北京大學
PEKING UNIVERSITY

21ST ECRIS 2014

Emission Spectroscopy Diagnostic of Plasma Inside 2.45 GHz ECR Ion Source at PKU

Yuan Xu, Shixiang Peng*, Haitao Ren, Jie Zhao, Jia Chen, Tao Zhang, Jingfeng Zhang, Zhiyu Guo and Jia'er Chen

State Key Laboratory of Nuclear Physics and Technology&
Institute of Heavy Ion Physics

ECRIS14, Nizhny Novgorod, Russia

August 25, 2014

Outline

- Background
- Physical processes in hydrogen discharge
- Emission spectroscopy diagnostic
- Preliminary results and analysis
- Conclusion

Outline

- Background
- Physical processes in hydrogen discharge
- Emission spectroscopy diagnostic
- Preliminary results and analysis
- Conclusion

Basic principles of 2.45 GHz ECR ion source

Hydrogen discharge extraction ion beam including: H^+, H_2^+, H_3^+ etc.

Ion source principle

ECR Source ➔ Resonance zone :

$\omega = e B / m$

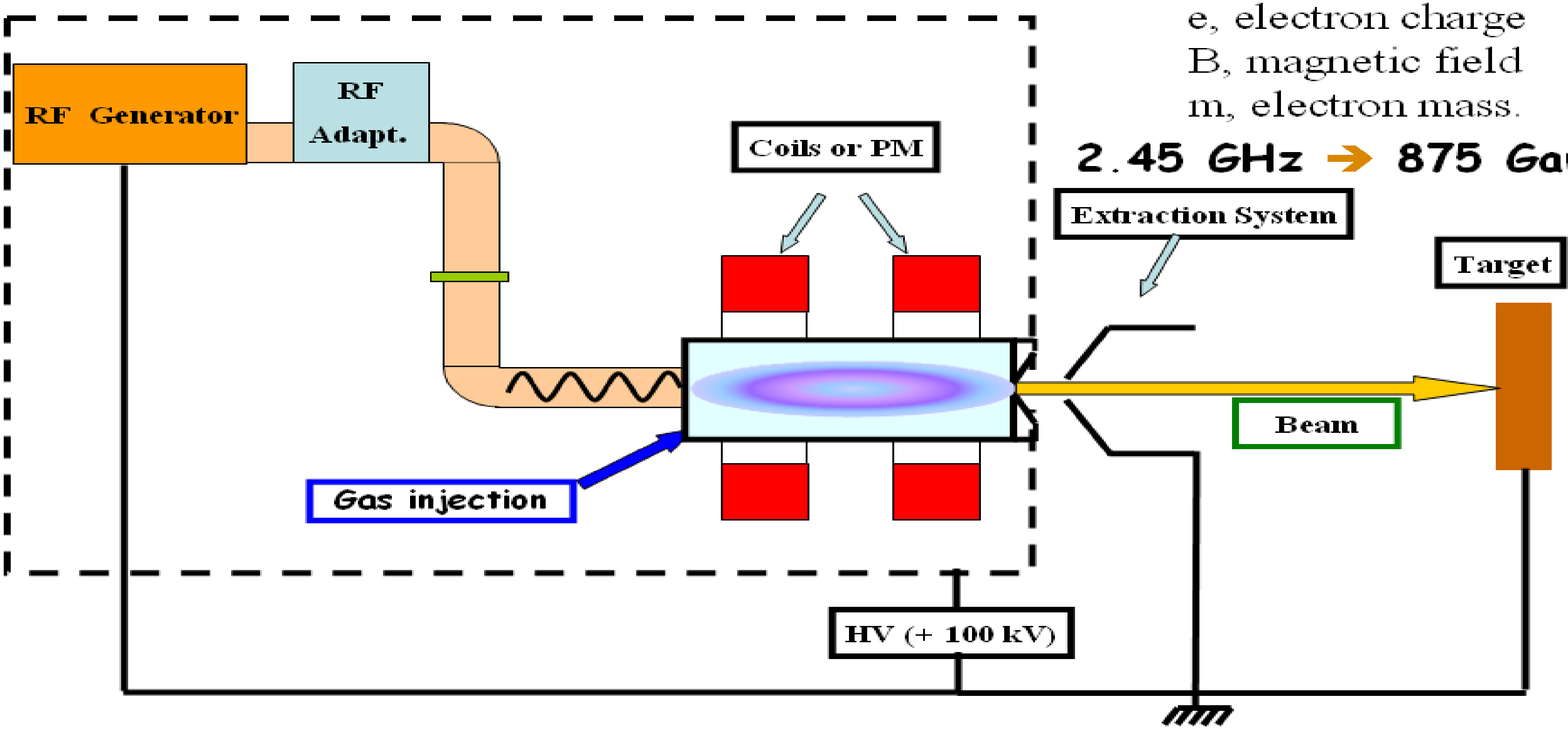
ω, pulsation

e, electron charge

B, magnetic field

m, electron mass.

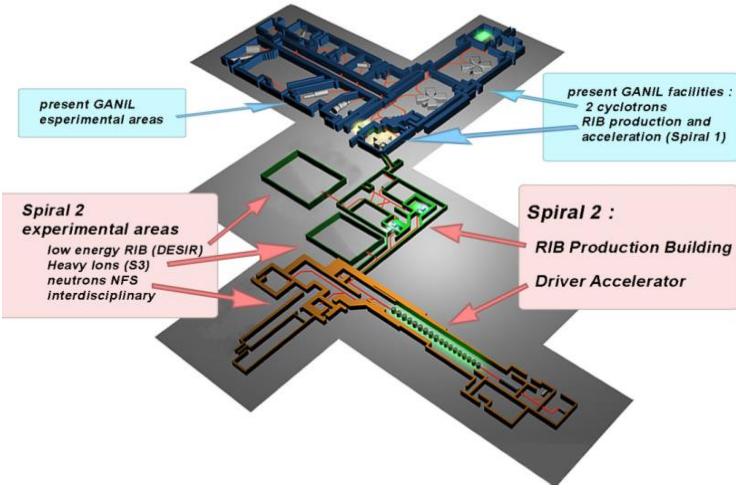
2.45 GHz ➔ 875 Gauss



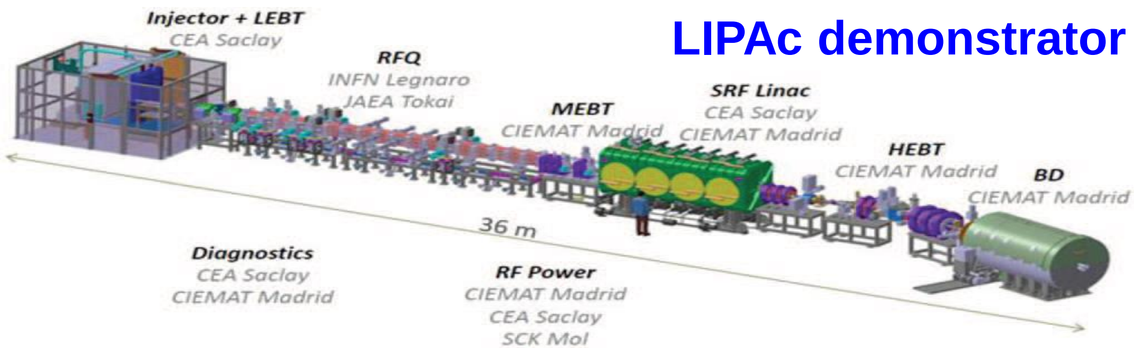
*R. Gobin, CEA/Saclay, report.

