CEPC Linac injector R&D status

CEPC international workshop 2023, 23-27 Oct, 2023

Jingru Zhang

On behalf of linac group, Institute of High Energy Physics, CAS

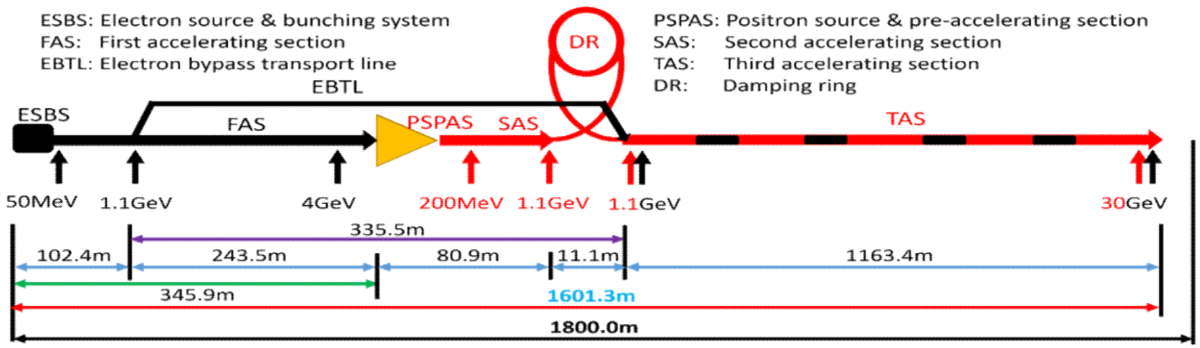
Content

- **Introduction**
- **Design Parameters / Requirement List**
- **Key technology R&D**
  - Electron gun
  - Positron source
  - S-band RF system
  - C-band RF system
  - 5 cell cavity for DR
  - LLRF and phase reference line for linac
- **Summary**

Design Parameters / Requirement List

Parameter	Symbol	Unit	Baseline
Energy	E_{e-}/E_{e+}	GeV	**30**
Repetition rate	f_{rep}	Hz	100
Bunch charge		nC	1.5 (3)
Energy spread	σ_E		1.5×10^{-3}
Emittance	ε_r	nm	6.5

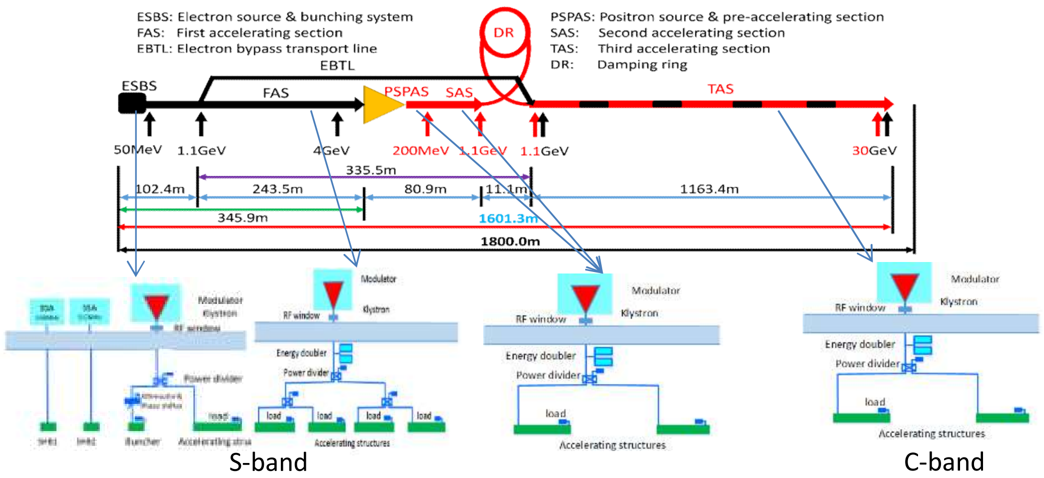
- 30 GeV linac provides electron and positron beams for booster with 1.1GeV damping ring
  - Electron gun: thermal cathode
  - Positron source: Conventional scheme (fixed target)
  - 30 GeV normal conducting accelerating structures including bunching system
    - S-band Linac: FAS: 4GeV + PSPAS: 200MeV + SAS: 1.1GeV
    - C-band Linac: TAS： 1.1GeV→30GeV
  - 1.1GeV damping ring with two 5 cell normal conducting cavities
- The linac tunnel length is 1.8km
    - Linac is about 1.6 km
    - 200 m as reserved space



Design Parameters / Requirement List

- RF distribution of the 30 GeV linac
  - S-band, 80 MW klystron, the number of S-band Acc. Structure is 93, big hole s-band structure after the positron source is 16. the number of pulse compressor is 33
    - 1-1(ESBS), 1 accelerating structure, 22MV/m
    - 1-4 (FAS), 21 sets, 84 standard accelerating structures, with pulse compressor, 22MV/m
    - 1-2(PSPAS), 8 sets, 16 big hole accelerating structures, 22MV/m, with pulse compressor
    - 1-2(SAS), 4 sets, 8 accelerating structures, 27MV/m , with pulse compressor
  - C-band, 50 MW klystron, C-band structures: 470, with 235 pulse compressors
    - 1.1GeV-30GeV, 1-2(TAS), 235 sets, 470 accelerating structures, ~40MV/m,

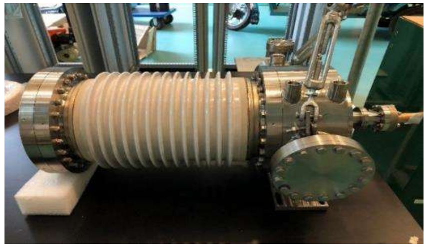
Parameter	Unit	S-band		C-band
Frequency	MHz	2860		5720
Length	m	3.1	2.0	1.8
Cavity mode		2π/3		3π/4
Aperture	mm	19~26	25	12~16
Gradient	MV/m	22/27	22	40
Cells (include coupler cells)		86	55	89
Number of Acc. Stru.		93	16	470
Number of Klystron		33		236
Klystron Power	MW	80		50



Successful key technology for HEPS (S-band)

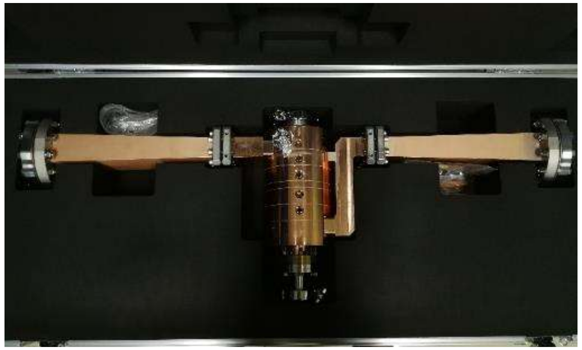
- The HEPS linac is a 500MeV S-band normal conducting RF system
- 2023.3.9 ~14:30， the exit energy reached 500MeV
  - 2 SHBs, 1 prebuncher, 1 buncher , 9 accelerating structures, 4 SLAC type pulse compressors
- Until now, the operation has been stable

