Overview of High Gradient Research Activities at IHEP

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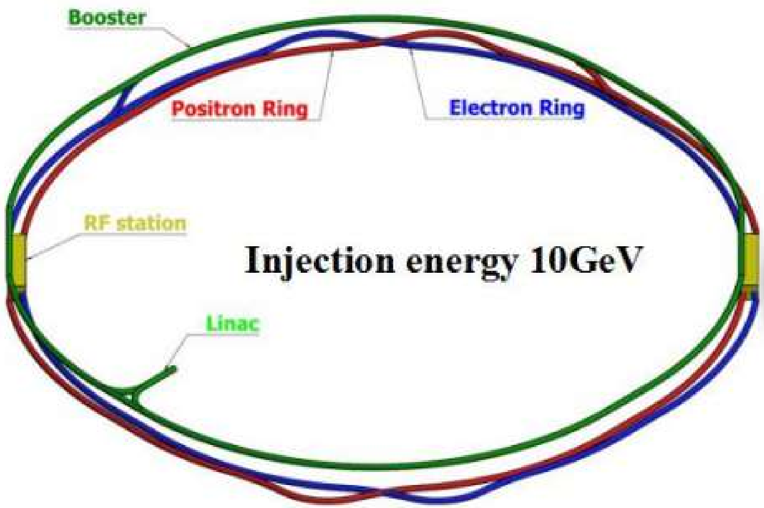
Outline

1. S-band accelerating structure of CEPC
2. S-band spherical cavity pulse compressor of CEPC
3. Microwave system for linac of HEPS
4. Summary

CEPC Linac design

- CEPC consists of Linac, Booster and Collider
  - The energy electron and positron of the Collider is 120 GeV
  - The booster and collider circumference is about 100 km
  - The injector linac provides 10 GeV electron and positron beam to the Booster
  - The length of the linac is about 1.2 km



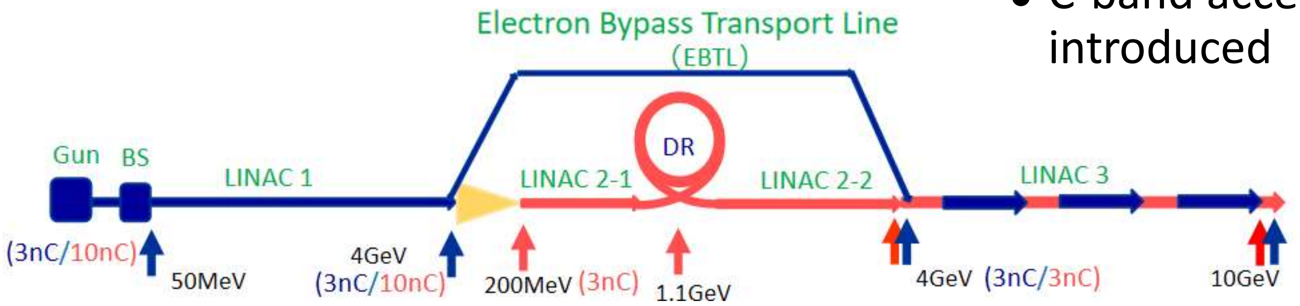
CEPC Linac design

- The requirements of the booster to the Linac
  - Baseline scheme: S-band
  - Alternative: S+C-band

Parameter	Unit	Baseline (CDR→TDR)	Alternative (S+C)
beam energy	GeV	10	**20**
Repetition rate	Hz	100	100
Bunch numbers per pulse	-	1	1
bunch population	-	9.4×10^{9}	
	nC	1.5	
Energy spread		2×10^{-3}	
Emittance	nm	100→**40**	**40**

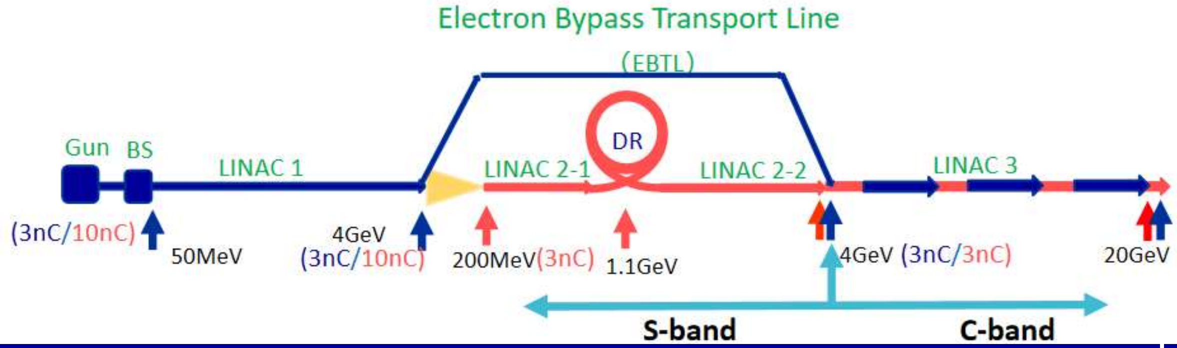
CEPC Linac design

- Electron linac
  - Pre-injector+Linac 1+EBTL+Linac 3
- Positron linac
  - (Pre-injector+Linac 1+PS+Linac 2-1+DR+Linac 2-2+Linac 3)
- Mature technologies



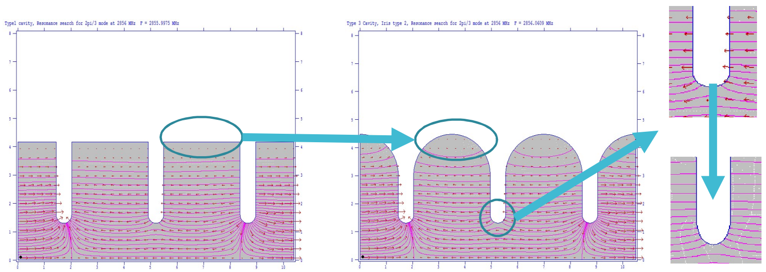
- Energy rises from 10GeV to 20GeV
  - Reduce the difficulty of the Booster design
  - Reduce the technical risk of low magnetic field magnets of the Booster
  - C-band accelerating structures are introduced

Alternative design



Accelerating structure

- 3 meters long S band accelerating 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%



Superfish is used to optimize the single cell

- The main parameters of the structure

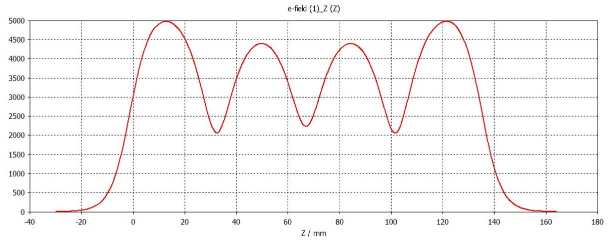
Parameters	Values	Unit
No. of Cells	84+2*0.5	-
Phase advance	2π/3	rad
Total length	3.1	m
Length of cell (d)	34.988	mm
Disk thickness (t)	5.5	mm
Shunt impedance (Rs)	60.3~67.8	MΩ/m
Quality factor	15465~15373	-
Group velocity: Vg/c (%)	2% ~ 0.94%	-
Filling time (t_f)	784	ns
Attenuation factor (τ)	0.46	Np
Power (@30MV/m)	74	MW

Accelerating structure

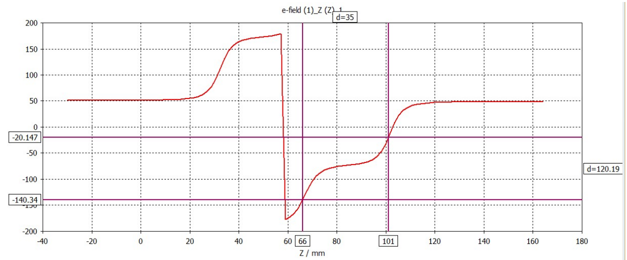
- Coupler design
  - The asymmetry of the coupling cavity will cause emittance growth
  - The shape of the coupling cavity is racetrack dual-feed type

$$\varepsilon_{n-final} = \sqrt{\varepsilon_{n-initial}^2 + \sigma_x^2\left(\frac{\sigma_{\Delta p_x}}{mc}\right)^2}$$

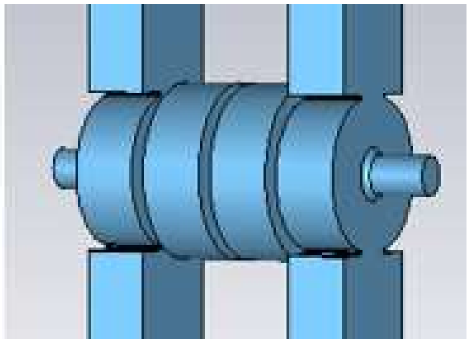
$$\Delta p_x = -\frac{e\Delta z E_0}{2\omega a}[\Delta\theta * sin\varphi - \frac{\Delta E}{E_0}\cos\varphi]$$



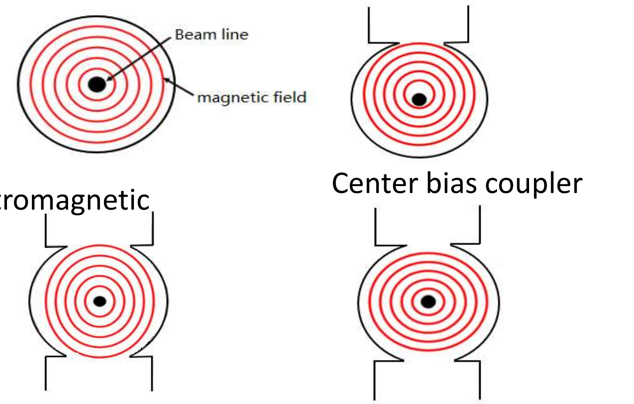
The *distribution of* the electric field on axis



Phase advance per cell



The calculation model



Ideal electromagnetic structure

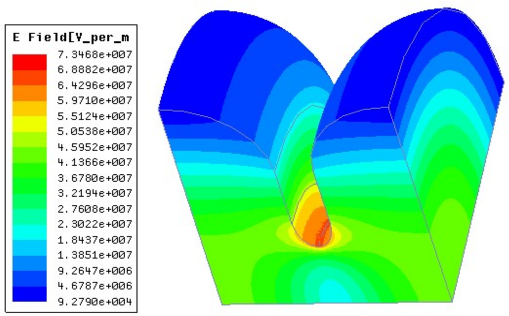
Center bias coupler

Dual feed coupler

Dual feed racetrack coupler

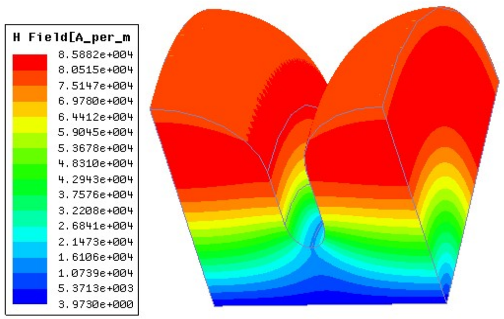
Accelerating structure

- Factors to limit the gradient (cavity):
  - 3D program CST is used to confirm the design
  - The 1st cell is simulated for Pin=75 MW
  - The values are safe. Both E_peak and Sc locates at the iris area



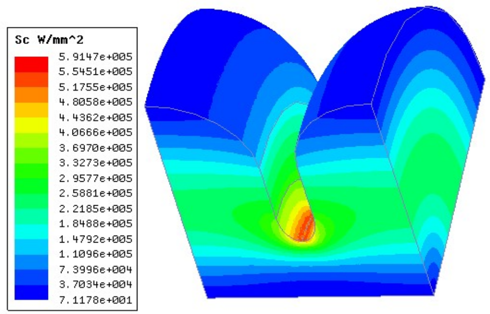
E_peak=73 MV/m.

