Klystrons and RF Power Sources for CEPC

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On behalf of CEPC RF power source team
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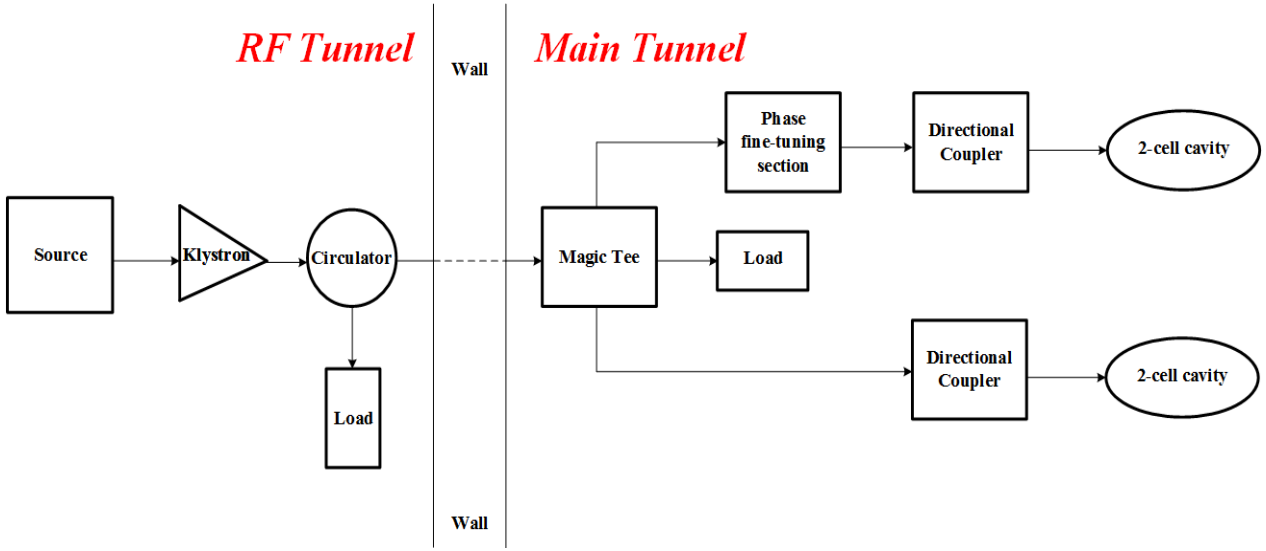
Outline

- **Klystron**
  - Design consideration
  - R&D Status
    - 1st prototype
    - 2nd (HE klystron) conditioning
    - 3rd (MBK) design and fabrication progress
    - C&S band klystron design
- **CEPC RF power sources**
- **Summary**

Design consideration

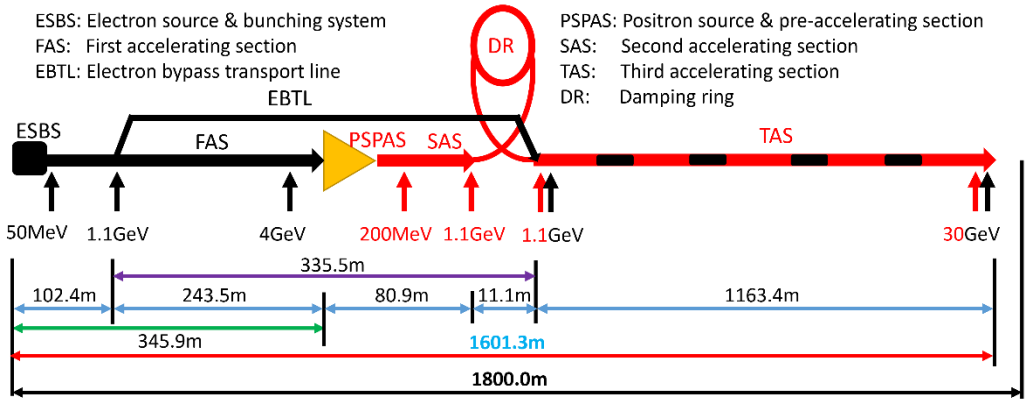
P band klystron for CEPC Collider

Parameters	Value
Freq.(MHz)	650
Klystron QTY.	**120**
Klystron power(kW)	**800**
1 to 2 SC cavity	



C&S band klystron for CEPC Linac

Parameters	S	C
Freq.(MHz)	2860	5720
Klystron QTY.	**33**	**236**
Klystron power(MW)	**80**	**50**
RF structure distribution	1-to-2&1-to-4	1-to-2



R&D Status

RF Power source choice

The Collider beam power is more than 60 MW. The increase in efficiency of RF power sources is considered a high priority issue.

RF power sources - efficiencies

	Tetrodes	IOTs	Klystrons	SSA	Magnetrons
f range:	DC–400MHz	(200–1500)MHz	300 MHz – 1 GHz	DC – 20 GHz	GHz range
P class (CW):	1 MW	1.2 MW	1.5 MW	1 kW @ low f	< 1MW
typical η:	85% - 90% (class C)	70%	65%	60%	90%
Remark	Broadcast technology, widely discontinued			Requires P combination of thousands!	Oscillator, not amplifier!

High power klystrons are the more attractive choice because of their high efficiency, low cost and more stable than IOT and SSA for CEPC collider.

System overall efficiency

CEPC Collider SRF Wall Plug Efficiency

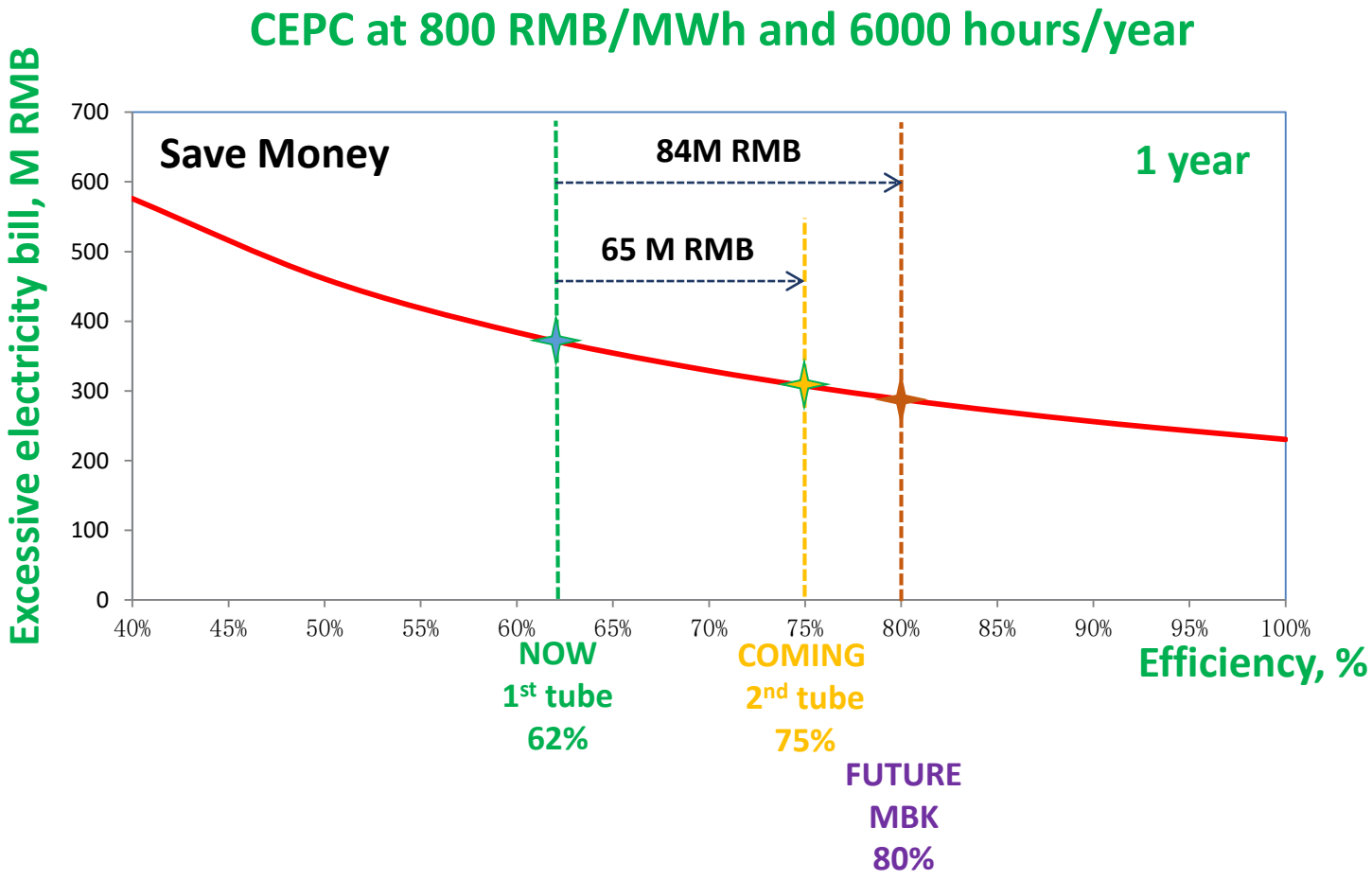
Wall to PSM power supply/modulator	95%
Modulator to klystron	96%
Klystron to waveguide	75%
Waveguide to coupler	95%
Coupler to cavity	~100%
Cavity to beam	~100%
Overall efficiency	**~65%**

The critical factor is klystron efficiency

Much higher efficiency, less energy consumption.

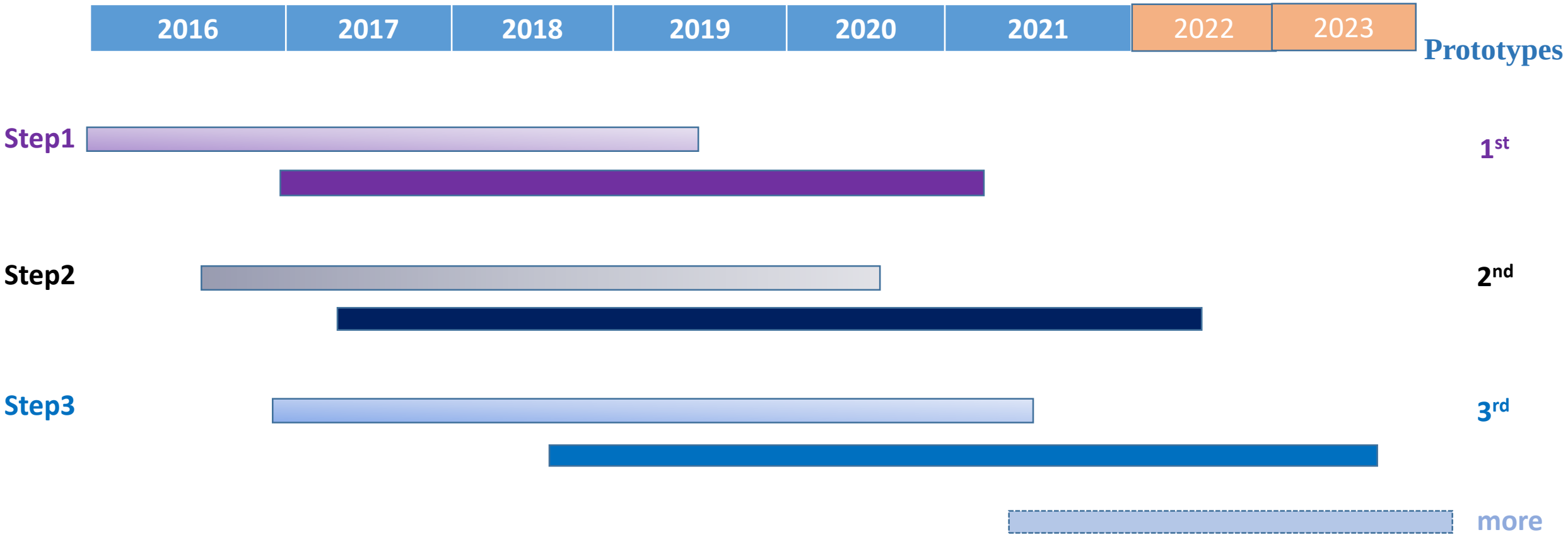
Cost consumption

Efficiency impact on operation cost *(Only considering operation efficiency of klystrons)*



R&D strategy and plan (2016 to 2021)

3 or more klystron prototypes

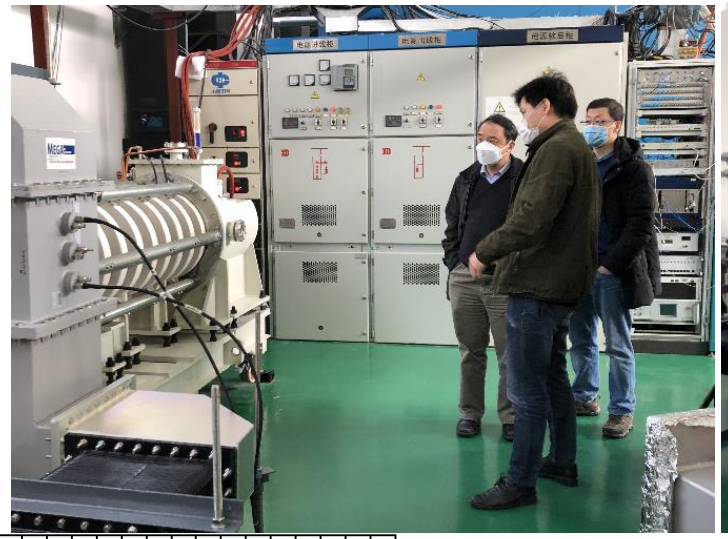


Efficiency: 60% - - - - → 70% - - - - → 80%

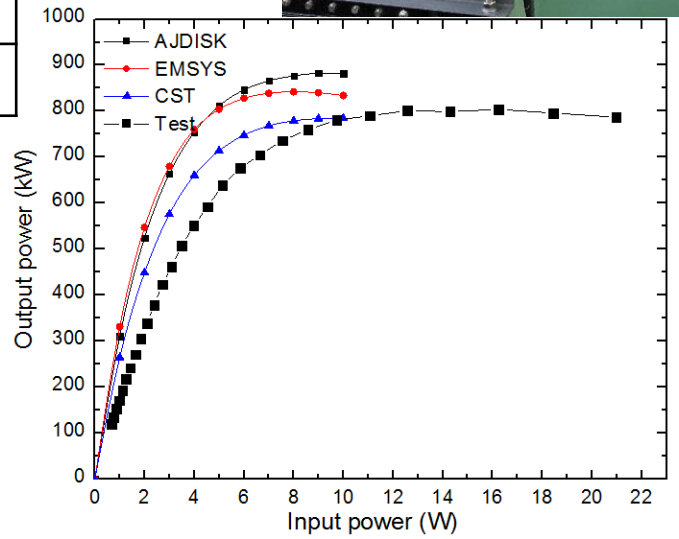
1st prototype high power test results

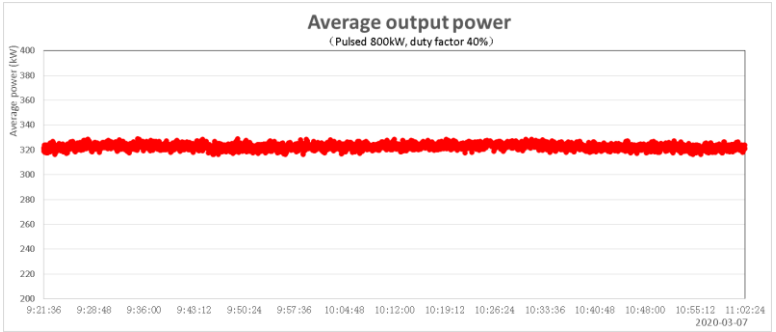
◆700kW CW and 800kW pulsed power with 62% efficiency

