# Development of the C-band photocathode gun in SSRF/SARI

Cheng Wang, Wencheng Fang, Jianhao Tan, Xiaoxia Huang, Chengcheng Xiao, Zhentang Zhao, SARI/SSRF

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# Outlines

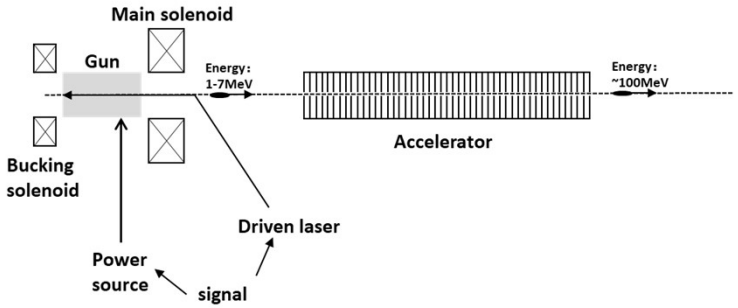
- Considerations of Photoinjectors
- The 3.6-cell C-band photocathode gun
  - RF design and features of the gun
  - Experimental results
- The cryogenic photocathode gun
  - Considerations and design of the cryogenic gun
  - Low-power test of the cryogenic gun

# Brief introduction

1980s
1-2 photocathode gun projects

2000s
mature photocathode gun design

-2020s
Novel gun proposal




*High brightness photocathode injector*

*Higher gradient*

*New materials*
*Surface processing*
*DC vs rf, higher frequency*
*Local enhancement*
*……*

*Brightness preservation:*

*Emittance compensation*
*Beam shaping*
*……*

*Mean Transverse Energy*

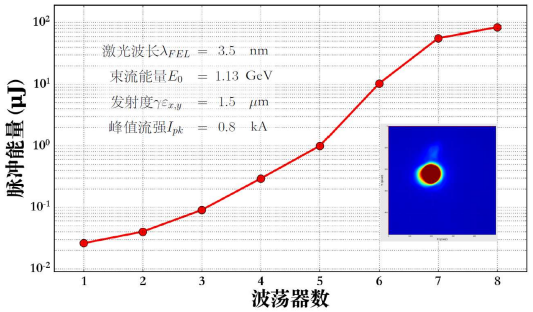
*New material*
*Cryogenic cathode*
*……*

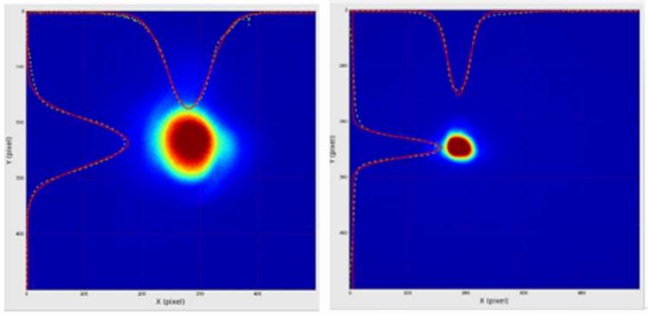
$$\frac{\varepsilon_{nCathode}}{\sigma_r} = \sqrt{\frac{\Delta E_C}{3mc^2}}$$

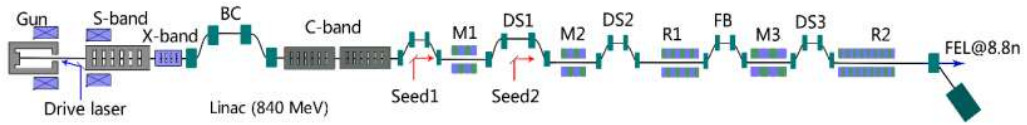
$$\varepsilon_{sc} = \frac{\pi}{4}\frac{2mc^2}{eE_0}\frac{1}{\sin\phi_0}\frac{I_p}{I_A}\mu(A)$$

# Brief introduction

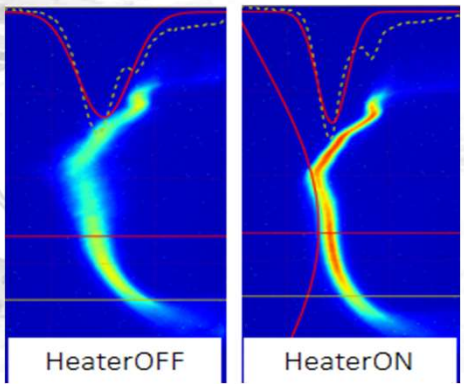
- SXFEL has lasing at 5.6nm and 2nm



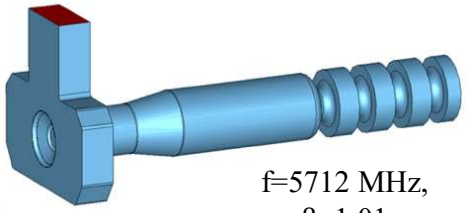



- S-band gun
- 500pC, 10ps electron beam from the gun was compressed below 1ps by chicanes
- Micro-structure caused by the long laser profile shaped by the stacking technique
- Shorter initial beam
- Maintaining the current low emittance

