Tsinghua University

Photocathode RF gun R&D for SHINE project at Tsinghua University

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on behalf of Accelerator Laboratory

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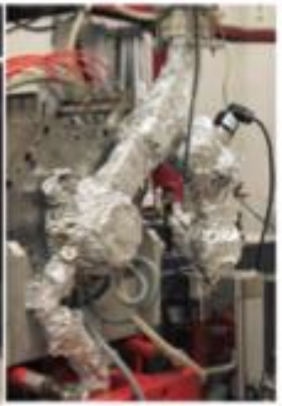
Contents

The history of the photocathode RF gun study at THU

2006:
First beam at THU



2001-2006: 1st

Modifications of BNL gun

2006-2009: 2nd

Collaboration with BNL

Lower dark current
Max cathode field:
80-110MV/m

2009-2018: 3rd

Single feed, dipole and quadruple field are suppressed with 4-port, large mode separation, removable or fixed cathode

100-120MV/m with low dark current and low BDR, successfully applied at TTX, DCLS, SXFEL, XGLS

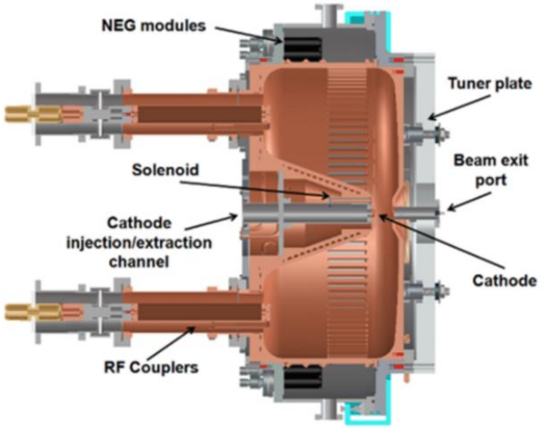
- XZ He, CX Tang, et al, HEP&NP, Vol.30, Supp.1,(2006)81-83
- X. Guan, CX Tang, et al, NIM A 574 (2007) 17–21
- XH Liu, CX Tang et al, IPAC2011, T06, p116-118
- HJ Qian, YC Du, et al, FEL2012, MOPD55
- Zhe Zhang, CX Tang, PRSTAB 18, 053401 (2015)
- LM Zheng, et al, submitted to PRAB
- ...

Gun R&D at Tsinghua University for SHINE

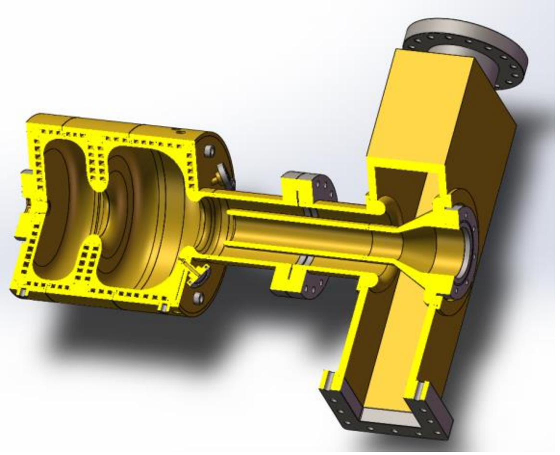
Tsinghua University

2019.03.08, MOU sign between Tsinghua and SHINE

- **VHF NC RF gun, CW mode**

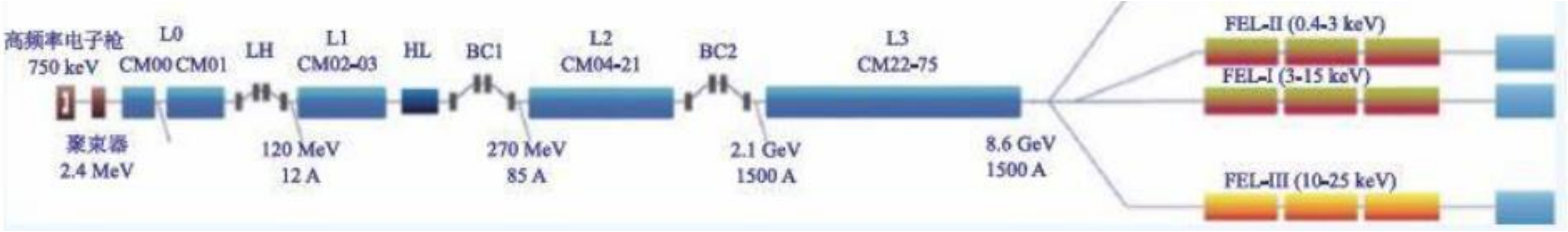


- **L-band NC PITZ-type gun, kHz operation**



- **Two photocathode RF guns will be developed for SHINE at Tsinghua.**

2、R&D of the VHF CW gun



SHINE facility's requirements for CW electron gun:

parameters	value	unit
Gun operation mode	CW	
Gun cathode gradient	>25	MV/m
voltage	≥750	kV
Bunch charge	10-300	pC
Repetition rate	1	MHz
Emittance at the end of the photoinjector	<0.4 @1mm rms@100pC	um
Dark current	<400	nA
Vacuum in the gun	$<2\times10^{-9}$	Torr

Physical design of the CW gun

Basic consideration on VHF gun design

The Gun resonant frequency is designed to be 216.67 MHz(1300/6).
This frequency is higher than the APEX gun (186 MHz).

Advantage:

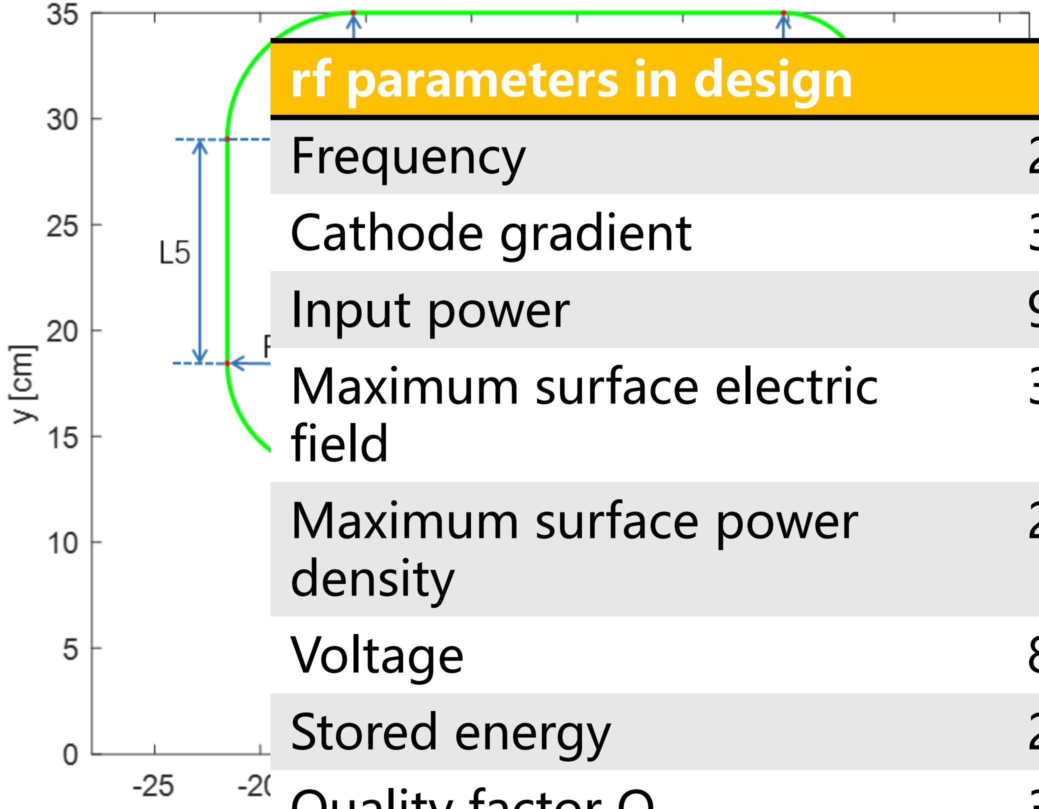
1. Compact
2. Higher cathode gradient

Disadvantage:

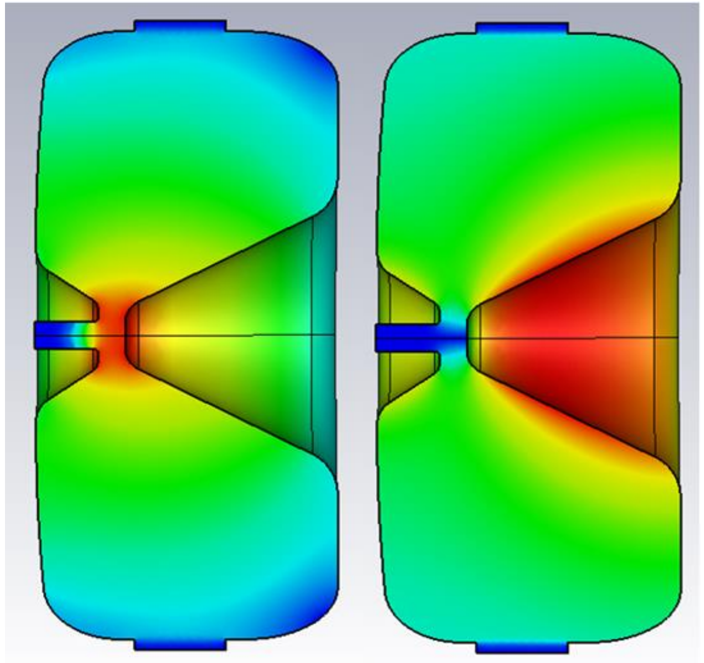
1. Higher surface electric field
2. Higher wall power density

Physical design of the CW gun

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 keV
Stored energy	2.24 J
Quality factor Q_0	33717
Shunt impedance	8.34 MΩ



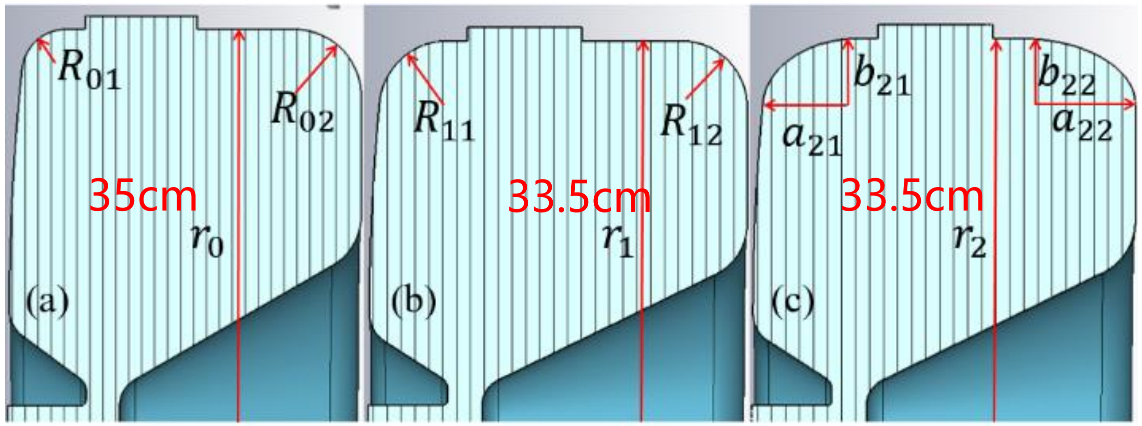
E field H field

Physical design of the CW gun

Tsinghua University

Gun profile optimization to reduce the multipacting:

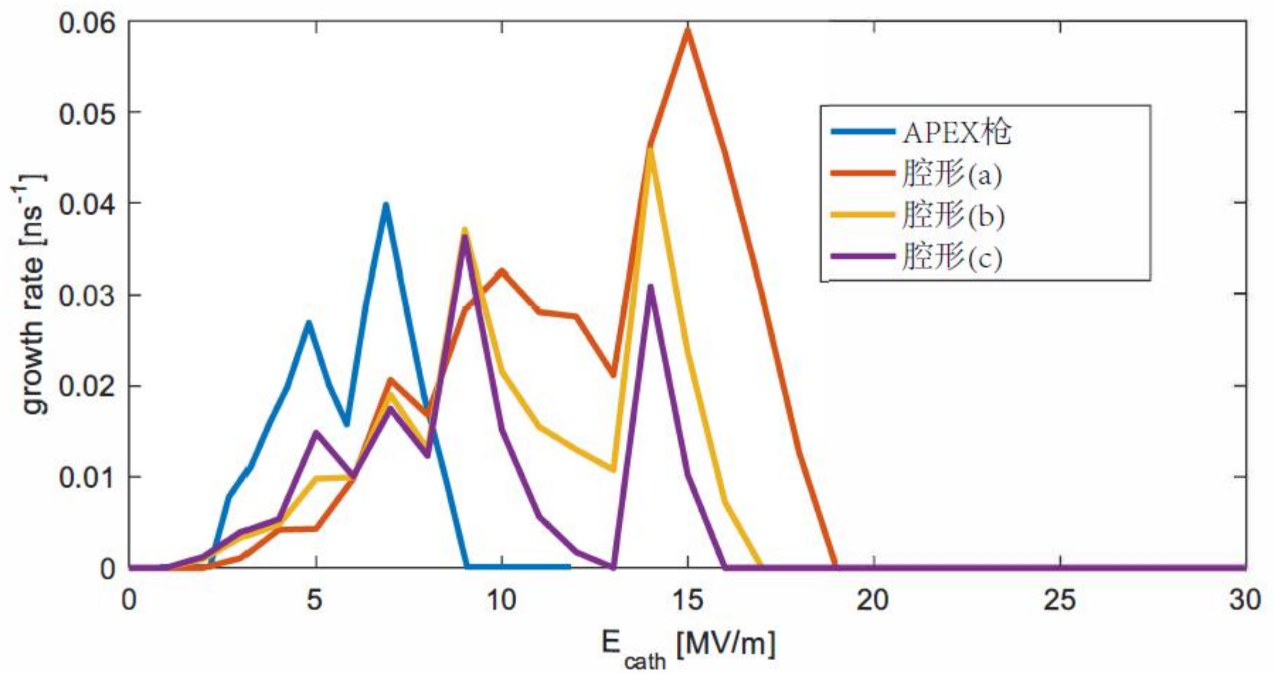
$N_e(t) = N_0 \times 10^{\alpha t}$, α is the growth rate



