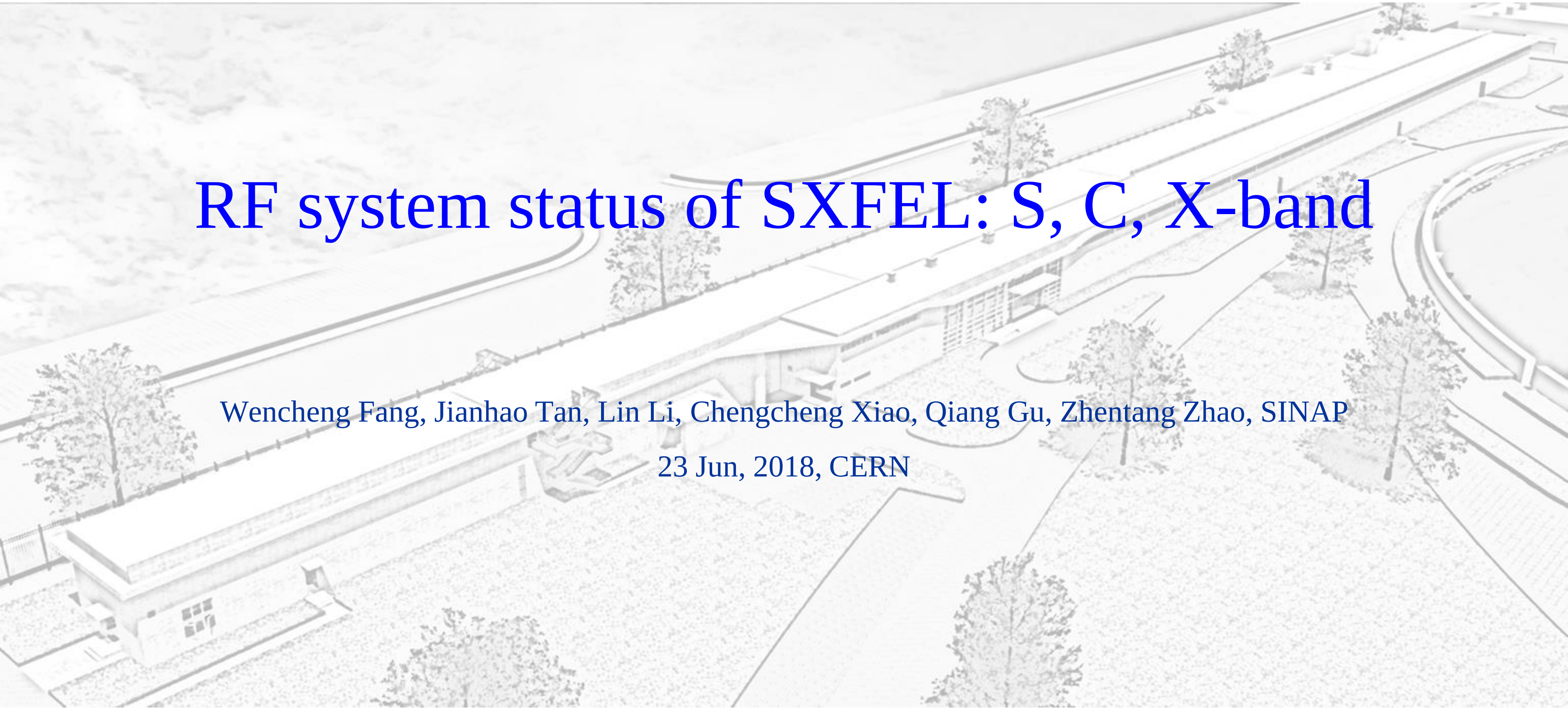


RF system status of SXFEL: S, C, X-band

Wencheng Fang, Jianhao Tan, Lin Li, Chengcheng Xiao, Qiang Gu, Zhentang Zhao, SINAP

23 Jun, 2018, CERN

SINAP
中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Outline

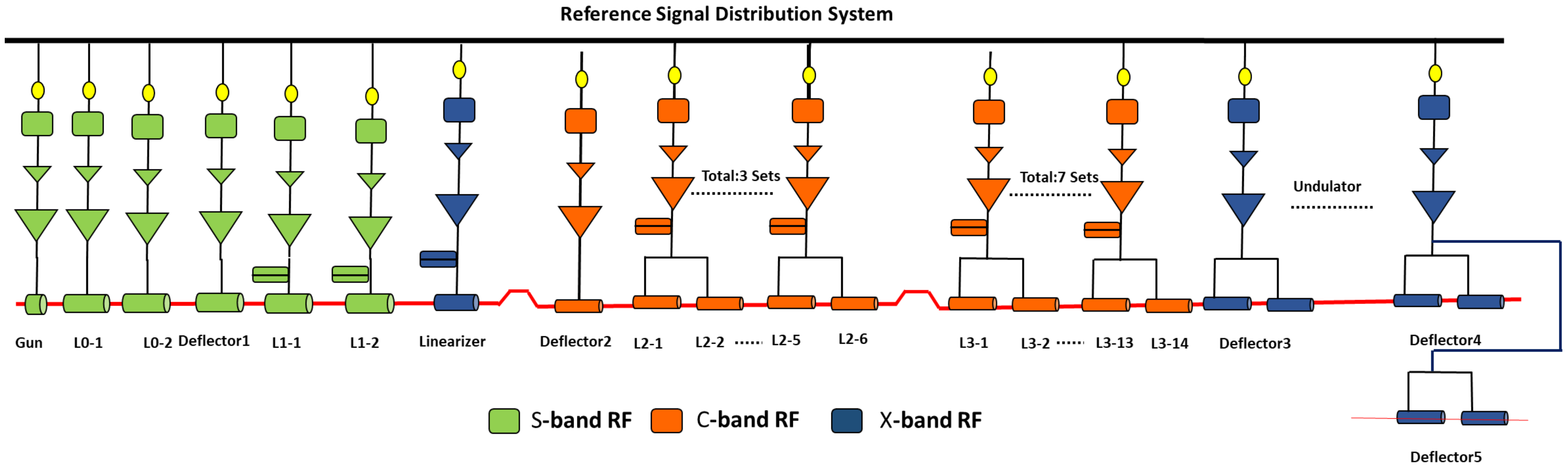
- RF system layout in SXFEL
- RF structures: S, C, X-band
- Low-level RF system and control
- Breakdown monitor and protection control.
- Summary

SXFEL bird-view

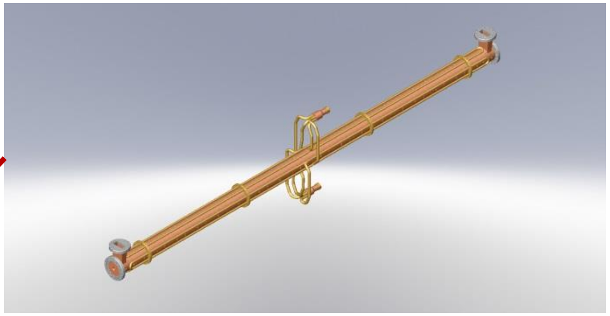
SXFEL test facility

RF system upgrading of SXFEL user facility

1. Beam energy up to 1.5GeV (Phase II) from 0.84GeV (Phase I)
2. Injector is composed of e-gun, two S-band accelerating structure.
3. Main linac is based on two S-band RF units, 10 C-band RF units.
4. One S-band deflector in end of injector, one C-band deflector after BC1.
5. One X-band RF unit for linearizer, two X-band units for deflector

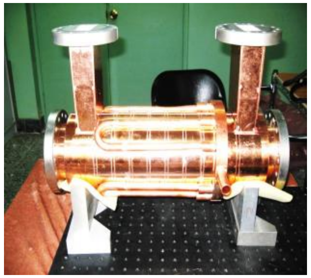


S-band RF structures for injector and linac-I

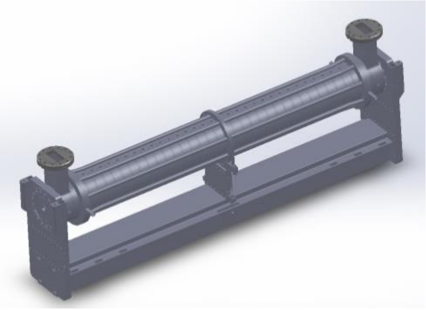


Two 3m S-band accs for linac-I
17MV/m gradient designed
Outer water cooling
dipole and quadrupole field exit.

Two 3m S-band accs for injector
22MV/m gradient required
Outer water cooling
No dipole and quadrupole field.