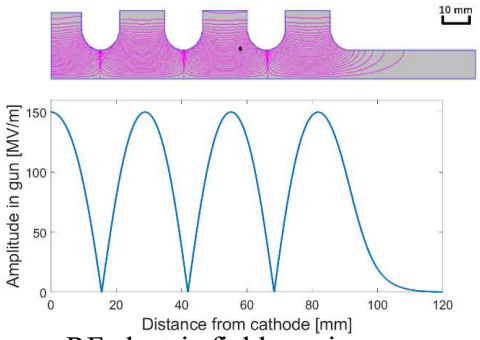


# 3.6-cell C-band Photocathode RF gun

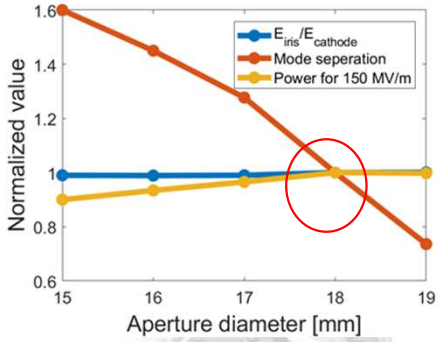
- RF design
- Optimization
  - Mode separation
  - Electric field on the axis and surface
  - Pulsed heat



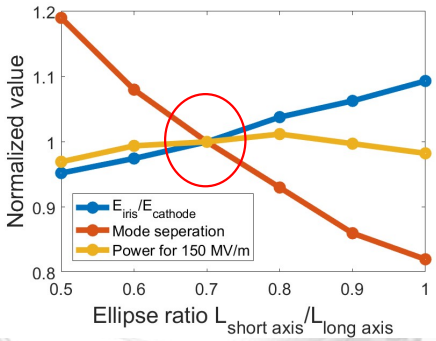
f=5712 MHz,
β=1.01




RF electric field maximum flatness is better than 99%



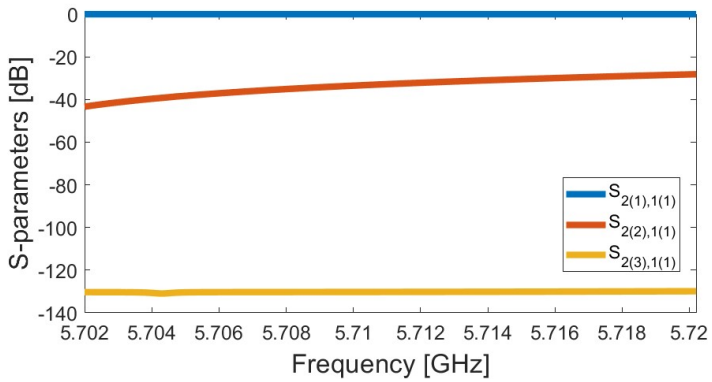

The mode separation varies widely with the aperture diameter, and the peak E varies widely with Lshort/Llong.

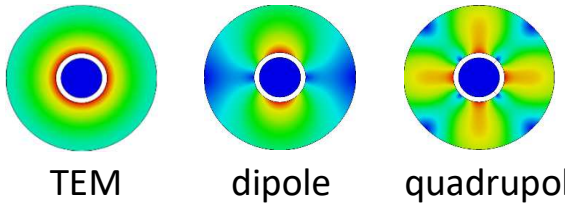


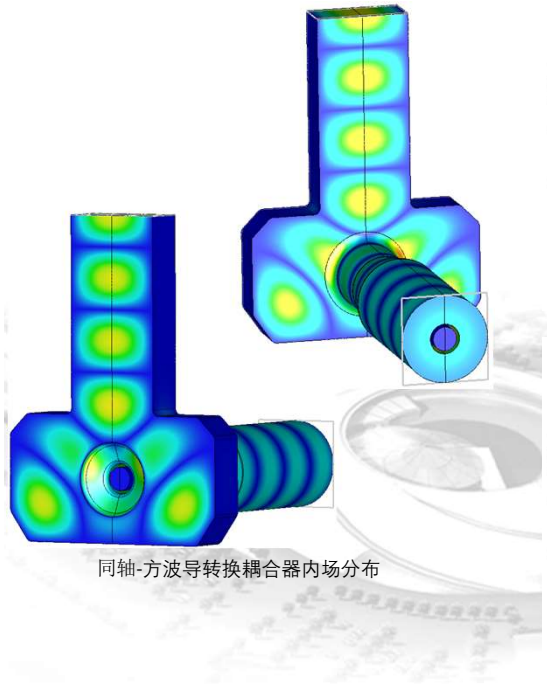

The aperture is 18 mm, and the ratio of the short axis to the long axis of the ellipse is 0.7

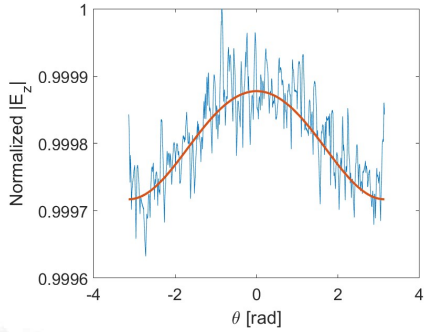
# RF design

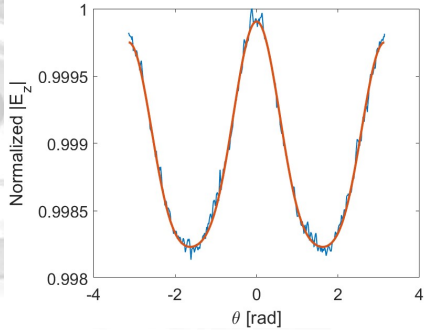
- RF coupler
  - Rectangular waveguide – coaxial cable
  - Eliminate asymmetries
    - Optimized single-feed coupler
    - Dipole-mode is eliminated (almost -40dB)
  - S-parameters of the coupler
    - $S_{2(2),1(1)}$ is the dipole mode
    - $S_{2(3),1(1)}$ is the quadrupole mode



