Status of Hydrogen Ion Sources at PKU

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CYC2016, ETH Zürich , Switzerland

Sep. 15th, 2016

Outline

- Background
- Ion sources developed at PKU
  - Overview
  - H^+ ion source
  - Molecular ion source (H_2^+ & H_3^+)
  - Microwave-driven Cs-free negative hydrogen ion source
- Conclusion

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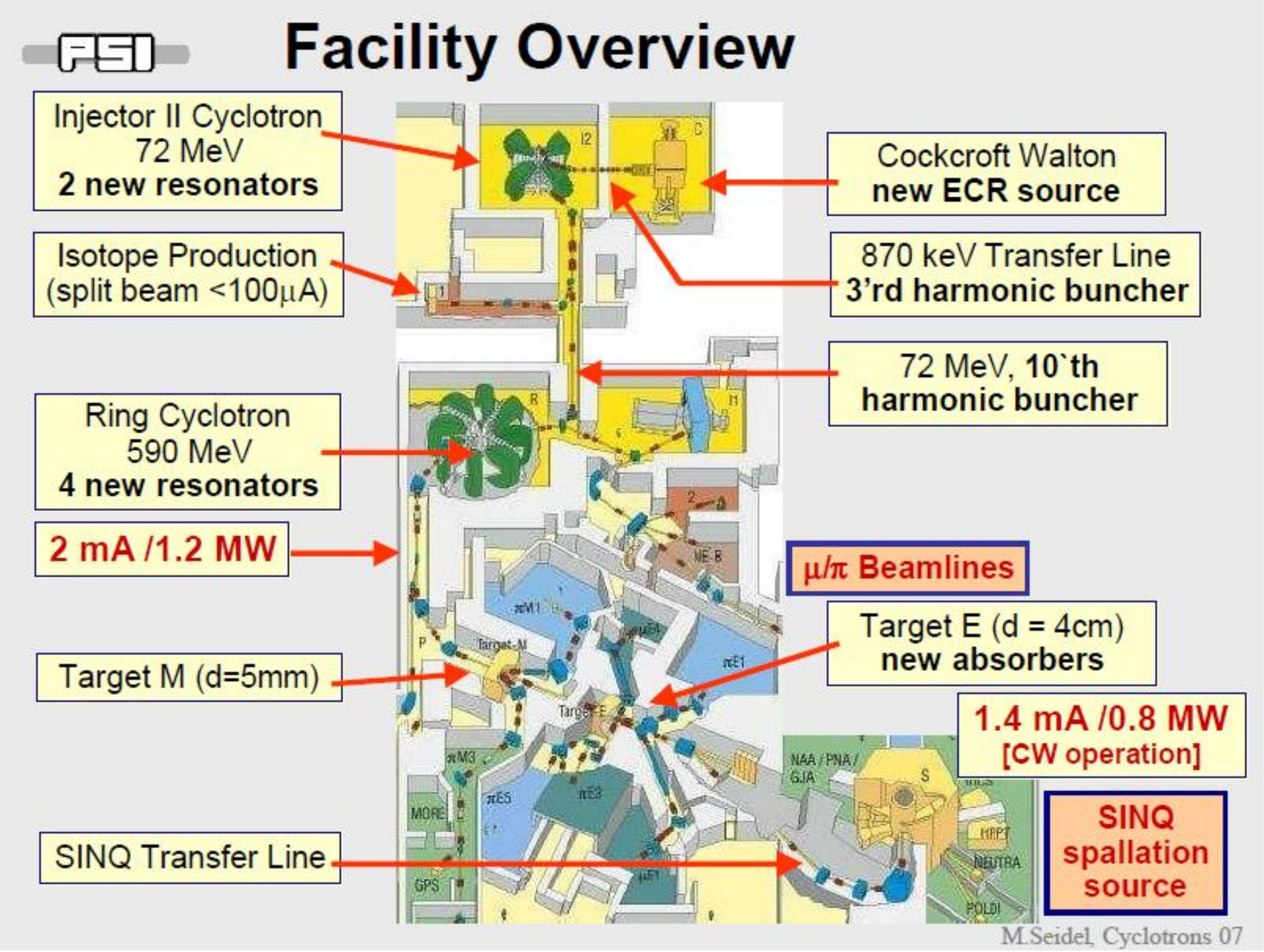
Background

➢ Requirements of H^+ ions

Proton cyclotrons are needed in fundamental physics research, spallation source, medical therapy and radioisotopes production etc. Recently, high current high power is a important trend for cyclotrons.

Proton beam can be generated by accelerating several hydrogen ions in cyclotrons: H^+, H^-, H_2^+, or H_3^+.

For example, the upgrade of PSI Cyclotron Facility needs to accelerate 3 mA proton beam to 590 MeV. The requirement for the ion source is around 10 mA.

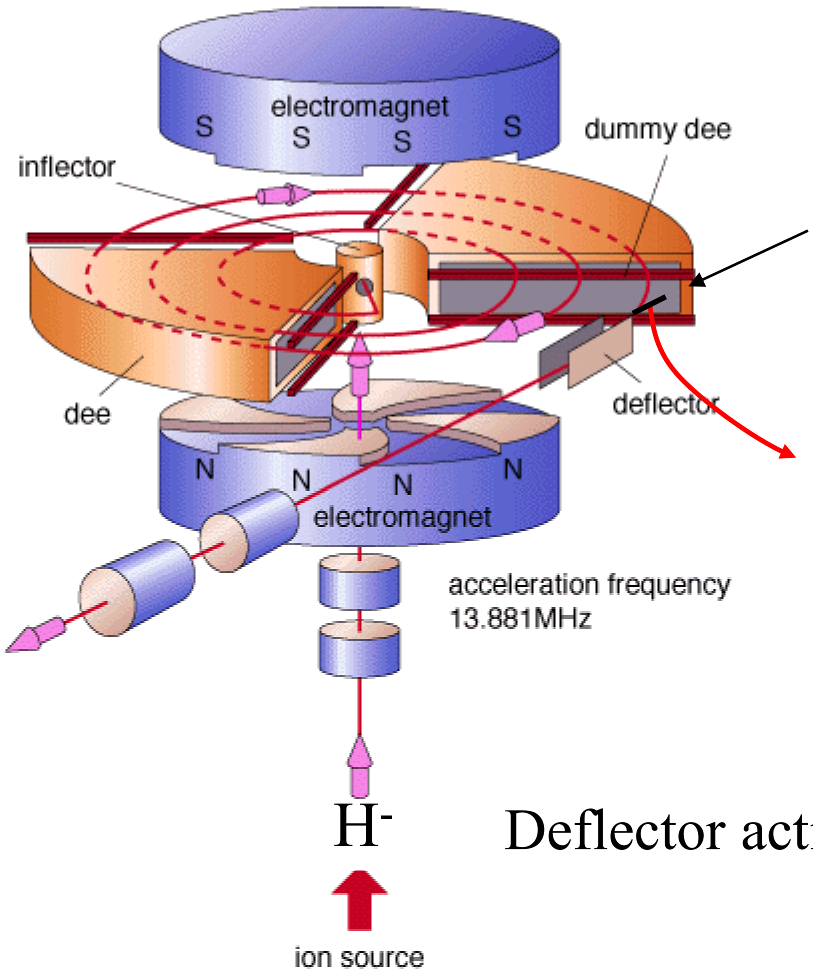


Proton cyclotron at PSI

- Requirements of H^- ions

Charge exchange method has a relatively high efficiency.

$H^- \xrightarrow{\text{Strip}} H^+$



Stripper foil

Charge exchanged beam deflected

H^+

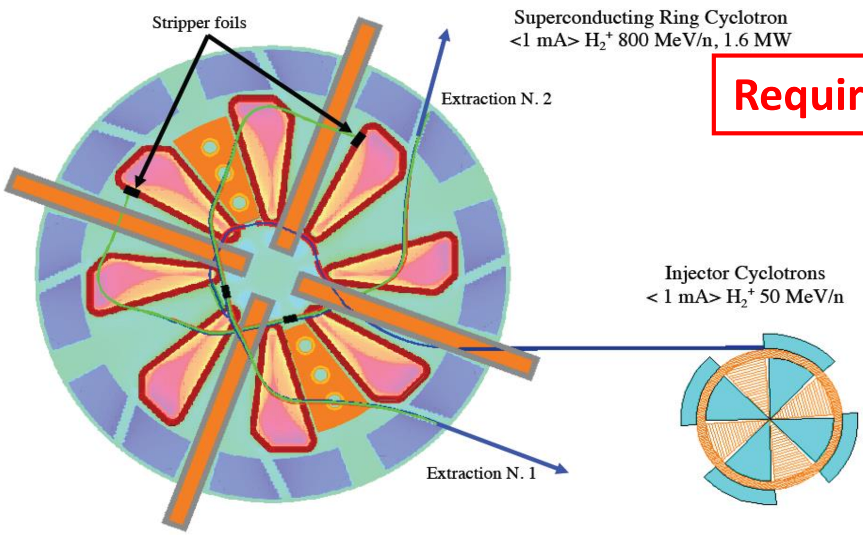
Conventional extraction

H^-

Deflector activation problematic

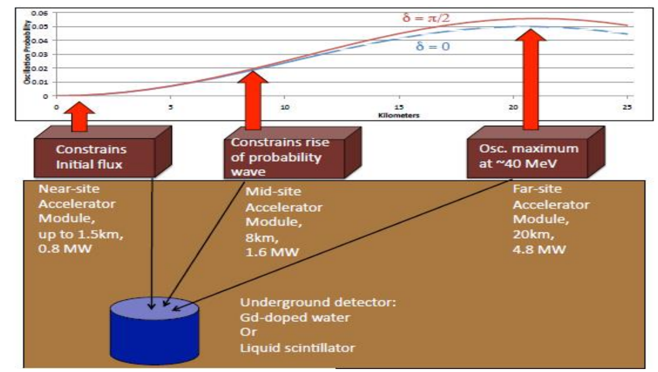
Background

➢ Requirements of H_2^+ & H_3^+ ions



Require 10 mA H^+

The DAEδALUS - π^+ decay-at-rest (DAR) experiment



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.