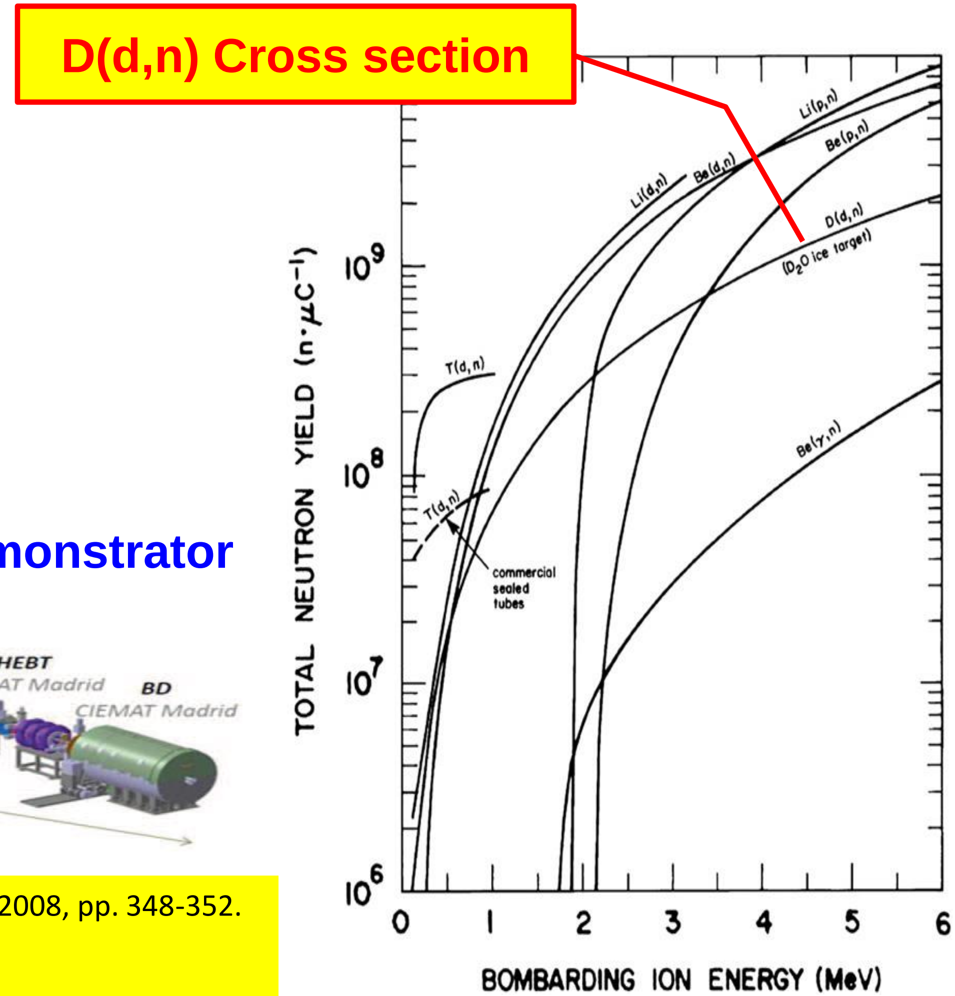
Requirements of H_2^+ ions

H_2^+ can be the substitute of D^+ in the commissioning phase of high current deuteron linac for diminishing neutron radiation as they have the same q/m ratio.



LIPAc demonstrator

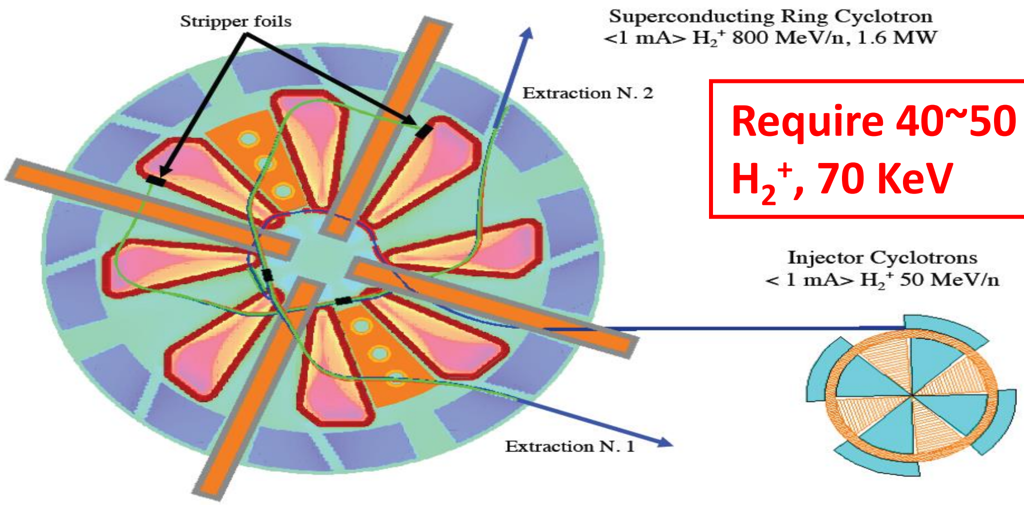




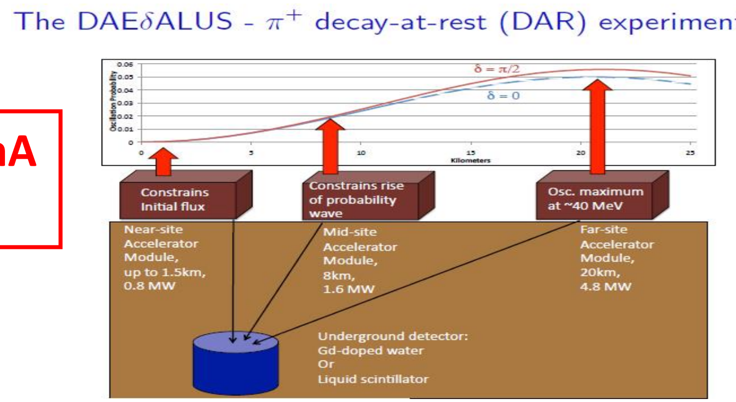
1. Tomas Junquera, *Proceedings of LINAC08*, Victoria, BC, Canada, 2008, pp. 348-352.
2. M.R. Hawkesworth, At. Energy Rev. 15 (1977) 169.
3. R. Gobin *et al.,* Rev. Sci. Instrum. **85**, 02A918 (2014).

PEKING UNIVERSITY

Requirements of H_2^+ ions



Require 40~50 mA H_2^+, 70 KeV



generalized perveance K:

$$K \propto \frac{qI}{m \cdot \gamma^3 \beta^3}$$

Space Charge Effect

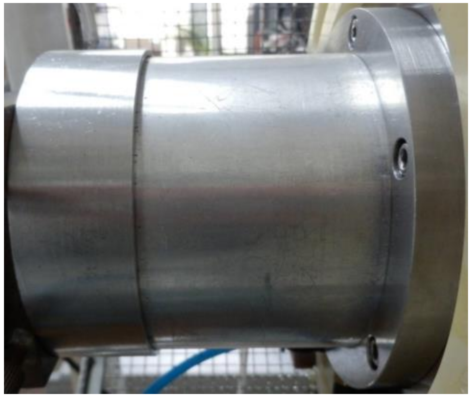
Table 1: Perveance values of proton and H_2^+ beams at various energies.

	$E_p=E_{H2}$ 30 keV	$E_p=E_{H2}$ 800 MeV	E_p=30 keV E_{H2}=70 keV
H_2^+, I=5 mA	$0.881\ 10^{-3}$	$0.151\ 10^{-9}$	$0.247\ 10^{-3}$
P, I=10 mA	$1.245\ 10^{-3}$	$1.075\ 10^{-9}$	$1.245\ 10^{-3}$
K_{H2}/K_p	0.707	0.141	0.198
P, I=2 mA	$2.491\ 10^{-4}$	$2.15\ 10^{-10}$	$2.491\ 10^{-4}$
K_{H2}/K_p	3.537	0.703	0.992

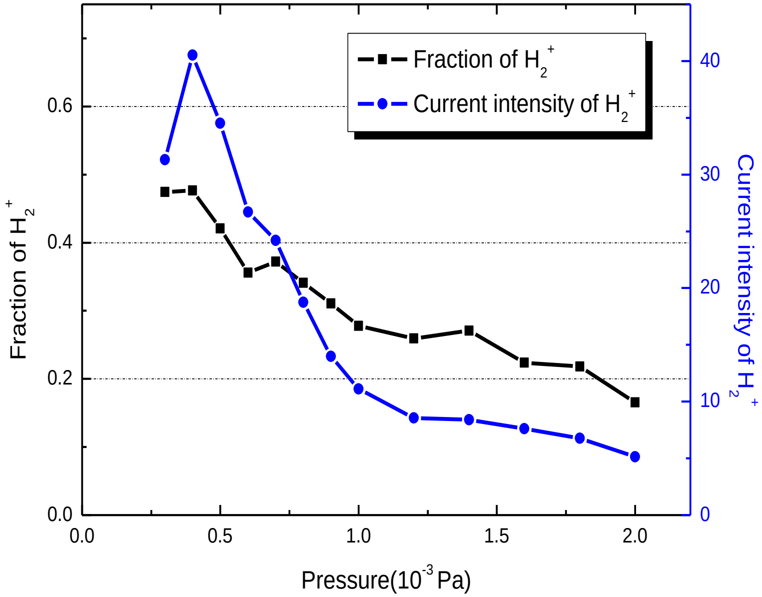
By accelerating H_2^+ ions, and stripping them at extraction area can decrease the space charge effect obviously, so the load of accelerator from beam loss can be decreased.

*L. Calabretta *et al*, Prilimilary design study of high-power H_2^+ cyclotrons for the DAEδALUS expriment, 2th July, 2011.

