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Investigation into Transient Processes on PKU Microwave Driven Hydrogen Ion source

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Introduction

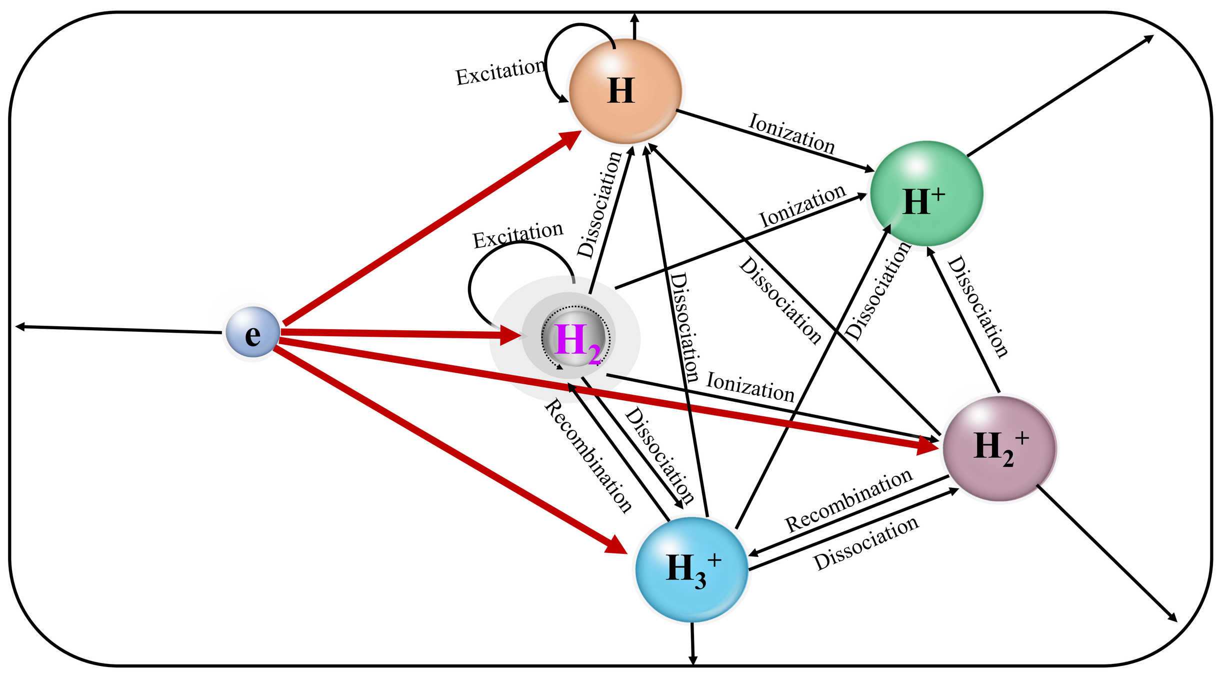

Fig. 1 Schematic diagram of main reaction processes in hydrogen plasma

2.45 GHz microwave driven ion sources (MDIS) have advantages of producing high beam intensity with low emittance and long life, have been wildly used in high energy physics, medical and archaeology, etc. H^+、H_2^+、H_3^+ ions are main components in hydrogen MDIS. To better understand the mechanisms underlying the hydrogen plasma discharges, a Transient Global Model (TGM) was proposed at PKU. Recently TGM was validated on a PKU 2.45 GHz miniature microwave driven ion sources (MMDIS) and **a 22 mA DC H_2^+ beam** was obtained [1].

Among thousands prosesses within a hydrogen discharging chamber, 17 reactions (shown in Table. 1) are selected to investigate the transient processes of number density and energy of electron, H^+, H_2^+, H_3^+, H and H_2.

Table. 1 Equations of main reaction processes in hydrogen plasma

No.	Reaction	Type	No.	Reaction	Type
1	$e+H_2 \to e+H_2$	Elastic collision	10	$e+H_3^+ \to 3H$	Dissociation
2	$e+H_2 \to e+H_2$	Excitation	11	$e+H_3^+ \to H_2+H^{*2}$	Dissociation
3	$e+H_2 \to e+H+H$	Dissociation	12	$e+H_2^+ \to H+H^{*2}$	Dissociation
4	$e+H_2 \to e+H+H^{*2}$	Dissociation	13	$e+H_2^+ \to H+H^{*3}$	Dissociation
5	$e+H_2 \to 2e+H_2^+$	Ionization	14	$H_2+H_2^+ \to H_3^+ +H$	Dissociation
6	$e+H_2 \to 2e+H+H^+$	Ionization	15	$e+H_2^+ \to H^+ +H+e$	Dissociation
7	$e+H \to e+H$	Elastic collision	16	$e+H_3^+ \to 2H+H^+ +e$	Dissociation
8	$e+H \to e+H^{*2}$	Excitation	17	$e+H_2^+ \to 2H^+ +2e$	Dissociation
9	$e+H \to 2e+H^+$	Ionization			