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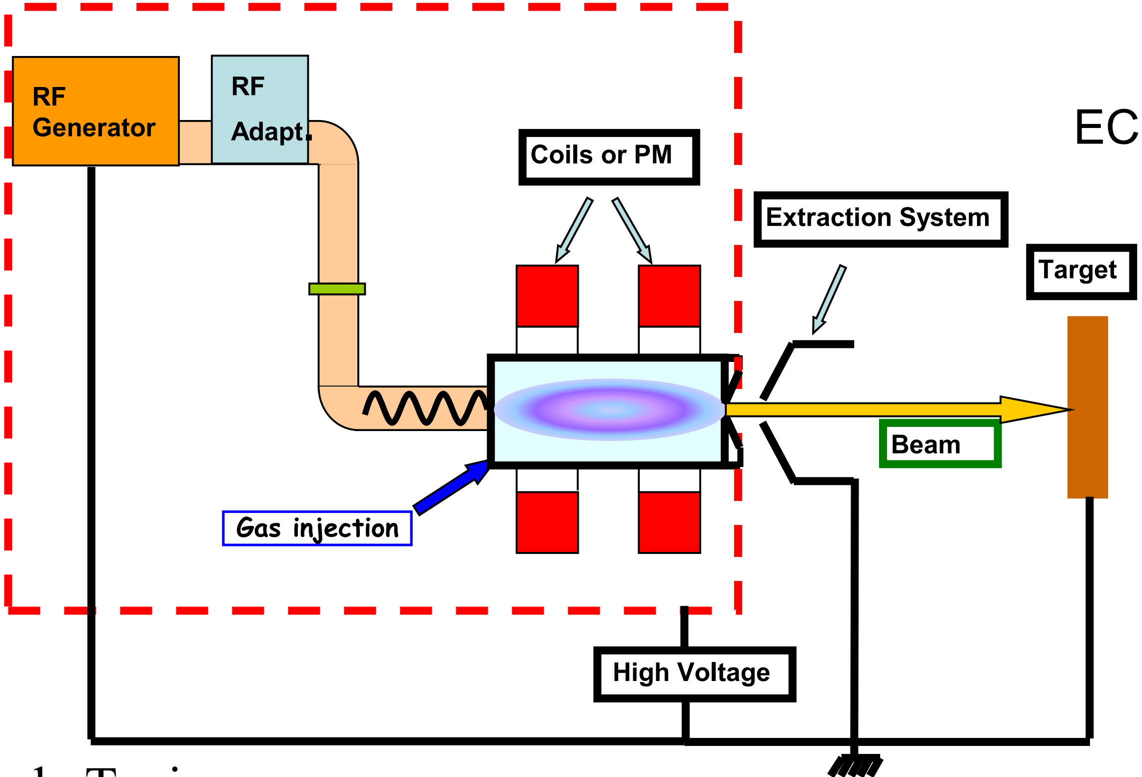
Ion source principle



ECR Source → Resonance zone :

ω = e B / m

ω, pulsation;

e, electron charge;

B, magnetic field;

m, electron mass.

2.45 GHz → 875 Gauss

*R. Gobin, CEA/Saclay, reports.

Study Topics

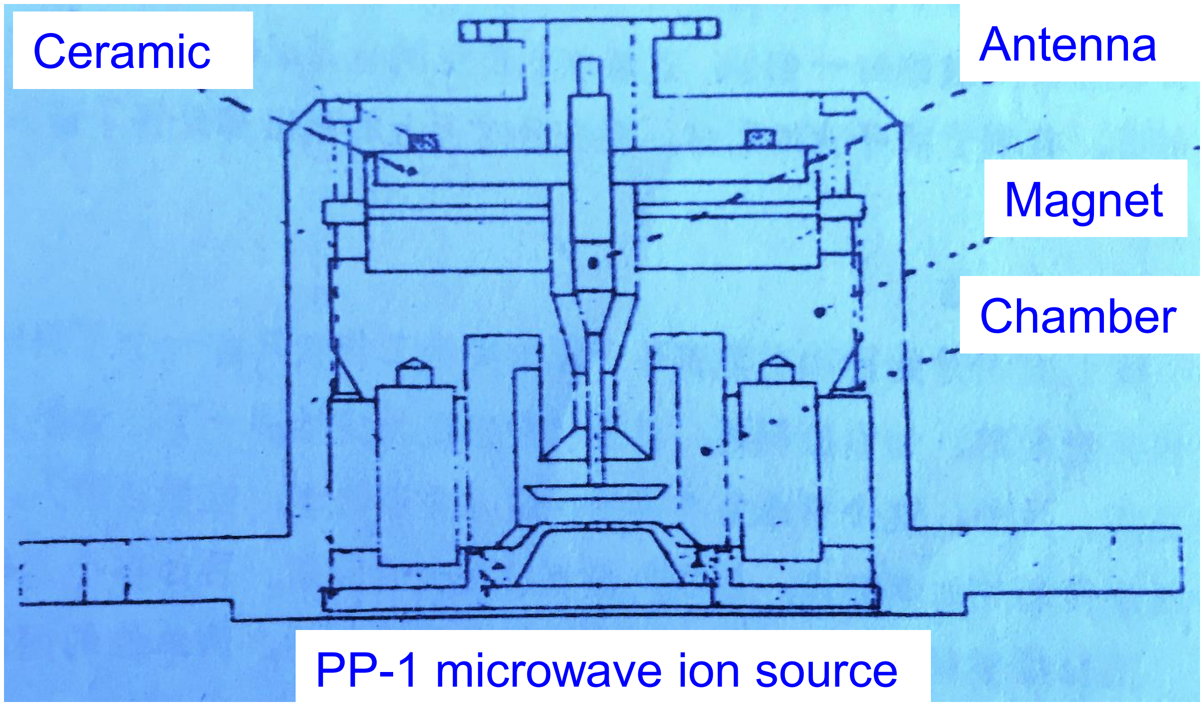
1)RF matching: ridged waveguide, dielectric microwave window, T-shape antenna;

2)B Field Generation: electromagnetic coils, electromagnetic coil plus permanent magnetic rings, or only permanent magnet;

3)Beam Formation and Handing: Geometry of the electrodes, Electric field configuration.

Overview

- The First PKU 2.45 GHz ECR Ion Source in 1980s



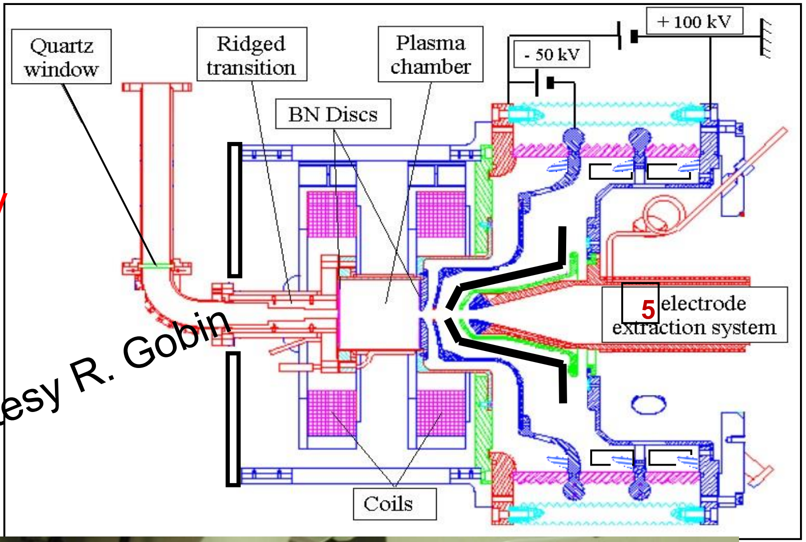
- Prototype at very beginning
- Antenna coupling
- 2.45 GHz
- Permanent magnet
- Aperture <1 mm
- Low current ~100 uA

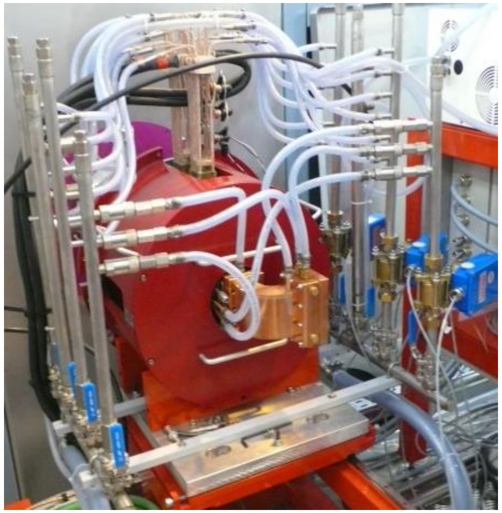
*Zhao Kui, Song Zhizhong, Wang lifang, Zhao Weijiang, Xiao Min, A compact Microwave Ion source with co-axis coupling type.1987, Proceedings of The Third Symposium on Ion Sources and Beams, Lanzhou, China, Sep. ,1987.

