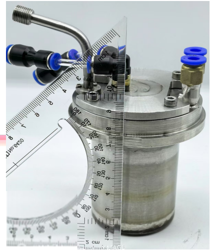


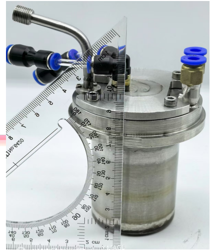
Compact 2.45 GHz Microwave Driven Ion Sources Developed for Accelerator Based Radiation Therapy Facilities at Peking University

Shixiang Peng, Bujian Cui, Tenghao Ma, Wenbin Wu, Kai Li, Yicheng Dong, Jianbin Zhu, Zhiyu Guo and Jiaer Chen

SKLNPT & IHIP, School of Physics, Peking University. No.201, Chengfu Road, Beijing, China

WEA2， 15th - 19th Sept. 2024, Welcome Hotel, Darmstadt, Germany.

E-mail: sxpeng@pku.edu.cn



Outline

1. 2.45GHz Microwave Driven Ion Source Family at PKU

2. Why Named as Microwave Driven Ion Source

3. Commissioning Results of Proton Therapy(PT) Facility

4. CW/pulsed Proton Injector for AB-BNCT Machine

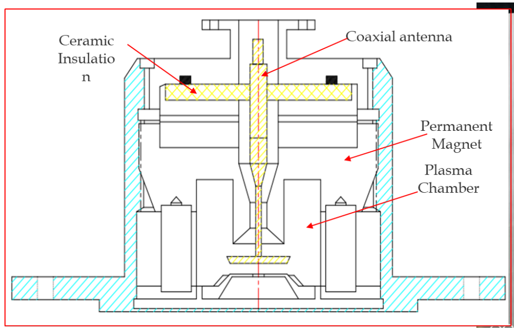
5. Summary and Outlooks

1. 2.45GHz Microwave Driven Ion Sourcs family at PKU

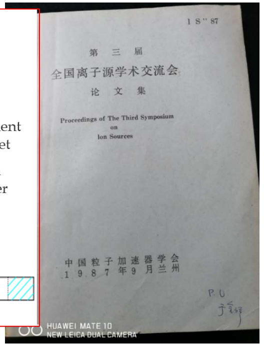
15-19 九月 2024

➢ 1987: Initial attemptation

Z. Z. Song, etc., Lanzhou, 1987.7P. 199-200



ϕ0.8mm,100μA@10kV

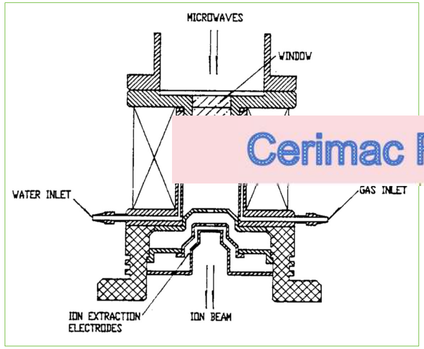

第 三 届
全国离子源学术交流会
论 文 集
Proceedings of The Third Symposium on Ion Sources
中国粒子加速器学会
1987年9月 兰州

Antenna may not be efficient RF matching method.

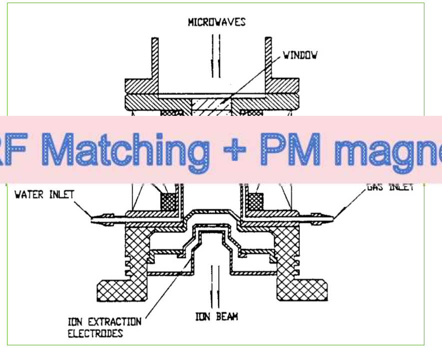
➢1996: RF matching and B filed generation

Z. Z. Song, etc., *RSI* **67**, 1003 (1996).

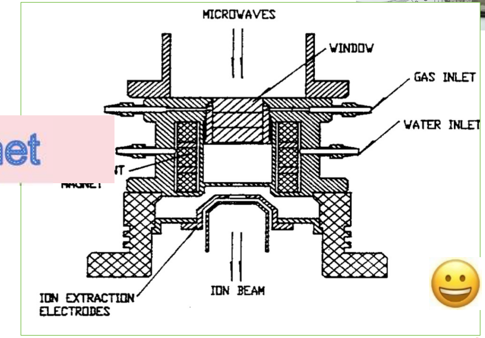
Cerimac RF Matching + PM magnet



Electromagnetic(**EM**) coils

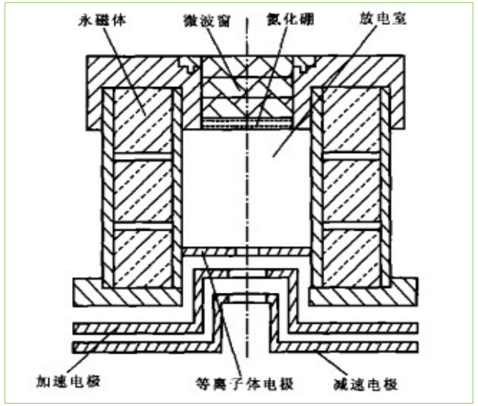


EM coils + **PM** rings



Permanent Magnet **(PM)** rings √

➢ 2004: Curent increased and Problematic[1~2]



Results:

Pulsed mode (4ms/50 Hz), **100 mA@45kV** H^+ beam, beam diesity ~ 500 mA/cm^2. CW mode, **60 mA@40 kV** H^+ beam, Beam intensity ~300 mA/cm^2. O^+ 26mA, N^+ 28mA, He^+ 32mA.

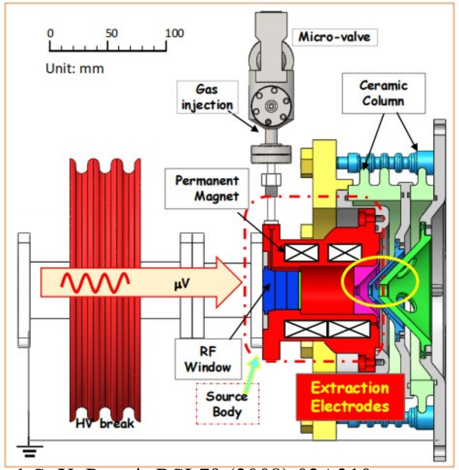
Ploblems: 1)The beam divergence is too large; 2) Lots of sparks come up in CW mode.

1. Z. Z. SONG et al., 38(Suppl). July 2004.
2. Z. Y. Guo, S. X. Peng, etc., TUP10, LINAC 2004,:312-315.

➢ 2008: PKU Typical PMECRs

Key points

1. 2.45GHz μW
2. Permanent Magnet
3. Cerimac RF Window
4. No HV Platform
5. Half/Full Embeded Structure
6. Water-Cooled Extraction
7. Compact and Simple



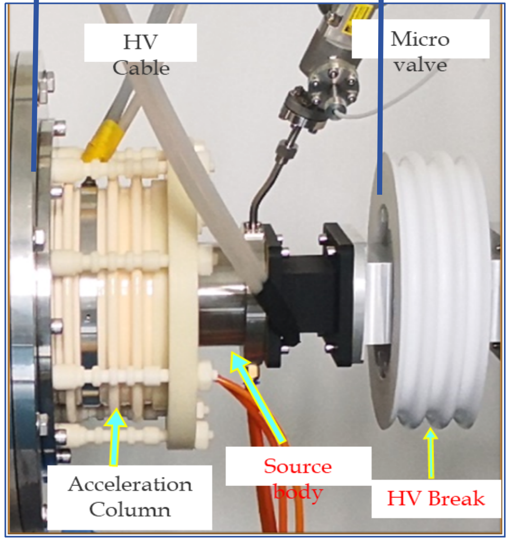
1.S. X. Peng*, RSI 79 (2008):02A310.
2.H. T. Ren, S. X. Peng*, RSI 83 (2012):02B905.
3.M. Zhang, S. X. Peng*, RSI 81 (2010):02B715.

北京大学

2.45GHz Microwave Driven Ion Source Family at PKU

SMIS: PKU **S**tandarded Permanent Magnet 2.45GHz **M**icrowave Driven **I**on **S**ource

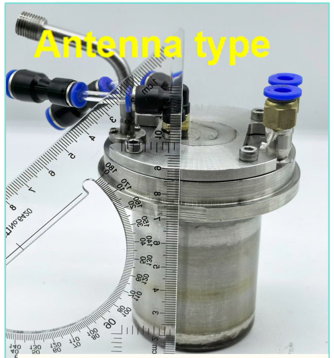
160mm x ϕ180mm



16kg@130mA

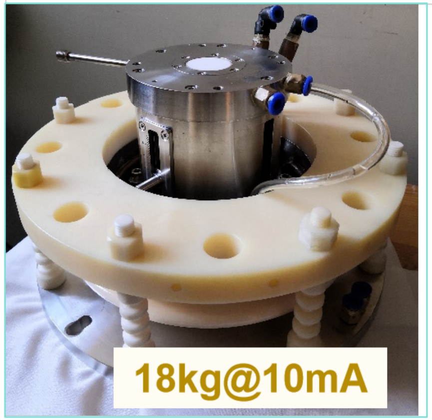
MMIS: **M**iniaturized **M**icrowave Driven **I**on **S**ource

2.5kg
100W@42mA

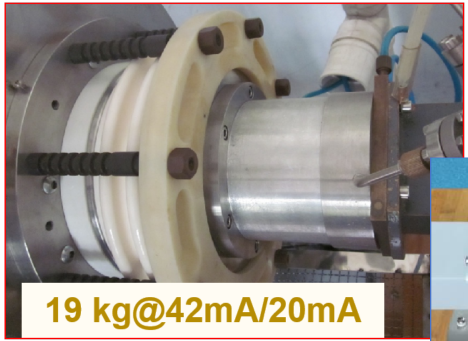


1.5kg
40W@8.5mA

Microwave Driven
H^- ion source@Xi'PUF



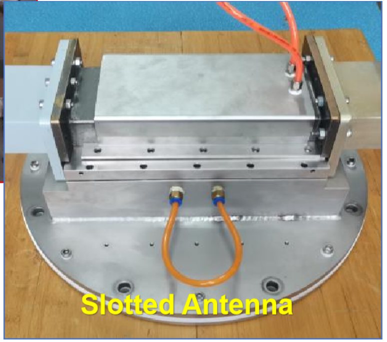
H_2^+/H_3^+ Ion Source

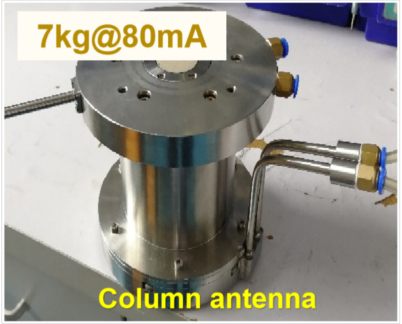


C^{2+} /O^{3+} ion Source

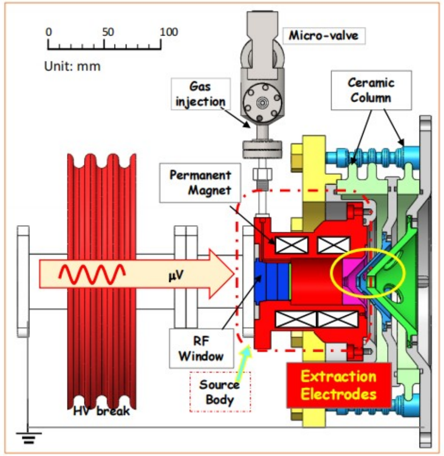
Multi-Charged C^{2+}/ O^{3+}/ Ar^{3+} Ions Beam Generation

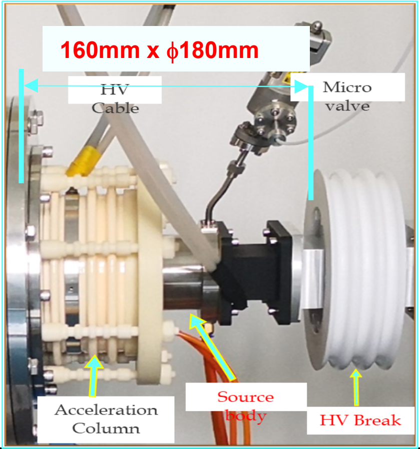
Surface Plasma Electron Source(**E-Gun**) for Implantation machine

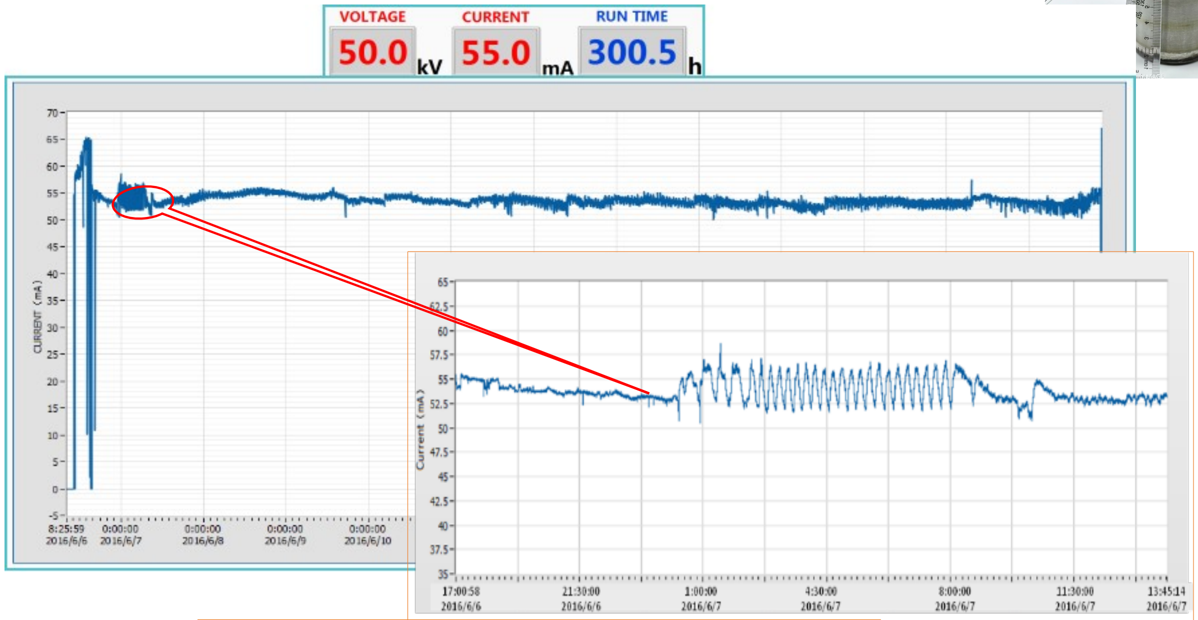




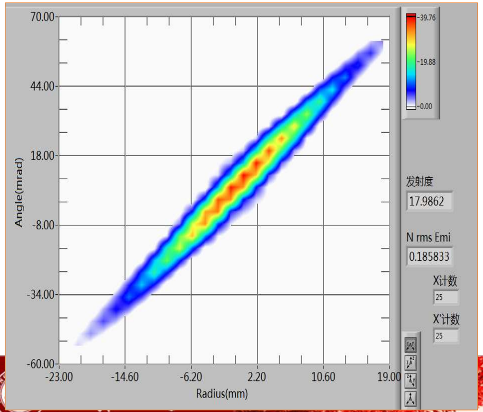
1) PKU Standart 2.45GHz Permanent Magnet Ion Sources - SMIS







Ion type	H^+	D^+	He^+	O^+	Ar^+	N^+
Current[mA]	130	83	65	70	70	84
Intensity[mA/cm^2]	460	294	230	247	247	297



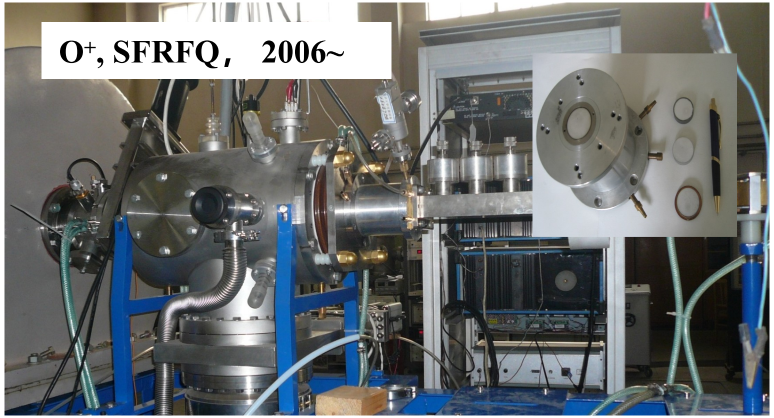
$$\varepsilon = 0.18\pi \cdot mm \cdot mard$$

for 50keV@130mA
Proton beam

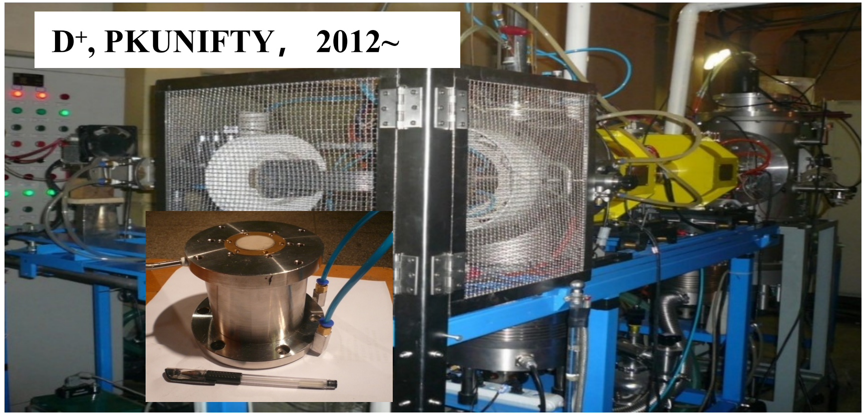
16kg=5.5kg+11.5kg

Shi-Xiang Peng*, CPB, 26(2) (2017): 025206.

