The 2020 International Workshop on the High Energy Circular Electron Positron Collider
(Oct. 26-28, 2020)

CEPC Linac and damping ring R&D

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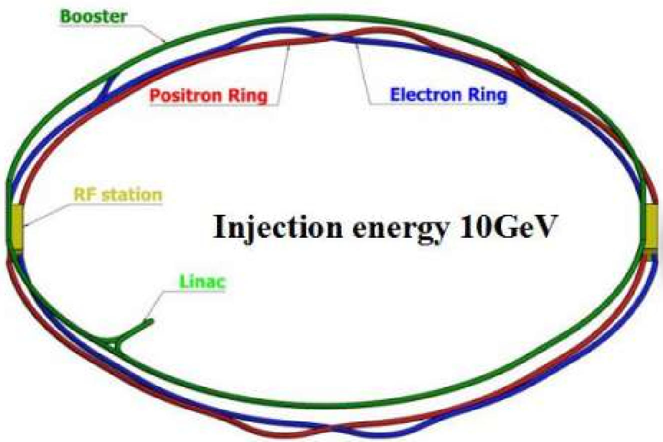
Outline

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



Linac design

- The requirements of the booster to the linac

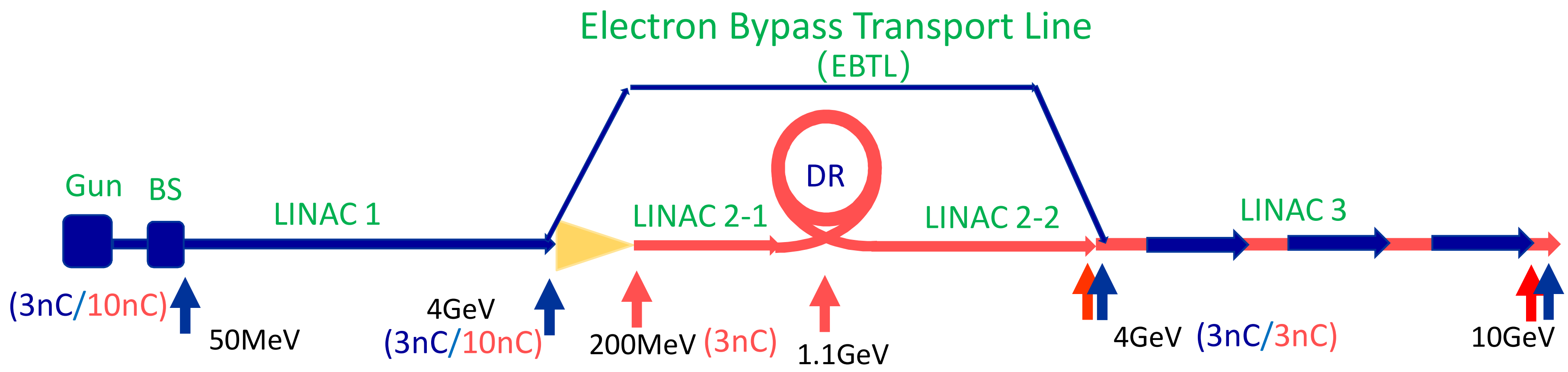
Parameter	Symbol	Unit	Value
e^- /e^+ beam energy	E_{e-}/E_{e+}	GeV	10
Repetition rate	f_{rep}	Hz	100
Bunch numbers per pulse			1
e^- /e^+ bunch population	$Ne-/Ne+$		$>9.4\times10^{9}$
		nC	>1.5
Energy spread (e^- /e^+)	σ_E		$<2\times10^{-3}$
Emittance (e^- /e^+)	ε_r	nm	<40

Linac 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

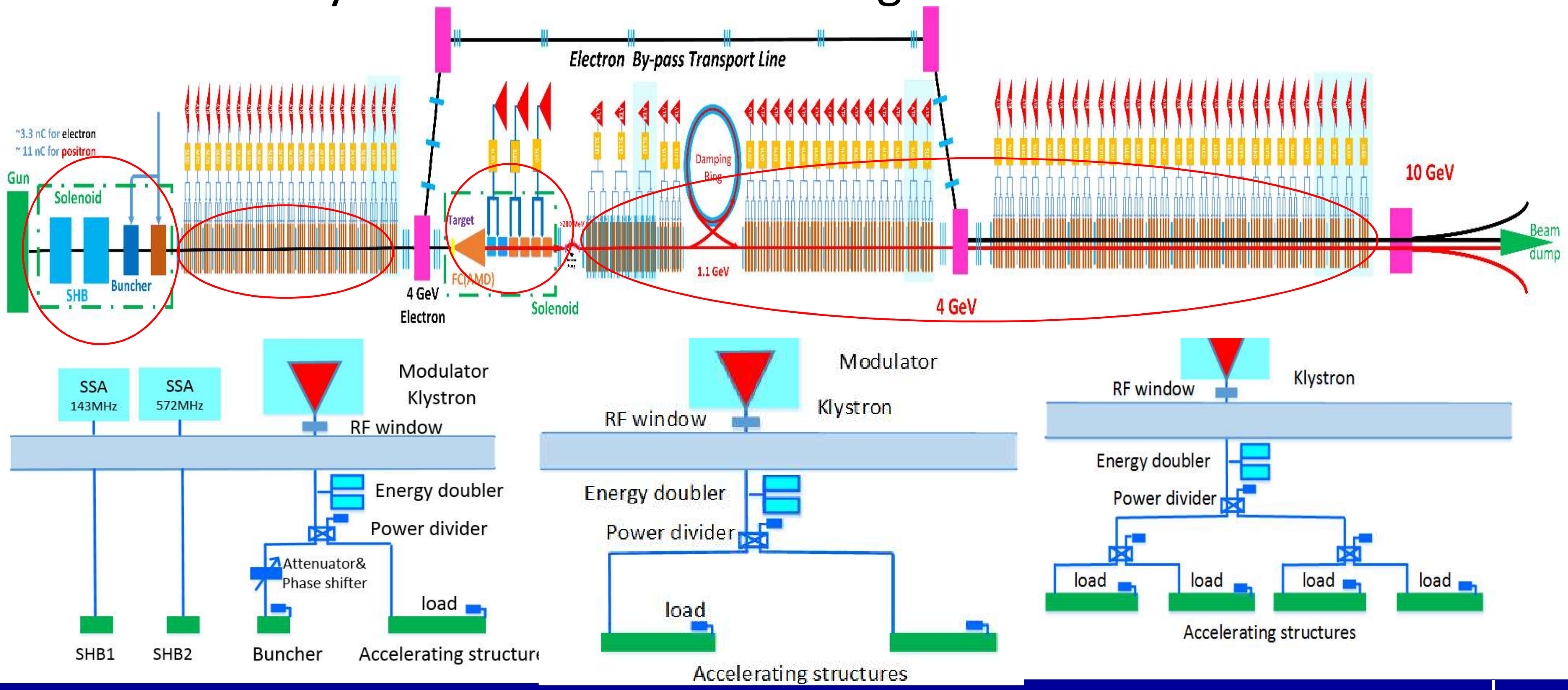
Linac design

- Layout of 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)
  - Mature technologies： Thermionic gun， Fixed positron target， S-band RF system



Linac design

- RF distribution of the linac (80MW klystron)
  - Bunching system
  - Big hole accelerating structure after positron target
  - One klystron to four accelerating structures



