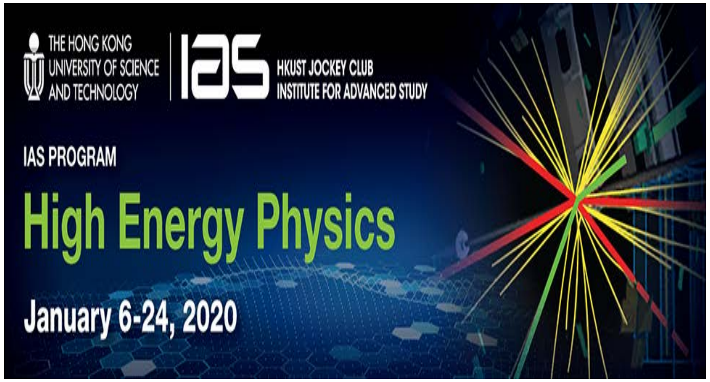
CEPC Linac Injector R&D



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On behalf of CEPC linac team

Institute of High Energy Physics, CAS

Outline

1 Linac baseline design

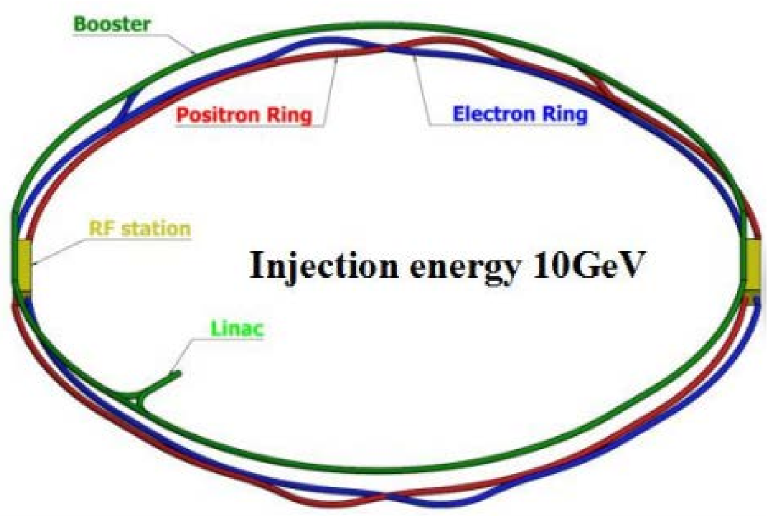
2 Linac alternatives

3 R&D activities

4 Summary

Linac baseline 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 linac injector provides 10 GeV electron and positron beam to the Booster
  - The total length of the linac is about 1.2 km

Linac baseline design

- The requirements of the booster to the linac

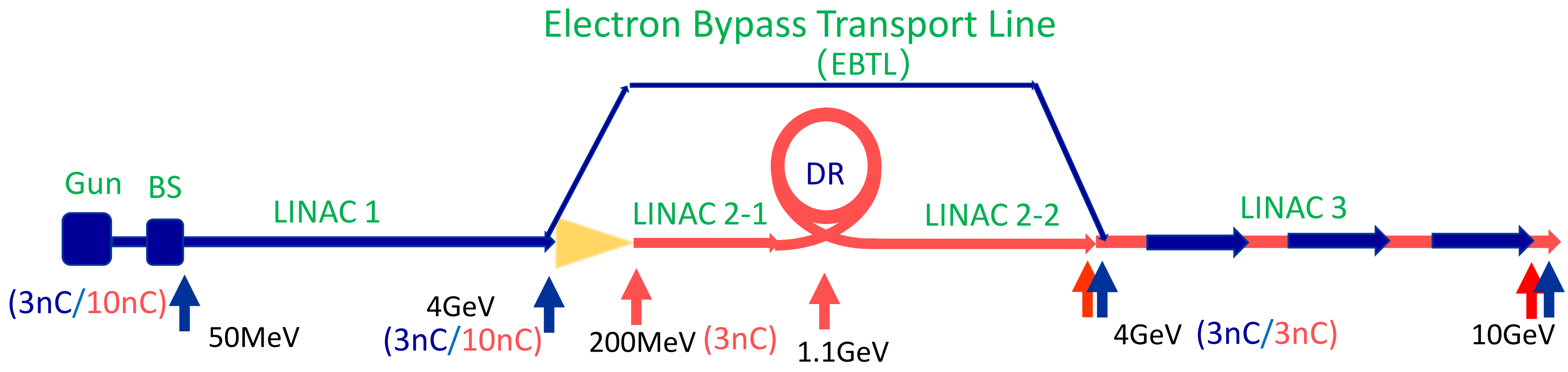
Parameter	Symbol	Unit	Value
e^- /e^+ beam energy	E_{e-}/E_{e+}	GeV	10
Repetition rate	f_{rep}	Hz	100
Bunch numbers per pulse			1
e^- /e^+ bunch population	$Ne-/Ne+$		$>9.4\times10^9$
		nC	>1.5
Energy spread (e^- /e^+)	σ_E		$<2\times10^{-3}$
Emittance (e^- /e^+)	ε_r	nm	<40

Linac baseline design

- Linac design goals
  - Meet the requirements of Booster injector
  - Top-up injection can be implemented
  - High availability and reliability
    - About 15% backups for linac RF units
  - More potential
    - Have potential to provide electron/positron beam with bunch charge large than 3 nC
    - Lower emittance with more cycles in Damping Ring

Linac baseline design

- Layout of the linac
  - 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)



Outline

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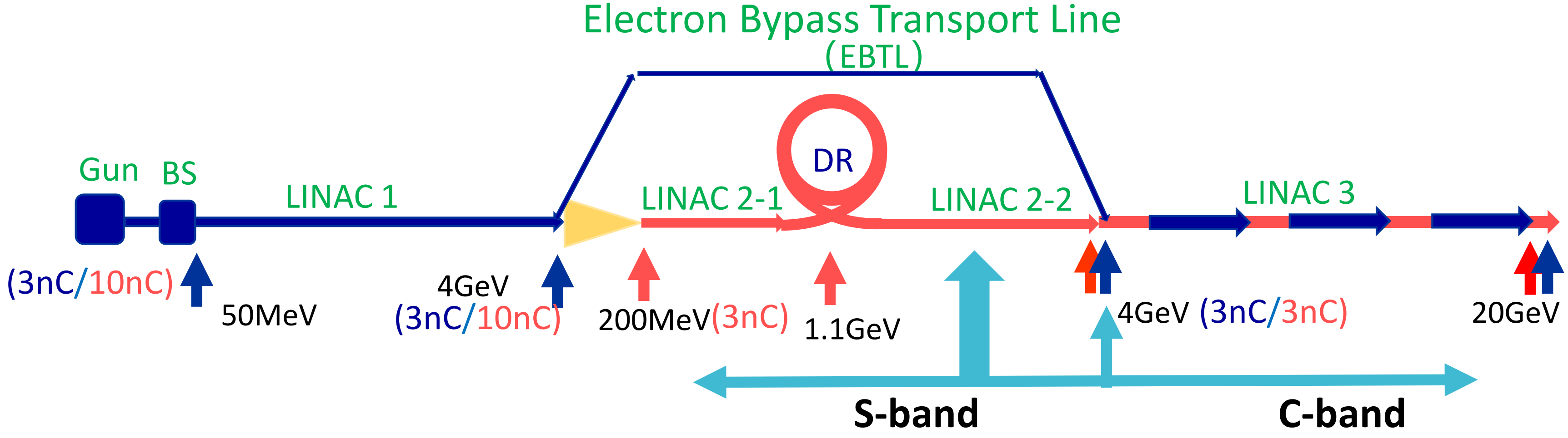
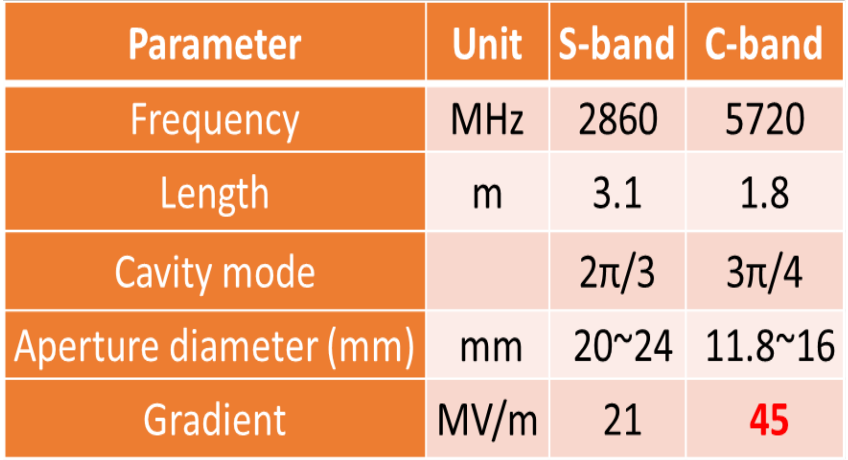
Linac alternative (1)