Parameters	Design	Test
Operating frequency (MHz)	650	650
Beam Voltage (kV)	81.5	80
Beam Perveance ($\mu A/V^{3/2}$)	0.65	0.7
Efficiency(%)	65	62
Saturation Gain(dB)	≥45	47
Output power(kW)	800	800
1 dB Bandwidth(MHz)	≥1	1.8



High power test stand





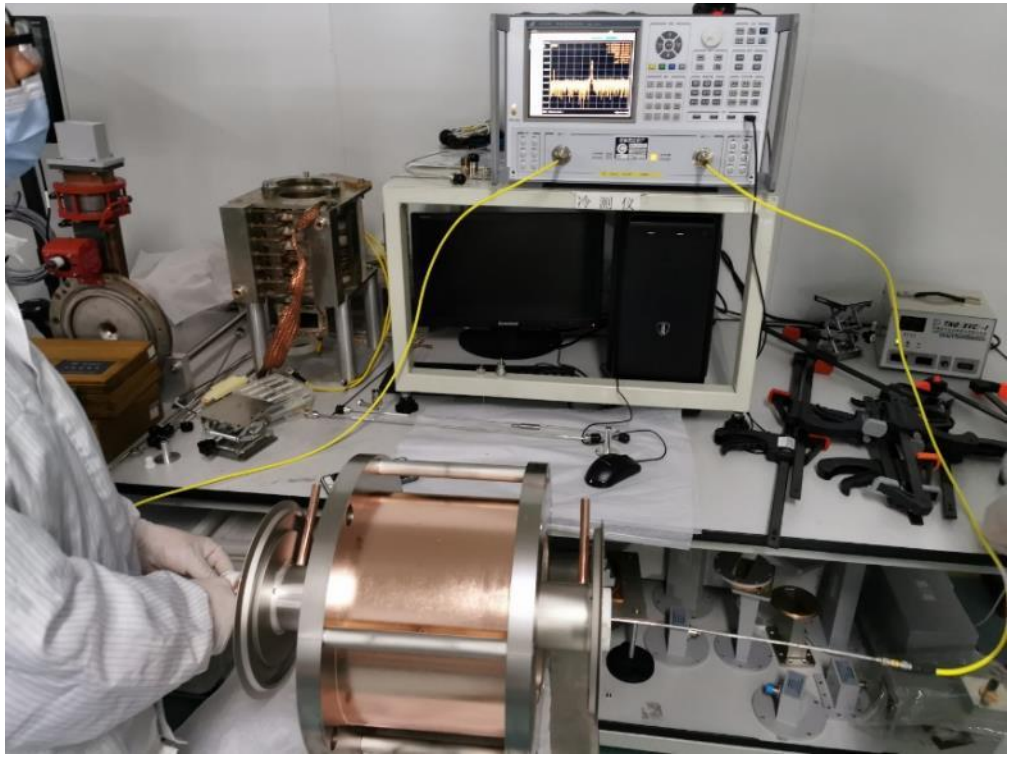
Pulsed 800kW

HE Klystron Milestone

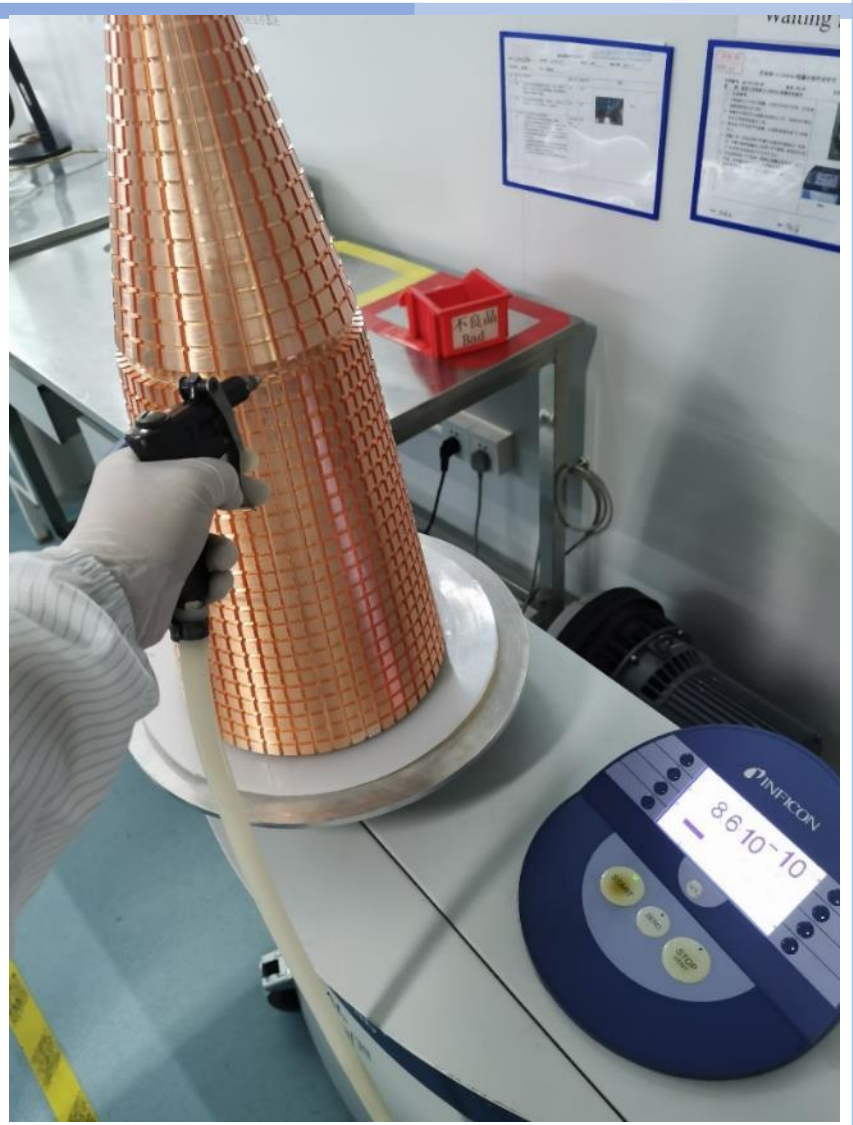
- Jan., 2021: Klystron manufacture started
- Jul., 2021: Parts fabrication completed
- Nov., 2021: Gun processing and klystron baking out
- Dec., 2021: Klystron delivered to IHEP
- Mar., 2022: Klystron conditioning started
  - ① Cold high voltage conditioning
  - ② Cathode activation
  - ③ High voltage conditioning
  - ④ RF Conditioning(Pulsed and CW)
- Jul., 2022: **CW 630kW/Eff. 70.5%**

