High gradient activities at SSRF/SARI

Wencheng Fang

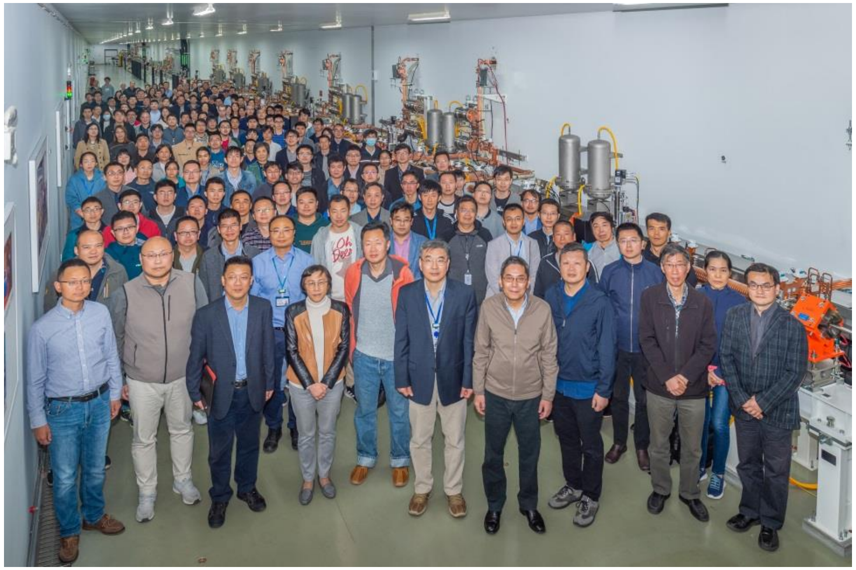
CLIC project meeting, 10th Dec. 2020

Outline

- National acceptance test of SXFEL-TF
- X-band new plan at SXFEL
- 3.6-Cell C-band photocathode gun
- C-band photocathode gun in cryostat
- Summary

SSRF-SXFEL campus

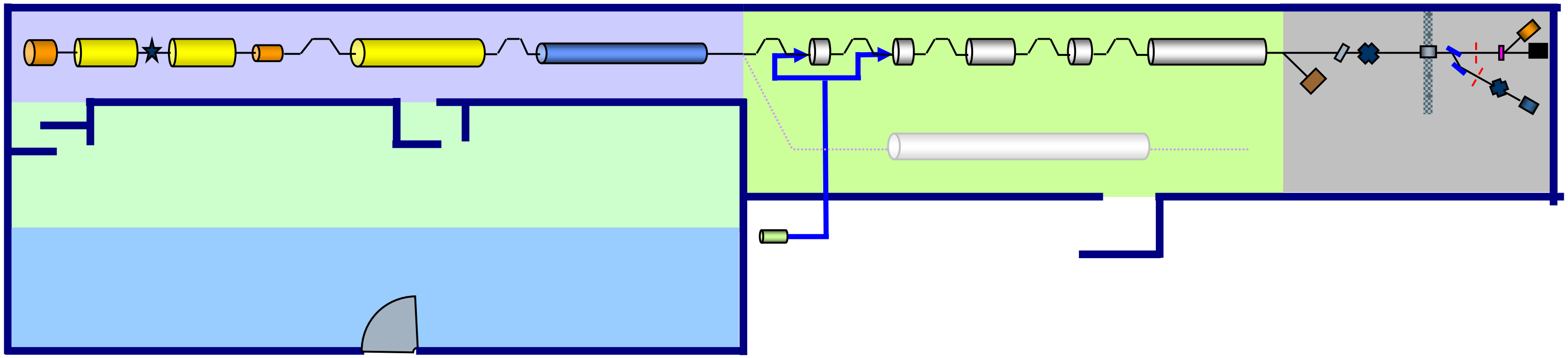
National acceptance test (30th Dec. 2014~4th Nov. 2020)



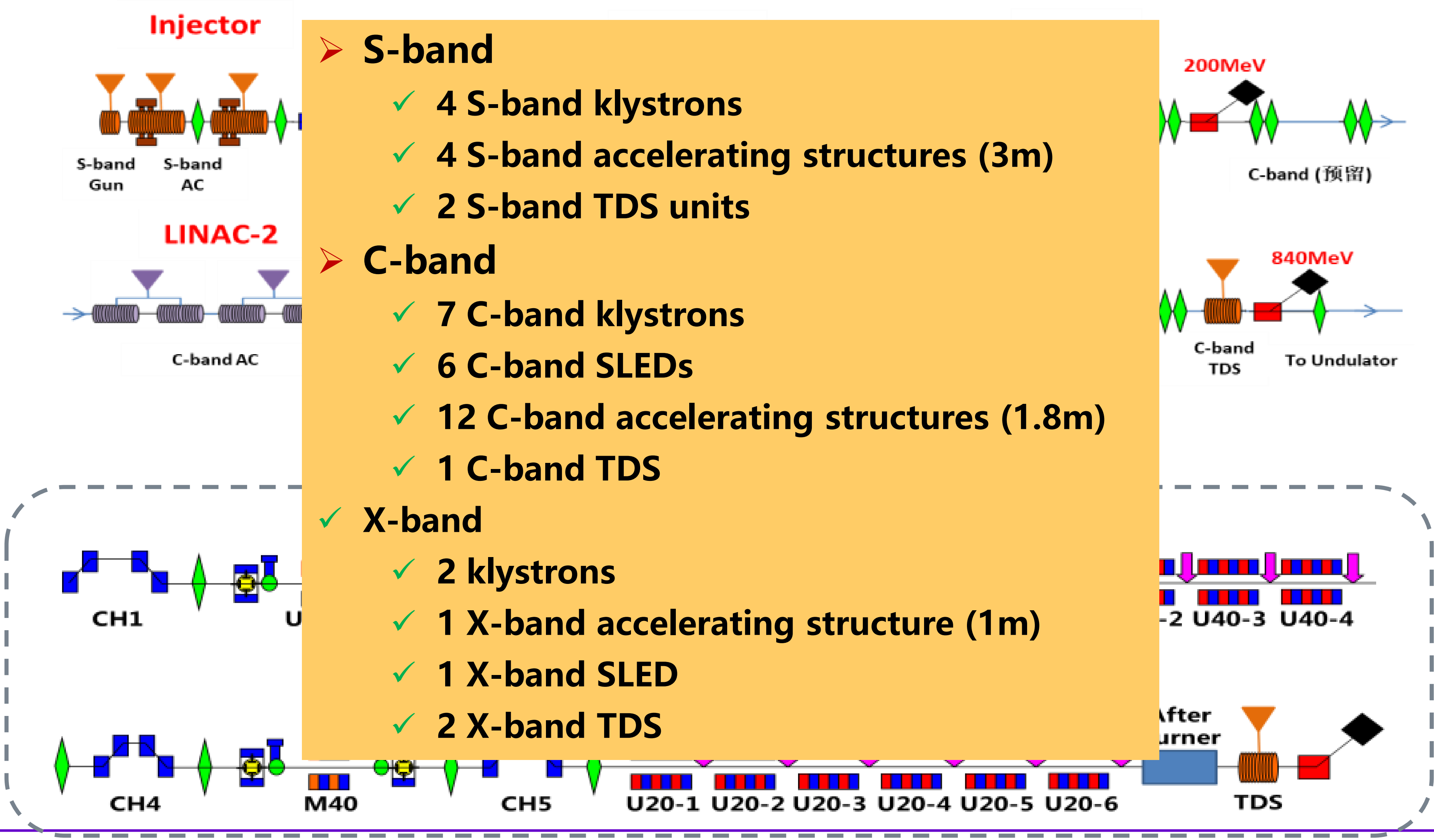
Shanghai X-ray FEL test Facility

- Proof test for the fully coherent X-ray FEL operation scheme
- R&D on key components and technology
- Test facility for the hard X-ray FEL in China for the future
- Length: 273 meters

Parameters	Value	Unit
Output Wavelength	8.8	nm
Bunch charge	0.5	nC
Energy	0.84	GeV
Energy spread	0.1	%
Norm. emittance	2.5	mm.mrad
Pulse length	1.	ps
Peak current	~0.5	kA
Rep. rate	10	Hz



SXFEL-TF layout



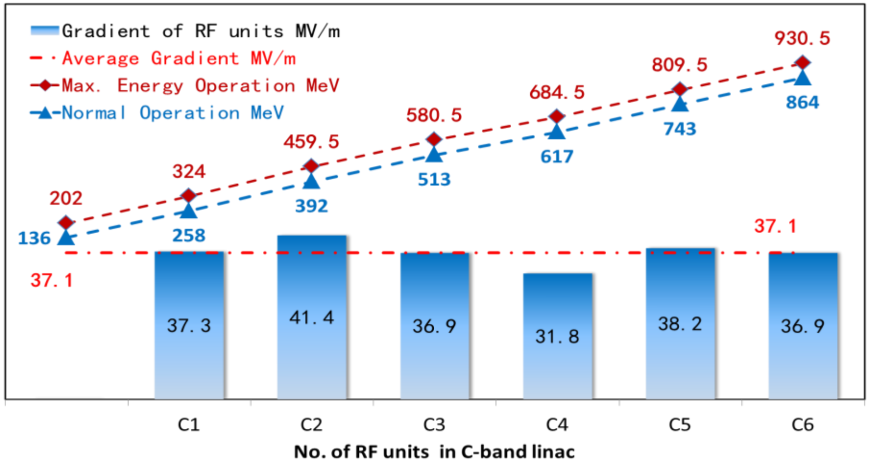
- S-band
  - ✓ 4 S-band klystrons
  - ✓ 4 S-band accelerating structures (3m)
  - ✓ 2 S-band TDS units
- C-band
  - ✓ 7 C-band klystrons
  - ✓ 6 C-band SLEDs
  - ✓ 12 C-band accelerating structures (1.8m)
  - ✓ 1 C-band TDS
- ✓ X-band
  - ✓ 2 klystrons
  - ✓ 1 X-band accelerating structure (1m)
  - ✓ 1 X-band SLED
  - ✓ 2 X-band TDS