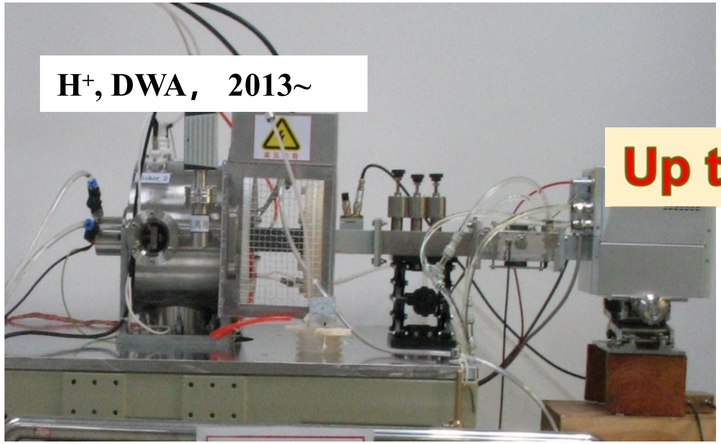
2) Some Applications of SMIS



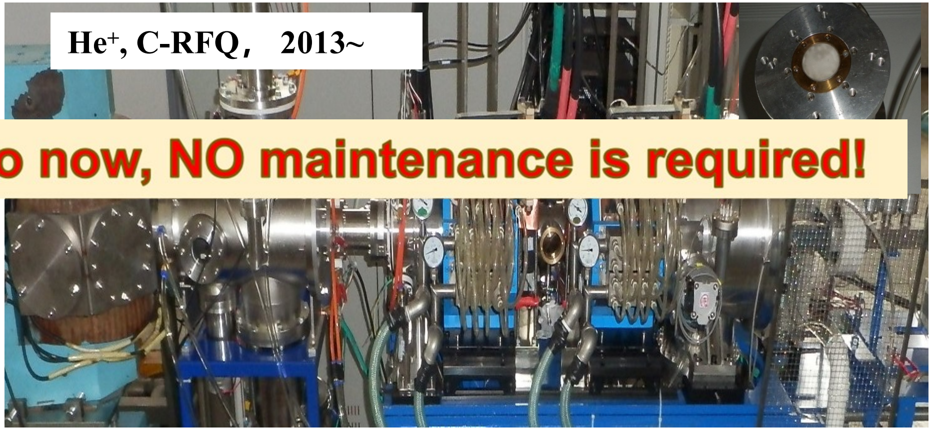
S. X. Peng*, RSI 79 (2008):02B706



H. T. Ren, S. X. Peng*, SRI 81 (2010)02B714



S. X. Peng*, NIMA 763 (2014):120-123



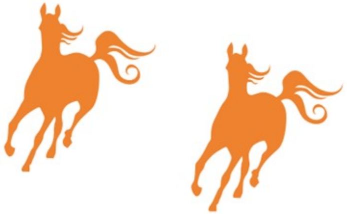
Up to now, NO maintenance is required!

S. X. Peng*, RSI 85 (2014):02A712

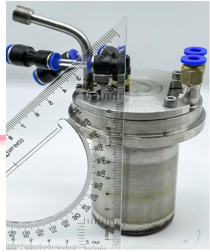
ABRT： Accelerator Based Radiation Therapy Facilities

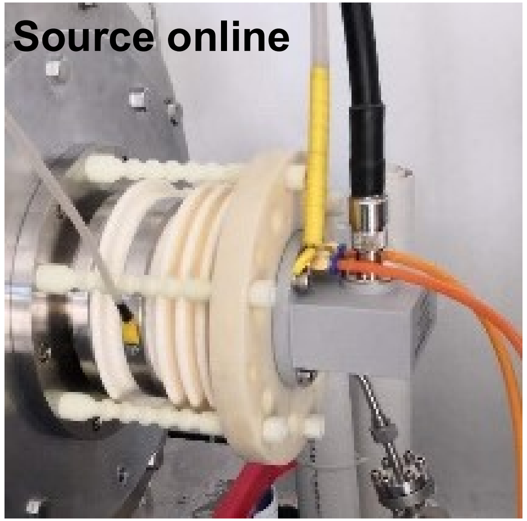
1)Proton Therapy(PT)

2)Boron Neutron Capture Therapy (BNCT)



3) Miniaturized Microwave Ion Source(MMIS) Cerimac window

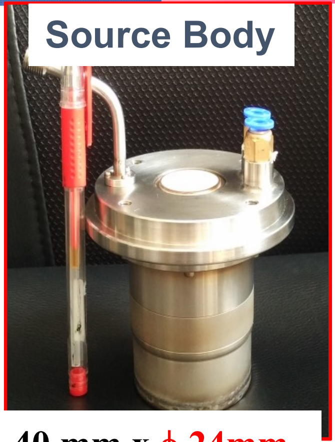




Ion source characters	
Microwave frequency	2.45 GHz
Microwave power	40-100 W
Beam energy	30-50 kV
Magnets	Full permanent magnet
Extraction hole	6 mm
Source body	88 mm × ϕ90 mm， **2.5 kg**
The Whole Source	130 mm × ϕ180 mm, **7.3kg**
RF Matching	1) Ceramic plus Co-axial cable
	2) Ceramic plus BJ 32 waveguide
Operation mode	Pulsed / DC
Total current	**DC: 42mA@100W RF**
	Pulsed: 72mA@100Hz/10%@1800W
Applications	Neutron source，PFG, etc.

J.M. Wen, S.X. Peng*, CPB 27(5) (2018): 055204
S. X. Peng, J. Appl. Phys. 132, 083305 (2022)

3) MMIS Resluts - Cerimac window



40 mm x ϕ 24mm

Pulsed mode @40kV

1.8kW, 100Hz@1ms @**74mA**

CW@40kV

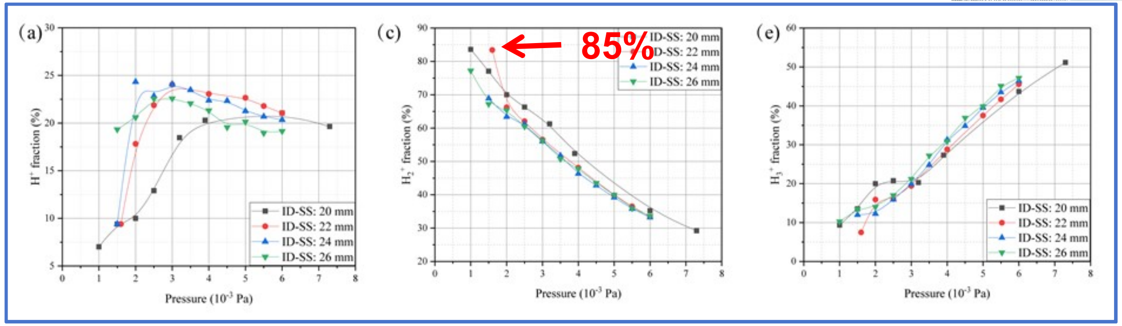
RF **100W@ 42mA Hydogen beam**

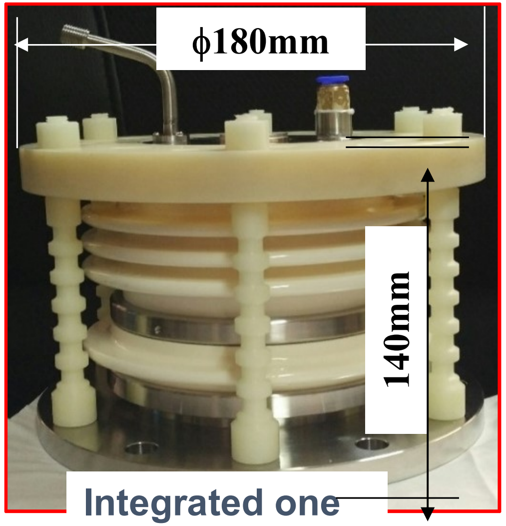
RF **10W@3mA** H^+ **1.7mA** He^+

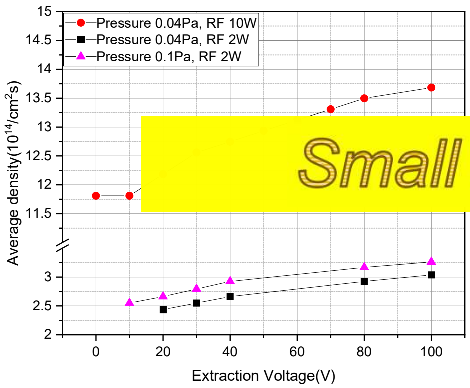
CW@100V

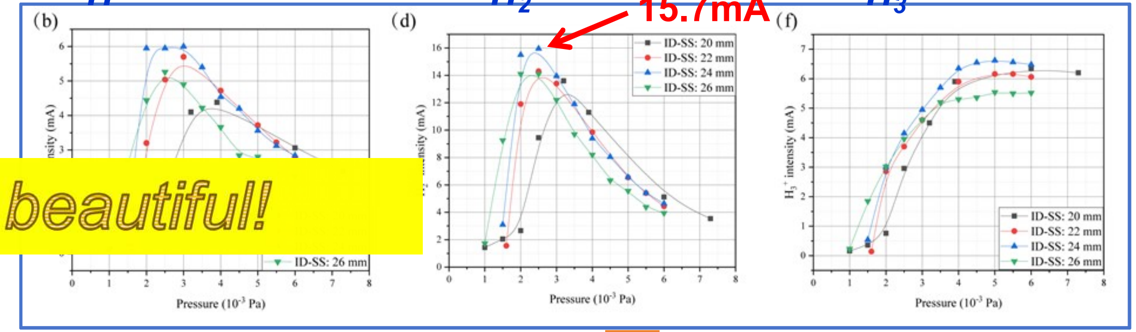
He^+ **1.7mA@10W**

ϕ24mm @ 42mA@100W, H_2, CW









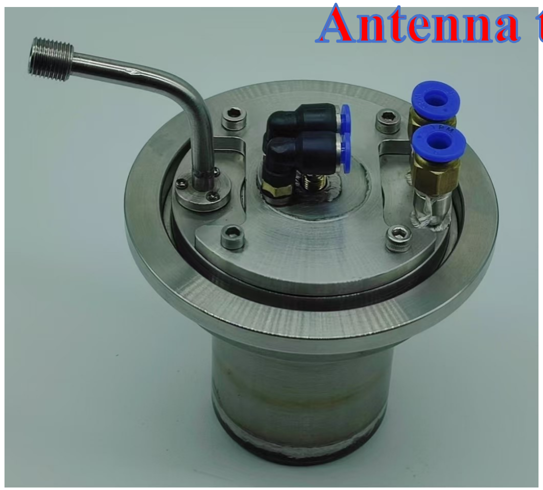
Small is beautiful!

- How to generate a density plasma (**HDH**).
- What is the critical factor on $H^+/H_2^+/H_3^+$ generation（**Global model**）

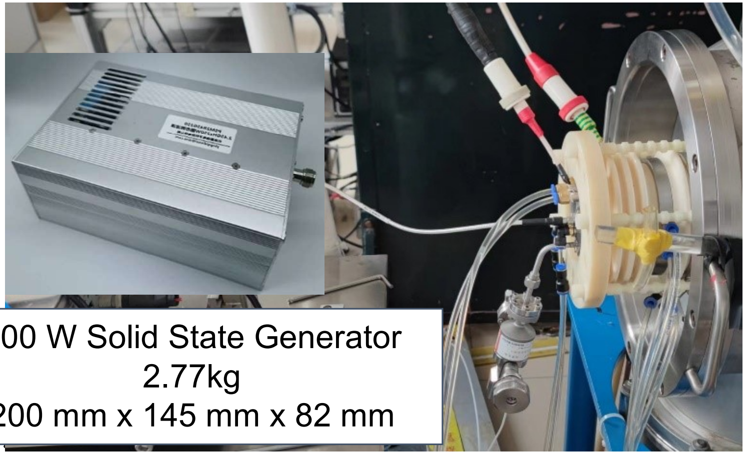
[1] S.X. Peng, etc., CPB, 27(5) (2018): 055204.编辑推荐文章
[2]S. X. PENG，etc., SAP2023, 四川西昌
[3] S.X. Peng, etc., NIMA 1011 (2021) 165586.
[4]W.B. WU, etc., J. Appl. Phys. 132, 083305 (2022)

4) Miniaturized Microwave Ion Source(MMIS) Antenna type

Antenna type



Full embeded



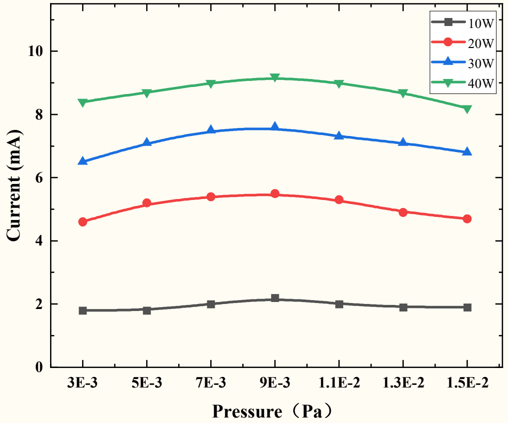
200 W Solid State Generator
2.77kg
200 mm x 145 mm x 82 mm

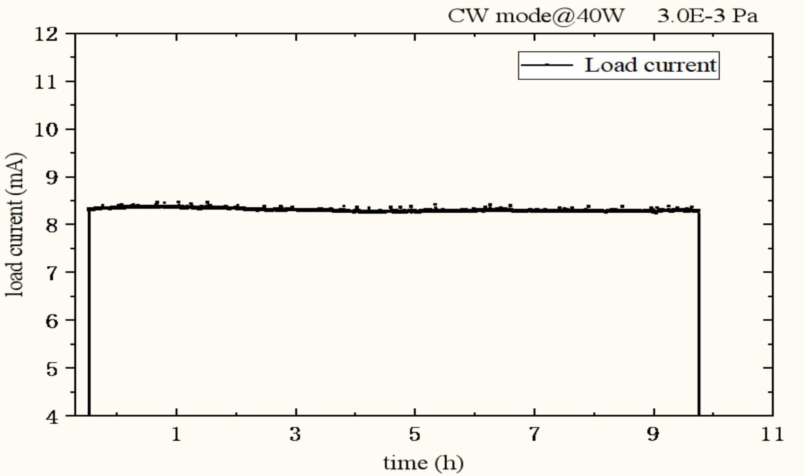
S. X

Ion source characters	
Microwave frequency	2.45 GHz
Microwave power	10 - 100 W
Beam energy	30-50 kV
Source body	60 mm × ϕ50 mm， **1.5 kg**
Magnets	Full permanent magnet
Extraction hole	6 mm
RF transportation	Co-axial cable
Discharge Chamber	**39 mm × ϕ 10 mm**
RF Matching	Antenna
Operation mode	DC/Pulsed
Current	**CW: 8.5mA@40W**
	Pulsed: 21mA@180W(peak)
Applications	Neutron source, PFG, etc.

