X-band and C-band RF activities at SSRF/SINAP

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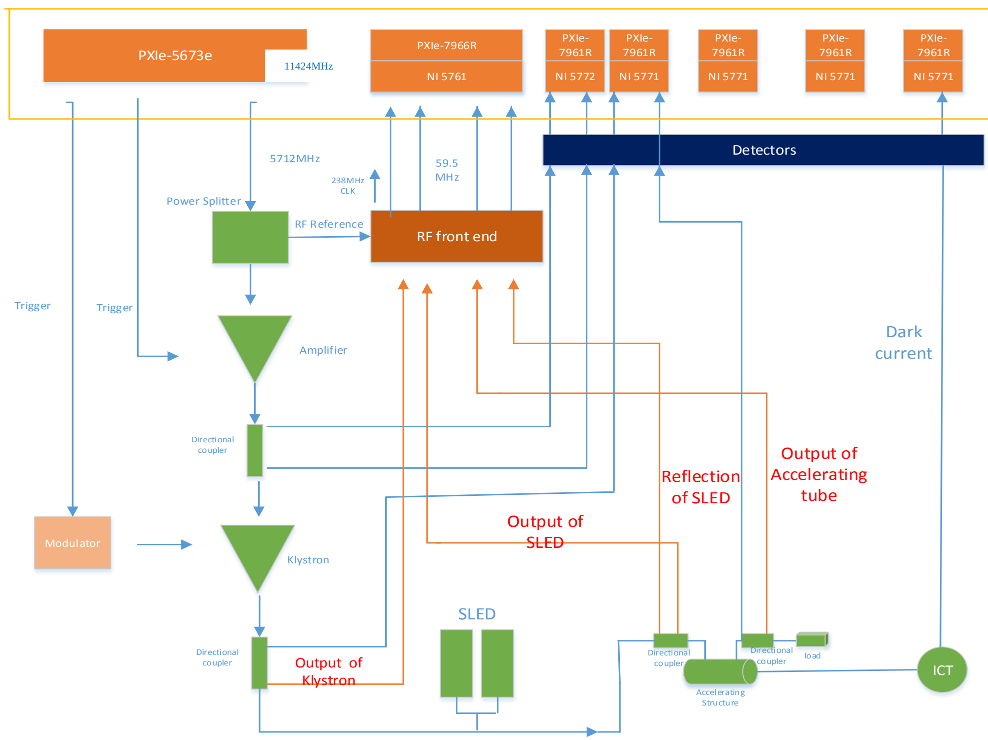
Outline

- X-band RF activities
  - X-band high power test platform
  - T24 X-band accelerating structure
  - X-band spherical pulse compressor
  - X-band deflector cavity
  - New development of one-meter X-band accelerating structure
- C-band RF activities
  - C-band linac status at SXFEL
  - C-band spherical pulse compressor
  - Extension of C-band RF technology
  - C-band photoinjector
- Summary

The X-band RF activities

Layout of X-band high power test setup

1. 50MW maximum power source from klystron are provided, and the maximum of 150MW could reached after one pulse compressor;
2. LLRF system is based on NI hardware based on Labview software;
3. It’s driven by a 1.2kW SSA and a 200MW modulator with PFN and thyratron;
4. The setup could be widely used for high power test of any RF X-band (11424MHz) structure, such as accelerating structure, pulse compressor, waveguide, load and so on.



Klystron+Modulator

LLRF

1.2kW X-band SSA

Some problems on high power tests

1. Klystron has not been conditioned with any power yet, and the running status is unclear;
2. The serious high voltage spark in oil tank happens in the first running in 2018, and the oil tank was delivered back to manufacture, and then repaired;
3. The modulator originally was designed for 80MW S-band klystron, so to some extent mismatch exists between the modulator and X-band klystron;
4. SSRF lab was separated officially from SINAP/CAS to SARI/CAS in Oct. 2th 2018, however separation of all projects and properties are not finished yet, and the building of high power test setup is stopped, and it may need half or one year to restart;
5. Several X-band RF structures are ready for high power test, so we should find other way to continue research on X-band high power test.

SINAP

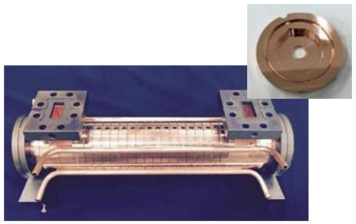
SSRF lab including HG team.

SARI/CAS

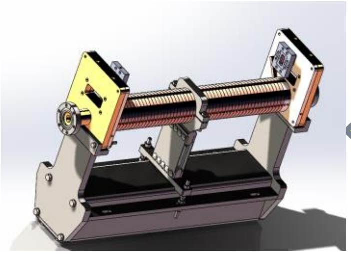
Overview work of X-band RF structures at SSRF

D20(11.424GHz-KEK) →1m Acc. (11.424GHz) → PC(11.424GHz) →T24(11.424GHz)→ New Acc._1m(11.424GHz)

-> 20-cell TDS (12GHz)->TDS_0.65m(11.424GHz) ->TDS_1m(11.424GHz)



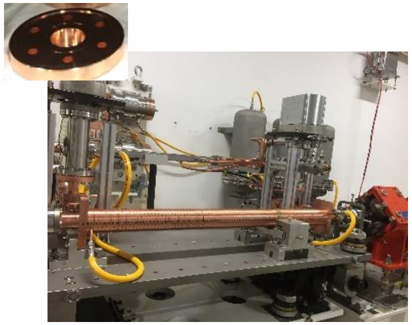
Deflector (KEK)
(2016)



0.65m-1m TDS
(2019, 2020)

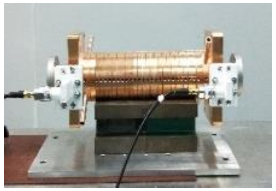
New 1 meter acc.
Goal: 65MV/m, 80MV/m
(2019)

12GHz 20-cell TDS (CERN)
(2019)

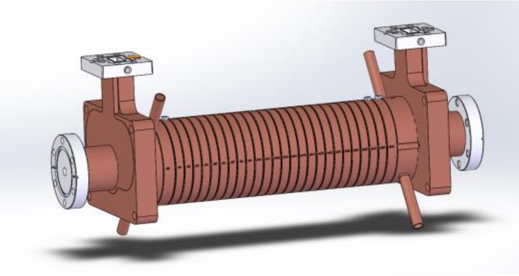


1m X-band acc.
SXFEL linearizer
(2017)

2 X-band spherical pulse compressors
(2018)

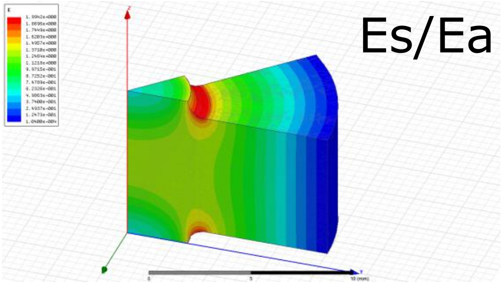


T24 (2018)

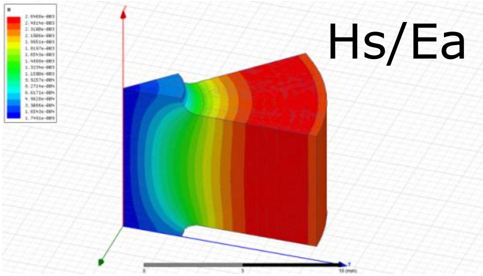


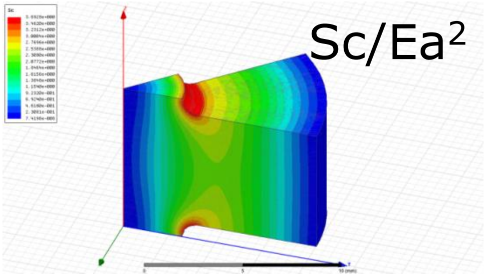
T24(11.424GHz) prototype structure

1. The T24 was redesigned based on CLIC-type T24;
2. The frequency is changed from 12GHz to 11.424GHz;
3. 24 cells are optimized again to get optimum performance;
4. Mode-launch coupler is designed.

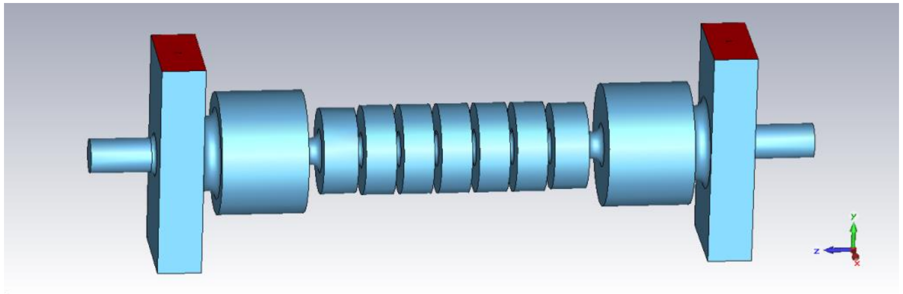


Frequency, f	11.424 GHz
Phase advance	2π/3
Cell No.	24 + 2
Cell length, D	8.7475 mm
Iris thickness, t	1.67 - 1.00 mm
Diameter, 2b	20.834 - 20.404 mm
Ratio of elliptic radius, $2t_b/t$	1.26-1.22
Aperture, a	3.15 – 2.35 mm
Group velocity, V_g/c	1.67% - 0.83%
Shunt resistance, R_a	108.05 – 146.56 MΩ/m
Q-factor, Q	6775 - 7099