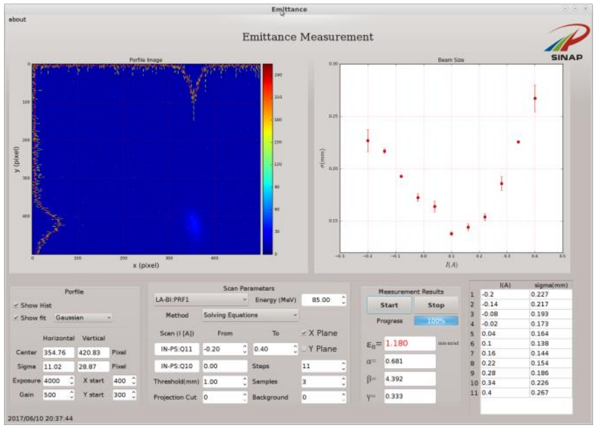
0.5m S-band deflector for
injector with 2MV voltage

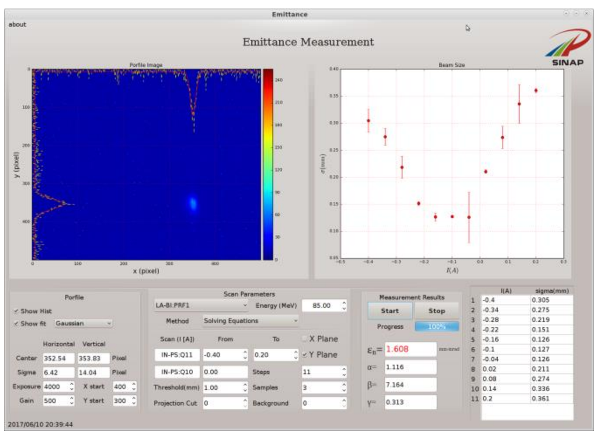


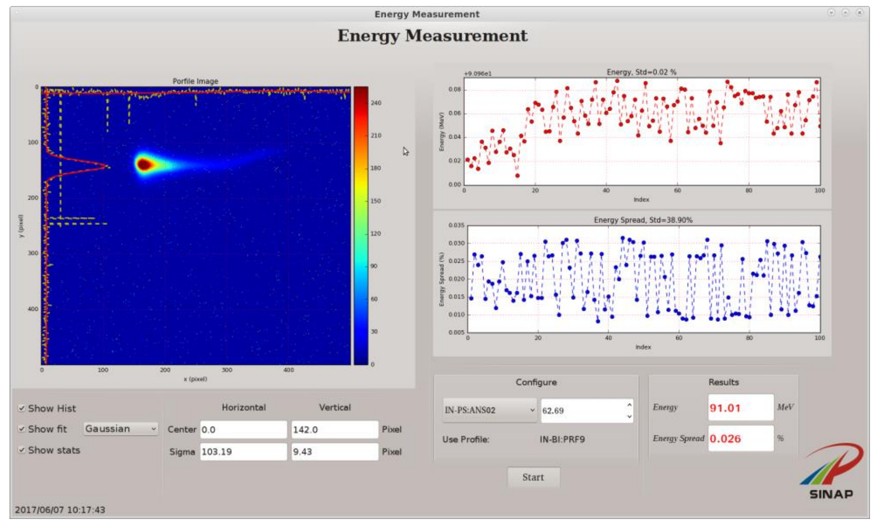
1.4m S-band deflector after
BC1 with 10MV voltage

Beam results of injector and linac-I

1. Gradient didn't reach target, injector energy is only 90MeV, less than target of 130MeV.
2. Quadrupole field exits in the coupler of IN-S1, makes x, y emittance is more than target 1.

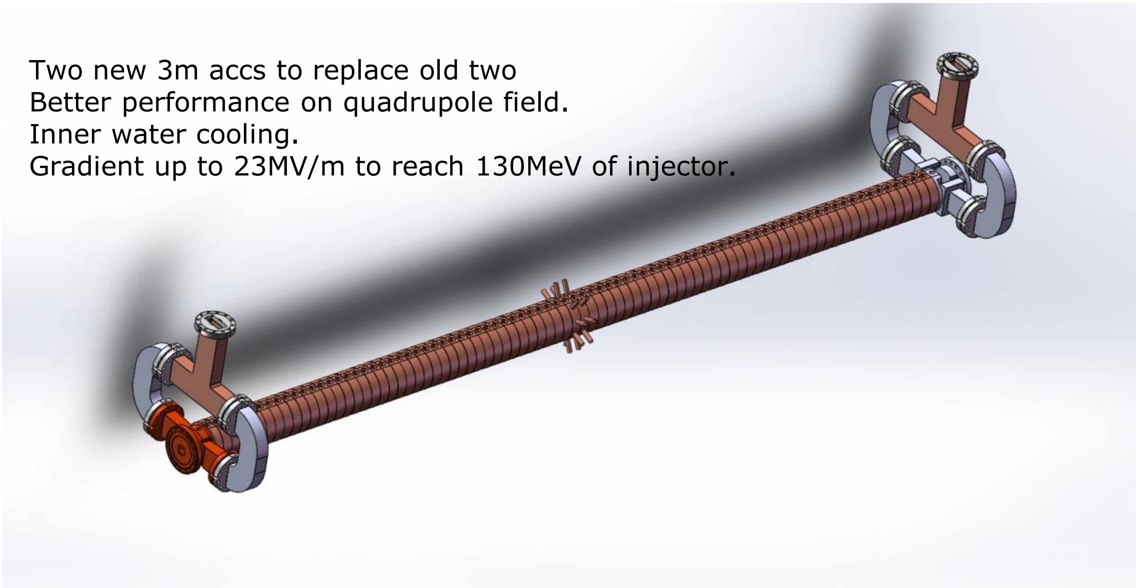




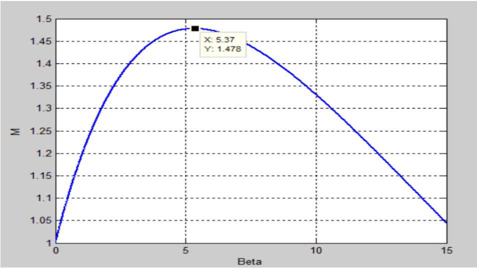


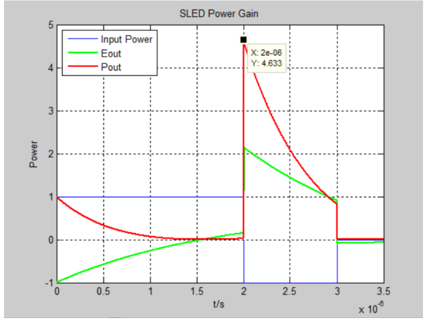
90MeV of injector energy.
0.02% energy stability

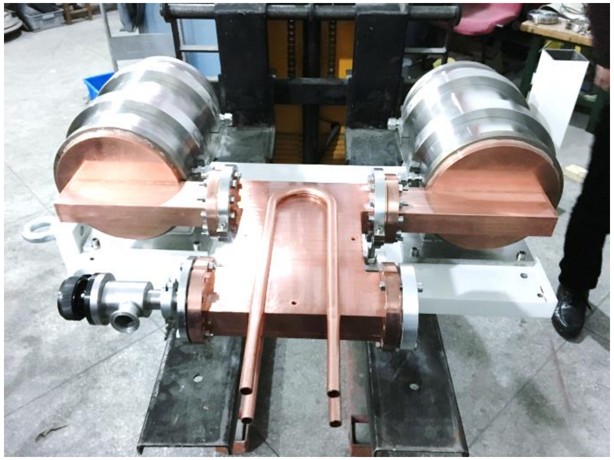
Upgrading of S-band RF



1. Two S-band SLEDs will be added in linac-I.
2. Improve Li-S1, S2 from 17MV/m to 27MV/m.
3. Compressing 3us power to 1us width.
4. Peak power is 100MW to input Li-S1, S2.
5. Increase energy to 265MeV from 205MeV.





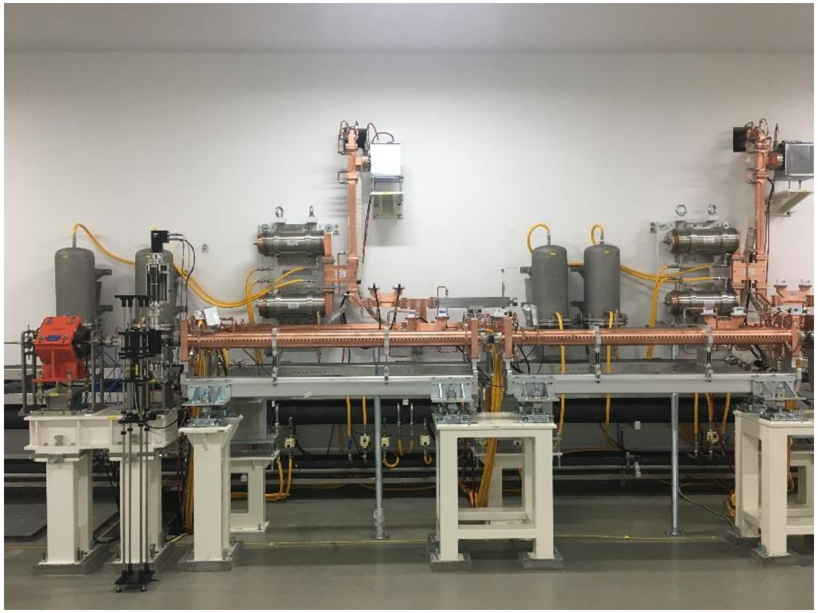


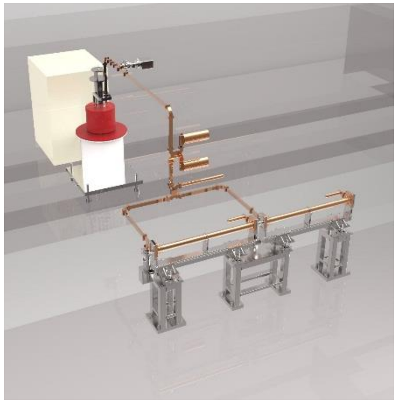
C-band RF structures for main linac

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.