- 20 GeV linac
  - Reduce the difficulty of the Booster design
  - Reduce the technical risk of low magnetic field magnets of the Booster
- S-band+C-band RF system
  - C-band start energy: 4GeV
  - If the DR can provide lower emittance, the C-band start energy can move forward



Linac alternative (1)

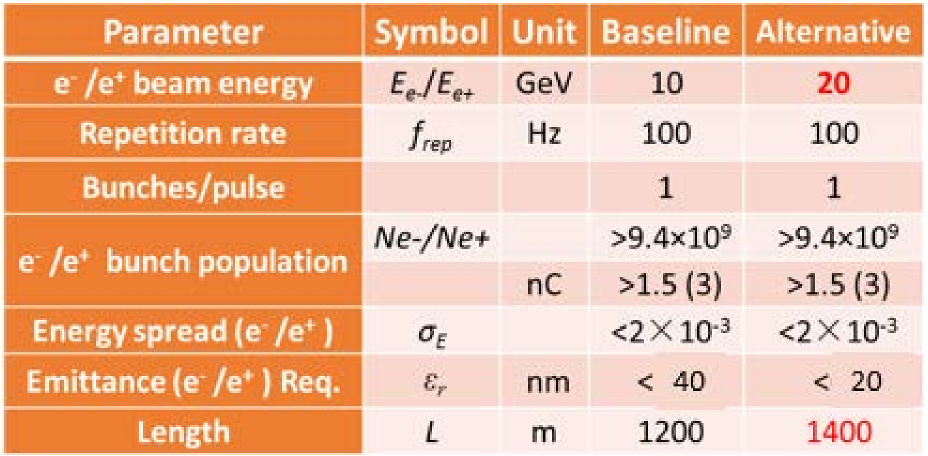
- 20GeV linac (S-band + C-band)
  - The gradient of C-band structure is 45 MV/m
  - The total length is 1.4 km, 200 m longer than the baseline design



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)	mm	20~24	11.8~16
Gradient	MV/m	21	45

The main parameters of the C-band structure

The main parameters of the linac exit

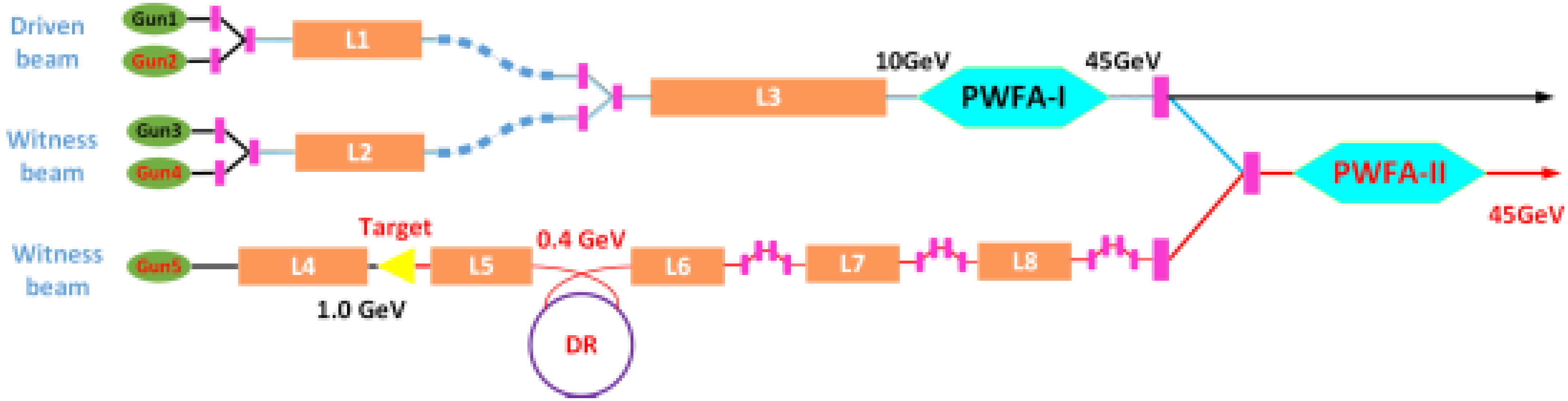


Parameter	Symbol	Unit	Baseline	Alternative
e^-/e^+ beam energy	E_{e-}/E_{e+}	GeV	10	20
Repetition rate	f_{rep}	Hz	100	100
Bunches/pulse			1	1
e^-/e^+ bunch population	$Ne-/Ne+$		$>9.4\times10^9$	$>9.4\times10^9$
		nC	>1.5 (3)	>1.5 (3)
Energy spread (e^-/e^+)	σ_E		$<2\times10^{-3}$	$<2\times10^{-3}$
Emittance (e^-/e^+) Req.	ε_r	nm	< 40	< 20
Length	L	m	1200	1400

Linac alternative (2)

- Plasma wakefield accelerator (45GeV linac)
  - Electron linac
    - 10GeV driver linac+Plasma linac→45GeV
    - The Plasma linac is like a power transformer
  - Positron linac
    - 45GeV or 30GeV driver electron beam +positron beam→45GeV

W. Lu



Outline

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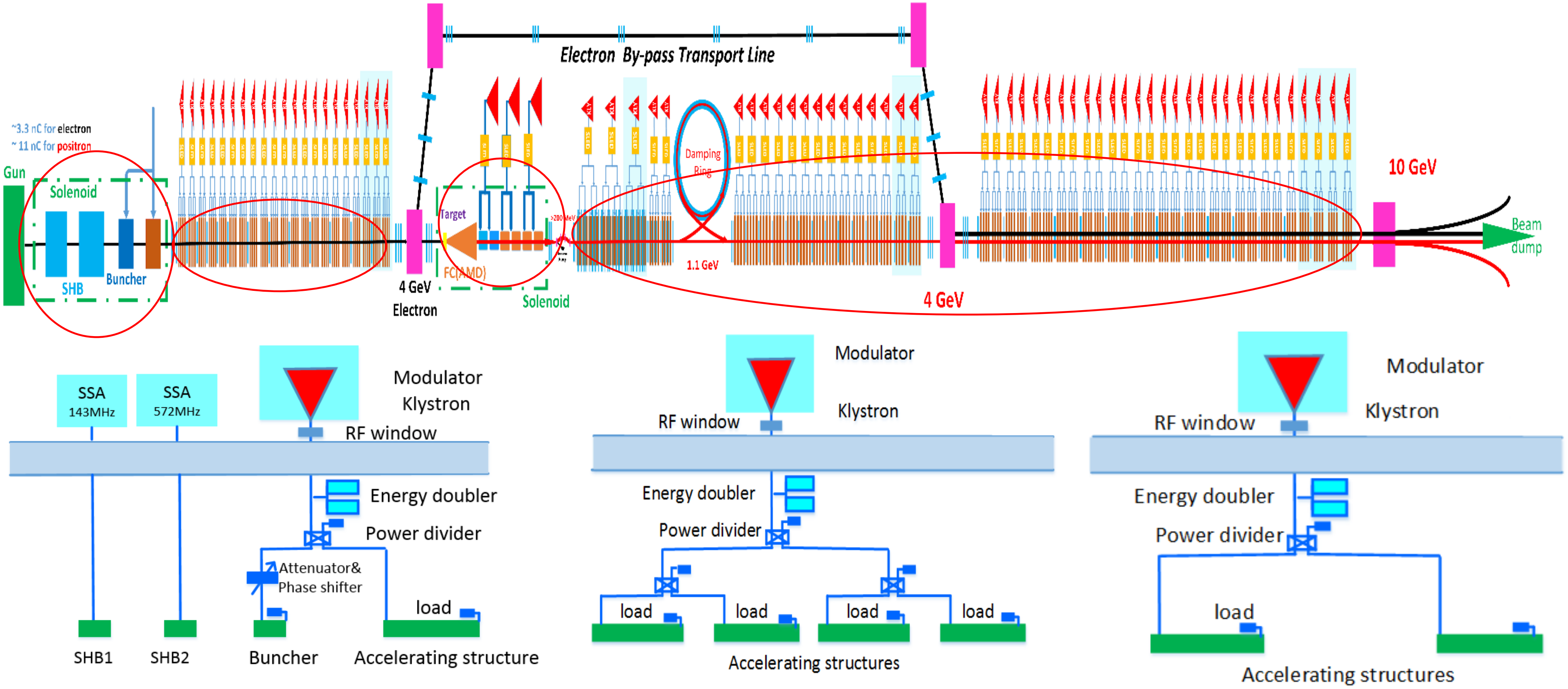
R&D activities