Overview

➢ 2.45 GHz ECR Ion Sources

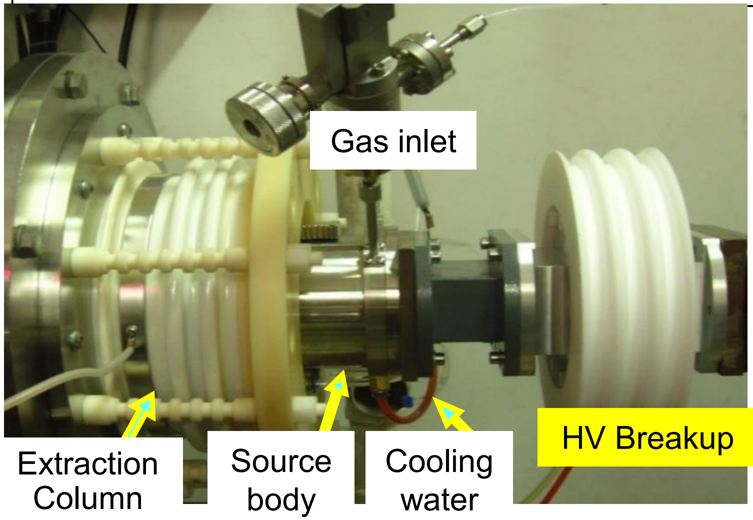
CEA/ Saclay

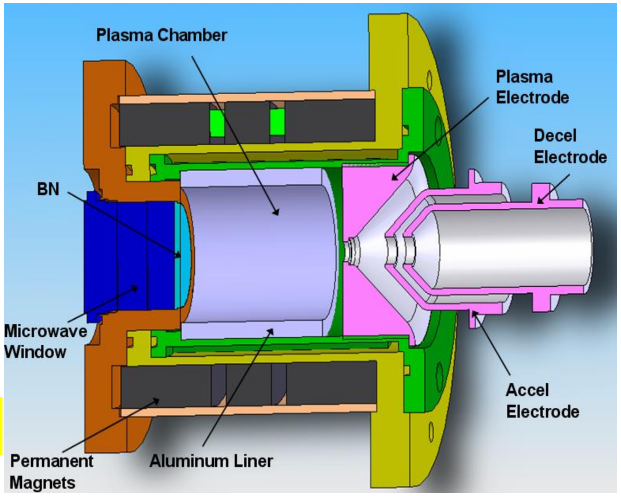




- ➢ Ridged waveguide
- ➢ Electromagnetic coils
- ➢ Five electrodes beam extraction
- ➢ About 50 cm*50 cm

PKU

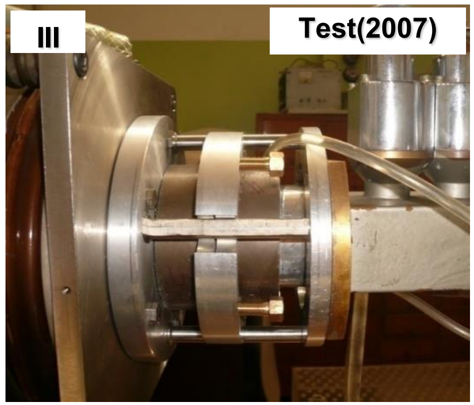


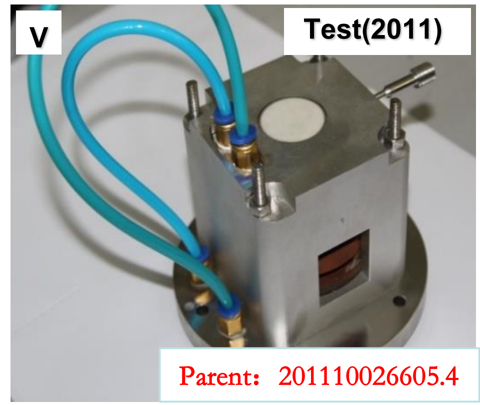


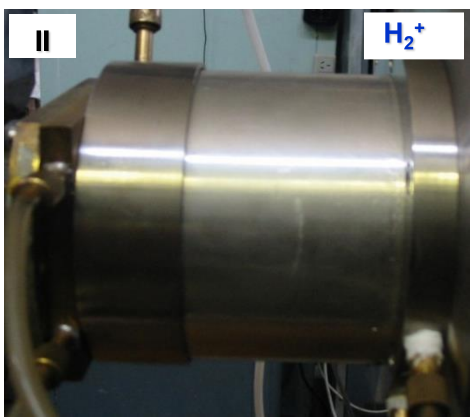
- ➢ Microwave window
- ➢ Permanent magnet
- ➢ Three electrodes beam extraction
- ➢ Compact (about 5 kg, 10 cm*10 cm)

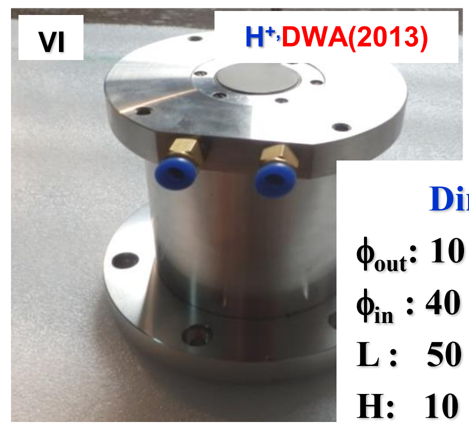
Overview

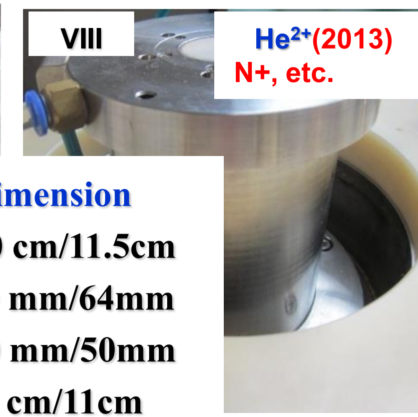
➢ PKU Permanent Magnet ECR Ion Source (PKU PMECRIS)











Dimension

ϕ_{out}: 10 cm/11.5cm

ϕ_{in} : 40 mm/64mm

L : 50 mm/50mm

H: 10 cm/11cm

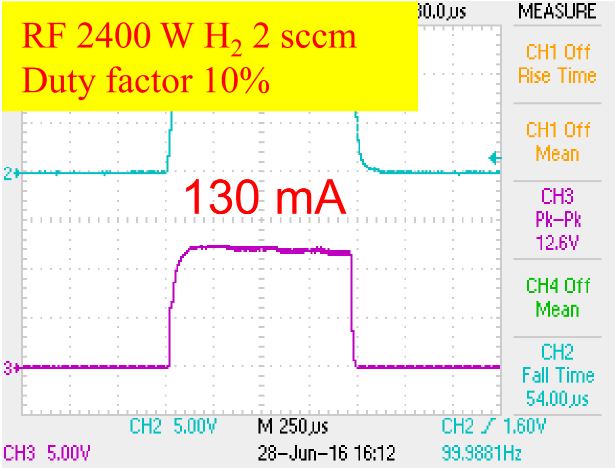
A series of 2.45 GHz microwave-driven ion sources were designed and fabricated at PKU. Ions such as 130 mA H^+, 83 mA D^+, 65 mA He^+, 63 mA N^+, 70 mA Ar+, 50 mA O^+ and H_2^+, H_3^+,H^- can be extracted from the ion source.

