Over 7200 hours commissioning of RF-driven negative hydrogen ion source developed at CSNS

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- Introduction to the CSNS accelerator and the front end system
- Structure of the ion source
- Operation status in last run cycle (2021.9-2022.7)
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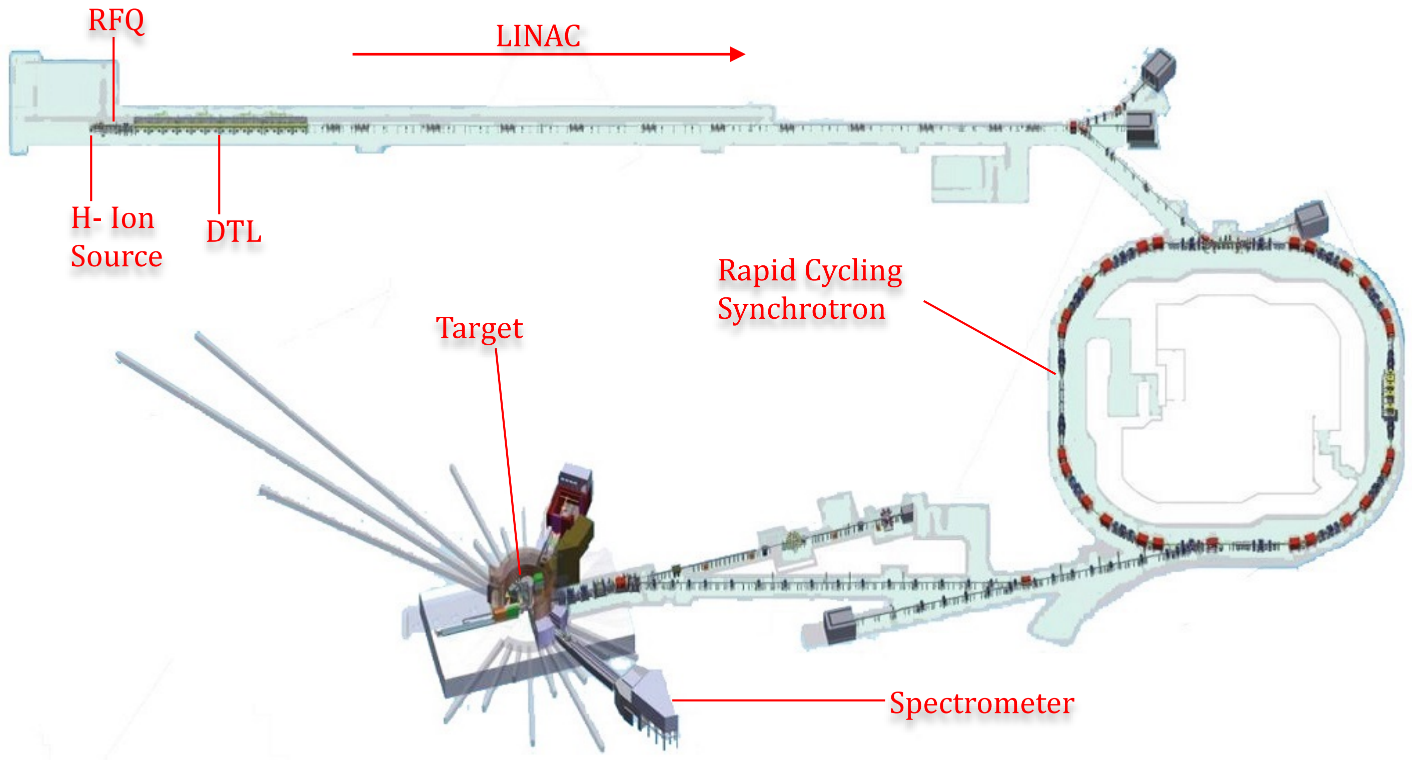
Motivation

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

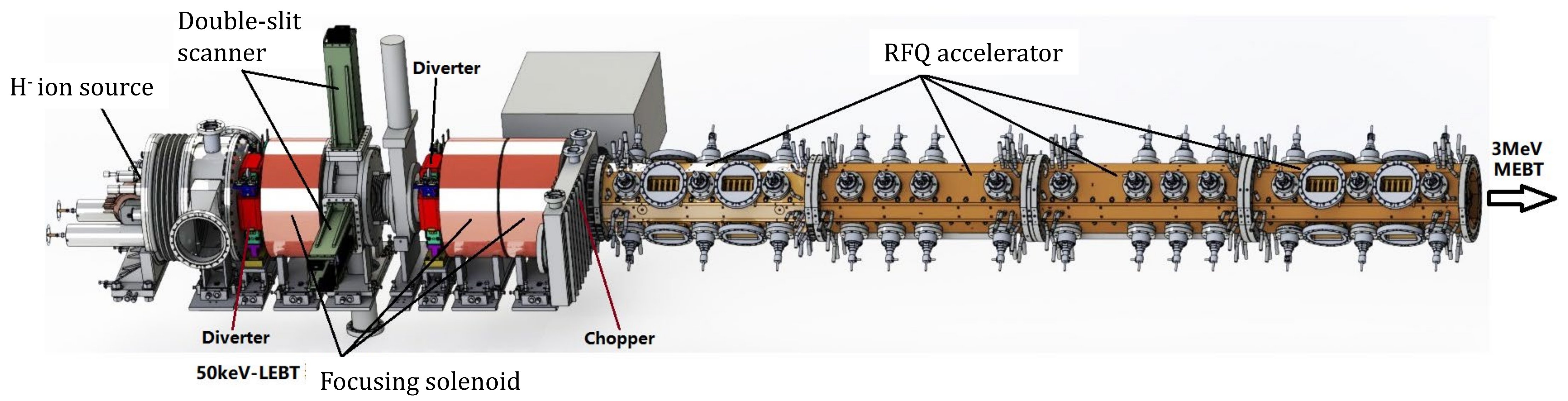
500 kW | 40~55 mA | 1.6 GeV | 500-600 us | 25 Hz | 50-60%



Parameters	CSNS-I	CSNS-II
I.S. Current (mA)	>12	40~55
Repetition Rate (Hz)	25	25
Pulse-width (us)	415	500-600
Chopping Factor	42%	35-50%
LINAC Components	R.T.	R.T.+SC
LINAC-energy (MeV)	80	300
RCS-energy (GeV)	1.6	1.6
Beam Power (kW)	100	500

The front end system

The front end of the CSNS accelerator

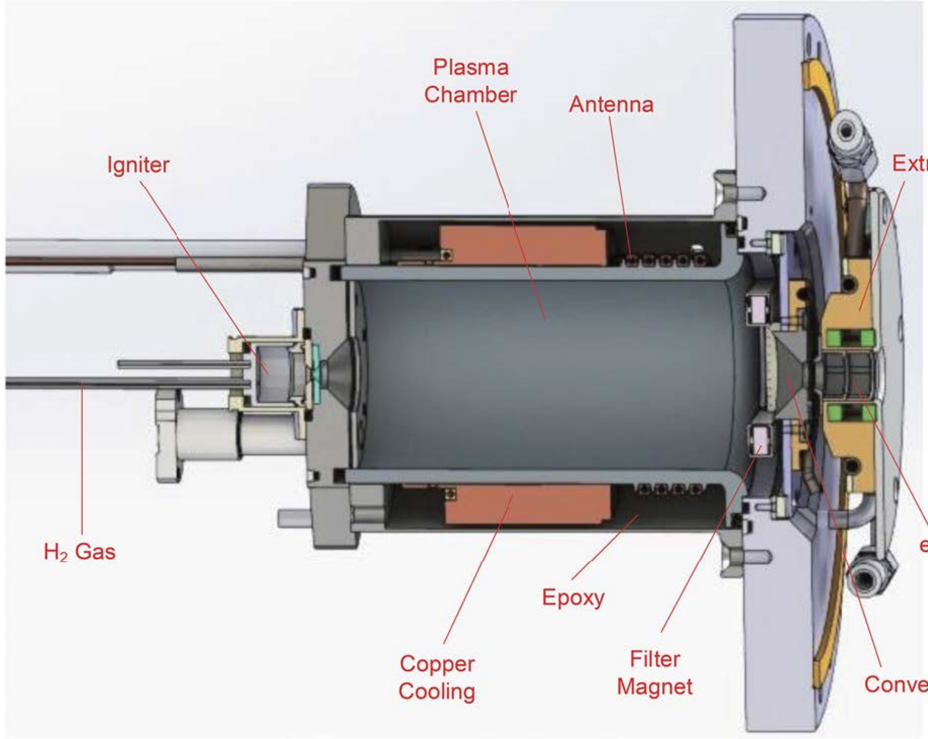


- The LEBT has 3 solenoids, initially designed for the former penning ion source.
- Since Sep. 8th 2021, the penning source has been replaced by RF-driven H^- ion source.
- Currently the beam power on target is 125 kW, and 150 kW is ready for service.
- In operation, the ion source produces 37~40 mA, and throttled to 12 mA by a collimator installed before RFQ.

