Status of CEPC LINAC

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Outline

1	LINAC Physics design
2	LINAC R&D activities
3	Summary

Requirements for linac

- The requirements of the booster to the Linac
  - Old baseline: S-band
  - New baseline: S+C-band

Parameter	Unit	Old Baseline (S)	New Baseline (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(3*)	
Energy spread		2×10^{-3}	1.5×10^{-3}
Emittance	nm	40	**10**

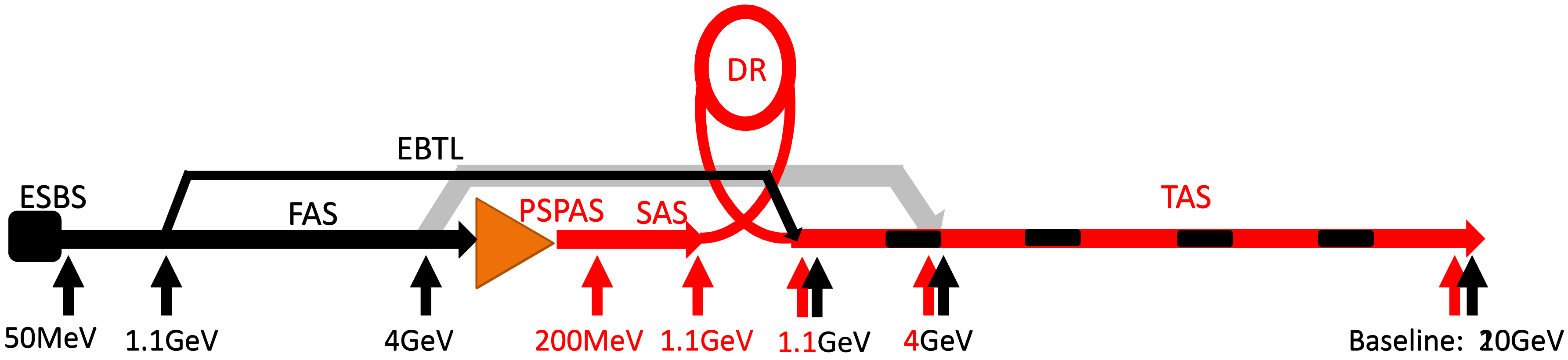
* The Linac designed value to preserve future upgrade potential

LINAC Physics design

- New baseline
  - Design difficulties of booster dipole and power supply
    - Large magnetic field range
      - keep the potential of energy up to 180GeV
    - Low magnetic field @ low injection energy
      - ~29 Gs @ 10GeV
  - Increasing the energy of the Linac is the simplest and most effective measure to mitigate the difficulties
    - Redefined the Linac scheme, the Linac energy is **20** GeV
    - Considering high luminosity scheme at Higgs energy, the required emittance is decreased to **10** nm

LINAC Physics design

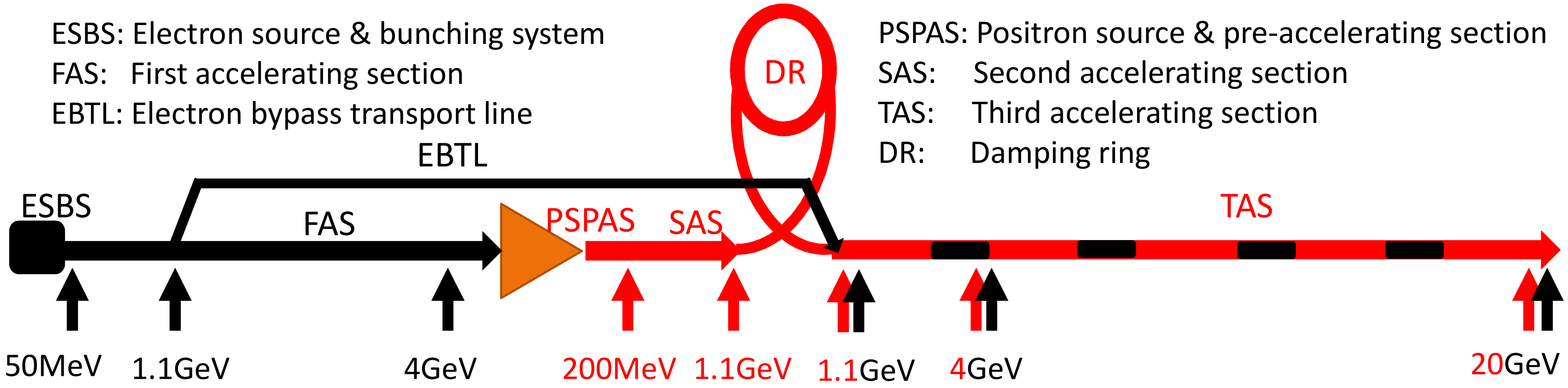
- Linac Layout
  - The energy of electron bypass transport line (EBTL) is from 4GeV to 1.1 GeV
    - Reduce the layout design difficulty of the positron source section
      - The layout of the positron source is very **complicated**
      - No need consider the EBTL magnets
    - Better compatibility between different schemes
      - Can use c-band acceleration structure more, the starting energy can be from 1.1 GeV
      - All sections before the TAS could be fixed



LINAC Physics design

- Linac Layout

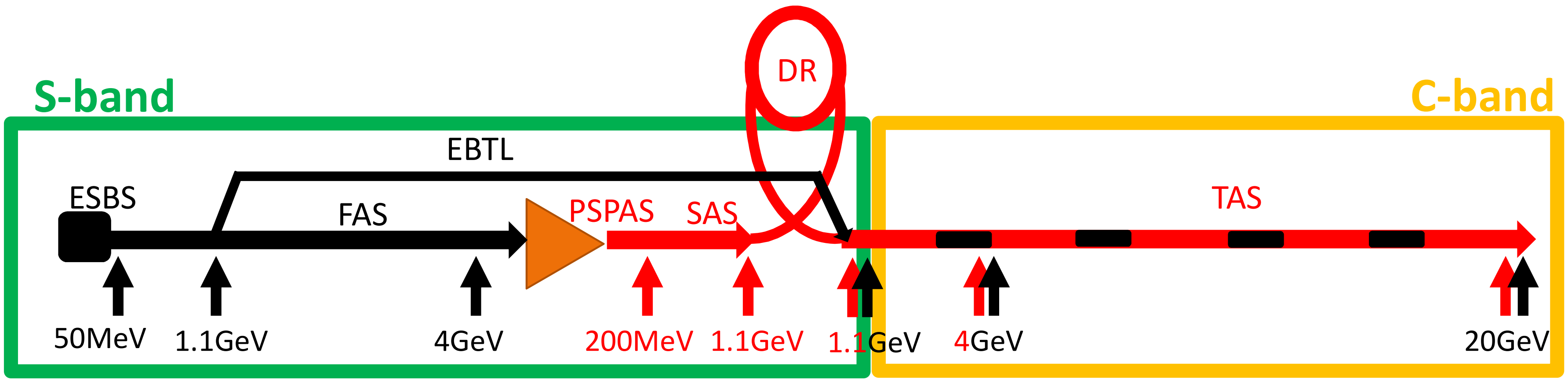
- The deflection direction of the EBTL is from horizontal to vertical, the distance between EBTL and main linac is from 2 m (H) to 1.2 m (V)
  - Easier layout design to avoid the interference with energy analyzing station, transport lines between the Linac and damping ring, waveguide and positron source
  - Reduce the tunnel width and no need to increase the height (3.5m)



LINAC Physics design

- Emittance → 10nm @ 20GeV
  - Electron beam
    - Norm. RMS. emittance is 100 mm-mrad → 2.6 nm
    - Meet the requirement
  - Positron beam
    - Norm. RMS. Emittance < 300 mm-mrad
    - Lower emittance Damping ring is under design

