Ion sources used for neutron production developed at CSNS

Weidong Chen

CSNS accelerator front-end group

Nov. 1st, 2023

Outline

- Neutron production processes
- Ion sources developed in CSNS
    - Penning ion sources
    - RF-driven H- source
    - Electron Cyclotron Resonance (ECR) ion source
    - Hollow-cathode ion source
- Summary and outlook

Neutron production processes

Fusion/Fission used for neutron production

Exothermic reaction

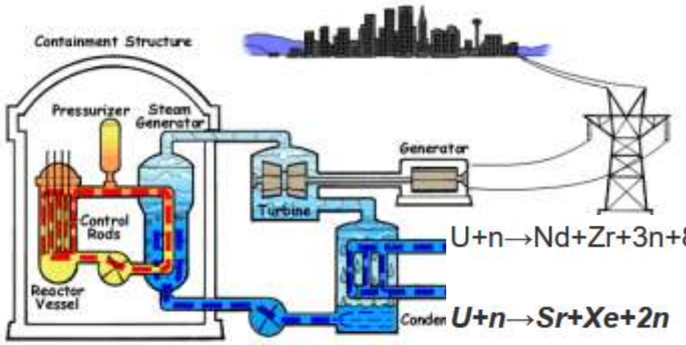
$D + D \rightarrow p + T + 4.032\text{MeV},$

$D + D \rightarrow n + {}^{3}\text{He} + 3.266\text{MeV},$

$D + T \rightarrow n + {}^{4}\text{He} + 17.586\text{MeV}.$

D^{+}/D^{-} soure required.

Reactor

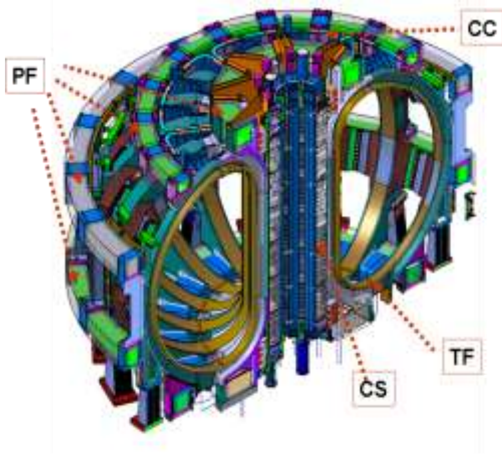


U+n→Nd+Zr+3n+8e

U+n→Sr+Xe+2n

U+n→Ba+Kr+3n

Confined Fusion



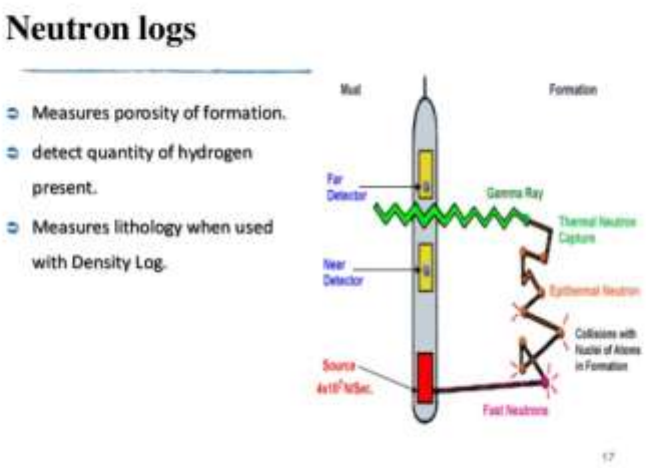
Endothermic reaction

${}^{7}_{3}Li + {}^{1}_{1}H \rightarrow 2\times {}^{4}_{2}He$

${}^{7}_{3}Li + {}^{1}_{1}H \rightarrow {}^{7}_{4}Be + n$

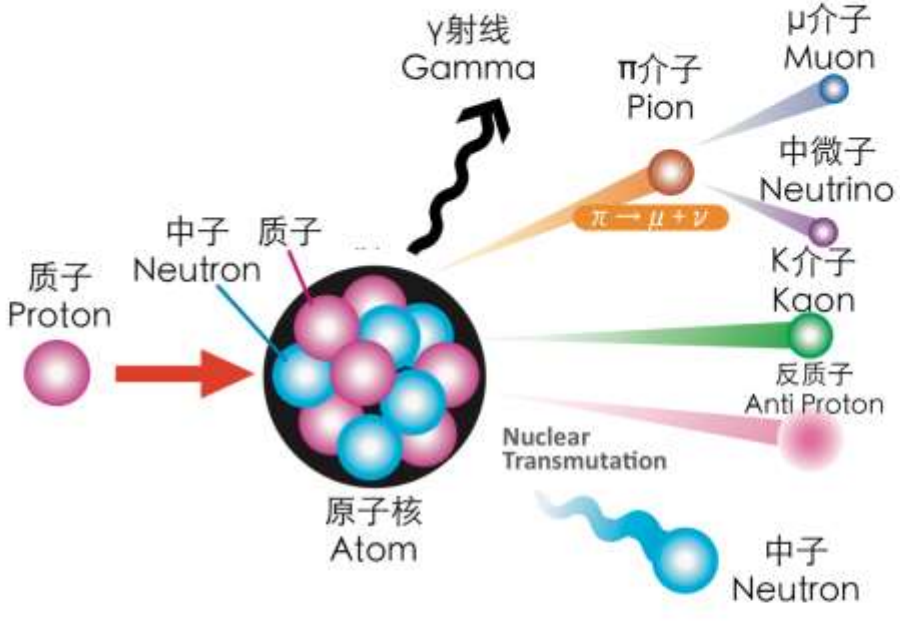
${}^{9}_{4}Be + {}^{1}_{1}H \rightarrow {}^{9}_{5}B + n$

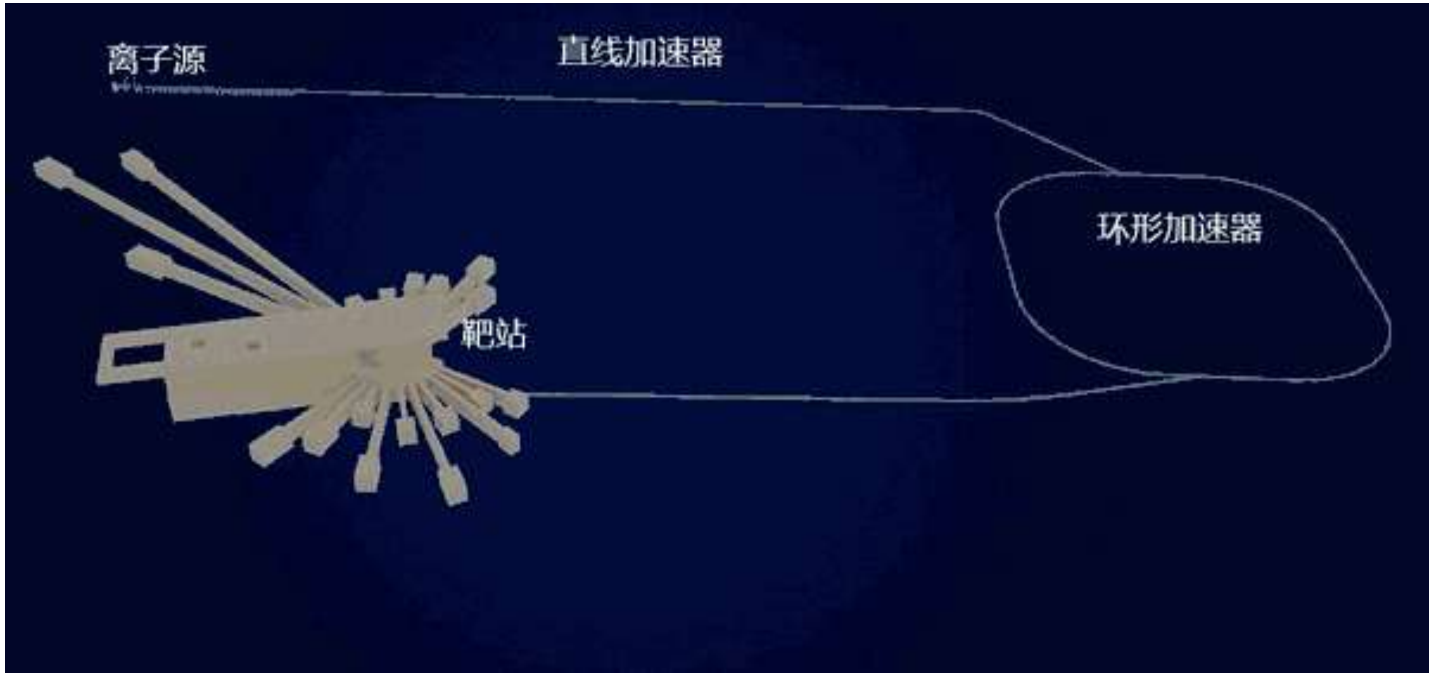
p/H^{-} source required.