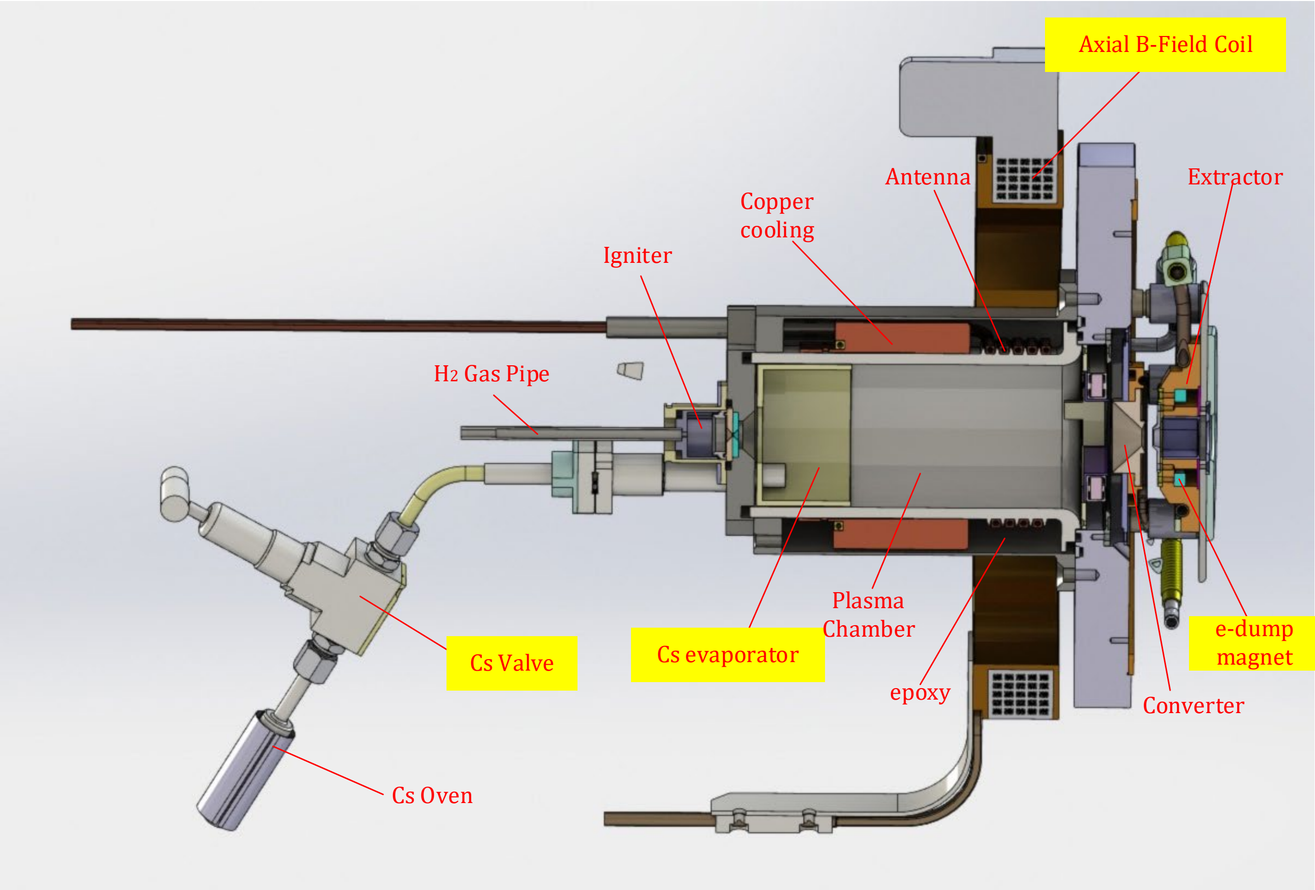
Structure of the ion source

- 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

Structure of the ion source

Why silicon nitride?

- High flexural strength (900 MPa)
- Relative high thermal conductivity (16~60 W/m.K)
- High heat shock (800 ℃)
- Inert to acid or alkali (when <900 ℃)
- Low porosity (<5%), low degas rate

Before epoxy filled

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

Incipient concerns in ceramic selection in 2016：

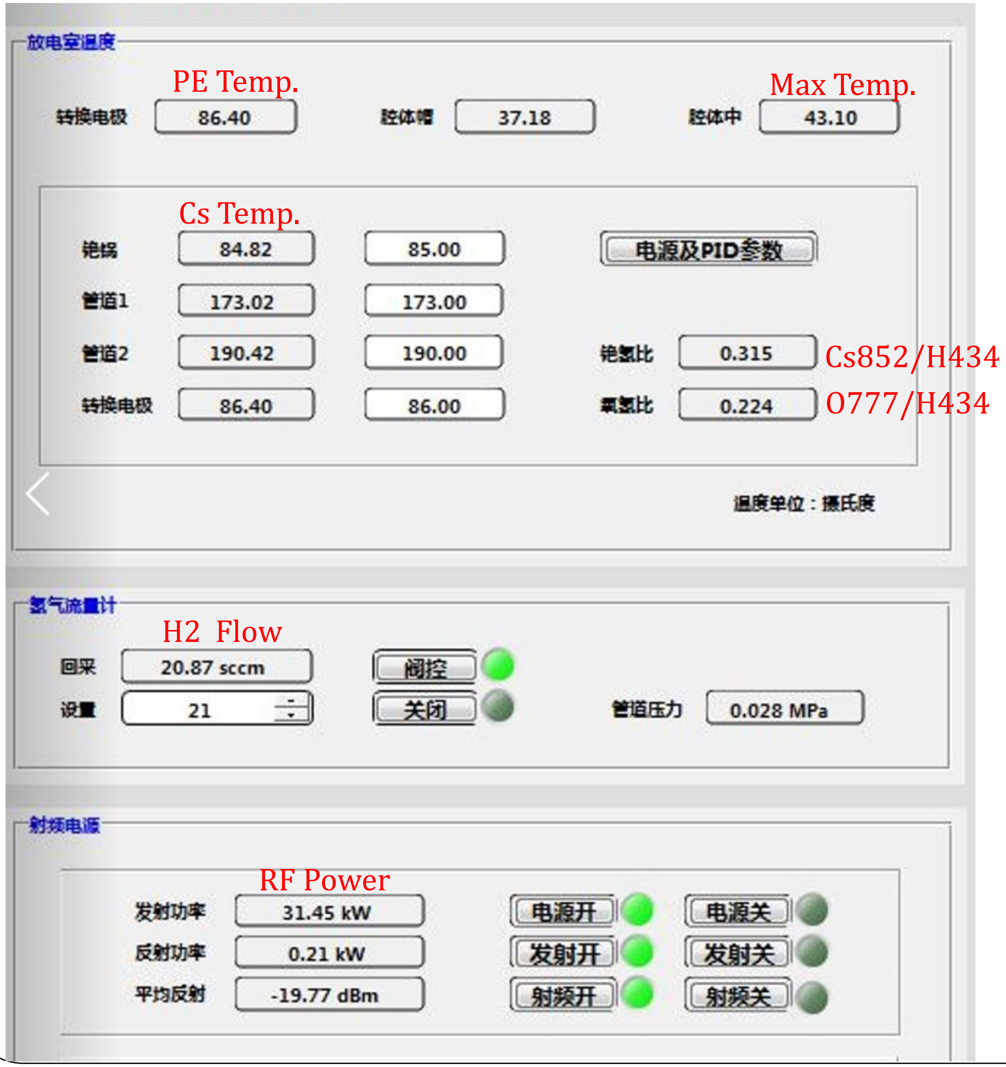
Al_2O_3—Possibly break during the heating up and cooling down for high power operation.

AlN—Possibly react with alkali (CsOH), absorb water in room temperature. It needs to be heated up in vacuum to degas before use, which is critical for Cs injection.

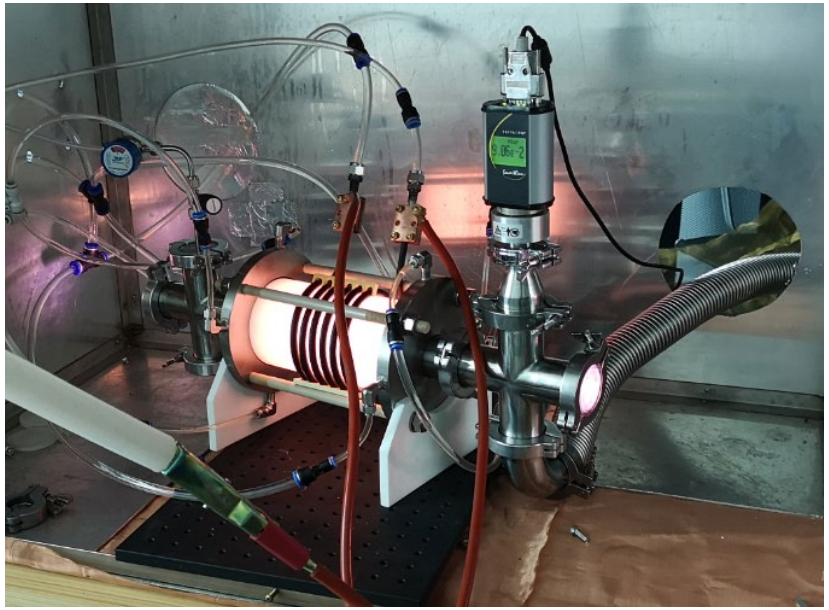
Si_3N_4 is chosen because it has no such uncertainties, although it is hard to machine.
Recently we start to verify these uncertainties of other ceramics.

Structure of the ion source

Operation parameters in Apr. 28, 2022, max temperature of the chamber is 43 °C, average power 535 W.



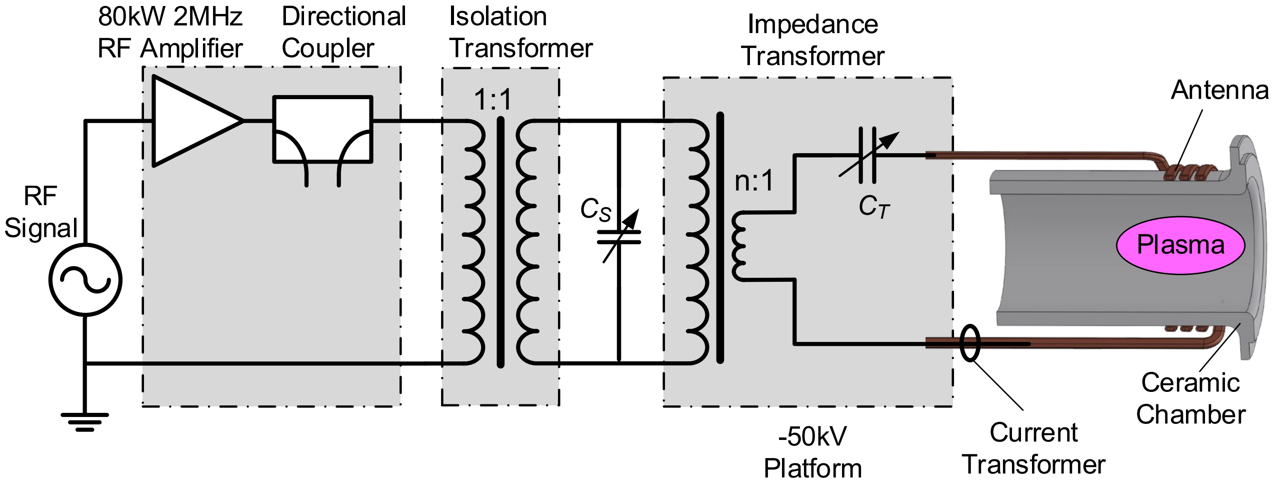
RF test with an alumina tube in IPP Hefei, China. Alumina can not block visible light and ultraviolet (>250 nm). So another concern arises—ultraviolet photon possibly damages the molecule-chain of epoxy surrounding the chamber.



