



# CEPC high efficiency & high power RF sources

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# Content



- System design consideration
  - Collider ring
  - Booster ring
  - Linac injector
- R&D
  - High efficiency (P band 800kW CW klystron/Energy recovery klystron)
  - High power (C band 80MW klystron)

# Collider RF sources



## ■ Requirement list:

Klystron	96	650MHz/800kW
PSM Power Supply	96	130kV/16A and 60kV/22A
Circulator	96	650MHz/800kW
Load	96	650MHz/800kW
Phase shift	96	650MHz/800kW
Waveguide	96	Power divider/directional coupler
LLRF	96	Phase stabilization <0.1 degree, Amplitude stabilization <0.1%
Pre-amplifier	96	650MHz/100W

## ■ Requirement list:

Klystron	96	650MHz/800kW	Higher efficiency
PSM Power Supply	96	130kV/16A and 60kV/22A	Mature product
Circulator	96	650MHz/800kW	Mature product
Load	96	650MHz/800kW	Mature product
Phase shift	96	650MHz/800kW	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/100W	Mature product

# Booster RF sources



## ■ Requirement list:

SSA	96	1300MHz/25kW
Circulator	96	1300MHz/25kW
Load	96	1300MHz/25kW
Waveguide	96	Directional coupler
LLRF	96	Phase stabilization <0.1 degree, Amplitude stabilization <0.1%

# Booster RF sources



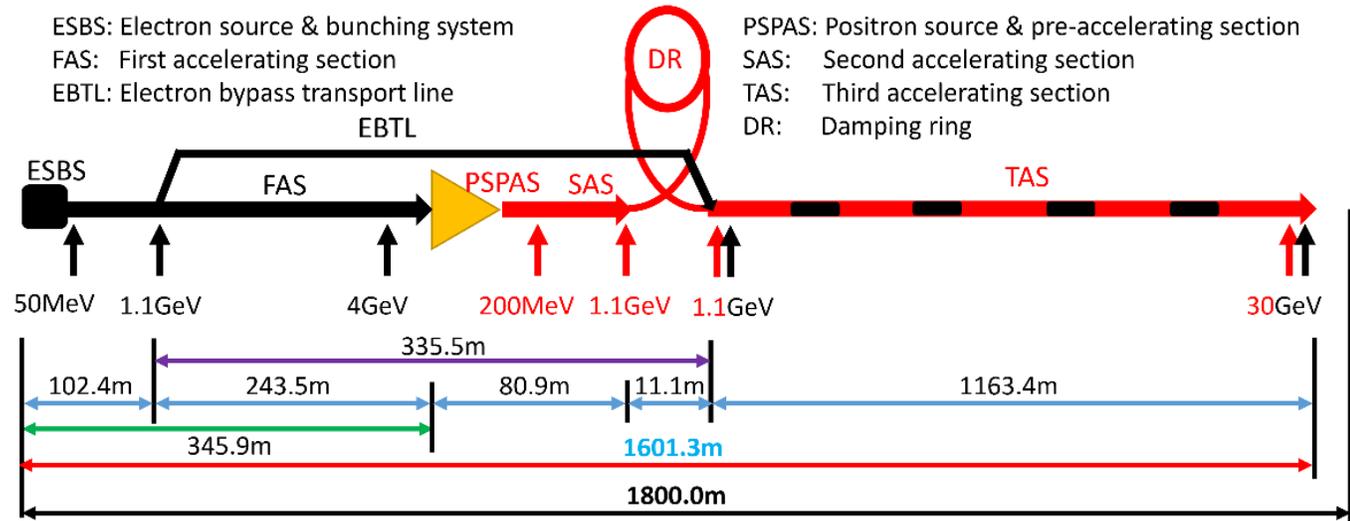
## ■ Requirement list:

SSA	96	1300MHz/25kW	Mature product
Circulator	96	1300MHz/25kW	Mature product
Load	96	1300MHz/25kW	Mature product
Waveguide	96	Directional coupler	Mature product
LLRF	96	Phase stabilization <0.1 degree, Amplitude stabilization <0.1%	Mature product