HEPS linac tunnel

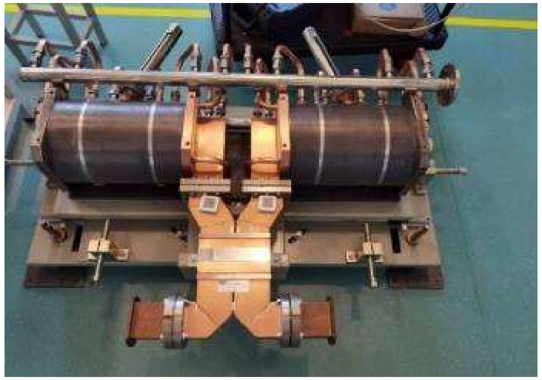


Electron gun

SHBs



Buncher

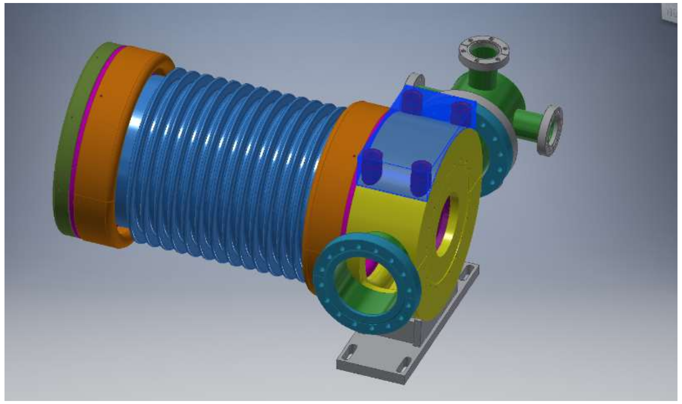


SLAC type pulse compressor

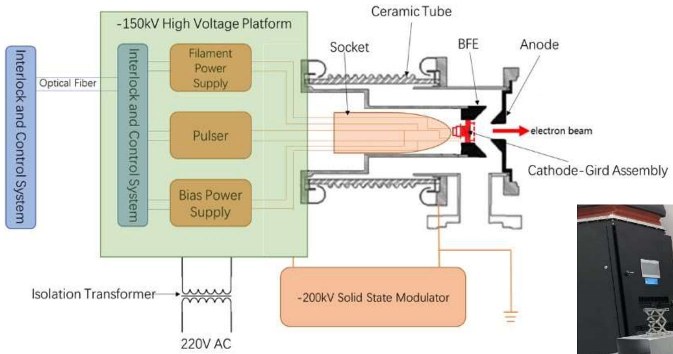
S-band accelerating structure

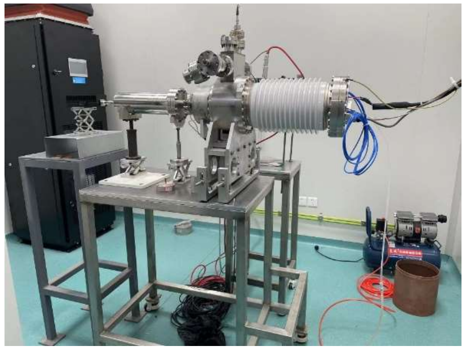
Electron gun

- Traditional thermionic triode gun
- A 1.5 nC bunch charge for electron injection, and a 10 nC bunch charge for positron production
- The parameters is similar to HEPS and BEPCII electron gun at IHEP



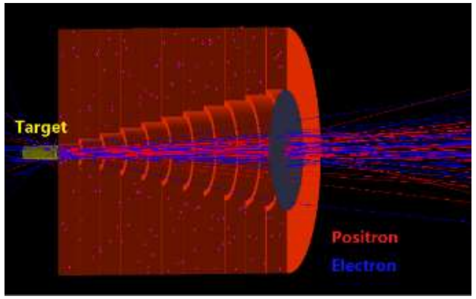
Parameter	Unit	Value
Type	-	Thermionic Triode Gun
Cathode	-	Dispenser cathode
Beam current	A	> 10
High voltage of anode	kV	150
Bunch charge 1	nC	3.3 (e^- injection)
Bunch charge 2	nC	11 (e^+ production)
Repetition rate	Hz	100
Pulse duration	ns	1



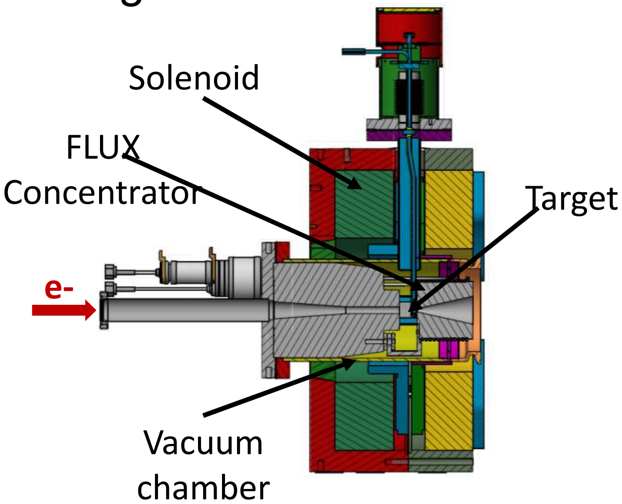


The parameters and design of the electron gun

Positron Source

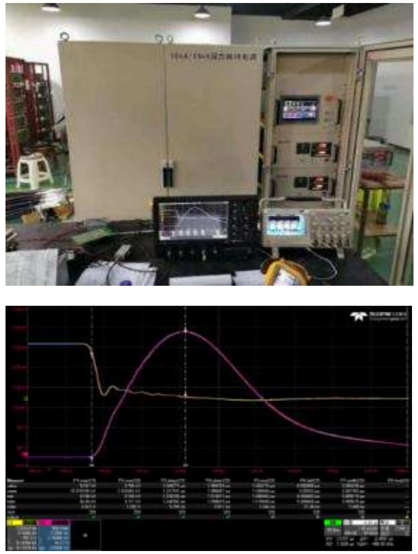


- Fixed Target (Conventional, tungsten,15mm thickness)
- FLUX Concentrator R&D
  - A flux concentrator prototype had been successfully developed
  - A 15 kA solid-state modulator had also been developed for driving FC
  - A peak magnetic field of 6.2 T had been obtained inside the FC at a 15kA driving current



Design of positron converter device

The FLUX conentrator

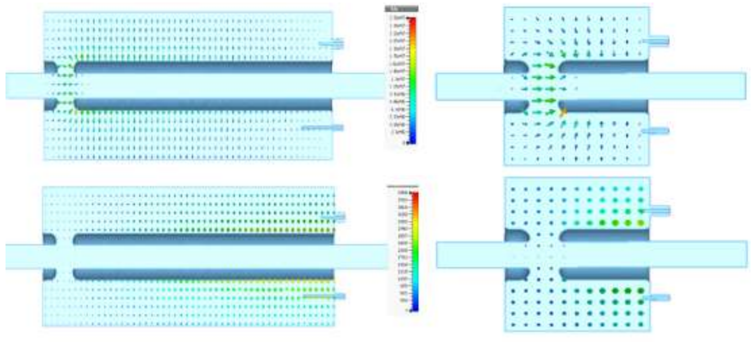


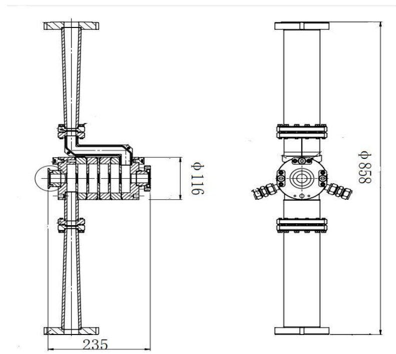
The 15kA solid-state modulator

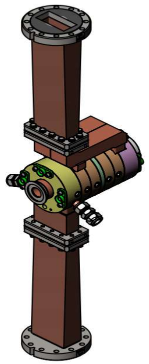
Bunching system

- Sub-harmonic buncher (SHBs)
  - Capacitively loaded structure
- Buncher
  - Travelling wave
  - 2π/3
  - β=0.75, 6 cells
- The same as HEPS only frequency a little difference

Parameters	Unit	Value	
		SHB1	SHB2
Frequency	MHz	158.89	476.67
Shunt Impedance	MΩ	1.46	2.53
Unloaded Q	-	8475	12431
VSWR	-	< 1.05	< 1.05
$E_{surface, max}$ @100 kV	MV/m	6.4	6.1
Required power @100 kV	kW	10	7
RF Structure type	-	Re-entrant SW	Re-entrant SW


SHB1 SHB2



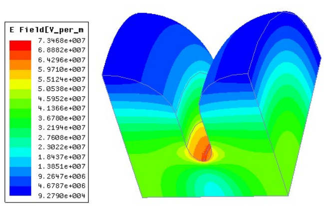


Parameters	Unit	Value
Frequency	MHz	2860
Phase advance	-	2π/3
Cell number	-	6
Phase velocity	-	0.75
Group velocity	-	0.0193
Attenuation constant	Np/m	0.147
Shunt impedance	MΩ/m	33.2
Unloaded Q	-	11083
Bunching voltage (Max)	MV	1.2
VSWR	-	<1.2
Input power	MW	6
RF Structure type	-	TW/CI

S-band accelerating structure

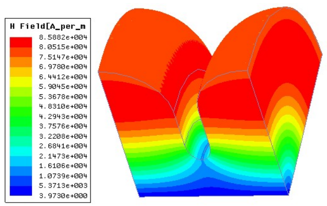
- 3-meters long constant gradient structure
  - Cavity shape optimization
  - Rounding the cell
    - Improve the quality factor by >12%
    - Reduce the power consumption
    - Increase the shunt impedance by ~10.9%
  - Elliptical the irises shape (r2/r1=1.8)
    - Reduce the peak surface electrical field by 13%

Parameters	Values	Unit
No. of Cells	84+2couplers	-
Phase advance	2π/3	rad
Total length	3.1	m
Length of cell (d)	34.988	mm
Disk thickness (t)	5.5	mm
Shunt impedance (Rs)	60.3~67.8	MΩ/m
Quality factor	15465~15373	-
Group velocity: Vg/c (%)	2% ~ 0.94%	-
Filling time (t_f)	784	ns
Attenuation factor (τ)	0.46	Np
Power (@30MV/m)	74	MW