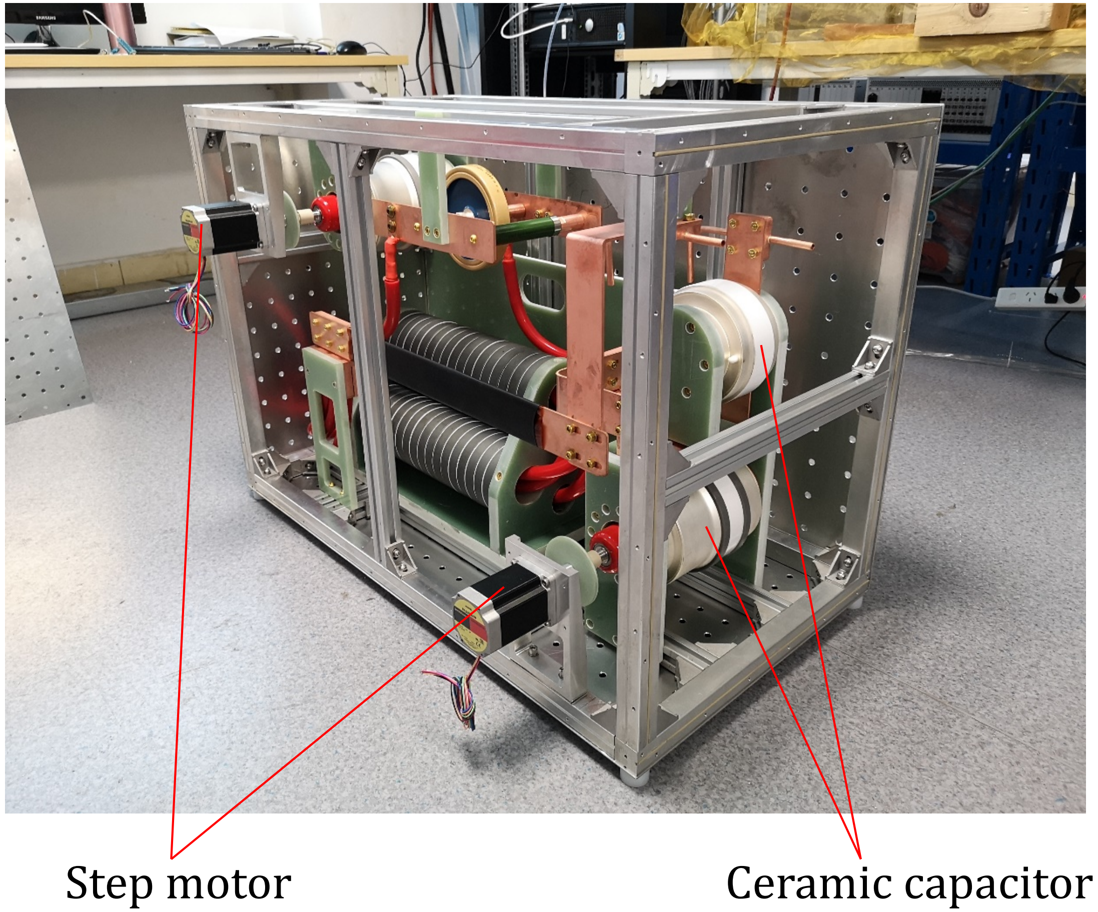
Si_3N_4 is opaque to ultraviolet photon from the hydrogen plasma.

In thermal and mechanical aspects, alumina is also able to stand 1500 W average power with the same design. A long term (>1 year) high power (>1000W avg.) test is carried out in CSNS.

RF power matching circuit

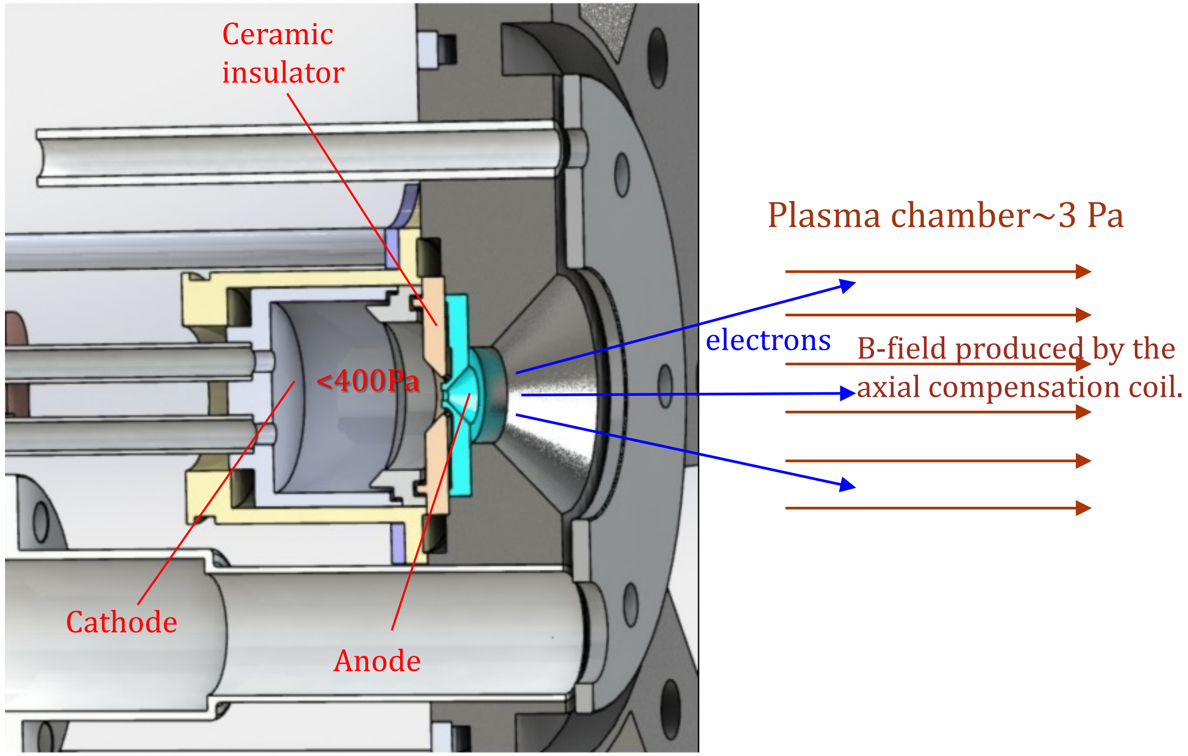


- Maximum 80 kW RF power
- 1.8-2.2 MHz tunable
- 3:1 turn-ratio
- 100 kV isolation tested
- Above 90% power transmission after RF amplifier

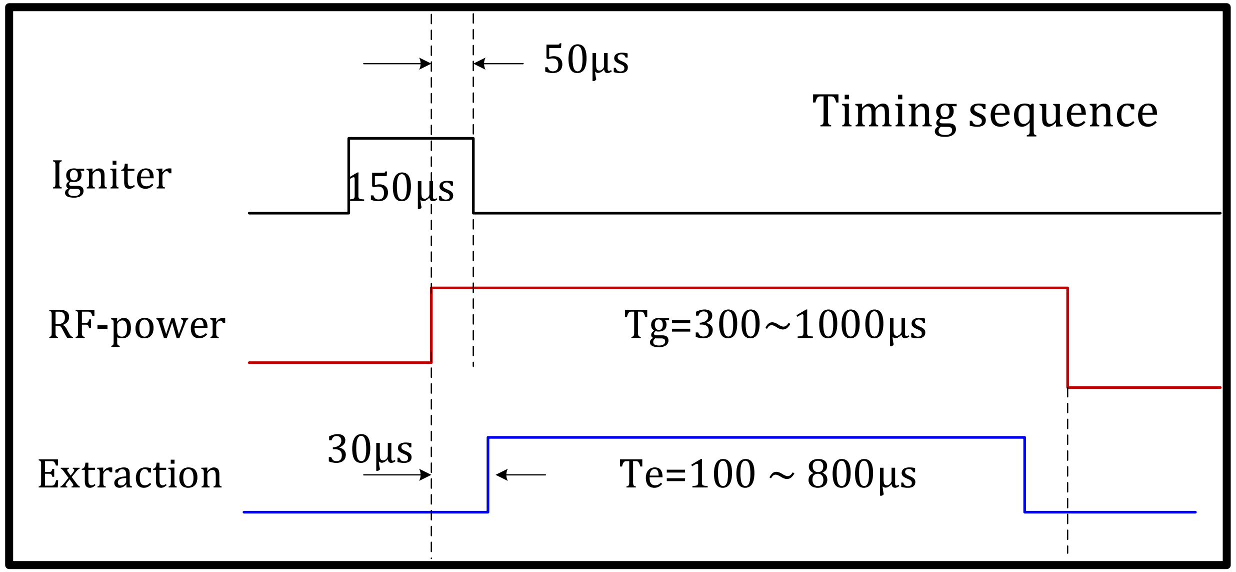


The glow discharge igniter

- Simple structure
- Pulsed 560 V DC voltage
- Average power less than 0.5 W

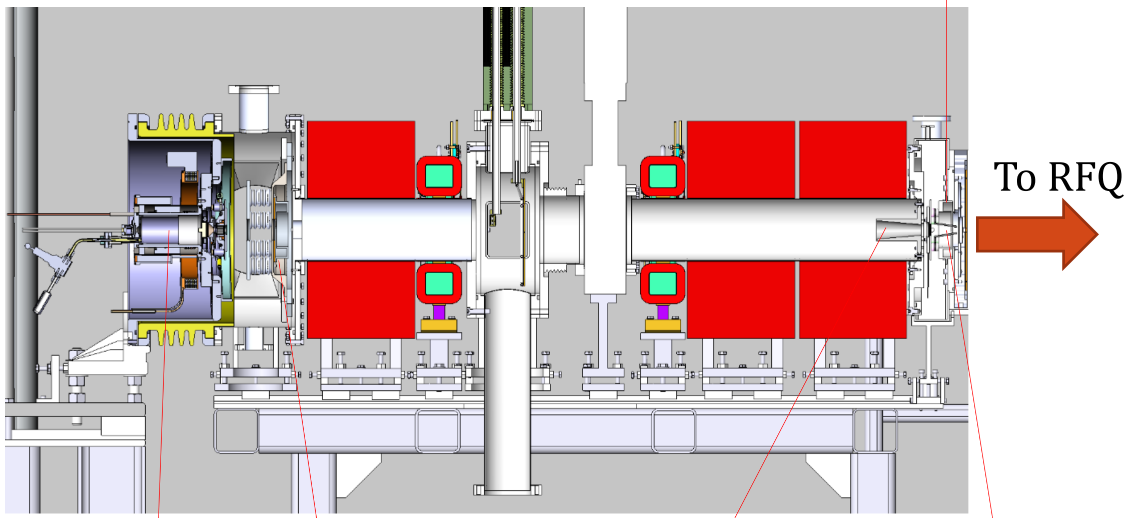


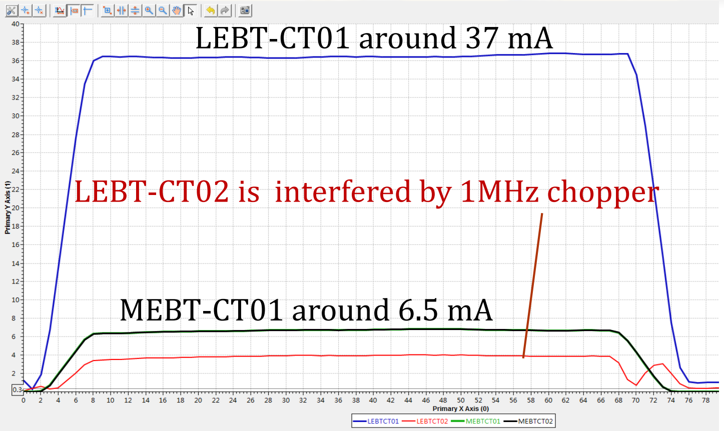
Since the pressure in the igniter is 200~400 Pa, the seed electrons are blew to the plasma chamber and guided by the weak axial magnetic field produced by the magnetic coil, which is mainly used to compensate the magnet field of solenoid in LEBT.