# 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.

# 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

# 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

# Why we need R&D?

# 1<sup>st</sup>-Collider RF sources

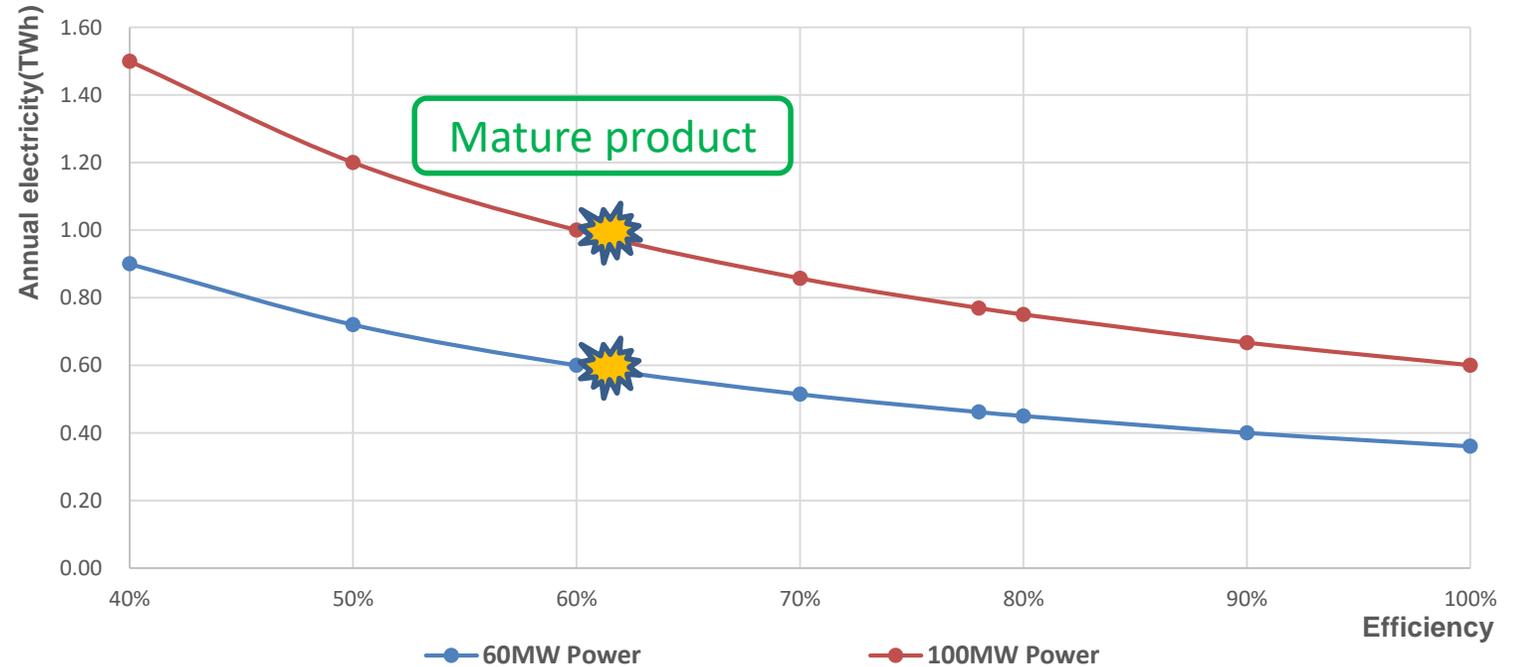