Surface electric field



H_peak=86 kA/m.

Surface magnetic field



Sc_max=0.59 MW/mm^2.

Modified Poynting vector

- E_peak < 160MV/m at S-band
- 2.3 MW/mm^2 @ 1μs pulse length

Accelerating structure

- Factors to limit the gradient (coupler):
  - To reduce the pulsed heating, the coupler window edge is rounded
  - For S-band copper: $\Delta T[^0c]=127\left|H_{||}[MA/m]\right|^2\sqrt{f.[GHz].t_p[uS]}$
  - For 75 MW input power, the maximum value of the peak surface magnetic field is $2.1*10^5$ A/m. for 1μS pulse length, ΔT=9.4^{0}C

$$\Delta T=\frac{\left|H_{||}\right|^2\sqrt{t_p}}{\sigma\delta\sqrt{\pi\rho c k}}$$

Magnetic field

RF Pulse length

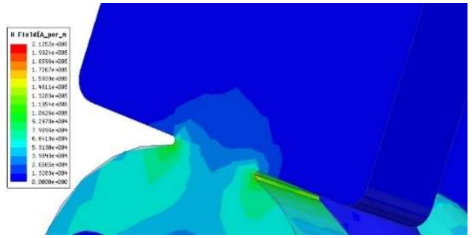
Electric conductivity

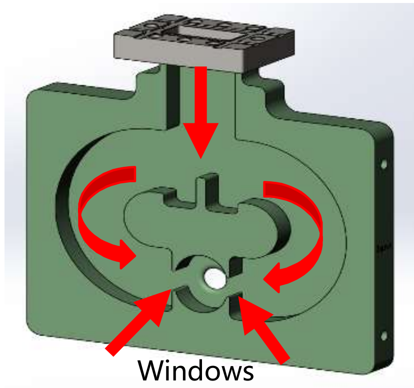
Skin depth

Material density

Specific heat

Thermal conductivity

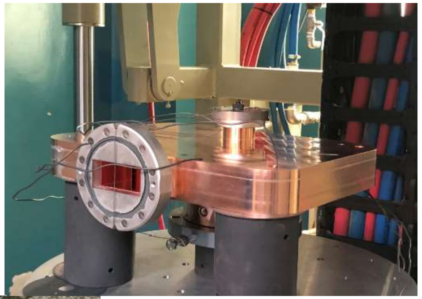




- S-band ΔT < 50°C is safe

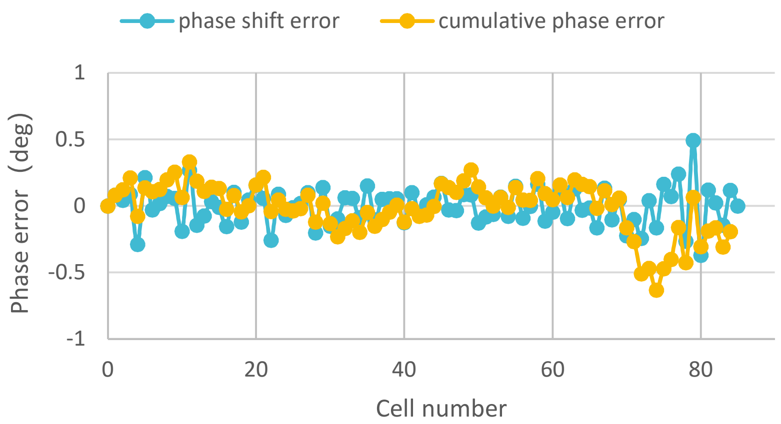
Accelerating structure

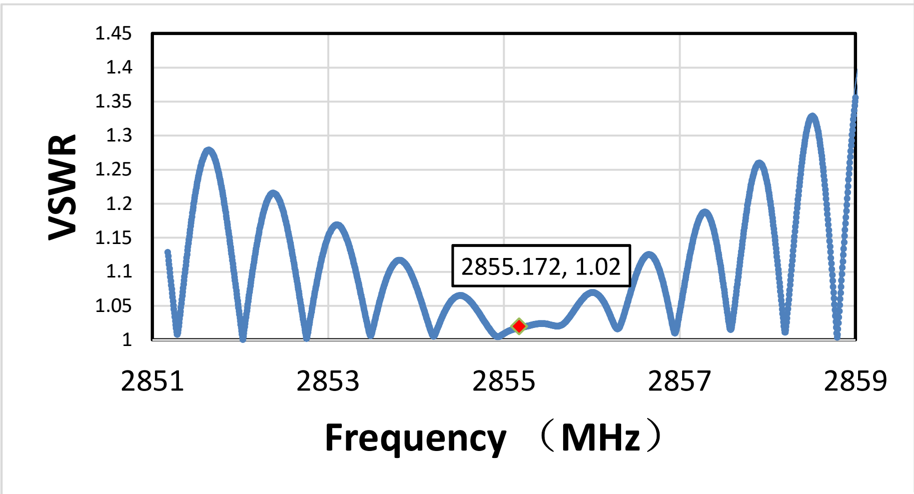
- Mechanical design
  - Inner water-cooling has been adopted. 8 pipes are around the cavity.
  - Compact coupler arrangements. The splitter is milling together with the coupling cavity.
  - Two tuners are outside the cavity.

Accelerating structure

- Cold test result
  - The phase shift and the cumulative phase shift are less than 1 deg
  - The VSWR is 1.02 at working frequency
  - Filling time is 780 nS
  - The total attenuation is 4.2 dB

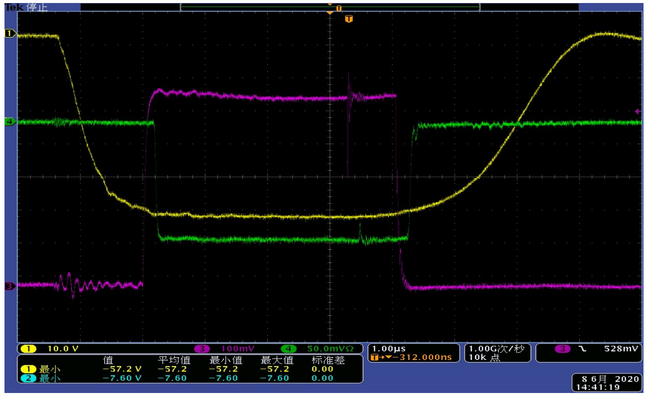




Accelerating structure

- High power test result (with SLED)
  - The modulator voltage is 37.5 kV
  - the SLED energy multiplication factor： 1.8
  - The tested gradient has reached 33 MV/m

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

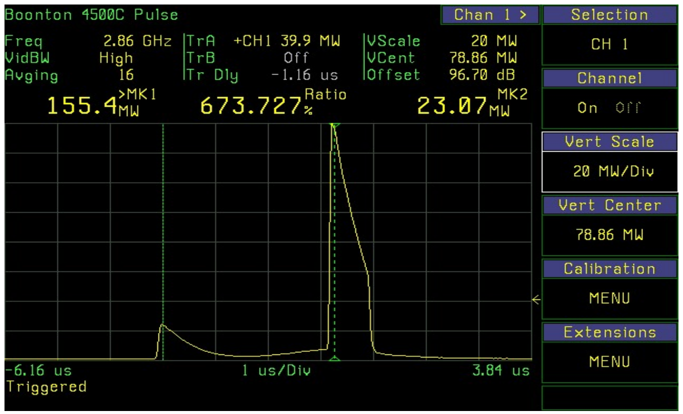


The waveform without SLED

Modulator and klystron

High power test bench

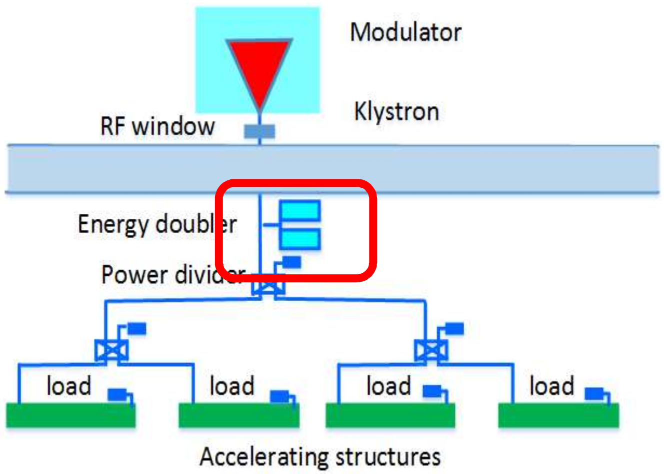
The input power with SLED

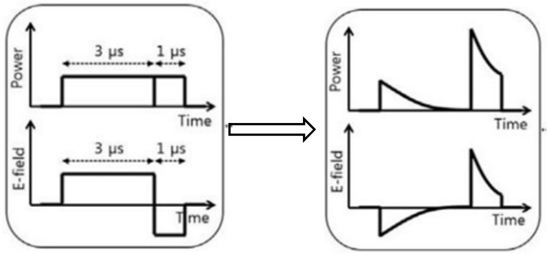


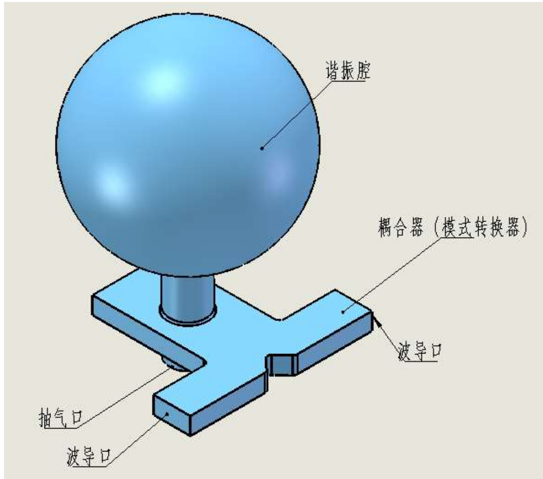
Pulse compressor

- It is used to improve the peak power from the klystron and saving cost
  - Input power: 80 MW
  - Pulse width: be compressed from 4uS→0.8uS
  - Mode converter & spherical cavity

