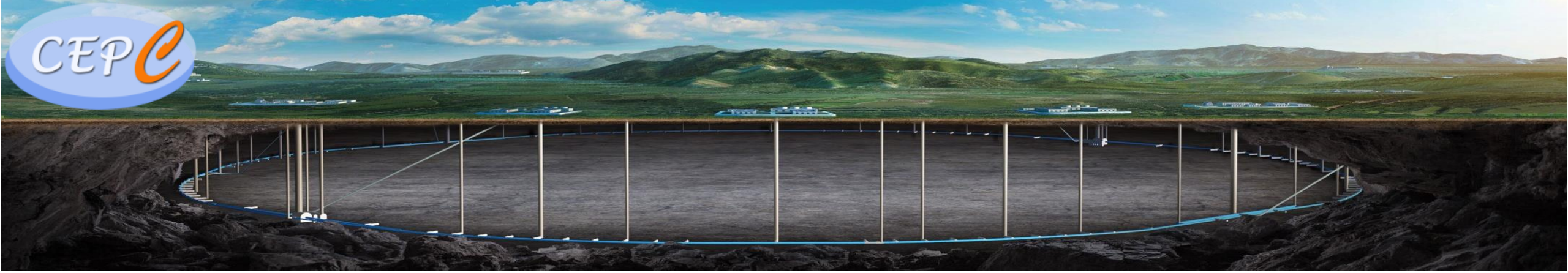

CEPC RF Power Source and Distribution System Development in EDR

Zusheng Zhou

On behalf of CEPC klystron R&D team

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

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  - Design consideration
  - R&D Status
    - 650MHz/800kW klystron
    - 5720MHz/80MW
    - Energy recovery klystron
    - PPM klystron
- RF power distribution system
  - Collider ring
  - Booster ring
  - Linac injector/Damping ring

Design consideration for Collider RF sources

- Considering klystron lifetime, power redundancy and cost, the 2 cavities will be powered with one CW klystron capable to deliver more than 800 kW.
- High voltage DC power supply for high power and high efficiency klystron.
- Distributions of RF power to the cavities, including waveguide, power divider, phase shifter, circulator and load.
- Other Auxiliary PS, interlock and controls, LLRF, pre-amplifier are also included in RF power source system.

Design consideration for Collider RF sources

- Requirement list:

Klystron	96	650MHz/700kW
PSM Power Supply	96	130kV/16A
Circulator	96	650MHz/700kW
Load	96	650MHz/700kW
Phase shift	96	650MHz/700kW
Waveguide	96	Power divider/directional coupler
LLRF	96	Phase stabilization <0.1 degree, Amplitude stabilization <0.1%
Pre-amplifier	96	650MHz/200W

Design consideration for Collider RF sources

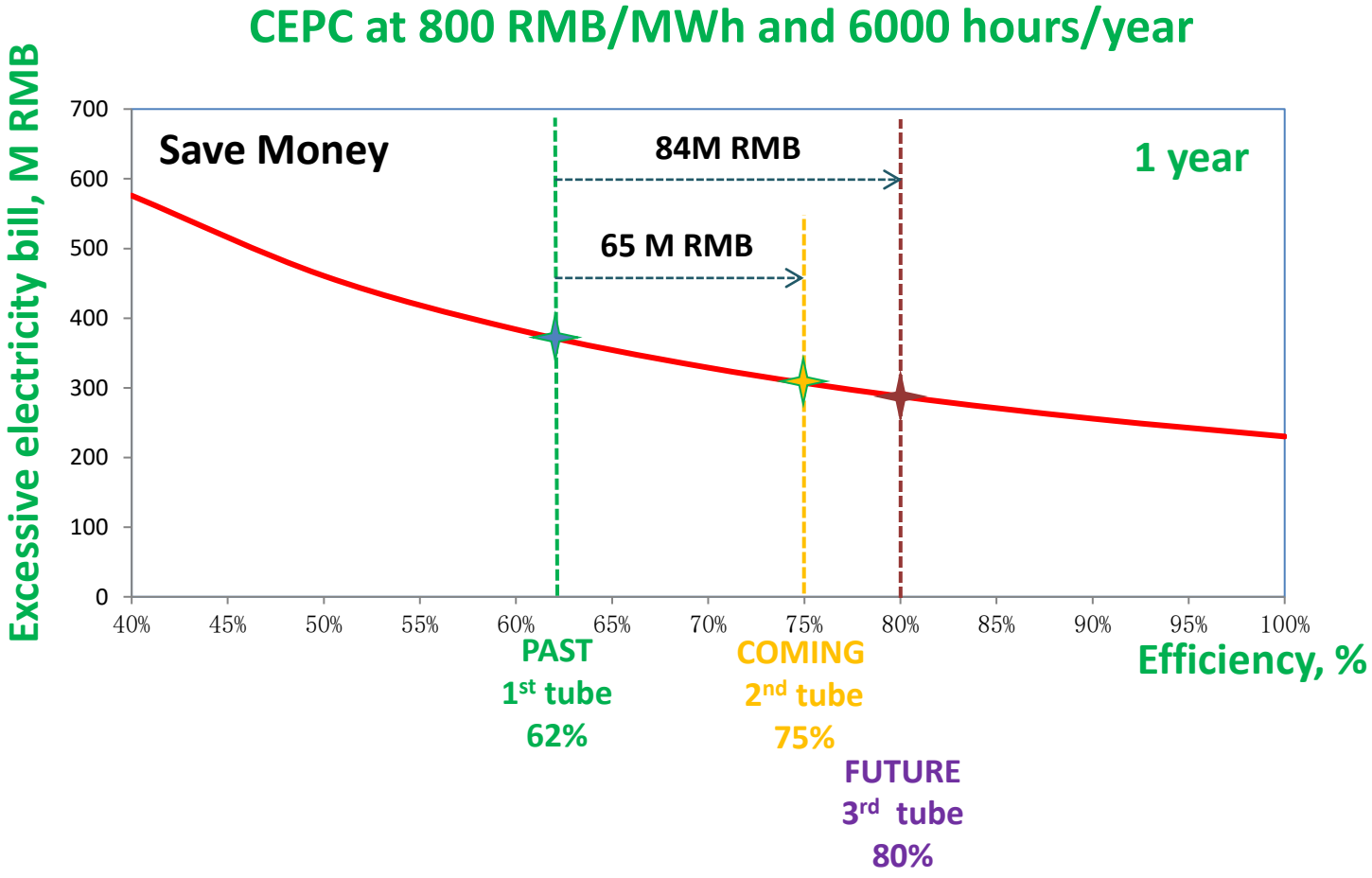
- Requirement list:

Klystron	96	650MHz/700kW	Higher efficiency
PSM Power Supply	96	130kV/16A	Mature product
Circulator	96	650MHz/700kW	Mature product
Load	96	650MHz/700kW	Mature product
Phase shift	96	650MHz/700kW	Mature product
Waveguide	96	Power divider/directional coupler	Mature product
LLRF	96	Phase stabilization <0.1 degree, Amplitude stabilization <0.1%	Mature product
Pre-amplifier	96	650MHz/200W	Mature product