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

Reduce the radius

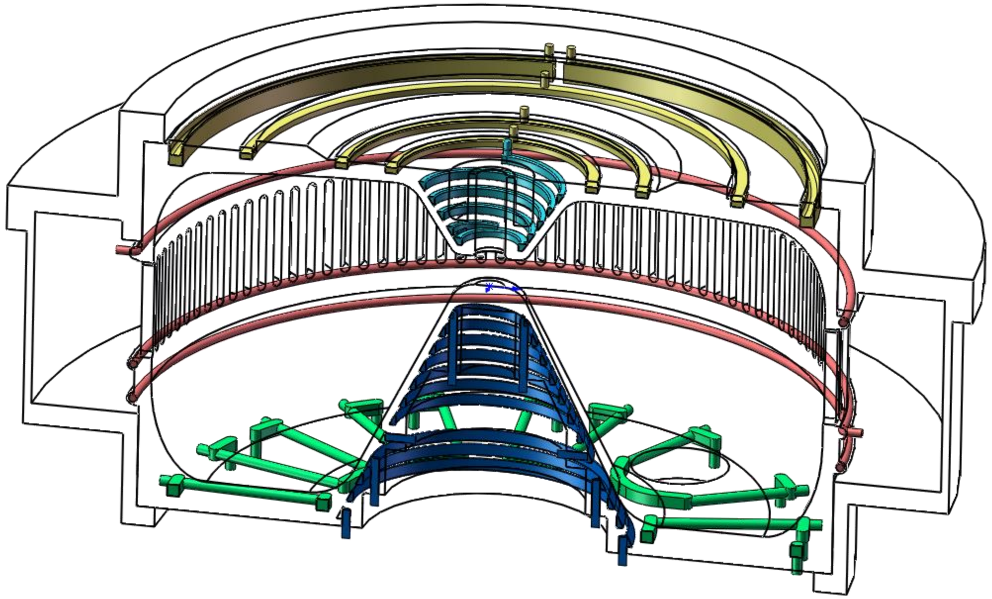
Change rounded corners to elliptical



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

Physical design of the CW gun

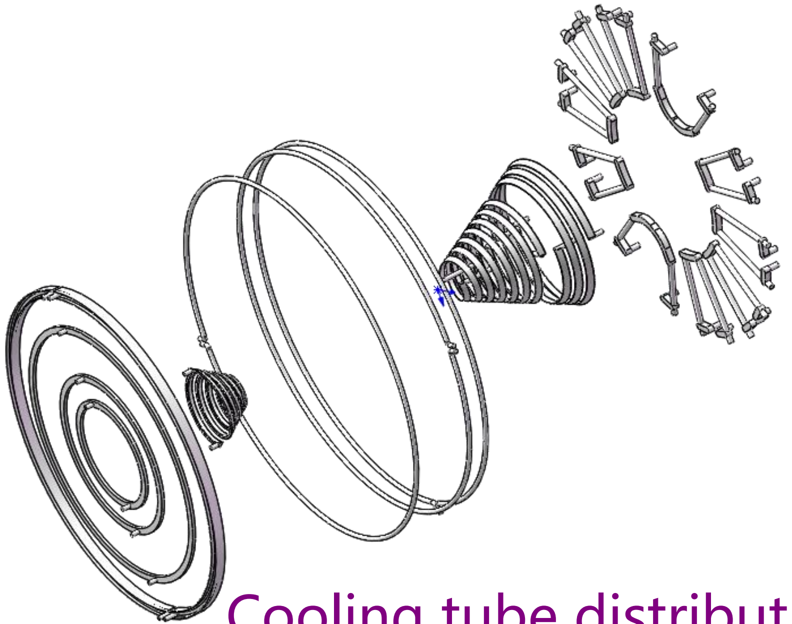
Cooling tube design of the VHF gun:



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.

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

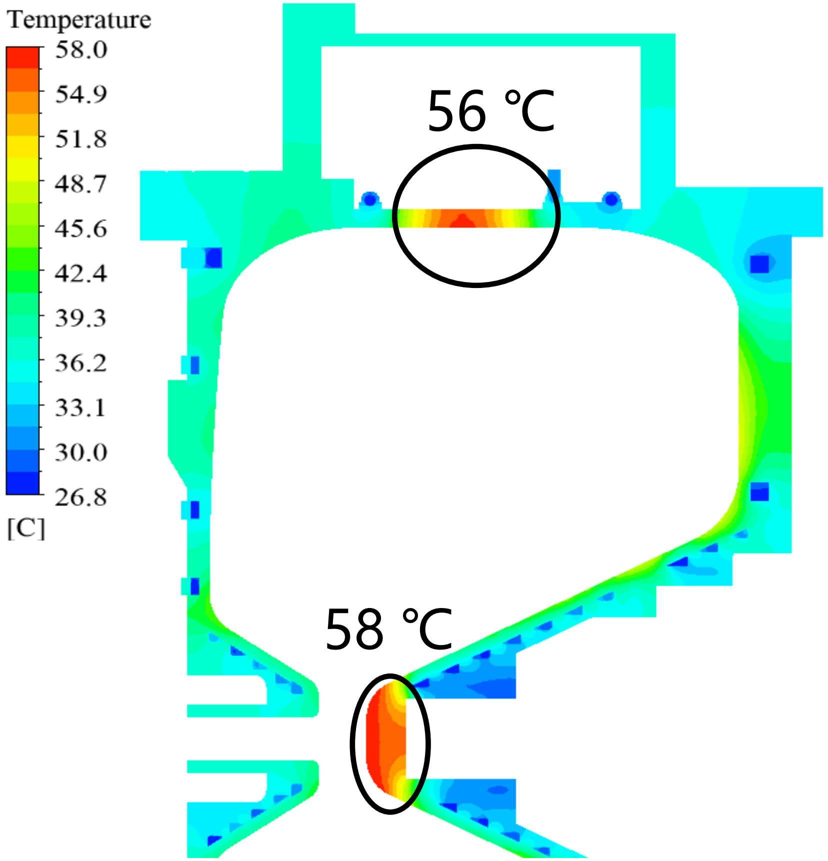


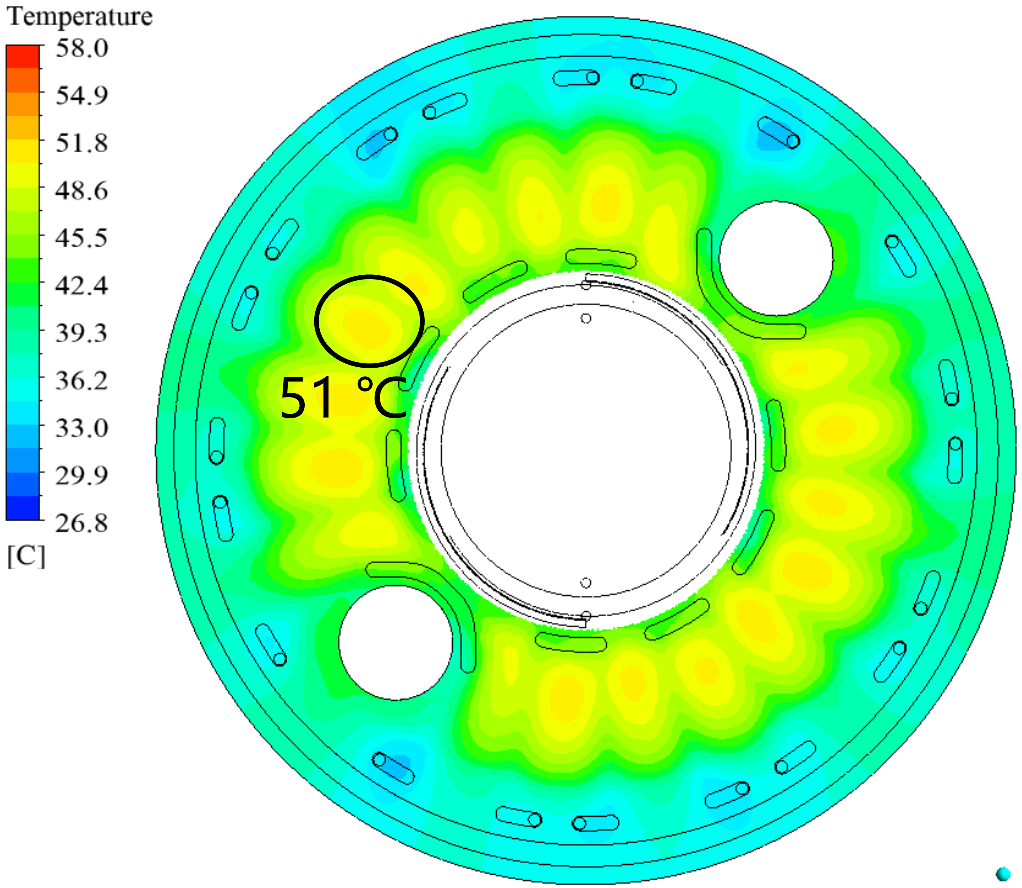
Cooling tube distribution

Physical design of the CW gun

Temperature distribution of the VHF gun:

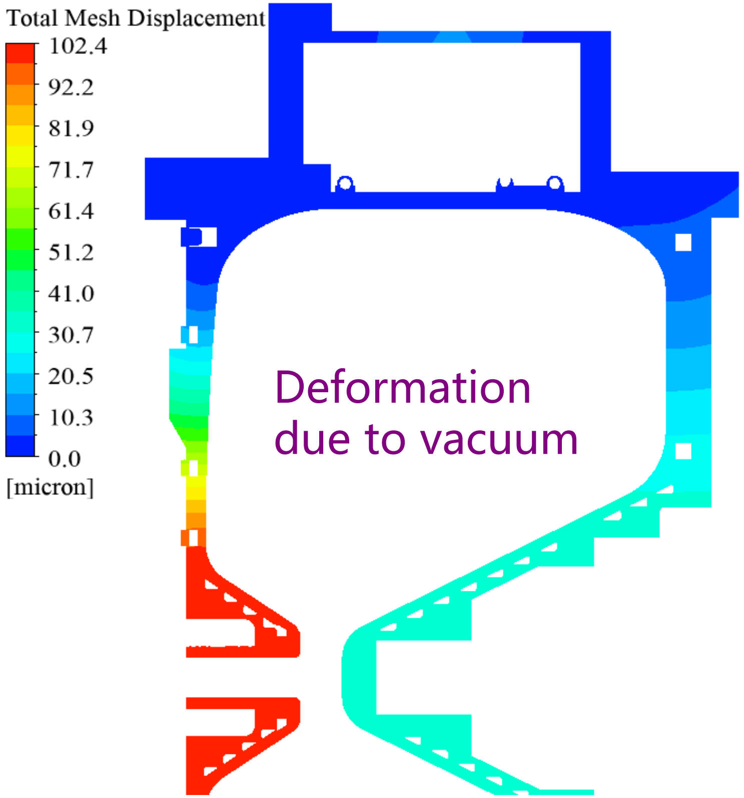
Input power: 90.5kW
Cathode gradient: 30MV/m



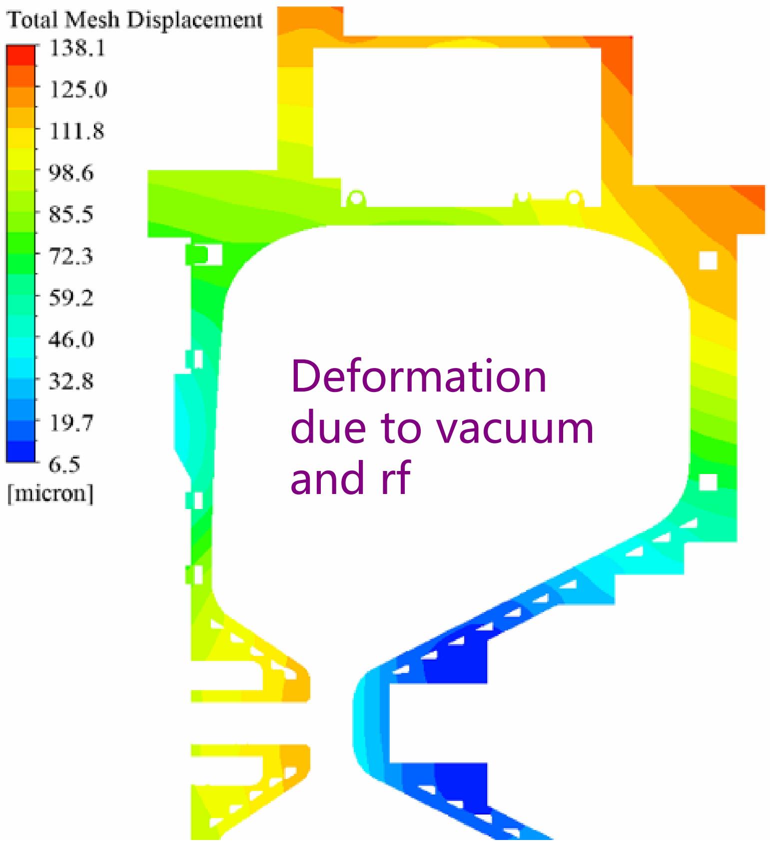


Physical design of the CW gun

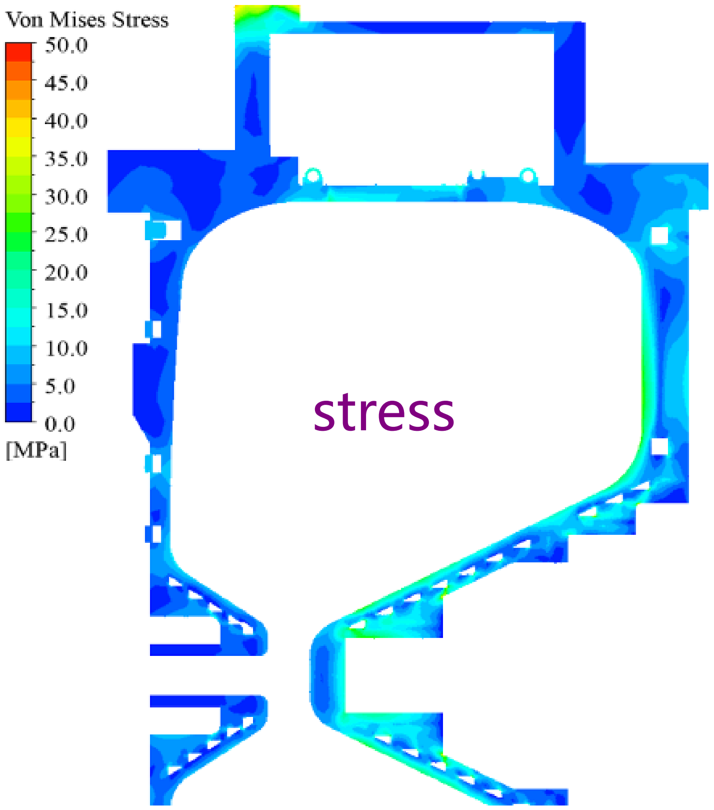
Distribution of deformation and stress:



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



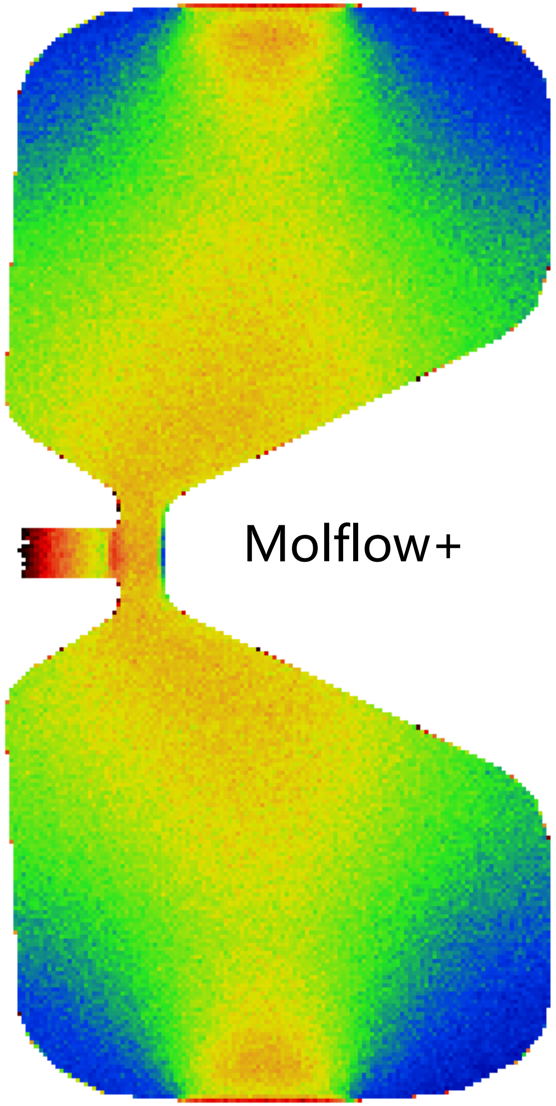
The gap between anode and cathode is reduced by 155 um due to the vacuum and rf, corresponding to a 138 kHz frequency shift.