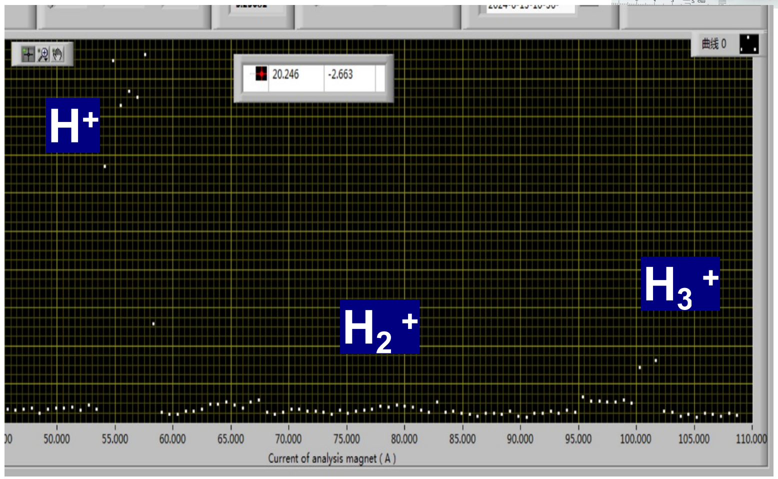
4) Antenna type MMIS Antenna type

➢ CW mode

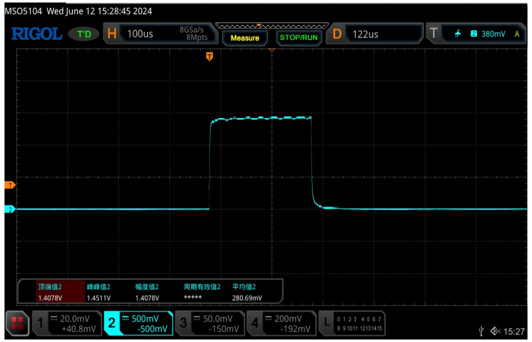




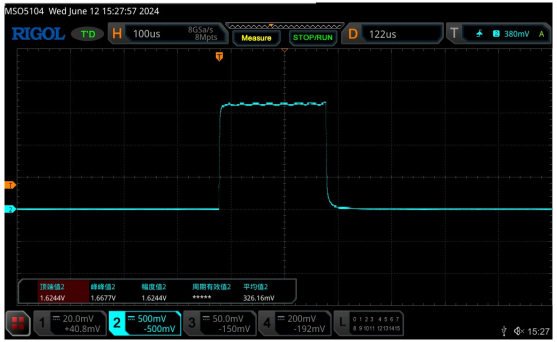
Ion factors H^+: 85%



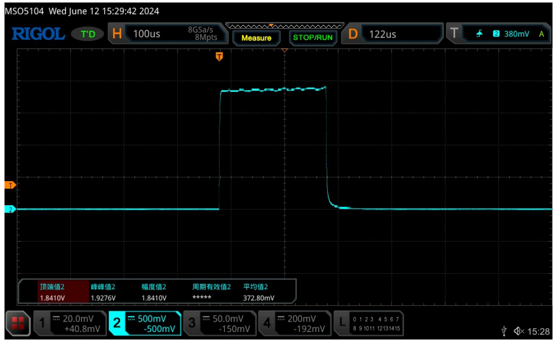
➢ Pulsed mode，50Hz，10% duty



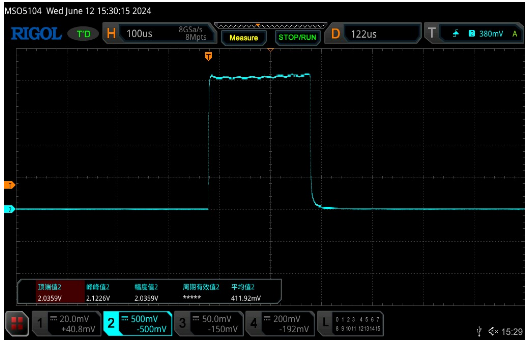
100W(peak)，14mA



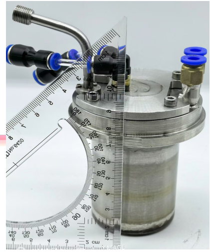
120W，16mA



150W，19mA



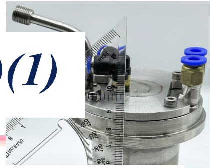
180W，21mA



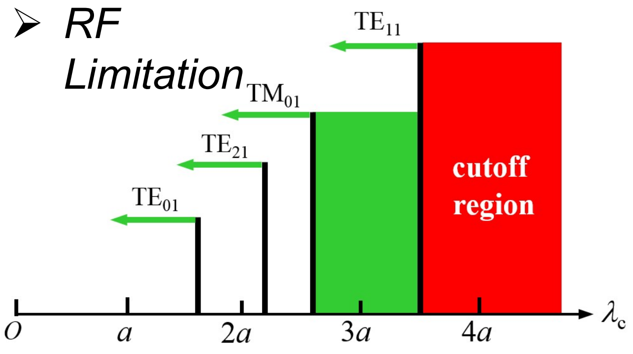
Outline

1. 2.45GHz Microwave Driven Ion Source Family at PKU
2. **Why Named as Microwave Driven Ion Source**
3. The LINAC Commissioning Results of PT Facility
4. CW/pulsed Proton Injector for AB-BNCT Machine
5. Summary and Outlooks

2. Why Named as Microwave Driven Ion Source: *Hybrid Discharge Heating Mode(HDH)(1)*

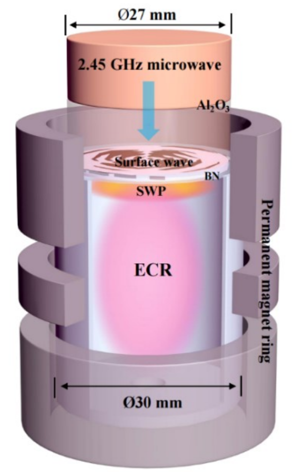


- *RF Limitation*



2.45GHz ~72mm

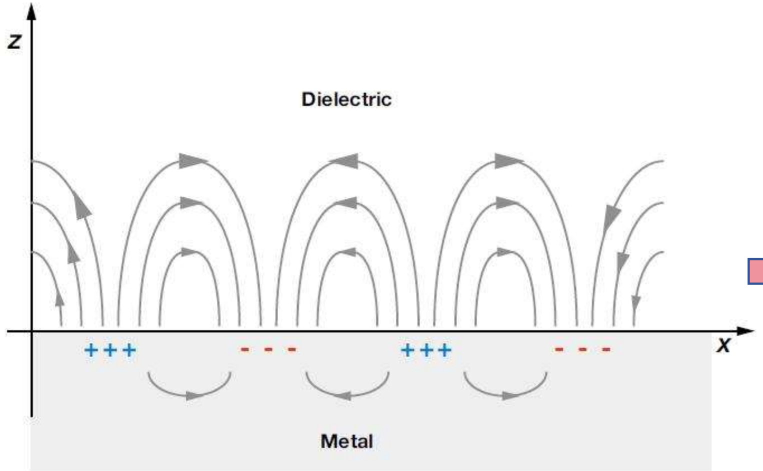
- *RF efficiency at PKU*

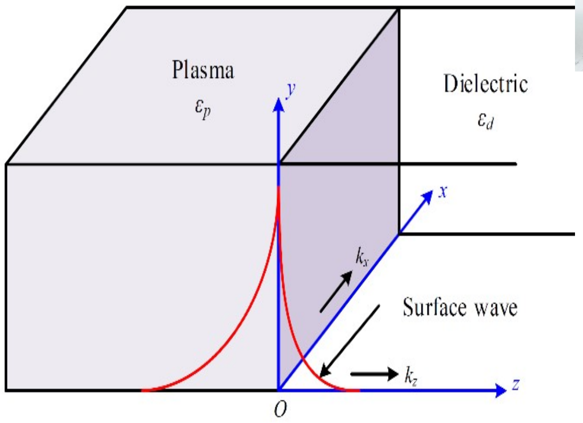


MMIS:

100W@42mA

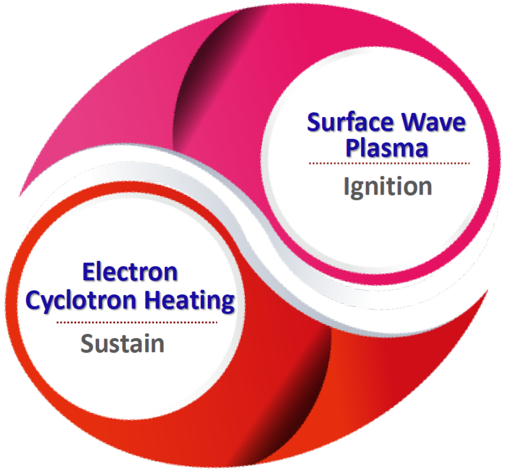
SMIS: 500W@55mA





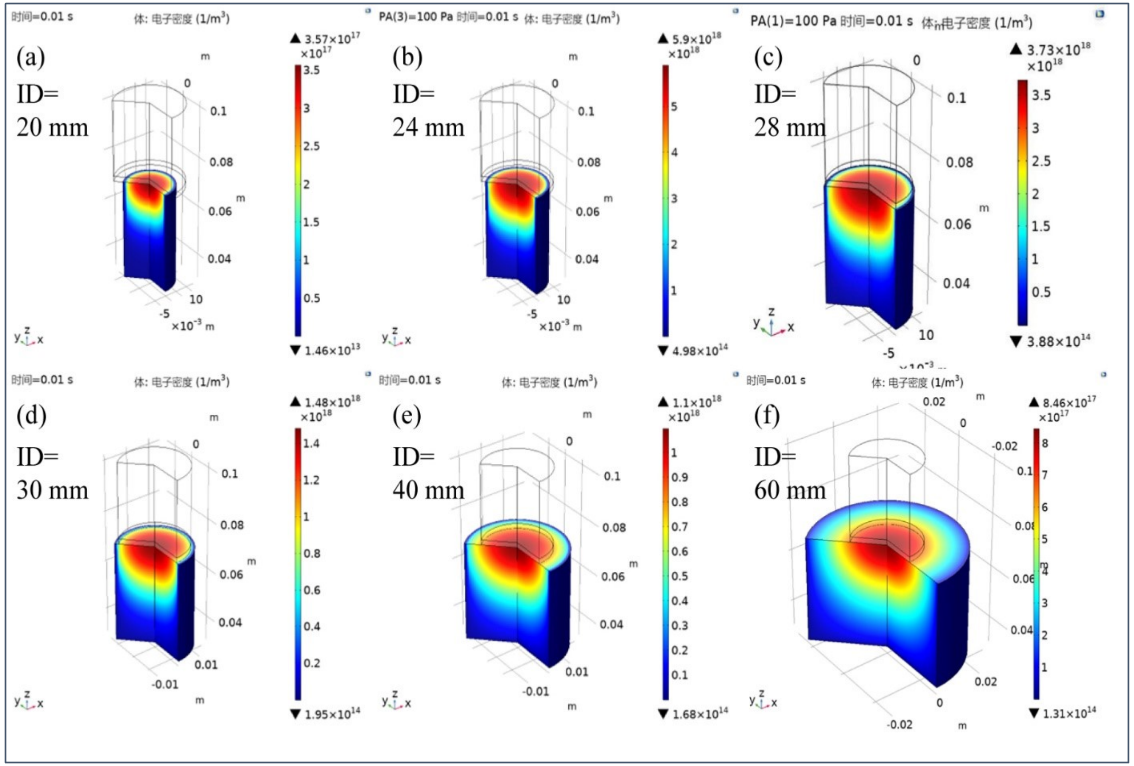
No.	Reactions	Description
1	$e + H_2 \rightarrow 2H + e$	Dissociation
2	$H + H + wall \rightarrow H_2 + wall$	H wall recombination
3	$e + H \rightarrow H^+ + 2e$	H ionization
4	$e + H_2^+ \rightarrow H^+ + H + e$	Dissociative excitation
5	$e + H_2 \rightarrow H_2^+ + 2e$	Molecular ionization
6	$e + H_2^+ \rightarrow H + H^*$	Dissociative recombination
7	$H_2^+ + H_2 \rightarrow H_3^+ + H$	H_3^+ ion formation
8	$e + H_3^+ \rightarrow 2H + H^+ + e$	Dissociative excitation
9	$e + H_3^+ \rightarrow 3H$	Dissociative recombination
10	$e + H_2 \rightarrow H^+ + H + 2e$	Dissociative ionization
11	$e + H_2^+ \rightarrow 2H^+ + 2e$	Dissociative ionization
12	$e + H_2^+ \rightarrow H^+ + H^* + e$	Dissociative excitation

- A 3D fluid model for MMIS;
- The Initial stage is based on SPPs;
- The maintenance is based on ECH.
- Main equations are solved by COMSOL.



Microwave Driven Ion Source: *Hybrid Discharge Heating Mode (HDH)(2)*

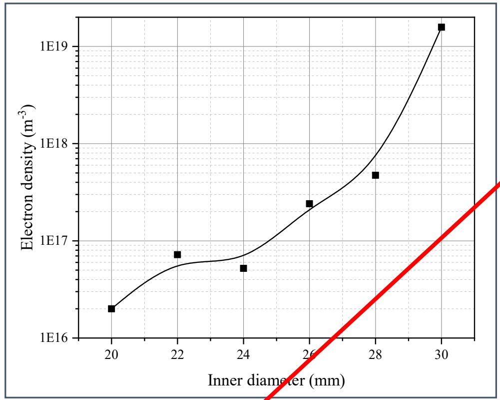
Plasma simulation based on a fluid model

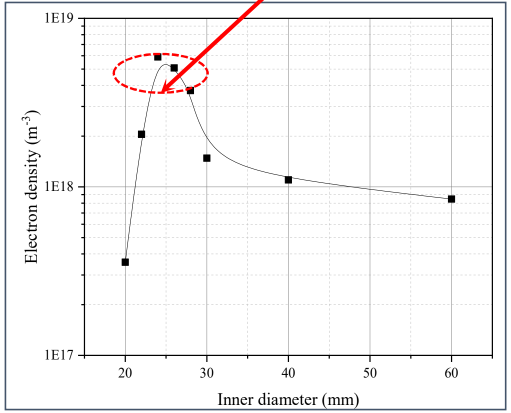


- When the diameter > 20 mm，electron density is far larger than the critical density of microwave discharge 7.2×10^{17} m^{-3}. This result indicated that the discharge mode is a surface wave discharge.

