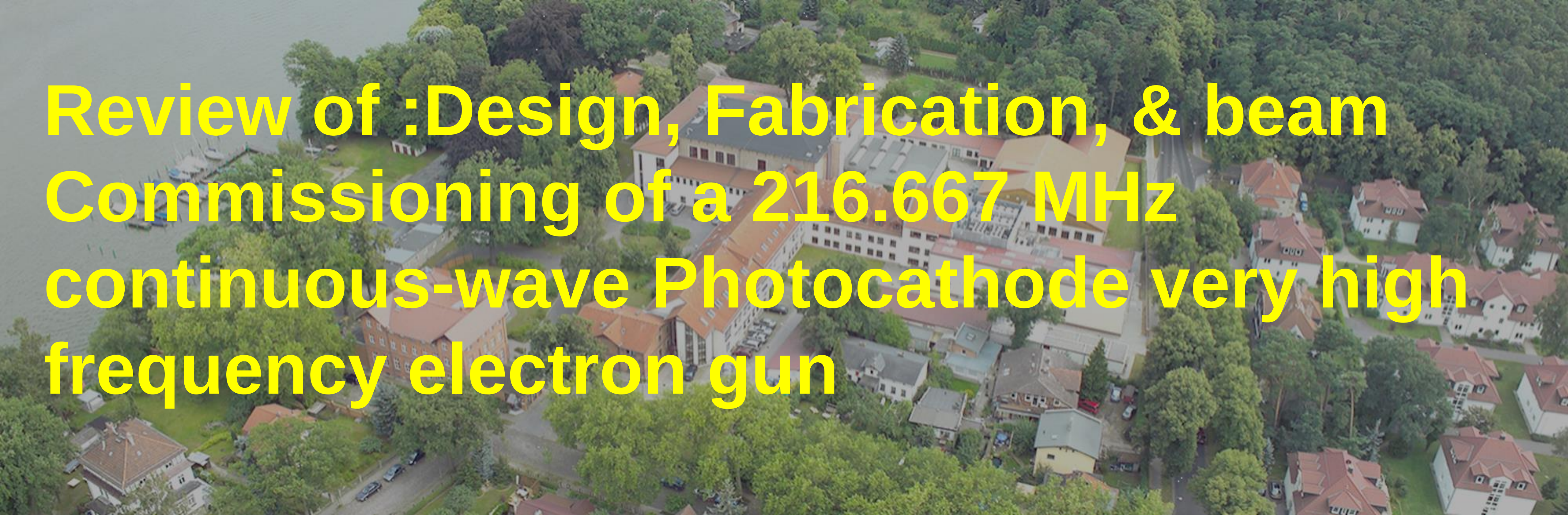
Review of :Design, Fabrication, & beam Commissioning of a 216.667 MHz continuous-wave Photocathode very high frequency electron gun



PHYSICAL REVIEW ACCELERATORS AND BEAMS 26, 103402 (2023)

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Motivation

- X-ray free electron lasers (XFELs) play a crucial role in various fields such as physics, chemistry, structural biology, and material science
- The use of x-rays generated by XFELs has enabled direct observation of the fracture and formation of chemical bonds, analysis of protein structure and function, and visualization of material's femtosecond lattice dynamics
- One of the main directions for the further development of XFELs is to increase the duty cycle
    - LCLS II in U.S. is proposed to work in CW mode
    - SHINE in China , MHz XFEL in CW
- SHINE is a high repetition rate XFEL facility based on an 8 GeV CW SC RF LINAC. Inspired by the success of the APEX gun, the SHINE facility chose a room temperature VHF gun as the electron source
- The MHz-class repetition rates significantly reduce the time required to collect data to accomplish an experiment and enable experiments that require a large number of photon pulse interactions
- There are three types of electron guns that can support cw operation of superconducting (SC) cryomodules of high repetition rate XFELs:
    - direct-current guns
    - normal-conducting (NC) very-high-frequency (VHF) guns
    - SC RF guns

Three types of gun for CW operations

- **DC guns** naturally have the flexibility to support high repetition rate operation, which can produce DC electron beams or bunches with any repetition rate. The cathode gradient of a state-of-the-art dc gun is 10 MV/m. The gun voltage typically ranges from 200 to 500 kV.
    - Cornell University demonstrated that the electron beams produced from 400 kV DC gun, can meet the XFEL beam quality requirements, with a cathode gradient of less than 5 MV/m and a low thermal emittance cathode
- **SC RF gun's** wall power dissipation is orders of magnitude less than that of an NC RF gun, thus SC RF gun CW operation is easier to achieve. The compatibility of the SC RF environment of a cavity and the high quantum efficiency semiconductor cathode has been successfully demonstrated with an RF choke system
- **NC VHF guns** can operate in CW mode because a lower cavity frequency significantly reduces the power density on cavity walls, thus conventional water cooling techniques can solve the heat dissipation problem in CW mode. After several years of effort, the APEX gun developed by Lawrence Berkeley National Laboratory has achieved stable operation in CW mode
- The resonant frequency of the gun is 185.714 MHz. It can produce up to 300 pC electron bunches with 1 MHz repetition rates and 750 keV beam energy. The cathode gradient is about 20 MV/m. The success of the APEX gun proves the maturity of the VHF gun as an electron source for XFELs, and the APEX gun has been chosen as the electron source for LCLS-II

Main Parameters

Requirements of the SHINE facility for the gun rf parameters and the beam quality			PITZ based on EuXFEL and FLASH requirements	
Parameters	**Value**	**Units**		
Gun operation mode	cw		Pulsed	
Resonant frequency	1/n of 1300	MHz	1.3	GHz
Cathode gradient	≥ 25	MV/m	60	MV/m
Beam energy at the gun exit	≥ 750	keV	7	MeV/c
Bunch charge	10–300	pC	0.001-4	nC
Beam repetition rate	1	MHz	10	Hz
Pulse length			≤ 650	μs
No. Of pulses in a train			≤ 2700	
95% normalized emittance for 100 pC @1 mm rms bunch length	< 0.4	mm mrad	0.9 (for 1nC)	mm mrad
Dark current	< 400	nA		
Input Power	75	kW		

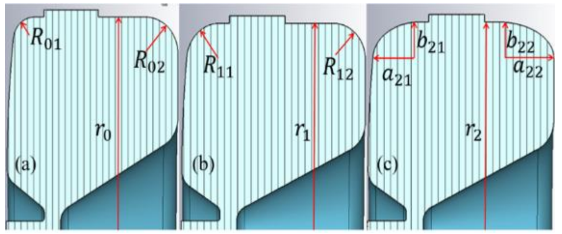
Parameters	FLASH	European XFEL
max. RF repetition rate	10 Hz	10 Hz
max. train length	800 μs	650 μs
bunch spacing	1 μs	0.2 – 1 μs

RF AND MULTIPACTING OPTIMIZATION

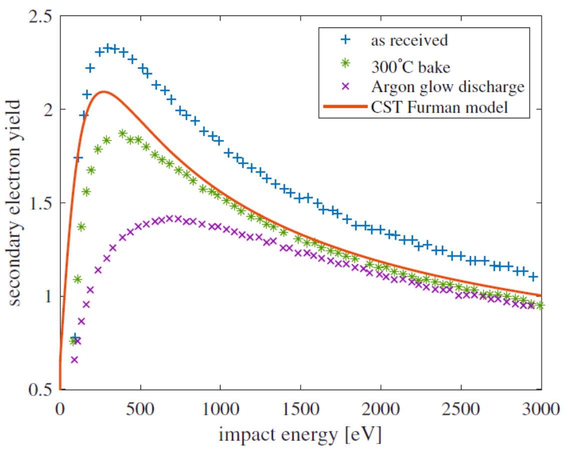
- The gun resonant frequency should be compatible with the frequency of SHINE SC rf linacs (1300 MHz), i.e., 1300/n MHz, where n is an integer
- Of the VHF wave band: (216.667, 185.714, 162.5 MHz) , 216.667 MHz frequency based on the following considerations
  - the f of the APEX gun (185.714 MHz) is not compatible with the existing XFEL timing system at SHINE
  - a higher frequency has the potential to achieve a higher cathode gradient under the breakdown limit based on Kilpatrick's criterion
- The multipacting was simulated in CST Particle Studio with a tracking solver, (CST Furman model for material 2ndry e yield)
- Multipacting zone is primarily located at the outer circle of the cavity shape (the region with a larger radius r)
- α denotes the growth rate, which can be used to characterize the multipacting intensity
- If the number of particles decreases with time, indicating that no multipacting occurs, we set α = 0
- there is no multipacting when the cathode gradient is larger than 16 MV/m

TABLE II. key geometry parameters of the three gun shapes in the multipacting optimization.

