Development and commissioning of 217 MHz VHF cw gun for SHINE

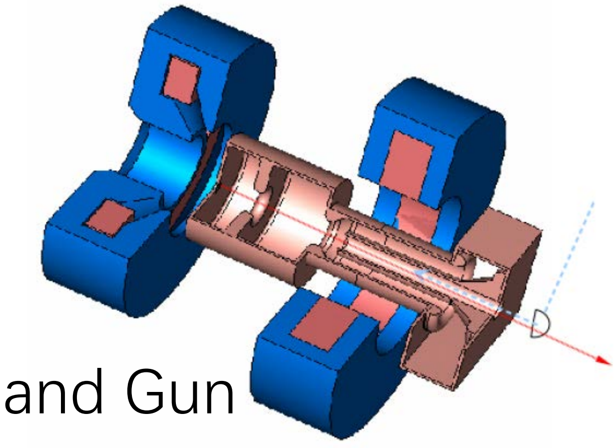
Lianmin Zheng
on behalf of Accelerator Laboratory

Department of Engineering physics, Tsinghua University,
Beijing 100084, China
zhenglm2019@mail.tsinghua.edu.cn

Contents

Motivation

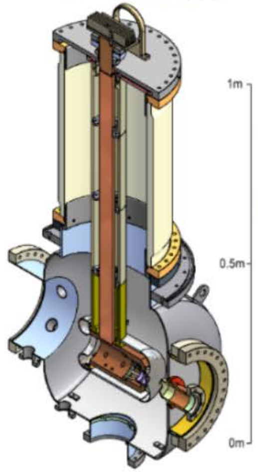
Different guns that can support MHz-class repetition-rate FELs



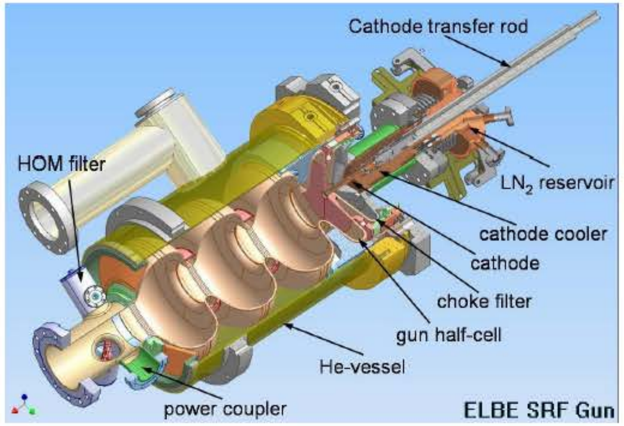
L-band Gun

- 4.5 MHz electron bunches in an rf pulse.
- repetition-rate of the rf pulses: 10 Hz.
- 27,000 electron bunches can be produced per second.

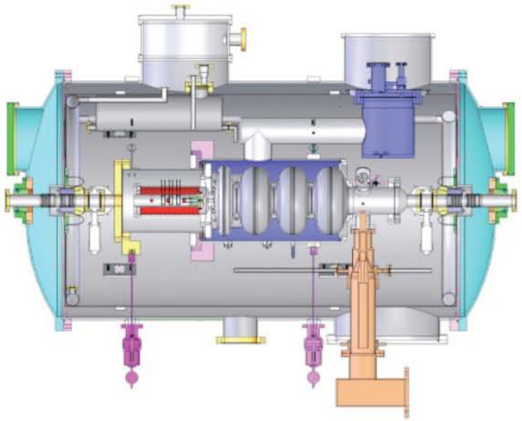
DC Gun



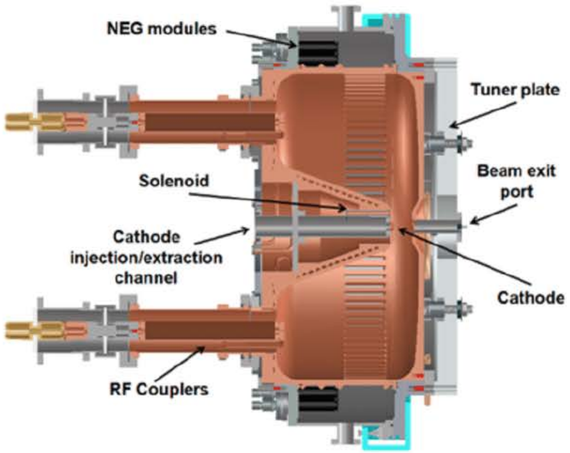
SRF Gun



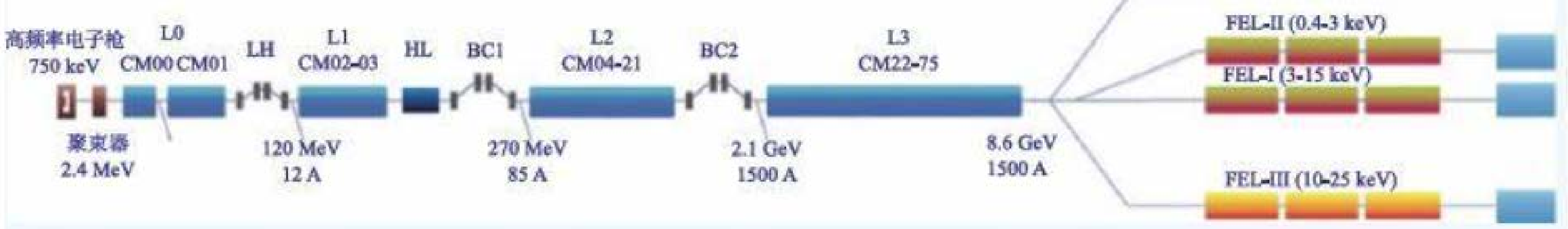
DC-SC Gun



VHF Gun



Motivation



SHINE facility's requirements for VHF gun:

parameters	value	unit
Gun operation mode	CW	
Gun cathode gradient	>25	MV/m
voltage	≥750	kV
Emittance at the end of the photoinjector	<0.4 @1mm rms@100pC	um
Dark current	<400	nA

Timeline of the VHF gun development

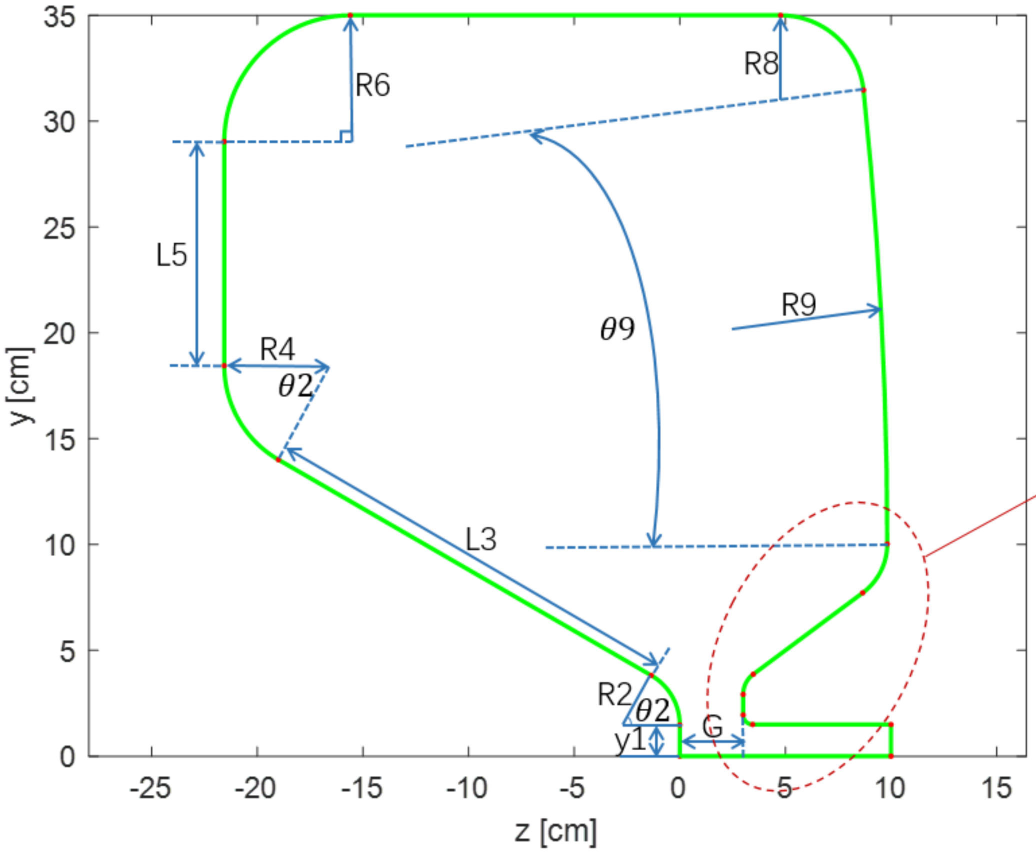
清華大學 Tsinghua University

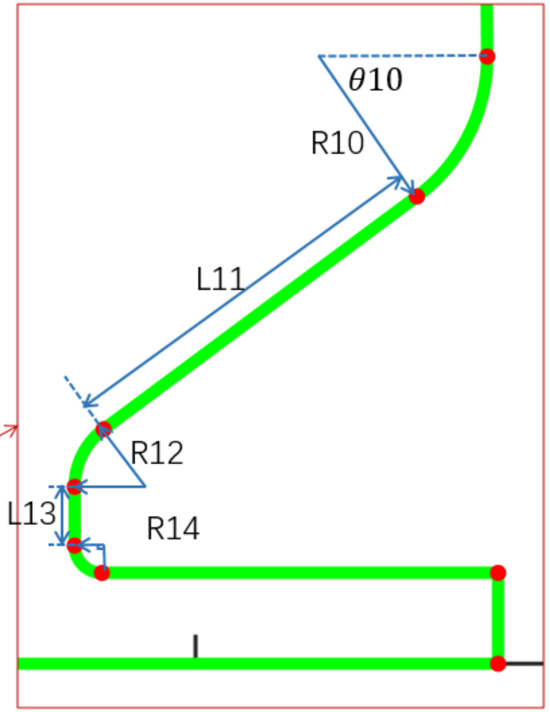
- 2019.03 MOU signed between Tsinghua and SHINE
- 2019.12 finish gun design， start manufacturing
- 2021.1 finish the manufacturing of the prototype gun
- 2021.12 achieve 30 kW CW operation of the prototype gun
- 2022.4 finish the manufacturing of the second gun
- 2022.8 achieve 70 kW CW operation of the second gun
- 2022.8 first photoelectron beam produced
- 2023.1 achieved good beam performance

Physical design of the VHF gun

清華大學 Tsinghua University

After careful optimization of the gun profile, the rf parameters are as follows:



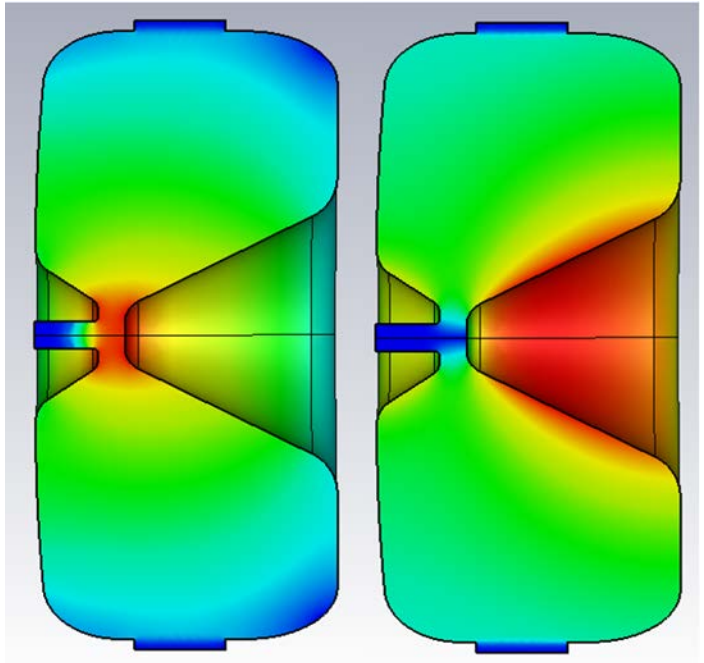


Physical design of the VHF gun

Tsinghua University

After careful optimization of the gun profile, the rf parameters are as follows:

rf parameters in design	
Frequency	216.67 MHz
Cathode gradient	30 MV/m
Input power	90.4 kW
Maximum surface electric field	36.99 MV/m (2.5kilp)
Maximum surface power density	28.45 W/cm^2
Voltage	868 kV

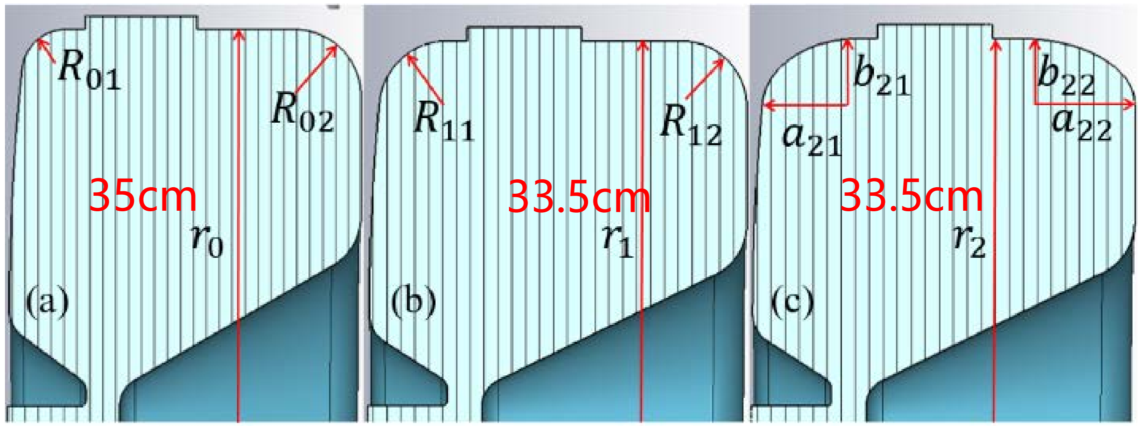


E field　　H field

Physical design of the VHF gun

Gun profile optimization to reduce the multipacting:

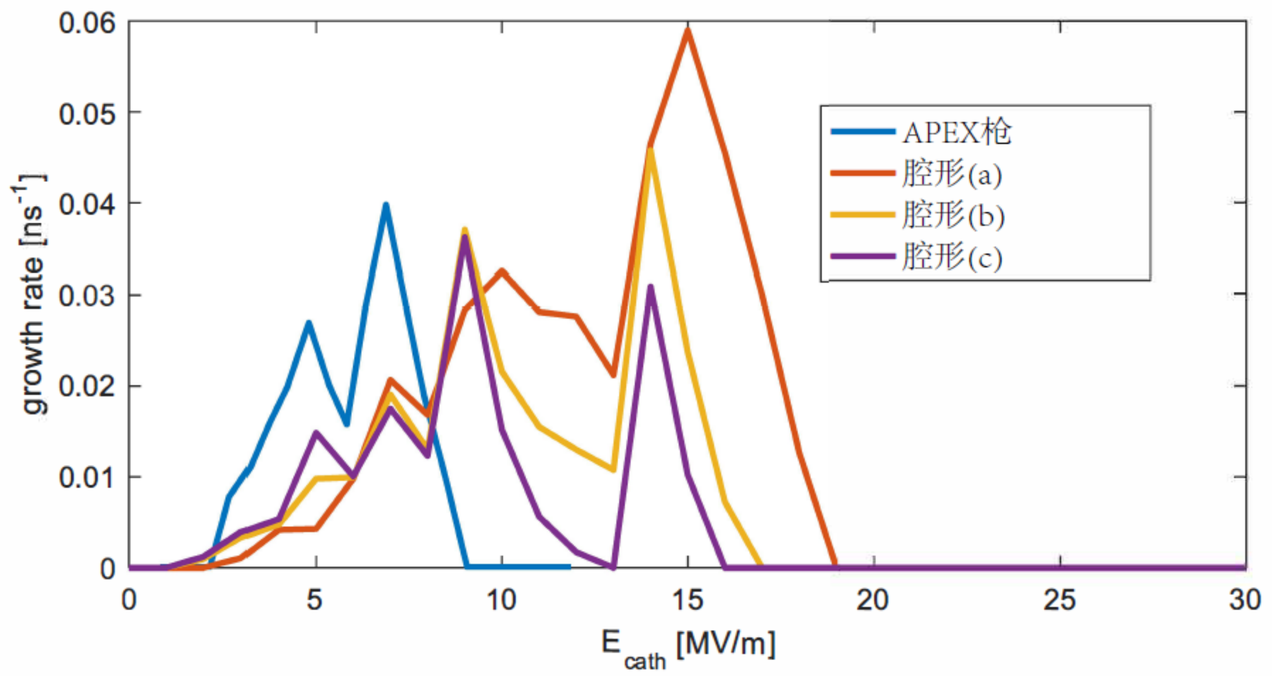
$$N_e(t) = N_0 \times 10^{\alpha t},\ \alpha \text{ is the growth rate}$$



(a) gun shape 1. (b) gun shape 2. (c) gun shape 3.