Model Establishment

Based on the steady global model (SGM) [2], energy balance equations of H^+、H_2^+、H_3^+、H and H_2 have been added to solve particle energy and calculate reaction rate.

Number Density Balance Equation

H^+: $$\frac{dn_{i1}}{dt} = n_e n_2 \sigma_6 + n_e n_1 \sigma_9 - \frac{n_1}{\tau_1}$$

H_2^+: $$\frac{dn_{i2}}{dt} = n_e n_2 \sigma_5 - n_e n_{i2} \sigma_{12} - n_e n_{i2} \sigma_{13} - n_e n_{i2} \sigma_{15} - n_e n_{i2} \sigma_{17} - \frac{n_{i2}}{\tau_2}$$

H_3^+: $$\frac{dn_{i3}}{dt} = n_2 n_{i2} \sigma_{14} - n_e n_{i3} \sigma_{10} - n_e n_{i3} \sigma_{11} - n_e n_{i3} \sigma_{16} - \frac{n_{i3}}{\tau_3}$$

H: $$\frac{dn_1}{dt} = 2n_e n_2 \sigma_3 + n_e n_2 \sigma_4 + n_e n_2 \sigma_6 + n_e n_{i3}(3\sigma_{10} + \sigma_{11} + 2\sigma_{16}) + 2n_e n_{i2}(\sigma_{12} + \sigma_{13} + 0.5\sigma_{13}) - n_e n_1 \sigma_9 - \frac{\Lambda^2}{D_{eff}}$$

H_2: $$\frac{dn_2}{dt} = n_{inj} + n_e n_{i3} \sigma_{11} - n_e n_2 (\sigma_3 + \sigma_4 + \sigma_5 + \sigma_6) - n_e n_{i2} \sigma_{14}$$

Energy Balance Equation

$$\frac{dE_{i1}}{dt} = P_{xi1} + P_{ii1} + P_{di1} - \frac{E_{i1}}{\tau_1}$$

$$\frac{dE_{i2}}{dt} = P_{xi2} + P_{ii2} + P_{di2} + P_{ci2} - \frac{E_{i2}}{\tau_2}$$

$$\frac{dE_{i3}}{dt} = P_{xi3} + P_{ii3} + P_{di3} + P_{ci3} - \frac{E_{i3}}{\tau_3}$$

$$\frac{dE_1}{dt} = P_{x1} + P_{i1} + P_{d1} + P_{c1} - \frac{\Lambda^2}{D_{eff}} T_1$$

$$\frac{dE_2}{dt} = P_{x2} + P_{i2} + P_{d2} + P_{c2}$$

P_{xj} : Excitation
P_{ij} : Ionization
P_{dj} : Dissociation
P_{cj} : Combination
$P = \sum n_j n_k \sigma_l T$

