Tsinghua University

R&D of normal conducting VHF gun at Tsinghua University

Yingchao Du
On the behalf of VHF gun team
dych@tsinghua.edu.cn

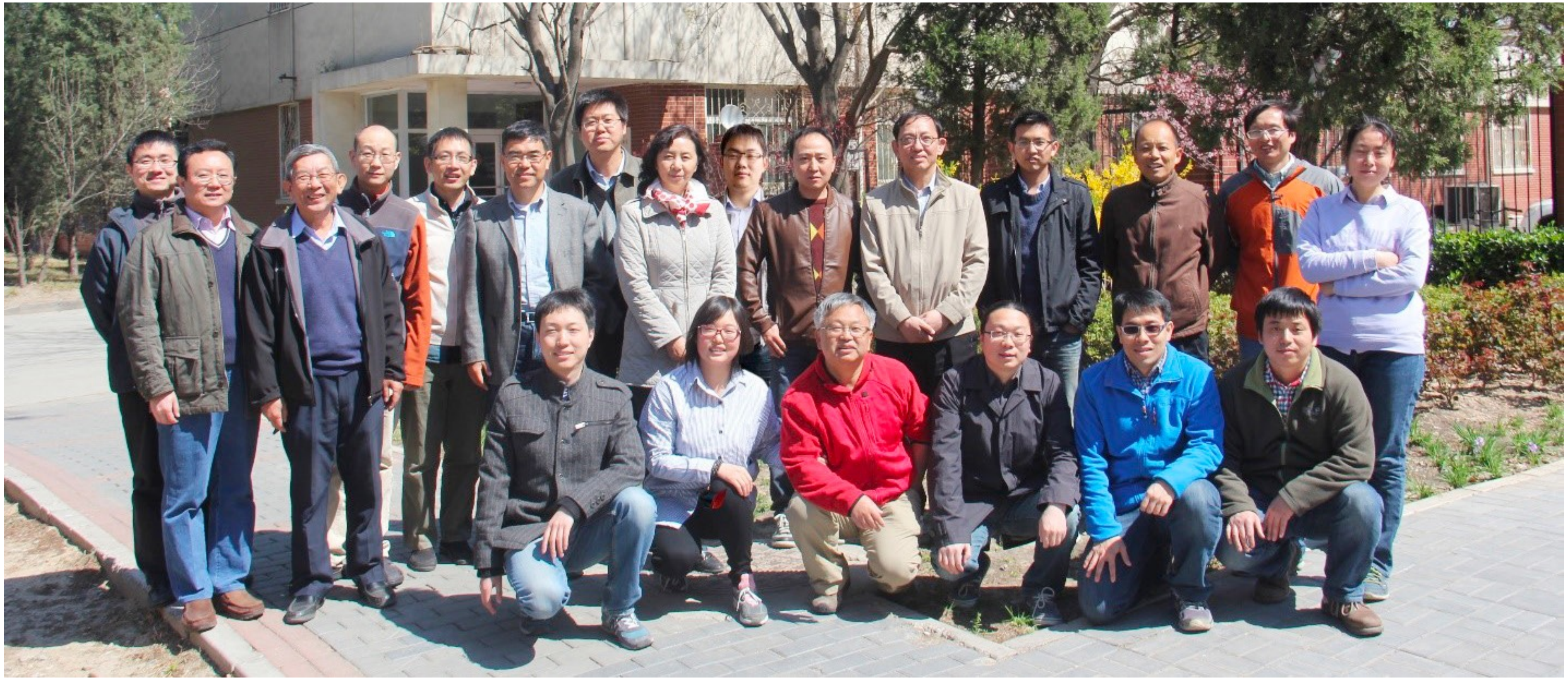
Department of Engineering Physics， Tsinghua University
Beijing, China,100084

Outline

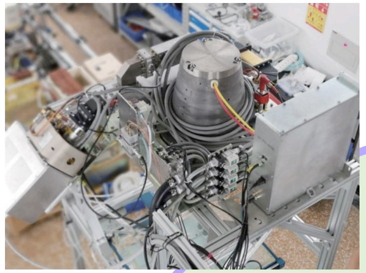
1. Introduction
2. R&D of the VHF gun
   2.1 Design and optimization
   2.2 Manufacturing and cold testing
   2.3 RF conditioning and beam testing
3. Summary and outlook

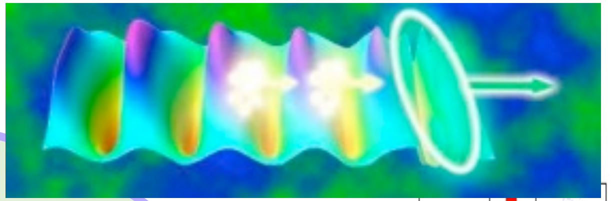
Accelerator lab at Tsinghua University

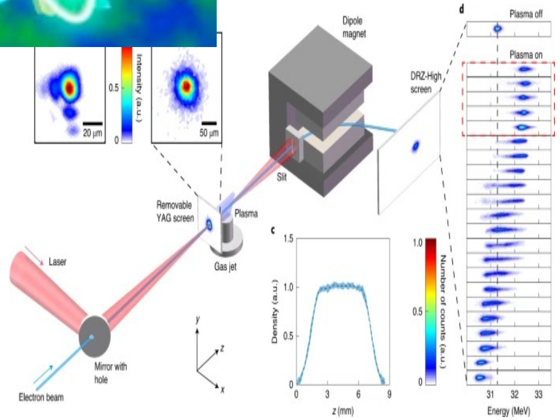
- Founded in 1956
- 17 faculties, ~10postdocs and more employees
- More than 60 graduate students

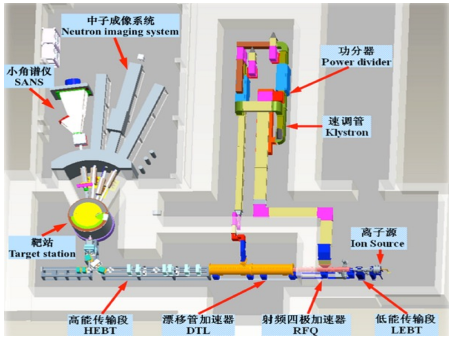


Accelerator Lab at Tsinghua University









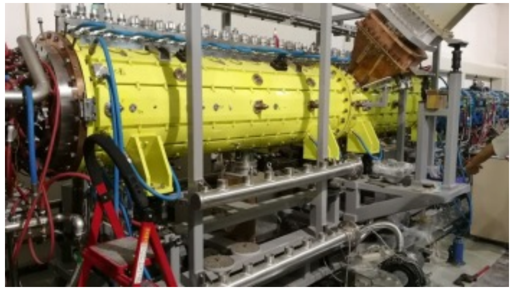
Accelerator physics and applications

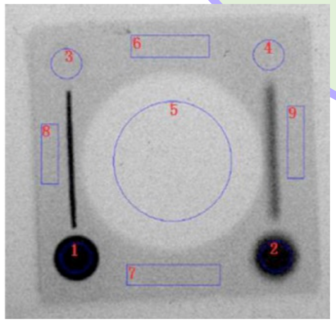
Low energy Linac for industry and medical

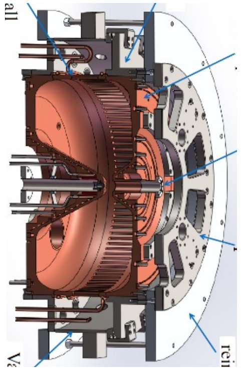
Plasma wake-field accelerator and applications

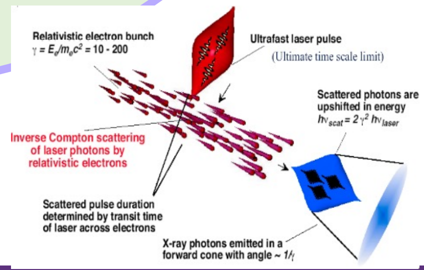
Compact Pulsed Hadron Source and applications

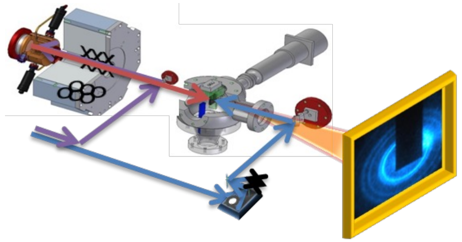
High brightness electron source and applications







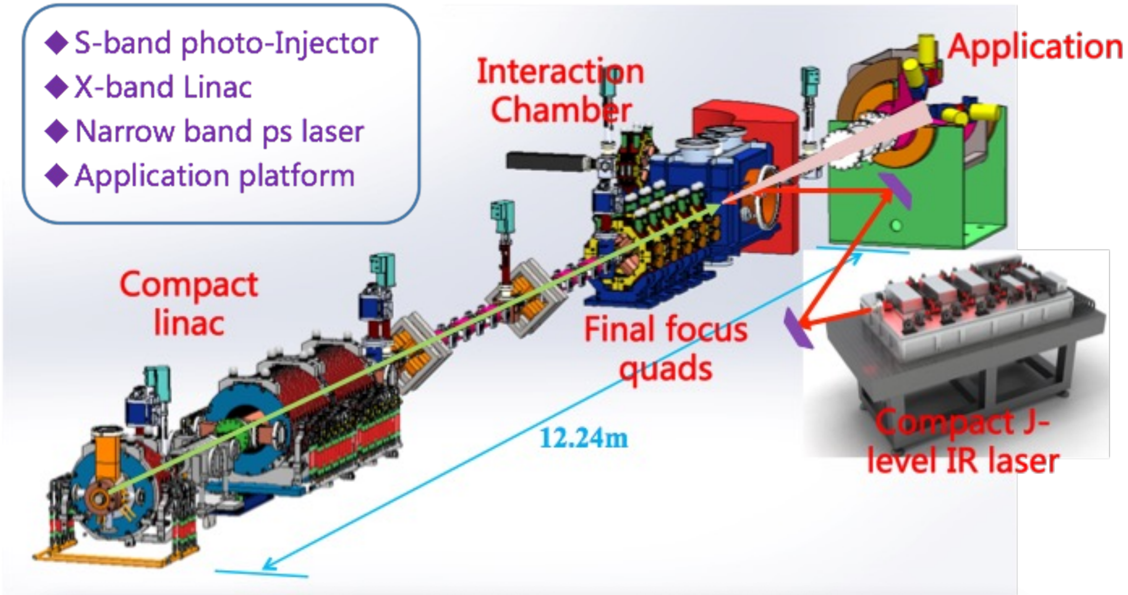




Accelerator Lab at Tsinghua University

● High brightness electron source and applications (from 2001-now)

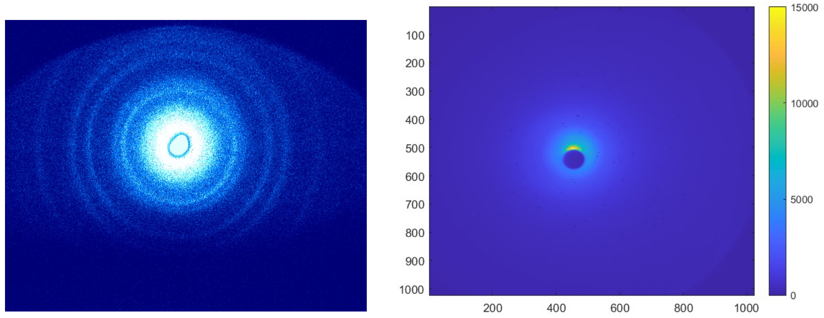
- Inverse Compton scattering (Thomson scattering) X/γ-ray source



γ-ray energy: 0.2-4.8MeV
Bandwidth with collimator : <1.5%
Total photon flux(ph/s): >4×10⁸@0.2-2.4MeV; >1×10⁸@2.4-4.8MeV
Photon flux with 1.5% Bandwidth(ph/s): >4×10⁶@0.2-2.4MeV; >1×10⁶@2.4-4.8MeV
controllable polarization from linear to circle

VIGAS: very compact inverse Compton scattering gamma-ray source

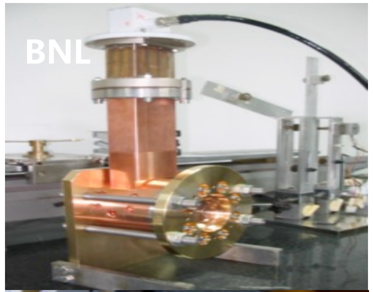
- MeV Ultrafast electron diffraction and Microscopy

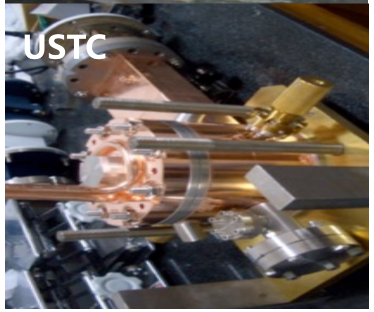


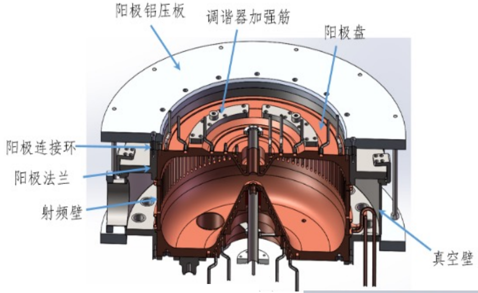
FORTRESS :Facility fOr Relativstic Time-Resolved Electron Sources and Scattering

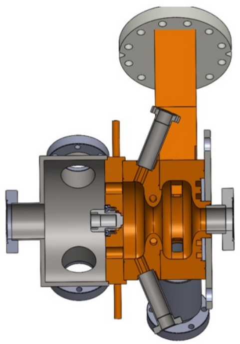
R&D of the photocathode RF gun at Tsinghua

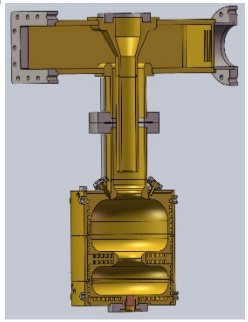
More than 30 photocathode RF guns were made at THU











2000-2006

Low dark current, Max. cathode filed: 80-110MV/m

Collaboration with BNL

2006-2009

2009-2018

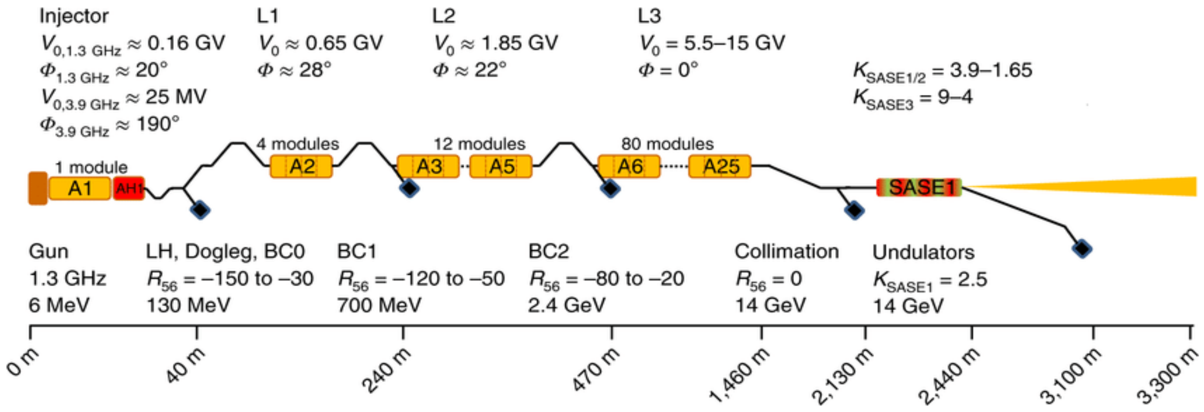
Low dark current and BDR, Max. cathode filed: 100-120MV/m, successfully applied at TTX, DCLS,SXFEL, etc. al