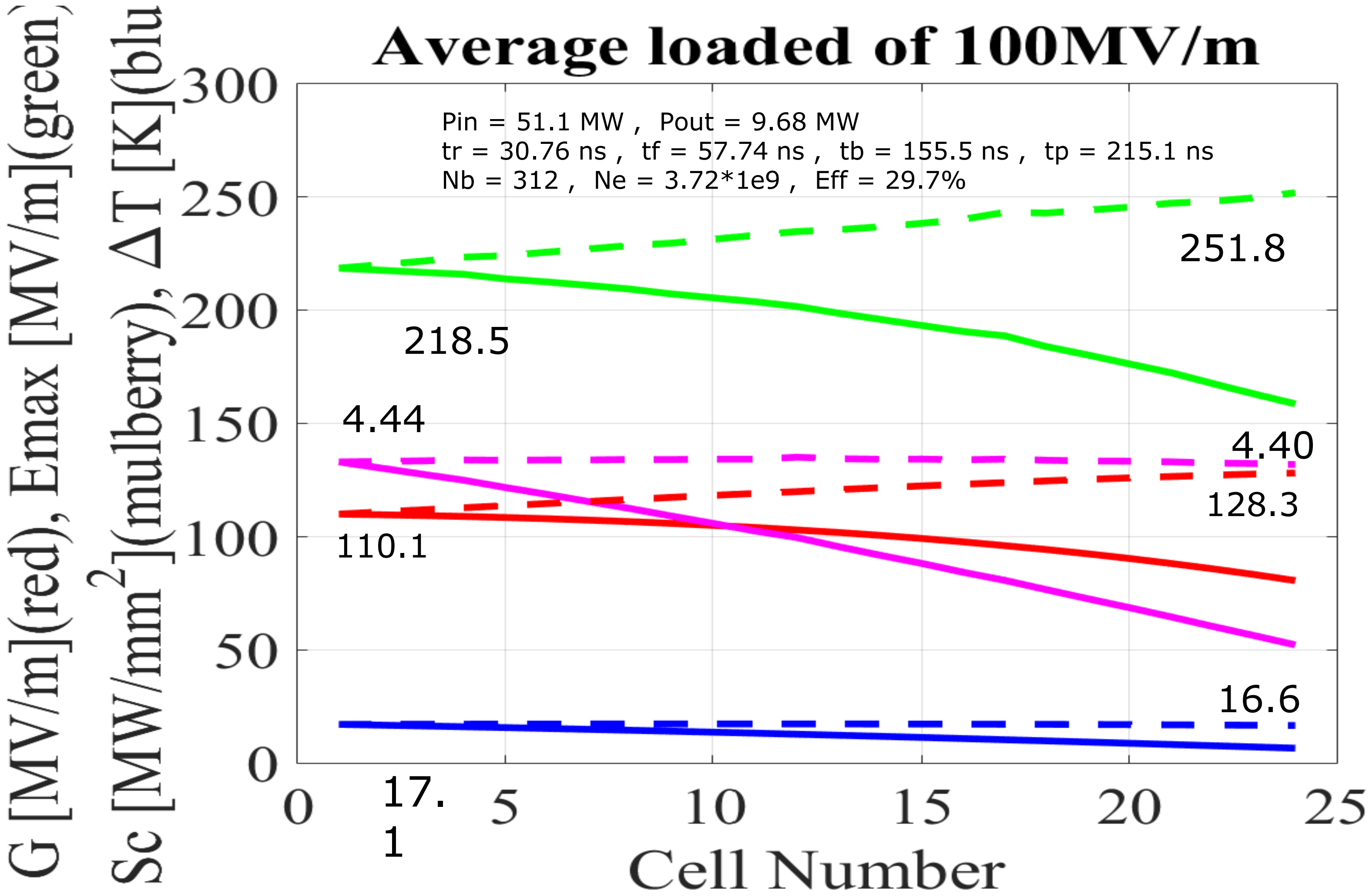




Coupler design

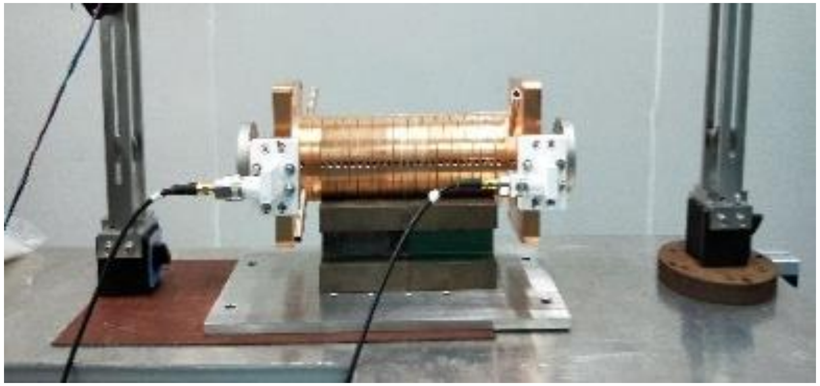


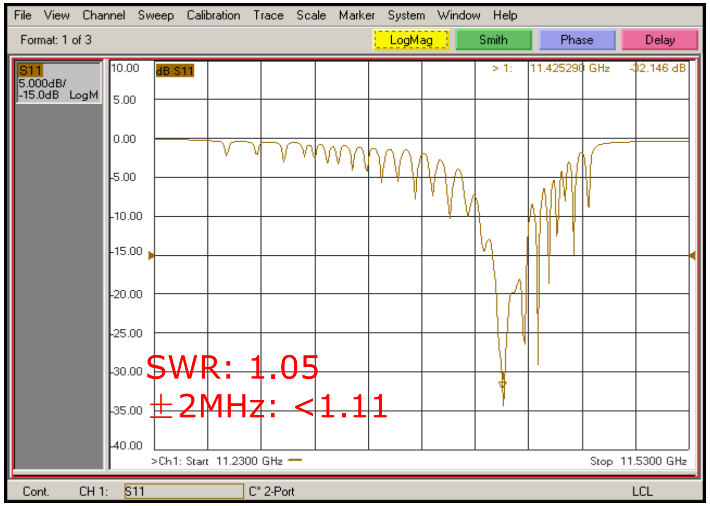
Field distribution in T24

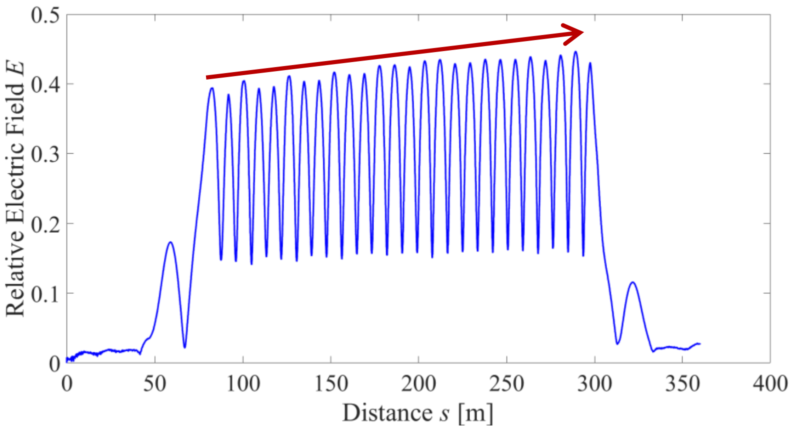


T24(11.424GHz) prototype structure

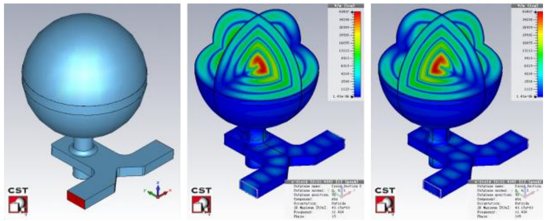
1. The T24 has been tuned to matching;
2. It’s brazed, not diffusion;
2. This structure is ready for high power test;
3. Our test setup is not ready, and we will find other way to continue high power test.

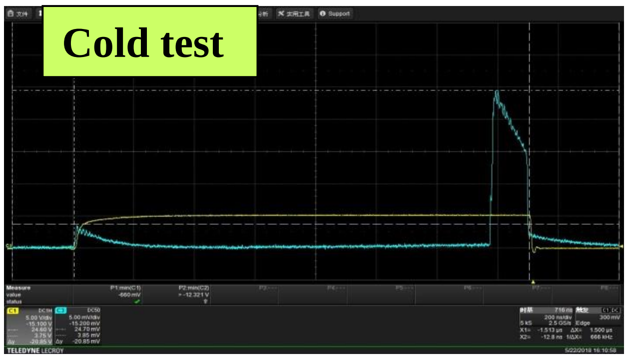


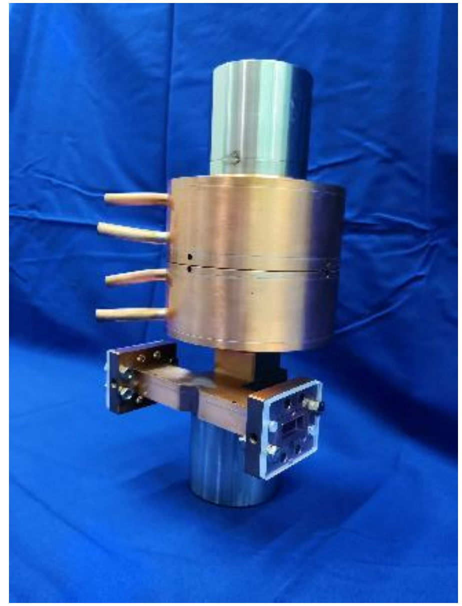




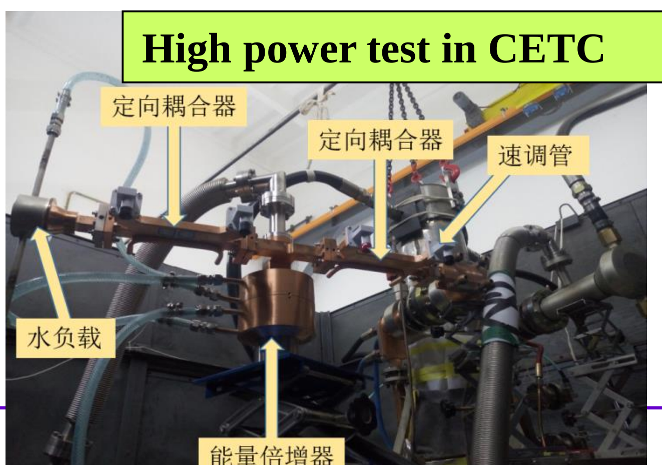
New spherical X-band pulse compressor

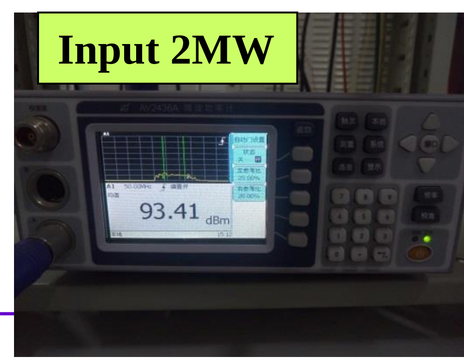


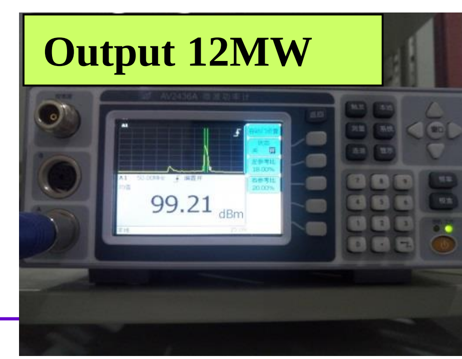




Frequency, f	11424 MHz
Mode	$TE_{1,1,4}$
Q_0	9.5×10^4
Coupling coefficiency	4.6
Energy factor	2.02
Average power factor	4.4
Peak power factor	6.4