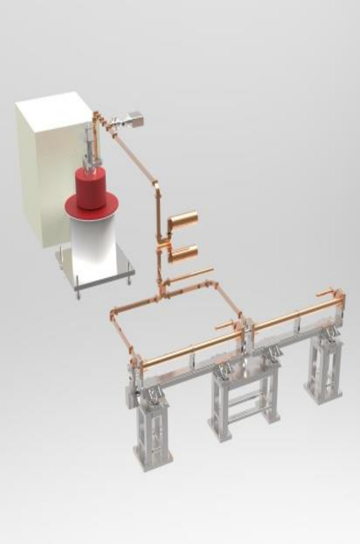
The current tunnel of SXFEL-TF

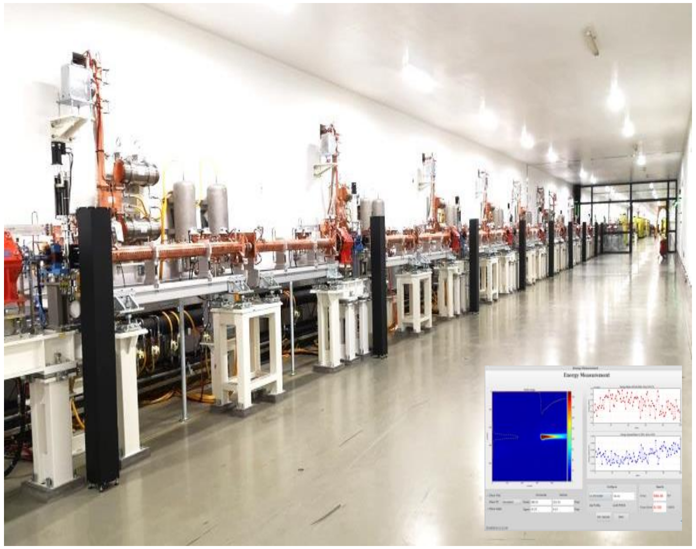
It just has been acceptance test by Government on 4th Nov. 2020

C-band RF structures at SXFEL

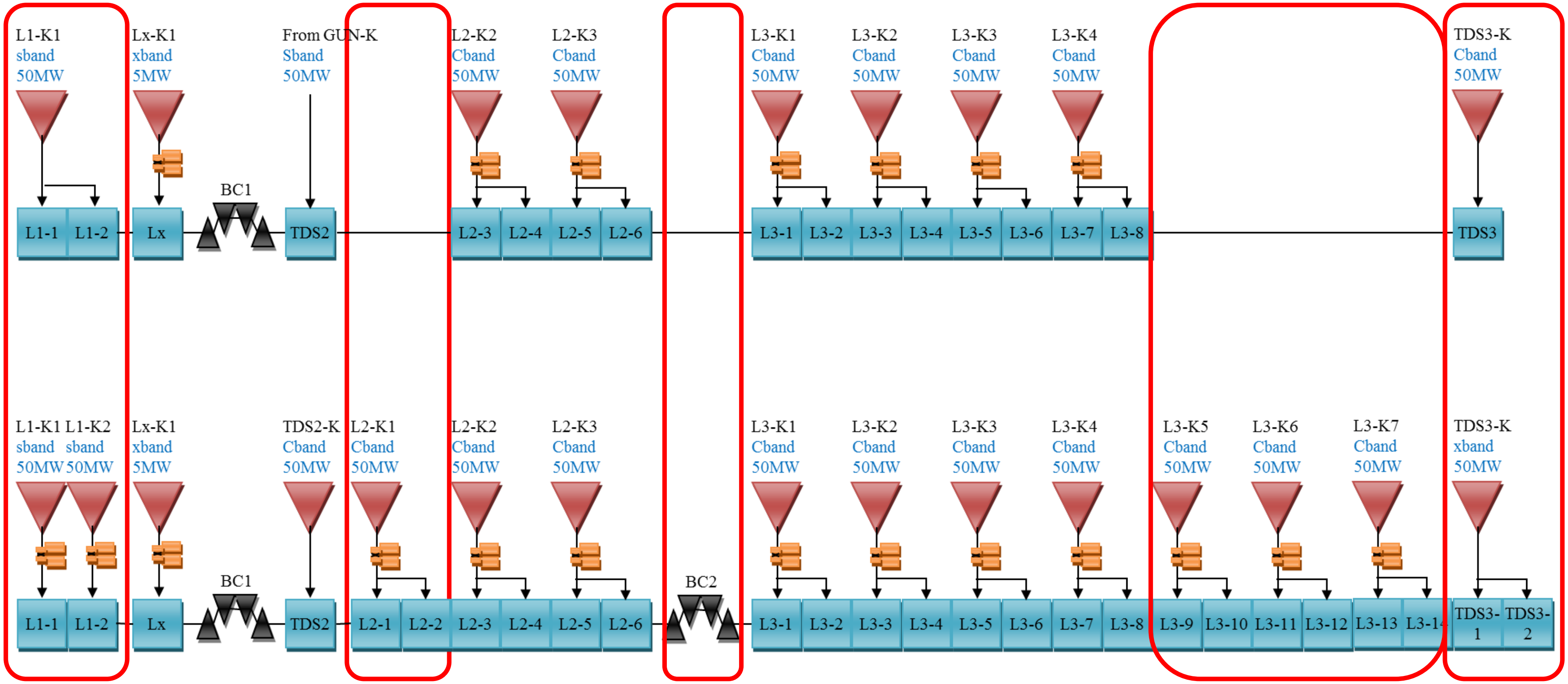
- 6 RF units at SXFEL
- Average gradient 37.1 MV/m.
- Maximum gradient 41.7 MV/m
- C-band deflecting cavity







Upgrading for SXFEL user facility

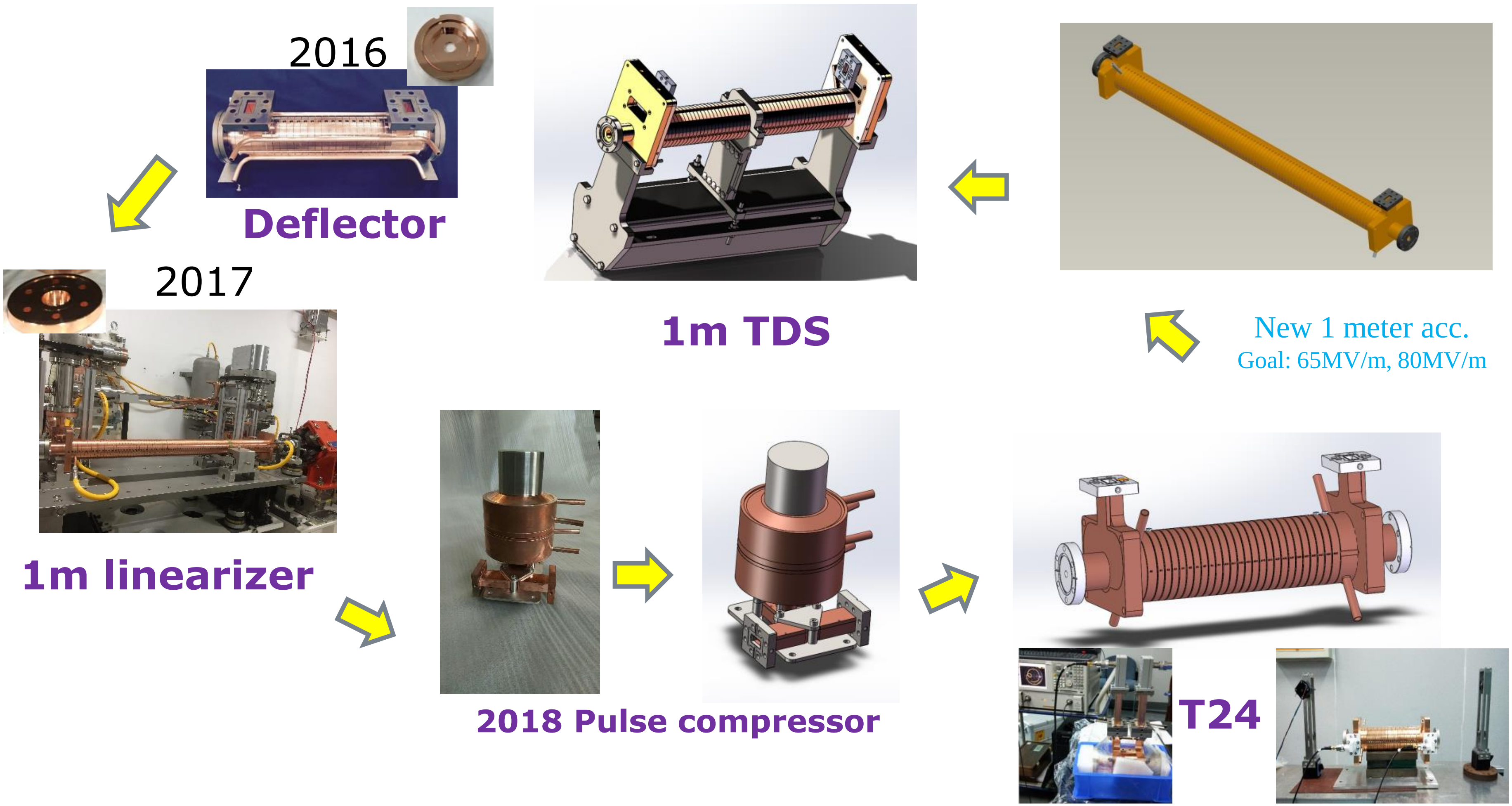


The installation has been started yesterday on 11th Nov. 2020

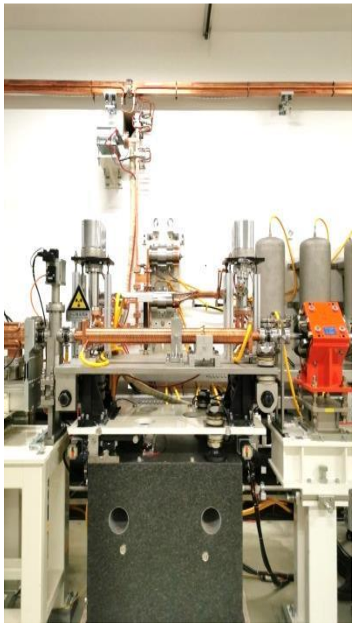
Current status of upgrading

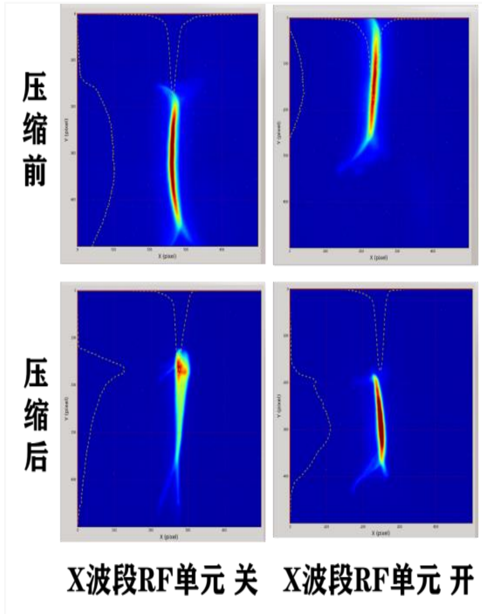
X-band activities at SSRF/SARI

D20(11.424GHz-KEK) →Acc. (Linearizer) → PC(11.391GHz-CETC) → PC(11.424GHz-SINAP)
→T24(11.424GHz-SINAP)→ Acc._1m->TDS_1m(SINAP)