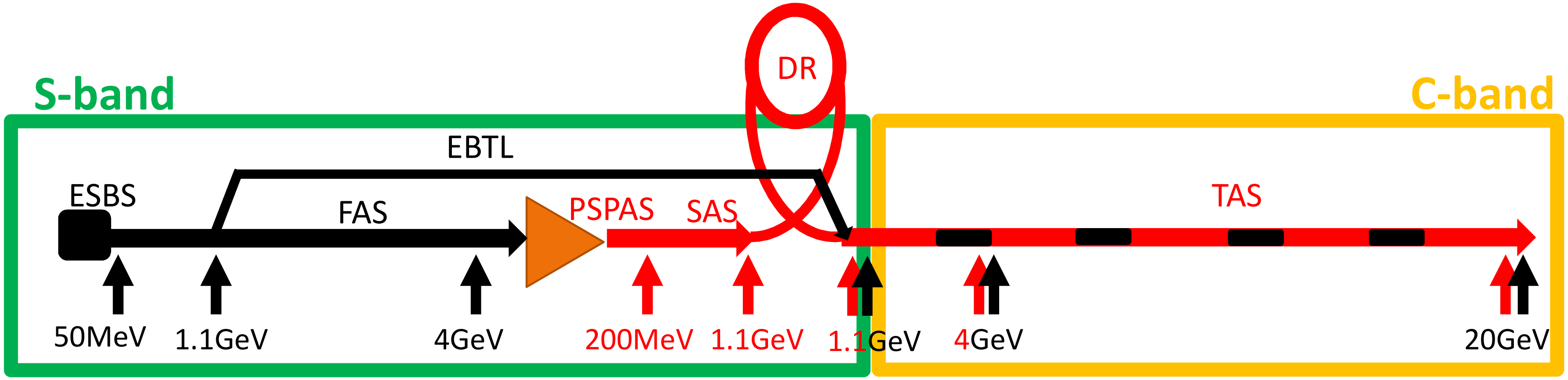
Parameter	Unit	S-band	C-band
Frequency	MHz	2860	5720
Length	m	3.1	1.8
Cavity mode		2π/3	3π/4
Aperture diameter	mm	20~24	11.8~16
Gradient	MV/m	21	**45**



LINAC Physics design

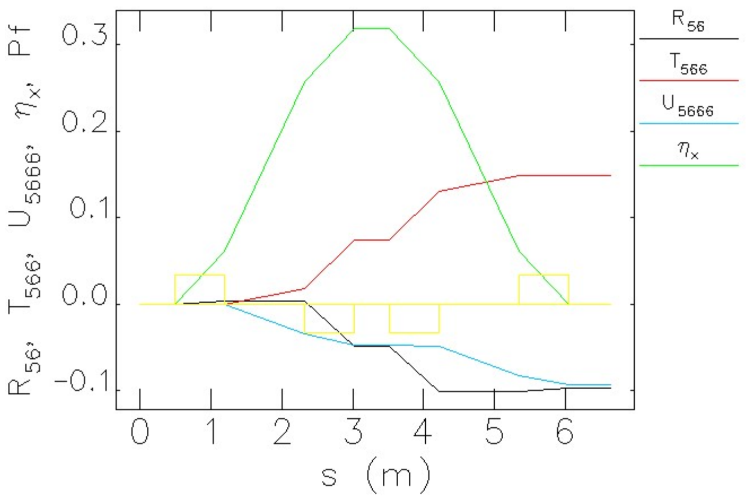
- Emittance → 10nm @ 20GeV
  - C-band accelerating structure from 1.1GeV
    - Transverse: emittance is 140nm@1.1GeV
    - Longitudinal: short bunch length ~ 0.5mm
      - Bunch compressor
    - Wakefield

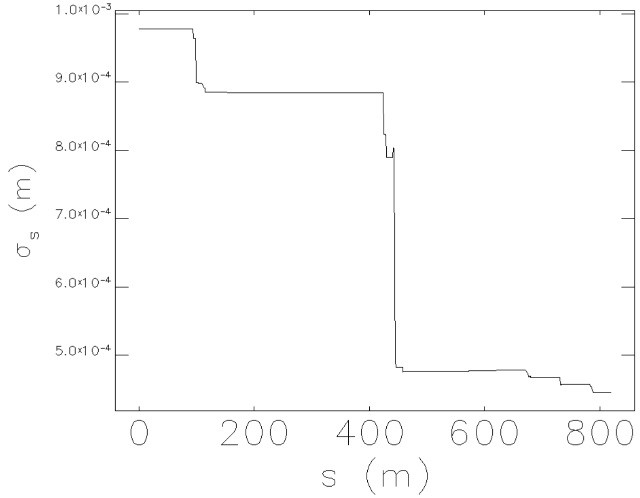
Parameter	Unit	S-band	C-band
Frequency	MHz	2860	5720
Length	m	3.1	1.8
Cavity mode		2π/3	3π/4
Aperture diameter	mm	20~24	11.8~16
Gradient	MV/m	21	**45**



LINAC Physics design

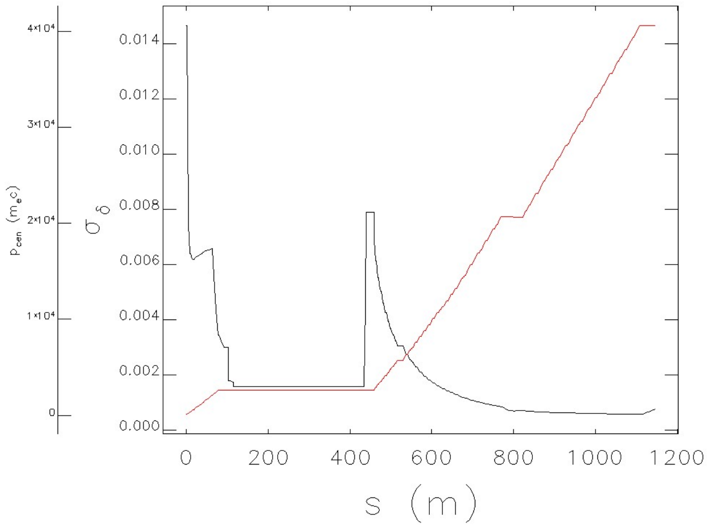
- Chicane
  - A chicane at the beginning of TAS was introduced to compress bunch length for C-band accelerating structure.
  - C-type Chicane as bunch length compressor
    - Angle: 175mrad
    - R56=-0.1m

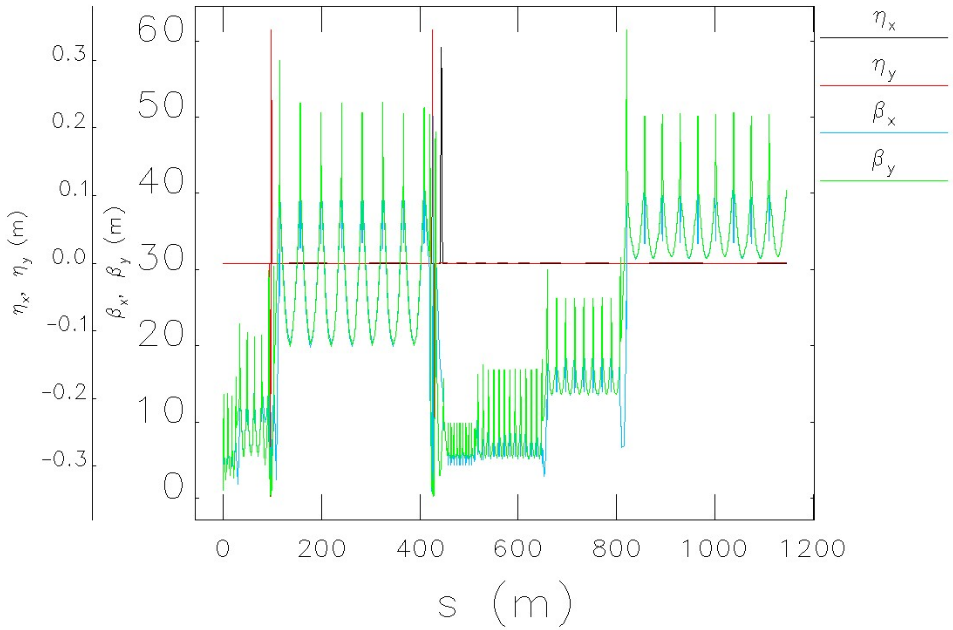




LINAC Physics design

- Optics function
  - Dynamics results
    - Due to higher order effect of ETBL and Chicane, emittance growth is about 20%
    - Under optimization