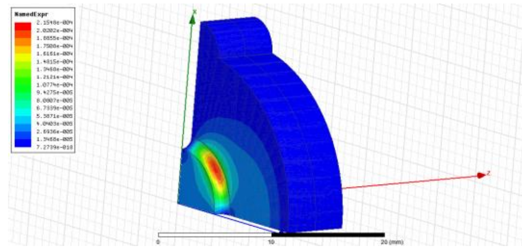


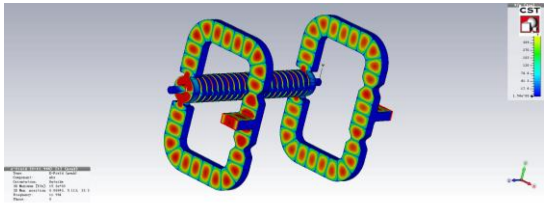


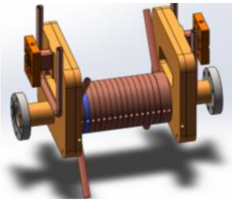
X-band deflectors for CERN, SXFEL and SHINE

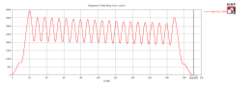
20-cell deflector for CERN	
Operating frequency	11.994 GHz
Phase advance per cell	120°
Length of cell	8.3317 mm
Structure length	230 mm
Iris aperture 2a	8 mm
Iris thickness	2.6 mm
Quality factor Q	6222
Group velocity: Vg/c	2.69%
Filling time	21 ns
Attenuation factor t	0.751
Input power	50 MW
Pulse length	100ns
Peak surface electric field	153 MV/m
Peak surface magnetic field	489 KA/m
Peak modified Poynting vector	4.5 MW/mm^2
Peak pulse surface heating	32K

20-cell prototype TDS @12GHz



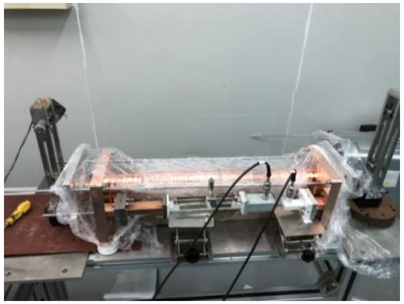


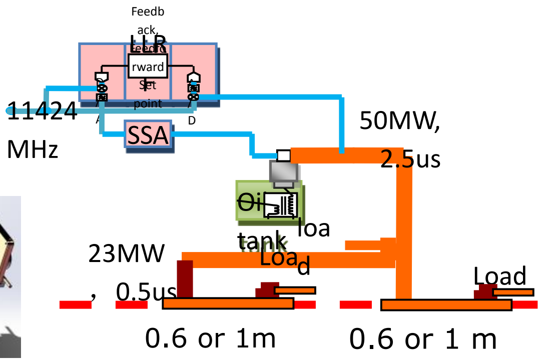




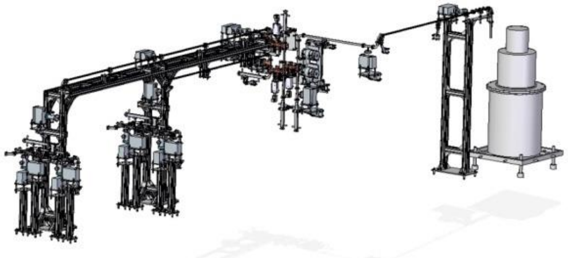
Deflector for SXFEL and SHINE		
Parameters	Value	Units
Frequency	11.424	GHz
Phase advance	120	Deg
Maximum power	50	MW
Transverse voltage	0~50	MV
Iris aperture 2a	10	mm
Repetition frequency	50	Hz

0.6m deflector for SXFEL user facility



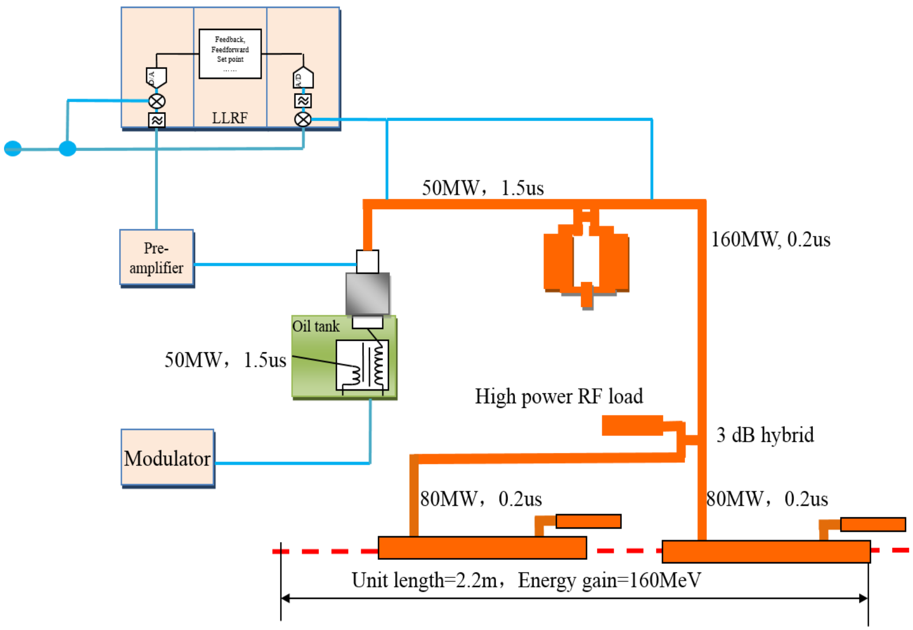


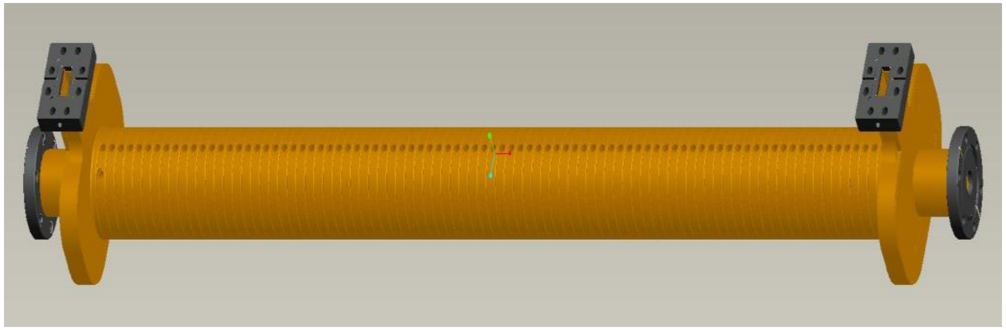
TDS unit for SXFEL linac or SHINE



TDS RF unit for two undulator lines of SXFEL

X-band RF acceleration Unit (80MV/m)

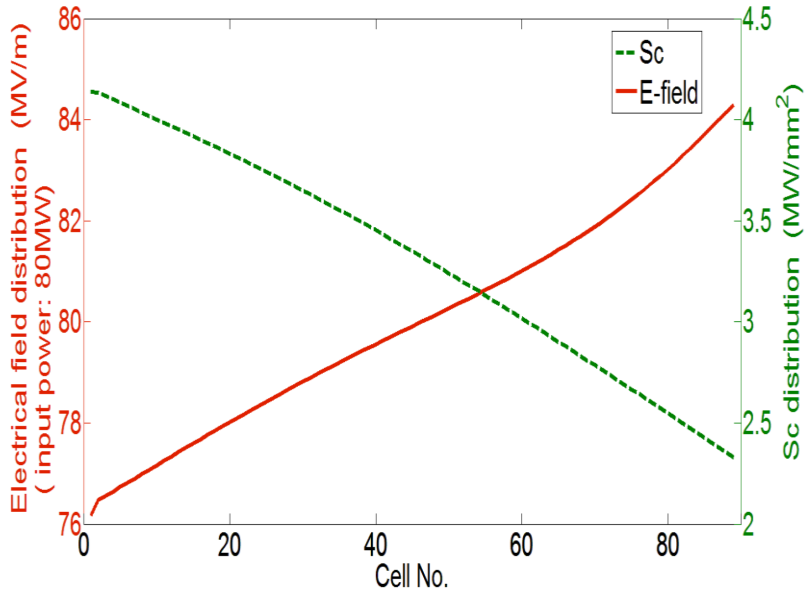


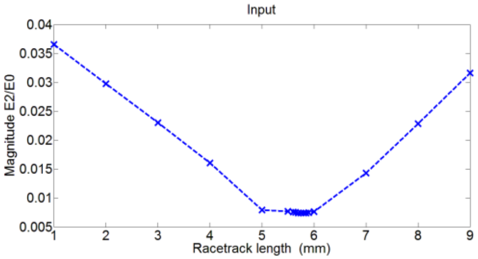


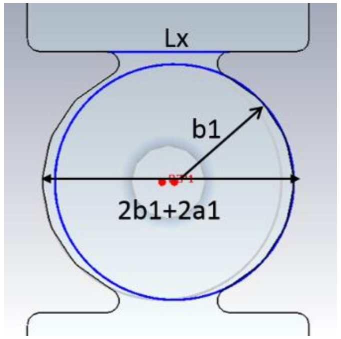
Frequency	11424MHz
Phase advance	4π/5
Cell No.	89+2
Effective length	944.73mm
Cell length, d	10.497mm
Iris thickness, 2a	1.5 mm
Ratio of elliptic radius	1.8
Aperture, a_r	4.3~3.05.mm
Group velocity, Vg/c	3.45%~1.12%
Shunt impedance, R	93.93–125.62 MΩ/m
Attenuation factor, τ	0.61
Filling time, t_f	150 ns
Sc	4.14~2.33 MW/mm^2
Emax/E0	2.68~2.02
Hmax/E0	2.68~2.39 mA/V
Input power, P_{in}	80MW @80MV/m

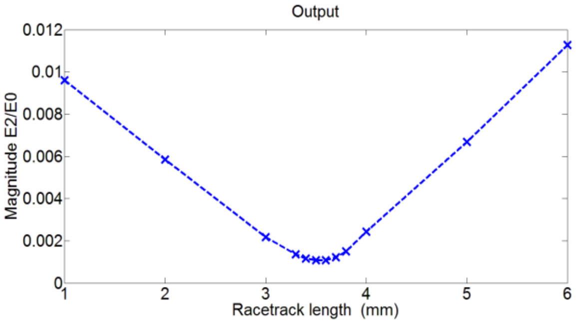
One-meter accelerating structure

- Aperture 2a is 7.4mm at least to suppress short-range wakefield;
- Accelerating gradient is increased from upstream to downstream, so that it’s good to optimize Sc, as well as beam loading;
- Dual-port and racetrack coupler is designed to eliminate dipole and quadrapole field.