Neutron production processes

Spallation





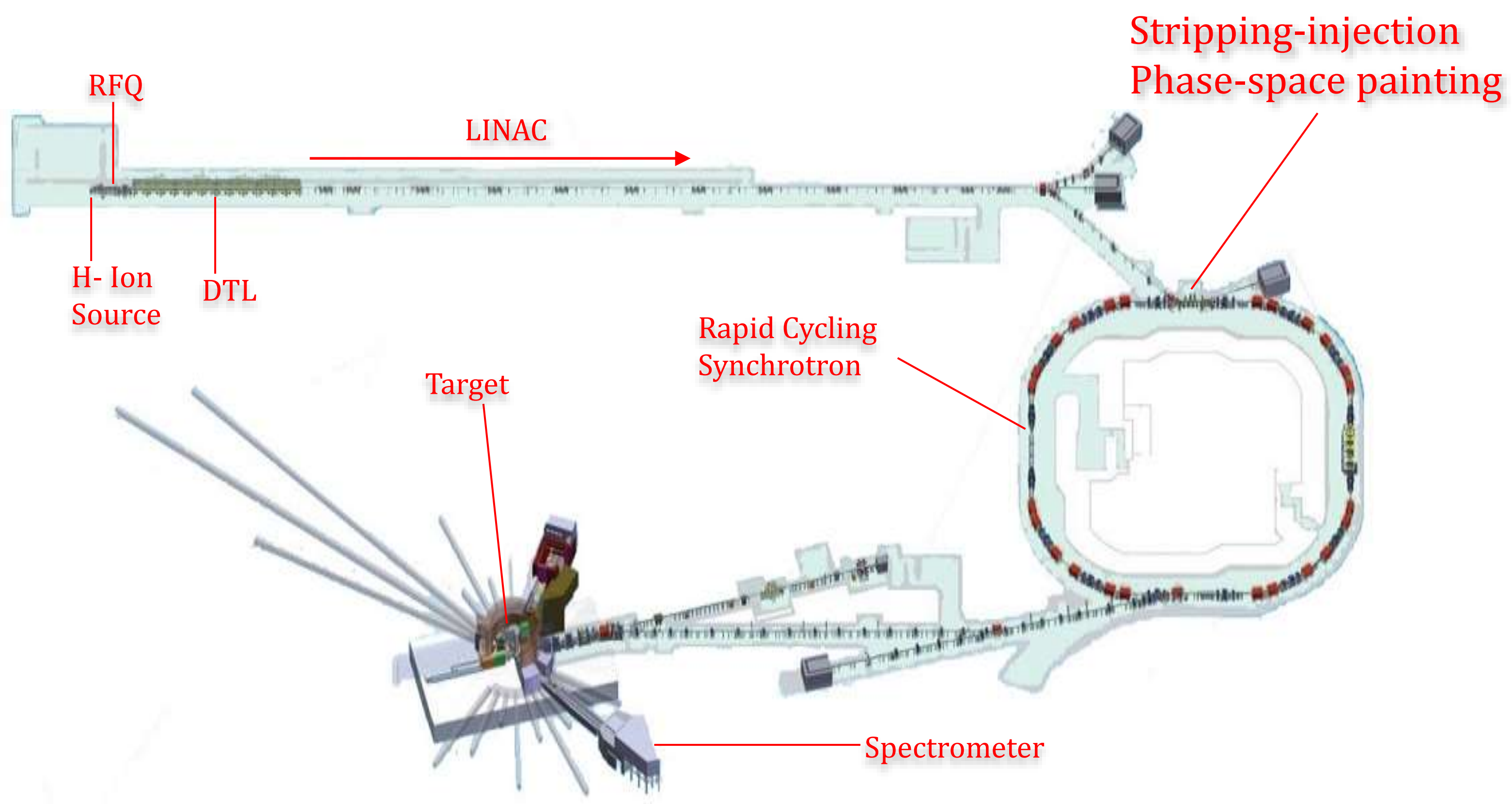
One proton with energy of 1.6 GeV bombarding on W target can produce 30~50 neutrons.

p/H^- source required.

China spallation neutron source

Beam-power=Current × Energy × Pulse-width × Repetition × Chopping factor

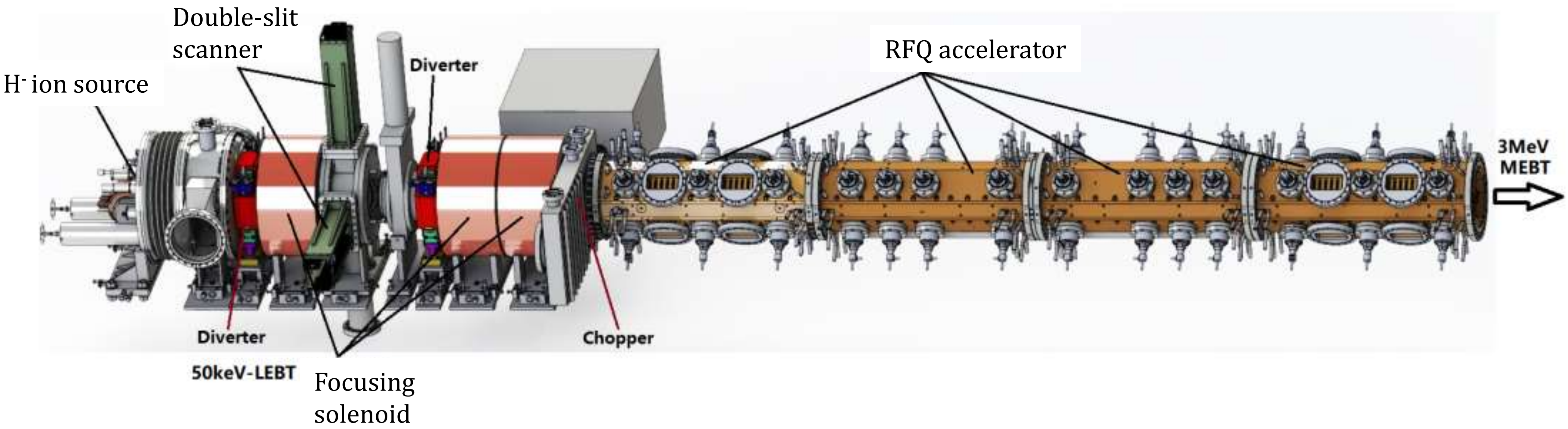
500 kW | 40~55 mA | 1.6 GeV | 500-600 us | 25 Hz | 50-65%



Parameters	CSNS-I 2020	CSNS-II 2029
I.S. Current (mA)	>12	50~55
Repetition Rate (Hz)	25	25
Pulse-width (us)	415	500-600
Chopping Factor	42%	50-65%
LINAC Components	R.T.	R.T.+SC
LINAC-energy (MeV)	80	300
RCS-energy (GeV)	1.6	1.6
Beam Power (kW)	100	500

Penning ion source

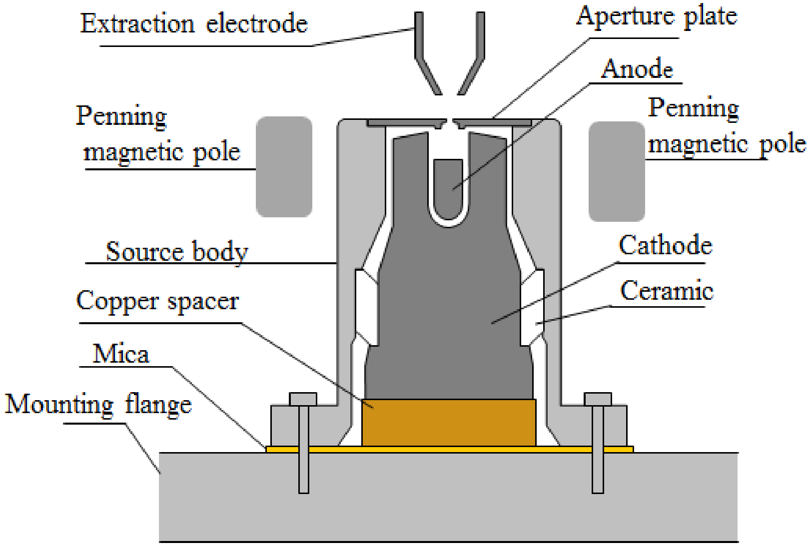
The front end of the CSNS accelerator



- The LEBT has 3 solenoids, initially designed for the former penning ion source.
- The penning source has been replaced by RF-driven H^- ion source in Sep. of 2021.
- The ion source produces 37~42 mA, and throttled to 12 mA by a collimator before RFQ.