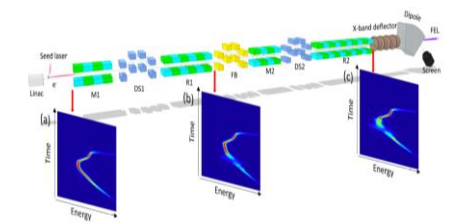
Typical application of X-band at SXFEL

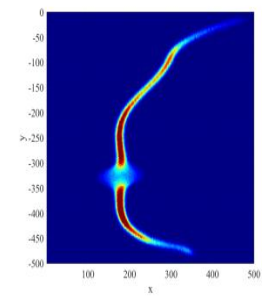


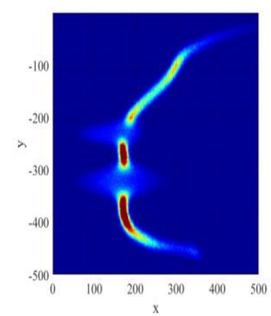


Linearizer
based X-band RF unit

Beam-laser synchronization
Cascading radiation diagnostics

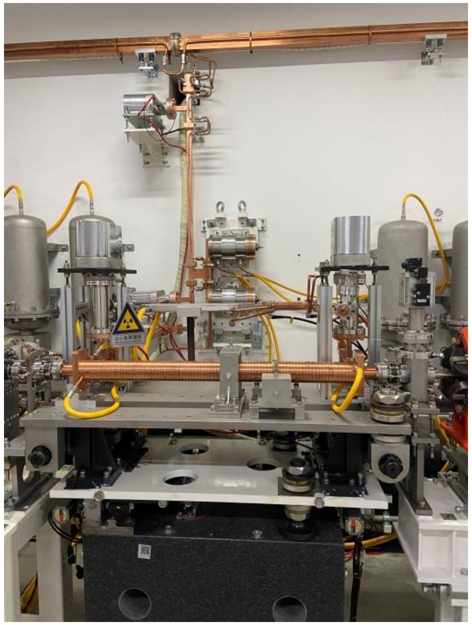






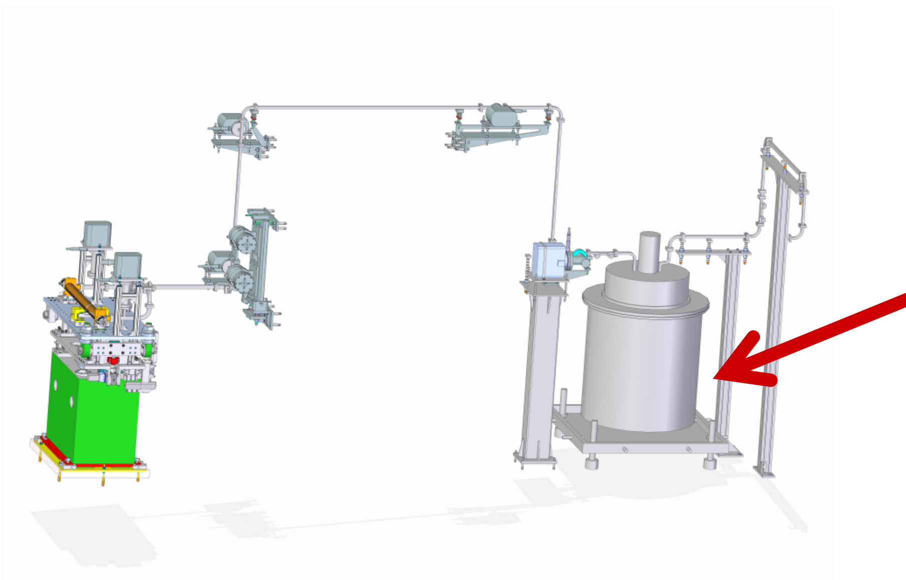
Problems on current X-band linearizer

- 6MW Toshiba klystron 11.424 GHz modified from 12GHz, power stability, power level.
- Pulse length of specification is 1.5 us, not 4 us as that at CERN.
- Energy gain 13 MeV recently, not enough for SXFEL-UF, should be 20 MeV, klystron is not able to produce enough power.
- 1 meter is a little long to generate strong wakefield, not good for beam quality



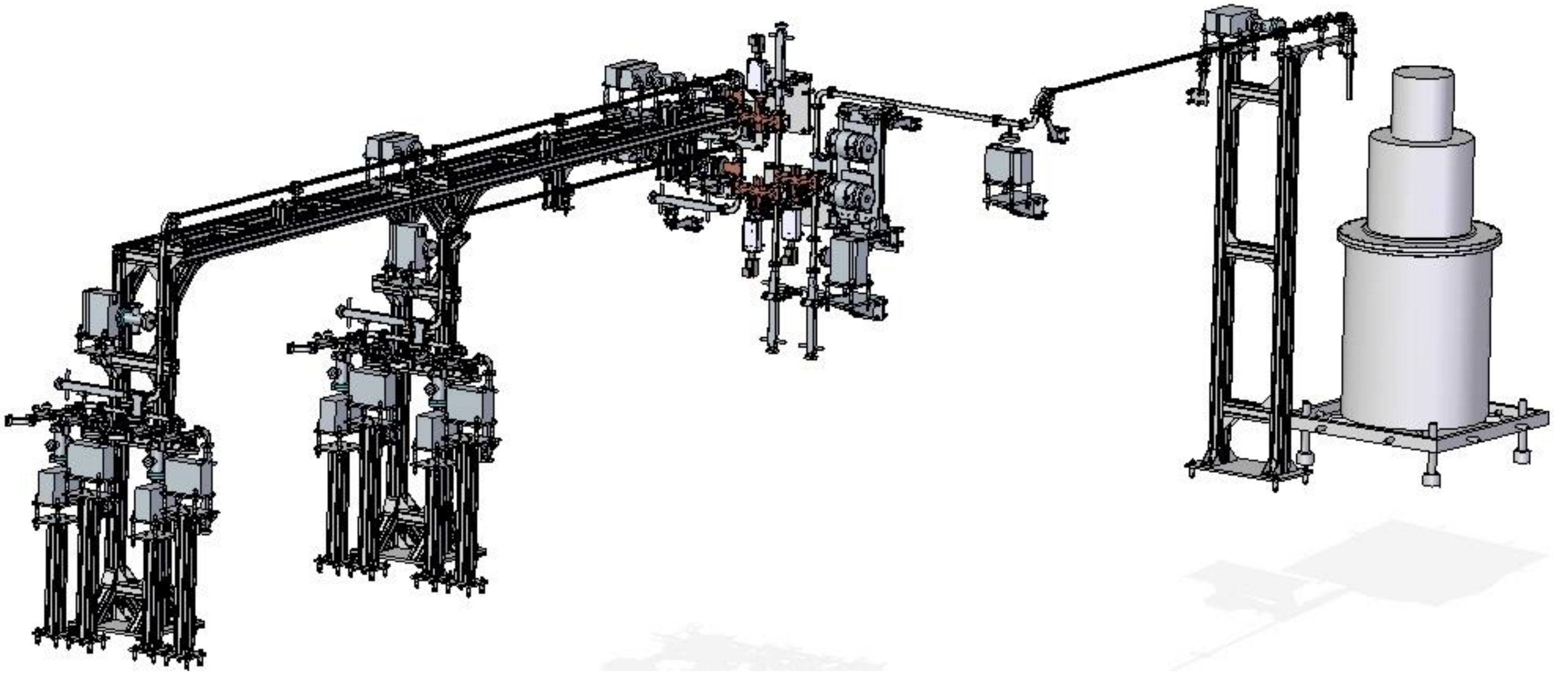
Upgrading for X-band linearizer, and plan on HG activities

- Replace 6 MW X-band klystron by 50 MW from X-band TDS system
- Replace 1 m X-band acc. By new 0.6 m acc.
- Working with SLED to achieve 80 MV/m at least with beam test at SXFEL
- Actually only 40MV/m is required for linearizer, to generate 20 MeV energy.



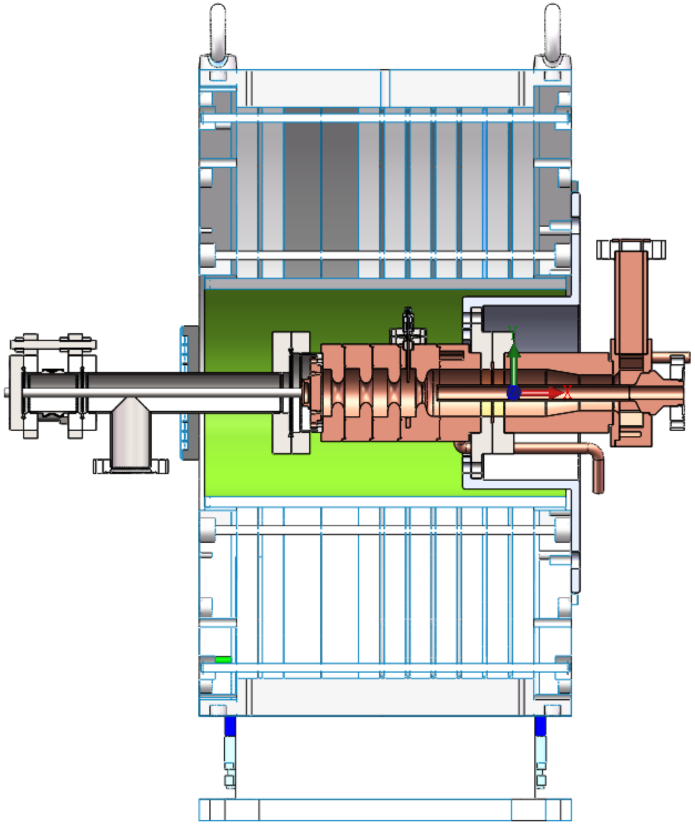
New X-band TDS unit for SXFEL-UF

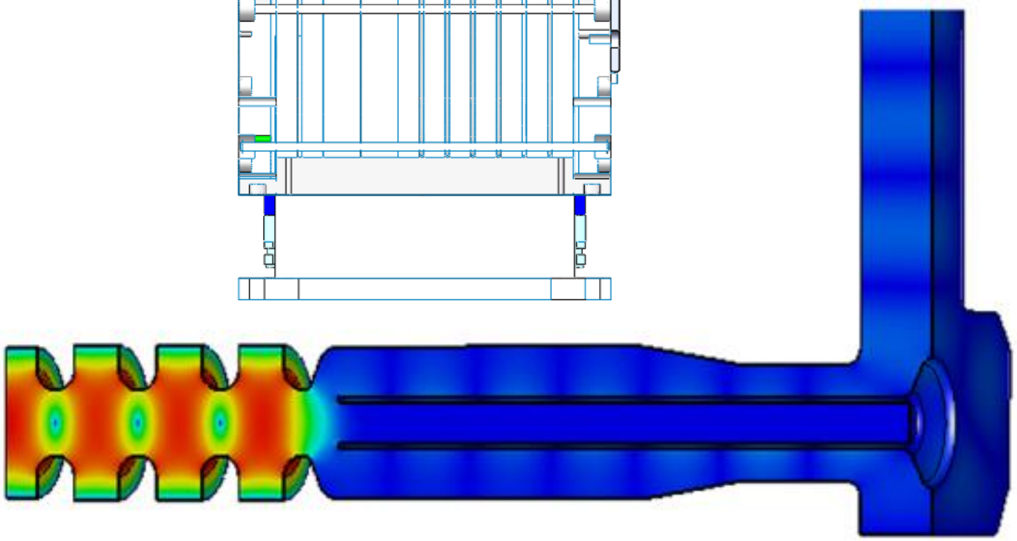
1. 50 MW X-band CPI klystron, one SLED to generate 120 MW
2. Feeding two units of TDS, each includes two X-band deflectors
3. 3 variable power dividers and 2 phase shifter included