Fabrication processing

Electron gun



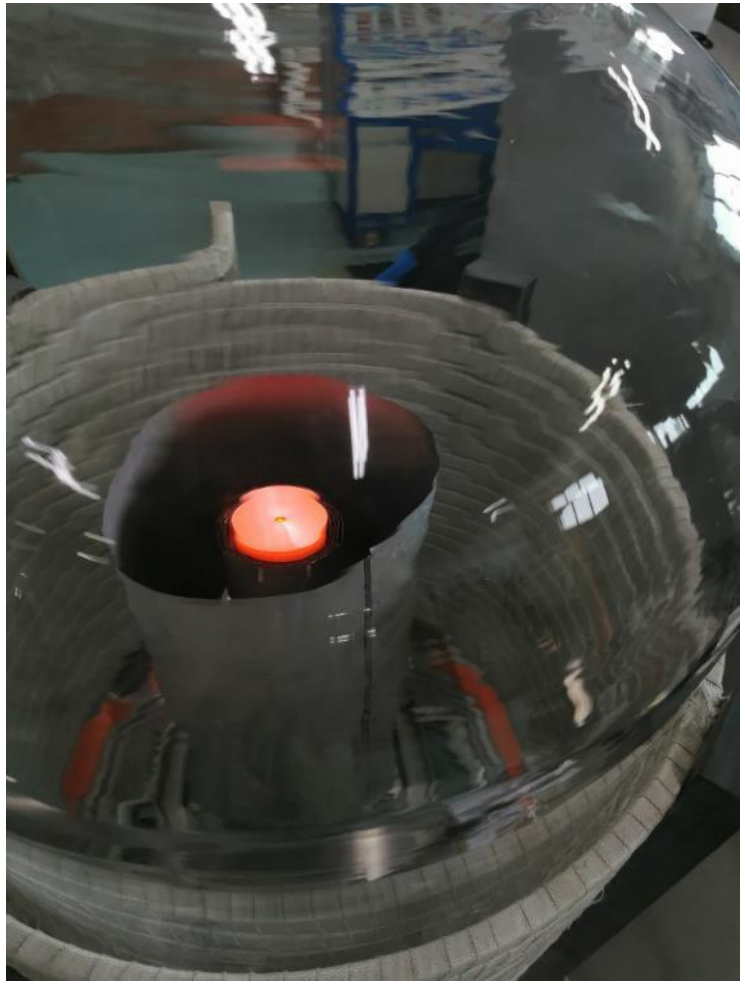
Cold test



Collector body

Electron gun processing

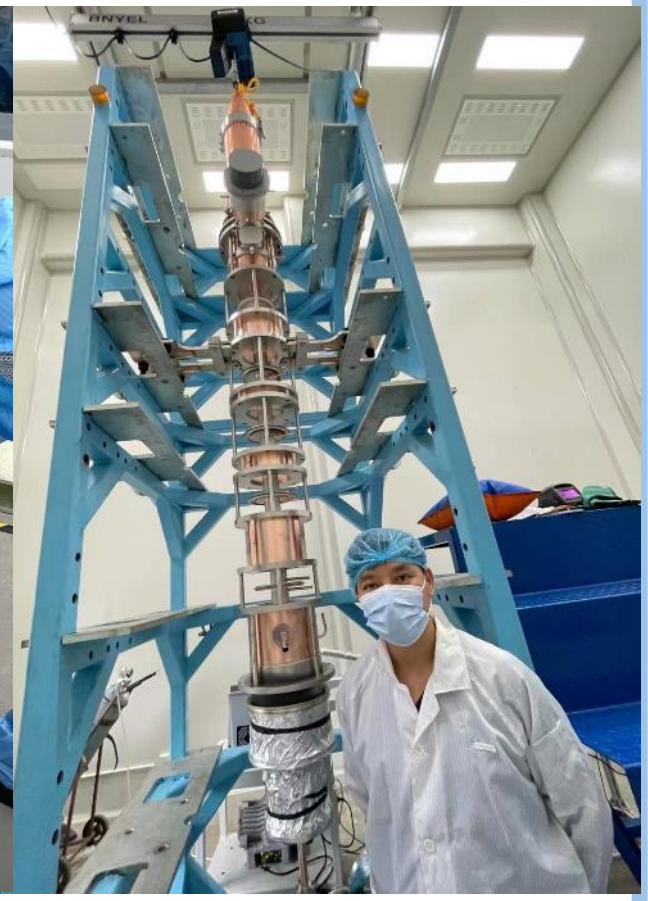
Cathode Temp. 975 degree C @Fil. 27V/6A



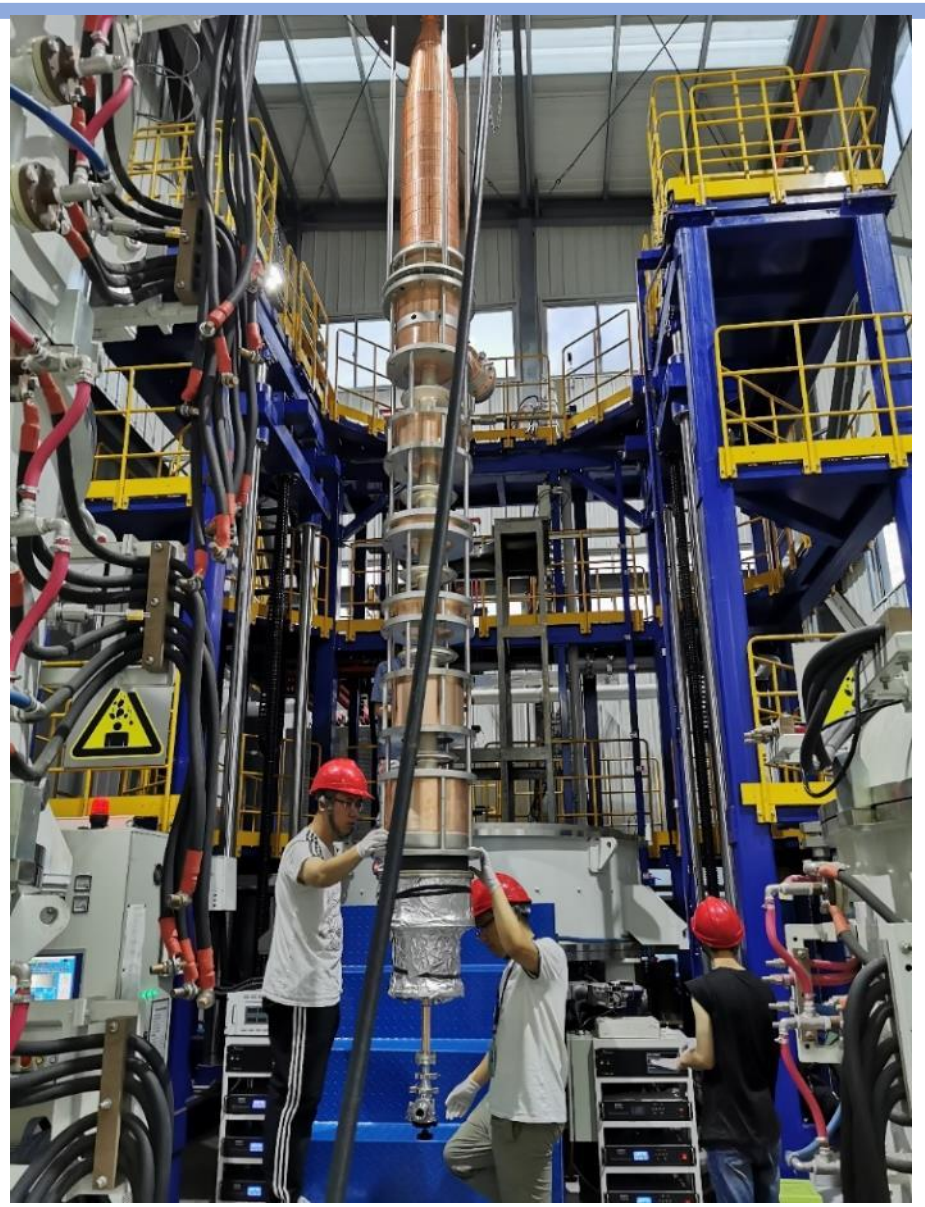
Klystron final assembly

Klystron final assembly

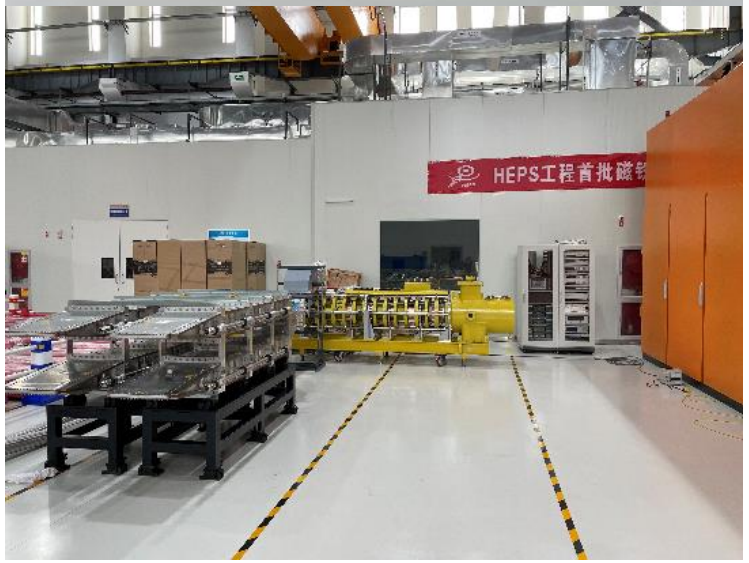


Klystron baking out

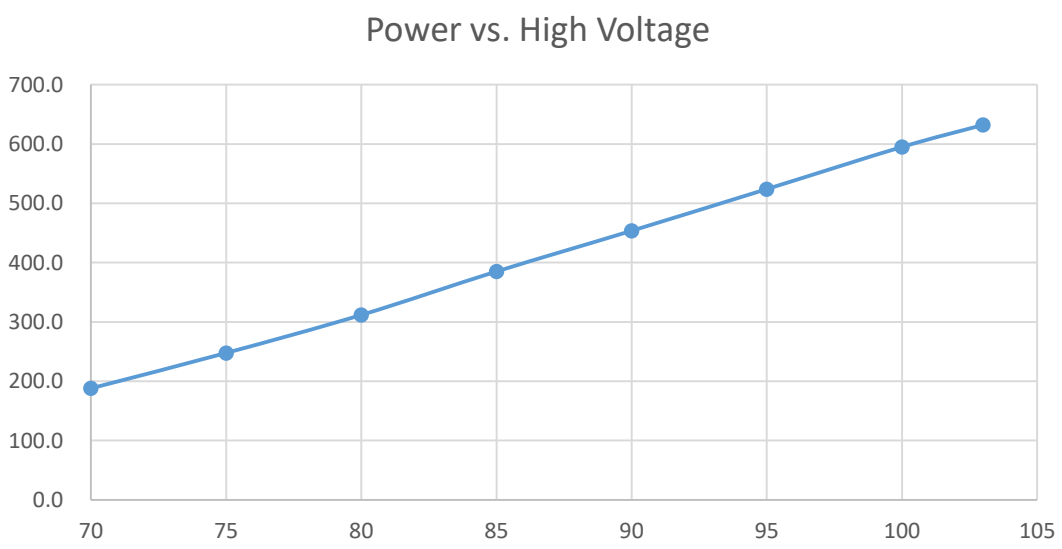


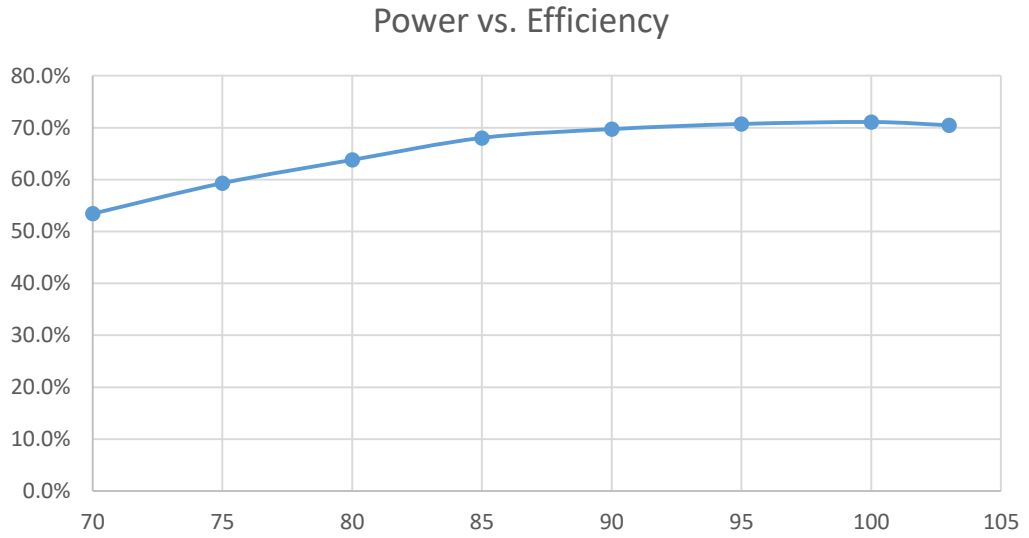
High power test preparation



Klystron is in place in IHEP PAPS site

High power conditioning





On Jul.5, 2022

CW power: 630kW

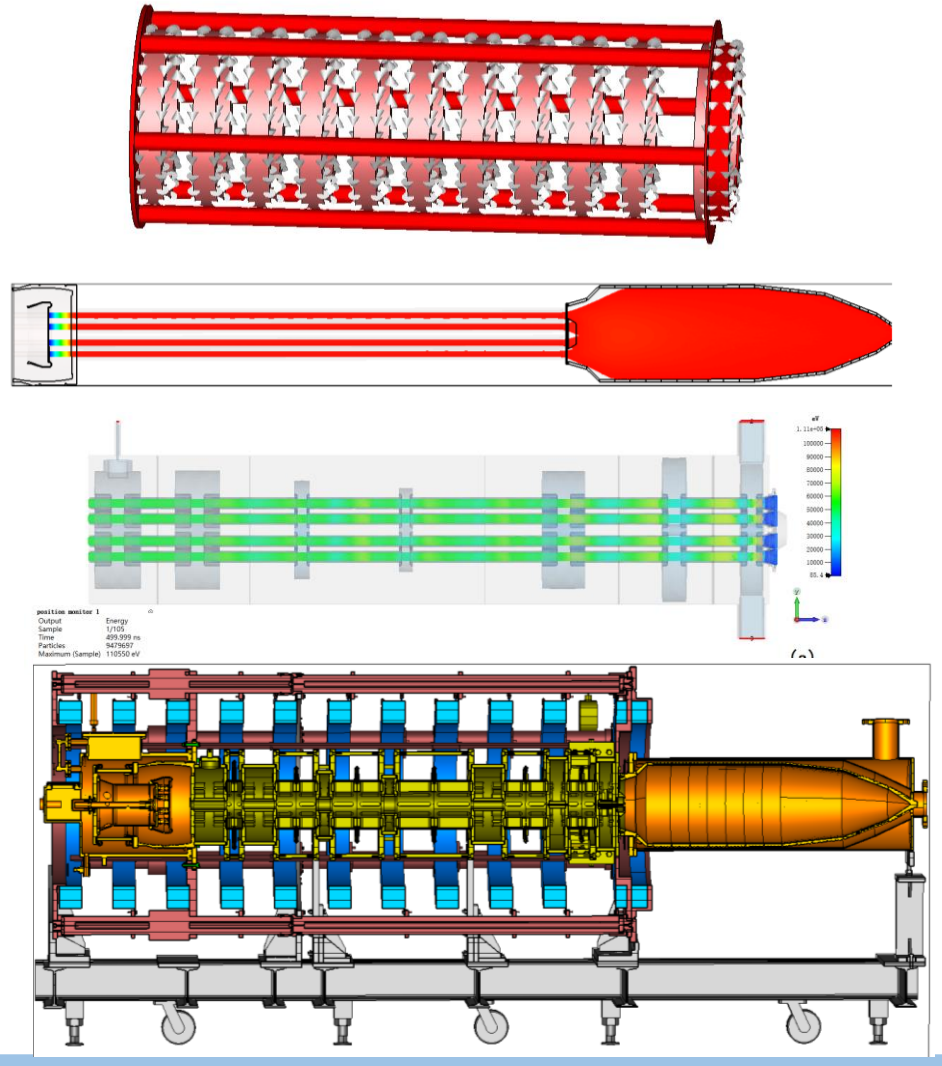
Eff. : 70.5%

MBK design and fabrication status

MBK physical and mechanical design

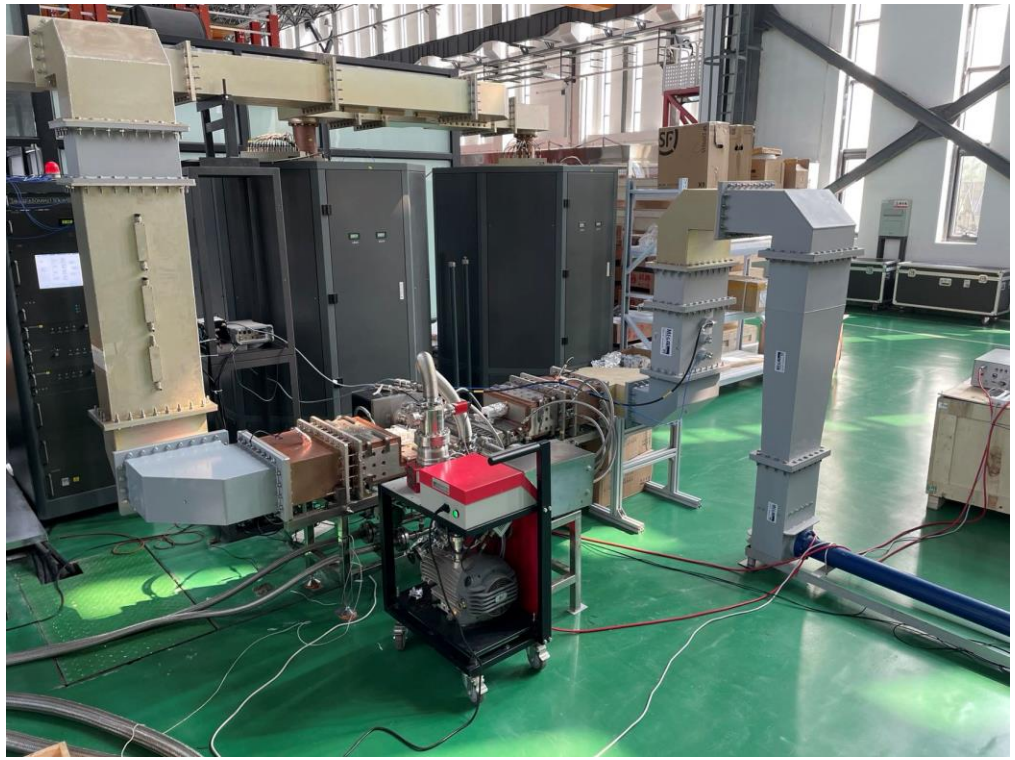
- Final physical and mechanical design was completed at the end of 2021.

Parameters	Value
Frequency	650 MHz
Output Power	800 kW
Efficiency	80.5%
$1dB$ bandwith	±0.75 MHz
Beam voltage	54 kV
Beam current	2.51*8 A
Beam number	8

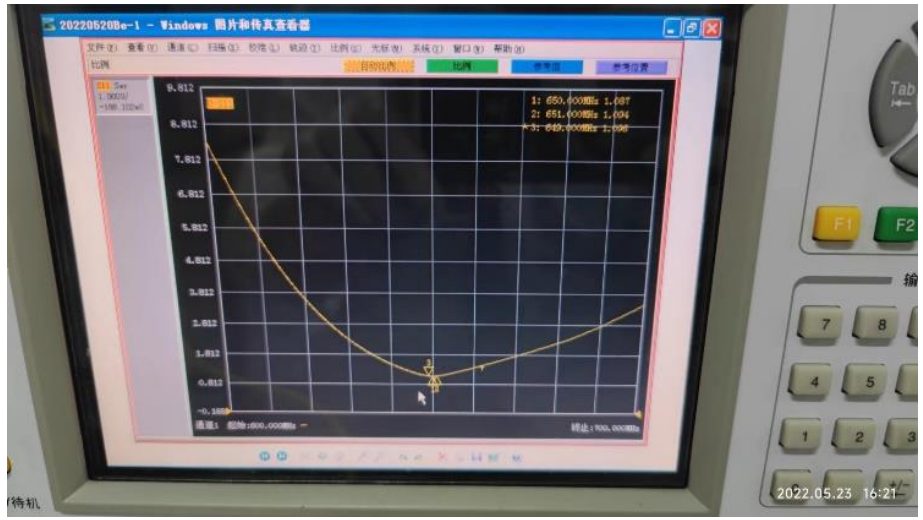


MBK Fabrication Status

- Fabrication of two types of output window prototype is completed.
- The high power conditioning was been processed with solid state amplifier at PAPS site.



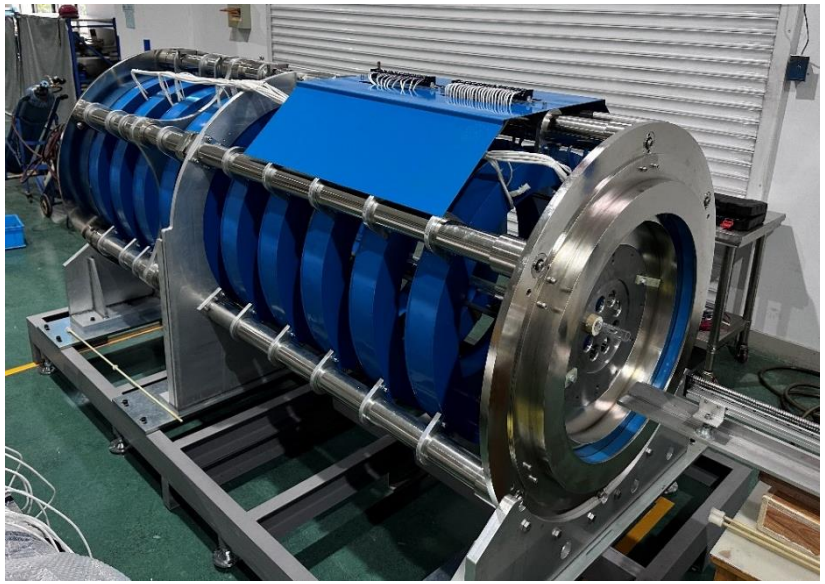
High power conditioning site



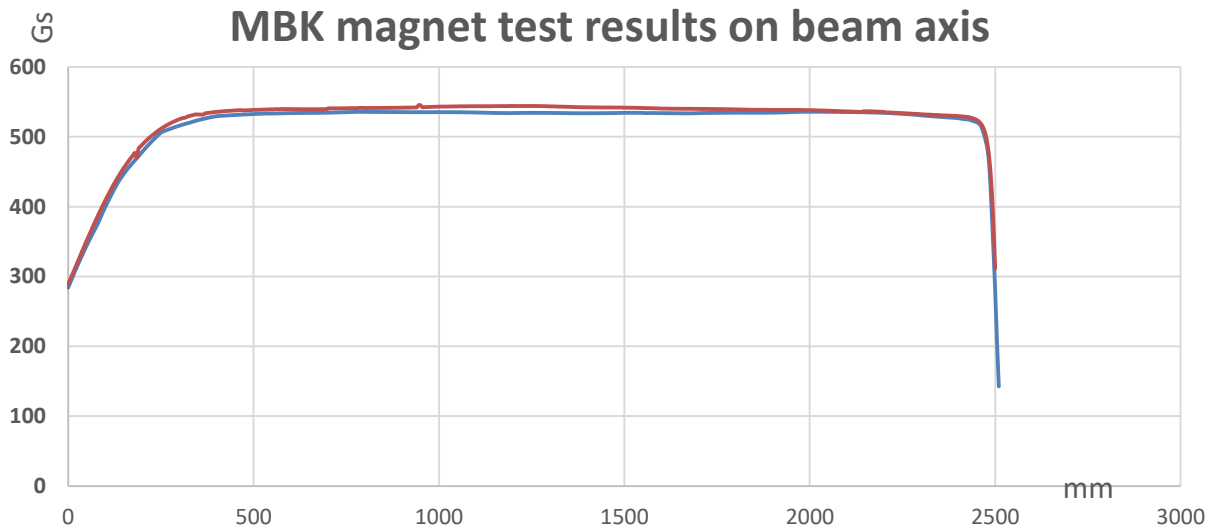
Test result	Alumina	Beryllium oxide
VSWR@651MHz	1.048	1.089
VSWR@650MHz	1.034	1.084
VSWR@649MHz	1.052	1.096

MBK Fabrication Status

- The experimental cavity is completely manufactured with mechanical tuning device.
- Fabrication of MBK beam tester is completed(including electron gun, collector, focusing coil) and will be delivered to IHEP for high power test on next month.