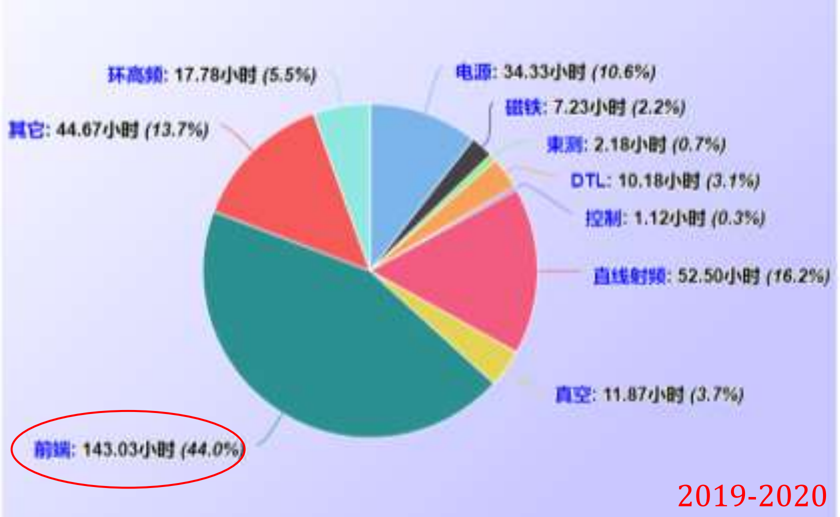
Penning ion source

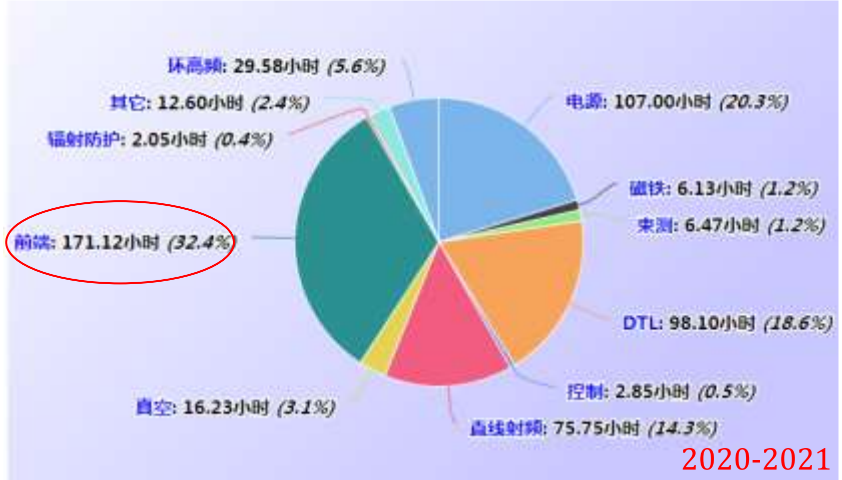
Structure of the penning ion source
A clone of ISIS ion source



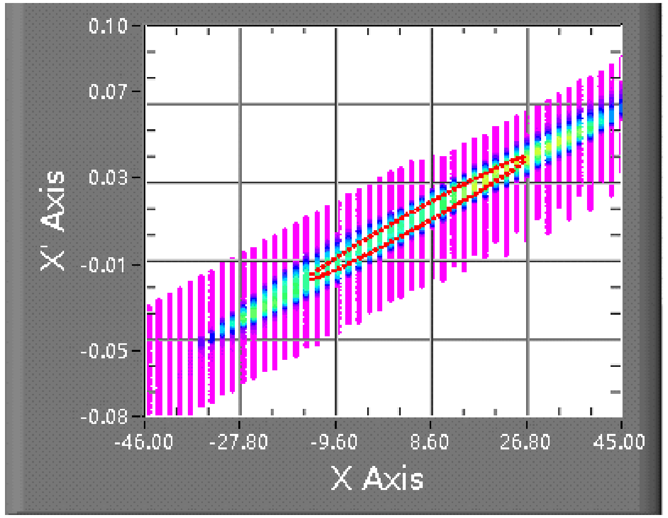
Maximum current: 50~60mA,
Pulse width: 500us,
Repetition rate:25Hz,
Life time: 4~6 weeks
RMS Emittance: ~0.8π •mm•mrad.
Less than 25 mA is within RFQ's acceptance

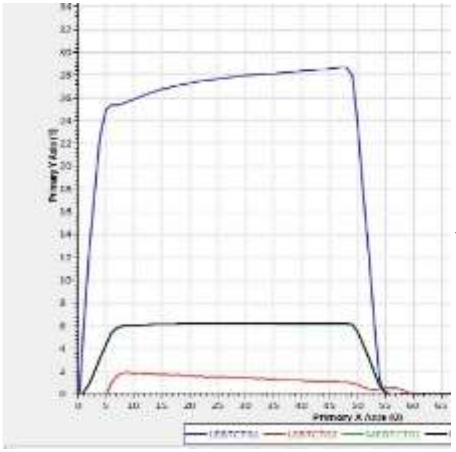
Percentage of accelerator breakdown time