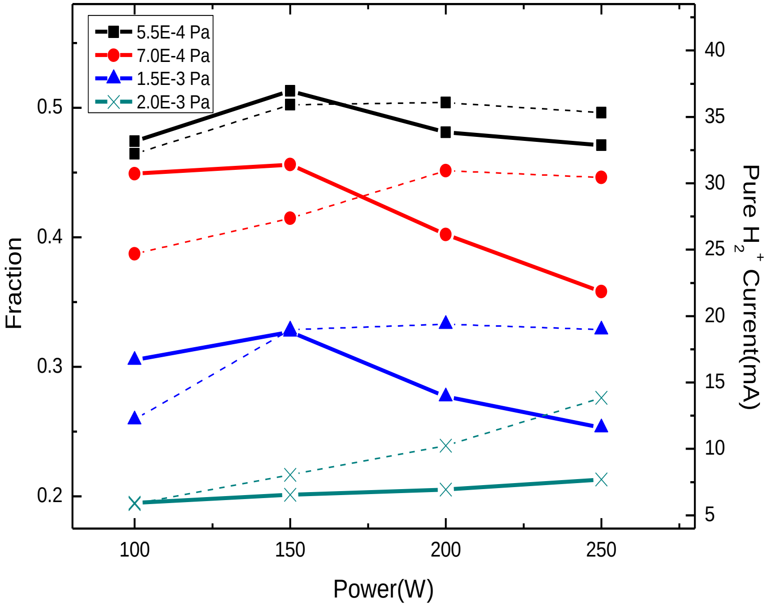
Study of H_2^+ ion source at Peking University



With 2.45 GHz permanent magnet ECR ion source (PMECR) at PKU, we investigated the influence of discharge chamber dimension, pressure, RF power, pulsed duration etc.



H_2^+ *vs* operation pressure



H_2^+ *vs* RF power

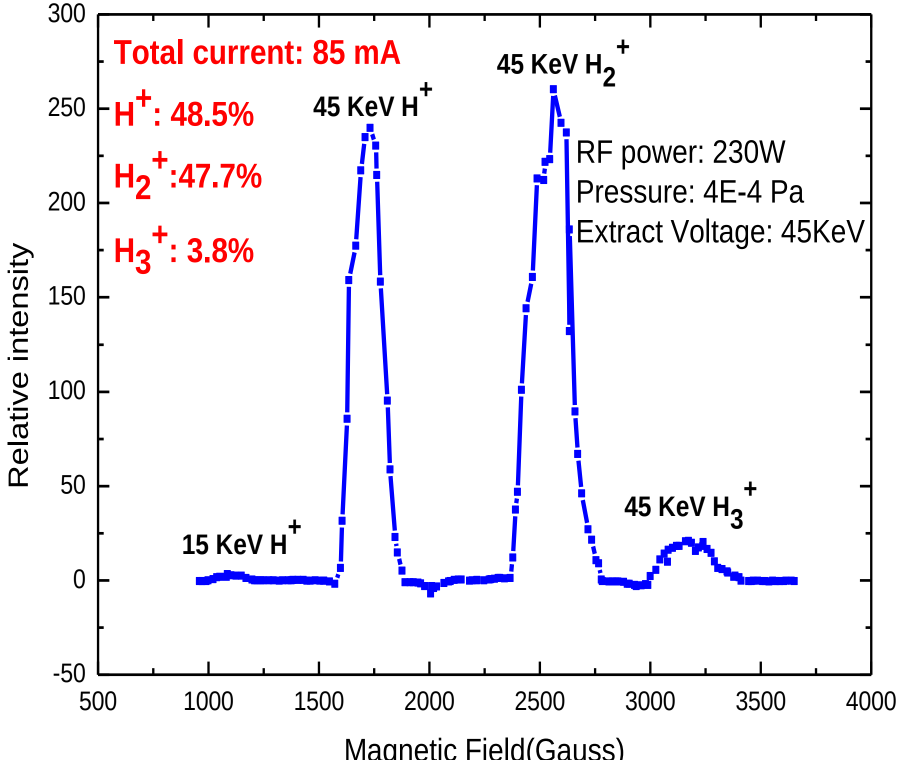
1. Y. Xu *et al.*, *Proceedings of IPAC2013, Shanghai*, China MOPFI035, pp. 363–365 (2013).
2. Yuan Xu *et al.*, Rev. Sci. Instrum. **85**, 02A943 (2014).

The yield of H_2^+ increased dramatically with decreasing of pressure. **With 4×10^{-4} Pa, 47.7% H_2^+ can be extracted with total current 85 mA, so the pure H_2^+ ions can be as high as 40 mA.** We also got some interesting results with H_3^+, more than 20 mA H_3^+ can be extracted with high pressure and low power.

1. R.J. Barlow, A. Bungau, A.M. Kolano, etcetc., IPAC13, **MOPFI071**, *Proceedings of IPAC2013*, Shanghai, China, 12th-17th May, 2013: 446-448. ISBN 978-3-95450-122-9.
2. N. Joshi, M. Droba, O. Meusel, U. Ratzinger, NIM **A** 606 (2009) 310–313.
3. Y. Xu *et al.*, *Proceedings of IPAC2013, Shanghai*, China MOPFI035, pp. 363–365 (2013).

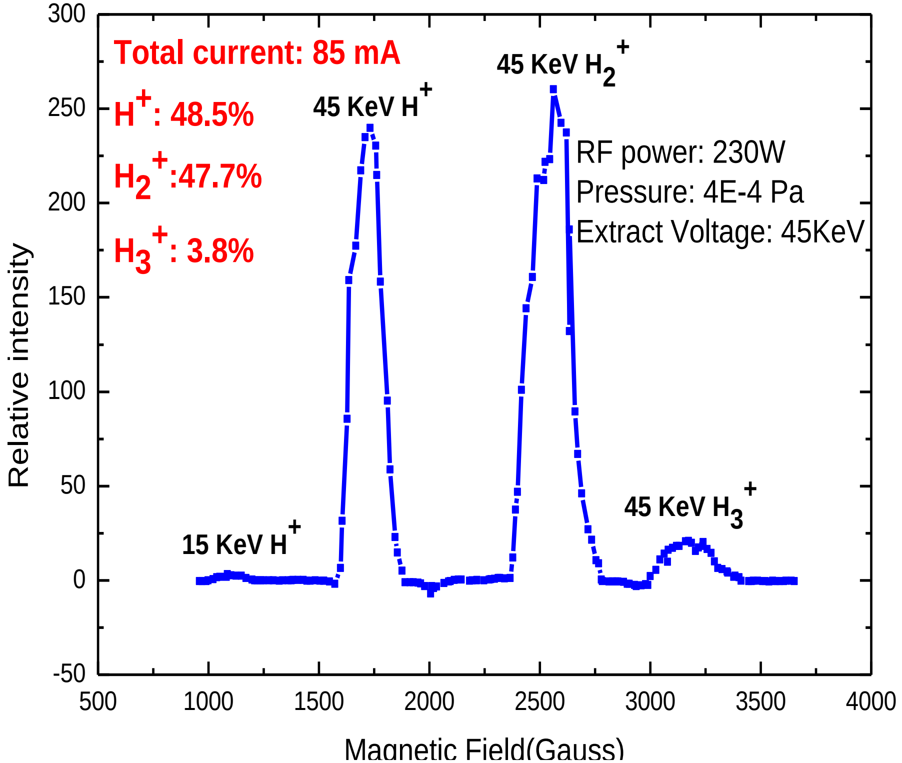
PEKING UNIVERSITY

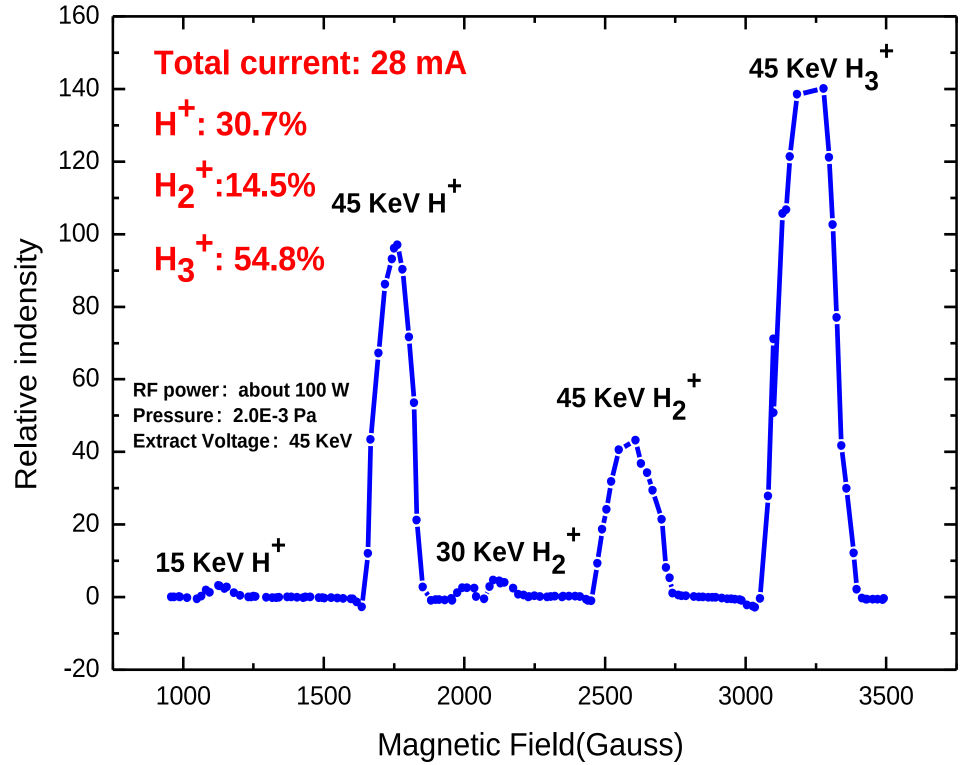
The yield of H_2^+ increased dramatically with decreasing of pressure. **With 4×10^{-4} Pa, 47.7% H_2^+ can be extracted with total current 85 mA, so the pure H_2^+ ions can be as high as 40 mA.** We also got some interesting results with H_3^+, more than 20 mA H_3^+ can be extracted with high pressure and low power.