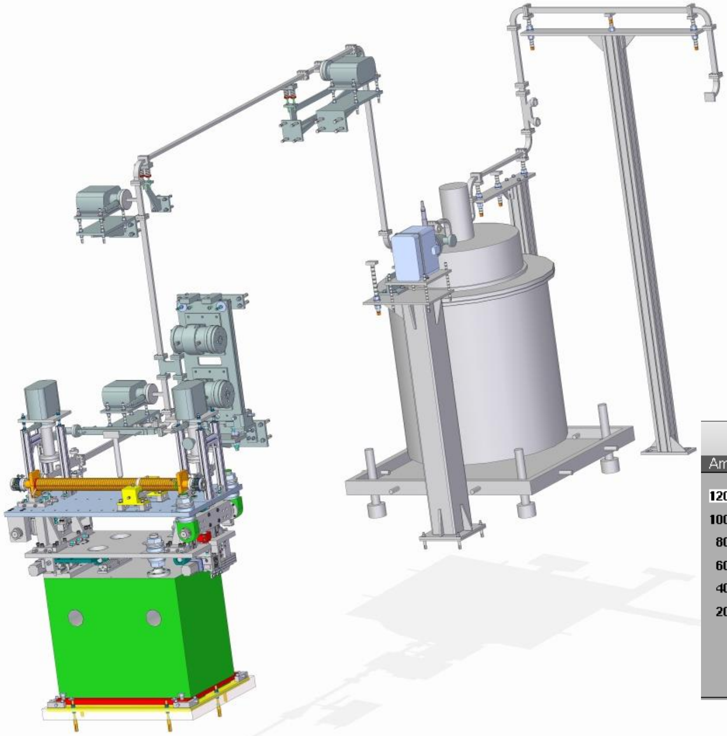


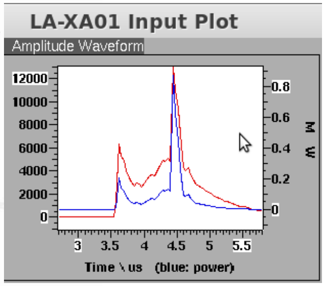


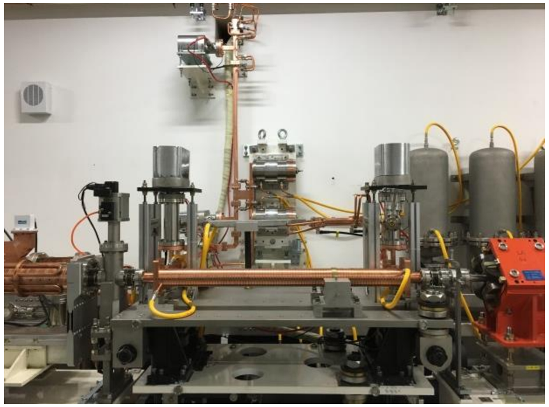


First X-band RF unit for SXFEL as linearizer

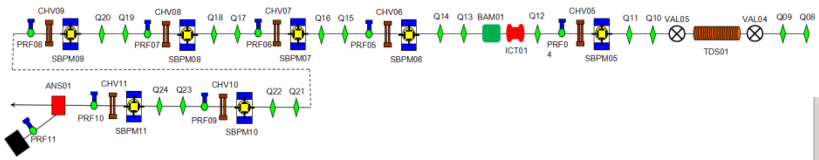
1. 6MW X-band klystrons;
2. 20MW modulator by SINAP;
3. One-meter length X-band accelerating structure;
4. Waveguide connection between amplifier and klystron;
5. One pulse compressor with TE0116, stabilized by two independent stable chiller;
6. Gradient not less than 20MV/m.
7. Movable support with 1um accuracy to suppress wakefield.



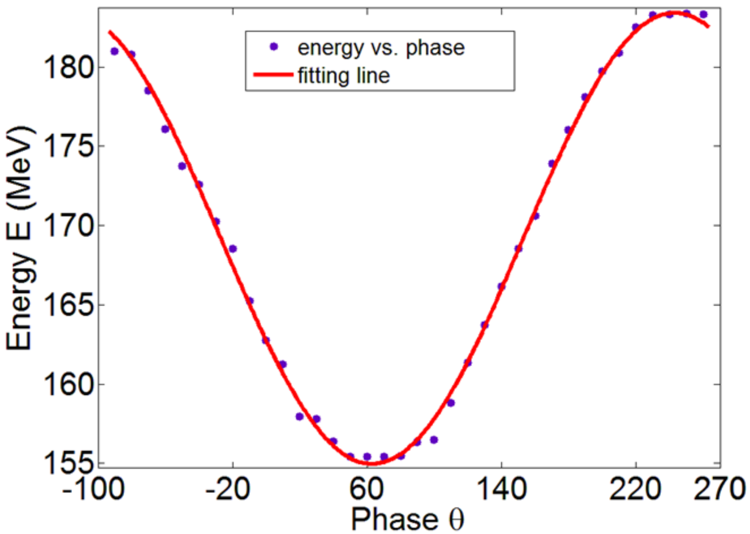




Beam operation results

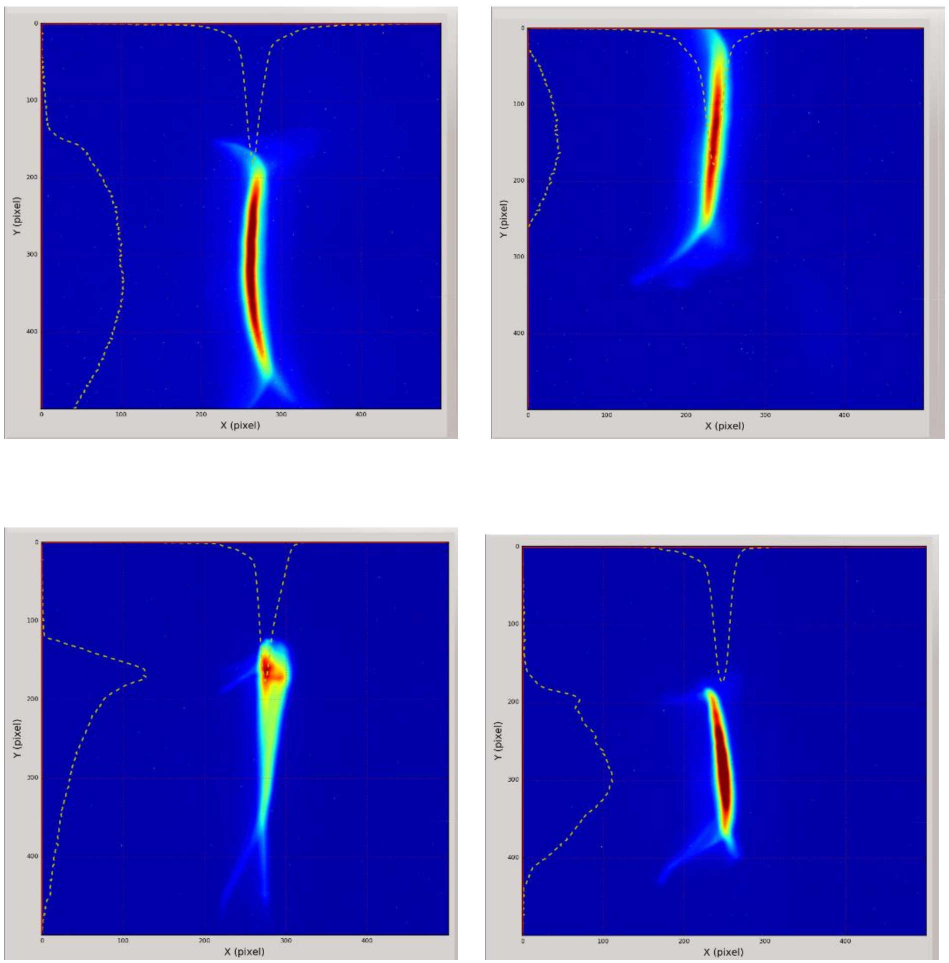


$$E = E_0 + A \cdot \sin(\theta + \theta_0)$$



1. Only 15MV/m gradient reached.
2. Klystron output is unstable for different operation voltage.
3. Maybe klystron is not optimized to reach full power.

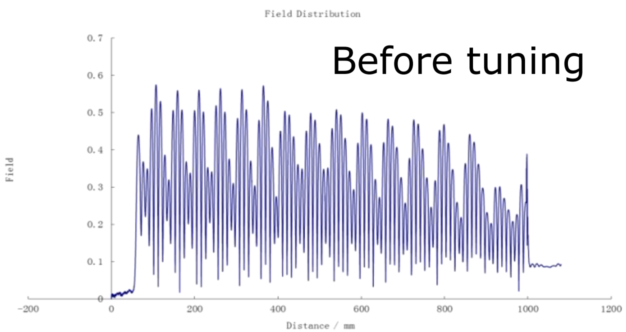
X-band Off **X-band On**



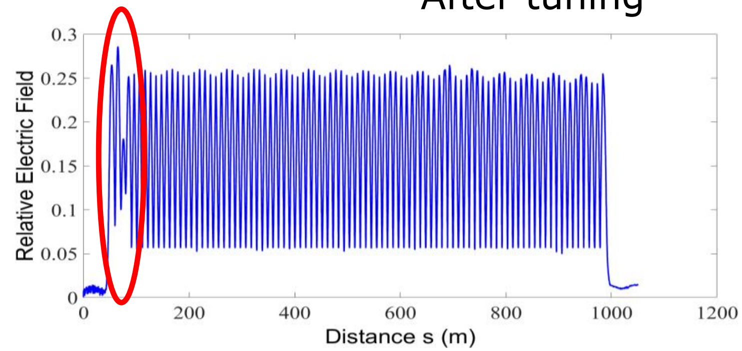
New one-meter X-band accelerating structure

1. Prototype is the first try for design, fabrication, brazing and tuning, many problems happened, and it not good matching before and after tuning.
2. After prototype, one new structure is under fabrication now.