Reduce the radius

Change rounded corners to elliptical

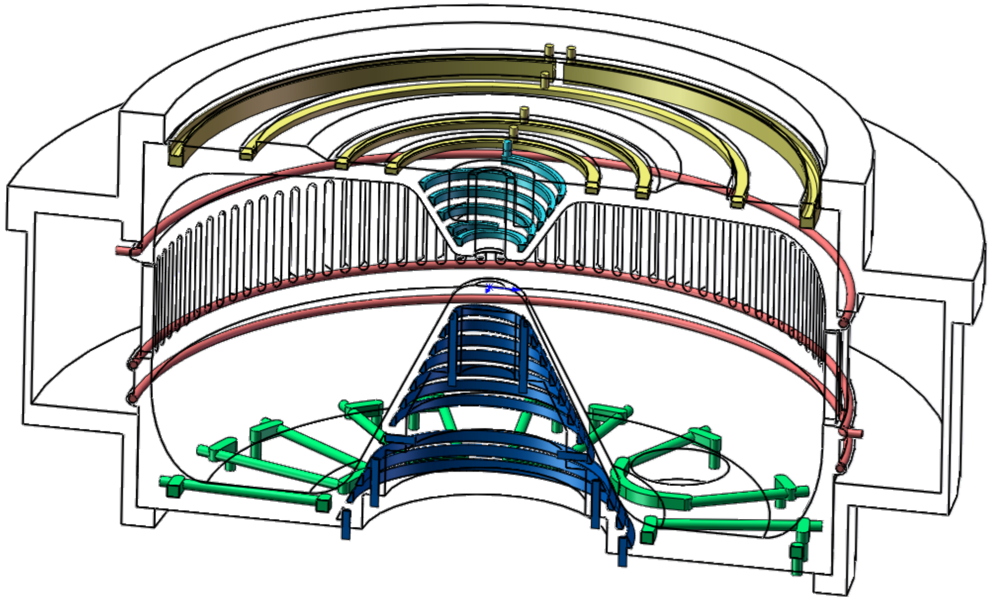


The designed cathode gradient：30 MV/m
No multipacting for gradient higher than 16 MV/m

Physical design of the VHF gun

Tsinghua University

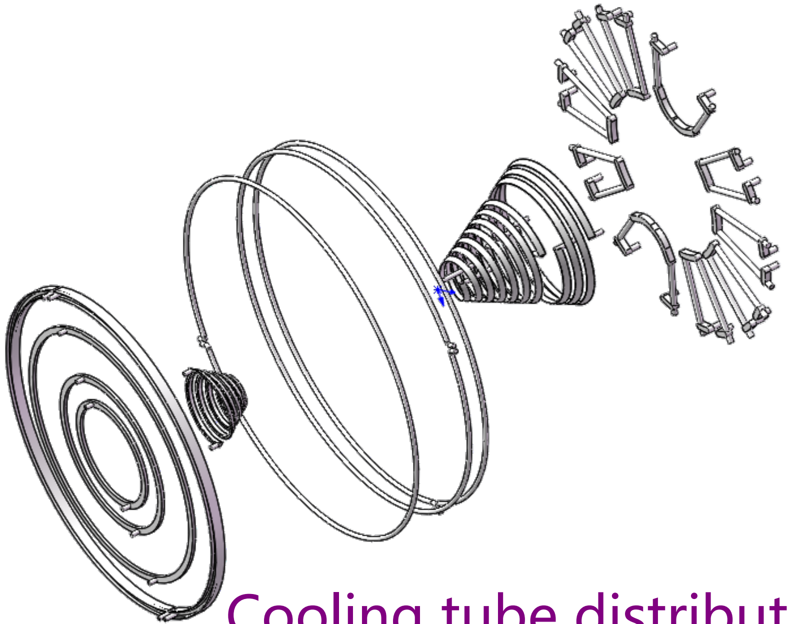
Cooling tube design of the VHF gun:



Initial water temperature: 300 K
Maximum pressure difference in the pipe : 0.12MPa
Total flow rate : 25.7 m^3/h

23 independent water cooling pipes :

- 10 in the cathode end cap;
- 4 in the cathode nose;
- 5 in the anode end cap;
- 1 in the anode nose;
- 3 on the rf wall.



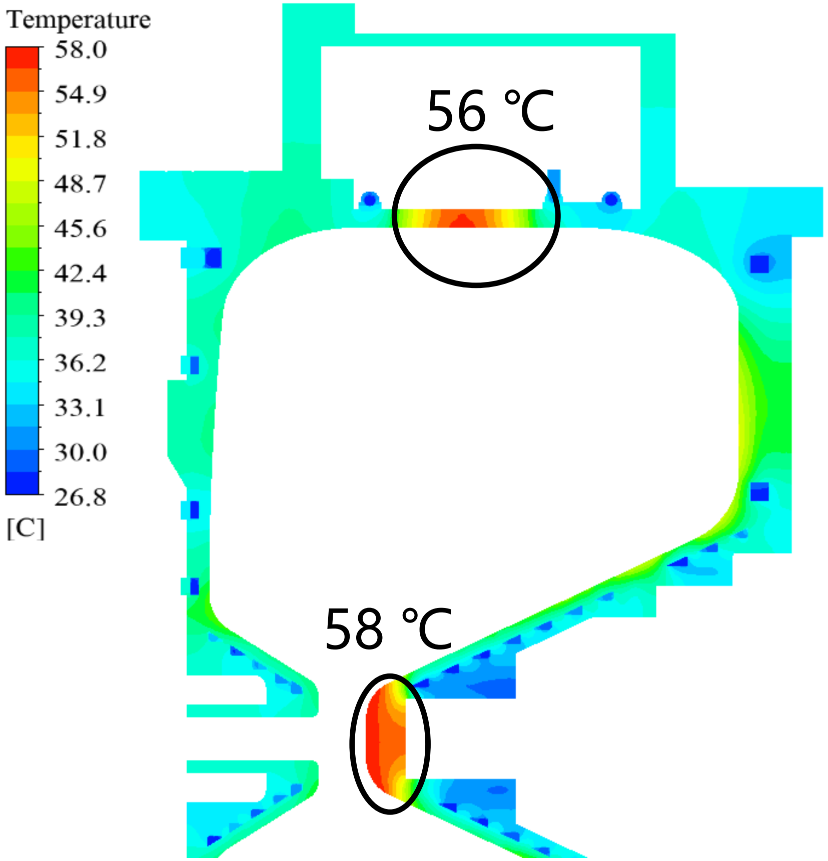
Cooling tube distribution

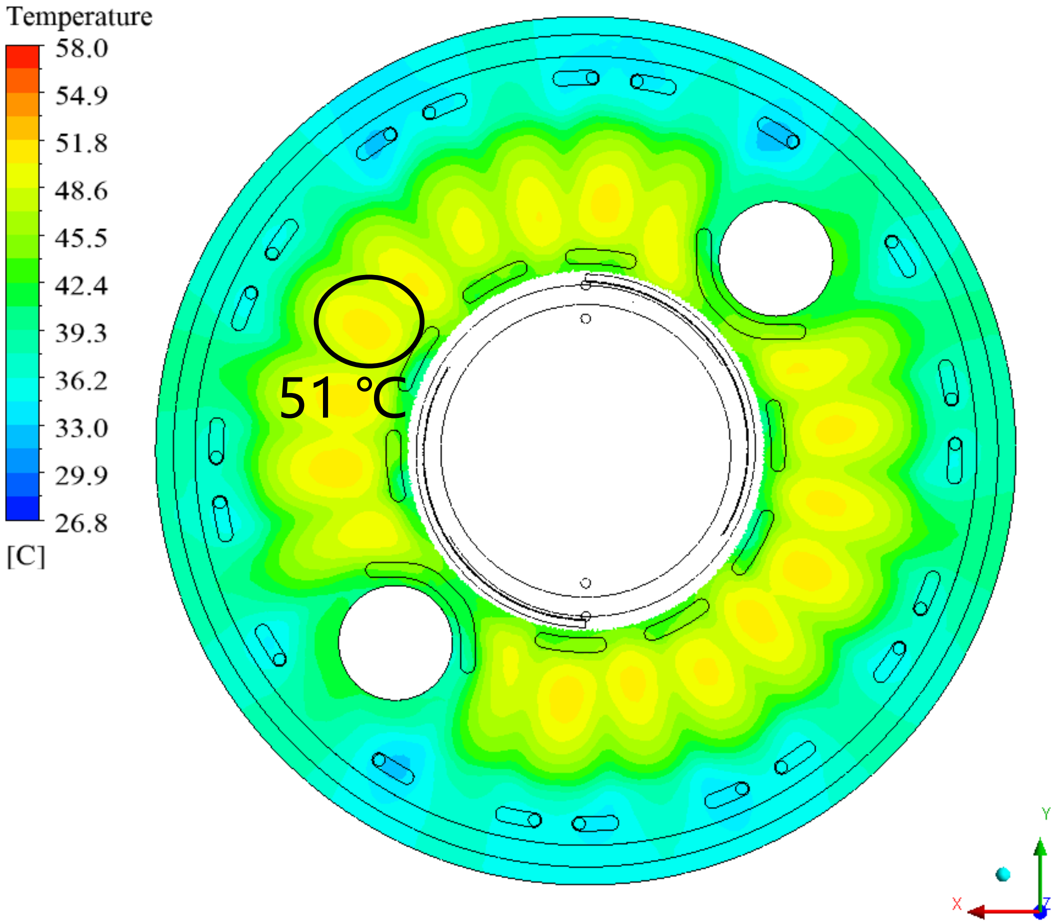
Physical design of the VHF gun

Tsinghua University

Temperature distribution of the VHF gun:

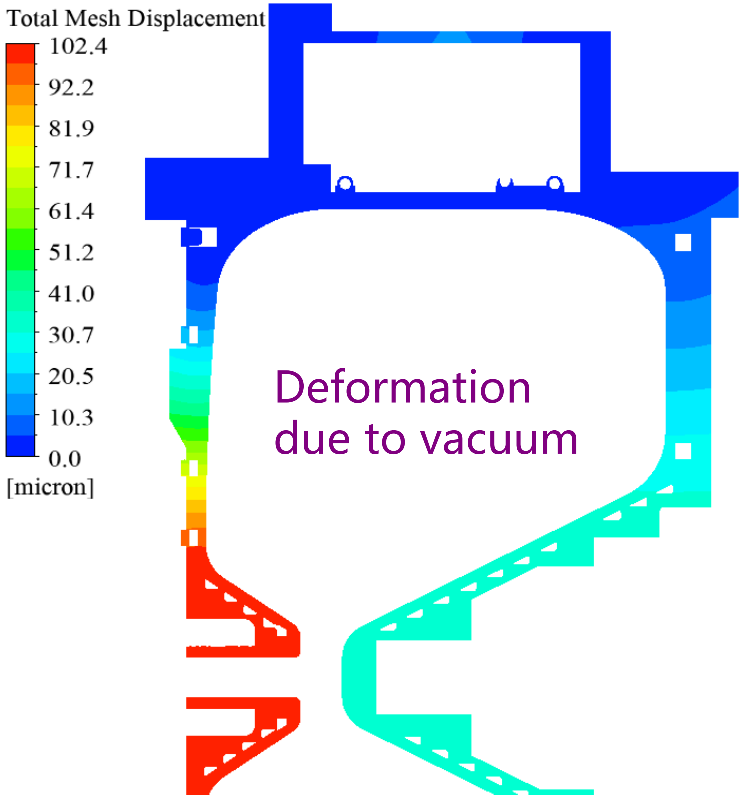
Input power: 90.5 kW
Cathode gradient: 30 MV/m



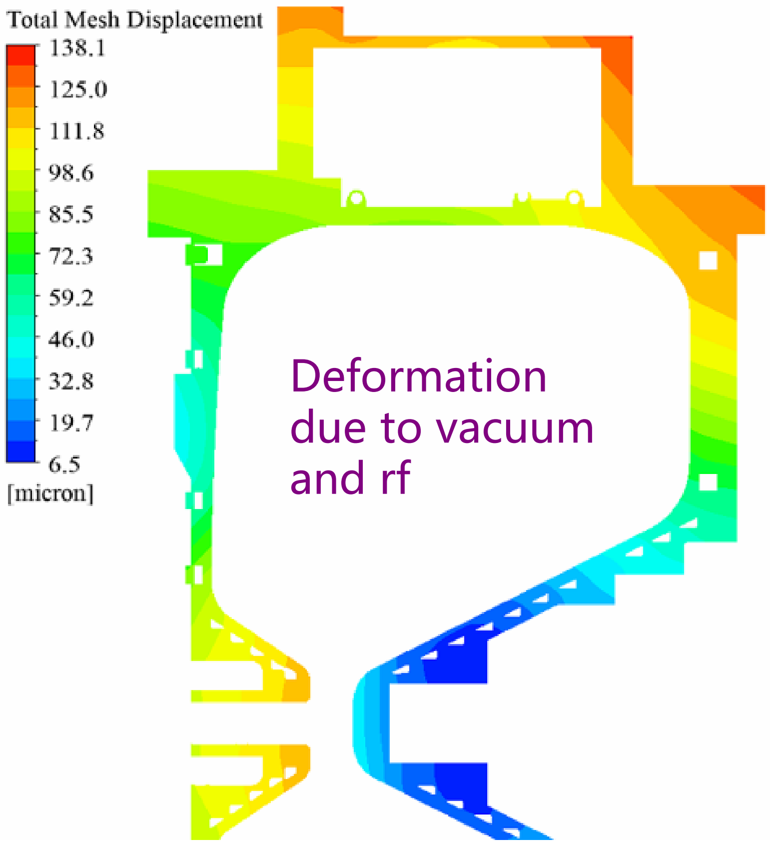


Physical design of the VHF gun

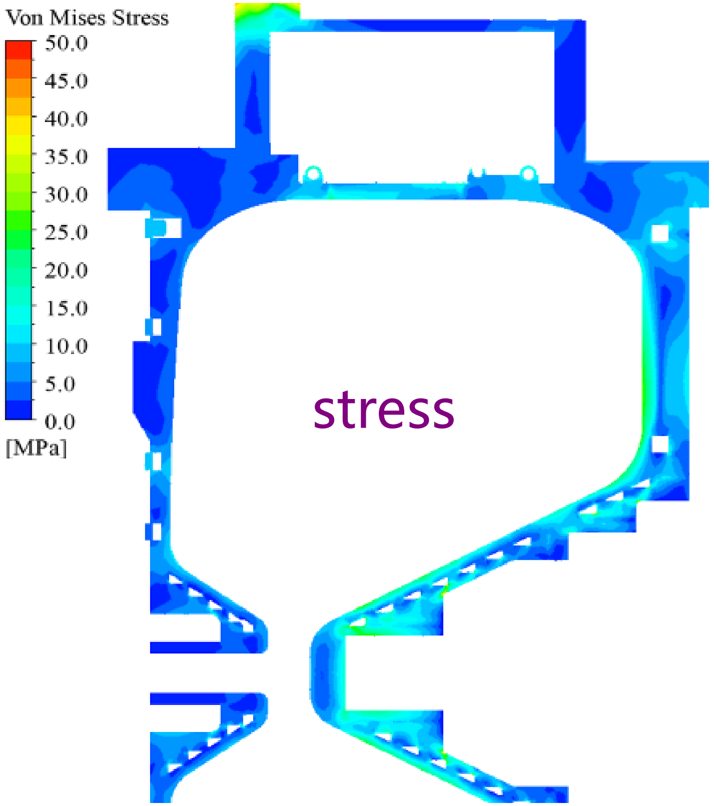
Distribution of deformation and stress:



The gap between anode and cathode is reduced by 133 um due to the vacuum



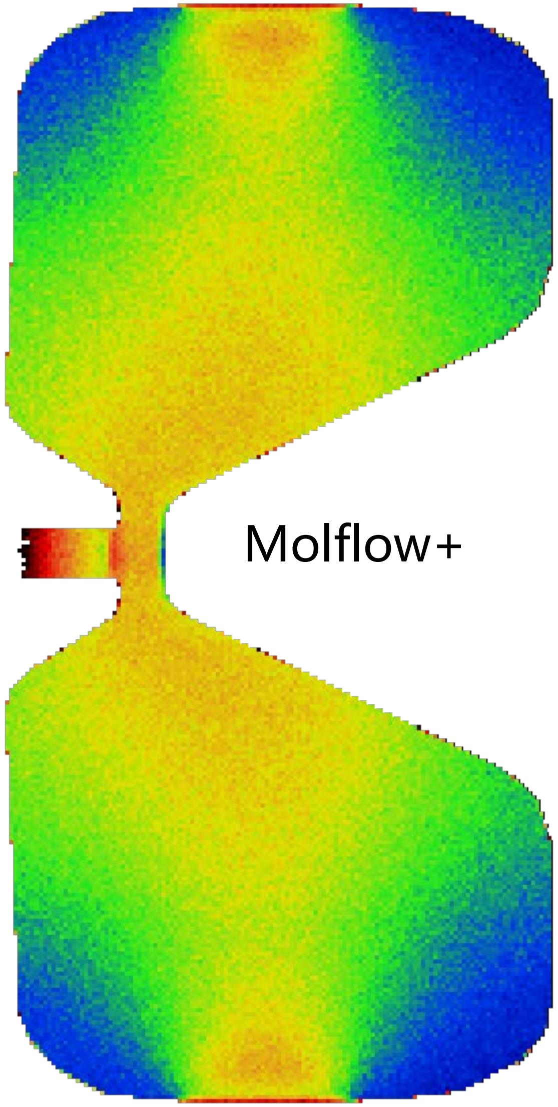
The gap between anode and cathode is reduced by 155 um due to the vacuum and rf, corresponding to a 138 kHz frequency shift.



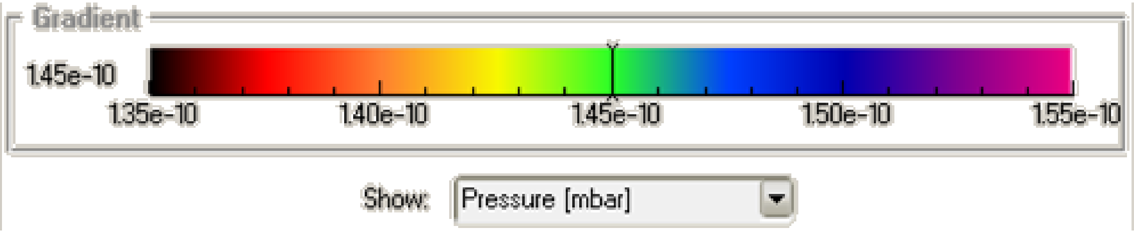
The maximum stress in the copper part is less than 30 MPa

Physical design of the VHF gun

Vacuum simulation：



Molflow+

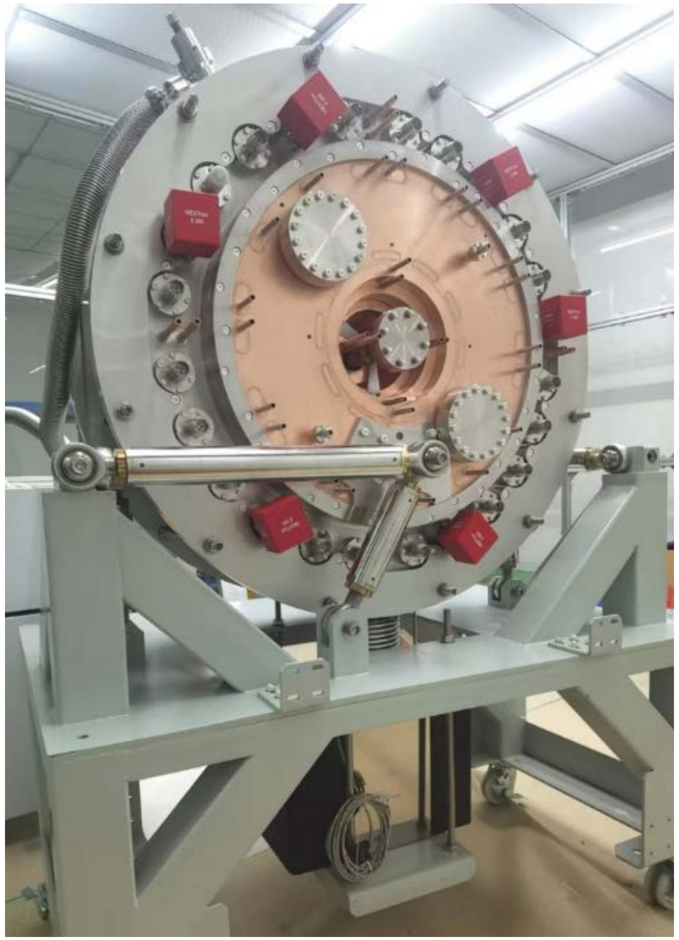


outgassing/area (mbar*l/s/cm^2):

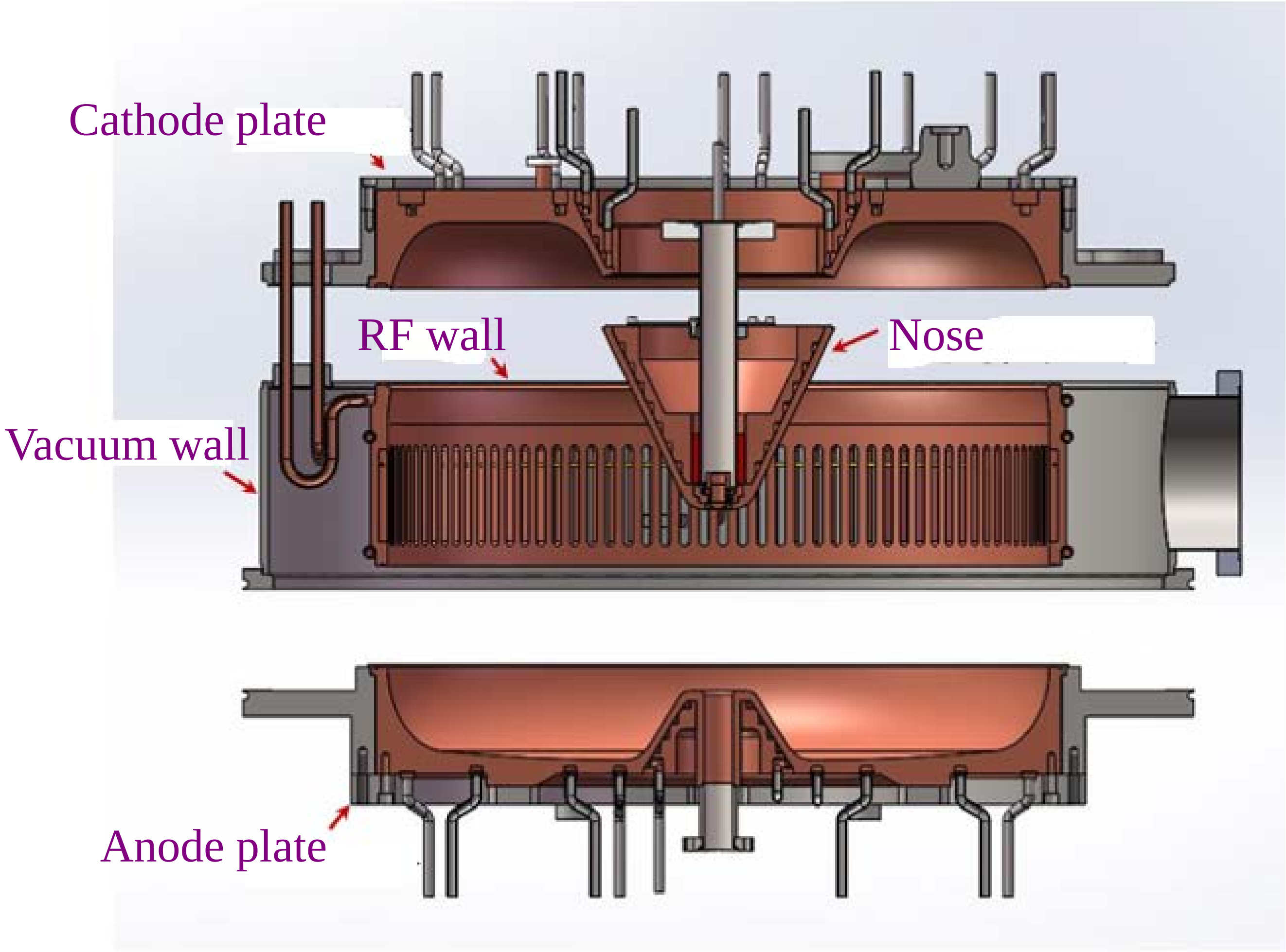
copper	4.5e-11	(OHFC mech. Poli 25h)
stainless steel	3.0e-12	(304 Varian std cleaning)