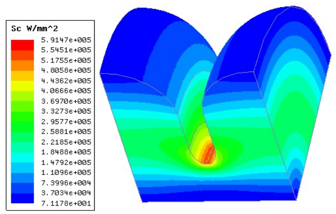
E_peak=73 MV/m

Surface electric field



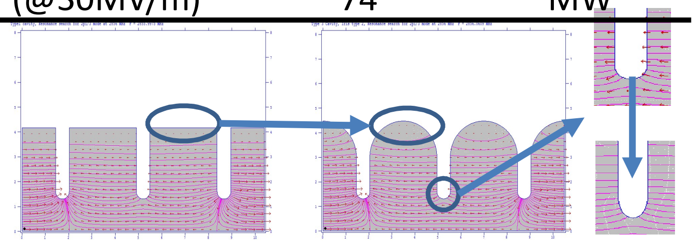
H_peak=86 kA/m

Surface magnetic field



Sc_max=0.59 MW/mm^2

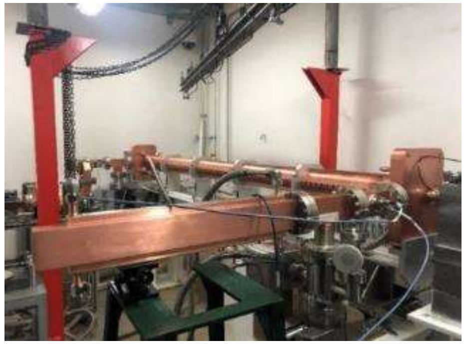
Modified Poynting vector



Superfish is used to optimize the single cell

S-band accelerating structure

- High power test result
  - The tested average gradient has reached 33 MV/m at high power test (with SLED)
  - This familiar design (the frequency is deferent) also used in HEPS and now the gradient is 26MV/m with beam (Limited by the power)

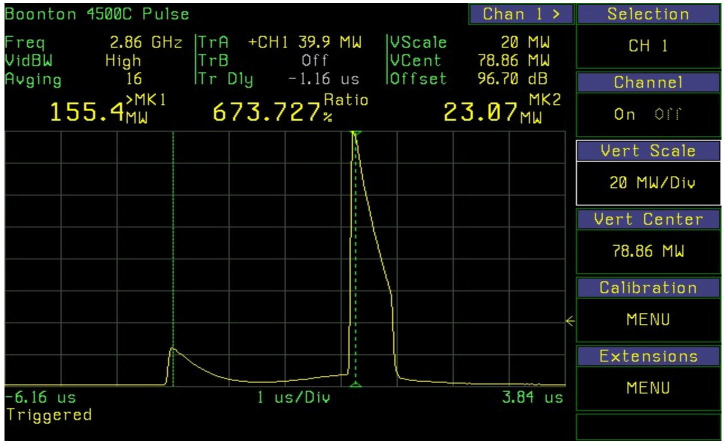


High power test bench

Modulator and klystron

$$P_{in} = \frac{(V*L)^2}{RL(1-e^{-2\alpha L})M^2}$$

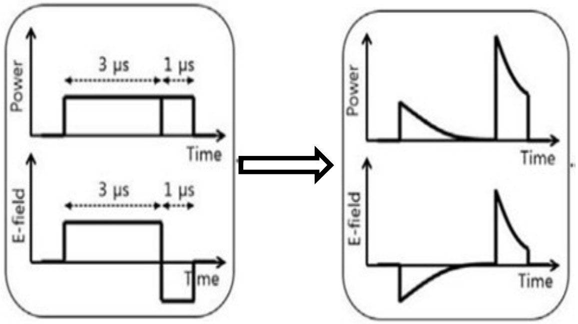
The input power with SLED



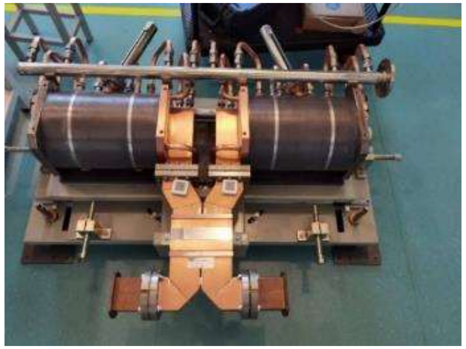
S-band pulse compressor

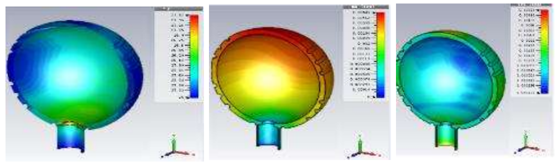
- Dual cavity structure technology is traditional and mature
- Spherical cavity pulse compressor(TE_{113})
  - Finished RF simulation, thermal stress, vacuum pumping speed and vacuum level analysis
  - The prototype has completed
  - S-band 80MW klystron high power test bench is ready, high power test will be conducted recently

Parameter	Value
Klystron output power	80 MW
Pulse width	4 μs
Pulse repetition rate	100 Hz
AS Filling time	780 ns



4uS→0.8uS


HEPS pulse compressor

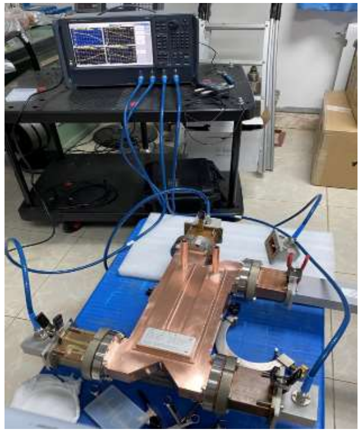

Temperature *Deformation* *Stress*


Pulse compressor for CEPC

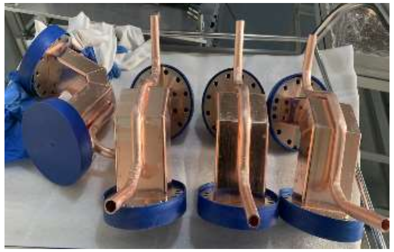
S-band waveguides

- Waveguide, load, directional coupler, 3dB power hybrid, extraction waveguide, loads etc. used in HEPS
- The directivity of the directional coupler is