Design consideration for Collider RF sources

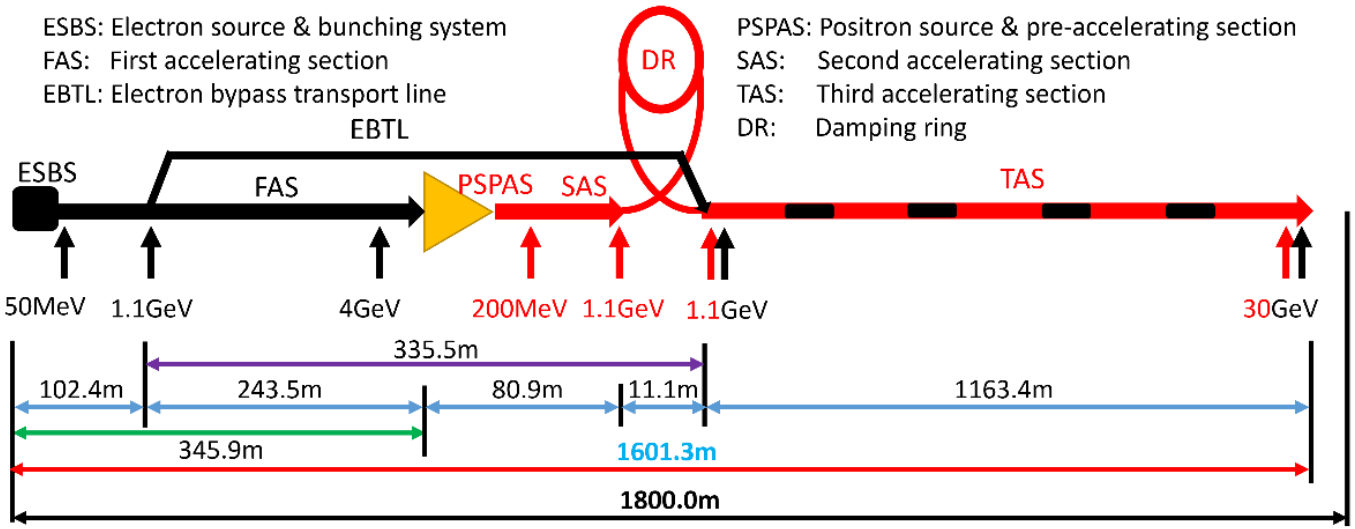
- Cost consumption

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



Design consideration for Linac RF sources

- The main high power RF sources components are 33 units of 80MW S-band klystron, 236 units of 50MW C-band klystron and related modulators.



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.

Design consideration for Linac RF sources

- Requirement list:

S band klystron	33	2860MHz/80MW
Modulator of S band klystron	33	400kV/500A
C band klystron	236	5720MHz/50MW
Modulator of C band klystron	236	350kV/400A

Design consideration for Linac RF sources

- Requirement list:

S band klystron	33	2860MHz/80MW	Mature product
Modulator of S band klystron	33	400kV/500A	Mature product
C band klystron	236	5720MHz/50MW	Mature product
Modulator of C band klystron	236	350kV/400A	Mature product

Design consideration for Linac RF sources

- Why we do C band 80MW klystron?
  - Only C band of **50MW** klystron is mature product in the world.
  - 1 klystron only power to 2 accelerator structures (CEPC Linac baseline).
  - QTY of C band klystron is very large (**236 set**).

- IF output power of C band klystron is up to 80MW, the number of klystron will be reduced by half. (1 klystron power to 4 accelerator structures)

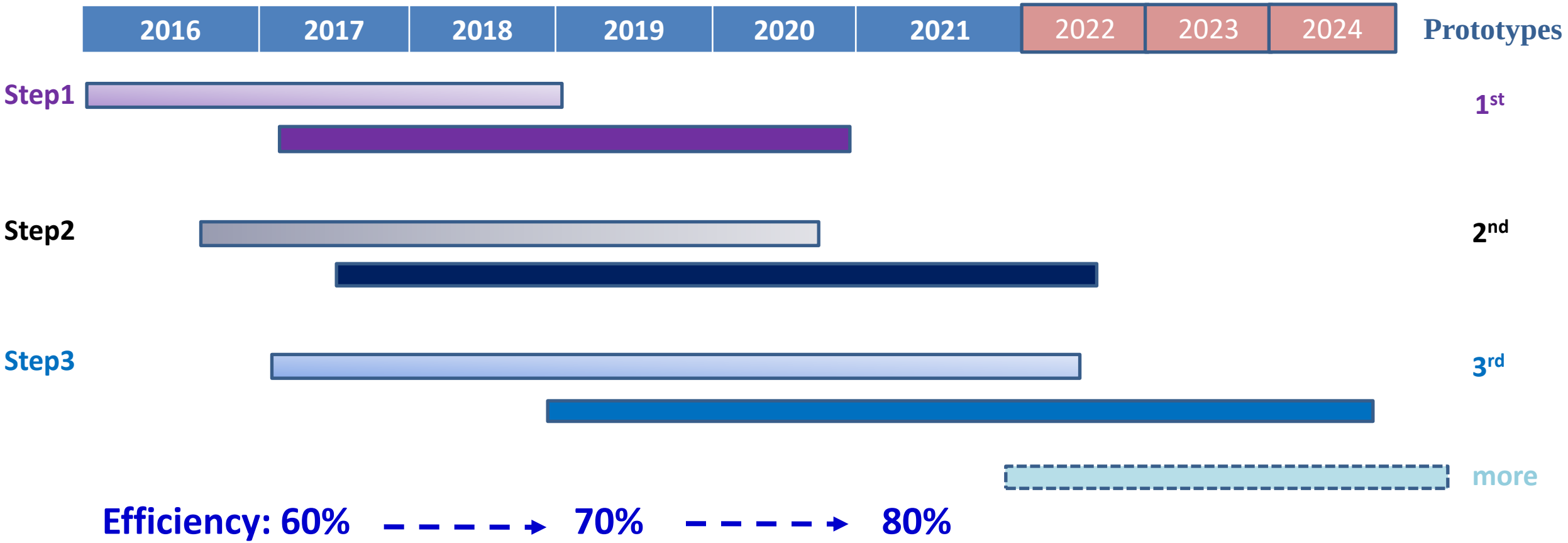
R&D Strategies

- 650MHz/800kW klystron with higher efficiency design for CEPC Collider.
- 5720MHz/80MW klystron for CEPC Linac cost reduction.
- Energy recovery klystron for much higher efficiency.
- PPM klystron for more simple auxiliary system.