- Higher efficiency
- Less power consumption

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

## CEPC annual electricity @6000 hours/year

Annual electricity consumption vs. Efficiency



# 1<sup>st</sup>-Collider RF sources

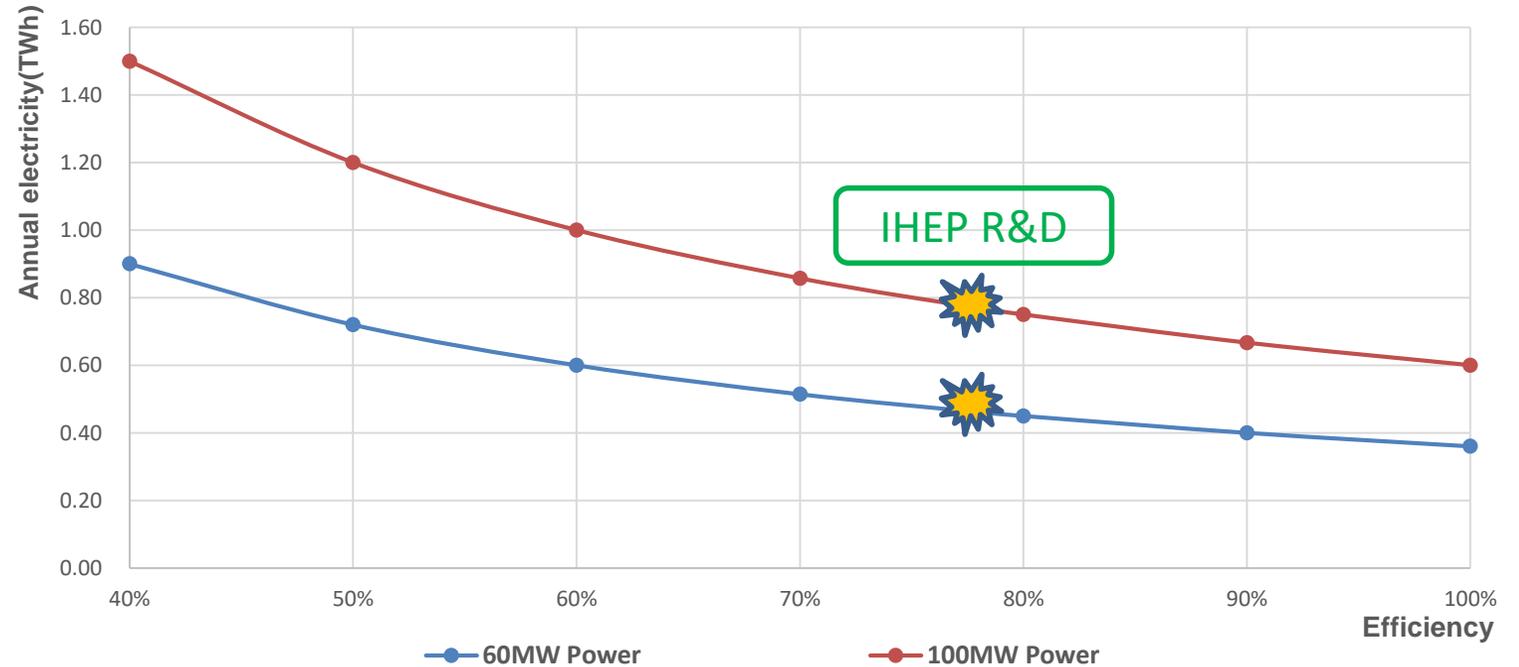