SImulation

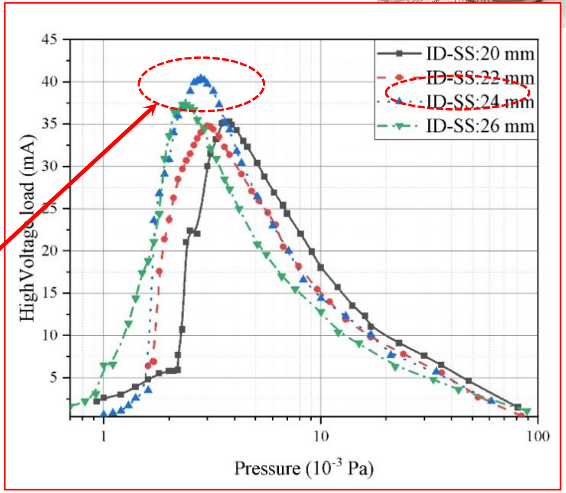
ECR Discharge

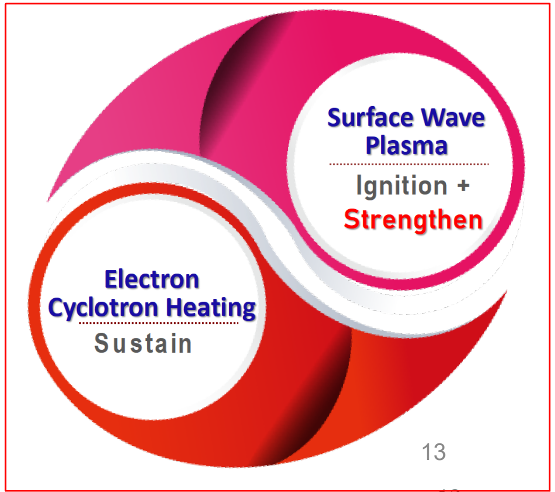




Microwave discharge, NO Magnet

RF 100W CWmode

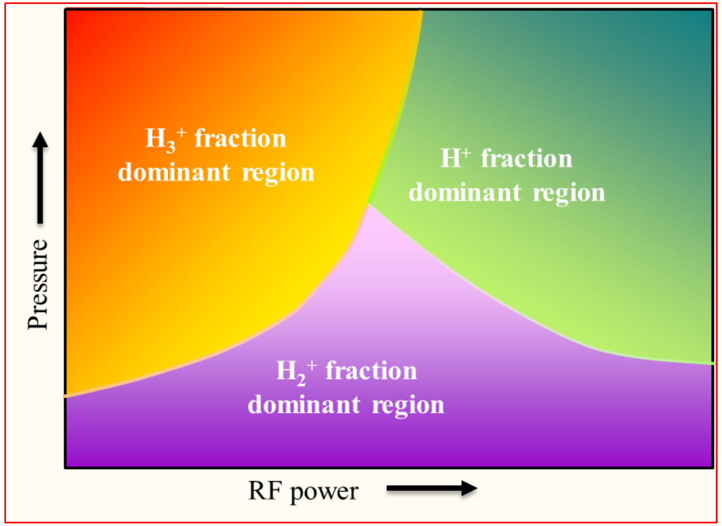




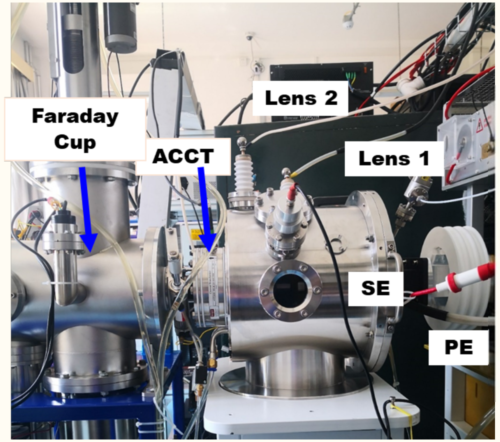
1. T. H. Ma, S. X. Peng, etc., The improvement scheme of proton fraction by the oxygen gas mixing within a miniaturized 2.45 GHz ECR ion source[J].

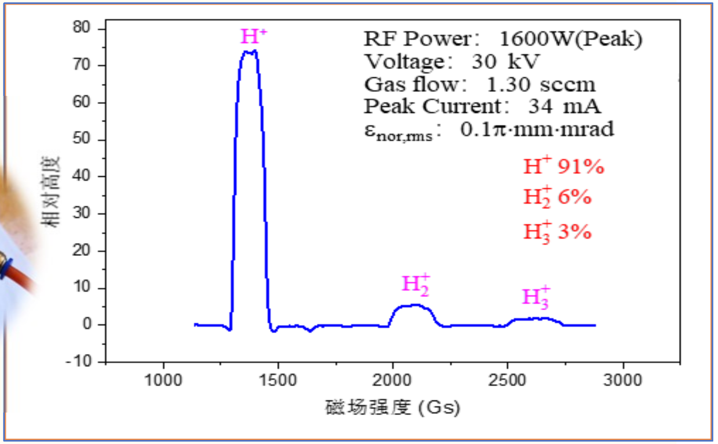
Global model on H^+, H_2^+ and H_3^+ generation (1)

1) Three phase of hydrogen plasma

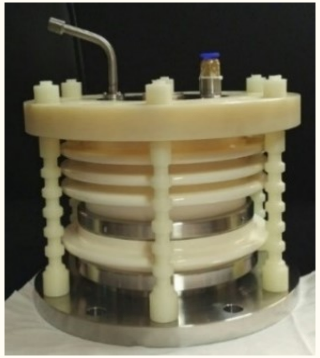


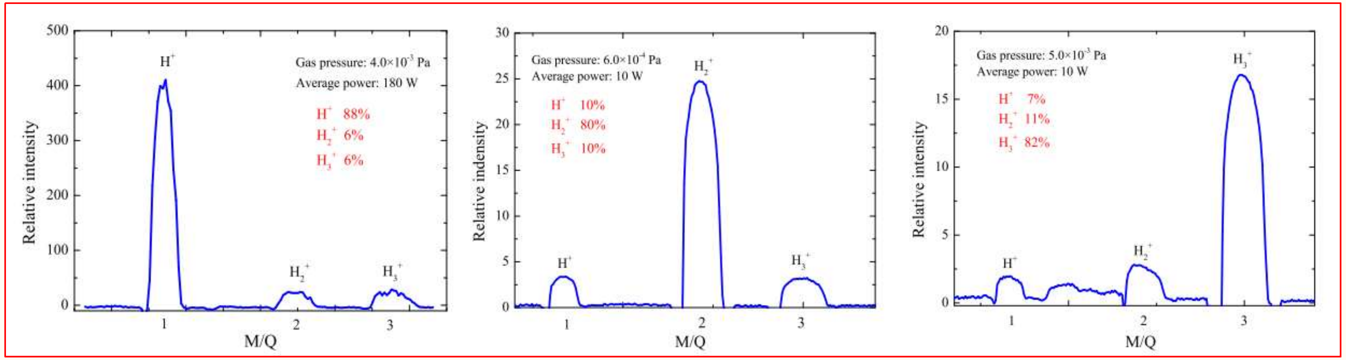
2) Application (Proton therapy facility)





3) MMIS application





1. W. B. Wu, S.X. Peng, RSI 90 101501(2019)
2. S.X. Peng, RSI 90 123305(2019)
3. W. B. Wu, S.X. Peng, Vacuum, 182, 109744(2020)

Global model on H^+, H_2^+ and H_3^+ generation (2)

Electronic equilibrium equation

Basic equation

$$\frac{dn_i}{dt} = s_{in} + \sum_j \pm N_j \alpha_j \prod_l n_{R,l} - \frac{n_i}{\tau_i} = 0,$$

$$H(D) + H(D) + wall \rightarrow H_2(D_2) + wall$$

$$n_e N_2(2\alpha_1 + \alpha_{10}) + n_e n_2(\alpha_4 + 2\alpha_6 + \alpha_{12}) + n_2 N_2 \alpha_7 + n_e n_3(\alpha_8 + 3\alpha_9)$$

$$+\gamma^+(n_1/\tau_1 + n_3/\tau_3) - N_1\alpha_2 - n_e N_1 \alpha_3 - \frac{N_1}{\tau_4} = 0,$$

$$\alpha_2 = \left[\frac{\Lambda_0^2}{D_{eff}} + \frac{2V(2-\gamma)}{A\bar{v}\gamma}\right]^{-1},$$

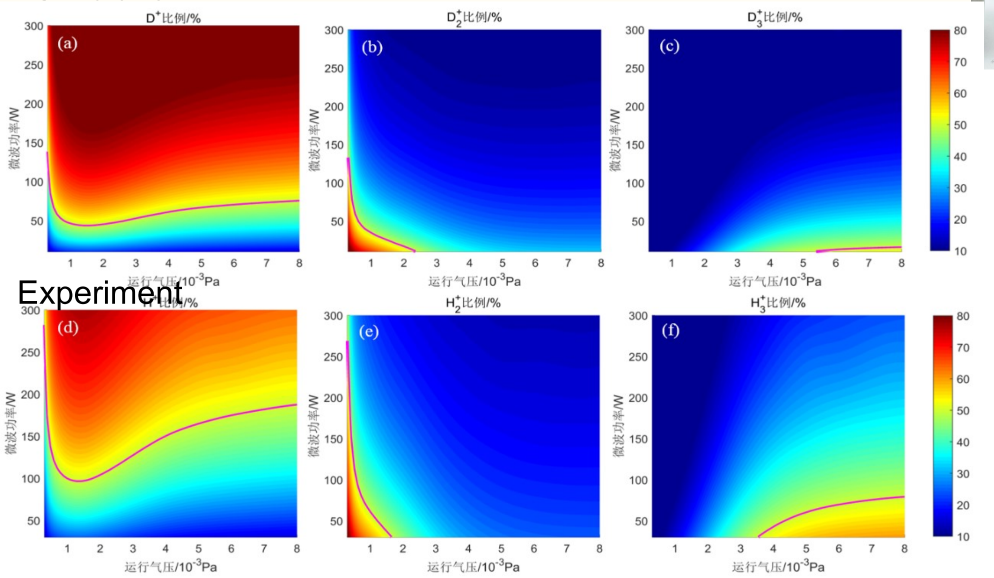
Traditional method

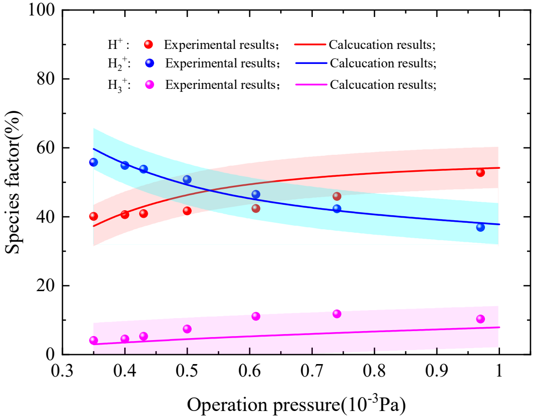
$$N_2 - \frac{1-D}{2D} \cdot N_1 = 0 \qquad D[\%] = exp.data(OES).$$

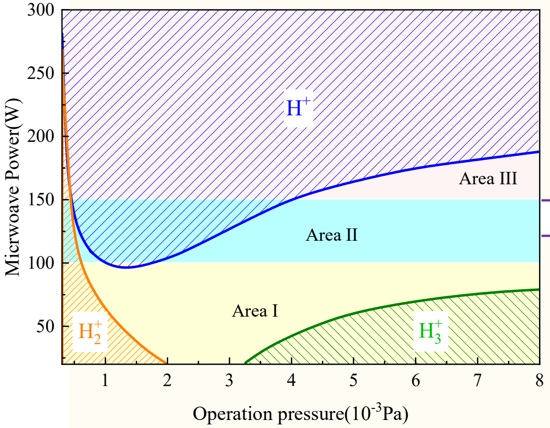
New equation

Simulation

Experiment







- **Advantages:** It can increase a large number of particle types and processes without significantly increasing the amount of calculation, and establish the causal relationship between the input parameters and the spatial average physical quantities.
- **Disadvantages:** It can not provide the spatial dynamic behavior of plasma; dissociation degree depends on the input initial measurement data.

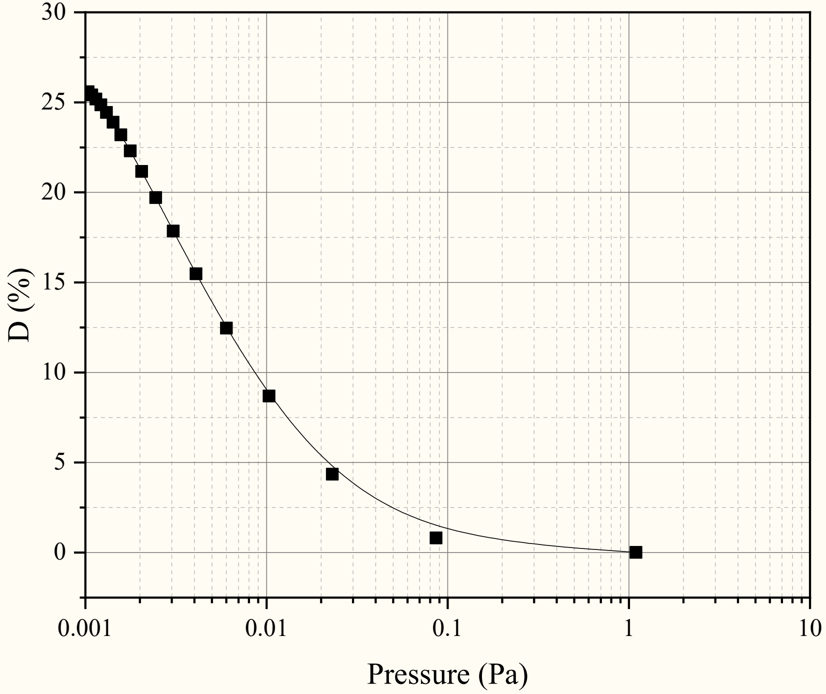
Global model on H^+, H_2^+ and H_3^+ generation (3)

◆ Theory improvement

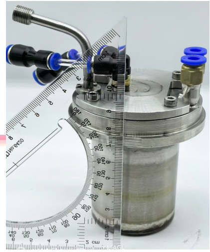
Add four excited state，
n=2, 3, 4, 5

No.	Processes	Description	Reaction energy(eV)
1	$e + H_2 \rightarrow 2H + e$	Dissociation	10
2	$H + H + wall \rightarrow H_2 + wall$	H wall recombination	--
3	$e + H \rightarrow H^+ + 2e$	H ionization	13.6
4	$e + H_2^+ \rightarrow H^+ + H + e$	Dissociative excitation	2.4
5	$e + H_2 \rightarrow H_2^+ + 2e$	Molecular ionization	15.4
6	$e + H_2^+ \rightarrow H + H^*$	Dissociative recombination	0
7	$H_2^+ + H_2 \rightarrow H_3^+ + H$	H_3^+ ion formation	--
8	$e + H_3^+ \rightarrow 2H + H^+ + e$	Dissociative excitation	14
9	$e + H_3^+ \rightarrow 3H$	Dissociative recombination	0
10	$e + H_2 \rightarrow H^+ + H + 2e$	Dissociative ionization	18
11	$e + H_2^+ \rightarrow 2H^+ + 2e$	Dissociative ionization	14.7
12	$e + H_2^+ \rightarrow H^+ + H^* + e$	Dissociative excitation	14

◆ Experimental results (dot) Vs simulation ones (curve)



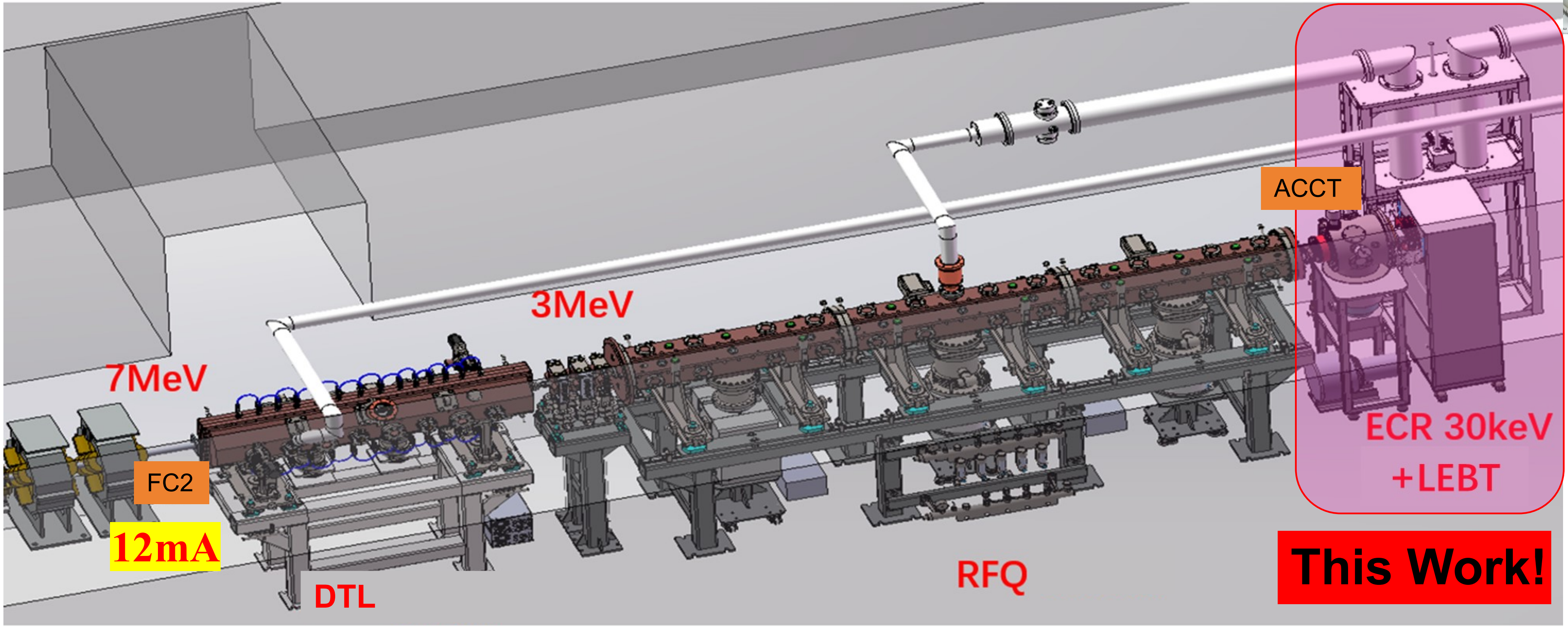
1. R. K. Janev, W. D. Langer, and K. Evans, Jr., Elementary Processes in Hydrogen-Helium Plasmas: Cross Sections and Reaction Rate Coefficients, (Springer-Verlag Berlin Heidelberg, 1987.)
2. S. X. Peng[1, †], T. H. Ma, W. B. Wu, B. J. Cui, A. L. Zhang, Y. X. Jiang, Z. Y. Guo, J. E. Chen, New Progress of the Miniaturized Microwave Ion Source at Peking University. SAP2023, Xichang, Si chuan,2023.7.9-12.
3. T. H. Ma, S. X. Peng, et al., Under review.