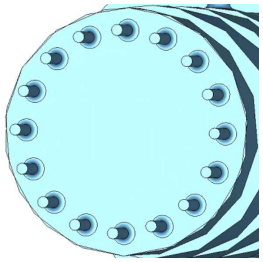



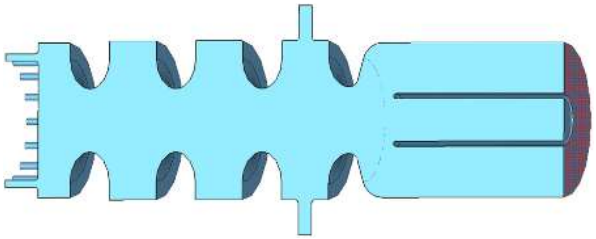




With pick-up port

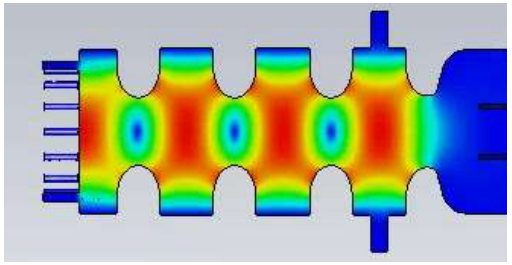
# RF design

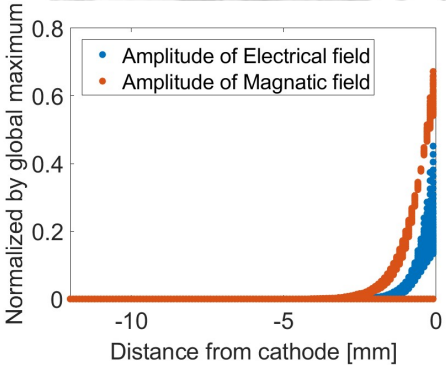
- Additional vacuum port on cathode plate.
  - The vacuum ion pump is far away from the cathode
    - Maintaining the quantum efficiency of the cathode
    - Extending photocathode life

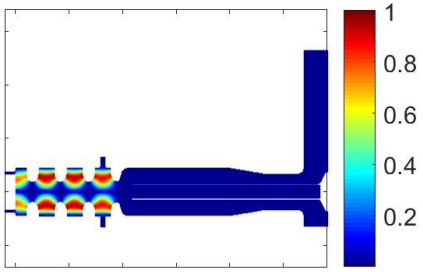




  - The additional holes are away from the high field area
    - Rapid decay
    - Will not lead to a significant increase in the chance of breakdown

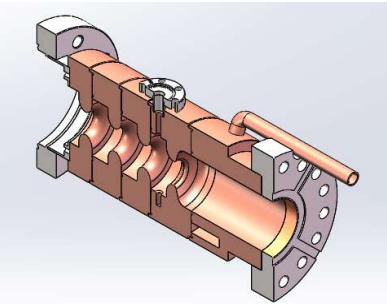


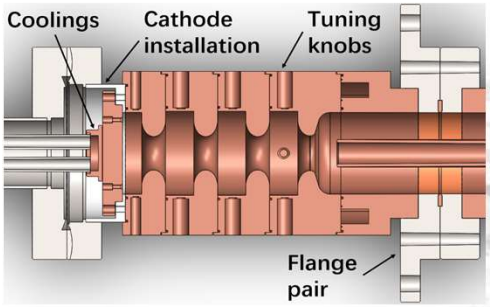


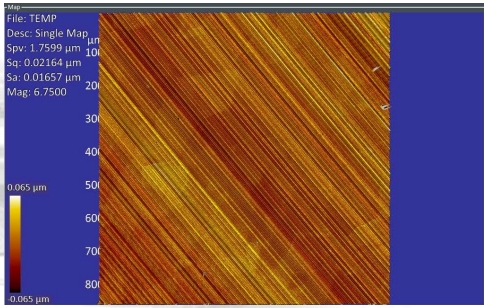



# RF design

- Removable cathode
  - Mount on the gun cavity (instead of brazing)
  - External cooling head outside
  - The surface roughness of the non-cathode parts is 0.2 μm.
  - Off-center machining with lathe： RMS roughness → 0.022 μm。
  - Dry ice cleaning： Removes contaminants such as particles and dirt while maintaining dry



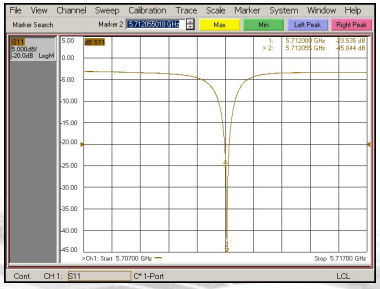


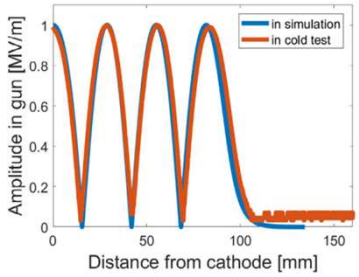



# RF design

- RF performance of the C-band gun

| | | |
|---|---|---|
| Frequency （π mode） | 5712 | MHz |
| Frequency （2π/3 mode） | 5693.61 | MHz |
| Q0 | 10884 | |
| Esmax/Ec | 0.94 | |
| Shunt impendence | 7.414 | Mohm |
| Adjacent mode （cathode） | 0.02 | |
| Adjacent mode (cell 1) | 0.01 | |
| Adjacent mode (cell 2) | 0.005 | |
| Adjacent mode (cell 3) | 0.01 | |
| Design gradient | 150 | MV/m |
| Peak RF power | 14 | MW |
| RF pulse | 2.5 | μs |
| Max(Sc) | 2.7 | $W/\mu m^2$ |