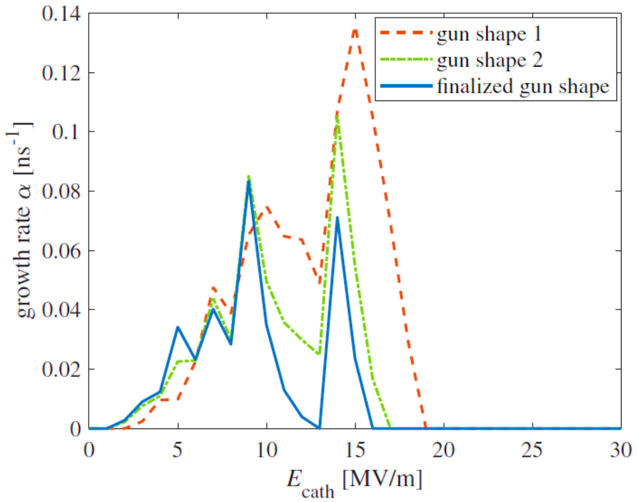
Gun shape 1	Gun shape 2	Finalized gun shape
$r_0 = 35$ cm $R_{01} = 3.94$ cm	$r_1 = 33.5$ cm $R_{11} = 6$ cm	$r_2 = 33.5$ cm $a_{21} = 8.38$ cm
$R_{02} = 5.96$ cm	$R_{12} = 5.81$ cm	$b_{21} = 6$ cm $a_{22} = 10$ cm $b_{22} = 5.7$ cm



Different gun shapes during multipacting optimization: (a) gun shape 1, (b) gun shape 2, (c) finalized gun shape



Secondary emission yield of copper as a function of primary energy of electrons with different surface treatments



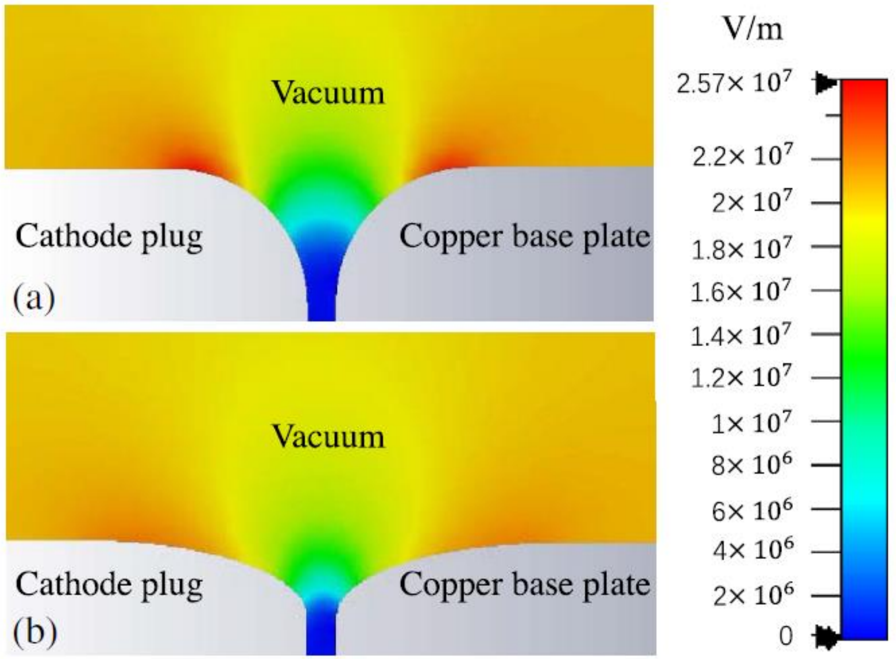
Growth rate α of different gun shapes as a function of the cathode gradient E_{cath}

Dark Current optimization

- In RF simulation, the corners at the joints of the cathode plug and the copper base plate were not considered
- These corners can result in electric field enhancement compared to E_{cath} and become the main source of dark current downstream of the gun.
- As these corners are close to the gun axis center, the dark current emitted from these corners is more easily transported out
- the electric field distributions shown for two geometries
  - A round corner with a r =1 mm, same as the APEX gun
  - An elliptical corner with a major and minor axis of 1.5 & 0.5 mm
- If the electric field at the center of the cathode plug is 30 MV/m
  - Peak surface electric field at the round corner is 37 MV/m
  - Peak surface electric field at the elliptical corner is 32.5 MV/m.
- Therefore, the elliptical corner has been adopted for our gun, which helps to suppress dark current emission and reduce the possibility of breakdown in this region

TABLE III. Gun rf parameters after optimization.

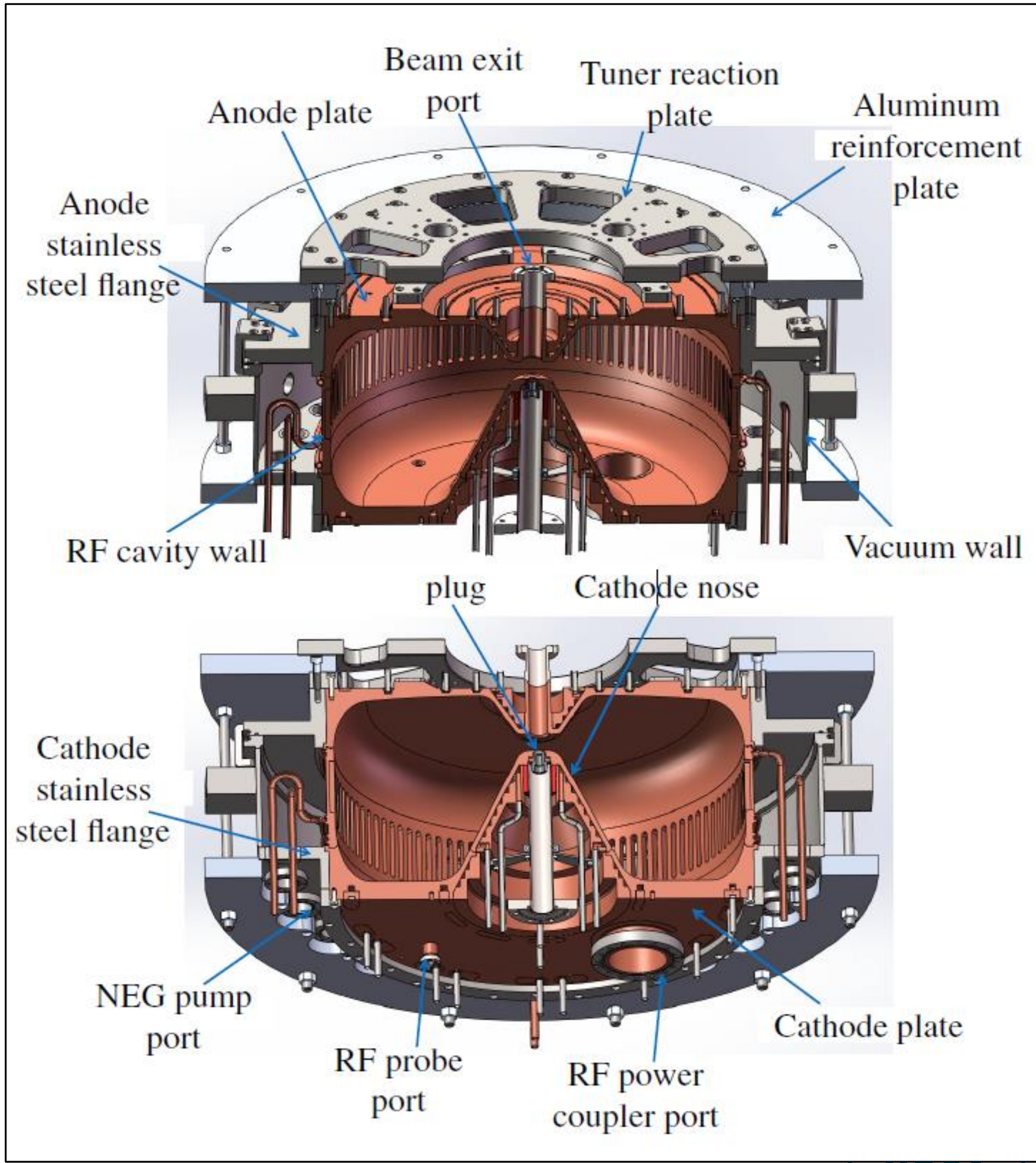
Parameters	Value	Unit
Frequency	216.667	MHz
Cathode gradient	30	MV/m
Input power	90.4	kW
Peak surface electric field	37.0	MV/m
Peak surface power density	28.45	W/cm^2
Voltage	868	kV
Stored energy	2.24	J
Quality factor	33717	
Shunt impedance	8.34	MΩ