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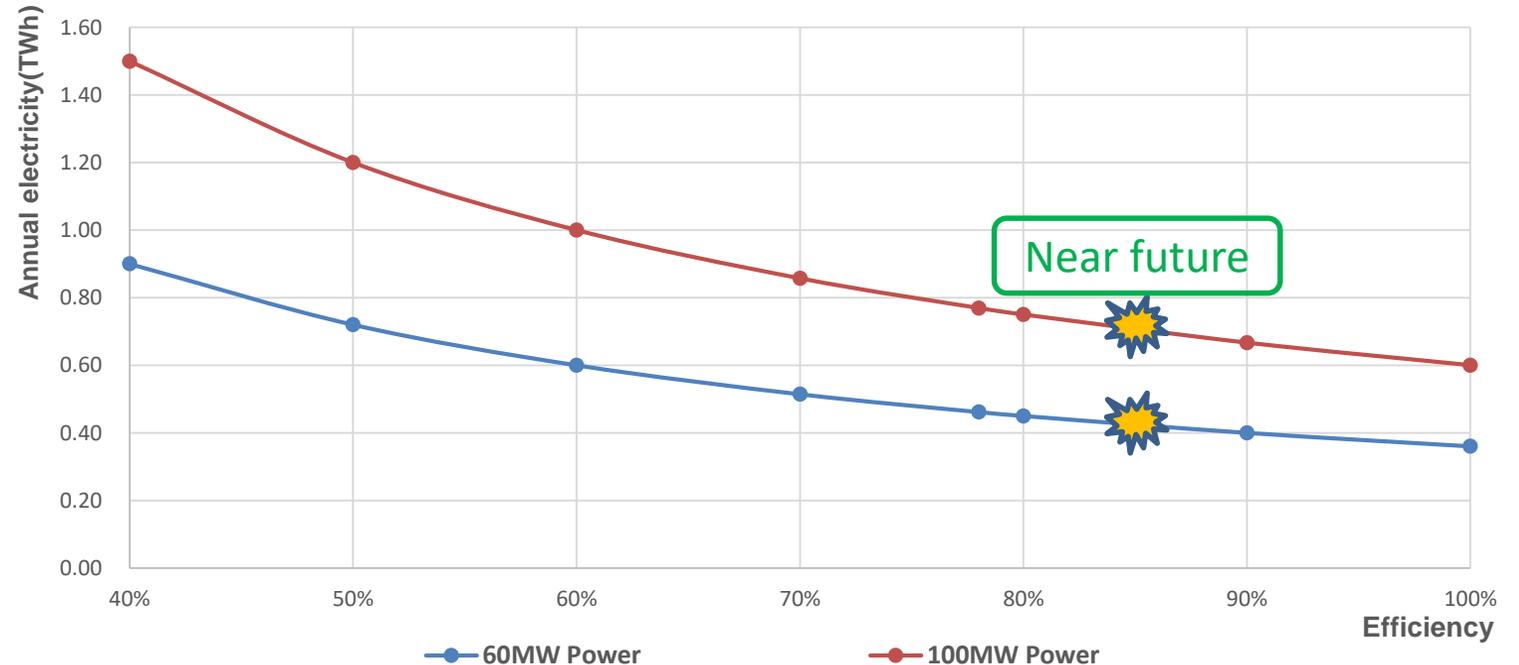


- Higher efficiency
- Less power consumption

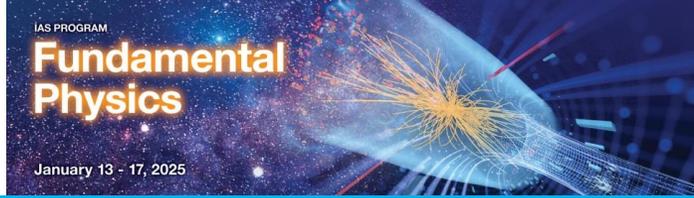
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# 1<sup>st</sup>-Collider RF sources