Other consideration

- High luminosity scheme at Z energy
  - 200Hz
  - Two-bunch acceleration
    - Bunch space
      - Bunch space is about 77ns
      - If RF gun is used, the bunch space is more flexible
    - Energy
      - SLED timing for energy compensation
        - need more klystrons
      - BPM can distinguish the orbits of the two bunch
        - energy measurement and orbit correction
    - Challenge
      - Orbit correction
      - beam commissioning
      - LLRF
      - BPM
      - ……

	frequency		Multiple	Period	
Common frequency	13	MHz	1	76.9231	ns
Two bunch	13	MHz	1	**76.9231**	ns
SHB1	143	MHz	11	6.9930	ns
SHB2	572	MHz	44	1.7483	ns
LINAC	2860	MHz	220	0.3497	ns
Booster	1300	MHz	100	0.7692	ns
Ring	650	MHz	50	1.5385	ns

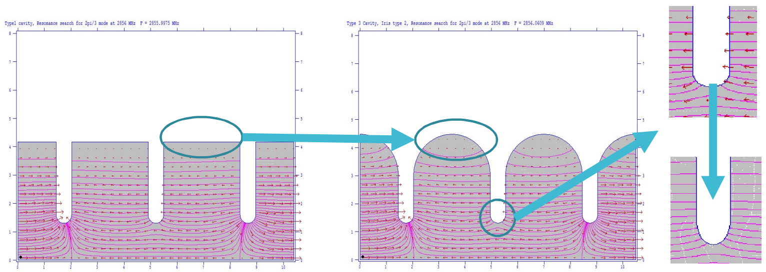
1 LINAC Physics design

2 LINAC R&D activities

3 Summary

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

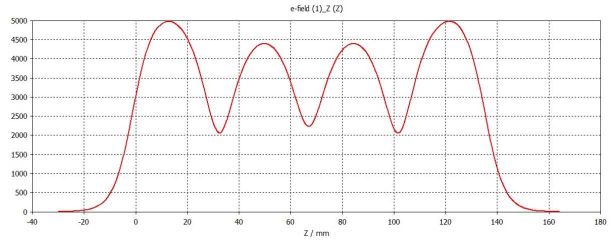
Parameters	Values	Unit
No. of Cells	84+2*0.5	-
Phase advance	2π/3	rad
Total length	3.1	m
Length of cell (d)	34.988	mm
Disk thickness (t)	5.5	mm
Shunt impedance (Rs)	60.3~67.8	MΩ/m
Quality factor	15465~15373	-
Group velocity: Vg/c (%)	2% ~ 0.94%	-
Filling time (t_f)	784	ns
Attenuation factor (τ)	0.46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

Accelerating structure

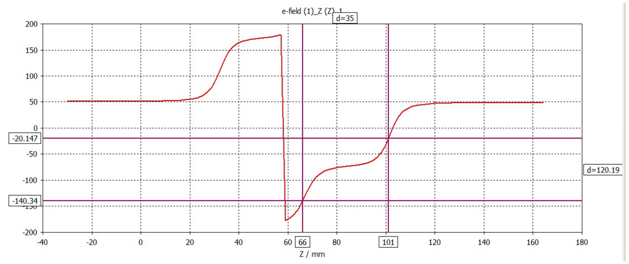
- Coupler design
  - The asymmetry of the coupling cavity will cause emittance growth
  - The shape of the coupling cavity is racetrack dual-feed type

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

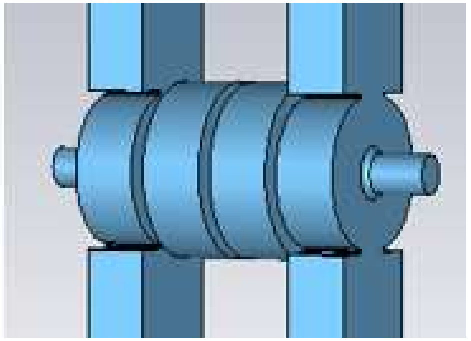
$$\Delta p_x = -\frac{e\Delta z E_0}{2\omega a}[\Delta\theta * sin\varphi - \frac{\Delta E}{E_0}\cos\varphi]$$

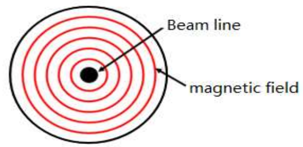


The *distribution of* the electric field on axis

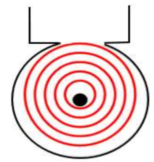


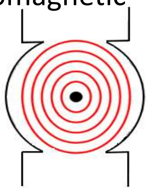
Phase advance per cell

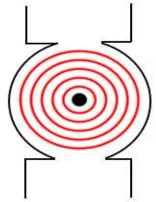

The calculation model



Ideal electromagnetic structure

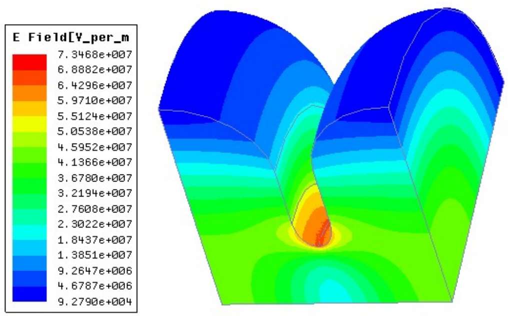

Center bias coupler


Dual feed coupler


Dual feed racetrack coupler

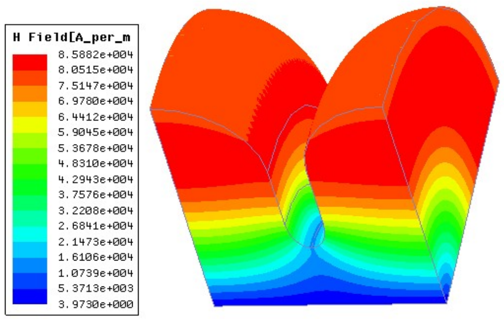
Accelerating structure

- 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



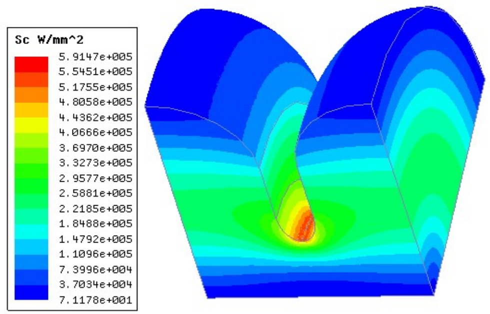
E_peak=73 MV/m.