Electric field distributions at the corners of the joints of the cathode plug and the copper base plate with (a) round corners and (b) elliptical corners

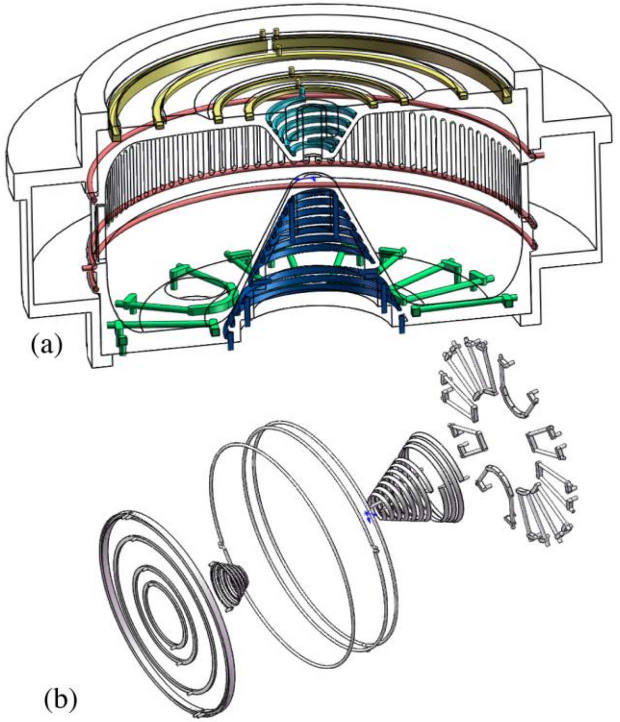
MECHANICAL DESIGN

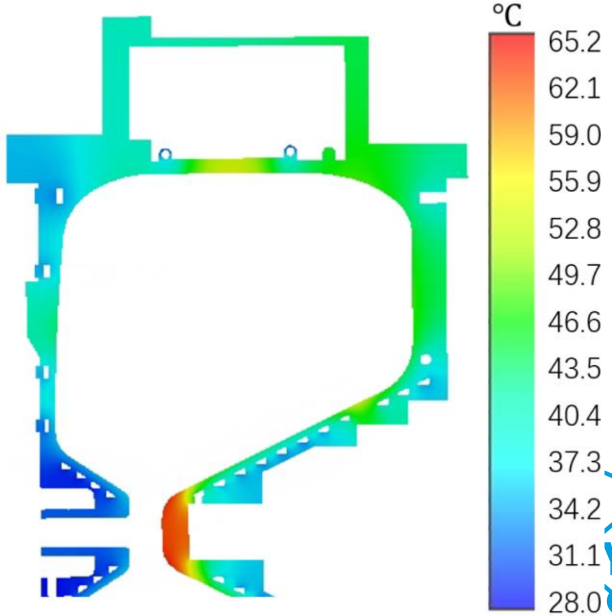
- The cavity structures is oxygen-free electrolytic copper
- The vacuum chamber, including the vacuum wall and the large flanges on the cathode and anode, and all Conflat (CF) flanges and vacuum pipes, are machined with 316L stainless steel
- An array of 108 slots measuring 10 mm in width, 14 mm in depth, and 100 mm in length are milled through the rf cavity wall to connect the cavity and the stainless steel vacuum chamber
- There are 24 CF-35 flanges electron beam (Ebeam) welded to the large cathode stainless steel flange for connection to the vacuum pumps, including 20 Capacitorr Z400 NEG & 4 NexTorr NEG-ion pumps from SAES
- One CF-150 flange and six CF-35 flanges on the vacuum wall,
  - CF-150 flange to connect 300 L/s ion pump
  - six CF 35 flanges are used to connect rough pumping valves, residual gas analyzer, vacuum gauges, etc
- Simulation shows that the vacuum at the plug top surface can reach 1.45 × 10^{-8} Pa
- There are two CF-100 flanges and two CF-16 flanges on the cathode plate, to connect rf power couplers and RF probes respectively



Cooling Assembly

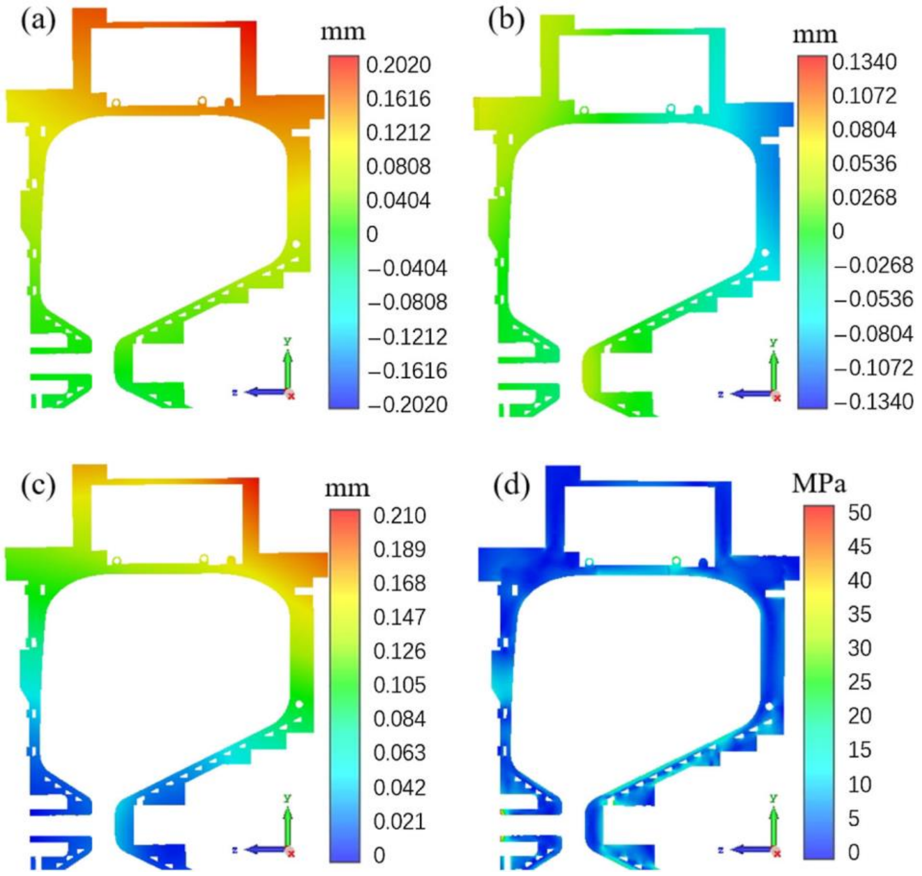
- High average power → RF thermal effects
- For stable operation → 23 independent cooling channels
- The water flow rate of the two spiral channels in the cathode nose is assumed to be 15 L/min, flow velocity is 5.9 m/s,
- while the other 21 channels have a flow rate of 10 L/min and velocity of 2.1–3.3 m/s
- Coupled electromagnetic-thermal- structural finite element analysis using ANSYS
- The RF parameters simulated in HFSS → total RF surface loss of 90.4 kW assumed on the cavity wall and the loss distribution imported into Fluent as a heat source
- The steady state temp distribution shows
  - Highest temp (65.2 °C) at top of cathode nose
  - Temp at the slots on the rf cavity wall ~ 54 °C
  - in other locations < 50 °C.
  - The temperature rise of all the cooling channels is < 9 °C



