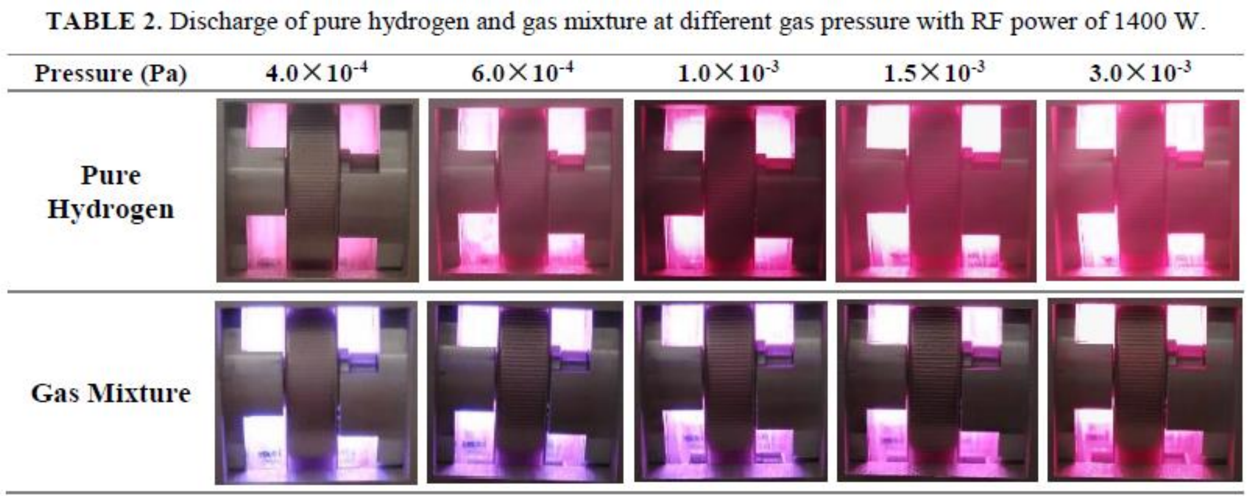



TABLE 2. Discharge of pure hydrogen and gas mixture at different gas pressure with RF power of 1400 W.




The color of pure hydrogen plasma is pink and the gas mixture (hydrogen and diagnostic gas) plasma is purple. This can attribute to the distinction of spectral line for different atoms and their ions. What is more, the purple is more prominent at high RF power and low gas pressure for gas mixture plasma. A possible explanation is that it is beneficial for plasma generation of helium and argon under these conditions.

## RESULTS AND DISCUSSION

Electron temperature has an influence on the species fraction of the final extraction beam. Firstly, $H_2^+$ ions inside plasma are created by direct ionization of $H_2$, $H_2^+$ production cross section will decrease as pressure rises. Secondly, $H_3^+$ ions are produced by the dissociative attachment of $H_2^+$ with a threshold energy of 0 eV. This reaction rate increases as pressure rises.

Electron density also has an influence on the species fraction of the final extraction beam. $H_3^+$ have a large dissociative recombination cross section with electrons, thus low RF power is beneficial to fraction of $H_3^+$. And moderate RF power is recommended to the improvement of $H_2^+$ fraction. Firstly, low electron density is insufficient since the $H_2^+$ ions are created by direct ionization of hydrogen molecule with electrons. Secondly, high electron density will consume the $H_2^+$ ions since the dissociative recombination of $H_2^+$ with electron also has a large cross section.

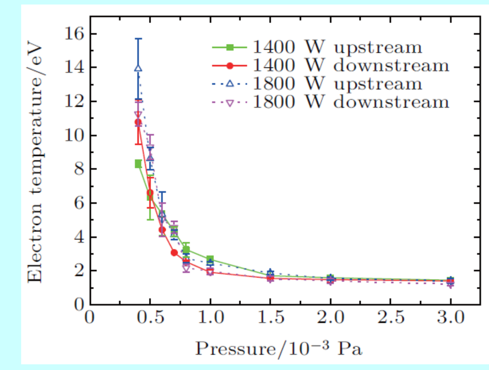



Fig. 4. Dependence of electron temperature on the gas pressure.

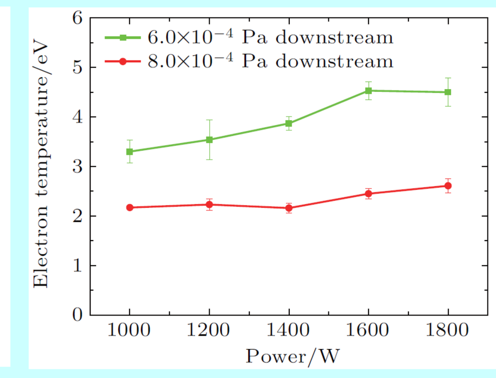



Fig. 5. Dependence of electron temperature on the RF power.