- RF distribution of the linac
  - S-band accelerating structures
  - 80MW klystron



R&D activities

- Key RF technologies of linac baseline
  - Electron gun (1)
  - SHBs (2)
  - Buncher (1)
  - **S-band accelerating structure (277)**
  - **Pulse compressor (72)**
  - **Positron source (1)**
  - Big hole accelerating structure (6)
  - DR 650MHz RF cavity (2)
  - LLRF (75)
  - Phase reference line (1)
  - ……

Accelerating structure

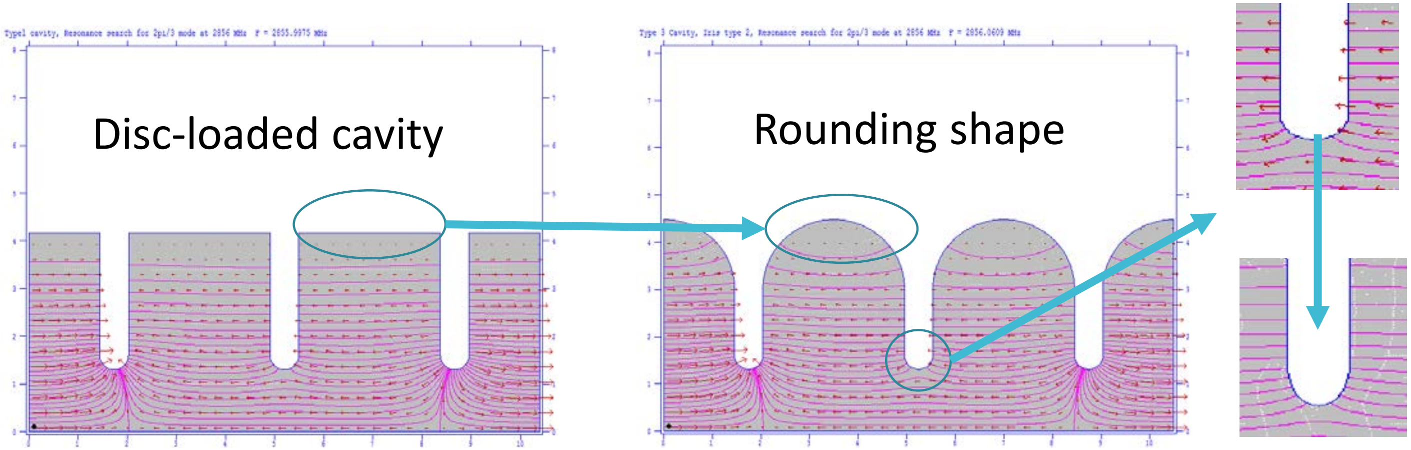
S-band accelerating structure design

- Motivation: It is more than 280 S-band (2860MHz) accelerating structures
- Goal: Accelerating gradient more than 30 MV/m @1μS

Accelerating structure

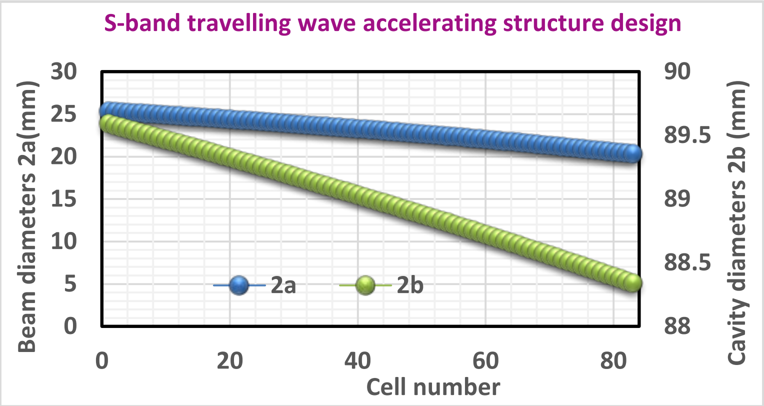
•Cavity shape optimization

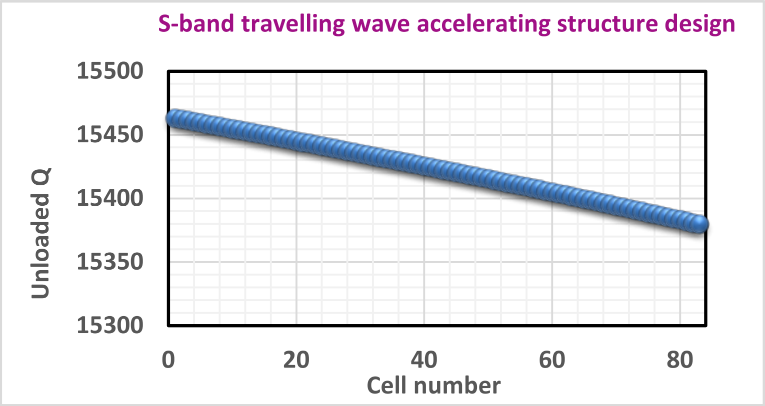
- Superfish is used to optimize the single cell
- Rounding the cell improves the quality factor by >12% and reduces the wall power consumption. At the same time, the shunt impedance increases by ~10.9%
- Irises with elliptical shape (r2/r1=1.8) can reduce the peak surface field by 13%

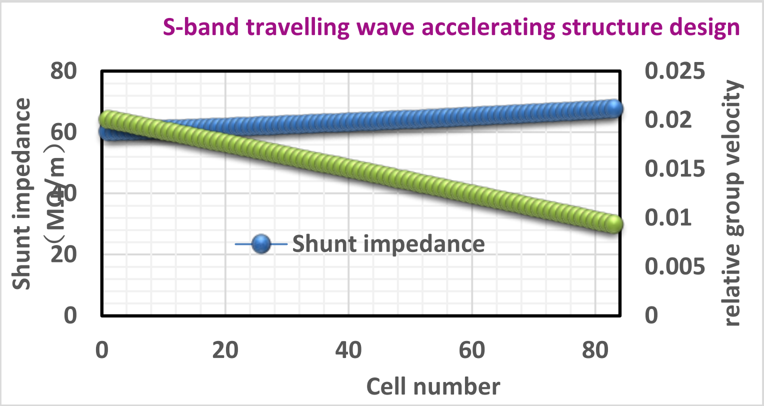


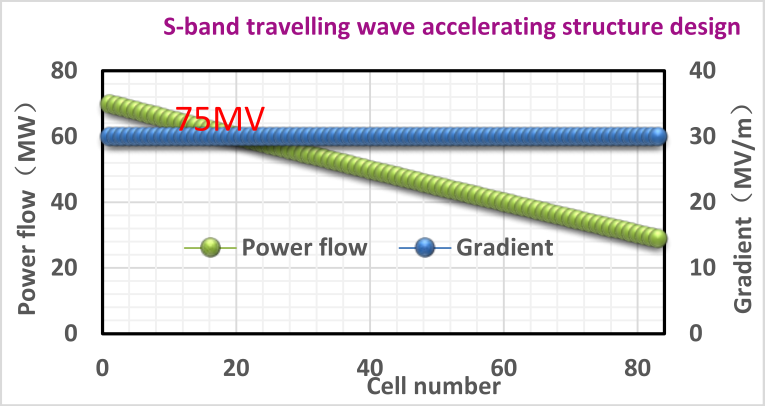
Accelerating structure

- The total number of cells of the tube is 84
- The average Q value is about 15400
- The input power is 75MW , the target gradient will reached