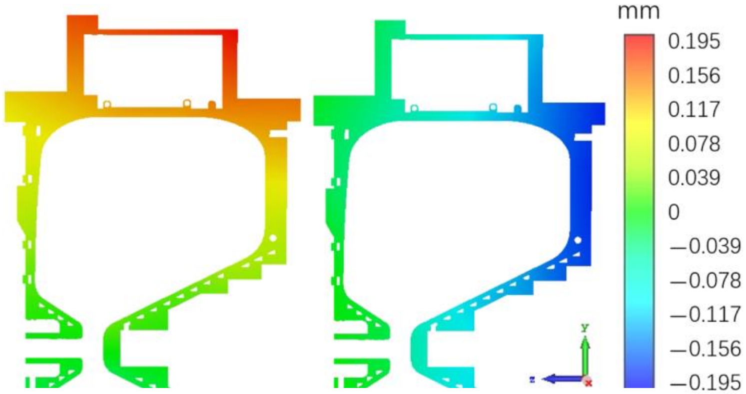


Deformation due to Thermal and Atmospheric Pressure effects

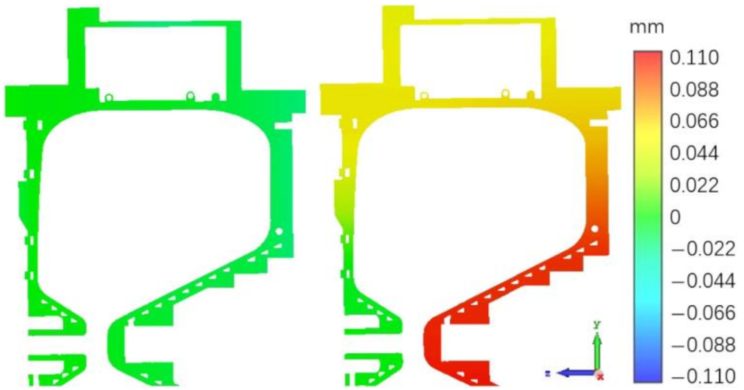
- The temp distribution calculated in Fluent → static structural module for mechanical simulations
- The radial expansion decrease frequency ~ 95 kHz
- Axial movements result in a frequency increase of about 34 kHz
- Total frequency decreases by about 61 kHz due to the thermal deformation
- The radial deformation due to atmospheric pressure is very small
- Under atmospheric pressure, both the cathode assembly and the anode assembly are inwardly concave, resulting in a 110 μm decrease in the cathode-anode gap and a frequency reduction of about 100 kHz



Radial (a), axial (b) and total (c) deformation of the VHF gun due to thermal expansion and atmospheric pressure. The distribution of the von Mises equivalent stress is also shown in (d)



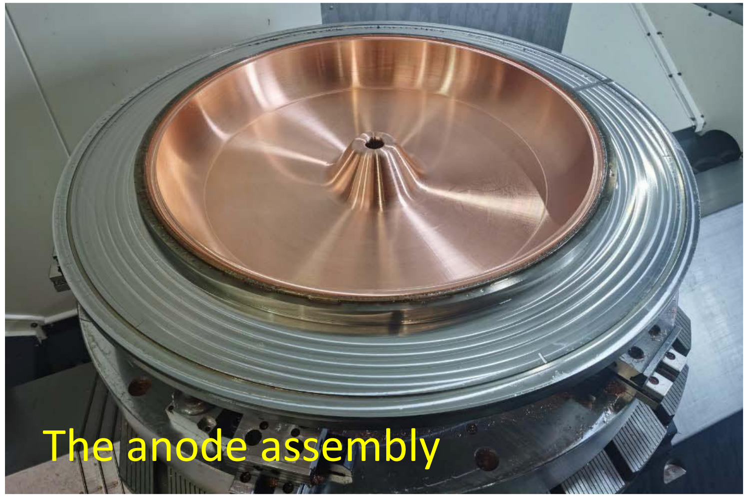
Radial (left) and axial (right) deformation of the VHF gun due to thermal expansion.



Radial (left) and axial (right) deformation of the VHF gun due to atmospheric pressure

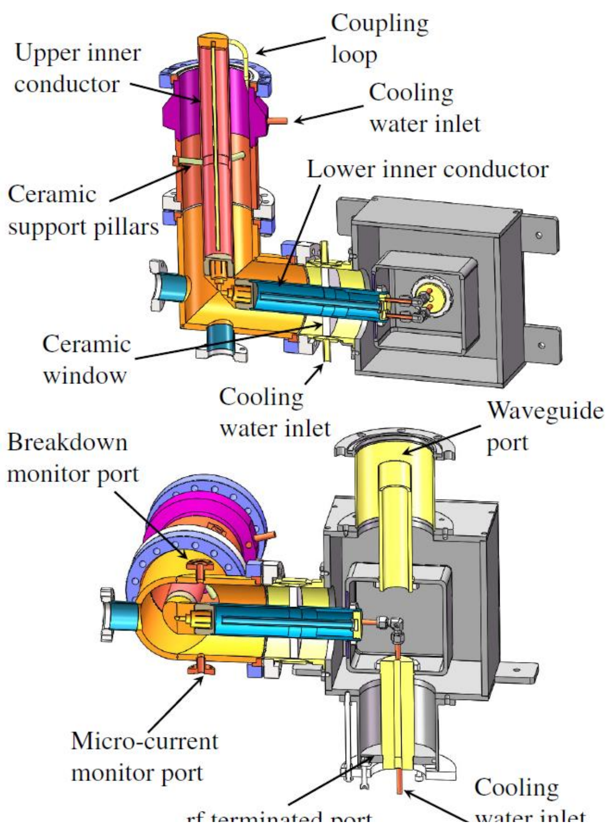
GUN ASSEMBLY

- During the final assembly process, the VHF gun is divided into two parts: the cathode assembly and the anode assembly
- The cathode assembly is welded together in the following steps:
  - Ebeam welding the vacuum wall to the cathode stainless steel flange
  - Ebeam brazing the cathode plate to the cathode stainless steel flange,
  - Ebeam welding the cathode nose to the cathode plate,
  - Ebeam welding the rf cavity wall to the cathode plate
- The anode assembly consists of the anode plate and the anode stainless steel flange, which are Ebeam brazed together
- After the cathode and anode are assembled together, the cathode-anode coaxiality is adjusted using a laser tracker, and the final coaxiality is less than 50 μm
- Finally, the stainless steel rims where the vacuum wall and the anode flange contact are TIG welded together to ensure vacuum sealing

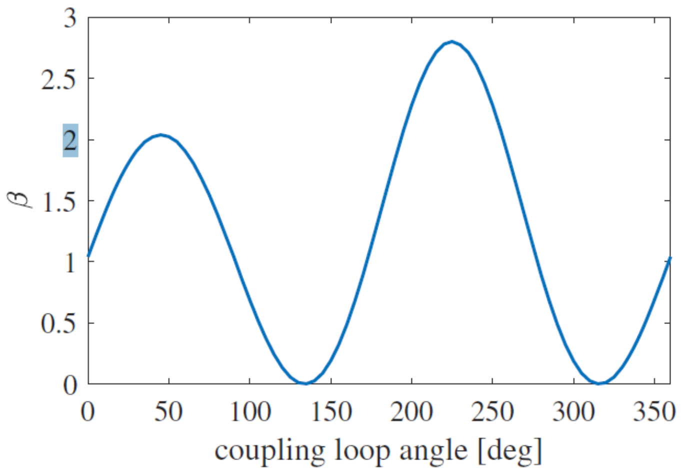


RF Power Couplers and Probes

- RF power couplers transfer RF energy from the solid-state power source to gun
- The coupler body is an L-shaped 4-1/16 inch coaxial waveguide
- Two magnetic loops connecting the inner & outer conductors used for power coupling at the end of the waveguide near VHF gun side
- Dimensions of the cuboids & length of RF terminated port are systematically optimized to match microwave transmission,
  - power reflection at the waveguide port after optimization < 1%
- Two CF 35 flanges on the outer conductor for vacuum pumping → NEG-ion pumps
- Two identical couplers installed on the VHF gun → the coupling factor of each adjusted by rotating the coupling loop
- Usual coupling factor of each coupler to 0.5 → total coupling factor β is 1
- Two **Electric probes** are also equipped on the VHF gun, and the coupling factor can be flexibly adjusted by changing the probe length.
- Generally, one probe is connected to the digital low-level rf (LLRF) system for closed-loop control, while the other probe is connected to an oscilloscope for real-time monitoring of the gun power.