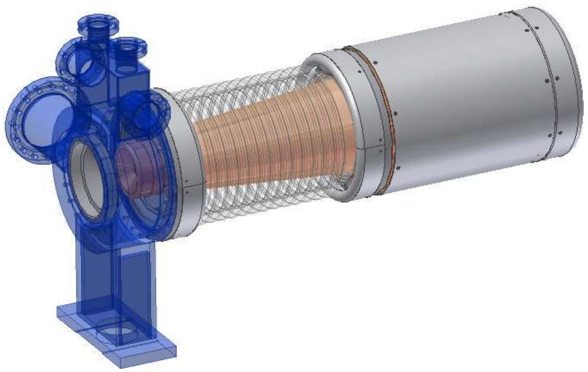
R&D activities

- Key components of baseline linac
  - **Electron gun**
  - **SHBs**
  - **Buncher**
  - **S-band accelerating structure**
  - **Pulse compressor**
  - **Positron source**
  - Big hole accelerating structure
  - **DR 650MHz RF cavity**
  - LLRF
  - Phase reference line
  - ……

Electron gun

- Tranditional thermionic triode gun

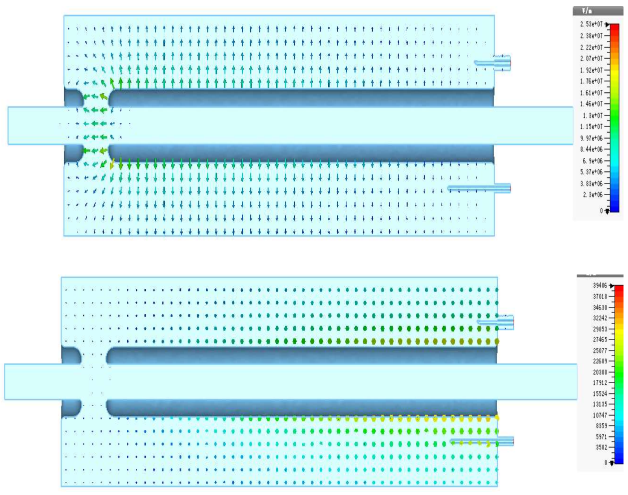
Parameter	Unit	Value
Type		Thermionic Triode Gun
Cathode		Y796 (Eimac) Dispenser
Beam Current (max.)	A	10
High Voltage of Anode	kV	120 ~ 200
Bias Voltage of Grid	V	0 ~ -200
Pulse duration	ns	1



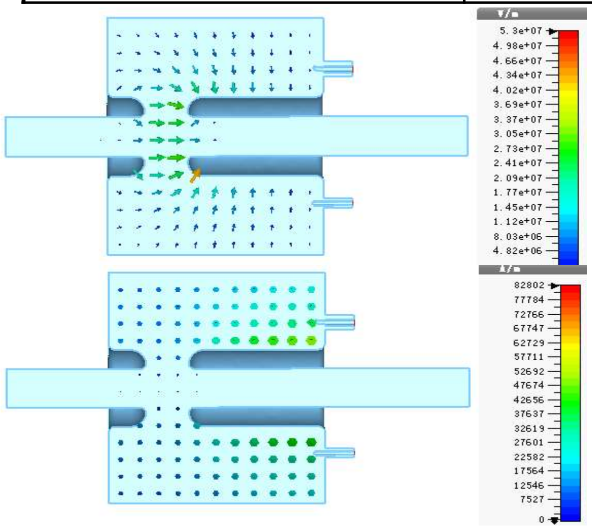
SHB & buncher

- Sub-harmonic buncher (SHB)
  - Capacitively loaded structure
- Buncher
  - Travelling wave
  - 2π/3
  - β=0.75, 6 cells

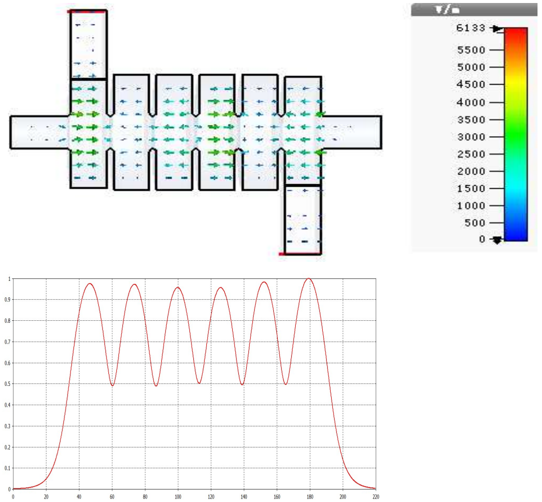
Parameters	Value			Unit
	SHB1	SHB2	B	
Frequency	143	572	2860	MHz
Shunt Impedance	1.39	2.89	7.5	MΩ
Unloaded Q	8139	13458	11083	-
Bunching Voltage(Max)	100	120	1200	kV
RF Structure	SW	SW	TW	-



SHB1



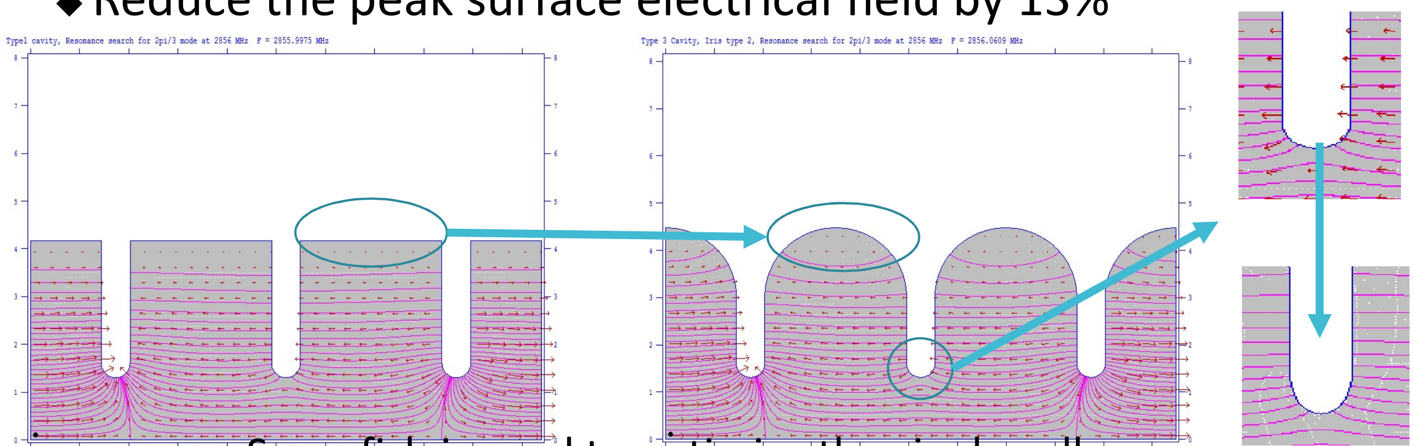
SHB2



Buncher

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

Accelerating structure

- The main parameters of the whole structure

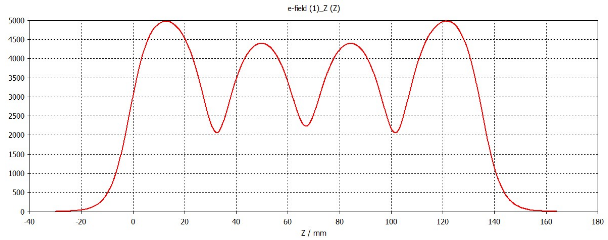
Parameters	Values	Unit
No. of Cells	84+2*0.5	-
Phase advance	2π/3	rad
Total length	3.1	m
Length of cell (d)	34.988	mm
Disk thickness (t)	5.5	mm
Shunt impedance (Rs)	60.3~67.8	MΩ/m
Quality factor	15465~15373	-
Group velocity: Vg/c (%)	2% ~ 0.94%	-
Filling time (t_f)	784	ns
Attenuation factor (τ)	0.46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