R&D Status

650MHz klystron R&D strategy and plan

- 3 or more klystron prototypes for klystron efficiency improvement



Design scheme

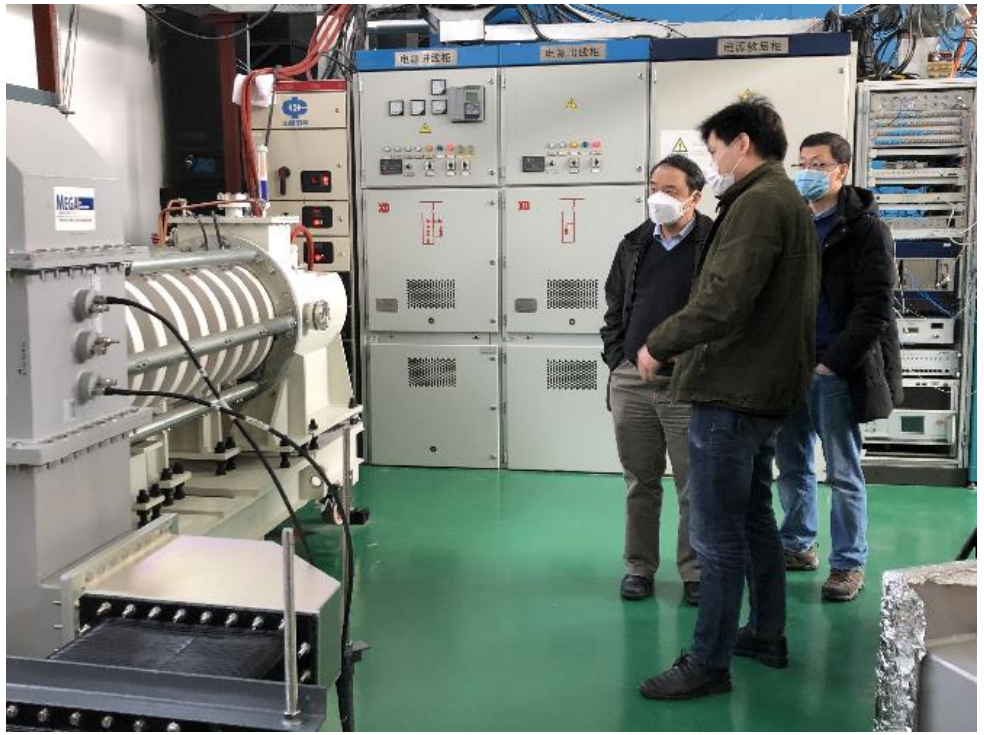
- Scheme 1: Traditional way for >60% efficiency
- Scheme 2: With high voltage gun (110 kV/9.1 A), low perveance (HE, >75%)
- Scheme 3: MBK, 54 kV/20A electron gun (8 beams) (HE, >80%)

Parameter	Scheme1(1st prototype)	Scheme2(2nd)	Scheme3(3rd)
Freq. (MHz)	650	650	650
Voltage (kV)	82	110	54
Current (A)	16	9.1	20(2.5×8)
Beam No.	1	1	8
Perveance (μP)	0.65	0.25	1.6(0.2×8)
Efficiency (%)	65	~80	>80
Power(kW)	800	800	800(100×8)

1st prototype milestone

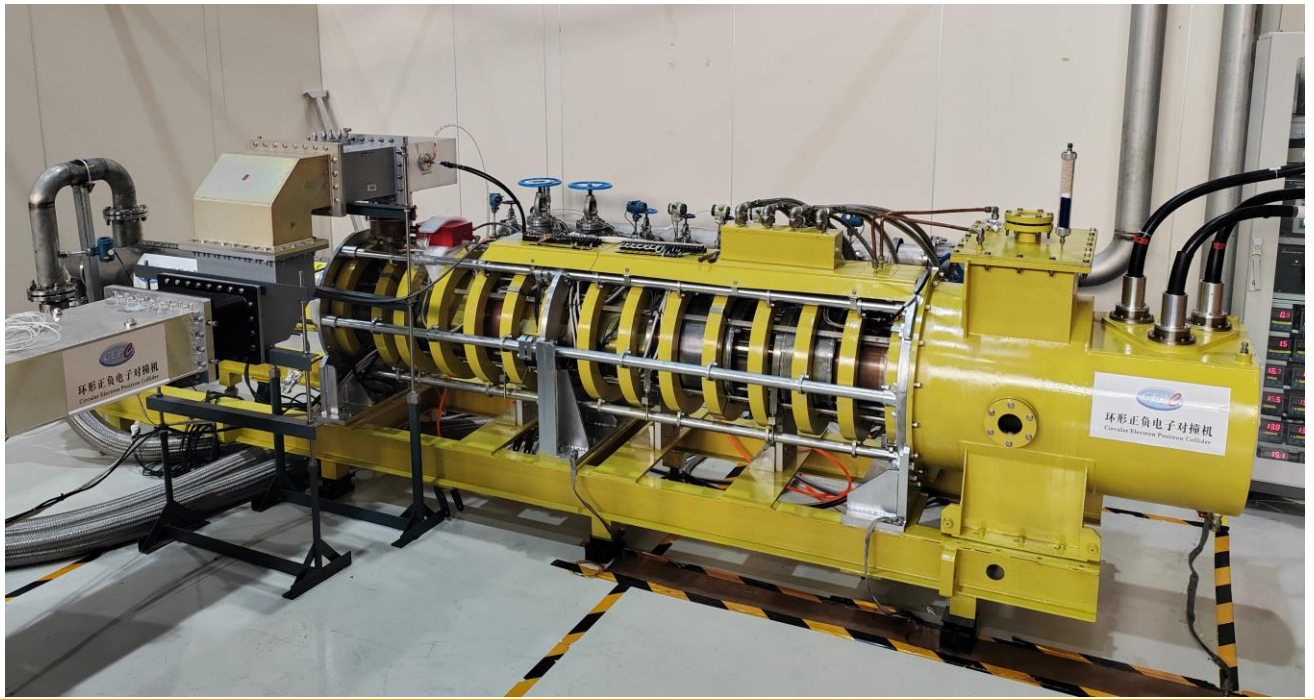
- Oct. 2017 Design report
- Mar. 2020 High power test at IHEP

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



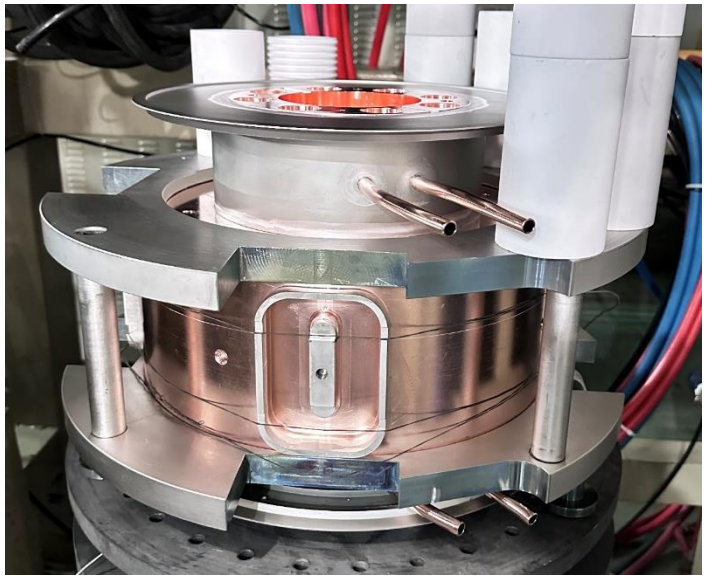
2nd prototype (HE design) milestone

- Jan., 2021: Klystron manufacture started
- Jul., 2022: CW 630kW with Eff. 70.5% (1st stage high power test)
- Jan., 2024: 2nd stage high power test startup



3rd prototype (Multi-beam design) milestone

- Dec., 2021: Klystron beam tester manufacture started
- Oct., 2023: Accomplishment of klystron beam tester high voltage conditioning and beam emission.
- Jan. 2024: Klystron manufacture is in progress.