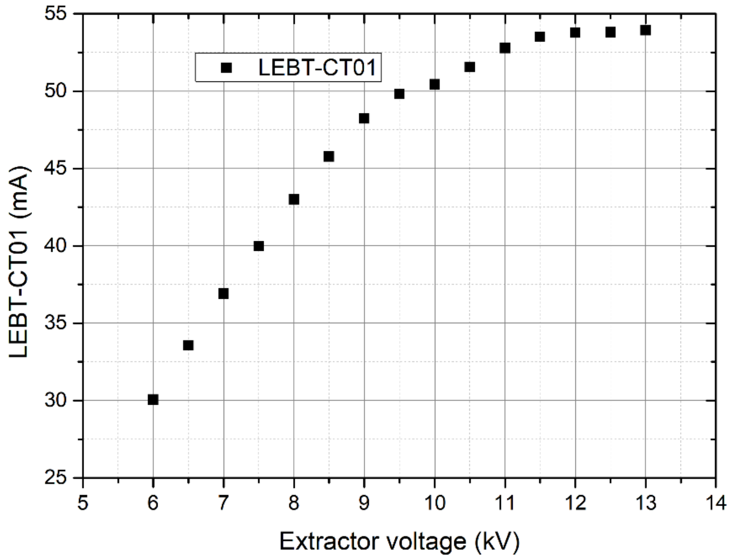
Operation status

Low energy beam transport





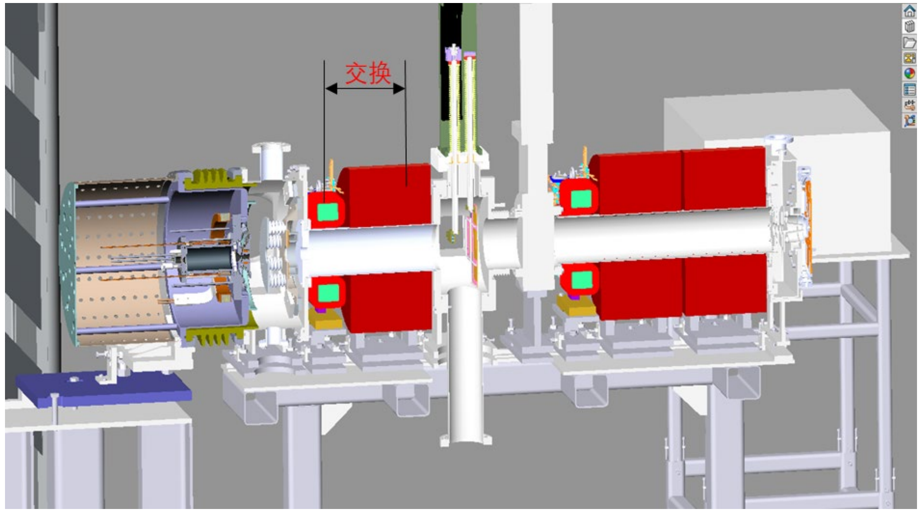
Typical current for 100 kW beam power operation



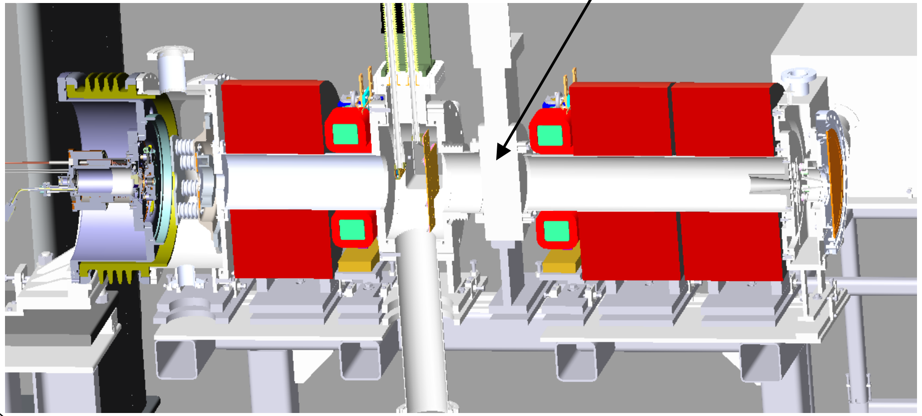
LEBT-CT01 vs extr. voltage
RF power=30-31 kW,
H_2=21 SCCM
53mA is produced.

A new 2-solenoid LEBT is under construction, expected to be installed in the accelerator in 2024.

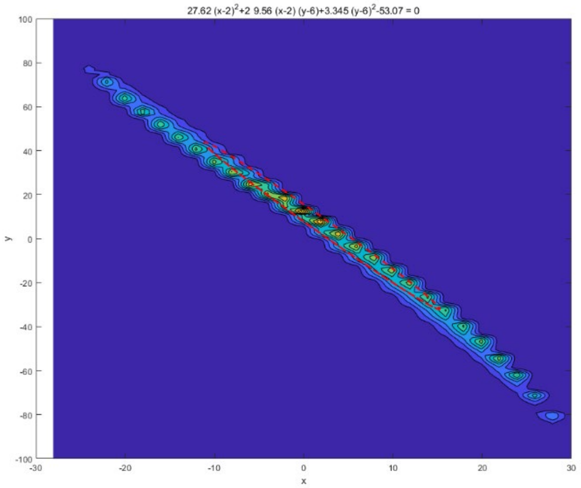
Emittance measurement (in lab)



Double-slit scanner

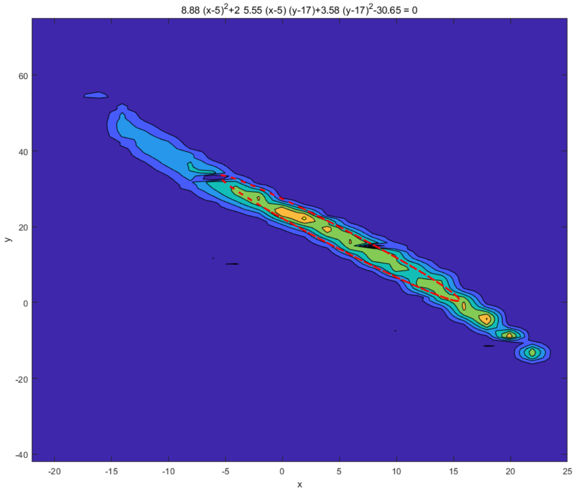


- The CST simulation shows that the emittance gets smaller when the solenoid is closer to the ion source.
- The possible reason is the envelope of the beam is smaller at the entrance of the solenoid. The aberration of the B-field is smaller when the beam is closer to the axis of the solenoid.
- The B-field at the double-slit scanner also contributes to the measured value of emittance.



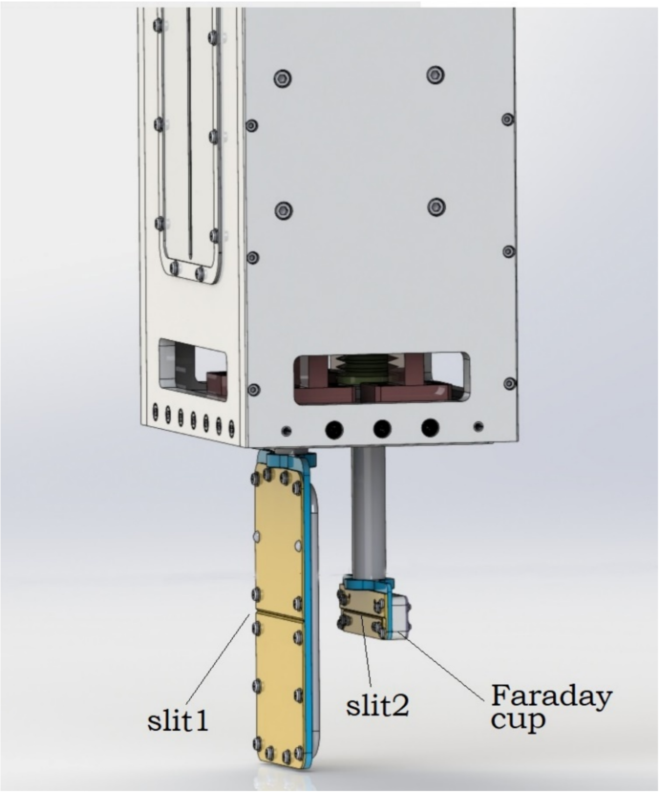
n-RMS emittance，
X-0.562 pi.mm.mrad
Y-0.531 pi.mm.mrad

magnets swapped

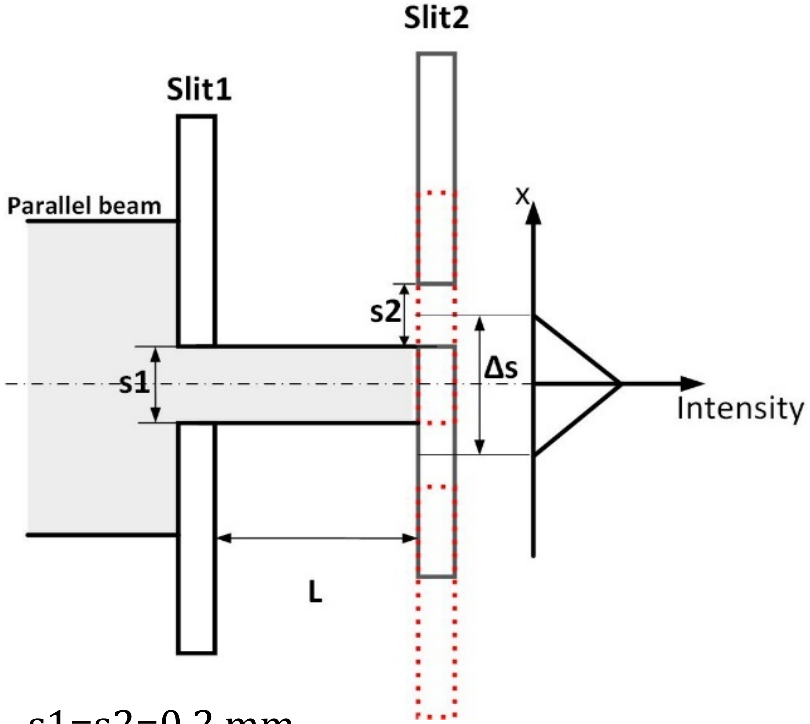


n-RMS emittance，
X-0.355 pi.mm.mrad
Y-0.307 pi.mm.mrad

Systematic error of double-slit scanner



Structure of the double-slit scanner



s1=s2=0.2 mm
L=52 mm
Minimum beam envelope~30-50 mm

The double-slit scanner itself will introduce extra emittance error comparable to the real value.