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

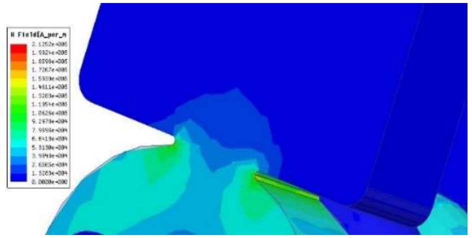
Electric conductivity

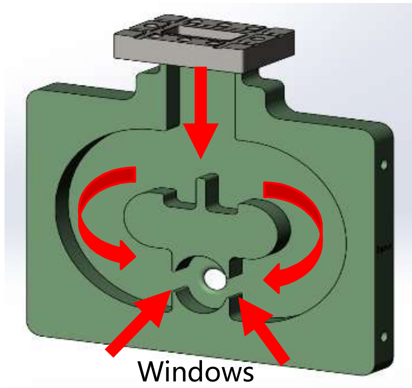
Skin depth

Material density

Specific heat

Thermal conductivity

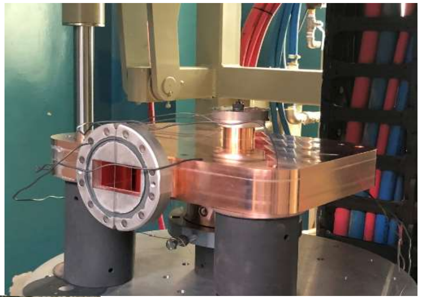




- S-band ΔT < 50°C is safe

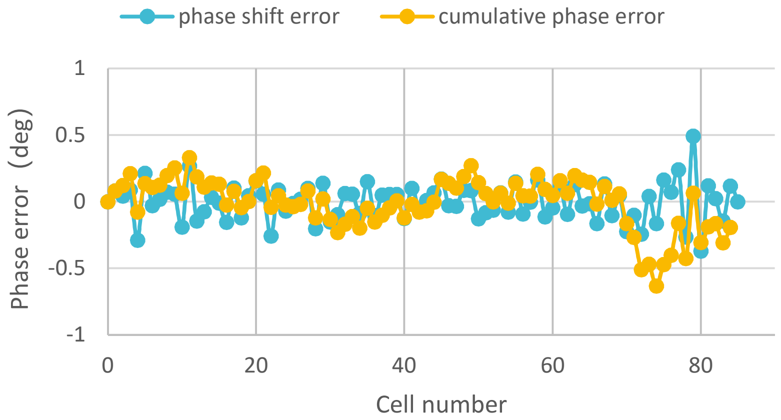
Accelerating structure

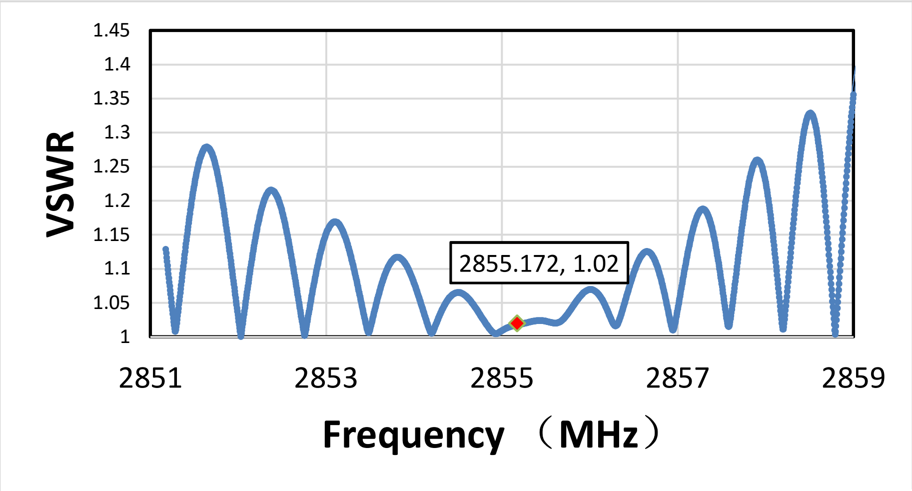
- Mechanical design
  - Inner water-cooling has been adopted. 8 pipes are around the cavity.
  - Compact coupler arrangements. The splitter is milling together with the coupling cavity.
  - Two tuners are outside the cavity.



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

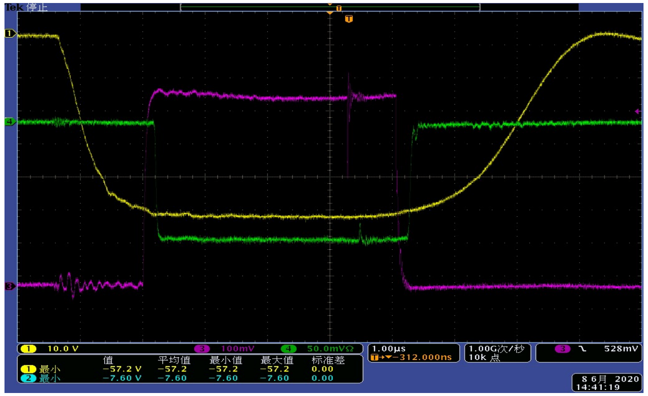




Accelerating structure

- 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

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

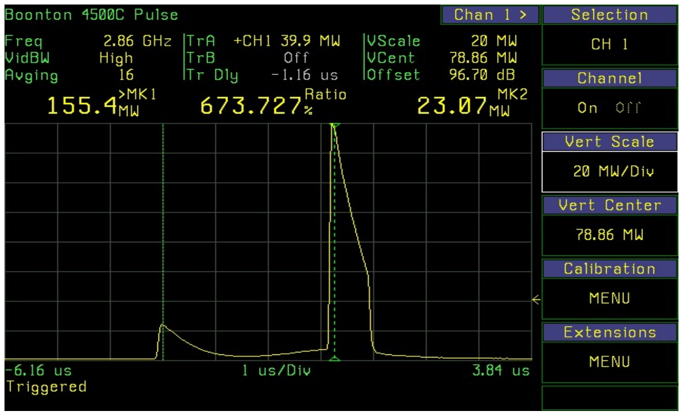


The waveform without SLED

Modulator and klystron

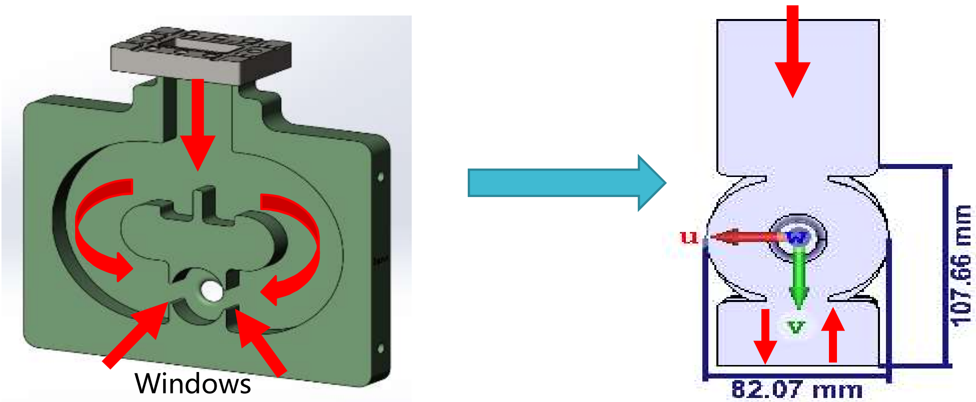
High power test bench

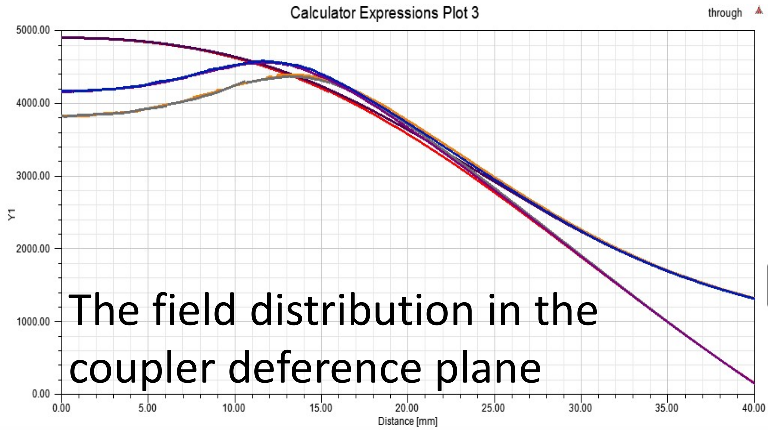
The input power with SLED

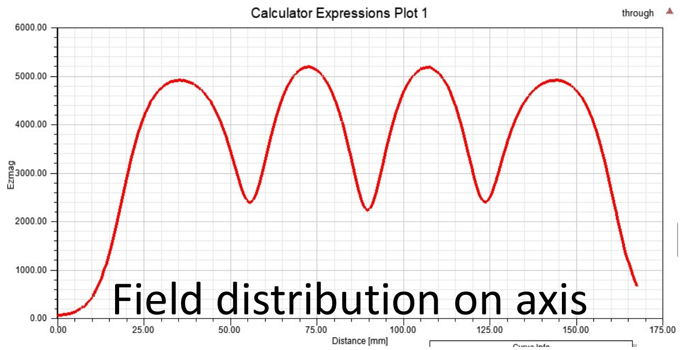


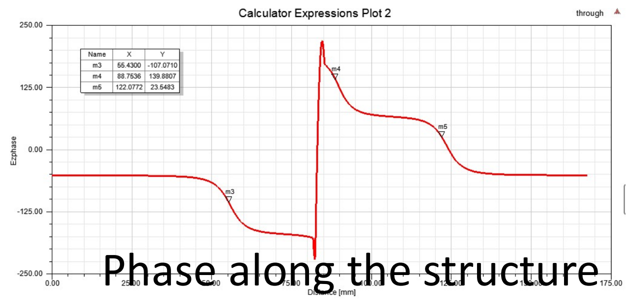
Accelerating structure

- The coupler design （λg/4）
  - The coupler is asymmetry. The cavities in the hydrogen furnace is not at the center place. That will make the welding temperature control difficult
  - λg/4 short plane opposite the input port will be used
  - The coupler cavity shape is racetrack shape