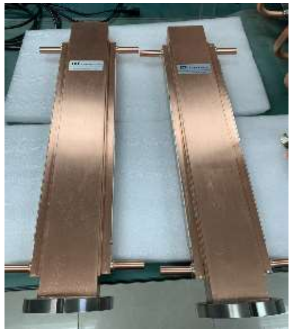
about 40dB



Straight waveguide



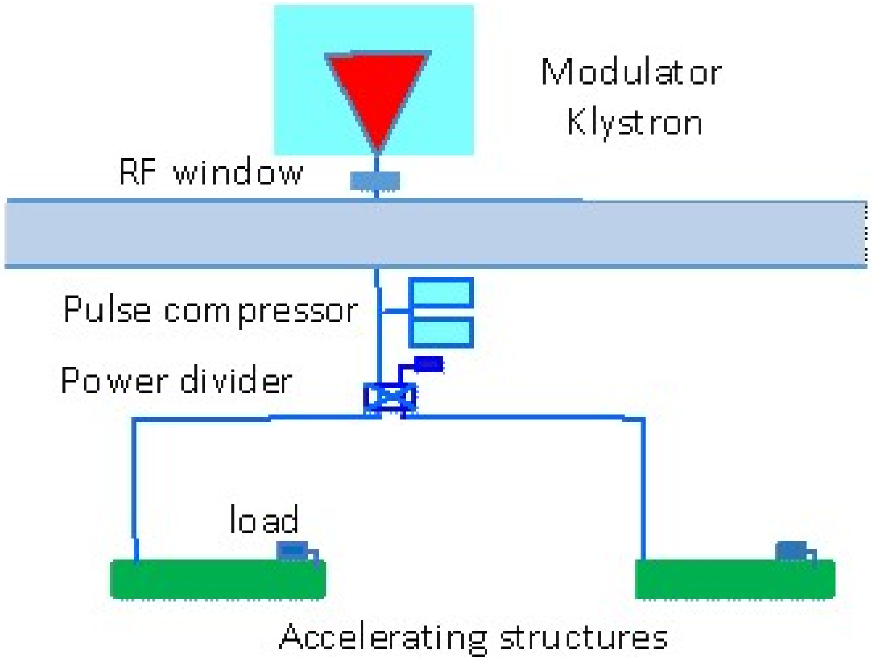
Bent waveguide

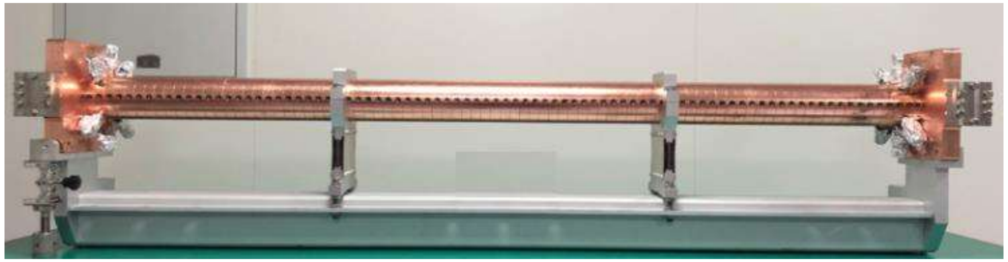


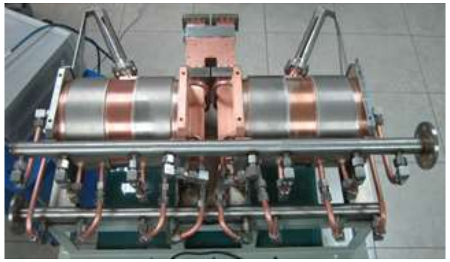
Dummy loads

Extraction waveguide

C-band RF system baseline design







C-band accelerating structure R&D states

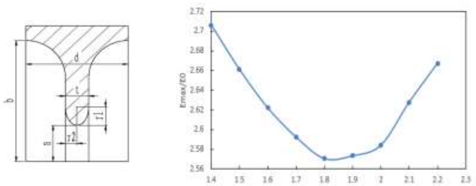
- Other labs
  - The maximum average gradient with beam is about 40MV/m

	IHEP	SARI	RIKEN	INFN	PSI
Frequency(MHz)	5712	5712	5712	5712	5712
Mode	$3\pi/4$	$4\pi/5$	$2\pi/3$	$2\pi/3$	$2\pi/3$
Length (m)	1.8	1.8	2	1.4	2
Gradient at high power test bench(MV/m)	-	50[1]	50.1[2]	36[3]	52[4]
Operating gradient with beam (MV/m)	-	41.7(maximum, private talk)	41.4	36	28

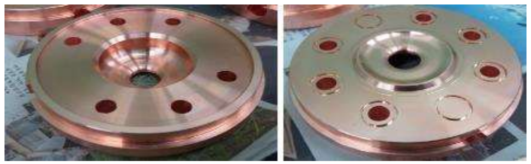
1. W. Fang, et al. THE C-BAND TRAVELING-WAVE ACCELERATING STRUCTURE FOR COMPACT XFEL AT SINAP . NIMA 2016
2. T. Sakurai, et al. C-band disk-loaded-type accelerating structure for a high acceleration gradient and high-repetition-rate operation. PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 042003 (2017)
3. D. Alesini, et al. HIGH POWER TEST RESULTS OF THE SPARC C-BAND ACCELERATING STRUCTURES. IPAC 2014
4. F. Loehl, et al. STATUS OF THE SWISSFEL C-BAND LINEAR ACCELERATOR. FEL 2013

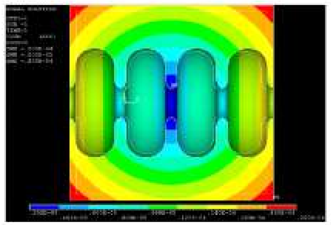
C-band accelerating structure

- The R&D of C-band accelerating structure at IHEP
  - The beam dynamics of linac based on this design
  - Constant gradient, 3π/4 mode, 1.8 meters long (Including mechanical length, Effective length is about 1.7m)
    - Round cavity shape
    - Racetrack symmetrical magnetic coupling
  - High power tests will be performed when C-band power source is available

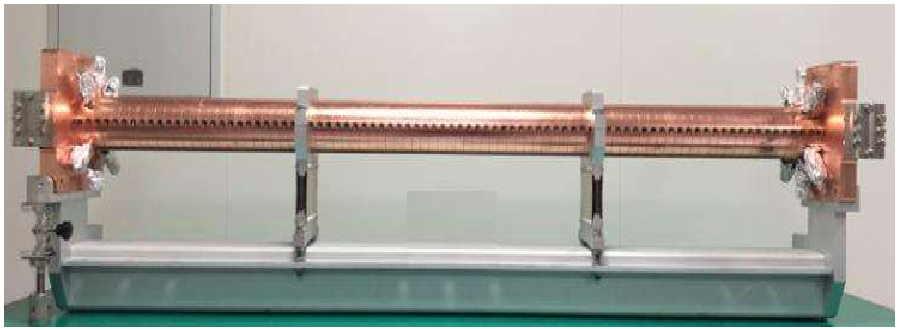


Cavity shape





The deformation caused by temperature variation



C-band accelerating structure

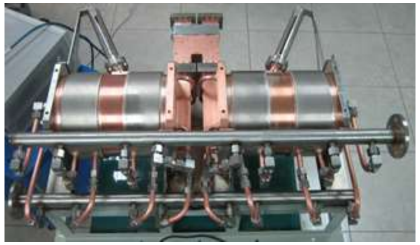
- The design parameters between different lab
  - Mode :3π/4, 2π/3, 4π/5
  - Length
  - Disc thickness
- Though the phase advance is deferent, the other key parameters is similar

	IHEP	Spring8	SINAP[1]
Frequency: f（MHz）	5712	5712	5712
No. of Cells	87+2	100 regular cells +2 coupler	89+2
Phase advance	3π/4	2π/3	4π/5
Total length(m)	1.8	2	1.784
Length of cell : d (mm)	19.675	17.495	20.994
Disk thickness: t (mm)	4.5	4	5
Average aperture: 2a (mm)	14.04	15.938~12.107	15
Average diameter : 2b (mm)	45.6	43.196~41.869	-
Shunt impedance(average) : Rs (MΩ/m)	66.05	66	62
Quality factor : Q	11358~11186	9300/8900(measured)	10470
Group velocity: Vg/c (%)	2.8% ~ 0.96%	2.3%(average)	1.7%(average)
Filling time : t_f (ns)	350	290	330
Attenuation factor : τ	0.56	0.59	0.585
Epeak/E0	2.57	2.6	2.6

1. W. Fang, et al. THE C-BAND TRAVELING-WAVE ACCELERATING STRUCTURE FOR COMPACT XFEL AT SINAP

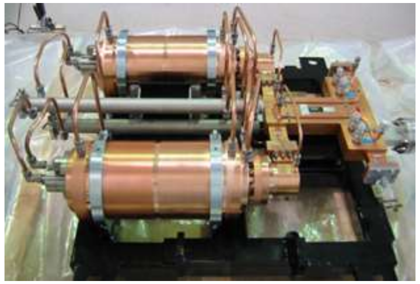
C-band pulse compressor

- The model selection of the pulse compressor
  - SLAC type (Two cavities)
  - BOC type
  - Spherical type （new technology)