Outline

1. *2.45GHz Microwave Driven Ion Source Family at PKU*
2. *Why Named as Microwave Driven Ion Source*
3. ***The LINAC Commissioning Results of PT Facility***
4. *CW/pulsed Proton Injector for AB-BNCT Machine*
5. *Summary and Outlooks*

3. The LINAC Commissioning Results of PT Facility



The Schematic View of this 7 MeV LINAC

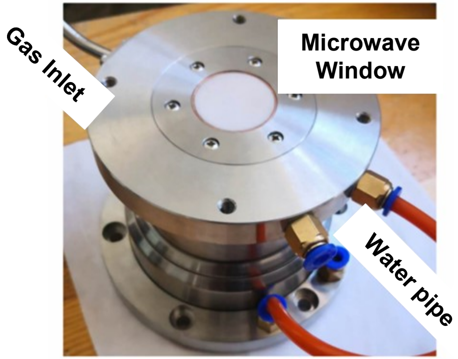
➢ Parameters required by this LINAC

Content		Parameters	Unit
Ion type		H^+	
Energy		30± 0.1	keV
Peak Current	Ion source	20~30	mA
	LEBT	>18	mA
Beam stability(LEBT)		±1	mA
Emittence (RMS, Norm)		≤0.2	π mm·mrad
Repeat frequency		0.5~10	Hz
Pulsed Length		40~100	μs
Raise edge		≤2.0	μs

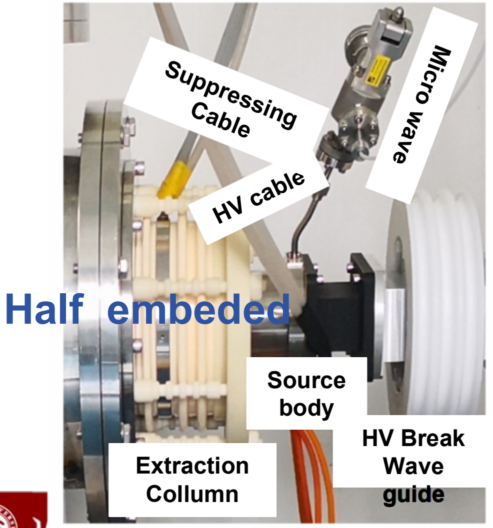
Proton Injector structure: PKU **SMIS** source + a solenoid.

➤ The PT SMIS source test

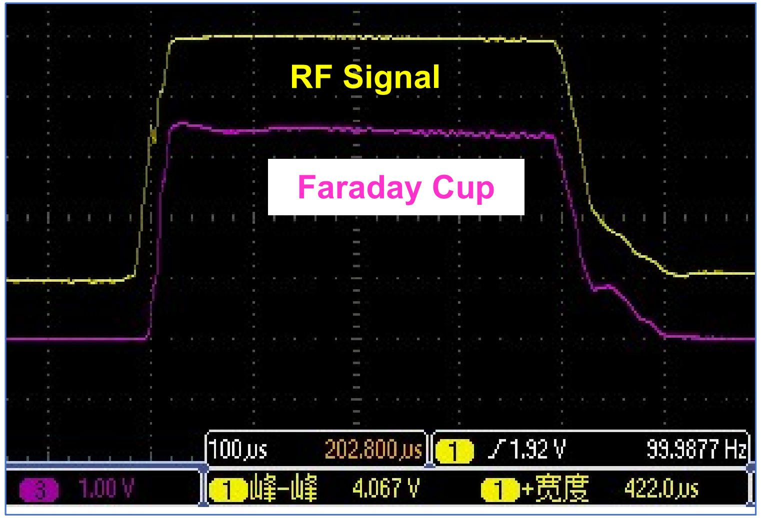
Source body



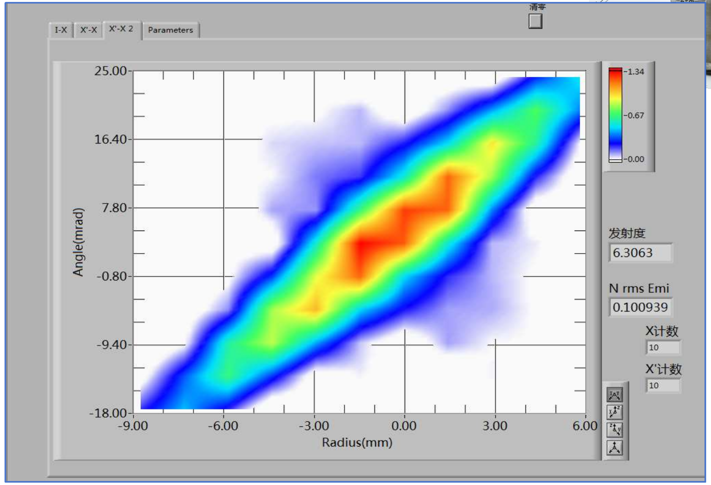
Integrated source

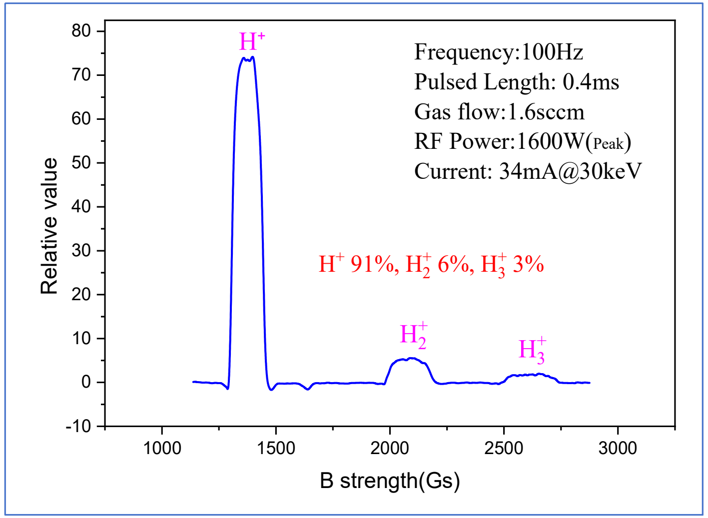


- **Ion Source; PKU SMIS**
- **Size:** ϕ200 mm × 150 mm
- **Beam ability**:**10 mA** to **90 mA** with duty factor of 3%-20% (100 Hz).
- Its rms emittance is **~0.1π·mm·mrad**.
- H^+ faction: **>90%**.

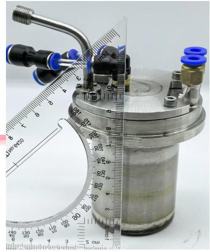


RF Power: SAIREM GMP 30K SM

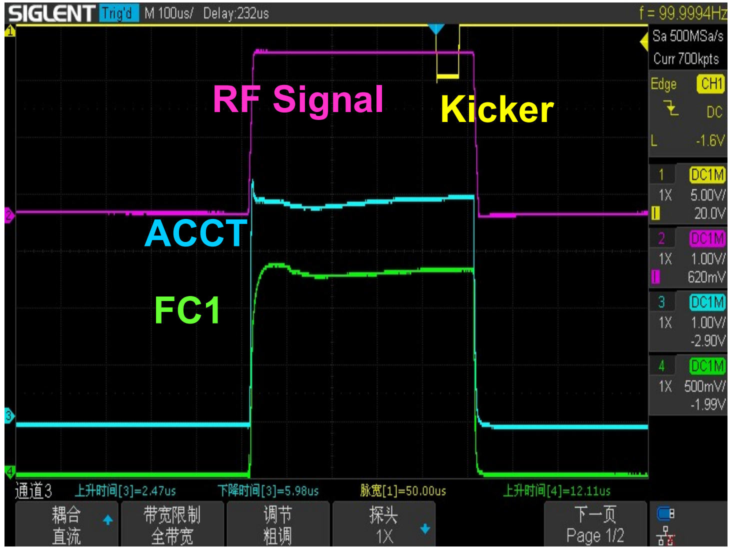




➤ The PT Injector Test Results



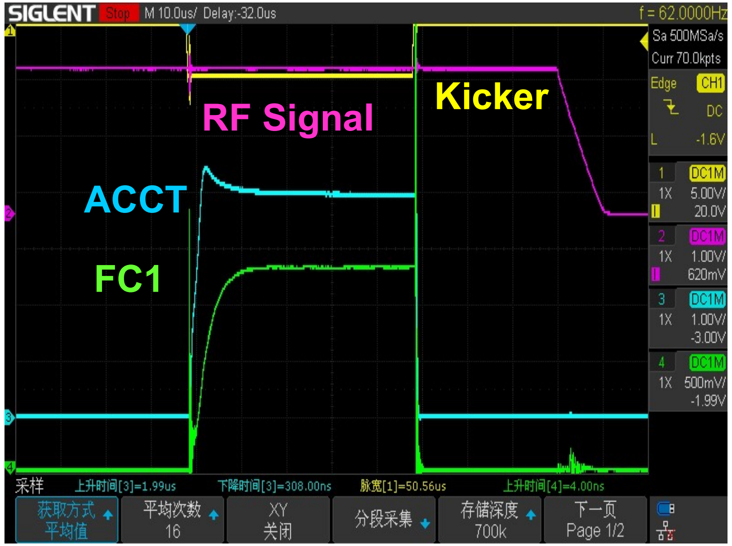
Kicker off



25mA/30kV

Raise edge：2.47us

Kicker on



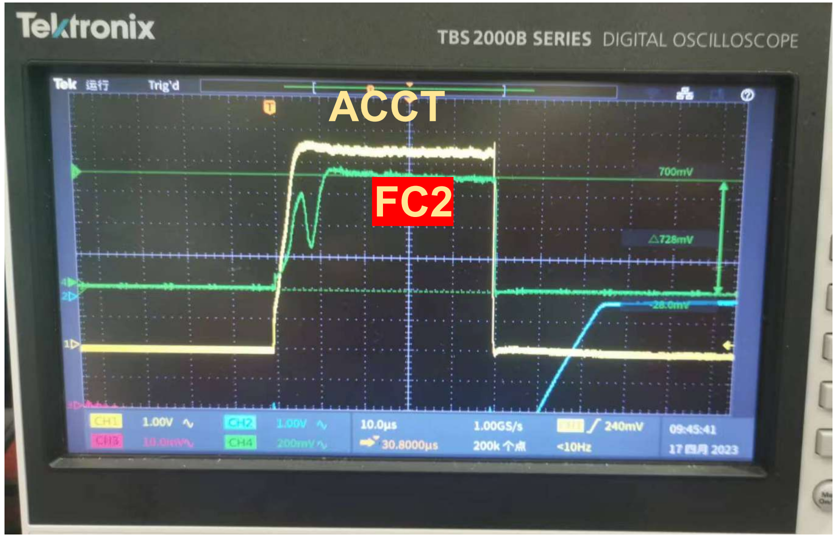
25mA/30kV

Raise adge: 1.99μs.

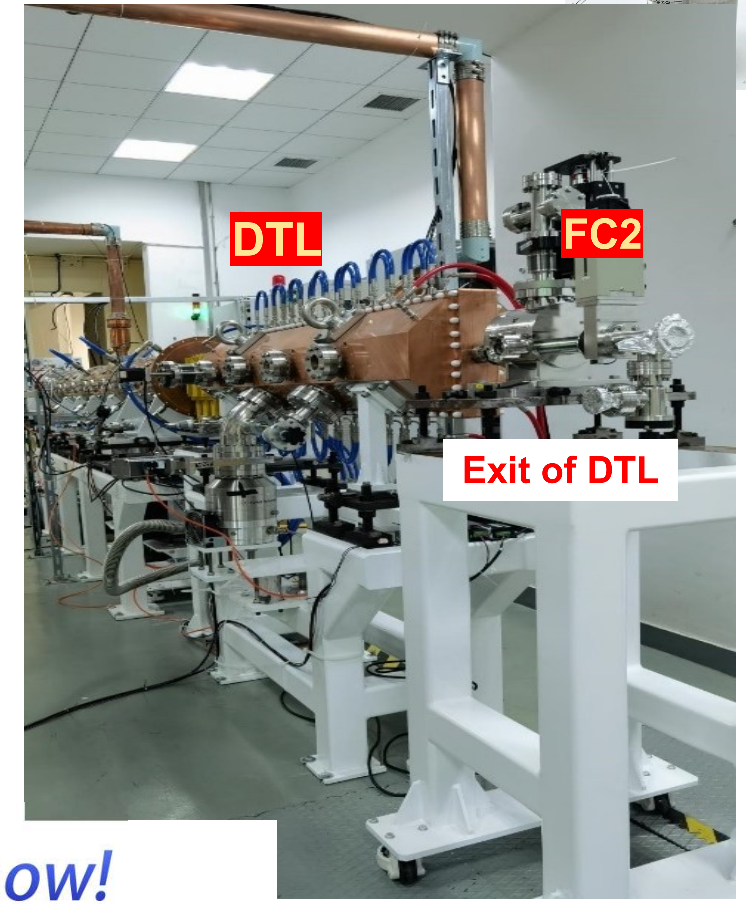
2.45 GHz microwave generator & Kicker power Supply:
Xian SIGNUM Company

➤ The PT LINAC Test Results

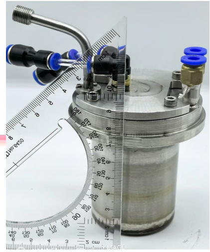
2023.4.14



I_{FC2}=14.4mA@7MV > 12mA@7MV!



NO SPARK appears up to now!