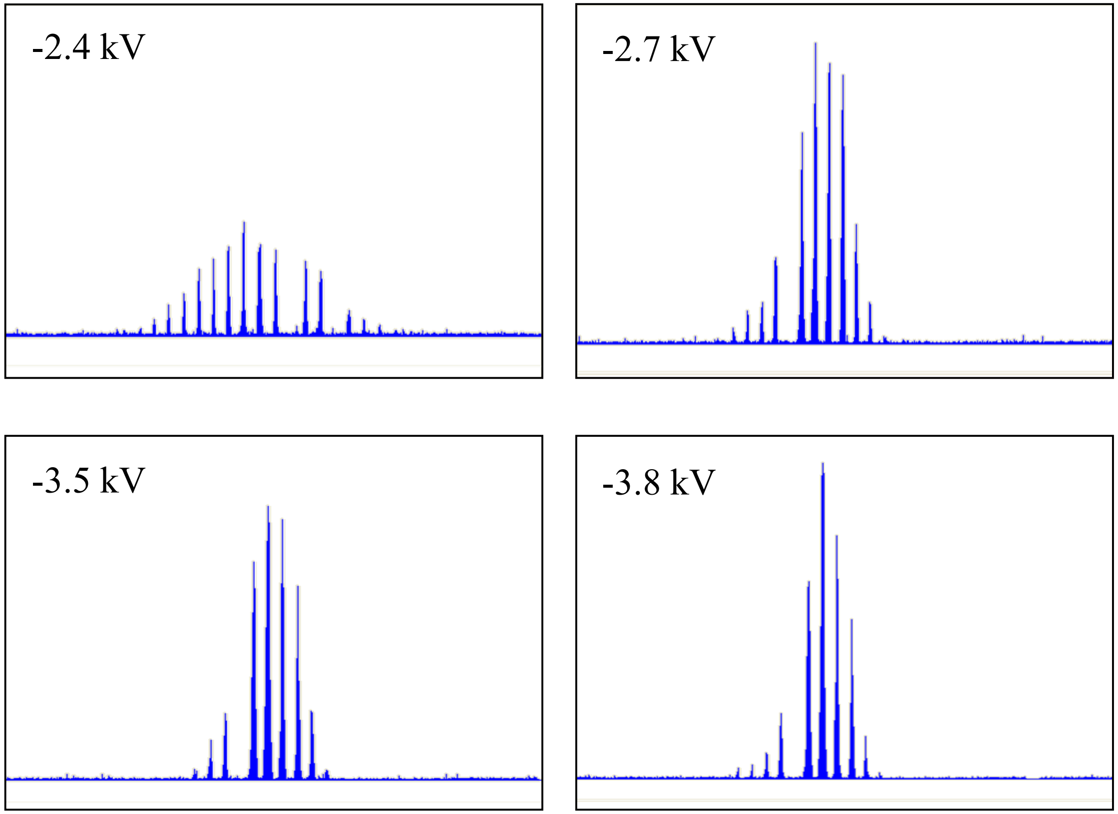
H^+ Ion Source

- Pulsed mode

Counting operation time is >1000 hours

Standard ECR ion source





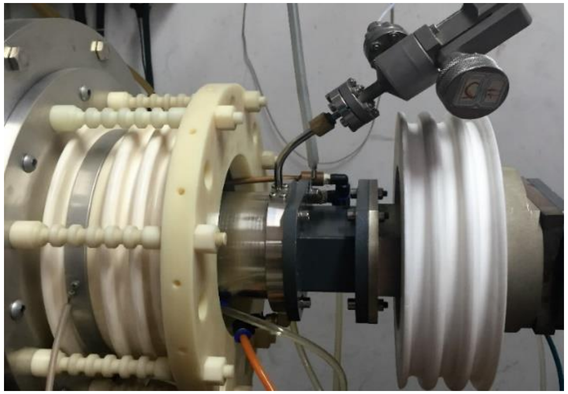
Influence of suppression voltage
Emmitance <0.20 pi.mm.mrad

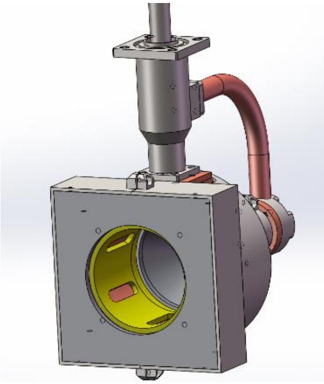
Beam Stability and Reliability

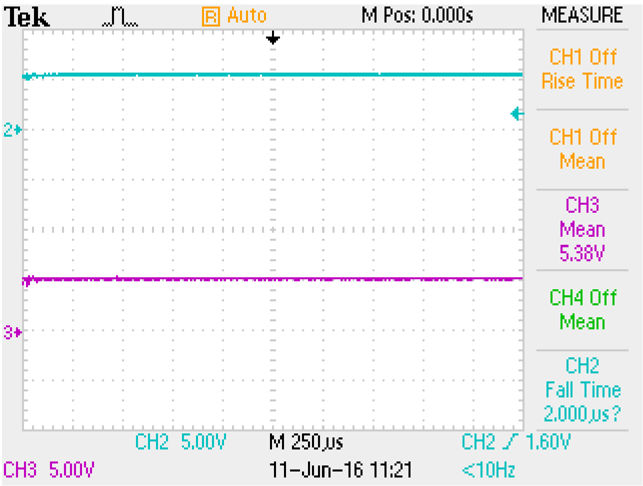
- CW mode

Improvements:

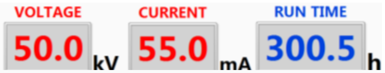
- Water-cooling
- Electrode material (SS ⟹ Mo)
- High current Faraday cup

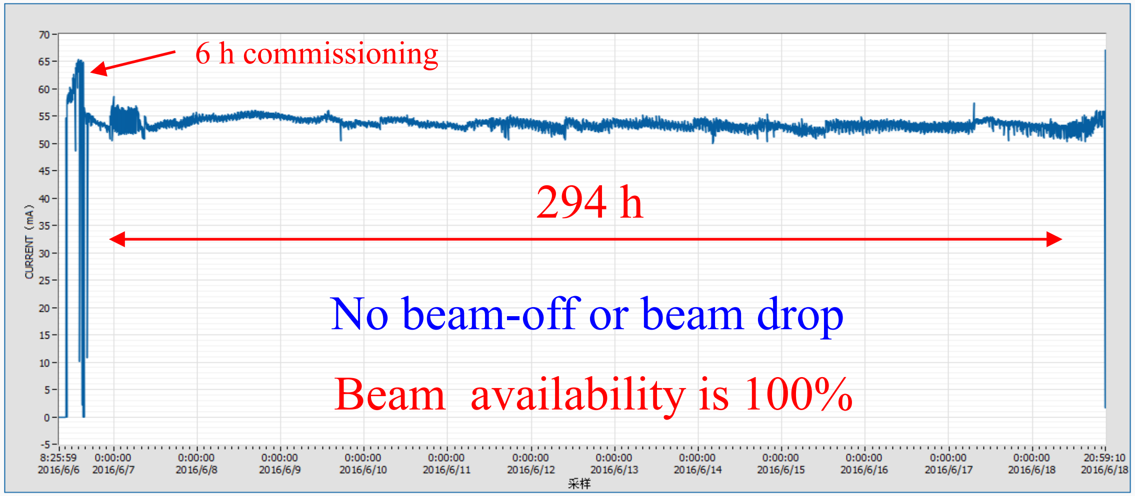






50 kV/ 50 mA H^+ CW beam
RF power 500 W





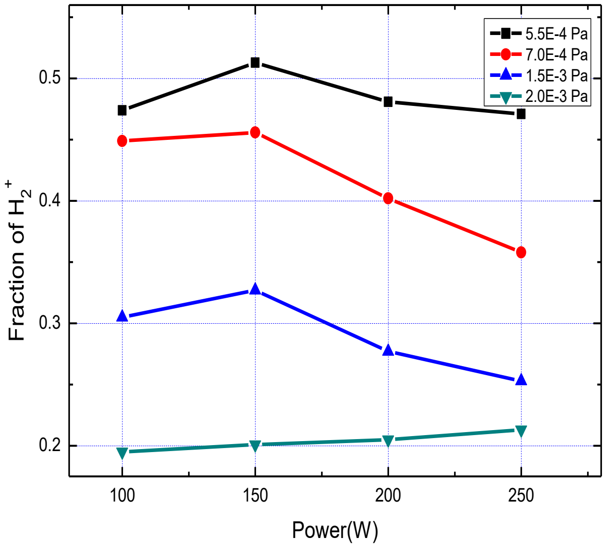
300 hours continuous experiment. (12.5 days)

Molecular ion source (H_2^+ & H_3^+)

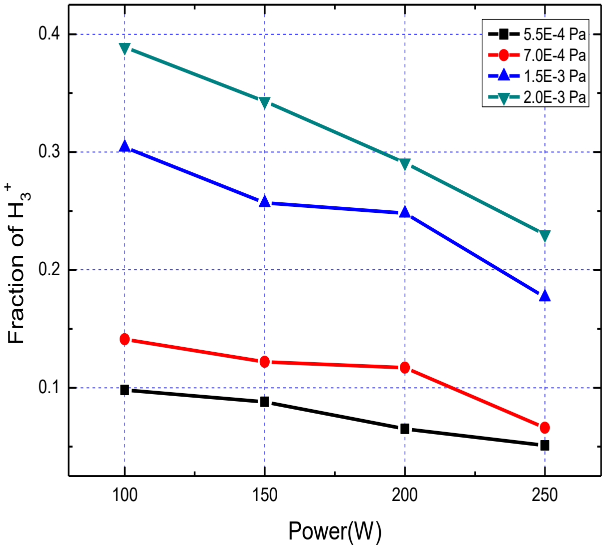
Comparing with proton ion source:

- Larger discharge chamber
- Different liner material of the cavity
- Different operation parameters

H_2^+ and H_3^+ are sensitive to RF power and pressure.



H_2^+ *vs* RF power at different pressure



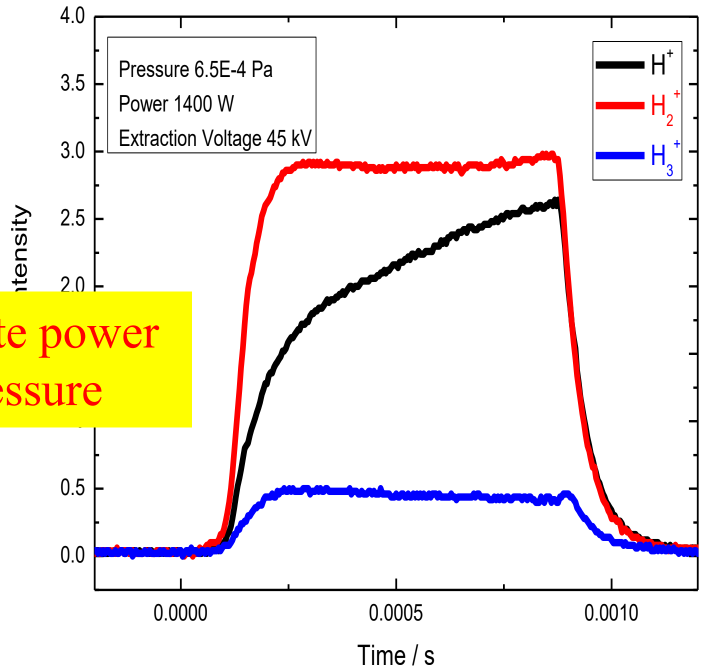
H_3^+ *vs* RF power at different pressure