S-band travelling wave accelerating structure design


S-band travelling wave accelerating structure design


S-band travelling wave accelerating structure design

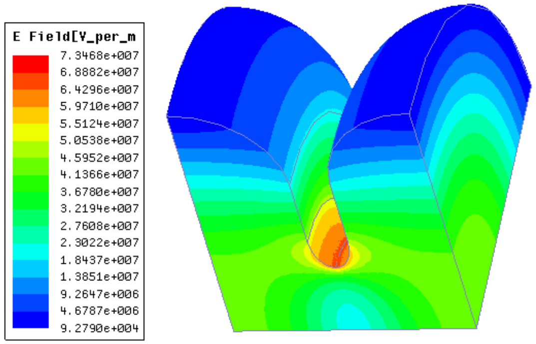

S-band travelling wave accelerating structure design

Accelerating structure

- Factors to limit the gradient (cavity):
  - Peak surface electric field (E_peak)
    - E_peak < 160MV/m at S-band
  - Peak surface magnetic field (H_peak)
    - Pulsed heating effect will cause the temperature rise at the coupler window. $\Delta T = \frac{\left|H_{||}\right|^2 \sqrt{t_p}}{\sigma\delta\sqrt{\pi\rho c k}}$, for S-band ΔT < 50°C is safe
  - Modified Poynting vector (Sc),
    - $S_c = Re\{\bar{s}\} + \frac{Im\{\bar{s}\}}{6}$, $\frac{S_c^{\,15} t_p^{\,5}}{BDR}$=const. If the beam break down rate is $1*10^{-6}$bpp/m, the safe value for 1μs pulse length is 2.3 MW/mm^2
  - Pulse length（1μS）

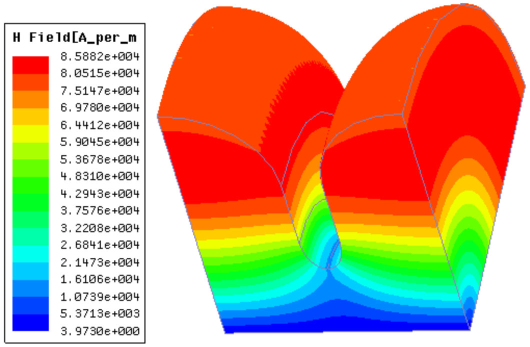
Accelerating structure

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



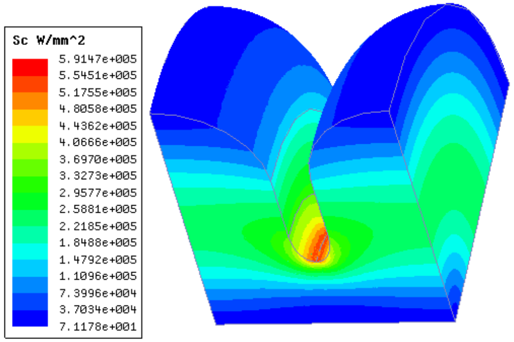
E_peak=73 MV/m.

Surface electric field



H_peak=86 kA/m.

Surface magnetic field



Sc_max=0.59 MW/mm^2.

Modified Poynting vector

Accelerating structure

- The main parameters of the whole structure
  - The filling time is 784 nS
  - The total attenuation is 0.46 Np

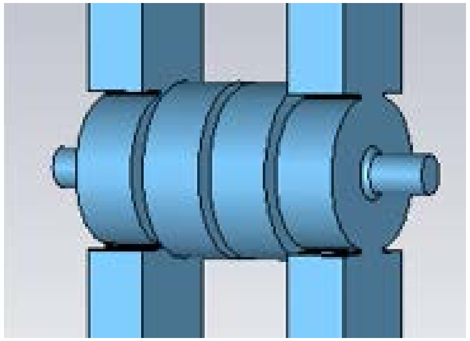
Parameters	**Values**	**Unit**
No. of Cells	84+2*0.5	-
Phase advance	2π/3	rad
Total length	3.1	m
Length of cell (d)	34.988	mm
Disk thickness (t)	5.5	mm
Shunt impedance (Rs)	60.3~67.8	MΩ/m
Quality factor	15465~15373	-
Group velocity: Vg/c (%)	2% ~ 0.94%	-
Filling time (t_f)	784	ns
Attenuation factor (τ)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

Accelerating structure

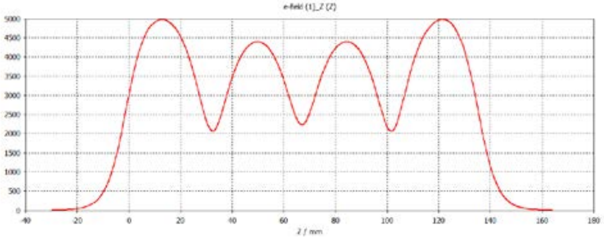
- Coupler design
  - The asymmetry of the coupling cavity will cause emittance growth
  - The shape of the coupling cavity is racetrack dual-feed type
  - Kyhl method is used to match the coupler

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

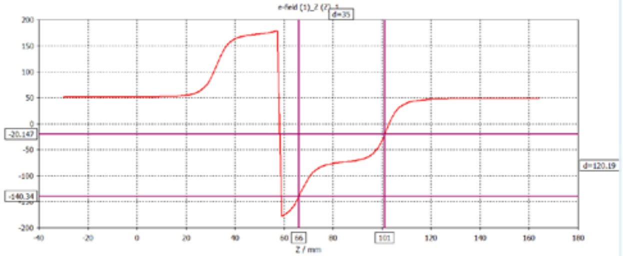
$$\Delta p_x = -\frac{e \Delta z E_0}{2\omega a}\left[\Delta\theta * sin\varphi - \frac{\Delta E}{E_0}\cos\varphi\right]$$



The calculation model



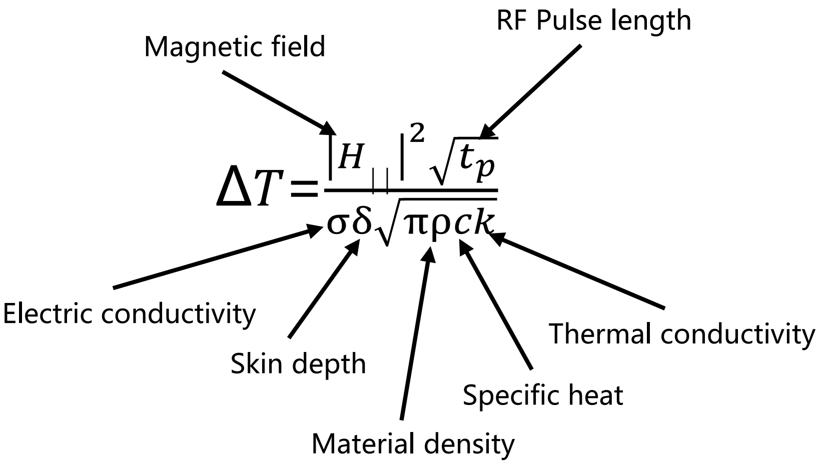
The *distribution of* the electric field on axis



Phase advance per cell

Accelerating structure

- Factors to limit the gradient (coupler):
  - To reduce the pulsed heating, the coupler window edge is rounded.
  - For S-band copper: $\Delta T[^0\mathrm{c}]=127\left|H_{||}[MA/m]\right|^2\sqrt{f.[GHz].t_p[uS]}$
  - 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, $\Delta T=9.4^0$C.