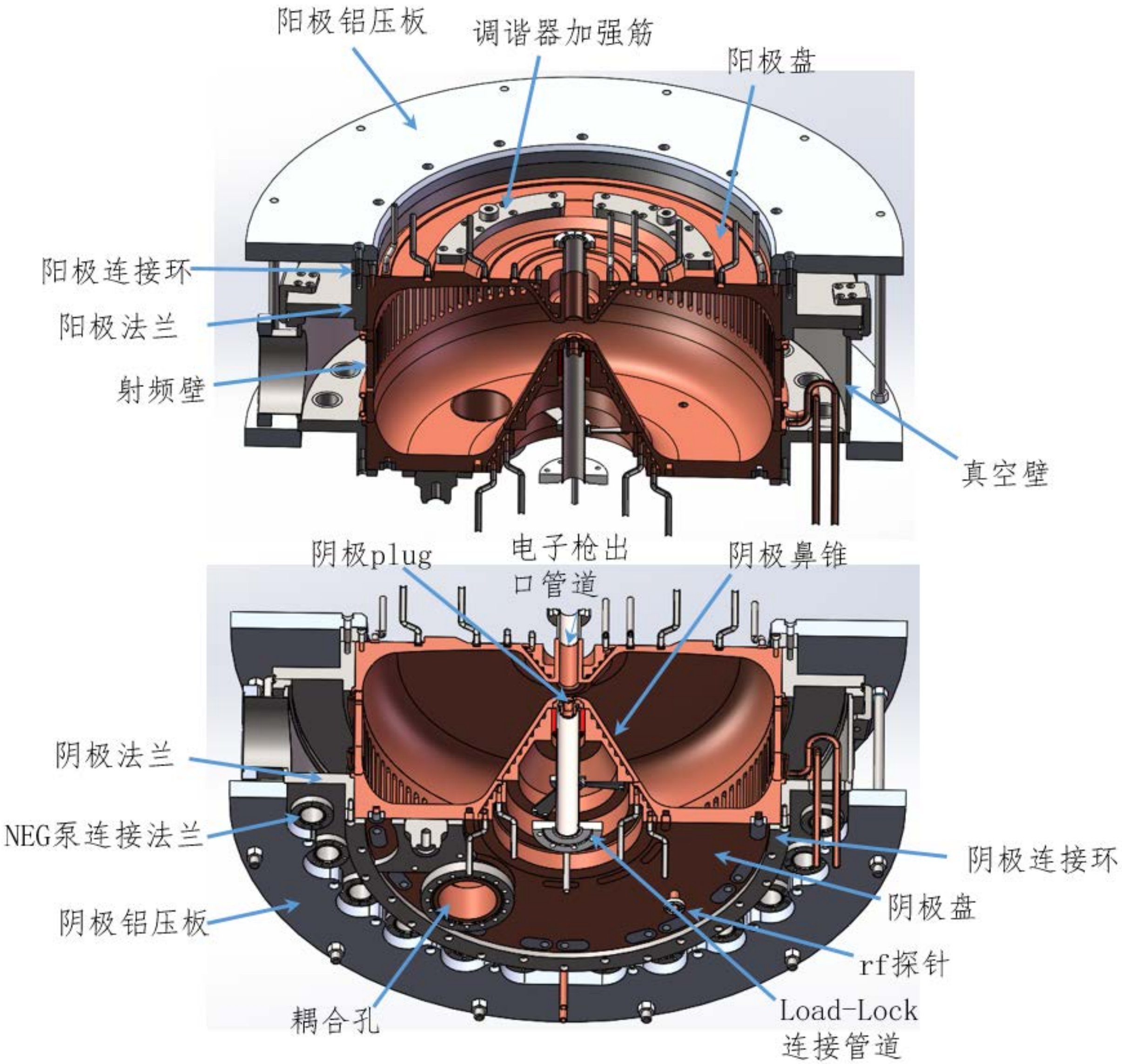
NEG pump：24*400 L/s;
Ion pump：300 L/s

cathode：1.45e-8 Pa



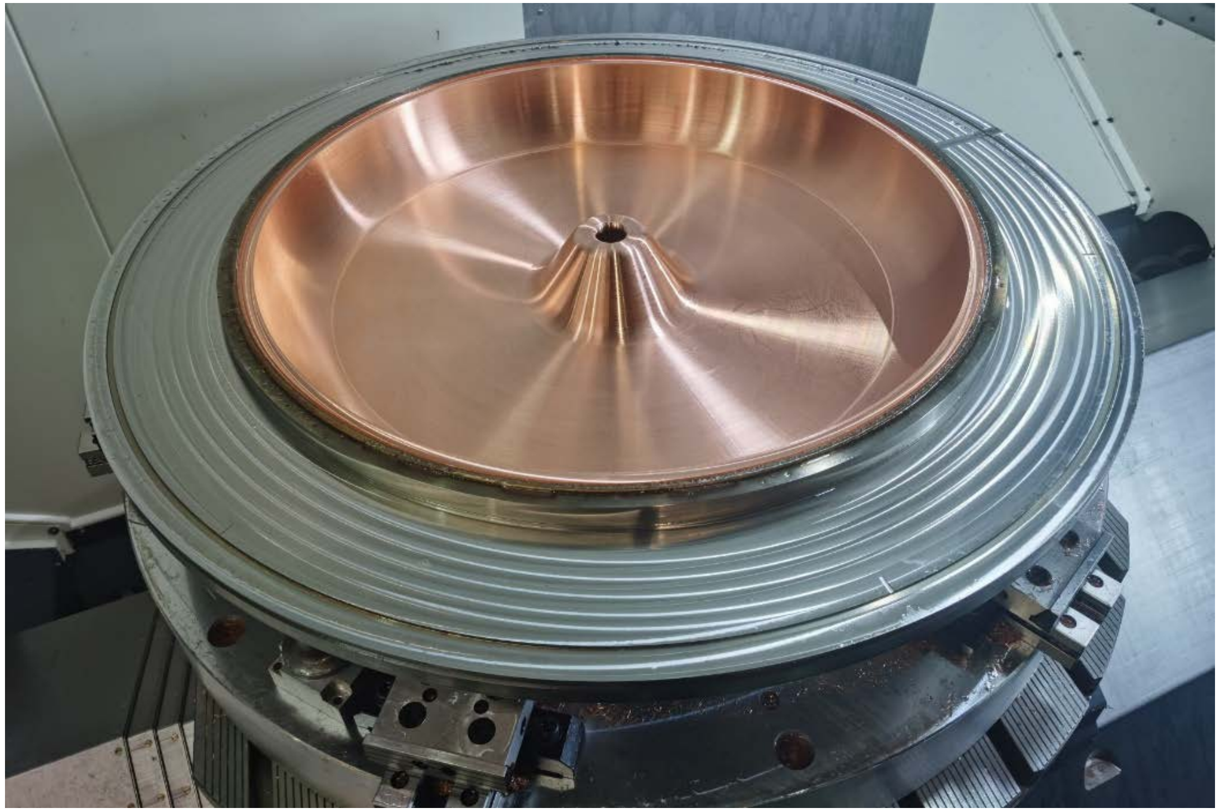
Mechanical design of the VHF gun



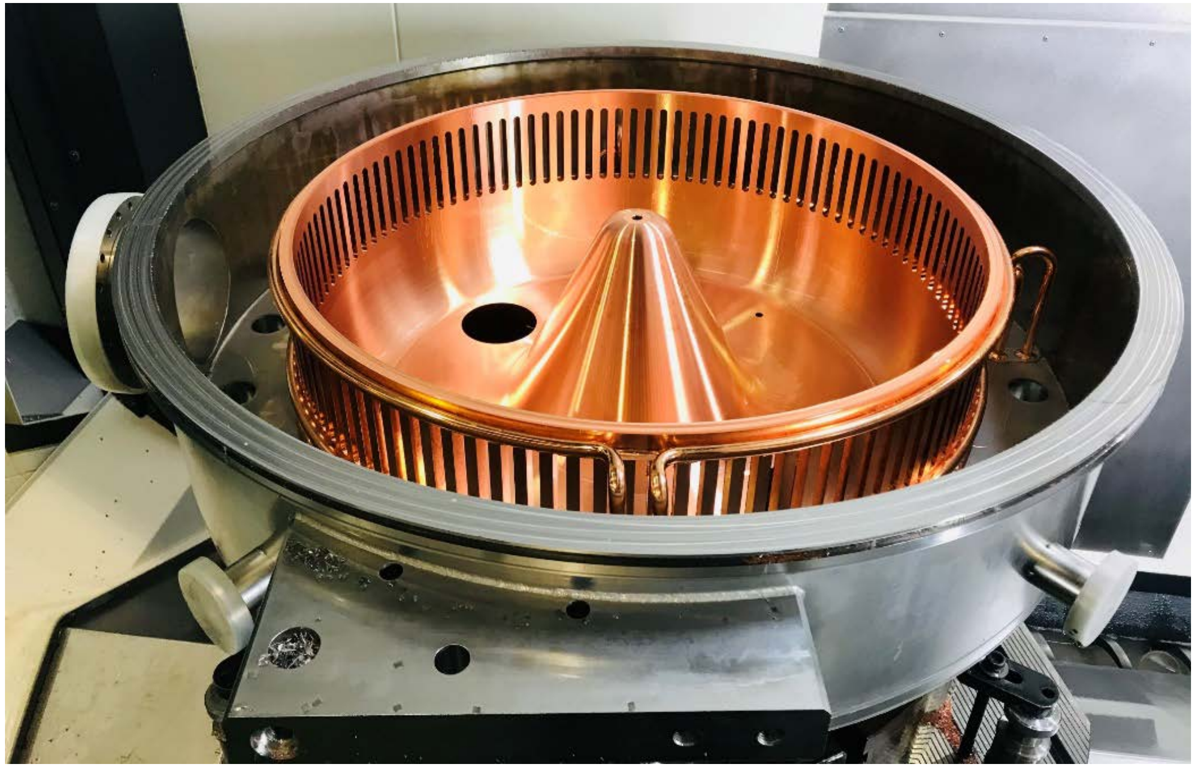


Machining of the VHF gun

Tsinghua University



Anode assembly after final machining

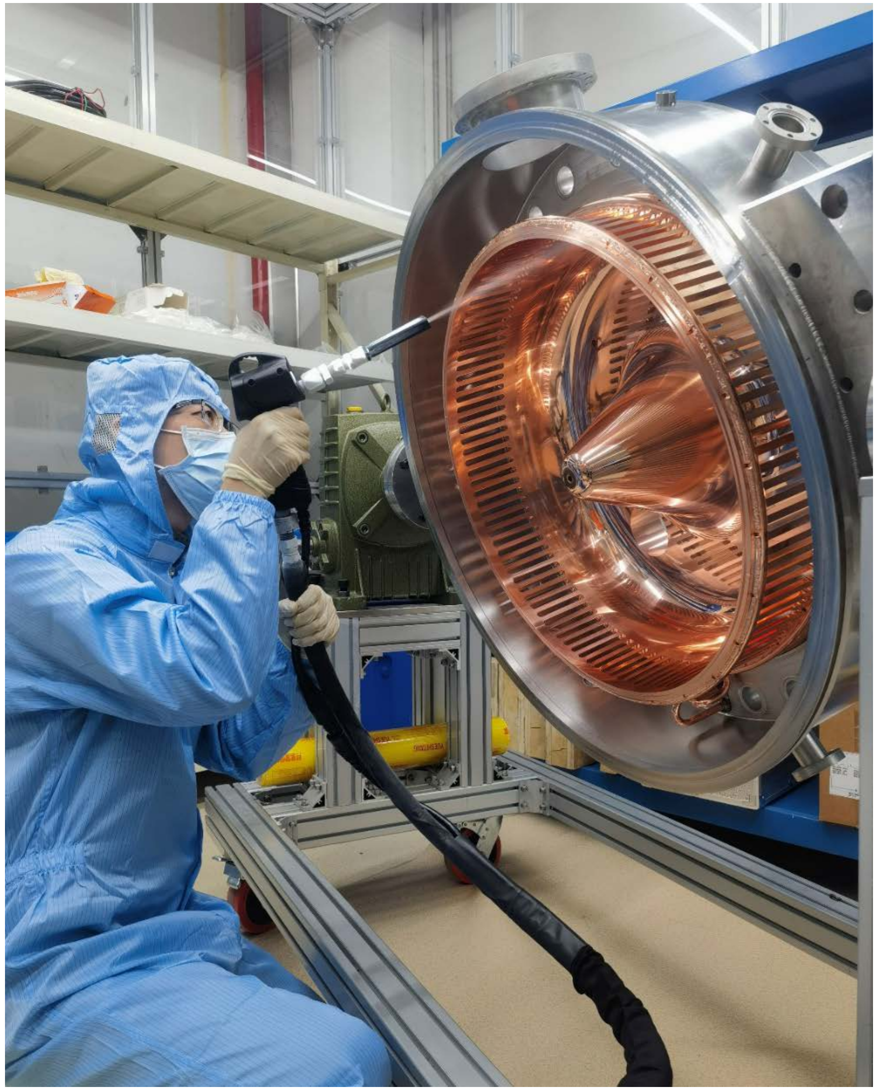


Cathode assembly after final machining

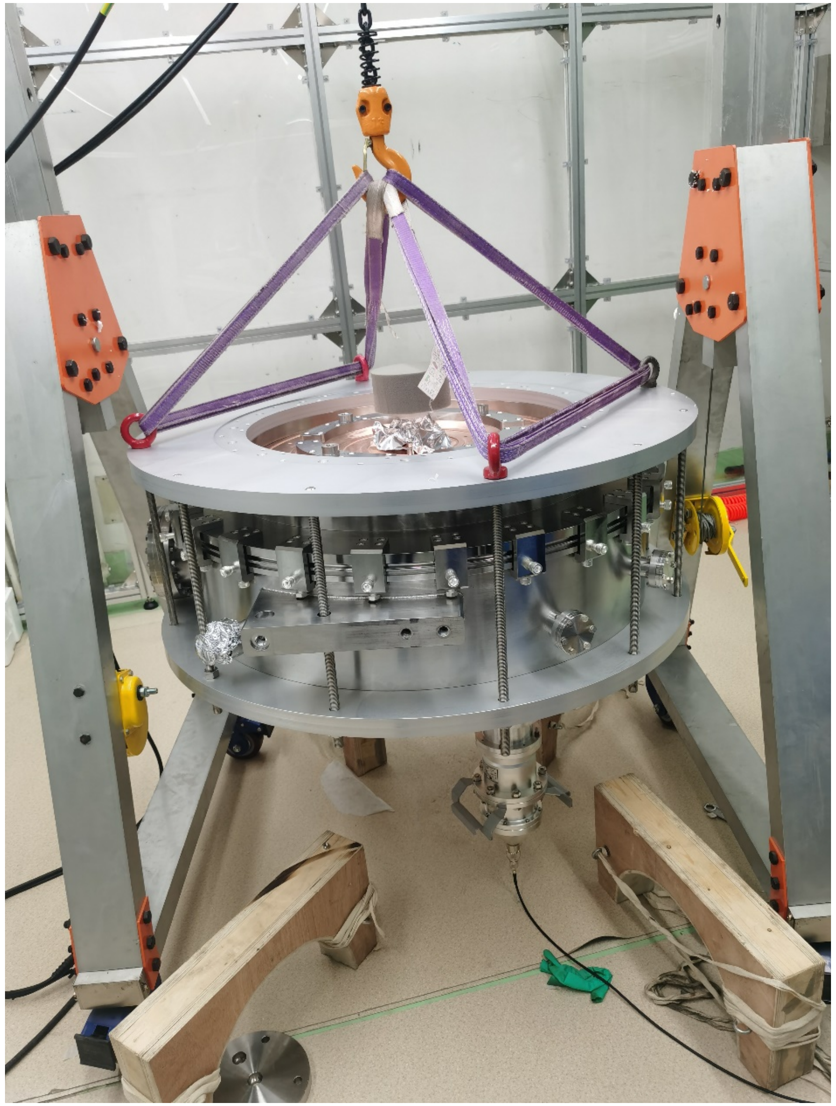
Machining of the VHF gun

Tsinghua University

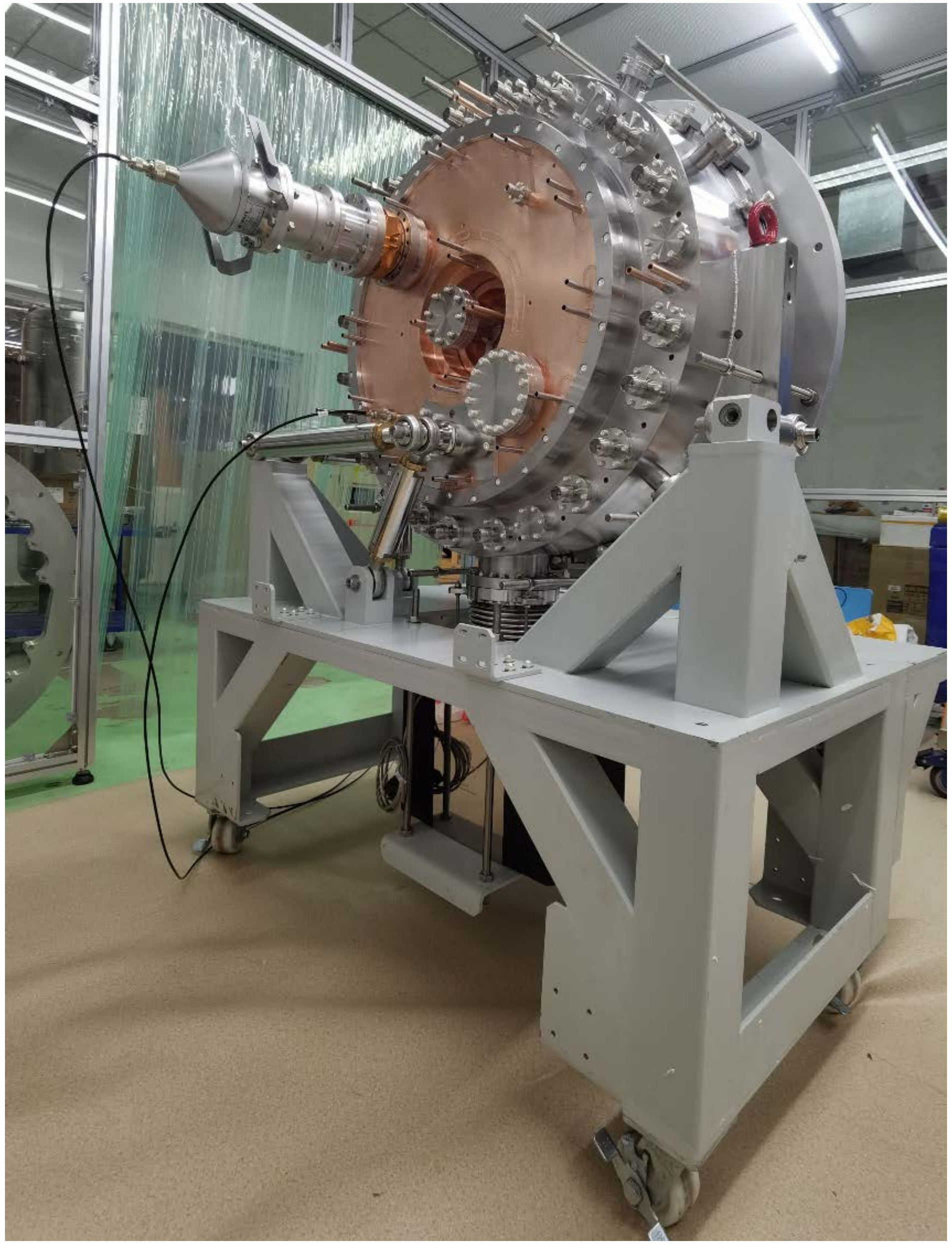
Dry-ice cleaning of copper surface

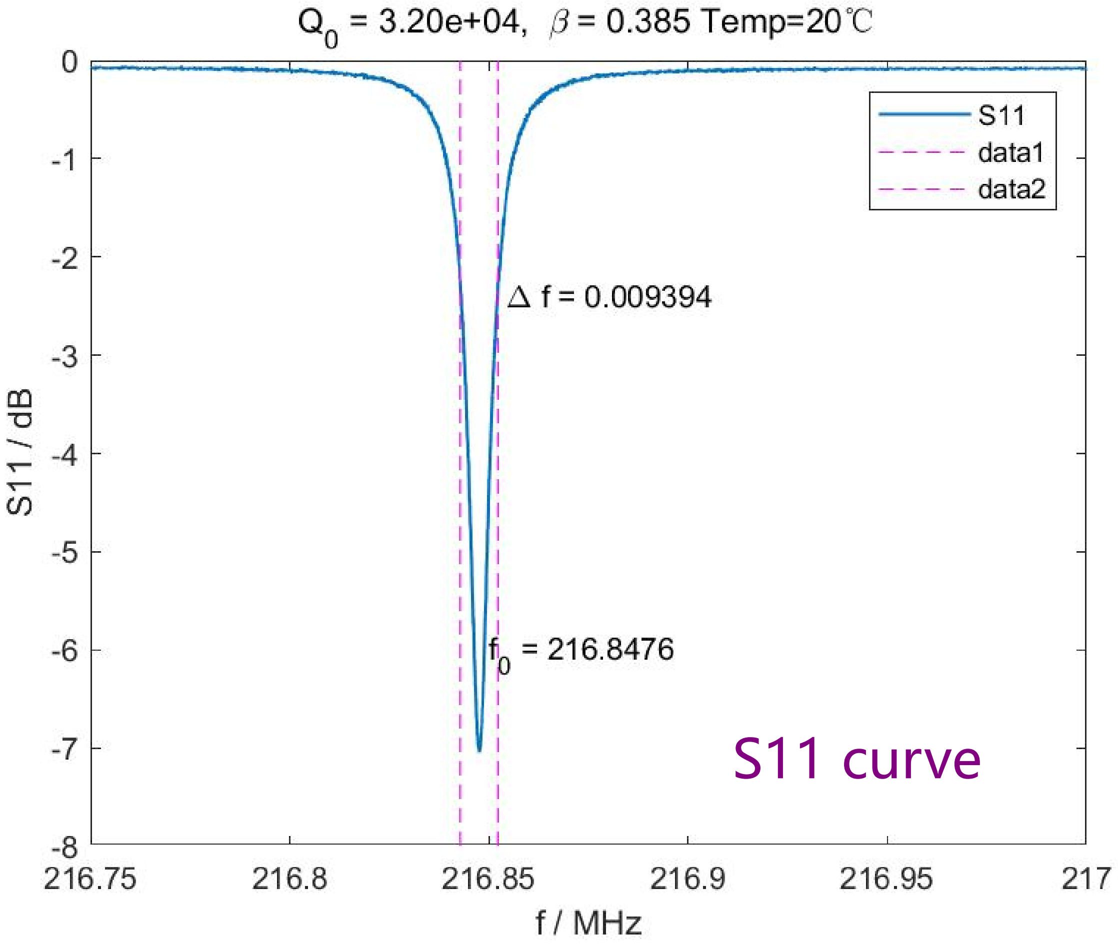


Installation of cathode and anode assemblies



Cold test of the VHF gun





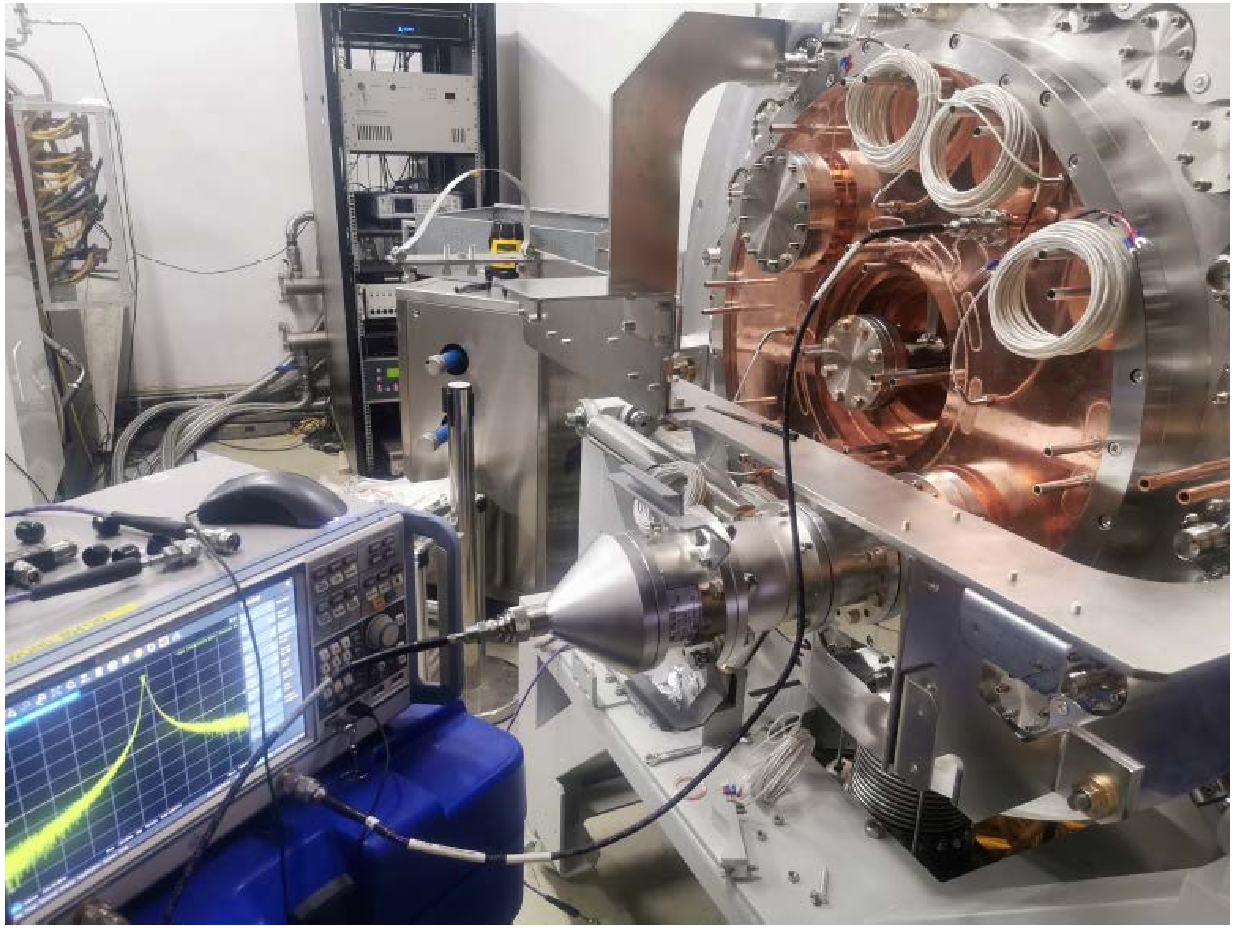
S11 curve

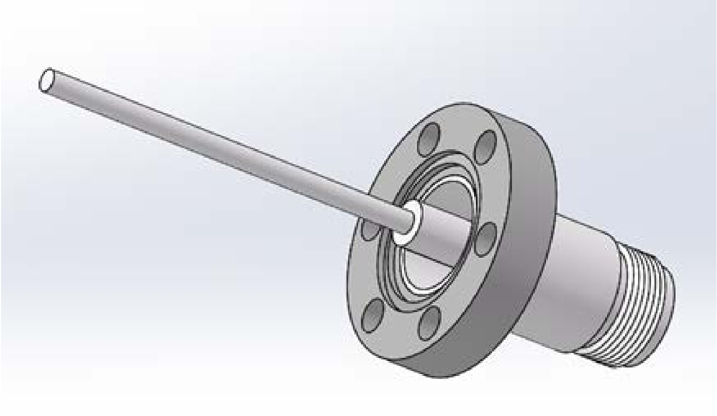
The measured frequency is in consistent with the design.
The quality factor is 5% less than the design.