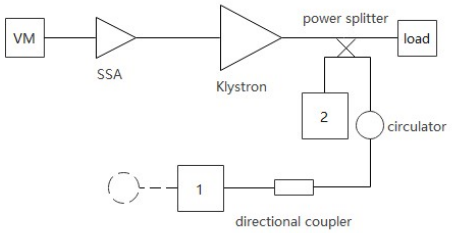


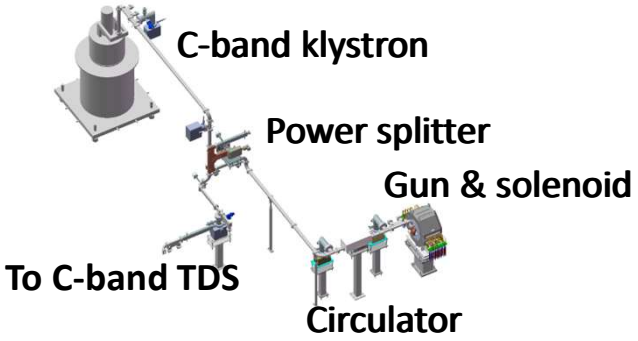



| Parameter | Unit | Simulation | Measurement |
|---|---|---|---|
| Frequency | MHz | 5712.0 | 5712.4 |
| Adjacent mode | MHz | 18.0 | 18.0 |
| Q | 1 | 10141 | 8709 |

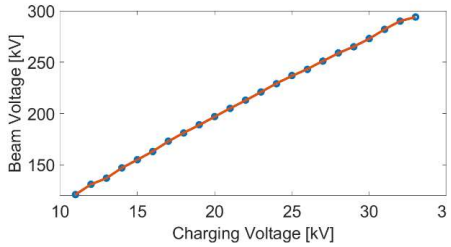
# Experimental result

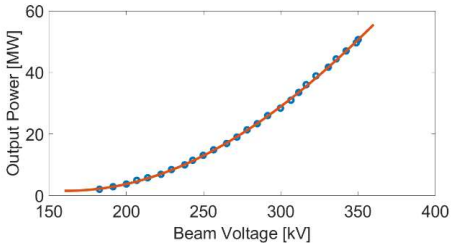
- Vacuum environment and correct temperature
- High power experiment set-up



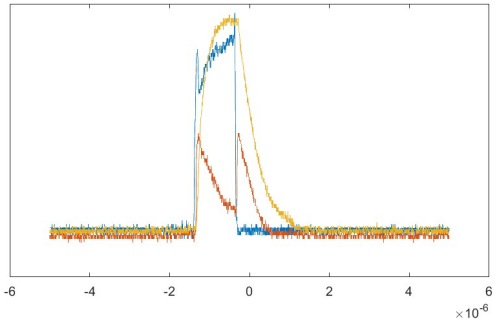

- 50MW C-band klystron;
- LLRF is for C-band based on SXFEL;

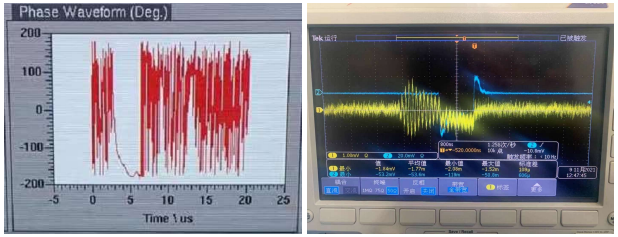


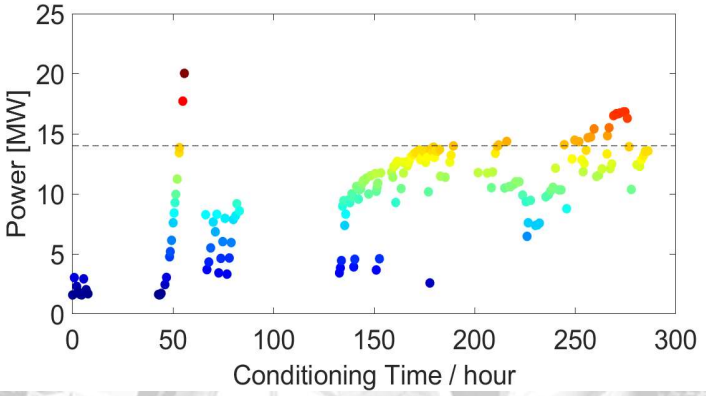



# Experimental result

- Repetition rate is 10Hz, and from 0.5μs to 2.5μs
- The gradient in the gun can be figured out from the klystron output
  - 28kV → 14 MW→150 MV/m
  - 31kV → 20 MW→180 MV/m
  - The gradient reached the goal successfully, and the maximum achievable gradient is 180MV/m




| Max E field on the gun[MV/m] | 130 | 140 | 150 | 160 |
|---|---|---|---|---|
| Beam energy[MeV] | 6.3 | 6.8 | 7.3 | 7.8 |
| Emittance of the injector [mm·mrad] | 0.63 | 0.47 | 0.44 | 0.43 |