2019-

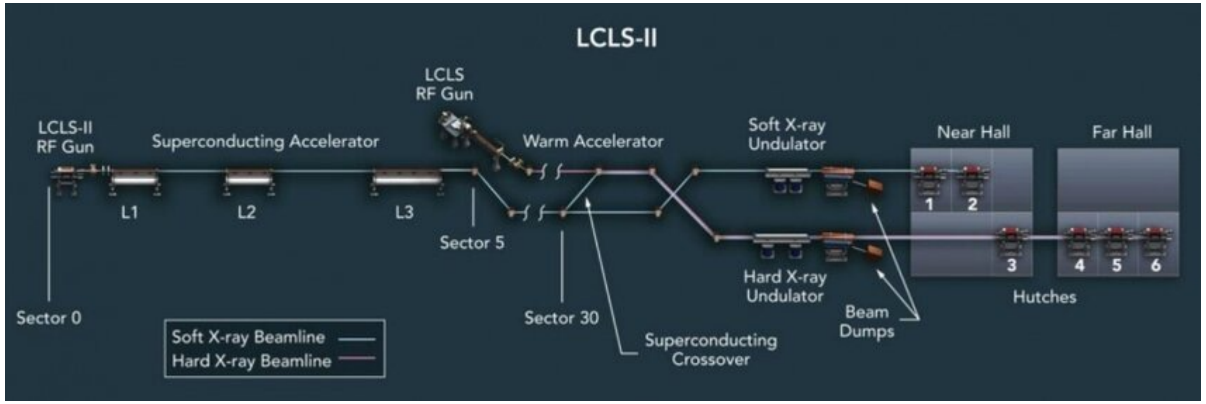
New guns with semiconductor cathode for middle or high repetition-rate beam

Gun's requirements for high repetition XFEL

- High repetition XFEL facilities



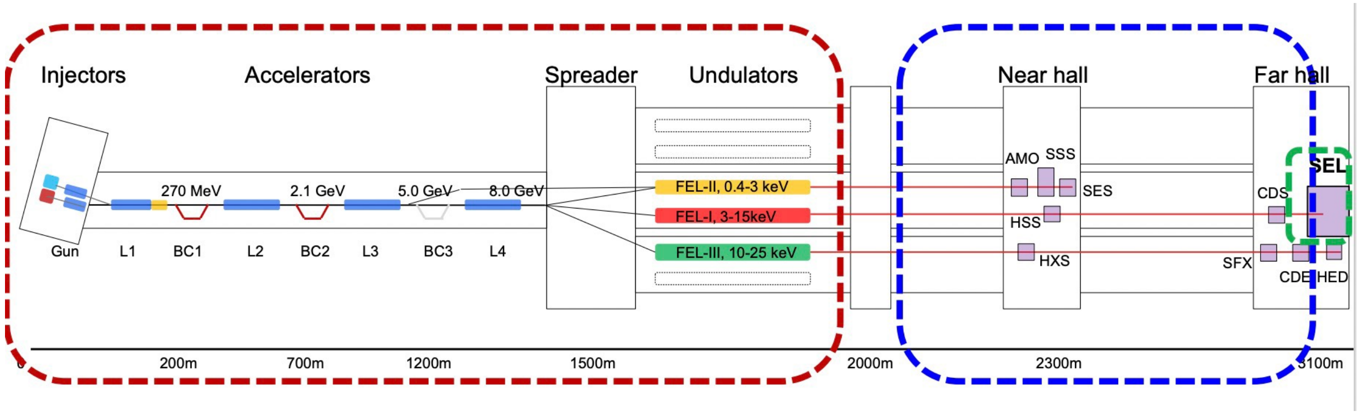
European XFEL:
Accelerator technology: Super-conducting
Maximum beam energy: 17.5GeV
Minimum wavelength: 0.05nm(25keV)
Number of light flashes: 27,000 (2700x10)



LCLS-II SCRF XFEL:
Accelerator technology: Super-conducting
Maximum beam energy: 5 GeV
Minimum wavelength: 0.25nm(5keV)
Number of light flashes: 1,000,000

Gun's requirements for high repetition XFEL

- High repetition XFEL facilities in China



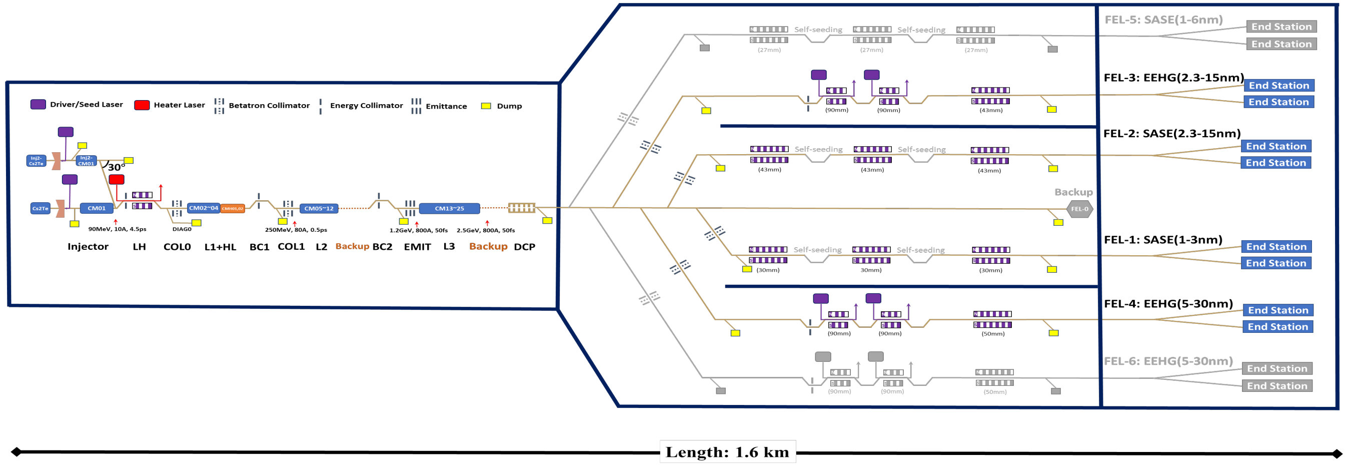
Shanghai High Repetition Rate XFEL and Extreme Light Facility(SHINE) :

Accelerator technology: Super-conducting

Maximum beam energy: 8 GeV

Minimum wavelength: 0.05nm(25keV)

Number of light flashes: 1,000,000



Shenzhen Superconducting Soft-X-ray Free Electron Laser(S^3FEL) :

Accelerator technology: Super-conducting

Maximum beam energy: 2.5 GeV

Minimum wavelength: 1nm(1.2keV)

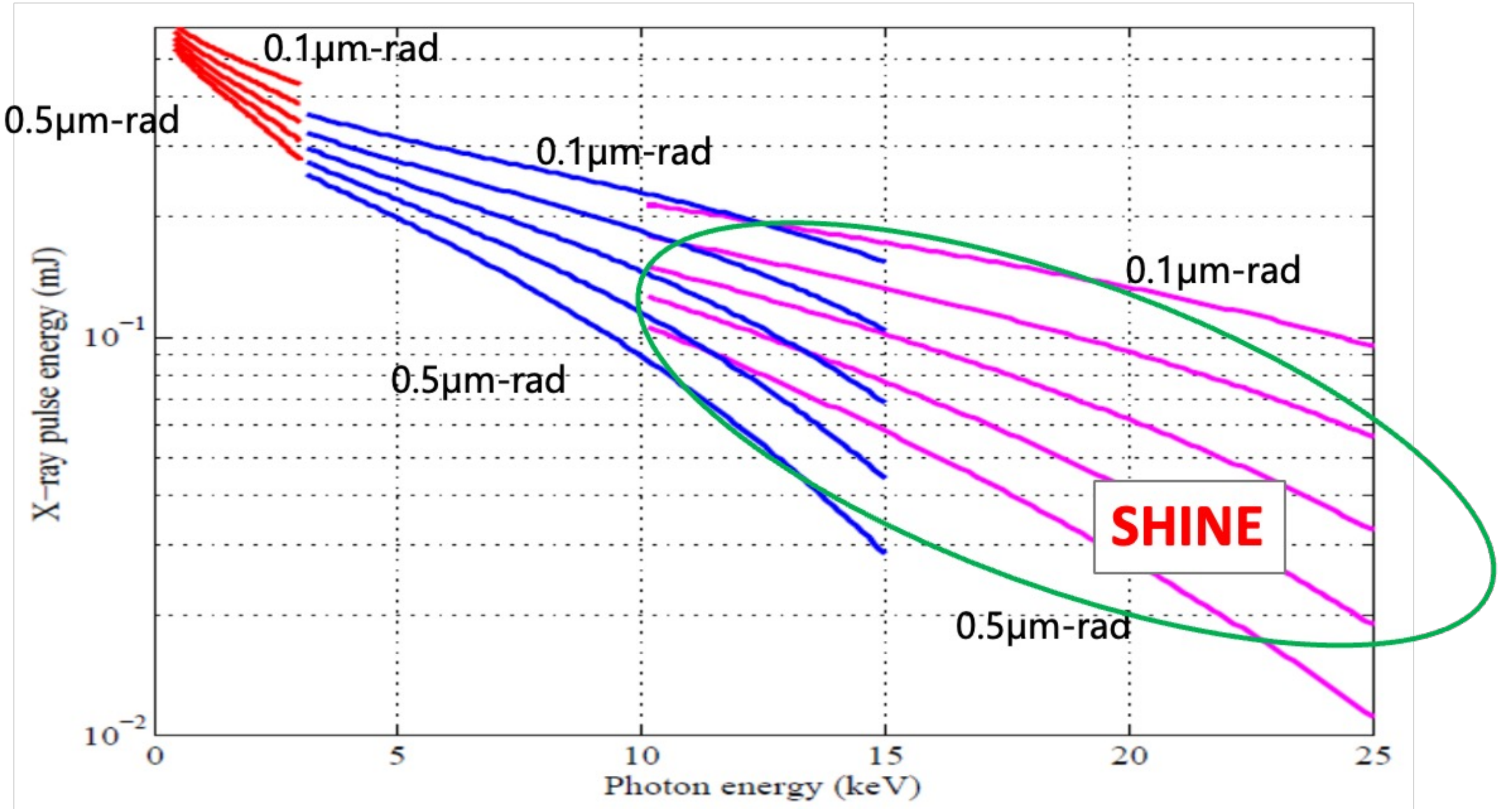
Number of light flashes: 1,000,000

Gun's requirements for high repetition XFEL

Requirements on SHINE injector

Courtesy: H. Deng

For SHINE: need to be better than 0.4 mm.mrad to get enough photons

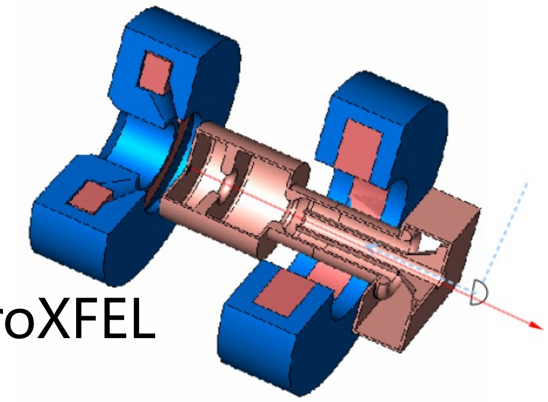


- CW operation
- 1 MHz repetition
- High charge, 20-300pC
- Low emittance, <0.4um@100pC

Gun's requirements for high repetition XFEL

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

L-band Gun@EuroXFEL

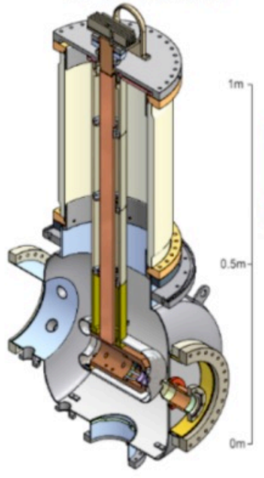


- ➢ Operated in long pulsed mode
- ➢ 4.5 MHz electron bunches in an rf pulse.
- ➢ 27,000 electron bunches can be produced per second.

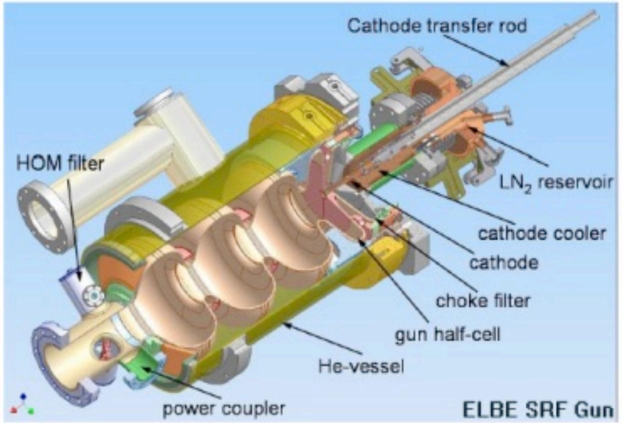
➢ Guns can be operated in CW mode

Gun's for LCLS-II SCRF

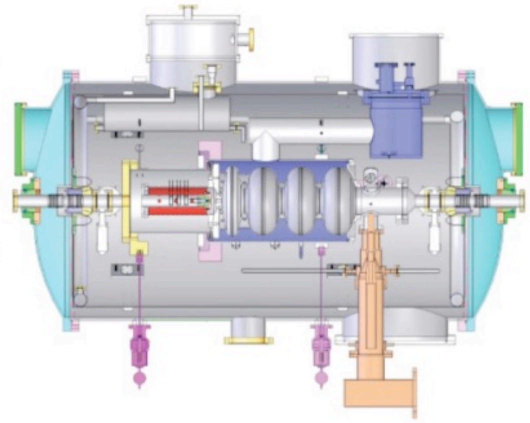
DC Gun



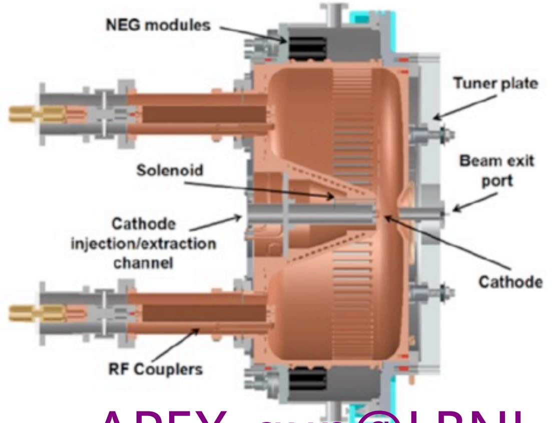
SRF Gun



DC-SC Gun



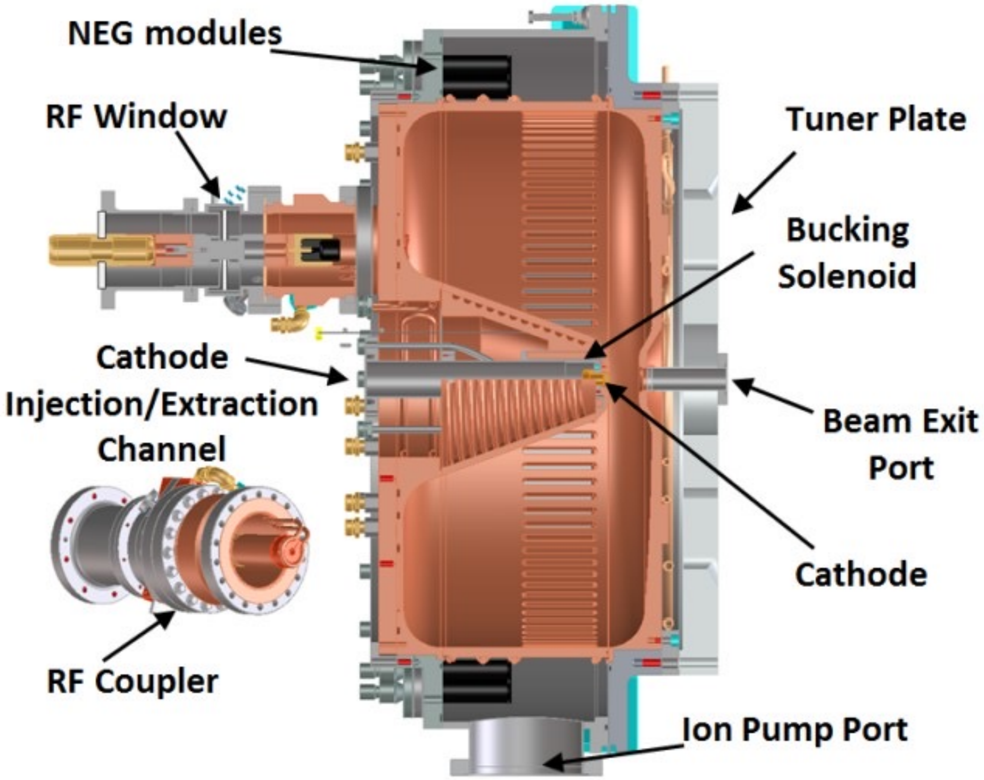
VHF Gun



APEX-gun@LBNL

Gun's requirements for SHINE project

- VHF photocathode gun: Baseline for SHINE and S³FEL project



APEX-gun@LBNL

- Advantages:
  - Normal conducting
  - High cathode gradient and cavity voltage
  - long wavelength, big size, low temperature increase, CW operation
  - Good vacuum performance, successfully operated with semiconductor cathode
  - Demonstrated for stable CW operation and MHz repetition rate beam generation at LBNL and SLAC
- 2019, MOU signed between Tsinghua and SHINE