Accelerating structure

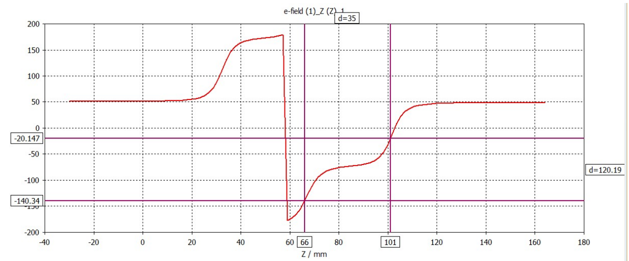
- Coupler design
  - The asymmetry of the coupling cavity will cause emittance growth
  - The shape of the coupling cavity is racetrack dual-feed type

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

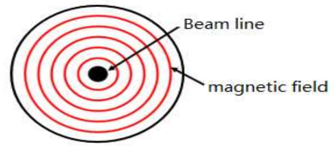
$$\Delta p_x = -\frac{e\Delta z E_0}{2\omega a}\left[\Delta\theta * sin\varphi - \frac{\Delta E}{E_0}\cos\varphi\right]$$



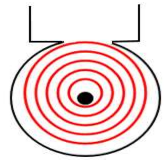
The *distribution of* the electric field on axis

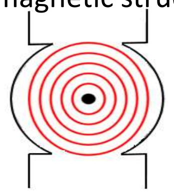


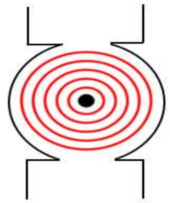
Phase advance per cell

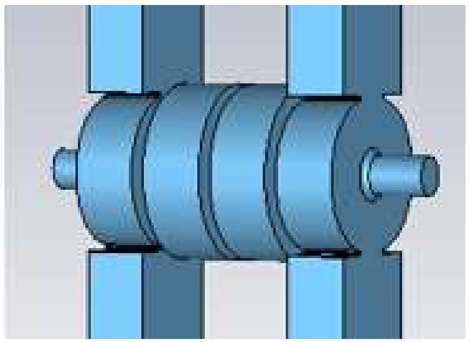


Ideal electromagnetic structure


Center bias coupler


Dual feed coupler


Dual feed racetrack coupler

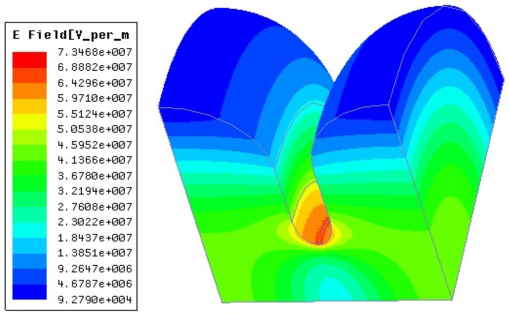

The calculation model

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

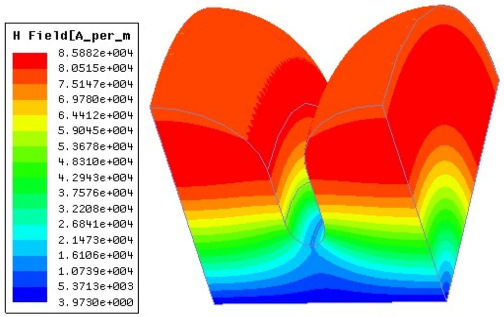
Accelerating structure

- 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



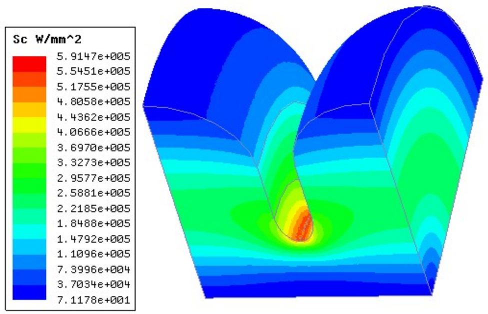
E_peak=73 MV/m.

Surface electric field



H_peak=86 kA/m.

Surface magnetic field



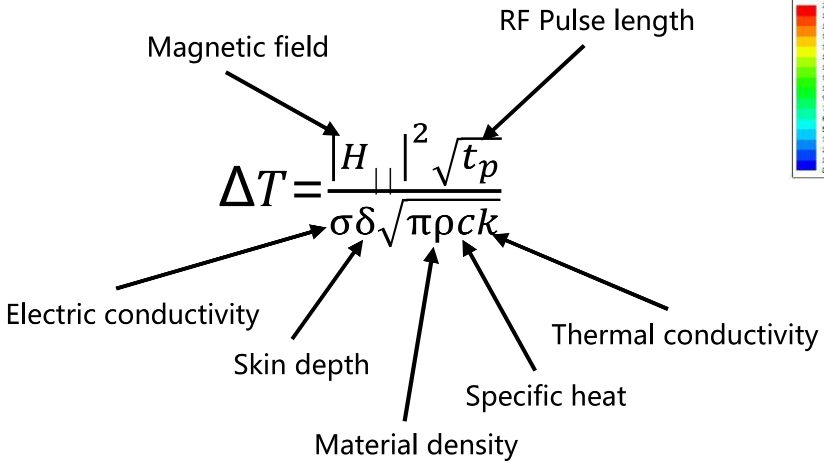
Sc_max=0.59 MW/mm^2.

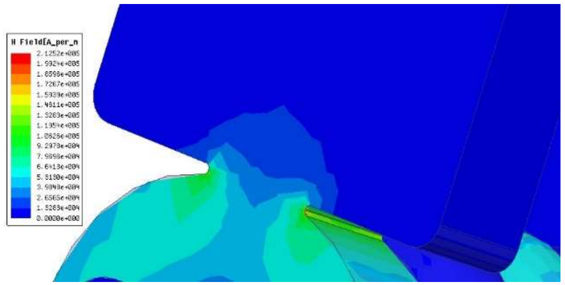
Modified Poynting vector

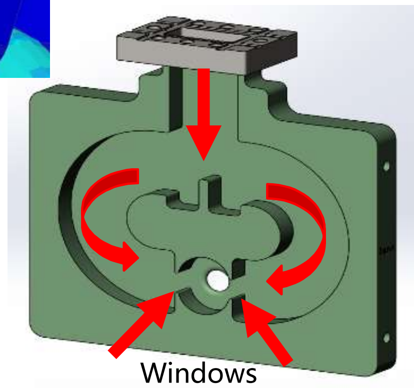
Accelerating structure

- 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.