Parameter	Value
SLED water temperature	30 ℃
Room temperature	25 ℃
Filling time	780 ns
Klystron output power	80 MW
Pulse width	4 μs
Pulse repetition rate	100 Hz

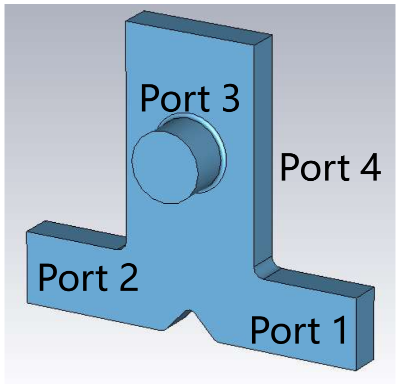




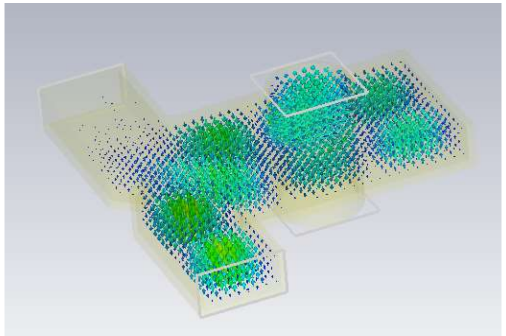


Pulse compressor

- Mode converter
  - The TE_{10} mode input from Port 1 will be converted into two degenerated TE_{11} modes at Port 3
  - There are two degenerated TE_{113} modes in the spherical cavity, The phase difference of the two modes is about 90°
  - The input port S_{11} is -62.7 dB
  - The S_{41} is -71dB for port 4 is for vacuum



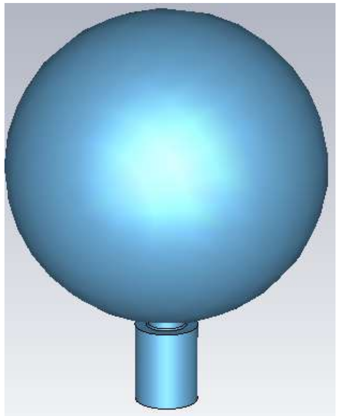
Vacuum model


Electromagnetic field

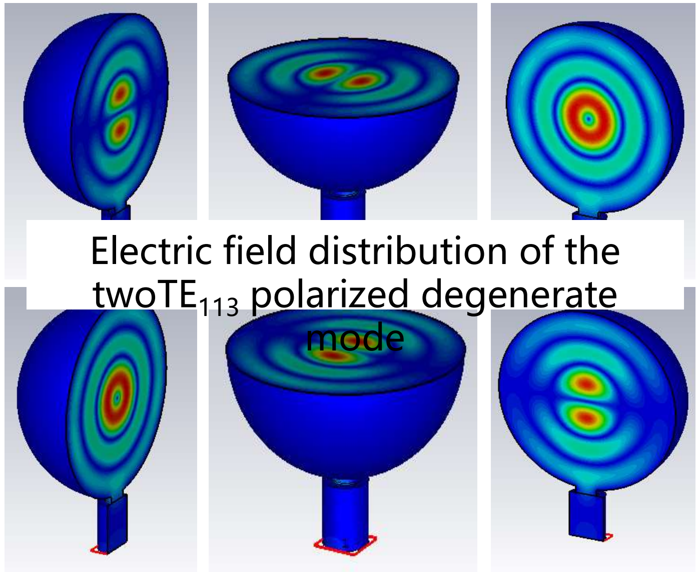
S11 / VSWR	-62.7 dB/1.0016
S21	-42.9 dB
S31(1)	-3.02 dB
S31(2)	-3.02 dB
Phase difference of two modes	89.89°
S41(1)	-70.9 dB
S41(2)	-71.0 dB

Pulse compressor

- Spherical cavity
  - Two degenerated TE_{113} modes in a single spherical cavity
  - f_0=2855.9986 MHz, 2855.9994 MHz,
  - Q_0=139583, 139551
- Cavity diameter
  - 365mm



Simulation model

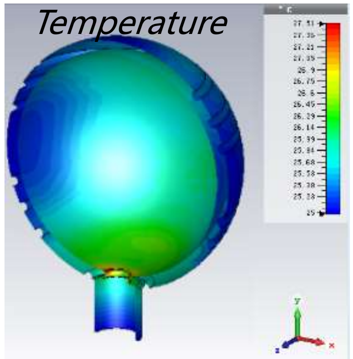


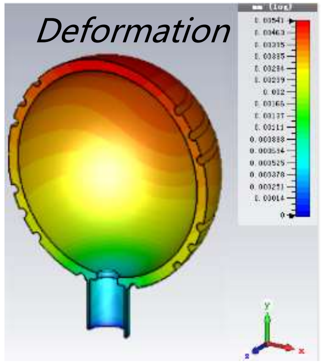
Electric field distribution of the twoTE_{113} polarized degenerate mode

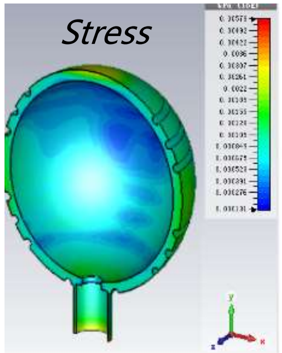
Parameter	value
VSWR	≤1.1
Coupling factor	~6.9
Tuning rang	≥±1 MHz
Peak power gain	≥7dB
Energy gain factor	~1.6

Pulse compressor

- Thermal stress analysis
  - The maximal temperature rise is on the coupling hole of 2.5 ℃ (the water cooling flow set as 50 L/min)
  - The frequency tunable range of ±1 MHz is enough for all the frequency shift resulted from the input power, vacuum pumping, air pressure, etc.



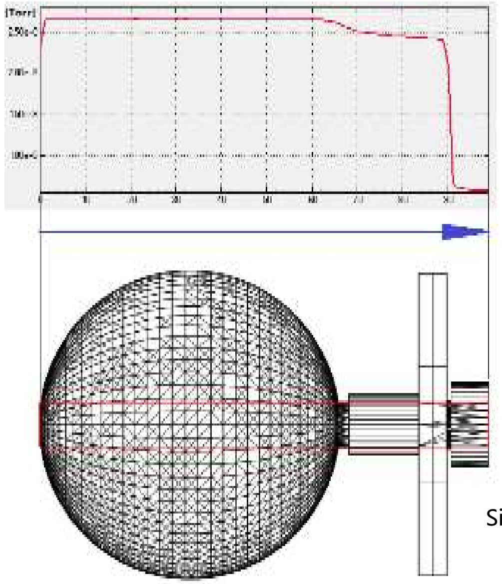




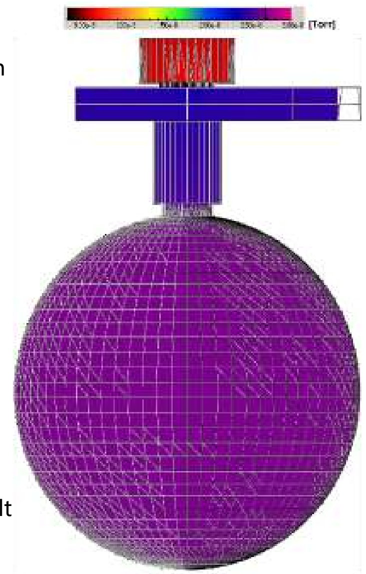
- Accordingly, if we use the water temperature to tune the frequency, the temperature need to be ±3.6 ℃ change

Pulse compressor

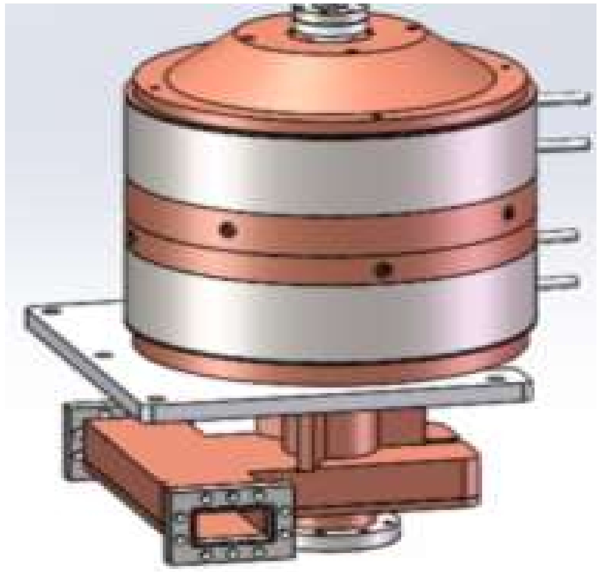
- Vacuum speed and vacuum level
  - The pumping speed of the ion pump 100 L/s is enough



Vacuum distribution

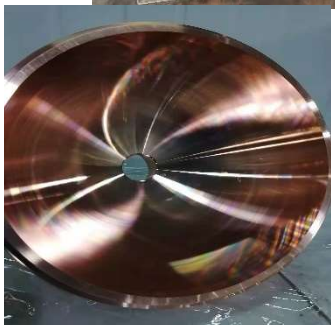


Simulation result

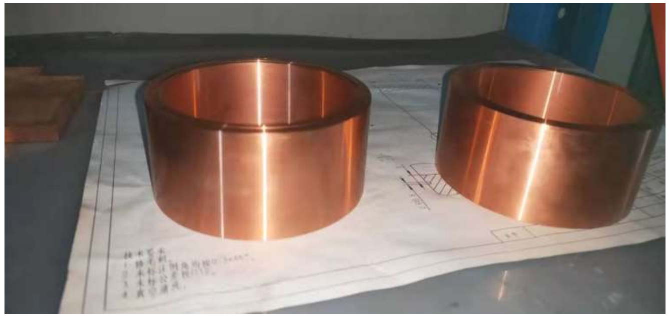


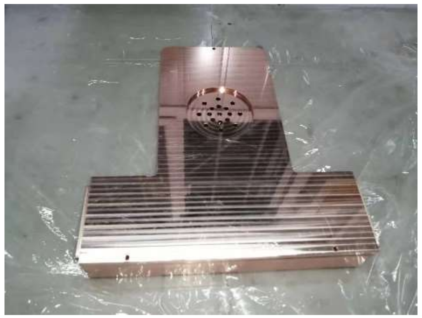
Pulse compressor

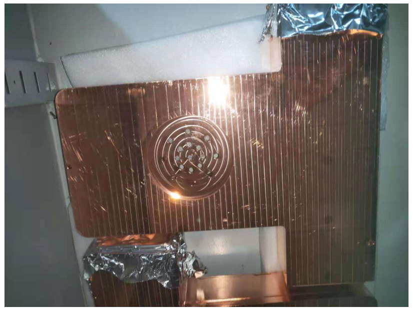
- Machining in progress
  - For the diameter (365 mm) is large, in order to reduce cost, Sheet Forming process has used
  - Then fine machining