Outline

Tsinghua University

1. Introduction
2. R&D of the VHF gun

   2.1 Gun design and optimization

   2.2 Manufacturing and cold test

   2.3 Conditioning and beam testing results
3. Summary and outlook

Basic considerations on VHF gun design

- **Design goal:** small beam emittance, high beam brightness

- **Gun frequency: 216.7 MHz**
  216.7 MHz (1300MHz/6) or 162 MHz (1300MHz/8) is compatible with SHINE timing system.
  The gun with higher frequency is more compact and possible higher cathode gradient

- **Cathode gradient: up to 30 MV/m**
  Higher gradient for beam brightness are expected. Higher gradient means higher dark current, high surface power density

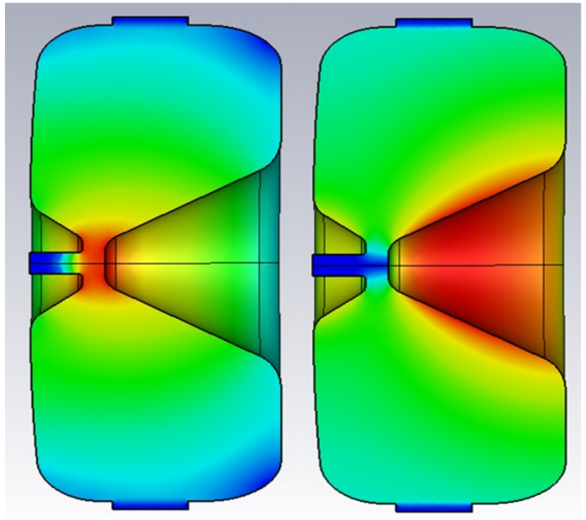
- **Gun voltage： ≥750 kV,** as higher as possible，achieved in APEX gun

- **RF power: < 100 kW**, limited by RF power source and windows

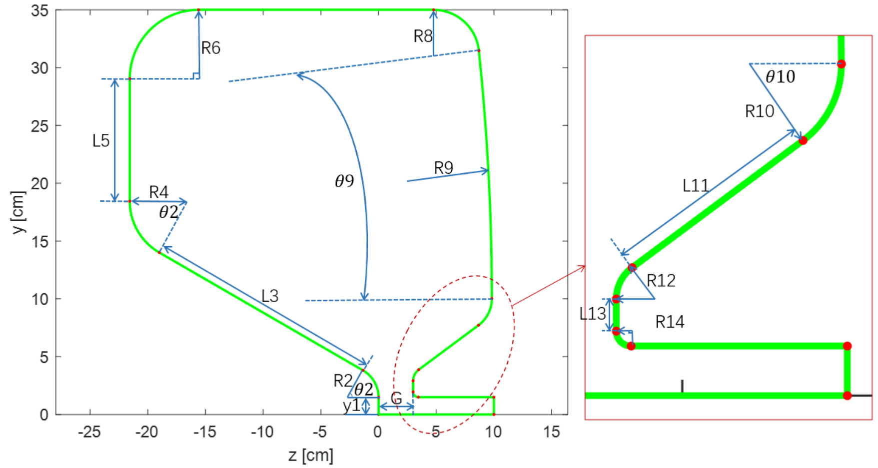
- **Max. wall power density: <30 W/cm^2** , limited by water cooling capacity

Gun design and optimization

- Optimized with CST:
  - Inner shape is parameterized and optimized in CST, especially for cathode nose and anode nose
  - **Design objectives**: fixed cathode gradient, max. surface field ↓, max. wall power density ↓, RF power ↓, gun voltage ↑
  - Multipacting
  - Dark-current



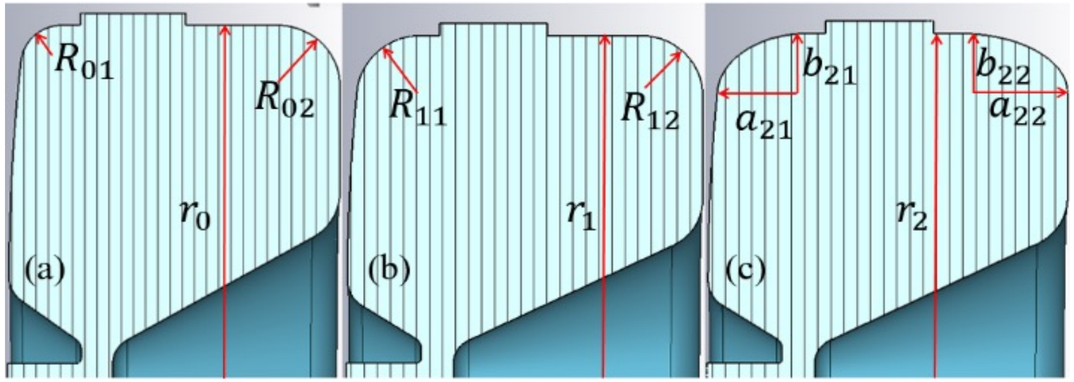
E field H field



RF parameters	VHF Gun@THU
Frequency	216.67 MHz
Cathode gradient	30 MV/m
Input RF power	90.4 kW
Max. E field	36.99 MV/m (<2.5kilp)
Max. P density	28.45 W/cm^2
Voltage	868 kV

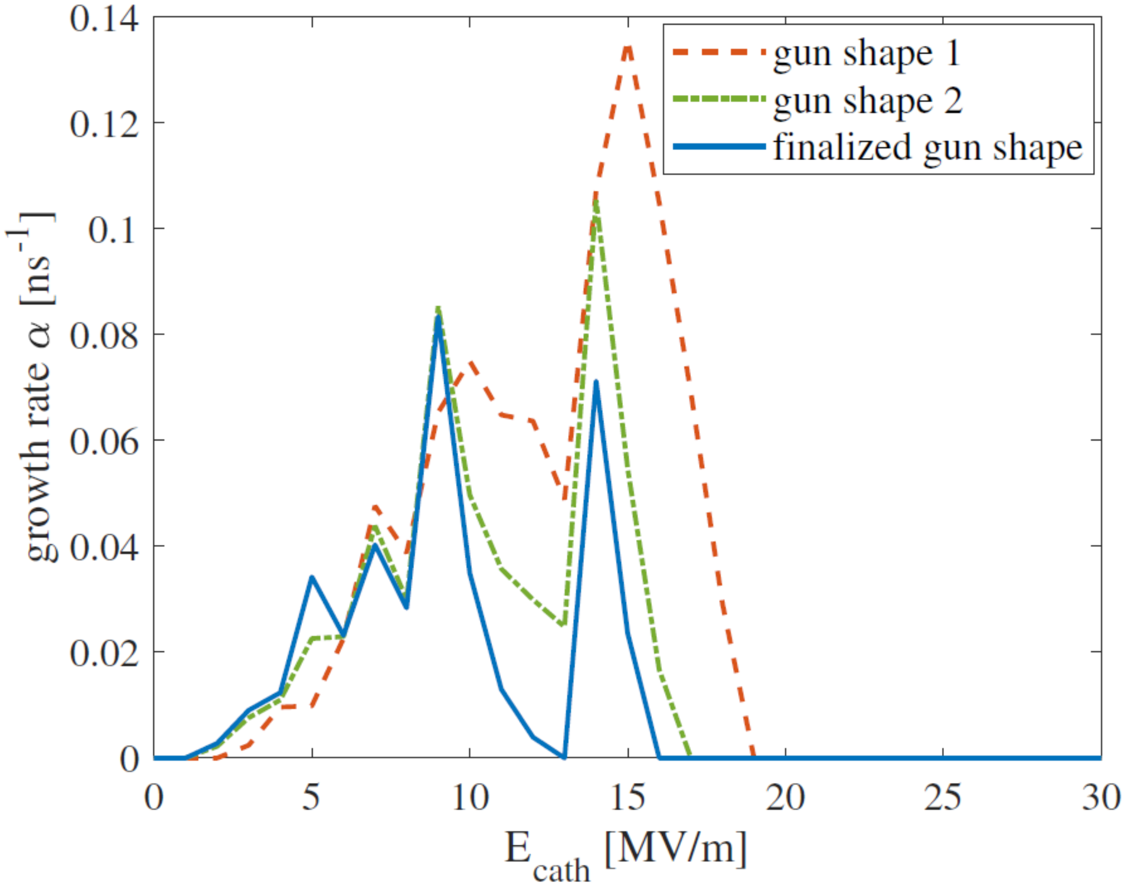
Gun design and optimization

- Multipacting simulation

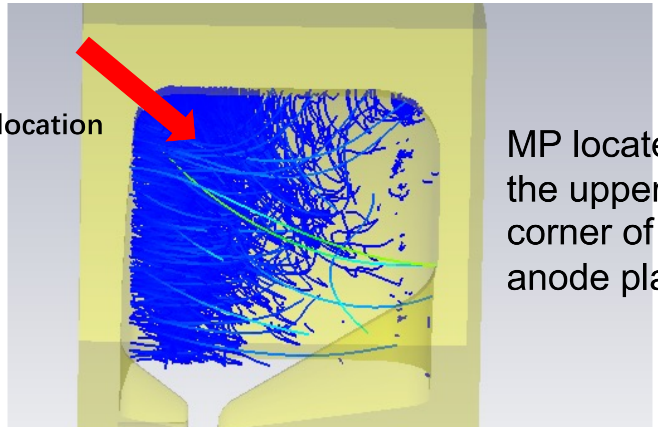


(a) gun shape 1. (b) gun shape 2. (c) finalized gun shape.

Reduce the radius → Change rounded corners to elliptical



multipacting location

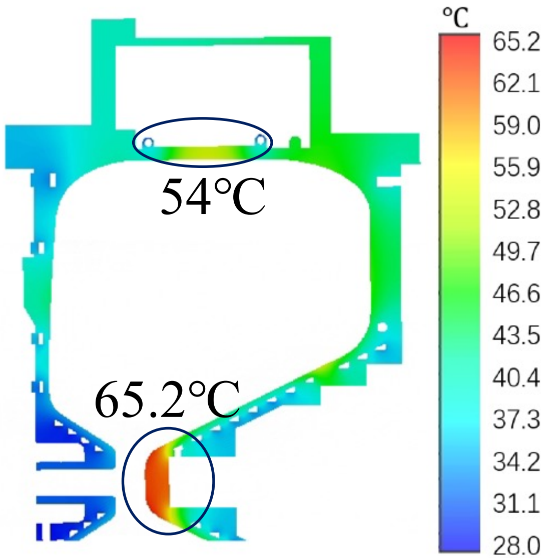


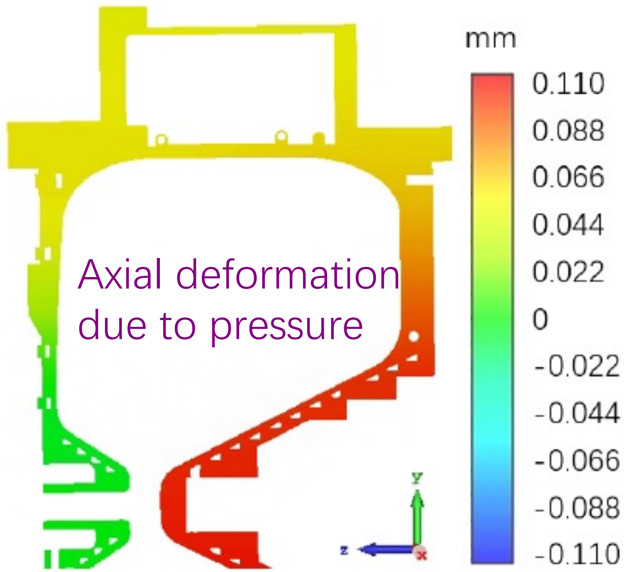
MP locates at the upper corner of the anode plate

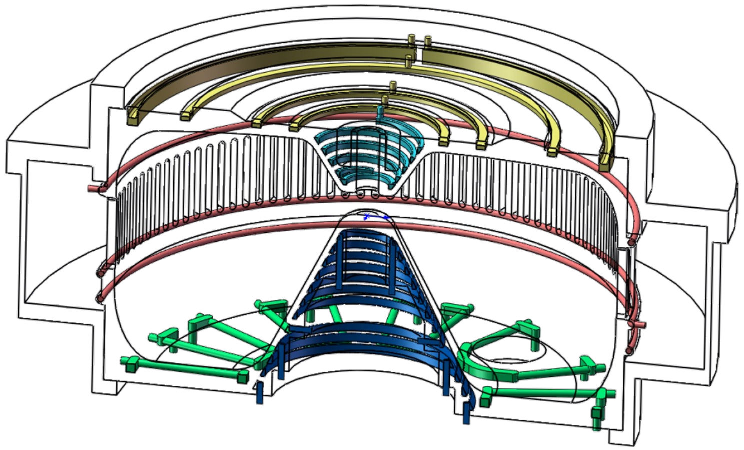
The designed cathode gradient：30 MV/m
No multipacting for gradient higher than 16 MV/m

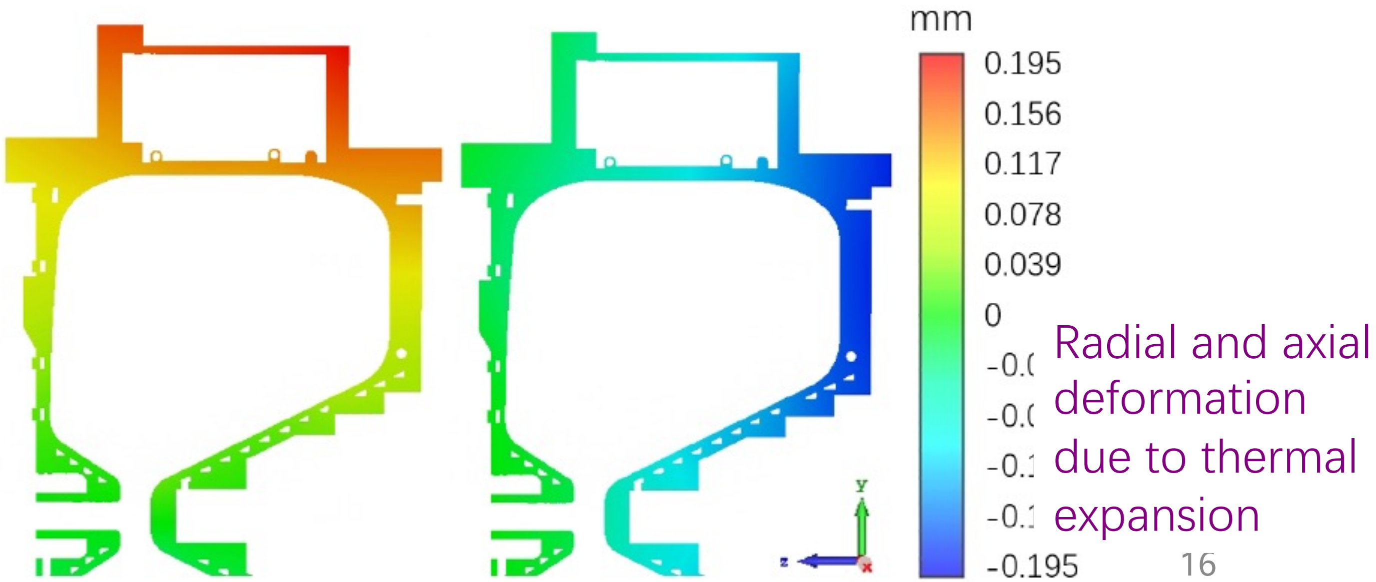
VHF gun RF design and optimization

- Cooling channels design
  - 23 independent water cooling pipes
  - Maximum temperature rise<40℃@90kW
  - Deformation due to vacuum and RF heating is less than 200 um
  - Frequency detuning due to RF heating<80kHz