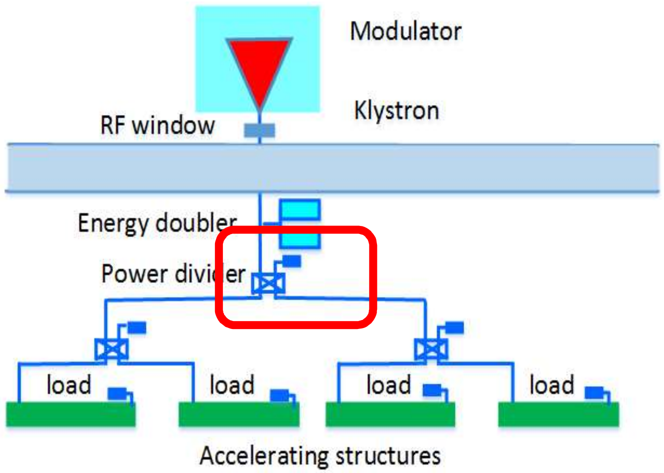


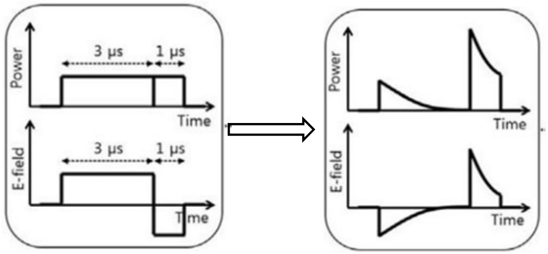


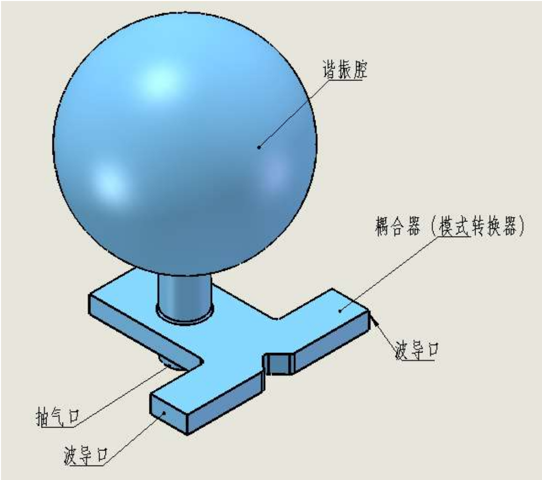
Pulse compressor

- 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

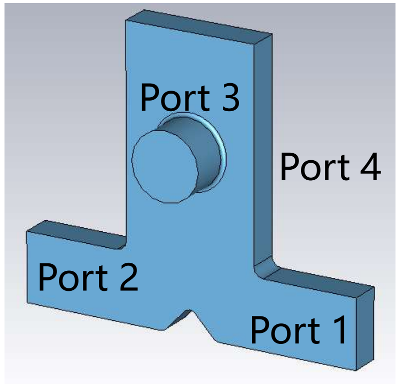




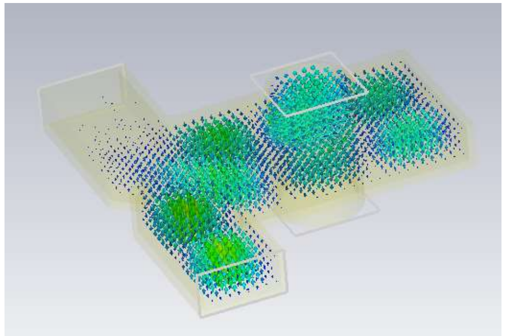


Pulse compressor

- 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

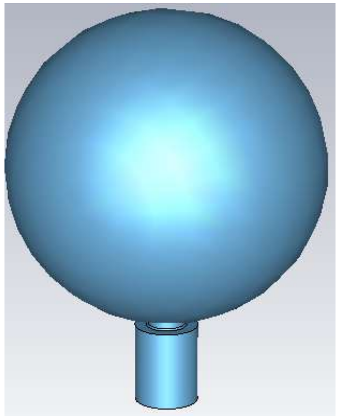


Electromagnetic field

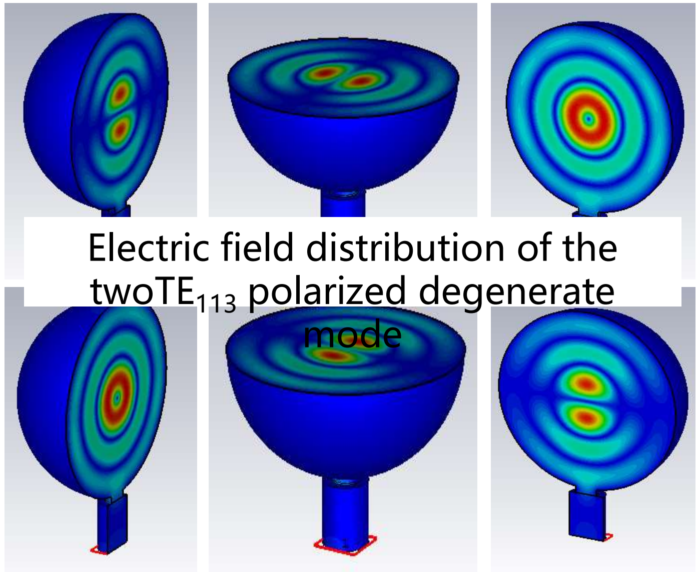
S11 / VSWR	-62.7 dB/1.0016
S21	-42.9 dB
S31(1)	-3.02 dB
S31(2)	-3.02 dB
Phase difference of two modes	89.89°
S41(1)	-70.9 dB
S41(2)	-71.0 dB

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

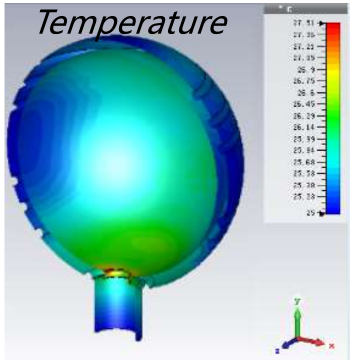


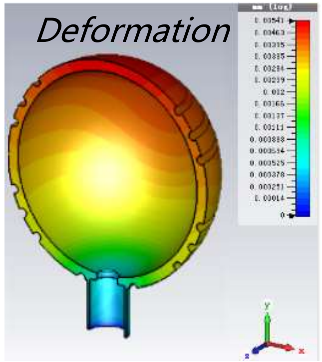
Electric field distribution of the twoTE_{113} polarized degenerate mode

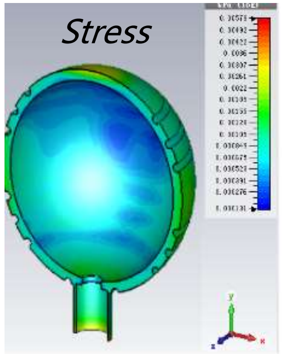
Parameter	value
VSWR	≤1.1
Coupling factor	~6.9
Tuning rang	≥±1 MHz
Peak power gain	≥7dB
Energy gain factor	~1.6

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.