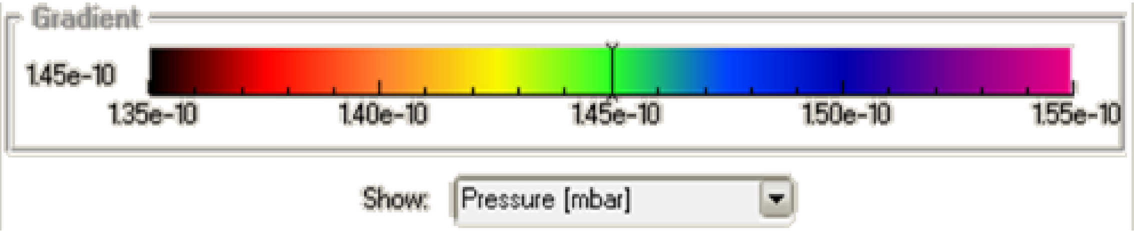
The maximum stress in the copper part is less than 30 MPa

Physical design of the CW gun

Vacuum simulation：



Molflow+



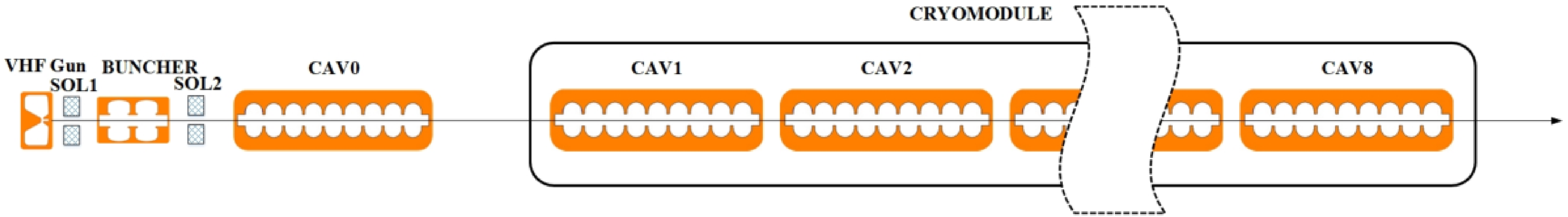
outgassing/area (mbar*l/s/cm^2):

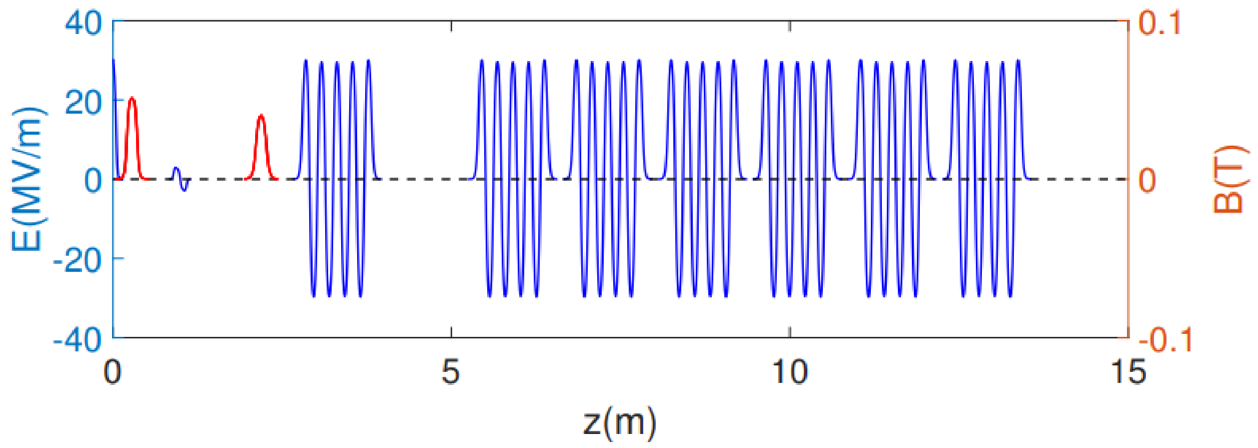
copper	4.5e-11	(OHFC mech. Poli 25h)
stainless steel	3.0e-12	(304 Varian std cleaning)

NEG pump：24*400 L/s；
Ion pump：300 L/s

cathode：1.45e-8 Pa

Beam dynamics simulation

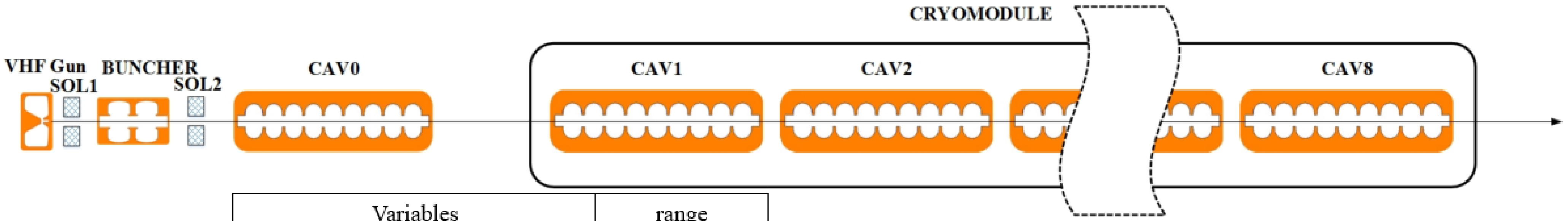




Optimization setup:

- A parallel processing MOGA is implemented to drive ASTRA simulations for optimizing the injector, written in Python language and using MPI for communication
- 18 variables. Objectives: emittance, bunch length
- 100 pC charge. 50000 macro particles. 1 mm mrad/mm thermal emittance.

Beam dynamics simulation

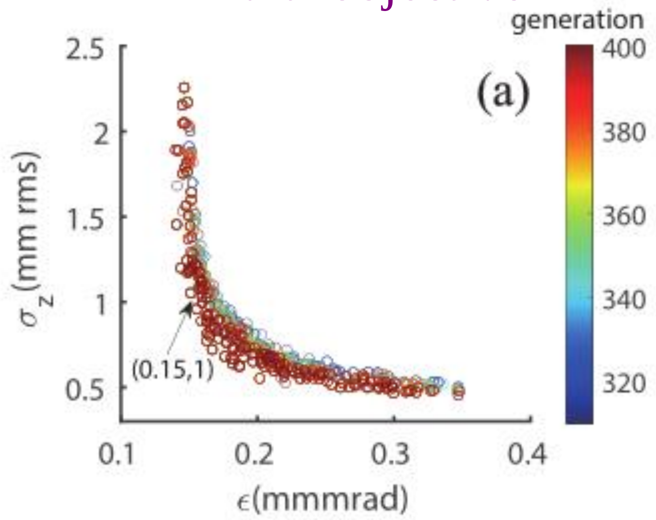


Variables	range
laser duration (ps)	(15,60)
beam size (rms mm)	(0.05, 0.4)
gun phase	(-20, 20)
SOL#1 position(m)	(0.3,0.35)
SOL#1 field (T)	(0.04,0.07)
BUNCHER to SOL#1 distance(m)	(0.5, 1)
BUNCHER phase	(-90, -30)
BUNCHER field(MV/m)	(1, 3)
SOL#2 to BUNCHER postion(m)	(0.5, 2)
SOL#2 field(T)	(0.01,0.07)
CAV#0 field(MV/m)	(10, 30)
CAV#0 to SOL#2 postion(m)	(1, 3)
CAV#0 phase	(-30, 30)
CAV#1 field(MV/m)	(10, 30)
CAV#1 to CAV#0 postion(m)	(2, 5)
CAV#1 phase	(-15, 15)
CAV#2 field(MV/m)	(20, 30)
CAV#2 phase	(-15, 15)

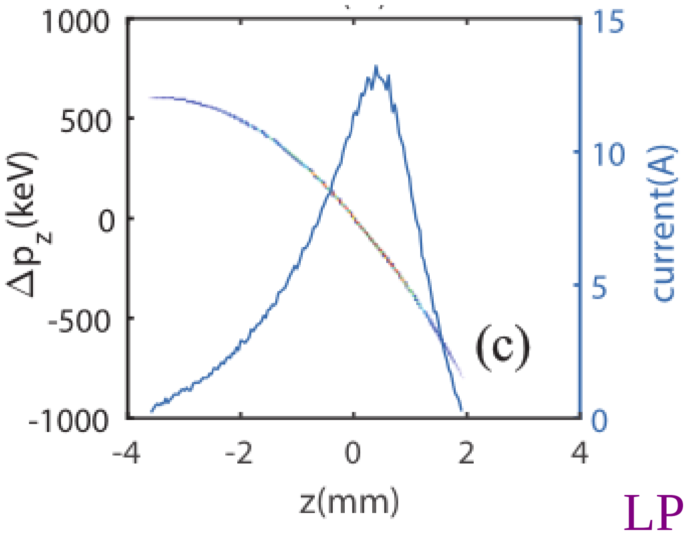
- temporal flattop laser with 2 ps edges
- transverse uniform distribution
- maximum cathode field 30 MV/m

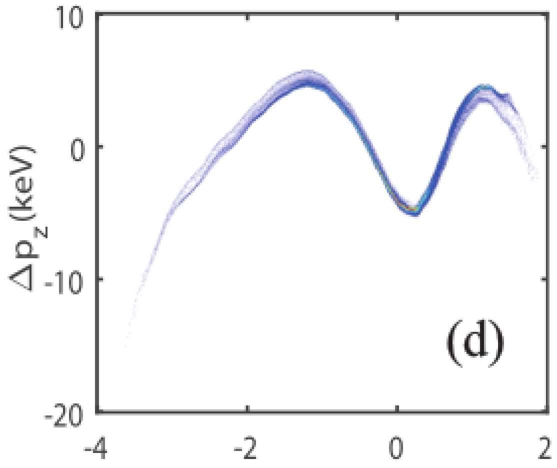
Beam dynamics simulation

multi-objective



100% emit	95% emit	Bunch length	H.O.energy spread
0.146um-rad	0.118um-rad	1.075mm rms	3.46keV rms

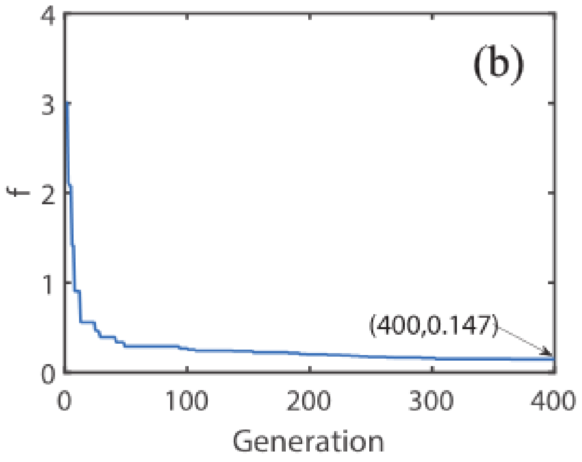




LPS with 1st and 2nd chirp correction

single-objective

f=emitx+ max((abs(sig-1)-0.1),0)*4

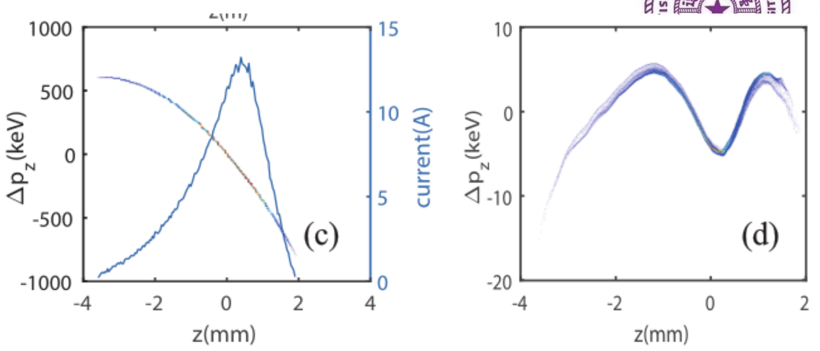


Set thermal emittance 0.5umrad/mm

100% projected emittance 0.1umrad

95% projected emittance 0.075umrad

Beam dynamics simulation



Emittance optimized at 1 mm rms bunch length

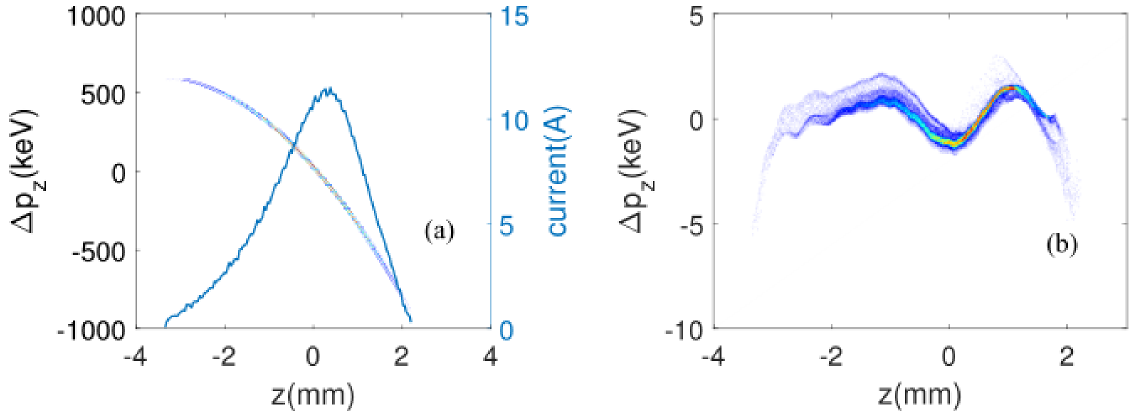
100% emit	Bunch length	H.O.energy spread
0.146um-rad	1.075mm rms	3.46keV rms