$$\Delta x_i' = \frac{\Delta s}{L} = \frac{s_1+s_2}{L} = \Delta x',$$

$$A_x = S_{en} \cdot \Delta x',$$

The emittance error is $\Delta\varepsilon_x = \frac{A_x}{\pi}$,

Solution:

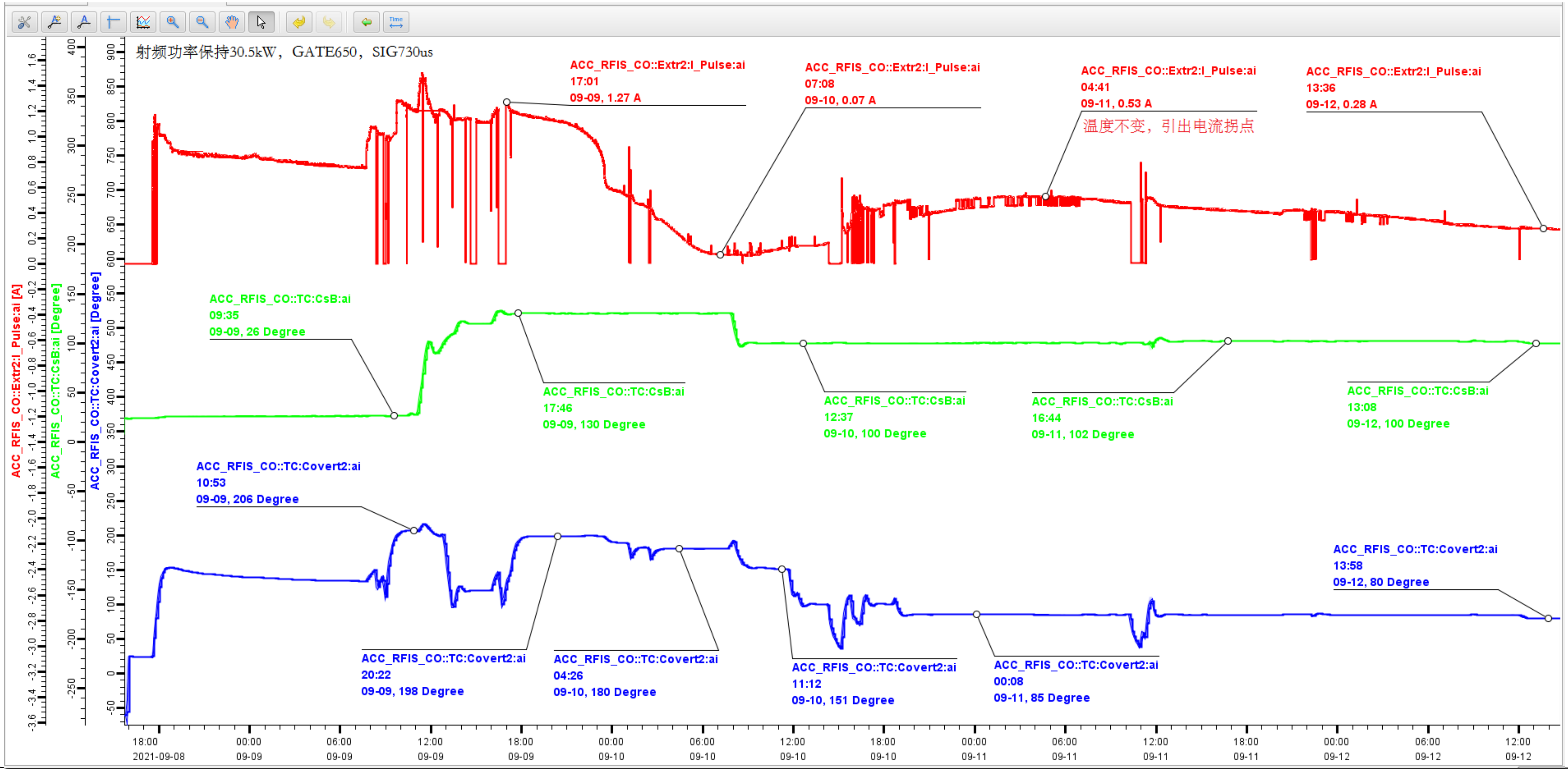
- New LEBT for smaller beam envelope.
- New scanner with 0.1 mm slit width.

They will be ready for test in the lab by the end of this year.

Operation status

Cesiation

Since it was the first service cycle in CSNS accelerator, we run the source with caution. The cesiation process takes 3 days before it started to deliver the beam to the accelerator for machine study. The parameters are fixed after ~10 days.



Cs oven temperature
130 °C →85 °C

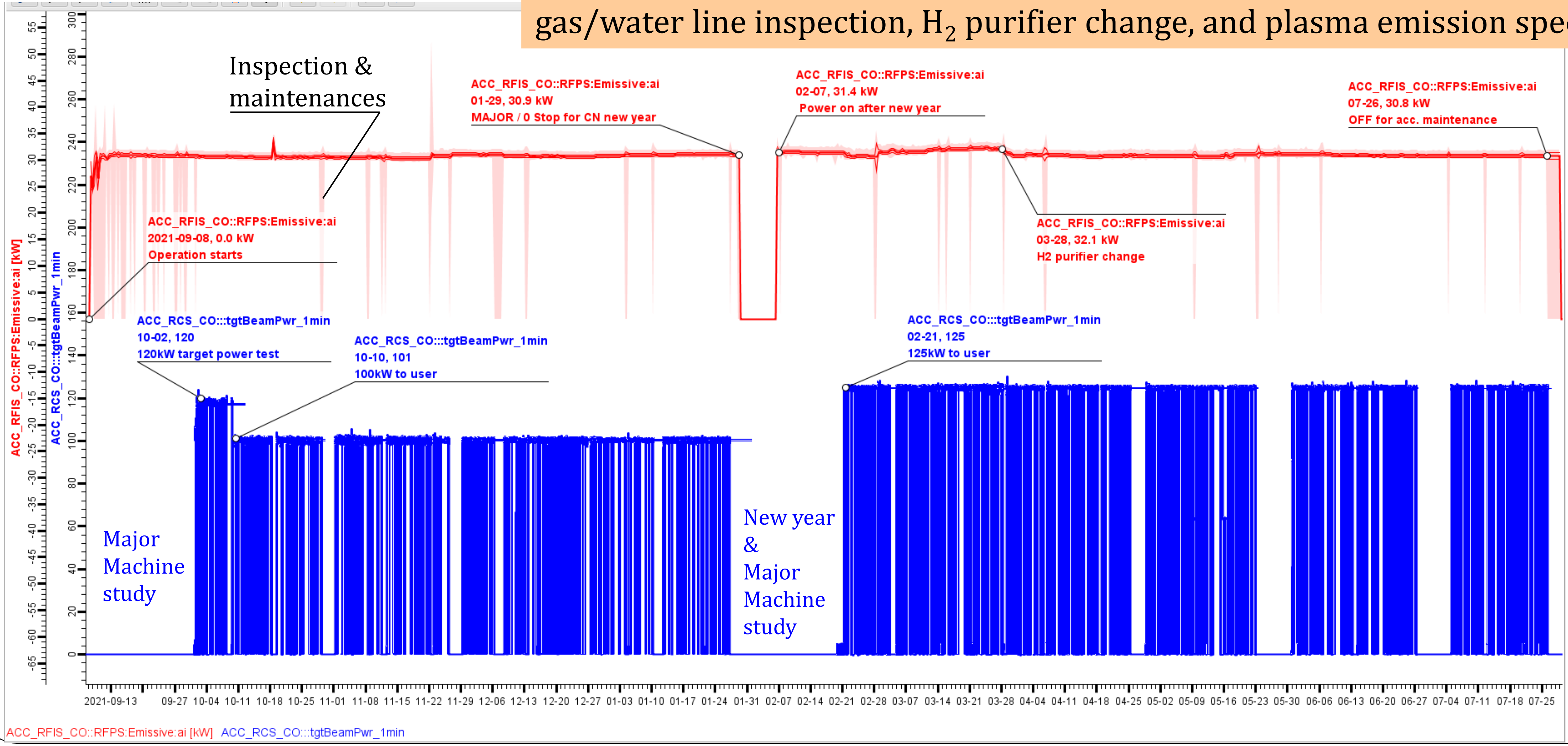
Extracted *e* current:
1.27 A →0.08 A

PE temperature:
200 °C →80 °C

Operation status

~310 days of operation

The maintenance was done when the whole accelerator is closed for inspection. The maintenance includes gas bottle replacement, 50 kV insulation cleaning, gas/water line inspection, H_2 purifier change, and plasma emission spectra check.