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

Molecular ion source (H_2^+ & H_3^+)

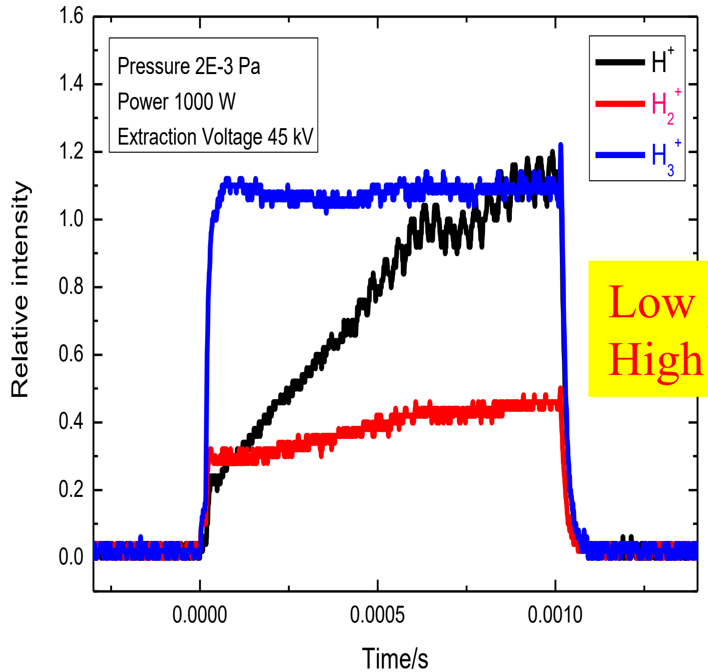
➢ Optimizing results with molecular ions

Moderate power
Low pressure



Pure H_2^+ 42 mA, 54%

Low power
High pressure



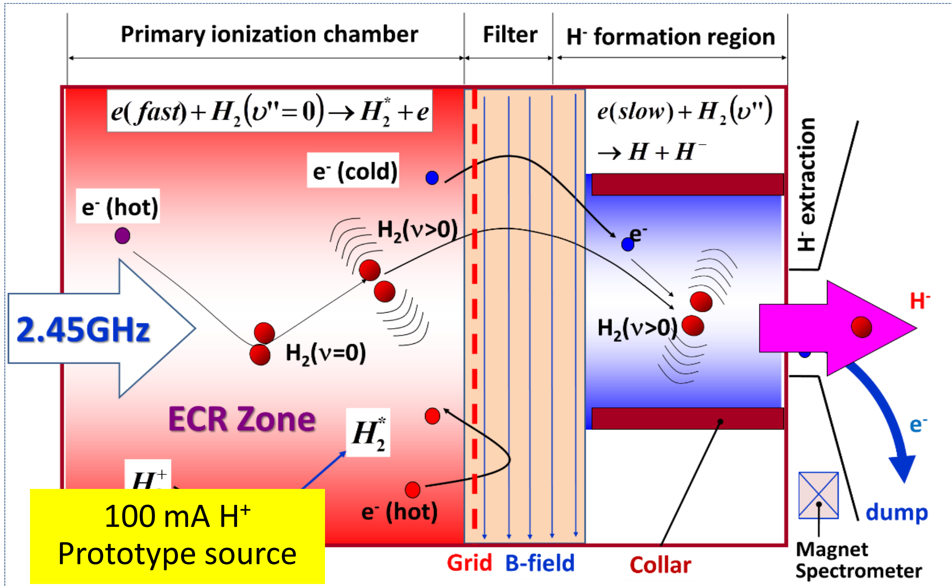
Pure H_3^+ 20 mA, 55%

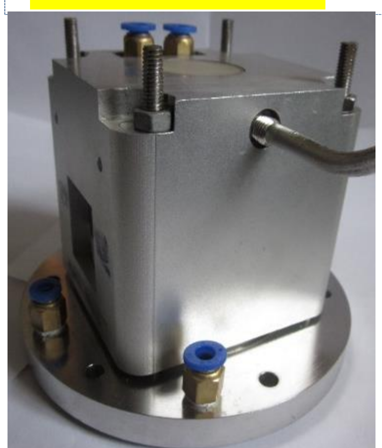
These results were got with different operation parameters and identical ion source PMECR II.

*Y. Xu *et al.*, *Proceedings of IPAC2013, Shanghai*, China MOPFI035, pp. 363–365 (2013).

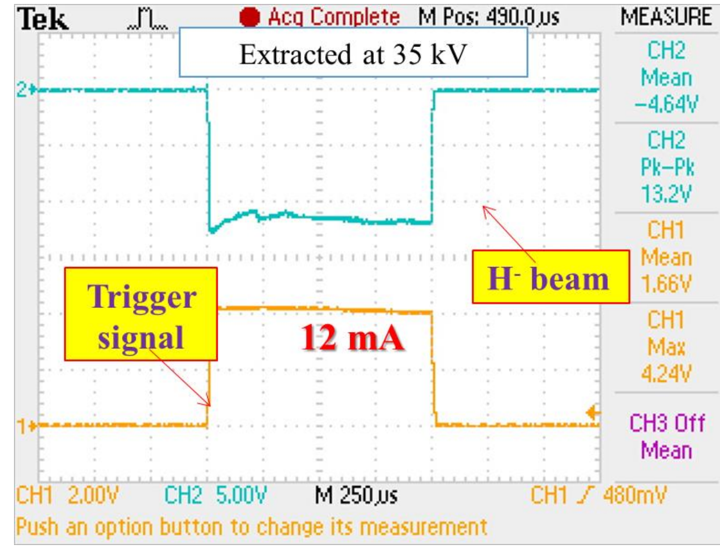
Microwave-driven Cs-free negative hydrogen ion source

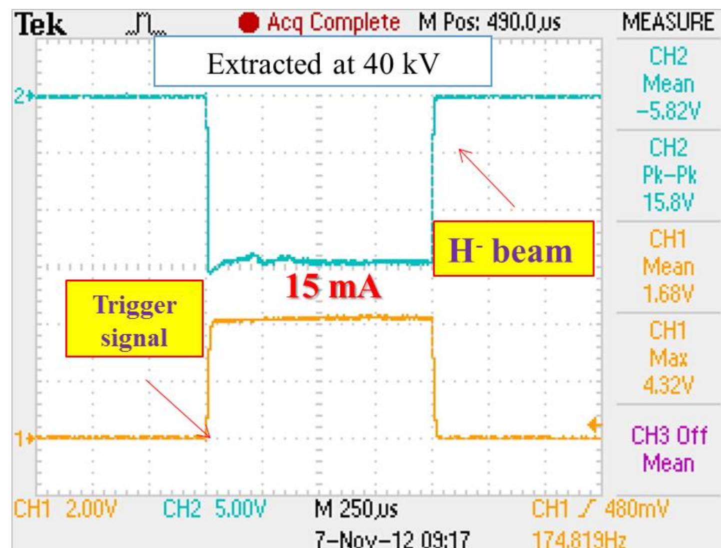
- Prototype H- Source 2012/10/28 - 2012/11/7





*Haitao Ren, **Shixiang Peng***, Jie Zhao, **MOPFI034,** *Proceeding of IPAC13*, Shanghai, China, May 12-17, 2013: 360-362.