MBK Coils and field value



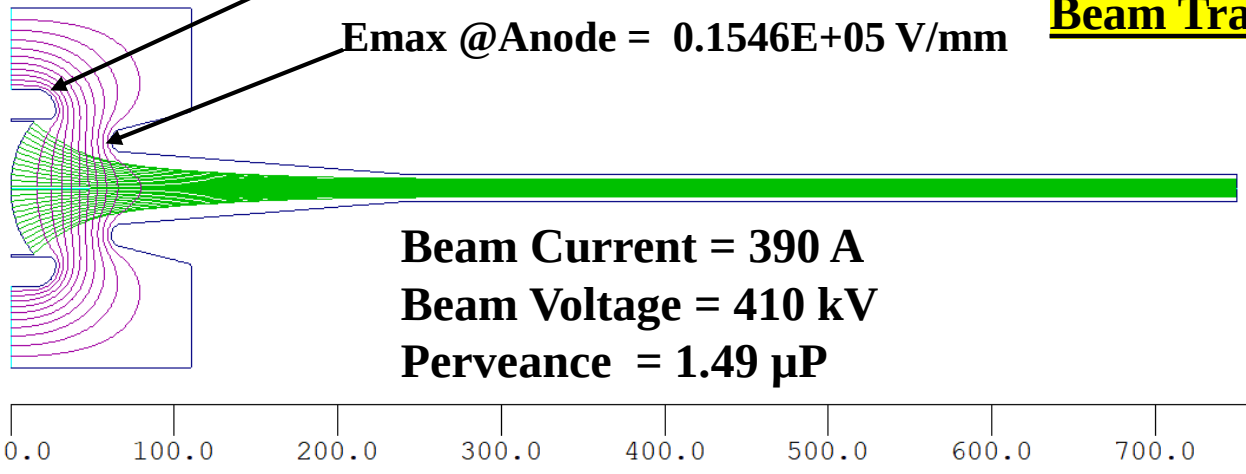
MBK beam tester

C band and S band klystron

Type	QTY	Freq.(MHz)	Structure type
S-band klystron	33	2860	1 1-to-1， standard-bunch 3 1-to-2， standard acc. structure. 8 1-to-2， large aperture acc. structure 21 1-to-4, standard acc. structure.
C-band klystron	236	5720	1-to-2， standard acc. structure.

80 MW C-Band(5720 MHz) klystron
Beam optics design simulation

Beam Trajectories

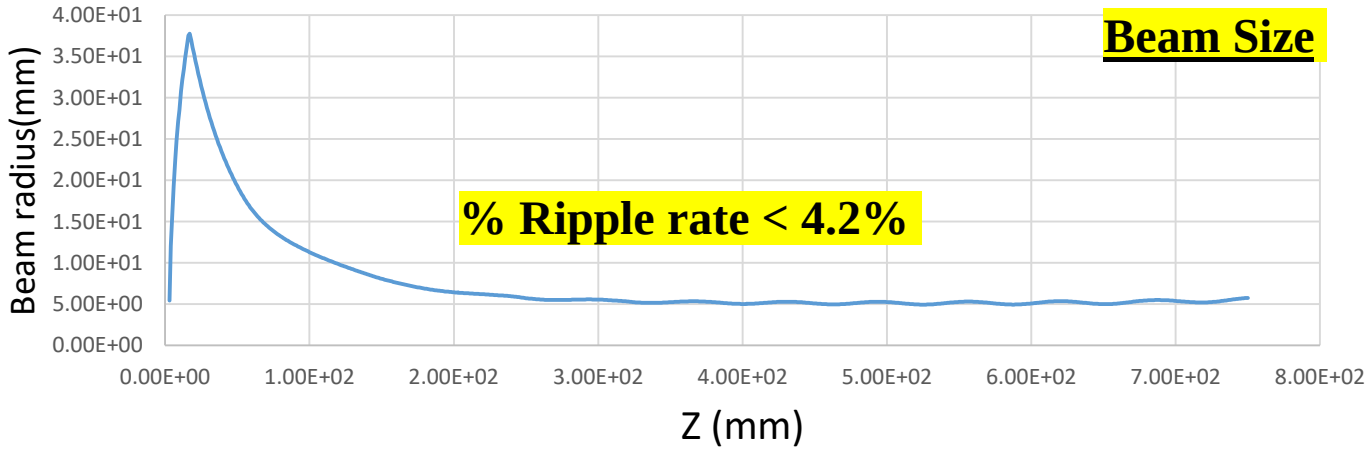


Beam Current

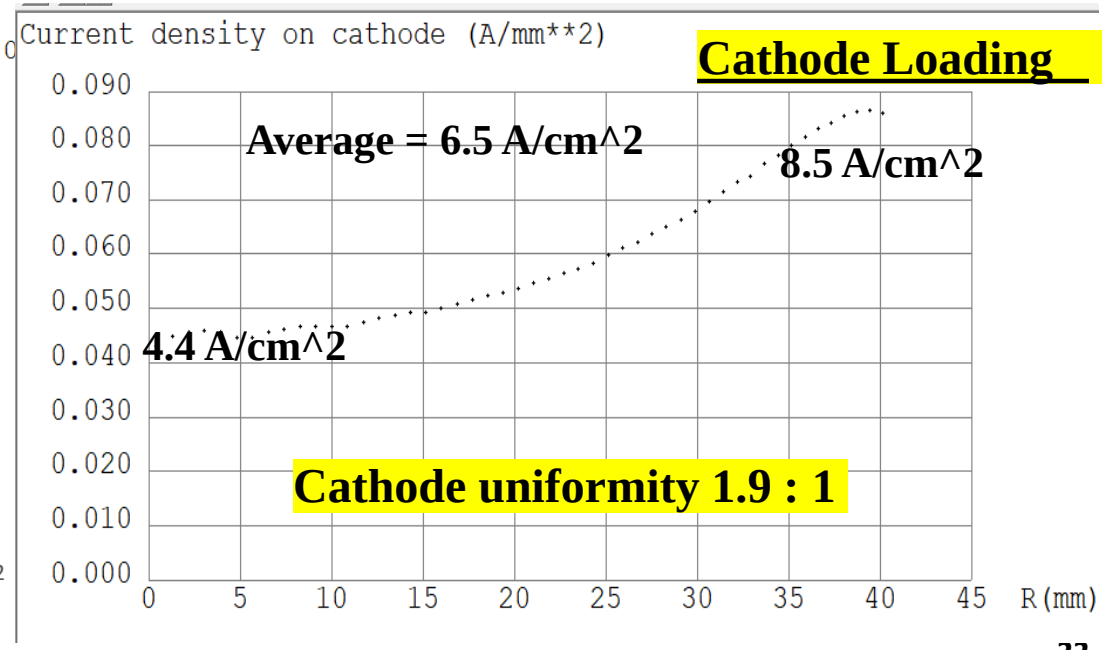
```
iteration n= 50
xr1=      0.9995 eps1=      1e-007
SLOR iterations n=  146 err= 9.753e-008
     Zcross      Rmax       Ibeam       Em.r
      100        11.29       390.1      0.05948
      125         9.51       390.1      0.07844
      150        8.047       390.1       0.1276
      175        7.032       390.1      0.09426
      200        6.433       390.1       0.1187
      225        6.148       390.1      0.08293

interval:          260 < z <          700
Rmax =       5.5739 mm,     Rmin =       5.1147 mm
```