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

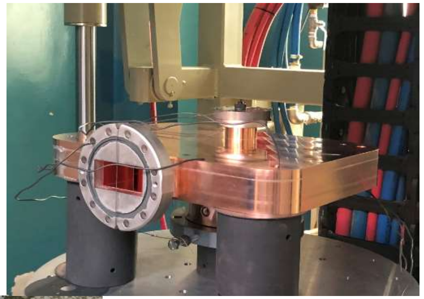






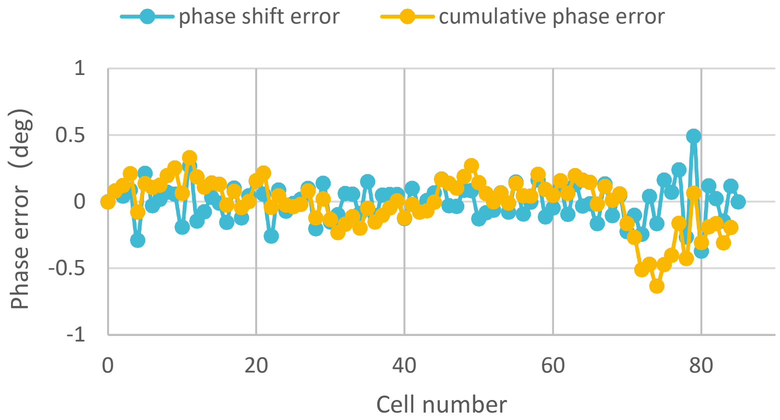
Accelerating structure

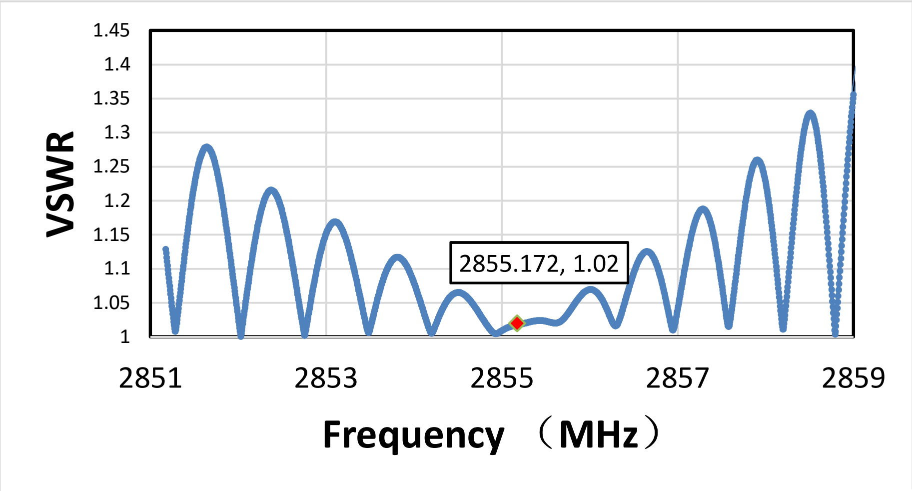
- Mechanical design
  - Inner water-cooling has been adopted. 8 pipes are around the cavity.
  - Compact coupler arrangements. The splitter is milling together with the coupling cavity.
  - Two tuners are outside the cavity.