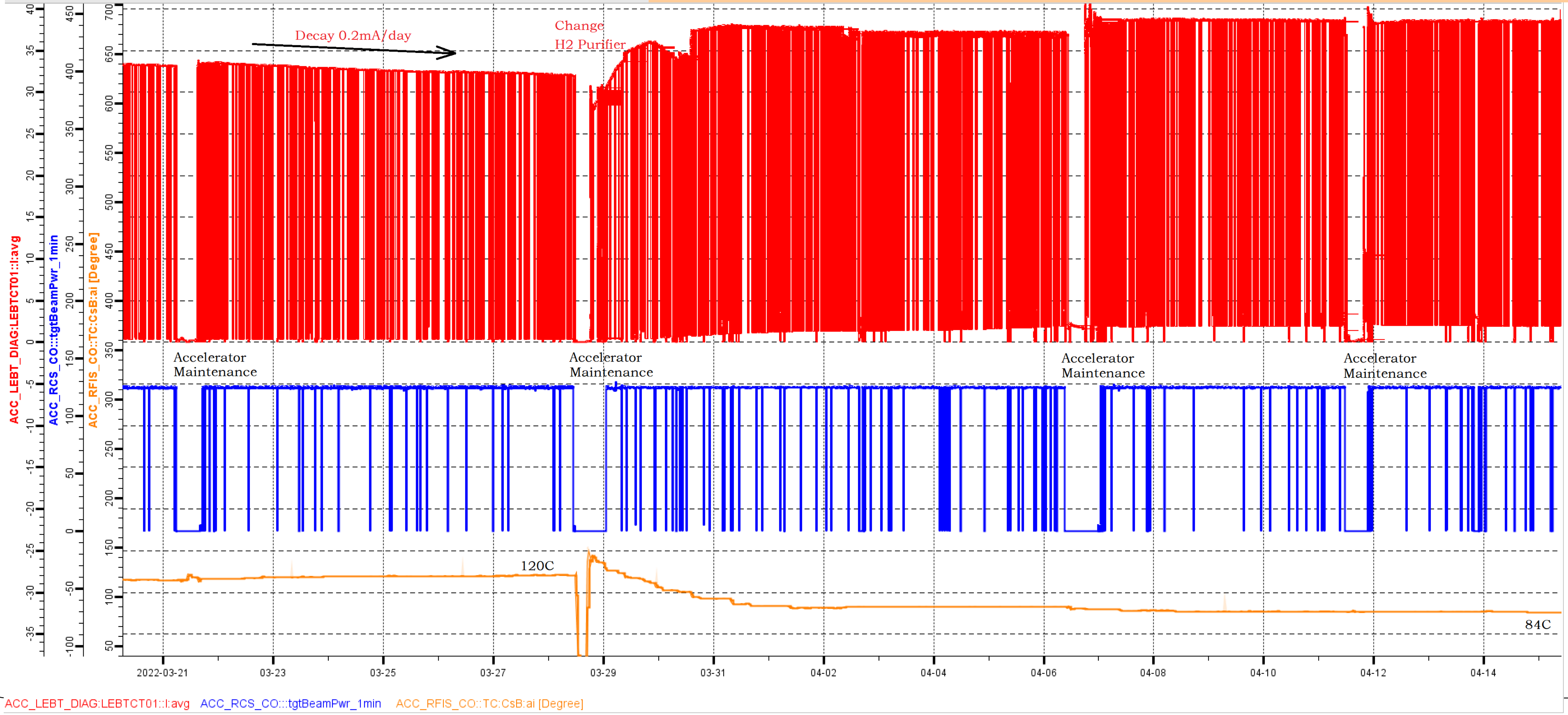
RF Power
1 sample/s

Target Power
1 sample/min

Issues in operation

Since Dec. 20th, 2021, O777 spectrum starts to increase slowly. The extracted electron current also started to increase, and LEBT-CT01 started to decay. Consequently, the cesium oven temperature is increased step by step to compensate the current decay. Up to Mar. 28th, 2022 it is heated up to 120 °C. No leakage to vacuum is observed. After the H_2 purifier is changed, the ion source recovered to the same parameters as in the early stage.

Current decay and recovering



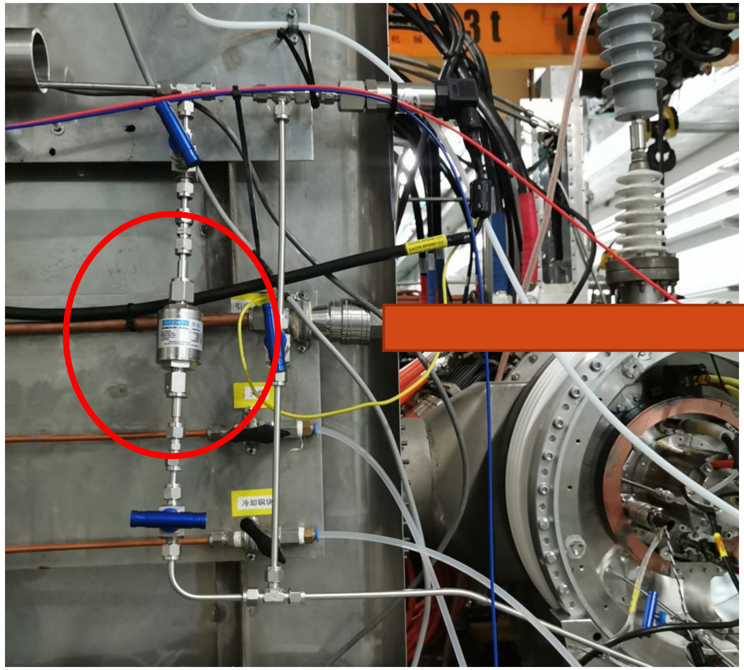
Issues in operation

Importance of vacuum condition and H_2 purifier

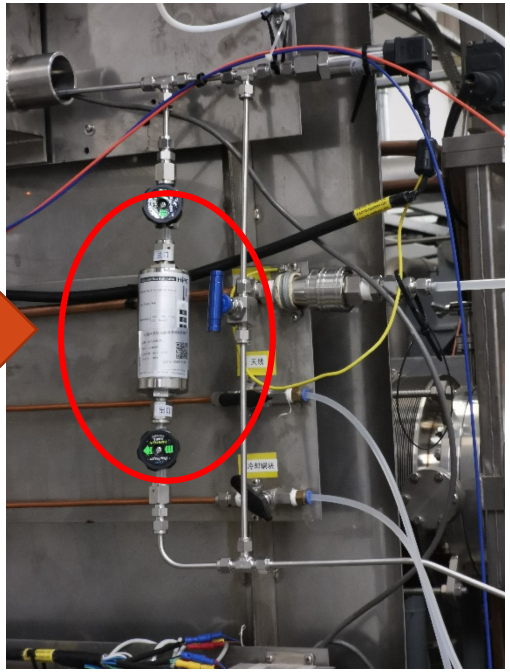
Typical H_2 consumption is 21 sccm, corresponding to ~10 m^3 per year.

For H_2 of 9999.99% purity, contains ~10 ml water/O_2. Extra *~0.24 g cesium is needed*.

For H_2 of 999.99% purity, contains ~30 ml water/O_2. Extra *~0.72 g cesium is needed*!



Changed to bigger one

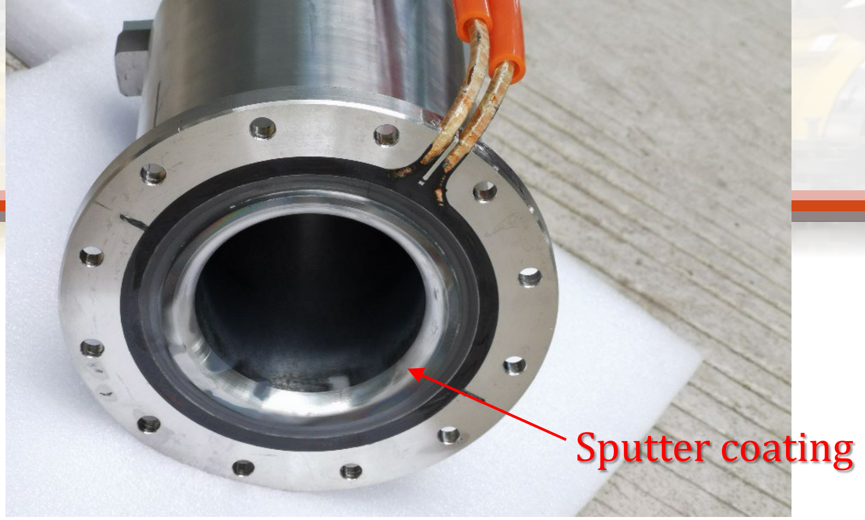


The hydrogen purifier eliminates the water/O_2 to less than 1 ppt according to the specification.

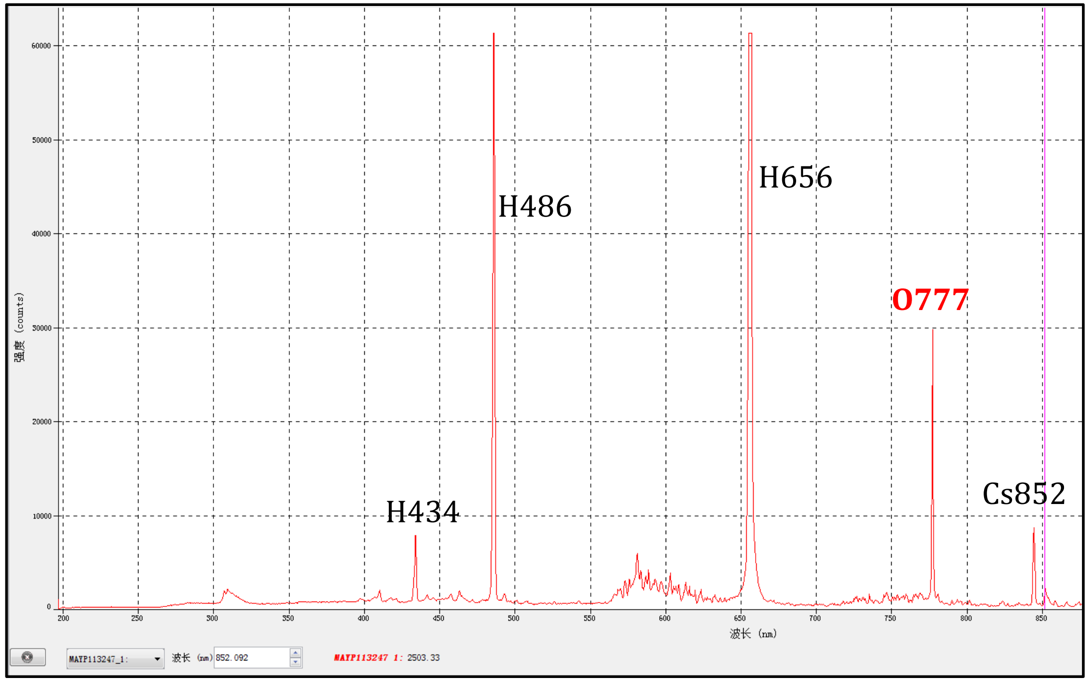
Issues in operation

Importance of vacuum condition and H_2 purifier

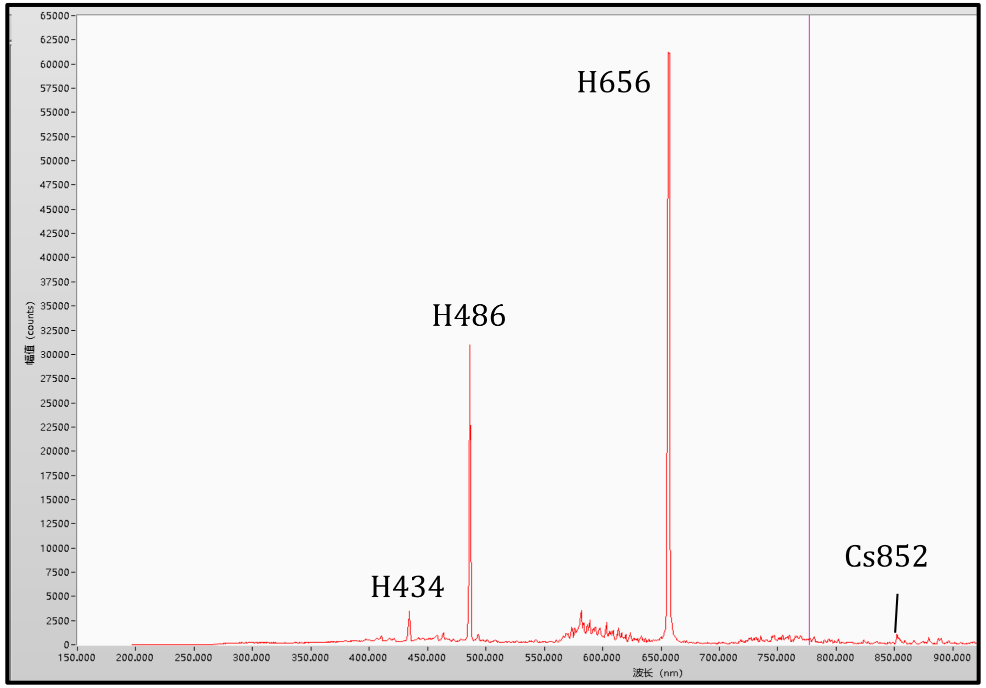
From 2019 to 2021, many efforts were made to decrease the O777 spectrum line. It is critical to increase the H- current, to decrease the co-extracted electron current, and to create a flat-top current pulse.