150 MV/m 3.6-cell C-band PC gun

- C-band gun
  - Shorter bunch length
  - Enhance beam brightness
    - $$B \propto \frac{(E_Z)^n}{k_B T}$$
- simulation
  - Gun profile
  - Solenoid
  - Beam dynamic





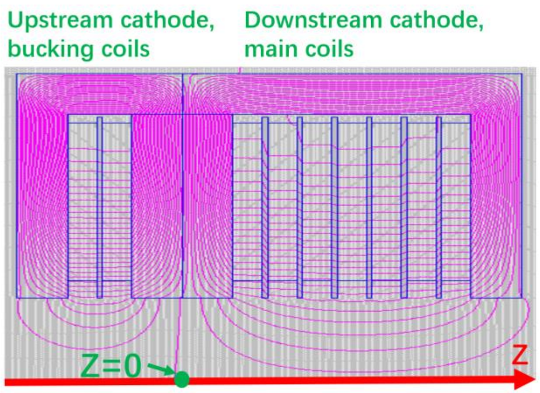
Beam dynamic

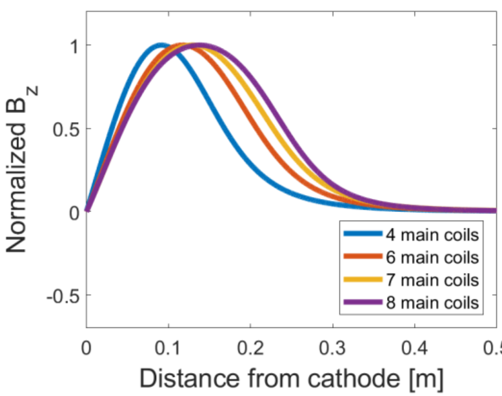
- Solenoid coils number
  - More coils
    - Higher achievable Bz
    - Lower required Bz

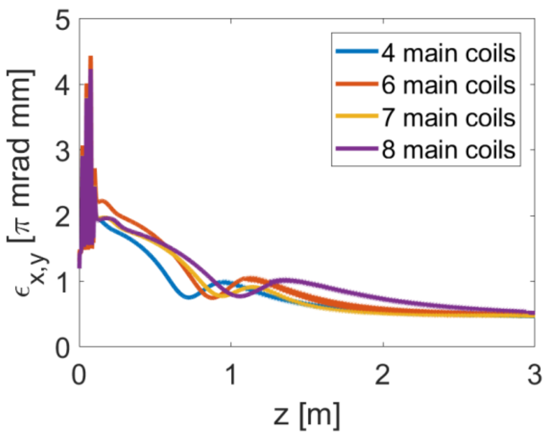
Requirement for different main coils number of injector exit transverse emittance 0.46 $mm \cdot mrad$

Coils number	Linac entrance[a] $[m]$	Peak B_z $[T]$	Slope[b] $[T/m]$	Integral[c] $[T \cdot m]$
4	0.91	0.432	7.041	0.028
6	1.07	0.392	4.743	0.046
7	1.17	0.373	4.103	0.052
8	1.22	0.350	3.605	0.056

[a] The linac entrance location distance from the cathode.
[b] Slope dB_z/ds at the cathode.
[c] The B_z integral from cathode to the end of the solenoid field .







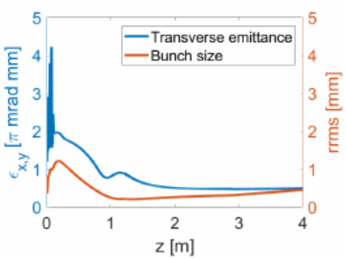
Beam dynamic

- 150 MV/m gun +40MV/m linac
- Emittance 0.46 mm.mrad
- Bunch length: 5 ps

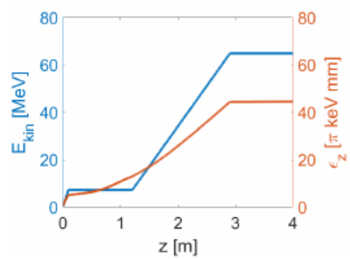
Simulated performance for the 3.5 cell C-band injector

Parameter	Unit	Value
Gun frequency	GHz	5.712
Gun design gradient	MV/m	150
Gun injection phase	°	205
Linac entrance position	m	1.17
Linac frequency	GHz	5.712
Linac design gradient	MV/m	55
Linac phase	°	10
Solenoid maximum field	T	0.375
Solenoid maximum field position	m	0.12
Gun output energy	MeV	7.3
Injector output energy	MeV	64.9
RMS bunch length	ps	1.5
Transverse emittance ϵ_n	mm·mrad	0.46
Mean slice emittance[a]	mm·mrad	0.37

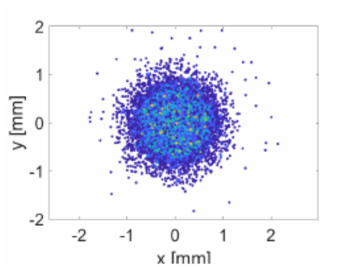
[a] Average over 100 slices with constant charge.
[b] Calculated by $B_{n,inj} = \frac{Q/t}{\epsilon_n^2}$, where Q is the bunch charge and t is the RMS bunch length [31].



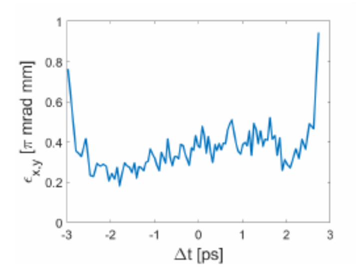
(a) Normalized transverse emittance and beam size



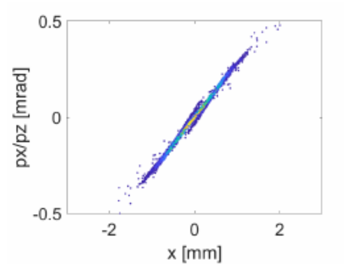
(b) Kinetic energy gain and normalized longitudinal emittance



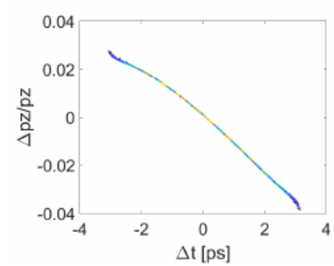
(e) Beam transverse distribution



(f) Slice normalized transverse emittance



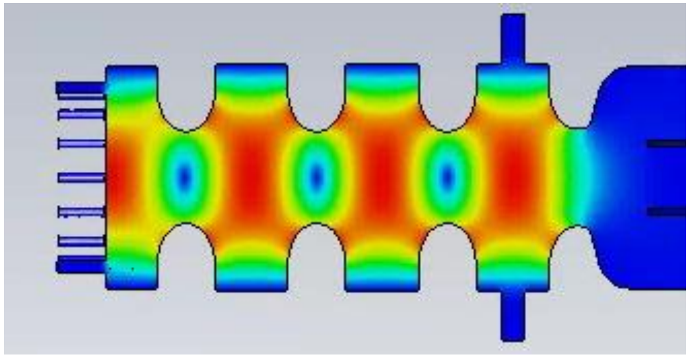
(c) X phase space of macroparticles

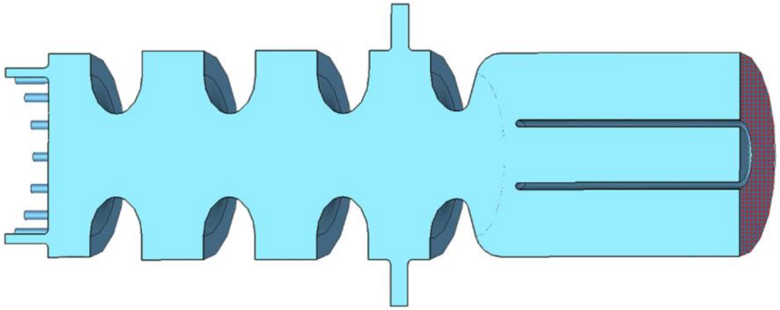


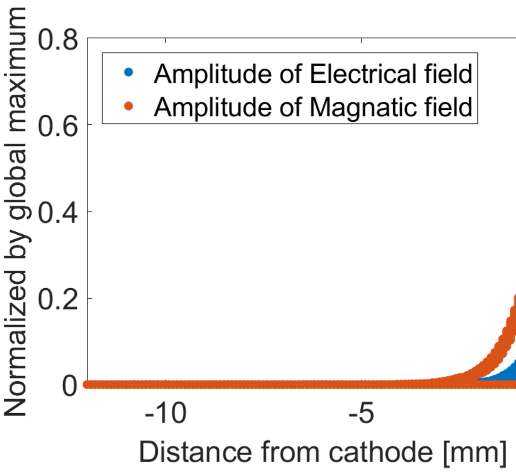
(d) Longitudinal phase space of macroparticles