Trans. Emittance- 0.8·π·mm·mrad

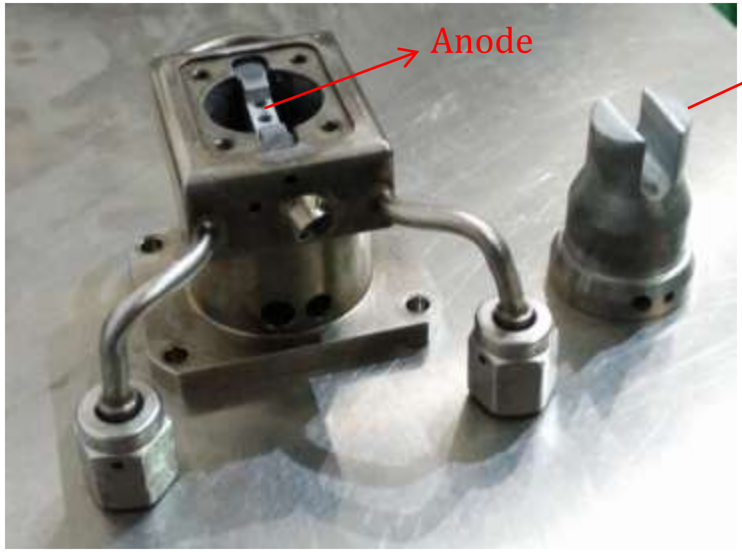


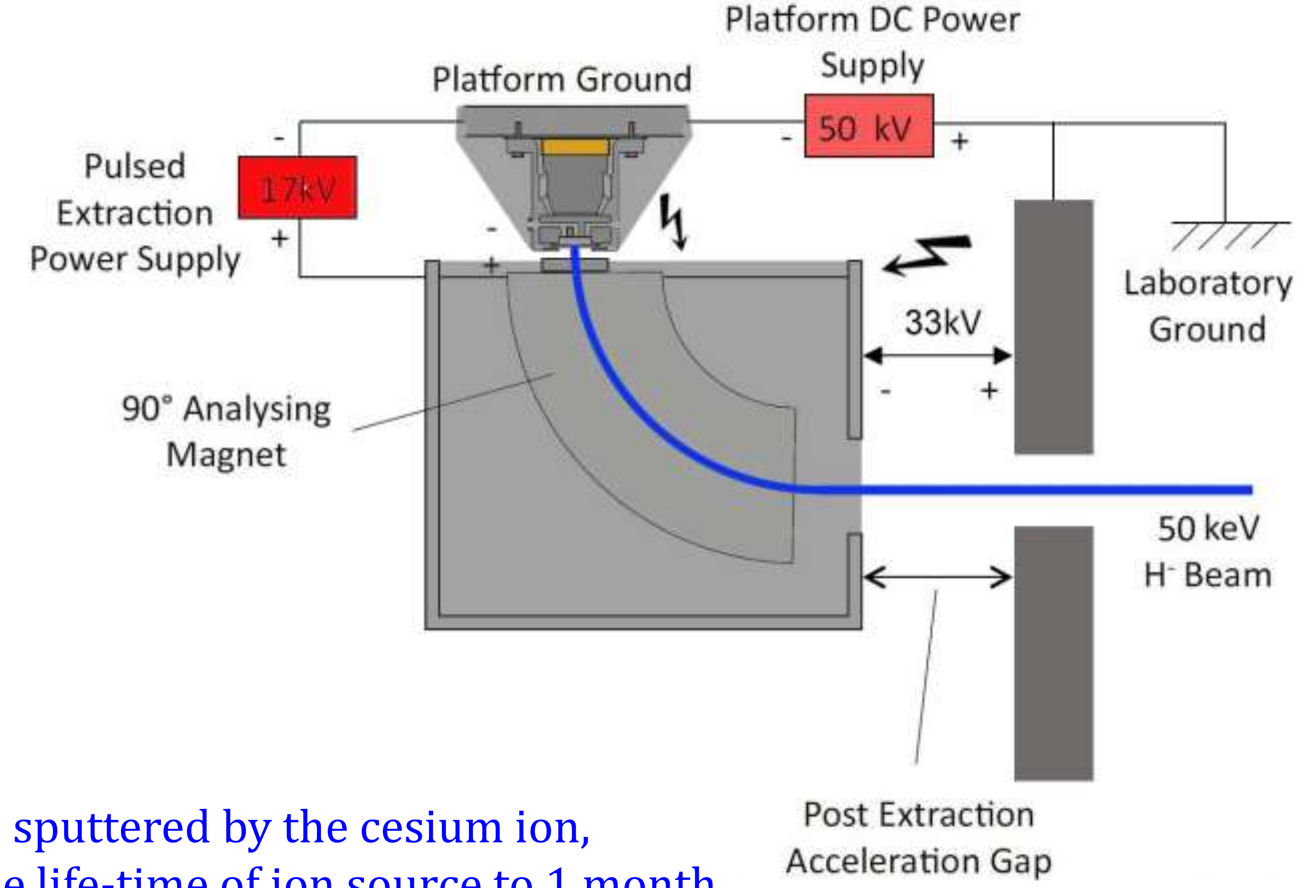


Waveform

Penning ion source

Cesium issues





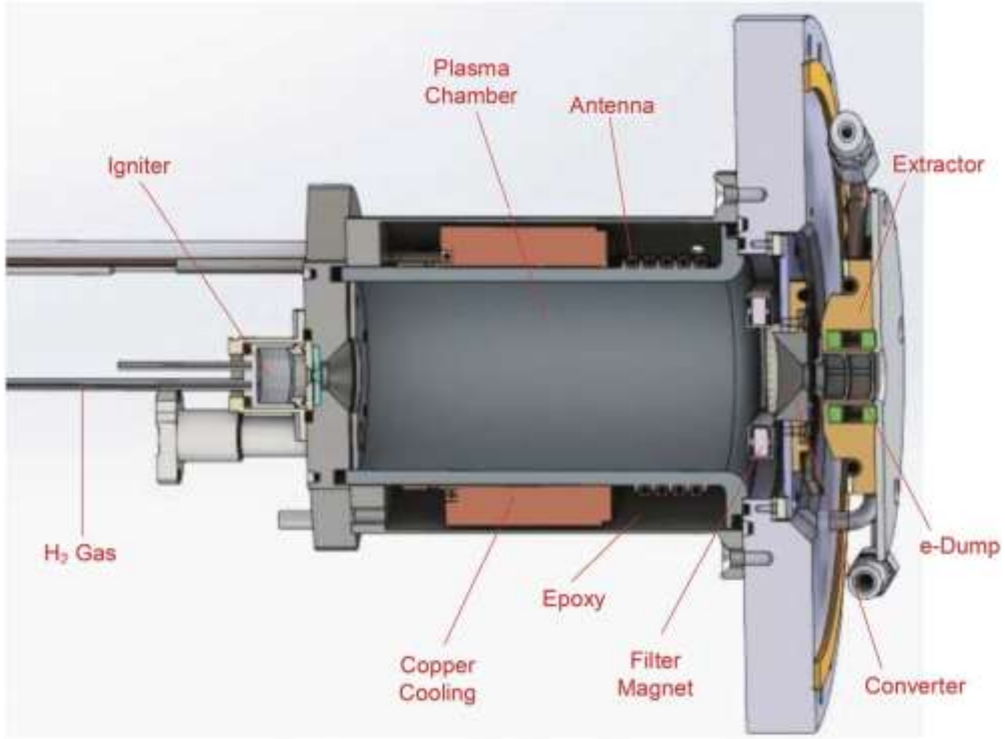
1. Cathode is sputtered by the cesium ion, limiting the life-time of ion source to 1 month.
2. Cesium vapor deposits on electrodes, causing HV sparks

Shengjin Liu， Chinese Physics C, 2014

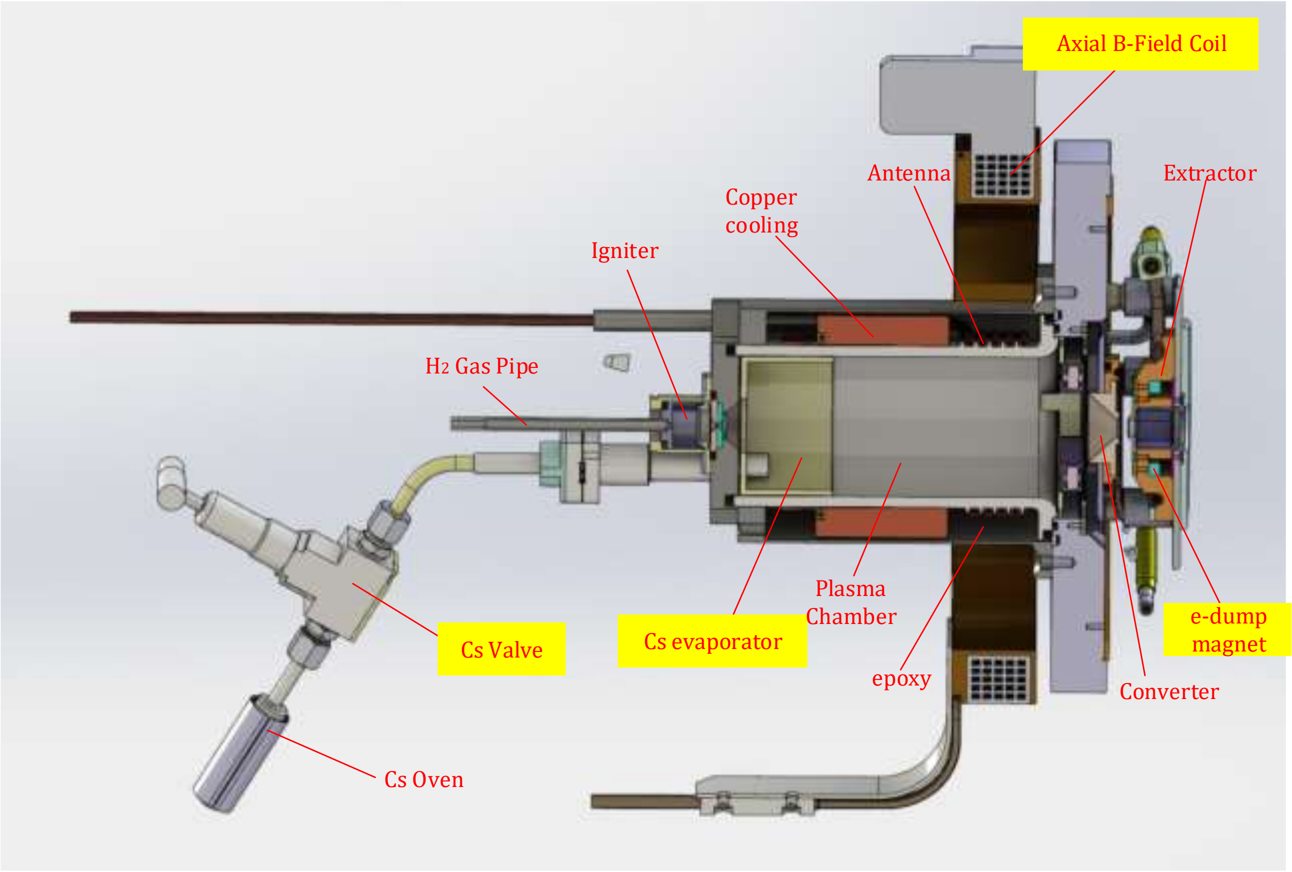
RF-driven H- ion source

- Silicon-nitride plasma chamber.
- Insulated by epoxy with high thermal conductivity.
- Glow discharge igniter in gas line.
- One pair permanent magnet for e-dumping (since 2021)
- Cs evaporator is used (since 2021, improved 2022)

- Axial B-field coil (since 2020)
- Cs injection system is used (since 2020).
- Remove cusp magnets (since 2021).