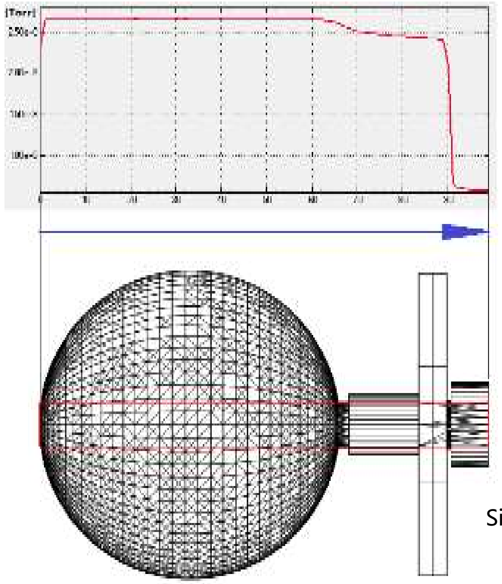




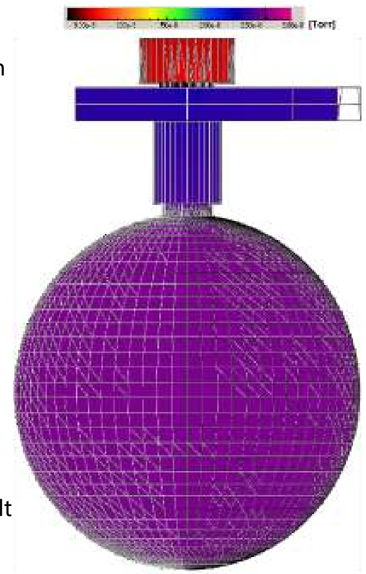
- Accordingly, if we use the water temperature to tune the frequency, the temperature need to be ±3.6 ℃ change

Pulse compressor

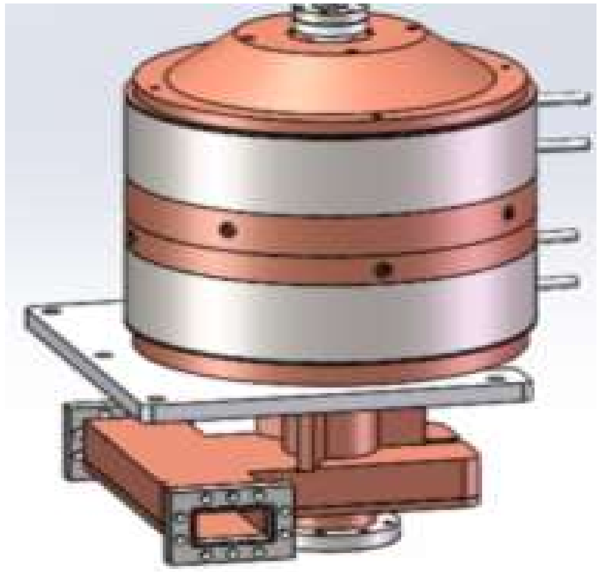
- Vacuum speed and vacuum level
  - The pumping speed of the ion pump 100 L/s is enough



Vacuum distribution



Simulation result



machenical design

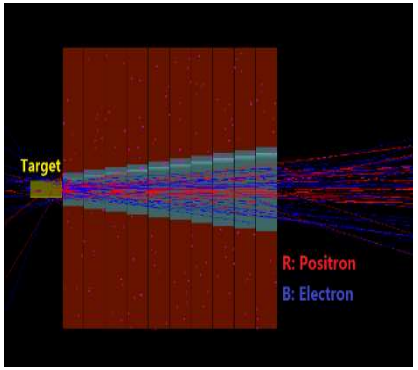
Pulse compressor

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

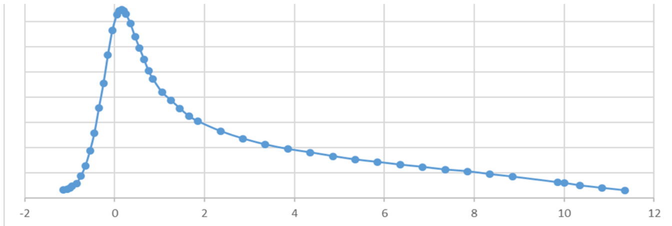
After fine machining

Positron Source

- The FLUX concentrator is the important part of the positron source
- It produces a pulsed magnetic field of 6 T to 0.5 T
- FLUX concentrator has made and finished high power test
- When cunrrent is 15kA , the center peak pulse magnetic field is 6.2T



Test result of the FLUX magnetic field

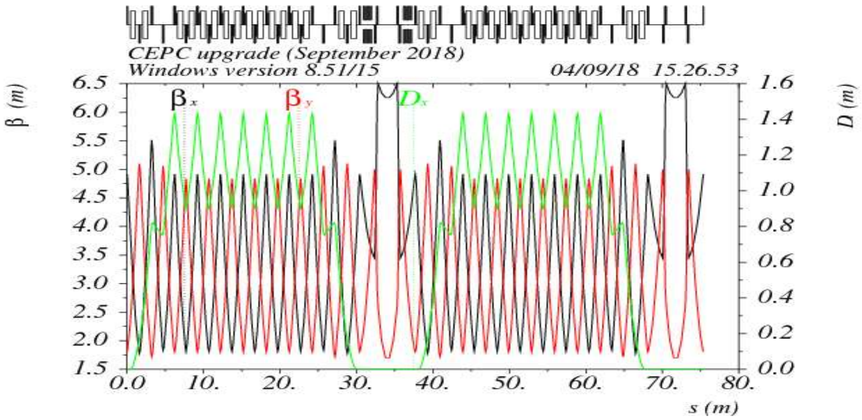


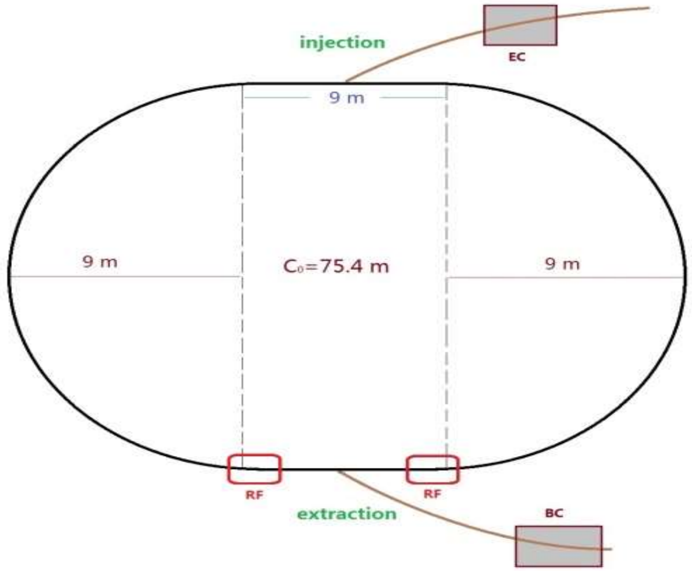
Damping Ring RF cavity

- Damping ring

D, Wang

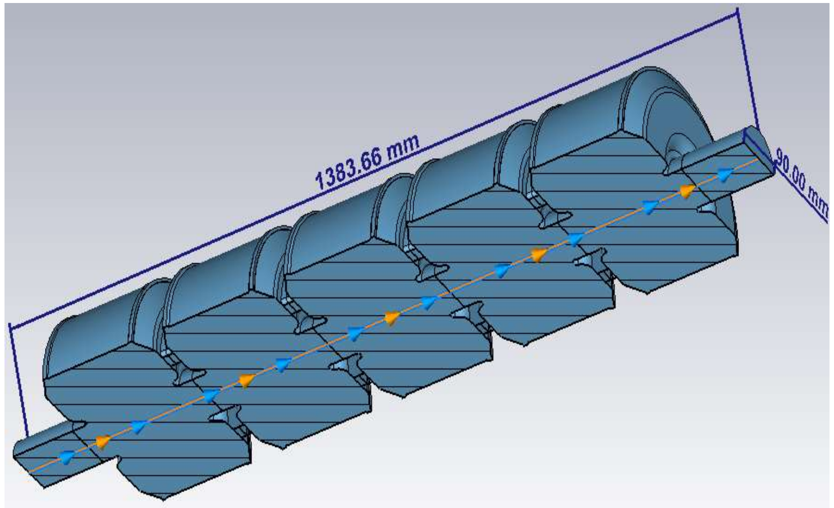
DR V2.0	Unit	Value
Energy	GeV	1.1
Circumference	m	75.4
Storage time	ms	20
Bending radius	M	3.565
Dipole strength B_0	T	1.03
U_0	keV	36.3
Damping time x/y/z	ms	15.2/15.2/7.6
δ_0	%	0.05
ε_0	mm.mrad	376.7
$\sigma_{z,\ inj}$	mm	5.0
Nature σ_z	mm	7.5
ε_{inj}	mm.mrad	2500
$\varepsilon_{ext\ x/y}$	mm.mrad	530/180
$\delta_{inj}/\delta_{ext}$	%	0.2/0.05
Energy acceptance by RF	%	1.0
f_{RF}	MHz	650
V_{RF}	MV	2.0