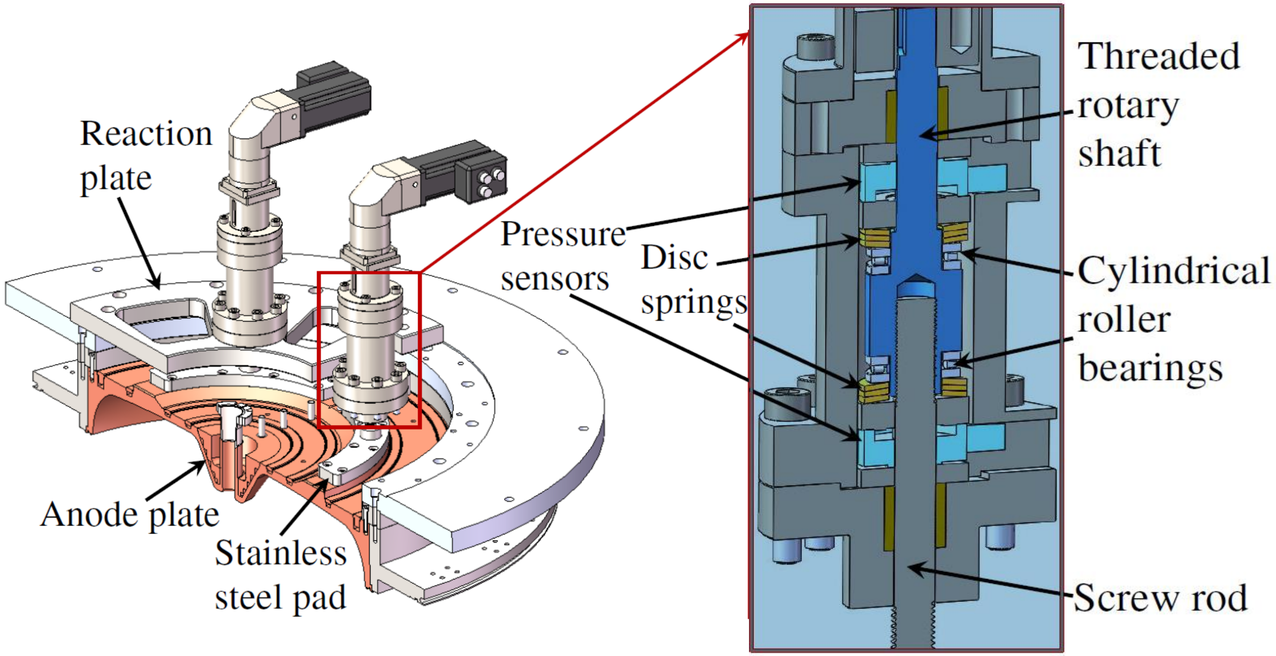


RF power coupler cross sections



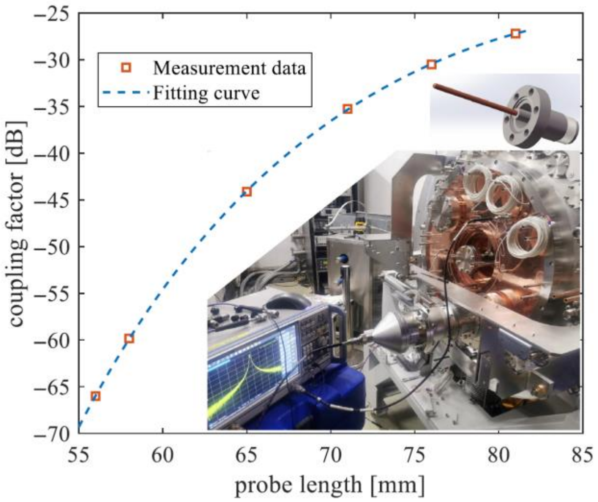
Frequency tuners

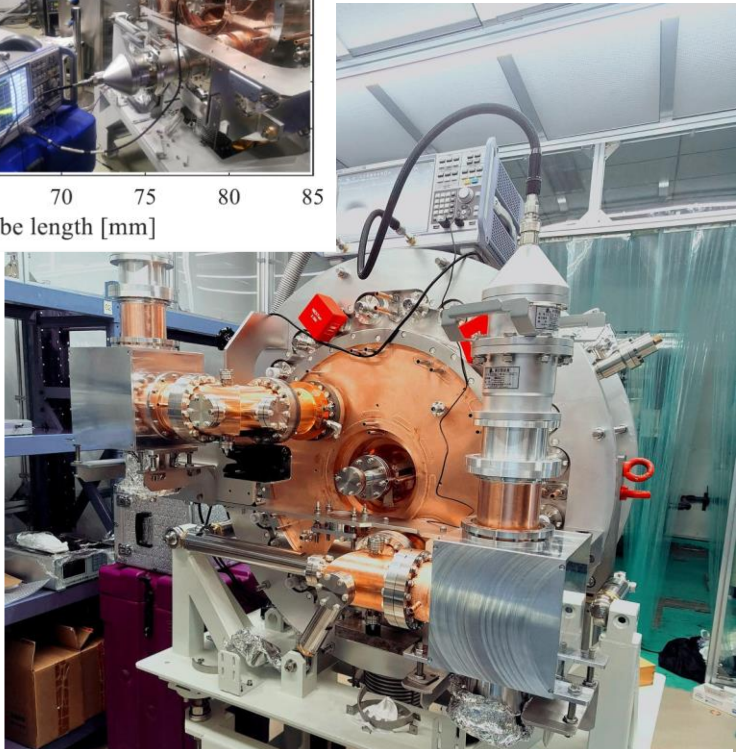
- The resonant frequency is stabilized by adjusting the cathode-anode gap through the elastic deformation of the anode plate
- achieved by pulling or pressing the anode plate through four tuners
- The base of the tuner is mounted on the reaction plate and bolted to the aluminum reinforcement plate and the large anode stainless steel flange.
- The tuners apply force to the anode plate through stainless steel pads, a stepper motor drives a threaded rotary shaft to rotate
- Each tuner is capable of up to 13 kN push or pull force on the anode plate, However, 11 kN limit