Layout of C-band unit

1. 50MW C-band klystron is from Mitsubishi.
2. PFN-thyratron type modulator is developed at SINAP.
3. Acc, PC and waveguide is developed at SINAP
4. C-band load was made by Tsinghua University.
5. Low-level hardware system based on MTCA is from Struck company in Germany, and developed by SINAP.





C-band klystron PV-5050

1. All 7 C-band klystrons are from Mitsubishi.
2. 35MW power is required in the first step for 34MV/m.
3. 50MW power is required in the second step for 40MV/m.

Electrical specifications

	Parameter	Rated value
1	Frequency	5712 MHz
2	RF peak output power	50 MW
3	Voltage pulse width	6.2μs
4	RF pulse width	2.5μs
5	Peak beam voltage	350kV
6	Peak beam current	320A
7	Peak driver power	130W (200W max)
8	Pulse repetition frequency	50Hz
9	No spark time at nominal ratings	2hours min
10	Efficiency	43%min
11	Gain	54dB min
12	Heater voltage	120V max
13	Heater current	4.5A max
14	Heater power	500W max
15	Preheating time	1hour
16	Ion pump voltage	3.0-5.0kV
17	Ion pump current	5μA max

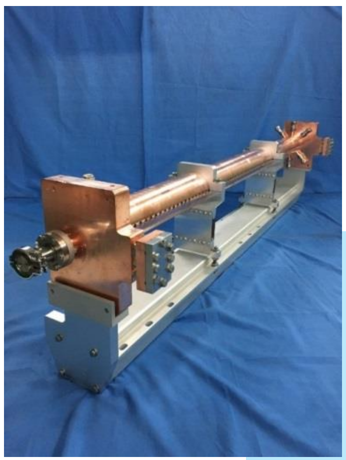
Modulator (PFN + Tharatron)

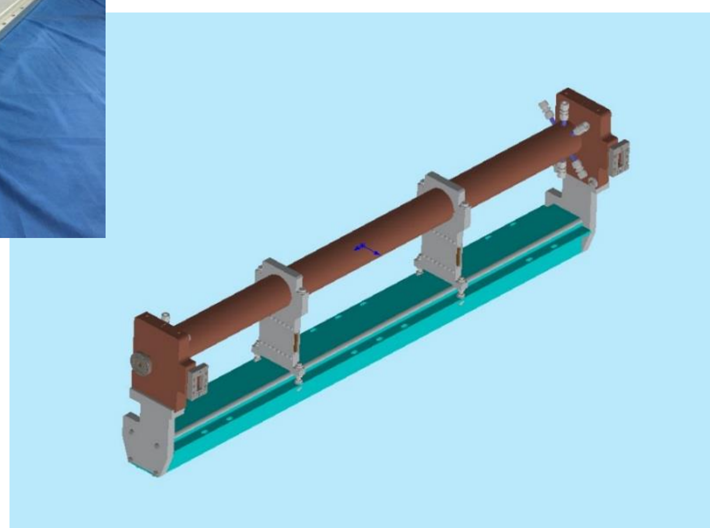
Item	Value	Unit
Pulse voltage	350	kV
Pulse current	320	A
Pulse power	112	MW
Pulse width (flat-top)	3	μs
FWHm	5.5	μs
Repetition rate	10	Hz
Average power	7	kW
Transformer ratio	1:16	
PFN voltage	45	kV
Switch current	5200	A
PFN type	20 cells	
PFN impedance	4.33	Ω
PFN capacity	0.635	μF
Charging voltage	50	kV
Charging current	480	mA
Flatness	<±0.25	%
Amplitude stability（rms）	400	ppm
Rise edge jitter（rms）	< 10	ns

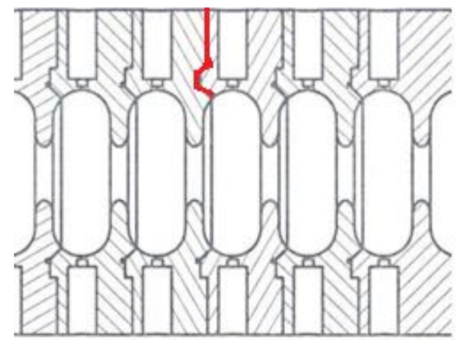
1. Developed by SINAP;
2. Stability is not good enough;
3. New stable charger to replace old one.
4. Feedback will be used to stabilize high voltage.

C-band accelerating structures

1. This structure is constant gradient, phase advance is 4pi/5, target is 40MV/m at least.
2. Rounded cell for higher impedance, and tuner is remained.
3. Compact coupler with single port, inner water cooling.
4. So far 18 structure have been manufactured, and more 8 is ongoing of fabrication.



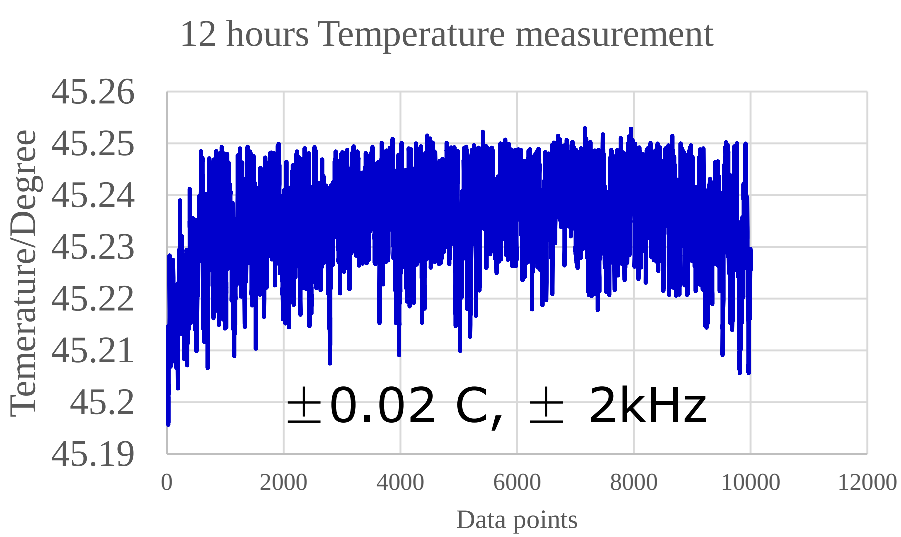


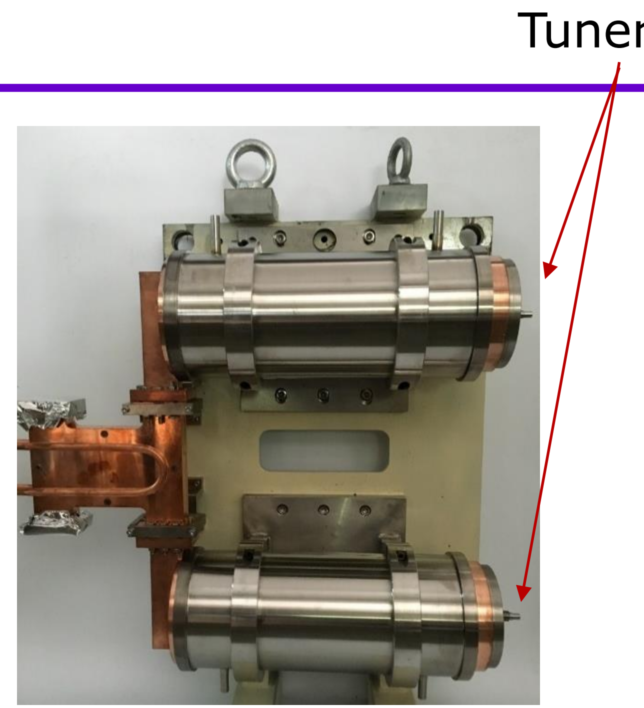


C-band Pulse compressor

1. Pulse compressor was first tuned by mechanical tuner.
2. During operation, advanced Chiller are used to make temperature stable, and also to tune PD slightly.