Quality factor in design: 33717
Quality factor measured: 32000

Cold test of the VHF gun

Tsinghua University

The coupling of the electric probes on the gun measured by a vector network analyzer.



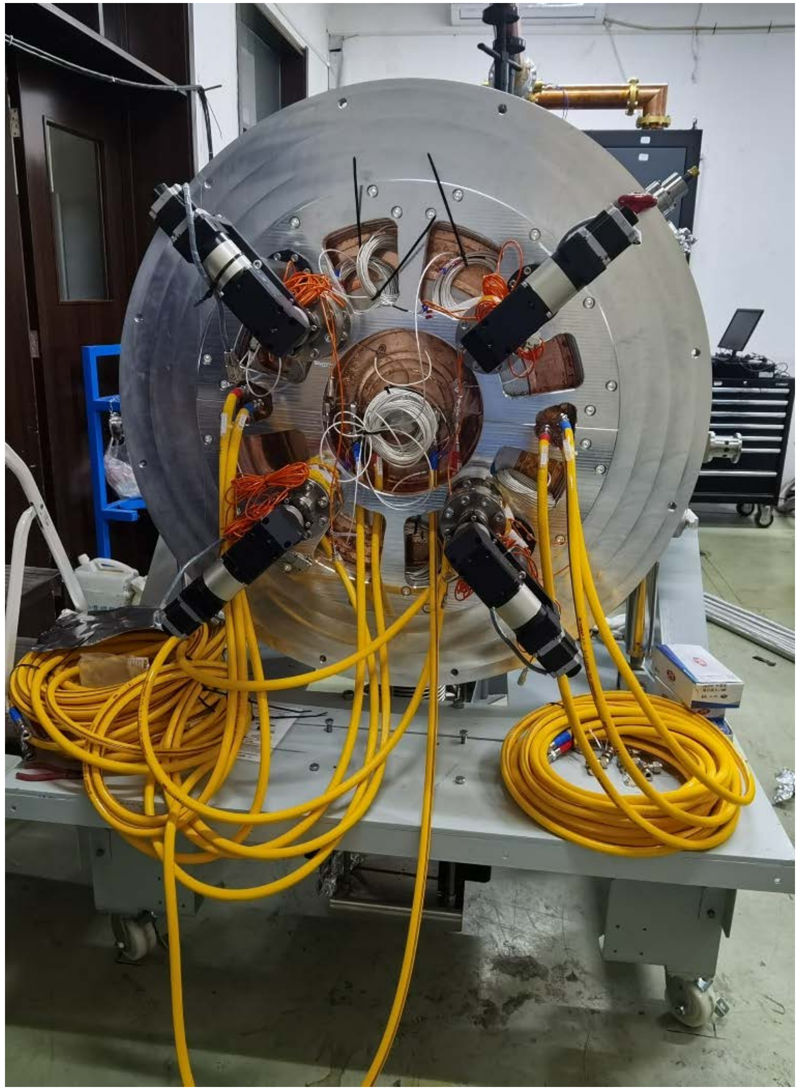


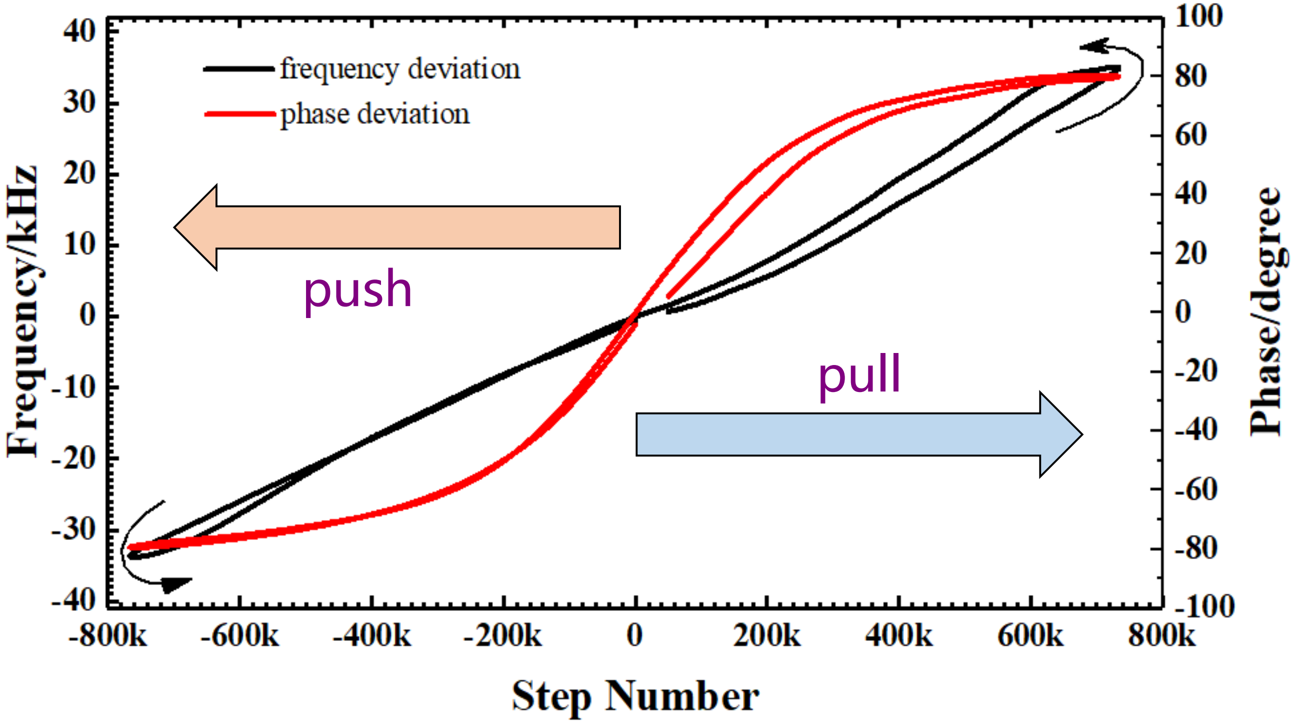
Coupling -58 dB

The degree of coupling can be flexibly adjusted by changing the length of the probe

Cold test of the VHF gun

Tuner test：



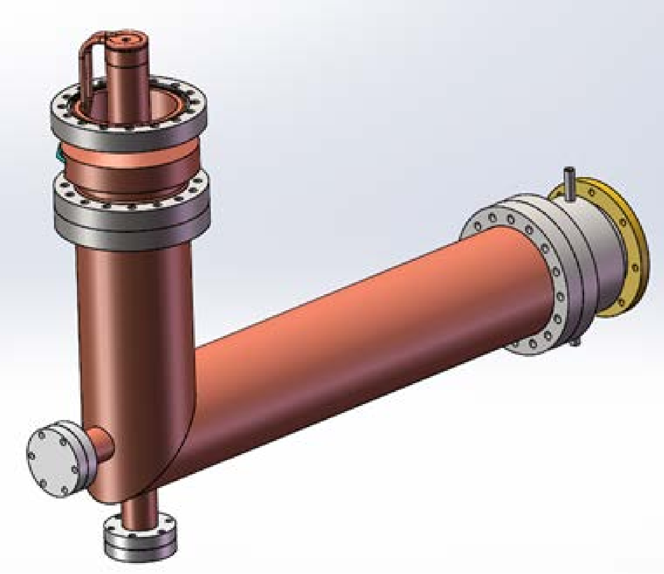


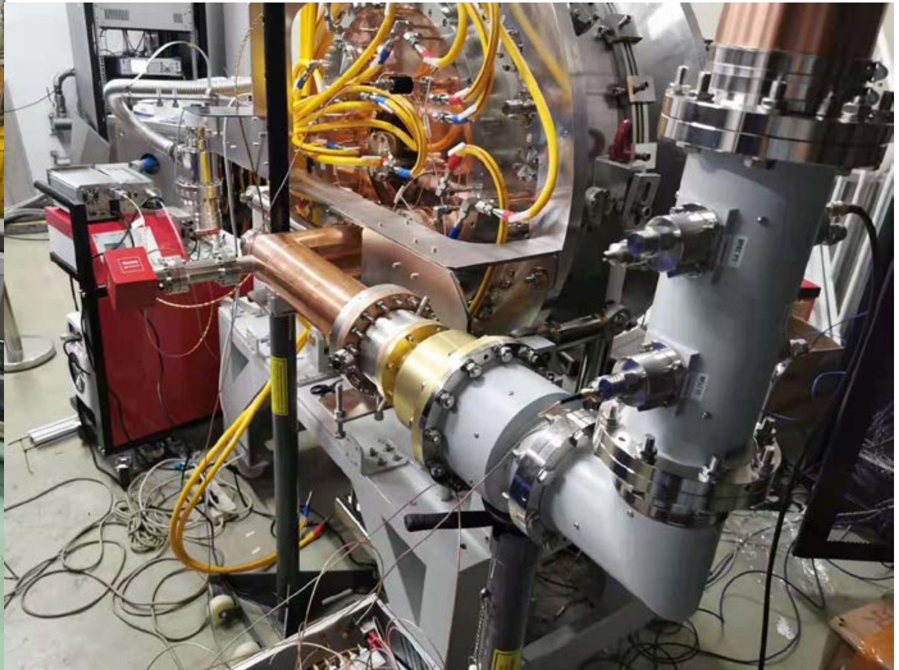
-3kN 0 3kN

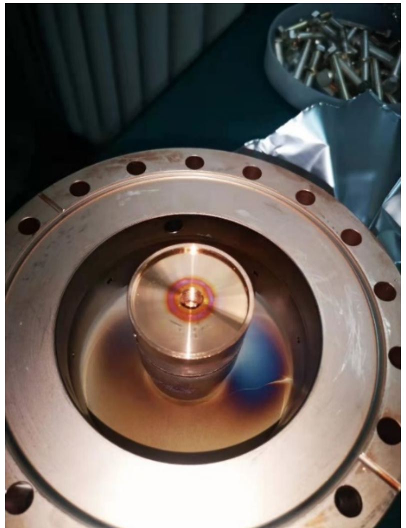
- The frequency shifts from -30 kHz to 30 kHz when the force of a single tuner scans from -3 kN to 3 kN. The frequency shift sensitivity is 2.5 kHz/kN. The phase change range is (-80 deg, 80 deg).
- The maximum total force of the four tuners is (-40 kN, 40 kN), thus the maximum frequency shift is (-100 kHz, 100 kHz)

