



# CEPC linac and C3 technology development

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**On behalf of the linac group**



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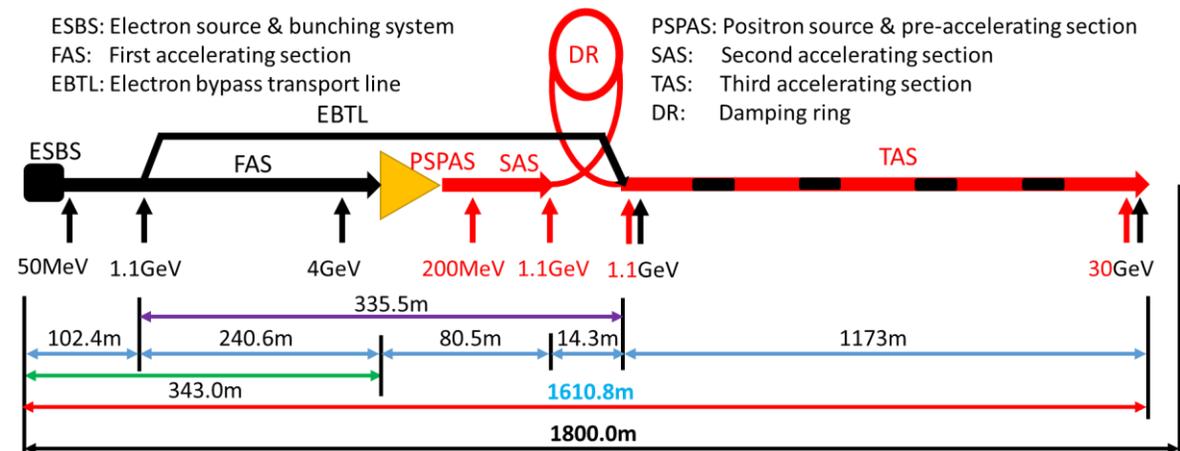
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# Introduction: CEPC Linac

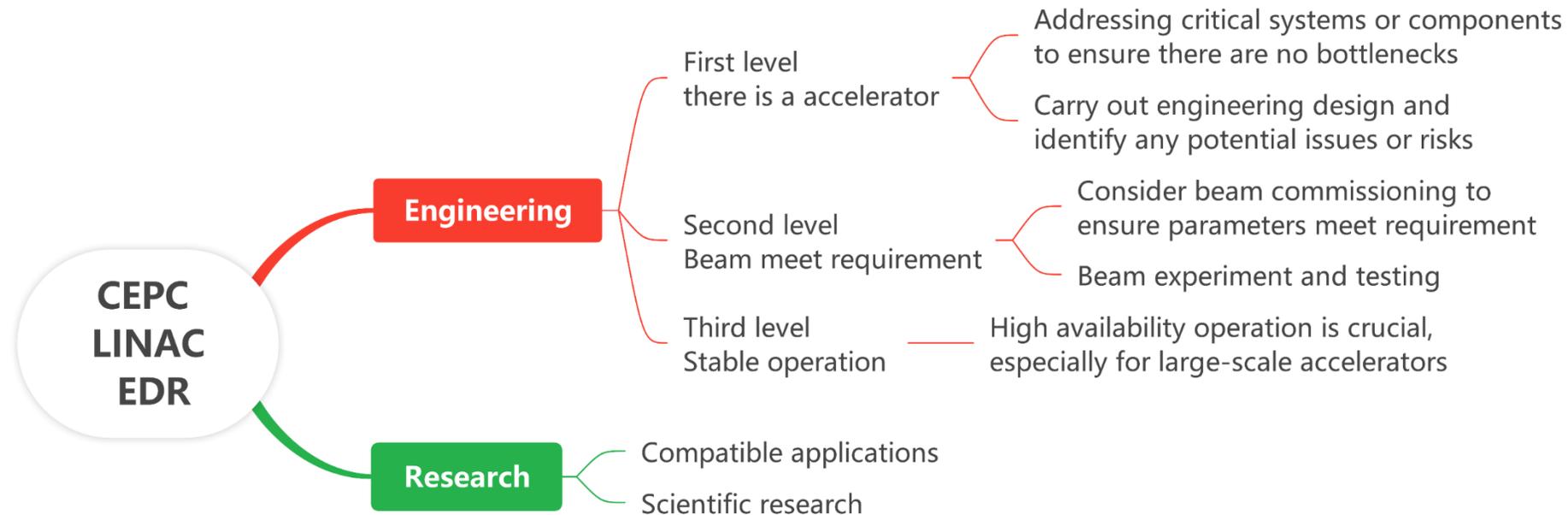
- The CEPC Linac is a normal-conducting linear accelerator that produces 30-GeV electron and positron beams, based on S-band and C-band RF technology
- It is designed to function as a high-energy XFEL facility capable of producing photons with energies greater than 50 keV
- An alternative linac scheme based on PWFA technology is currently under development

Parameter	Symbol	Unit	Baseline
Energy	$E_{e^-}/E_{e^+}$	GeV	30
Repetition rate	$f_{rep}$	Hz	100
Bunch number per pulse			1 or 2
Bunch charge		nC	1.5 (3)
Energy spread	$\sigma_E$		$1.5 \times 10^{-3}$
Emittance	$\epsilon_r$	nm	6.5
Switch time for electron and positron		s	3.0



# Introduction: CEPC LINAC

- CEPC Linac, as the first-stage accelerator, needs to be constructed and commissioning first
- The EDR target for the CEPC Linac is structured at two levels, as outlined below
  - [Engineering] The top priority is to ensure readiness for construction and commissioning
  - [Research] The secondary focus on having potential for upgradability and scalability



# Introduction: CEPC LINAC

- It comprises two key aspects
  - software aspect, which focuses on physics design
  - hardware aspect, which involves technical design and verification
- Physics design
  - Survey and plan
  - High energy XFEL design
  - Key physics issues in PWFA
- Technical design and verification
  - Equipment design
  - High power test
  - Double-bunch acceleration experiment

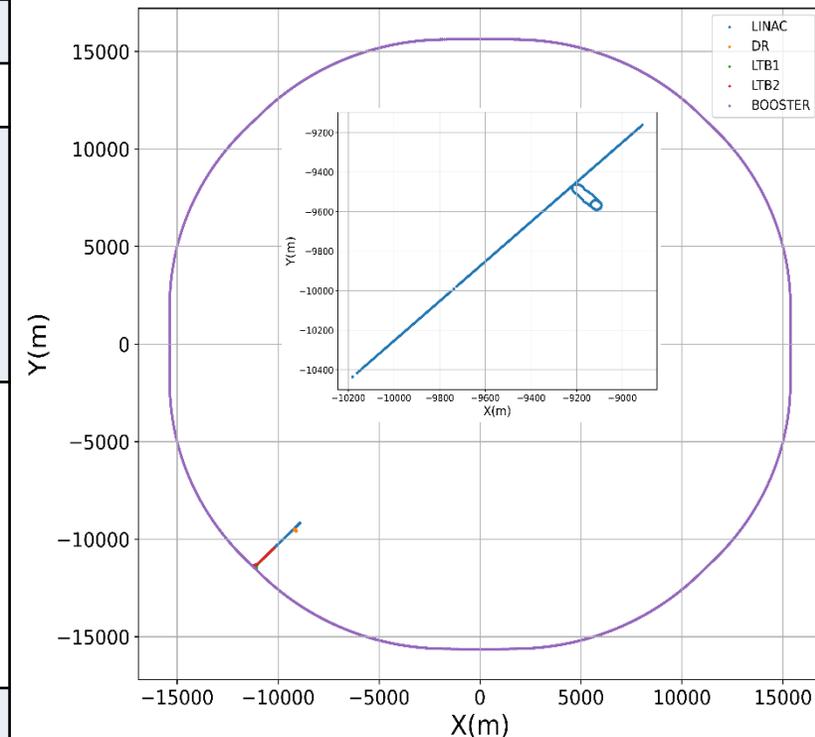
	Numbers	Designed	High power tested	Operated with beam	Need upgraded
Electron gun	1	Yes	Yes	Yes	Two bunch
Positron source	1	Yes	Yes	Yes	Power increase
SHBs/Buncher	2/1	Yes	Yes	Yes	
S-band 3m AS	93	Yes	Yes	Yes	the water cooling to 100Hz
S-band PC	33	Yes	Yes	Yes	the water cooling to 100Hz
S-band big hole AS	16	No→Yes after EDR	No need	No need	
S-band 1m AS	2	No→Yes after EDR	No need	No need	
S-band dummy load	190	Yes	Yes	Yes	
S-band waveguide system	36	Yes	Yes	Yes	
S-band LLRF	42	Yes	Yes	Yes	
C-band AS	370	Yes	No→Yes after EDR	No	
C-band PC	235	No→Yes after EDR	No→Yes after EDR	No	
C-band dummy load	706	Yes	No→Yes after EDR	No	
C-band deflector	1	No→Yes after EDR	No need	No need	
C-band waveguide system	236	Yes	Yes	No need	
C-band LLRF	236	No→Yes after EDR	No→Yes after EDR	No need	phase drift compensation
Linac phase reference line	1	Yes	Yes	Yes	performance of long distance
DR copper cavity	2	Yes	No	No	
S-band & C-band power source		Zusheng Zhou will report the details			