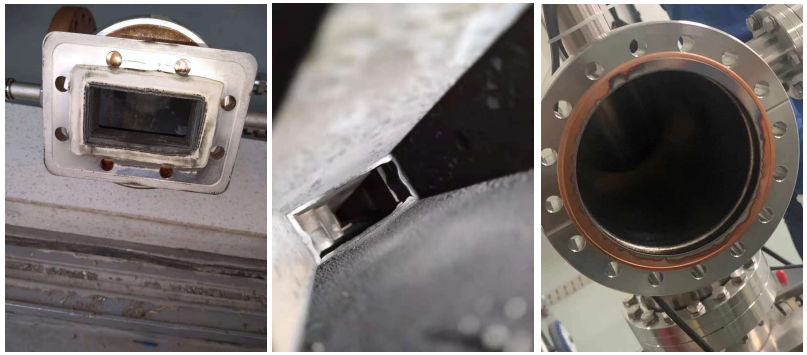
500pC, 5ps

# Experimental result

- Lessons learned

**2020.12-2021.1**

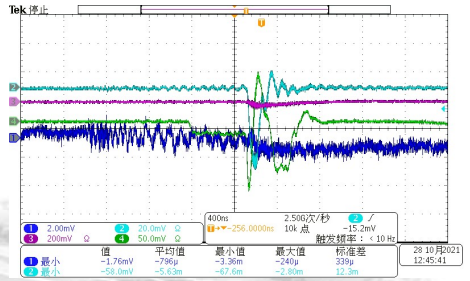
First test, Charring of the rubber gasket at the pumping waveguide

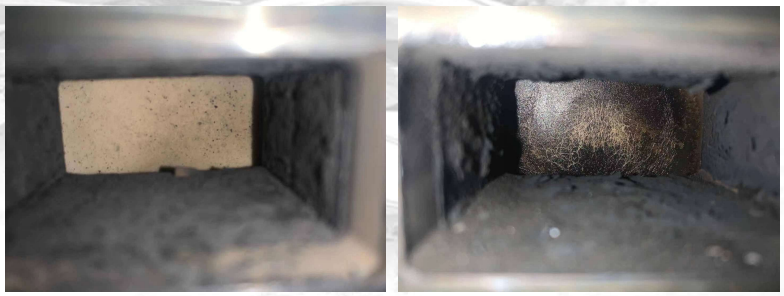


Gas area was contaminated.
New circulator and RF windows.
All flanges based on vacuum type， instead of flat flange.