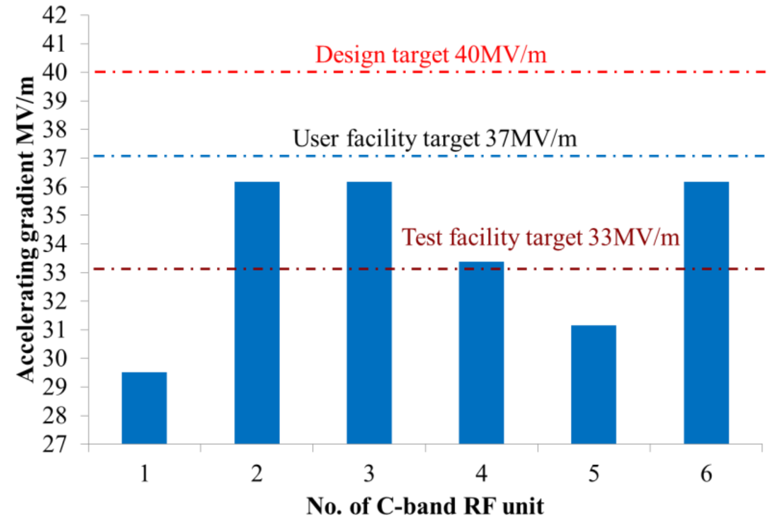
Frequency	5712MHz
Quality factor	About 180000
Coupling coefficient	About 7.5



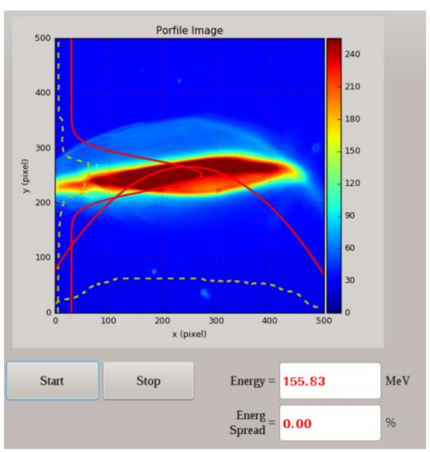


High power and beam operation results of C-band linac

- Average gradient is 33MV/m, reaching test facility target.
- Three RF units reach 36.5MV/m, almost carries out user facility target.
- C-band RF units will continue to be conditioned again to reach 40MV/m after scheduled FEL experiments.

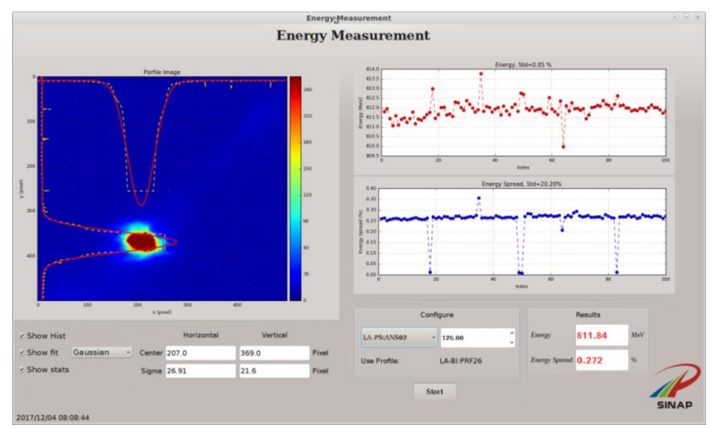


Input energy 155.83MeV



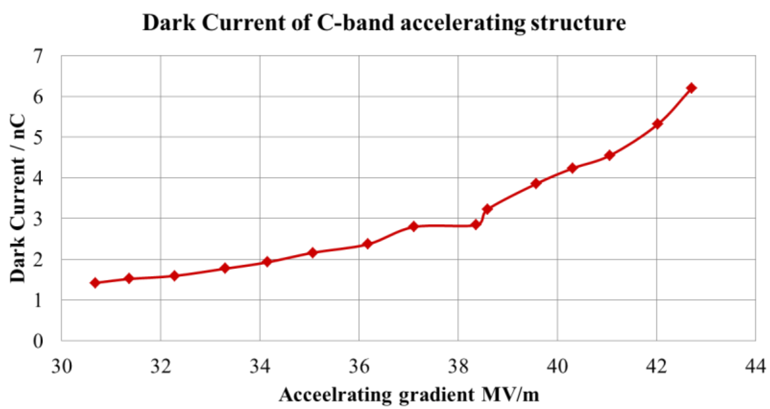
C-band linac

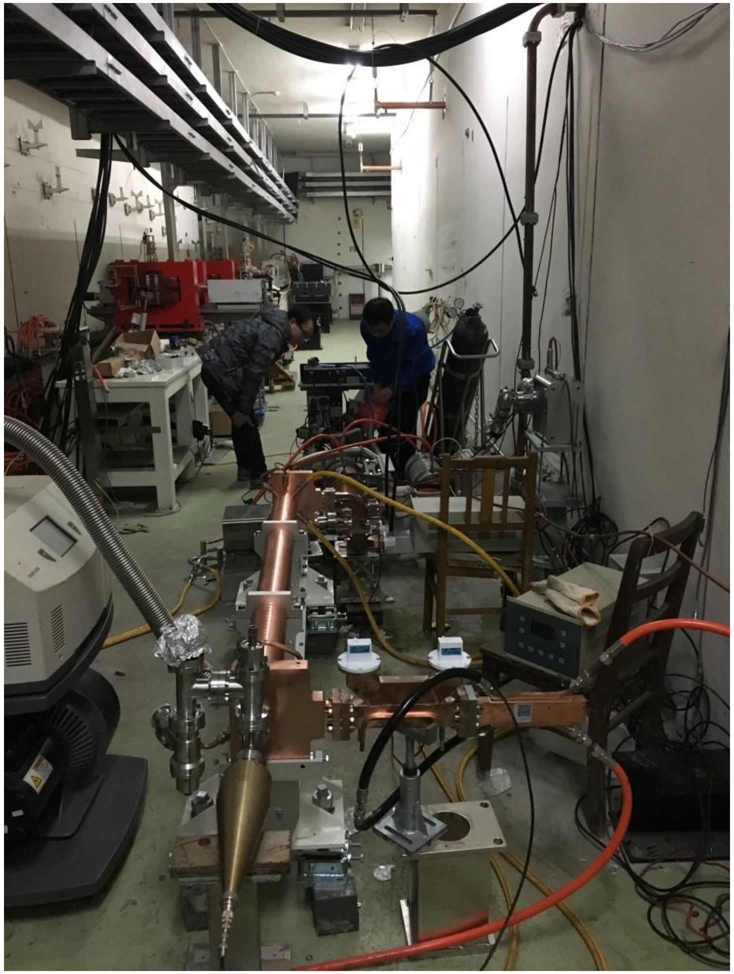
Final energy 811.84MeV



High power test of single C-band accelerating structure to 43MV/m

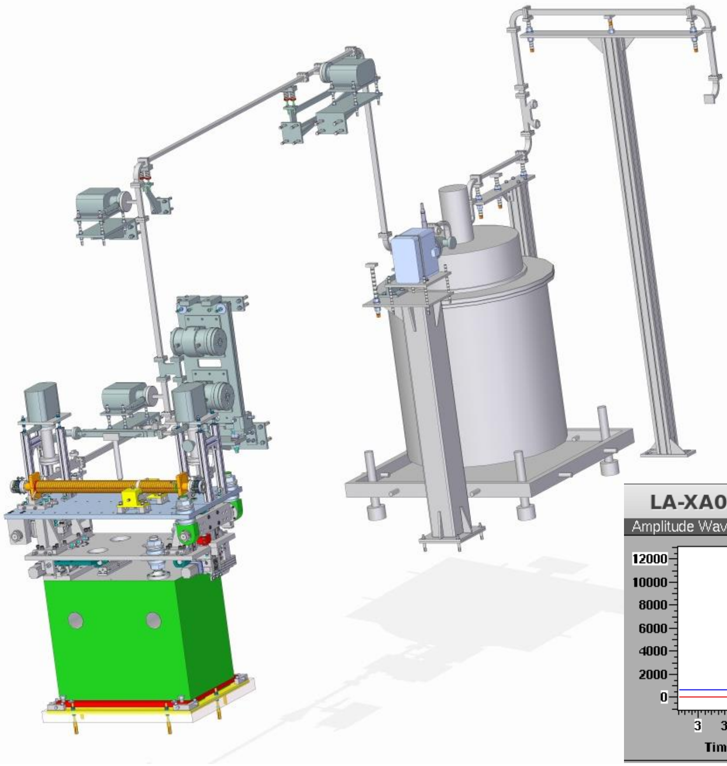
- One new C-band accelerating structure was installed in the dedicated high test platform.
- Only one month were cost for RF conditioning to reach 43MV/m finally.
- Dark current is acceptable when 43MV/m without obviously increasing as same as results before, so 40MV/m is a reasonable target for beam operation.
- Facility environment is very important for high gradient conditioning and operation, it's should be controlled strictly.