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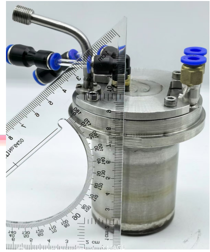
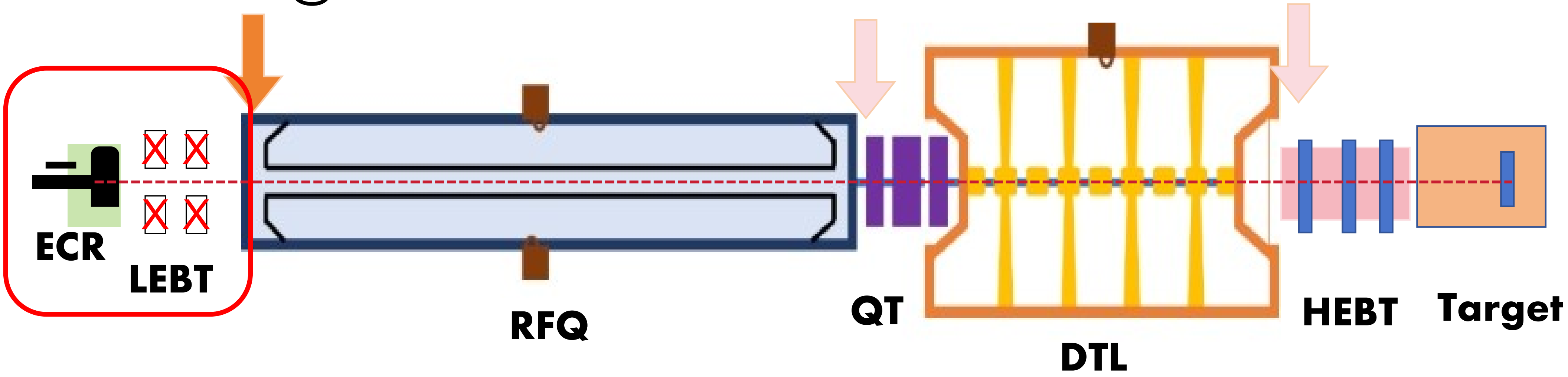
4. CW/pulsed Proton Injector for AB-BNCT Machine



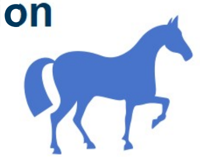


The schematic view of **AB-BNCT**(**B**oron **N**eutron **C**apture **T**herapy)

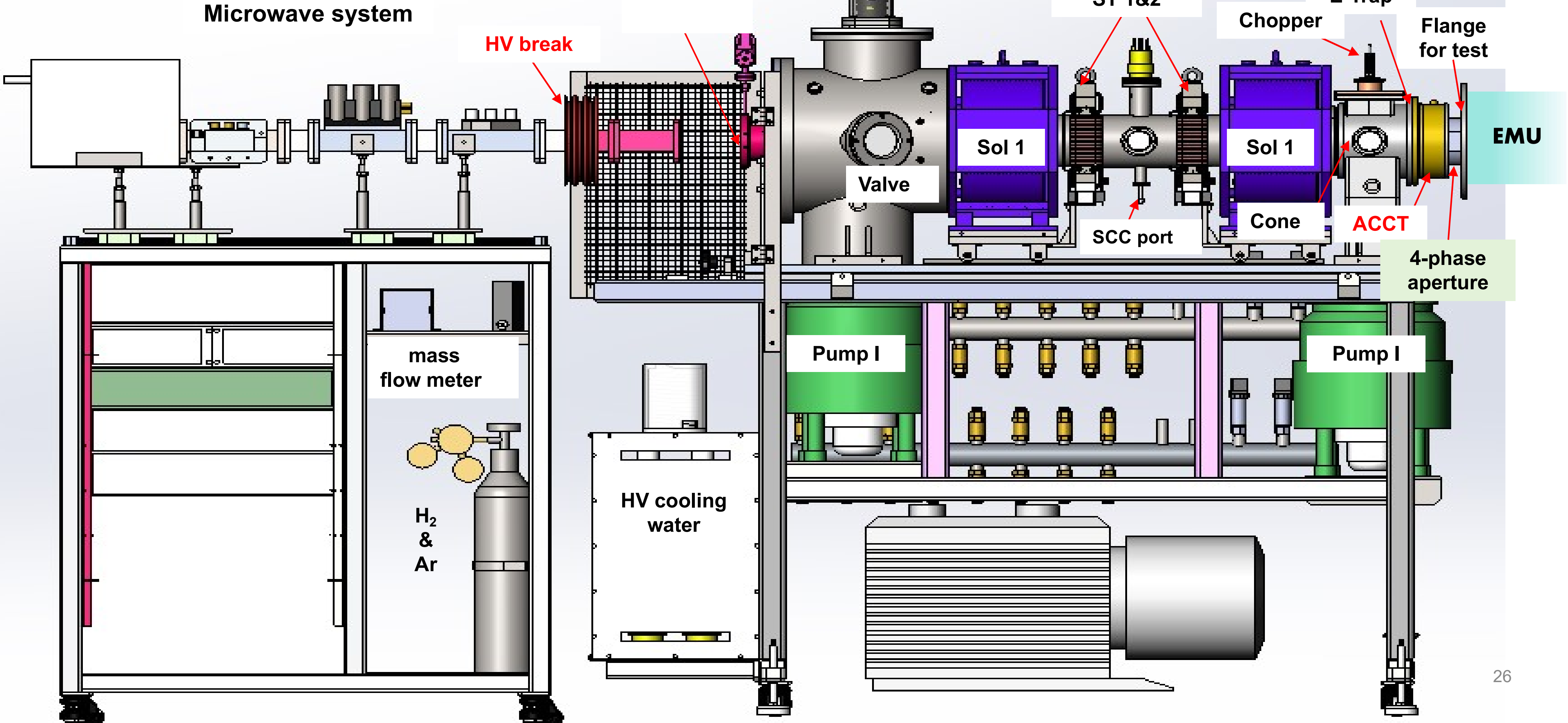
The total length of acceleration section (RFQ+ DLT) is 6.1 m when the output energy reached 3.0 MeV with the operation frequency of 165 MHz.

➢ Parameter at the entrance of RFQ

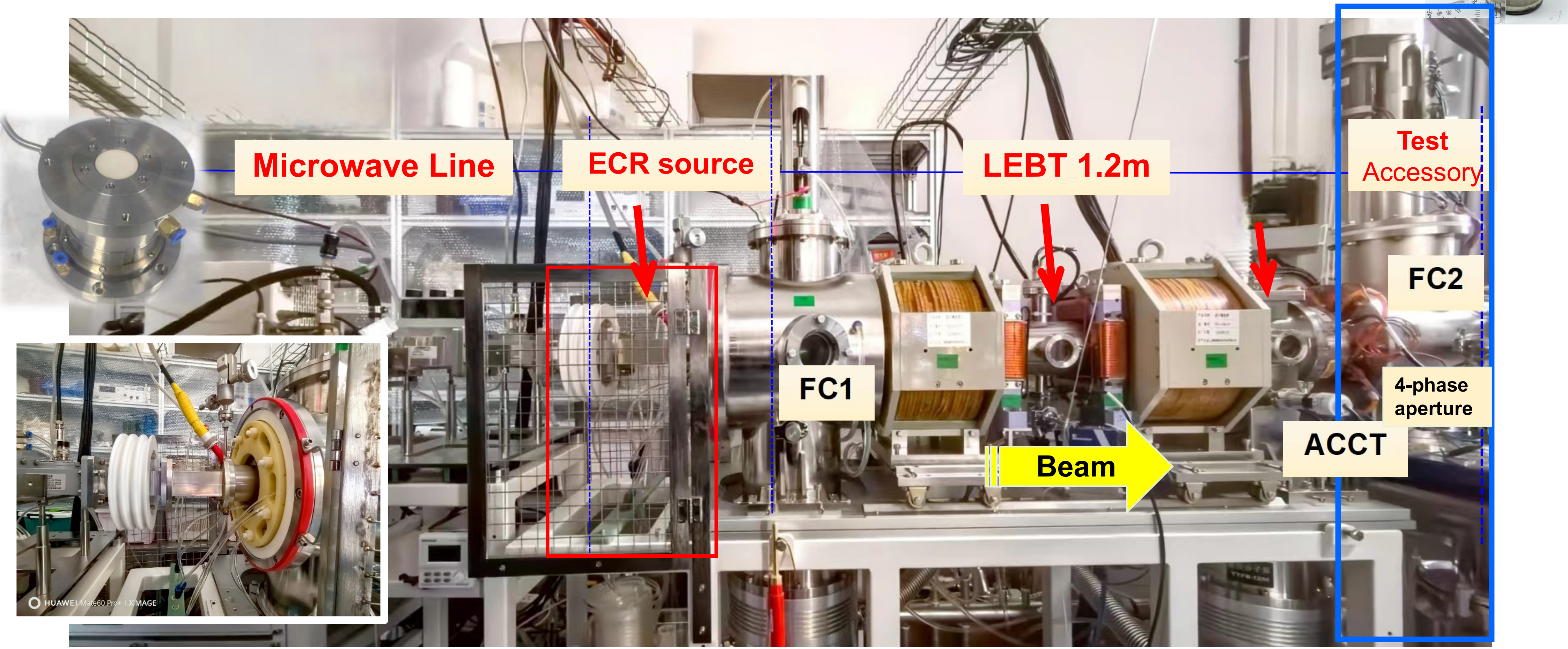
Content	Parameter	Method
Particle	Proton	H_2
Operation mode	CW (rare)	CW & Long Pulsed: Microwave power Short Pulse: Plus Chopper
	Pulse: 1~500Hz, 200Hz specific, 0.5%~100%, pulse length >200 μs	
Energy	40 keV	Well water-cooled three- electrode extraction system
Beam Current	> 30 mA	PKU standard PMECR ion source(SMIS)
Normalized rms emittance at LEBT exit	< 0.20 π mm·mrad	
H+ fraction	> 80%	
Stability	24h	
Twiss parameter at RFQ entrance	α=1.484, β=5.622cm/rad	Two solenoids LEBT + SCC
Mismatching degree of TWISS parameter	< 30%	
Raise/Full edge	< 1ms	



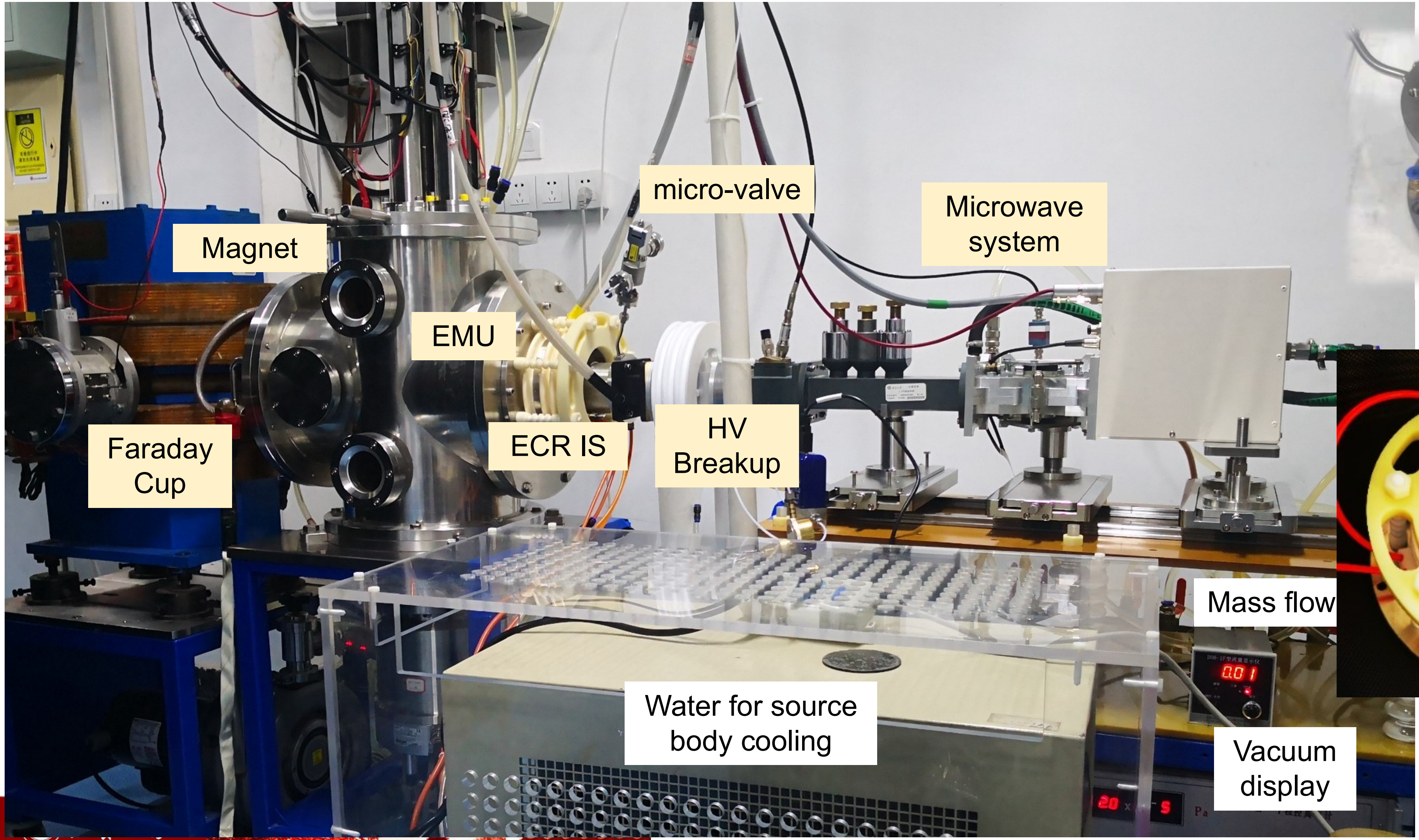
➢ A screenshot of H^+ injector

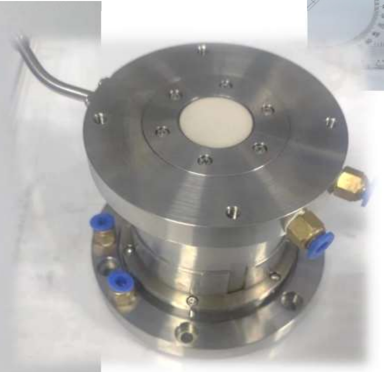


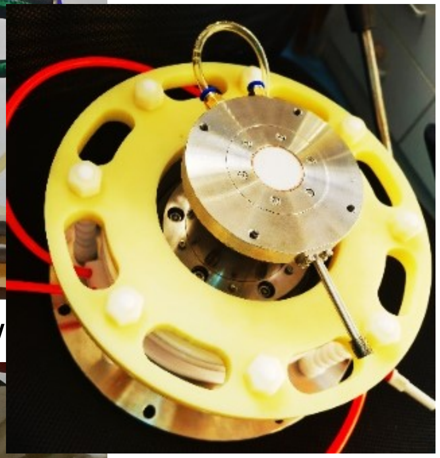
➢ A Photo of AB-BNCT H^+ Injector



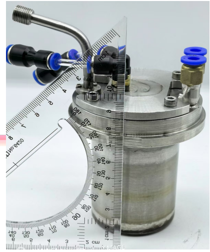
➢ The Performance of AB-BNCT SMIS







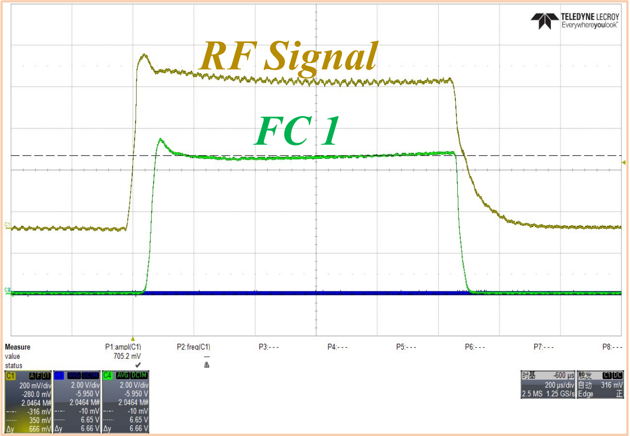
➢ The Performance of PMECR Ion source at 200 Hz



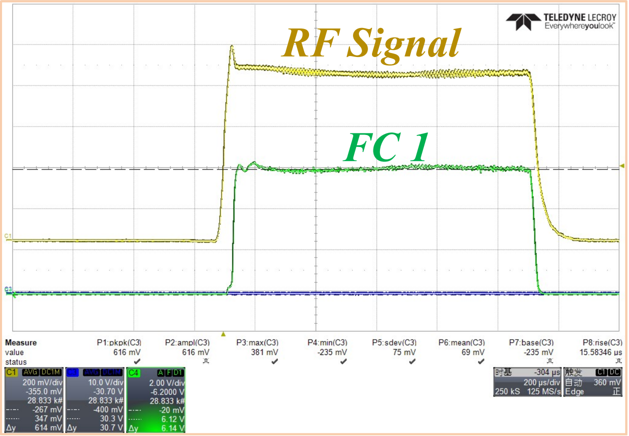
Duty factor[%]	Total Current[mA]	H^+ faction[%]	Emittance[π·mm·mrad]
10	62	91	0.092
100Hz/10%	60	91	0.094
20	61	90	0.093
30	66	86	0.103
40	64	94	0.103
50	61	85	0.105
55	62	87	0.105
60	58	83	0.107
70	56.6	86	0.106
75	53.6	86	0.106
80	51	84	0.106
85	50	83	0.107
90	51	85	0.106
95	51	87	0.110
100	58	85	0.112