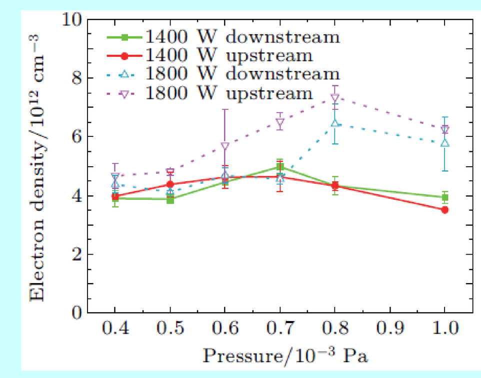



Fig. 6. Dependence of electron density on the gas pressure.

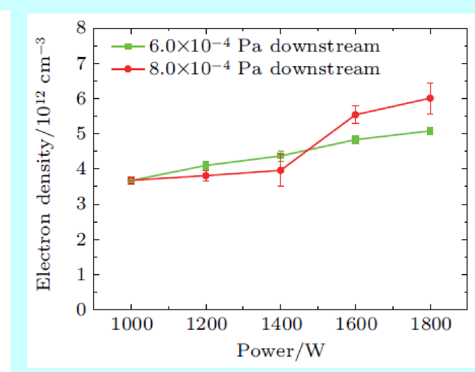



Fig. 7. Dependence of electron density on the RF power.

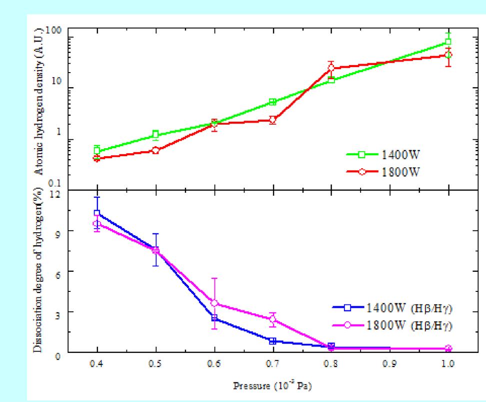


Fig. 8. Dependence of dissociation degree on the gas pressure.

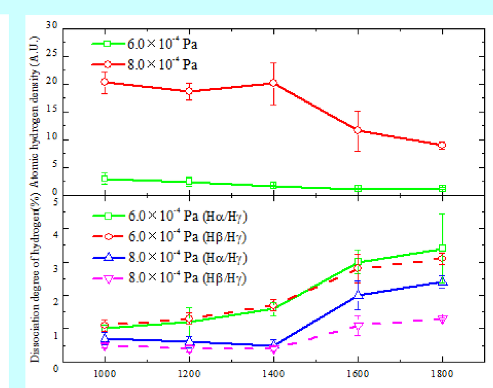



Fig. 9. Dependence of dissociation degree on the RF power.

For low temperature plasma inside our ion source, a multiple collision process works as RF power increases. Firstly, more hydrogen atoms are produced by dissociation of hydrogen molecules. Therefore, the dissociation degree increases. Meanwhile, more hydrogen atoms are ionized to protons caused to the decrease of atomic hydrogen density. In other word, high RF power is crucial for proton generation.

$$H_2 + e \rightarrow 2H + e \qquad E_{th} = 9.2\ eV,$$
$$H + e \rightarrow H^+ + 2e \qquad E_{th} = 13.6\ eV.$$

$$H_2 + e \rightarrow H_2^+ + 2e \qquad E_{th} = 15.6\ eV,$$
$$H_2^+ + e \rightarrow H^+ + H + e \qquad E_{th} = 12.1\ eV,$$
$$\text{or } H_2^+ + e \rightarrow 2H^+ + 2e \qquad E_{th} = 17.0\ eV.$$

More than 20 mA $H_3^+$ ion beam with species fraction 54.8% and 42.3 mA $H_2^+$ ion beam with species fraction 52.9% were obtained with a specially designed cluster ion source at PKU.

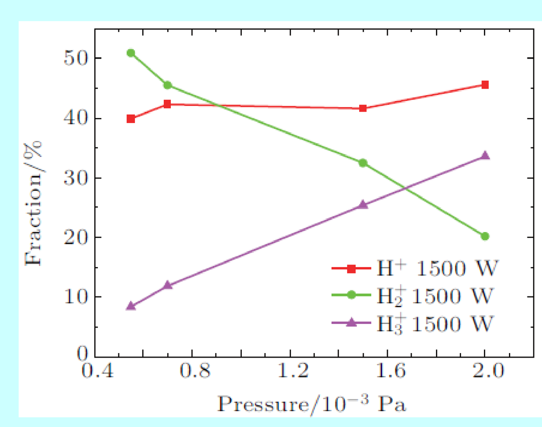



Fig. 10. Dependence of species fraction on the gas pressure for cluster ion source.