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

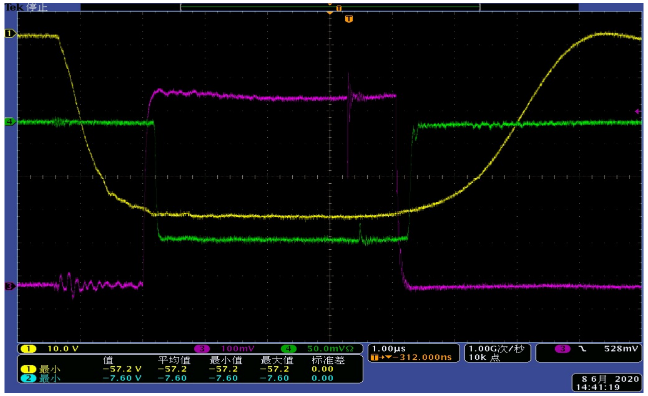




Accelerating structure

- 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

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

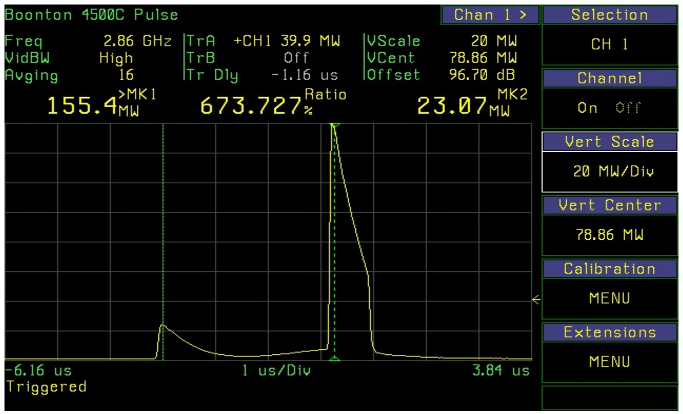


The waveform without SLED

Modulator and klystron

High power test bench

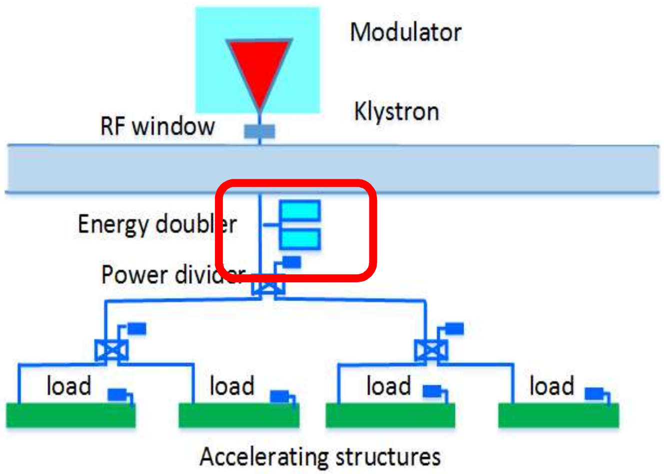
The input power with SLED

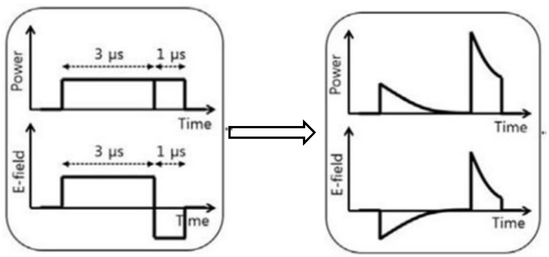


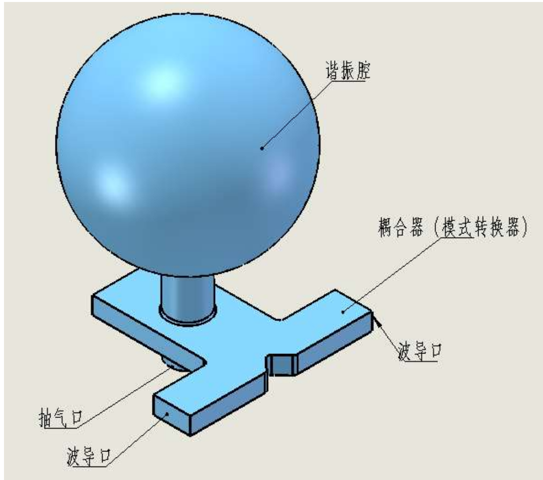
Pulse compressor

- 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

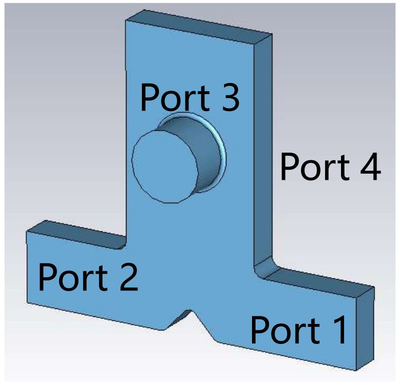




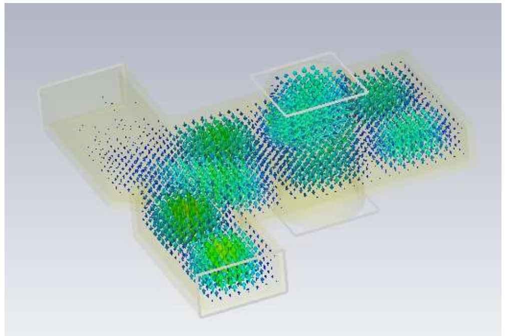


Pulse compressor

- Mode converter
  - The TE10 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



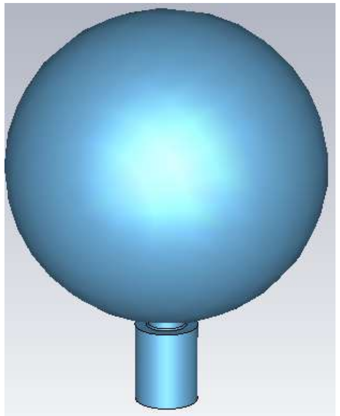
Vacuum model


Electromagnetic field

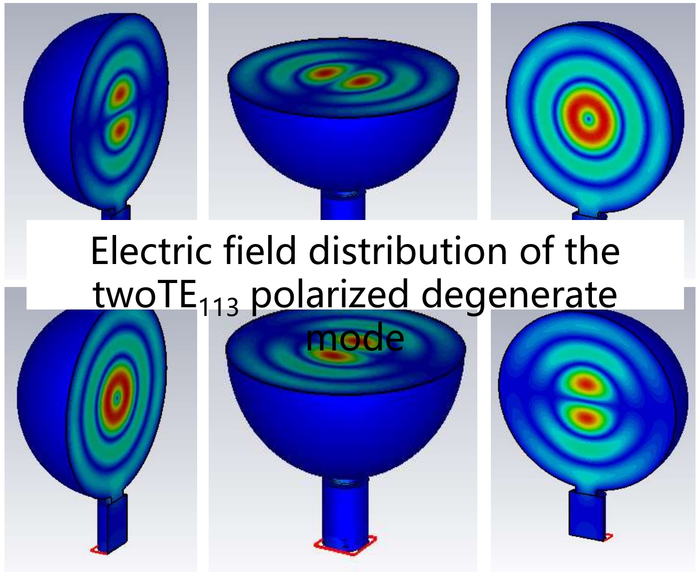
S11 / VSWR	-62.7 dB/1.0016
S21	-42.9 dB
S31(1)	-3.02 dB
S31(2)	-3.02 dB
Phase difference of two modes	89.89°
S41(1)	-70.9 dB
S41(2)	-71.0 dB

Pulse compressor

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



Simulation model

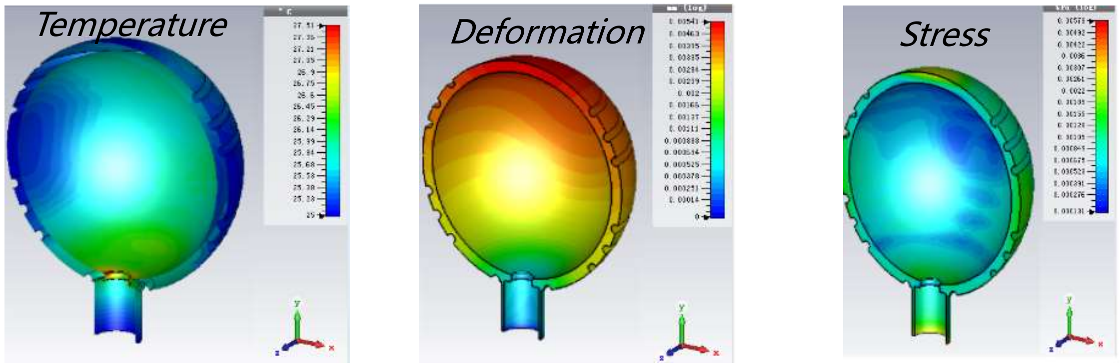


Electric field distribution of the twoTE_{113} polarized degenerate mode

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

Pulse compressor

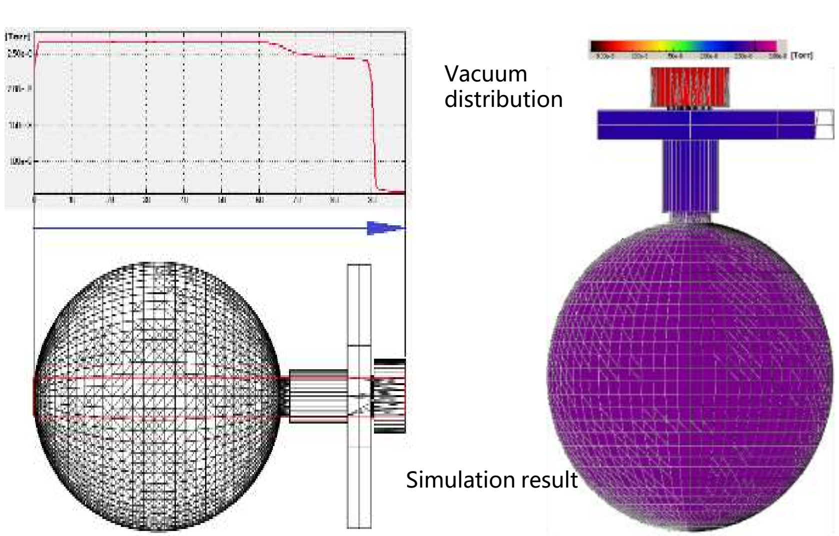
- Thermal stress analysis
  - The maximal temperature rise is on the coupling hole of 2.5 ℃ (the water cooling flow set as 50 L/min)
  - The frequency tunable range of ±1 MHz is enough for all the frequency shift resulted from the input power, vacuum pumping, air pressure, etc.