Conditioning of the VHF gun

RF power coupler similar to APEX gun is used in the prototype gun

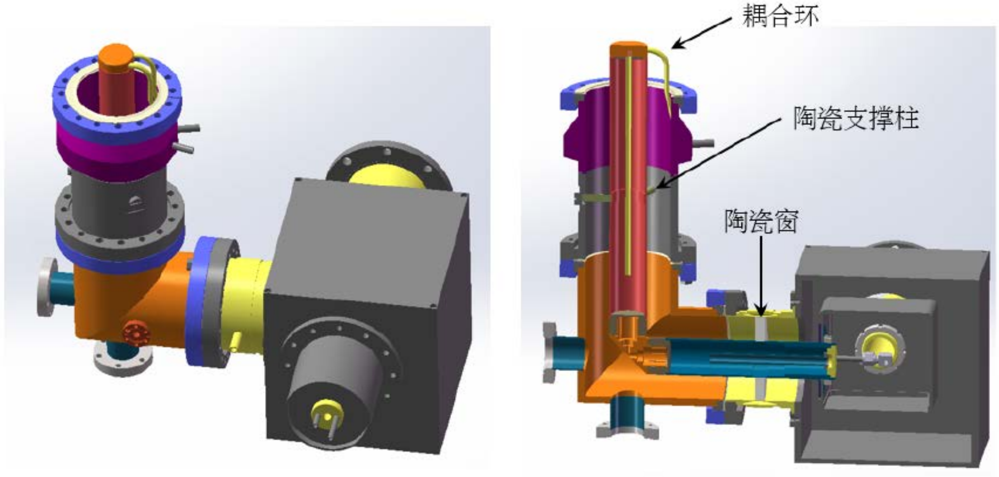






Conditioning of the VHF gun

RF power coupler update

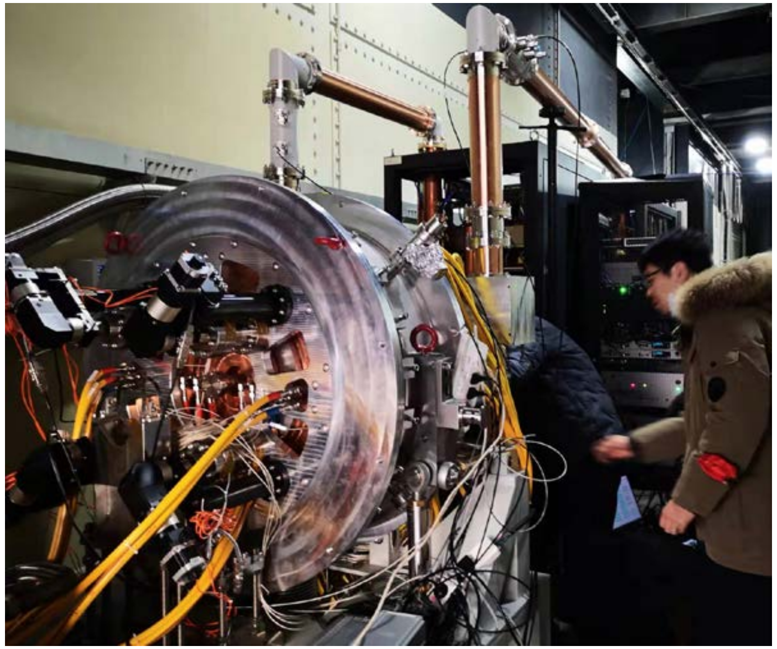


A. More water cooling channels

B. temperature monitoring

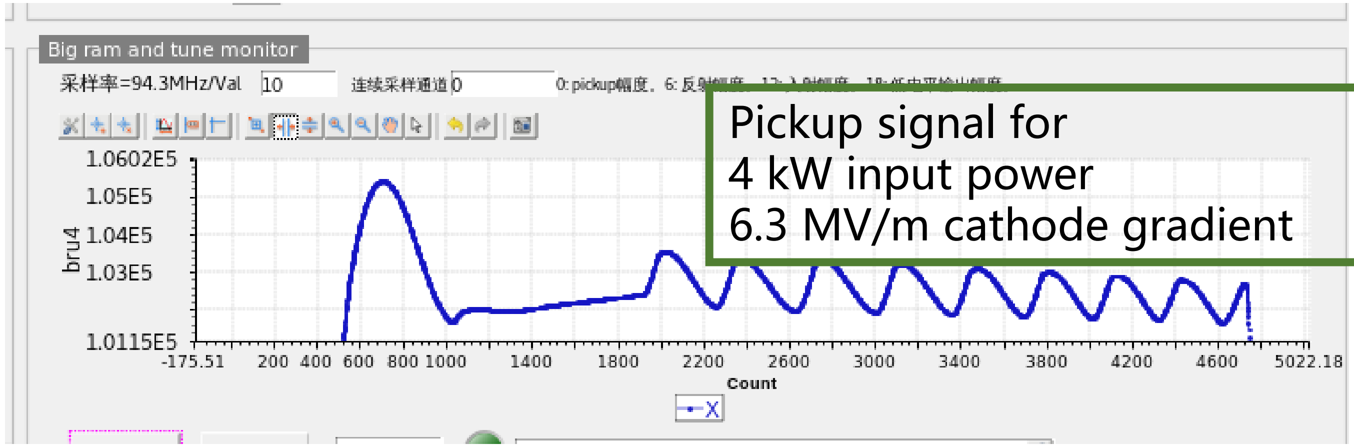
C. Breakdown monitoring

D. Microcurrent monitoring

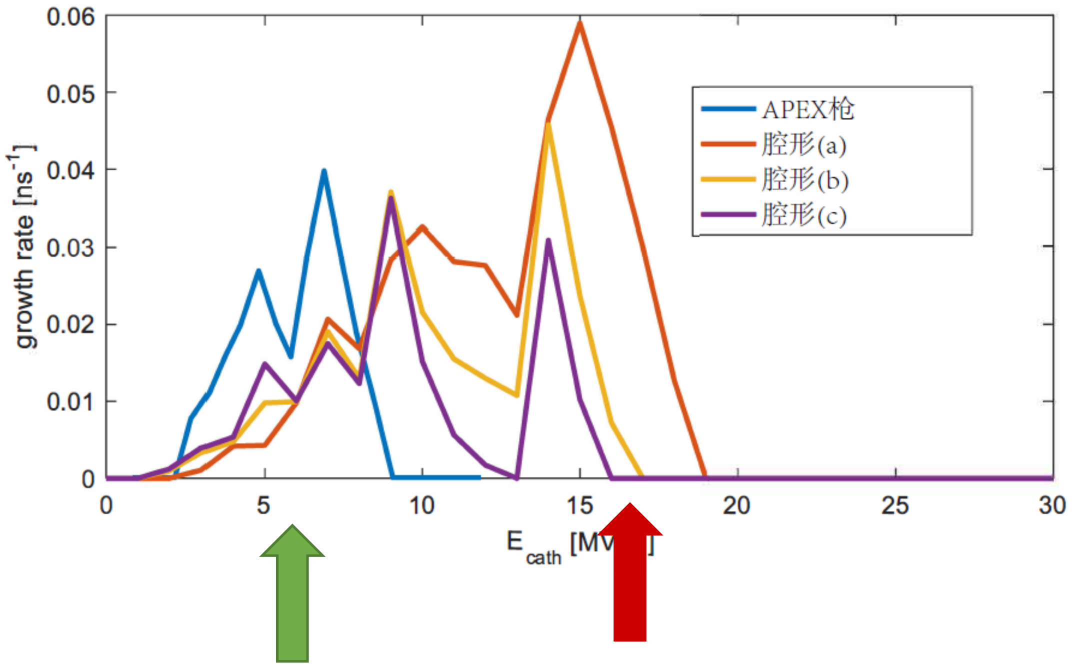


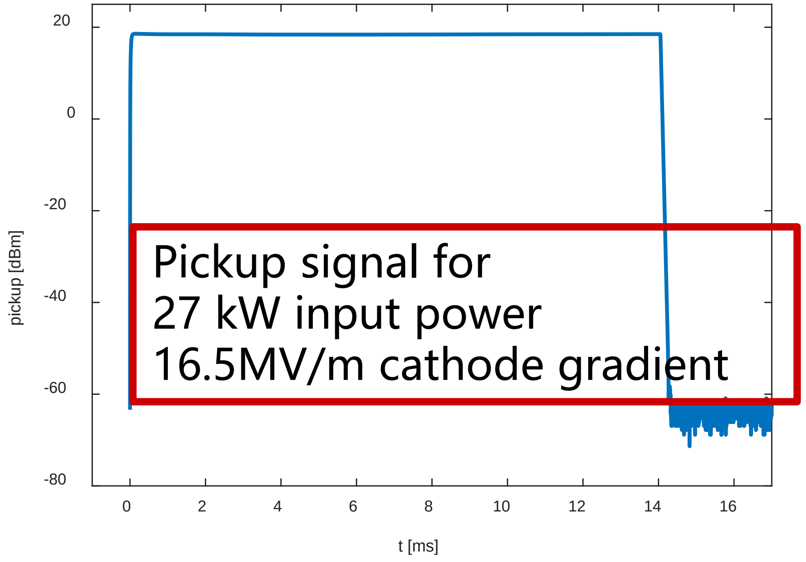
Conditioning of the VHF gun

Multipacting observation:



Pickup signal for
4 kW input power
6.3 MV/m cathode gradient





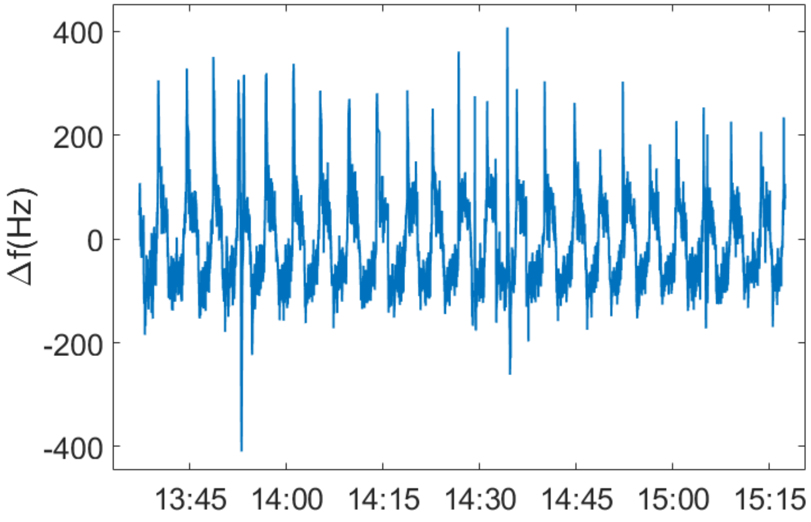
Pickup signal for
27 kW input power
16.5MV/m cathode gradient

The experimental results are consistent with the simulation.

Conditioning of the VHF gun

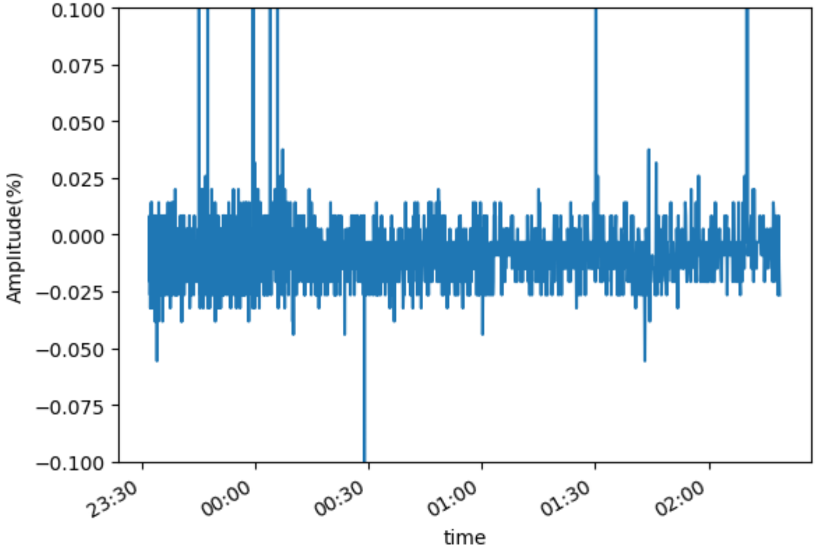
Operate at 216.667 MHz with 70 kW input power

$\Delta f \pm 200Hz$

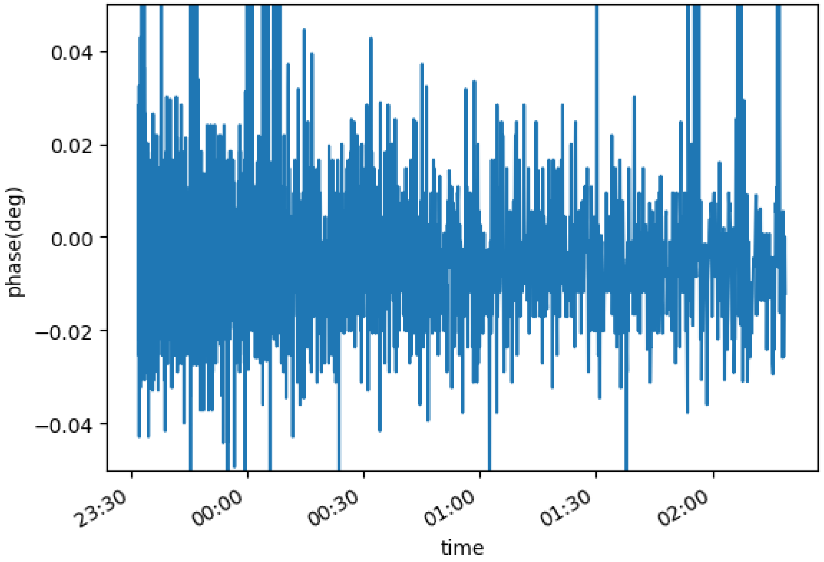


Stability:

amplitude jitter with closed-loop control， **1.1‱**



phase jitter with closed-loop control， 0.0148 deg



Conditioning of the VHF gun

RF performance

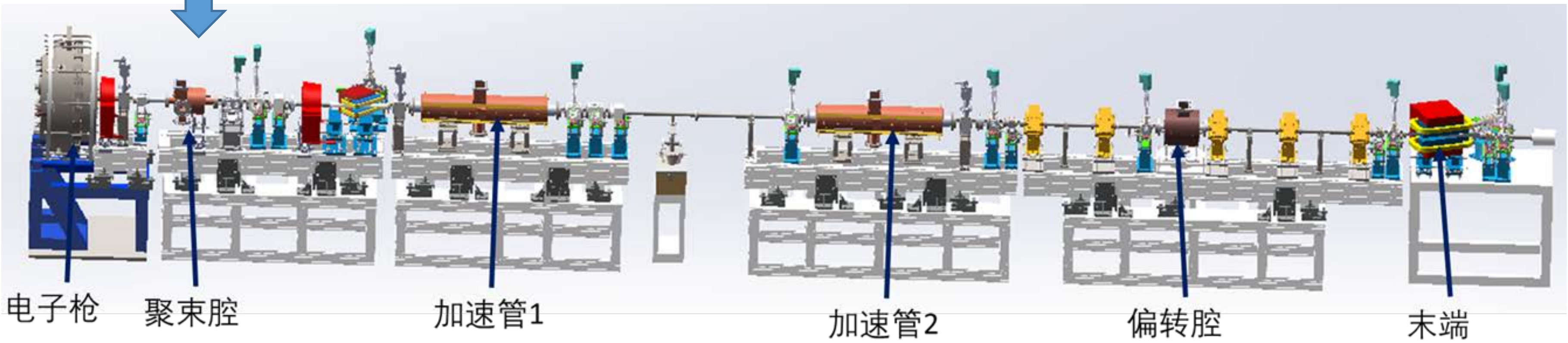
rf parameters	in design	achieved
Operation mode	CW	CW
Cathode gradient	30 MV/m	27 MV/m
Input power	90.4 kW	75 kW
Voltage	868 keV	780 keV

75 kW
Gun resonant frequency reduced about 80 kHz.