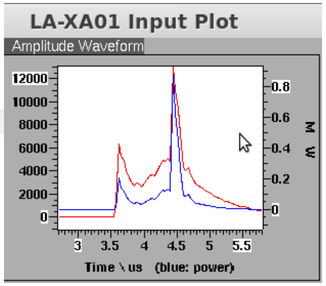


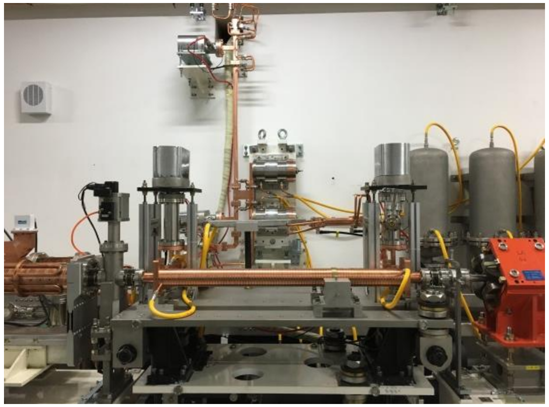


Layout of X-band RF unit as linearizer

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

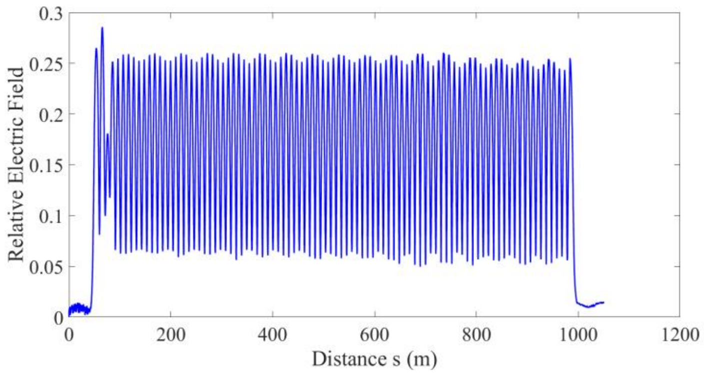


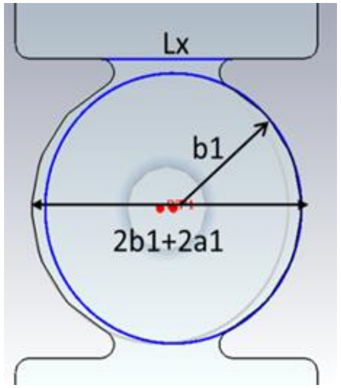


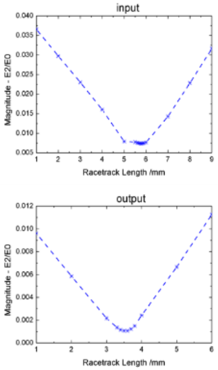


X-band accelerating structure

1. Originally designed 80MV/m for compact FEL
2. 4pi/5 mode for large aperture.
3. 1 meter length with 91 cells
4. Dipole and quadrupole field suppression.
5. Ag-Cu brazing technique.

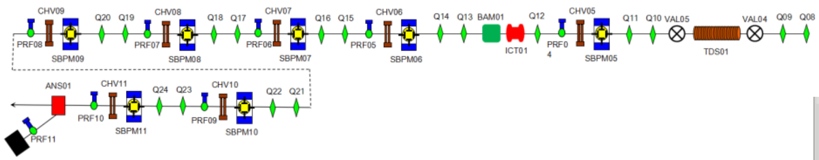




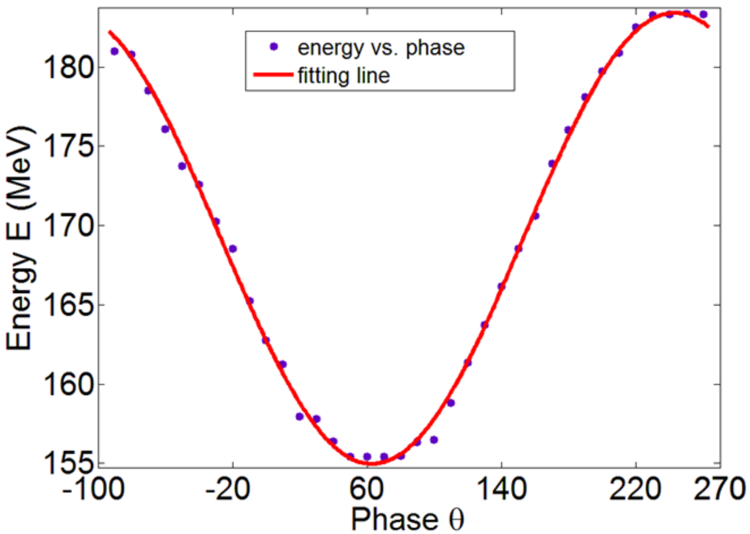


Frequency	11424MHz
Phase advance	$4\pi/5$
Cell No.	89+2
Effective length	944.73mm
Cell length, d	10.497mm
Iris thickness, 2a	1.5 mm
Diameter, 2b	23.382~22.556 mm
Ratio of elliptic radius, b_a	1.8
Aperture, a_r	4.3~3.05.mm
Group velocity, Vg/c	3.46%~1.12%
Shunt impedance, R	93.93~125.62MΩ/m
Attenuation factor, τ	0.61
Filling time, t_f	150 ns
Sc	4.14~2.33 MW/mm^2
Emax	215~178 MV/m
Hmax	214~211 kA/m
Input power, P_{in}	79MW @80MV/m

Beam operation results

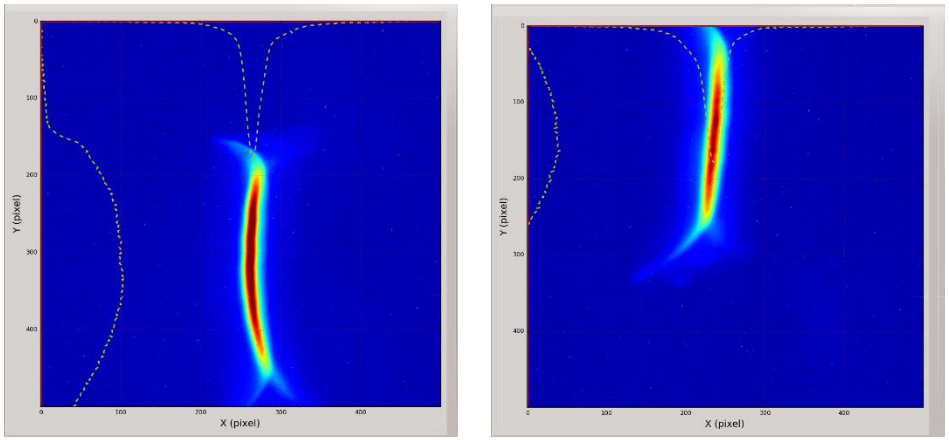


$$E = E_0 + A \cdot \sin(\theta + \theta_0)$$

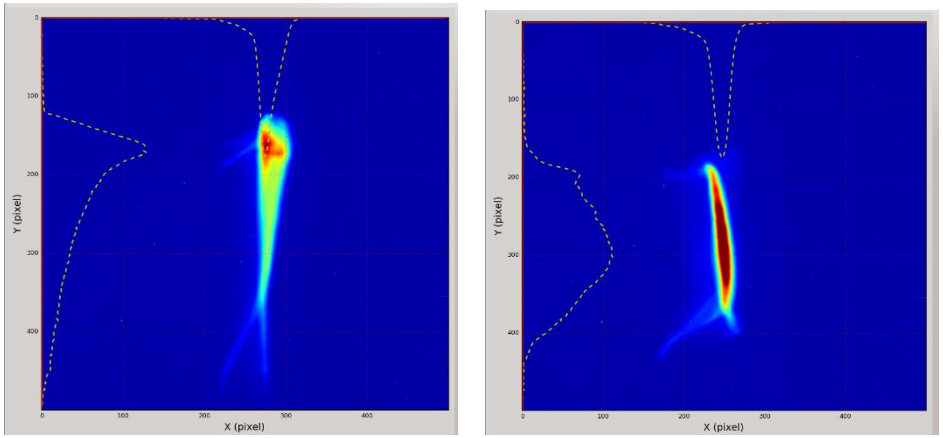


1. Only 15MV/m gradient reached.
2. Klystron output is unstable for different operation voltage.
3. Maybe klystron is not optimized to reach full power.