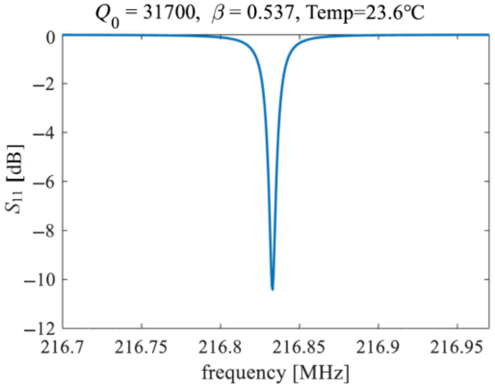


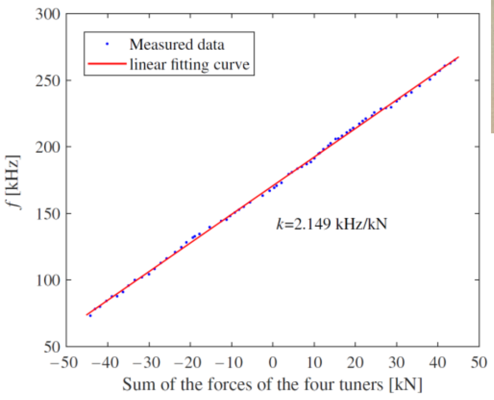
COLD TEST

- **Coupling of electric probes**
  - The coupling factor of both probes was tuned to be about −60 dB, in other words, each probe can couple out 90 mW of power when there is 90 kW of power in the gun.
- **Coupling of the RF power couplers**
  - The coupling factor (0.537) and quality factor (31,700) from S11 curve was measured for coupler 1 with 2 being short circuited
  - For 2, Coupler 1 & 2 were connected to the two ports of the VNA, respectively. The S11 and S22 curves were repeatedly measured while the coupling loop of Coupler 2 was rotating, until the two curves completely overlapped, indicating that these two couplers have the same coupling factor
- **Frequency Vacuum drift**
  - Measured gun frequency decreases by about 100 kHz from the atmos to vacuum
  - Calculation → should increase by 65 kHz due to media change
  - Conclusion: deformation due to atmospheric pressure decreases frequency about 165 kHz, which is slightly larger than the simulation prediction (100 kHz)
- **Resonant frequency tuning**
  - The sum of the forces of the four tuners to the anode plate changed from approximately −44 up to 44 kN, during which the gun frequency increased
  - A linear fitting shows that the response of the gun frequency to the applied force is 2.149 kHz/kN in this process.
  - The maximum tuning range of the tuners is approximately ± 96 kHz









Baking of VHF Gun

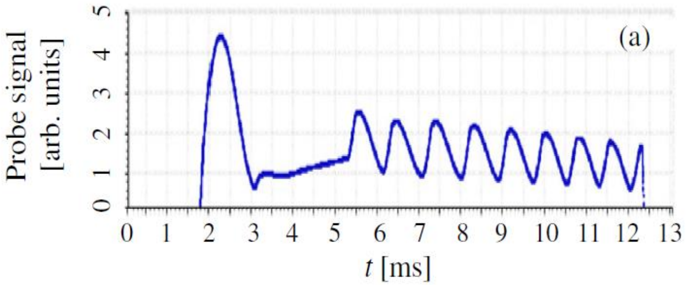
- Before high power conditioning, the gun was baked to achieve good vacuum performance
- The stainless steel chamber of the gun was heated to 120 °C by conventional heating tapes. The large ion pump used a built-in heater to bake.
- The copper part of the gun was baked using **RF heating**
- Water cooling of the gun was turned off completely, and the water cooling of the couplers remained open.
- The RF peak power fed into the gun was 30 kW, and the duty cycle was 10%, i.e., about 3 kW of average RF power was applied to the cavity
- There were eight temperature probes on the cathode and anode plates to monitor the rise of the cavity temperature in real-time.
- The temperature of the cathode and anode plates was maintained at about 140 °C.
- Despite the absence of a temperature probe on the cathode nose, the temperature of the nose was anticipated to exceed 140 °C based on the simulated power density distribution on the cavity inner surface.
- After approximately 30 h of baking, all NEG pumps were activated and all ion pumps were turned on
- At this time, the vacuum pressure in the gun without RF power was reduced to 2×10^{-8} Pa.

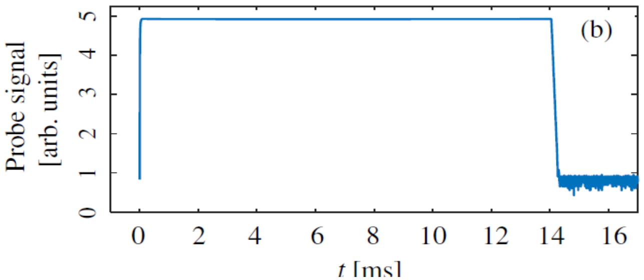
High Power Conditioning

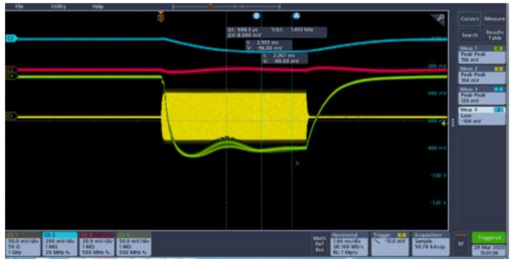
- Each of the two coupler ports was connected to a 60 kW solid-state amplifier (SSA) via a 4.5 inch coaxial waveguide
- The microwave generated by the SSA was transmitted through a waveguide and a coupler before being fed into the VHF gun
- An LLRF system generated two RF signals, and each signal was used to drive an SSA
- The amplitude and phase of the two driving signals are independently adjustable
- so that the amplitude and phase of the two channels of RF power fed into the gun were the same, and thus the probe detected the maximum power in the gun
- When the gun started to operate, the LLRF system worked in a self-excited loop mode, in which the frequency of the LLRF drive signals followed the resonant frequency of the gun.
- At the beginning, the VHF gun operated in pulse mode, with a pulse repetition rate of about 100 Hz
- The peak power of the RF pulse was gradually increased. When the peak power reached a certain set power, the pulse width was increased until CW operation was achieved
- It took approximately 130 integrated hours for the gun to reach 75 kW CW operation after initiating pulsed power conditioning

High Power Conditioning

- In the pulsed operation mode, multipacting was observed in the gun under some gun powers
- The multipacting intensity could be judged based on the distortion of the probe signals
- The multipacting intensity varied with different RF powers. When the input power was below 23 kW, corresponding to a cathode gradient of 15 MV/m, the probe signal was distorted, indicating that multipacting had occurred

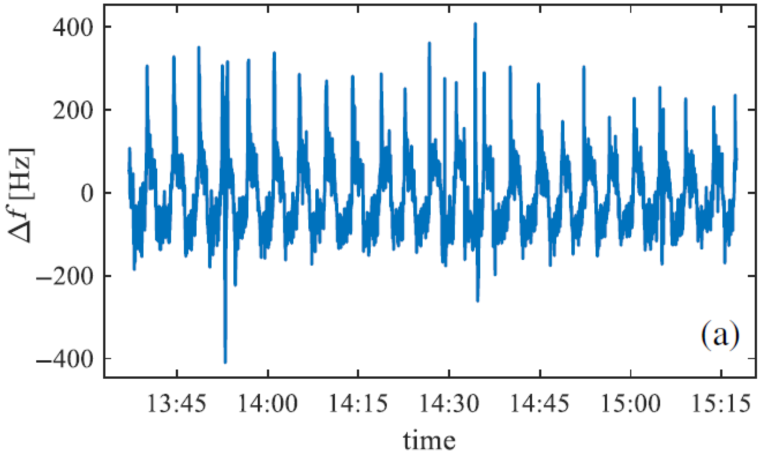




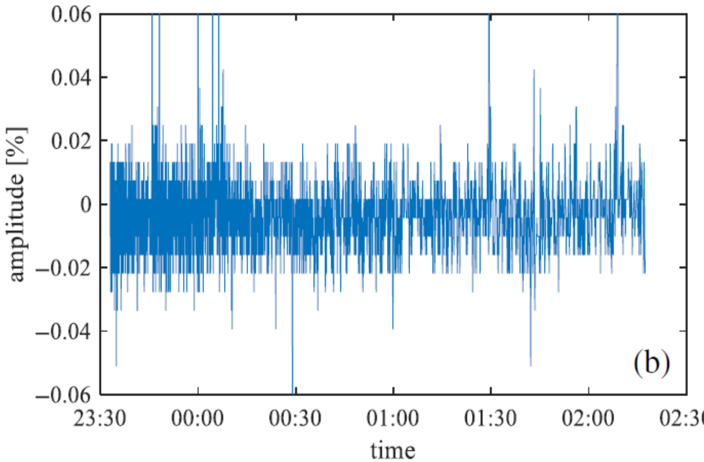


- When the input power was larger than 23 kW, the probe signal was clean and stable, indicating that no multipacting
- In addition, some current signals were detected by the microcurrent monitors on the couplers. These current signals indicate the occurrence of multipacting in the couplers.
- The signal amplitude varied with different RF powers and the vacuum pressure inside the coupler
- Signal amplitude of Coupler 1 always > Coupler 2, reason → titanium nitride coating of 1 was thinner than that of Coupler 2
- the current signal with an amplitude of 1 μA or less was considered acceptable in pulse mode
- Fortunately, the current signals of both couplers disappeared when operating in CW mode with 75 kW input power