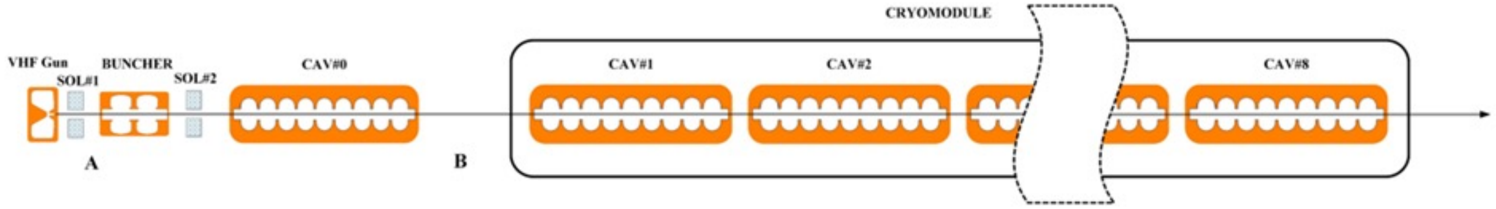


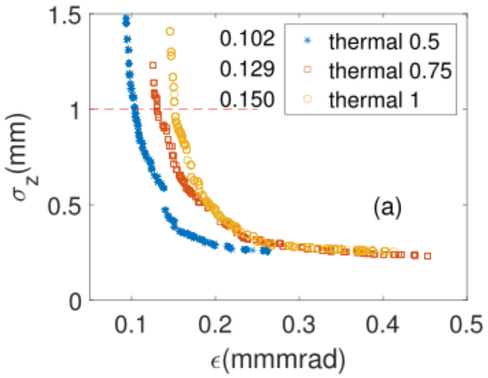




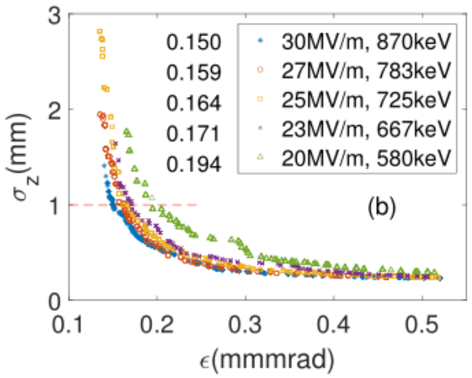
Gun design and optimization

- Beam dynamics simulation and optimization

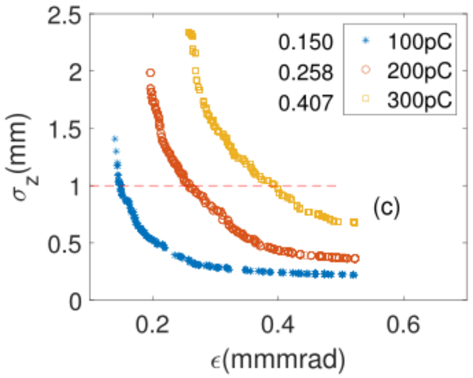




Different thermal emittance
30 MV/m 100 pC

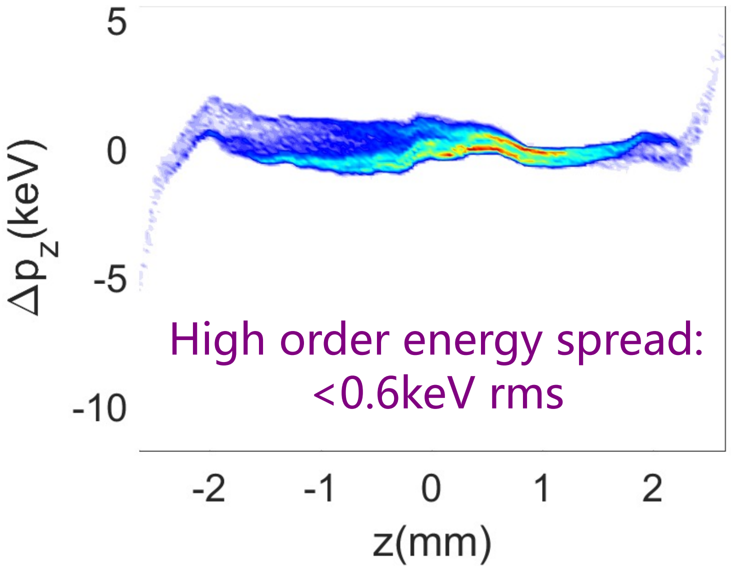


Different RF gradient (gun voltage)
1 um·rad/mm 100 pC



Different beam charge
1 um·rad/mm 30 MV/m

- MOGA with Astra, fourteen parameters
- Objectives: Low beam emittance and high order energy spread with 1mm rms bunch length



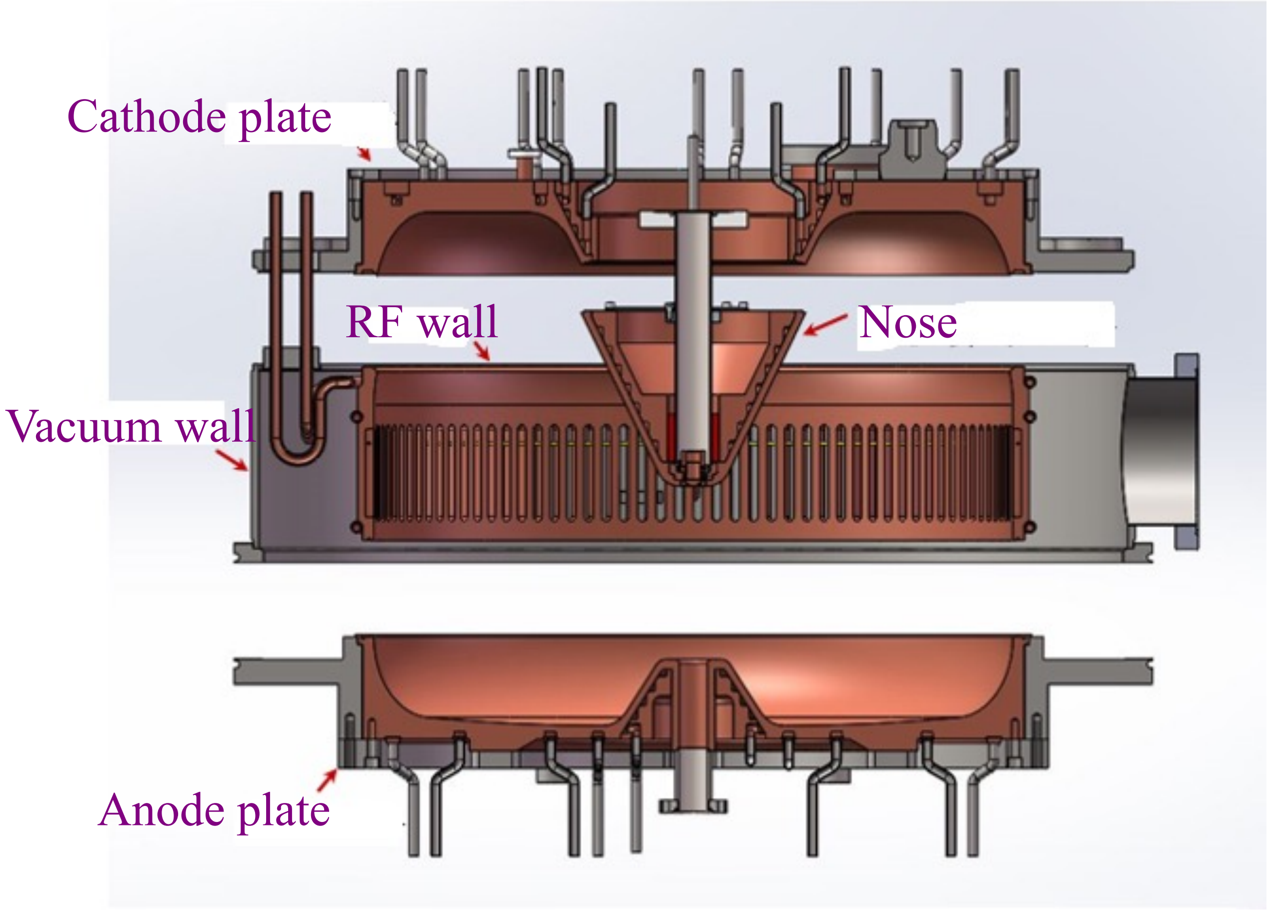
High order energy spread: <0.6keV rms

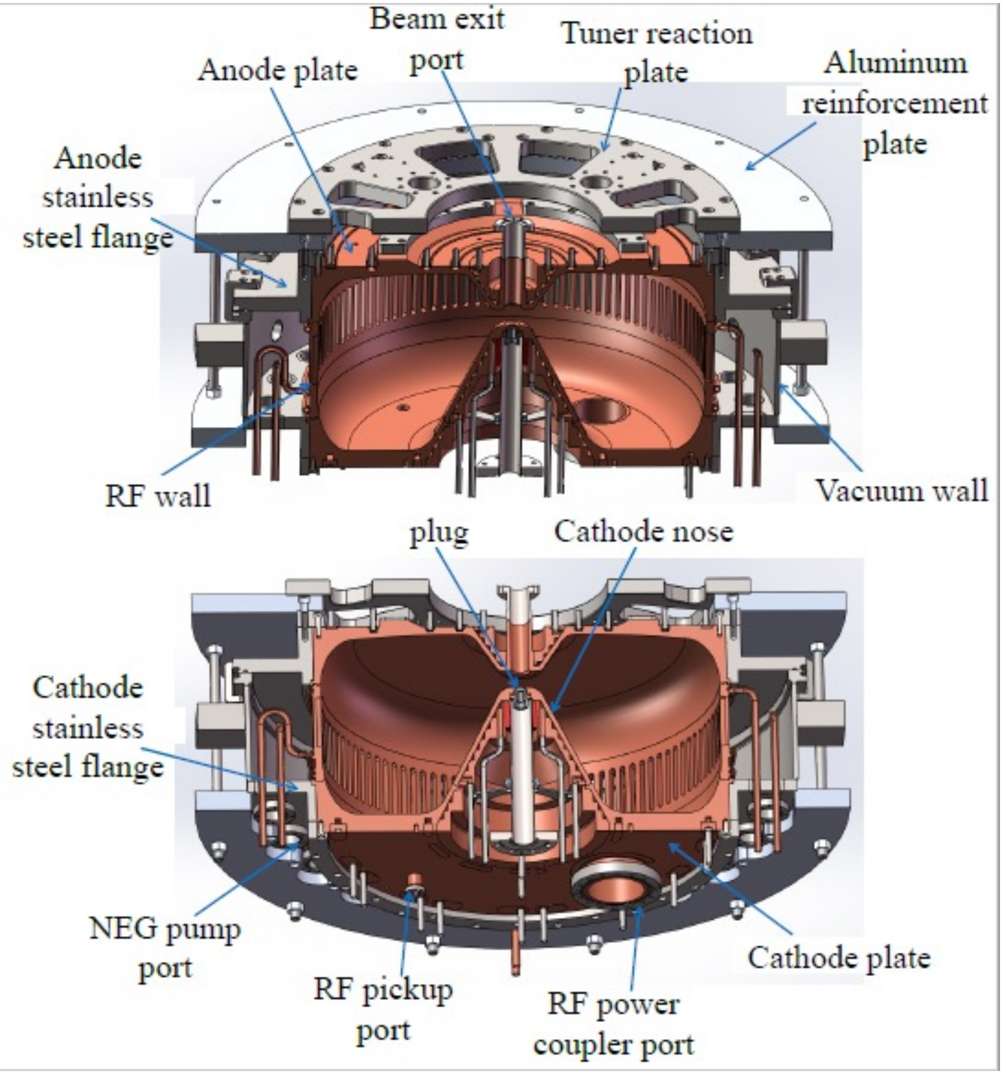
Outline

1. Introduction
2. R&D of the VHF gun
   2.1 Gun design and optimization
   2.2 Manufacturing and testing
   2.3 Conditioning and beam testing results
3. Summary and outlook

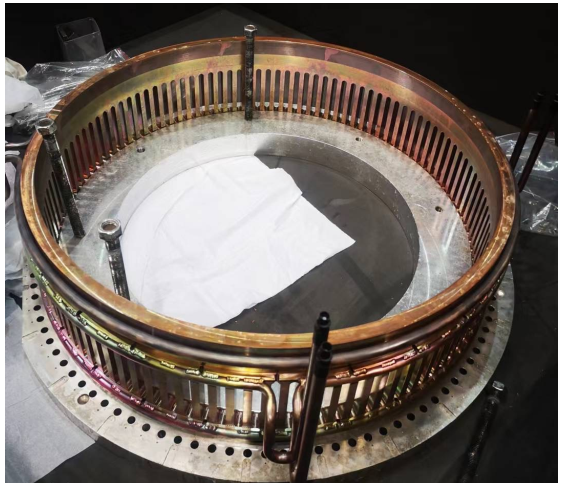
Main components of gun

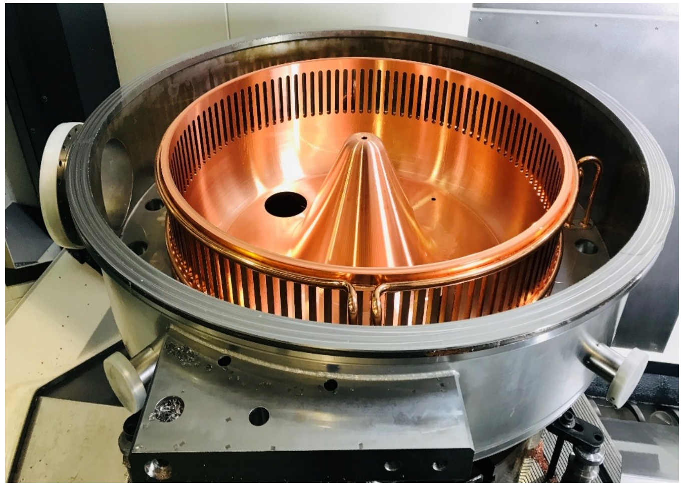
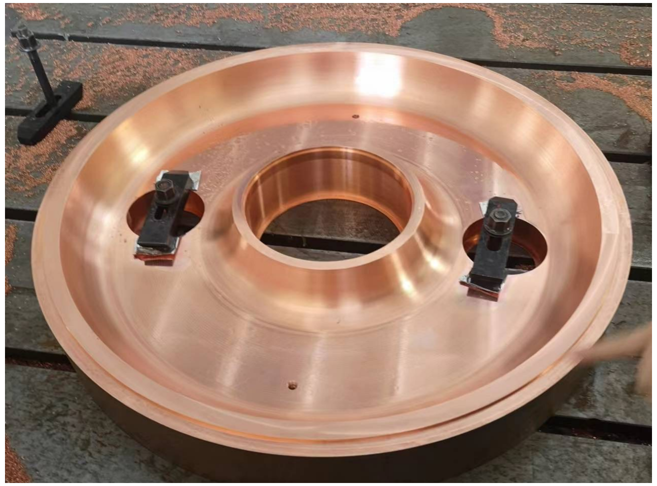
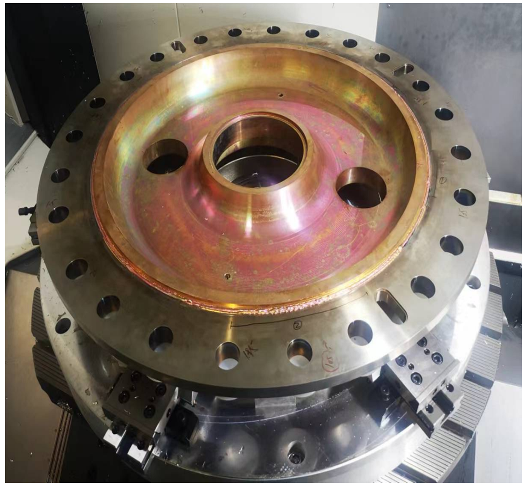
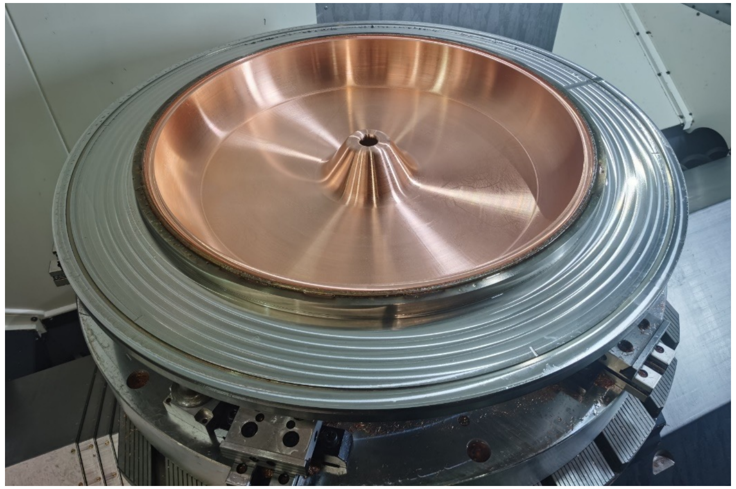
- Mechanical design