# EDR progress status

# Physics design: Survey and plan

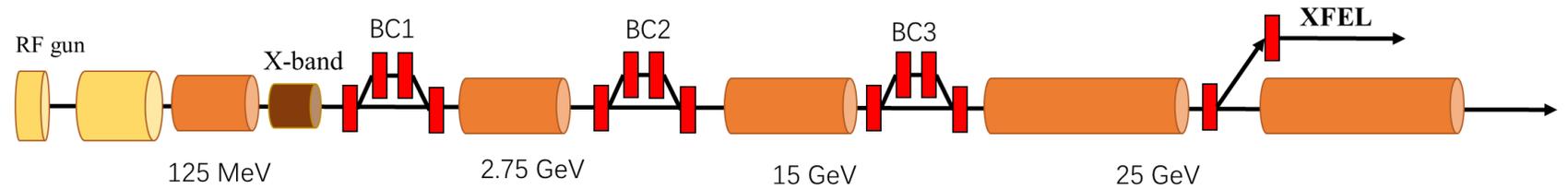
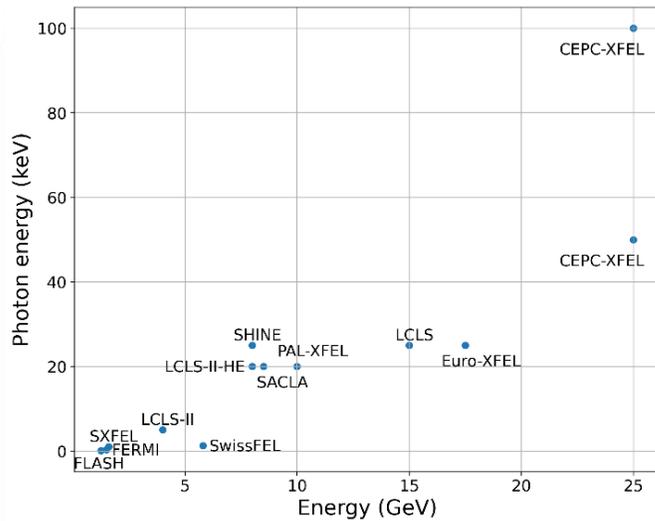
- In accordance with the CEPC naming convention, we have provided the survey file, which has taken into consideration all accelerating sections, damping rings (DR), transfer lines, and beam dump lines
- A preliminary construction plan has been developed

Major Task	Sub-task	Duration	
<b>Infrastructure</b>	Infrastructure (including water, electricity, gas)	4 years	
<b>Installation</b>	Alignment Surveying & Control Network Establishment	1 month	2 years
	Equipment Installation & Vacuum Sealing	21 months	
	Linac Alignment Adjustment	1 month	
	System Integration and debugging	1 month	
<b>Commissioning</b>	High-Power Conditioning, Troubleshooting & Maintenance	5 months	2 years
	Beam Commissioning	15 months	
	Fine Alignment	1 month	
	Re-commissioning & Trial Operation	3 months	
<b>Operation</b>	Linac Beam Delivery to Booster	2 years	

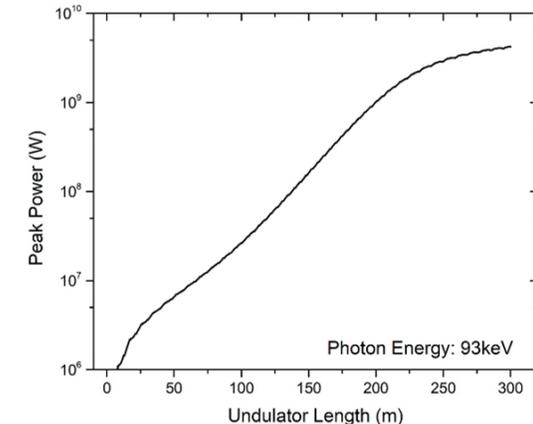
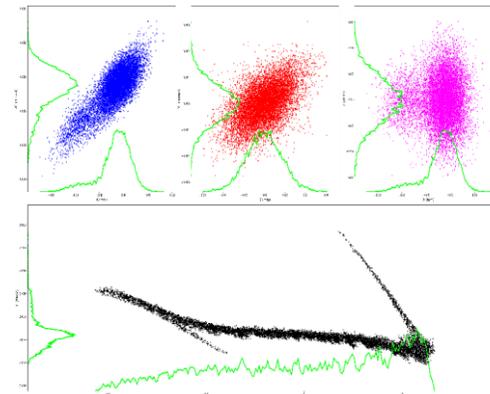


# Physics design: High energy XFEL

- The CEPC Linac can provide a high-energy beam, making it an excellent solution for XFELs with photon energies ranging from 50 keV to 100 keV
- Except for the Z mode, it can generally be ensured that 50% of the time is available for XFEL operation in other modes



Time (s)	Higgs	W	Z	tt
T0	20	36	71	32
T1	3			
T2	2.7	13	20	0.35
T3	3			
T4	13.3	6.1	63.8	14.24
T5	11.3	17	1.2	25.6
XFEL duty	57%	47%	2%	80%



# Technical design and verification: S-band spherical cavity pulse compressor and metal load test

- The high-power testing of the S-band spherical pulse compressor and metal load was completed
- The input power to the pulse compressor is 66 MW (corresponding to 80MW power source), and the energy multiplication factor is **1.8**
- The maximum pulse power input the metal load is **205 MW** (after pulse compressor), and the average power is 4.2 kW
- The pulse compressor will be used in RF system (80MW power source) of project PWFA linac at IHEP



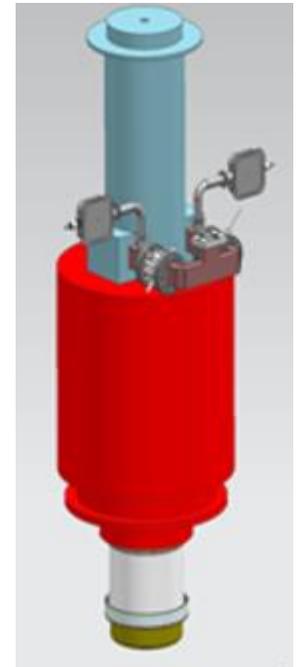
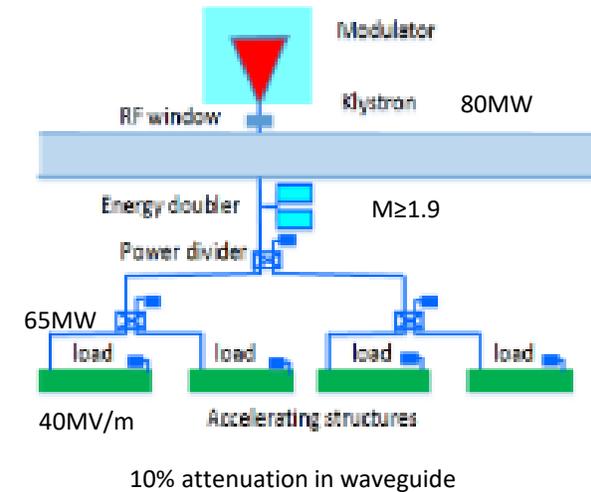
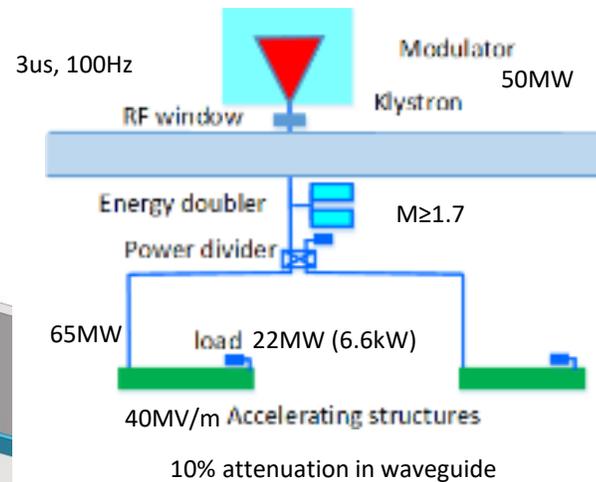
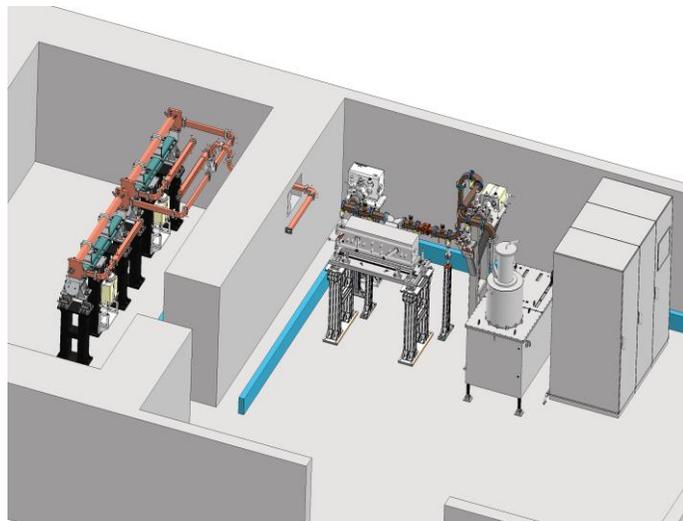
High power test system