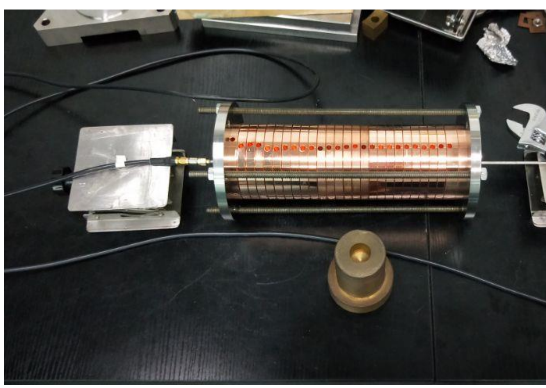
Before tuning

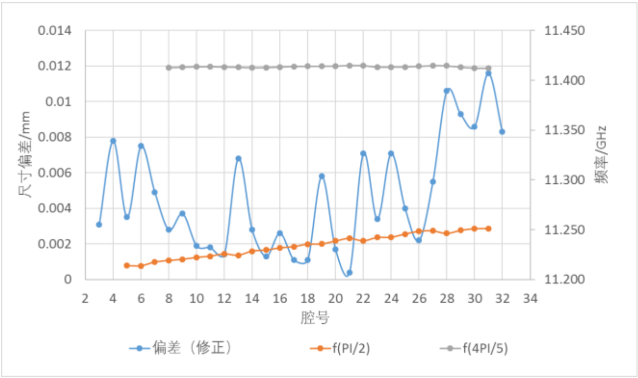


After tuning



New structure fabrication

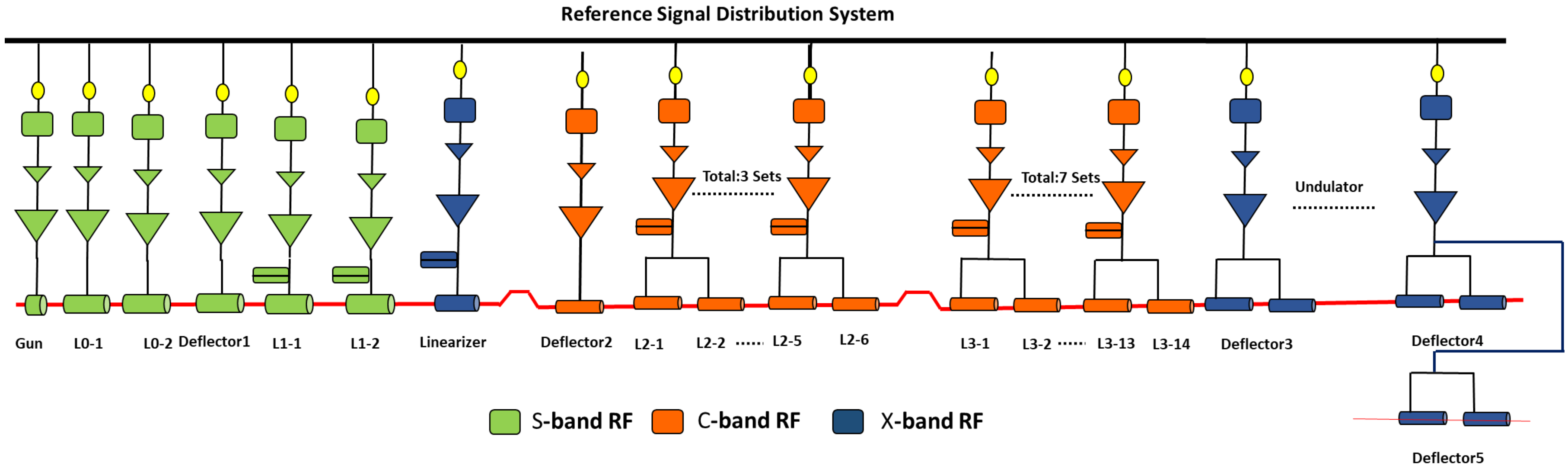




The C-band RF activities

The C-band linac at SXFEL

1. The final beam energy is up to 1.5GeV (Phase II) from 0.84GeV (Phase I)
2. 10 C-band RF units in final main linac, targeting on 37MV/m, which is designed on 40MV/m.
3. One 6MW X-band RF system for linearizer.
4. Two 50MW X-band TDS RF system for beam and optical measurement.

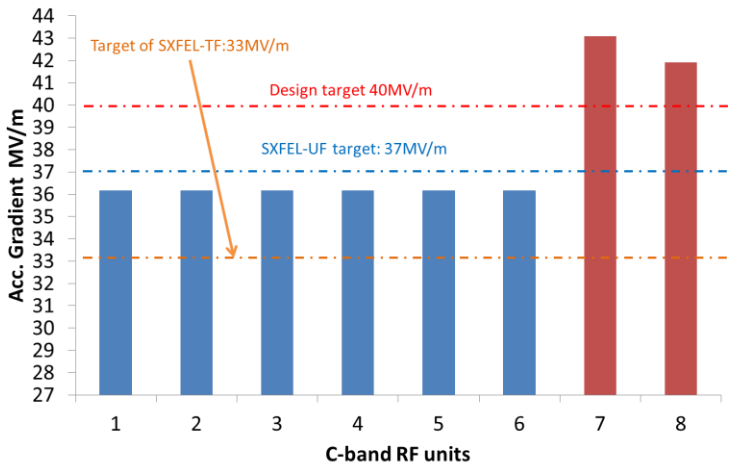


C-band RF structures for main linac

1. Recently there are 6 C-band RF units installed for main linac.
2. 6 klystrons, modulators and amplifiers as power source
3. 12 accelerating structures, 6 pulse compressor, and waveguides.

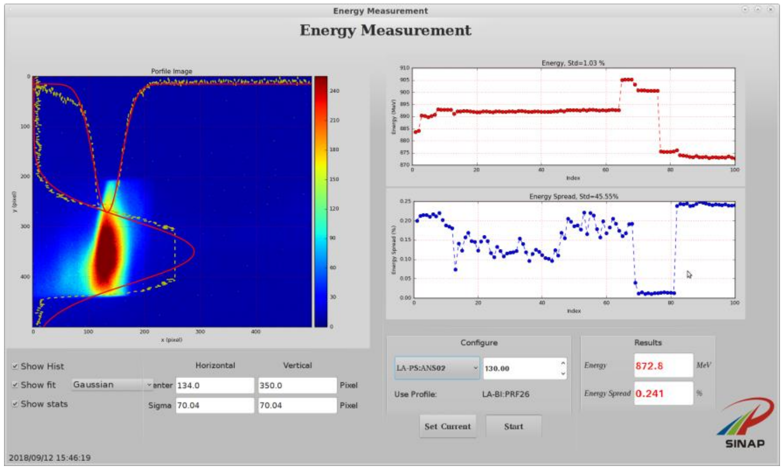
High power and beam operation results of C-band linac

- The final energy reached 872.8MeV, more than the target of 840MeV.
- All RF units reach 36.5MV/m, above target for SXFEL test facility.
- New two C-band accelerating structures were tested independently, and finally reached above 40MV/m.



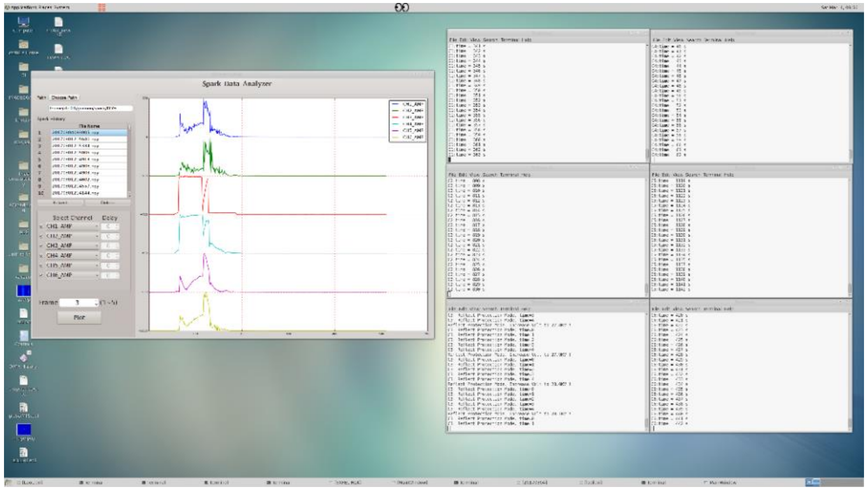
Final energy 872.8MeV

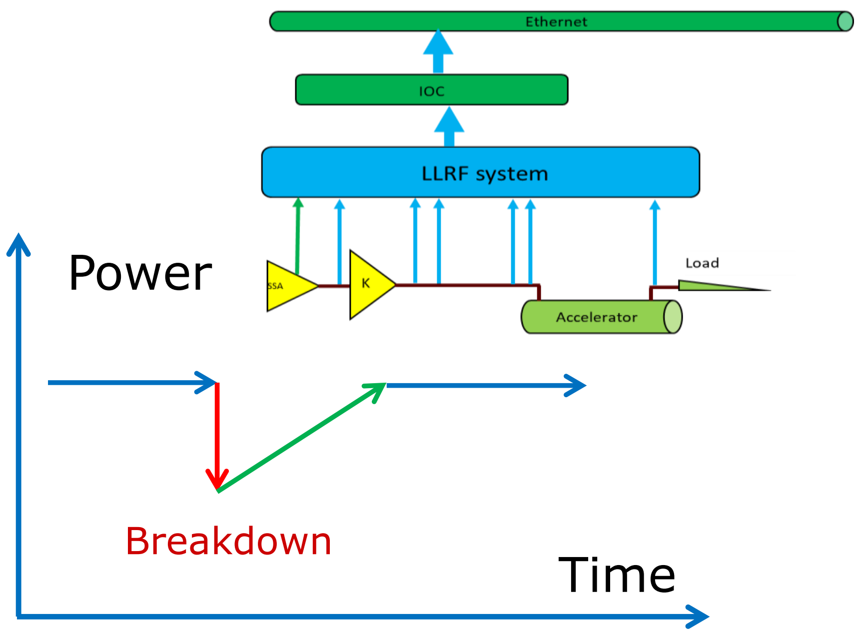
C-band linac

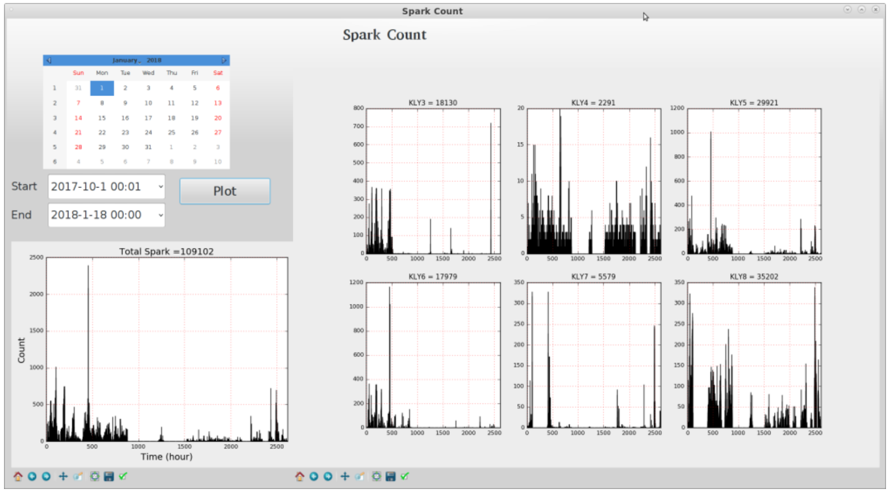


Breakdown monitor, protection and analysis system

1. Facility environment is more complicated, and RF structures are easy to interrupt to breakdown.
2. C-band high gradient operation should be monitored all time.
3. Structures are protected when breakdown happens, power is stopped 10s by LLRF, meanwhile dropped, and then ramped slowly.
4. All operation during breakdown events is control automatically based on EPICS system.
5. All breakdown data is stored, and could be analyzed for any time duration.