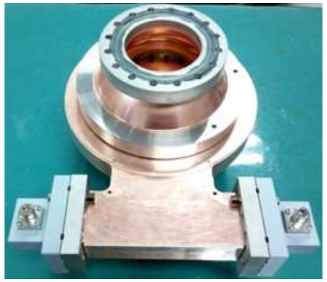


IHEP C-band SLED

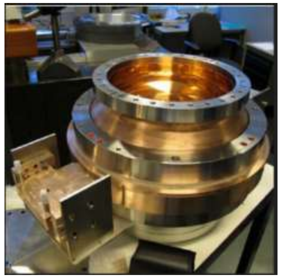
Test results of IHEP C-band SLED



SACLA C-band SLED



IHEP C-band BOC



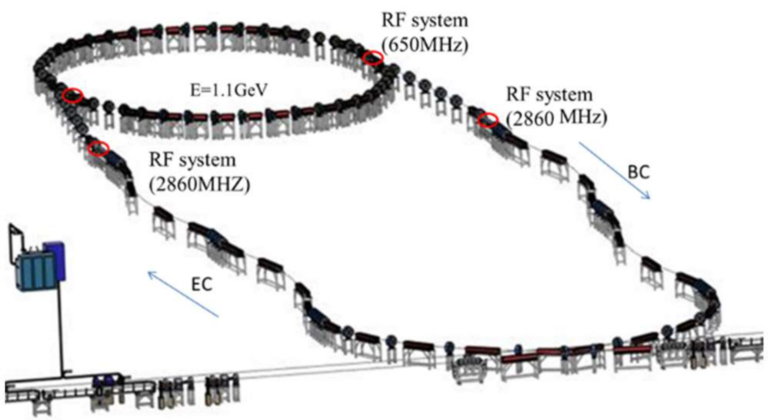
PSI BOC

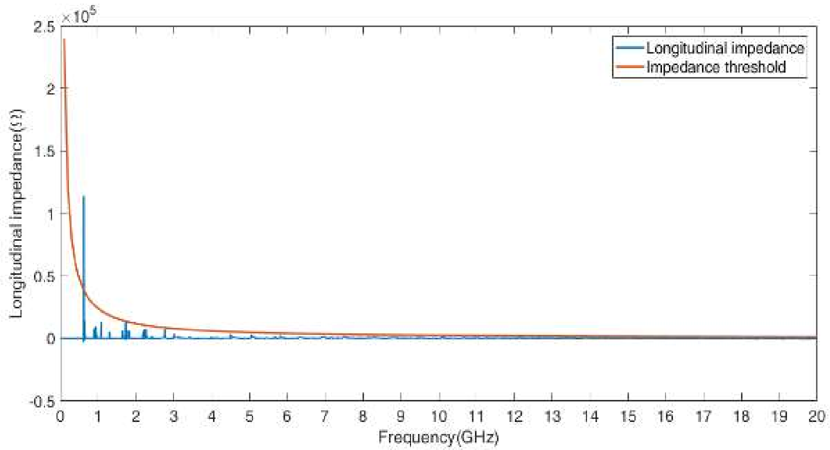
Spherical SLED（Xband of SLAC）

Damping Ring RF cavity

D. Wang, Y.D. Liu, X.H. Cui

- The total cavity voltage requirement is 2.5MV
- 5 cell cavity aperture is decided by impedance、HOM and instability threshold
  - Taking into account the simulation results for impedance threshold and HOM power, the 5-cell cavity with a 90 mm aperture is considered the best choice
- There are also two sets s-band structure at the transport line for energy and bunch length compression and the cavity voltage is about 20MV
  - 1 meters long S-band accelerating structure with 30MW power source

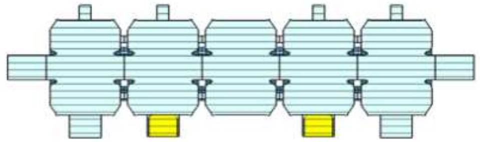


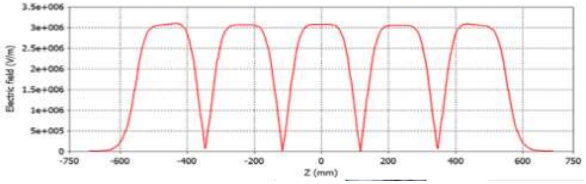


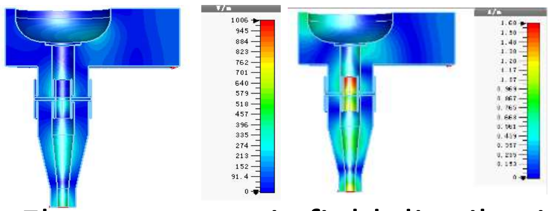
Damping Ring RF cavity

- The design of the 650MHz 5 cell cavity finished
  - RF cavity design
  - Input coupler and doorknob design
  - Vacuum design
  - Mechanical design

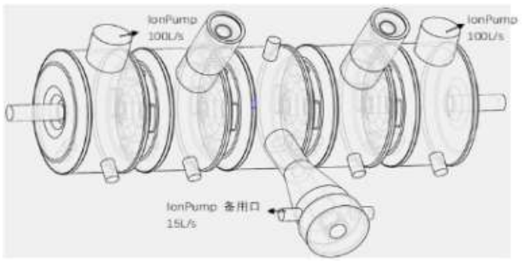
Parameters	Unit	Value
Operation frequency	MHz	650
Voltage per cavity	MV	1.25
Cell length	mm	5×230.61
Shunt impedance	M	16
R/(Q×l)	Ω/m	430
Q factor		32000
Dissipated power per cavity (20% margin)	kW	59
Emax	MV/m	8.5



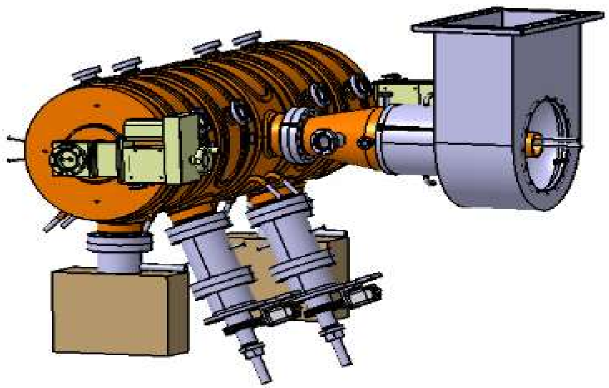




Electromagnetic field distribution



Ion pump distribution

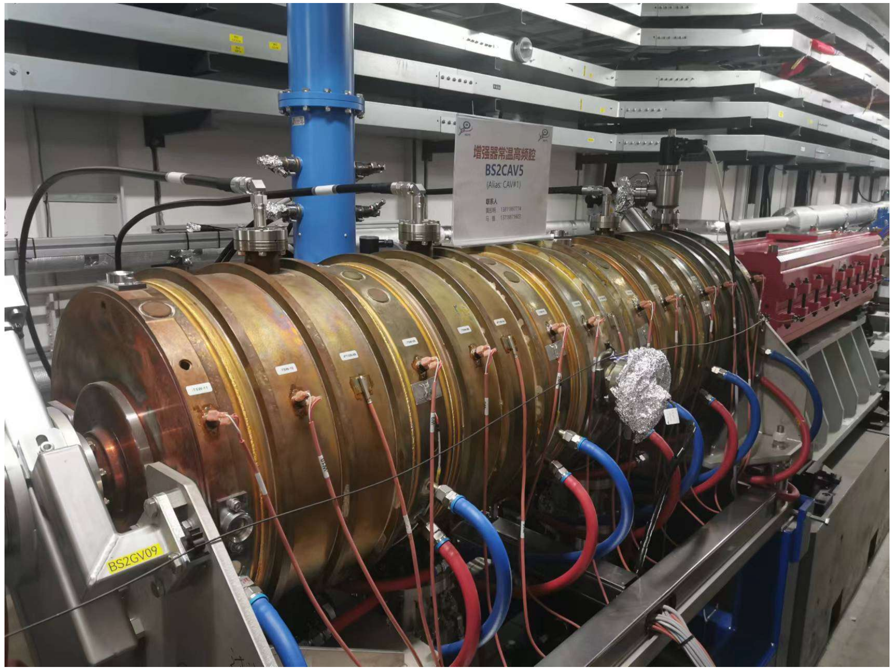


Mechanical design

Damping Ring RF cavity

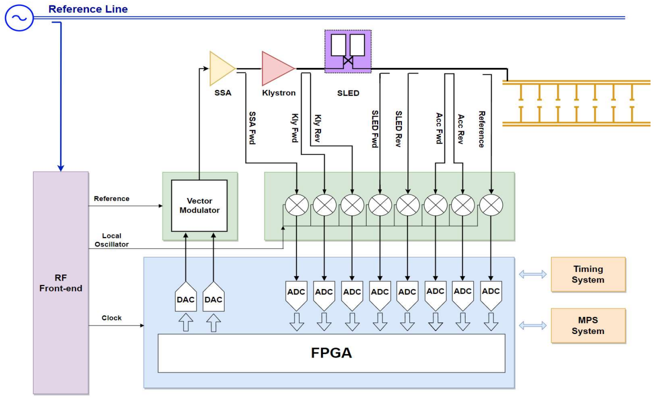
P. Zhang

- 5 cell normal conducting cavity at HEPS booster

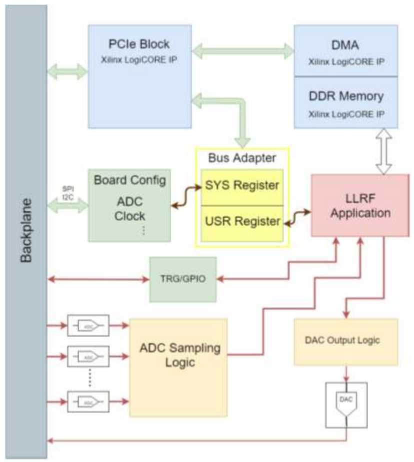


LLRF and phase reference line

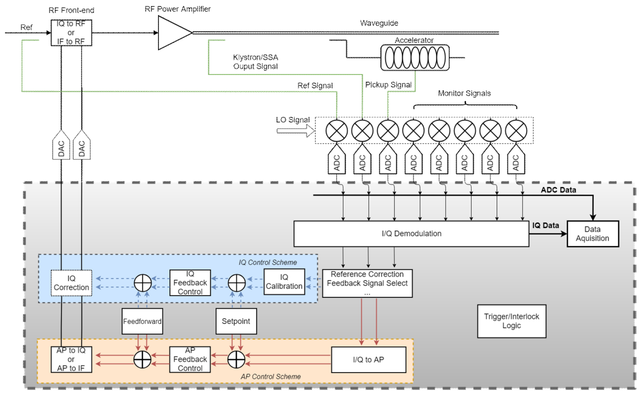
- Low Level RF design
  - Based on feedback control in which the RF signal is measured and compared to the desired set-point
  - The LLRF system mainly includes the following functions
    - Stabilization
    - System monitoring and diagnosis
    - Klystron linearisation
    - Exception handling
    - User interface