High power test waveform

# Technical design and verification: C-band high power test platform plan

- A C-band high-power test platform planned to be established in Huairou Park at IHEP
  - 2 accelerating structures (AS)
  - Pulsed compressor, waveguides, directional couplers, loads, bend and straight waveguides, etc.
- The 80 MW C-band klystron will be completed in 2026 (Zusheng Zhou's presentation)

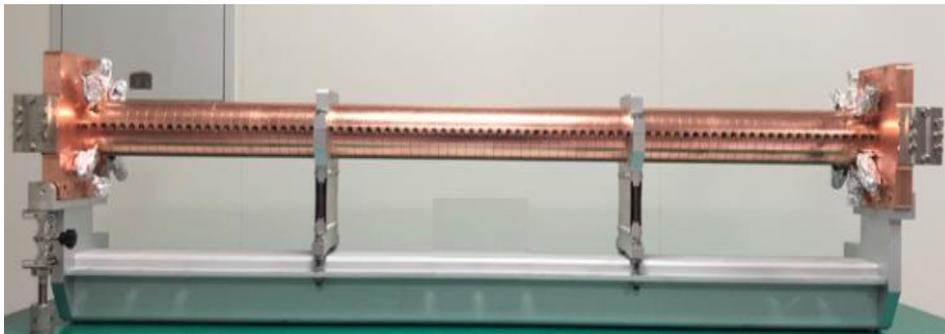


- Increase the energy multiplication factor of the pulse compressor or increase the efficiency of the AS

# Technical design and verification: C-band accelerating structure

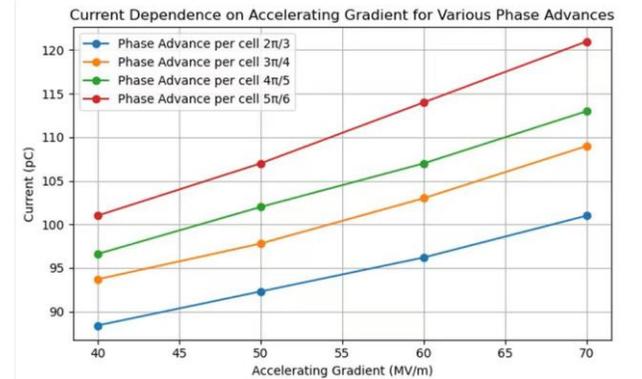
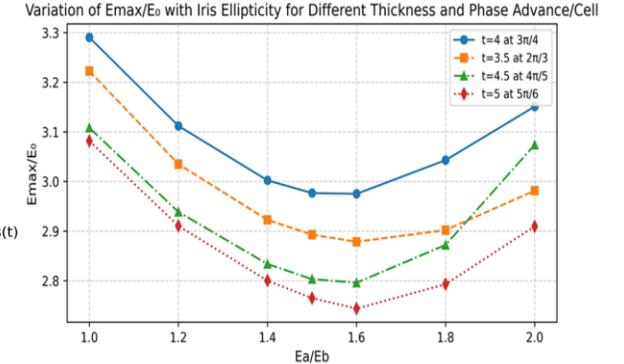
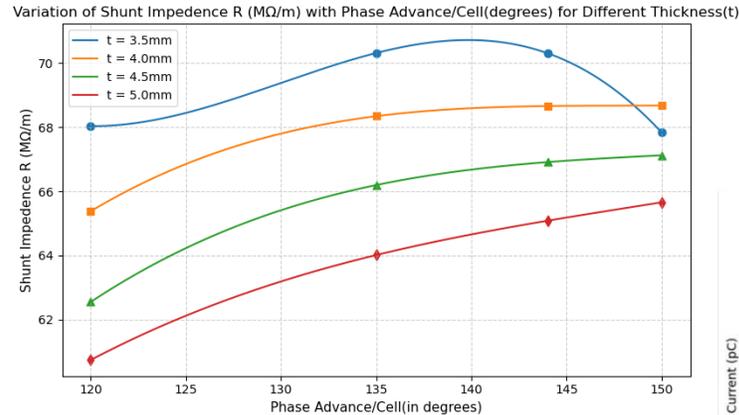
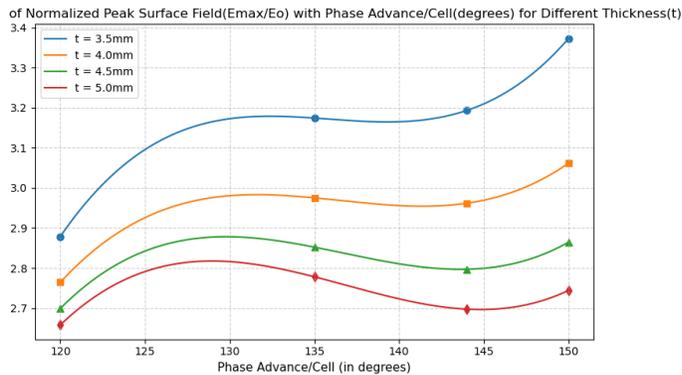
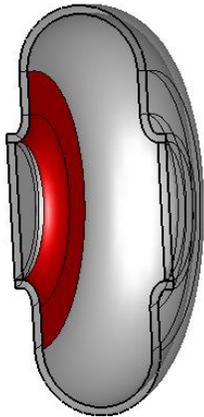
- The design parameters between different lab
  - Mode :  $3\pi/4$ ,  $2\pi/3$ ,  $4\pi/5$
  - Length
  - Disc thickness
- Though the phase advance is different, the other key parameters are very similar
- Our future research will focus on parameter optimization, with the goal of enhancing the efficiency of the AS

	IHEP	Spring8	SINAP
Frequency: $f$ (MHz)	5712	5712	5712
No. of Cells	87+2	100 regular cells +2 coupler	77+2
Phase advance	$3\pi/4$	$2\pi/3$	$4\pi/5$
Total length(m)	1.8	1.8	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) : $R_s$ (M $\Omega$ /m)	66.05	66	62
Quality factor : $Q$	11358~11186	9300/8900(measured)	10470
Group velocity: $V_g/c$ (%)	2.8% ~ 0.96%	2.3%(average)	1.7%(average)
Filling time : $t_f$ (ns)	350	290	330
Attenuation factor : $\tau$	0.56	0.59	0.585
Espeak/E0	2.57	2.6	2.6



# Technical design and verification: C-band accelerating structure

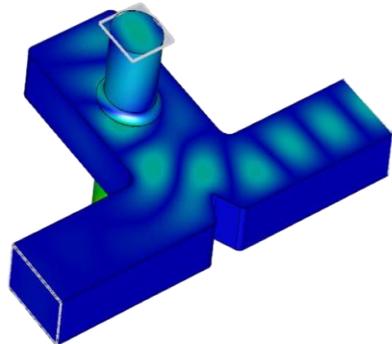
- The first cell of the structure is optimized
- The different modes and different thickness iris were compared. If the iris is thicker, the shunt impedance is increased. The surface electrical field is higher
- We try to find a group of values with clear advantages



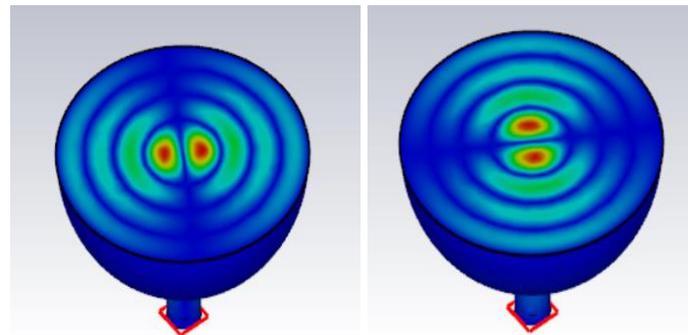
# Technical design and verification: C-band pulse compressor: Spherical cavity type TE<sub>1,1,4</sub>