e — **Charge Conservation Equation**

$$n_e = n_{i1} + n_{i2} + n_{i3}$$

$$\frac{dE_e}{dt} = P_{xe} + P_{ie} + P_{de} - \frac{E_e}{\tau_e}$$

Simulation Results

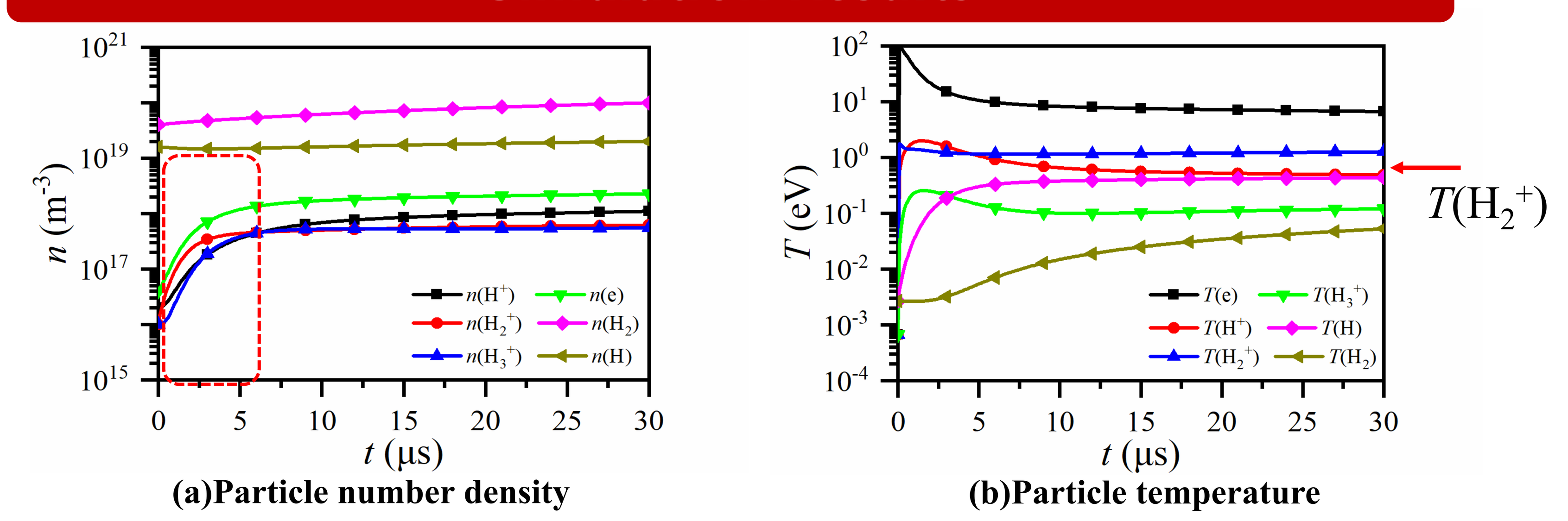

Fig 2. Transition variation diagram of particle number density and particle temperature

- **Questions:**
- **1. Why the fraction of H_2^+ is higher than H^+ at the initial stage?**
- **2. Why the temperature of H_2^+ is about 1eV?**

References

[1] B. Cui, et al. New progress on DC H_2^+ beam generation: Tens of mA output and 70% fraction from a 2.45 GHz microwave driven ion source (2025).

[2] W. Wu, et al. Plasma parameter diagnosis using hydrogen emission spectra of a quartz-chamber 2.45 GHz ECRIS at Peking University (2018).

[3] Y. Xu, et al. Multiple charge ion beam generation with a 2.45 GHz electron cyclotron resonance ion source (2014).

[4] R. Janev, et al. Elementary processes in hydrogen-helium plasmas: cross sections and reaction rate coefficients. (1987).