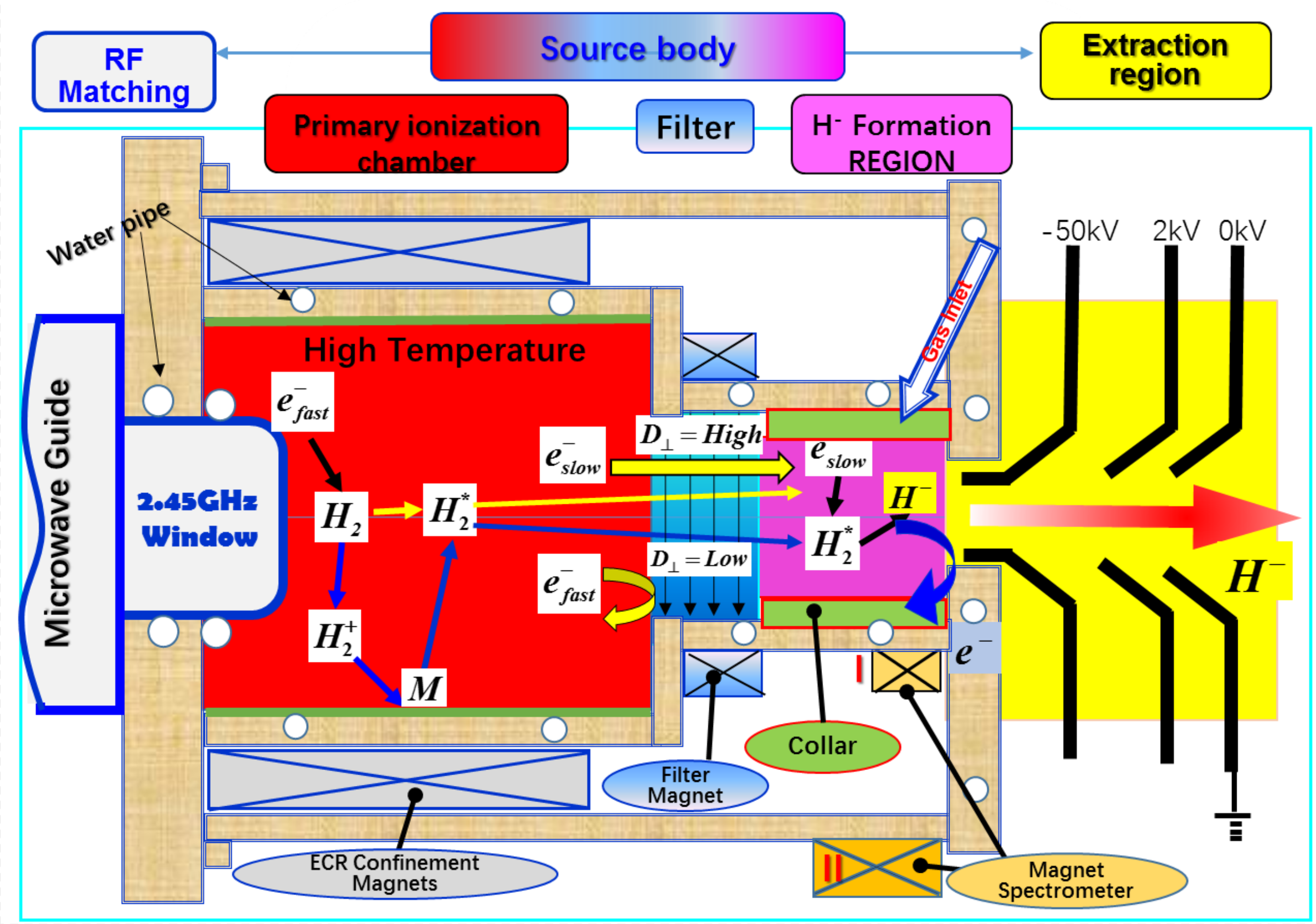




Microwave-driven Cs-free negative hydrogen ion source

➢ Principle of H⁻ Source Redesign (2013/3)

Microwave Driven Cs-free Volume H⁻ Ion Source at PKU



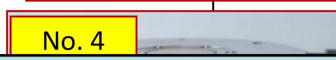
Improvements:

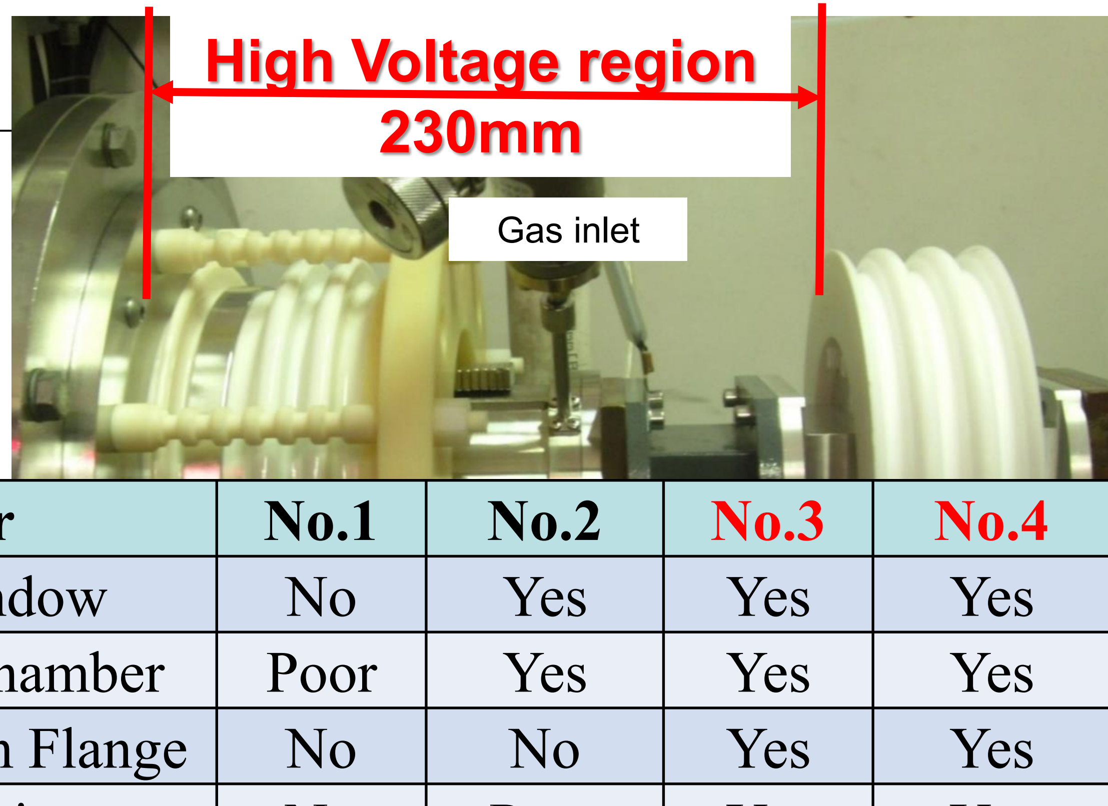
- ✓ ECR zone
- ✓ RF matching
- ✓ RF break-up
- ✓ Filter magnet
- ✓ E-dump
- ✓ Water-cooling
- ✓ Gas flow
- ✓ Tantalum

…

Microwave-driven Cs-free negative hydrogen ion source

➢ H^- Source Bodies and their best results



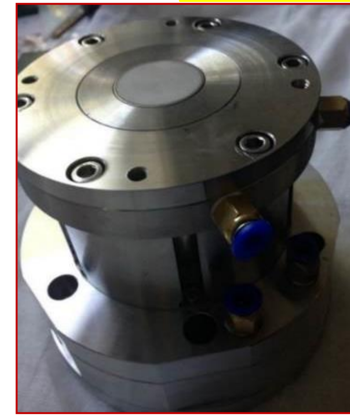


Source Number		No.1	No.2	No.3	No.4
Water Cooling	RF Window	No	Yes	Yes	Yes
	Plasma Chamber	Poor	Yes	Yes	Yes
	Connection Flange	No	No	Yes	Yes
	Extraction	No	Poor	Yes	Yes
E-Dump Position		I	II	II	I
Current (mA)	CW	8	10.8	25	29
	Pulsed(100Hz/1ms)	16	20	35	45

Microwave-driven Cs-free negative hydrogen ion source

➢ Duty Factor Variation Possibility

No.3 Source

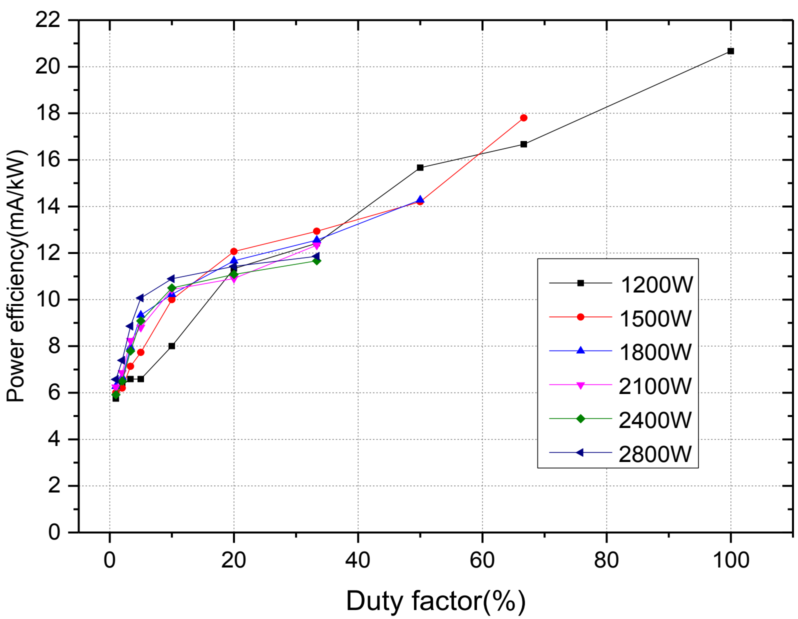


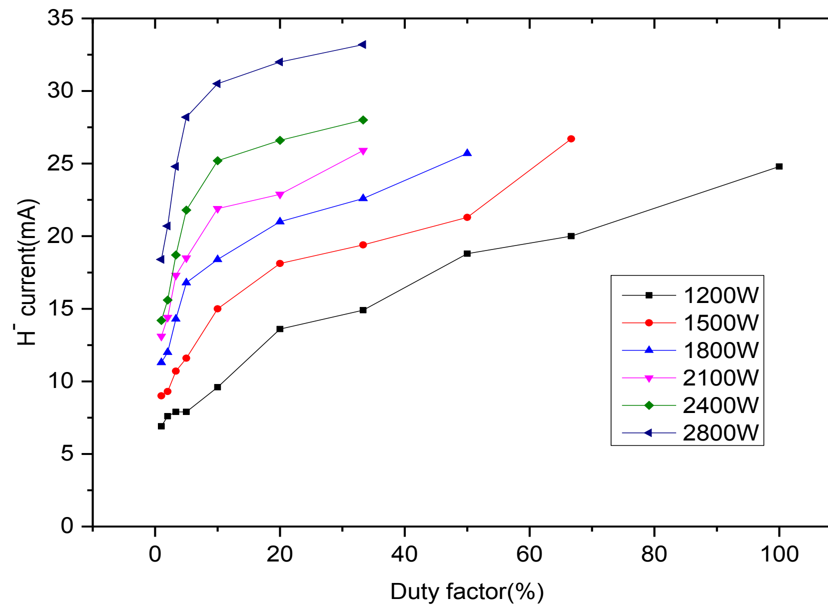
Operation pressure: 4×10^{-3} Pa

Extraction Voltage: -35 kV

CW mode: RF:1200W, **H^- 25mA,** Power efficiency: **20.8 mA/kW.**

Pulsed Mode: Duty factor variation: **1%** to **100%. H^- up to 35mA, Power efficiency up to 20 mA/kW.**