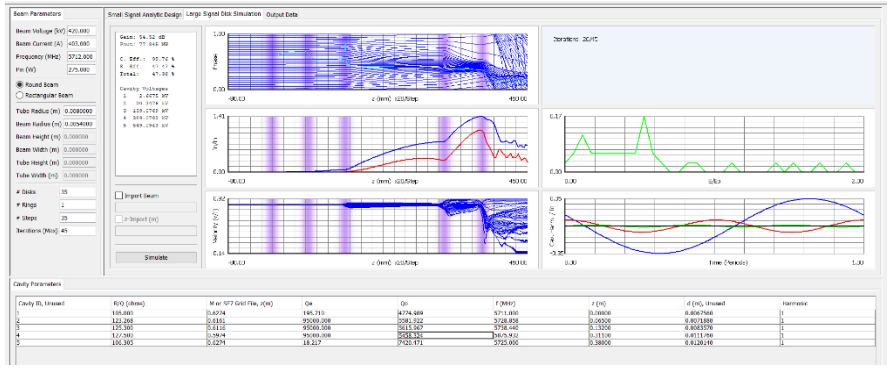
5720MHz klystron design

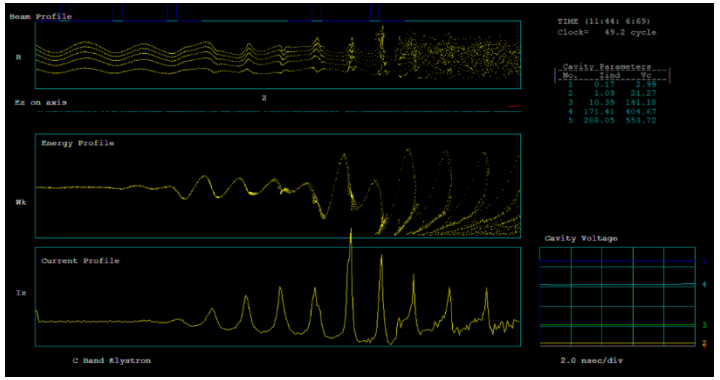
Design progress

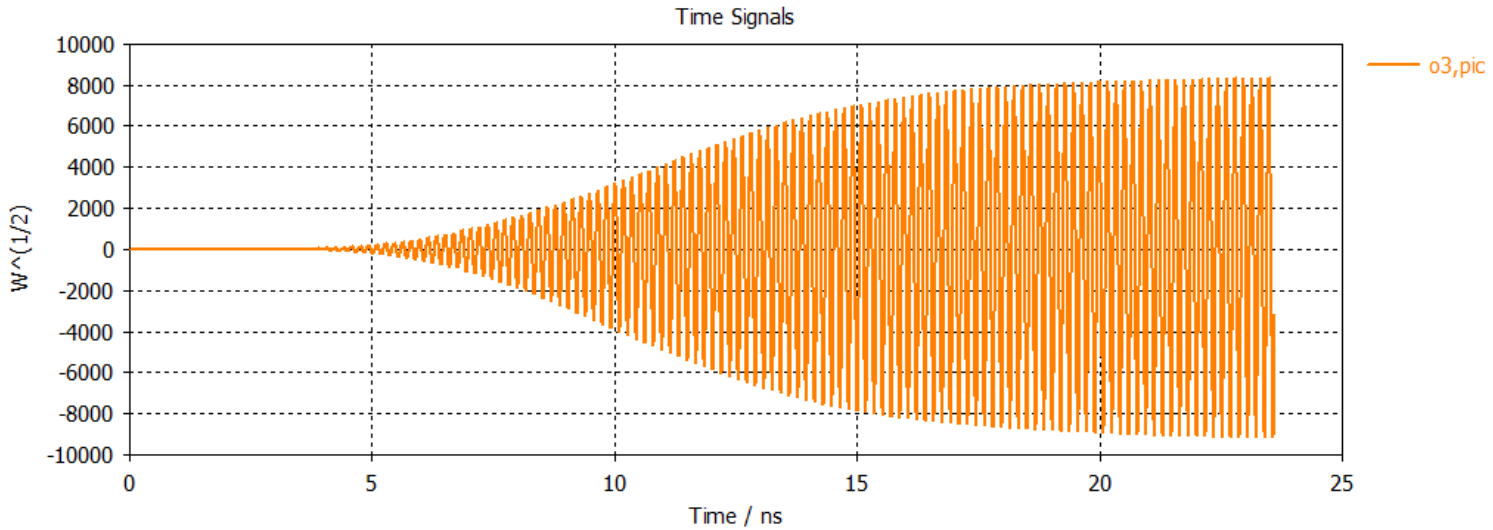
Main parameters

Parameters	Value
Frequency	5720 MHz
Output Power	80MW
Pulsed width	3us
Repetition rate	100Hz
Gain	54 dB
Efficiency	47%
$3dB$ bandwith	±5MHz
Beam voltage	420 kV
Beam current	403 A
Focusing field	0.27 T