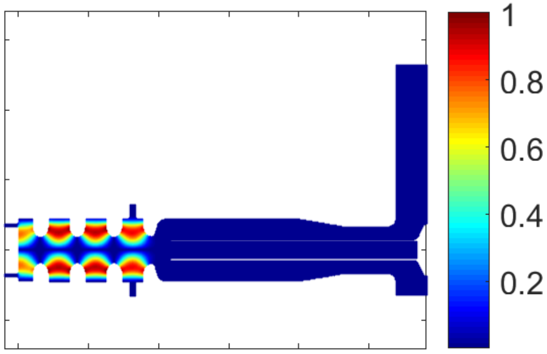
Cathode plate

- Replacable cathode
- Vacuum holes on cathode



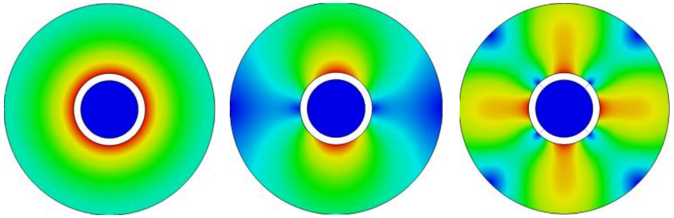


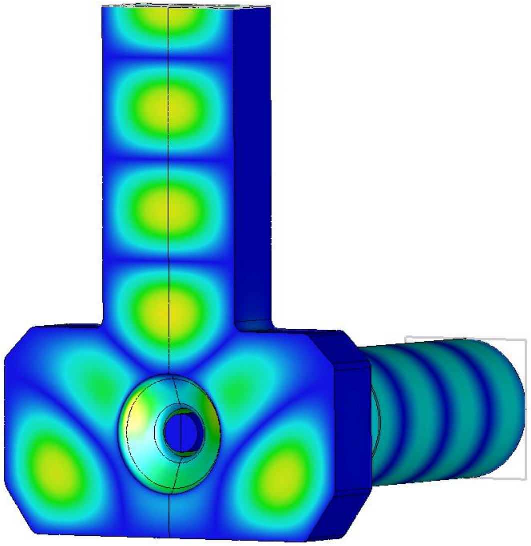


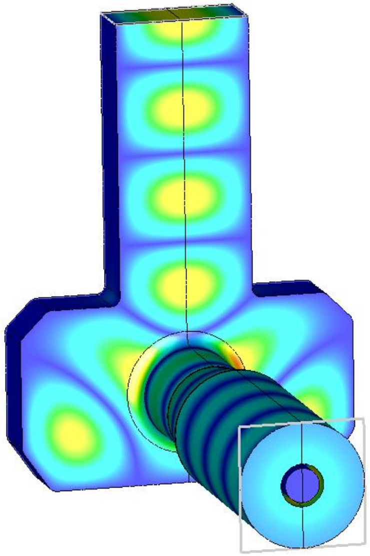


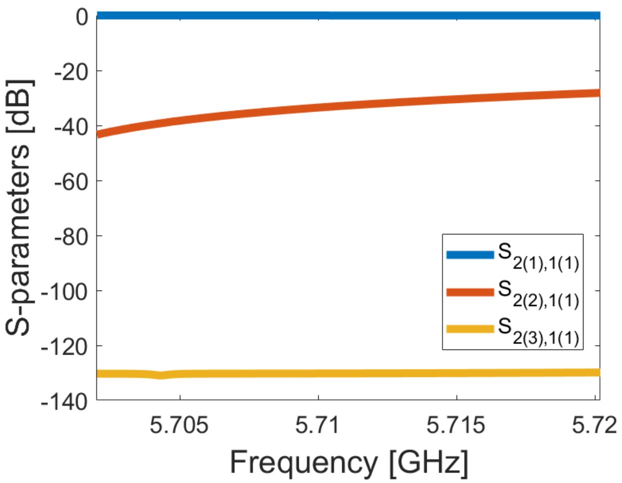
Coupler

- RF asymmetric
  - Coaxial coupler
  - Dipole mode transmission -40dB
  - Quadrupole mode is suppressed

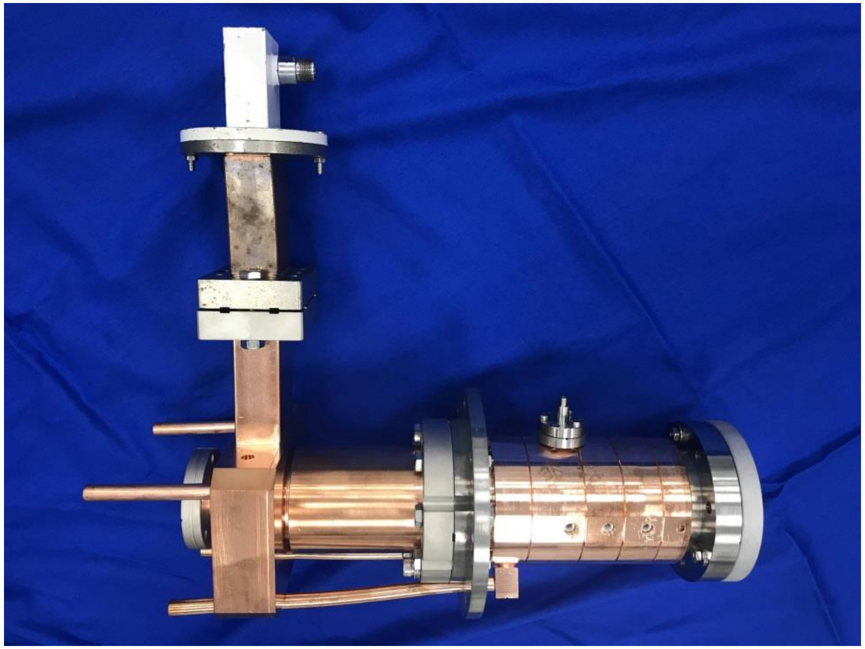








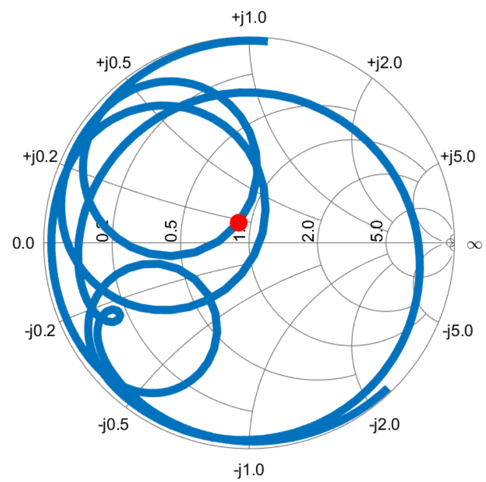
Cold-test results

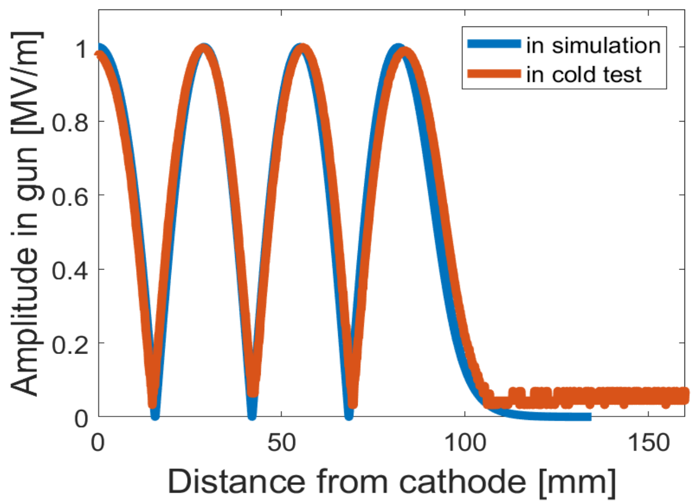


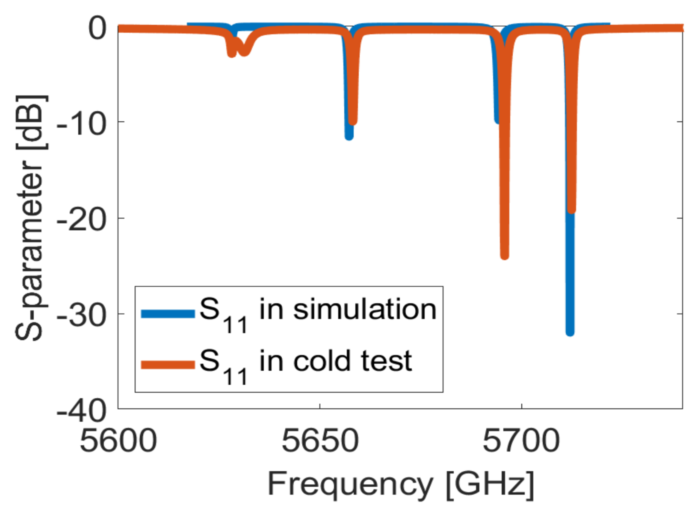
RF parameters and cold-test results

RF merit of the 3.5 cell C-band cavity

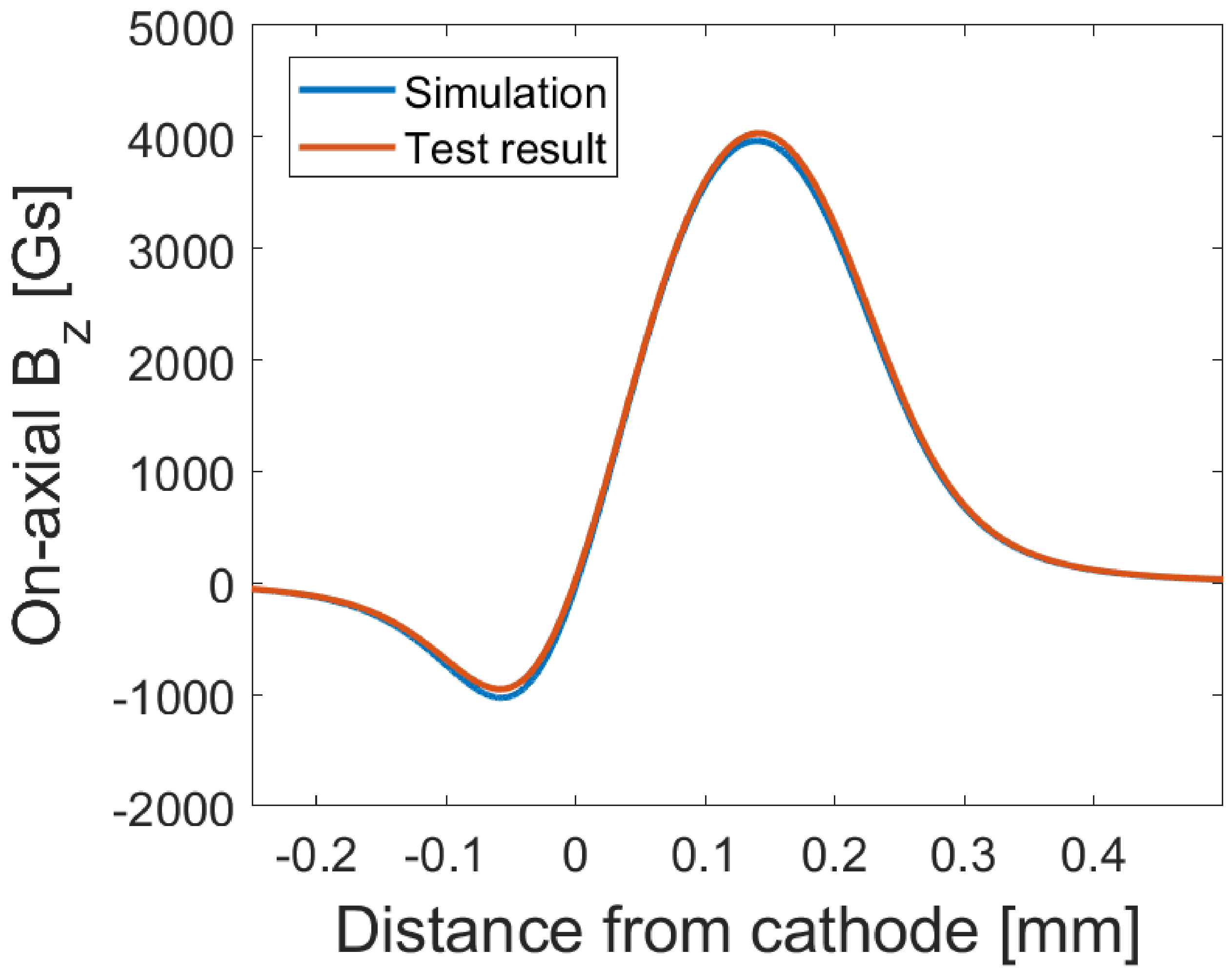
Parameter	Unit	3.5 cell C-band
Frequency	MHz	5712
Iris aperture	mm	18
Iris shape	1	Elliptical, 0.7 minor/major
Cathode peak field	MV/m	150
Mode separation	MHz	18
$E_{surfacepeak}/E_{amplitude}$	1	0.94
Shunt impedance	MOhm/m	55
Required input power	MW	14
Coupling Factor	1	1.0
Quality factor	10^4	1.01
Final kinetic energy	MeV	7