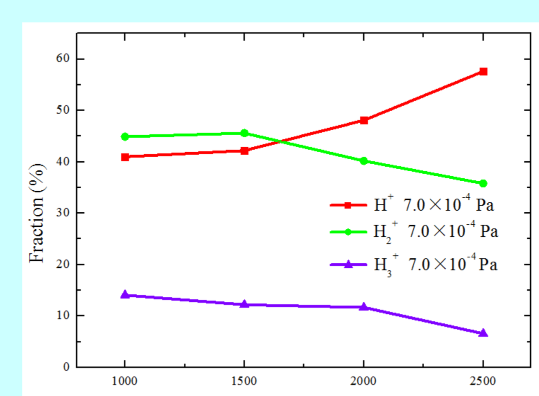



Fig. 11. Dependence of species fraction on the RF power for cluster ion source.

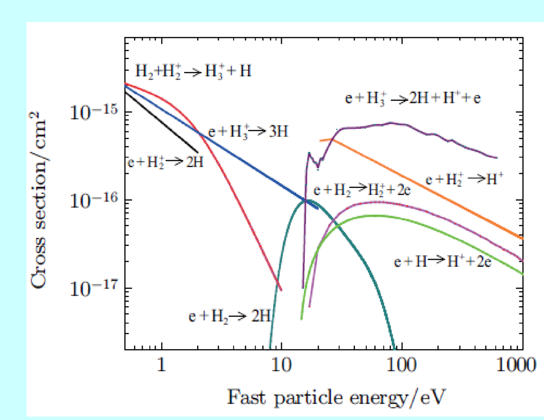



Fig. 12. Cross sections of some physical process inside hydrogen ion source.

In conclusion, moderate gas pressure and high RF power are recommended for an ion source to improve the ratio of proton. Low RF power and high gas pressure are beneficial to $H_3^+$ fraction, and moderate RF power and low gas pressure are crucial to improve the fraction of $H_2^+$. Therefore, the current with different dominant ion species can be extracted by adjust the working parameter of a hydrogen ion source.

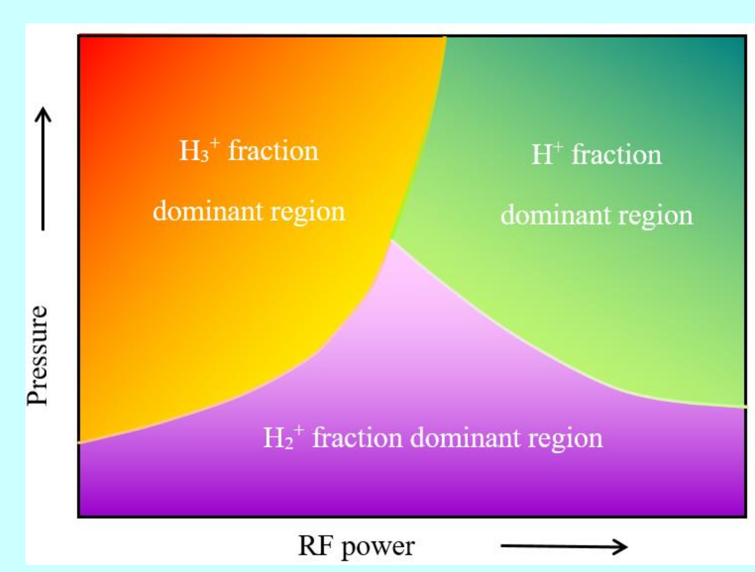



Fig. 13. Ion fraction dominant regions with different working parameter.

## SUMMARY

A quartz-chamber 2.45 GHz ECR ion source was designed at Peking University for diagnostic purpose. It can produce a maximum of 84 mA hydrogen ion beam at 50 kV with duty factor of 10% and the RMS emittance of the beam is smaller than 0.12 $\pi$· mm· mrad. To understand the hydrogen plasma inside the chamber, a diagnostic platform has been built. Photos under different operation gas pressure and different RF power are acquired with a camera and their spectra are obtained with a high resolution spectrometer. Relevant discussions are made based on these results. Line intensity ratio methods are selected for plasma parameters diagnosis, results show that electron temperature is between 1eV and 20 eV, electron density is about $10^{12}$~$10^{13}$ cm$^{-3}$ and dissociation degree of hydrogen is between 0.5% and 10%. In addition, hydrogen plasma processes and dependence of species fraction of the hydrogen ion beam on plasma parameters are discussed based on these results.

For a further comprehension of hydrogen plasma behavior inside the discharge chamber, both atomic and molecular emission spectroscopy of hydrogen will be investigated and applied for the determination of plasma parameters. Moreover, a new 2.45 GHz microwave driven H- ion source with a quartz window is designed for a further understanding on hydrogen plasma. All of these researches will be performed in the future.

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