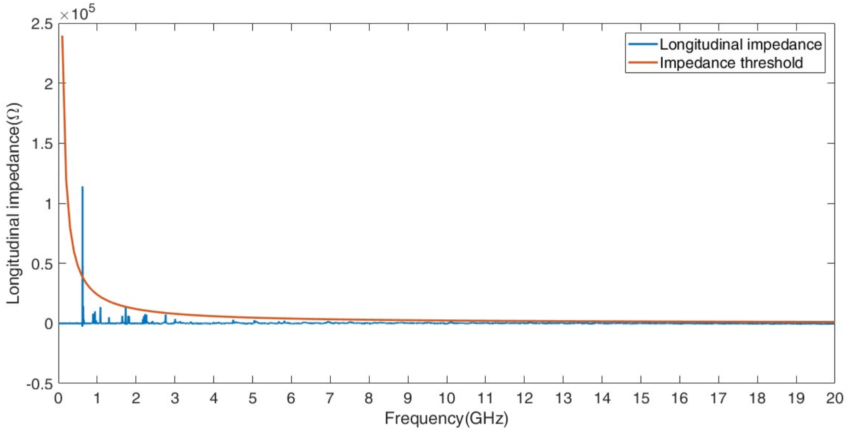
Damping Ring RF cavity

- Longitudinal loss factor and power(σ_z &5mm)
  - RF cavity model and longitudinal impedance
  - The cavity diameter is 90 mm



Beta tune	**3.84/4.81**
Bunch length	5mm
Bunch number	2
Synchtron tune	0.062
Beam current	10mA

k=4.12V/pC
P=51.8w&10mA

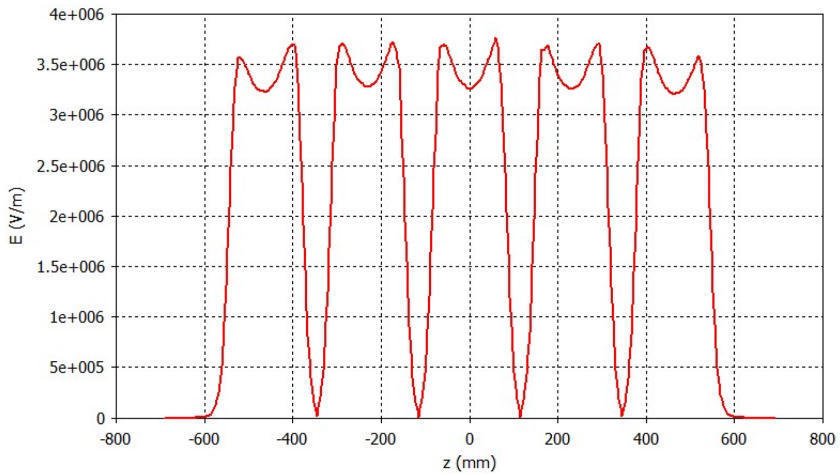


Damping Ring RF cavity

- cavity parameters

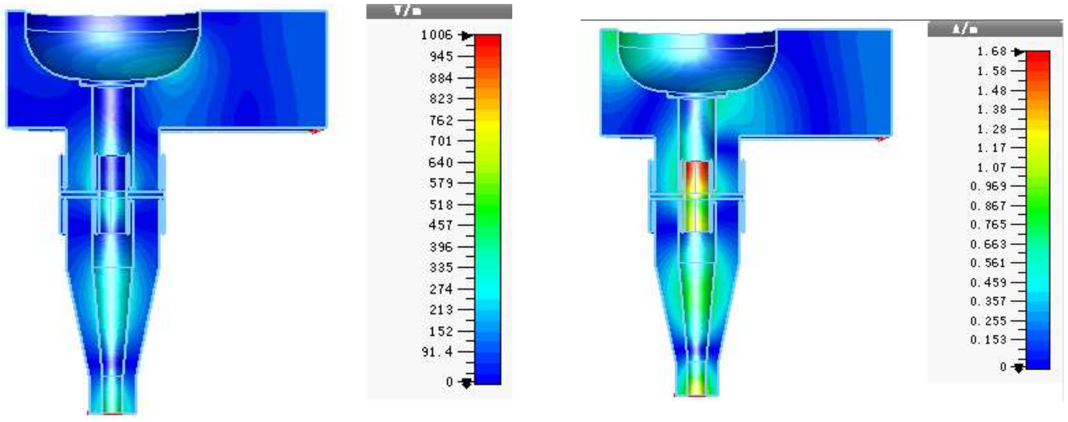
	Unit	Value
Beam tube aperture	mm	45
Total length	mm	1383.66
Cell length	mm	5*230.61
Outside diameter	mm	345
π-mode frequency	MHz	649.993
Q0		31665
R/Q	Ω	1316
Shunt impedance	MΩ	20.8
Accelerating voltage	MV	1.2 (2.0)
Accelerating gradient	MV/m	1.04 (1.73)
Dissipated cavity power (20% margin)	kW	45 (120)

- Diameter of the tuner
  - ϕ94
- Tuning rang (1.2MHz)
  - 649.635kHz (-30mm)
  - 650.829kHz (+30mm)