High order energy spread optimization

single-objective

f=emitx+ max((abs(sig-1)-0.1),0)*4+hosp/20

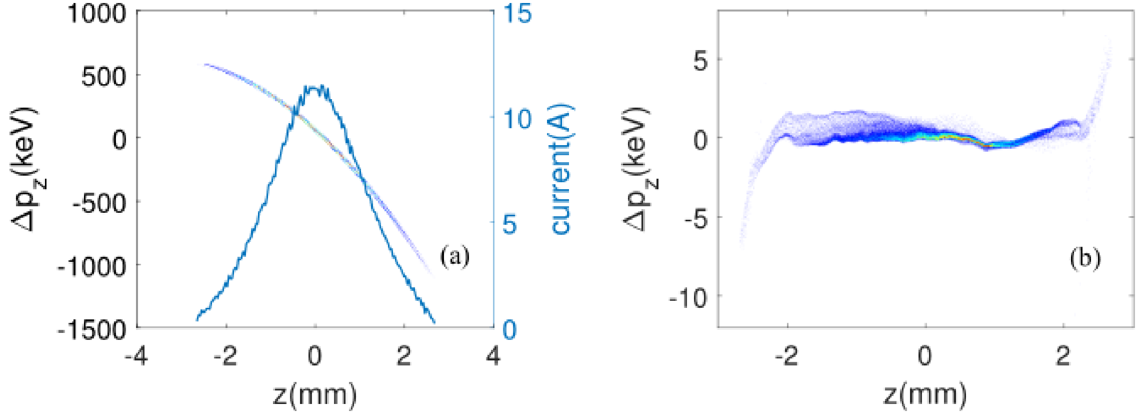
$$p(z) = p_0 + c_1 z + c_2 z^2 + O(z^3)$$



100% emit	Bunch length	H.O.energy spread
0.179um-rad	1.081mm rms	0.92keV rms

3.9 GHz harmonic cavity added

Voltage of the cavity is 70 kV



100% emit	Bunch length	H.O.energy spread
0.193um-rad	1.03mm rms	0.6keV rms

Beam dynamics simulation

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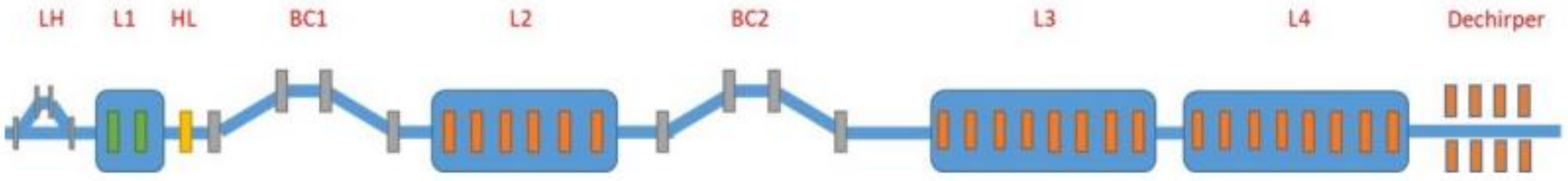
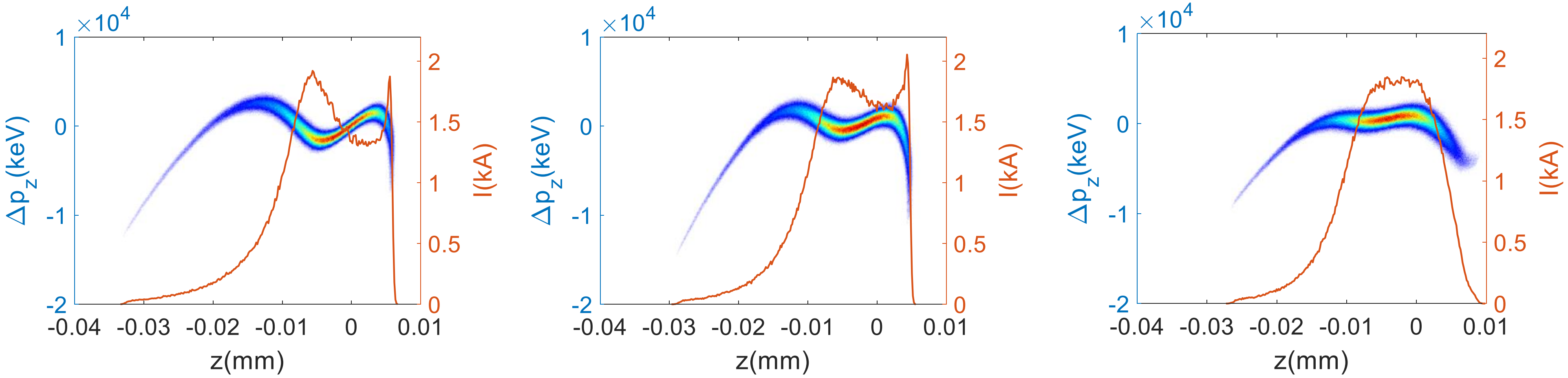


Litrack is used to simulate the longitudinal dynamics in the main accelerator. The voltage and phase of L1 and HL, the phase of L2, and R56 of BC1 and BC2 are selected as the variables to optimize the final current distribution, targeting for flattop distribution. The dechirped is assumed to perfertly remove the first order chirp.

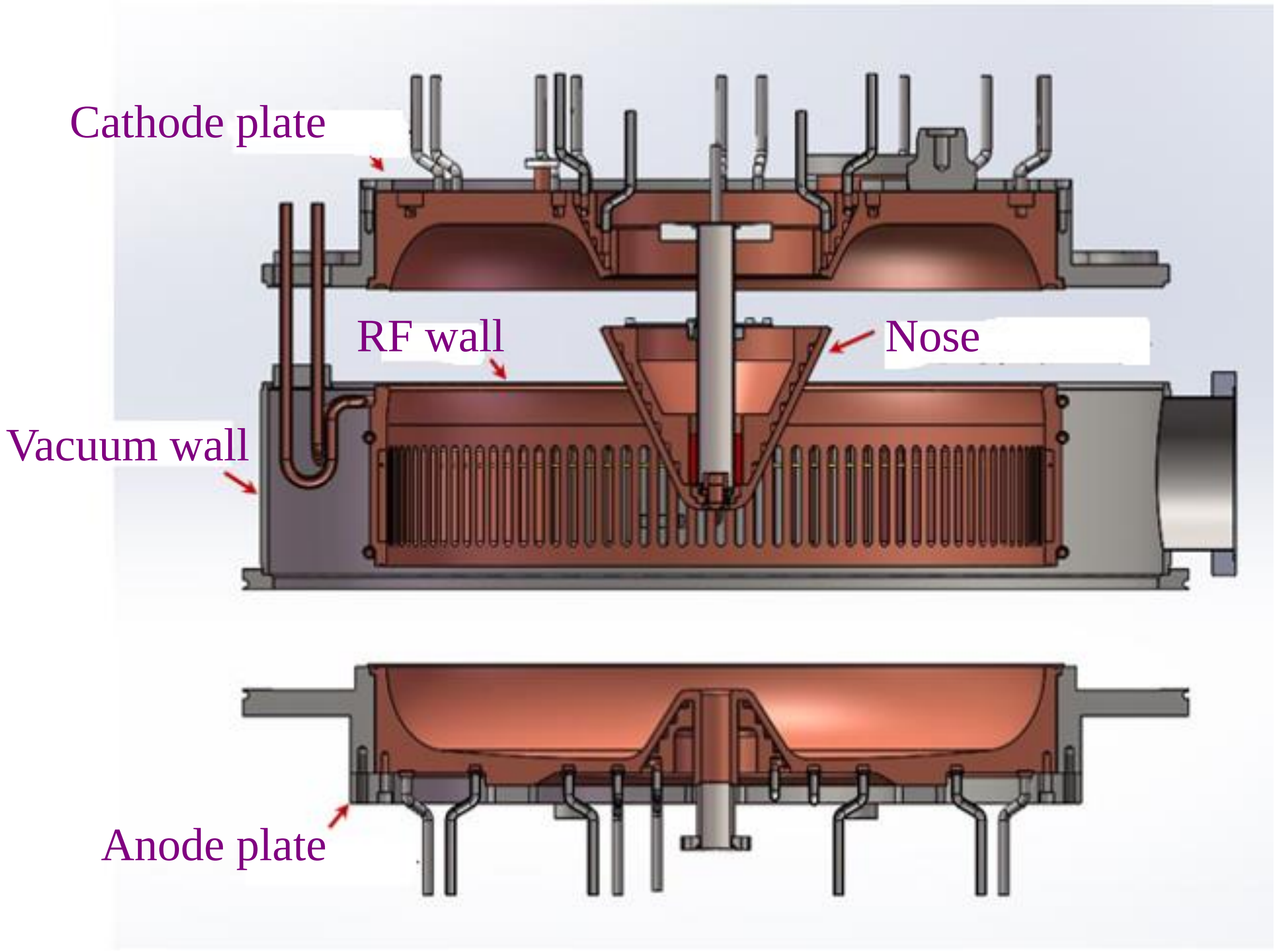
Longitudinal phase space and current distribution

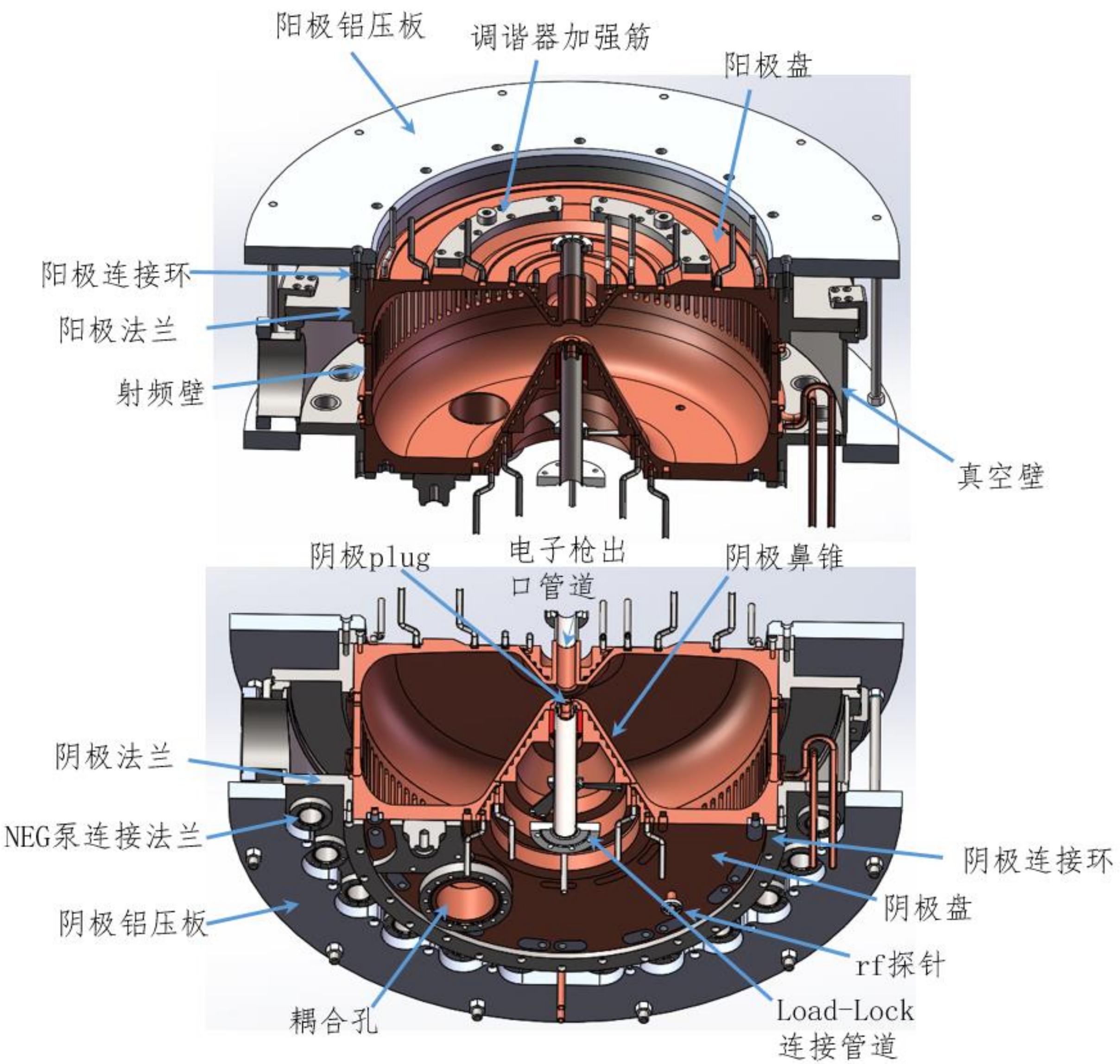
1.8kA



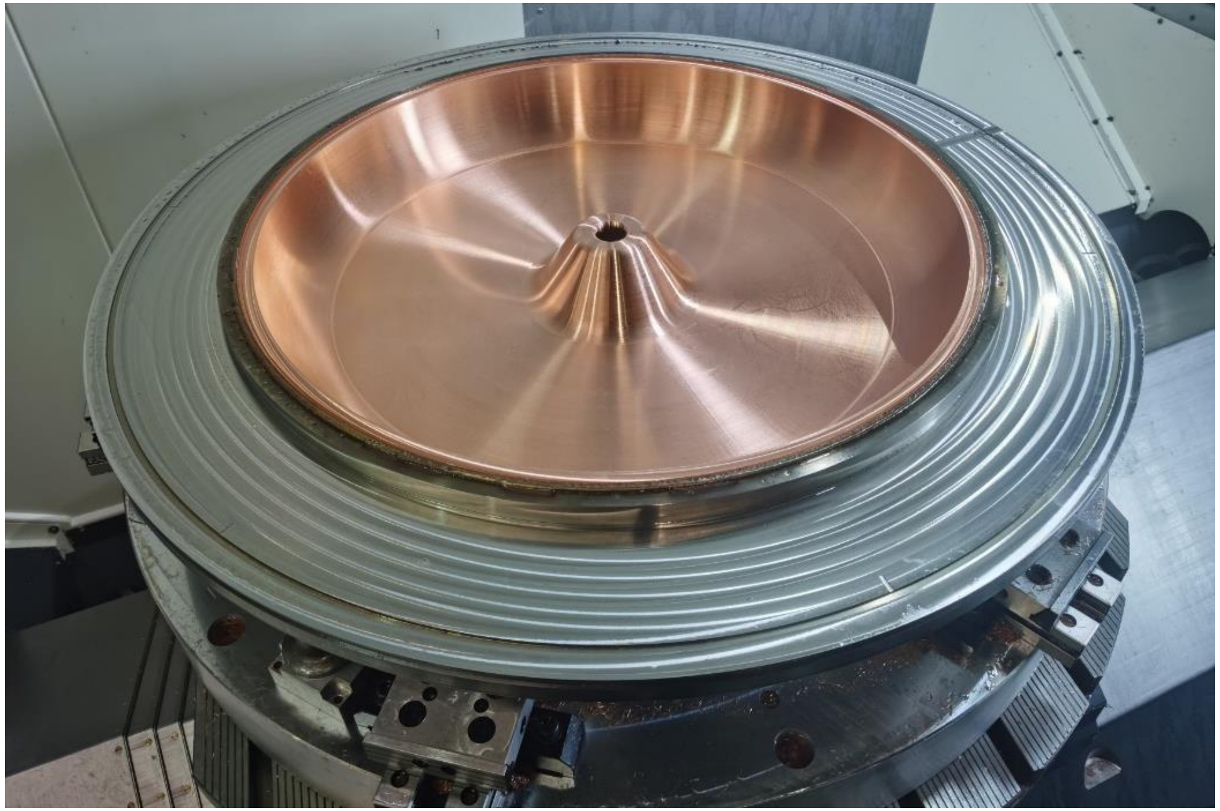
Machining and cold test of the prototype gun