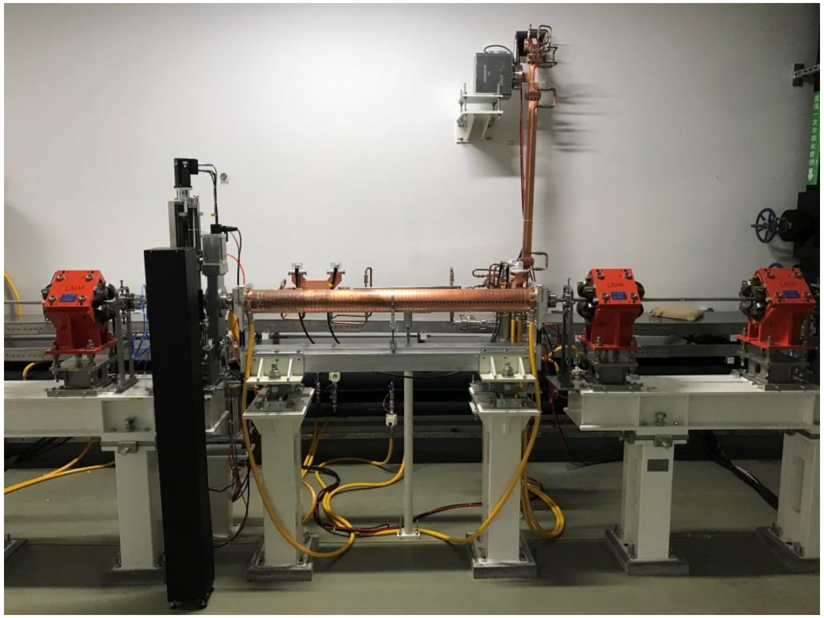


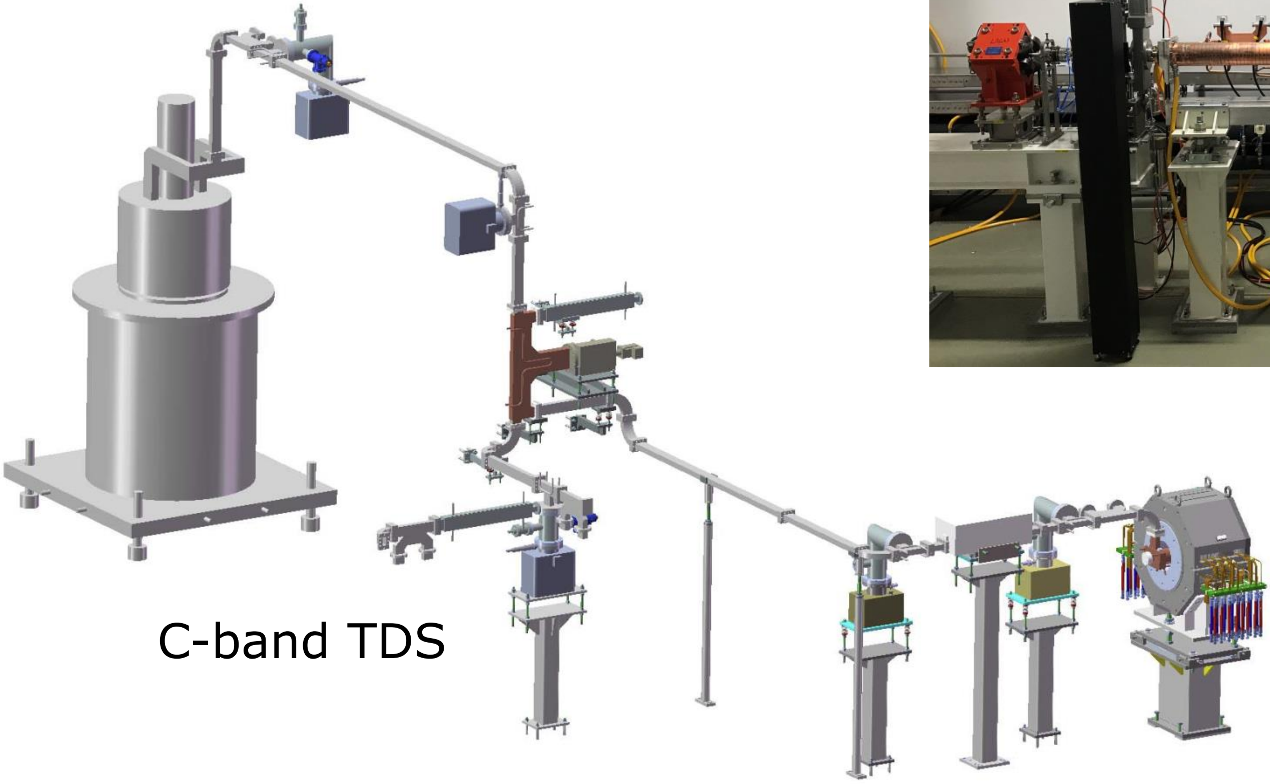
Field curve of solenoid



High power test setup under installation at SXFEL

Current C-band TDS

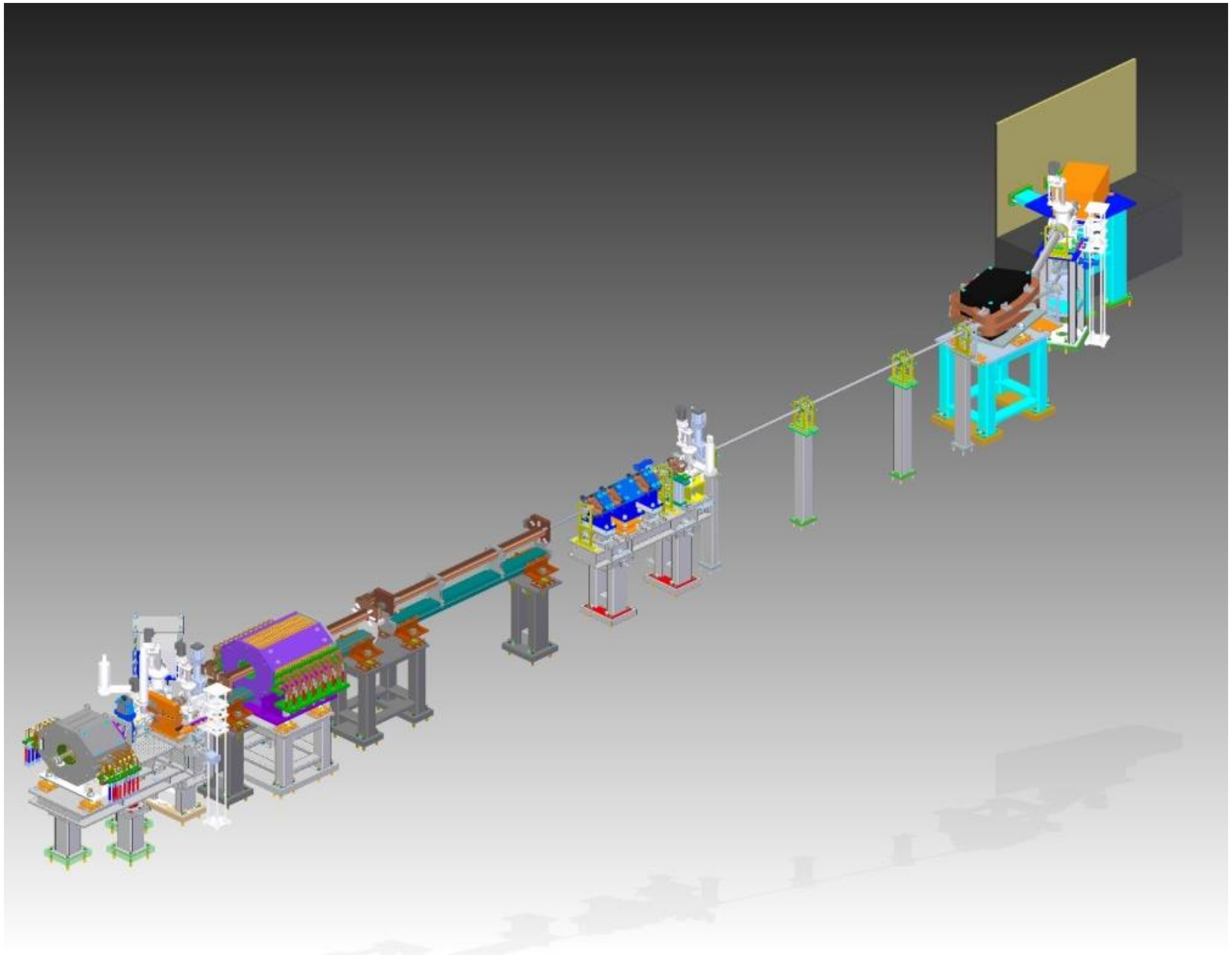




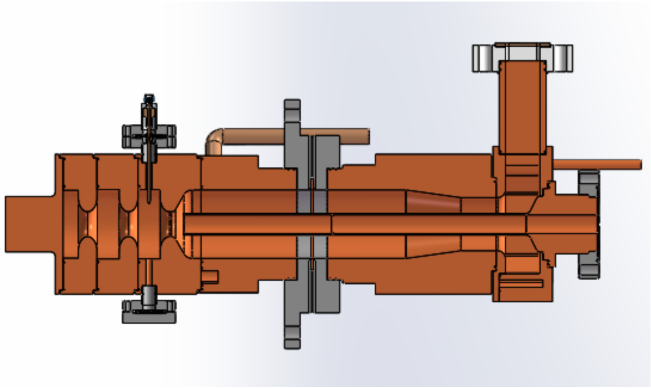
C-band TDS

C-band PC Gun

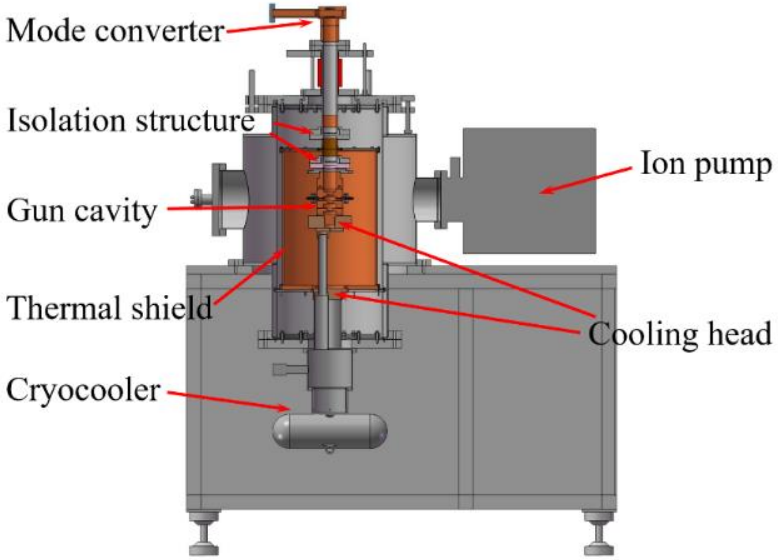
Beam test plan at SXFEL in the future

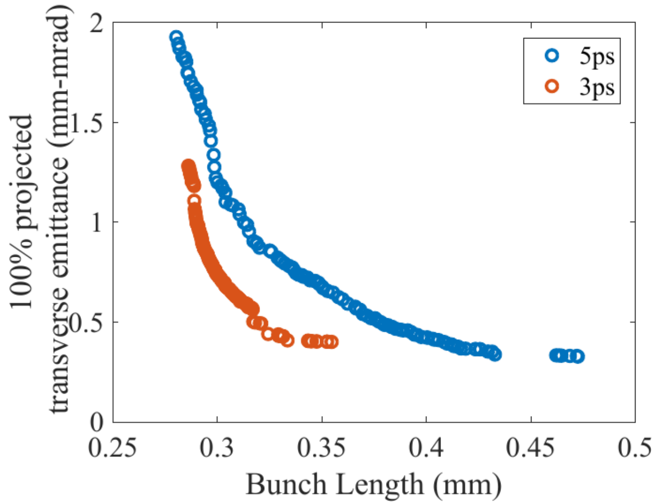


2.6 cell PC gun in cryostat

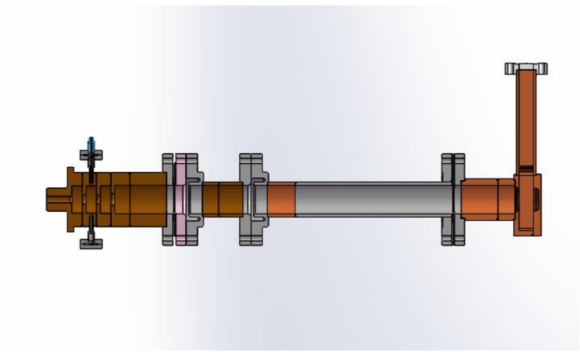


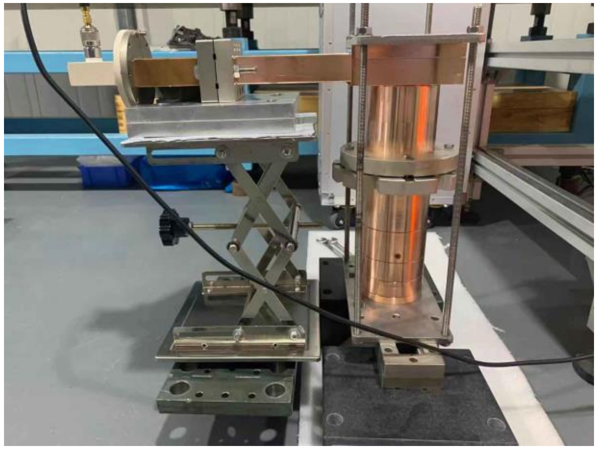
Initial bunch	5ps	3ps
Cathode gradient	200MV/m	
Bunch charge	500pC	
Spot size	0.3mm	
Thermal emittance	0.2mm-mrad	

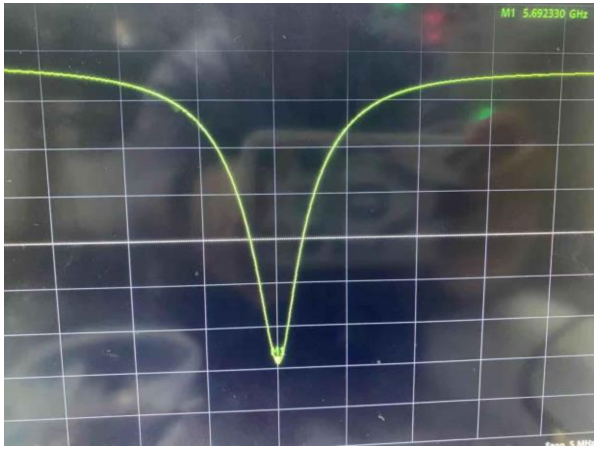




3-cell Model Fabrication and cold test in air





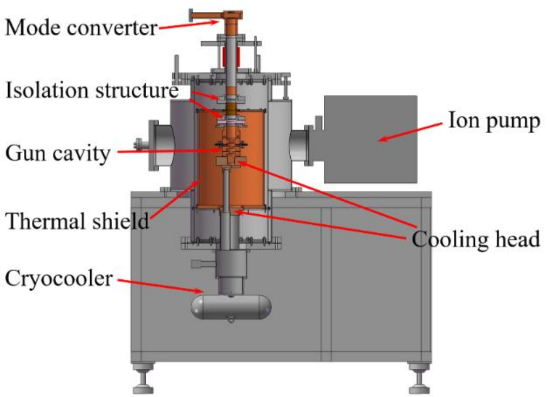


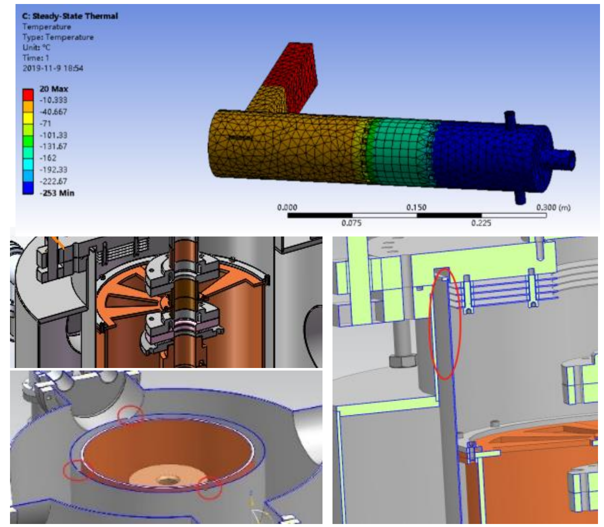