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

Magnetic field

RF Pulse length

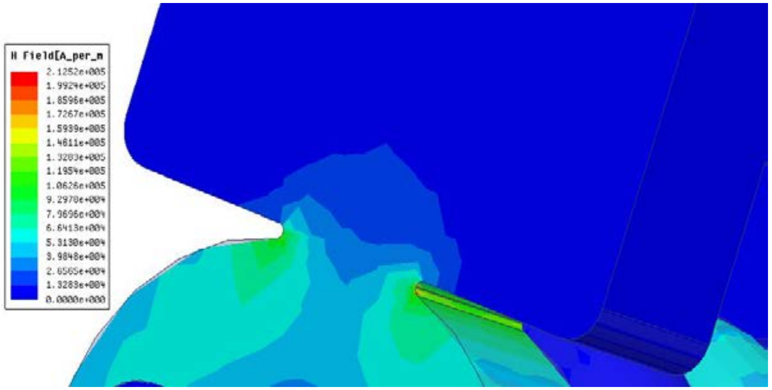
Electric conductivity

Skin depth

Material density

Specific heat

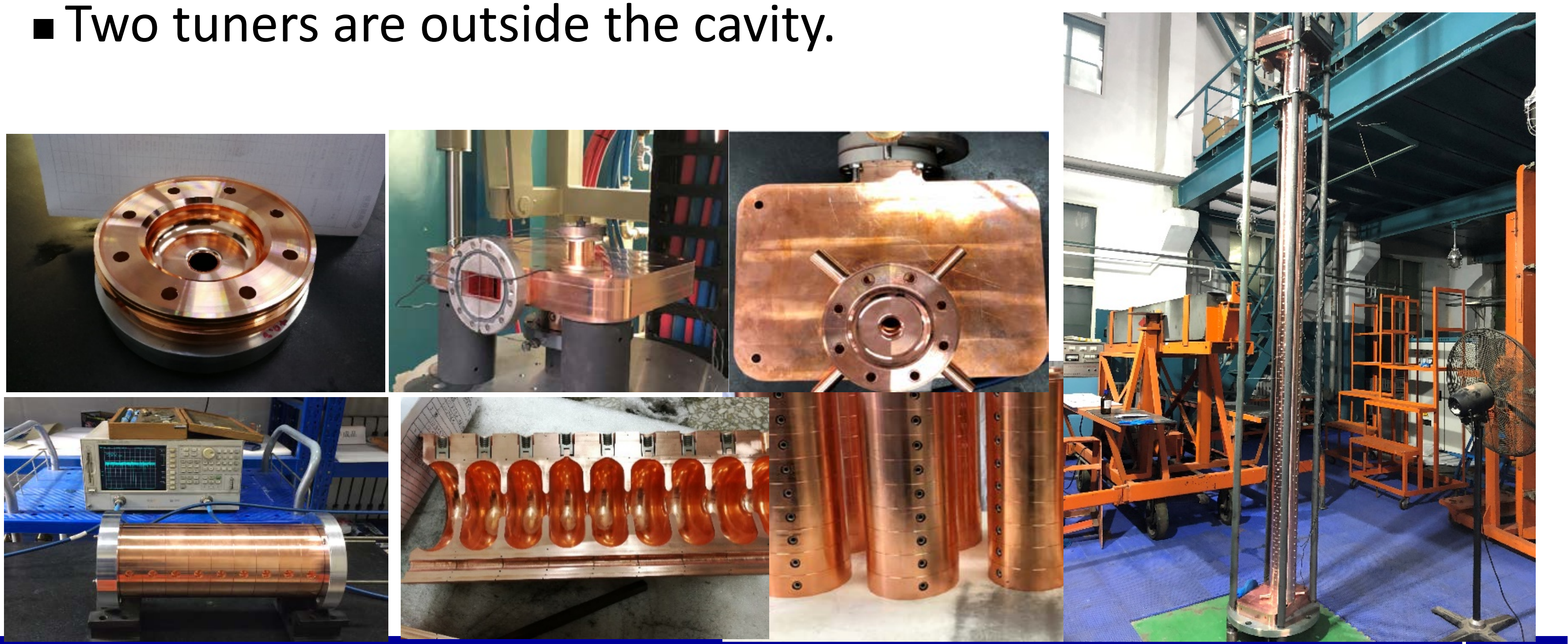
Thermal conductivity



Accelerating structure

Mechanical design

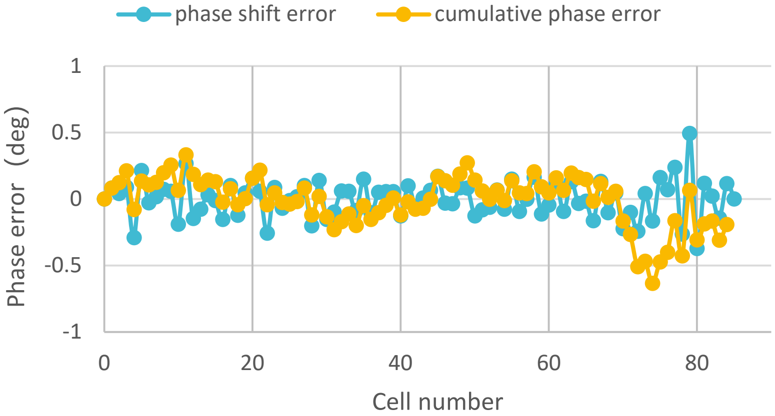
- Inner water-cooling has been adopted. 8 pipes are around the cavity.
- Compact coupler arrangements. The splitter is milling together with the coupling cavity.
- Two tuners are outside the cavity.

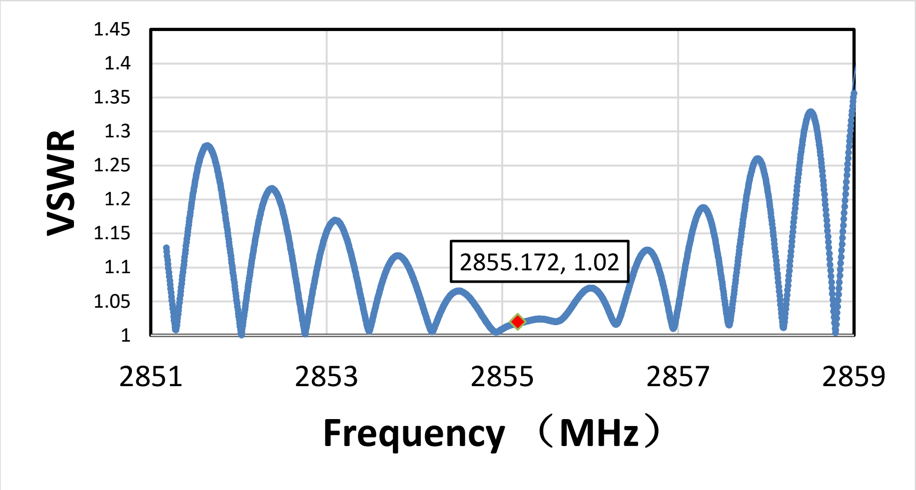


Accelerating structure

•Cold test result

- The phase shift and the cumulative phase shift are less than 1 deg
- The VSWR is 1.02 at working frequency



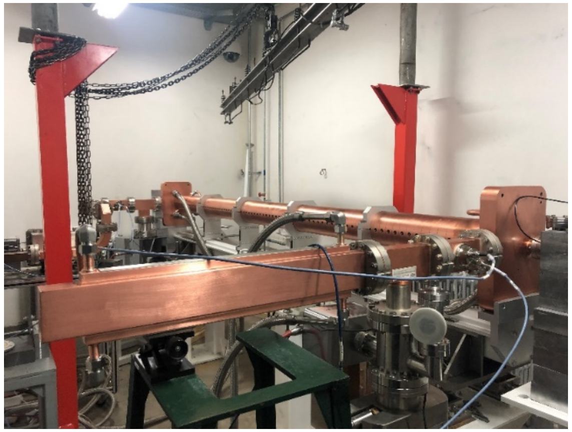


Accelerating structure

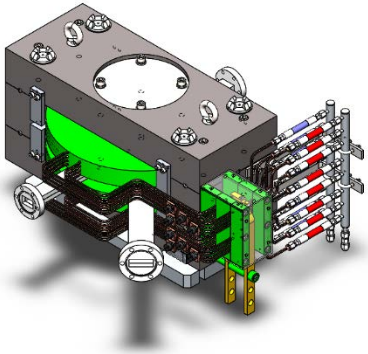
High power test

- Two faraday cups are in upstream and downstream of the structure to detect dark current respectively
- The high power test gradient has been more than 25 MV/m
- Higher gradient practice is in progress