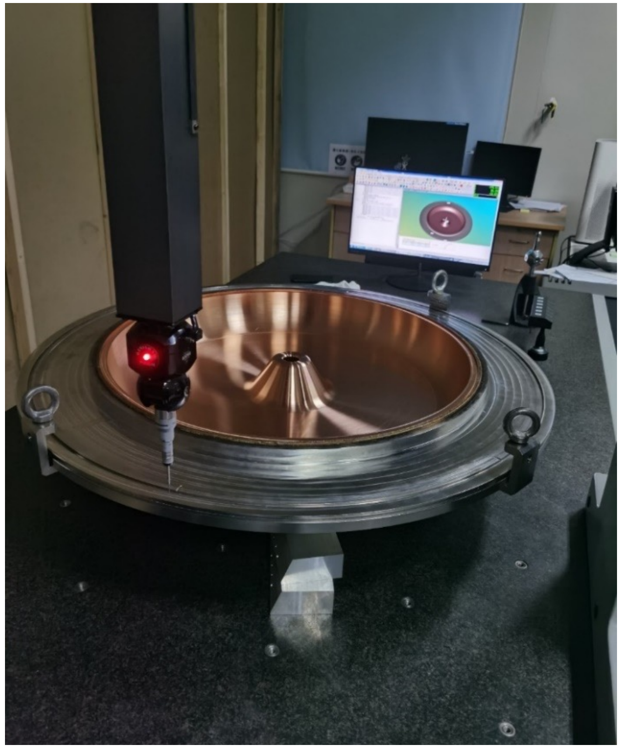
Machining of the VHF gun

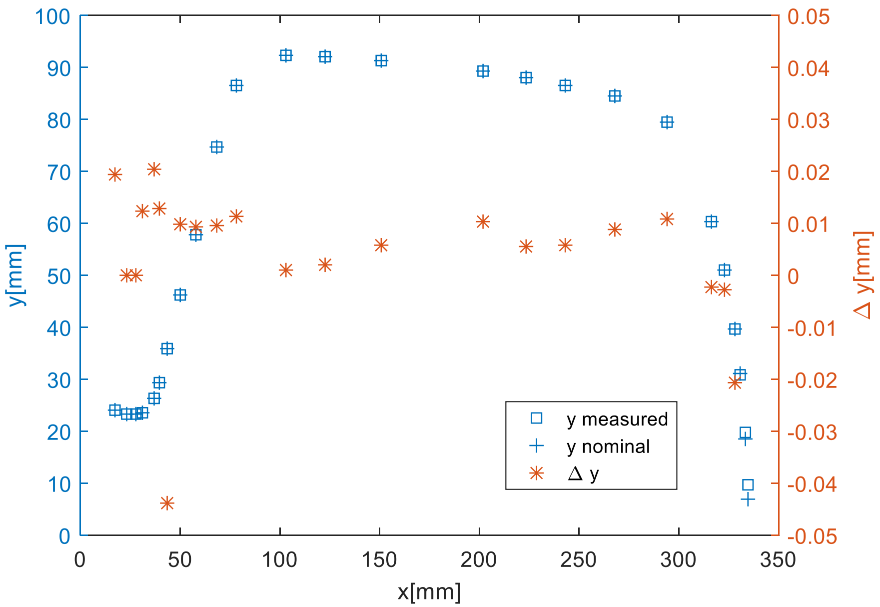



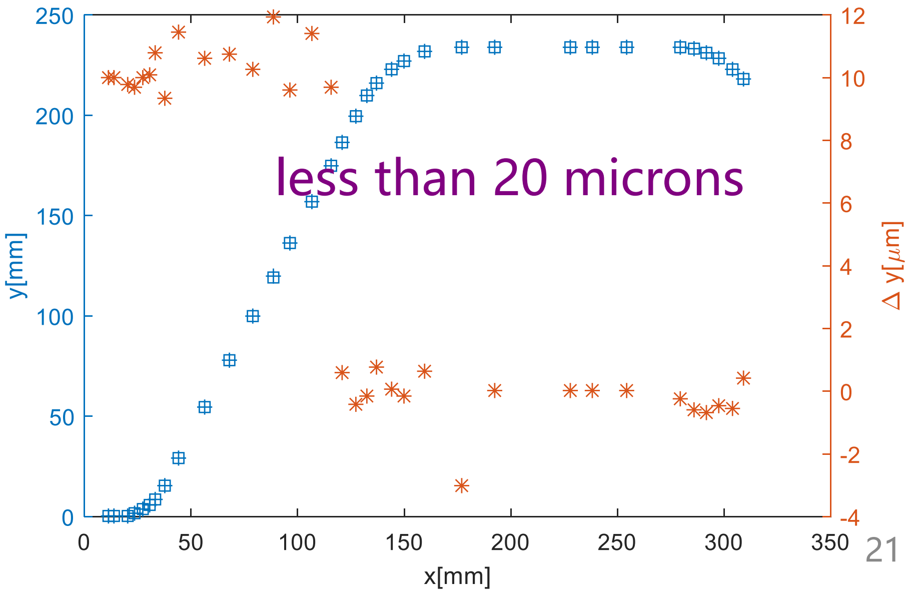





Machining of the VHF gun

- Inner profile is measured using a three-coordinate instrumentation, the error is less than 20 microns

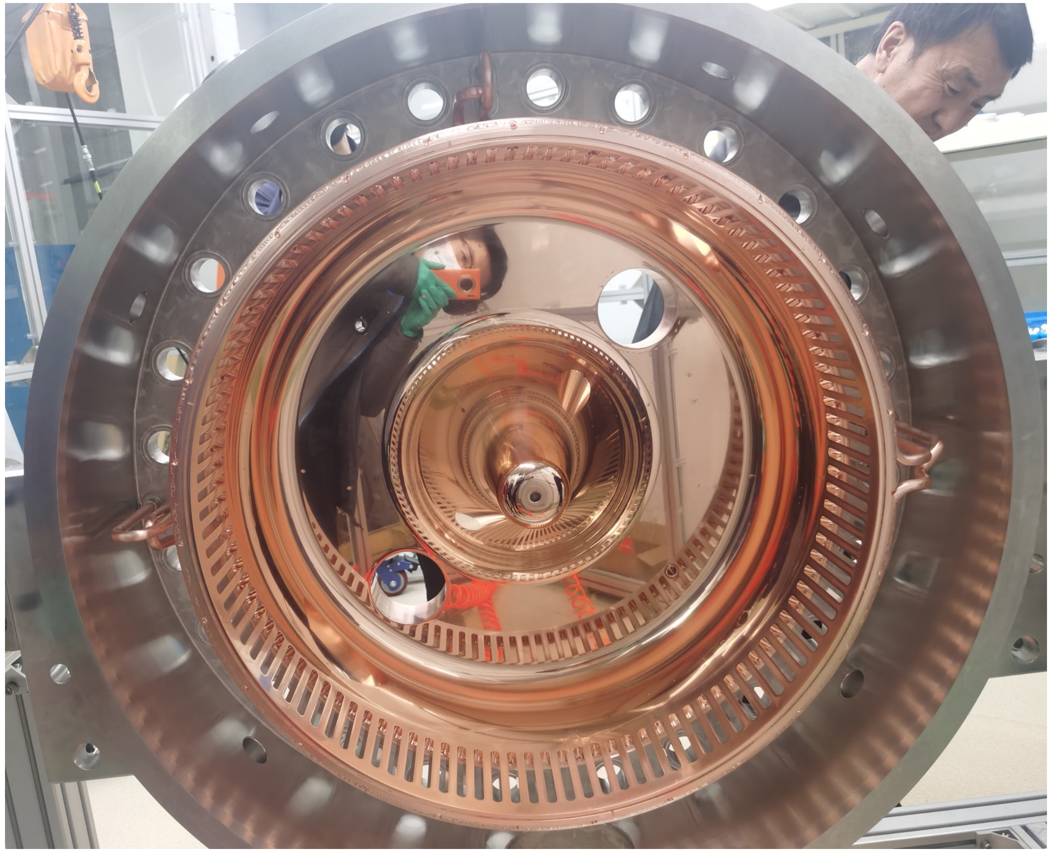




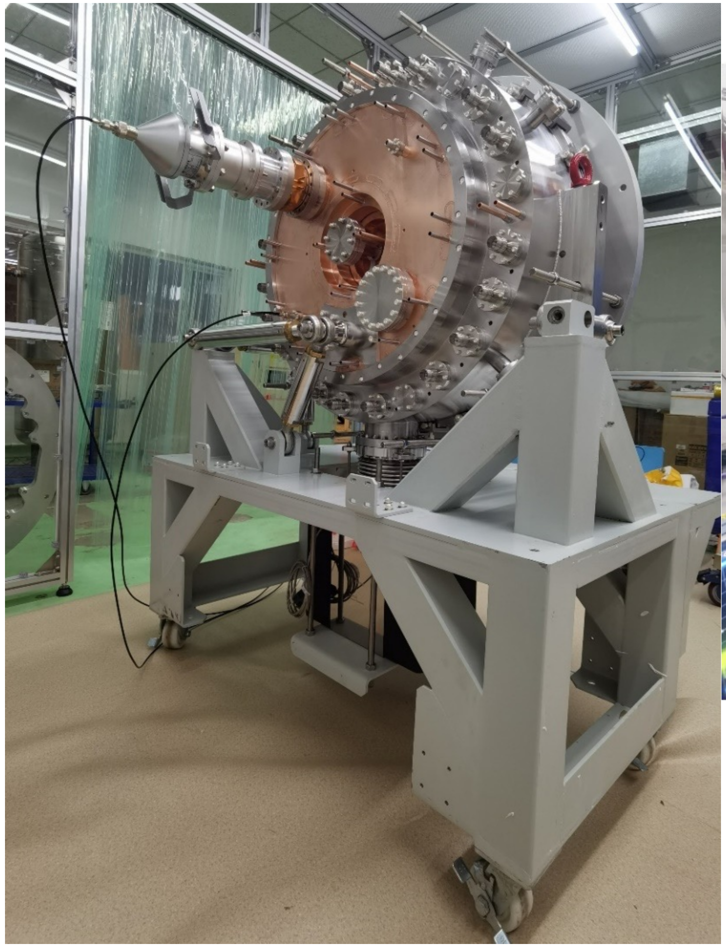


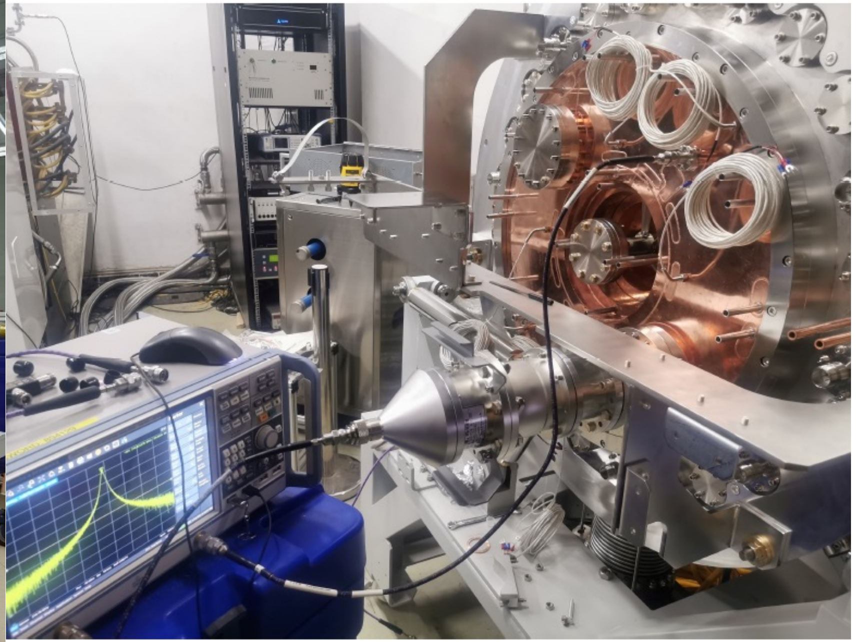
Machining of the VHF gun

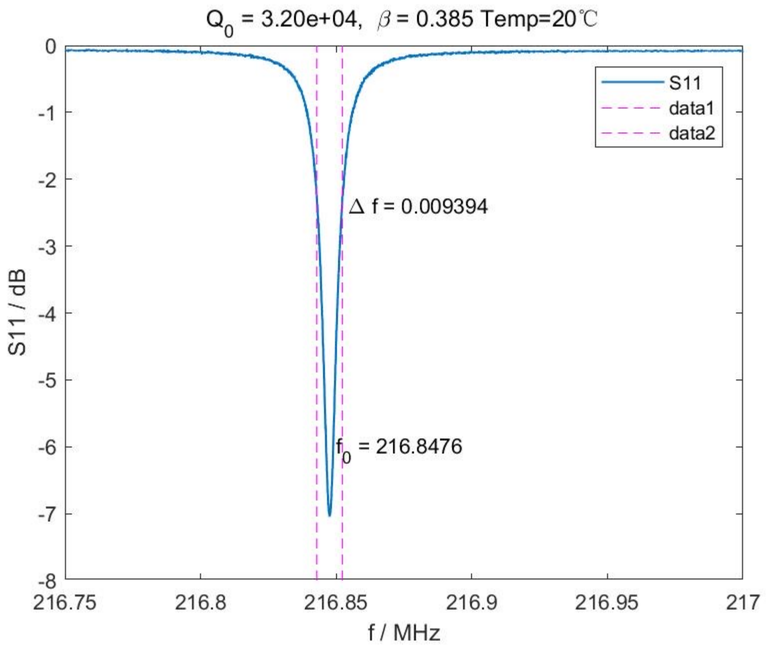
- Manual mechanical polishing of copper surface, roughness of the copper surface is less than R0.05