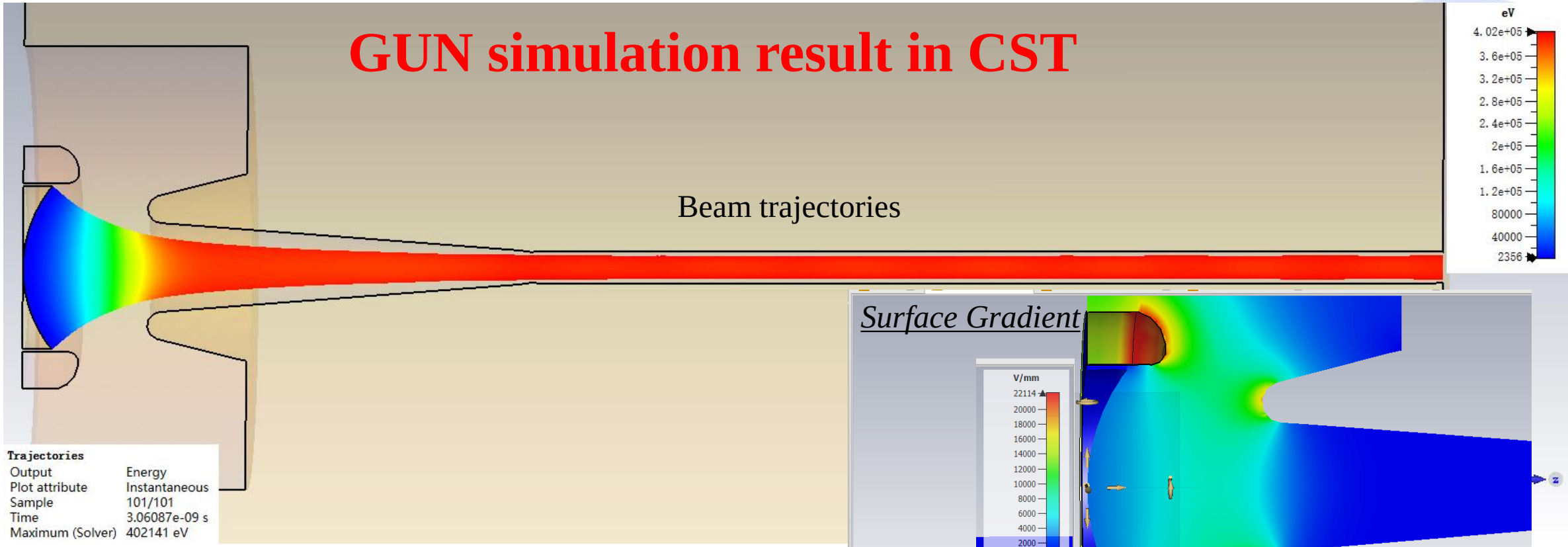
Beam Size

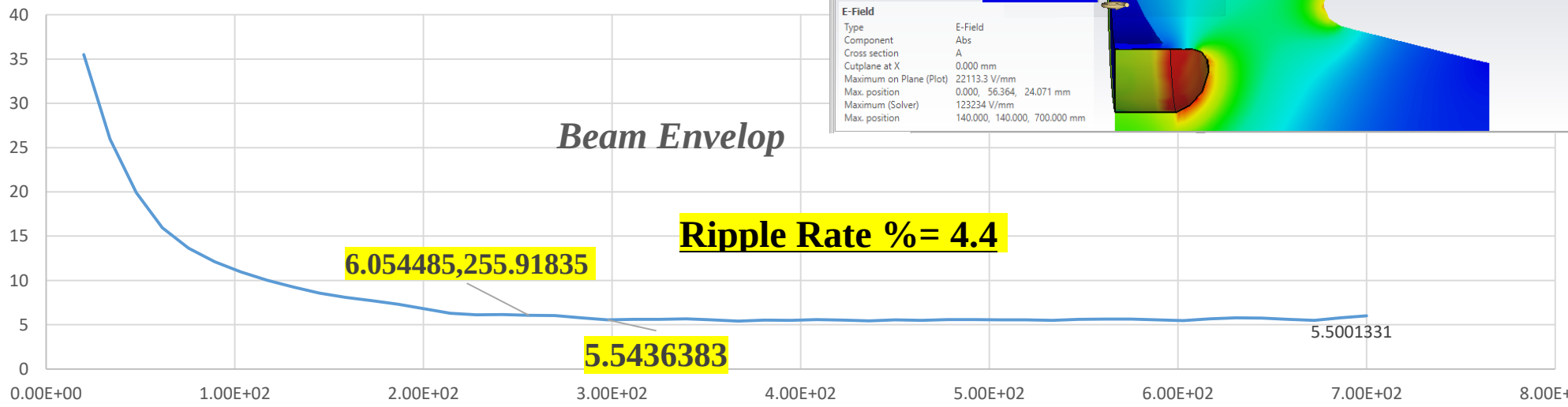


Cathode Loading

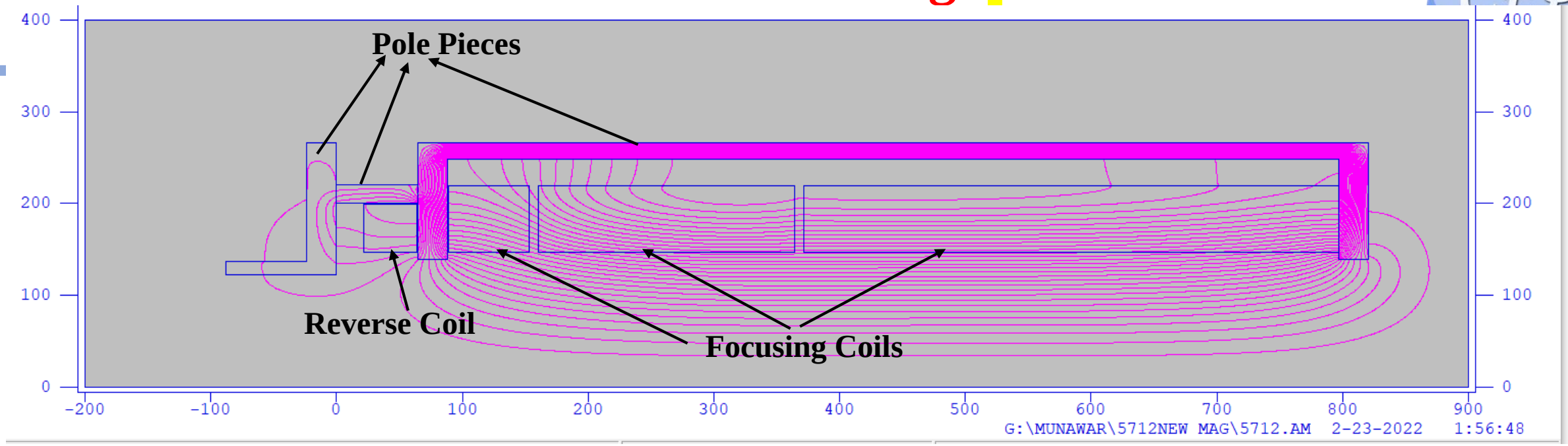


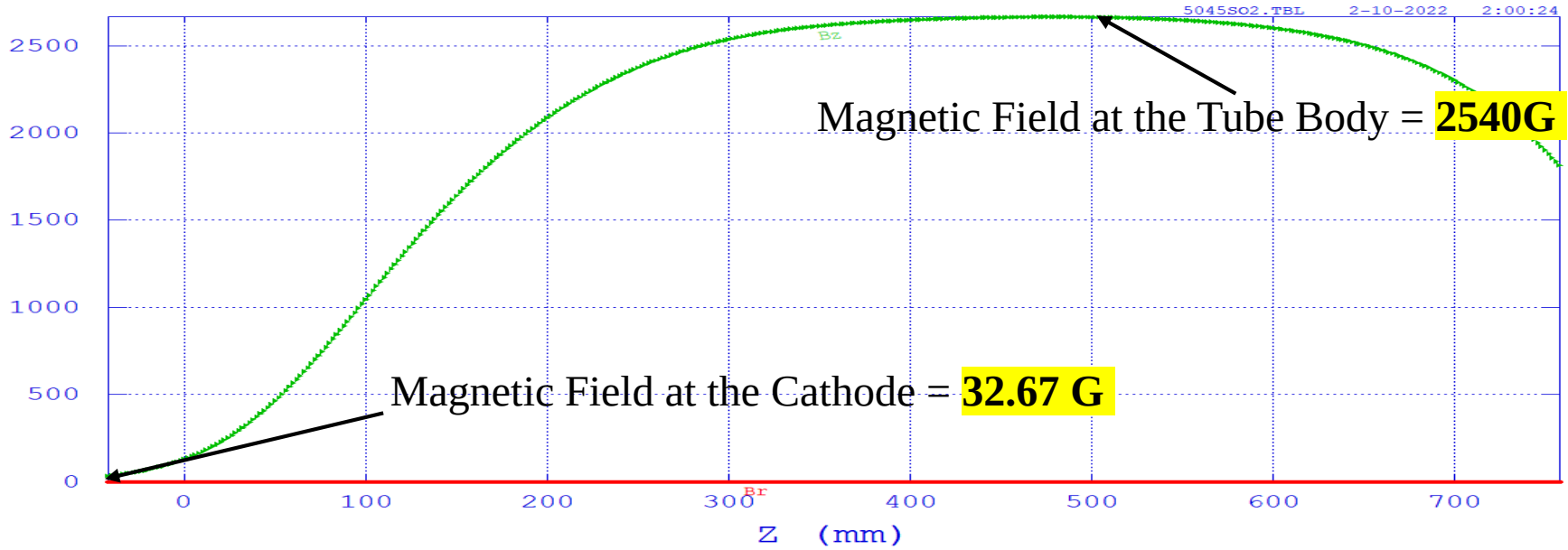
GUN simulation result in CST



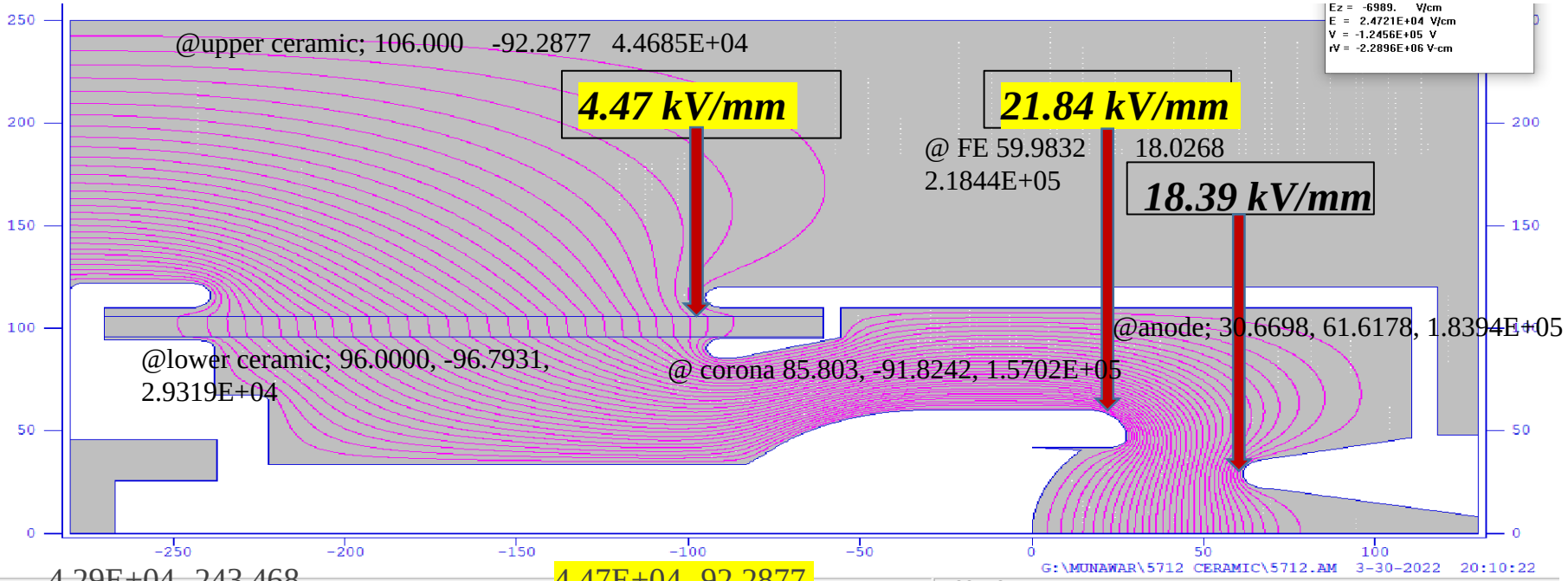


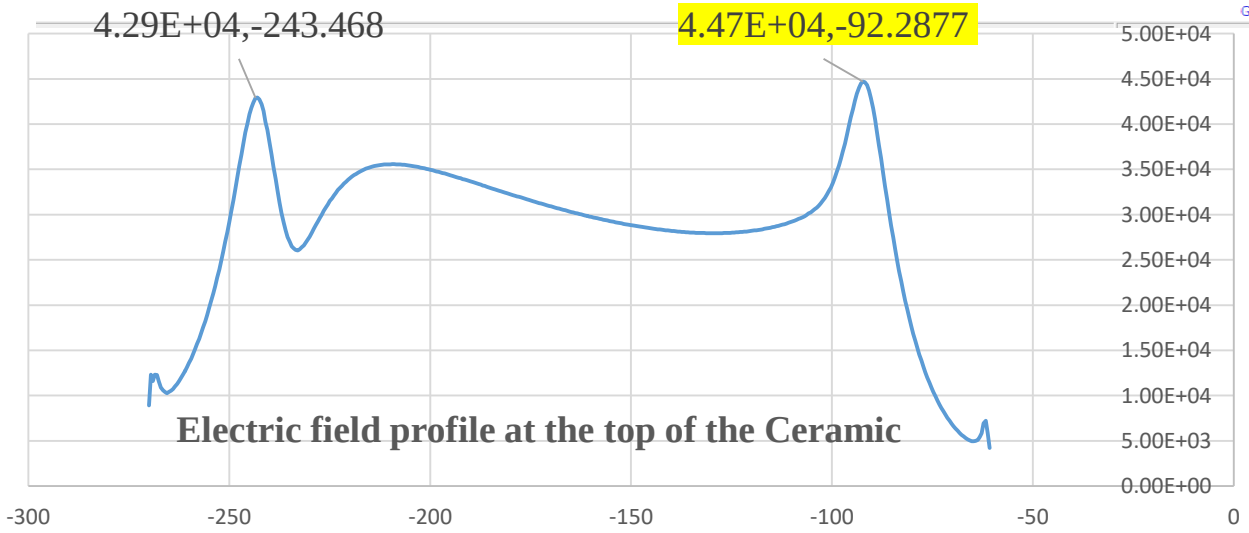
Solenoid Design

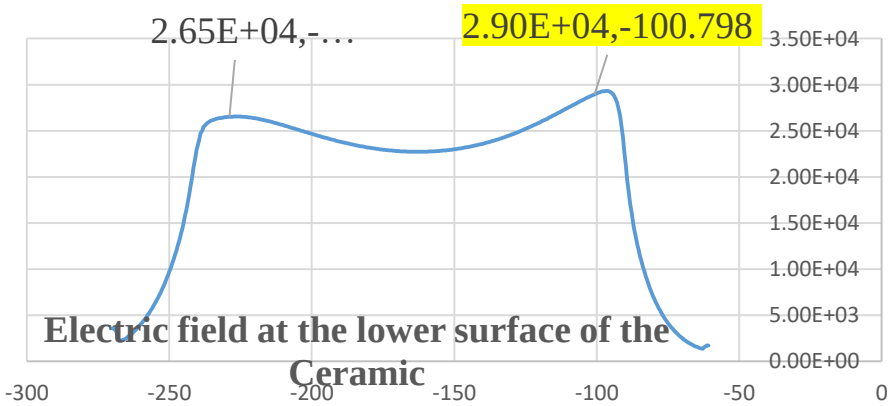




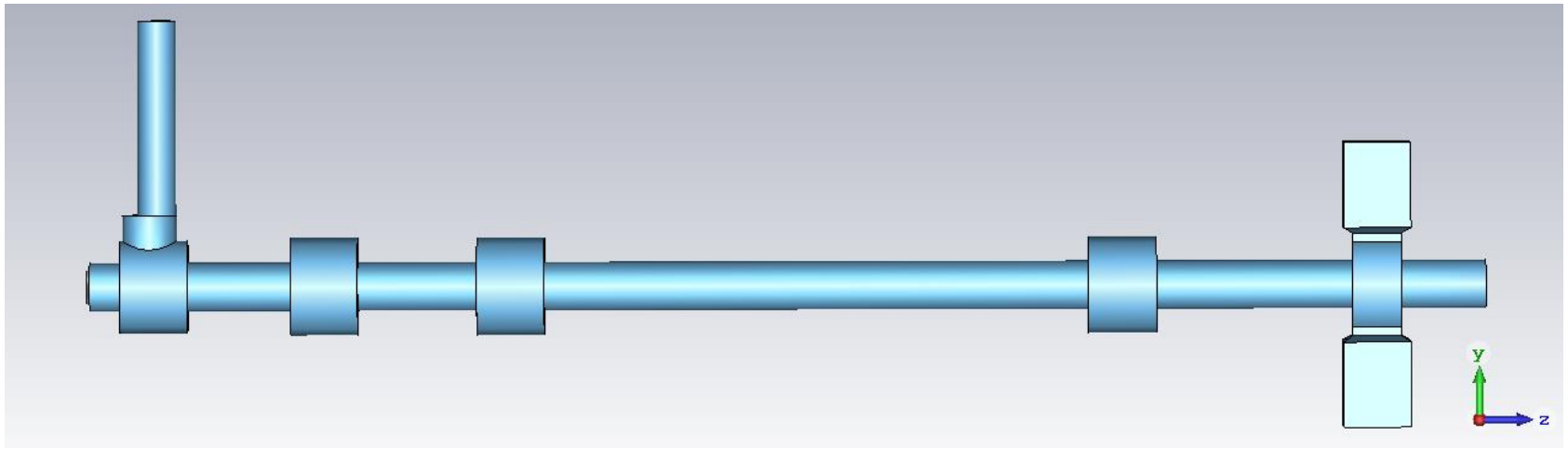
Surface gradient at beam optic & ceramic





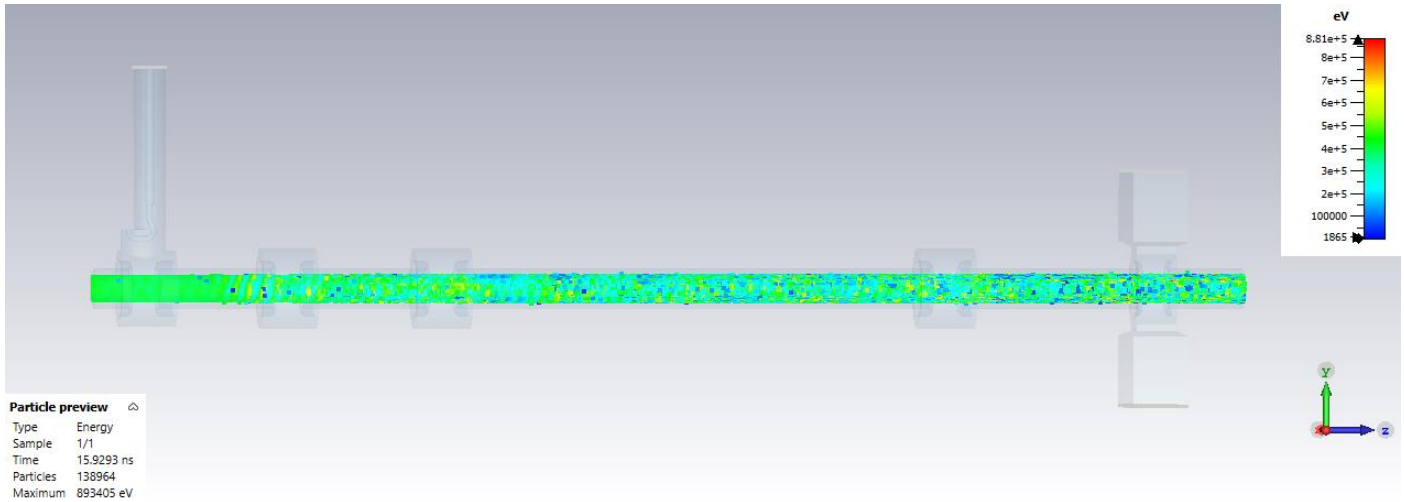


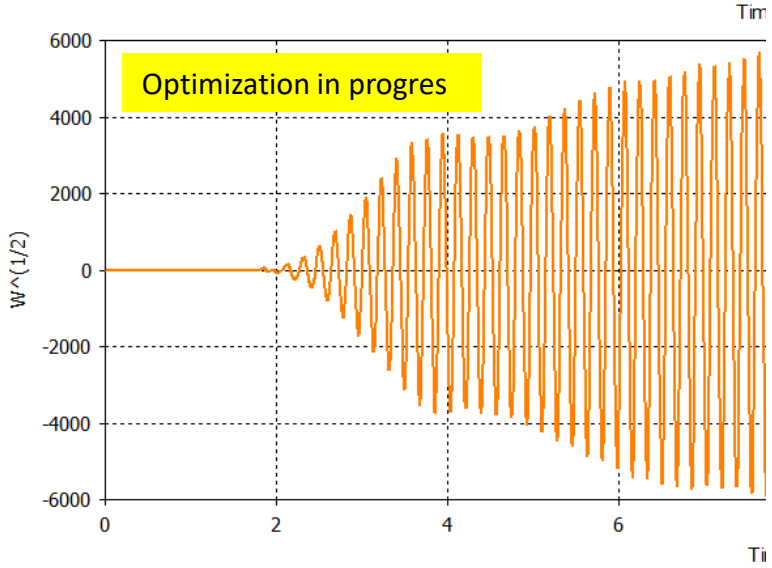
Beam dynamic simulation of C band klystron

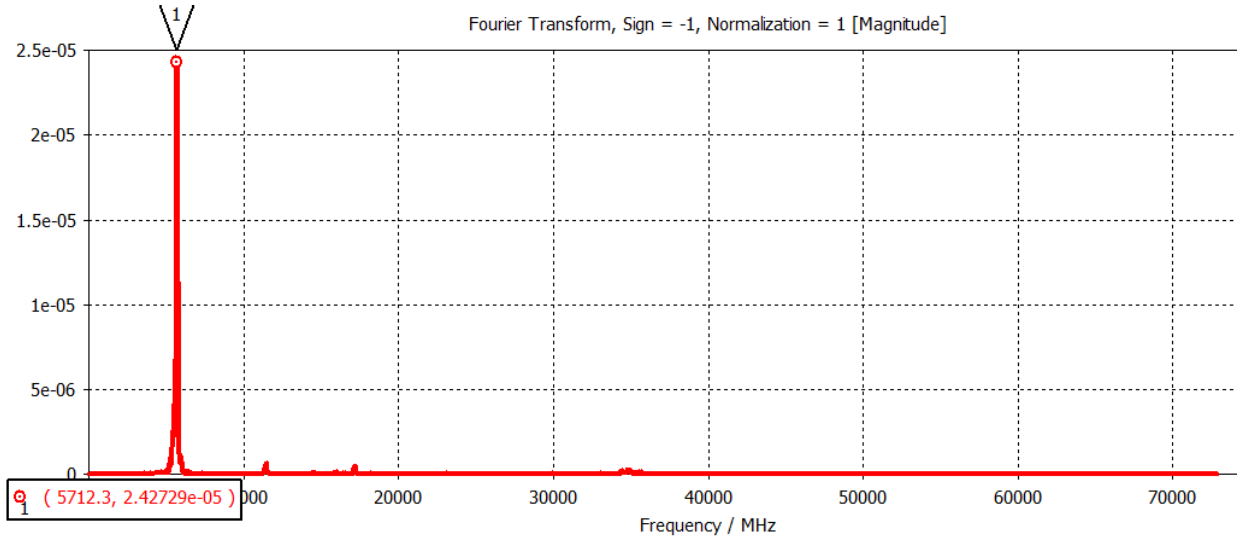


Parameters	Value
Frequency	5720 MHz
Output Power	80MW
Efficiency	45%
Beam voltage	420 kV
Beam current	403 A
Beam number	1