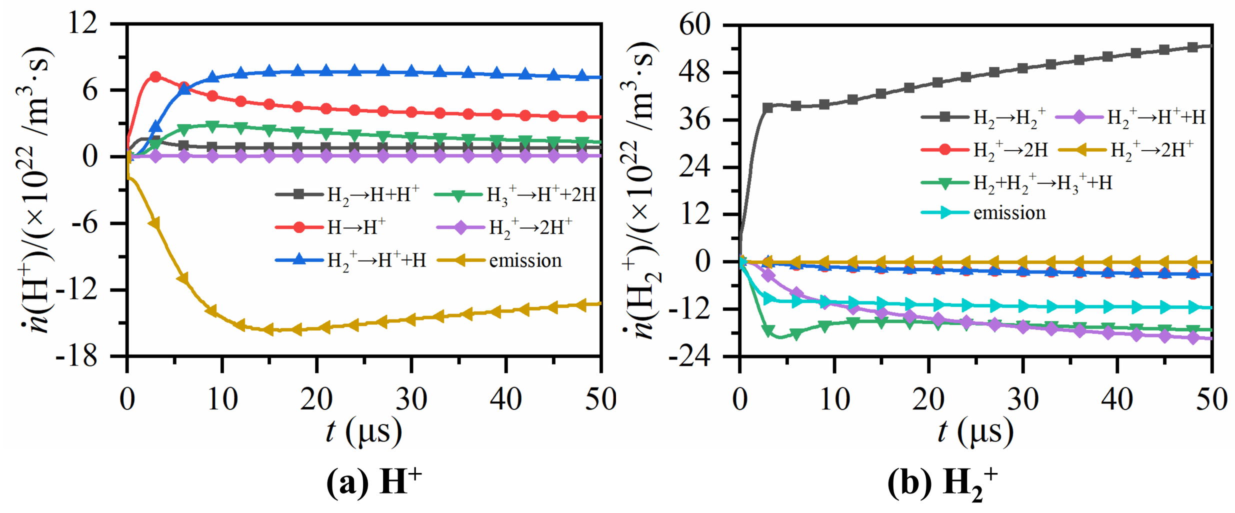

Fig 3. Change rate in particle number density of each reactions

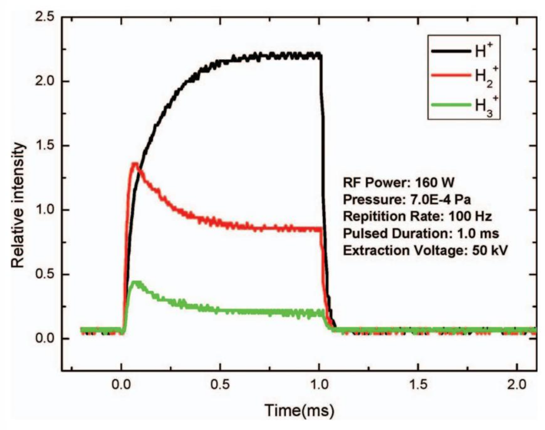

Fig 4. Experimental result [3]

Question 1

- **H_2 generates H_2^+ rapidly within the initial 10 μs, while the H_2^+ generates H^+ slowly. Therefore, H_2^+ accumulates continuously during this stage. At the same time, ionization rate of H is not high, so the rate of H^+ generation is lower than that of H_2^+.**

1. $e+H \to 2e+H^+$
2. $e+H_2 \to 2e+H_2^+$; $e+H_2^+ \to H^+ +H+e$

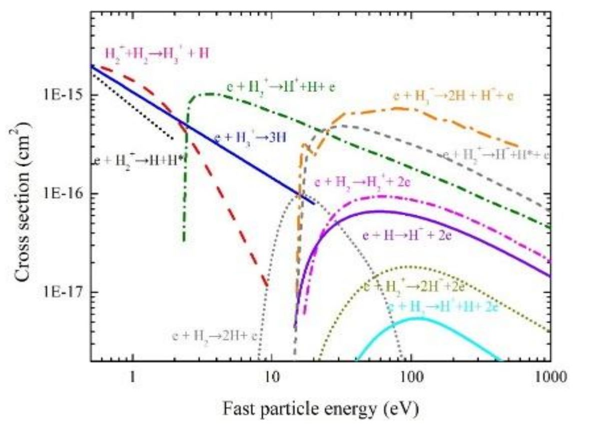

Fig 5. Cross sections of main reactions [4]

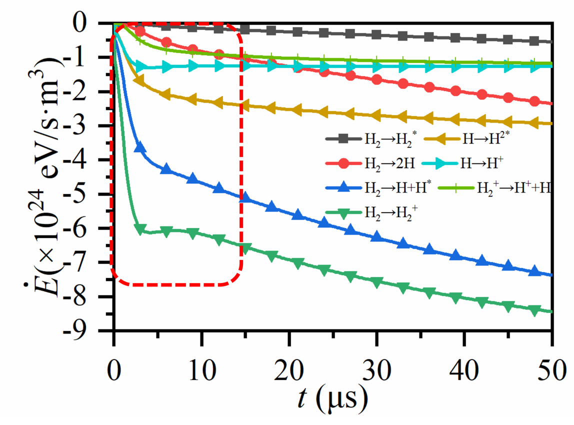

Fig 6. Change rate in particle temperature of each reactions

Question 2

- **Dissociation ($e+H_2 \to 2e+H_2^+$) consumes the maximum rate of electron energy.**
- **H_2^+ is the "medium" for energy transfer, receiving energy from electrons and transferring it to other particles.**
- **A high reaction rate does not mean a fast energy transfer.**