Cold testing of the VHF gun



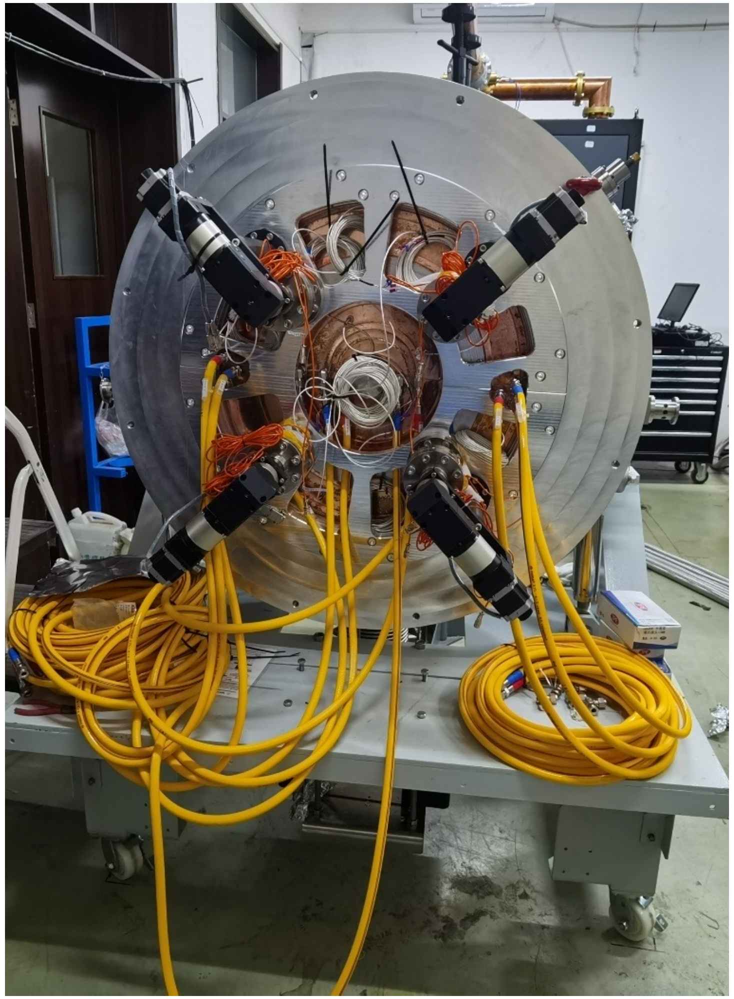


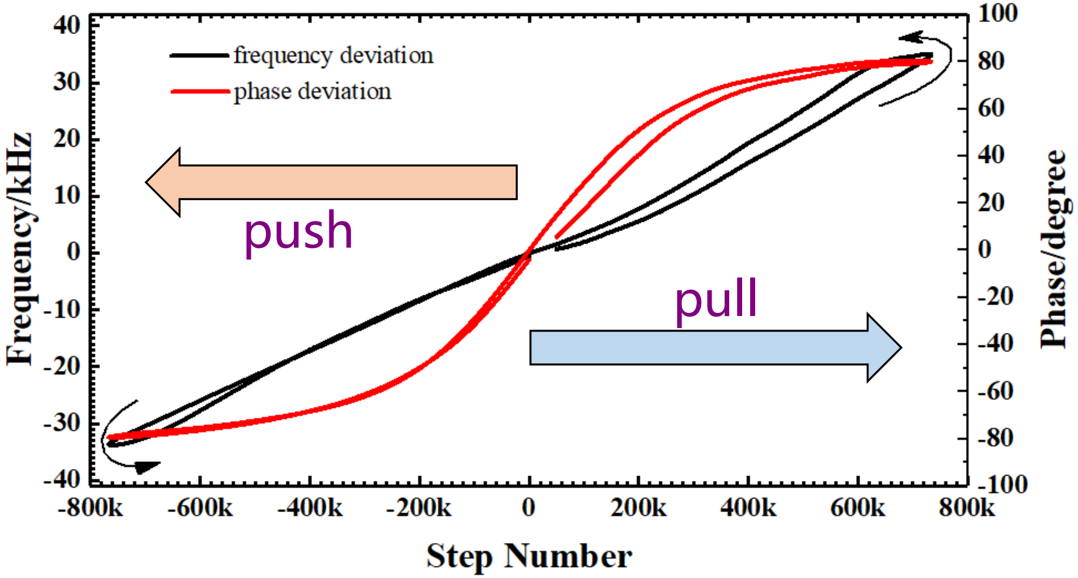


The measured frequency is in consistent with the design.
The quality factor is 5% less than the design.
Quality factor in design：33717
Quality factor measured：>32000

Cold testing of the VHF gun

- Tuner test





- 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 maximum total force of the four tuners is (-40 kN, 40 kN), thus the maximum frequency shift is (-100 kHz, 100 kHz)

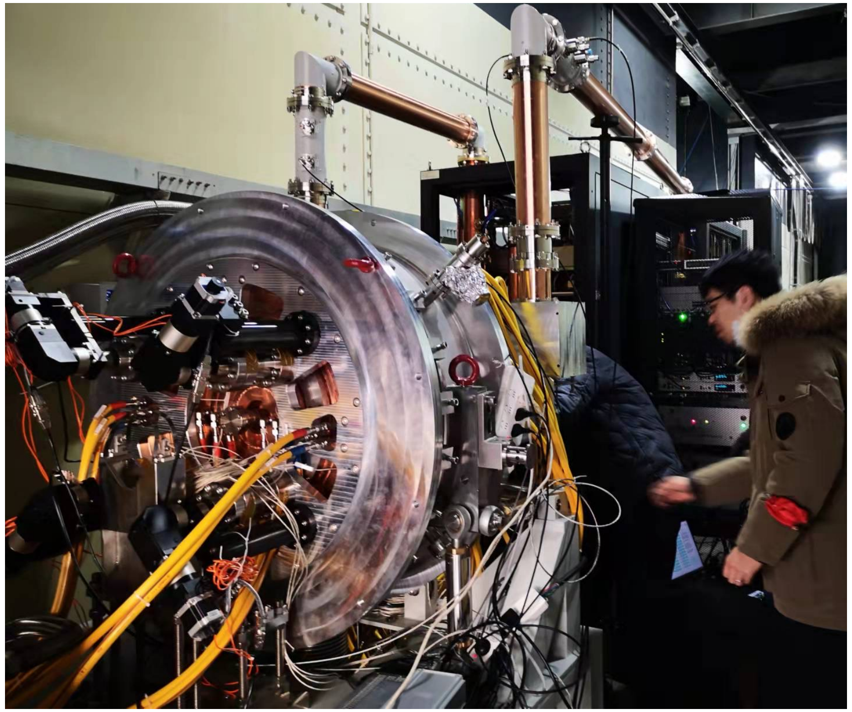
Outline

清華大學
Tsinghua University

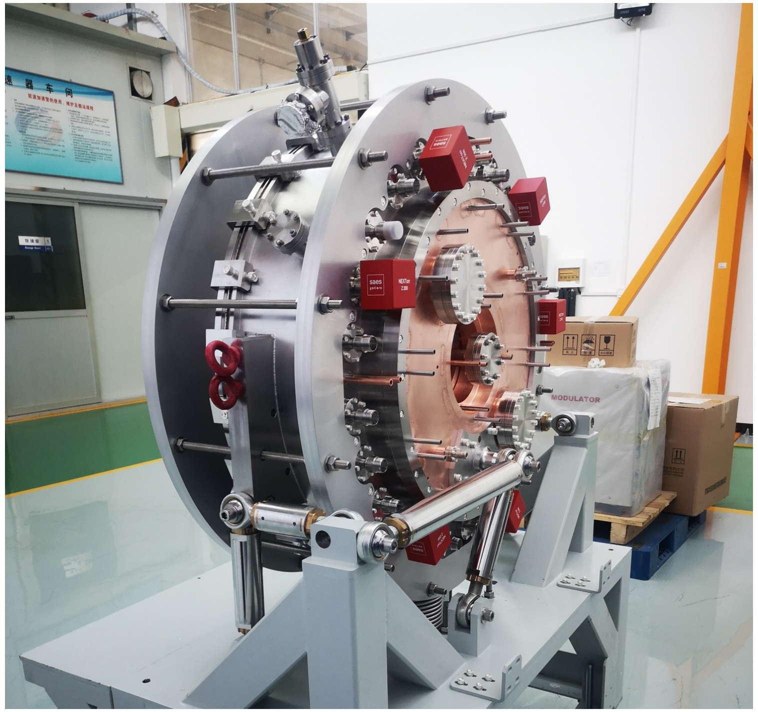
1. Introduction
2. R&D of the VHF gun
   2.1 Gun design and optimization
   2.2 Manufacturing and testing
   2.3 Conditioning and beam testing results
3. Summary and outlook

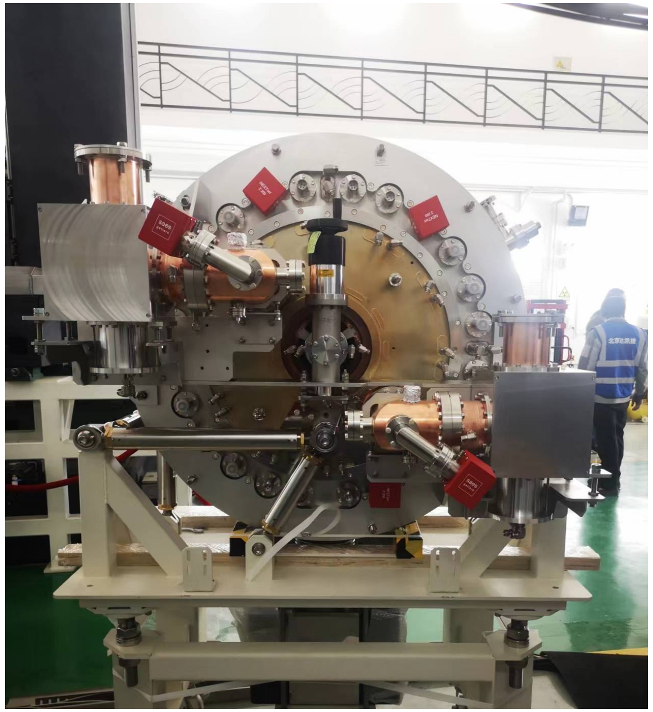
High power testing

- 3 guns have been made for process testing and beam commissioning



Prototype gun for machining process testing

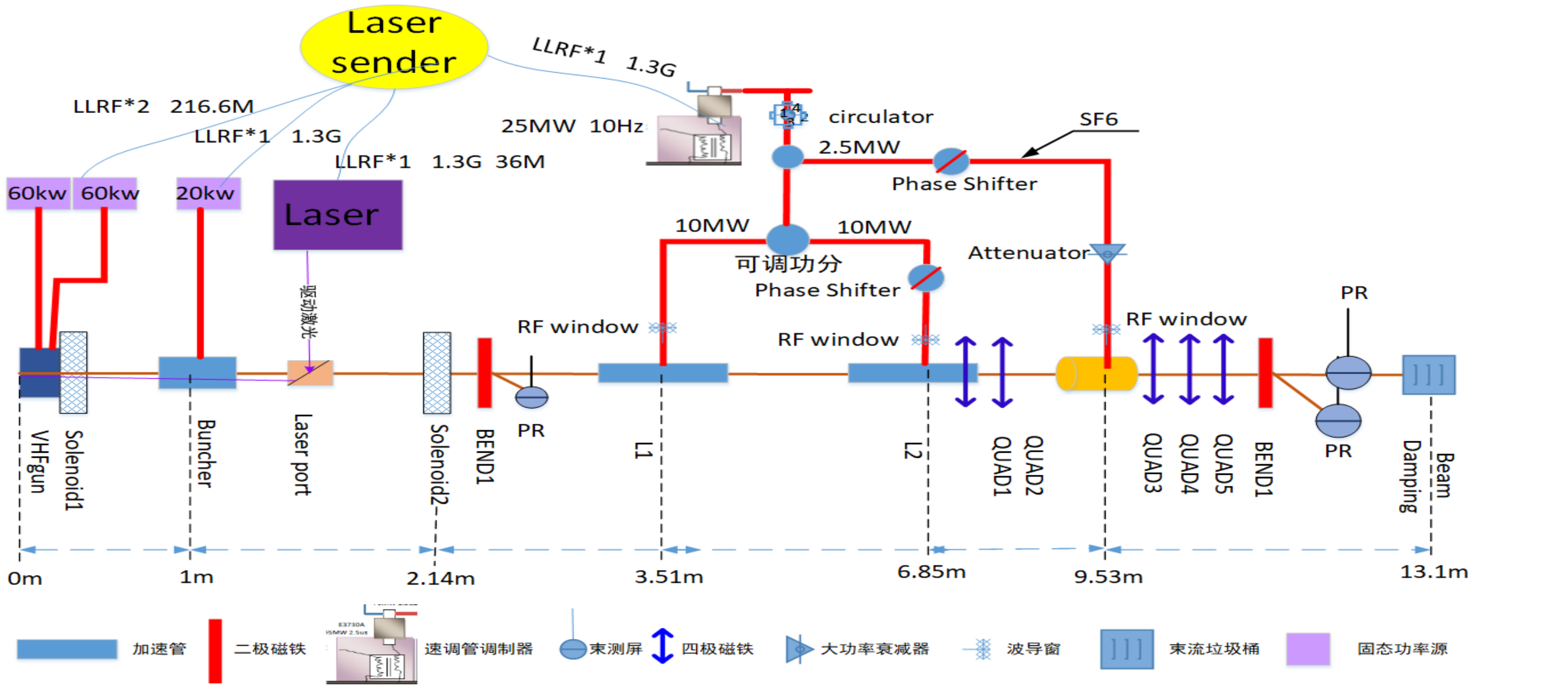


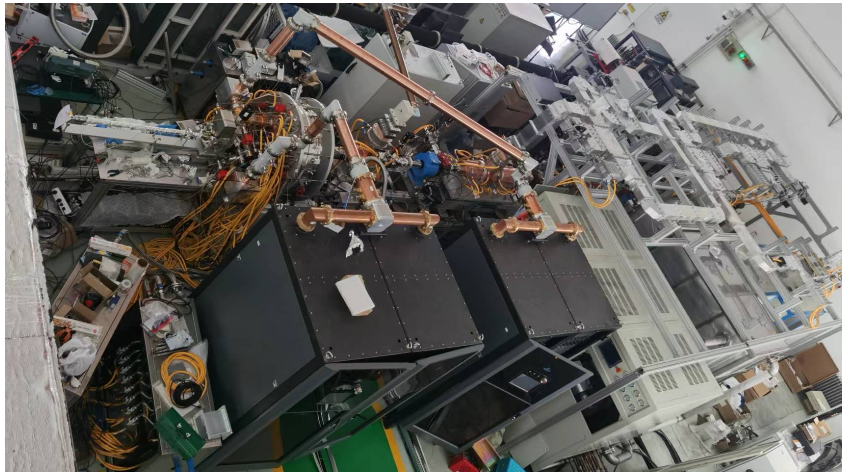


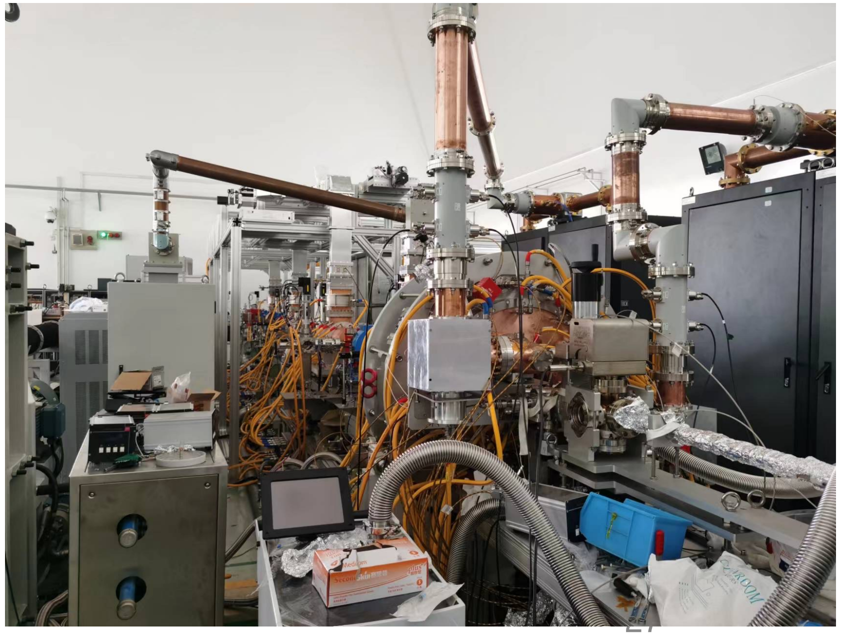
Gun 2 and 3，>75kW CW stable operation(limited by power supply system) with low dark current

High power testing

- 30MeV beamline for gun beam testing
- One 400kV Buncher powered by 20kW SSA
- Two tubes and one deflecting cavity powered by a 20MW klystron operated in pulse mode.