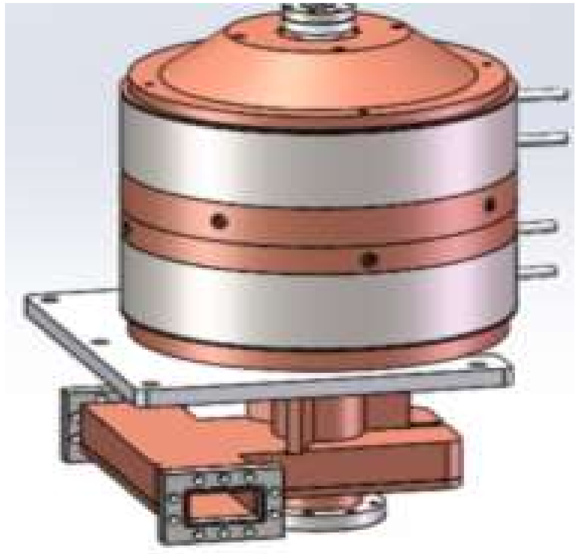


- Accordingly, if we use the water temperature to tune the frequency, the temperature need to be ±3.6 ℃ change

Pulse compressor

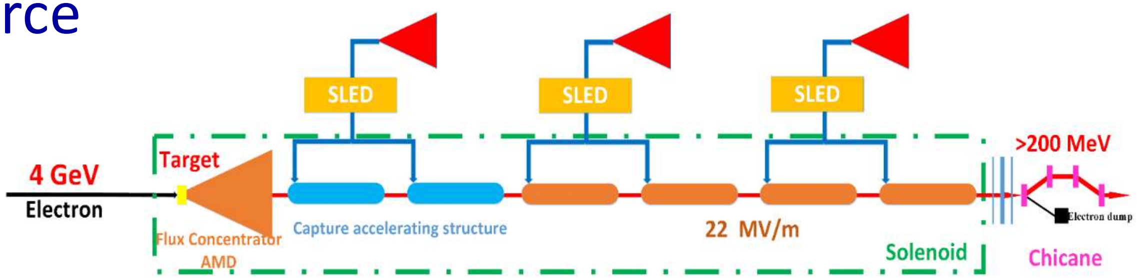
- Vacuum speed and vacuum level
  - The pumping speed of the ion pump is 100 L/s
- Finished mechanical design

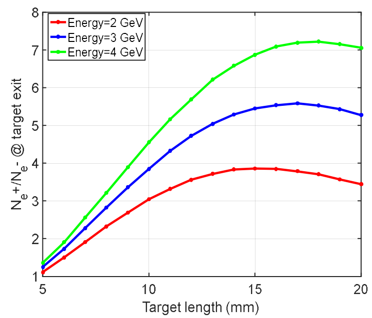


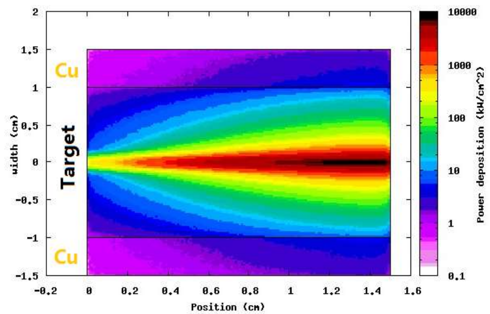


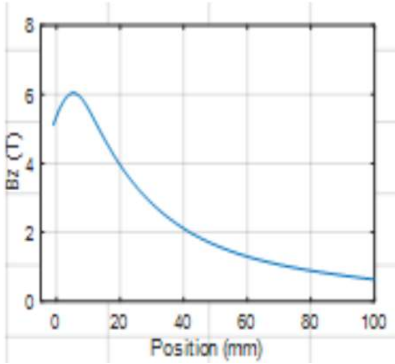
Positron Source

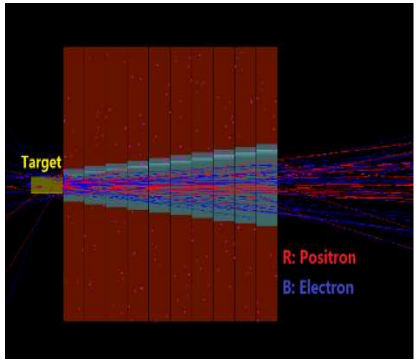
- Layout of positron source
  - Target (Conventional)
    - ✓ tungsten@15 mm
    - ✓ Beam size: 0.5 mm
  - Electron Beam
    - ✓ 4GeV/10nC/100Hz
    - ✓ Beam power 4kW
  - Energy deposition
    - ✓ 0.784 GeV/e- @ FLUKA
    - ✓ 784 W → water cooling
  - AMD (Adiabatic Matching Device)
    - ✓ Flux Concentrator
    - ✓ Length: 100mm
    - ✓ Aperture: 8mm→26mm
    - ✓ Magnetic field: (5.5T→0T) + 0.5T





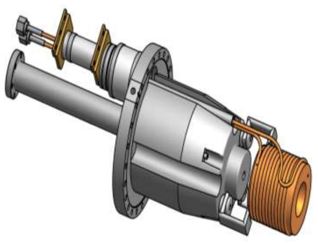






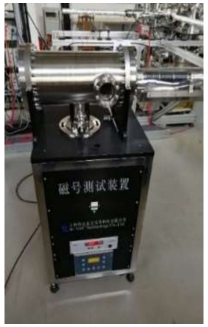
Positron Source

- FLUX concentrator
  - It produces a pulsed magnetic field of 6 T to 0.5 T
  - The maximum output value of the solid-state pulsed power generator is 15 kA / 15 kV / 5 μs



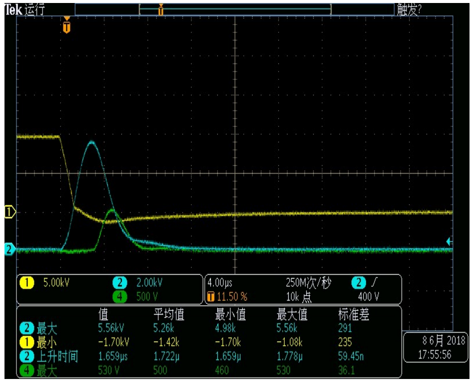
The mechanical design of FLUX concentrator