Ver2020



Ver2022

Details in *W. Chen et al 2023* ***JINST*** *18 P04030*

Why silicon nitride?

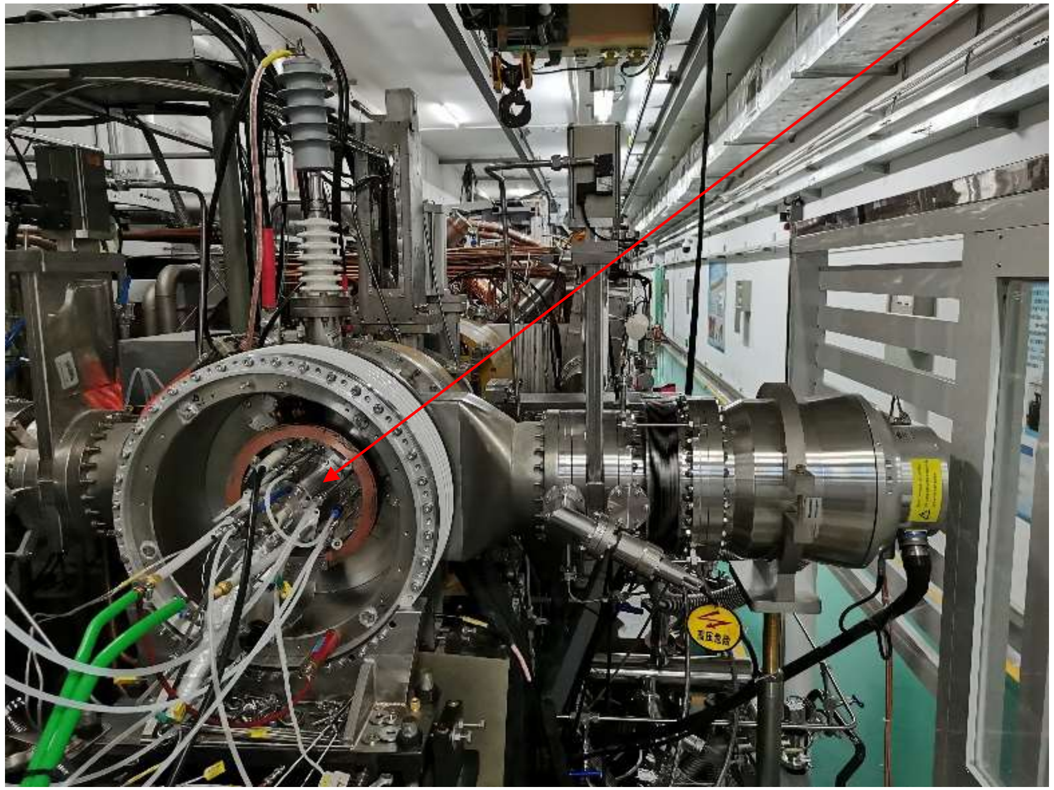
- High flexural strength (900 MPa)
- Relative high thermal conductivity (16~60 W/m.K)
- High heat shock (800 ℃)

Before epoxy filled

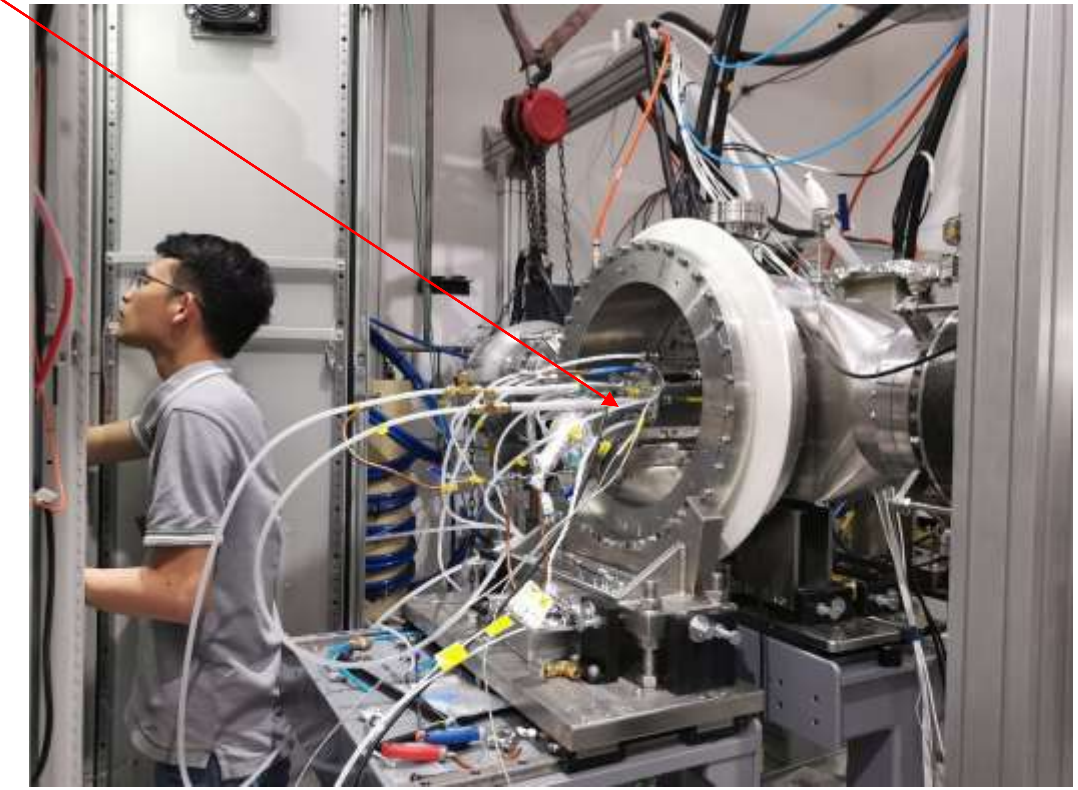
Al_2O_3 (left) and Si_3N_4 (right) plasma chambers for thermal and mechanical test

RF-driven H- ion source

RF-driven negative hydrogen ion source.



Old LEBT with 3-solenoids, **1.65 meters** in length, **used in accelerator tunnel.**