**2021.9-2021.11**

Test again, Breakdown of the circulator

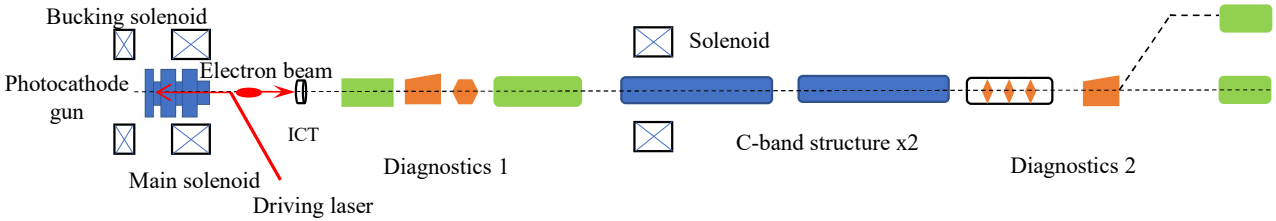


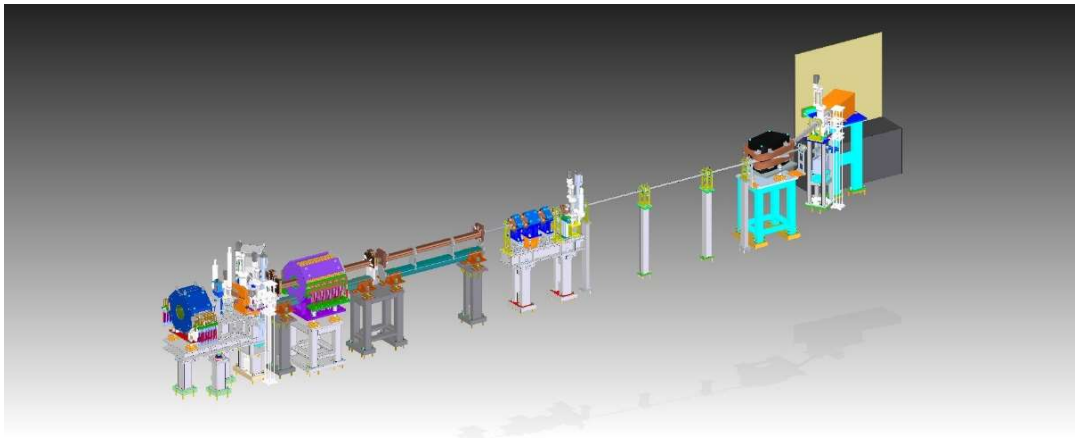


Circulator, above 10MW

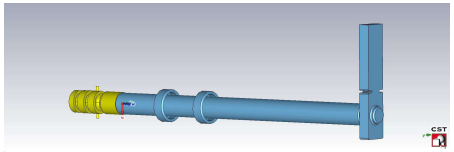
# Prospect

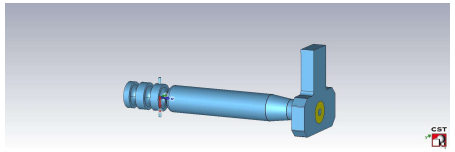
- Beam testing of the 3.6-cell gun

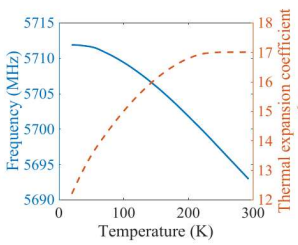


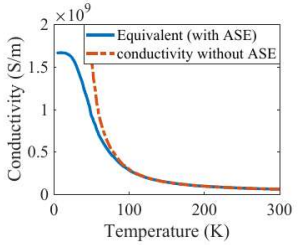



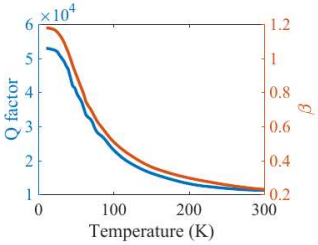
# Cryogenic RF gun







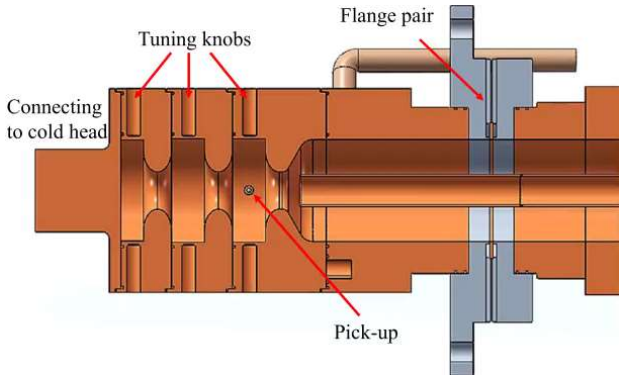



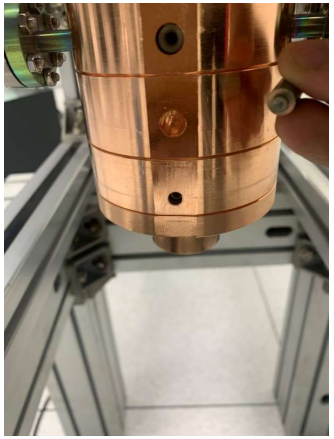




- RRR=500, with ASE in cryo. tem.
- Equivalent conductivity increase by 29
- Q factor, beta, impedance increase by 5.5

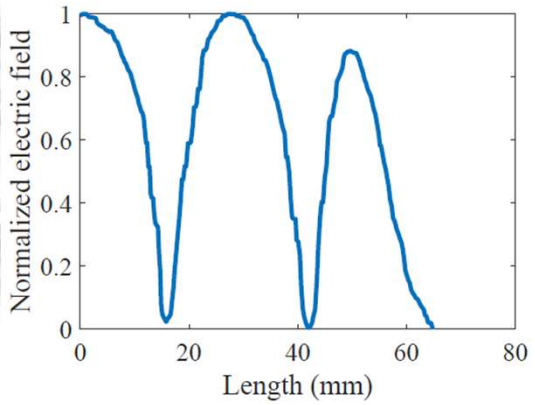
| | Room temp. | Cryo temp. | |
|---|---|---|---|
| π mode | 5692.9 | 5712 | MHz |
| 1/2π mode | 5674.5 | 5693.6 | MHz |
| 0 mode | 5647 | 5666 | MHz |
| Q0 | 9852.46 | 54000 | |
| Esmax/Ec | 0.914 | | |
| Shunt impendance | 6.285 | 34.455 | Mohm |
| Adjacent mode （cathode） | 0.0289 | 0.0094 | |
| Adjacent mode （cell 1） | 0.0074 | 0.0024 | |
| Adjacent mode （cell 2） | 0.0226 | 0.0073 | |
| Target gradient | 200 | | MV/m |
| Peak RF power | 16.773 | 3.07 | MW |
| RF pulse | 2 | | μs |
| Peak temperature rise | 75.45 | 7.8 | K |