Mechanical design of the prototype gun





Machining and cold test of the prototype gun

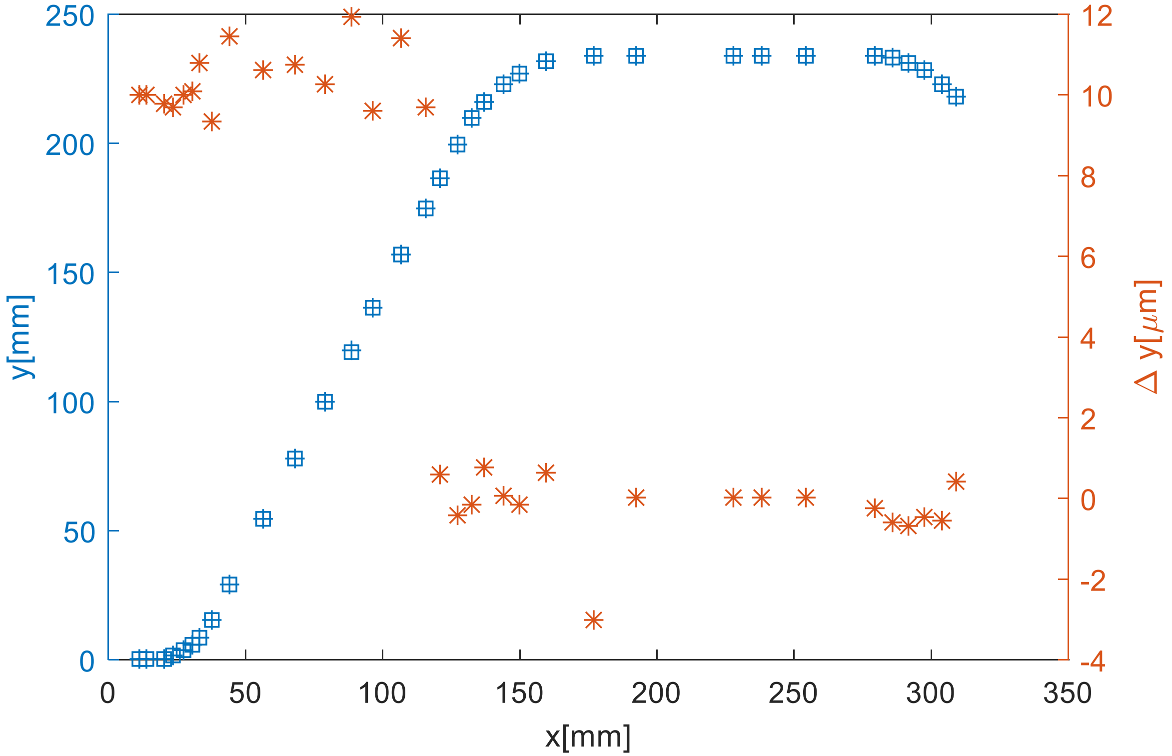


Anode assembly after final machining

Cathode assembly after final machining

Machining and cold test of the prototype gun

Cathode assembly three-coordinate measuring results：

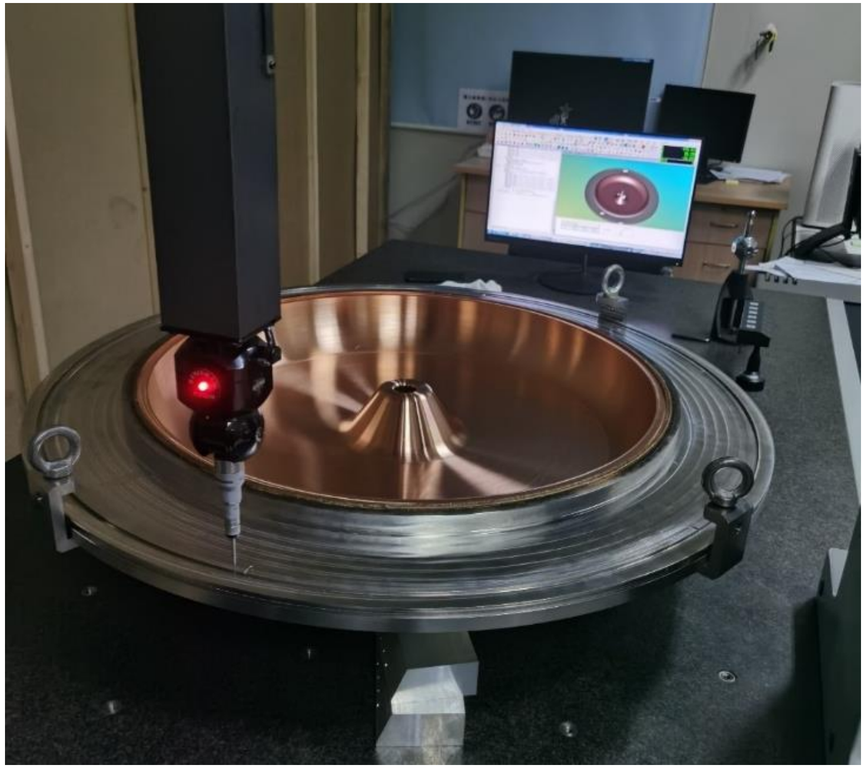


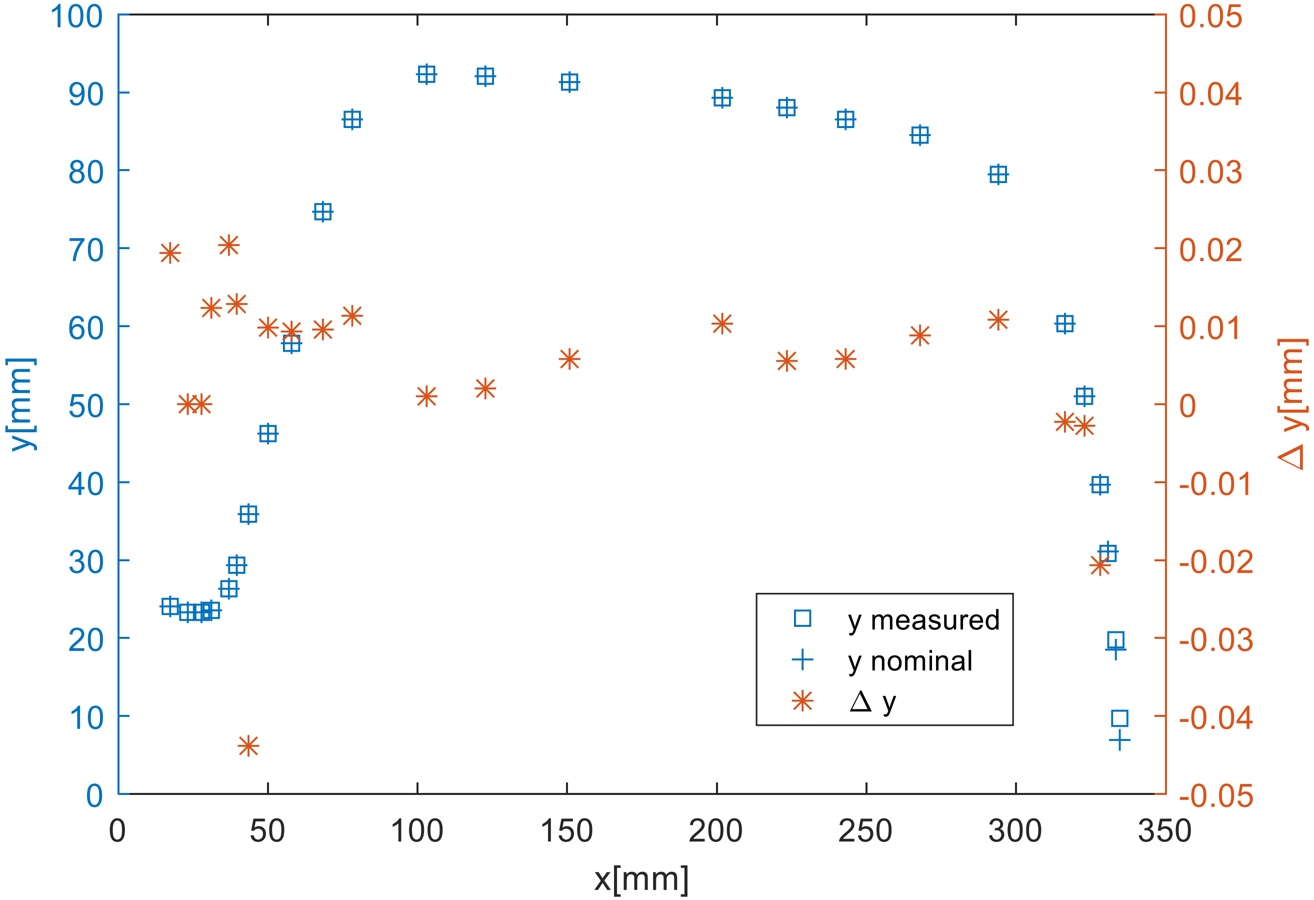
The inner profile machining error is less than 12 microns

Machining and cold test of the prototype gun

清華大學 Tsinghua University

Anode assembly three-coordinate measuring results：

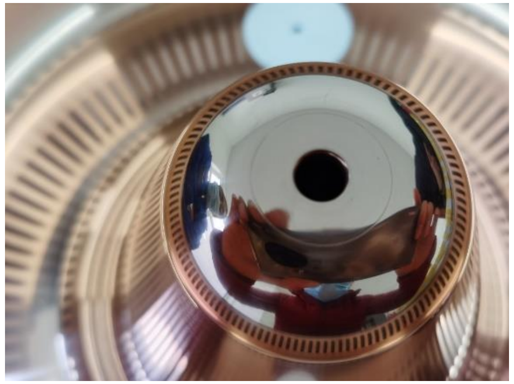




The inner profile machining error is less than 20 microns

Machining and cold test of the prototype gun

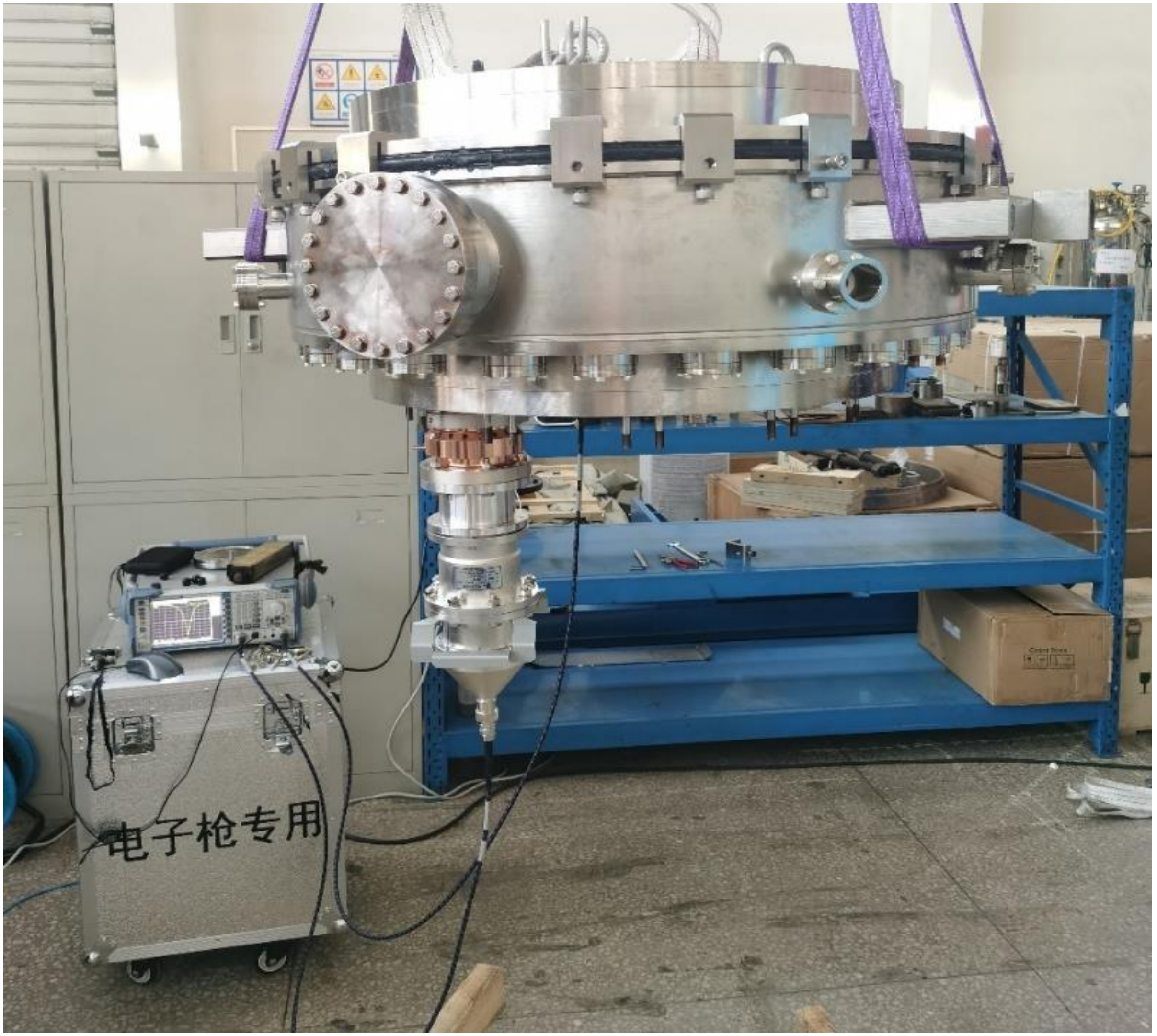
Manual polishing of copper surface

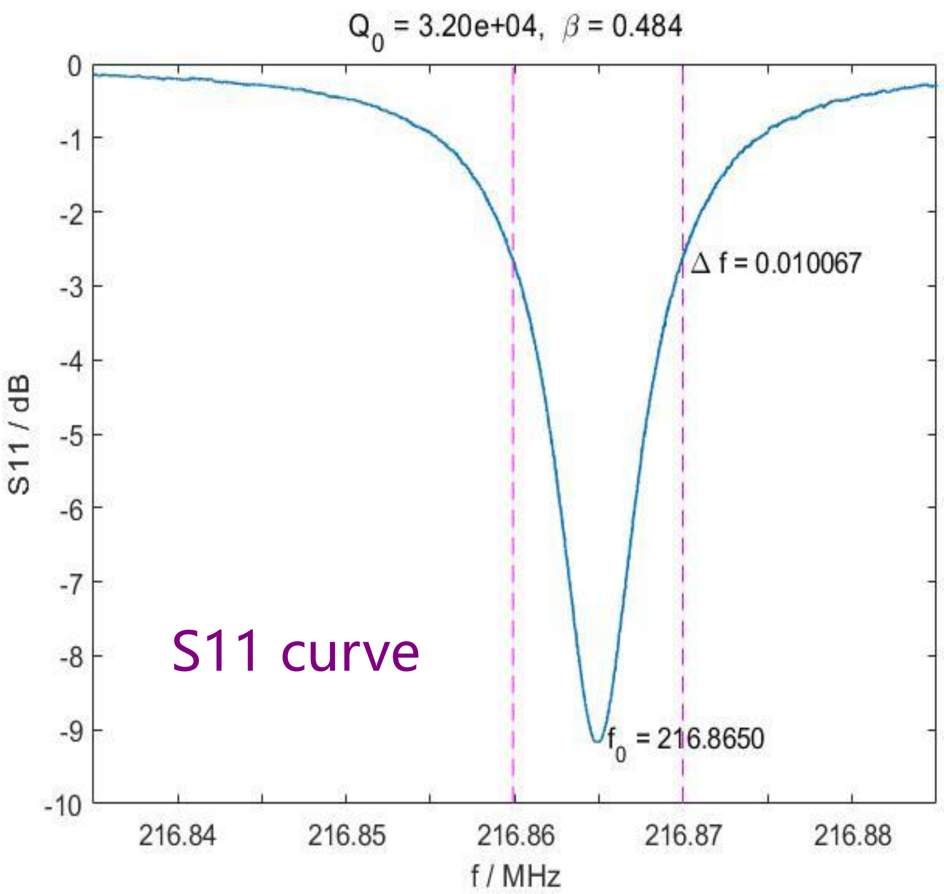


Roughness of the copper surface is less than R0.1

Machining and cold test of the prototype gun

Cold test of the prototype gun:



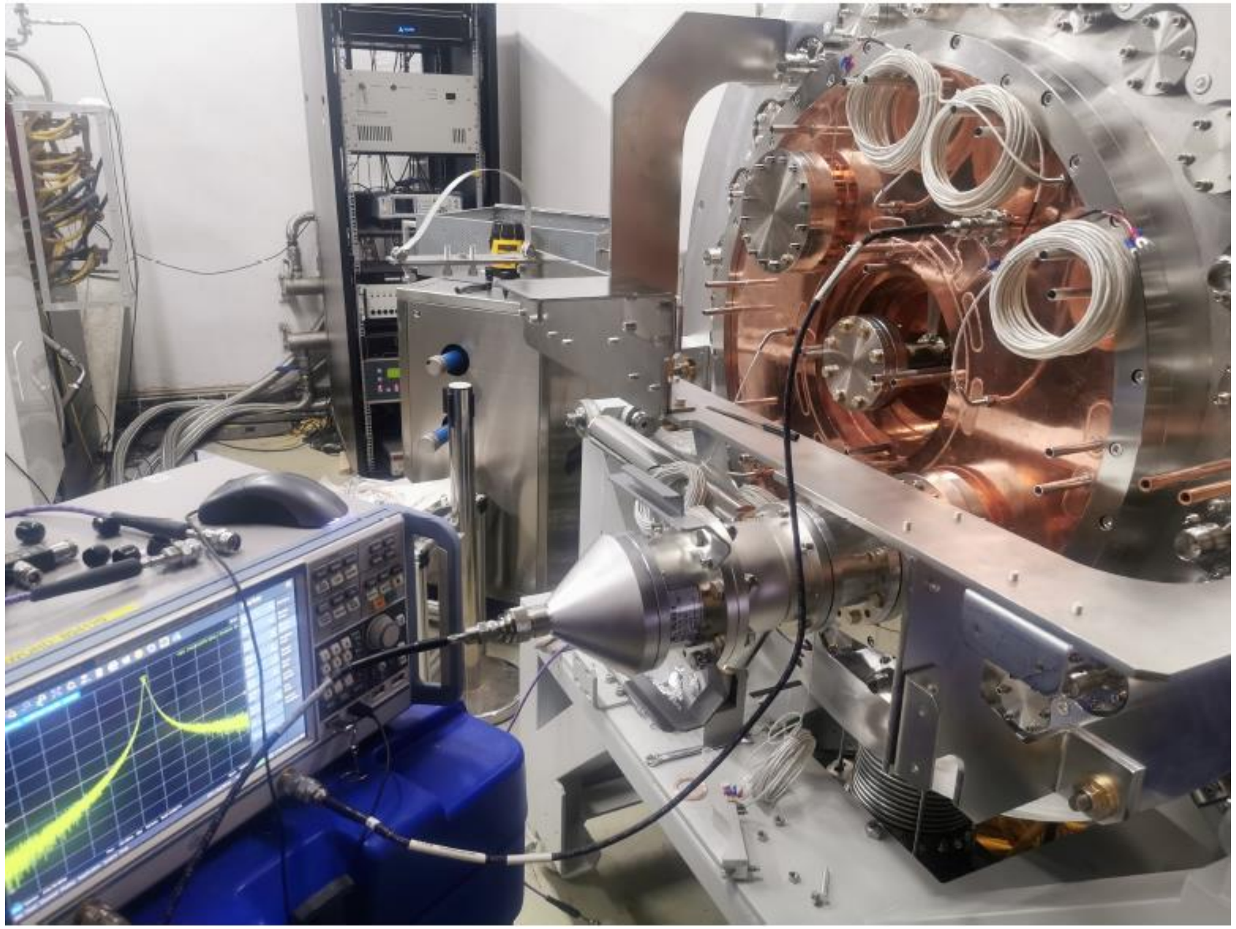


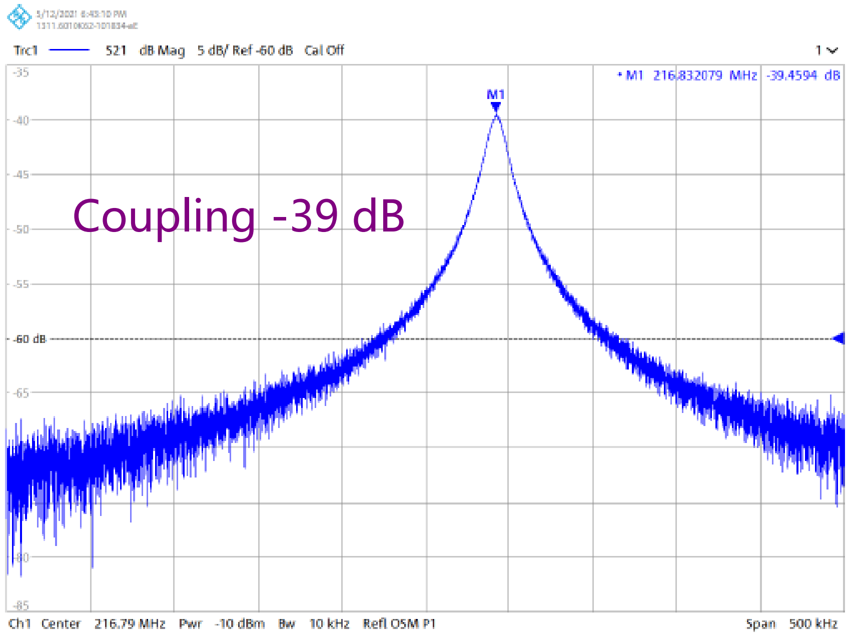
The measured frequency is in consistent with the design.
The quality factor is 5% less than the design.
Quality factor in design: 33717
Quality factor measured: 32000

Machining and cold test of the prototype gun

Cold test of the prototype gun：

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



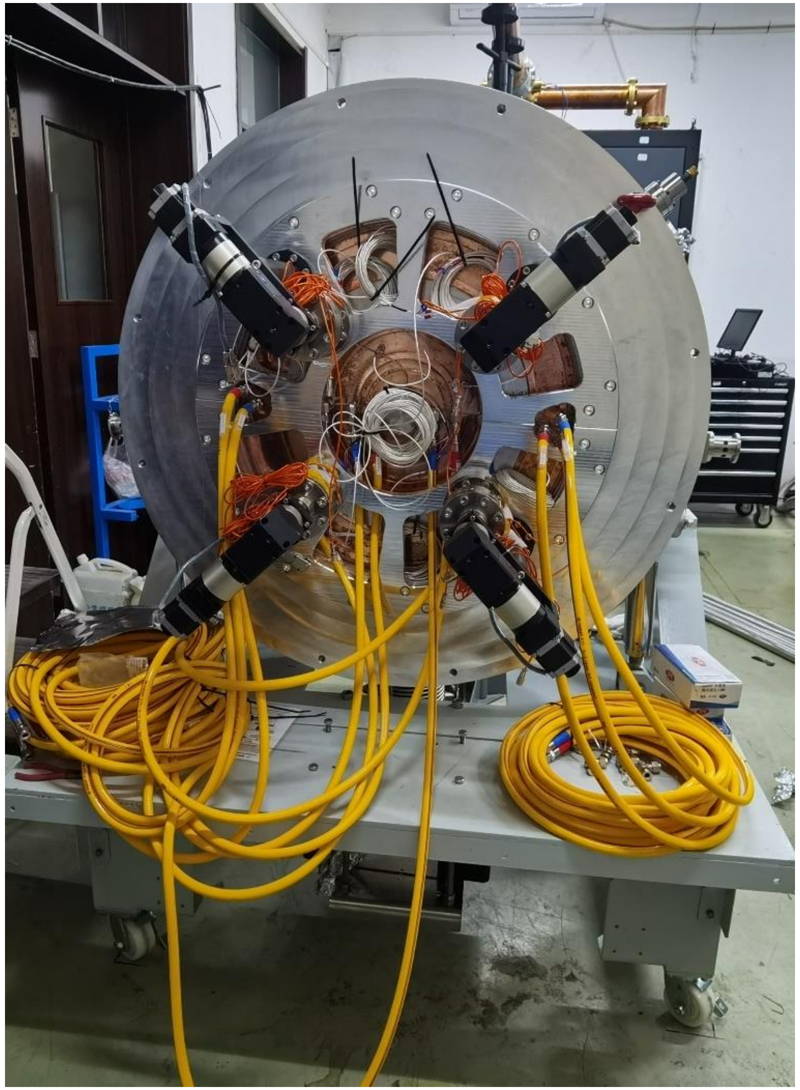


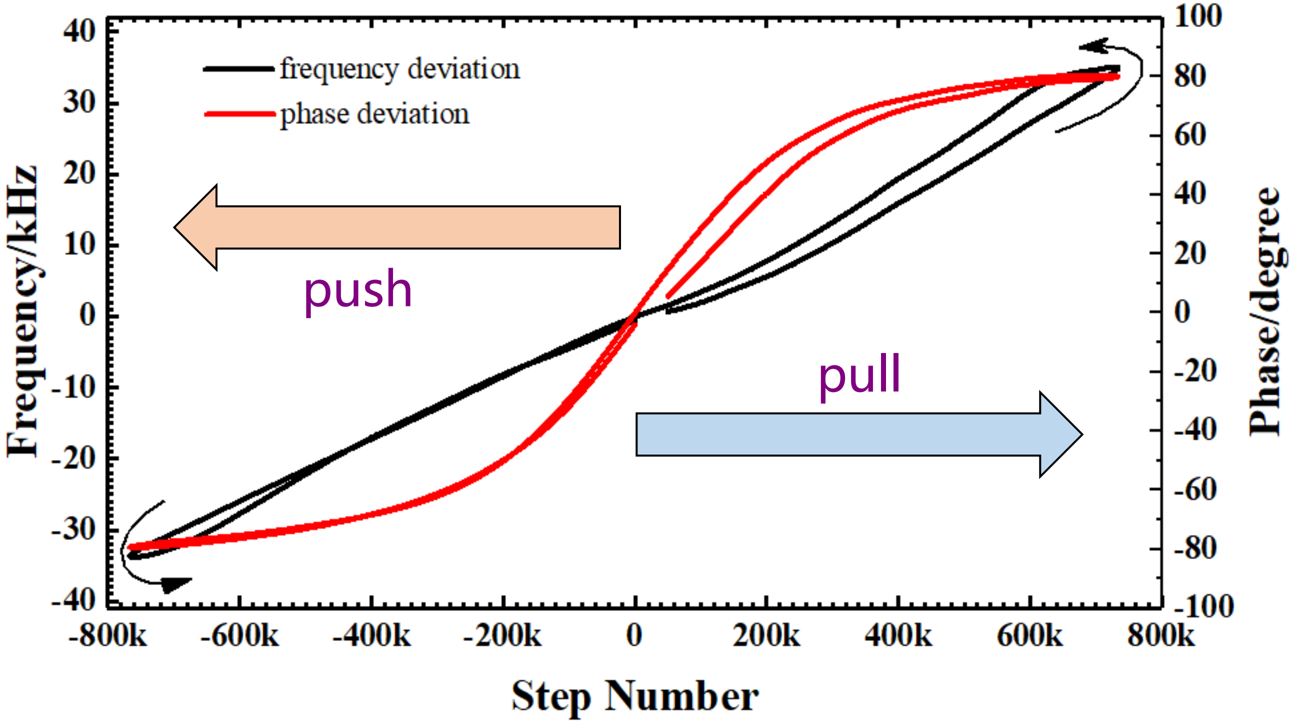
(a) Probe1 冷测参数

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

Machining and cold test of the prototype 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 prototype gun

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The power source and the electron gun are connected by a coaxial waveguide：