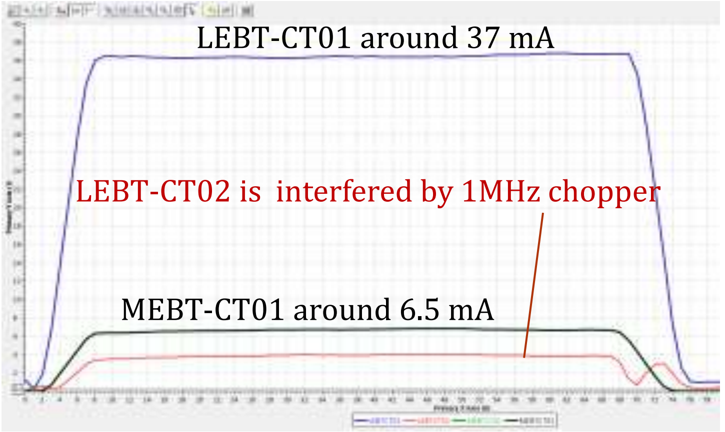


New LEBT with 2-solenoids, **0.8 meters** in length, **tested in the lab.**

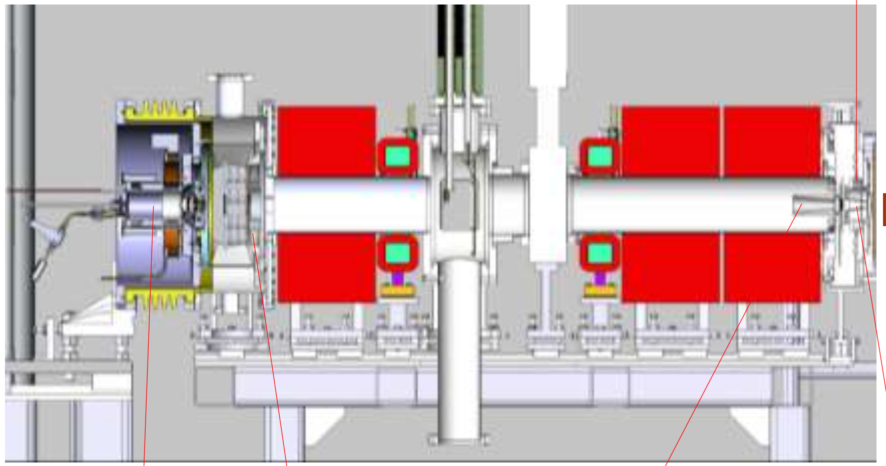
RF-driven H- ion source

Typical operation parameter for user service and experimental study

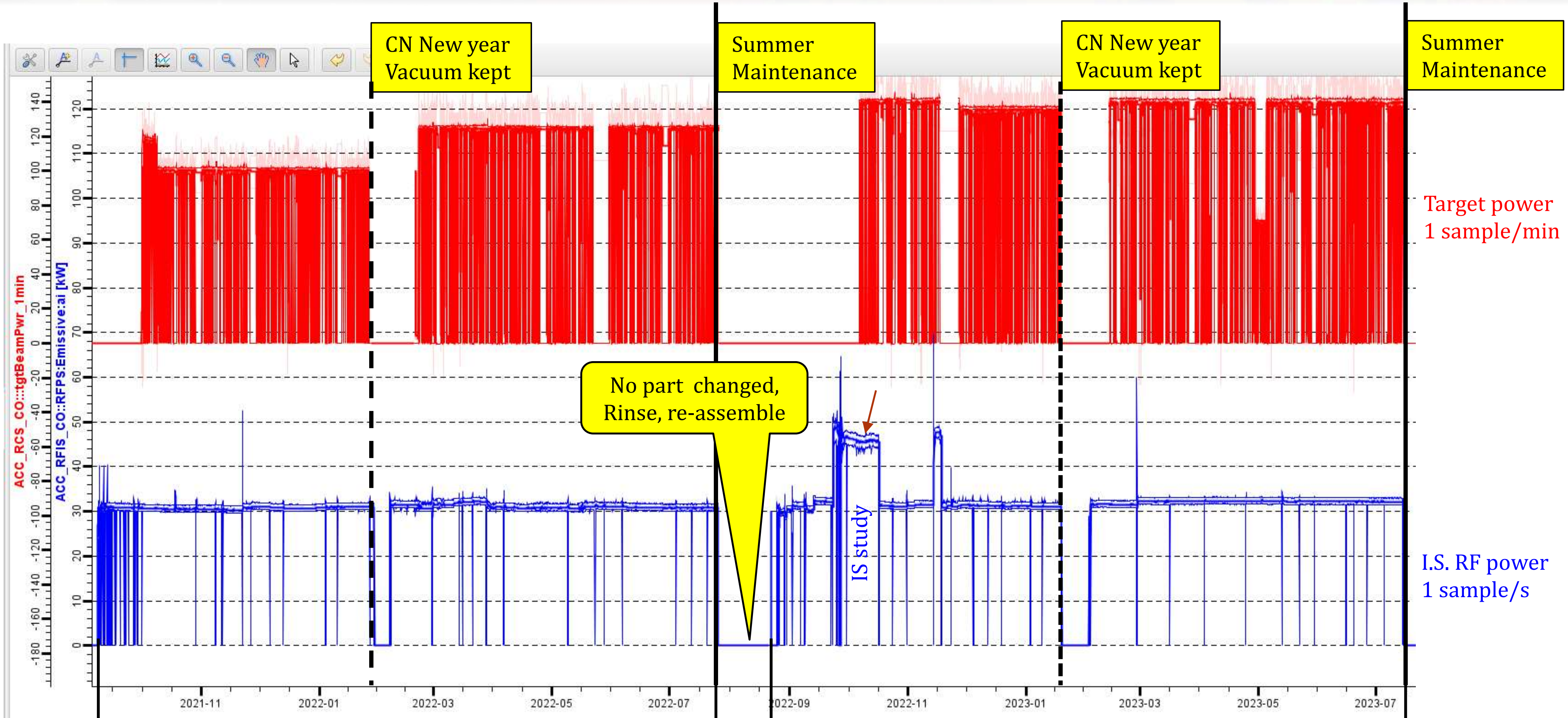
	CSNS service	Test bench study
Peak RF-power	31 kW	25~40kW
H2 flow rate	21 SCCM	18~24 SCCM
Repetition rate	25 Hz	25 Hz
Plasma pulse width	680 µs	500~1000µs
Beam pulse width	540 µs	100~600 µs
H- peak current	37 mA	50~60mA
Cs reservoir temp	80~87C	77~120°C
Service cycle	>7700 hours	
Beam energy	50 keV	50 keV
Norm. RMS emitt.	Not measured	<0.31π.mm.mrad



Typical current for 100 kW beam power operation



RF-driven H- ion source

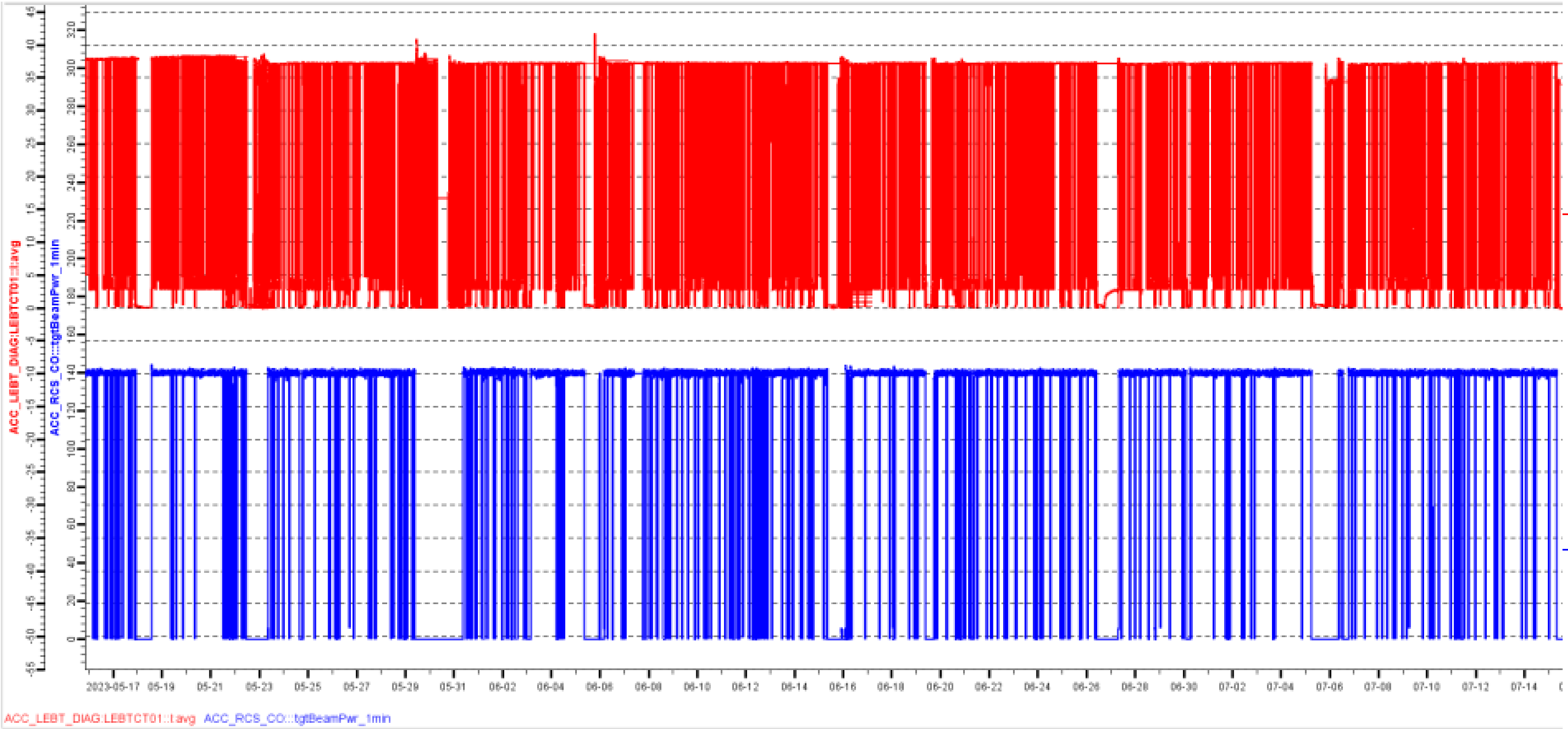


Ion source, 2021.9-2022.7 run cycle,
310 days accumulated, 100% availability

Ion source, 2022.8-2023.07 run cycle,
323 days accumulated, 100% availability

RF-driven H- ion source

The ion source runs unattended. The routine maintenance includes gas bottle replacement, 50 kV insulation cleaning, gas/water line inspection, H_2 purifier change, and plasma emission spectra check.



Ion source beam current and target beam power from *May 16th to July 15th 2023*.
When parameters reaches equilibrium in 30 minutes, the beam current output fluctuation is less than 1%.