# Experimental results of the cryogenic structure

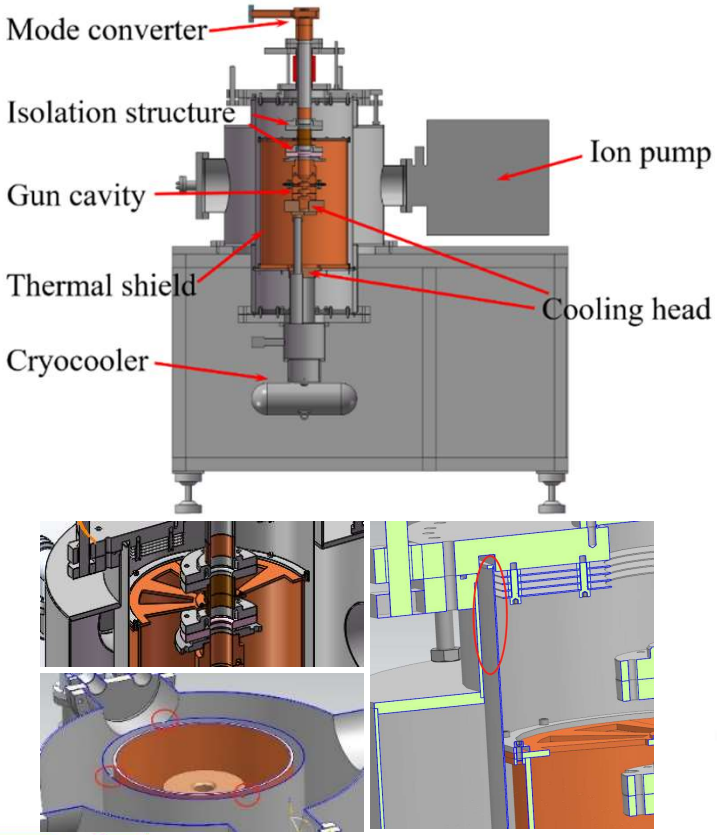


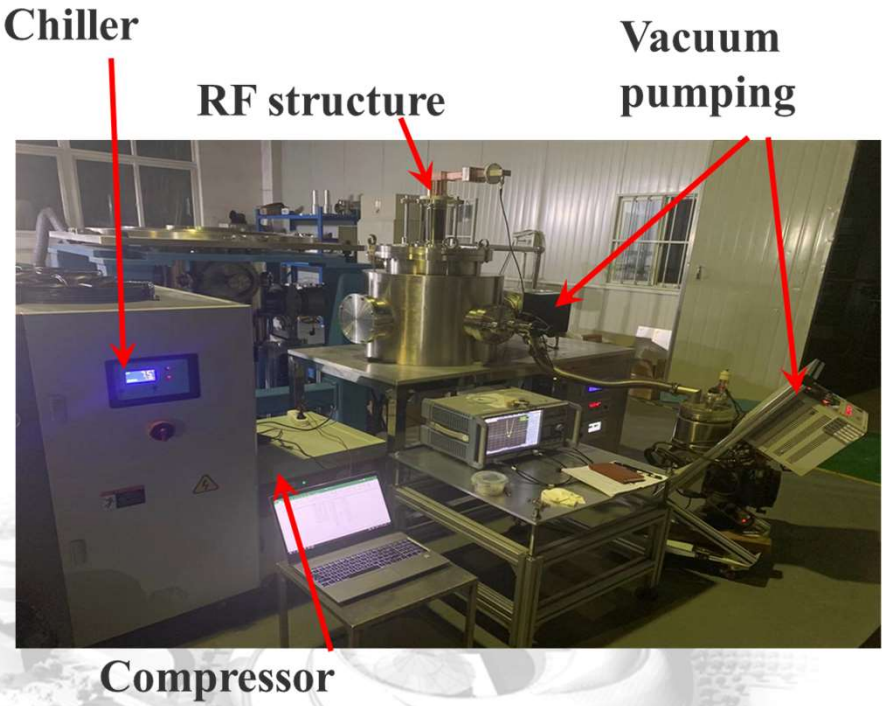



- The prototype cryogenic gun had been fabricated
- Tuning pin disengaged during the low-power test
- Frequency 5695MHz in vacuum, RT
- Field balance 1.12.



# Experimental results of the cryogenic structure



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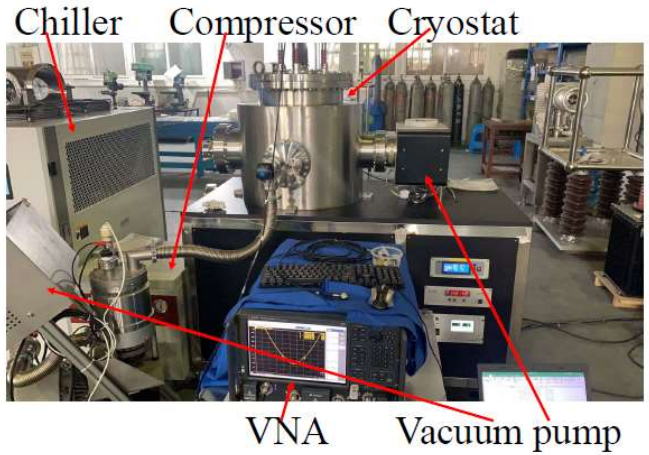
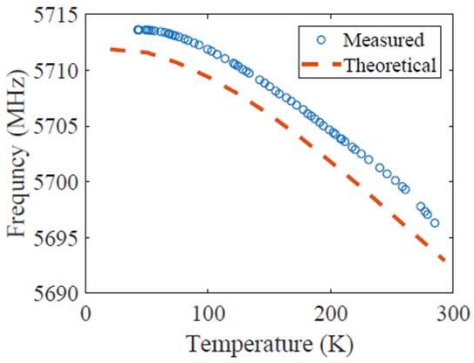
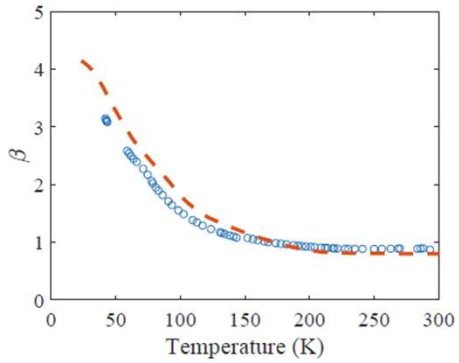
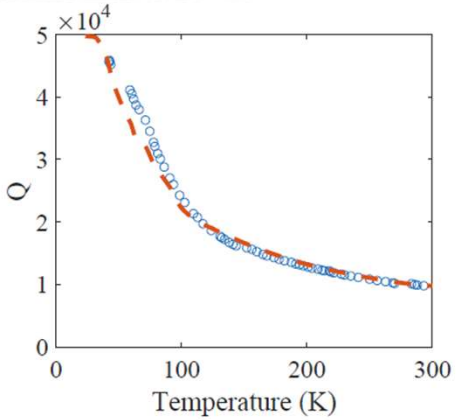