The finished FLUX concentrator



The test bench of the FLUX concentrator

solid-state pulsed power generator



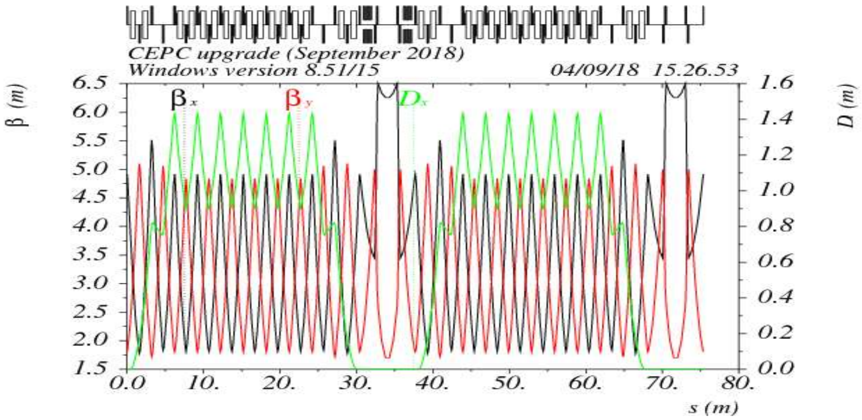
The output of 10kA measurement

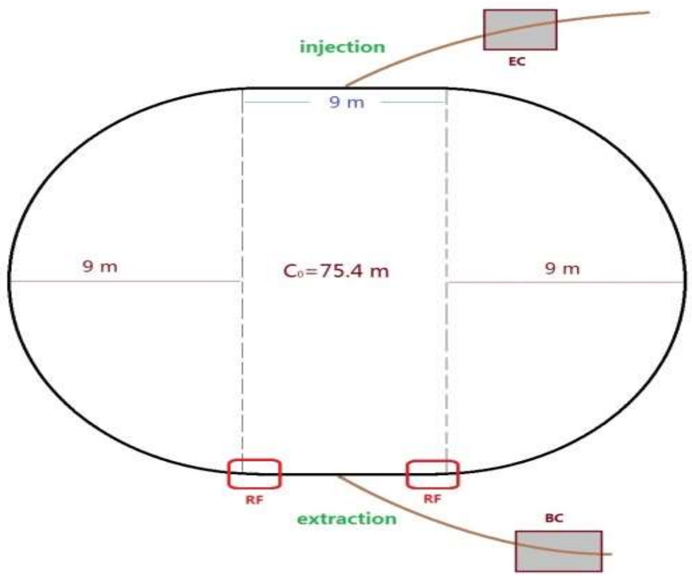
Damping Ring RF cavity

- 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

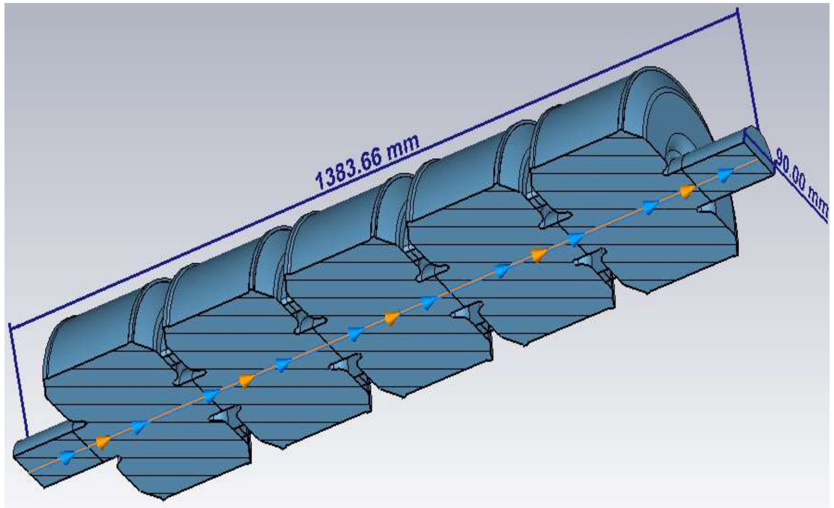




Damping Ring RF cavity

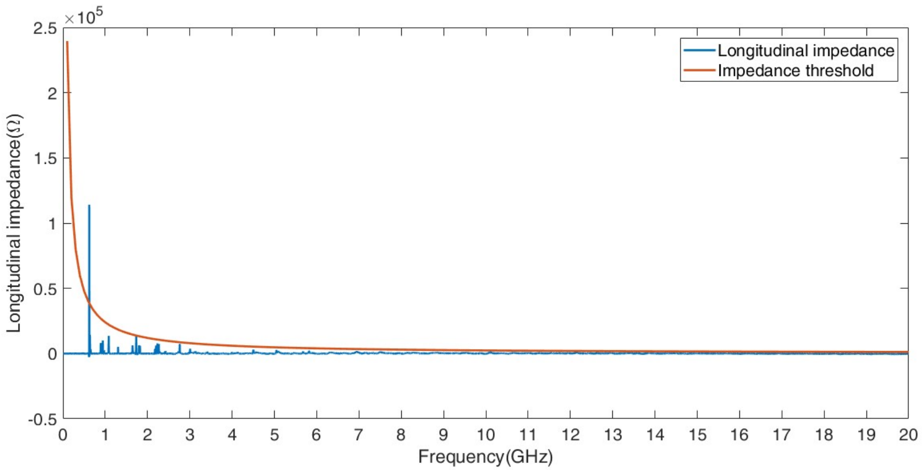
- HOM longitudinal impedance & threshold **Y.D. Liu**
  - The cavity diameter is 90 mm

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



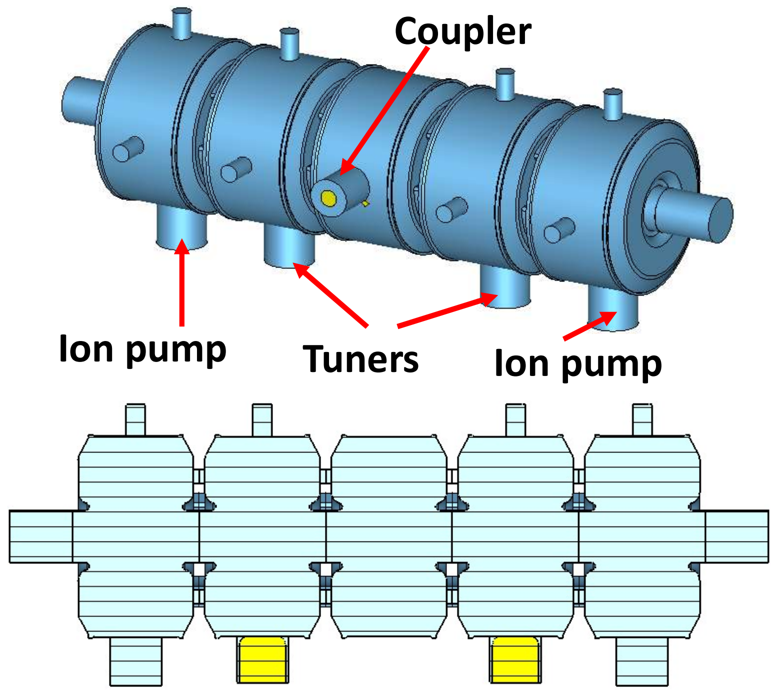
k=4.12V/pC
P=51.8w&10mA

Longitudinal loss factor and power(σ_z &5mm)

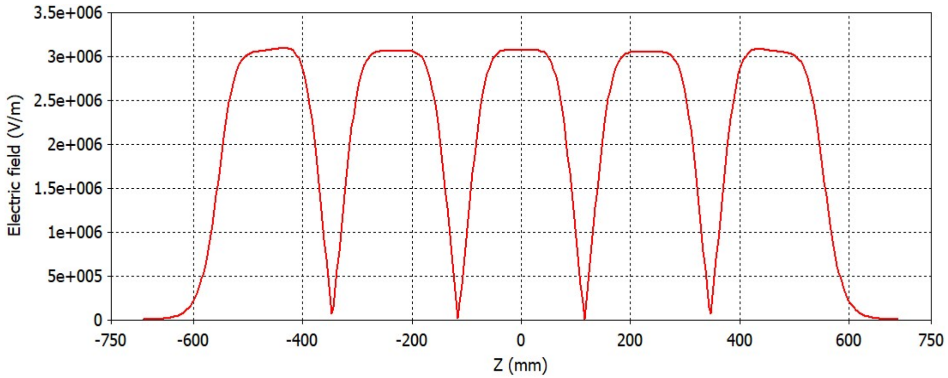


Damping Ring RF cavity

- Cavity design
  - Fundamental mode: TM_{010}
  - Parameters at field balancing

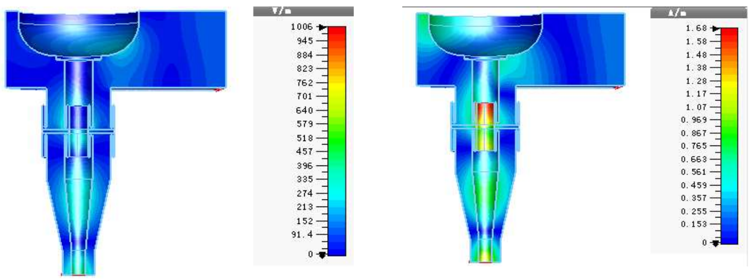


	Unit	Value
Beam tube aperture	mm	90
Cell length	mm	5*230.61
π-mode frequency	MHz	650.0
Q_0		32000
Shunt impedance	MΩ	16
R/(Q*l)	Ω/m	430
Accelerating voltage	MV	1.0 (1.2)
Accelerating gradient	MV/m	0.87 (1.04)
Dissipated cavity power (20% margin)	kW	38 (54)