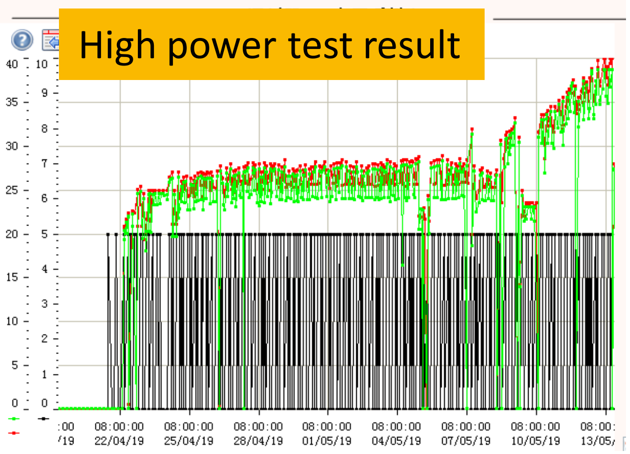
Modulator and klystron



High power test bench



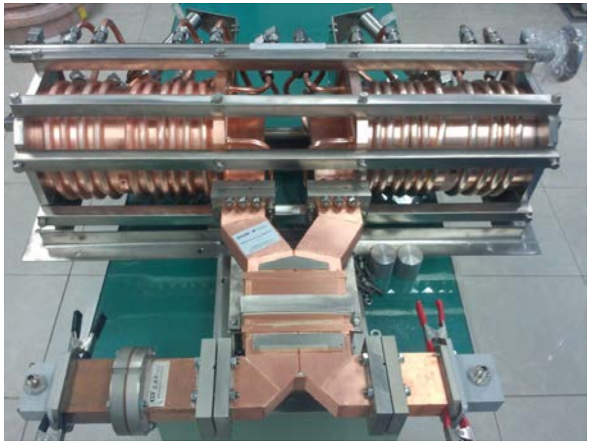
Analyzing Magnet



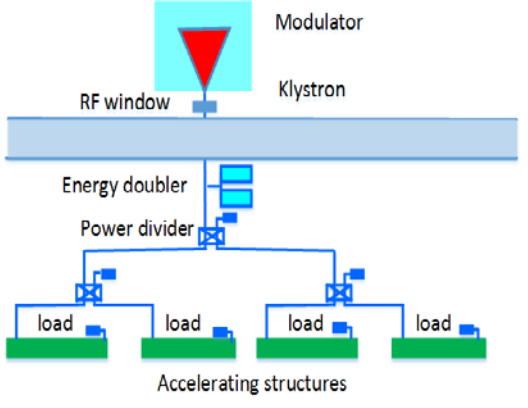
High power test result

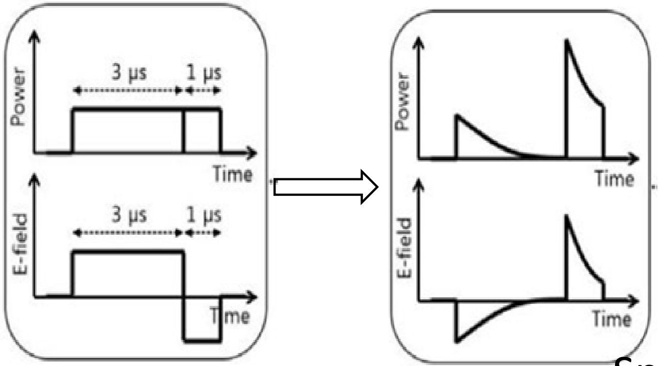
Pulse compressor

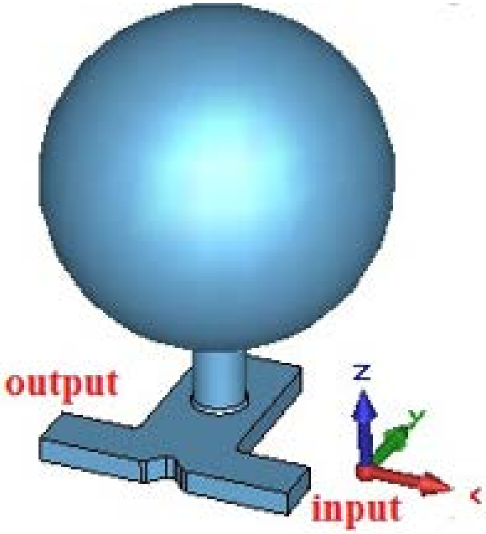
- It is used to improve the peak power from the klystron and saving cost
  - The input power is 80 MW
  - The pulse width has been compressed from 4uS→1uS
- The traditional pulse compressor is two cavities SLED type
- The new one is spherical cavity type



SLED



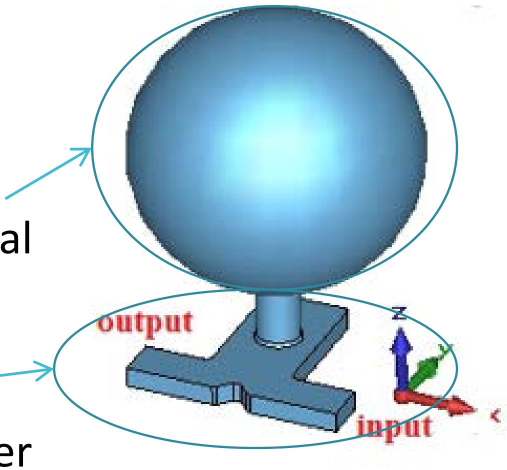




Spherical cavity pulse compressor

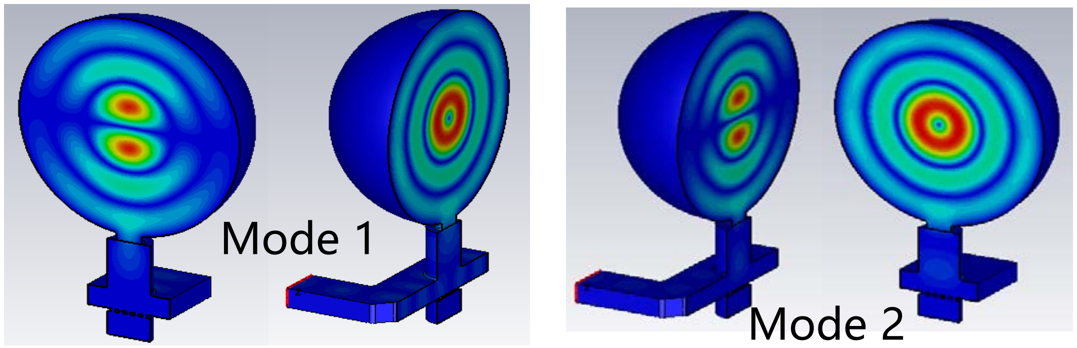
Pulse compressor

- The advantage of the spherical cavity pulse compressor
  - Only one cavity is needed, which is more compact, lower processing cost
  - Surface loss is smaller than that of the cylindrical cavity
  - Good in mechanical stability and little in environmental impact
- TE_{113} mode is selected
- Two polarized degeneracy mode are in one cavity
- The structure includes mode converter and spherical cavity



Spherical cavity

mode conerter

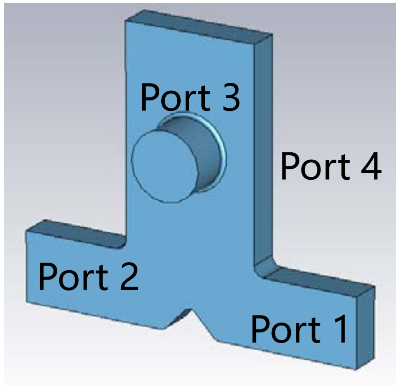


E-field distribution of the polarized degenerated modes

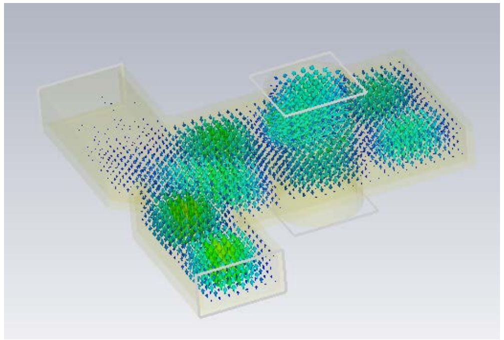
Pulse compressor

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 and 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

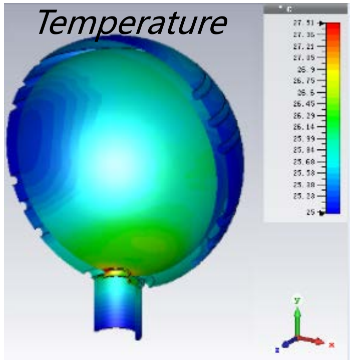
Pulse compressor

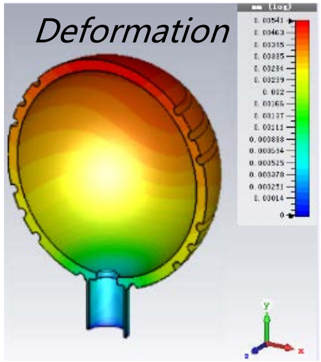
•Thermal stress analysis

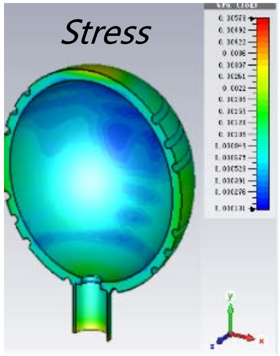
- The maximal temperature rise is on the coupling hole of 2.5 ℃ (the water cooling flow set as 50 L/min)
- The frequency tunable range of ±1 MHz is enough for all the frequency shift resulted from the input power, vacuum pumping, air pressure, etc.