Cesium consumption measurement

The ion source is dismounted during summer maintenance. It was disassembled into pieces. All of the parts (except the cesium injection system) were put into a big bucket filled with water to collect all of the cesium.

The concentration of cesium is 0.12%, measured with an ICP-MS.

2021.09~2022.07: 380mg cesium is used in ~310 days of operation, which is a little higher than expected. The cesium oven temperature was raised from 85 °C gradually to 120 °C in 3 months to compensate saturation of H_2 purifier.

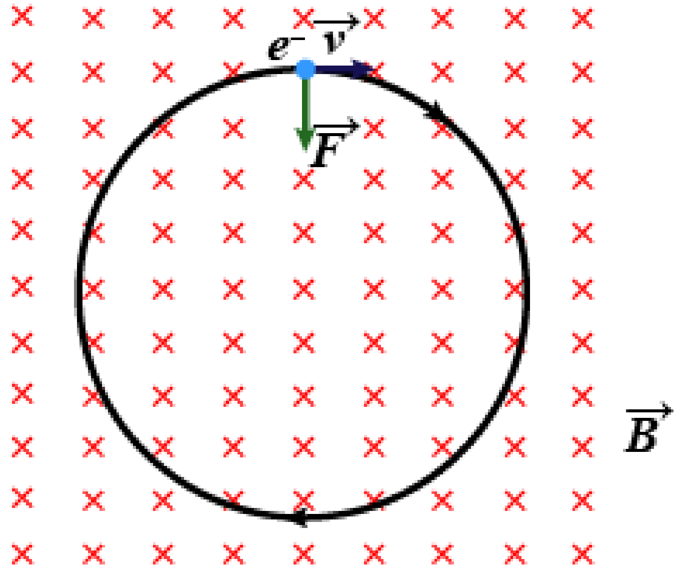
2022.08~2023.07: 97mg cesium is used in ~323 days of operation.

Cs^+solution

ICP-MS

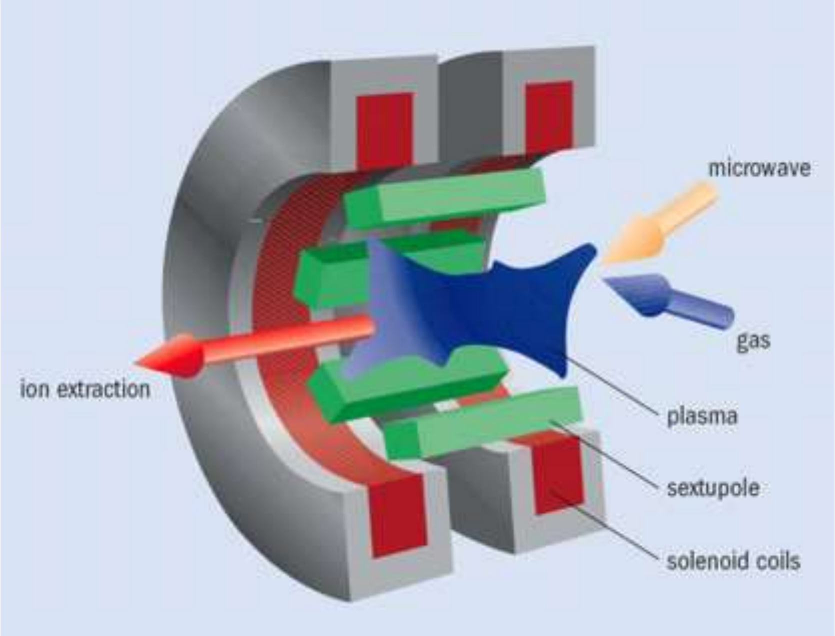
Plasma + mass spectroscopy

Electron Cyclotron Resonance Ion Source



$$qBv = ma \rightarrow \omega_e = \frac{qB}{m_e}\frac{1}{\gamma}$$

Microwave frequency
= *e* cyclotron frequency

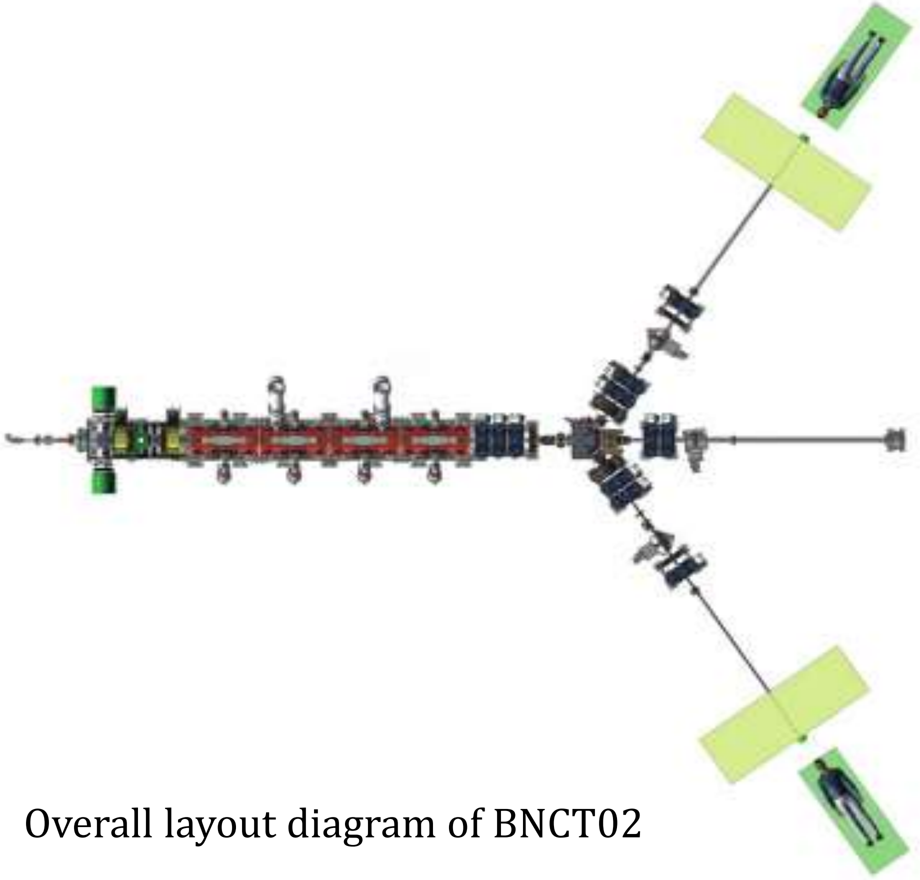


Advantage:

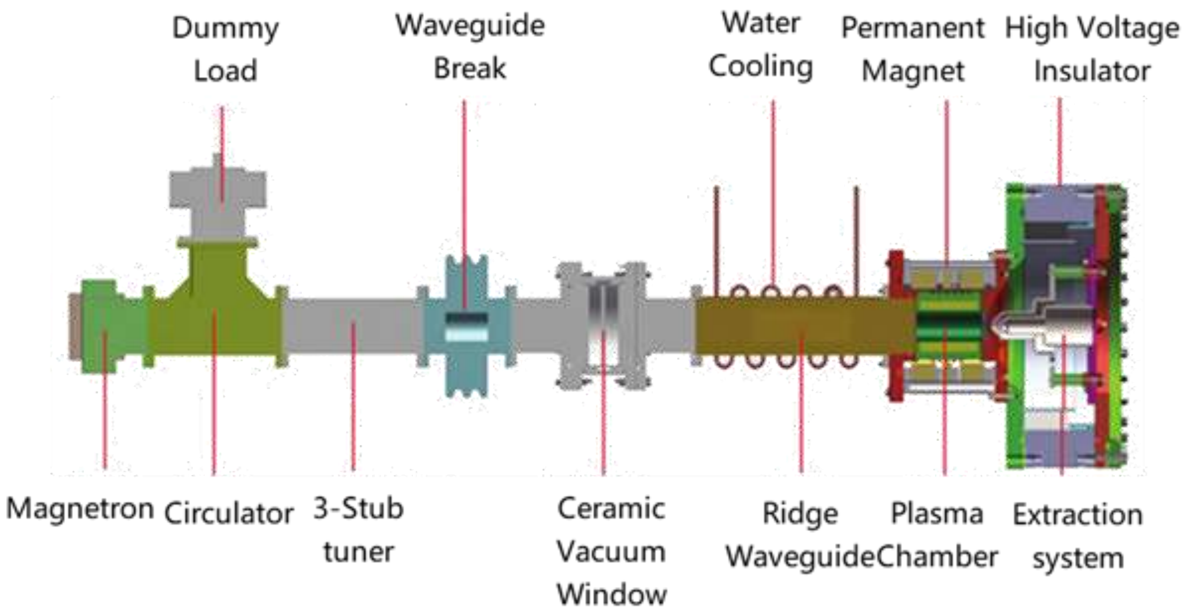
- stronger ion beams
- high-quality ion beams
- high production rates
- long lifetime
- cost-effective