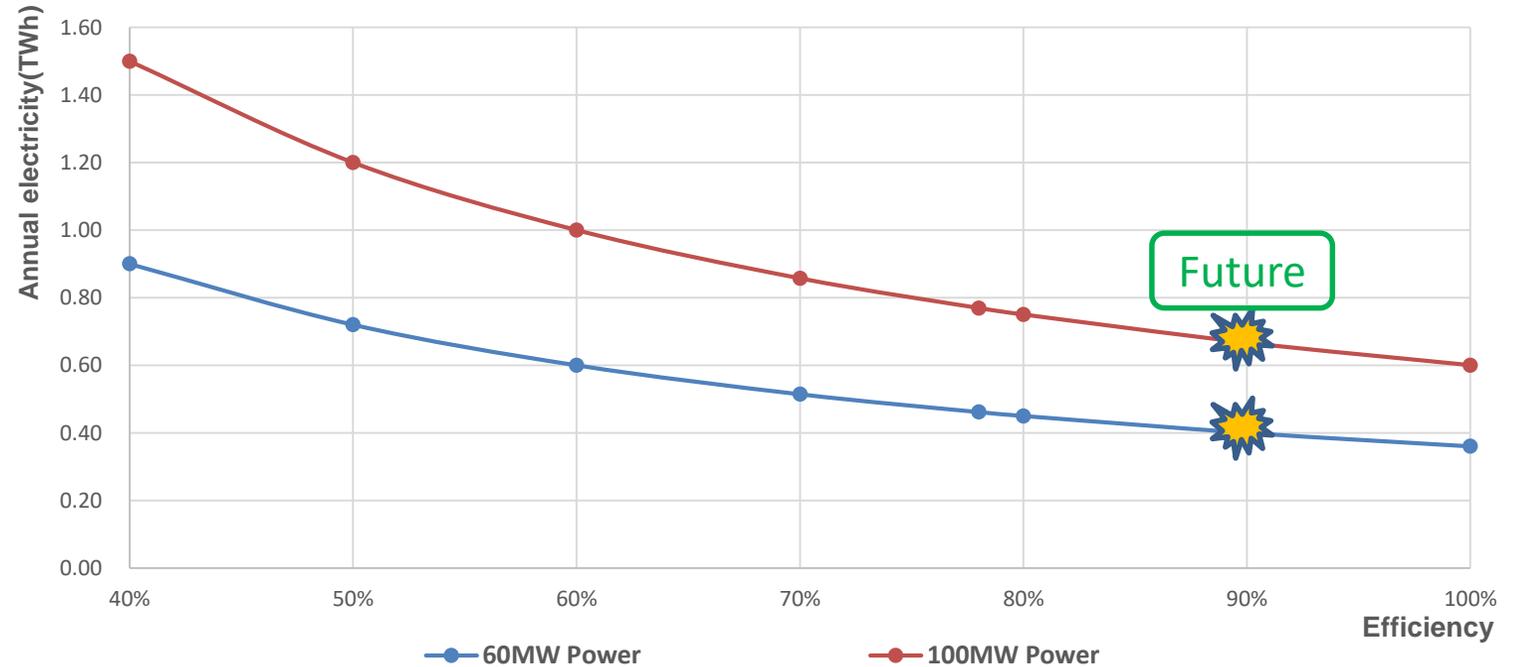


- Higher efficiency
- Less power consumption

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

## CEPC annual electricity @6000 hours/year

Annual electricity consumption vs. Efficiency



# 2<sup>nd</sup>-Linac RF sources



- Higher power
- Smaller number
- Now

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.

CEPC Linac baseline

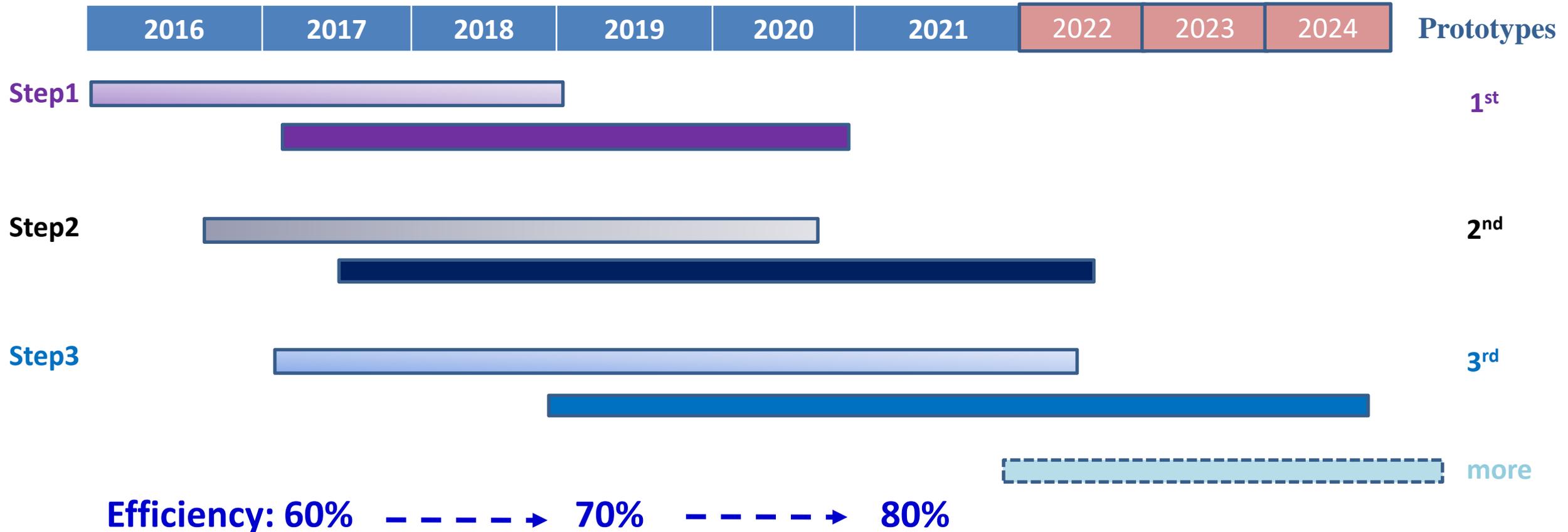
- Only C band of **50MW** klystron is mature product in the world. 1 klystron only power to 2 accelerator structures (CEPC Linac baseline).
- Number of C band klystron is very large (**236 set**).
- IF output power of C band klystron is up to **80MW**, the number of klystron will be reduced by half. (1 klystron power to 4 accelerator structures). The cost of Linac RF sources will be decreased more than **30%**.