CEPC parameter

Parameter	Value
SLED water temperature	30 ℃
Room temperature	25 ℃
Filling time	730 ns
Klystron output power	80 MW
Pulse width	4 μs
Pulse repetition rate	100 Hz







- the water temperature will be used to tune the frequency.
- Accordingly, the water temperature need to be ±3.6 ℃ change

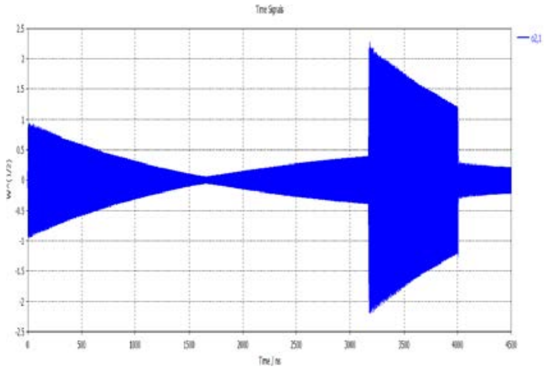
Pulse compressor

The parameters

- The Q_0 is 146000
- The energy gain factor is ~1.6

For input signal:

$$f(t)=\begin{cases}\sin(2\pi f_0 t) & 0\le t<3.17\,\mu\mathrm{s}\\ \sin(2\pi f_0 t+\pi) & 3.17\,\mu\mathrm{s}\le t<4\,\mu\mathrm{s}\\ 0 & 4\mu\mathrm{s}\le t<4.5\,\mu\mathrm{s}\end{cases}$$

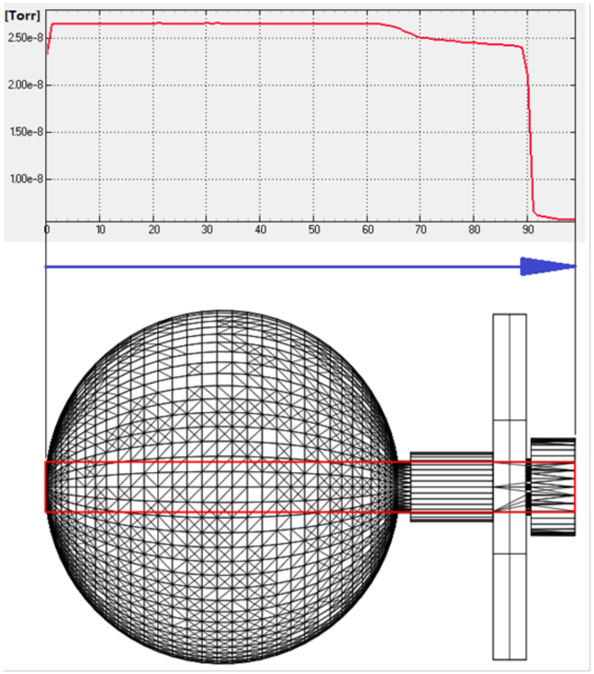


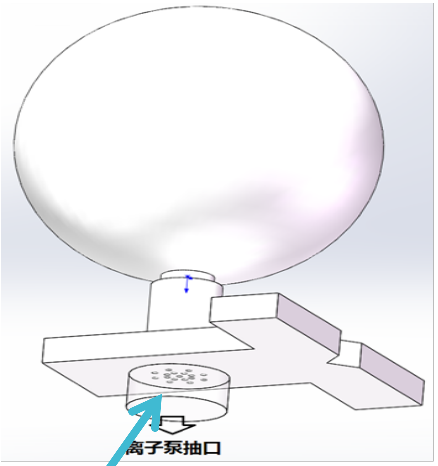
Simulated compressed pulse

Parameter	value
Frequency	2856 MHz
Mode	TE113
Q_0	~146000
VSWR	≤1.1
Coupling factor	~6.9
Tuning rang	≥±1 MHz
Input power	≥80MW
Repetition fre.	100Hz
Pulse width	~4μs
Pulse width after compress	~0.83μs
Peak power gain	≥7dB
Energy gain factor	~1.6
Working temperature	30±0.1°C

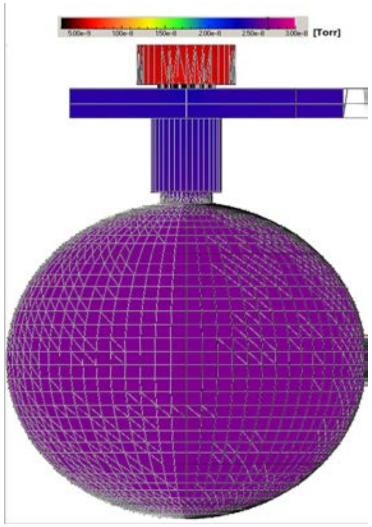
pulse compressor

- Vacuum analysis
  - Pumping speed of ion pump is 100 L/s
  - Copper outgassing rate: 1E-10 Torr.L/s/cm^2
  - Pressure distribution: vacuum degree less than 3E-8Torr





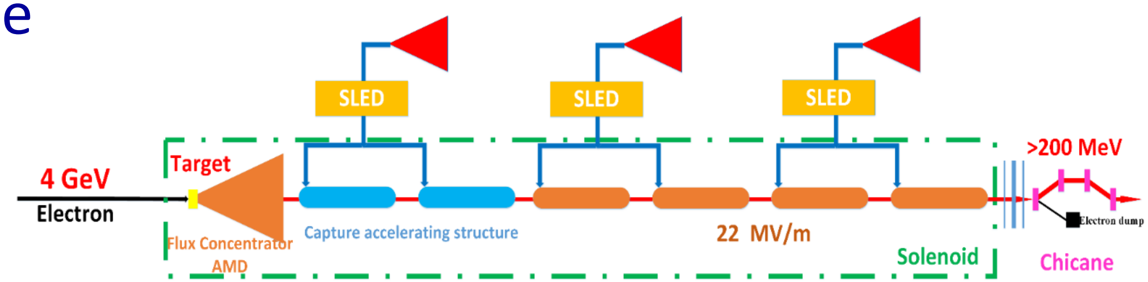
Ion pump port

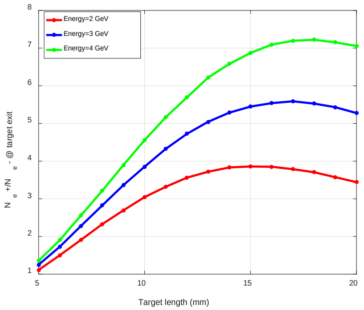


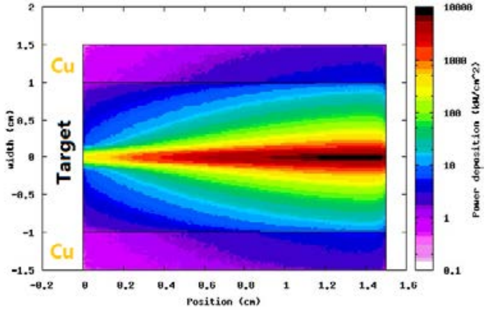
Pressure distribution of longitudinal section

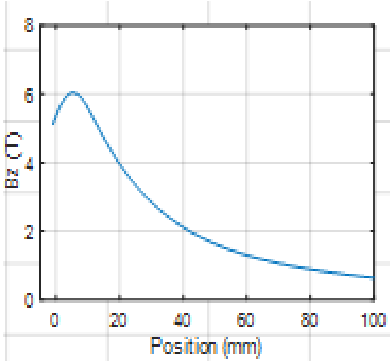
Positron Source

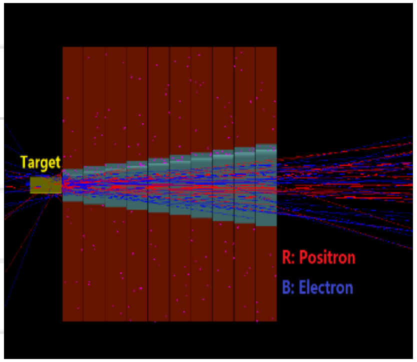
- Layout of positron source
  - ◆Target (Conventional)
    - ✓tungsten@15 mm
    - ✓Beam size: 0.5 mm
  - ◆Electron Beam
    - ✓4GeV/10nC/100Hz
    - ✓Beam power 4kW
  - ◆Energy deposition
    - ✓0.784 GeV/e- @ FLUKA
    - ✓784 W → water cooling
  - ◆AMD (Adiabatic Matching Device)
    - ✓Flux Concentrator