1. R.J. Barlow, A. Bungau, A.M. Kolano, etcetc., IPAC13, **MOPFI071**, *Proceedings of IPAC2013*, Shanghai, China, 12th-17th May, 2013: 446-448. ISBN 978-3-95450-122-9.
2. N. Joshi, M. Droba, O. Meusel, U. Ratzinger, NIM **A** 606 (2009) 310–313.
3. Y. Xu *et al.*, *Proceedings of IPAC2013, Shanghai*, China MOPFI035, pp. 363–365 (2013).

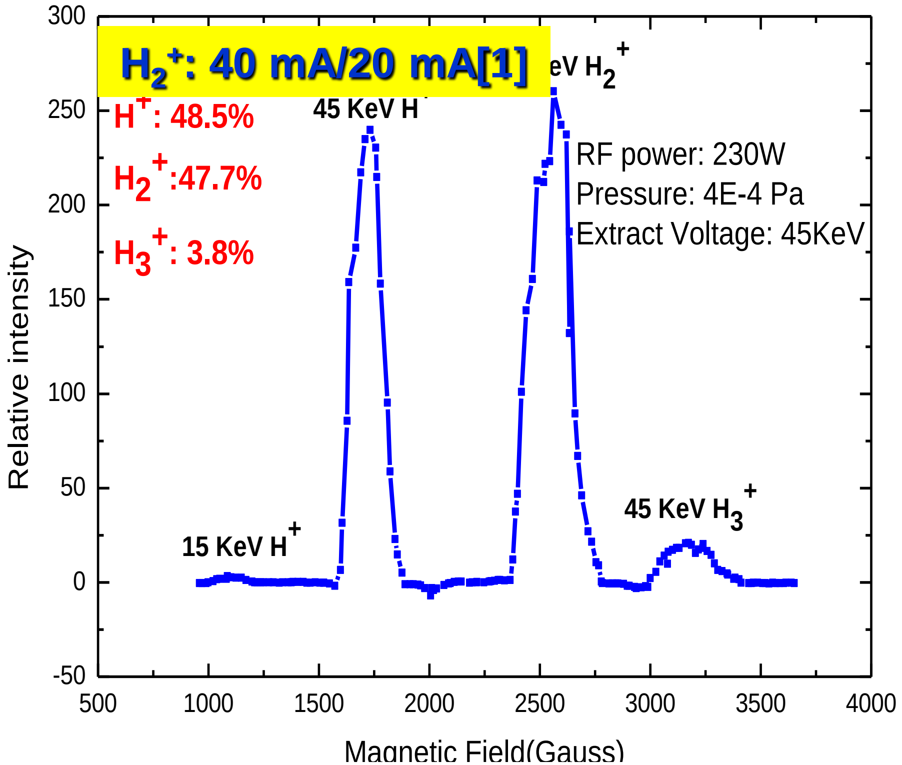
The yield of H_2^+ increased dramatically with decreasing of pressure. **With 4×10^{-4} Pa, 47.7% H_2^+ can be extracted with total current 85 mA, so the pure H_2^+ ions can be as high as 40 mA.** We also got some interesting results with H_3^+, more than 20 mA H_3^+ can be extracted with high pressure and low power.

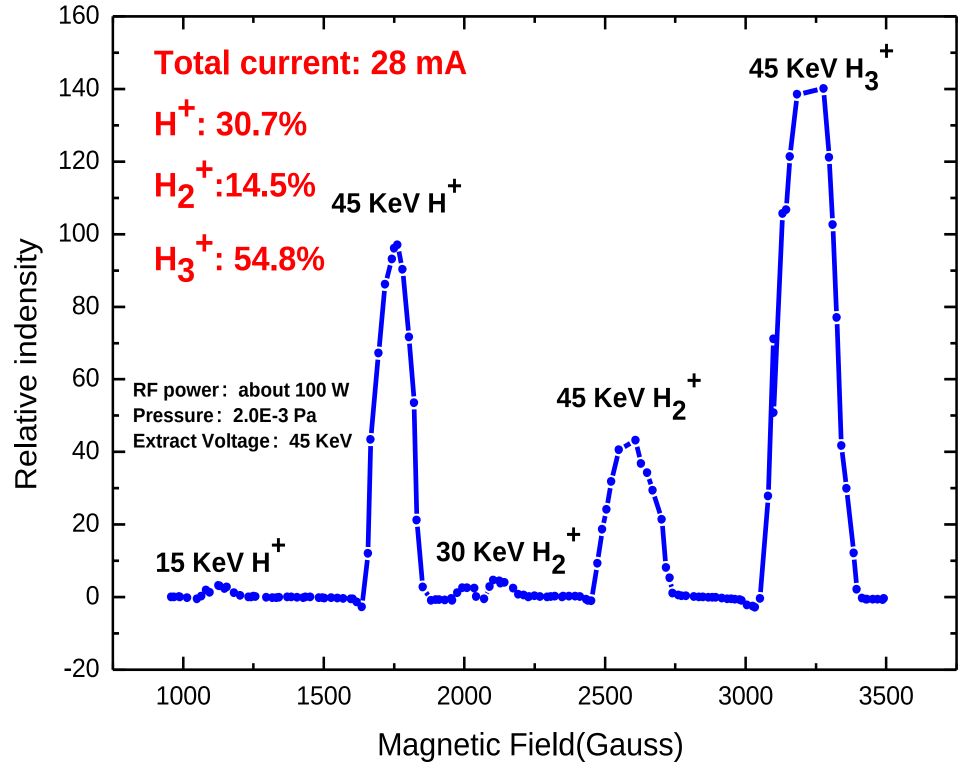




1. R.J. Barlow, A. Bungau, A.M. Kolano, etcetc., IPAC13, **MOPFI071**, *Proceedings of IPAC2013*, Shanghai, China, 12th-17th May, 2013: 446-448. ISBN 978-3-95450-122-9.
2. N. Joshi, M. Droba, O. Meusel, U. Ratzinger, NIM **A** 606 (2009) 310–313.
3. Y. Xu *et al.*, *Proceedings of IPAC2013, Shanghai*, China MOPFI035, pp. 363–365 (2013).

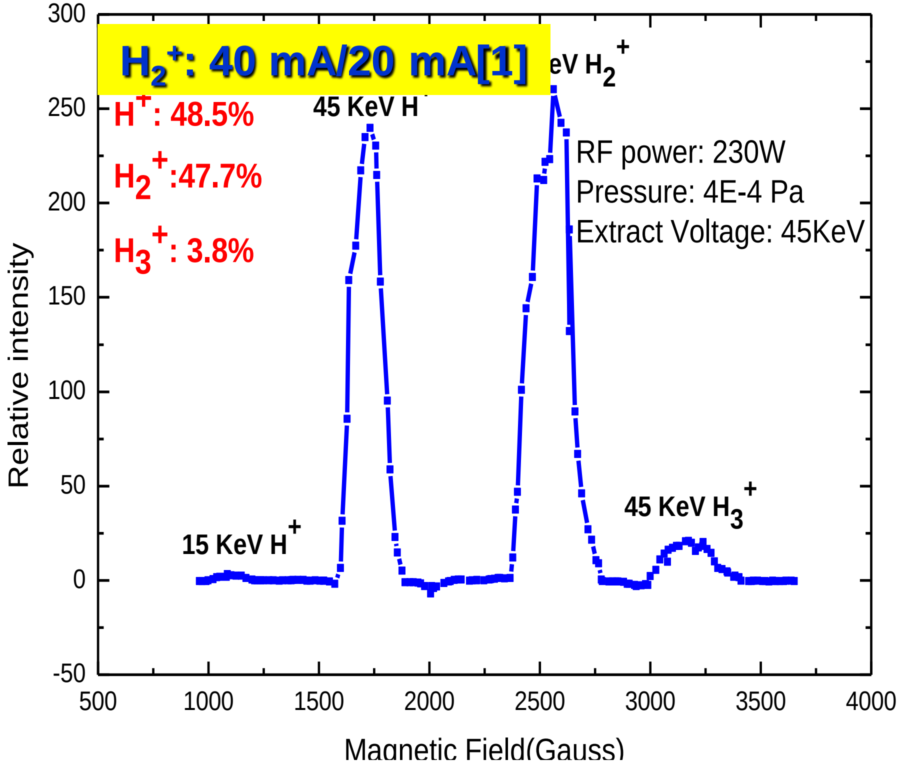
The yield of H_2^+ increased dramatically with decreasing of pressure. **With 4×10^{-4} Pa, 47.7% H_2^+ can be extracted with total current 85 mA, so the pure H_2^+ ions can be as high as 40 mA.** We also got some interesting results with H_3^+, more than 20 mA H_3^+ can be extracted with high pressure and low power.