Beam dynamics

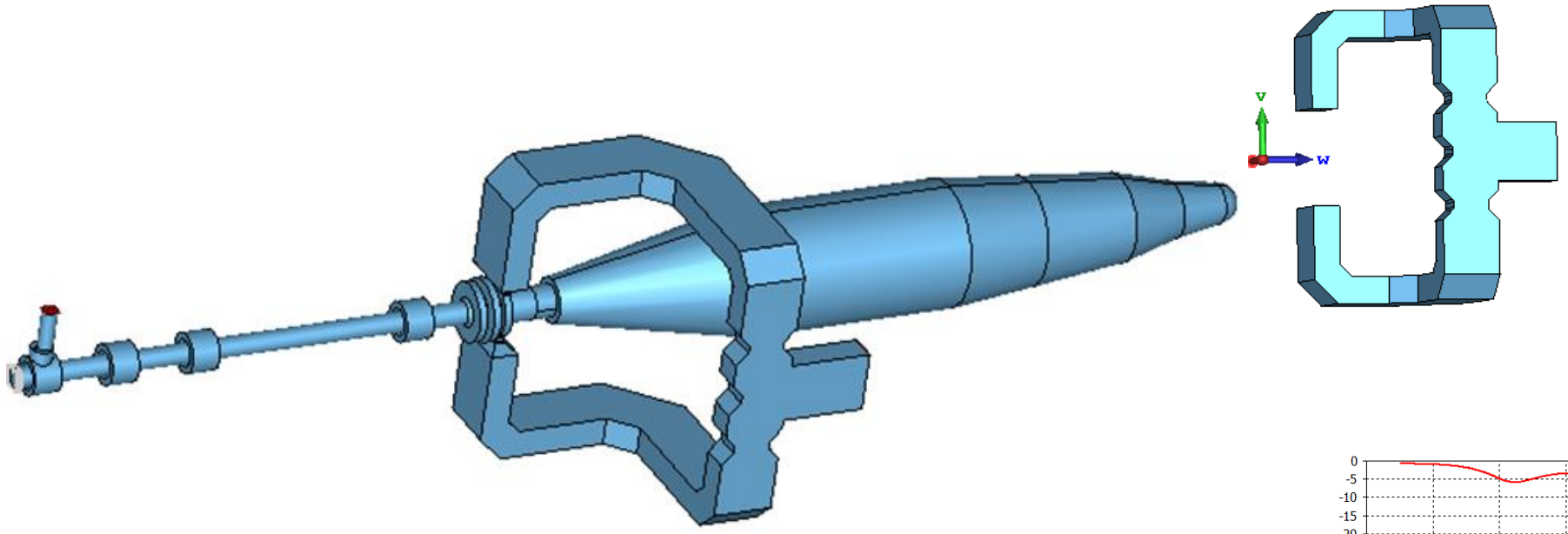




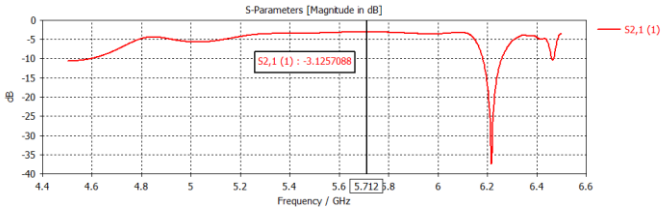


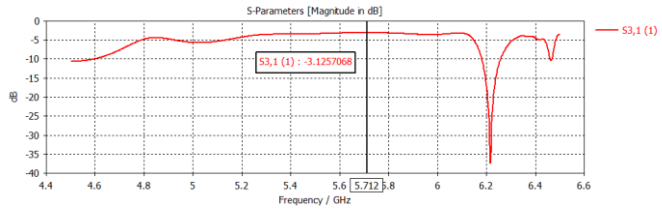
Design progress

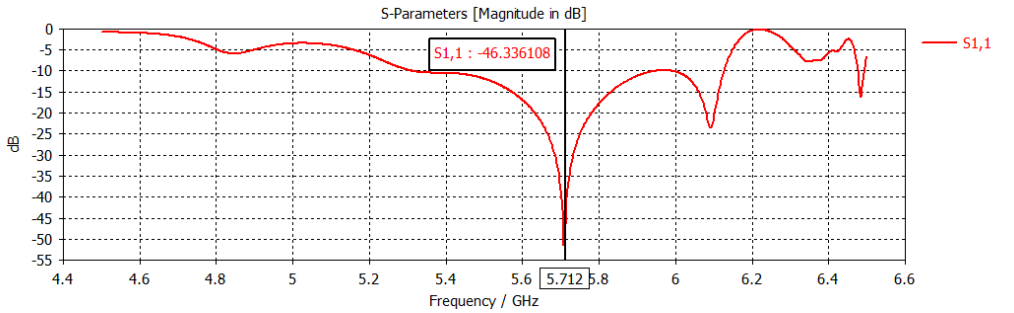
RF Power Combiner & Collector Connected with 80 MW C-band Klystron



RF Power combiner



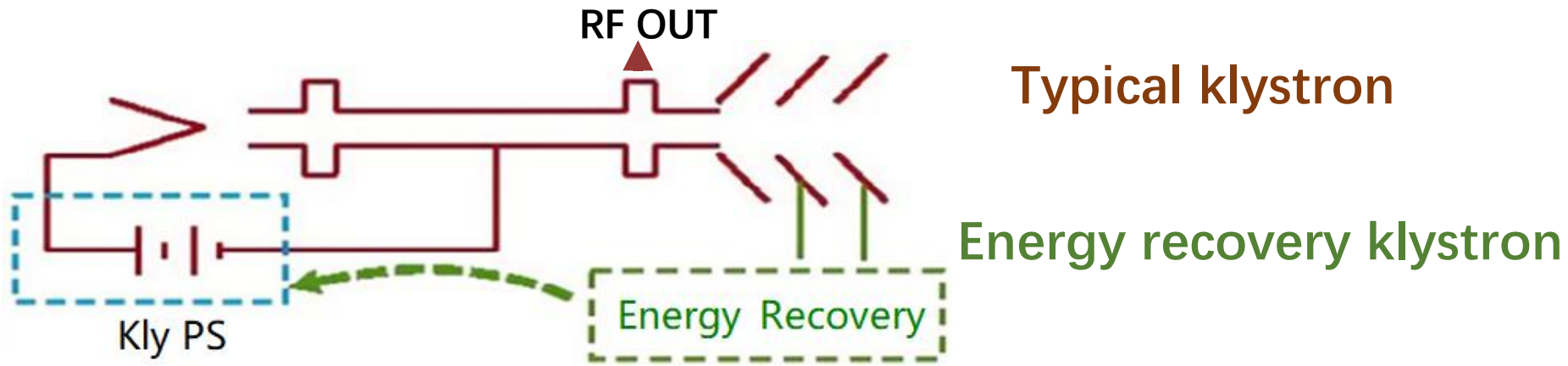




Energy recovery klystron

Energy recovery klystron

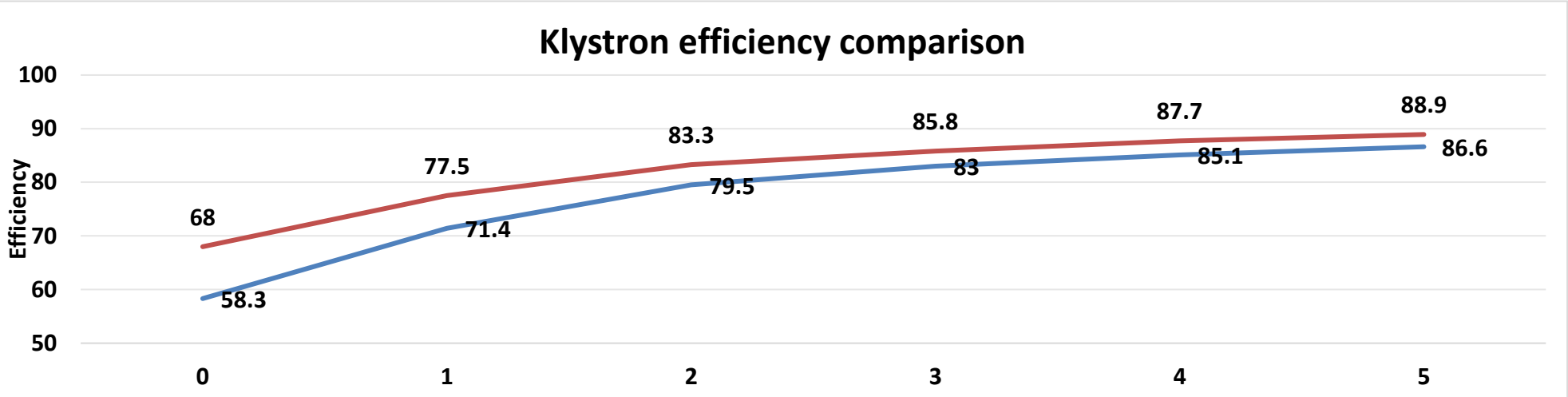
- If 60MW SR power (e+&e-) of CEPC, RF power demands 109.5MW, waster power is still about 49.5MW. (Klystron efficiency~70% @linear region and ~80%@saturate region).
- The energy recovery klystron recovers energy from the spent electron beam by multi-depressed collector, thereby reducing the power demand from the grid and significantly lowering operation.