- The TE<sub>10</sub> mode and TE<sub>20</sub> mode excite two polarization-degenerate TE<sub>11</sub> modes at the interface between the cylinder and the waveguide
- When we select TE<sub>114</sub> mode in the cavity, the energy multiplication factor is **2**
- The diameter of the cavity is 117 mm

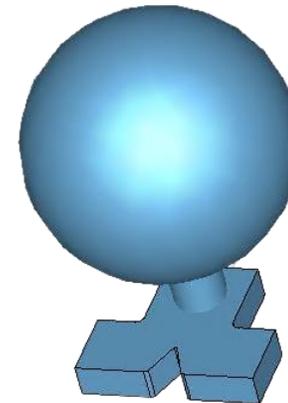
Parameters	Design values
Frequency (MHz)	5712
Input power(MW)	<b>80</b>
Working mode	TE <sub>114</sub>
Input pulse length (μs)	3
Compressed pulse length (μs)	0.5
Coupling coefficient (β)	5.43
Cavity Radius (mm)	116.88
Unloaded Q	126000
Energy multiplication factor	<b>2</b>



Electric field diagram of the mode converter



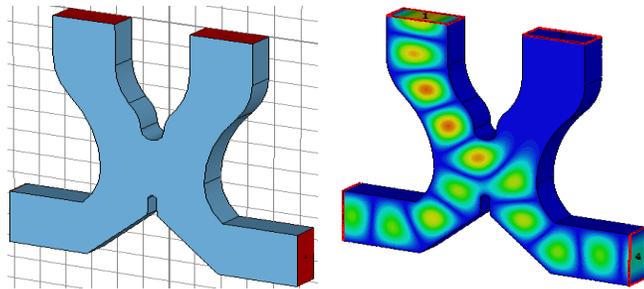
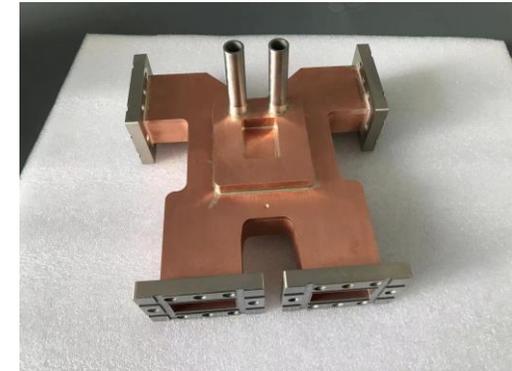
Spherical resonant cavity (TE<sub>114</sub>)



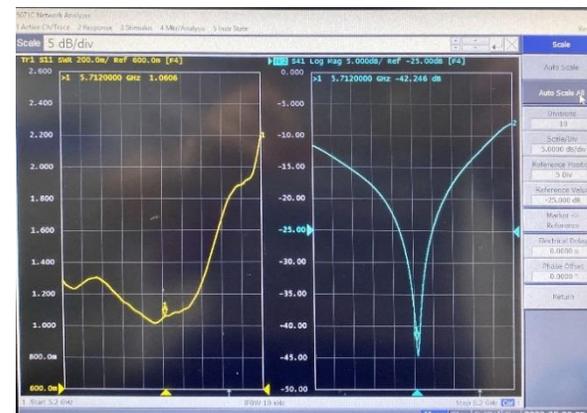
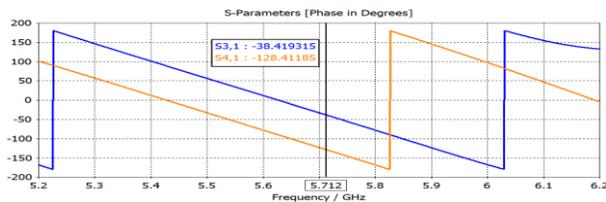
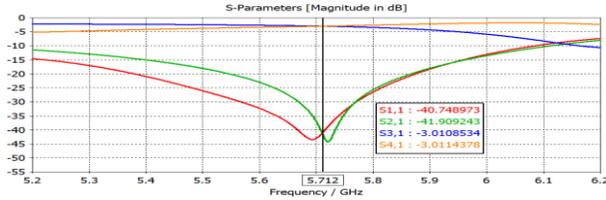
# Technical design and verification: C-band hybrid power divider design and test

## Hybrid divider

- VSWR: 1.06
- Amplitude imbalance: 0.13dB
- Phase imbalance degree:  $0.48^\circ$

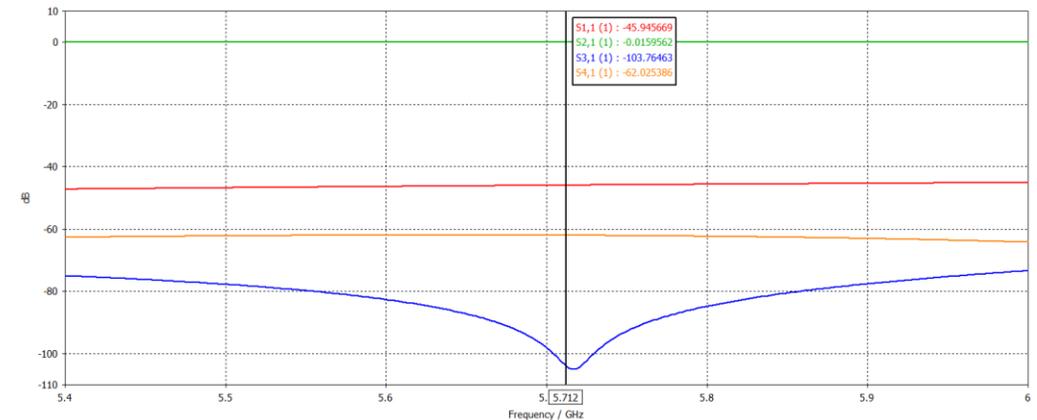
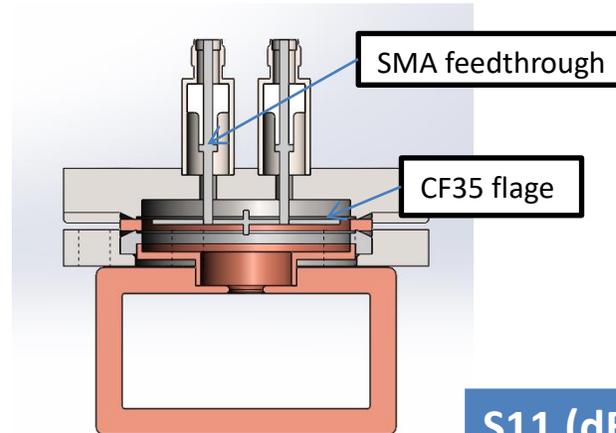
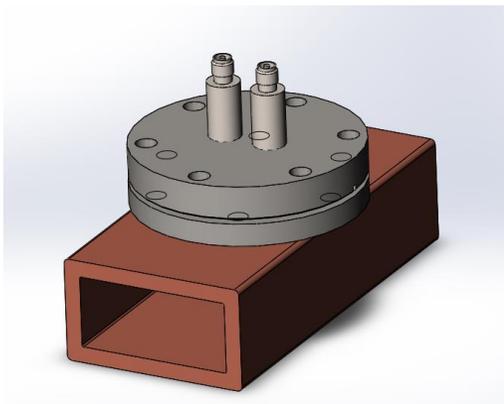
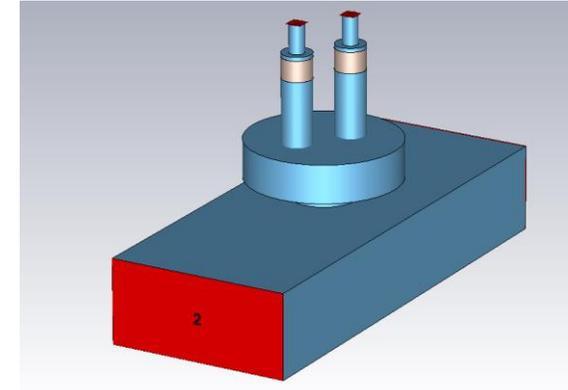


	Amplitude				Phase		
	S11	S21	S31	S41	S31	S41	Phase difference
Designed	-40.7	-41.9	-3.01	-3.01	-30.4	-120.4	90
Measured	-20.9	-42.2	-3.05	-3.18	137	-132.5	90.48