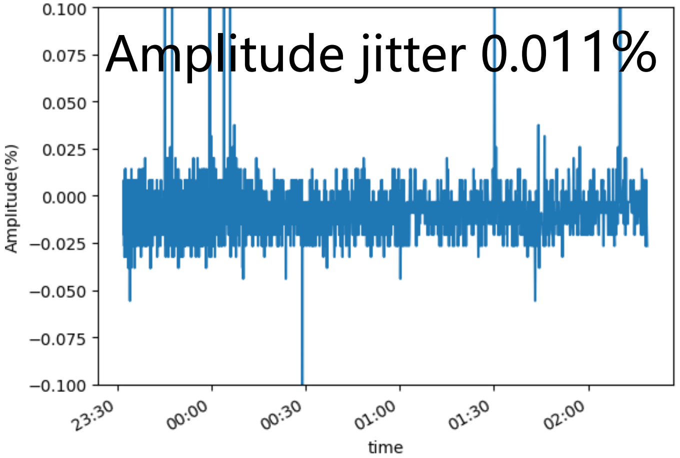


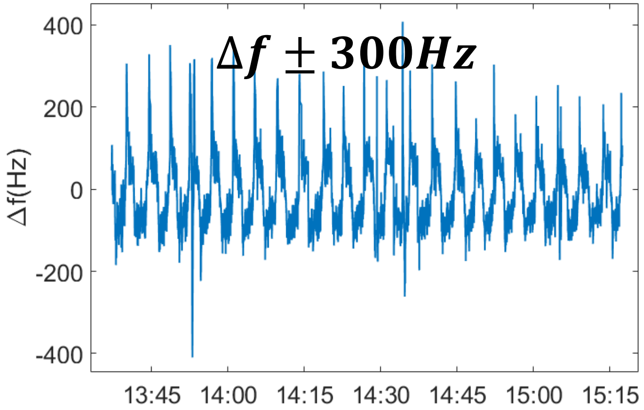


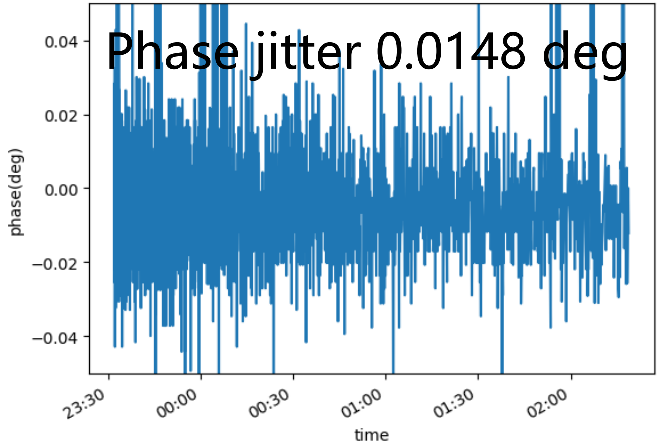


High power testing

- After ~20 hours RF commissioning, successfully operated in CW mode at 216.667 MHz with ~75 kW input power(limited by power supply system), or ~800kV voltage





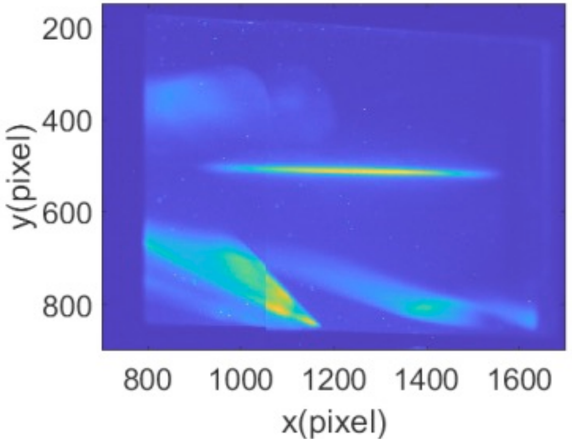


- Multipacting is observed with RF power lower than 25kW, which is in consistent with the simulation results.
- Good vacuum achieved in testing: ~$2.0\text{x}10^{-8}$ pa without RF, ~$9\text{x}10^{-8}$pa with 75kW CW RF power.

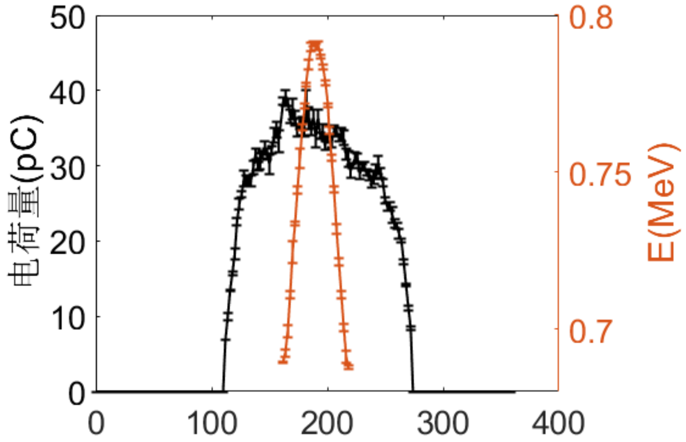
Beam testing

- First photoelectron beam generated with Cs_2Te cathode on August 23, 2022.

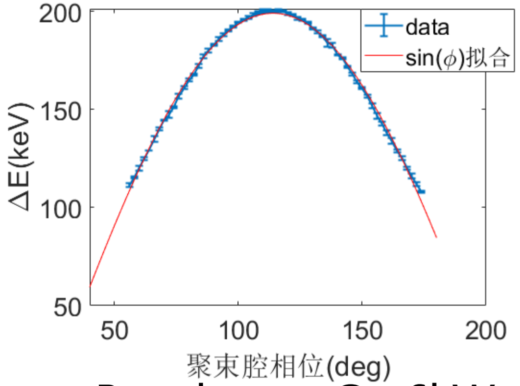
First photoelectron beam on
23 August, 2022 , QE: ~1%



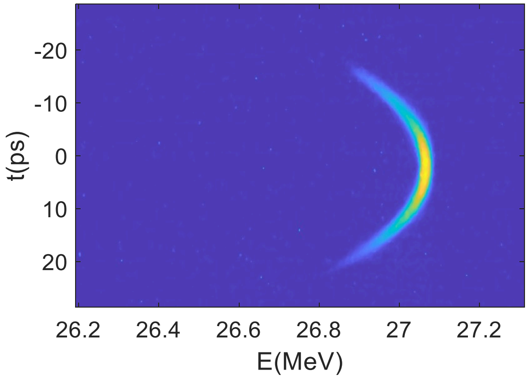
Bean profile after low energy bend magnet



Gun phase scan(70kW)



Buncher on@~6kW

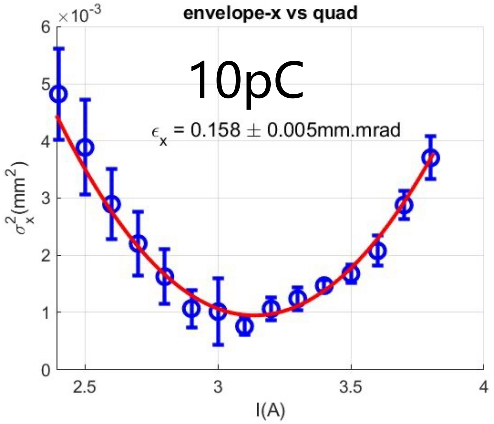


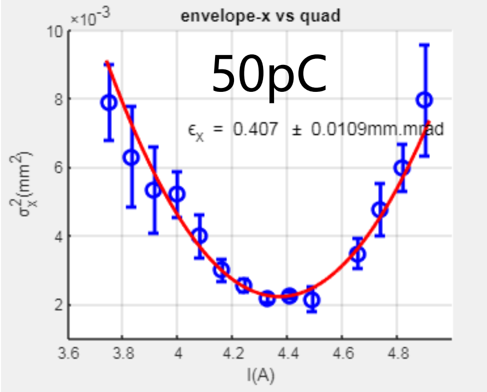
Deflecting cavity ON

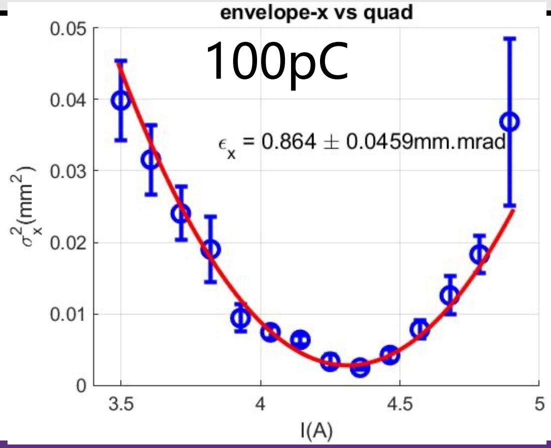
Beam testing

- Emittance measurement and optimization(preliminary results)
- No-ideal distribution of laser, dipole and quadrupole field in solenoid and RF structures, alignment

Bunch charge	Projected emittance （95%） $(um \cdot rad)$	Slice emittance （95%） $(um \cdot rad)$	Bunch length (mm rms)
10 pC	0.16	0.15	0.49
50 pC	0.41	0.38	1.15
100 pC	0.85	0.72	1.44

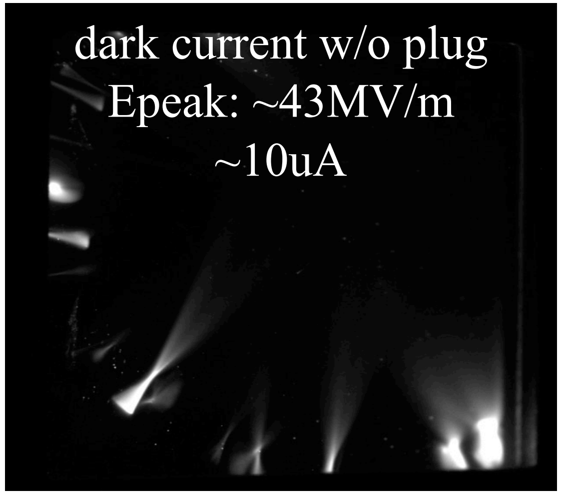


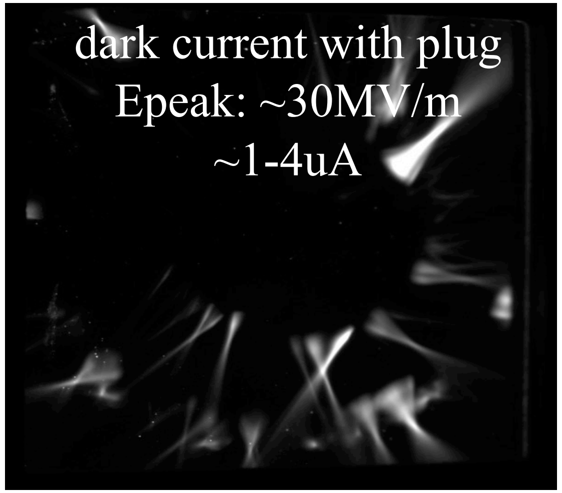


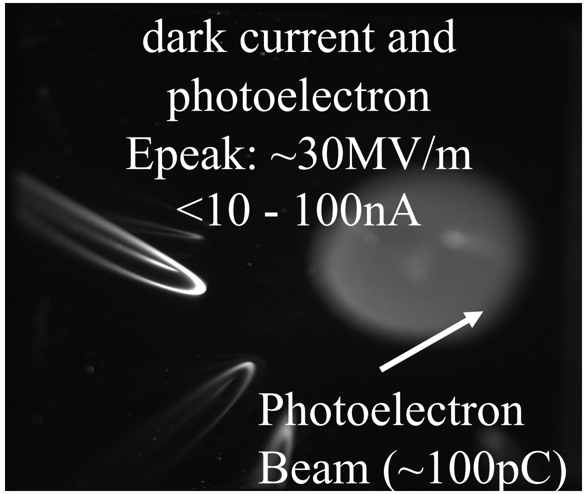


High power testing

- Dark current
  - High dark current during the first round running, 1-10uA
  - Significantly reduced after re-cleaning, less than 10nA with plug in.
  - Obvious dark current increasing from 10nA->~400nA during CW operation in about two months. And it also reduced to very low after re-processed.
  - Contamination (or dust) from cathode plug or downstream beam pipe?
  - In-situ cleaning technologies are necessary for long term operation.



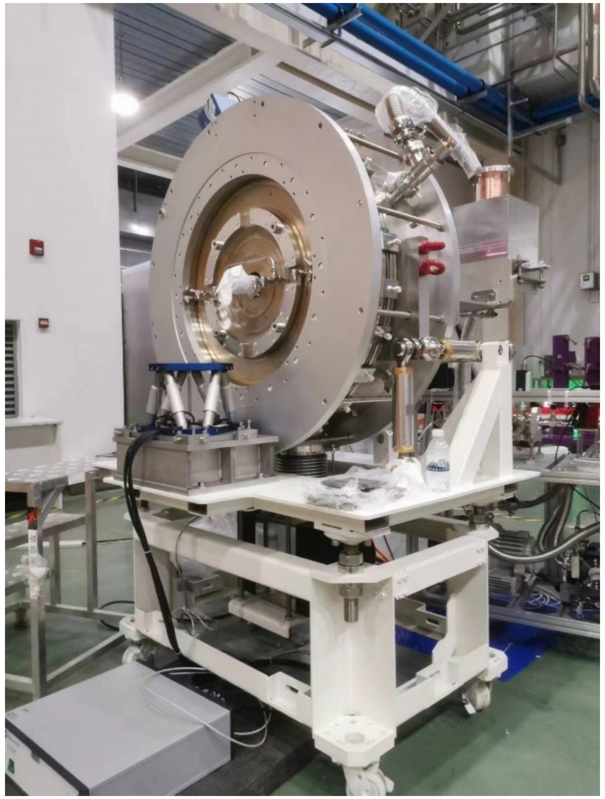


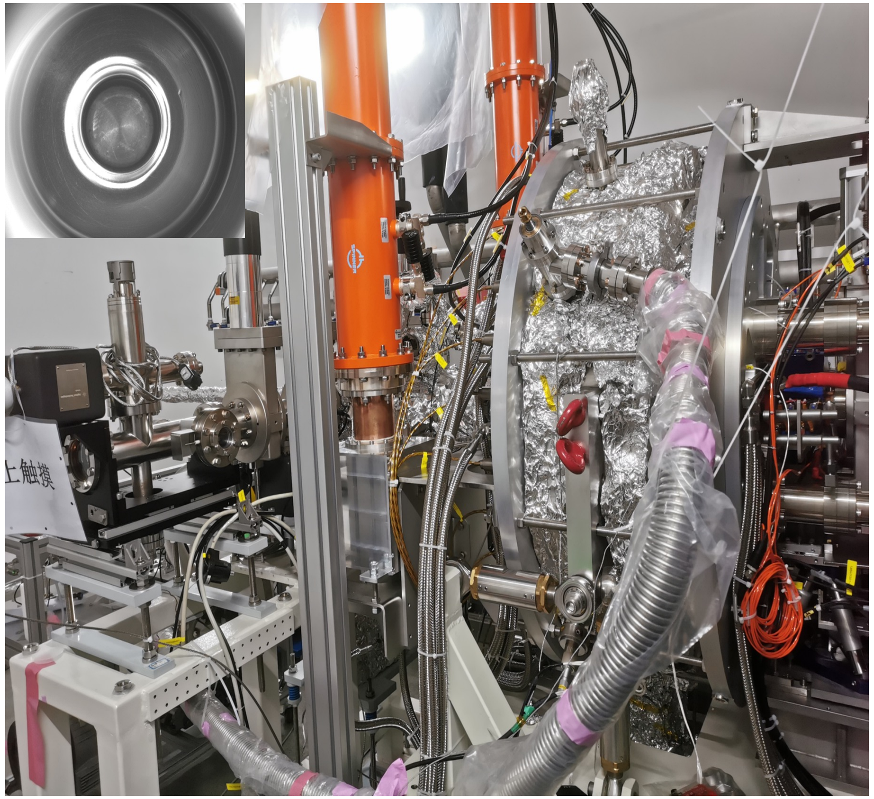


Dark current of the 2nd gun, without(left) or with plug in(mid), and after re-processed

SHINE VHF gun Progress

- 2023.04 Tsinghua VHF gun was delivered to SHINE project and installed as the first beam line component in tunnel.