LLRF system scheme



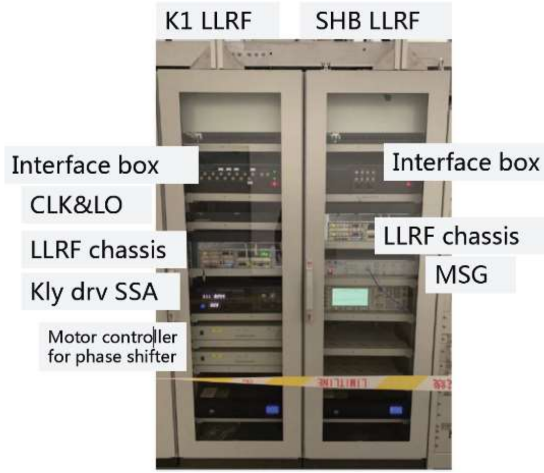
LLRF firmware scheme

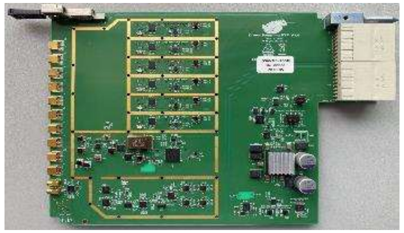


LLRF algorithm scheme

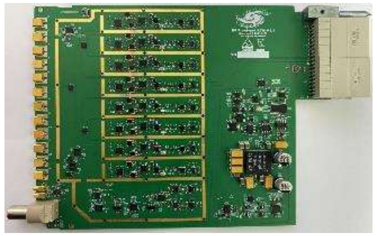
LLRF and phase reference line

- LLRF for HEPS
  - The digital LLRF has been adopted
  - It consists of a 2U MTCA.4 chassis, a MCH, an AMC computer board, a Struck SIS8300-KU card and a Struck DWC8VM1 rear transition-module with supporting clock/local oscillator (LO)/reference generation RF circuits
- System works steadily now





Down converter RTM
(For accelerating tube)



Direct-sampling RTM
（for SHB cavities）

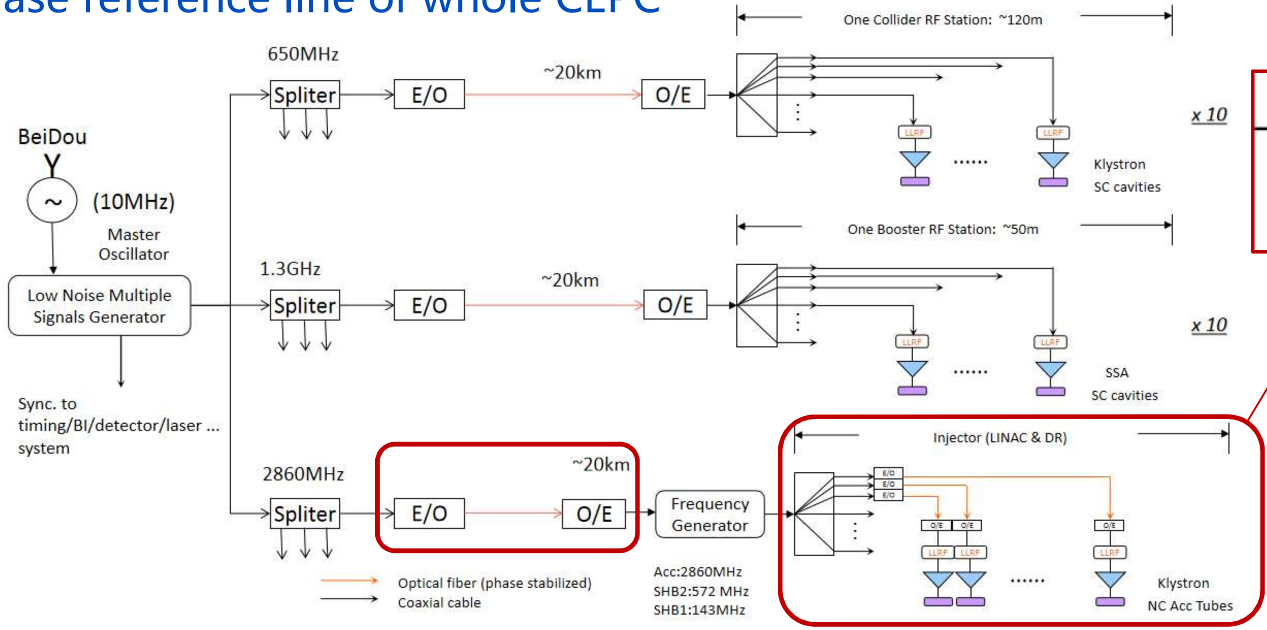
AMC IO board (used as timing and interlock signal interface)

Local oscillator signal generator
(Generate 2973.8MHz LO signal and 99.98MHz clock signal for LLRF system from 2998.8MHz reference)

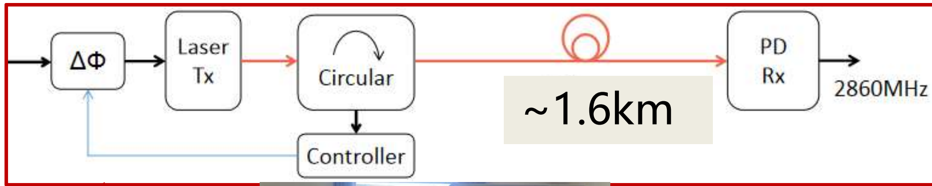
Phase reference line for CEPC Linac

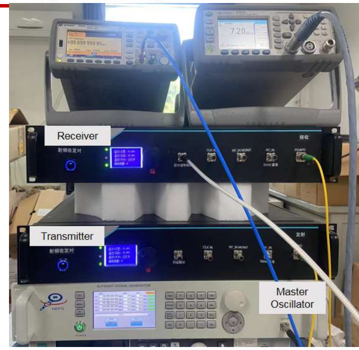
- Linac frequency 2860MHz derived from Master oscillator who provides frequency standard of the Main Ring(650MHz), the Booster(1.3GHz) and the Injector(2860MHz);
- The whole linac is 1.6 km long, transfer signal by coaxial cable not feasible due to attenuation/EMI…so optical fiber will be used. RF signals transferred by CW laser will be detected by comparing forward and backward optical phase, and compensated by phase shifter. The phase stability of 1.6 km transfer will be less than 0.1degree. Each LLRF will need one channel.

Phase reference line of whole CEPC



CEPC Linac's phase reference line

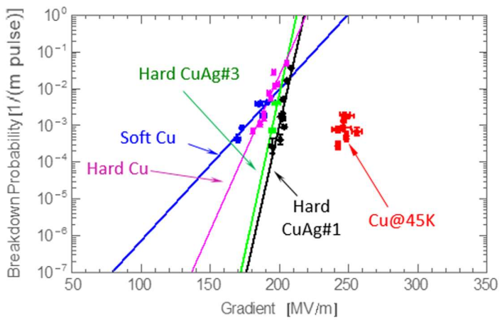


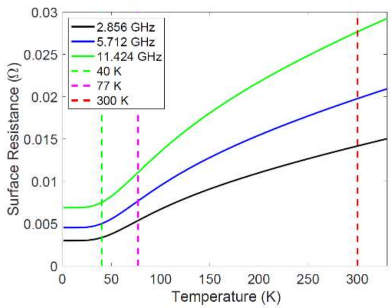


Tx-Rx pair of HEPS

Higher gradient of C-band accelerating structure

- C-band RF system is from 1.1GeV to 30GeV of the linac
- Higher gradient→Reduce RF breakdown rate→Using harder materials to reduce cyclic fatigue
- Low temperature operation
  - That can increase the hardness of the material, thereby reducing surface deformation and reducing the number of breakdown
  - At the same time reduce surface resistance, thereby increasing Q value and shunt impedance