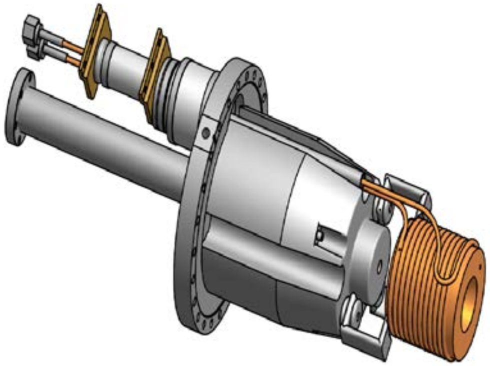




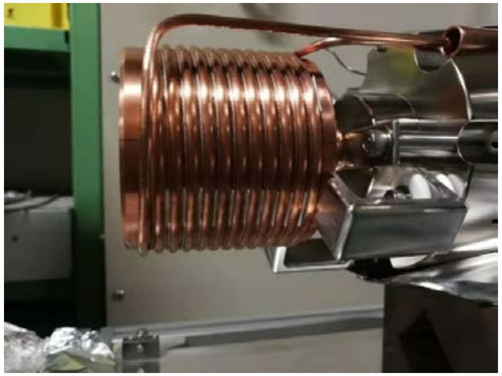


Positron Source

- FLUX concentrator is the important part of the positron source
  - ✓ Length: 100mm
  - ✓ Aperture: 8mm→26mm
  - ✓ Magnetic field: (5.5T→0T) + 0.5T
- FLUX concentrator has designed and manufactured



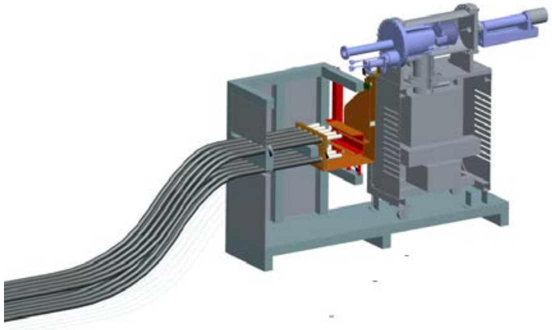
The mechanical design of FLUX concentrator



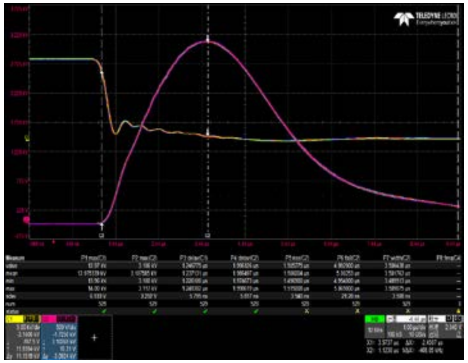
The finished FLUX concentrator

Positron Source

- Solide-state pulsed power generator
  - Solid state IGCT discharge switch module is used
  - The maximum output value of the solid-state pulsed power generator reached 15.6 kA / 15.1 kV / 5 µs, the waveform is perfect
  - It reached the design value
- High power test will begin



solid-state pulsed power generator



The output waveform of 15 kA

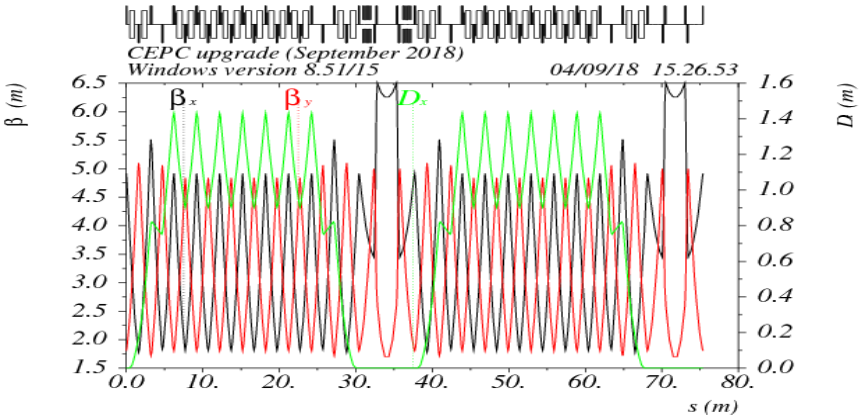
The test bench of the FLUX concentrator

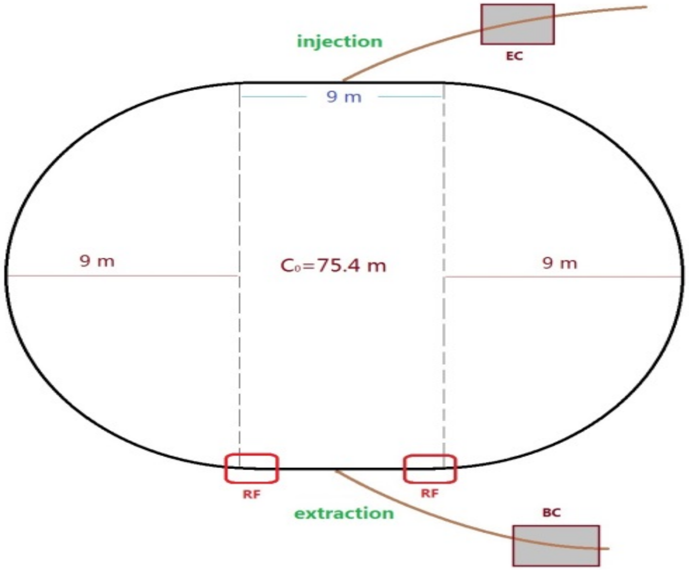
Damping Ring RF cavity

D, Wang

- Damping ring

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

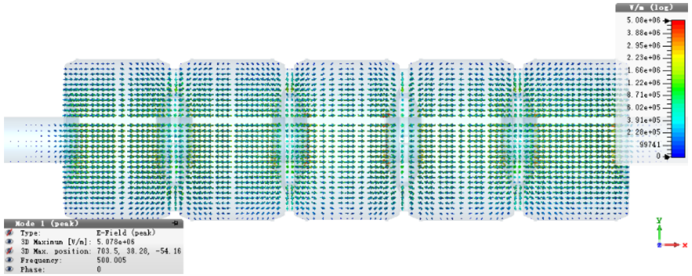




Damping Ring RF cavity

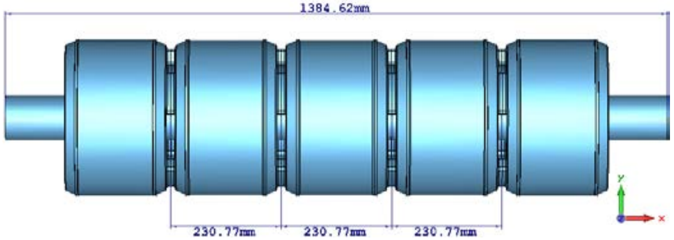
- 650 MHz 5-cell cavity

	Unit	650 MHz 5-cell
π-mode frequency	MHz	650.0
Unloaded quality factor		26080
R/(Q*l)	Ω/m	435
Shunt impedance	MΩ	13.1
Accelerating voltage	MV	1.2
Accelerating gradient	MV/m	1.04
Dissipated cavity power	kW	55

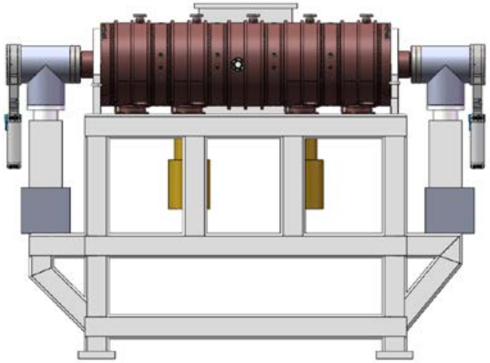


Mode 1 (peak)
Type: E-Field (peak)
3D Maximum [V/m]: 5.078e+06
3D Max. position: 703.5, 38.28, -54.16
Frequency: 500.005
Phase: 0

The electromagnetic distribution



The main dimensions



The mechanical design

Summary

- The baseline linac design is a 10 GeV S-band linac
- Two alternative schemes of linac have been suggested. One is 20 GeV S&C band linac, the other one is a plasma accelerator
- The key components of the linac baseline are being developed.
    - The accelerating structure is under high power test.
    - The spherical pulse compressor has designed and will be manufactured this years.
    - The FLUX concentrator has also finished and is under high power test.
    - The damping ring RF cavity is simulated.

Thank you for your attention!