➢ The Performance of PMECR Ion source at 200 Hz

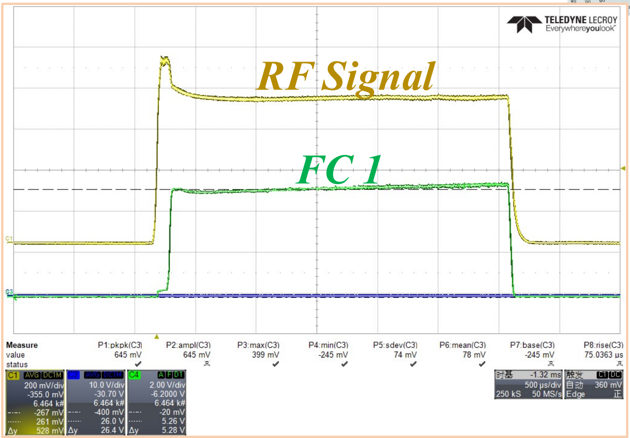
Duty Factor: 10%， I_T: 66mA, H^+: 91%



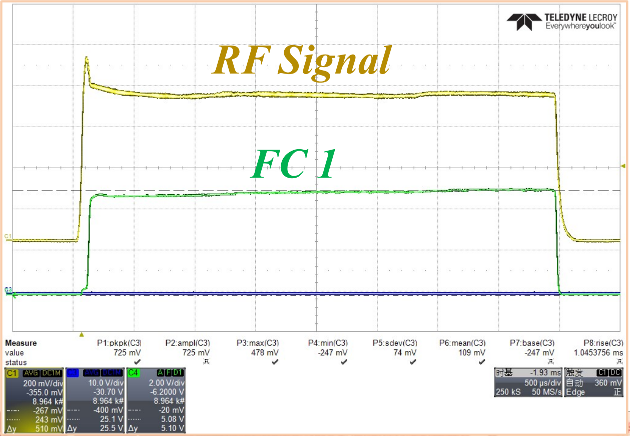
Duty Factor: 20%， I_T: 61mA, H^+: 90%



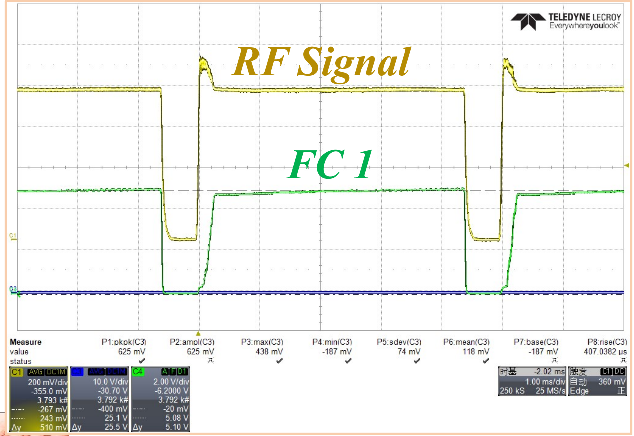
Duty Factor: 60%， I_T: 53mA, H^+: 83%



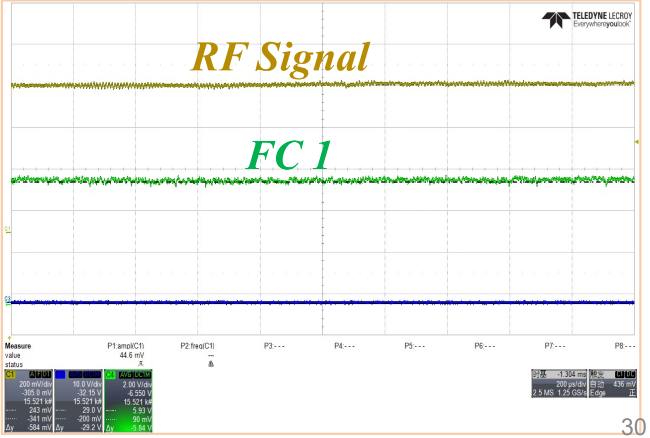
Duty Factor: 80%， I_T: 51mA, H^+: 85%



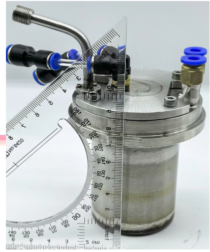
Duty Factor: 95%， I_T: 51mA, H^+:87%

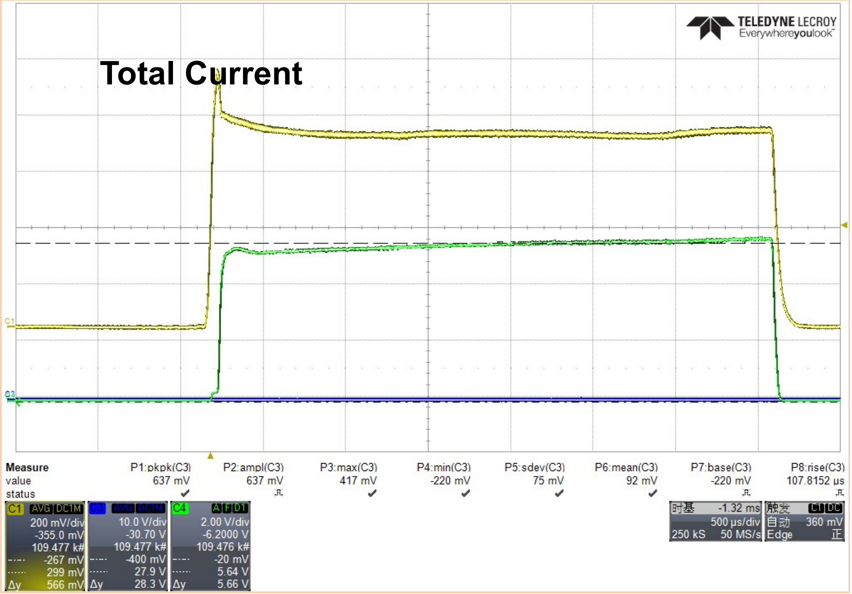


CW beam， I_T: 58mA, H^+:88%



➢ An example of species measurement results, 200Hz / 70%





Operation Parameter:

Gas flow: 2.7sccm

Peak RF power: 1470W

Yellow line: Microwave signal

Green line: Total current

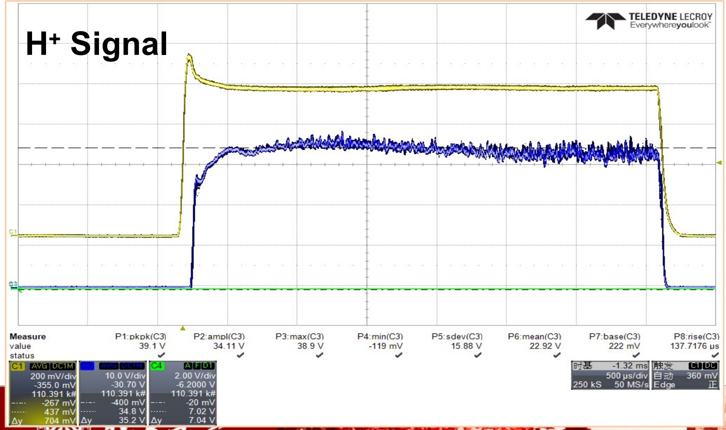
Blue line: Ion species

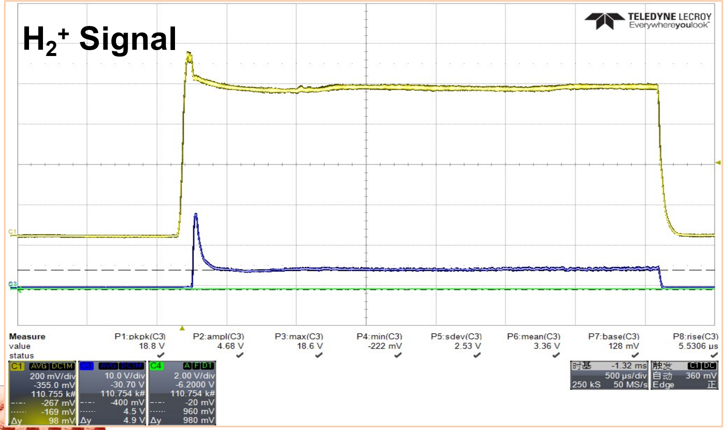
Result:

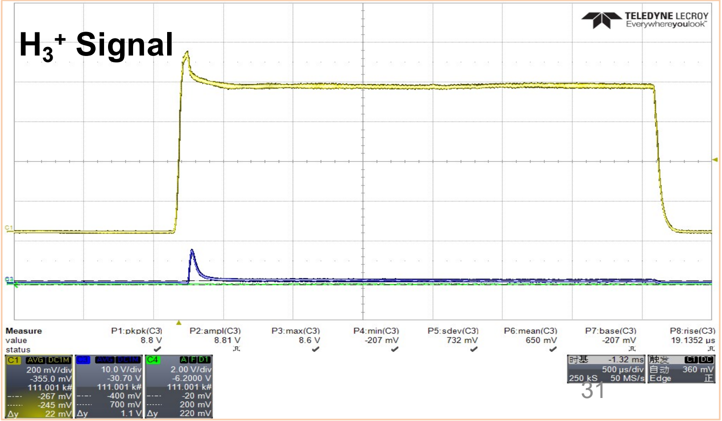
Total current: 56.6mA(above)

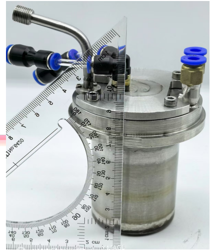
$H^+:H_2^+:H_3^+ = \mathbf{85.4\%}:11.9\%:2.7\%$

H^+ current: 48mA

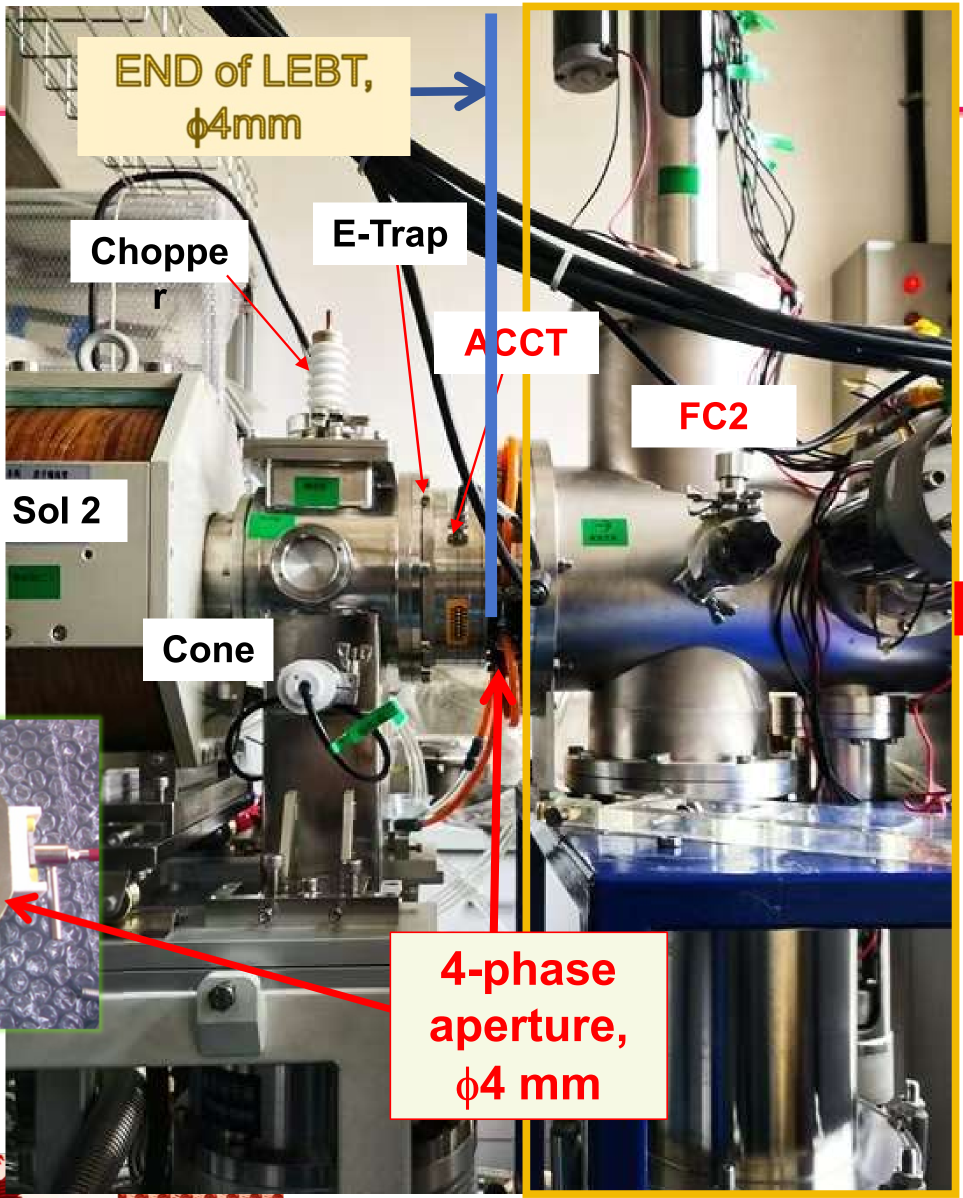


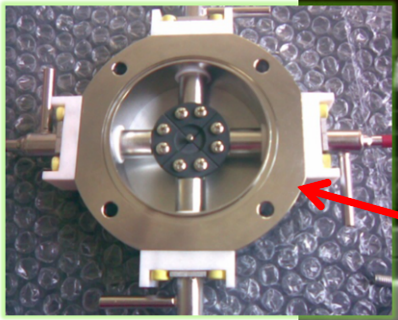






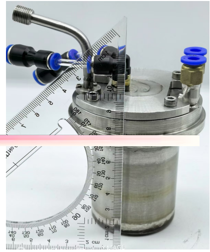
Accessory for LEBT tests





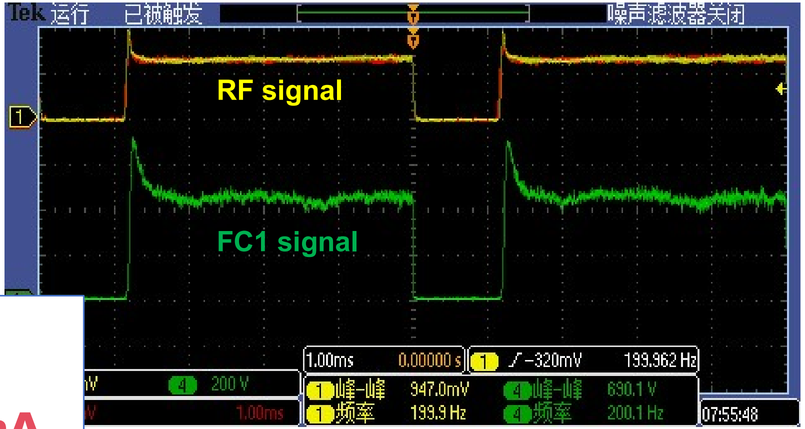
EMU (Slit-grid emittance measurement unit).