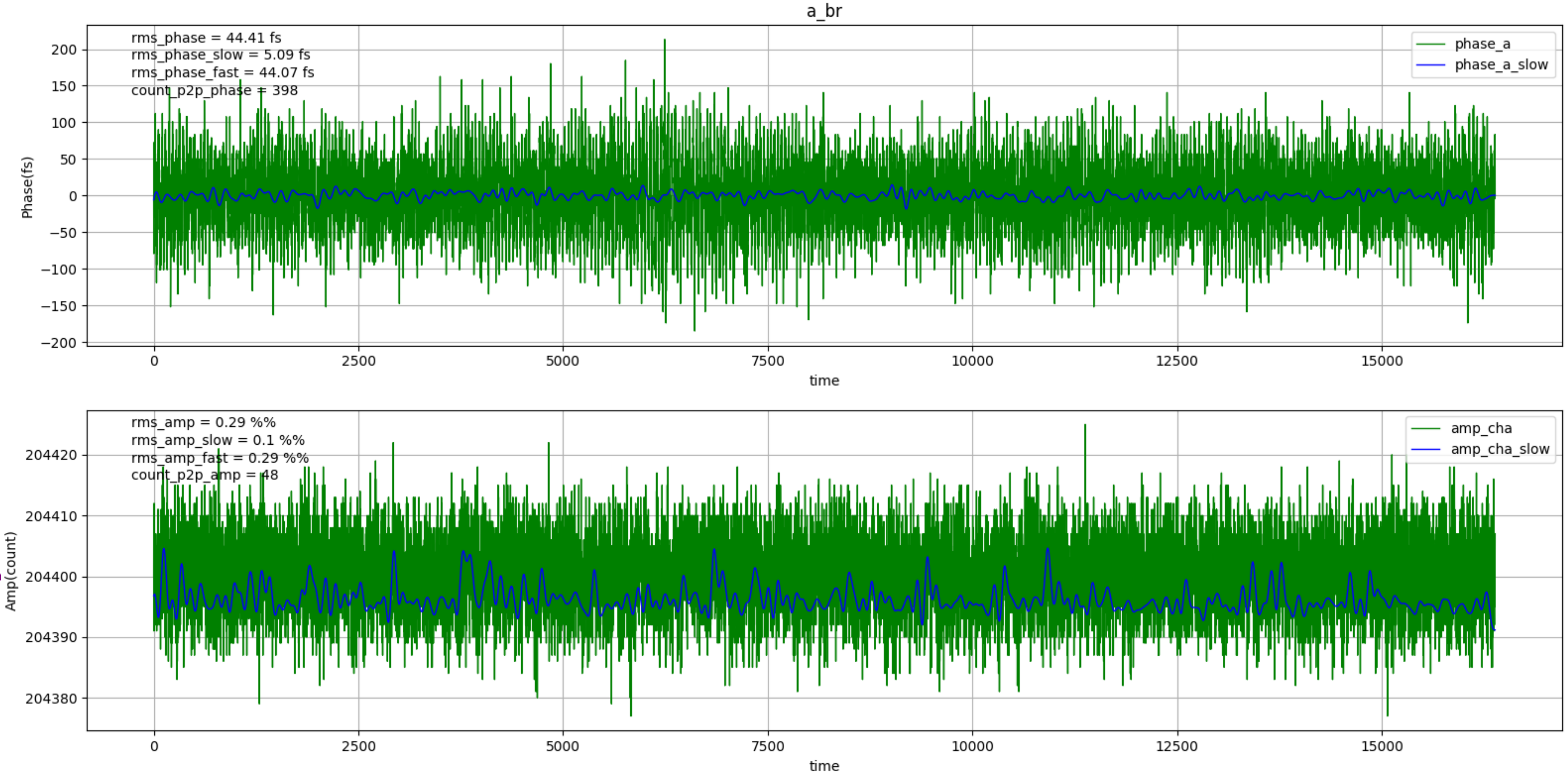
Conditioning of the prototype gun

Tsinghua University

Test of the LLRF when the input power is about 1 kW under CW mode
The time jitter under closed-loop control is 44 fs, and the amplitude jitter is 29ppm

phase

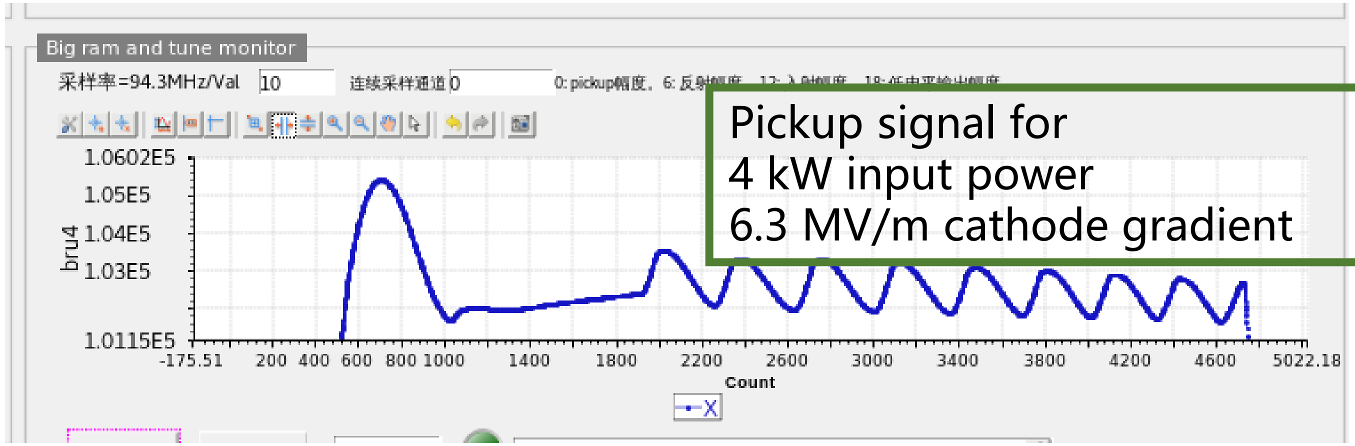
amplitude



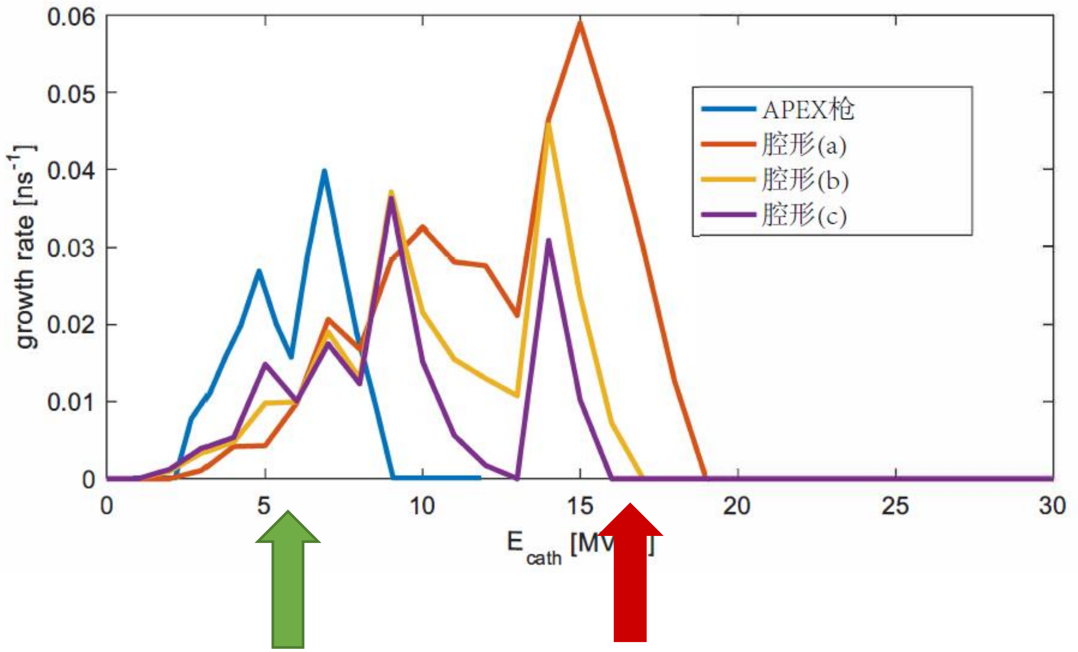
Conditioning of the prototype gun

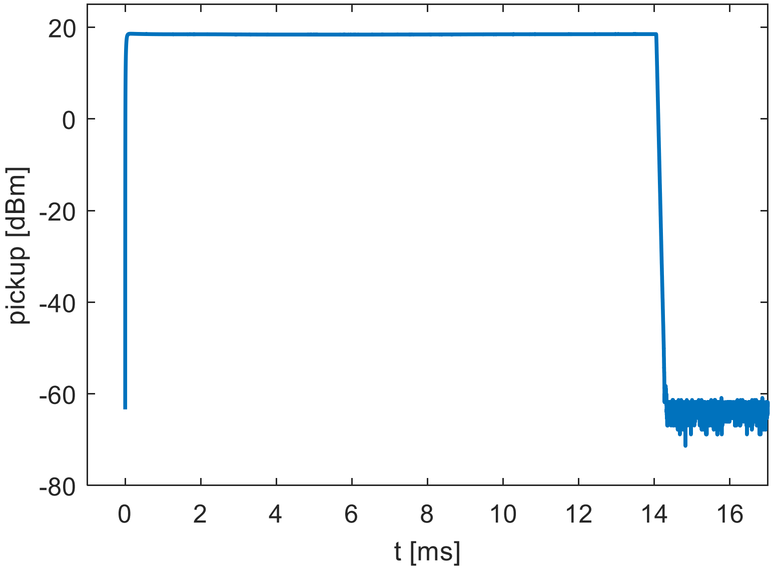
Tsinghua University

Multipacting observation：



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



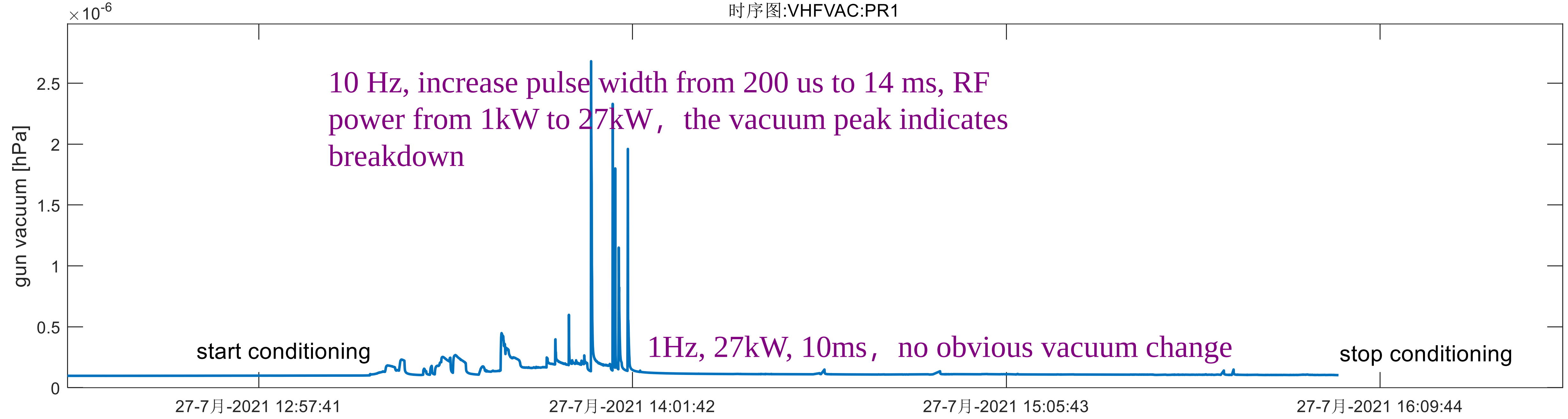


Pickup signal for
27 kW input power
16.5MV/m cathode gradient

The experimental results are consistent with the simulation.

Conditioning of the prototype gun

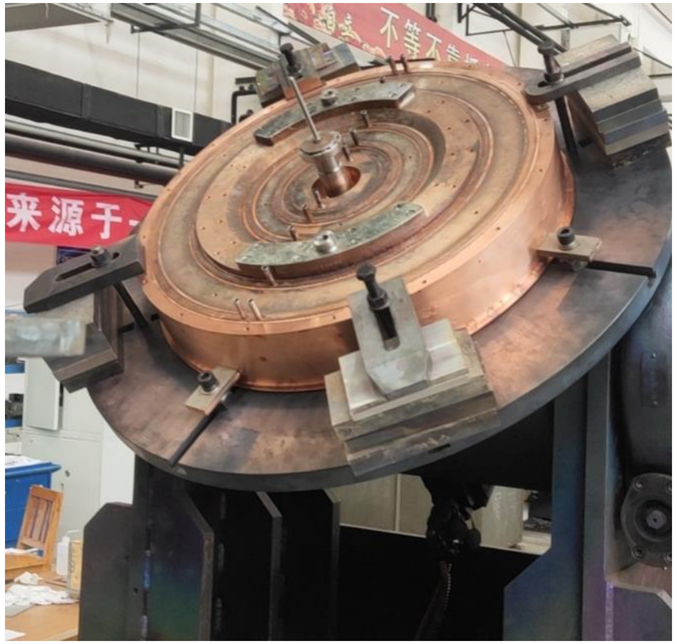
Vacuum change during the conditioning：



- A high power test with 27 kW input power, 10 Hz repetition rate and 14 ms pulse width has been achieved.
- Due to the lack of shielded room, it is very difficult to add more power or increase the pulse width.

Work continued

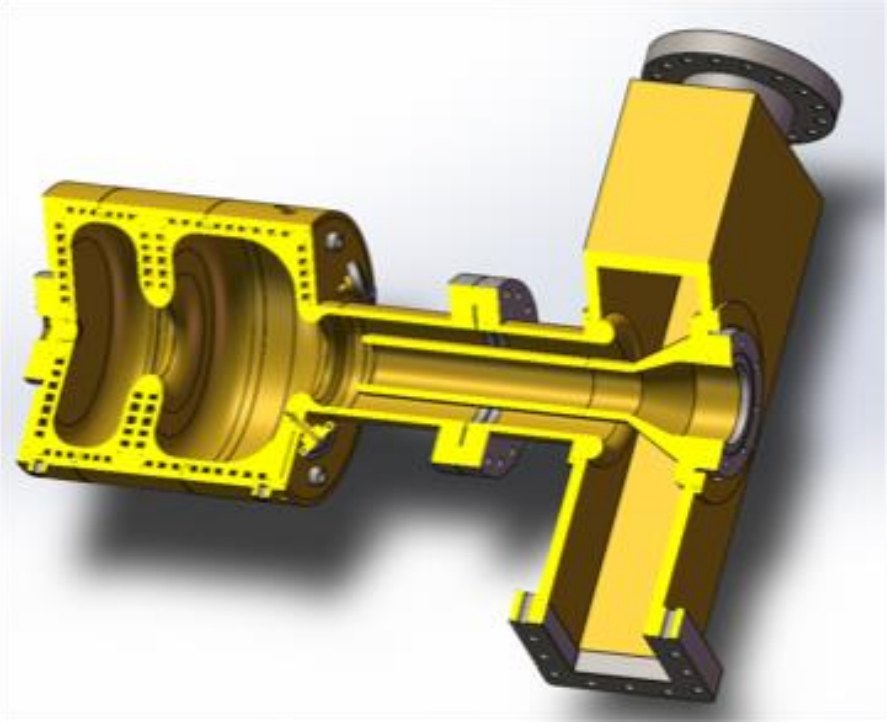
The second gun, i.e., the gun will be used on SHINE, is machining and welding now, and will be finished at the end of September. We are also machining the third gun as a backup.



- We have found a suitable shielded room to do the conditioning of the second gun. We hope we can achieve CW operation with >50 kW input power before the end of 2021.