Beam commissioning of the VHF gun

Test beamline

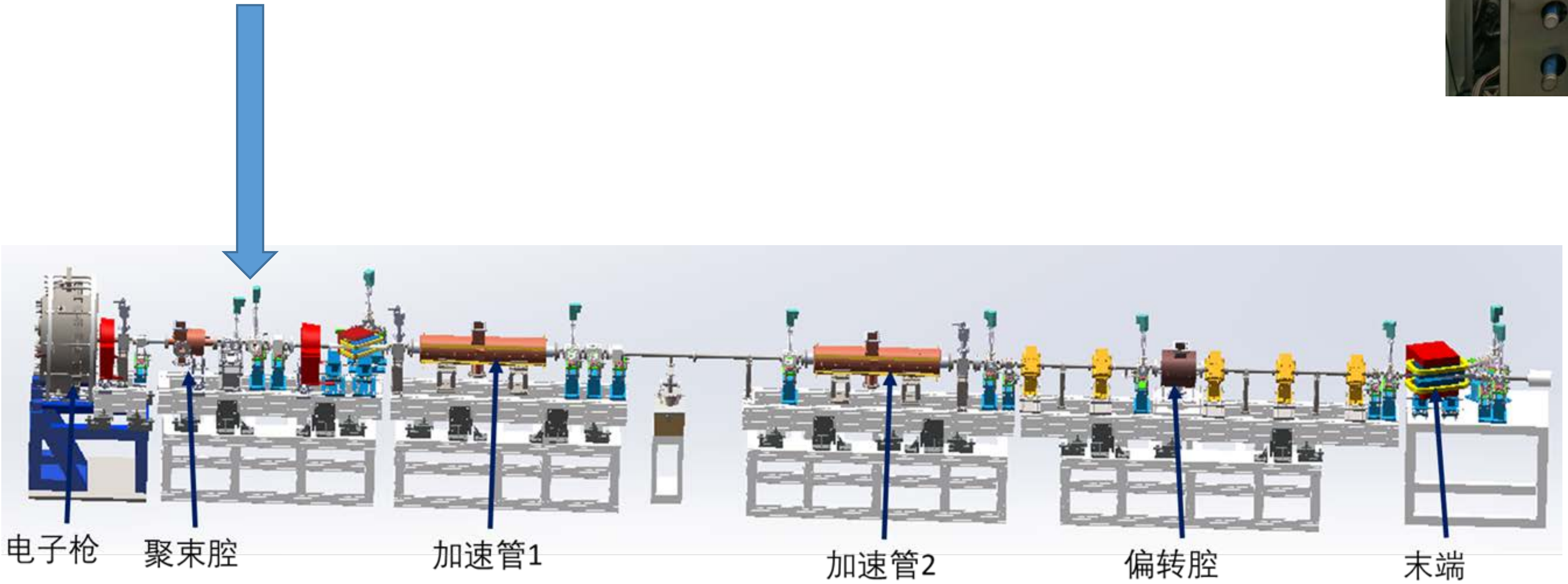
A buncher to compress the beam



Beam commissioning of the VHF gun

Test beamline

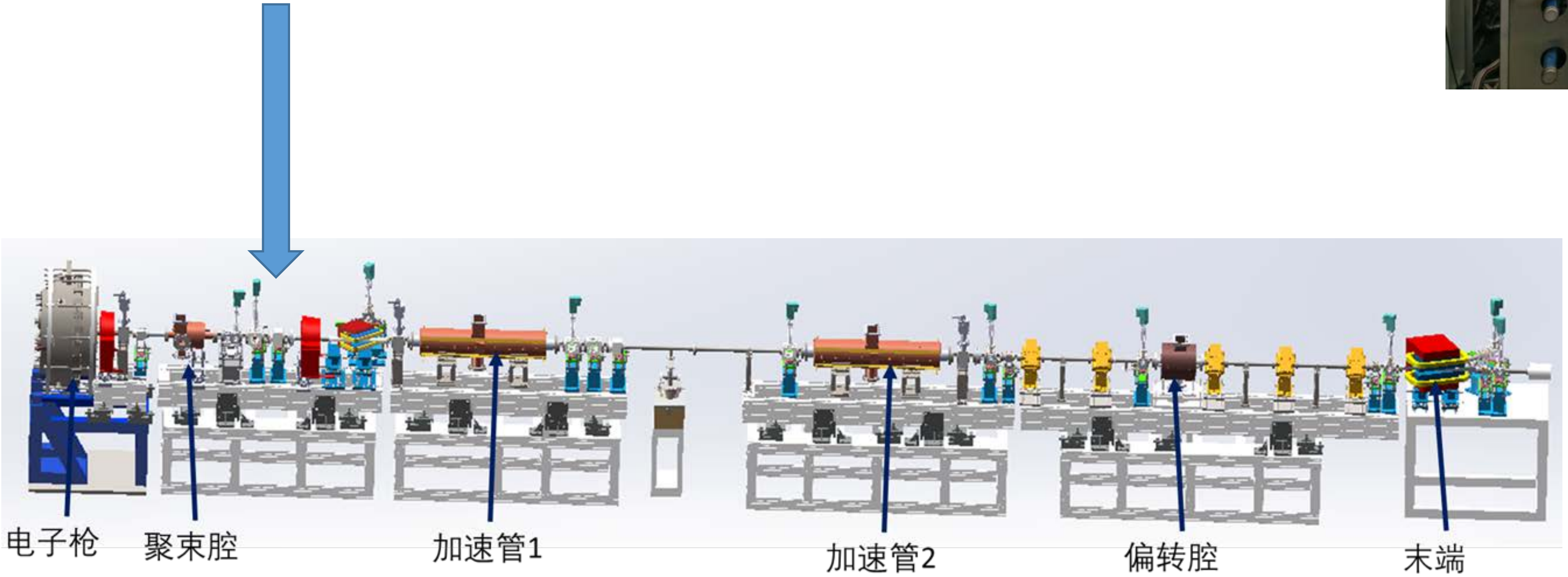
A Faraday cup (about 1.5 m downstream the gun exit) to measure the dark current



Beam commissioning of the VHF gun

Test beamline

An ICT to measure the bunch charge



Beam commissioning of the VHF gun

Test beamline

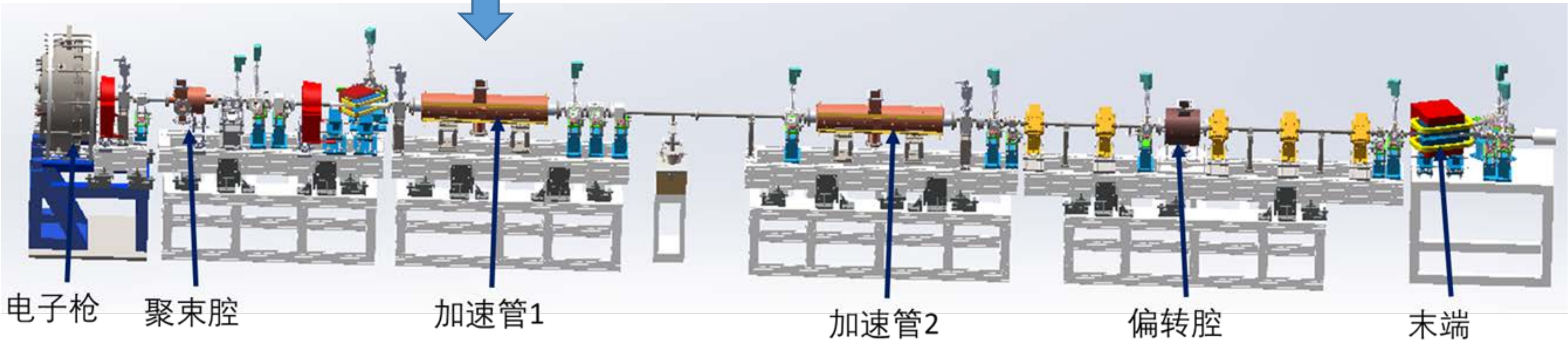
Low energy spectrometer to measure the gun voltage

Beam commissioning of the VHF gun

Tsinghua University

Test beamline

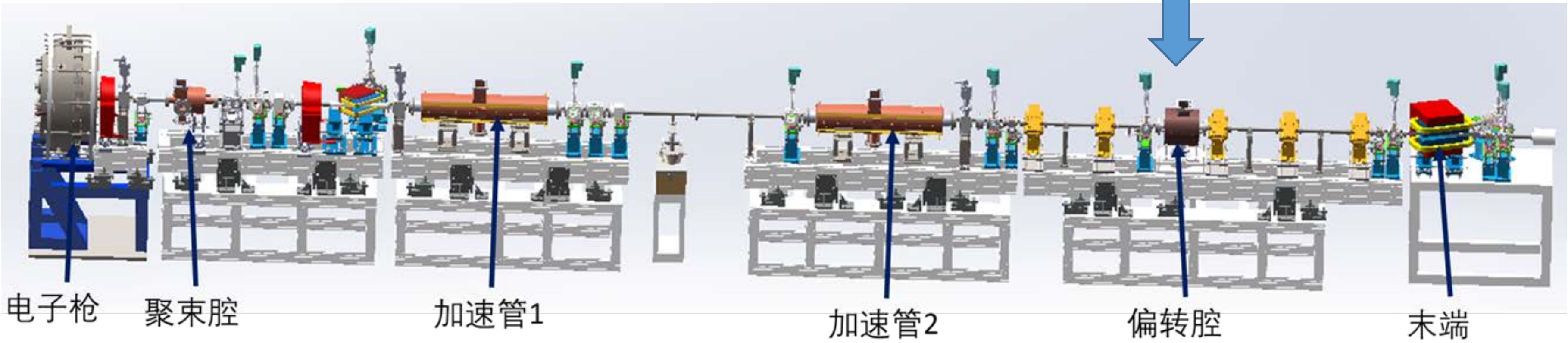
Two normal-conducting accelerating tubes to accelerate the beam to about 30 MeV



Beam commissioning of the VHF gun

Test beamline

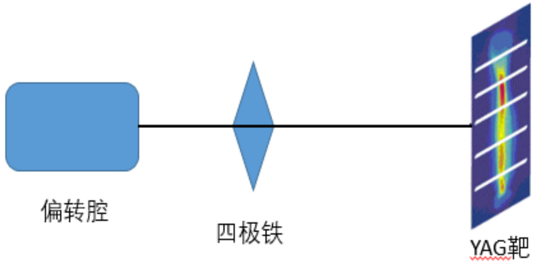
Deflecting cavity to measure the bunch length and slice emittance