# Technical design and verification: C-band high directional coupler

- The Bethy hole-type directional coupler has been selected
- In the design, we utilize the CF35 flange and SMA feed-through
- The coupling coefficient is 62 dB, while the directivity is 41.8 dB, it can effectively to differentiate between forward and backward waves
- Now it is under production

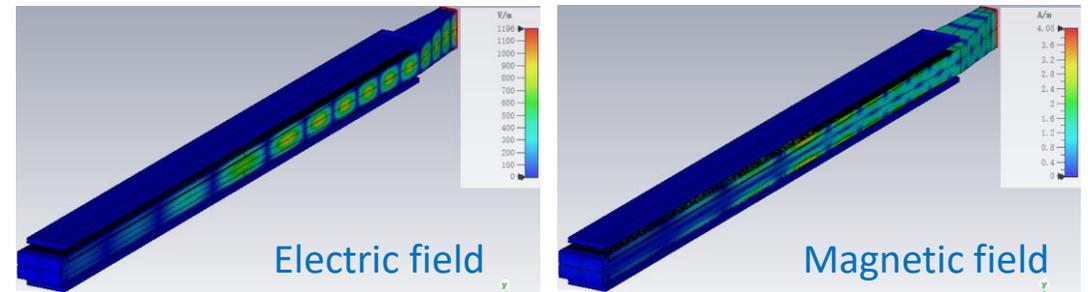


S11 (dB)	S12 (dB)	S13 (dB)	S14 (dB)
-45.9	0.016	-103.8	-62

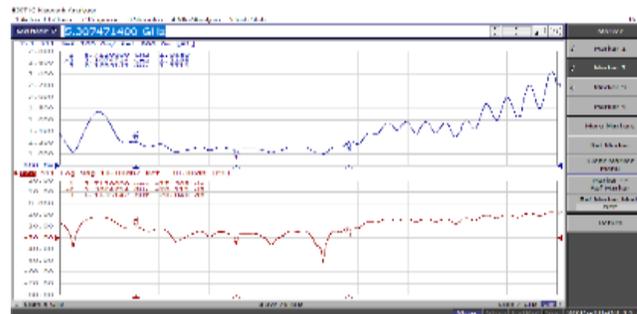
# Technical design and verification: C-band stainless steel metal load

- Pure SS430 load with BJ48 input port, composed of waveguide taper, match section, regular section and end cavity. 1.02 VSWR in 5712 MHz working frequency, and >400 MHz bandwidth ( $S_{11} < -20$  dB)
- It has been processed and completed, the measured VSWR is 1.08

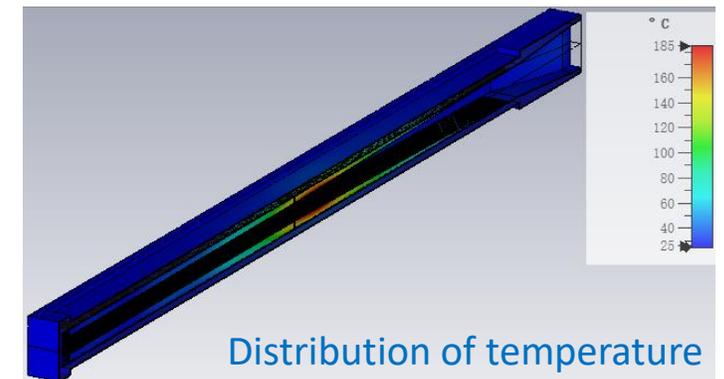
- Distribution of the electric and magnetic field,  $E_{max} \sim 30$  MV/m with 300 MW peak power input



- The maximum temperature reaches approximately 185 °C, accompanied by an average input power of 10 kW and a cooling water flow rate of 30 L/min



Cold test result



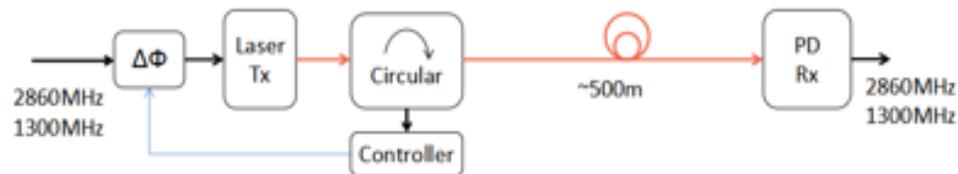
Distribution of temperature

# Technical design and verification: Linac phase reference line & LLRF

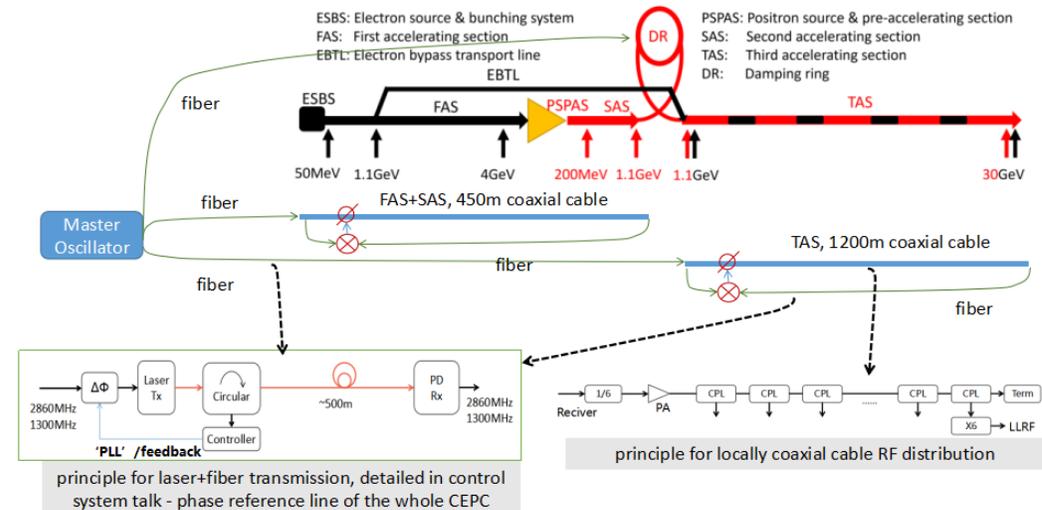
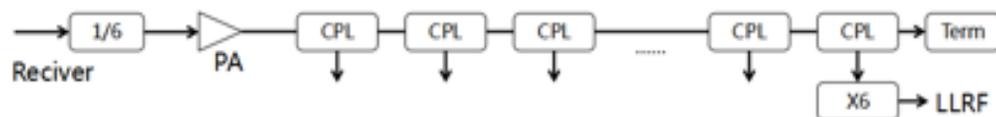
- The phase stability should be  $<0.2\text{deg}$  (rms) from beam physics
- The phase reference line shall provide signals to LLRF as follows:
  - Three laser+fiber based PRL for DR, transmitting 650MHz, FAS+SAS and TAS, transmitting 2860MHz, phase  $<0.02\text{deg}$
  - Two coaxial-cable based PRL for locally FAS+SAS and TAS:2860MHz divided to 476.67MHz, distributed along the cable to reduce signal attenuation, at the local LLRF receiver, multiplied back to 2860MHz and 5720MHz
  - Phase reference coaxial cables will be placed in the temperature-controlled duct with stability  $<0.1\text{K}$
  - Standard 7/8 inch coaxial cables are used with temperature coefficient  $\sim 5\text{ps/km/K}$ , 1km phase will  $<0.5\text{deg}$  (peak-peak, 0.1deg rms)

Linac LLRF signals	Value
Phase stability	0.2deg (rms)
Amplitude stability	0.2% (rms)
2860MHz number	33
5720MHz number	236
650MHz @DR number	2
Reference signal power	$>0\text{dBm}$
Reference signal jitter	$<80\text{fs(rms)}$

principle for laser+fiber transmission, detailed in control system talk - phase reference line of the whole CEPC



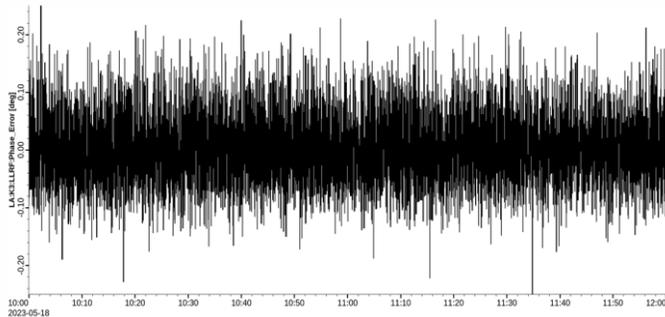
principle for locally coaxial cable RF distribution