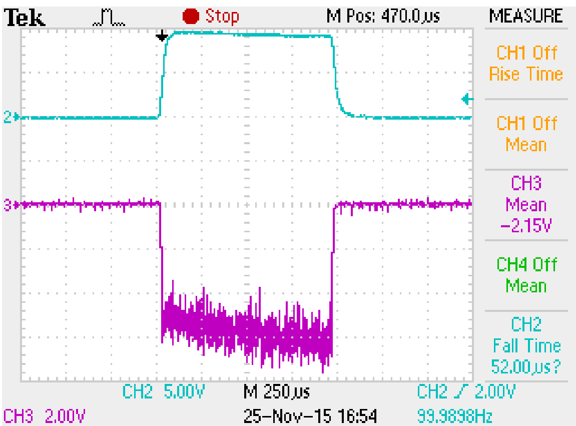




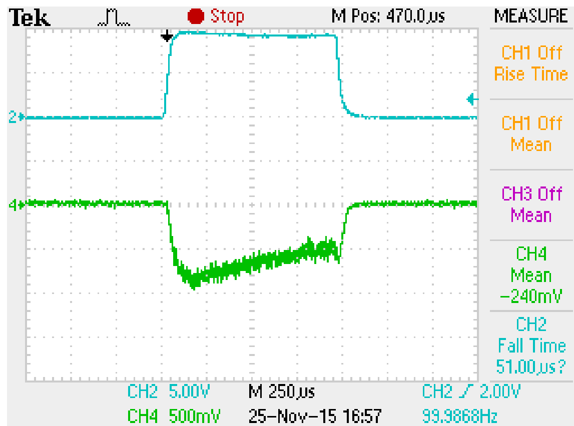
Microwave-driven Cs-free negative hydrogen ion source

No.4 Source

➢ Best results in pulsed mode

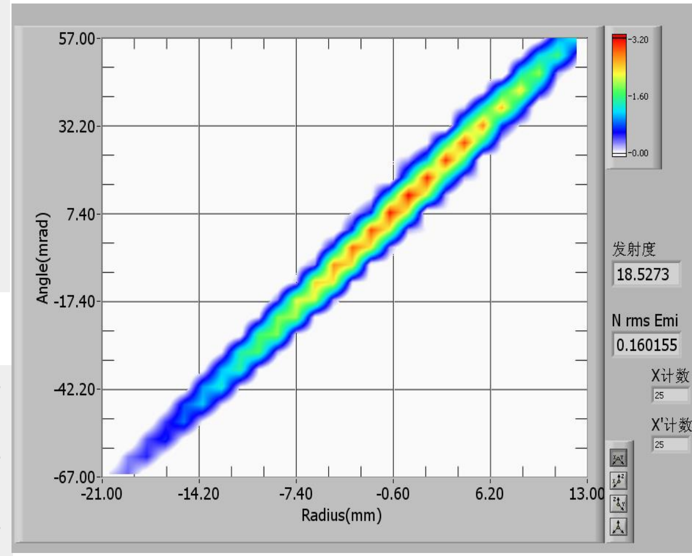


Total current

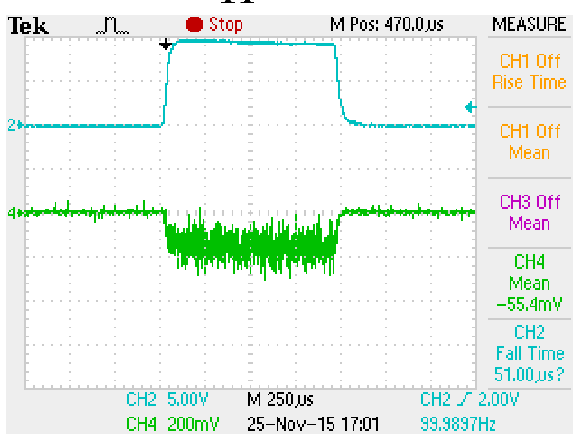


H^-

H^- 45 mA, H^-/e=4.39
Power efficiency 21 mA/kW



RF power 2100 W
Pressure 4.5E-3 Pa
Extraction voltage -35 kV



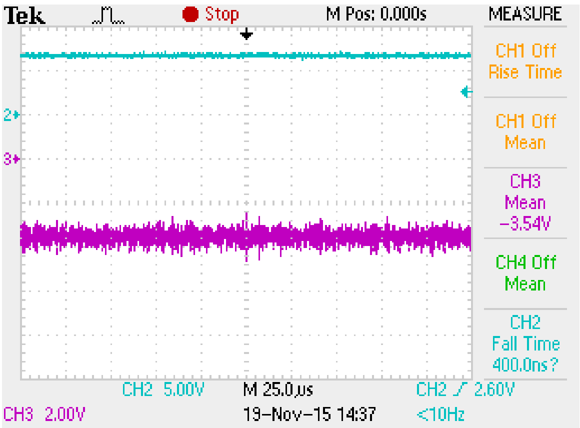
electrons

RMS emmitance
0.160 pi.mm.mrad

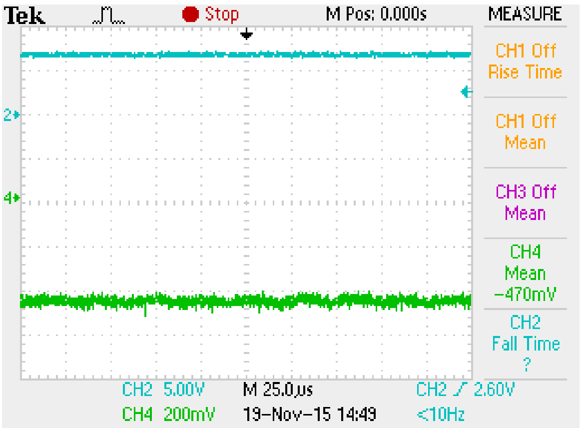
Microwave-driven Cs-free negative hydrogen ion source

➤ Best results in CW mode

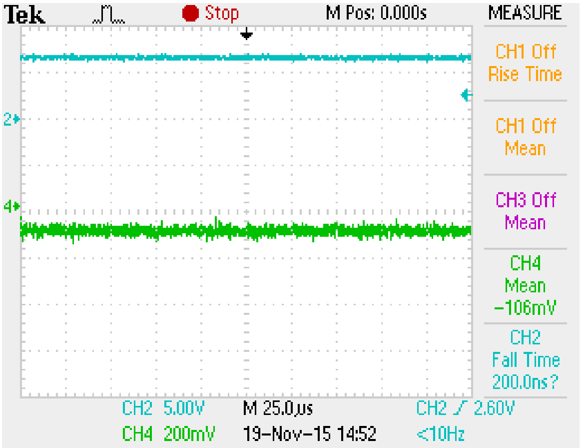
No.4 Source



Total current

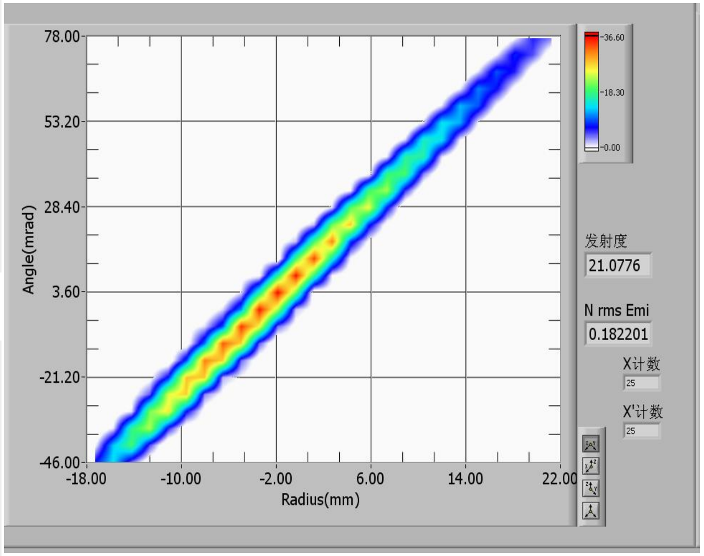


H^-



electrons

H^- 29 mA, H^-/e=4.7
Power efficiency 29 mA/kW



RF power 1000 W
Pressure 4.0E-3 Pa
Extraction voltage -35 kV

RMS emmitance
0.182 pi.mm.mrad

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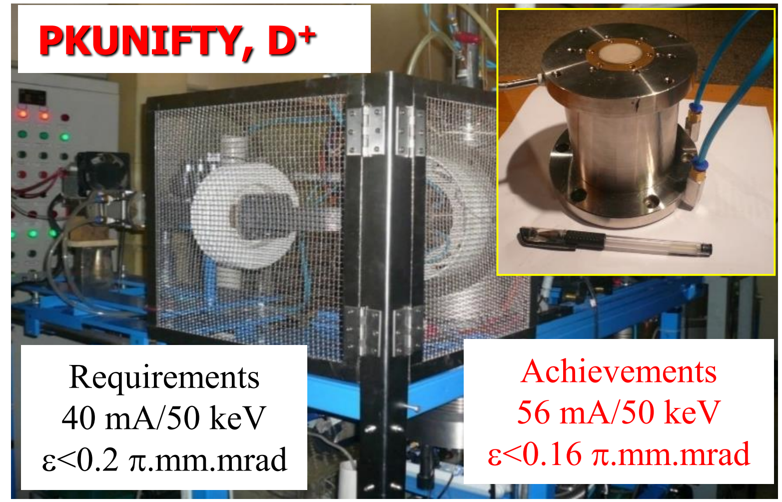
Accelerators implemented with PKU PMECRIS