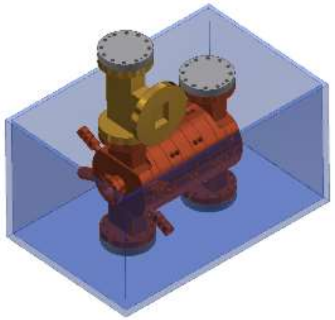


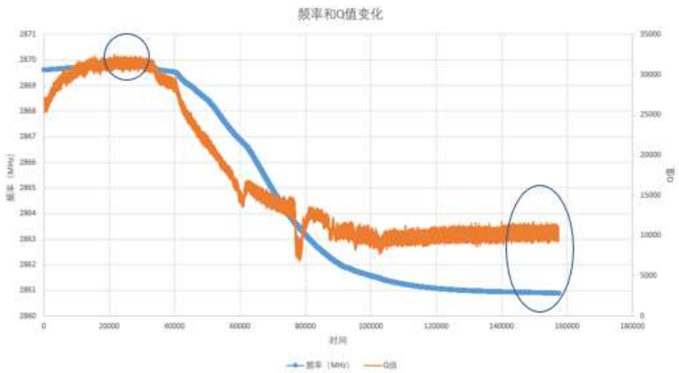
A. D. Cahill, et al., PRAB 21, 102002 (2018)
A. Cahill, et al, IPAC MOPMW038 (2016)
Mei Bai, et al., SLAC-PUB-17629, 2021

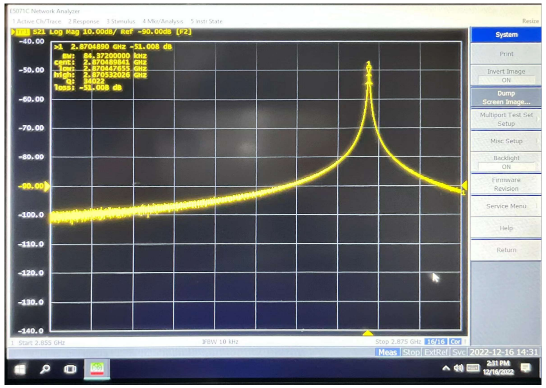
- With the support of the IHEP fund, we began to study the cold copper structure with 77k liquid nitrogen

Low temperature test of an S-band structure

- It is an S-band traveling wave structure
- The temperature is from 287.17k to 77.36K liquid nitrogen and naturally back to room temperature
  - The frequency change is 8.478MHz (theoretical value: 8.452MHz, with a difference of 26KHz)
  - Q value increases 3 times



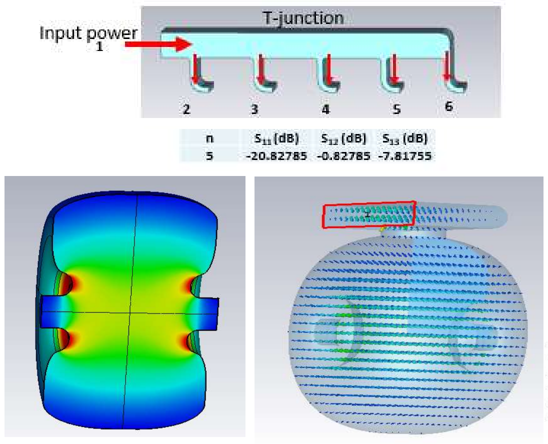




C-band parallel coupling structure design

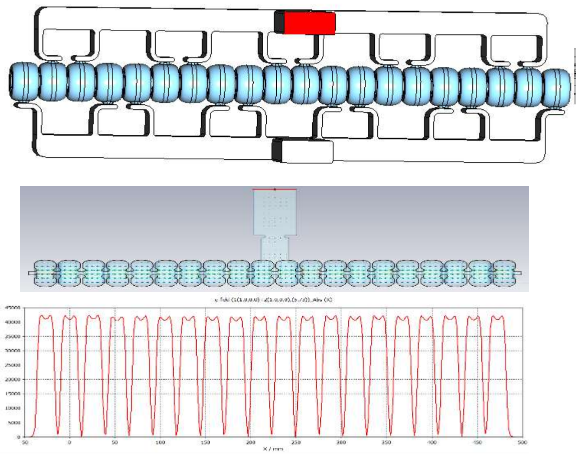
- Finished the RF design， including cavity optimization, coupling design, power distribution design
- 40MW input power, 2MW for each cavity
- The gradient can reach 139MV/m

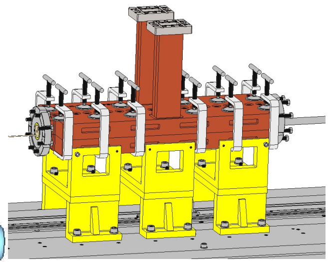
Parameters	Value
Fre (MHz)@77K	5712
Mode	π
Cavity numbers	20
Shunt impedance per meter(MΩ/m)@77K	303
E_0/Es	2.42
Q_0@77K	31905
Input power (MW)	40
Filling time(us) @90%	2.2
Gradient (MV/m)@40MW	139

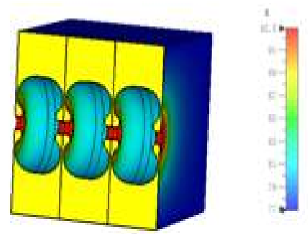


a=0.05*λ_0

Cavity optimization

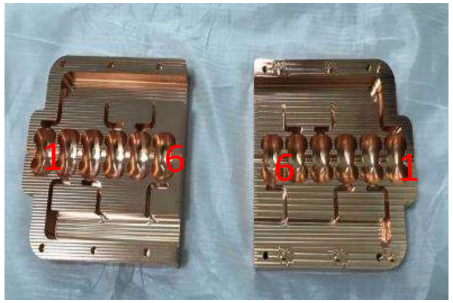

Field distribution

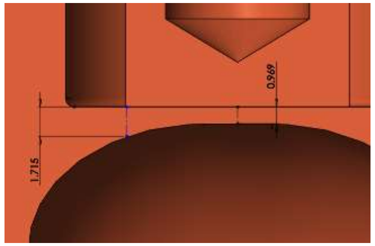

mechanical design

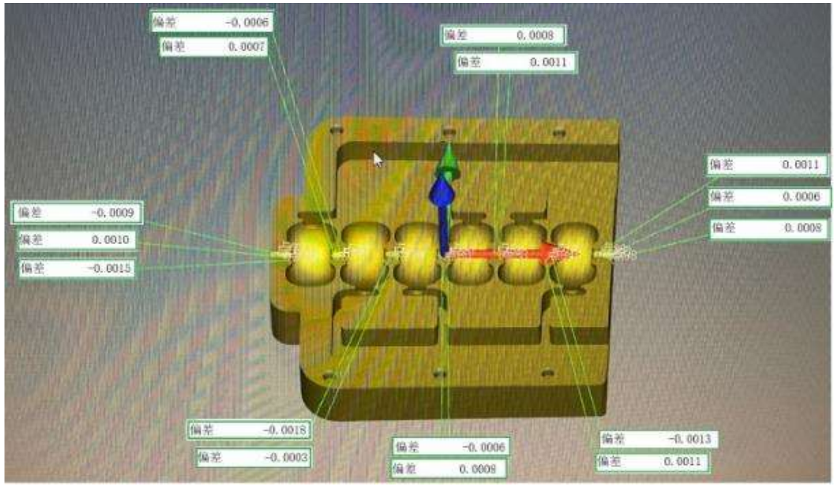

Thermal analysis

Progress of cavity manufacture

- Before the whole structure machining, 6 cells test cavity to verify machining accuracy and check the tuning range of the tuner
- Tuning range:-7MHz~2.5MHz







- The maximum profile tolerance error is about 5um

Progress of cavity manufacture

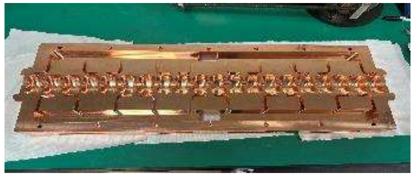
- The cavity wash, EBW, vacuum leak detection for the first prototype

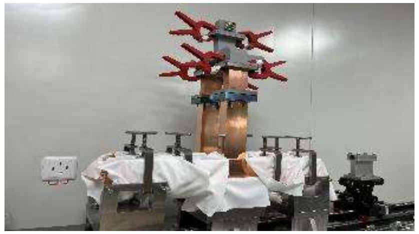
EBW

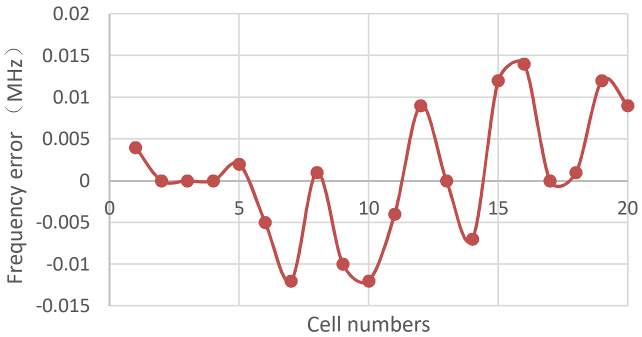
Leakage rate：
$3.5*10^{-11}$Torr*l/s

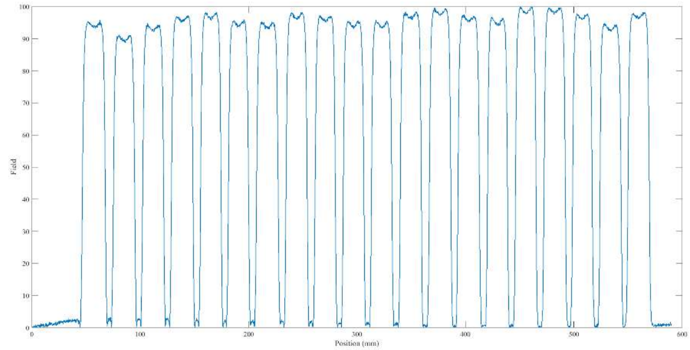
Cold test results after tuning

- Each cell frequency error is in ±15kHz
- The flatness of the field distribution is more than 90%