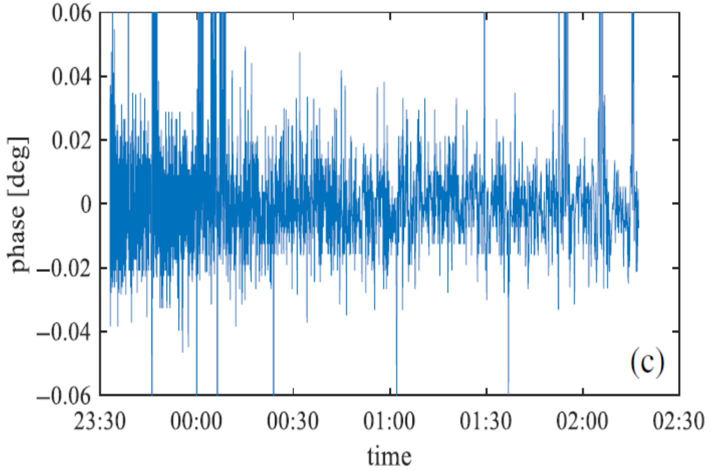
High Power Conditioning CW @ 75 kW



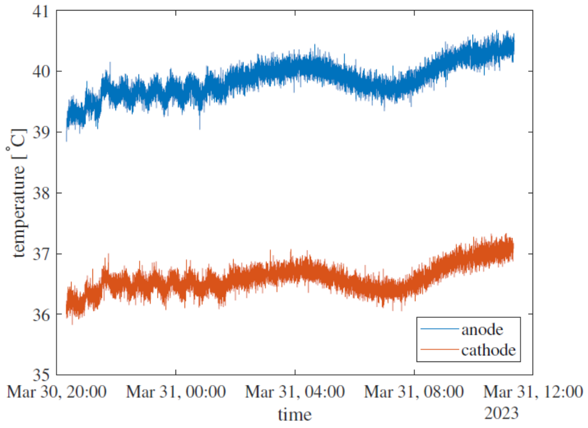
the change of the gun frequency within 1.5 h in active tuning mode.



Change of the amplitude of the probe signal within 3 h closed loop LLRF (0.011% or 0.00011)



Change of the phase of the probe signal within 3 h closed loop LLRF (0.0148)



The temperature change of the cathode and anode plates within 16 h of continuous high power conditioning

TABLE IV. Rf performance during high power conditioning.

rf parameters	In design	Achieved
Operation mode	cw	cw
Cathode gradient (MV/m)	30	27
Input power (kW)	90.4	75
Voltage (keV)	868	780

BEAM COMMISSIONING

- The VHF gun was situated at the beginning of the beamline.
- A cesium telluride photocathode was utilized during commissioning
- A room-temperature 1.3 GHz 2-cell buncher was employed to compress the bunches
- 1.3 GHz solid-state power source of 6.5 kW RF to operate buncher at 230 kV voltage during beam commissioning
- With careful water cooling design, the buncher could operate in CW mode also resonant frequency can be tunes using the independent cooling unit

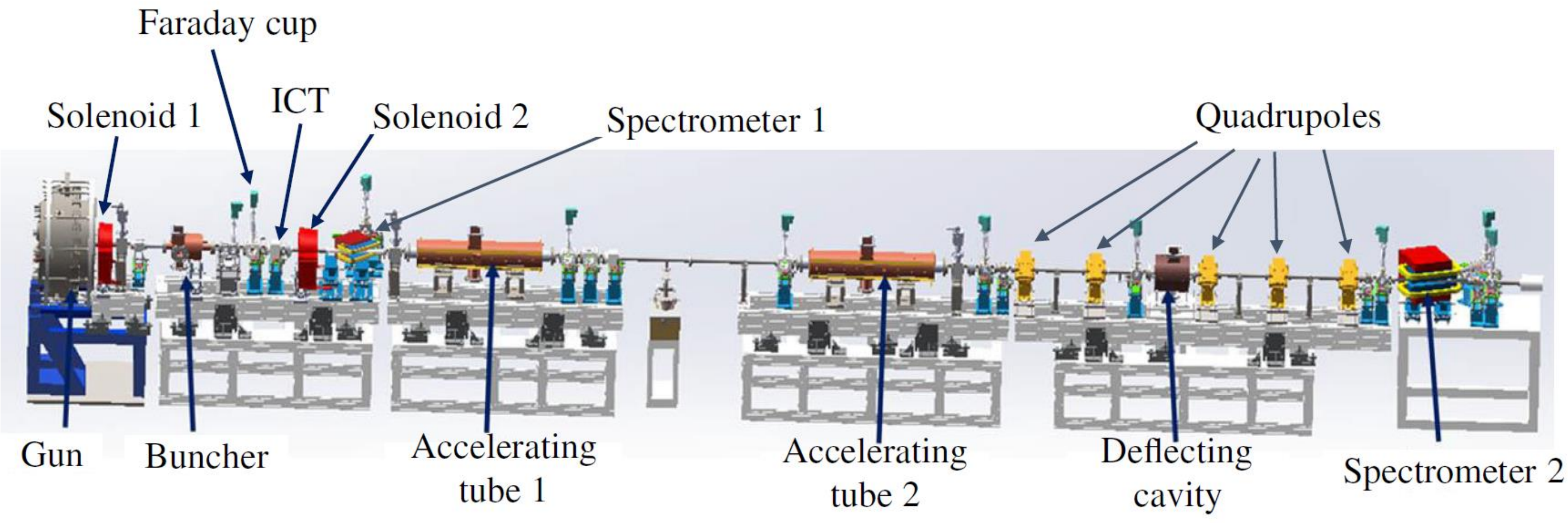


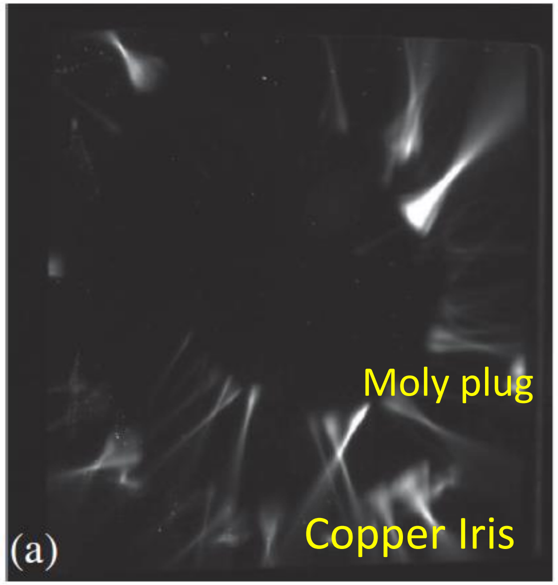
FIG. 27. Layout of the diagnostic beamline for the beam commissioning of the VHF gun.