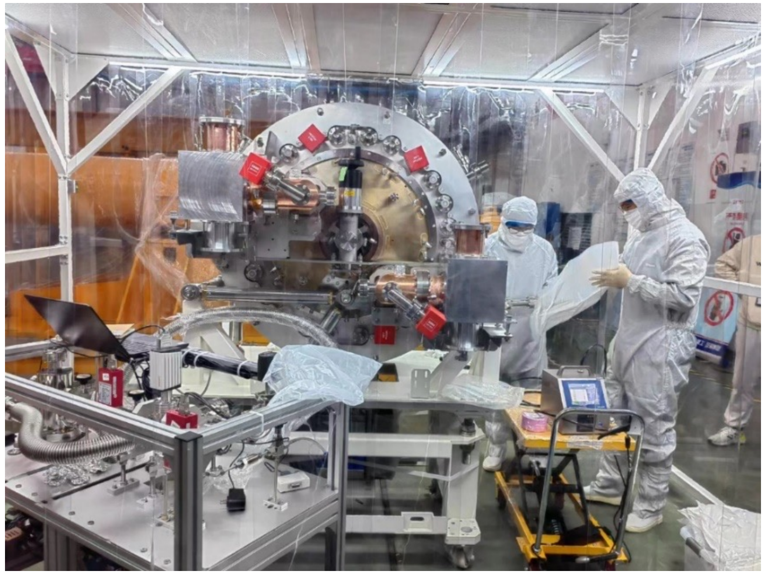


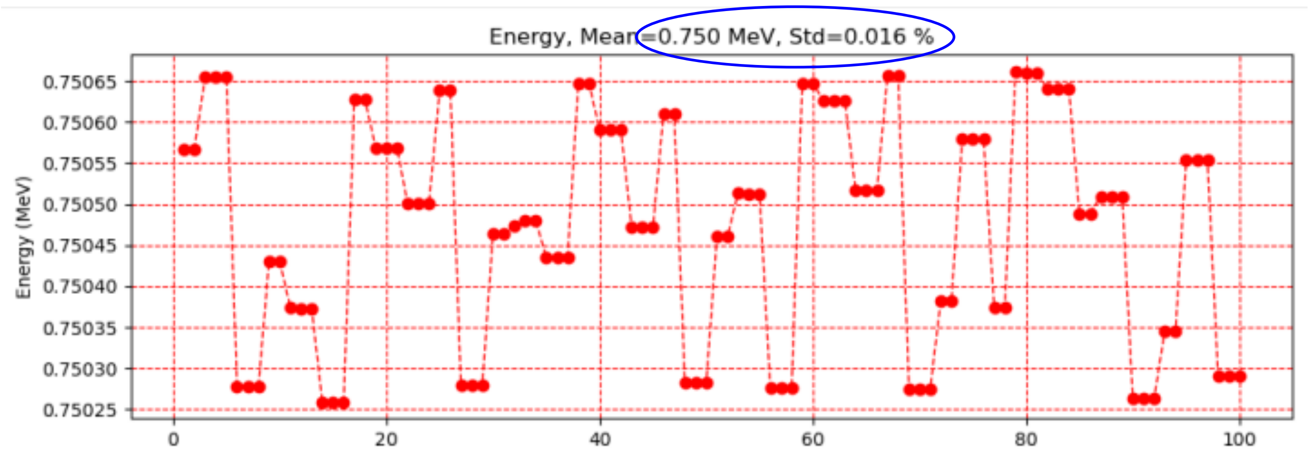


Gun installation and commissioning

■ Progress in 2023

- 2023.04, VHF gun delivered by Tsinghua team
- 2023.06, Cathode loadlock installed
- 2023.08, **Gun section beamline installed**
- 2023.10, Gun and buncher CW RF commissioning
- 2023.12, Gun section **beam commissioning started**



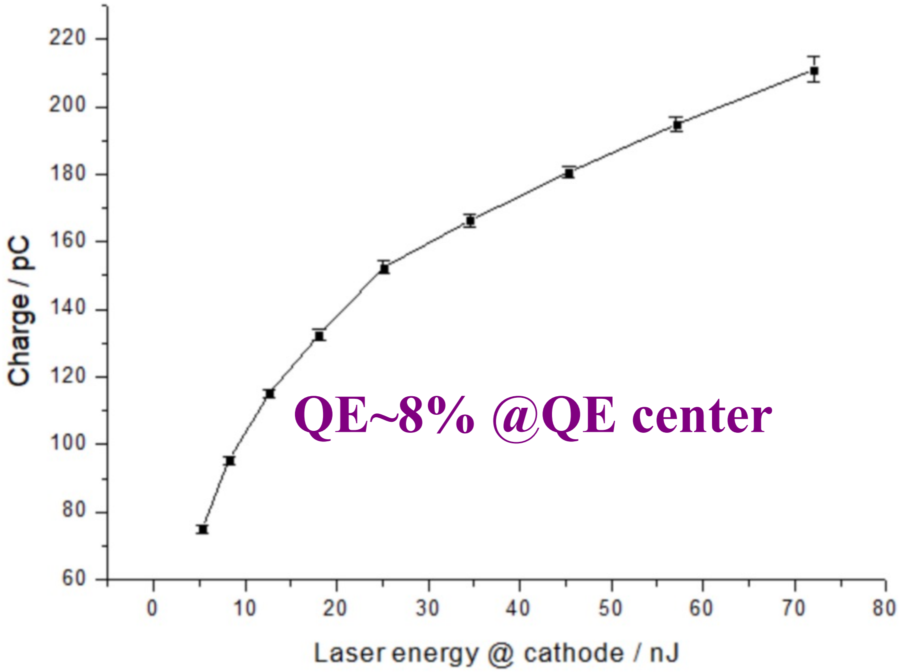


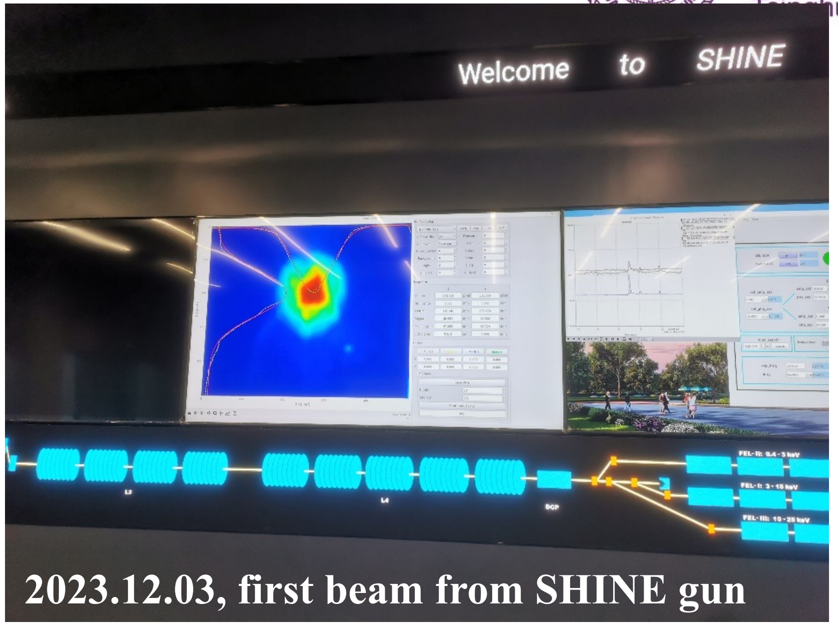
Courtesy of Houjun, SHINE

Gun beam commissioning

Cathode emission curve and QE

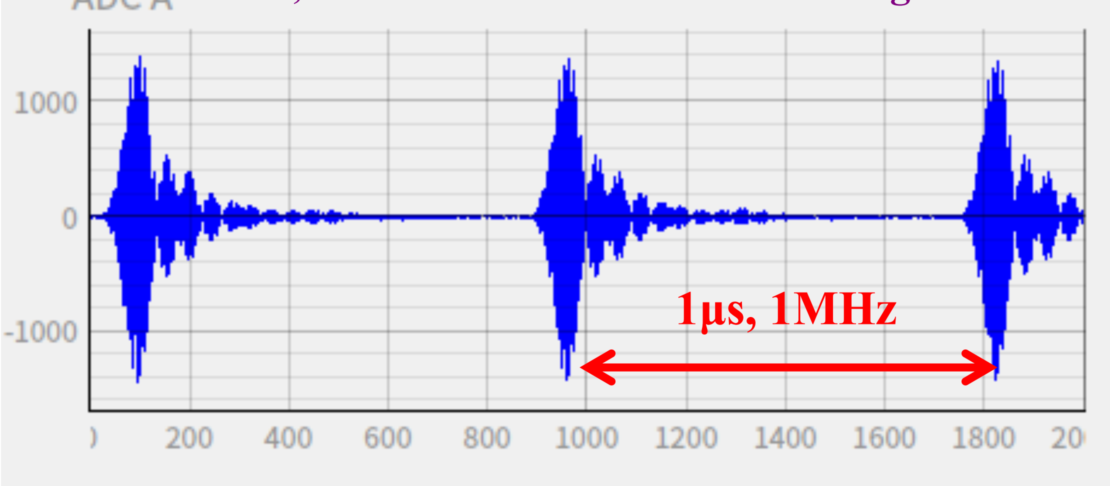
- Gaussian laser both in x and t





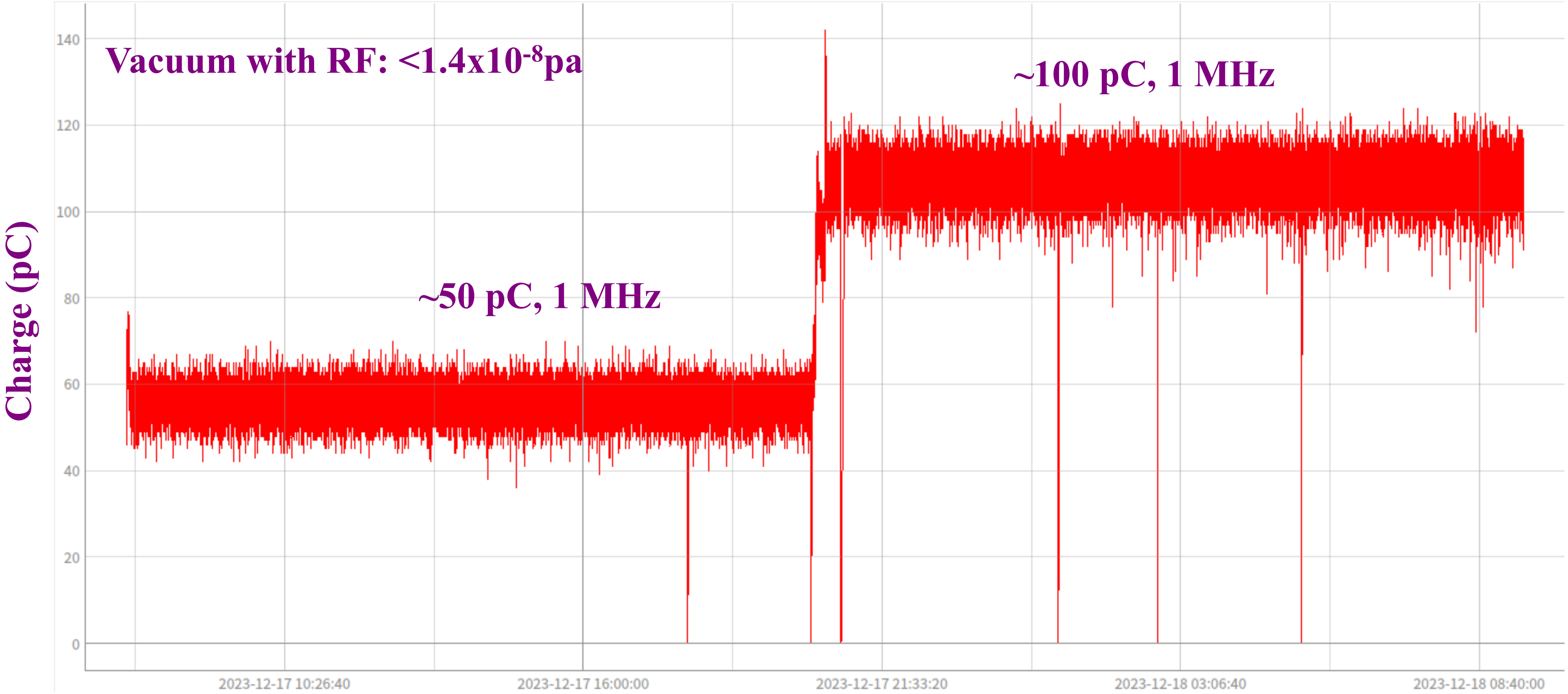
2023.12.03, first beam from SHINE gun

2023.12.14, first 1 MHz beam from SHINE gun



BPM ADC signal

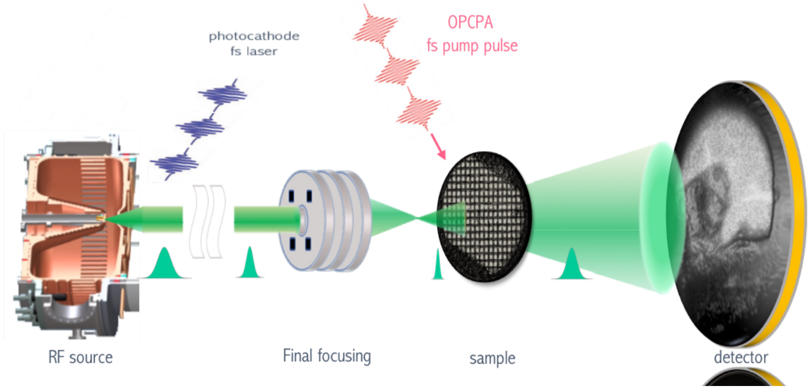
Gun beam commissioning

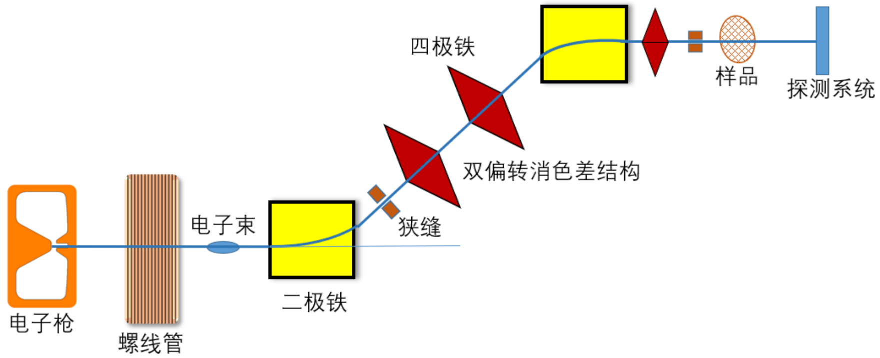


24-hour run, slow charge feedback on

Summary and outlook

- We successfully developed and delivered the VHF gun for SHINE project
- Further improve the gun performance and beam quality
  - Increase cathode gradient to 30MV/m, MHz repetition beam .
  - Beam emittance optimization.
  - New cathode testing with higher performance (green cathode).
  - *In situ* gun cleaning technologies.
- Applications with high repetition rate and high quality beam
  - High repetition MeV ultrafast electron diffraction and microscopy





Acknowledgement

- Collaborations and discussions with many colleagues
  - SHINE group
  - DCLS group from DICP CAS
  - S^3FEL group from ISAF
  - Peking University
  - IHEP
  - ……

Thanks