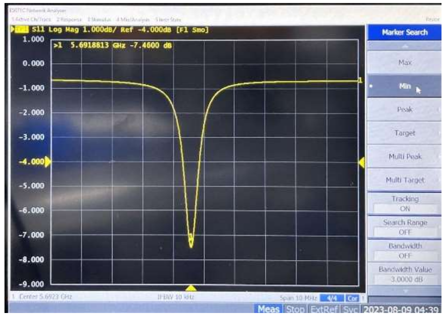


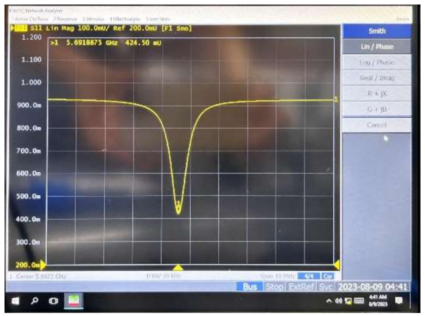


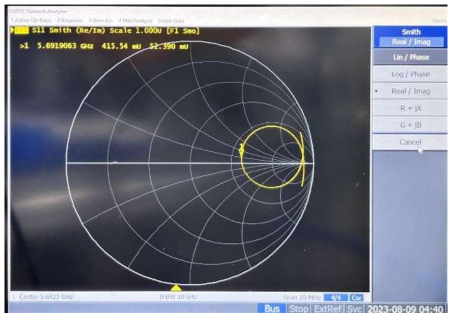




Field distribution



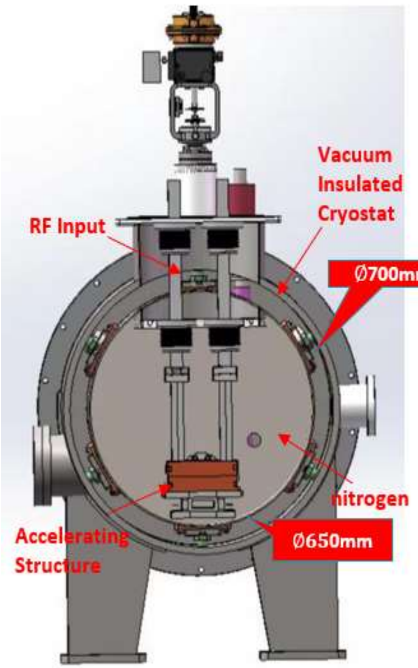


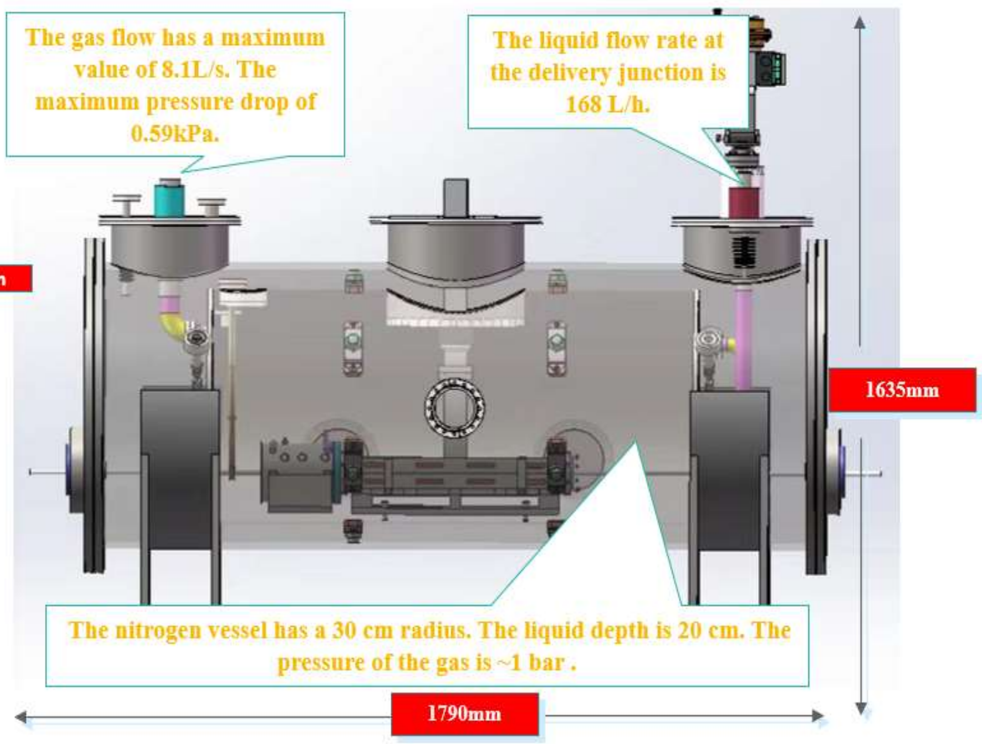


Room temperature measured s-parameters

Cryostat for the cold cooper structure

- The maximum heat load： 5kW（40MW*2.5uS*50Hz）
- It has been completed and is ready to transported to Dongguan test bench

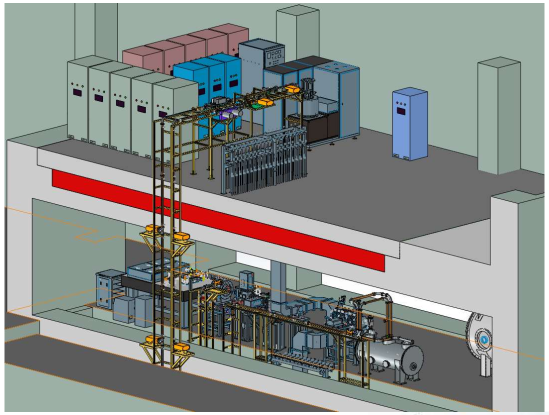




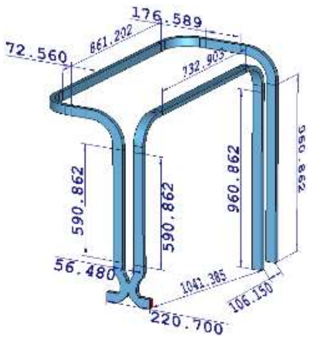
Pre-assembly of the cavity prototype

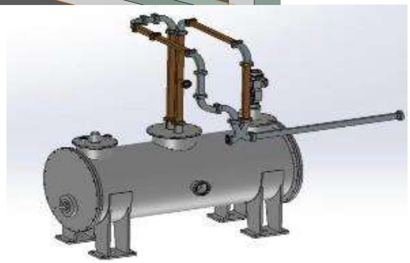
Test bench in progress

- The 50MW C-band test bench located in Dongguan branch of IHEP
- Modulator and klystron is in place and has been preliminary testing
- Completed the debugging of low-level RF and interlocking protection system

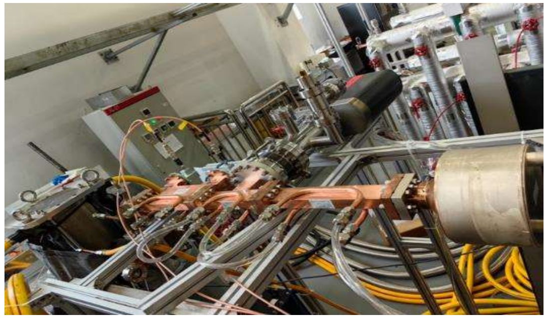


High power test bench





Waveguide layout design



waveguides

Summary

- The baseline design of CEPC linac is 30 GeV with S&C-band normal conducting accelerating structures
- S-band key technology has been verified in HEPS linac
- From 1.1GeV to 30GeV, C-band accelerating structure is used. 1.8 meter long structure has finished design and fabrication
- For high gradient, C-band high power test bench, cryostat and cold copper accelerating structure are under development

Thank you for your attention!