Big amount of oxygen element will cause the sputter erosion of electrodes in long term operation. The plasma chamber is coated with a layer of metal through sputtering, which changes the EM field distribution of the plasma.



Effect of H_2 purifier



Issues in operation and machine study

Cesium consumption measurement

The ion source is dismounted in August 2022. The ion source was disassembled into pieces. All of the parts (except the cesium injection system) were put into a jar filled with diluted sulfuric acid to collect all of the cesium.

The volume of the solution is 320 ml. The concentration of cesium is 0.12%, measured with an ICP-MS.

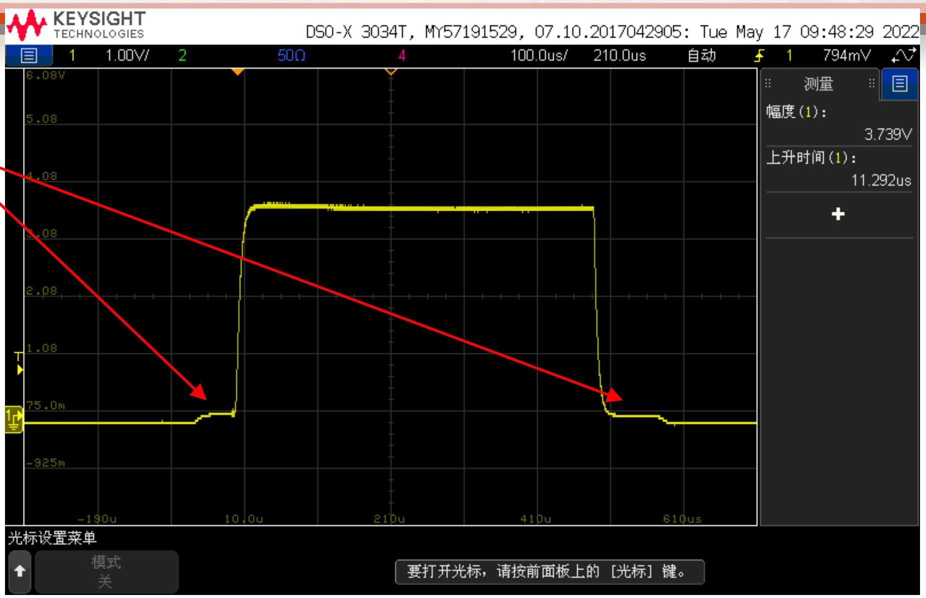
0.38 g cesium is used in ~310 days of operation, which is a little higher than expected. The cesium oven temperature was raised from 85 °C gradually to 120 °C in 3 months to solve the problem caused by saturation of H_2 purifier.

Estimating from the vapor-temperature curve of the cesium, less than 0.2g/year cesium will be used for normal operation.

Issues in operation and machine study

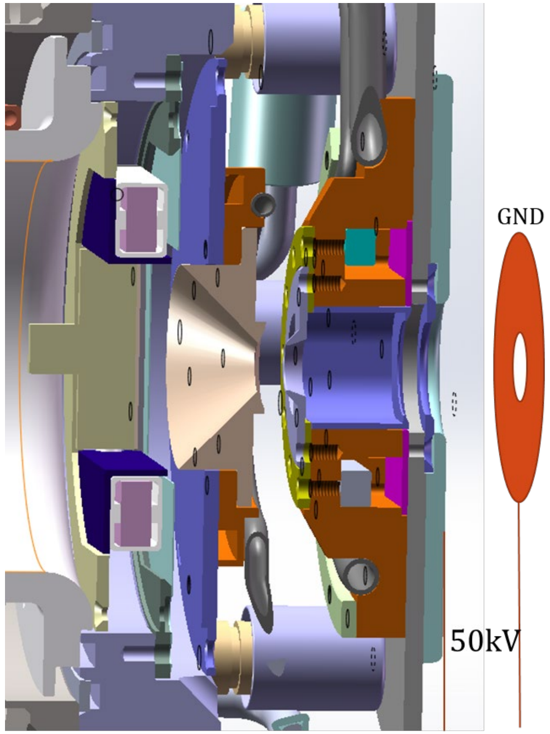
Dark current

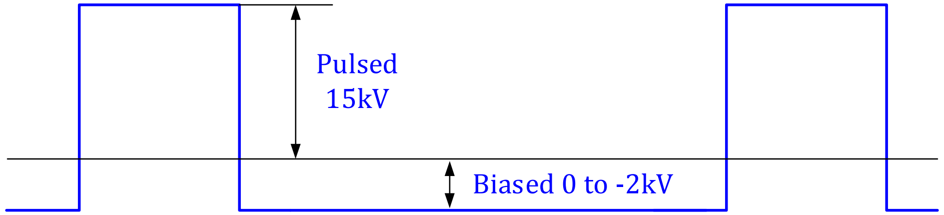
Dark current occurs when plasma is on and extractor is off

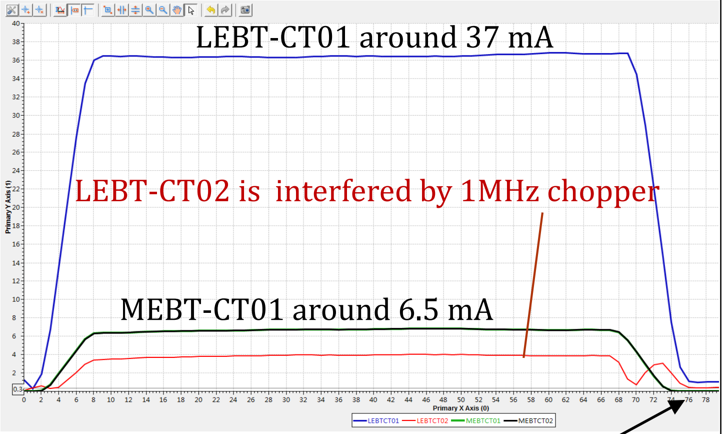


Origin of the dark current

- Fringe electric field of the ground electrode penetrates through the extractor electrode.
- High energy H^- ions effuse from the PE aperture.







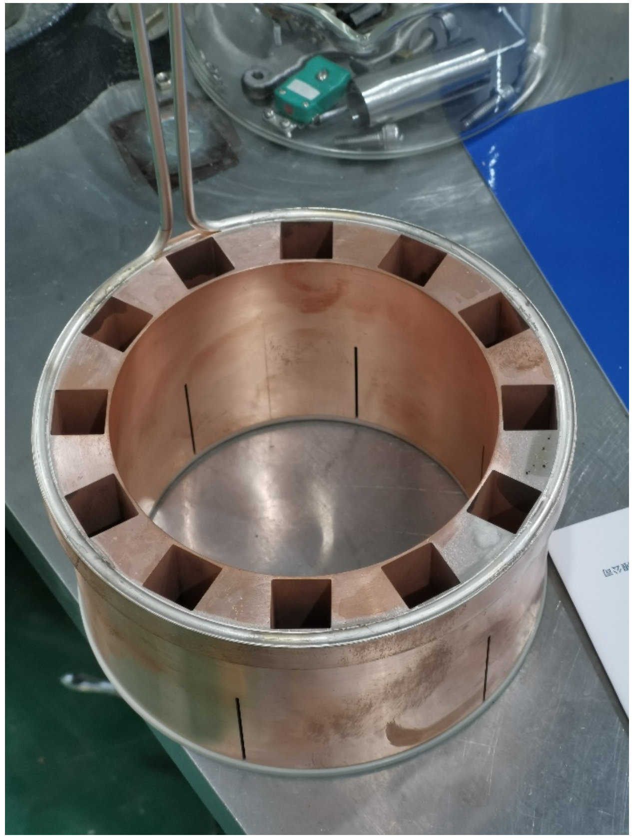
- Solution 1, bias extracting voltage negatively.
- Solution 2, timing the chopper before RFQ to deflect the dark current.

Dark current increase the beam loss of the RCS in injection period !