Electron Cyclotron Resonance Ion Source

Electron Cyclotron Resonance Ion Source



Overall layout diagram of BNCT02



Schematic diagram of the ECR ion source structure for BNCT02

Electron Cyclotron Resonance Ion Source

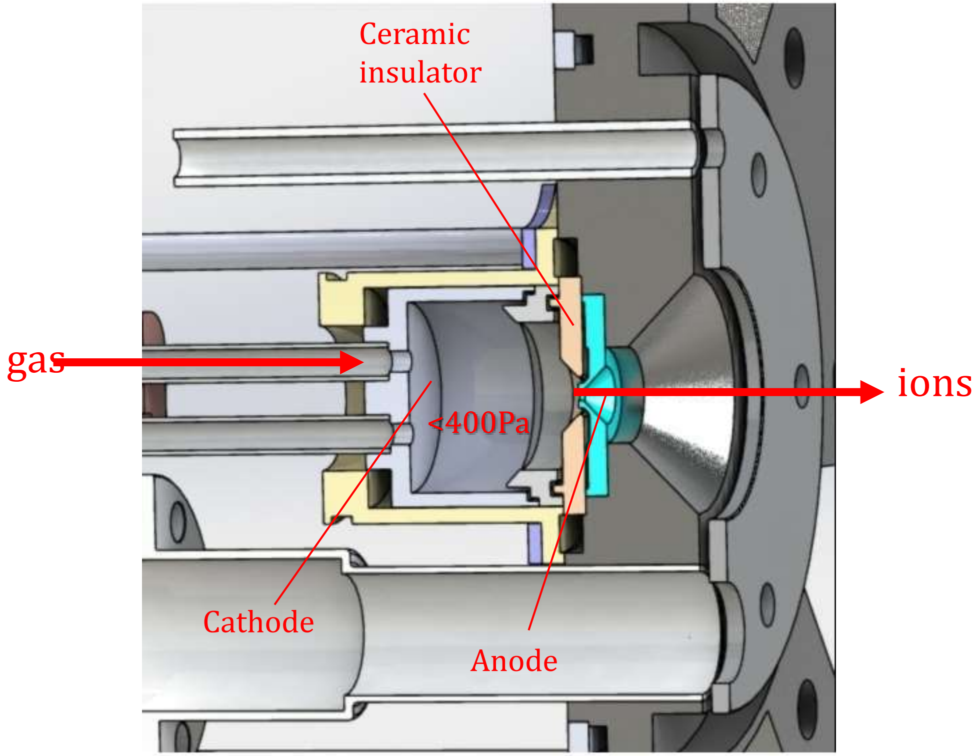
Partial operating parameters of BNCT01 and BNCT02 ECRIS[1,2]

BNCT01	
Frequency [GHz]	2.45
Power of Magnetron [W]	1.5
Output Energy [keV]	75
RMS Emittance [πmm·mrad]	0.197
Beam Current	60 Hz 1ms : 45mA

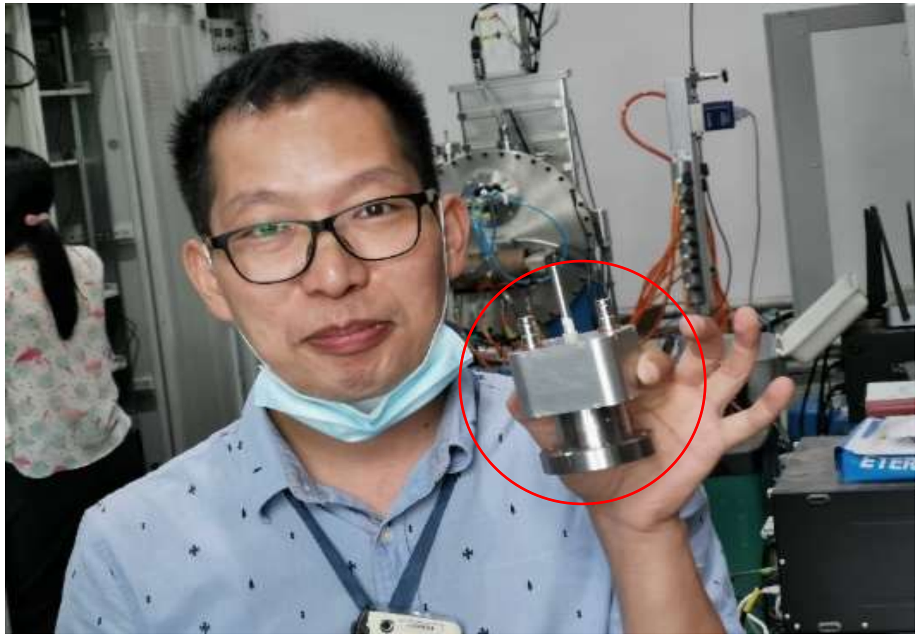
BNCT02	
Frequency [GHz]	2.45
Power of Magnetron [W]	1
Output Energy [keV]	35
RMS Emittance [πmm·mrad]	0.2
Beam Current	200 Hz 3ms : 35.04mA

[1] 欧阳华甫,肖永川,曹秀霞等.BNCT02加速器设计及离子源调试[J].白城师范学院学报,2022,36(05):1-8.
[2] 欧阳华甫,肖永川,刘盛进等.BNCT加速器设计和调试[J].白城师范学院学报,2020,34(02):1-9.

Hollow cathode ion source



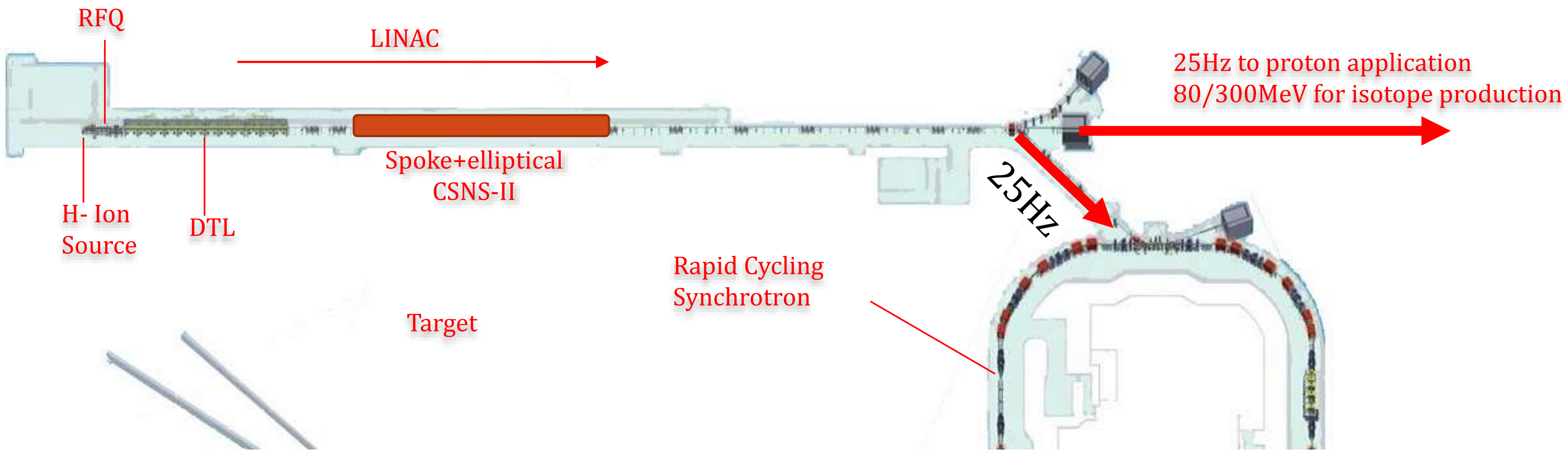
Glow discharge



- Compact CF35 flange interface
- Able to produce mA proton， pA-nA H- beam
- Suitable for atomic study and cyclotron accelerator
- Also used as plasma igniters for RF-driven sources.

Summary and outlook

- The penning ion source has a compact design, but short life time.
- The RF-driven H^- ion source with external antenna and Si_3N_4 chamber runs successfully in CSNS, with major maintenance interval more than 323 days, and availability nearly 100%
- ECR proton sources are also developed for BNCT application. It produces 35 beam current with 60% duty factor.
- The repetition rate of the CSNS ion source will be increased to 50 Hz for isotope-production in the future.



CSNS front-end group.

Thanks for your attention!