After fine machining

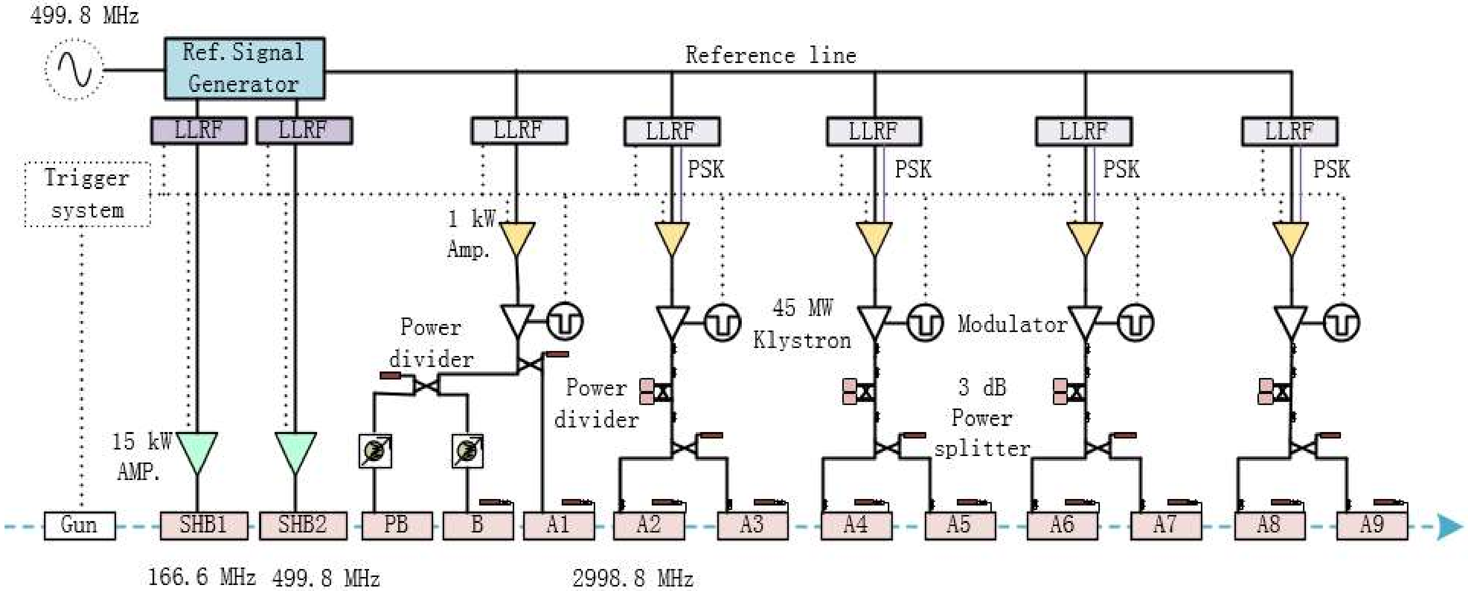






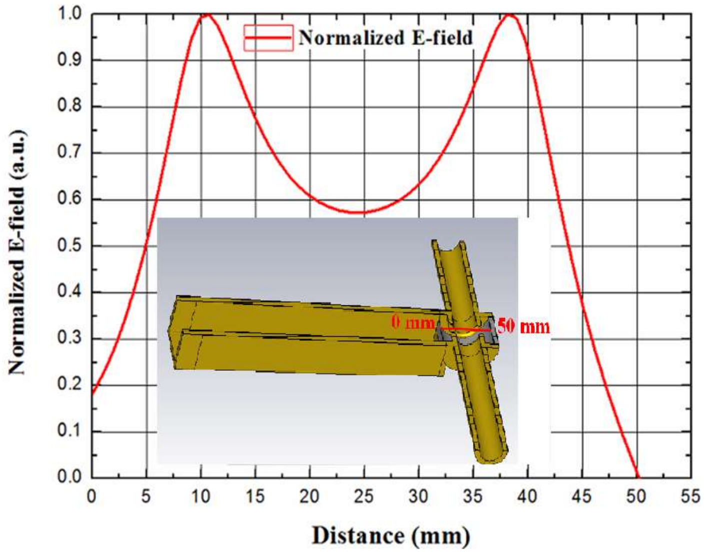
Microwave system for HEPS

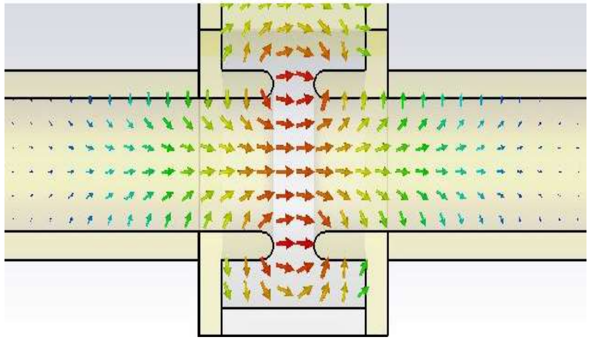
- High Energy Photon Source (HEPS)
  - It is a fourth-generation synchrotron light source with an ultrahigh brightness and under construction in Beijing, China
  - Its accelerator system is comprised of a 6-GeV storage ring, a full energy booster, a 500 MeV Linac and three transport lines
- Microwave system of the linac （The linac will be installed on Feb 8, 2022）

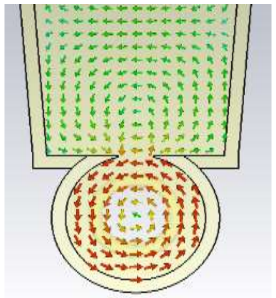


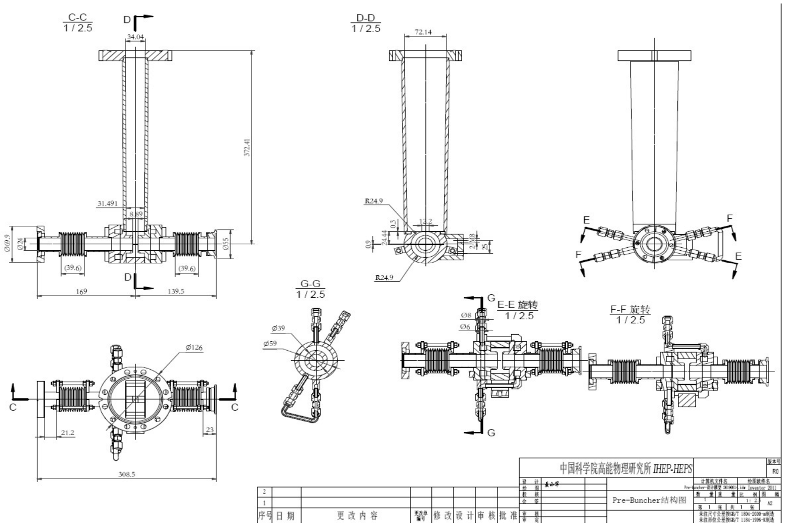
Microwave system for HEPS

- The bunching system
  - Prebuncher



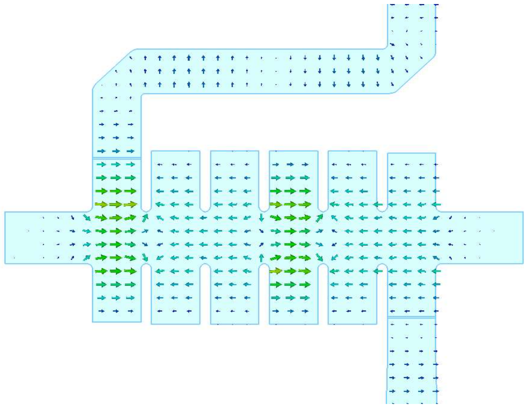


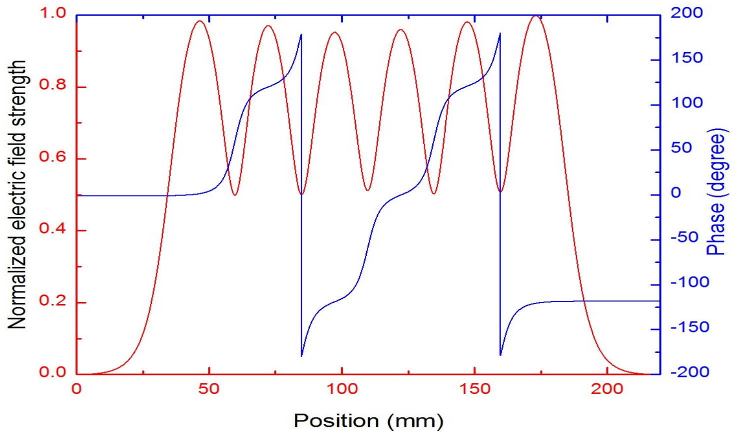


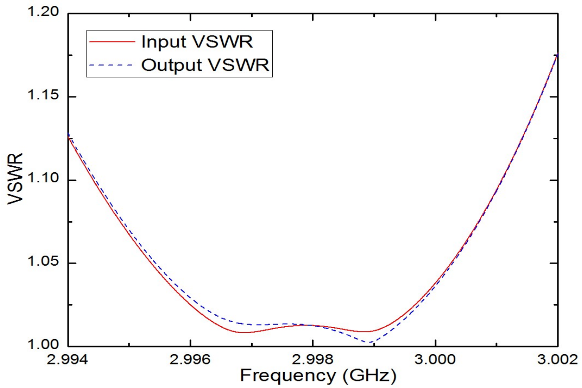


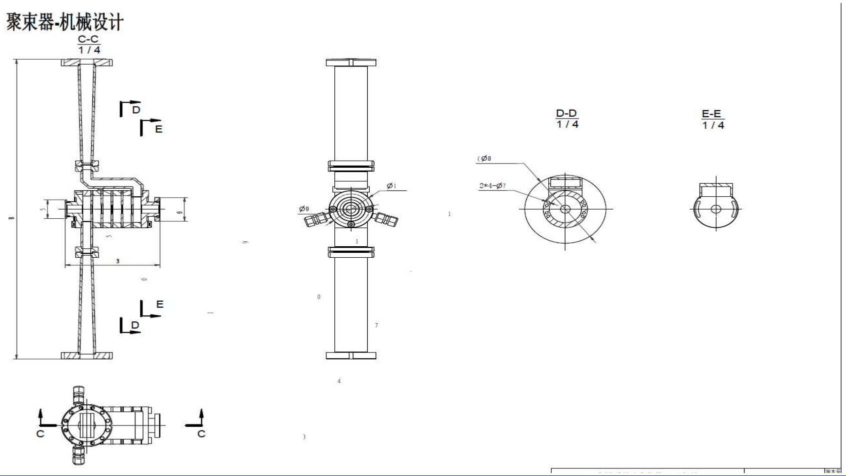
Microwave system for HEPS

- The bunching system
  - The buncher is 4 cavities and two couplers witch will provide 1200 kV cavity voltage