Roughly theoretical analysis

CEPC 1st klystron prototype		
Coll. Qty	Coll. Eff.	Kly. Eff.
0	0.00%	58.3%
1	31.4%	71.4%
2	50.9%	79.5%
3	59.2%	83.0%
4	64.3%	85.1%
5	67.9%	86.6%

CEPC 2nd klystron prototype		
Coll. Qty	Coll. Eff.	Kly. Eff.
0	0.0%	68.0%
1	29.8%	77.5%
2	47.7%	83.3%
3	55.6%	85.8%
4	61.4%	87.7%
5	65.2%	88.9%



PPM klystron

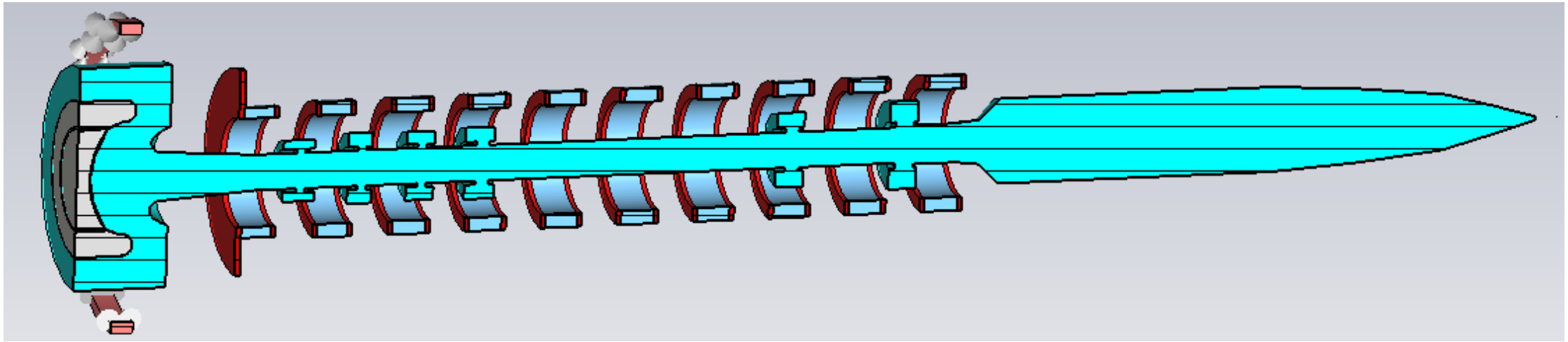
PPM advantage

- Small volume, light weight, and does not require water cooling and power supply.
- It saves the power consumption and cost of power supply, and on the other hand, it avoids the risk of power supply failure and water leakage.

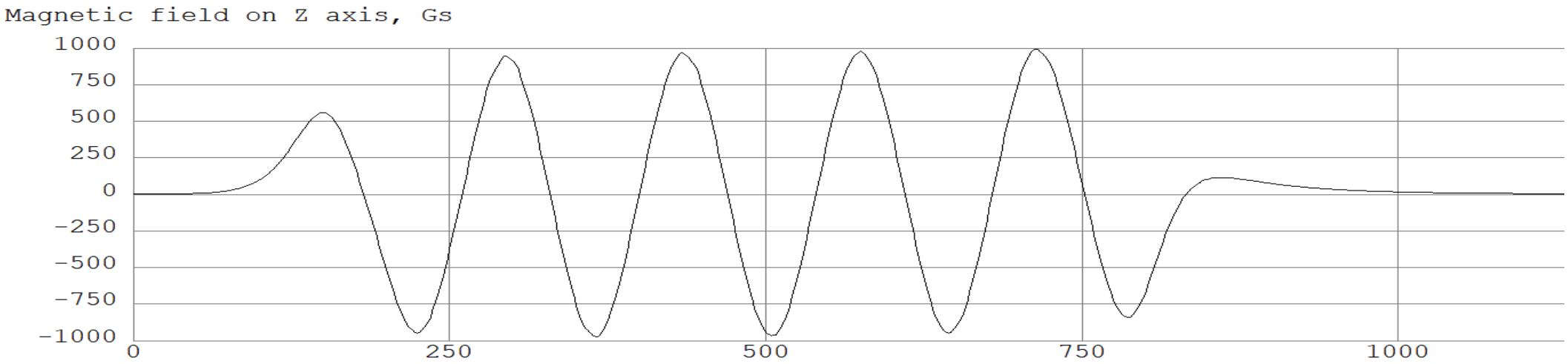
	E37212	E37302A
Frequency(MHz)	5712	2998
Output Power (MW)	51	47
Beam Power (MW)	118.3	123.5
Average Power (kW)	35.5	24.7
Solenoid Power (kW)	8.4	3.4
RF efficiency (%)	**43.1**	**38**
Overall efficiency(%)	**34.9**	**33.5**

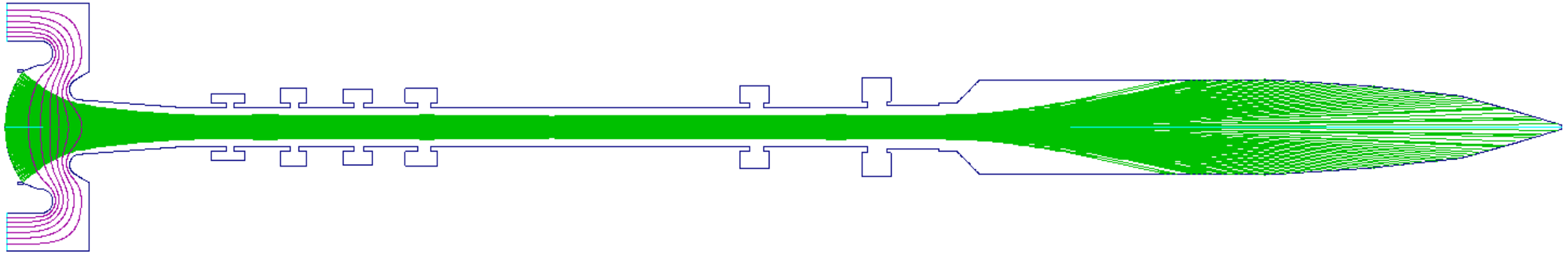
PPM klystron

- On the basis of the S band klystron, the electromagnetic focusing is being changed to PPM focusing structure.



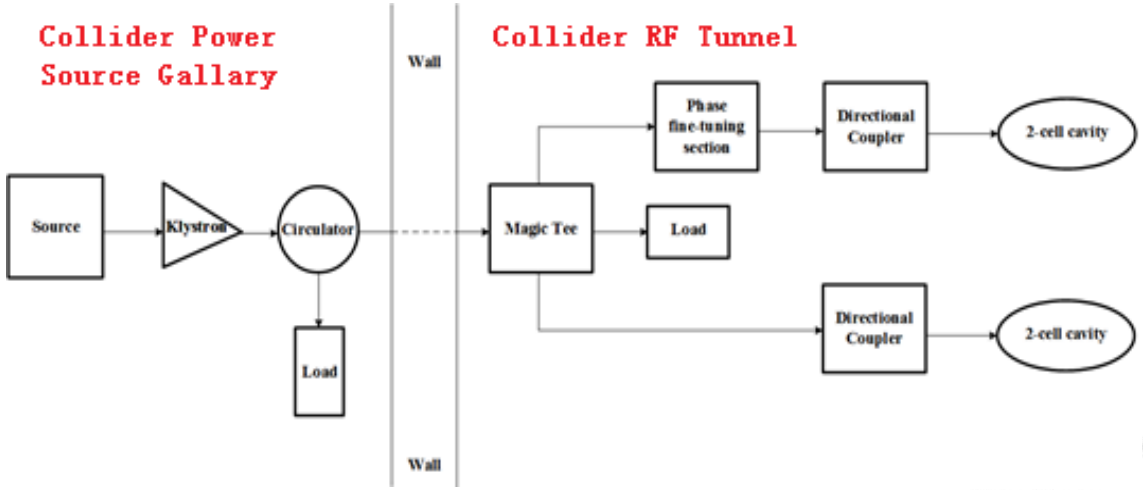
Beam optics


Magnetic field on Z axis, Gs
1000
750
500
250
0
−250
−500
−750
−1000
0
250
500
750
1000