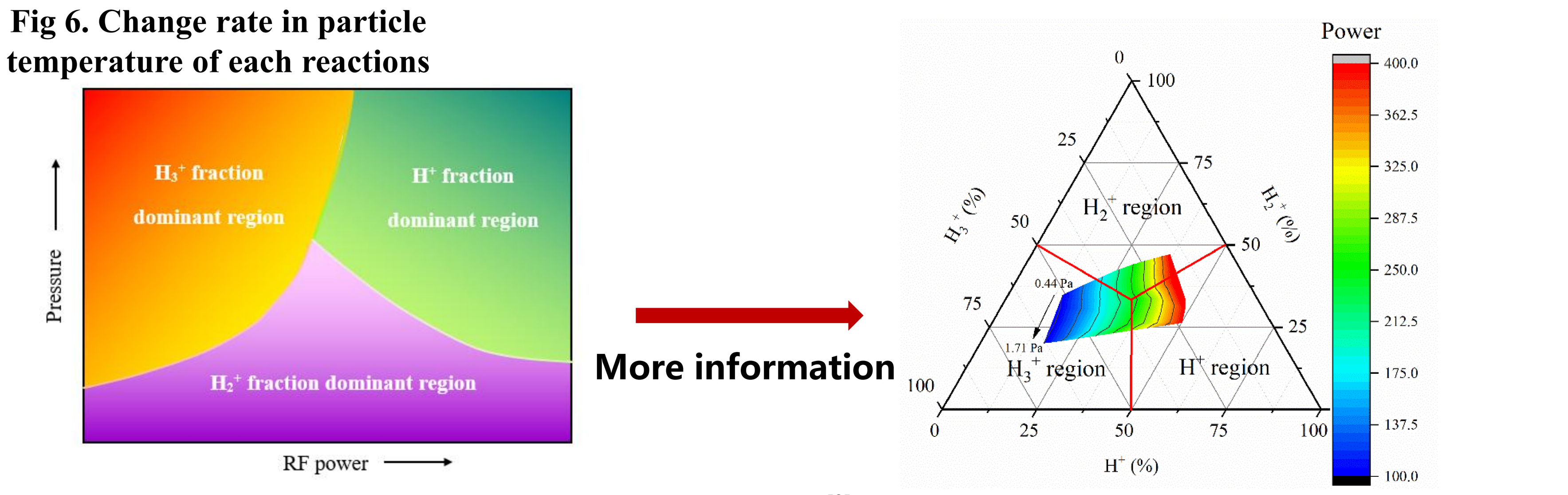

Fig 7. Three-phase diagram (qualitative) [2] and Ternary phase diagram (quantitative)

Regulation:

- **With the power growing up, fraction of H^+ and H_2^+ increasing, H_3^+ decreasing.**
- **With the pressure growing up, fraction of H^+ and H_3^+ increasing, H_2^+ decreasing.**

Experimental Results

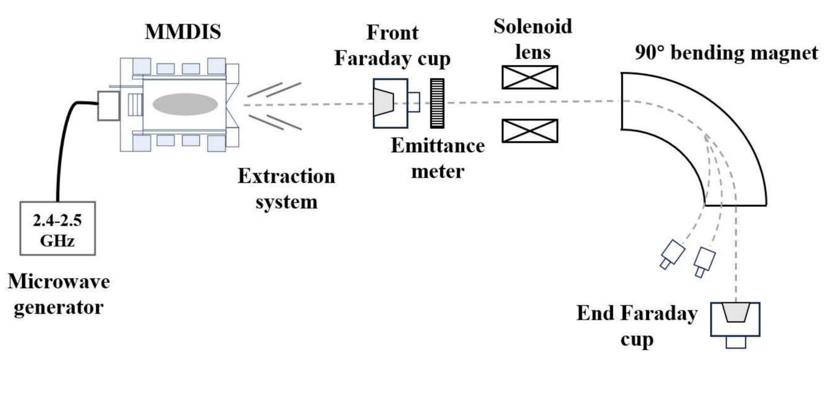

Fig 8. Schematic of experimental system

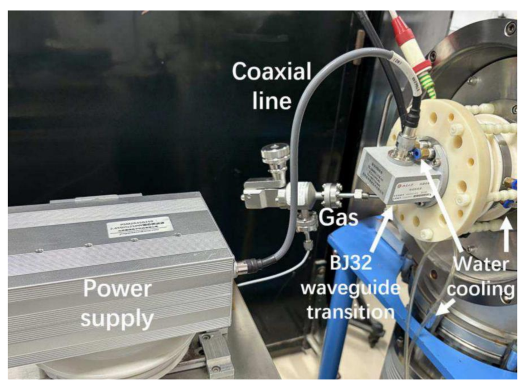

Fig 9. Photo of MMDIS

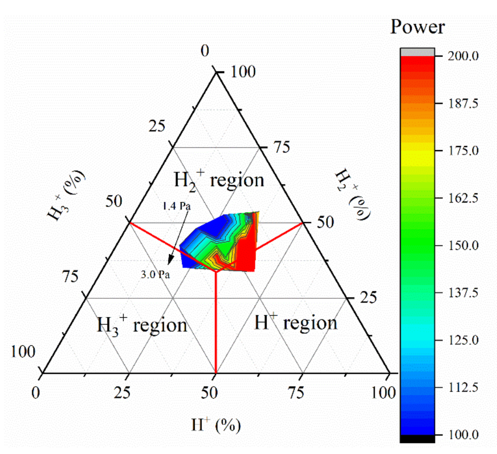

Fig 10. Ternary phase diagram of experimental result

The same variation patterns were obtained as the simulation model, verifying the effectiveness of TGM