- ◆Total beam current
- ◆Beam profile
- ◆Emittance
- ◆TWISS parameters



➤ Beam currents before/after RFQ entrance plane(H⁺ Injector)

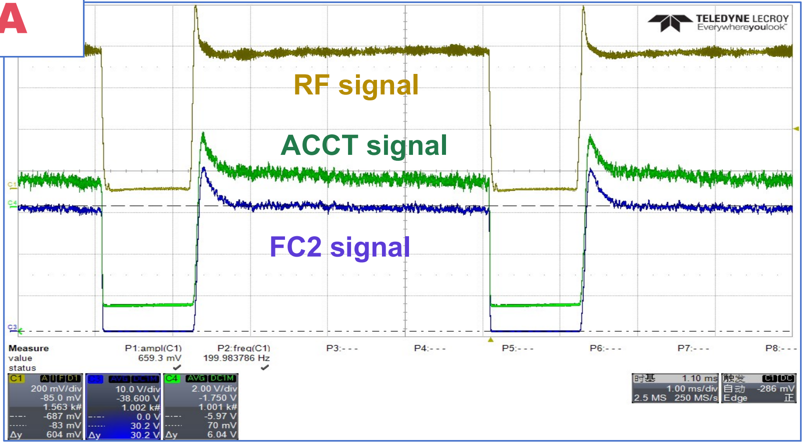
200Hz / 70%



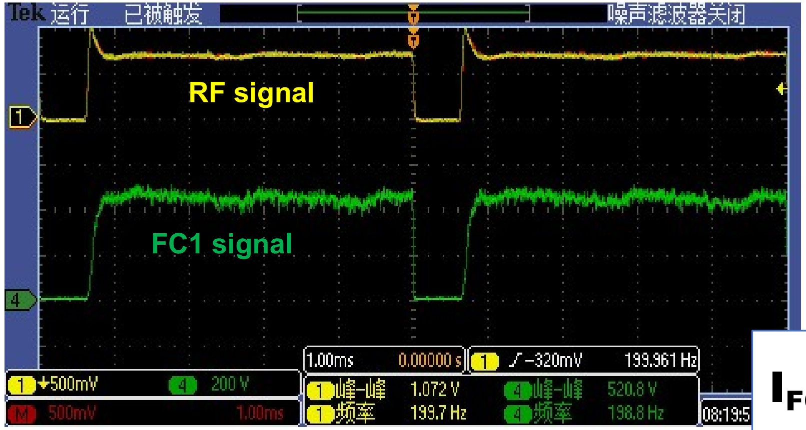
I_{FC1}:41m

I_{ACCT}: 30mA

I_{FC2}: 30mA



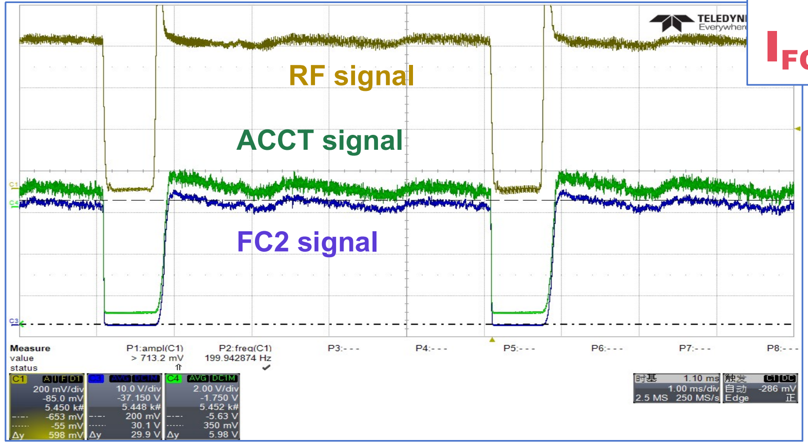
200Hz / 90%



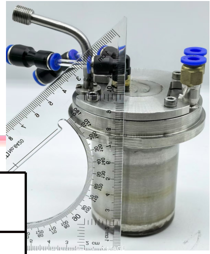
I_{FC1}:41m

I_{ACCT}: 30mA

I_{FC2}: 30mA

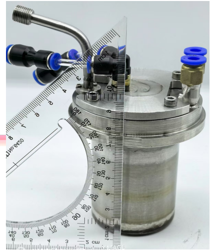


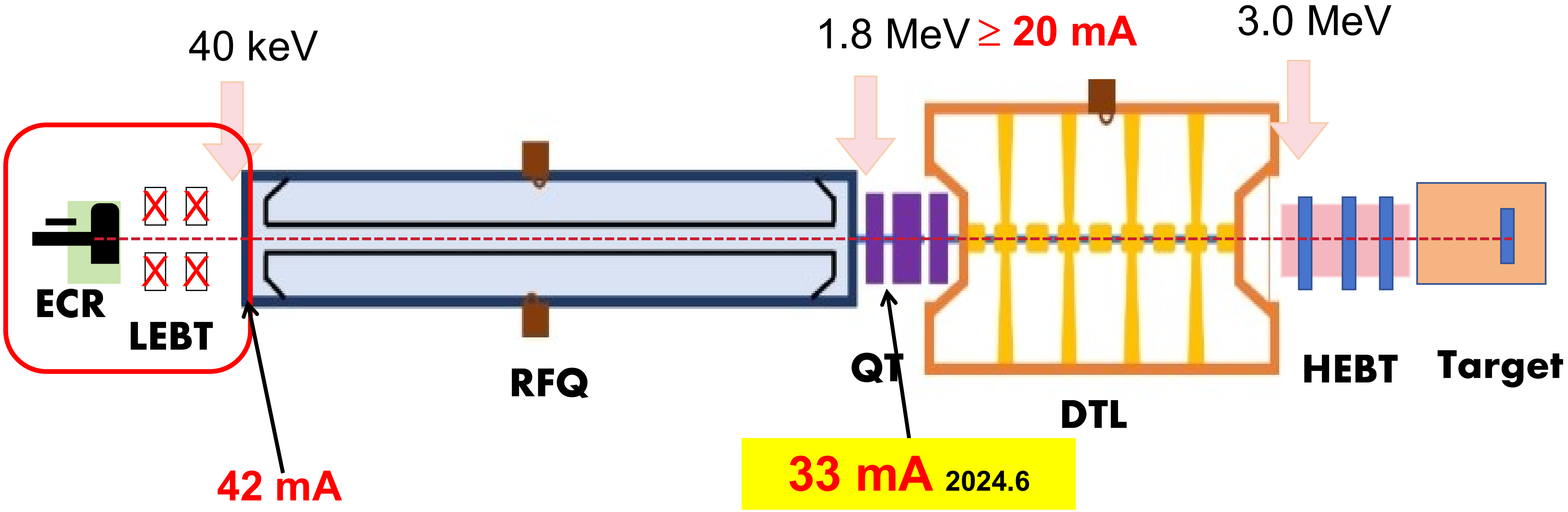
➢ TWISS Parameters at 10% and 80%



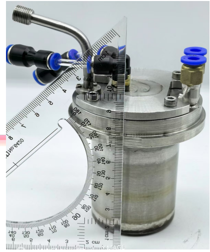
RF power	1250W/200Hz/**10%**				800W/200Hz/**90%**			
Gas Inlet	1.8 sccm				1.8 sccm			
Voltage PE/SE	40kV/-2kV				40kV/-2kV			
Slolenoids	1#： 140A		2#： 186A		1#： 140A		2#： 186A	
Steering Mangnet	1#： 0A	2#： 2A	3#： 0A	4#： 0A	1#： 0A	2#： 3A	3#： 0A	4#： 0A
Current	FC1		76 mA		FC1		44 mA	
	ACCT		58 mA		ACCT		30 mA	
	FC2		58 mA		FC2		29 mA	
rms emittance	0.1029 π mm×mrad				0.1156 π mm×mrad			
Twiss at EMU	α_2		-5.587		α_2		-5.267	
	β_2		0.7032 m/rad		β_2		0.688m/rad	
Twiss at RFQ entrance	α_1		1.285		α_1		1.128	
	β_1		0.05788 m/rad		β_1		0.08971m/rad	
Mismachting degree	*12.7%*				*18.2%*			

➢ Primary result at RFQ exit, June 2024





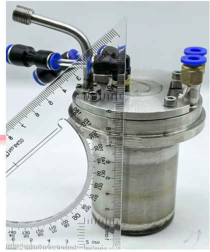
NO SPARK comes up untill now!

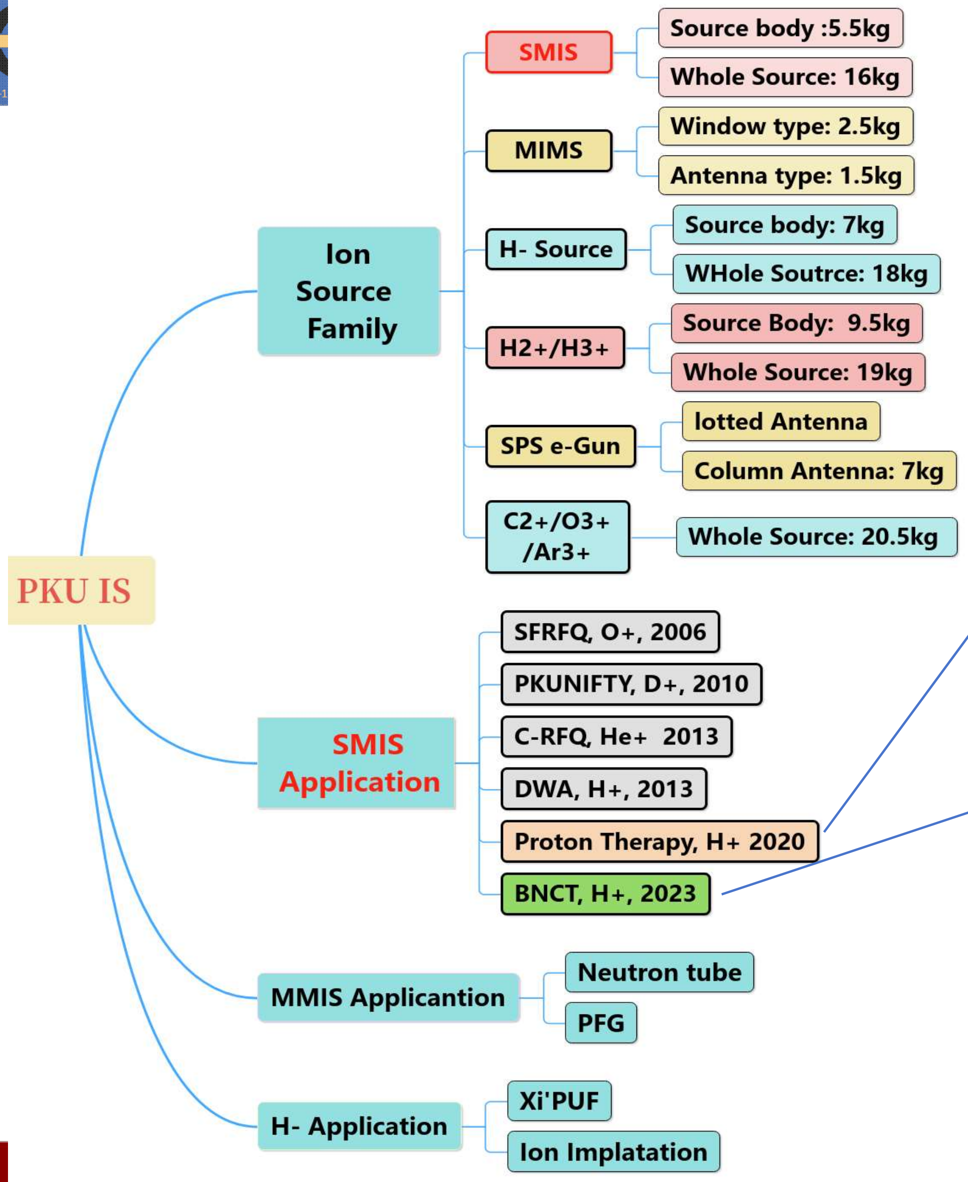


Outline

1. 2.45GHz Microwave Driven Ion Source Family at PKU
2. Why Named as Microwave Driven Ion Source
3. The LINAC Commissioning Results of PT Facility
4. CW/pulsed Proton Injector for AB-BNCT Machine
5. **Summary and Outlooks**

5. Summary and Outlooks





March 2023

DTL:14.4mA/7MV!

The results is much better than the machine wanted 12mA.

June 2024

RFQ:33mA/1.8MV!

The results is much better than the machine wanted 20 mA.

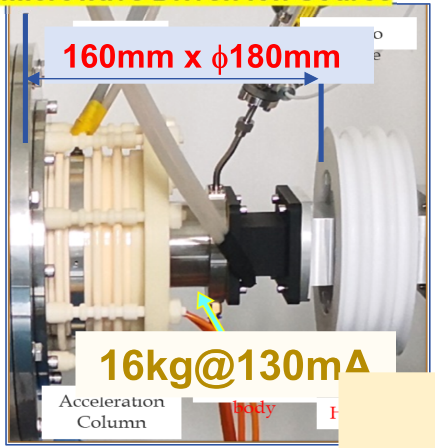
Near future

A New more Compact CW Ptoton Injectors will be built for dynamitron type LINAC for BNCT.

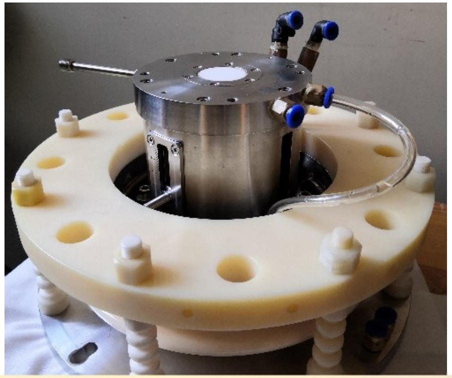
https://www.conveyi.com/en/

PKU 2.45GHz Microwave Driven Permanent Magnet Ion Source Family

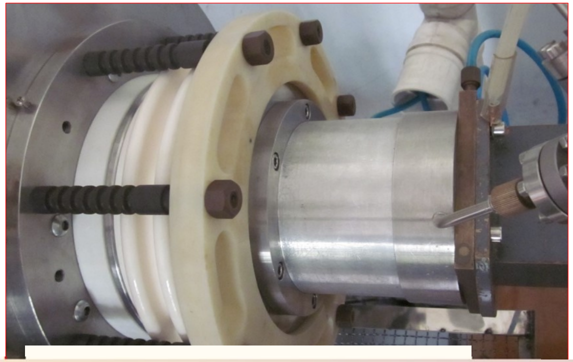
SMIS: PKU Standart Microwave Driven Ion Source



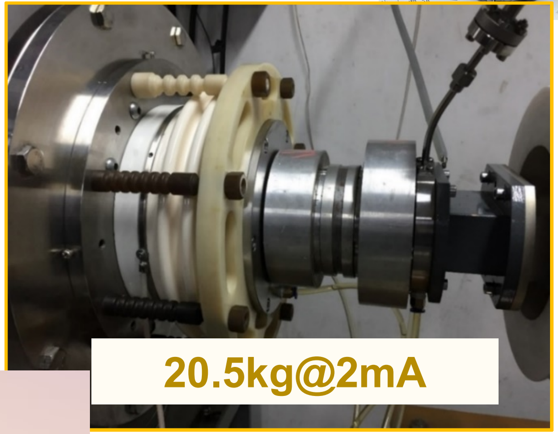
H⁻ Ion Source



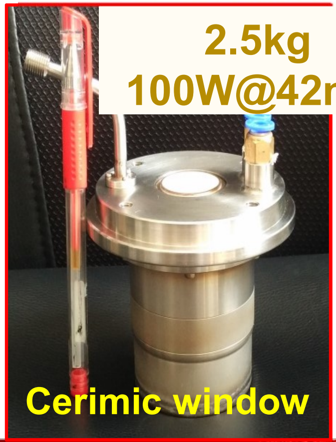
H_2^+/H_3^+ Ion Source



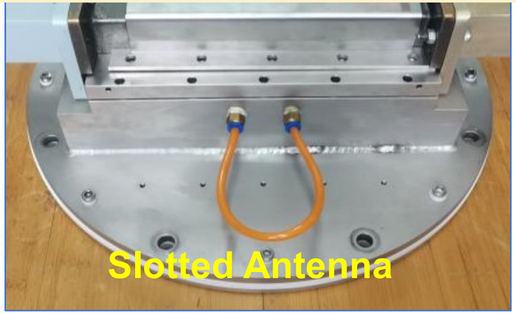
C^{2+} /O^{3+} ion Source

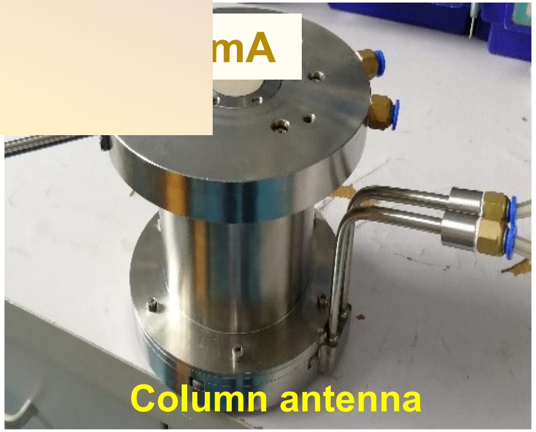


MMIS: PKU Miniaturize



on machine





Thank you for your attention!

感谢您的关注！