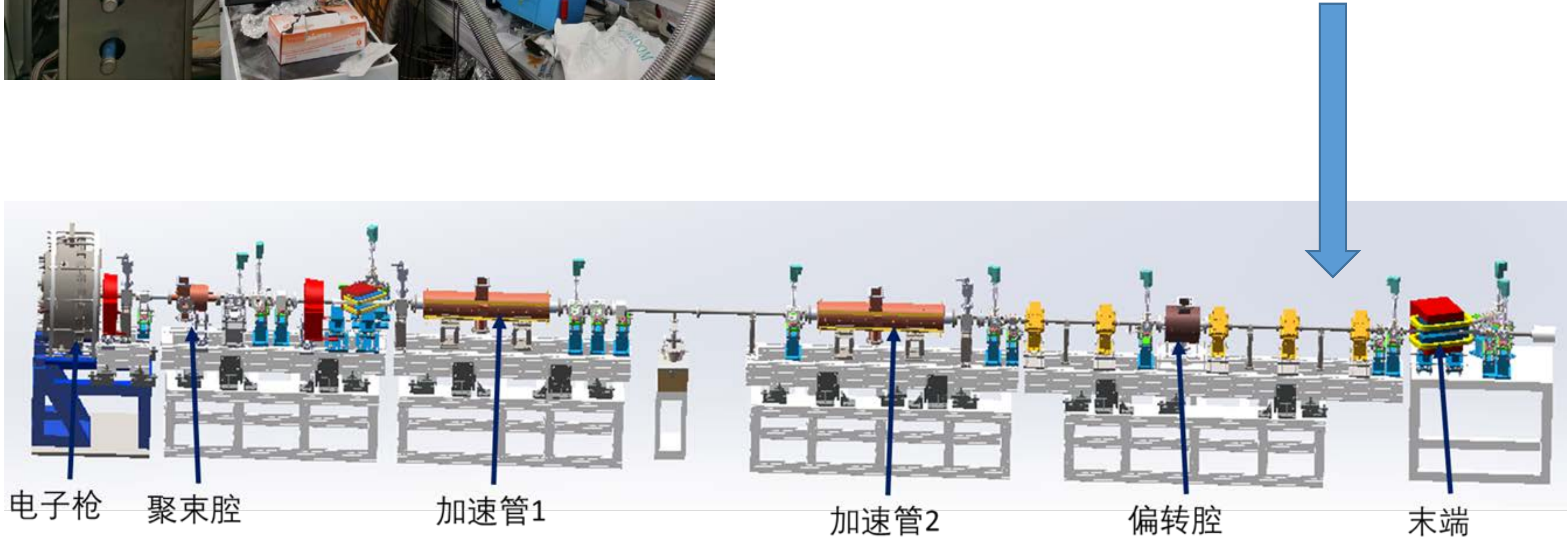


Beam commissioning of the VHF gun

Test beamline

Quadrupoles to measure emittance



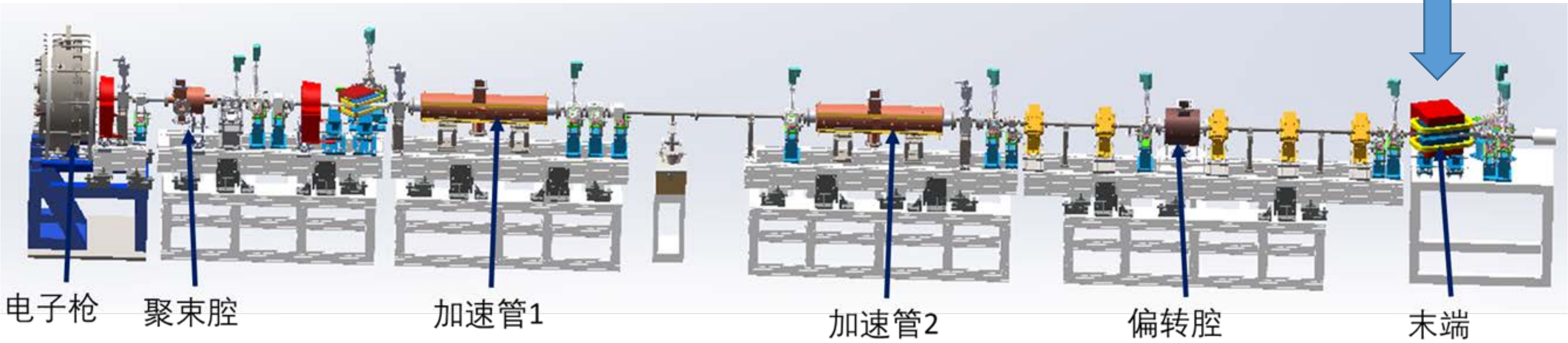


Beam commissioning of the VHF gun

Tsinghua University

Test beamline

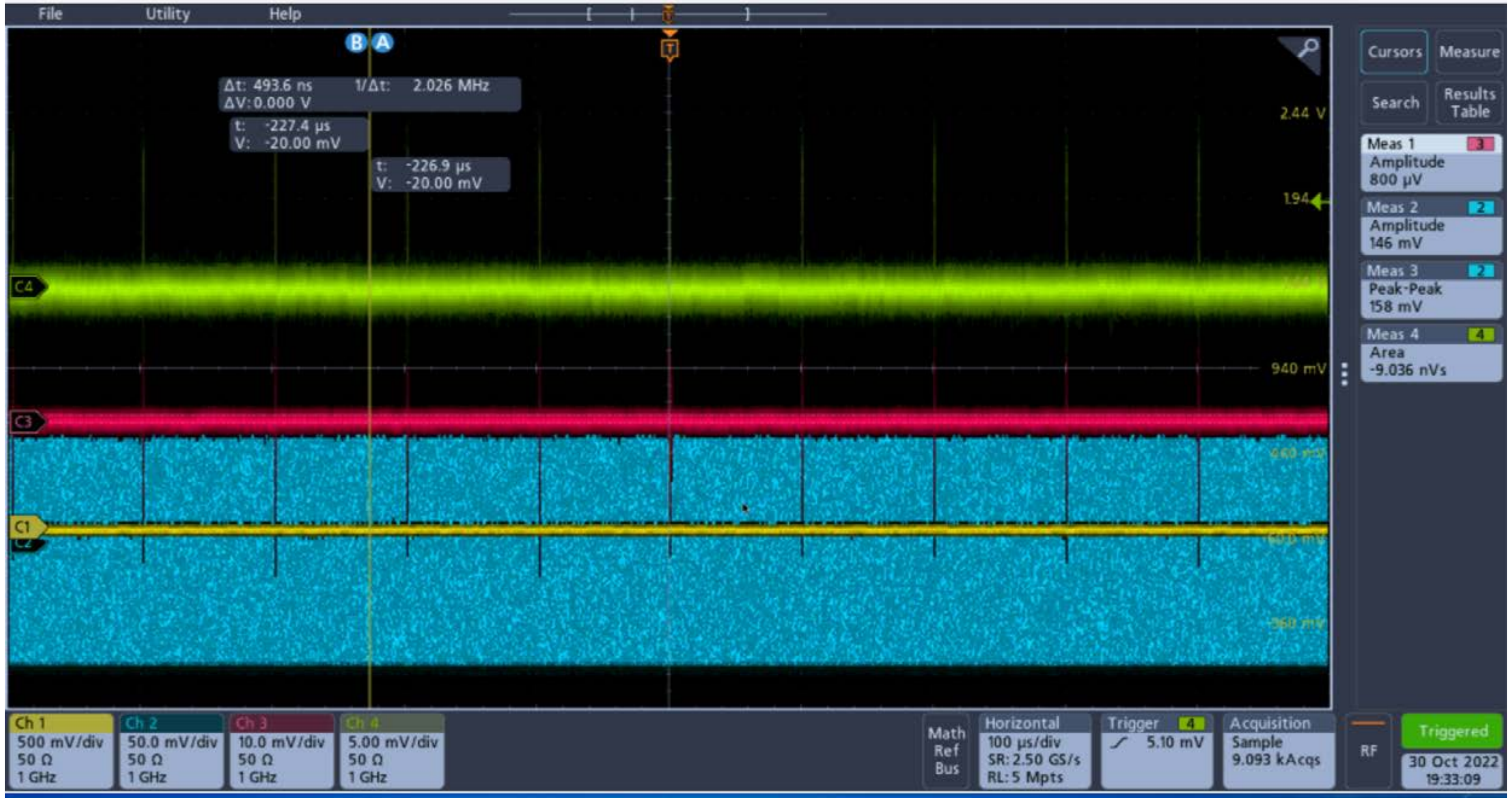
High energy spectrometer to measure the final beam energy



Beam commissioning of the VHF gun

Tsinghua University

Test beamline



100pC bunch charge with 10 kHz repetition rate can be stably produced

Beam commissioning of the VHF gun

Tsinghua University

E-beam quality measurements

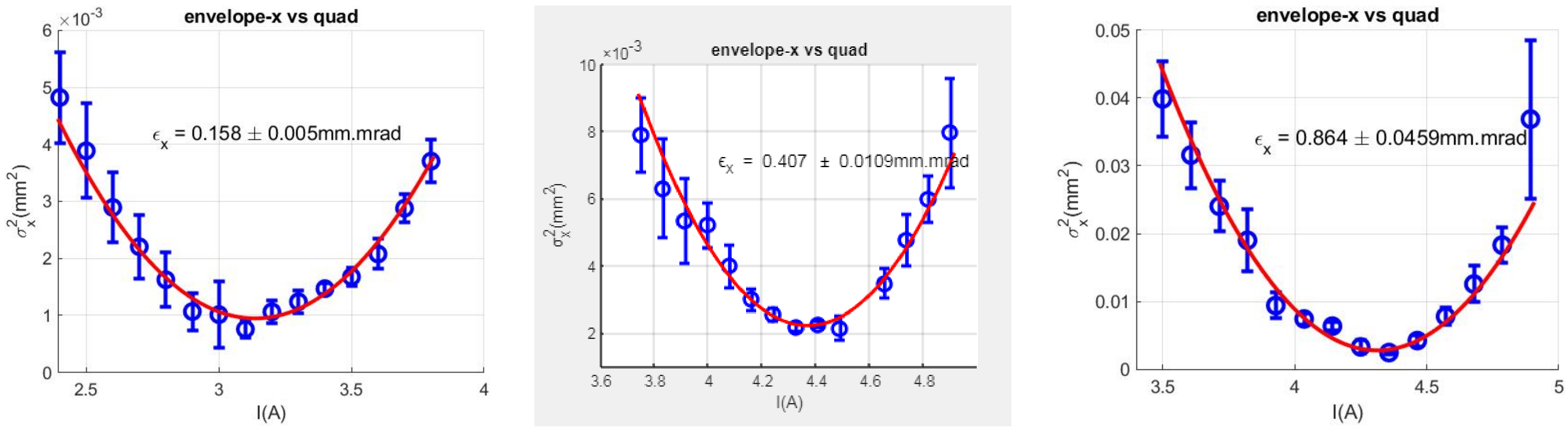
Bunch charge	Projected emittance (95%)	Bunch length
10 pC	0.16 mm mrad	0.49 mm rms
50 pC	0.43 mm mrad	1.15 mm rms
100 pC	0.85 mm mrad	1.44 mm rms

Quadrupole scan curves

10pC

50pC

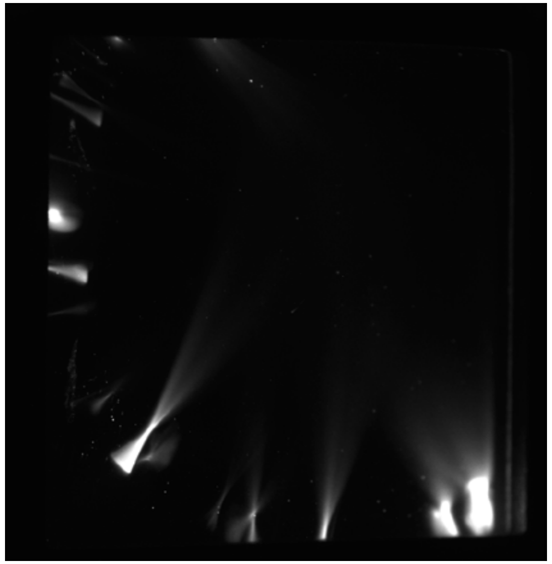
100pC

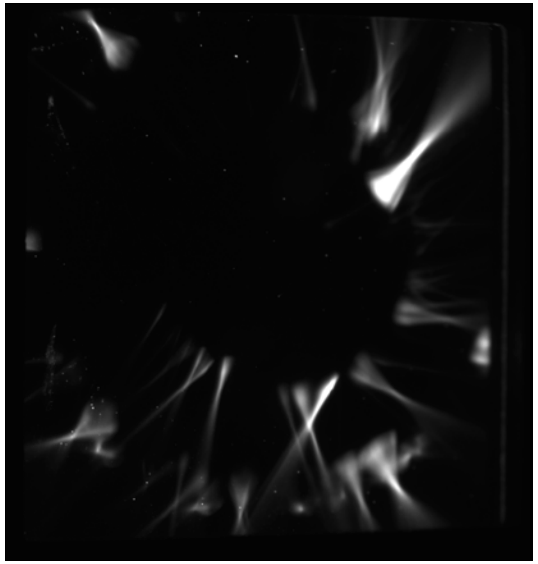


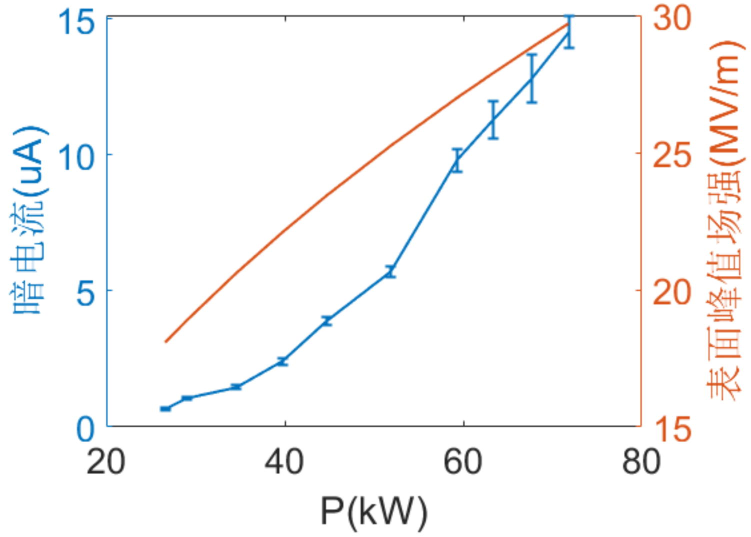
Beam commissioning of the VHF gun

- Dark current
- 2022.9-2022.10
- ~15-20 uA@80 kW@800 keV

Scratches was found on the corner of the plug







- ~6 uA with a new plug, almost all dark current comes from the copper

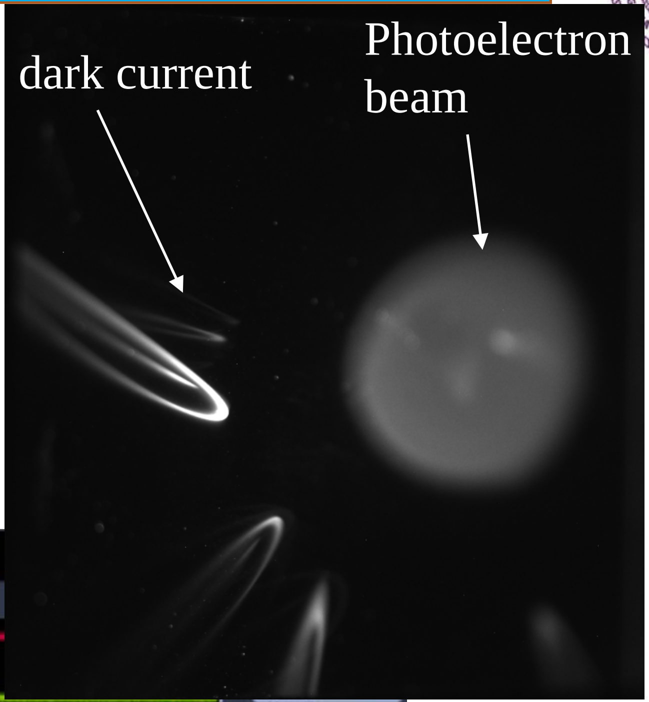
Beam commissioning of the VHF gun

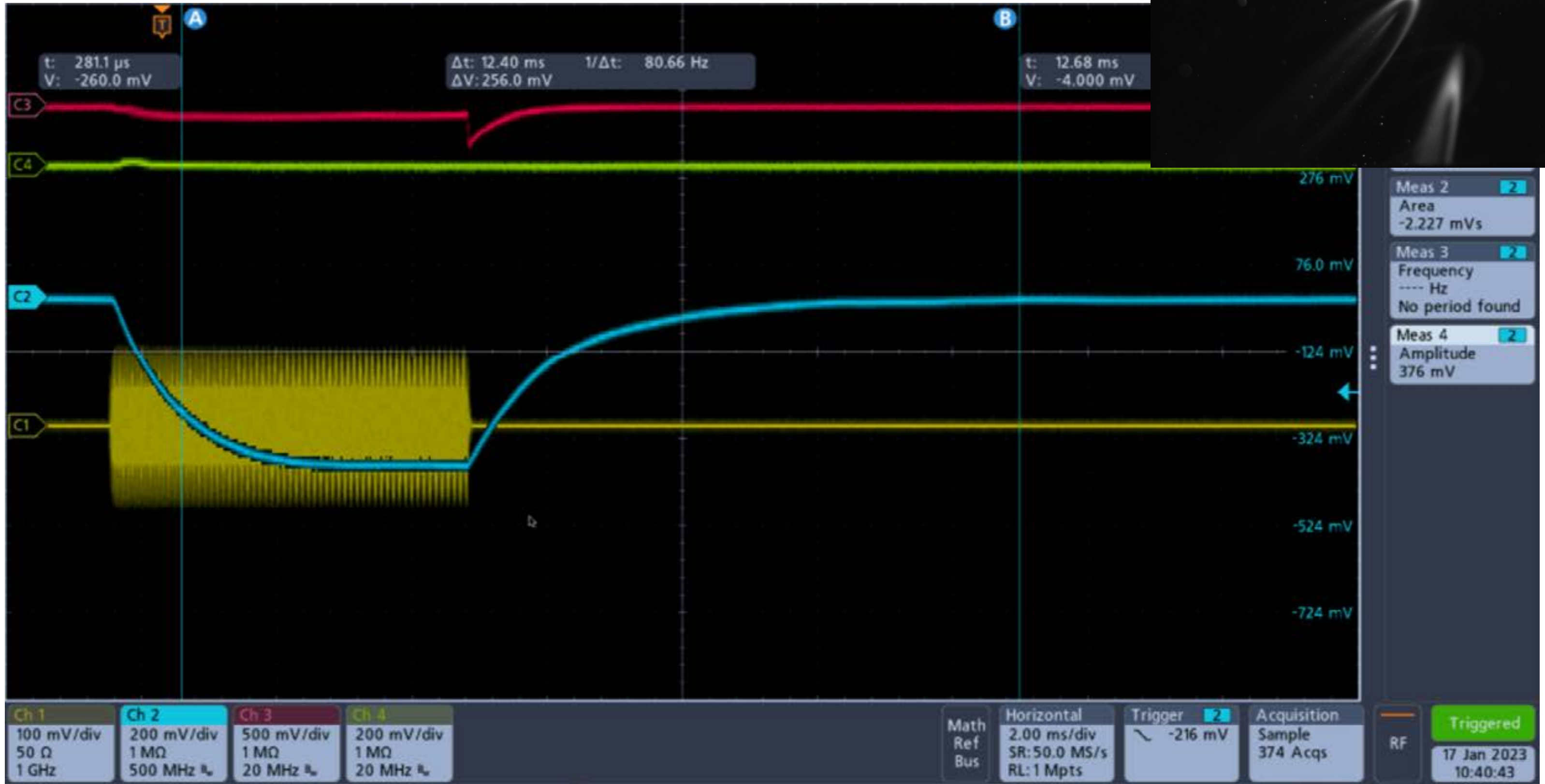
Tsinghua University

Dark current

After high pressure high purity water rinse

The maximum dark current collected by the Faraday cup downstream the gun was 376 nA by scanning the strength of the gun solenoid.





summary

- The gun can meet most of parameter requirements of the SHINE facility
- The gun will be transported to the SHINE tunnel in 20/3/2023
- Installation in Shanghai will begin after that…

Thanks for your attention