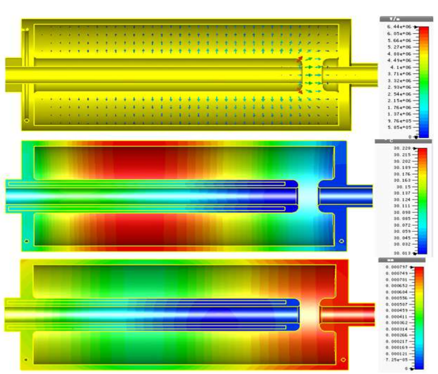




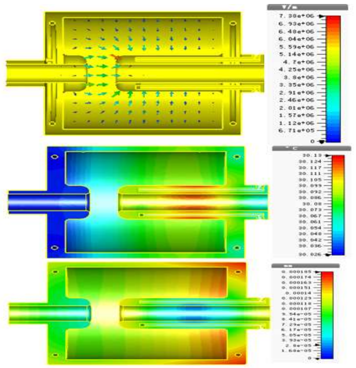
Microwave system for HEPS

- The bunching system
  - SHB1 & SHB2 have all used double-entry structure

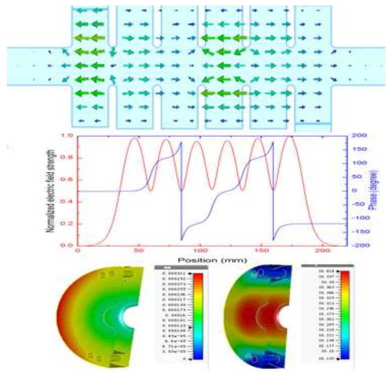
Parameters	Value			Unit
	SHB1	SHB2	B	
Frequency	166.6	499.8	2998.8	MHz
Shunt Impedance	1.52	2.68	7.5	MΩ
Unloaded Q	8813	13135	11083	-
Bunching Voltage(Max)	100	120	1200	kV
RF Structure	SW	SW	TW	-



SHB1 electromagnetic field and thermal distribution



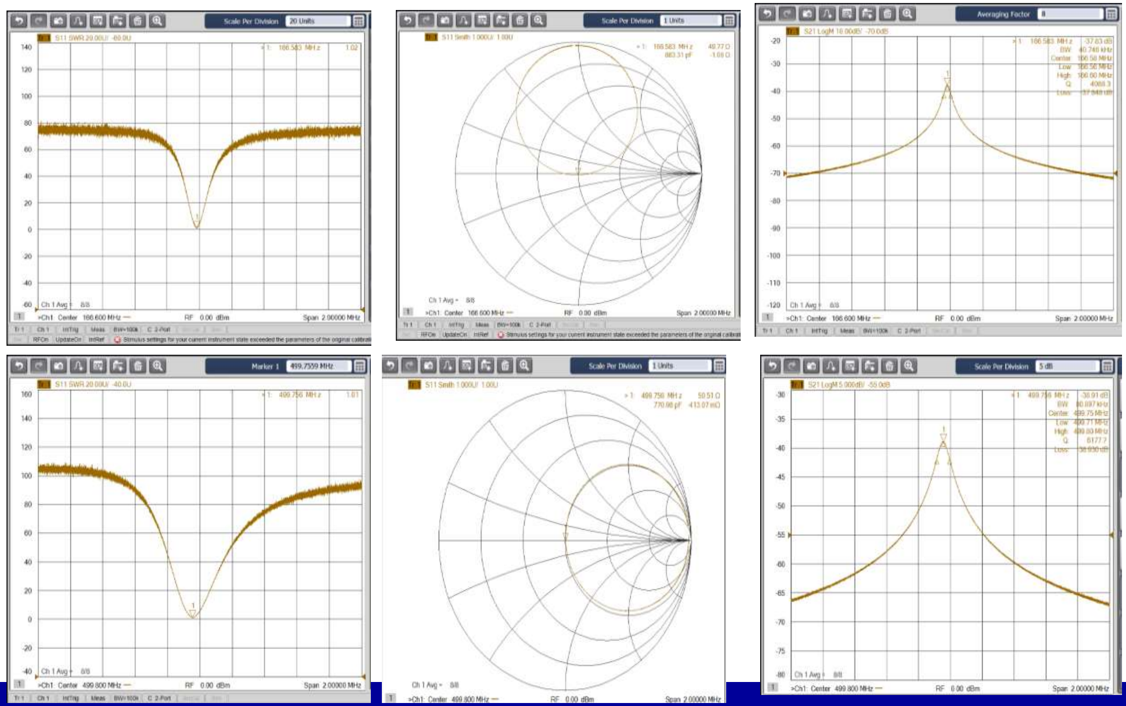
SHB2 electromagnetic field and thermal distribution

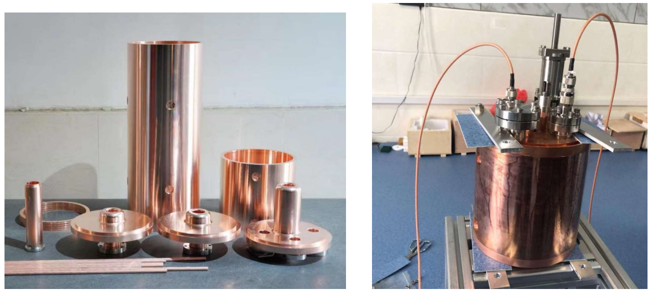


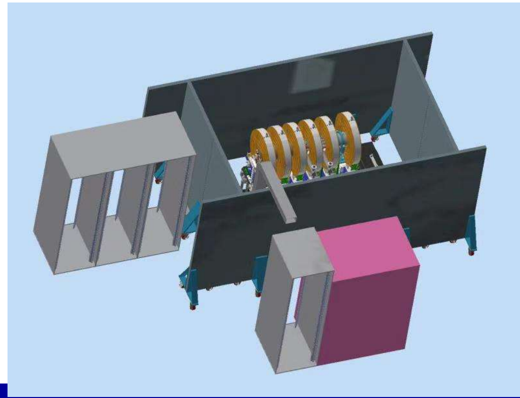
Buncher electromagnetic field and thermal distribution

Microwave system for HEPS

- The bunching system
  - The two cavities are finished
  - The cold test result is the same as the simulation
  - SHB1 Q_0=8176 , SHB2 Q_0=12300
  - They will be high power test in May with the solenoid outside



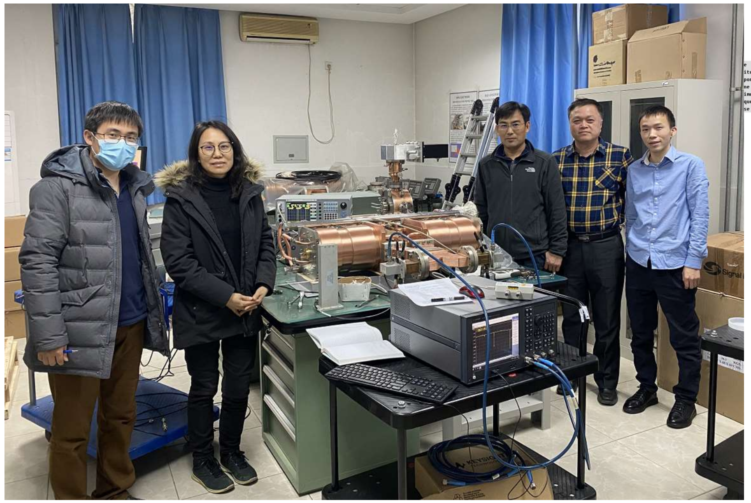


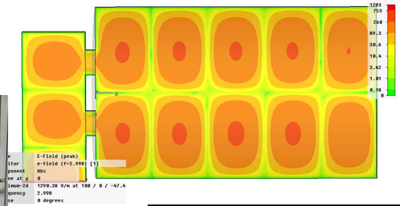


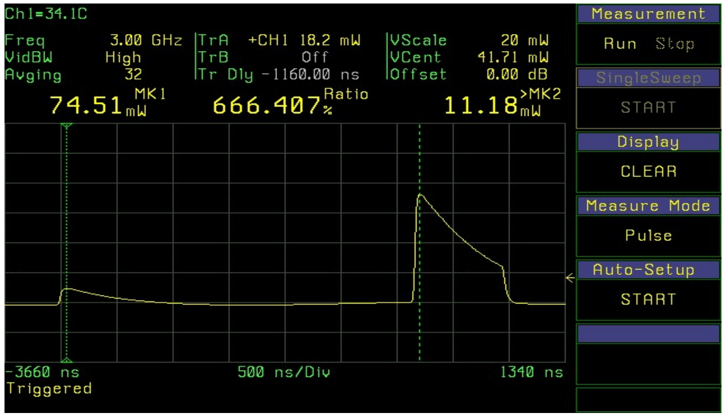
Microwave system for HEPS

- Pulse compressor
  - The working mode is TE_{015}
  - Two-hole narrow-wall coupled SLED type is adopted
  - The energy contribution will be 1.6 times compared to the situation without the pulse compressor

Item	value
Frequency	2998.8 MHz
Mode	$TE_{0,1,5}$
Unloaded quality factor	100,000±5,000
Coupling coefficient	~5
Insertion loss	≤0.2 dB
Frequency tuning range	> ±500 kHz
VSWR	< 1.1
Vacuum leakage rate	< 1×10^{-10} Torr·L/s