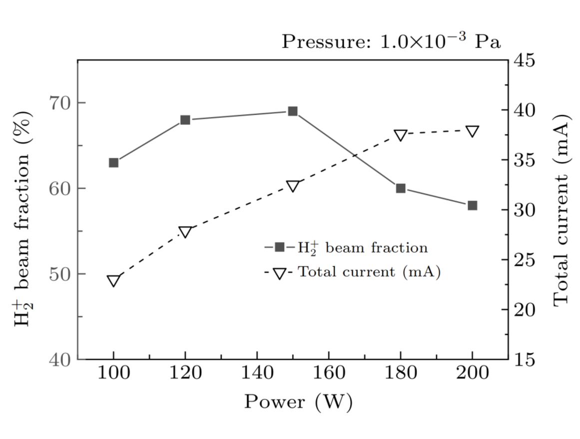

Fig 11. Total current and H_2^+ fraction under different power

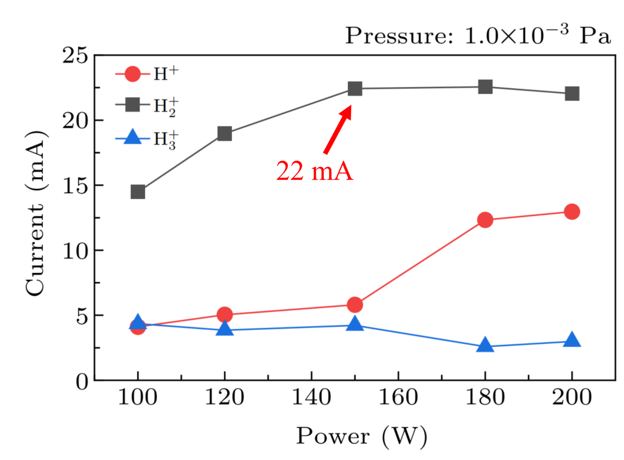

Fig 12. H^+, H_2^+ and H_3^+ beam currents under different power

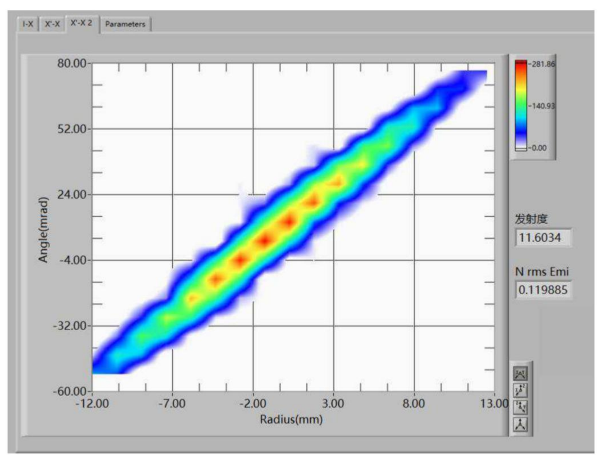

Fig 13. Phase space distribution of the mixed hydrogen ion beam

- **At a low input power of 150 W and a gas pressure of 1.0×10^{-3} Pa, a 22 mA H_2^+ ion beam at 30 kV with a fraction of 70% was generated in DC mode by MMDIS.**
- **The normalized RMS emittance of mixed beam is about 0.12 π·mm·mrad**
- **The 22 mA H_2^+ experimental results were consistent with the theoretical analysis of the ternary phase diagram.**

Conclusion

1. **The TGM reveals the transient changing regulation of number density and energy.**
2. **Ion fractions measurements results along with gas pressure and microwave power 22 mA H_2^+ beam with 70% fraction obtained with the PKU MMDIS is agree well with the TGM. The ternary phase diagram can provide more precise guidance for the operation of ion sources.**
3. **Tens of mA H_2^+ with high ion faction and low emittance can be achieved with a proper MDIS.**