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

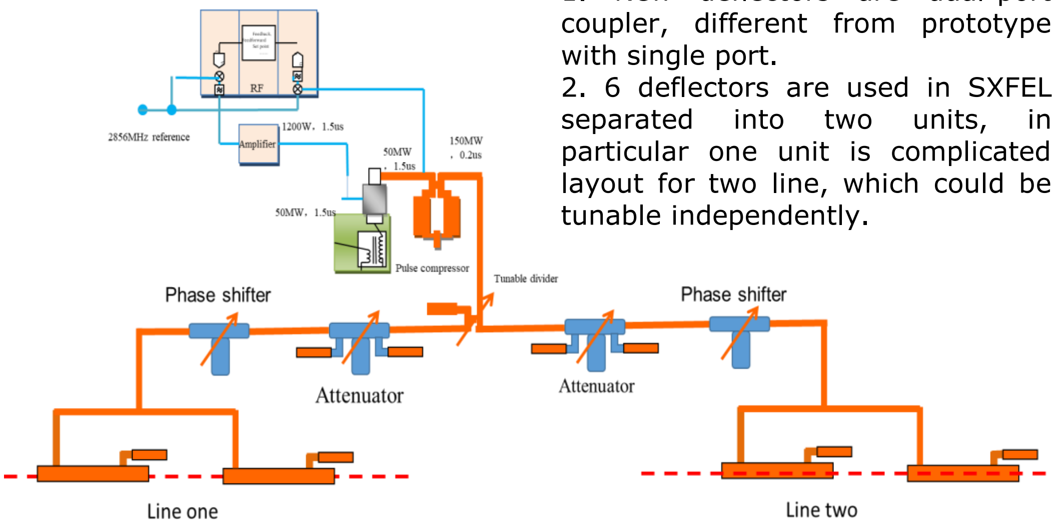


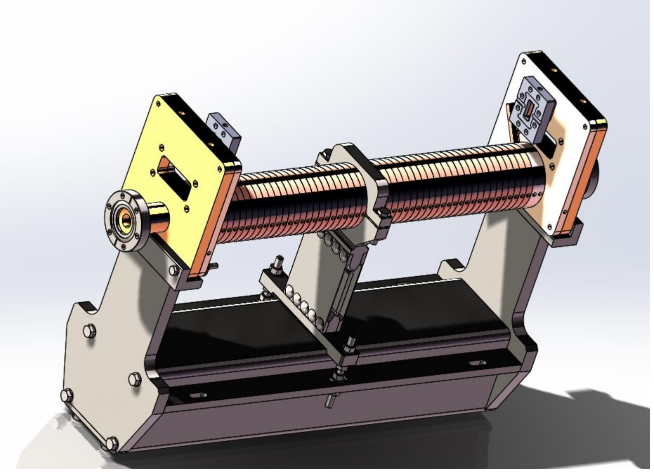
无压缩：横轴为能量，纵轴为束长。

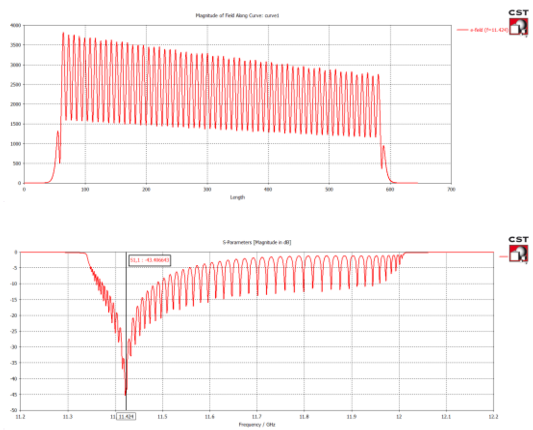


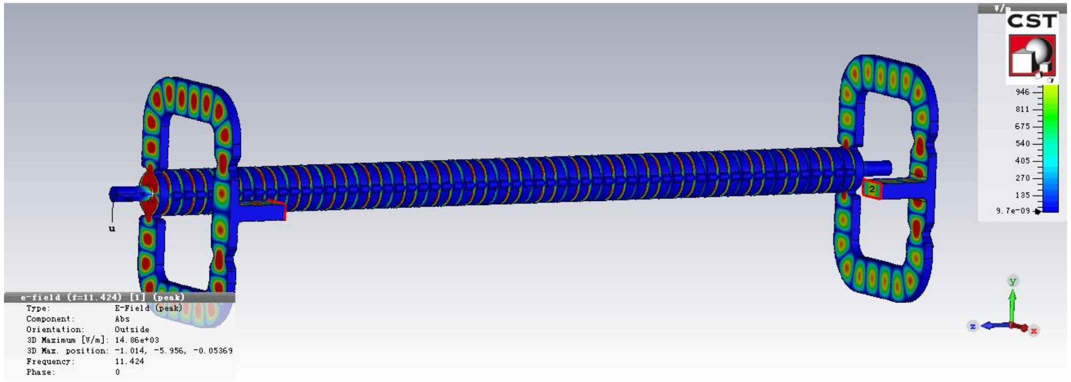
X-band deflecting unit

1. New deflectors are dual-port coupler, different from prototype with single port.
2. 6 deflectors are used in SXFEL separated into two units, in particular one unit is complicated layout for two line, which could be tunable independently.



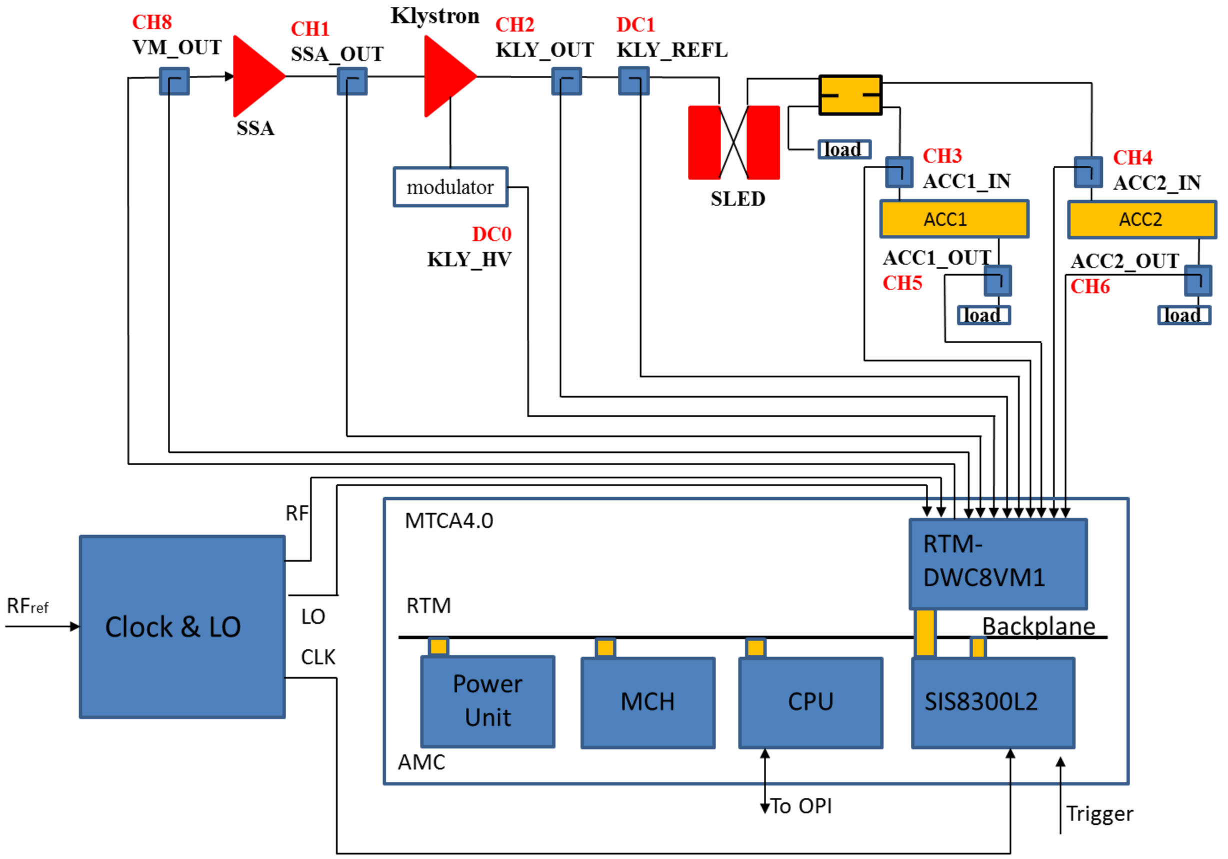




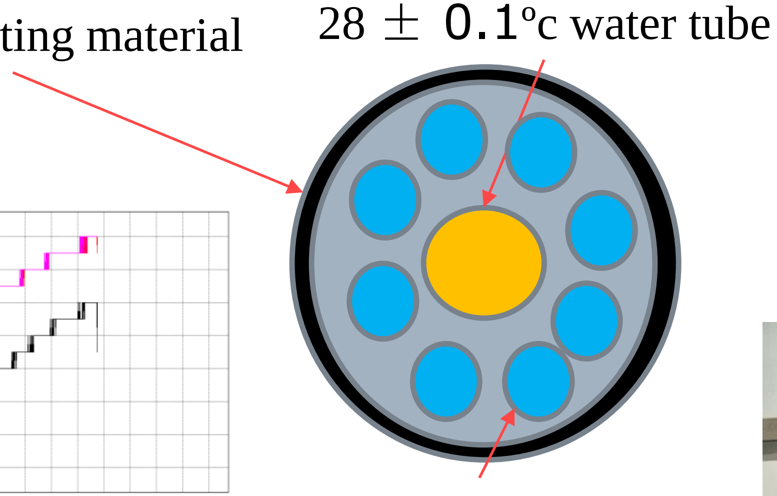


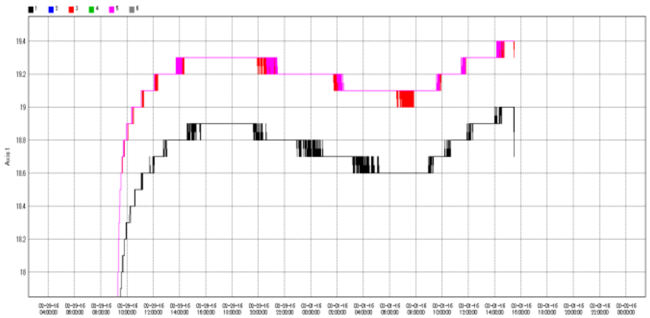
LLRF based on MTCA 4.0

1. LLRF system is based on MTCA 4.0 hardware and software driver, and was developed to carry out many functions, including amplitude and phase feedback and modulation, data acquisition and reflection protection.
2. 8 RF signals and 2 DC signals channels.