Beam dynamic simulation of C band klystron







S Band klystron parameters

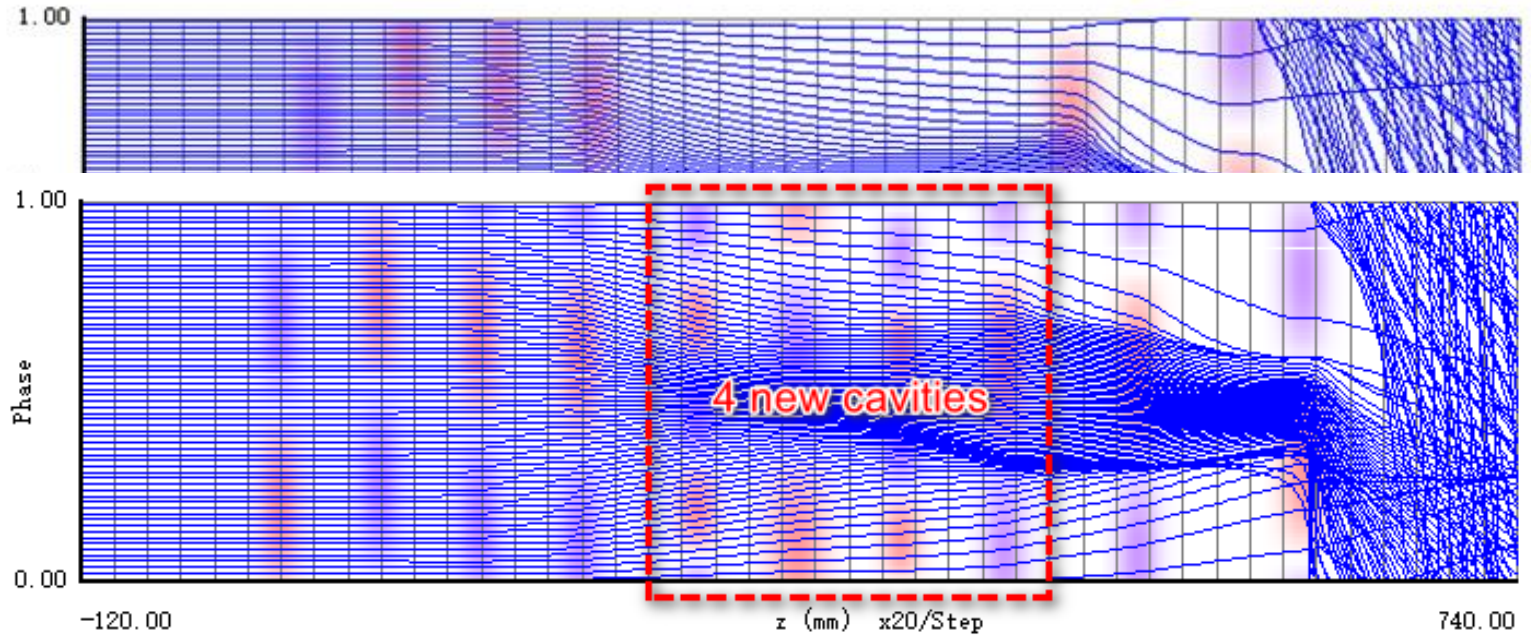
The RF power source system of CEPC LINAC includes 33 sets of pulsed klystron operating at a frequency of 2860MHz. The power of these klystron are excepted to be 80MW.

Parameters	Value
Operating frequency	2860MHz
Output power	80MW
RF pulsed width	4μS
Beam voltage	350kV
Beam current	414A
Beam μperveance	2.0
Efficiency	55%

Efficiency improvement

① The 1-D code AJDISK is suitable for the preliminary optimization of the interaction section parameters. Based on AJDISK, a 1-D automatic optimization code via NSGA-II was developed at IHEP.

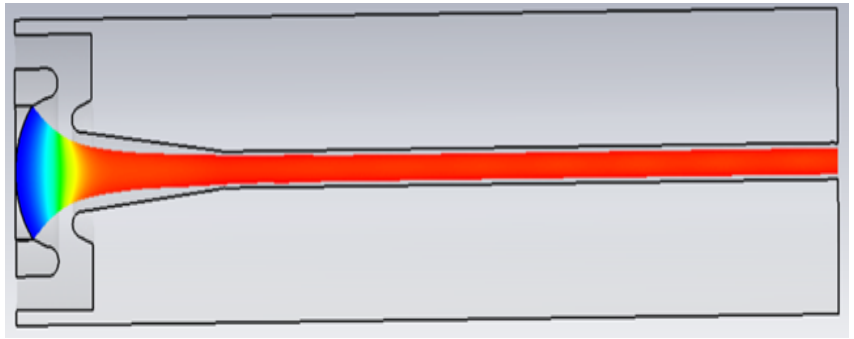
② The 1-D efficiency is about 64%.

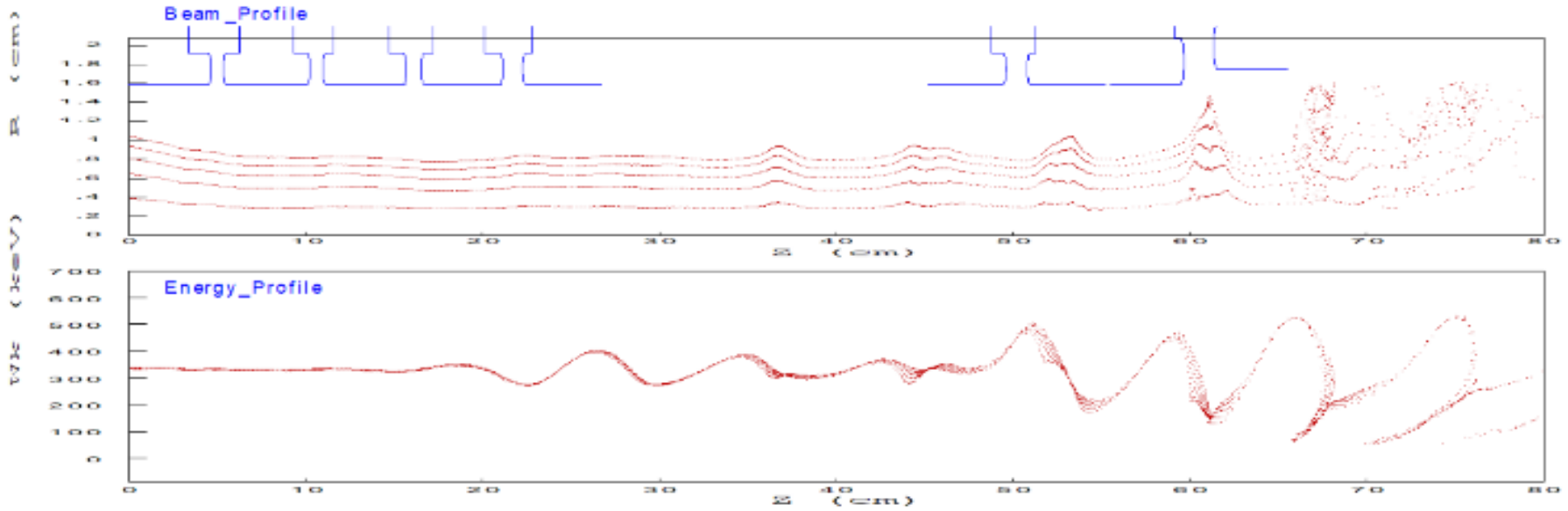


Efficiency improvement

③ The parameters obtained from AJDISK was checked by 2-D code EMSYS and 3D code CST.

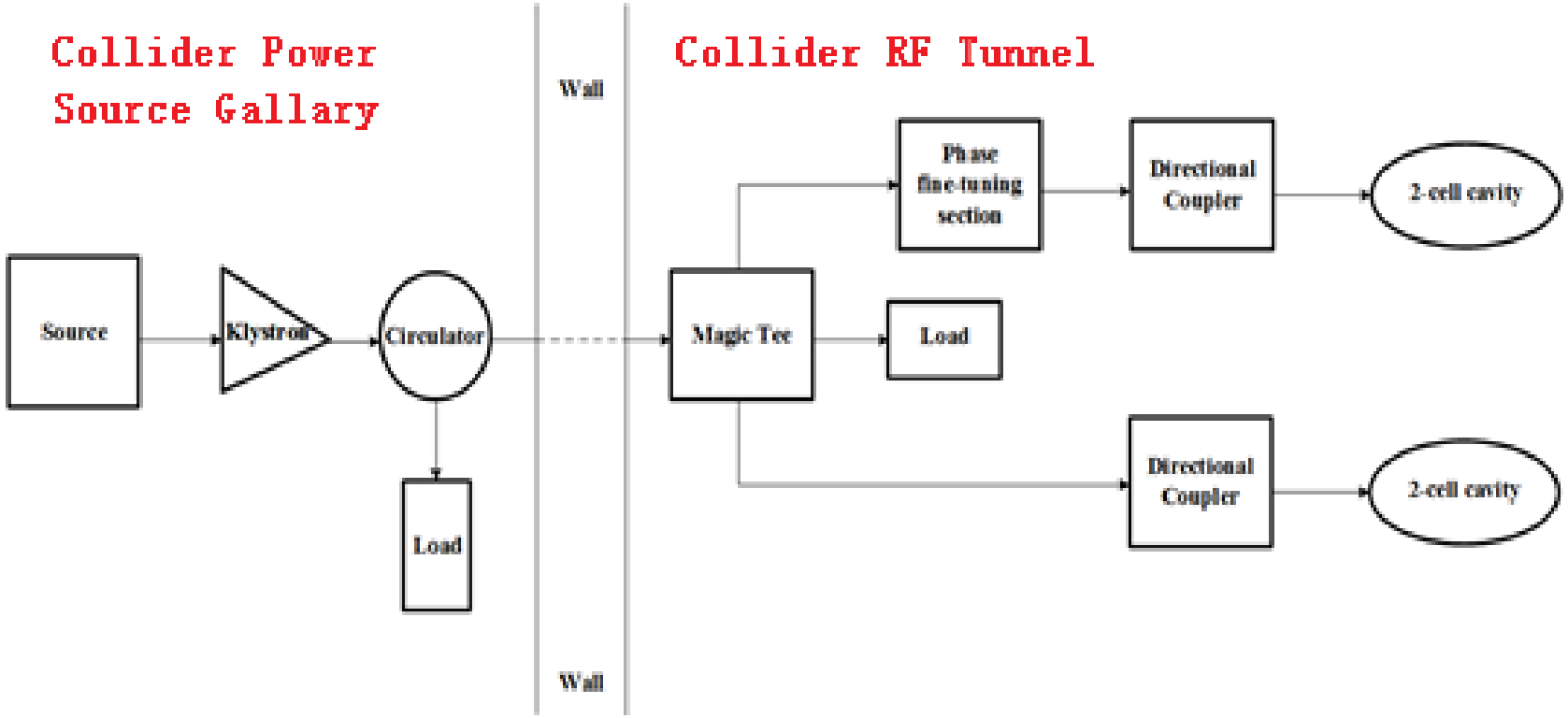
Parameters	DGUN	CST
Beam μperveance	1.978	1.997
Beam maximum radius	8.54mm	8.64mm
Beam minimum radius	7.93mm	8.02mm
Beam ripple	3.7%	3.6%





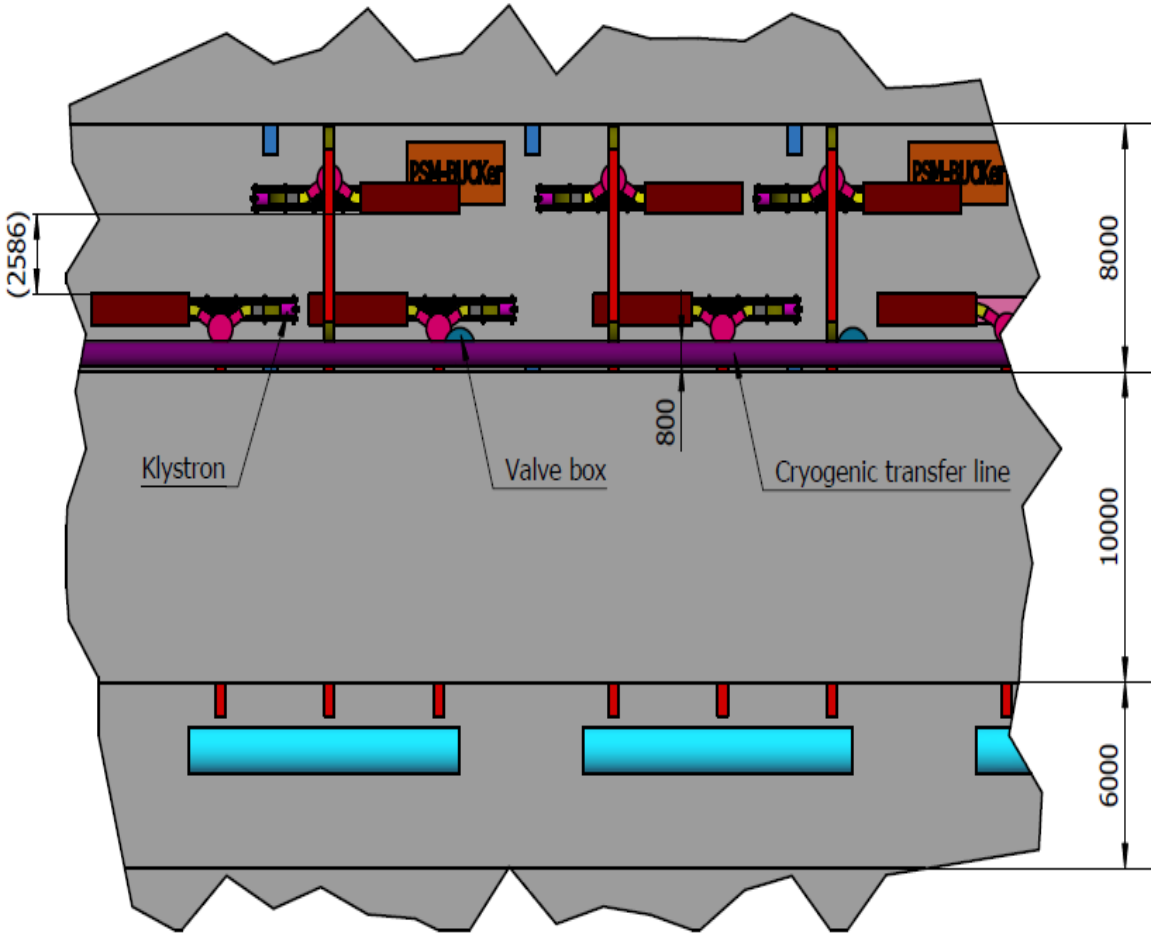
RF power sources

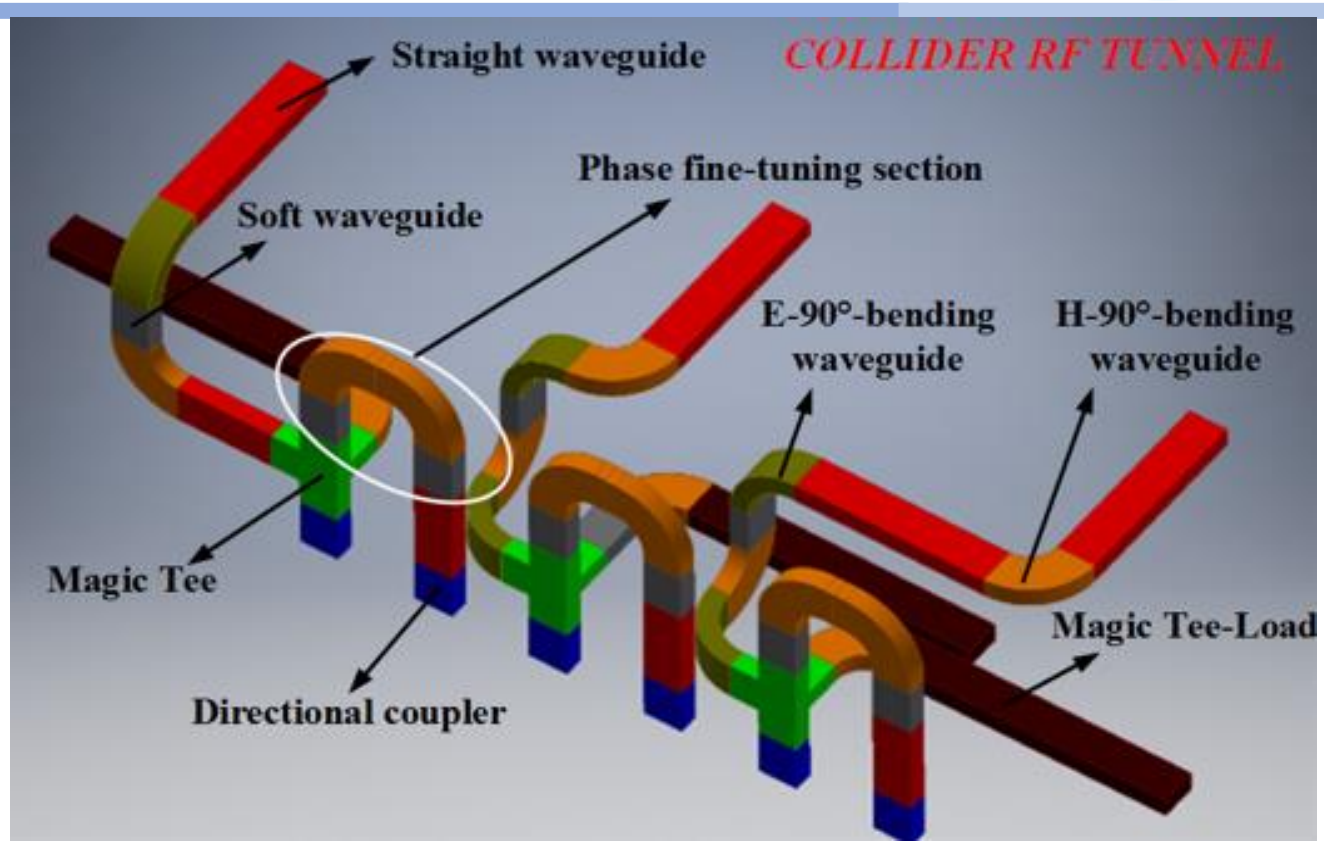
Collider transmission system



Collider infrastructure

Collider Power Source Gallery





High voltage power supply are placed on the ground.