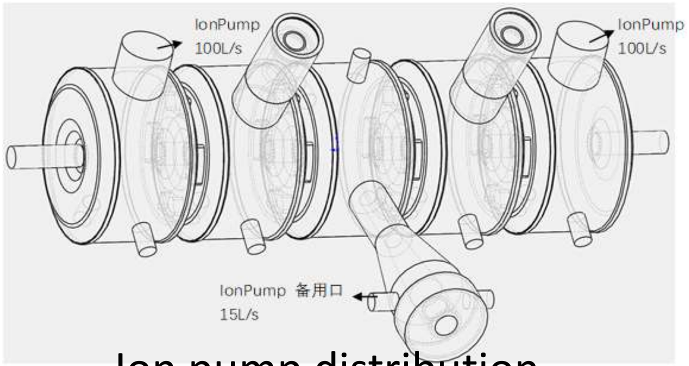


Damping Ring RF cavity

- Input coupler, doorknob and tuner
  - The diameters of neck tubes of tuner and vacuum ports are 94mm
- Vacuum
  - 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



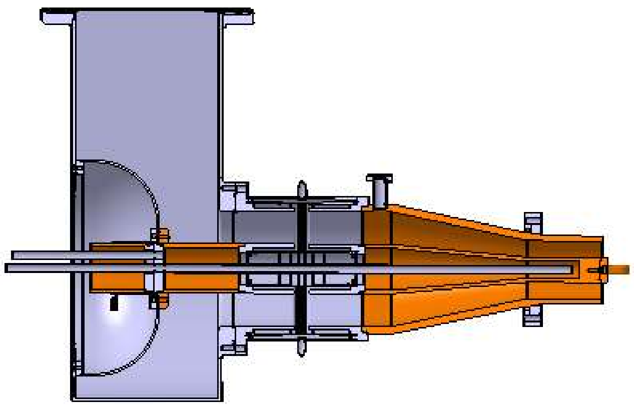
Electromagnetic field distribution

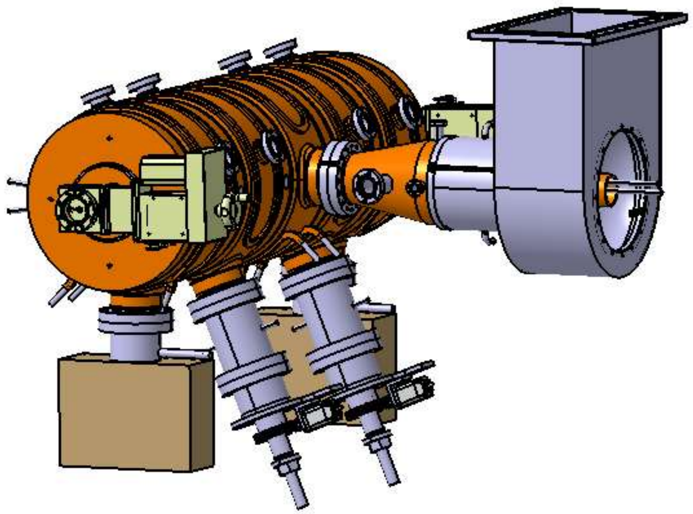


Ion pump distribution

Damping Ring RF cavity

- Mechanical design
  - The preliminary design has finished
  - Multiple iteration with the physical design of the DR, RF design and mechanical design is needed



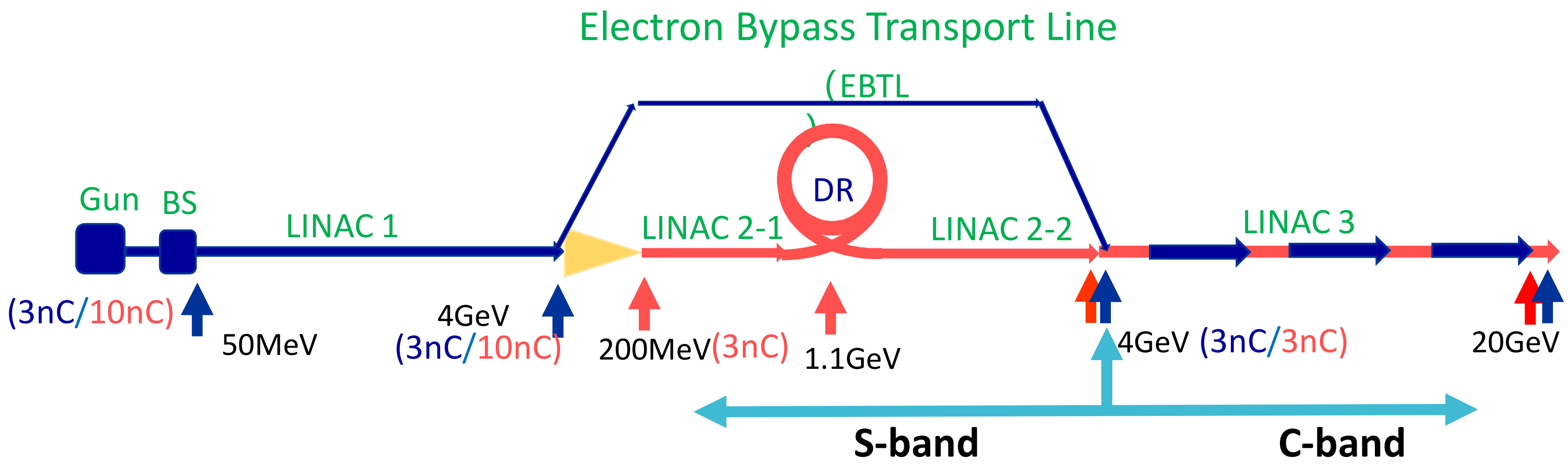


Linac alternative

- Linac design must match booster requirment
- As long as the booster requirement changes, the linac must give the corresponding design
  - High luminosity scheme at Higgs energy
    - The linac beam emittance 40nm (CDR)→10 nm
  - Full injection for Z(2T_39MW)

Linac alternative

- 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



Linac alternative

- 20 GeV 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

- Full injection for Z(2T_39MW)
  - Two bunches/pulse
    - Preliminary evaluation
      - Physics design/control systm/instrumentation
  - Repetition: 200 Hz
    - RF Power source: no mature product
      - Modulator: The price increased by 1 times
      - Klystron: The price increased by 1.5 times
    - RF system (The average power increase 1 times)
      - Load
      - Water cooling

Summary

- The linac baseline design is a 10 GeV S-band accelerator
- The key components of the linac baseline are being developed. The accelerating structure, the spherical pulse compressor, The FLUX concentrator and damping ring RF cavity
- According to the change of the booster requirement , the linac has made the corresponding considerations

Thank you for your attention!