SFRFQ O^+

Requirements
25 kV/ 10 mA O^+
ε_{RMS}<0.2 π.mm.mrad

Achievements
25 kV/ 25 mA O^+
ε_{RMS} < 0.12 π.mm.mrad

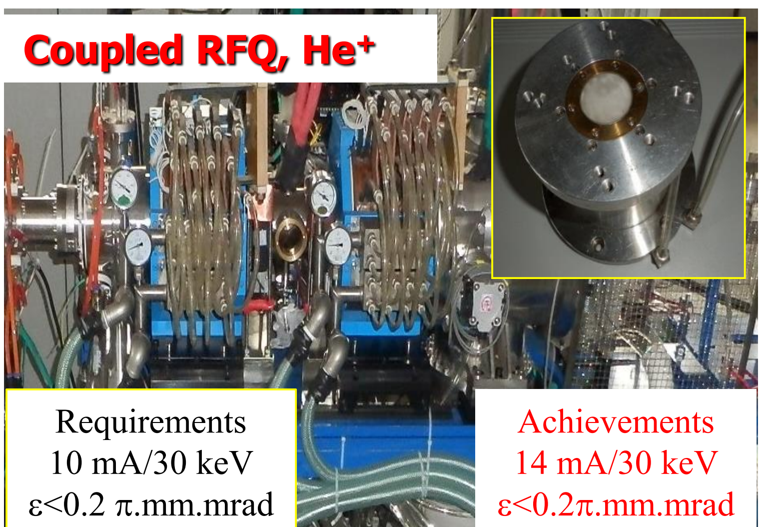
PKUNIFTY, D^+



Requirements
40 mA/50 keV
ε<0.2 π.mm.mrad

Achievements
56 mA/50 keV
ε<0.16 π.mm.mrad

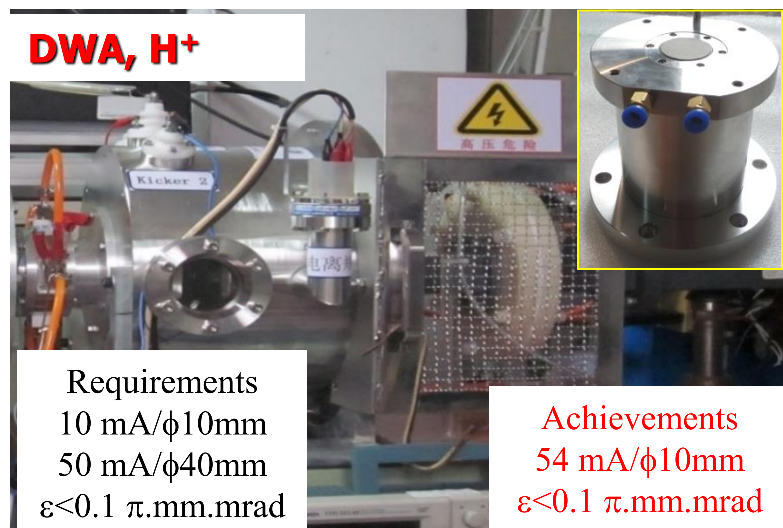
Coupled RFQ, He^+



Requirements
10 mA/30 keV
ε<0.2 π.mm.mrad

Achievements
14 mA/30 keV
ε<0.2π.mm.mrad

DWA, H^+



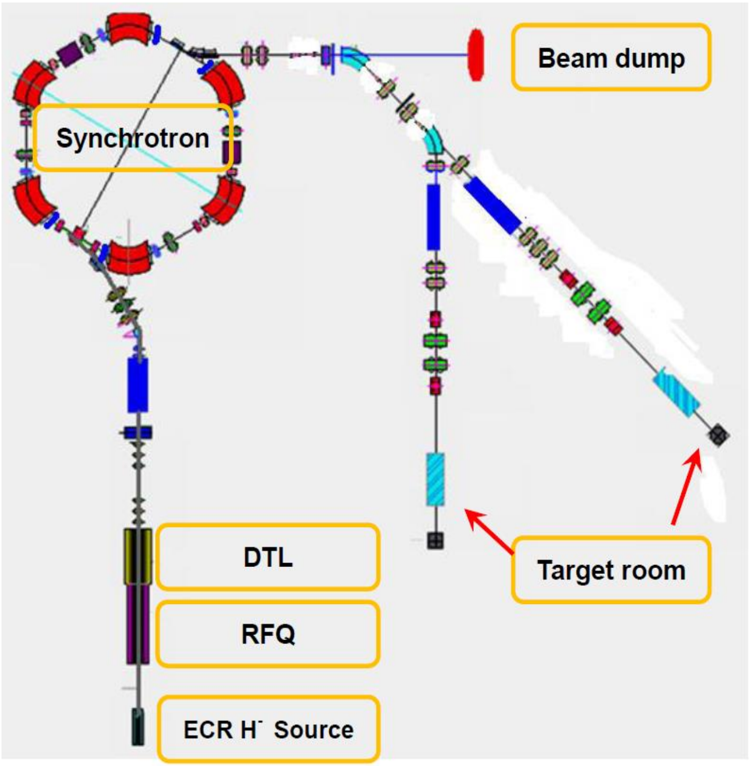
Requirements
10 mA/ϕ10mm
50 mA/ϕ40mm
ε<0.1 π.mm.mrad

Achievements
54 mA/ϕ10mm
ε<0.1 π.mm.mrad

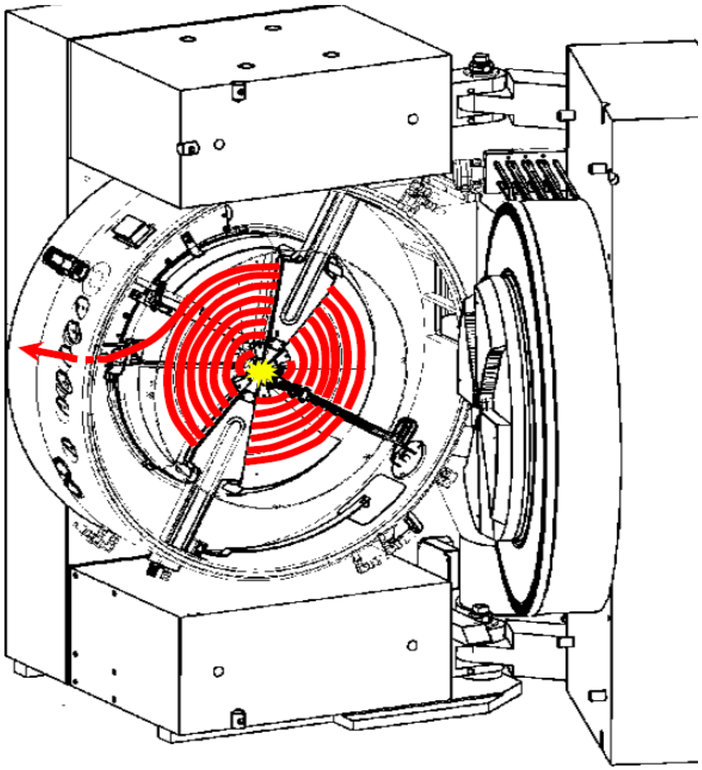
1. S. X. Peng *et. al.*, *Rev. Sci. Instrum.* **79**, 02B706 (2008).
2. H. T. Ren *et. al.*, *Rev. Sci. Instrum.* **81**, 02B714 (2010).
3. S. X. Peng *et al.*, *Rev. Sci. Instrum.* **85**, 02A712 (2014).
4. S. X. Peng *et. al. Nucl. Instr. and Meth. A*, **763** (2014) 120.

Accelerators implemented with PKU PMECRIS

- H^- ion source



Layout of XiPAF facility
10 mA H^- 10% duty factor



Potential application in cyclotron for isotope production

1. S. X. Zheng *et al., in proceedings of HB2016*, Malmö, Sweden, MOPR006 pp. 56 (2016).
2. P. W. Schmor, *in proceedings of CYCLOTRONS 2010*, Lanzhou, China, FRM2CIO01, pp. 419 (2010).

Outline

- Background
- Ion sources developed at PKU
  - Overview
  - H^+ ion source
  - Molecular ion source (H_2^+ & H_3^+)
  - Microwave-driven Cs-free negative hydrogen ion source
- Conclusion

Conclusion

- 2.45 GHz microwave driven ion sources have been developed at PKU for several decades. After improvements, the ion sources can already produce high current H^+, H_2^+, H_3^+ and H^- ions to fulfil the requirements of cyclotrons.
- For positive hydrogen ions, 130 mA H^+, 42 mA H_2^+, and 20 mA H_3^+ ion beam could be extracted in pulsed mode.
- Moreover, a 300 h long time continuous test with 50 mA CW H^+ beam was performed to demonstrate the stability and reliability of the ion source recently.
- For negative hydrogen ion source, 29 mA CW and 45 mA pulsed H^- beam was generated with very high power efficiency. In conclusion, it is promising to use 2.45 GHz microwave driven ion source at PKU in cyclotrons as it has very high reliability to generate both CW and pulsed beam.

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Thank you for your attention!