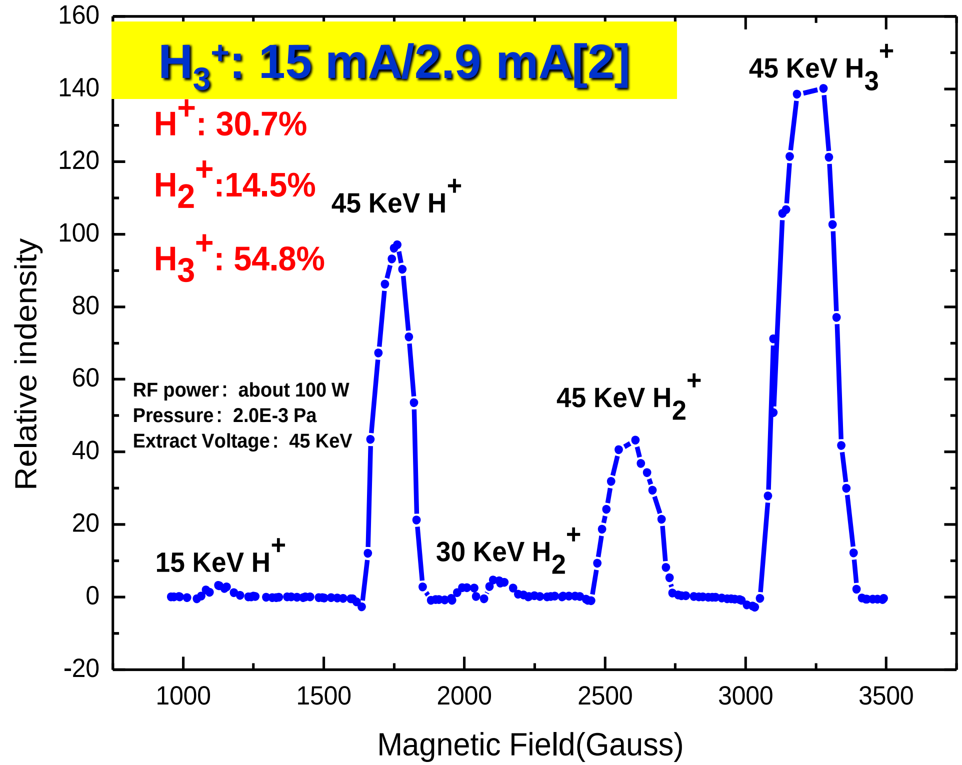




1. R.J. Barlow, A. Bungau, A.M. Kolano, etcetc., IPAC13, **MOPFI071**, *Proceedings of IPAC2013*, Shanghai, China, 12th-17th May, 2013: 446-448. ISBN 978-3-95450-122-9.
2. N. Joshi, M. Droba, O. Meusel, U. Ratzinger, NIM **A** 606 (2009) 310–313.
3. Y. Xu *et al.*, *Proceedings of IPAC2013, Shanghai*, China MOPFI035, pp. 363–365 (2013).

The yield of H_2^+ increased dramatically with decreasing of pressure. **With 4×10^{-4} Pa, 47.7% H_2^+ can be extracted with total current 85 mA, so the pure H_2^+ ions can be as high as 40 mA.** We also got some interesting results with H_3^+, more than 20 mA H_3^+ can be extracted with high pressure and low power.





1. R.J. Barlow, A. Bungau, A.M. Kolano, etcetc., IPAC13, **MOPFI071**, *Proceedings of IPAC2013*, Shanghai, China, 12th-17th May, 2013: 446-448. ISBN 978-3-95450-122-9.
2. N. Joshi, M. Droba, O. Meusel, U. Ratzinger, NIM **A** 606 (2009) 310–313.
3. Y. Xu *et al.*, *Proceedings of IPAC2013, Shanghai*, China MOPFI035, pp. 363–365 (2013).

Physical processes in hydrogen discharge

H_2^+ generation:

$e + H_2 \rightarrow H_2^+ + 2e$

H_2^+ destruction:

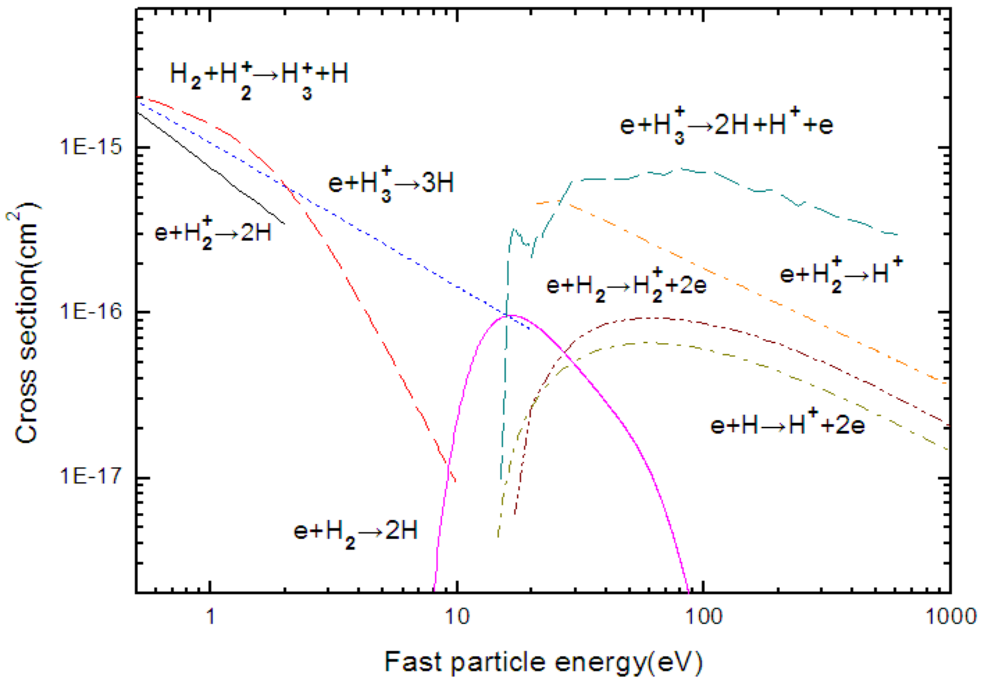
$H_2^+ + H_2 \rightarrow H_3^+ + H$

$e + H_2^+ \rightarrow 2H$

$e + H_2^+ \rightarrow 2H^+ + 2e$

$e + H_2^+ \rightarrow H_2^+ + H + e$

…



So, the yield of H_2^+ has relations with electron density, electron temperature inside ion source.

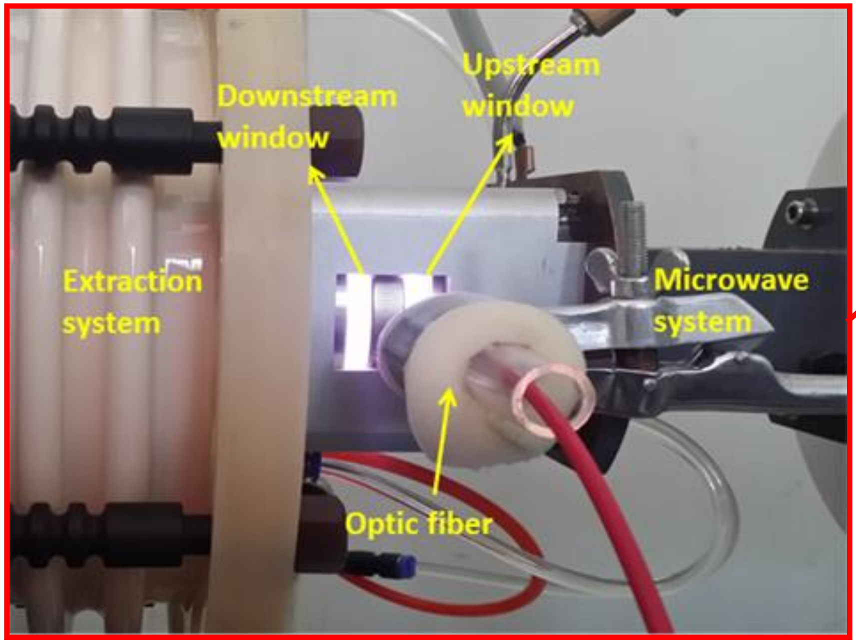
*Yuan Xu *et al.*, Rev. Sci. Instrum. **85**, 02A943 (2014).