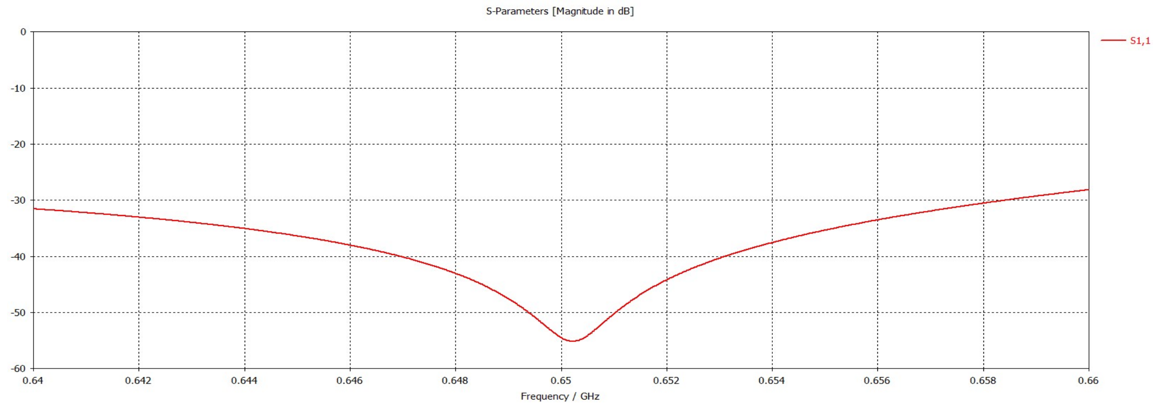


Damping Ring RF cavity

- Input coupler and doorknob for DR 5 cell cavity



Electromagnetic field distribution

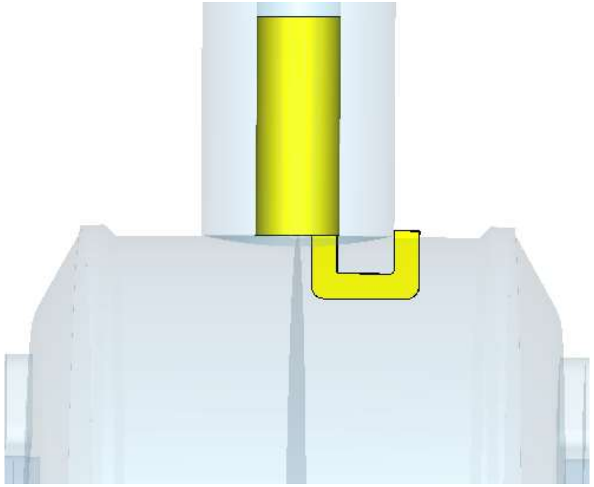


S11

Damping Ring RF cavity

H. Shi

- Coupling factor simulation

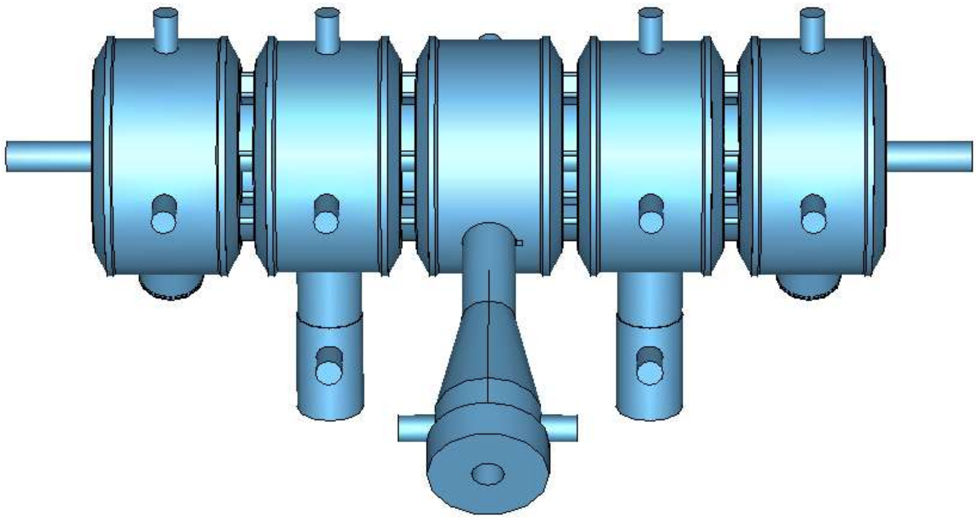


coupling loop angle (degree)	coupling degree
0	6.4
20	5.8
40	3.8

- The coupling ring is perpendicular to the direction of the magnetic field, and the coupling degree is 6.4
- Coupling degree ~ 5 at rotation angle ~ 28 degrees

Damping Ring RF cavity

- vacuum

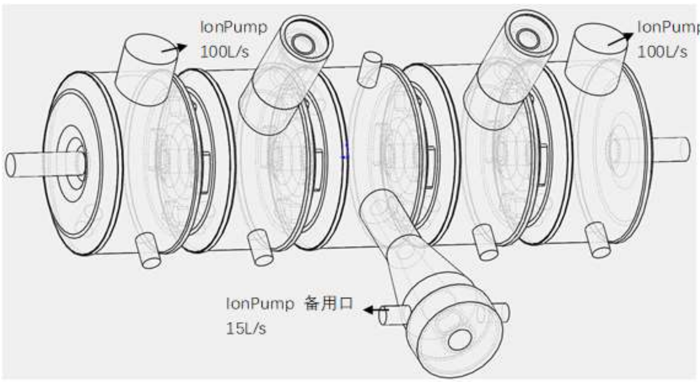


- The diameters of neck tubes of tuner and vacuum ports are 94mm
- 2 pump ports near the ceramic of coupler and 1 pump port for each tuner with flanges CF35 are considered. The inner diameters of these pump ports are 38mm
- The aperture plates are installed near the vacuum ports

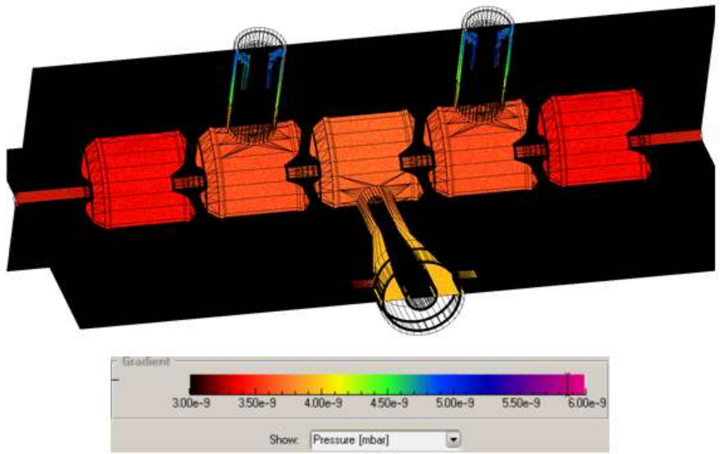
Damping Ring RF cavity

B.Q. Liu

- vacuum
  - Two 100L/s ion pump in the No.1 & N0.5 cavities, one 15L/s is in the coupler
  - The vacuum pressure distribution in the cavity is uniform, 3.0e-7 ~ 3.5e-7 Pa
  - The vacuum at the coupler position is about 3.4e-7 Pa
  - The vacuum at the tuner position is about 5.2e-7 Pa



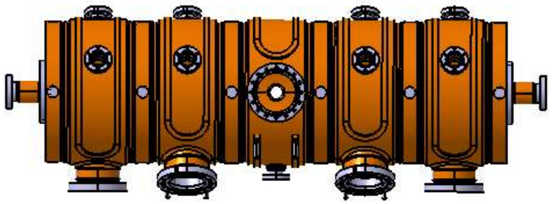
Ion pump distribution



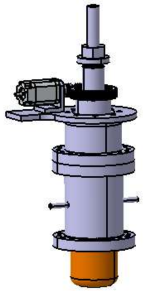
Vacuum degree distribution

Damping Ring RF cavity

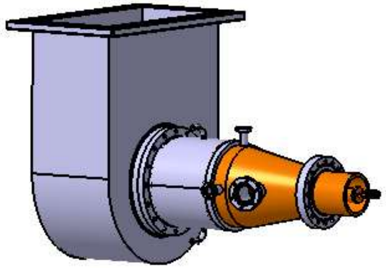
- Machenical design



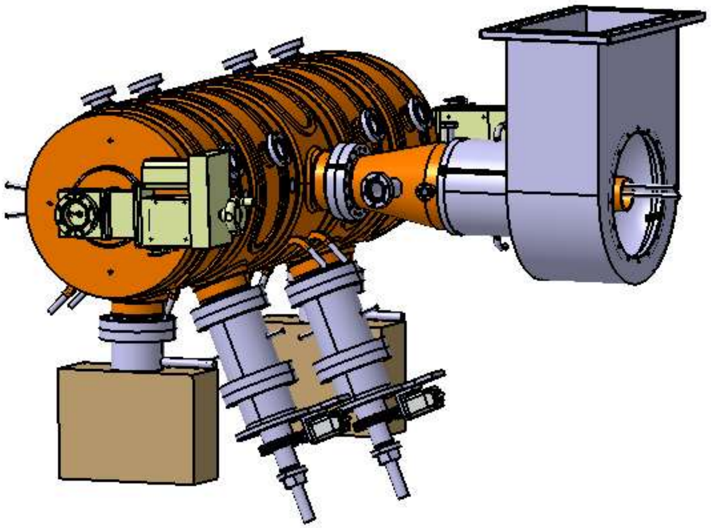
Cavity

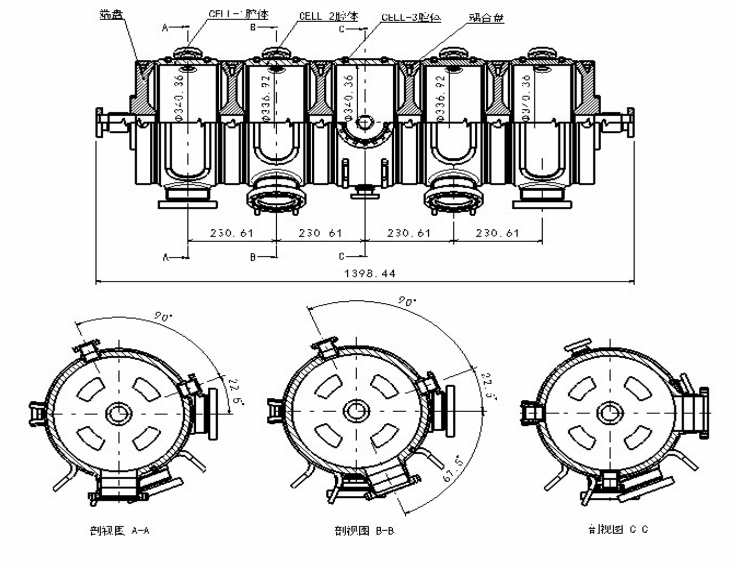


Tunner



Coupler





Summary

- In order to meet the booster requirements, the linac baseline design also change to 20 GeV
- The EBTL section changed from 4GeV to 1.1 GeV
- 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 is used
- The FLUX concentrator has finished
- The DR 5 cell cavity has designed

Thank you