Design parameter "field1"

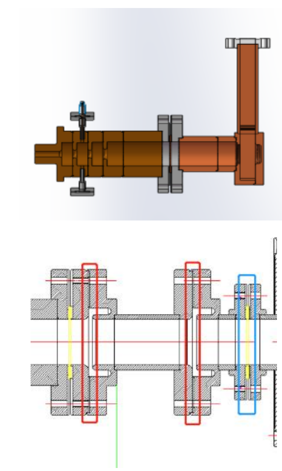
Mode	Frequency	Detuning of frequency	Est. displ. freq.
1	5.647174 GHz	0.01880684 GHz	5.665981 GHz
2	5.674506 GHz	0.01888865 GHz	5.693395 GHz
3	5.692925 GHz	0.0189523 GHz	5.711878 GHz
4	5.903191 GHz	0.01538645 GHz	5.918578 GHz
5	5.927084 GHz	0.006786964 GHz	5.933871 GHz
6	5.927085 GHz	0.00678715 GHz	5.933872 GHz
7	5.943518 GHz	-0.07298733 GHz	5.870531 GHz

Frequency	5692.906MHz
β	0.23
Q factor	10701

Design of cryostat







- The cooling temperature of the first cooling stage is 80K, and the second stage is 4K.
- With preliminary simulation in ANSYS, the cavity can be cooled below 20K in the static process.
- The cavity is designed alternatively. In room temperature, the cavity can be connected with the converter directly for low power test.