# Technical design and verification: Linac phase reference line & LLRF

- Proven down-conversion LLRF architecture with high phase stability for CEPC Linac
  - The LLRF system based on down-conversion architecture has already been widely applied at IHEP. There are 5 sets of 2998.8 MHz LLRF systems in the HEPS linac and 22 sets of 2856 MHz LLRF systems in the BEPCII linac
  - The long-term online phase stability of is  $0.08^\circ$  RMS and  $0.4^\circ$  peak-to-peak, meets CEPC linac phase stability requirements

- Phase jitter is 0.08 degree (std) and 0.4 degree (peak-to-peak) (2 hours)



BEPCII LINAC LLRF System



HEPS LINAC LLRF System



# C-band cryogenic copper technology development

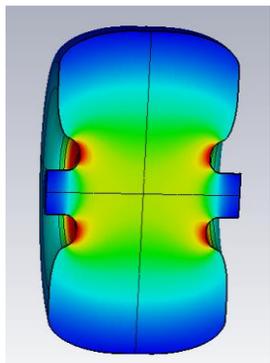
# R&D of C-band cryogenic copper accelerating structures

- The aforementioned details pertain to the preparation of a C-band normal temperature test bench, specifically tailored for the baseline design requirements of the linac RF system
- To achieve higher gradients of fixed power source, we have additionally developed cryogenic copper accelerating structures that operate within liquid nitrogen (77K)
- We have designed two types of parallel coupling structures
  - Type I: 20 cells,  $a=0.05*\lambda_0$ ,  $2a=5.25\text{mm}$
  - Type II: 40 cells,  $a=0.1*\lambda_0$ ,  $2a=10.5\text{mm}$

# C-band 20 cells parallel coupling structure design

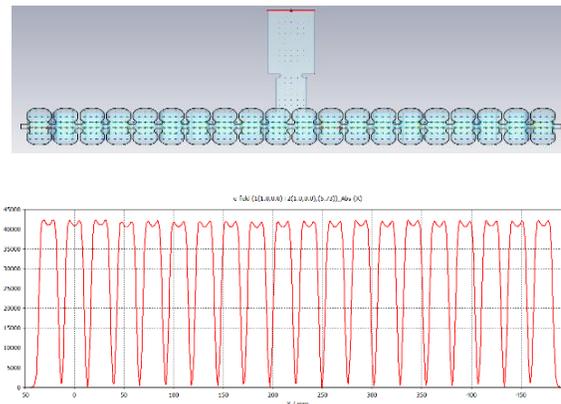
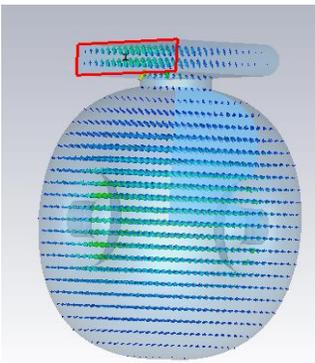
- It is a standing wave structure. This is the first model we examined. We completed cavity optimization, coupling design, and power distribution design
- The shunt impedance has been determined to be 303 MΩ/m at 77K
- Based on the experimental data, the  $Q_0$  value increase by a factor of 2.8 attains 34079

The whole structure parameters		
RF Parameter	value	Unit
Temp T	77	K
Frequency $f_0$	5712	MHz
Working mode	$\pi$	----
Cavity numbers n	20	----
Total length L	525	mm
The gradient of the total cavity $Grad/\sqrt{P}$	<b>24.8</b>	MeV/m/ $\sqrt{MW}$

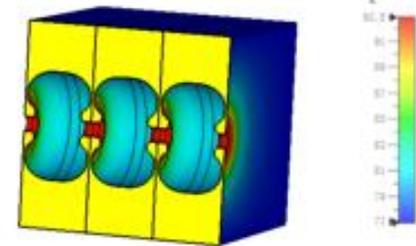


$$a=0.05*\lambda_0$$

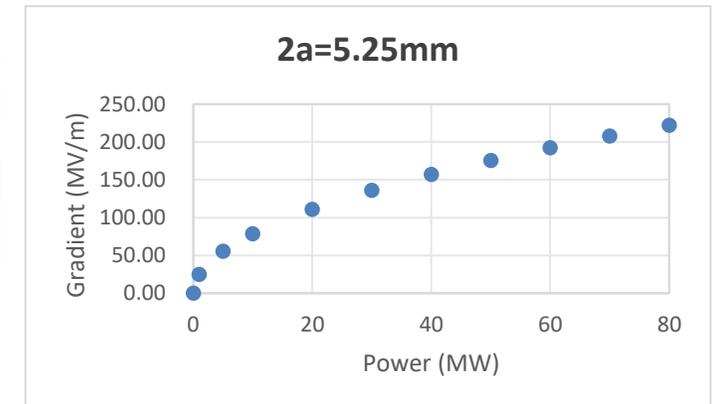
Cavity optimization



Field distribution

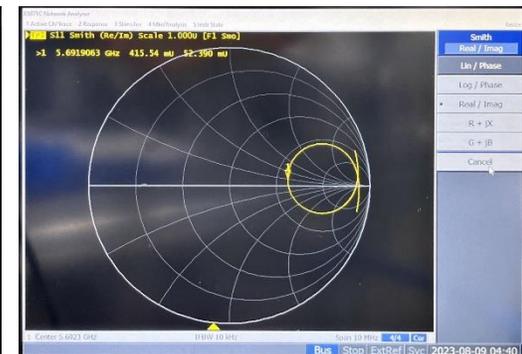
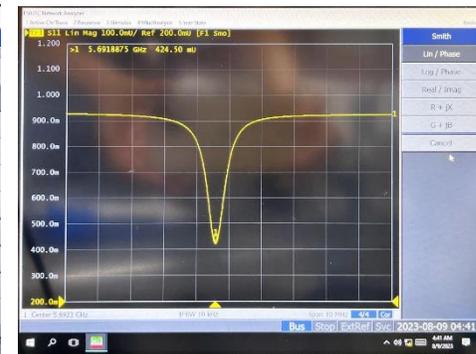
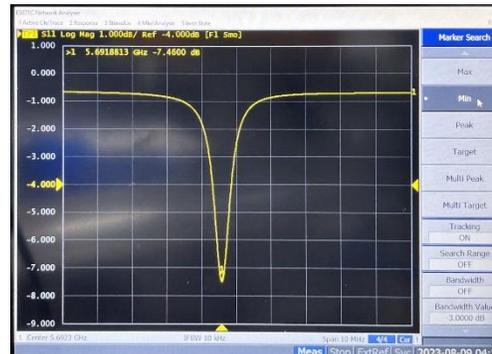
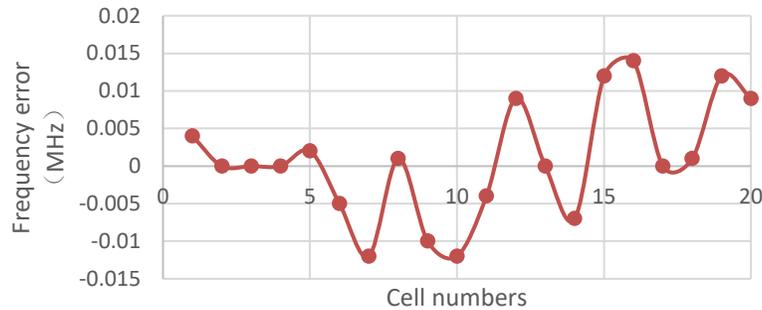


Thermal analysis

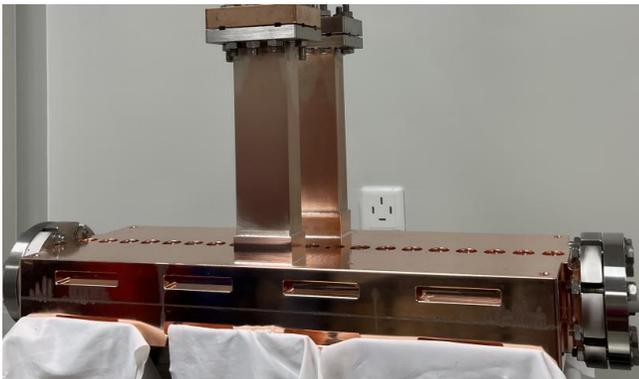


# Cold test results after tuning

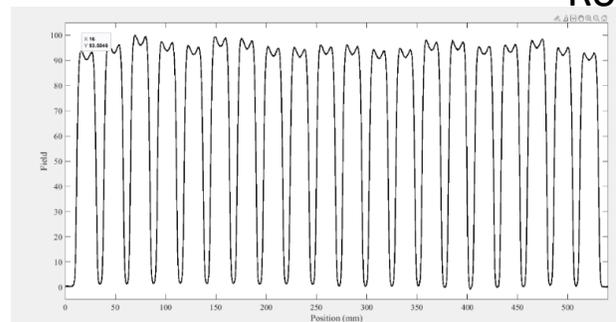
- We have finished the manufacturing and tuning processes, and the brazing technique was employed for all welding procedures
- The frequency error for each cell is within  $\pm 15$  kHz, and the field distribution exhibits a flatness of over 90%