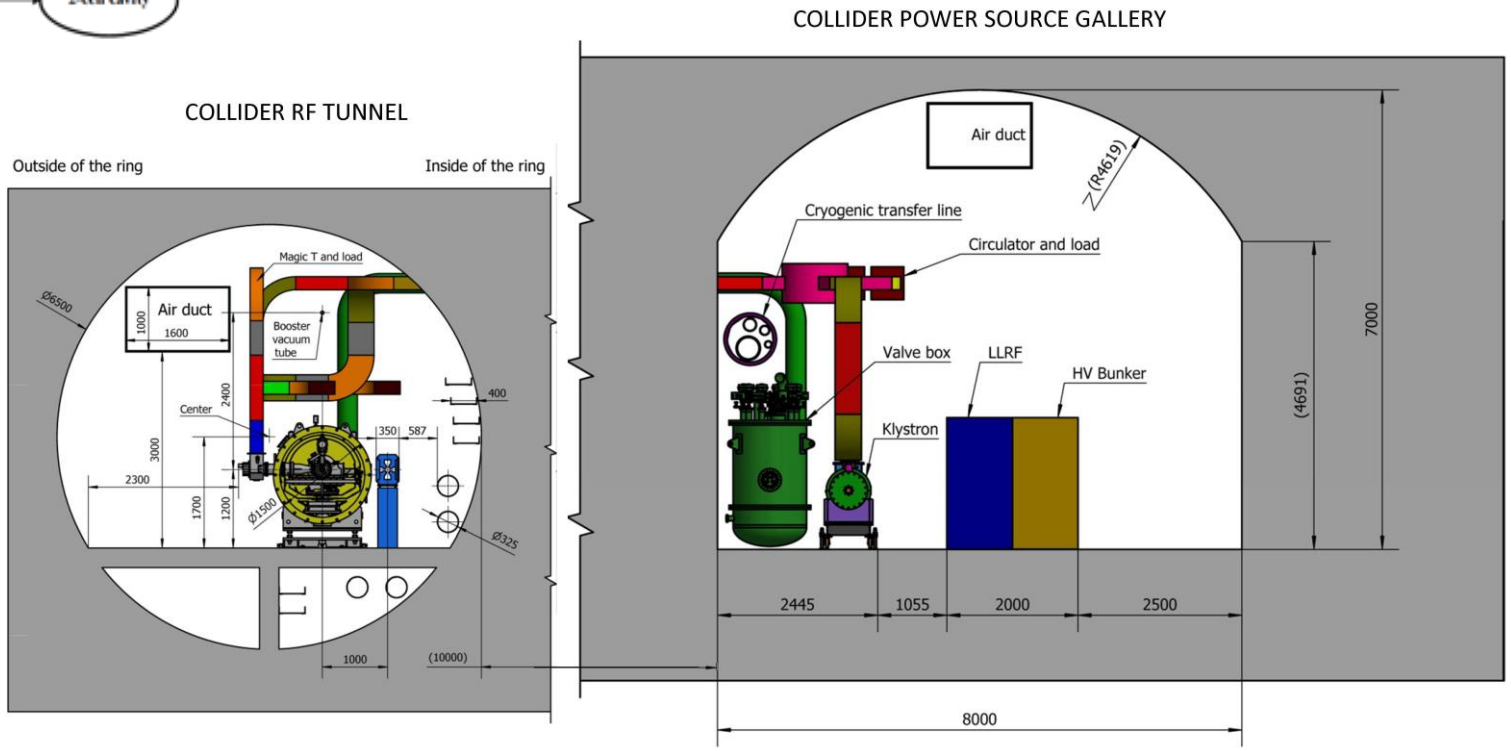


RF power sources distributions

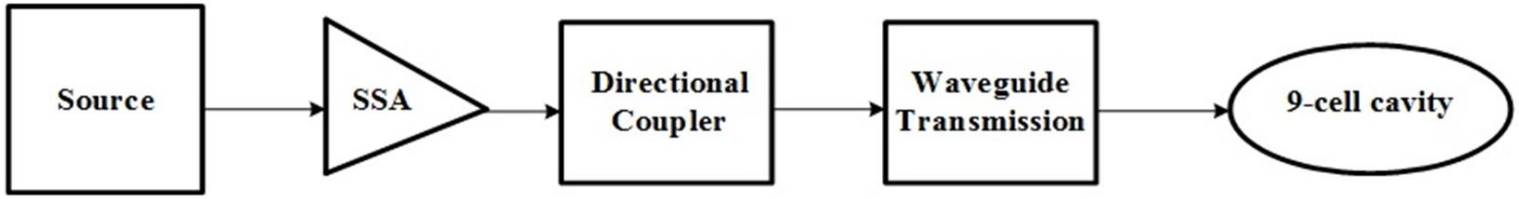
Collider power sources distributions



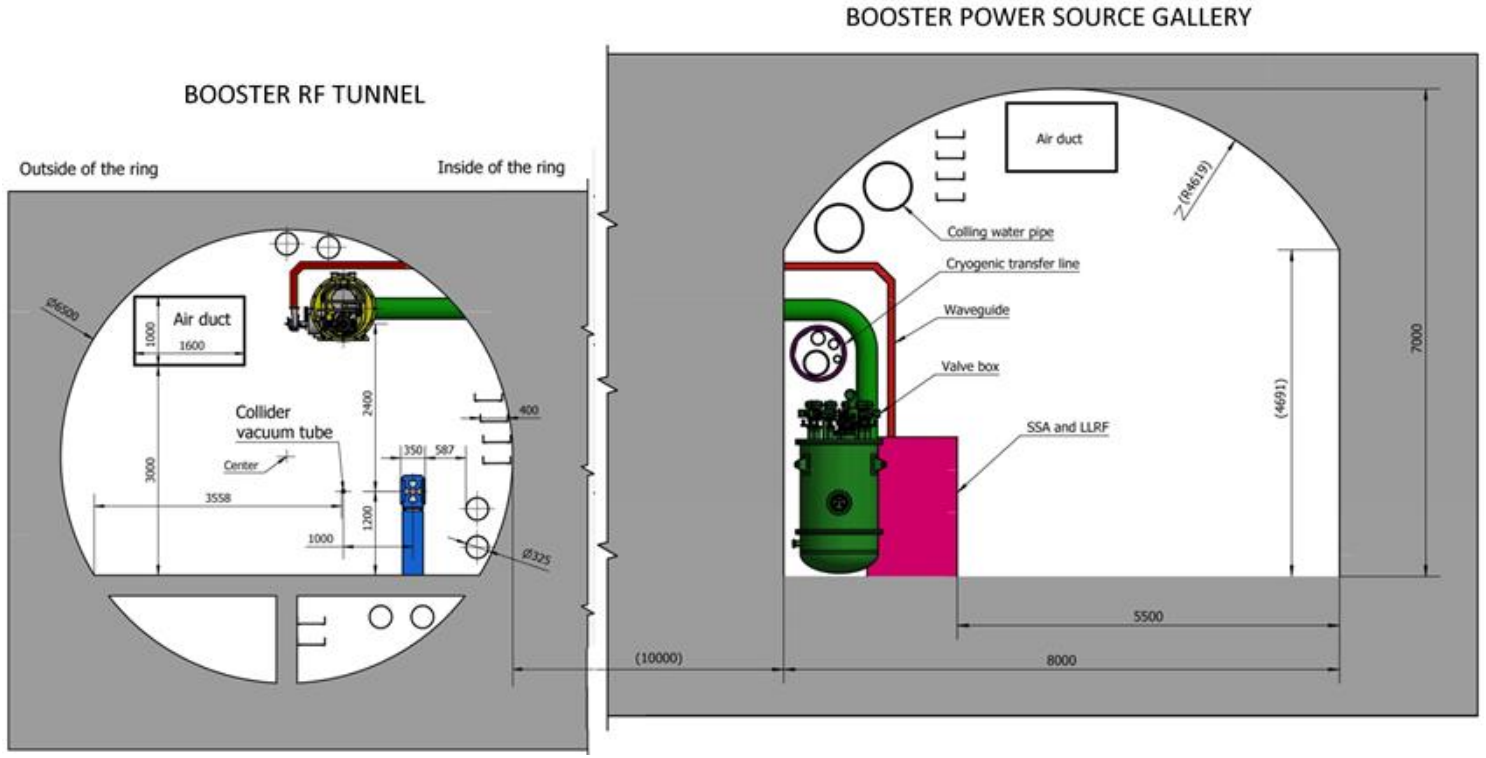
- High voltage power supply are placed on the ground.
- For space savings, transmission system in part are placed in RF tunnel.