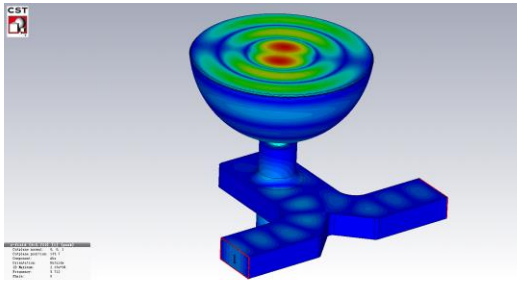


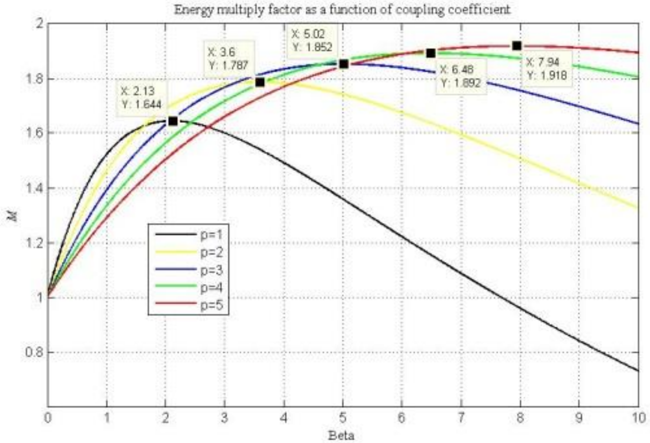


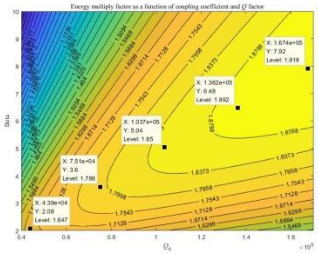


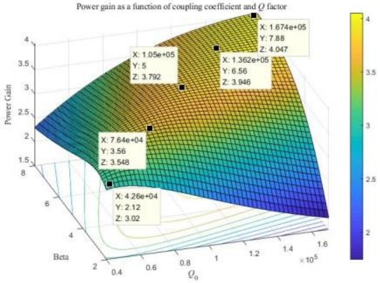
High power test of the C-band spherical pulse compressor

Mode	Cavity diameter [mm]	Q	Coupling coefficient	Energy factor	Power factor
$TE_{1,1,1}$	37.531	4.35×10^4	2.1	1.65	3
$TE_{1,1,2}$	64.528	7.48×10^4	3.6	1.79	3.5
$TE_{1,1,3}$	91.083	1.06×10^5	5	1.85	3.8
$TE_{1,1,4}$	117.5	1.36×10^5	6.5	1.89	3.9
$TE_{1,1,5}$	143.85	1.67×10^5	7.9	1.92	4





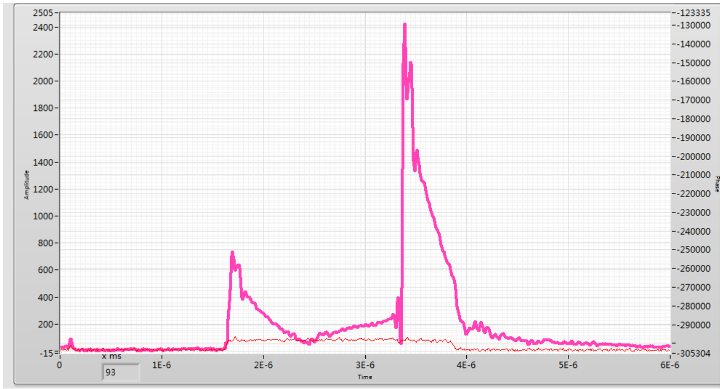




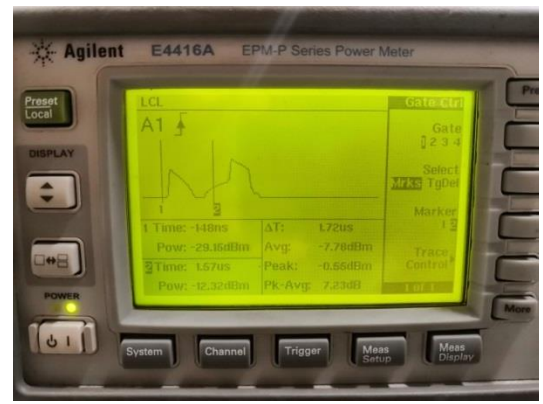
High power test of the C-band spherical pulse compressor

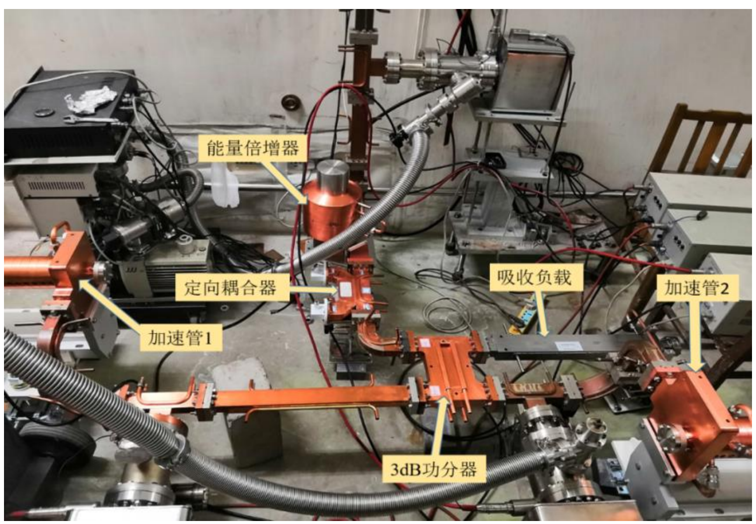
1. 50MW C-band klystron;
2. NI LLRF is moved for C-band;
3. One pulse compressor with two acc. Structure.

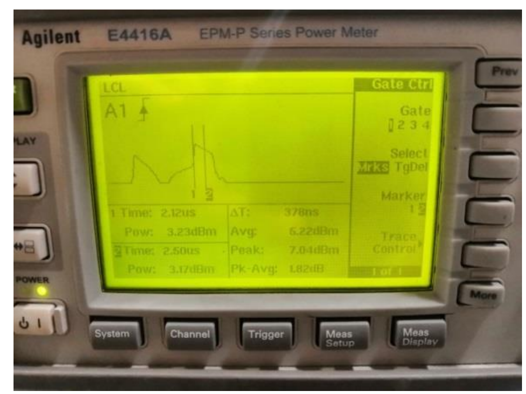
The current results of high power test



Output [dBm]		Multi. Factor		Design multi. factor	
Peak	Ave.	Peak	Ave.	Peak	Ave.
28MW	18MW	5.74	3.77	6.1	3.8