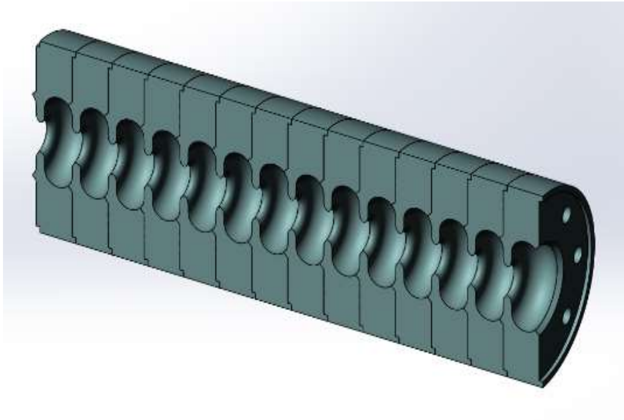


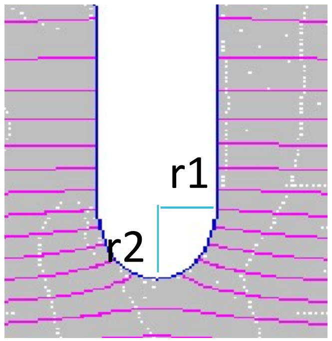


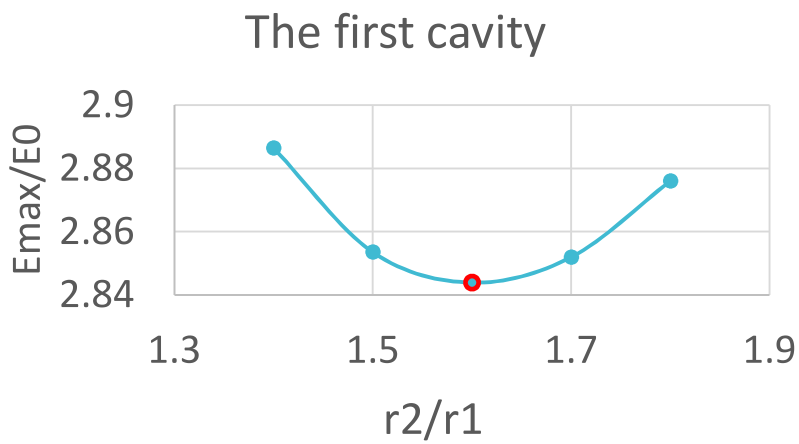


S-band accelerating structure for HEPS

- Cavity shape optimization
  - The frequency is 2998.8MHz
  - Continue to choose the disc with rounding cavity and elliptical section iris
  - The thick of the iris is 4.5mm
  - Ratio of major axis to minor axis is 1.6
- The total number of cells are 88

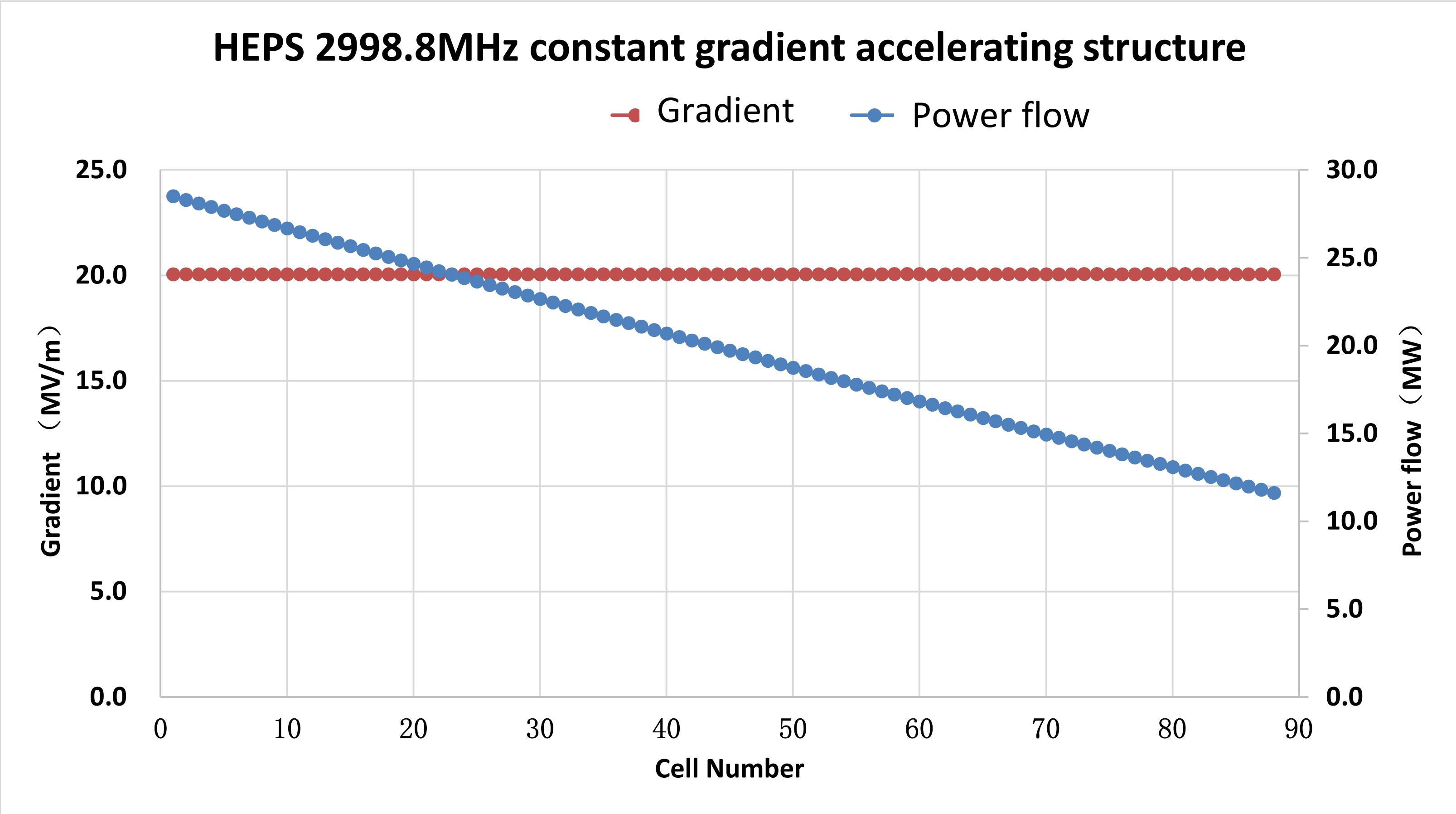






S-band accelerating structure for HEPS

- When input power is 28.5 MW， the gradient is 20 MV/m



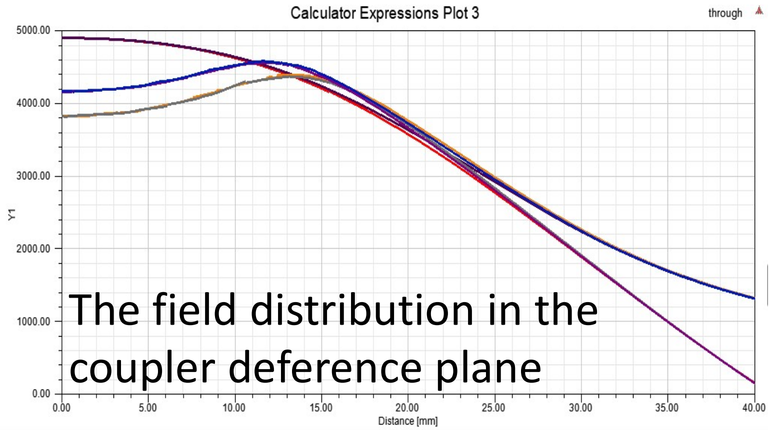
S-band accelerating structure for HEPS

- Main parameters

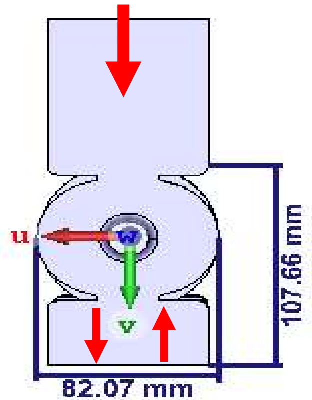
Parameters	value	unit
Frequency	2998.8	MHz
type	Constant gradient, travaling wave	-
Work mode	2π/3	rad
Cell number	88+2	-
Total length	3.101	m
Vg/vc	1.89~0.87	%
Attenuation	0.46	NP
impedance	65.2 ~ 73	MΩ/m
Average shunt impedance	69.8	MΩ/m
Filling time	740	ns
Power requirement @Eacc=20MV/m	28.5	MW
Espeak/Eacc 1st cavity	2.84	-
Hspeak 1st cavity @Eacc=20MV/m	70	kA/m
$K=\frac{E}{\sqrt{P}}$	11	-
Output power/input power	0.4	-

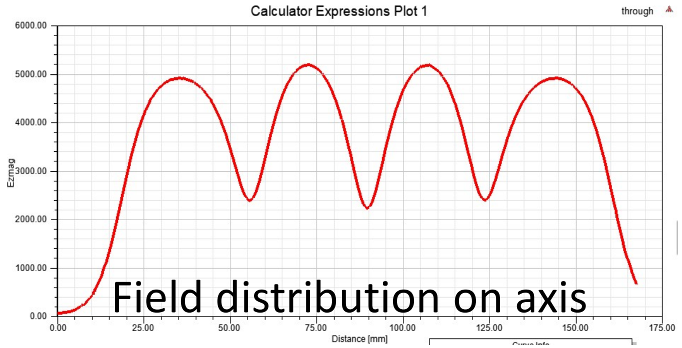
S-band accelerating structure for HEPS

- The coupler design （λg/4）
  - The cavity adjacent the coupler is bowl shape structure for the machining process
  - The coupler cavity shape is racetrack shape
  - λg/4 short plane opposite the input port

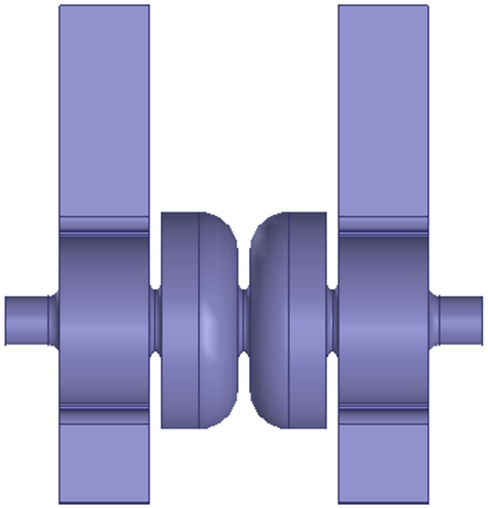


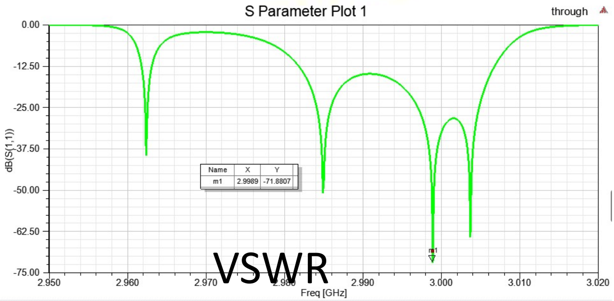
The field distribution in the coupler deference plane