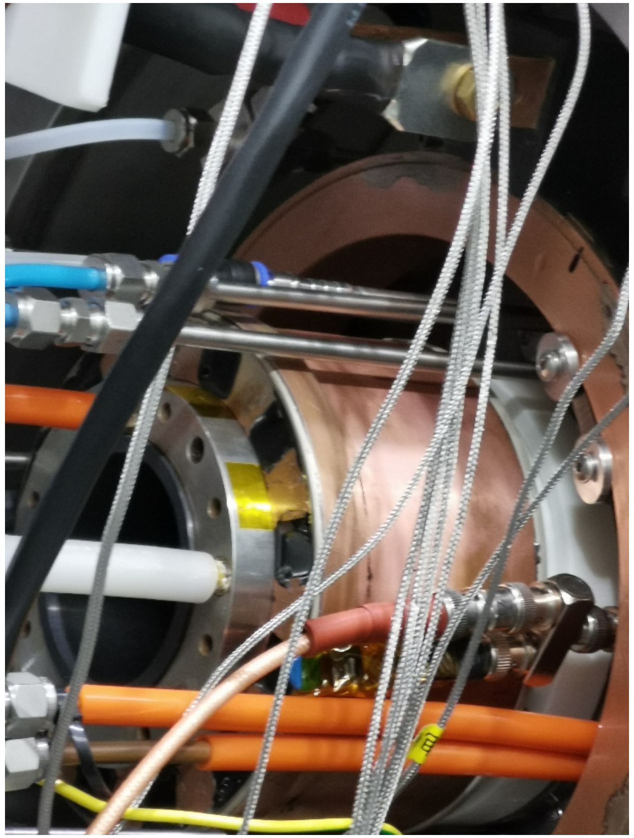
No dark current after RFQ

Issues in operation and machine study

Cusp magnets



Cusp magnet holder

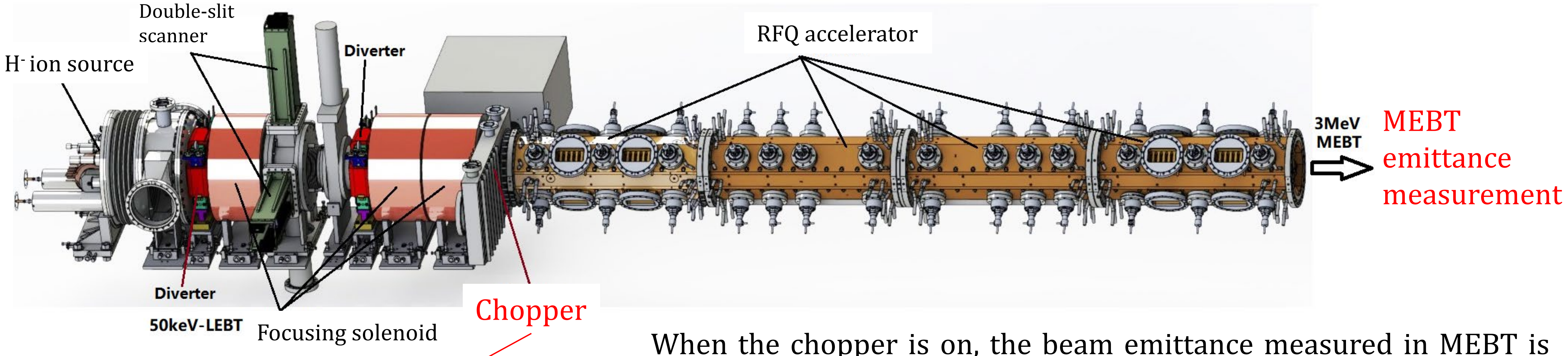


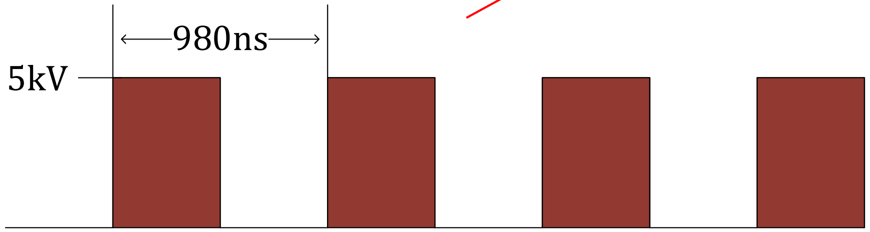
Cusp magnets were removed since 2021 due to:

1. Cusp field does not increase the beam production efficiency greatly in our test.
2. Cups field interferes with axial field used to guide the seed electrons, making the plasma start failure occasionally, specially before Cs is injected.
3. Cups field focuses ions into strips along the ceramic plasma chamber, producing hot and cold strips, which is not good for cesium transport. Strips of white compounds were observed after the chamber was exposed to air.

Issues in operation and machine study

Emittance growth caused by beam chopping



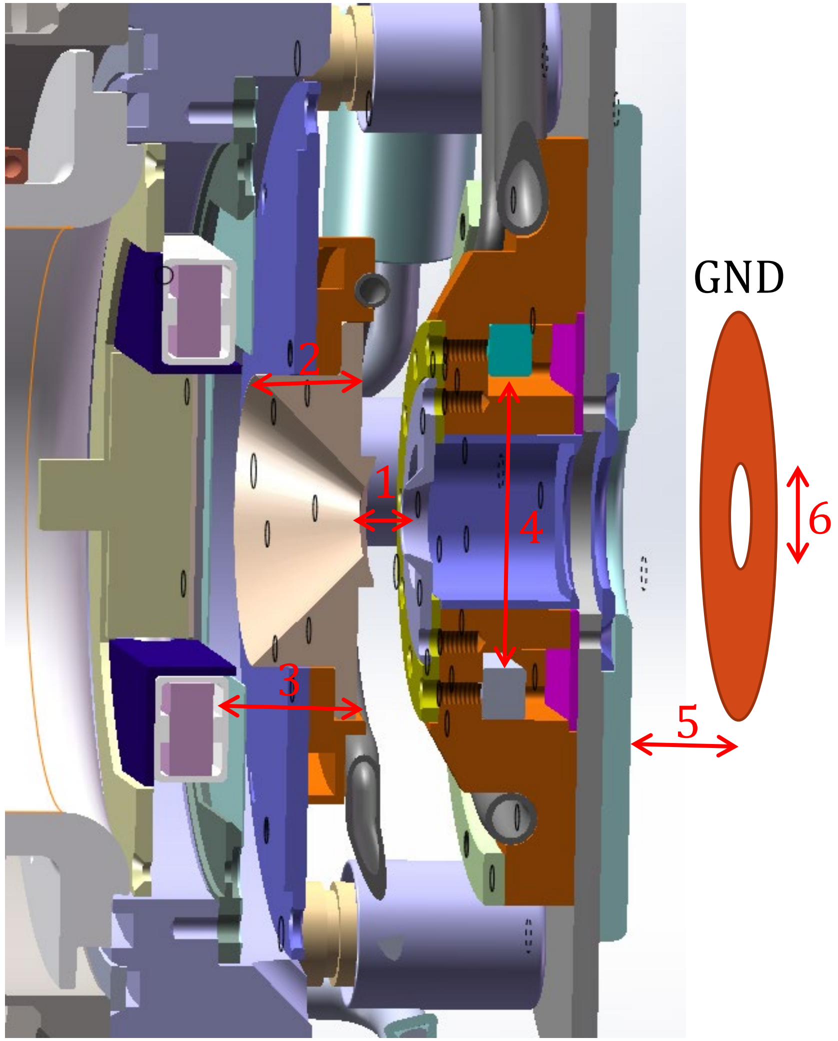


When the chopper is on, the beam emittance measured in MEBT is larger than that when chopper is off. The difference becomes obvious as the beam current increases. The reason behind is that the ~1 MHz chopper voltage destroys the H_2^+ ion cloud around the chopper. Consequently space charge compensation can not be built up around the chopper.

See more in poster Session 2 / 75 on Thursday.

Recent development

Optimization based on current structure



Changes in August 2022, guided by CST simulation

1. Extraction gap is increased to 3.7 mm
2. Thickness of PE electrode increased by 1 mm.
3. Distance from PE aperture to filter magnets increased by 1 mm.
4. Dumping magnet pair away by 1 mm.
5. Ground electrode closer by 8 mm.
6. Ground electrode inner diameter smaller by 2 mm.

Beam Transmission

LEBT CT01	60.201	mA
LEBT CT02	0.121	mA
MEBT CT01	0.005	mA
MEBT CT02	0.018	mA

Beam Transmission

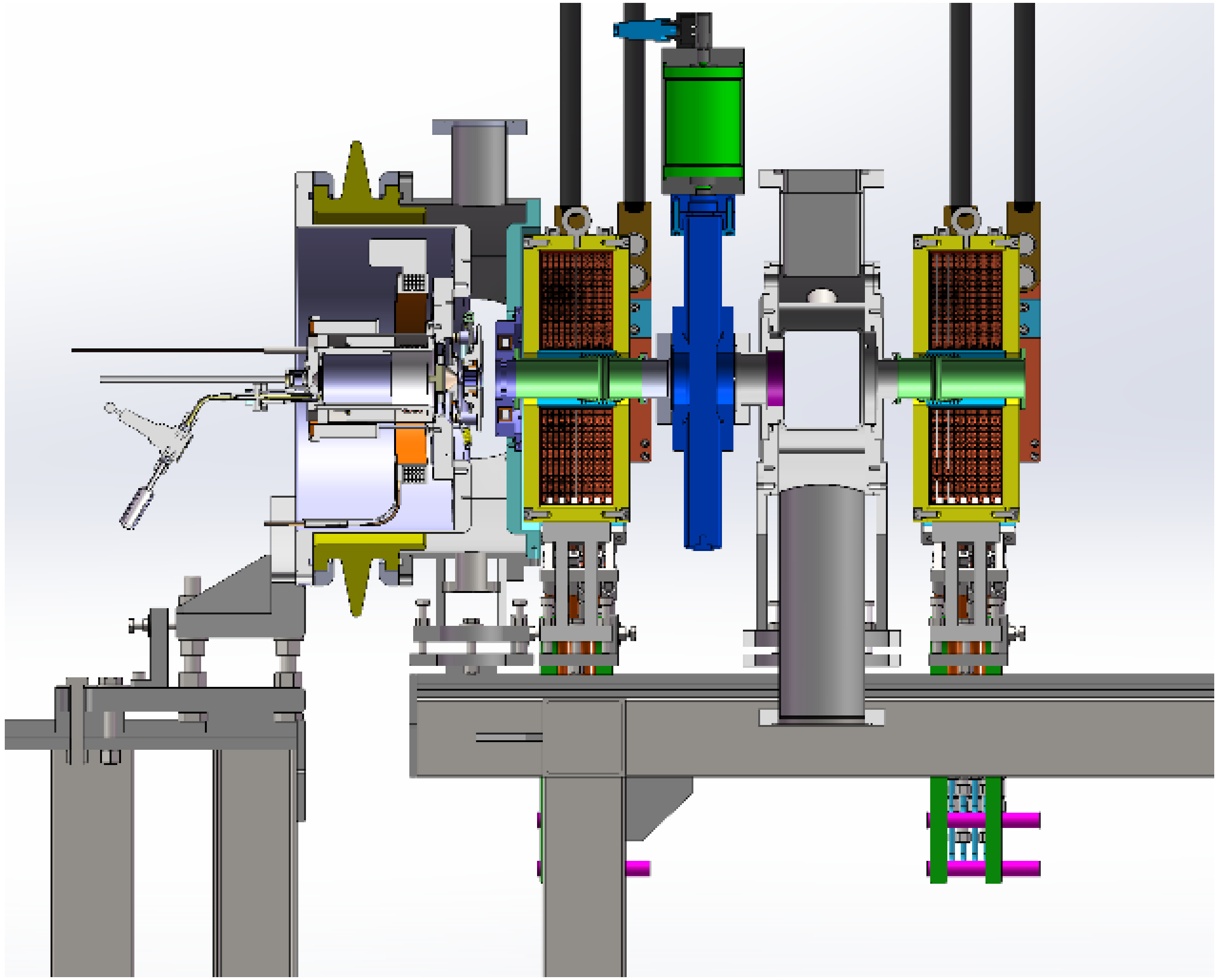
LEBT CT01	52.623	mA
LEBT CT02	37.518	mA
MEBT CT01	35.177	mA
MEBT CT02	0.004	mA
LEBT Trans Efficiency	71.3	%
RFQ Trans Efficiency	93.8	%
MEBT Trans Efficiency	0.0	%

After the optimization, over 60 mA H^- beam is produced at 32 kW RF power, hydrogen flow rate 22 SCCM.

About 35.2 mA out from RFQ , limited by beam collimator in LEBT.

Recent development

New LEBT



- Double solenoids.
- Optimized emittance growth.
- Higher transmission efficiency.
- Less than 0.75 m length.
- New double-slit scanner with smaller slit width.
- Ready for test in lab by the end of this year.

Summary

- The RF-driven H^- ion source with external antenna and Si_3N_4 chamber runs successfully in CSNS. It has been operated more than 310 days (even longer).
- The glow discharge igniter in gas line works efficiently.
- Vacuum condition and H_2 purifier are very important to promote the performance of the beam, and to minimize the usage of cesium.
- Dark current is efficiently removed by biasing the extractor negatively, and chopping the rising/fall fringe of beam.
- Cusp field is removed from the H^- ion source since 2021.
- New LEBT is under construction, which will enhance the performance of the ion source.

Members of CSNS front end group

Thanks for your attention !

nibs22