Outline

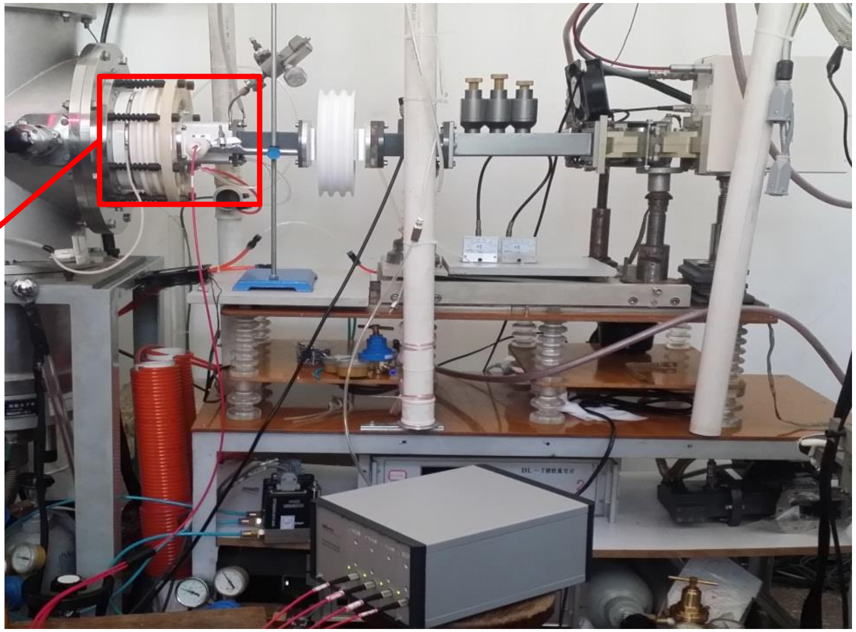
- Background
- Physical processes in hydrogen discharge
- Emission spectroscopy diagnostic
- Preliminary results and analysis
- Conclusion

Plasma spectroscopy diagnosis

Diagnosis is the most direct method to know the information in the plasma. Langmuir probe is a generally used method to diagnose ECR plasmas, but as we know Langmuir probe is sometimes hard to interpret under strong RF power and magnetic field environment. For this, spectrum method has been chosen as a no-invasive *in-situ* way to diagnose the plasma inside ion source.



ECR ion source with transparent quartz window for spectroscopy diagnosis.



Spectroscopy diagnosis system (Ion source, Optic fibre, high revolution spectrometer, computer etc.)

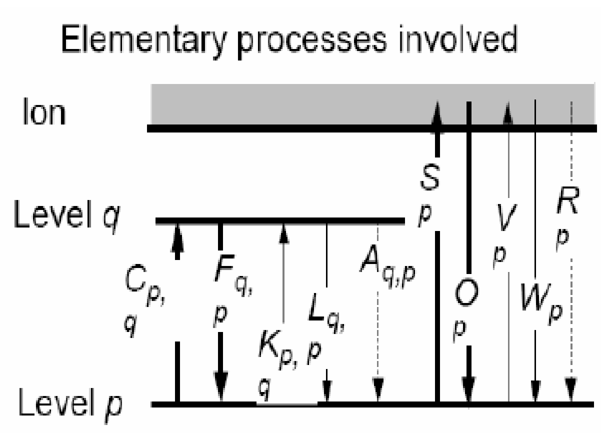
Collisional radiative (CR) model

Low electron density ⟶ Coronal Equilibrium

High electron density recombining plasmas
⟶ Local Thermodynamic Equilibrium (LTE)

Medium electron density ⟶ non-equilibrium plasma

As the plasma in 2.45 GHz ion source is low pressure, low temperature non-equilibrium plasma, collisional radiative (CR) model which considers both collisional and radiative processes can be used.



Particles equilibrium equation:

$$\frac{dN_i}{dt} = -N_i \sum_{j(\neq i)} R_{ij} + \sum_{j(\neq i)} N_j R_{ji} + \Gamma_{in} - \Gamma_{out} \qquad (1)$$

R_{ij} is the population coefficient from state i to state j. N_i is the particle number of state i.

PEKING UNIVERSITY 北京大學

Lines radiation ratio method

In hydrogen plasma, the generation of spectrum line like H-Balmer lines can be very complicated which can be from atom, molecule and also ions(H^+,H_2^+,H_3^+ etc.). So it's hard to get information from hydrogen lines.

$$H_\alpha = \varepsilon_{32} = n_e n_H X_{H_\alpha}^{eff,H} + n_e n_{H^+} X_{H_\alpha}^{eff,H^+} + n_e n_{H_2} X_{H_\alpha}^{eff,H_2} + n_e n_{H_2^+} X_{H_\alpha}^{eff,H_2^+} + n_e n_{H_3^+} X_{H_\alpha}^{eff,H_3^+} + n_e n_{H^-} X_{H_\alpha}^{eff,H^-} \quad (2)$$

The diagnosis will be simple as noble gases are introduced into plasmas. The population equation will be:

$$I_{ij} = n_e n_s X_{ij}^{eff,s}(n_e, T_e, \cdots) \quad (3)$$

where $X_{ij}^{eff}(T_e, n_e, \ldots) = R_0(i) \cdot A_{ij}$ is effective emission rate coefficient from state *i* to state *j* which is available from ADAS database.

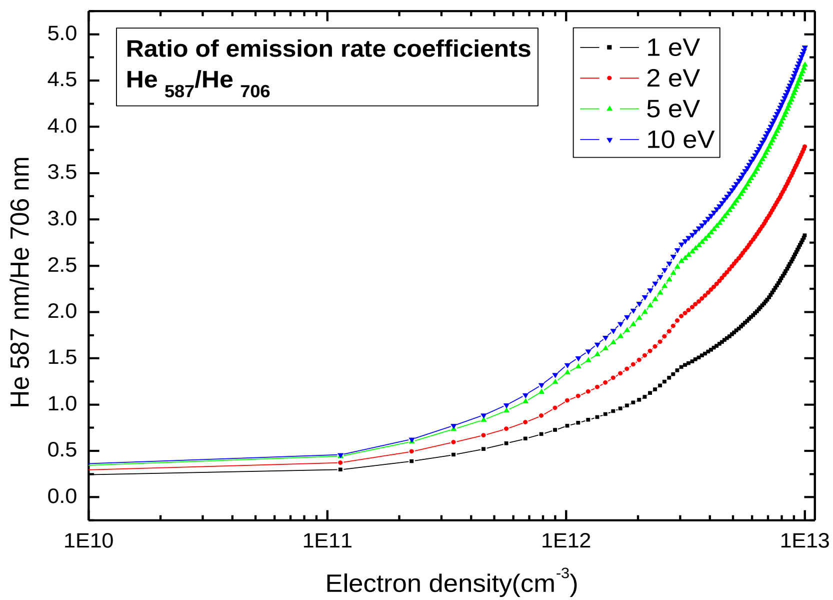
The line ratio method can cancel the dependence directly on electron density, solid angle and integral time etc.:

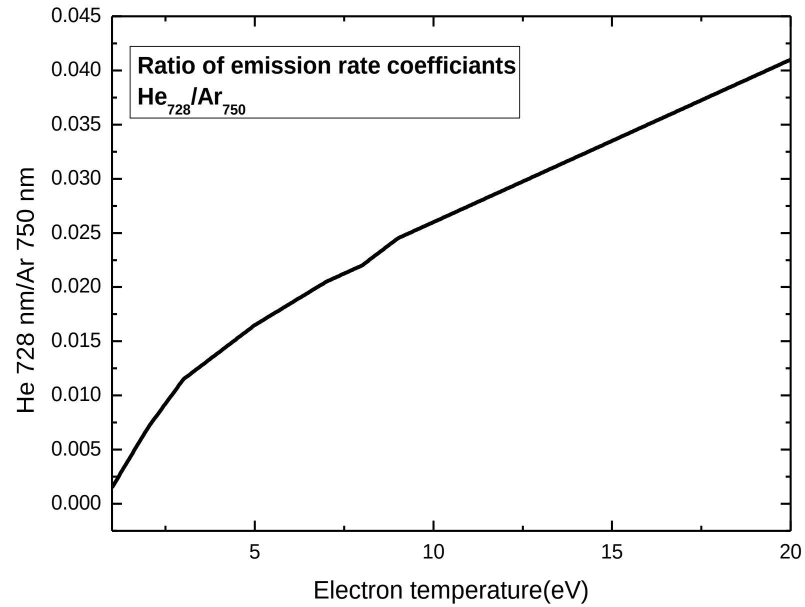
$$\frac{I_{pk}^1 = n_1 X_{pk}^{eff}(T_e, n_e, \ldots)}{I_{ij}^2 = n_2 X_{ij}^{eff}(T_e, n_e, \ldots)} \quad (4)$$

As line density *I*, particle intensity *n* can be measured with calibrated spectrometer and flow meters, the only unknown quantities are T_e *and* n_e.