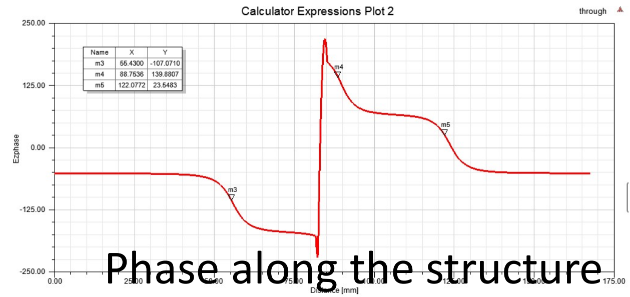


Field distribution on axis


Simulation model



VSWR



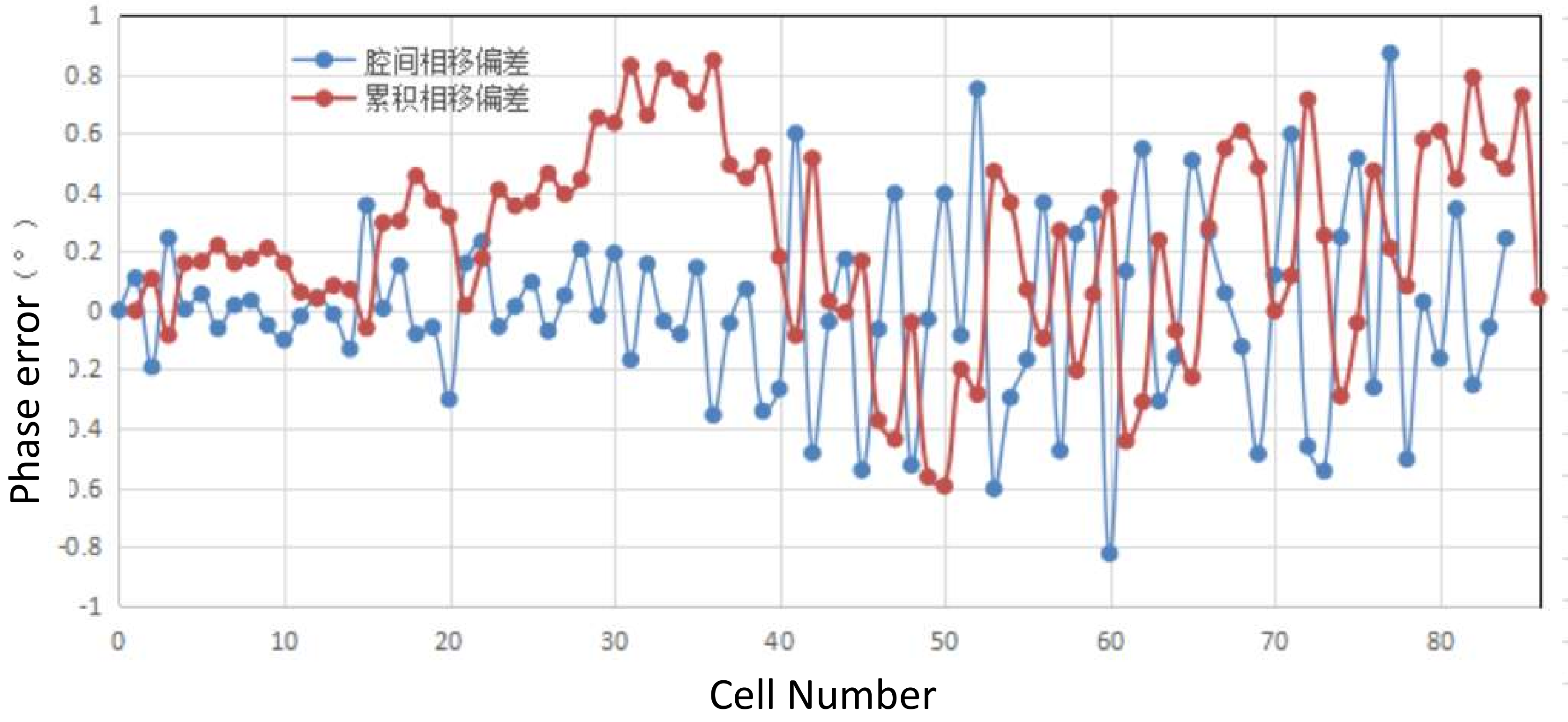
Phase along the structure

S-band accelerating structure for HEPS

- The structure in the lab before tuning

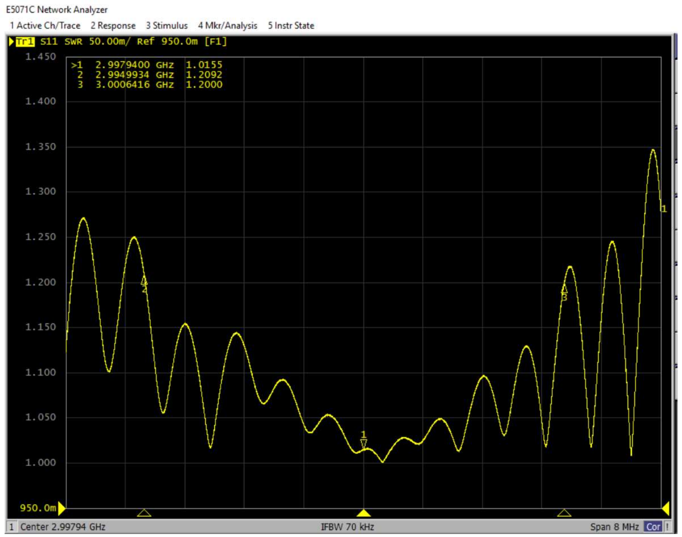
S-band accelerating structure for HEPS

- After tuning
  - Phase shift per cell and the accumulate phase within ±1°

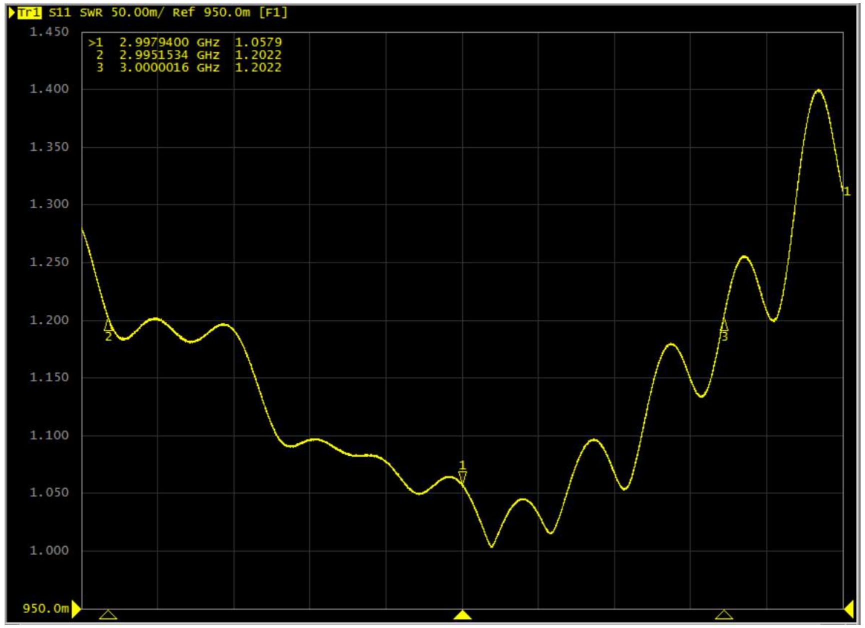


S-band accelerating structure for HEPS

- The whole
  - Input VSWR=1.01 @ 2998.8 MHz
  - VSWR≤1.2 is 2.96 MHz （3000.64 MHz -2994.99 MHz ）
  - Output VSWR=1.06
  - The attenuation is 0.5 Np
  - Filling time is 767 ns