Room temperature measured s-parameters



20 cells structure



Electric field distribution after tuning

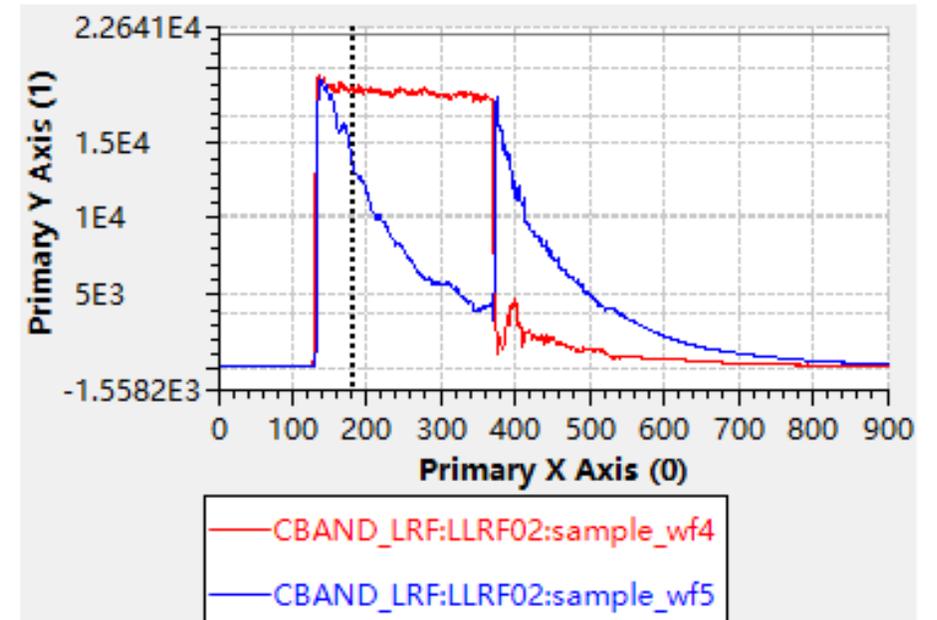


The structure installed in the cryostat



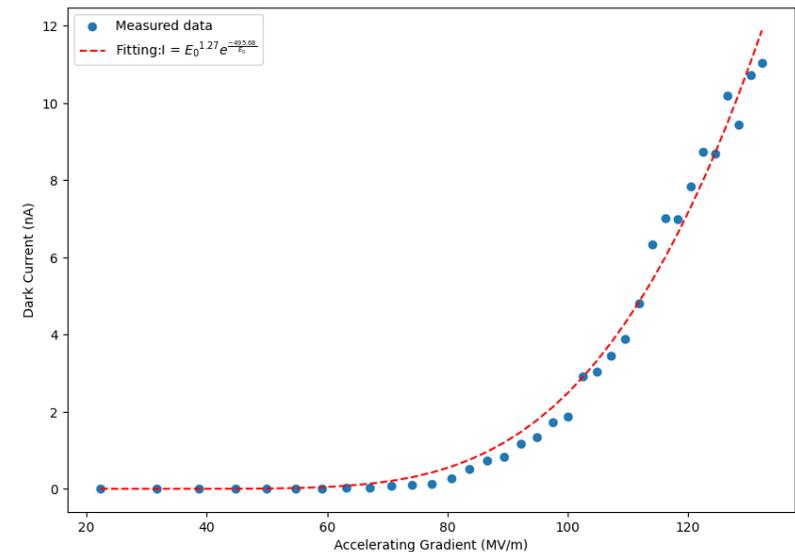
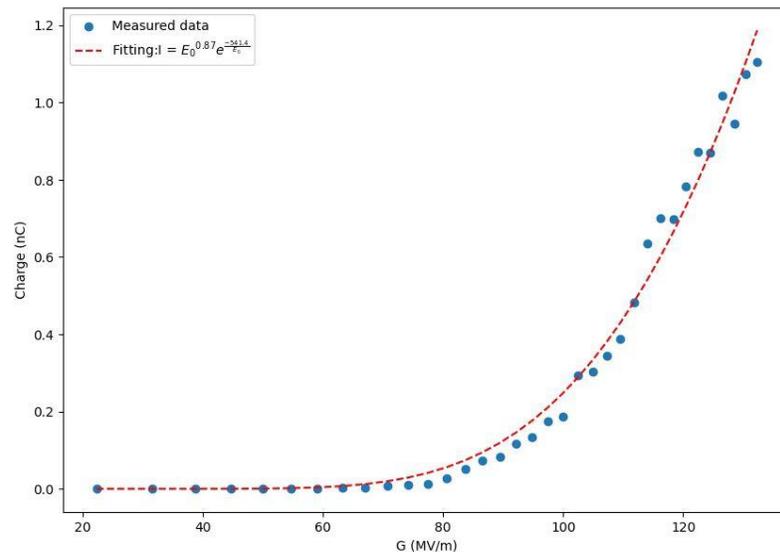
# High power test

- There is a C-band test platform in the Dongguan branch of the IHEP
- We carried out two rounds of high-power tests. The gradient reached 90.3 MV/m in the first round in March 2025
- The second round high power test in Nov. 2025, the gradient reached 128.5 MV/m @2.5  $\mu$ s, 32.45 MW



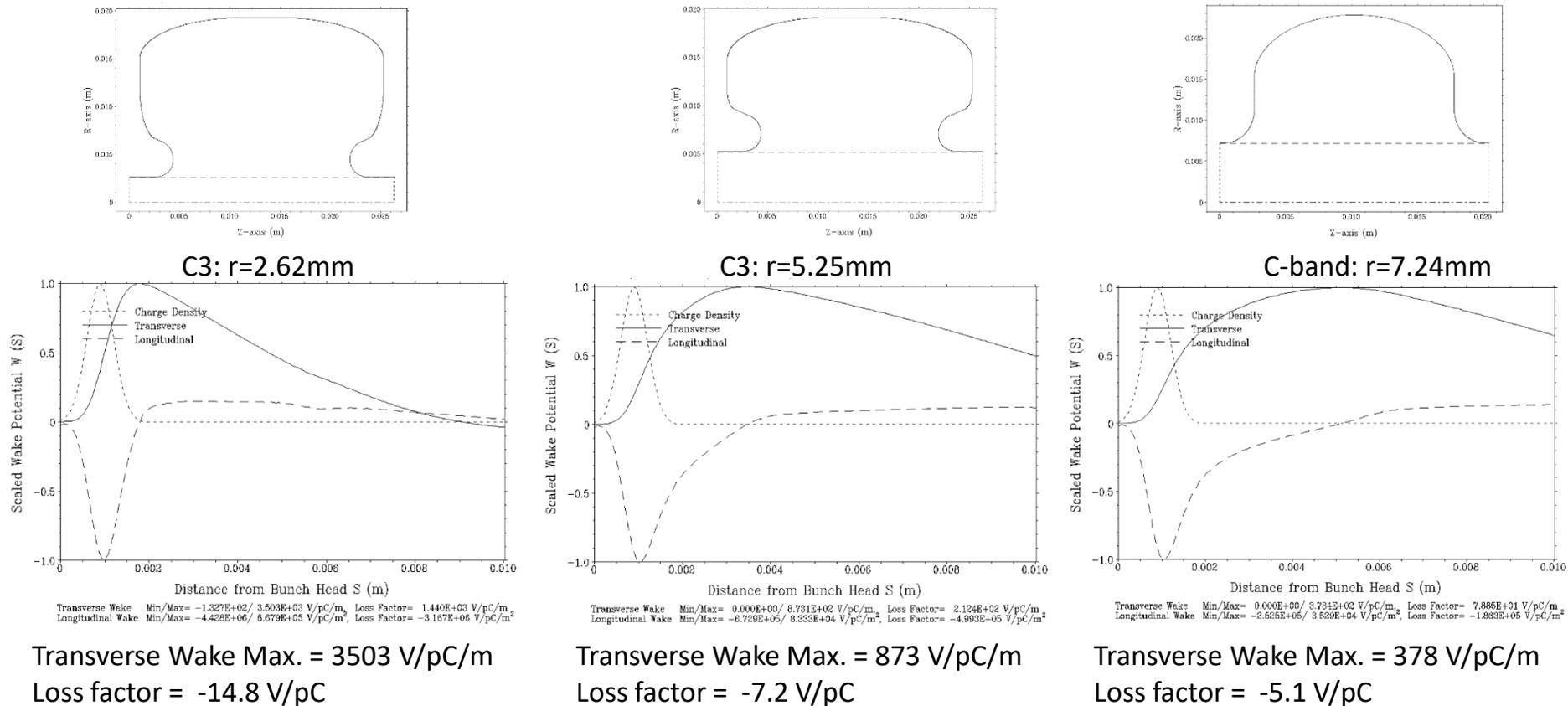
# Dark current

- At 10Hz, after approximately  $5 \times 10^6$  pulses, The dark current was measured using a Faraday cup. The dark current was measured to be approximately 1.1 nC per pulse at an accelerating gradient of 128.5 MV/m
- It was observed that the dark current exhibits a decreasing trend as the conditioning duration increases. However, we terminated the high-power test due to the requirement to repurpose the test bench for other applications