- The cooling time lasted more than 48 h.
- Electron gun reached 40K
- The experimental results are similar with the simulation, with Q factor and coupling about four times higher than at room temperature
- The trend in frequency is consistent with the simulation result, and is currently about 2 MHz off the design frequency due to the electron gun frequency of 5695 MHz



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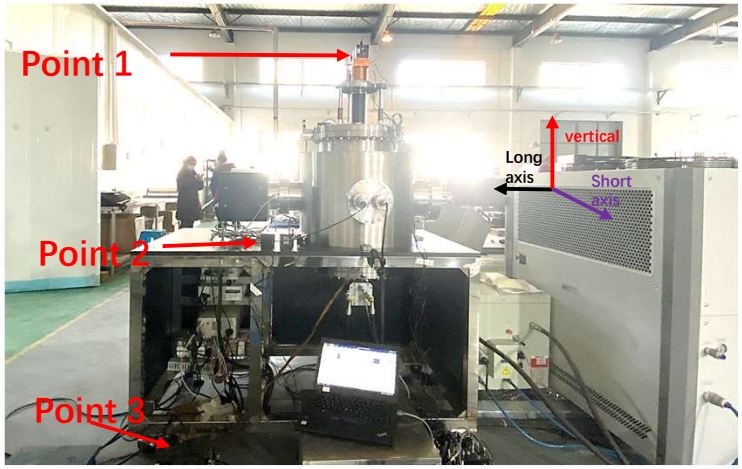
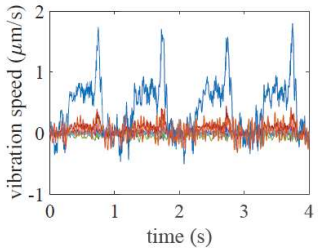
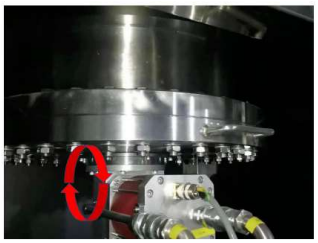
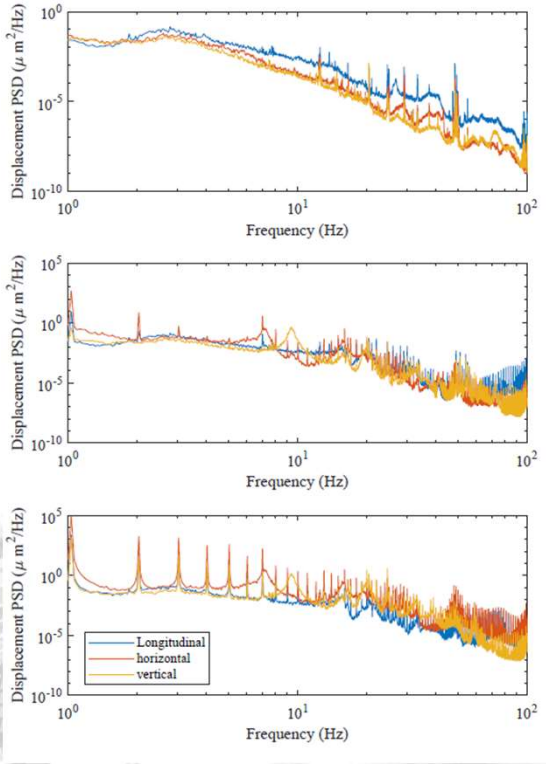


| | Vertical | Short axis | Long axis |
|---|---|---|---|
| Point3 (μm) | 0.4684 | 0.3426 | 0.2901 |
| Point2 (μm) | 0.7465 | 3.9236 | 0.6129 |
| Point1 (μm) | 8.9356 | 53.1349 | 7.1549 |

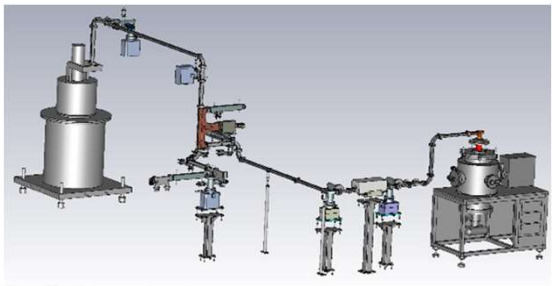


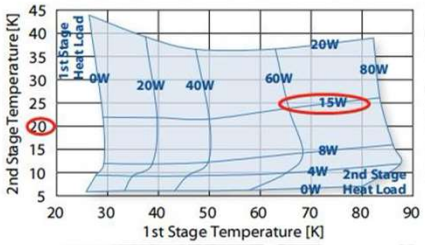

The vibration mainly occurs within the cross section of the cryo-cooler

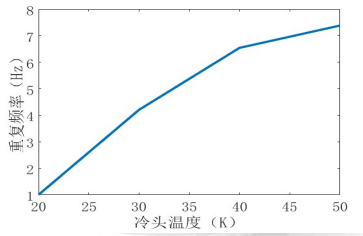
The measured vibration amplitude on the cavity is 50 μm

# Prospect

- High power study of the cryogenic gun
  - Stability of the operating environment
  - Achievable gradient





# Summary

- The development of the C-band electron gun has been largely completed.
- The gun can be operated at 150 MV/m, and can reach the peak gradient of 180MV/m.
- The beam test will be performed at an opportune time.
- The development of the cryogenic gun is underway.