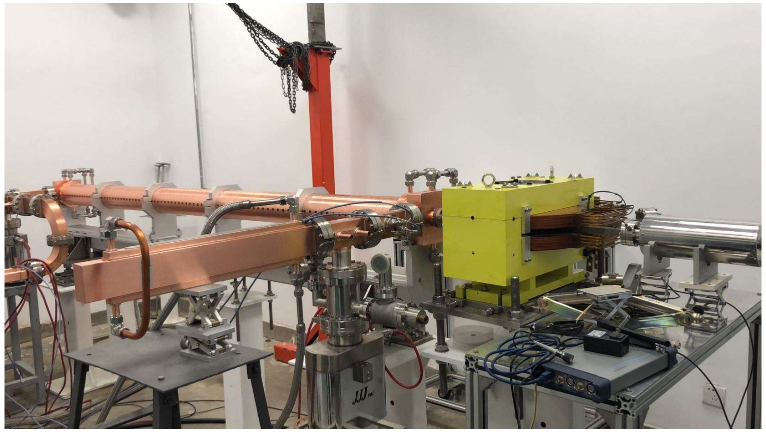
Input VSWR

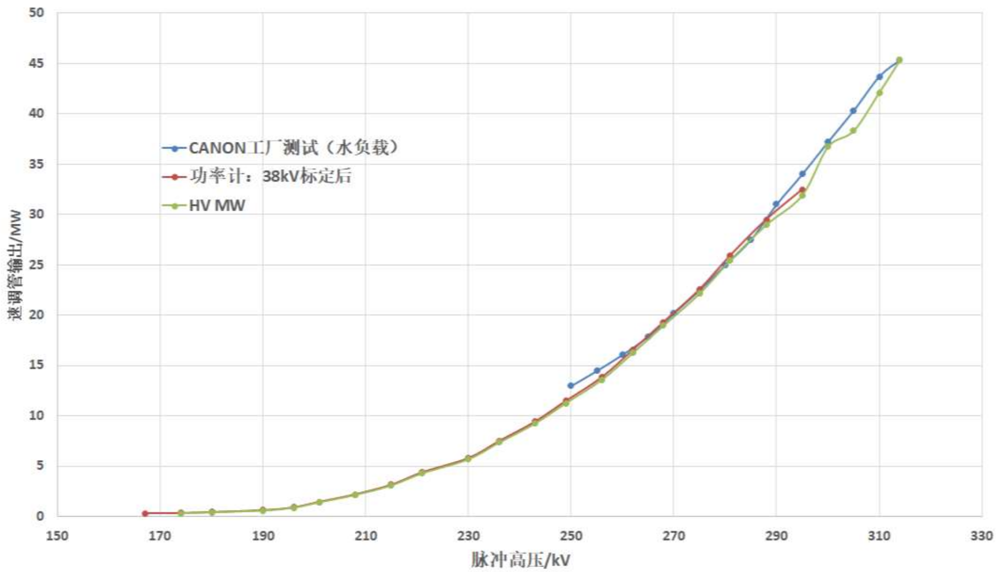


Output VSWR

S-band accelerating structure for HEPS

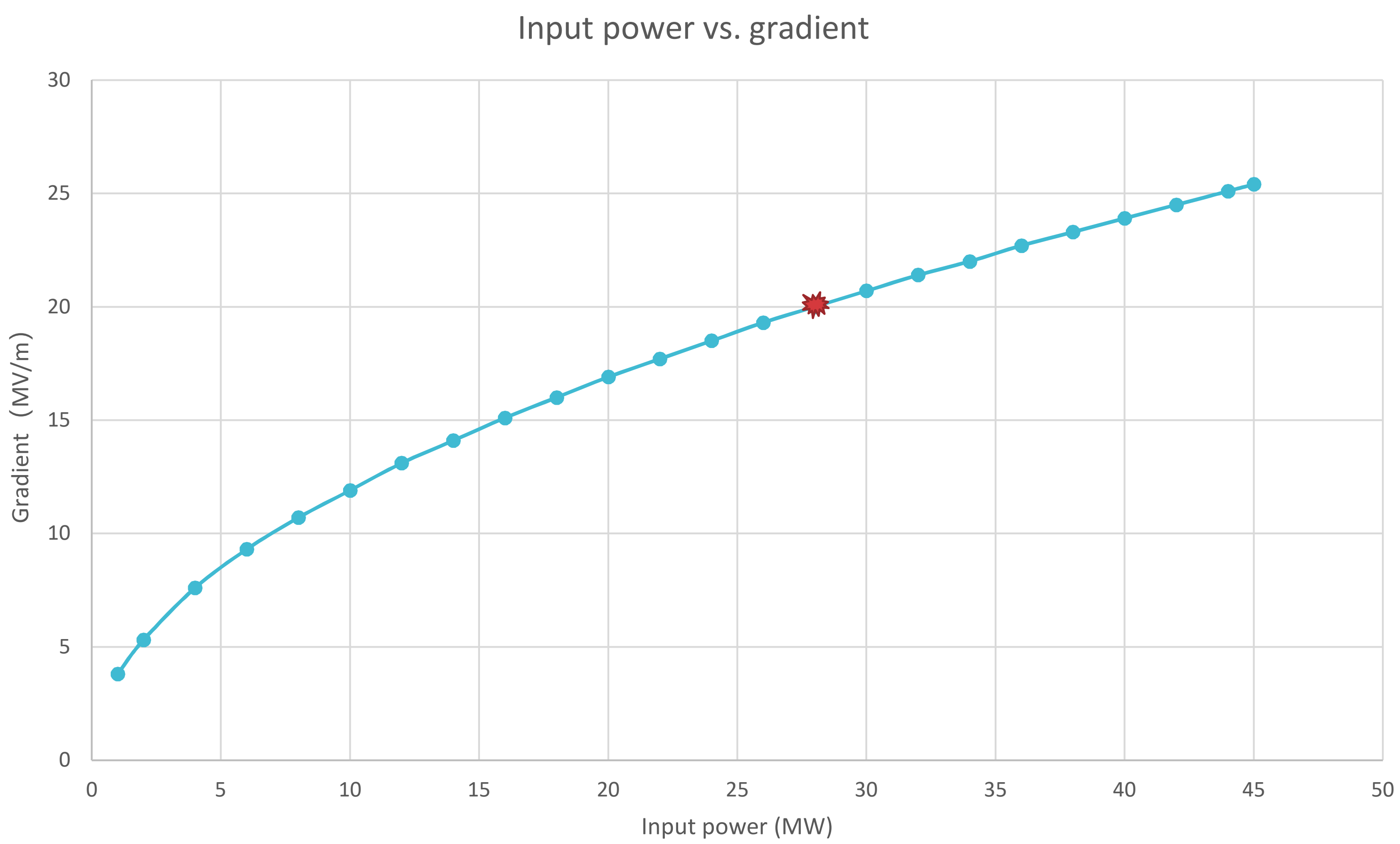
- High power test bench
  - 45 MW klystron (Conon company)





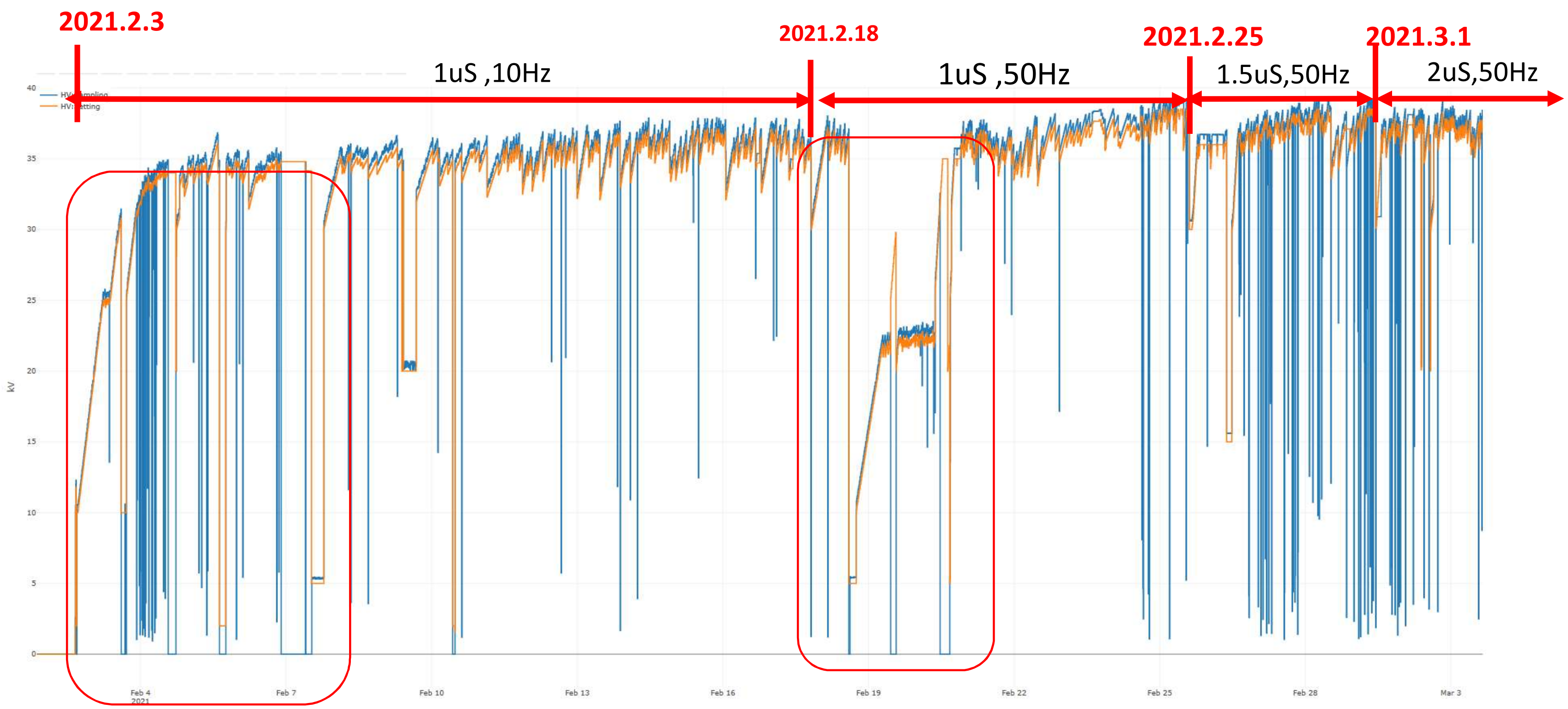
S-band accelerating structure for HEPS

- High power test bench



S-band accelerating structure for HEPS

- High power test
  - About 35 days to up to 20 MV/m

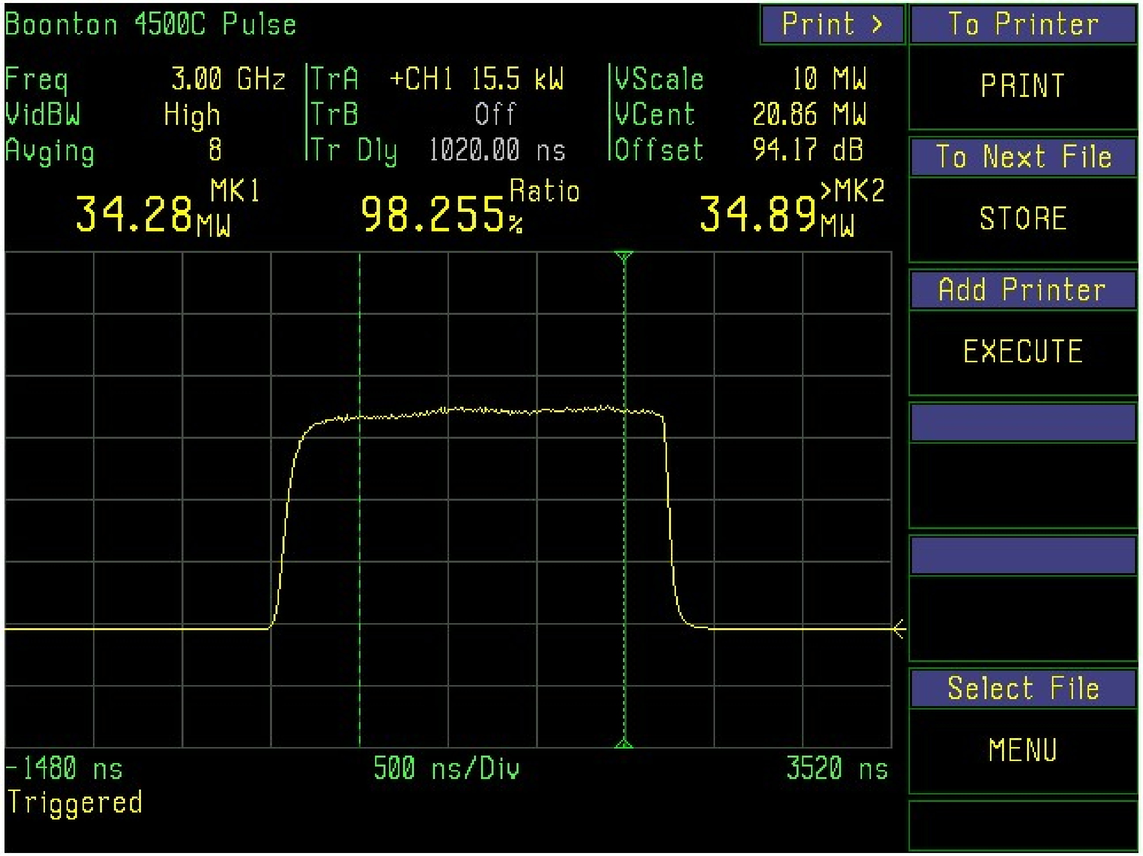


- Constant cooling water fault
- Optimize the system to add feedback of the vacuum
- ……

- Modulator fault
- False protection , then add filter
- ……

S-band accelerating structure for HEPS

- Final results
  - The power input the structure is 34.58 MW， the gradient is about 22MV/m



Summary

- The S band structure of CEPC has finished and the gradient up to 33MV/m on the test bench with SLED
- A spherical cavity compressor has developed. To reduce cost, sheet forming process id used
- The linac of HEPS will be installed on Feb 8, 2022 according the CPM
- RF components have all developed now. The first 3 meters long 2998.8 MHz accelerating structure finished high power test and meet the physical design requirement