Lines radiation ratio method

For electron density, the line ratio of **He 587.56 nm** and **He 706.52 nm** is recommended as the line ratio which is very sensitive on n_e and less sensitive on T_e with T_e ranging from 1~10 eV . And likewise, the line ratio of He line at **728 nm** to the Ar line at **750 nm** is suitable for T_e diagnosis which is particularly sensitive on electron temperature. Here, all the results are only **line-of-sight averaged parameters**.





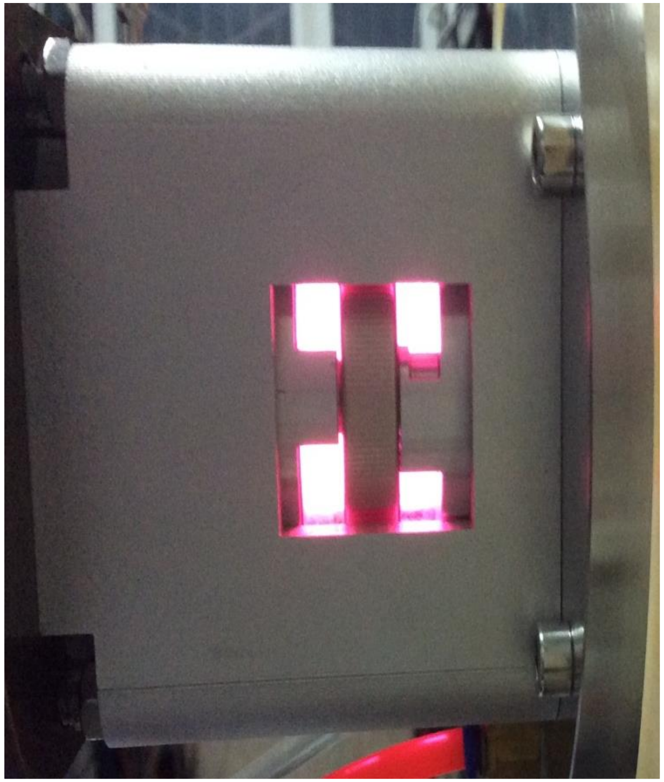
Less sensitive on electron temperature. **Less sensitive on electron density.**

*U. Fantz, *Contrib. Plasma Phys.* **44**, No. 5-6, 508 – 515 (2004).

Outline

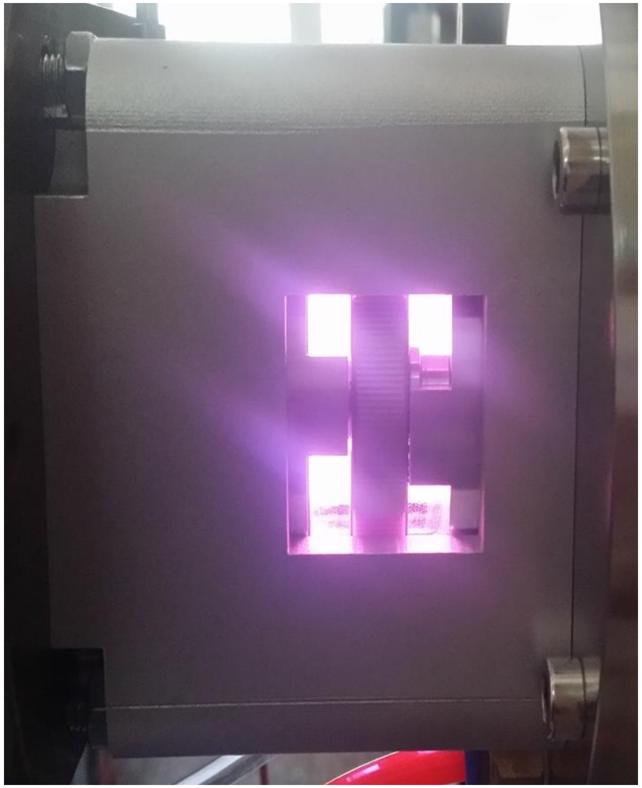
- Background
- Physical processes in hydrogen discharge
- Emission spectroscopy diagnostic
- Preliminary results and analysis
- Conclusion