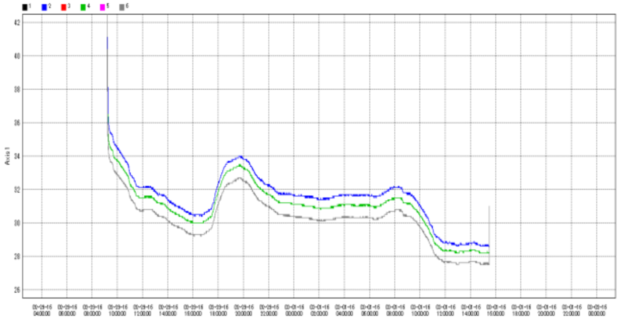


Temperature control of cabinet and cable for LLRF

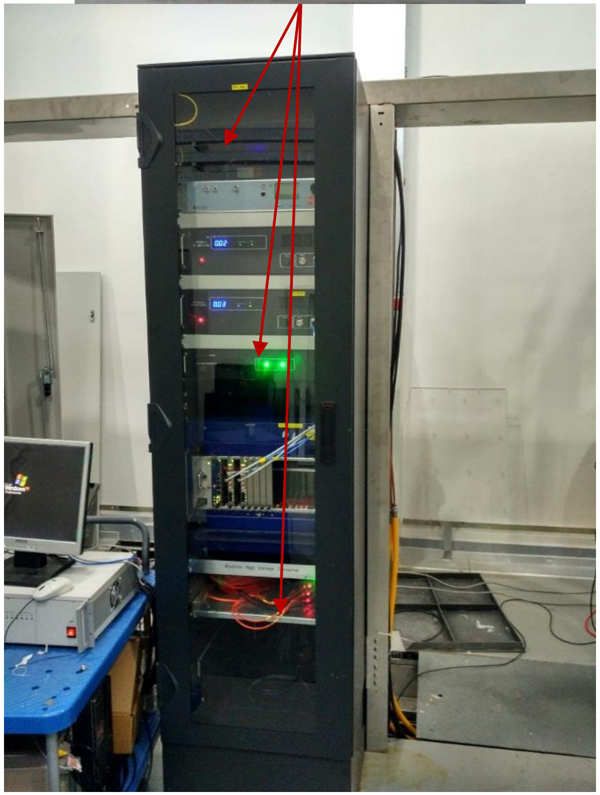




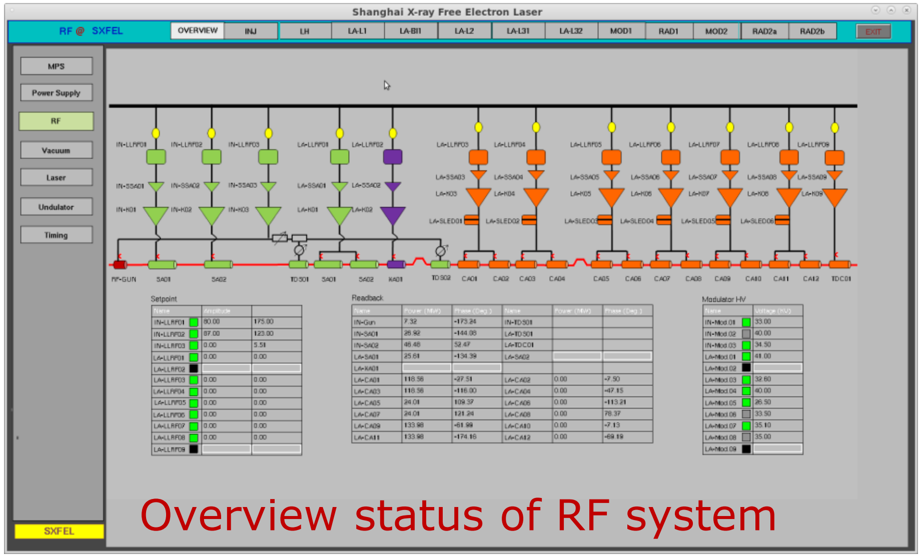
Three locations for temperature measurement
±0.1ºC stability during 29 hours

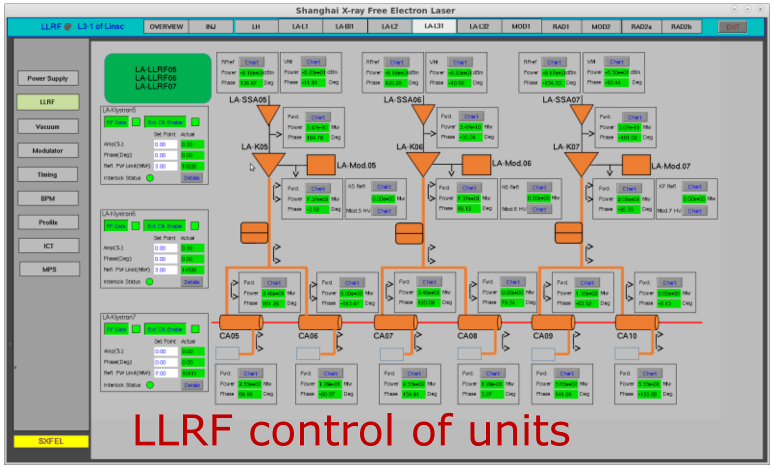


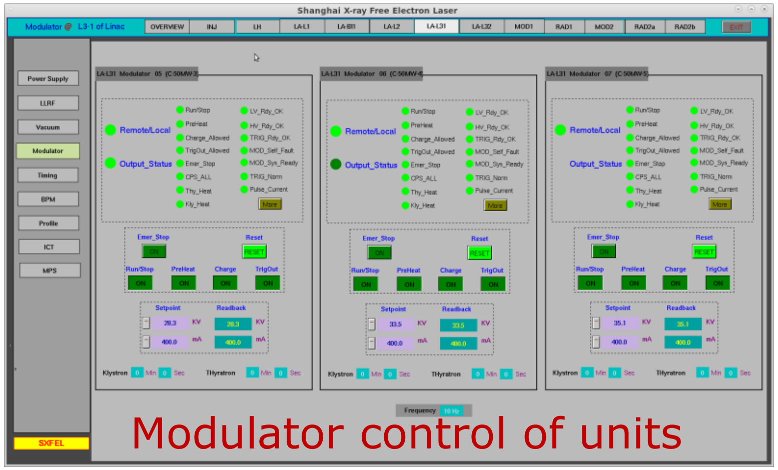
Three locations for humidity measurement
±2.8% stability during 29 hours