For space savings, transmission system in part are placed in RF tunnel.

Booster RF power source

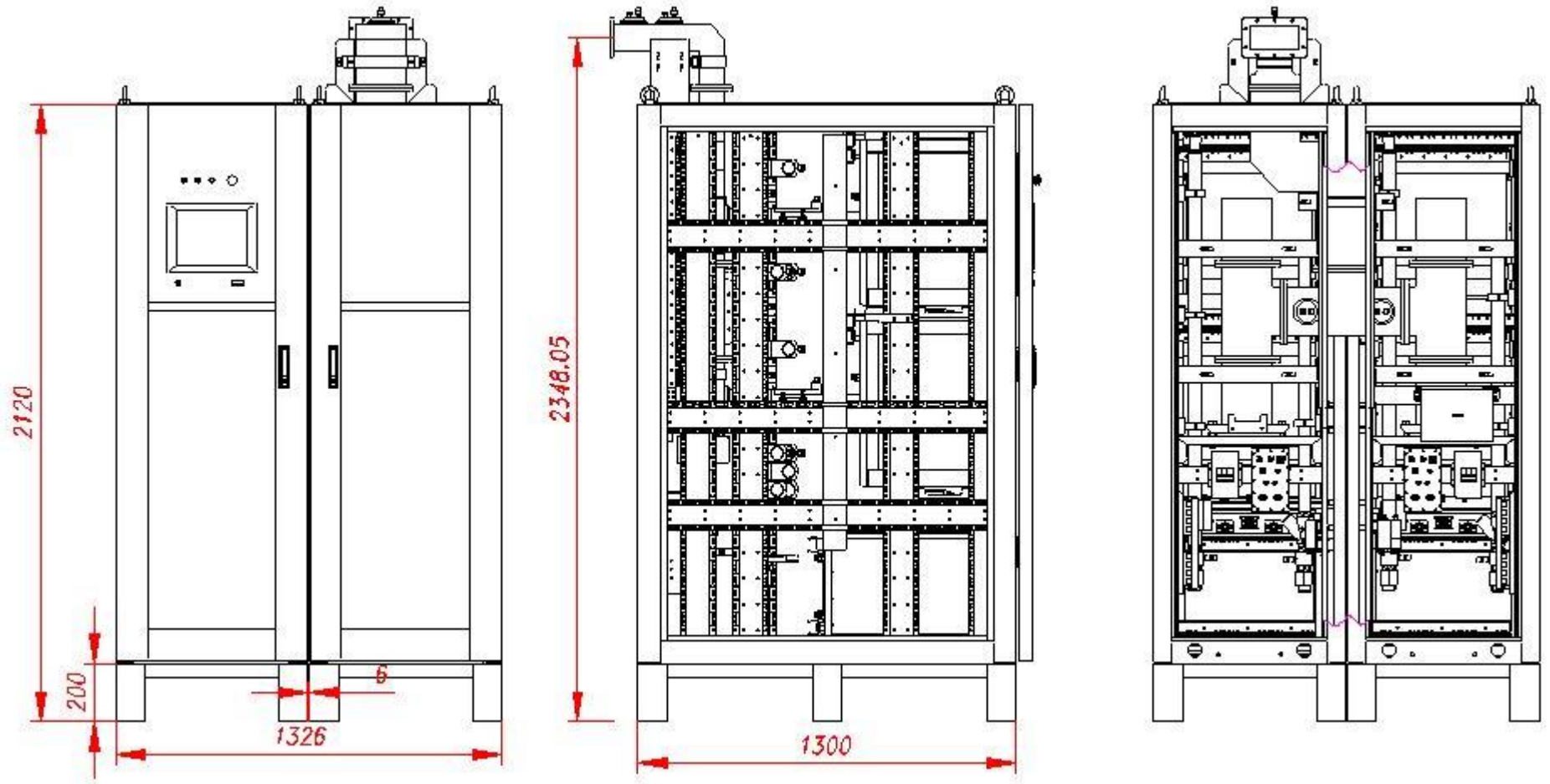
Design consideration

- The Booster RF system consists of 1.3 GHz superconducting RF cavities. There are 12 cryo-modules for Higgs operation, each containing eight 9-cell superconducting cavities.
- These cavities need 96 set 25kW power sources.
- SSA, their capabilities extend from a few kW to several hundred kW, reasonable efficiency (~50%), high gain, and modular design provide high reliability.
- So the SSA has been chosen for the Booster RF power source system.

1.3 GHz/25kW SSA Specifications

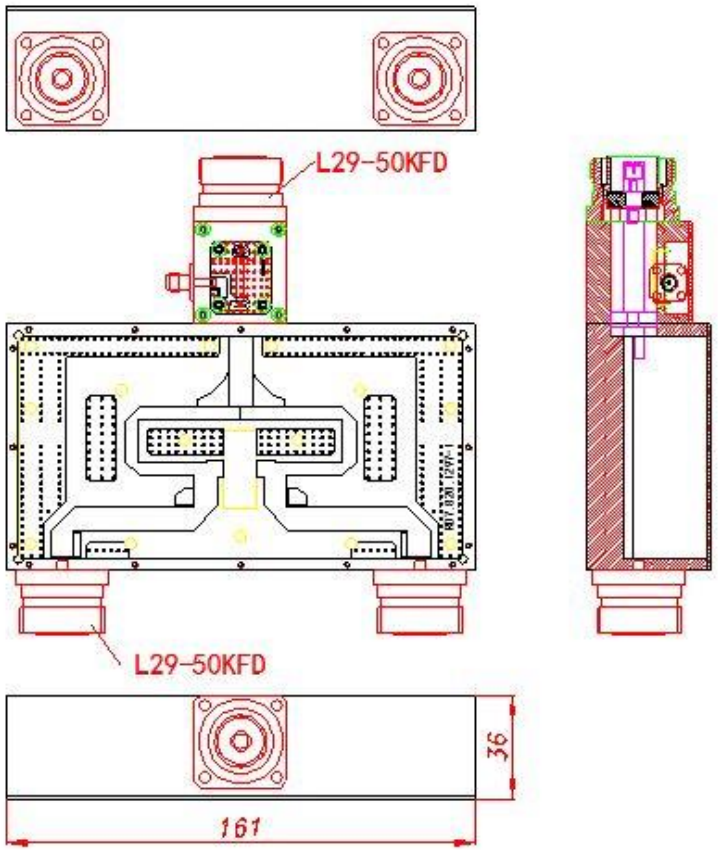
Parameters	**Values**
Frequency	1.3 GHz
Power	25 kW
Gain	≥65 dB
Bandwidth (1dB)	≥ 1 MHz
Amplitude stability	≤0.1% RMS
Phase stability	≤0.1° RMS
Phase Variation	≤10°
Harmonic	< -30 dBc
Spurious	< -60 dBc
Efficiency at 25kW	≥45%
MTBF	≥30000 h
Redundancy	1 power module failure

Booster SSA cabinet

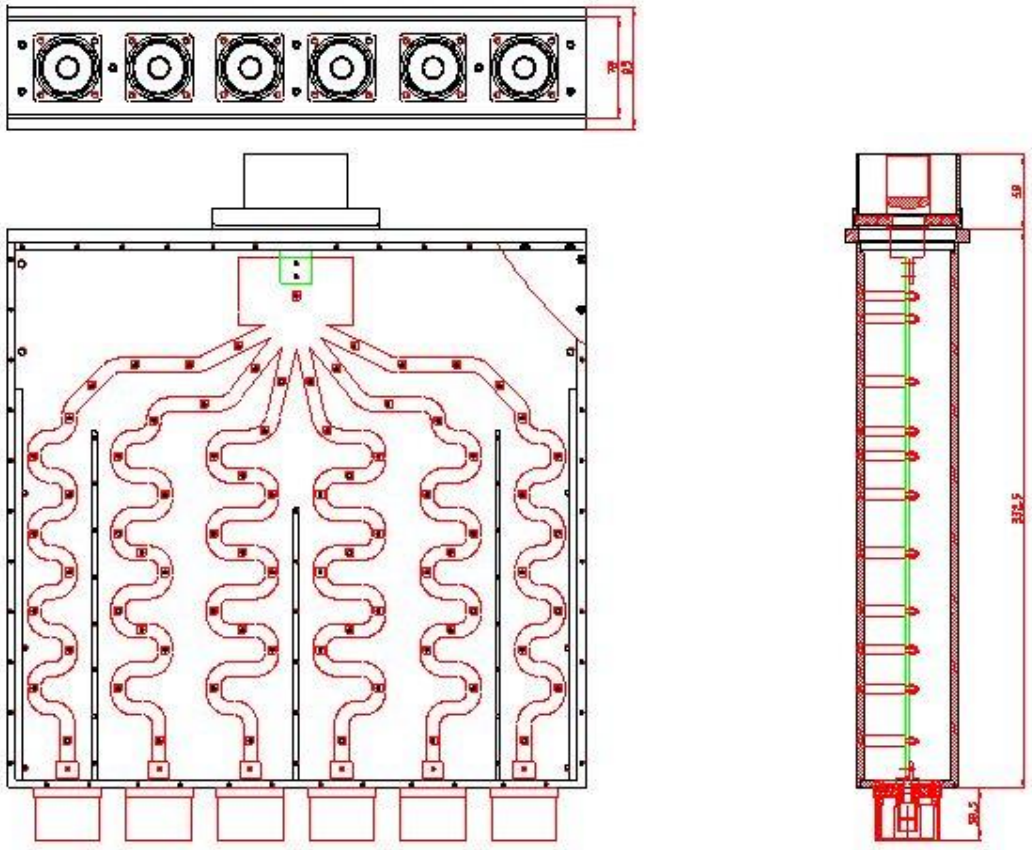


2120mm (H) ×1326mm (W) ×1300mm (L)