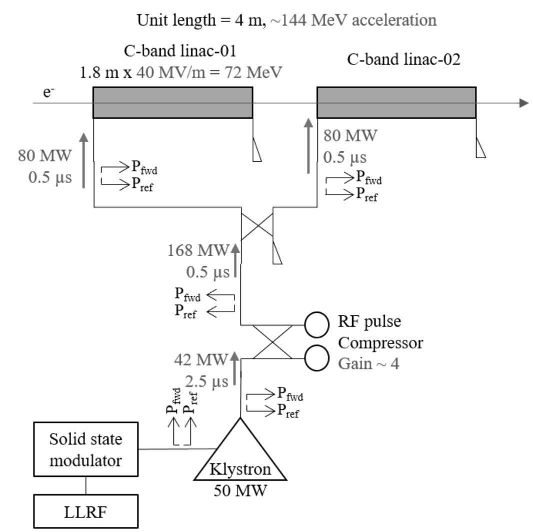


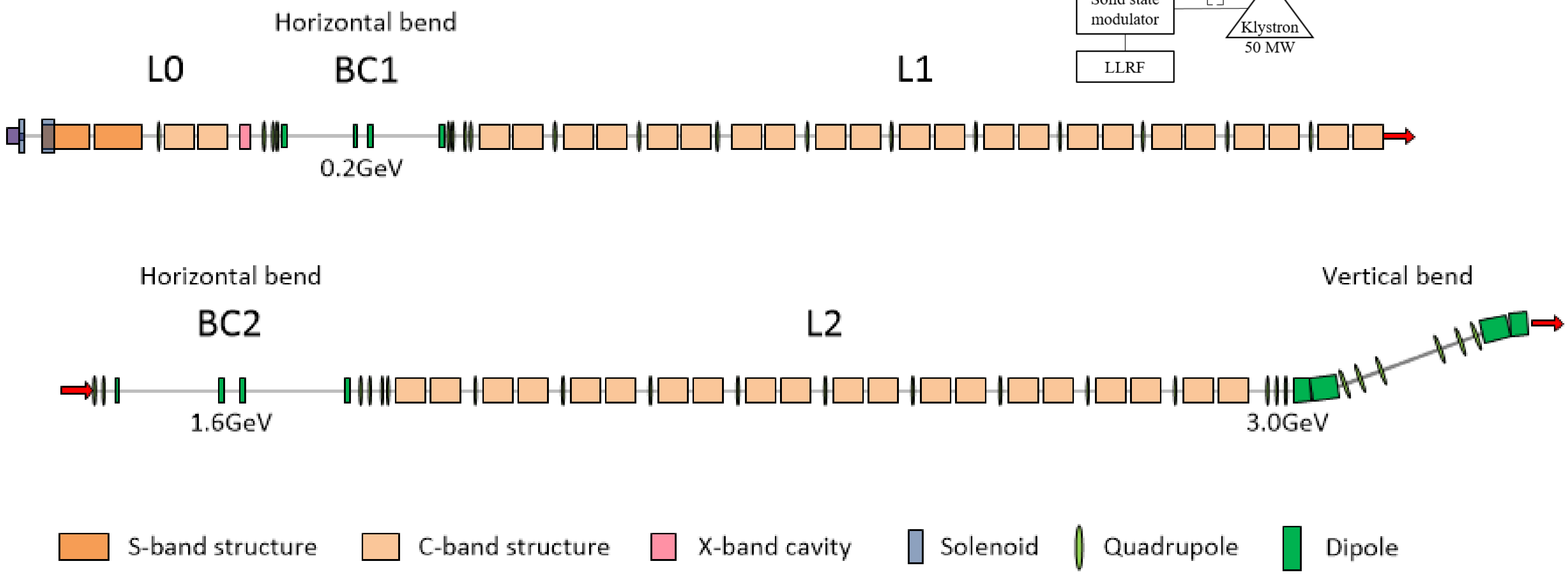




Collaboration on C-band linac design for Thailand light source

1 x Photocathode S-band e-gun
2 x S-band structures
1 x X-band structure
44 x C-band structures (@ 40 MV/m)
1 RF unit supplies 2 RF structures
One C-band RF unit can accelerate electron to 144 MeV

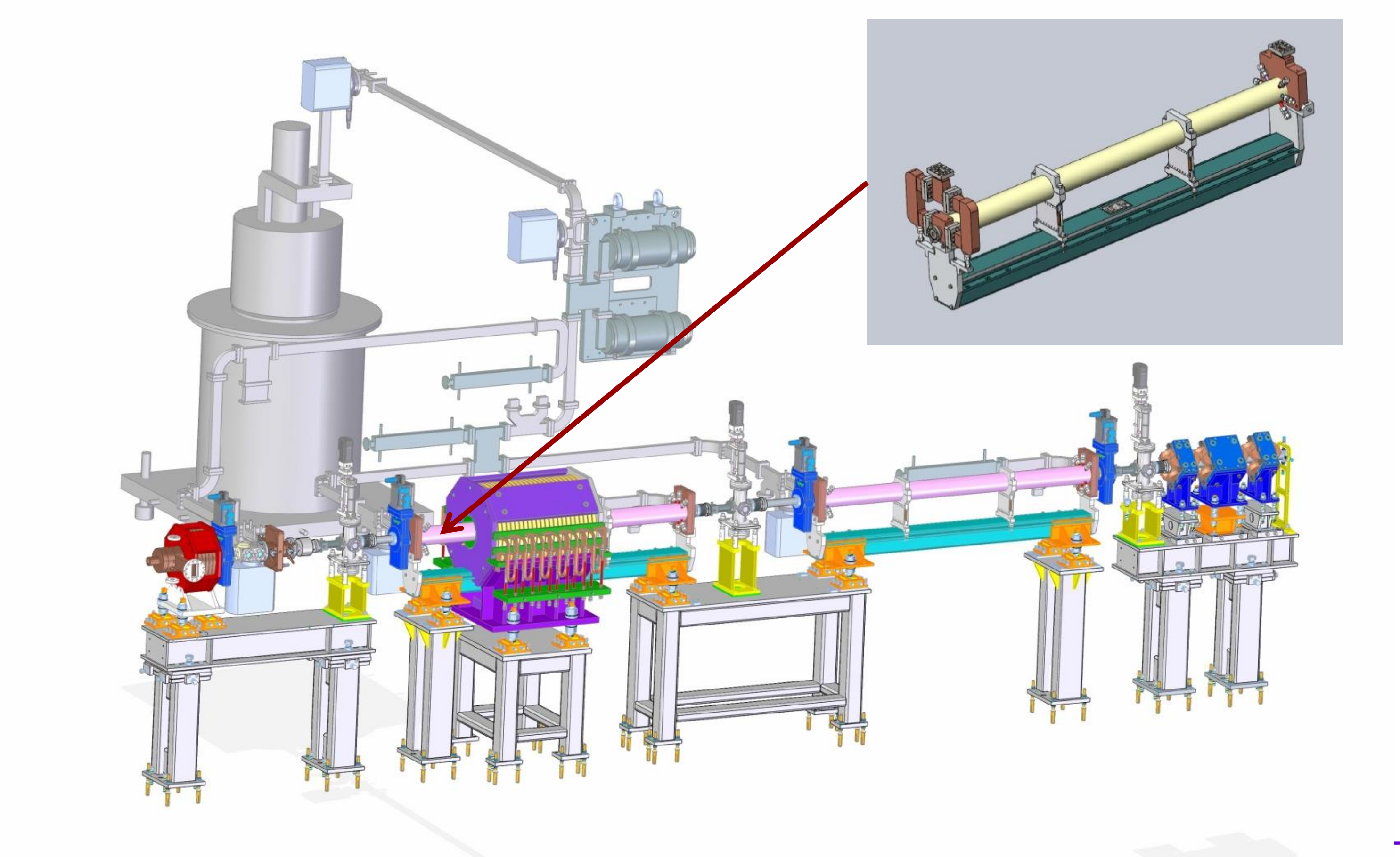




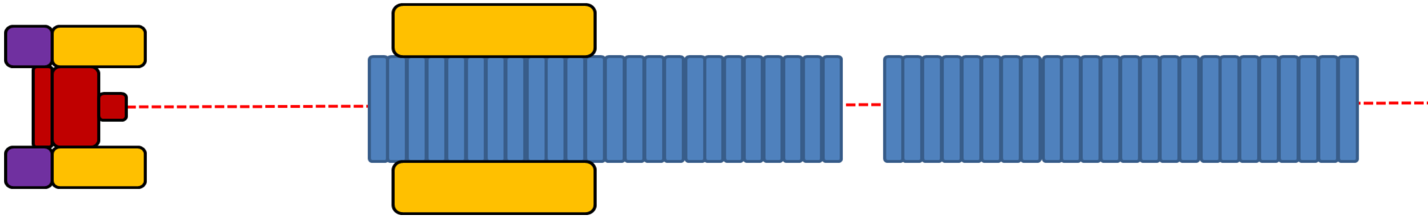
Courtesy of Nawin Juntong

C-band RF unit for UED

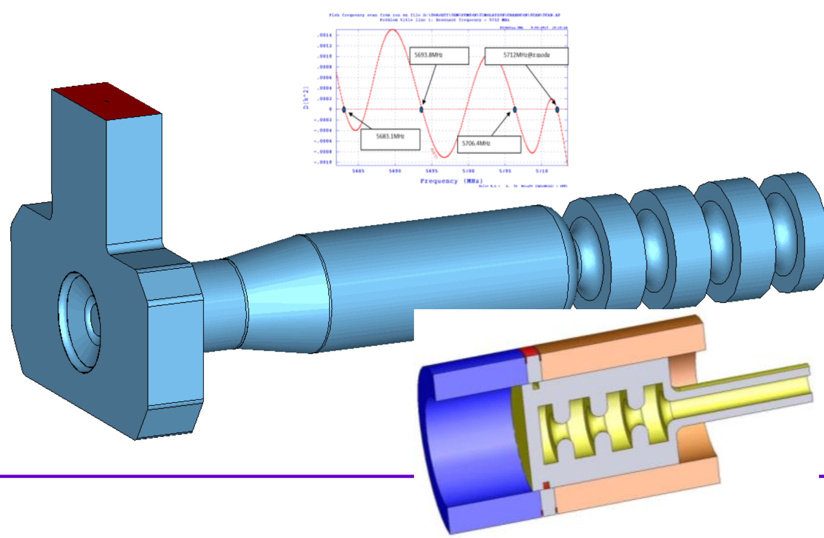
1. 100-130MeV based on C-band RF unit.
2. Maximum gradient is 40MV/m
3. For high energy UED

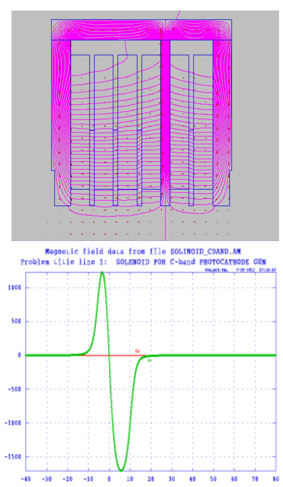


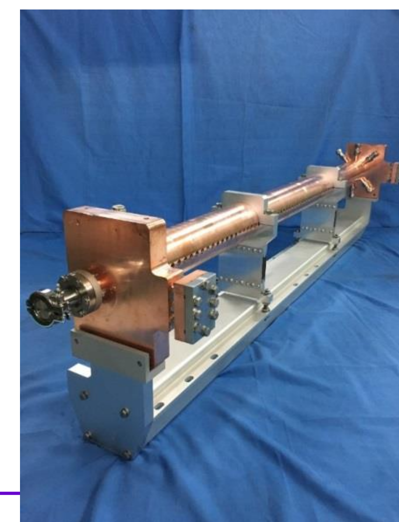
C-band photoinjector based on HG



1. The C-band photoinjector with high gradient is one attractive option for lower emittance with compactness, and the injector is composed of the 3.6-cell gun and two 1.8-meter C-band accelerating structures.
2. The gradient of 150MV/m on the cathode can reduce the laser spot which results in lower thermal emittance, and 45MV/m in the 1.8-meter structure can make facility more compact.
3. The solenoid with two halves placed around gun is designed for the emittance compensation, correspondingly a coaxial coupler is used for solenoid intallation, as well as to reduce dipole and quadrapole field in the coupler.