Pure H_2



Purple

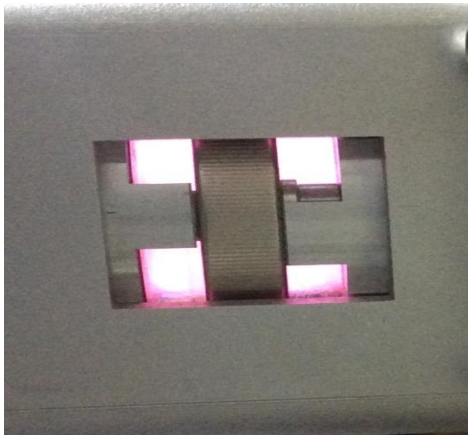
H_2 :He :Ar = 10:1:1



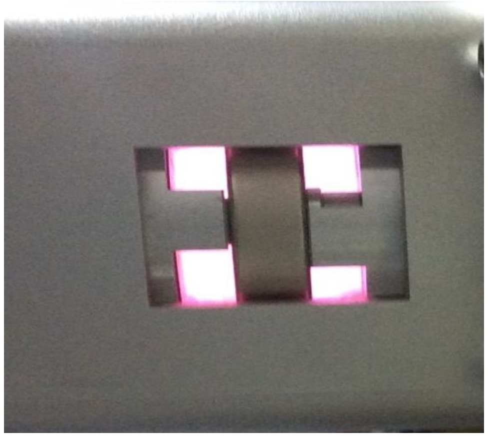
Become a little blue

Light intensity from plasma

Pure H_2



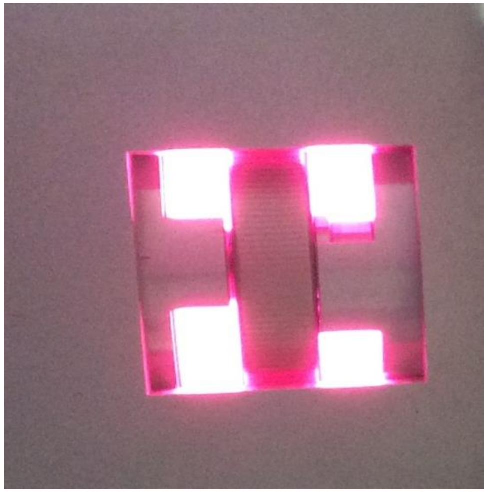
50 W



70 W

80 W

100 W

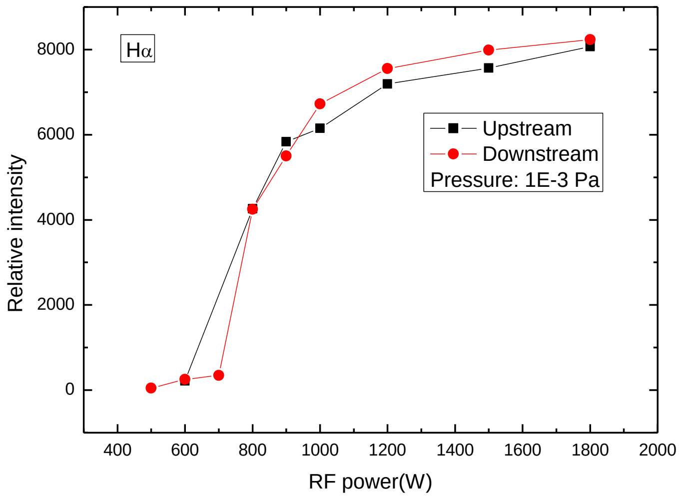


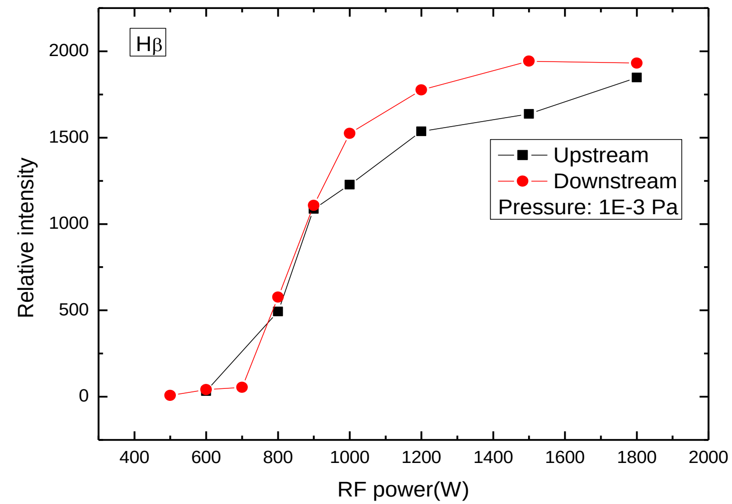
180 W

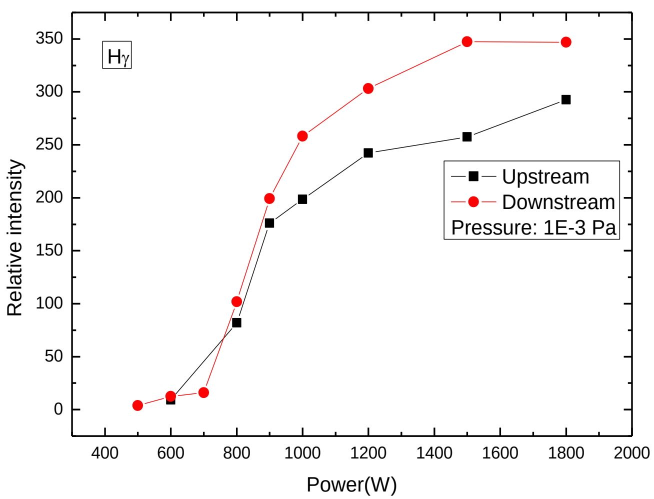
The light intensity from plasma increased obviously with RF power. The light can be very bright with 180 W average power.

H-Balmer lines

Pure H_2

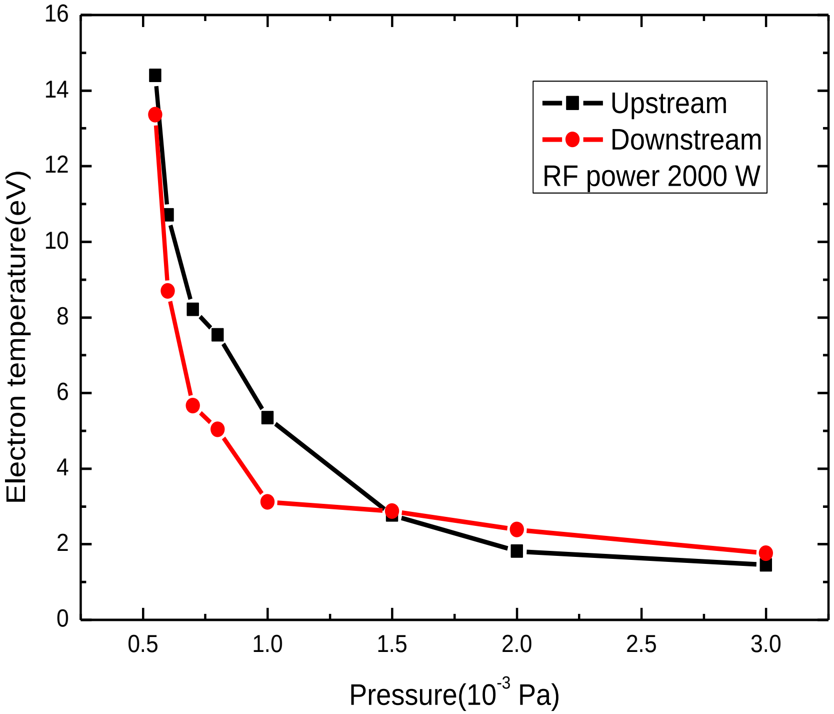




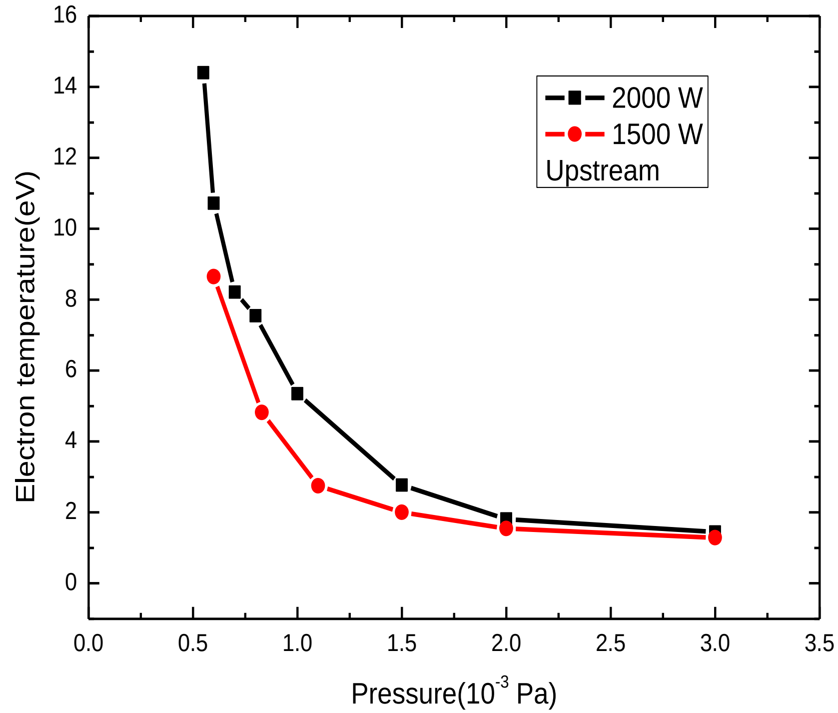


The intensity of Hα, Hβ, Hγ lines increased with RF power dramatically. Hγ line can indicate the relative intensity of atomic hydrogen as it is mainly generated from grounded state H but hardly from molecular, ions etc. So, the intensity of atomic H increased with RF power, and downstream is higher than upstream.

Preliminary results (mixed with He. Ar)



Average electron temperature vs operation pressure at upstream and downstream diagnosis point.



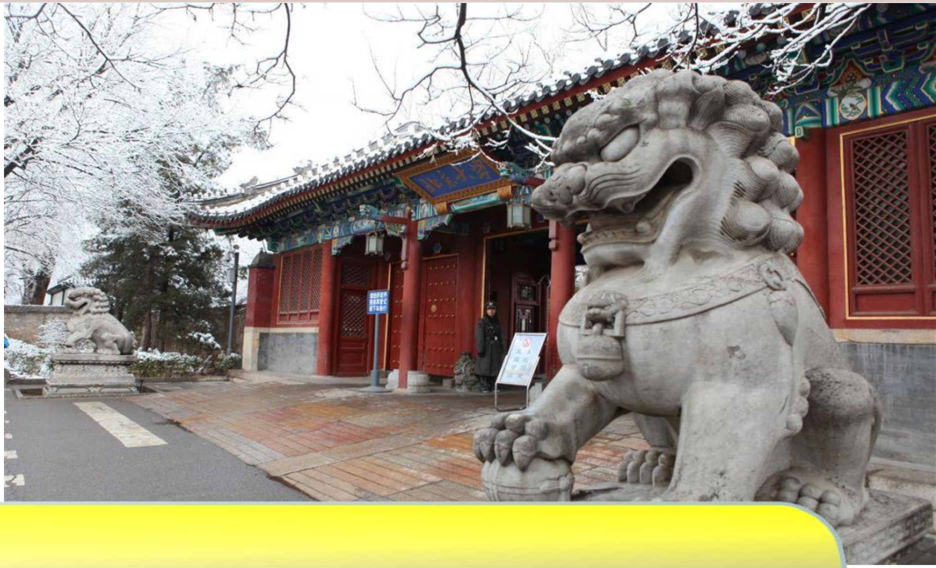
Average electron temperature vs operation pressure with different rf power at upstream diagnosis point.

Electron temperature increases obviously from 2 eV to 14 eV with pressure decreasing from 3×10^{-3} Pa to 6×10^{-4} Pa at upstream point. The T_e was slightly enhanced with more RF power. The electron density in the cavity ranged from 5.5×10^{11} cm^{-3} to 9.0×10^{11} cm^{-3} with 100 W RF power (10% duty factor).

Conclusion

1. Study on hydrogen molecular ions (H_2^+ and H_3^+) was performed at PKU for their potential applications in accelerators.
2. 40 mA H_2^+ and 20 mA H_3^+ can be generated in pulsed mode with species fractions approaching 50%.
3. Plasma emission spectroscopy method was chose for diagnosing plasma parameters with CR model by using lines ratio of specified emission lines of noble gases He and Ar.
4. Preliminary results show that the electron density in the plasma chamber was about ~ 10^{11} cm^{-3}, the average electron temperature ranged from 2~14 eV with pressure which was important in the generation of molecular.
5. Detailed experiment and error analysis will be carried out in the future.

北京大學
PEKING UNIVERSITY



Thank you for your attention!

北京大學
PEKING UNIVERSITY