Beam Commissioning

- **LASER**: The laser wavelength is 257 nm, with a FWHM 11 ps
- The laser pulse was divided into two beams by a Glan prism, and the interval adjusted by length of the delay line → combined to form a longitudinal stacked laser pulse FWHM: 22 ps, (more also possible). The repetition rate of the laser pulses was adjustable up to 1 MHz
- **Solenoid**: placed at the exit of the gun for emittance compensation and beam focusing. Another solenoid was placed downstream of the buncher to provide additional focus for the electron beam
- **Faraday cup:** placed about 1.5 m downstream of the gun exit to measure the dark current and the photoelectron beam
- **ICT:** placed behind the Faraday cup to noninvasively measure the charge of the electron bunches
- **Low Energy Spectrometer:** consisting of a dipole and a fluorescence imaging unit, to measure the energy of the electron beam at the exit of the gun -- determine the gun voltage
- **Booster:** Two 1.3 GHz room-temperature accelerating tubes (linacs) boost the beam up to 28 MeV
- **High-energy spectrometer:** to measure the beam energy after the acceleration of the linacs
- **Deflecting cavity:** to measure the bunch longitudinal distribution by applying a time dependent vertical kick on the beam
- **Quadrupoles:** were used to focus the beam and perform the emittance measurements
- **fluorescent screens:** to measure the transverse distribution of the electron beam using CCD cameras

Dark Current

- It was found that the dark current primarily originates from two rings.
  - Inner ring emanates from the edge of the molybdenum plug
  - Outer ring originates from the edge of the copper iris
- DC : 14 µA for a cathode gradient of 27 MV/m
- Source of 1st ring: scratches on the edge of the plug ,due to plug rubbing against the SS and copper pipes during the initial installation and collimation of the load-lock system → removed by new cathode installation → 6 µA
- 2nd Ring: e gun removed from test beamline and performed ultrapure water rinse on all copper and stainless steel inner surfaces → undetectable dark current
- Reappeared after several days of operation →the maximum dark current was 376 nA
- Re-growth of DC during operation concludes DC emission may be caused by the slow adhesion of dust from the test beamline to the gun copper iris, or by the ion back bombardment of the semiconductor cathode causing tellurium or cesium to adhere to the copper iris. The origin of the dark current at the copper iris still needs to be carefully studied



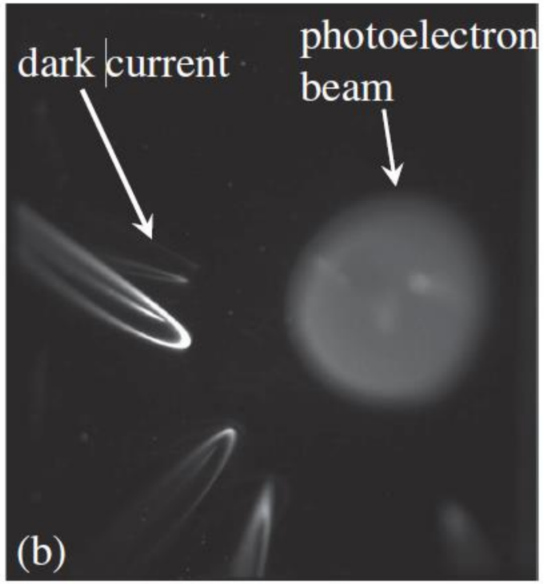
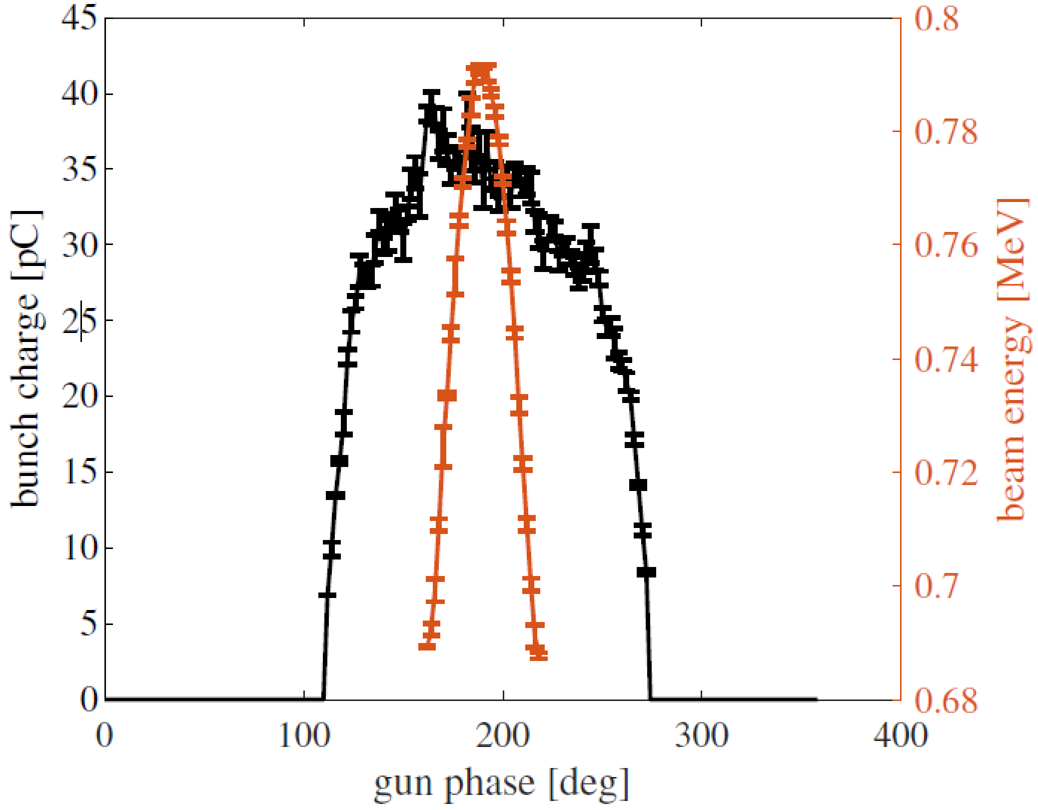


Photo-Cathode

- The quantum efficiency of the cesium telluride cathode typically exceeded 10% when prepared in a deposition chamber
- the cathode’s QE was typically around 1% upon insertion after transportation into the gun and commencement of electron beam production
- The QE of the cathode could be maintained above 0.5% for up to a month, which is acceptable in the current stage of beam commissioning
- The energy of the laser pulse on cathode ~200 nJ → bunch charge of > 200 pC
- Aperture with a exchangeable diameter was imaged onto the cathode plane through an image transfer system while optimizing beam brightness → Laser energy was blocked by the aperture
- During the emittance measurement and optimization, the bunch charge was limited to ≤100 pC
- laser injection phase scan curve, which plots the bunch charge and beam energy at the gun exit as a function of the gun extraction phase



Emittance Measurement

- The beam emittance measured using a quadrupole scan method
- To measure the projected emittance, the intensity of the last quadrupole in the beamline was scanned while the change in the transverse beam size was measured on a YAG screen 1.7 m downstream of the quadrupole
- To measure the sliced emittance, the deflecting cavity was turned on and kicked the beam in the vertical direction
- The beam spot on the YAG screen was divided into 11 equal segments vertically, with the central one selected for calculating the transverse beam size
- By fitting the transverse beam size and the quadrupole intensity, the beam moments and emittance can be calculated
- Conditions:
  - Laser spot size :550 um,
  - cathode gradient : 27 MV/m,
  - pulsed operation at 10Hz,
  - Beam Energy : 28 MeV

TABLE V. Emittance measurement results for different bunch charges.

Bunch charge (pC)	95% projected emittance (mm mrad)	95% sliced emittance (mm mrad)	Bunch length (mm rms)
10	0.161	0.154	0.49
50	0.429	0.383	1.15
100	0.853	0.842	1.44

SUMMARY

- SHINE is an MHz-class high-repetition-rate XFEL in China, requires an electron source operating in CW mode
- Tsinghua University developed VHF gun for SHINE (~ 4 yrs since 2018), and was installed in the SHINE tunnel
- The paper presented
  - Gun's physical design, including the optimization of the input power, surface electric field, surface power density, the suppression of multipacting, and the analysis of thermal effects, the mechanical design, including the VHF gun itself, the frequency tuners, the rf power couplers, the RF probes
- The quality factor in the cold test was 31700, (94% of the design value)
- A CW RF power of 75 kW has been successfully fed into the gun
- The cathode gradient reached about 27 MV/m and the gun voltage reached about 780 keV
- LLRF system working in closed-loop control mode, the amplitude rms jitter is 1.1 out of 10,000, and the phase rms jitter is 0.0148°
- Ultrapure water rinsing significantly reduced Dark current emission from the copper surface < 376 nA
- 95 % projected trans emittance , 0.161 mm mrad for 10pC, 0.429 mm mrad for 50pC, 0. 853 mm mrad for 100pC
- 95 % sliced trans emittance, 0.154 mm mrad for 10 pC, 0.383 mm mrad for 50 pC and 0.842 mm mrad for 100 pC
- In the next phase of experiments
  - New coupler design to reduce multipacting
  - the beam brightness will be optimized
  - ability to generate a 1 MHz repetition rate beam will be tested

Thank You