3、R&D of the L-band PITZ type gun

L-band PITZ-type PC RF Gun for kHz Operation



parameters	value	unit
Gun operation mode	Pulsed	
Gun cathode gradient	>60	MV/m
Repetition	**1000**	Hz
Bunch charge	10-1000	pC

Physical design of the L-band PITZ type gun

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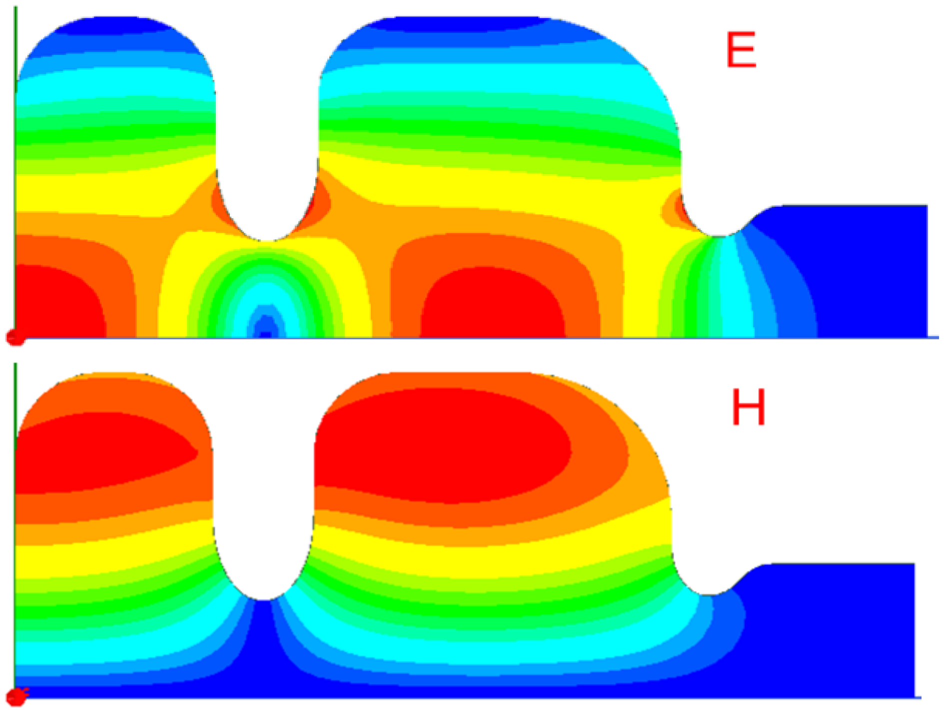
Optimizations of the gun profile:

- Increase the disk iris thickness
- Iris shape from circular to elliptical
- Curved gun corner



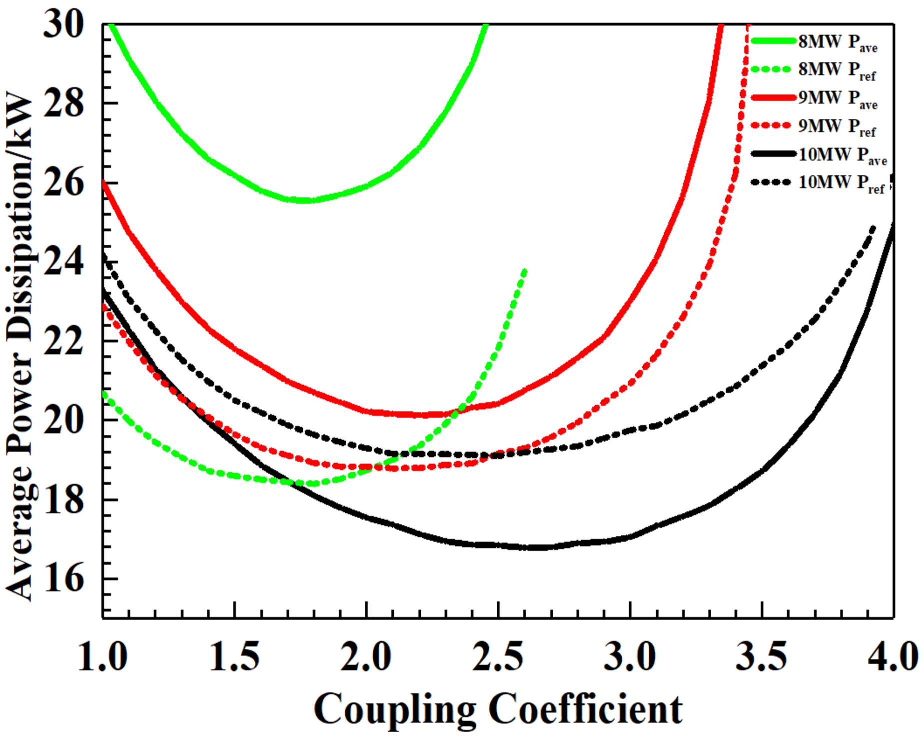
RF parameters in design	
Frequency of Pi mode	1300 MHz
Cathode gradient	60 MV/m
Mode separation between 0 mode and pi mode	6.81MHz
Quality factor Q_0	25718
Shunt impedance	6.45 MΩ
Es max/ Eacc	0.95
Input RF power(pulsed)	10MW max.

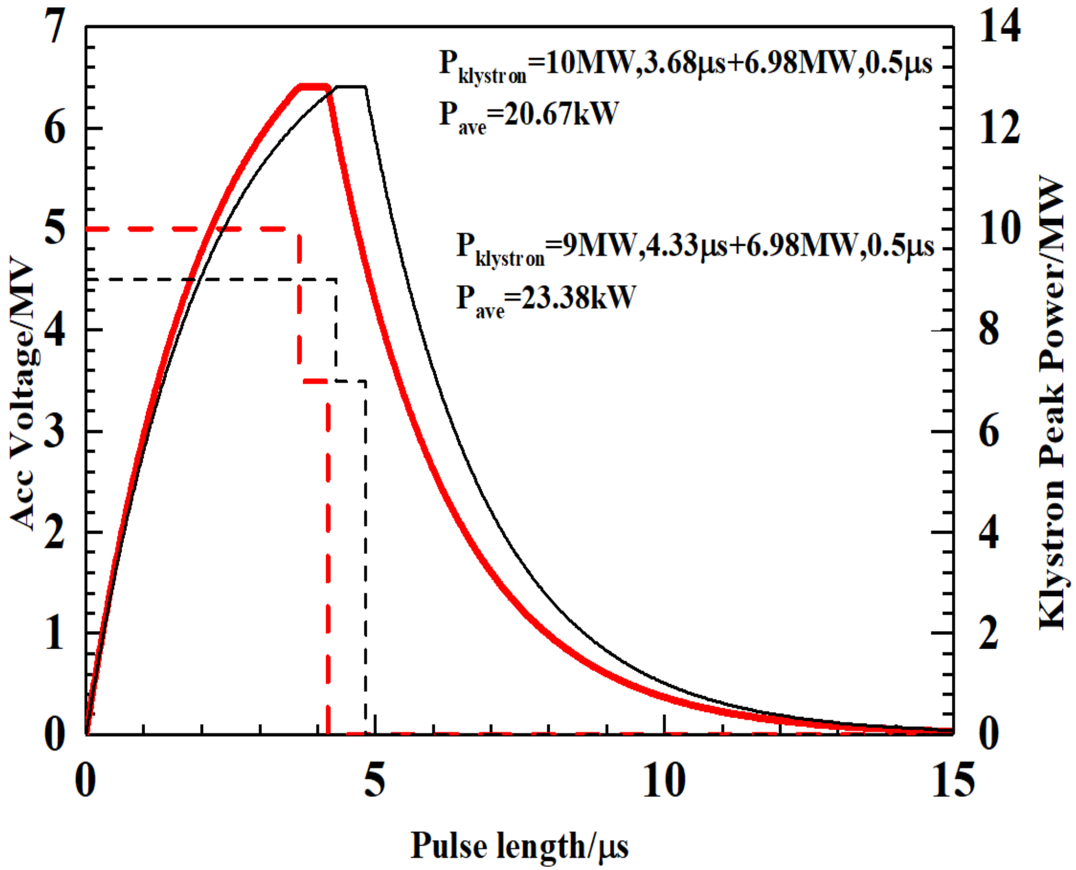
Physical design of the L-band PITZ type gun

Tsinghua University

Increase the coupling factor from 1 to 2

- Shorter required pulse length
- Reduce the average dissipation power and reflection power

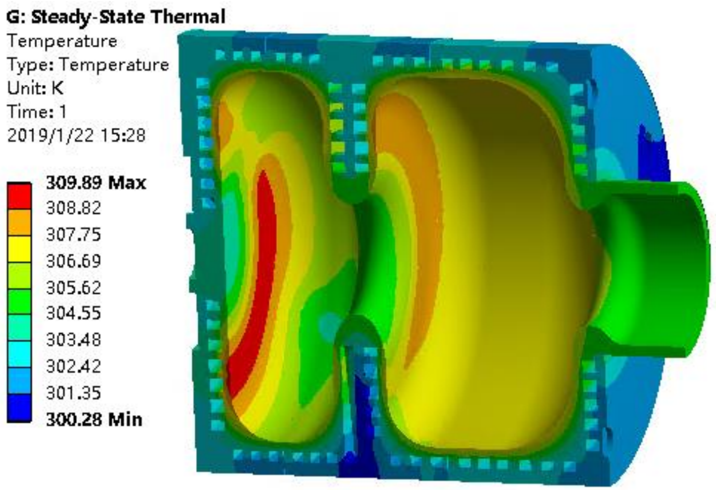




Physical design of the L-band PITZ type gun

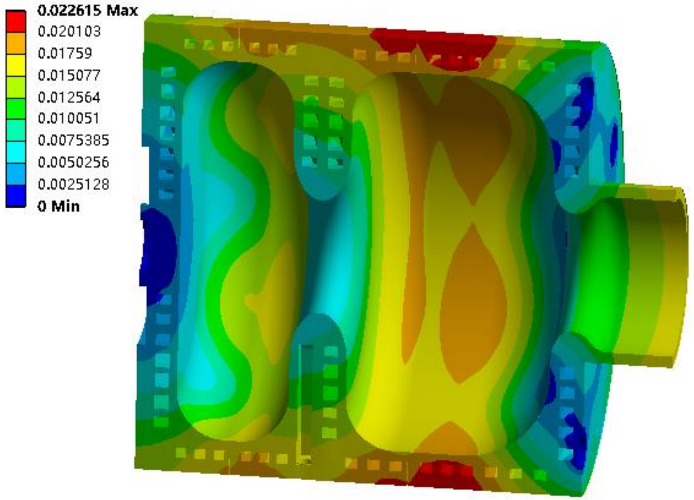
10 independent water cooling pipes：

- 1 in the cathode end cap；
- 2 in the disk iris；
- 2 on the half cell wall；
- 3 on the full cell wall；
- 2 in the full cell end cap.



Temperature distribution:

- Input power : 25kW
- Cooling water：300K & 3bar
- Max. temperature: <310 K

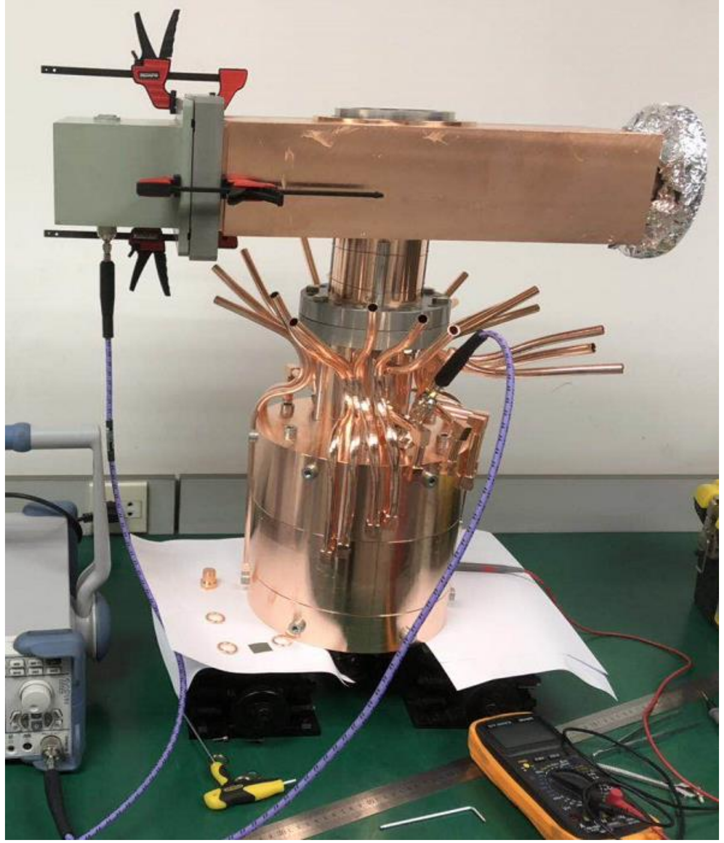
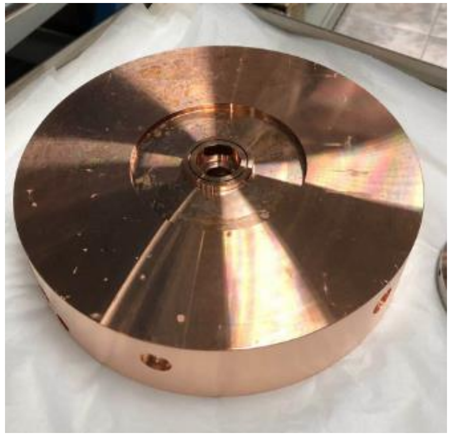


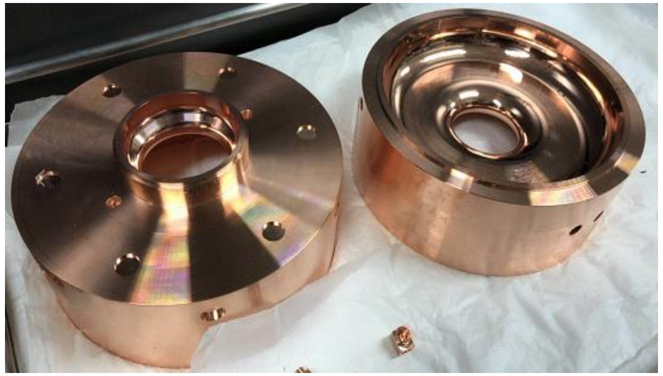
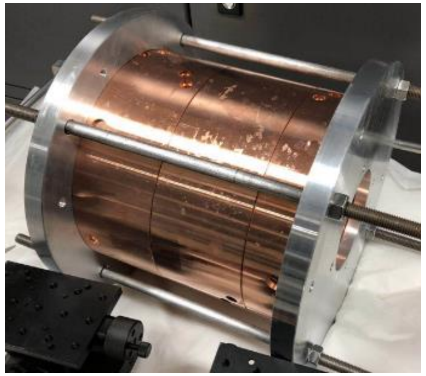
Deformation distribution:

- Max. deformation ~24um
- RF frequency shift: ~50K
- Max. stress: <53Mpa in Cu

Status of the L-band PITZ-type gun

- A prototype gun has been developed and tested successfully with low duty factor high power (~0.01%, 6.5MW) in the last year
- A new gun is being fabricated, and is expected to be brazed in October.


summary

- The designed parameters of the VHF electron gun can meet the needs of the SHINE facility
- The machining and welding of the VHF gun has matured, and the VHF gun II is expected to be completed by the end of September.
- The cold test shows good results. The frequency response in the tuner test is in line with expectations.
- The conditioning of the VHF gun is in progress.
- The L-band PITZ-type gun is being fabricated, and is expected to be brazed and cold testing in October.

Thanks for your attention