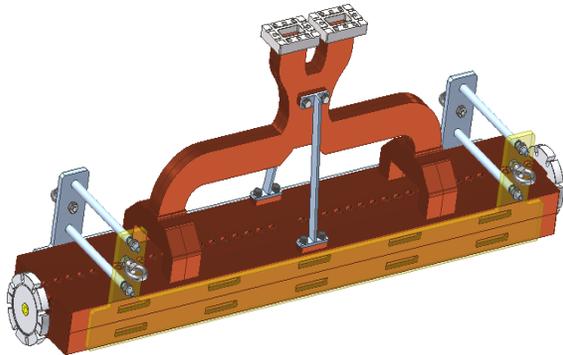
# Wakefield simulation

- Structural modeling was completed and the short-range wakefield was calculated
- For application in a CEPC injector, with a bunch charge ranging from 1.5 to 3 nC, a diameter of at least 10.5 mm is necessitated (Bunch length: 0.3 mm)



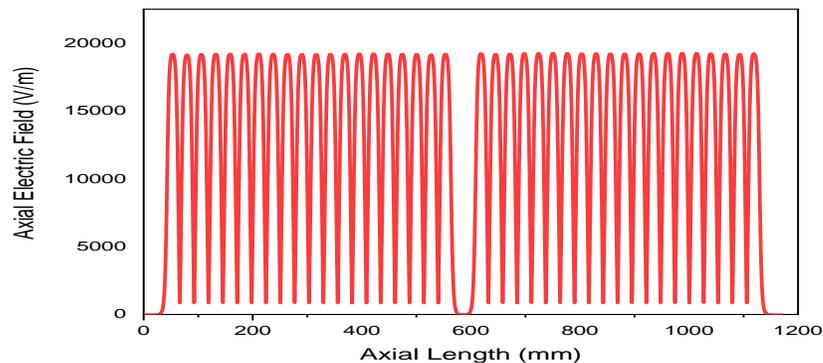
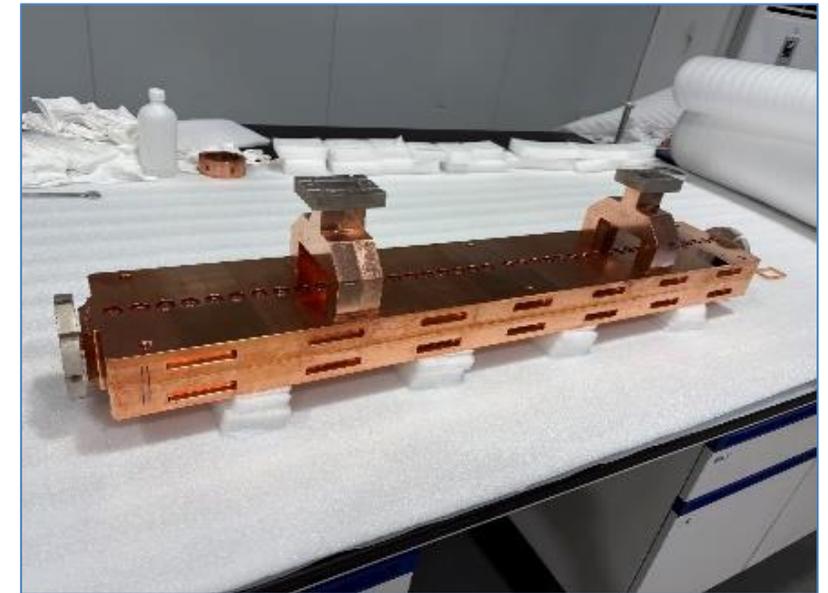
# 40 cells cryogenic accelerating structure design

- Type II:  $a=0.1*\lambda_0$  ( $2a=10.5\text{mm}$ )
- The shunt impedance and  $E_{\text{Smax}}/E_0$  both decrease when compared to the Type I
- The fabrication has been completed, and we are preparing for tuning in our lab



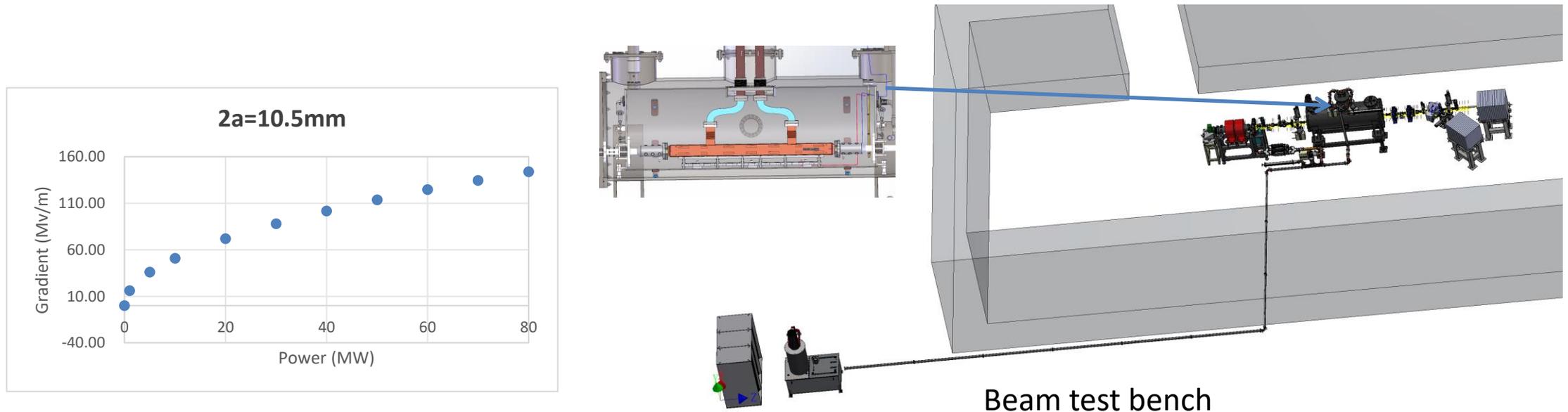
Crucial Parameters for the Single Cell (Without Coupler)

Sr.	RF Parameters	Value	Unit
1.	Temperature (T)	77	K
2.	Frequency (f0)	5712	MHz
3.	Working Mode	$\pi$	
4.	Aperture (2a)	10.487	mm
5.	Diameter (2b)	39.24	mm
6.	Nose Distance (D)	18.65	mm
7.	Cell Length (p)	26.24	mm
8.	Copper Conductivity ( $\sigma$ )	$2.8*2.8$	S/m
9.	Quality Factor ( $Q_0$ )	33071	
10.	Shunt Impedance ( $R_s$ )	259	M $\Omega$ /m
11.	$R_s / Q_0$	399	
12.	Filling Time ( $T_f$ )	2.303	$\mu\text{s}$
13.	$E_p/E_0$	1.96	
14.	Surface Resistance ( $R_{\text{surface}}$ )	$7.04 \times 10^{-3}$	$\Omega$
15.	Geometry Factor	233	$\Omega$
16.	Max Wake Loss Factor (Without Damp)	$\sim 3.7$	V/pC
17.	Max Kick Factor (Without Damp)	$\sim 8.04 \times 10^{-2}$	V/pC/mm



# High power test bench at Huairou testing platform

- Based on the 80MW C-band klystron, another C-band test bench is currently under development, with high-power testing scheduled in 2026
- It will reach 144MV/m with 80MW input theoretically, taking into account the actual operating power of the klystron (typically 80% of the design value), waveguide attenuation and other factors, our phase one target gradient is 80 MV/m



# Summary

- According to the booster and collider time line, the construction time for the linac is provided
- A C-band normal temperature test bench is currently being designed
- Type I cold copper structure high-power test gradient reached 128.5 MV/m
- Type II cold copper structure is being prepared for tuning. Subsequently, high-power tests will be conducted



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**Thank you for your attention**