Booster SSA parts

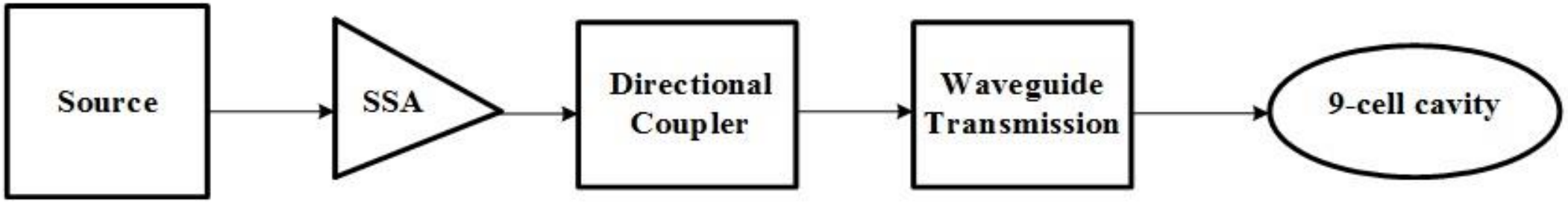


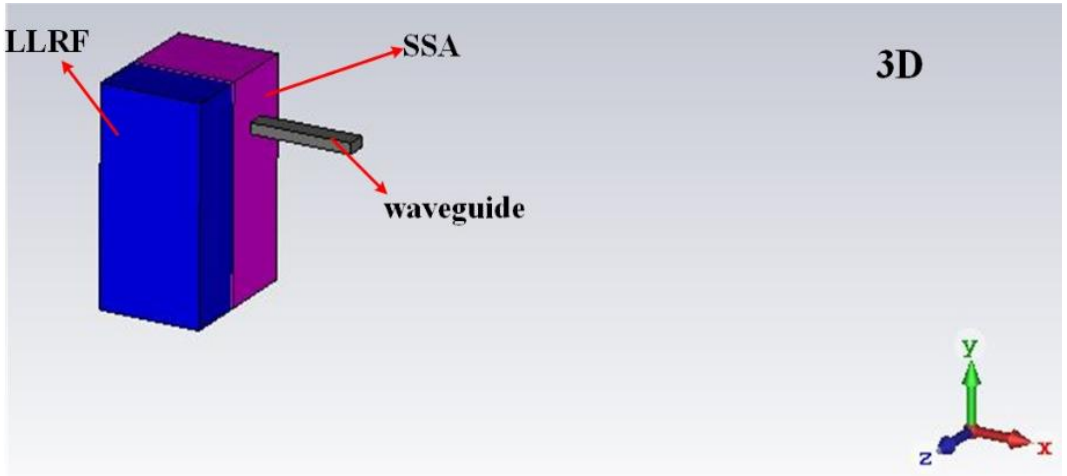
1:2 power divider



6:1 power combiner

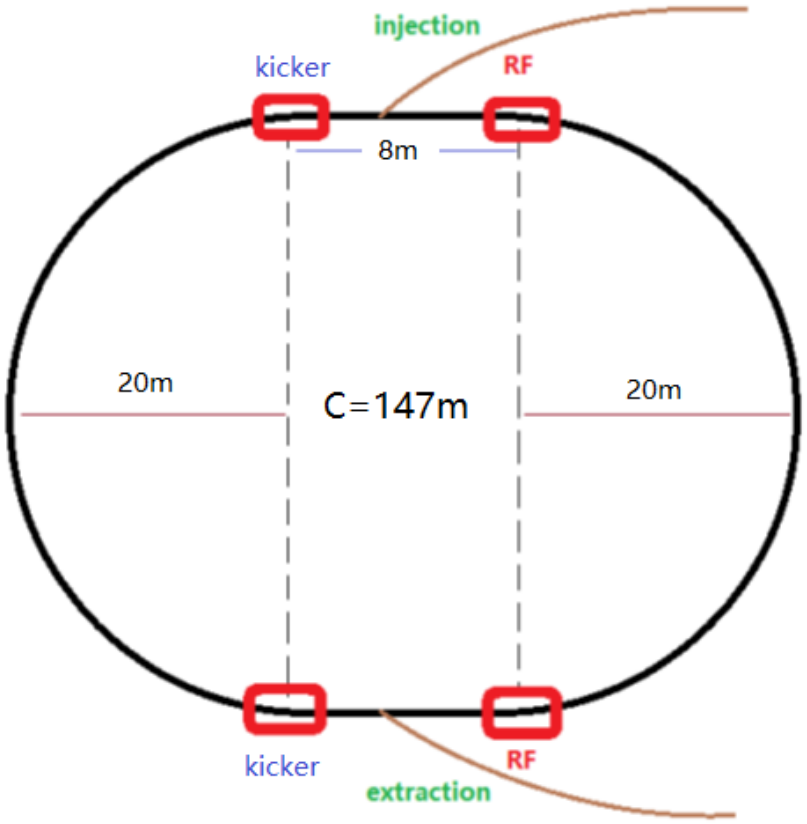
Booster RF transmission





Damping ring RF power source

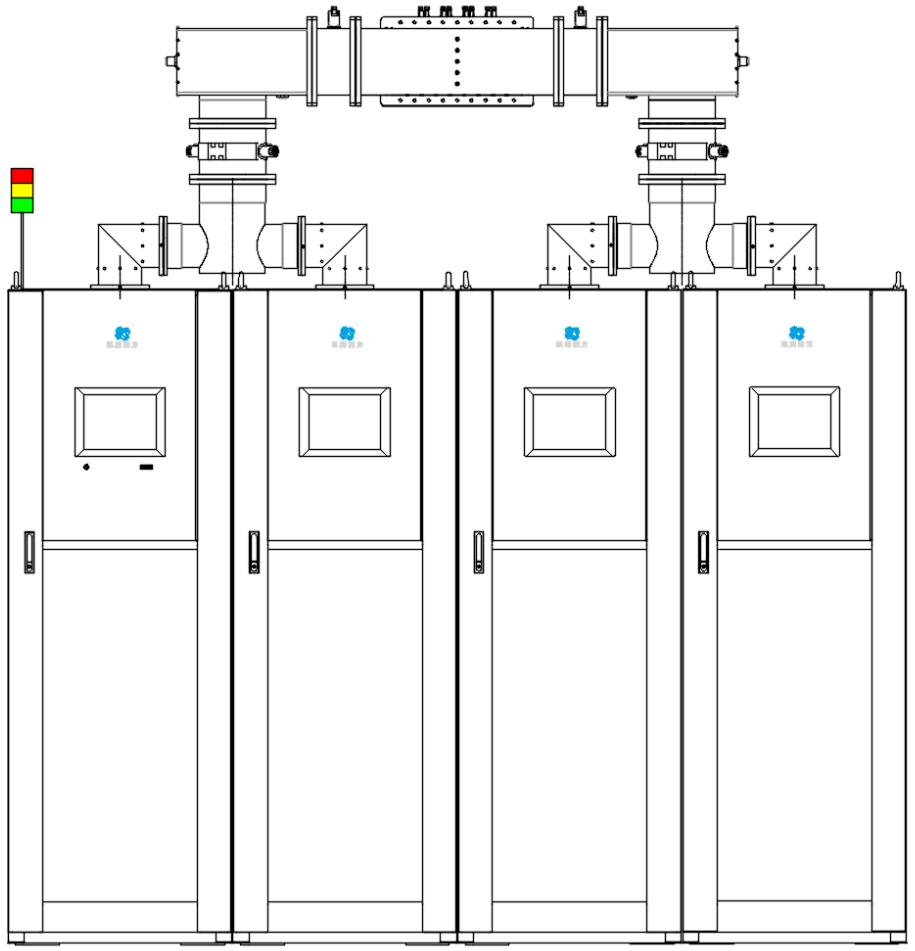
- There are 2 RF stations, RF power is 650MHz/90kW/station.

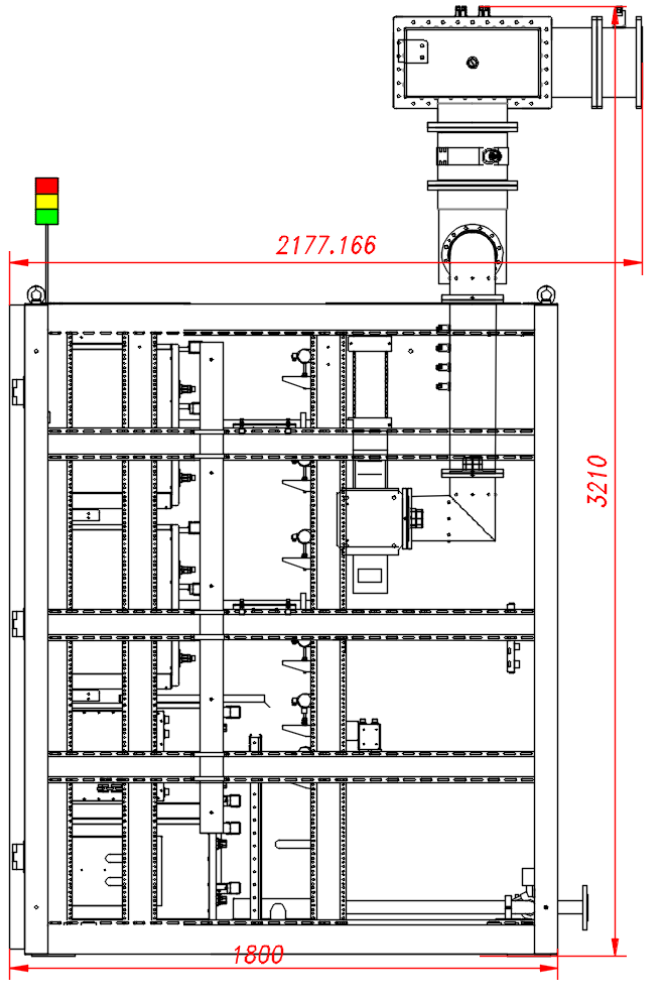


650MHz/90kW SSA Specifications

Parameters	Values
Frequency	650MHz
Power	90 kW
Gain	≥65 dB
Bandwidth (1dB)	≥ 1 MHz
Amplitude stability	≤0.1% RMS
Phase stability	≤0.1° RMS
Phase Variation	≤10°
Harmonic	< -30 dBc
Spurious	< -60 dBc

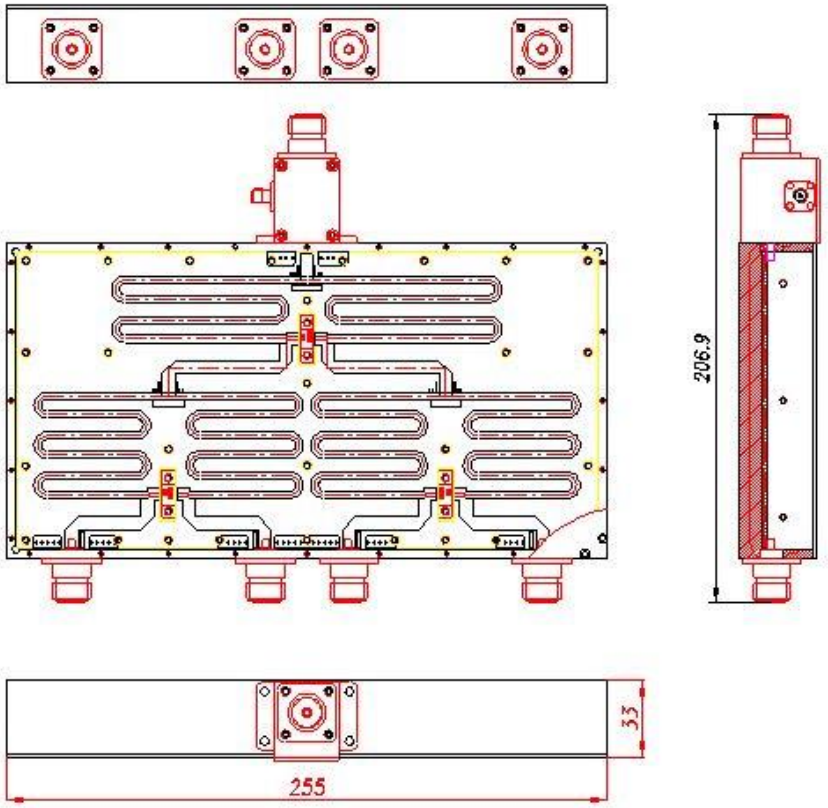
Damping ring SSA cabinet



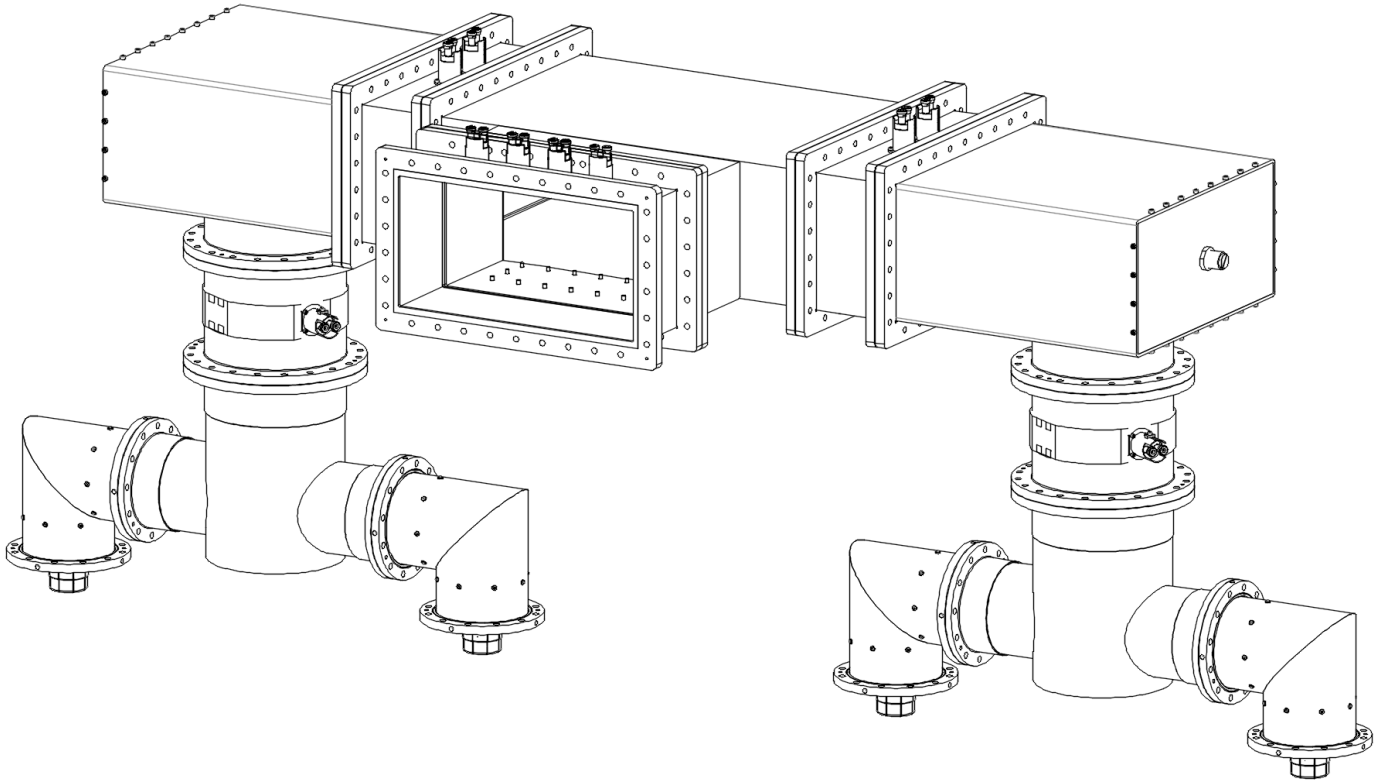


3210mm (H) ×3220mm (W) ×1800mm (L)

Damping ring SSA key components

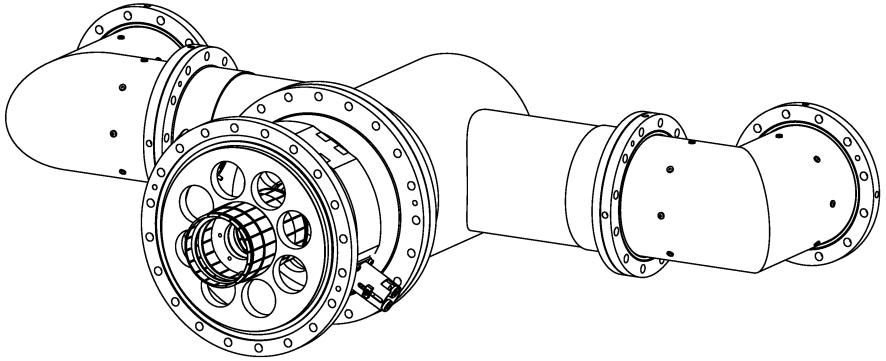


1:4 power divider

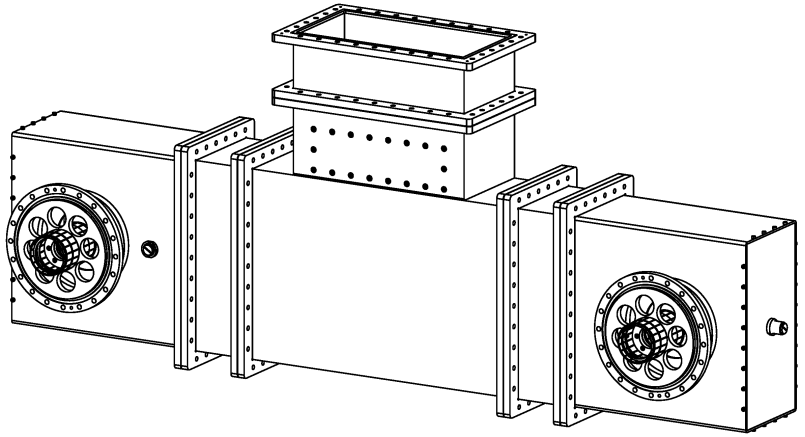


60kW 1:2 power divider

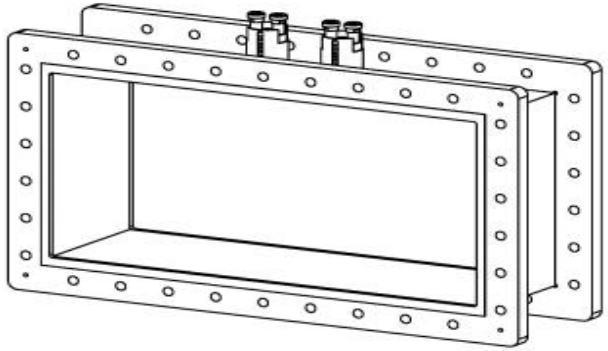
Damping ring SSA key components



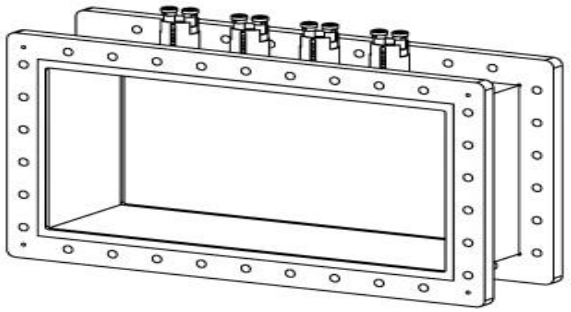
30kW 2:1 power combiner



60kW 2:1 power combiner



2 port directional coupler



4 port directional coupler

Summary

- HE klystron is being developed, efficiency of 60% and 70% has been achieved, 80% efficiency is expected to be reached by the end of this year.
- Development of S and C band 80MW klystron for CEPC Linac is also in progress.
- Design of RF power distribution system for collider, booster, damping ring and Linac is showed.
- SSA mechanical design for booster and damping ring is also showed.

Thanks for your attention!