Booster power sources distributions

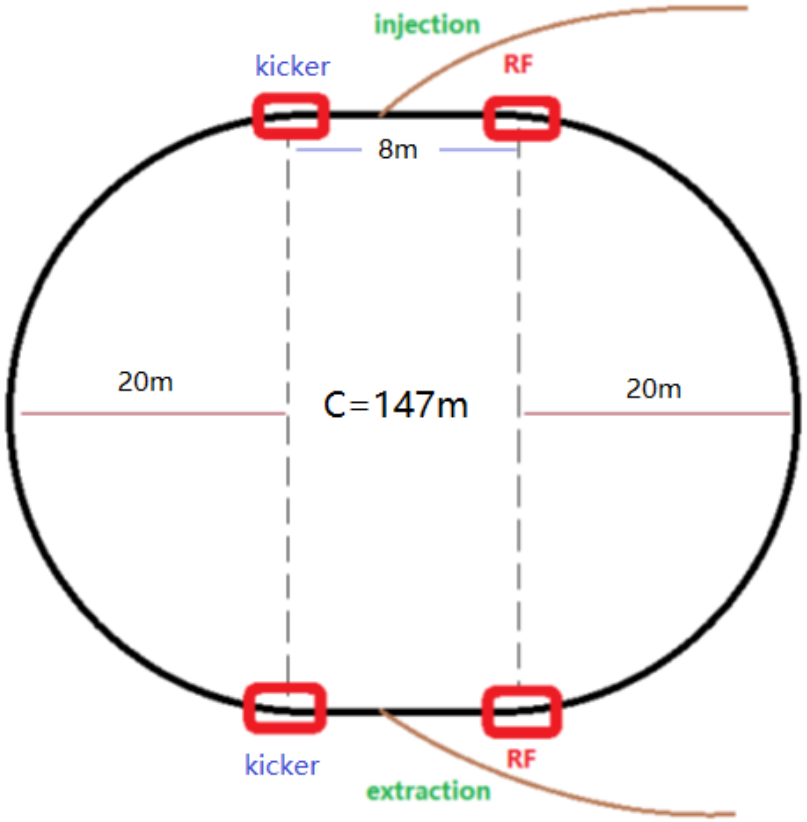


- The Booster RF system consists of 1.3 GHz superconducting RF cavities. There are 12 cryo-modules for Higgs operation, each containing eight 9-cell superconducting cavities.
- These cavities need 96 set 25kW power sources.



Damping ring power sources distributions

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

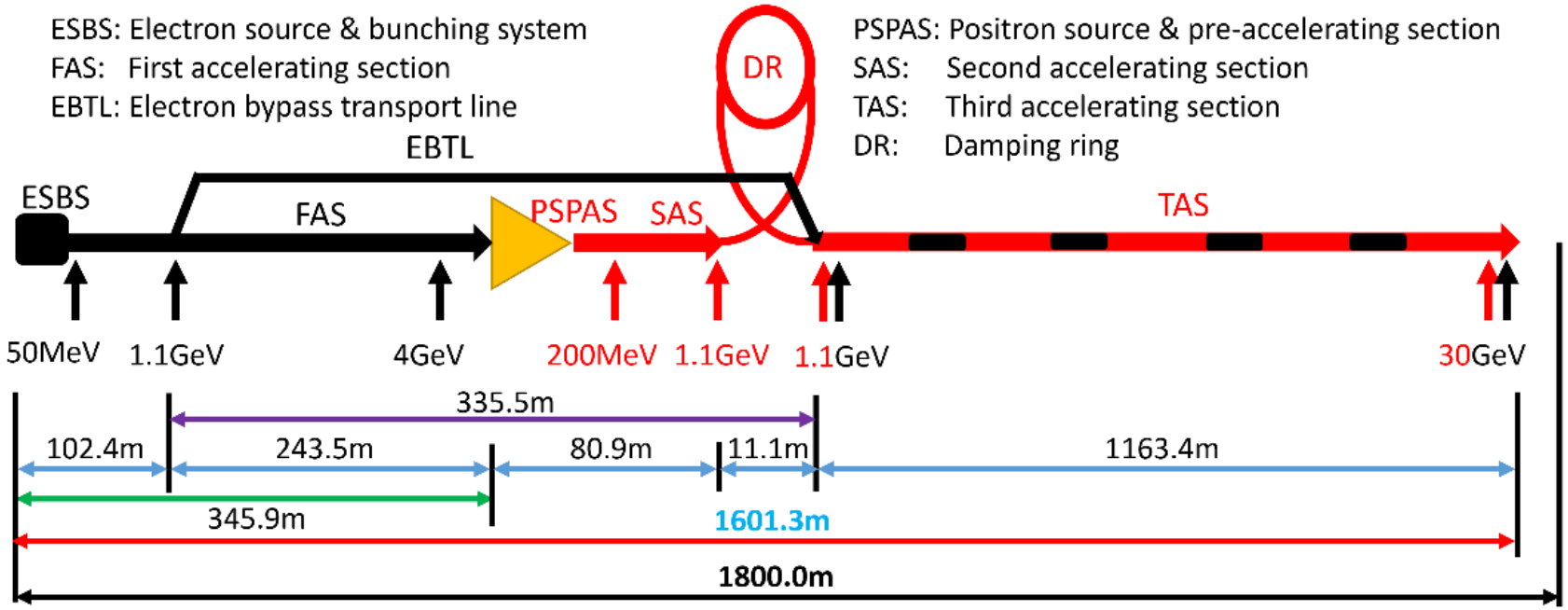


650MHz/90kW SSA Specifications

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

Linac power sources distributions

Type	Structure type
S-band klystron	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	1-to-2，standard acc. structure.



Summary

- Much higher efficiency and much less power consumption and system cost.
- The 2nd stage high power test of 650MHz high efficiency klystron is being done at IHEP PAPS test stand.
- Energy recovery klystron and PPM klystron are also being developed at IHEP.
- Design of C band 80MW klystron is almost accomplished design and will be manufactured in the near future.
- RF power source distributions are also under consideration.

Thanks for your attention!