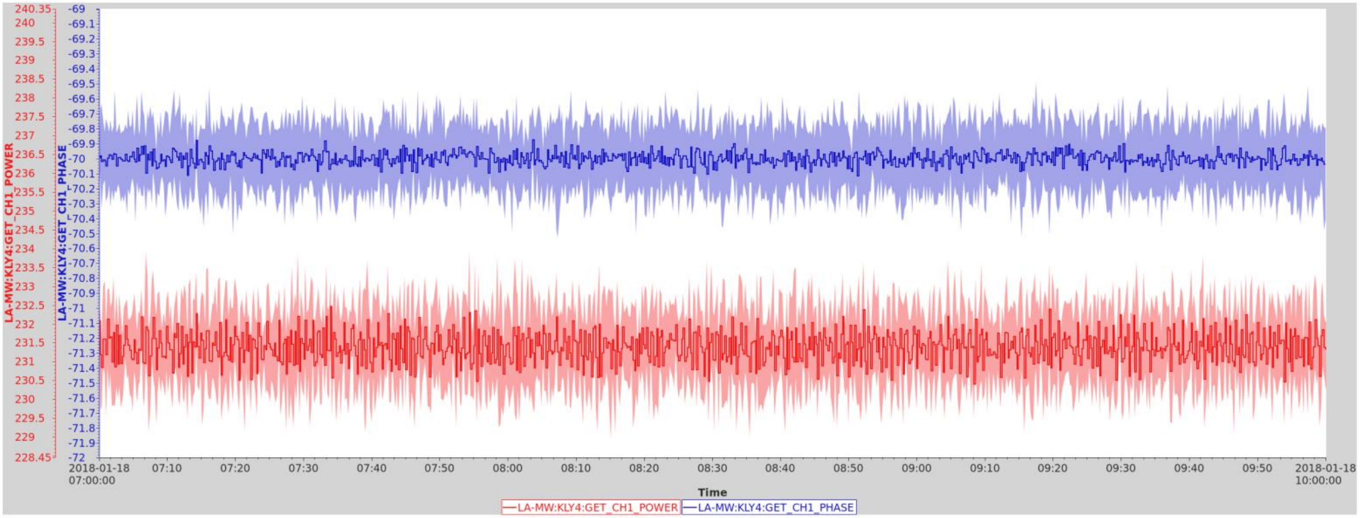
Control GUI of RF system







Close-loop operation of LLRF

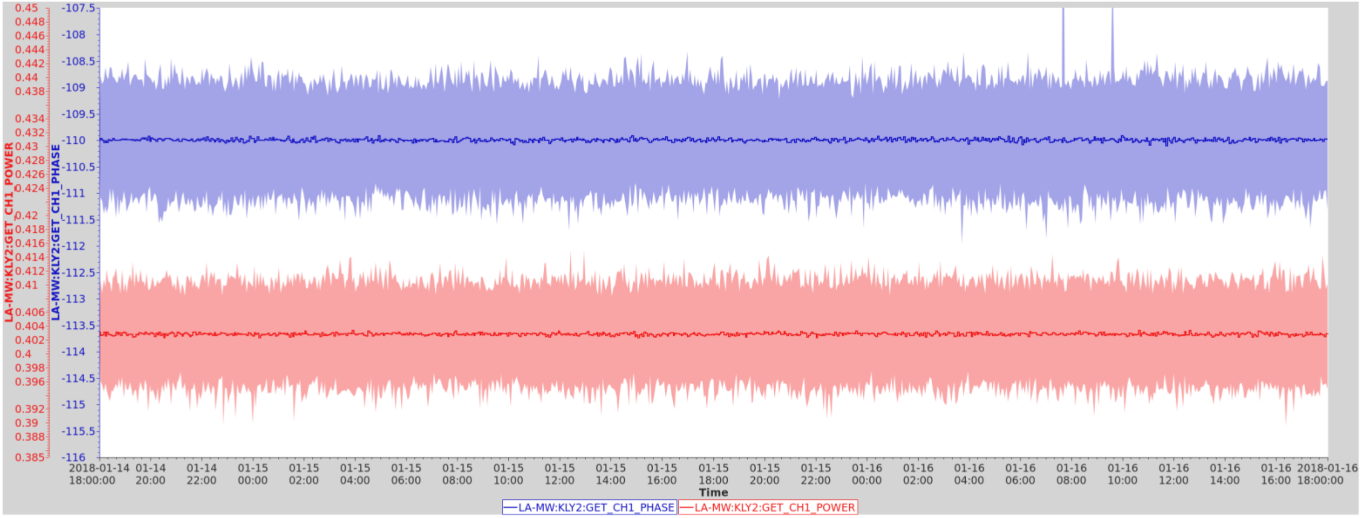


C-band typical operation

3 hours operation.

Phase: 0.15 degree (rms)

Amplitude: 0.7% (rms)



X-band operation.

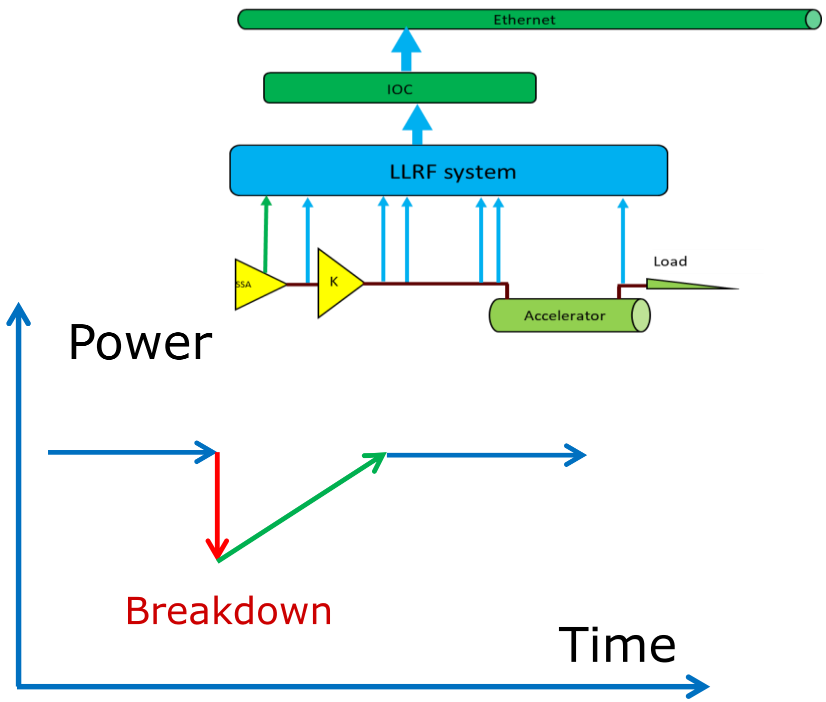
48 hours operation

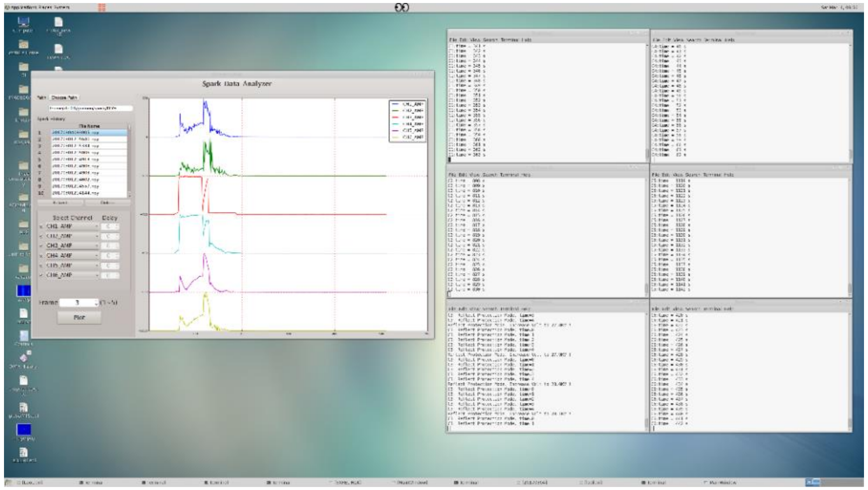
Phase: 0.5 (rms)

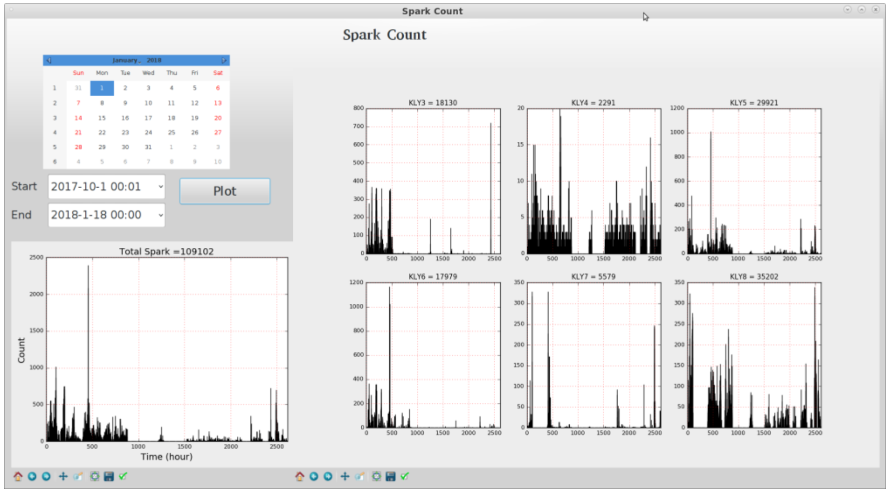
Amplitude: 0.8% (rms)

Breakdown monitor, protection and analysis system

1. C-band high gradient operation should be monitored all time.
2. Structures are protected when breakdown happens, power is dropped first, and ramped slowly.
3. All operation during breakdown events is control automatically based on EPICS system.
4. All breakdown data is stored, and could be analyzed for any time duration.







Conclusion

- SXFEL realizes operation with three types of frequency, including S, C and X-band RF system as functions of acceleration, pulse compression, deflecting and linearizer.
- High gradient operation in facility is more strict and complicated than test stand, and it should be considered on many factors, and then realized on target of high gradient.
- SXFEL has solved many technique challenges, and is ongoing with beam commissioning and FEL experiments.


SINAP
June 4-8, 2018
Shanghai Institute of Applied Physics,
Chinese Academy of Sciences
SINAP, Shanghai, China
International Workshop on
Breakdown Science and
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Walter Wuensch (CERN)
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Valery Dolgashev (SLAC)
Angeles Faus-Golfe (LAL)
Wencheng Fang (SINAP)
Local Organizing Committee
Wencheng Fang
Qiang Gu
Zhengchi Hou
Wenpeng Qi
Jianhao Tan
Xiaoxia Huang


Thank you.
See you in HG2018.
See you in Shanghai.