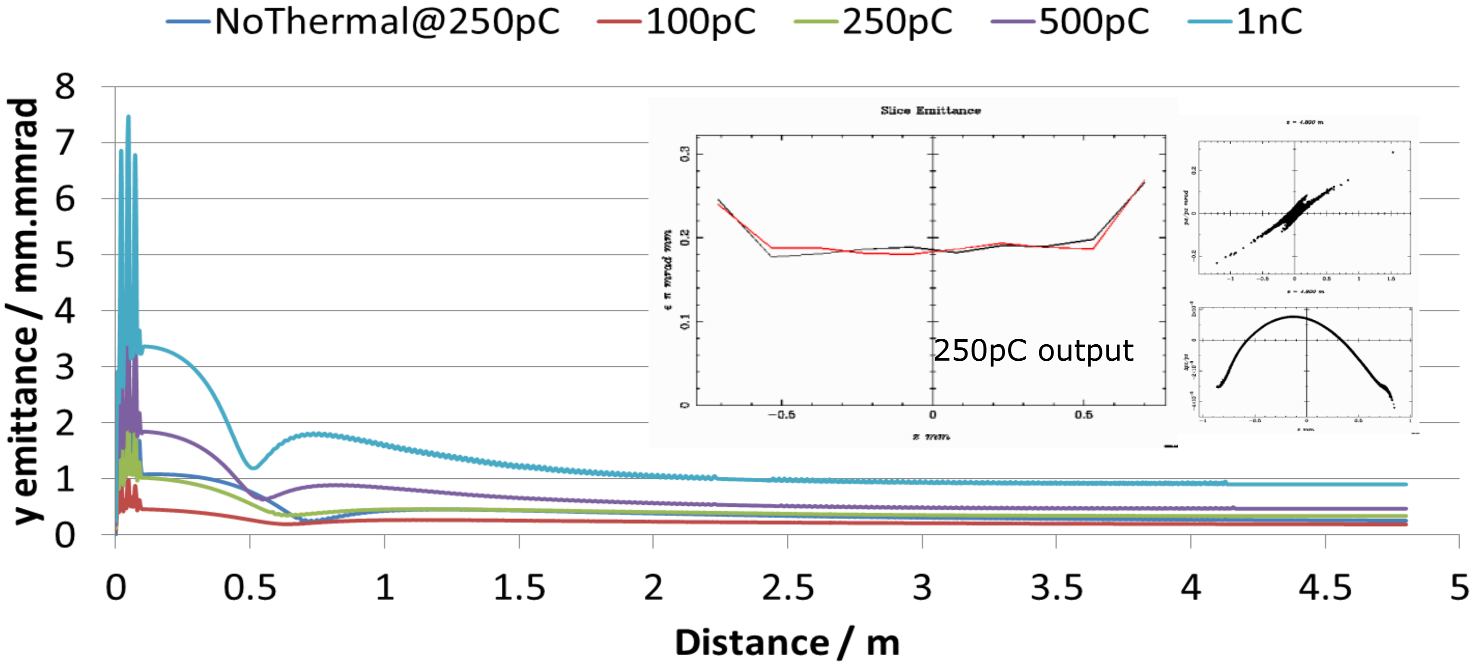






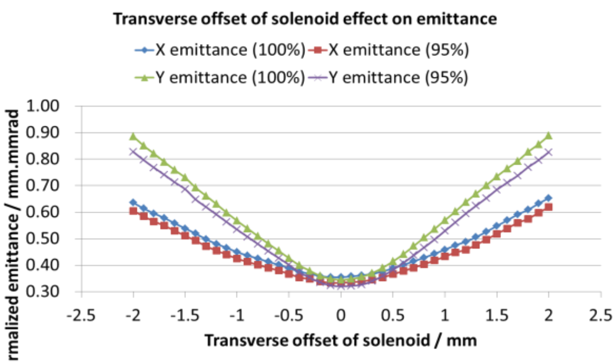
The emittance of different charges

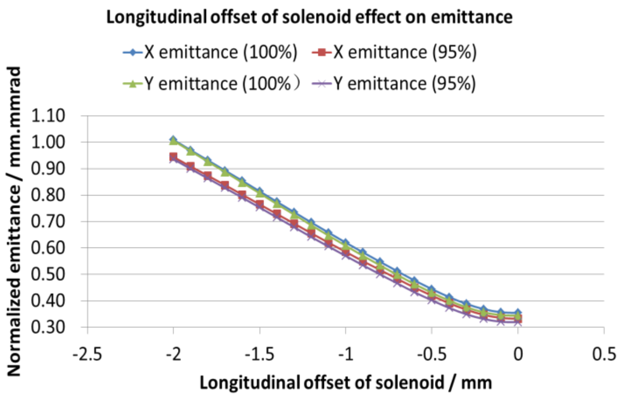
1. The emittance is different for different charge, results are 0.19, 0.34. 0.47, 0.9 mm.mrad for 100pC, 250pC, 500pC and 1nC respectively, moreover 0.13, 0.23, 0.33 and 0.62 mm·mrad for 95% cut-off.
2. 250pC is the typical charge of FEL operation, and its slice emittance is 0.19 mm.mrad in most range.

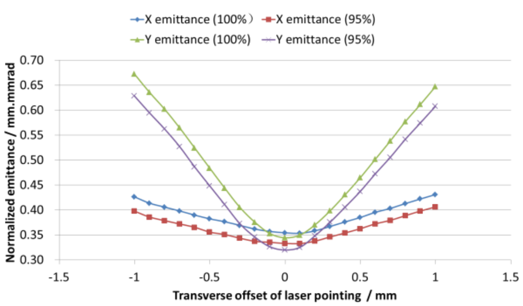


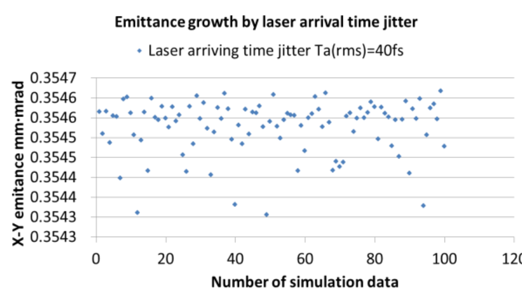
Jitters and errors: solenoid, laser, RF

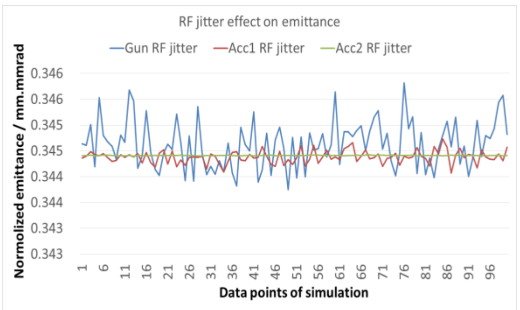
1. The emittance growth is most sensitive to solenoid transverse and longitudinal offset, and it's about 0.05mm.mrad increased by 0.1mm alignment tolerance.
2. The emittance growth also could be impacted by jitter of laser spot, arrival time, and RF magnitude and phase, however it's very slight by real laser and RF jitter. To some extent it could be neglected comparing with solenoid errors.
3. Totally all errors and jitters could produce emittance growth less than 0.06mm.mrad.





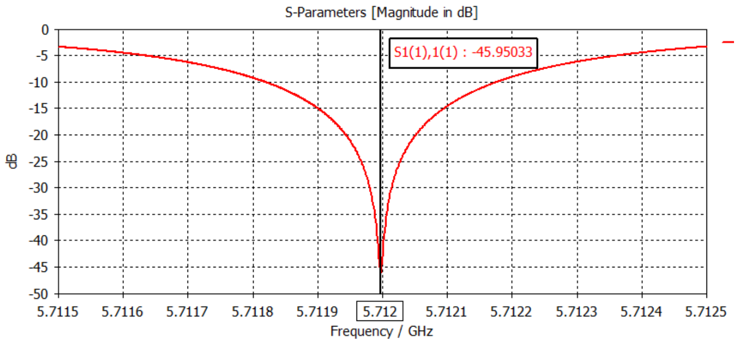


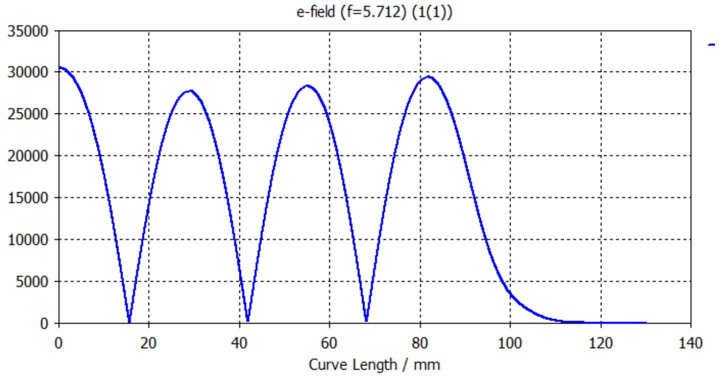


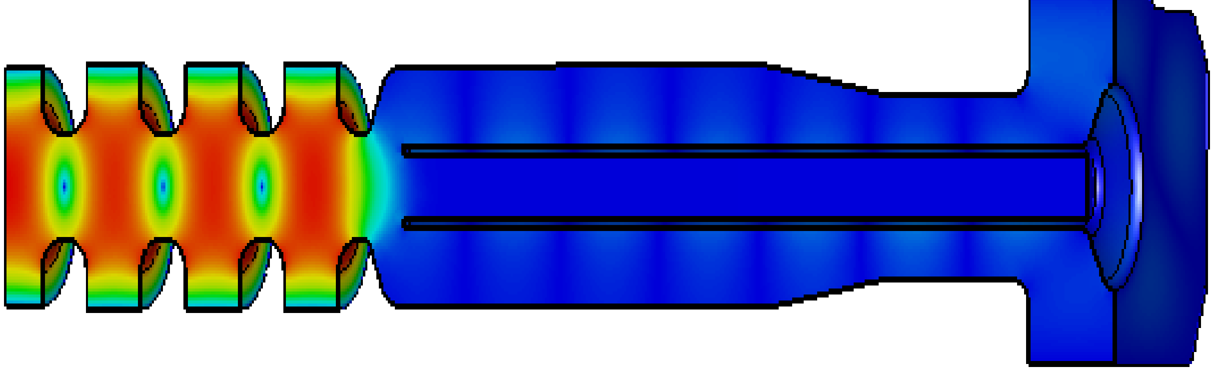


3-D RF design

1. The coaxial coupler is designed in order to have enough length for solenoid installation, as well as to eliminate dipole and quadrapole field in the coupler.
2. The coupling aperture and cell diameter are tuned for coupling coefficient, frequency and field flatness.







Summary

- The HG team at SSRF has done some work on X-band HG tech. such as accelerating structure, pulse compressor and others, and we will continue the R&D in the future;
- The C-band RF technology as mature technology has reached the target of 40MV/m, and now is being operated at 36.5MV/m at SXFEL;
- The C-band RF technology is extended to other applications or facilities, such as Thailand light source and UED;
- The C-band photoinjector based on HG is one attractive solution for lower emittance and compact facility, and we will continue the R&D.