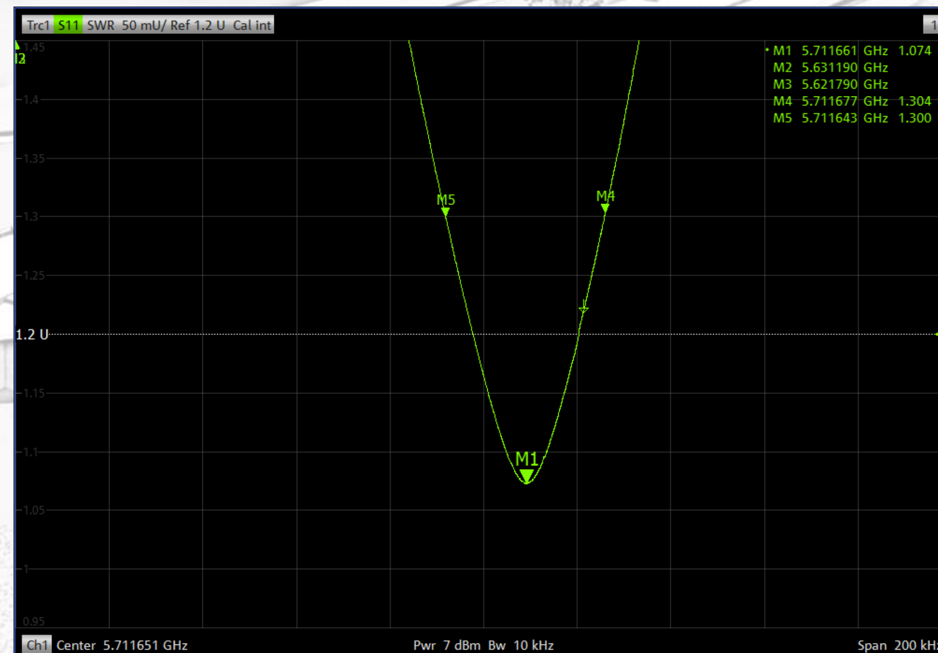
First cold test in the cryostat

Compressor

RF structure

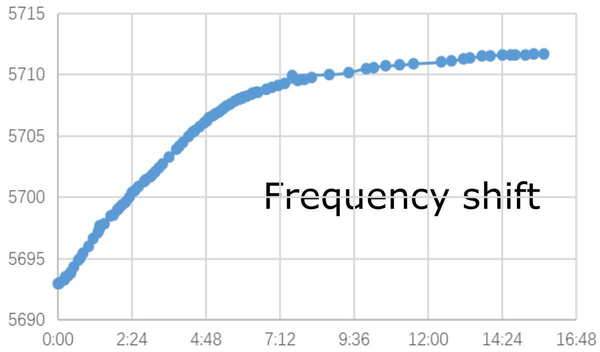
Vacuum pumping

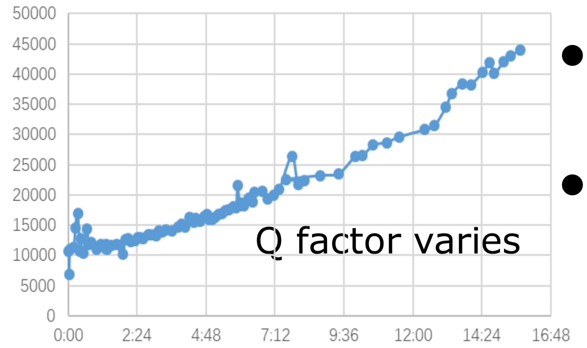
Remote monitor



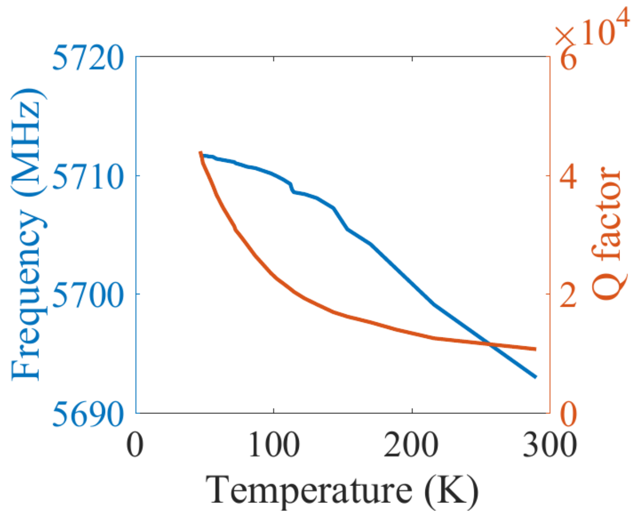
5711.661 MHz, Q=44000, β=1.074

Results of first cold test

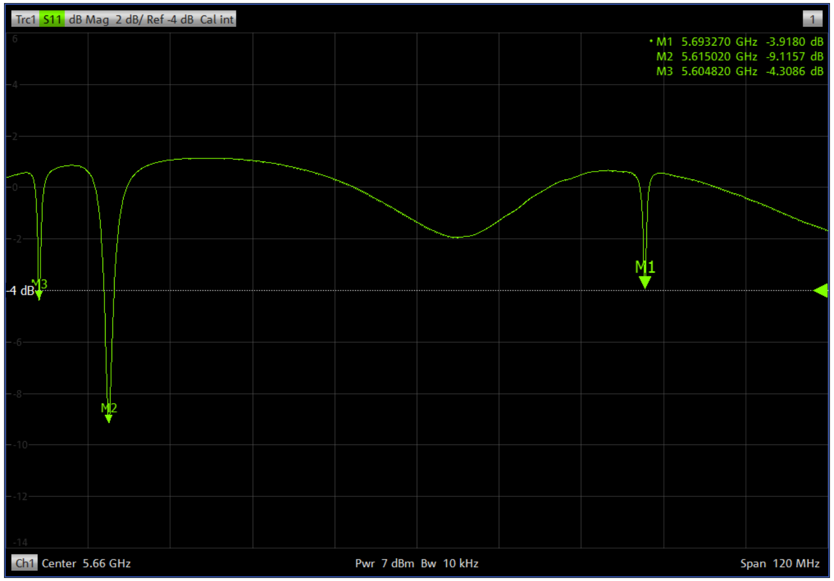




- The cooling time lasts 17 hours, and the second stage head reached 8K in 6 hours.
- However, the temperature is still decreasing. More cooling time is required.



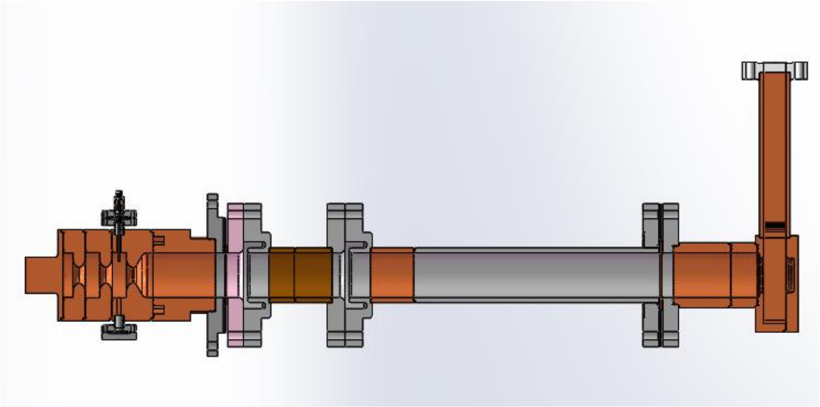
- The cavity frequency varies from 5692.9 MHz to 5711.660 MHz, and the Q factor rises to 44000 from 10701.



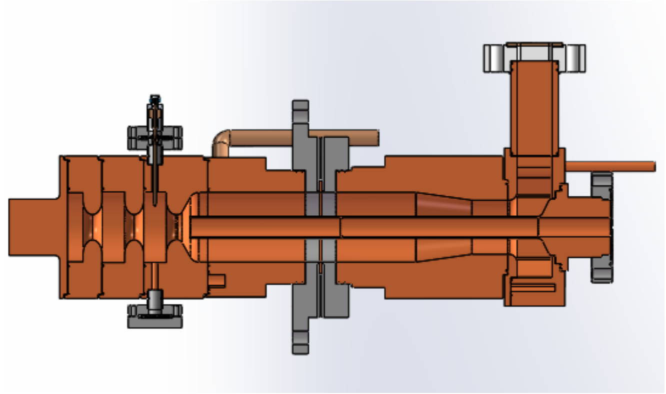
- The cavity frequency changes to 5693.27MHz after the temperature rising back to 293K.

Design of 2.6-cell gun

Gun in the cryostat



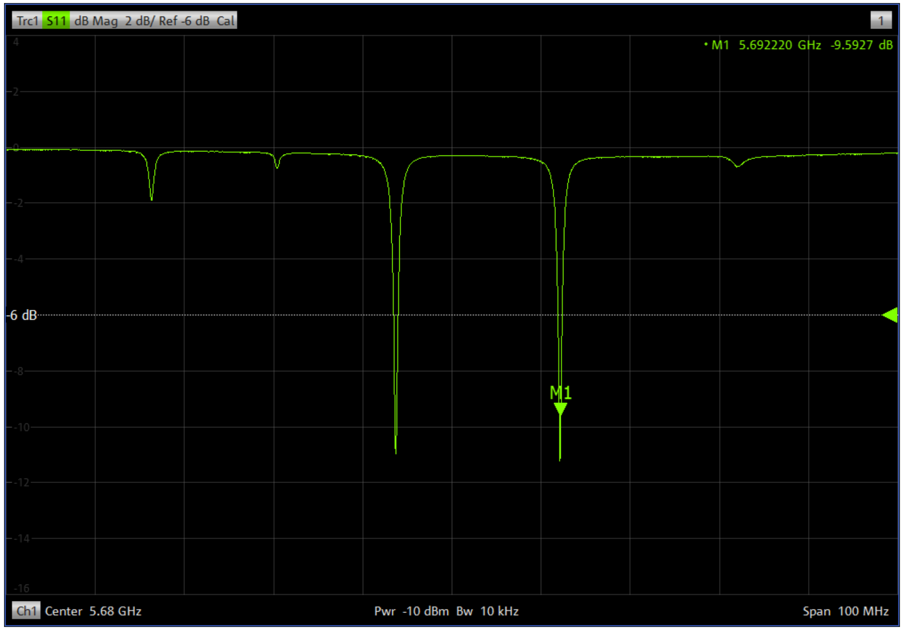
Gun in normal conducting



Parameter	Value(room)	Value(cryo)
f0	5692.9 MHz	5712 MHz
Q0	11030	59260
Shunt impendence	6.285 Mohm	33.77Mohm
Design gradient(cathode)		200MV/m
Power dissipation(200MV/m)	16.773 MW	3.122MW
Coupling coefficient	0.78	4.08
Output beam energy	6.92MeV	

- The RF gun is designed alternatively, a coaxial coupler is designed to test in room temperature, with the coupling coefficient of 1.
- The RF gun will be connected to the mode converter above, with the coupling coefficient of 4.078 in 20K.

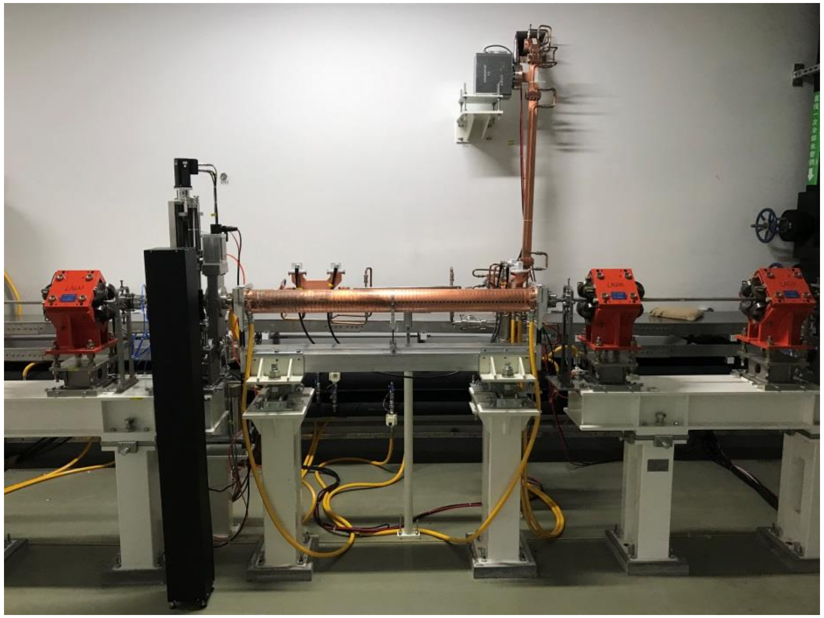
Cold test results before brazing



Parameter	Value(room)	Design
f0	5692.2 MHz	5692.9 MHz
Q0	9102.2	11030

Same plan of High power test at SXFEL

Current C-band TDS



C-band TDS

C-band PC Gun

Summary

- C-band high gradient technology is successfully used at SXFEL.
- X-band HG technology is under development at SXFEL, including accelerating structure and deflector.
- We are developing C-band photocathode gun, on both NC and cryostat, hoping to improve beam quality.

Thank you!!!