# **R&D Progress and Achievements**

# 650MHz klystron R&D



- 3 or more klystron prototypes for klystron efficiency improvement



# Design scheme



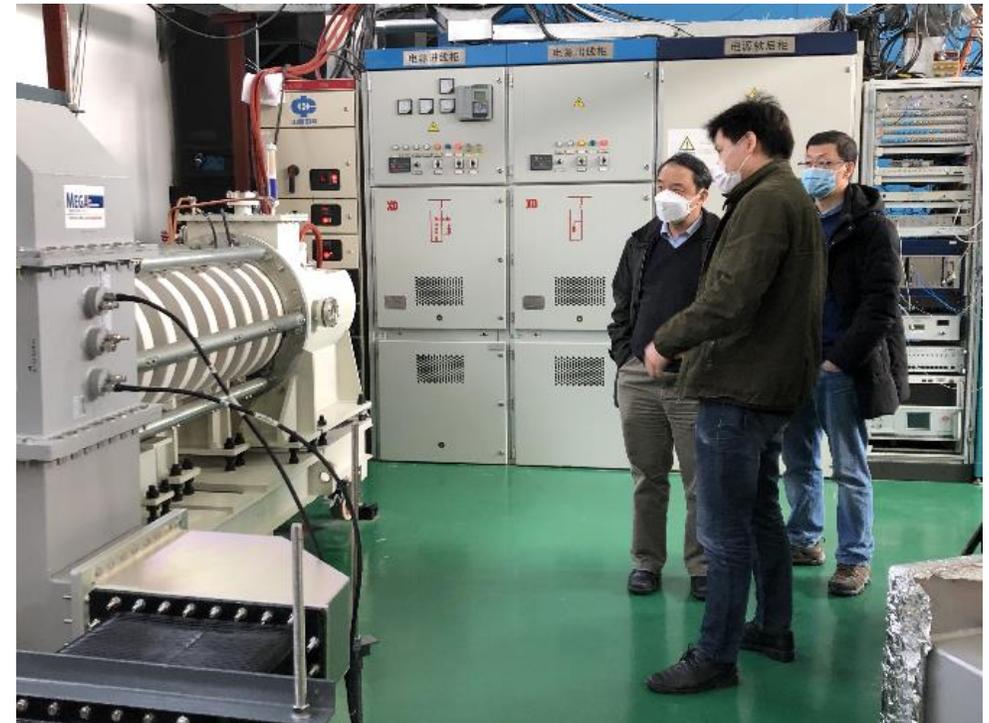
- Scheme 1: Traditional way for  $>60\%$  efficiency
- Scheme 2: With high voltage gun (110 kV/9.1 A), low perveance (HE,  $>75\%$ )
- Scheme 3: MBK, 54 kV/20A electron gun (8 beams) (HE,  $>80\%$ )

Parameter	Scheme1(1 <sup>st</sup> prototype)	Scheme2(2 <sup>nd</sup> )	Scheme3(3 <sup>rd</sup> )
Freq. (MHz)	650	650	650
Voltage (kV)	82	110	54
Current (A)	16	9.1	20(2.5 $\times$ 8)
Beam No.	1	1	8
Perveance ( $\mu$ P)	0.65	0.25	1.6(0.2 $\times$ 8)
Efficiency (%)	65	$\sim 80$	$>80$
Power(kW)	800	800	800(100 $\times$ 8)

# 1<sup>st</sup> prototype

- Oct. 2017 Prototype manufacture
- Mar. 2020 High power test at IHEP

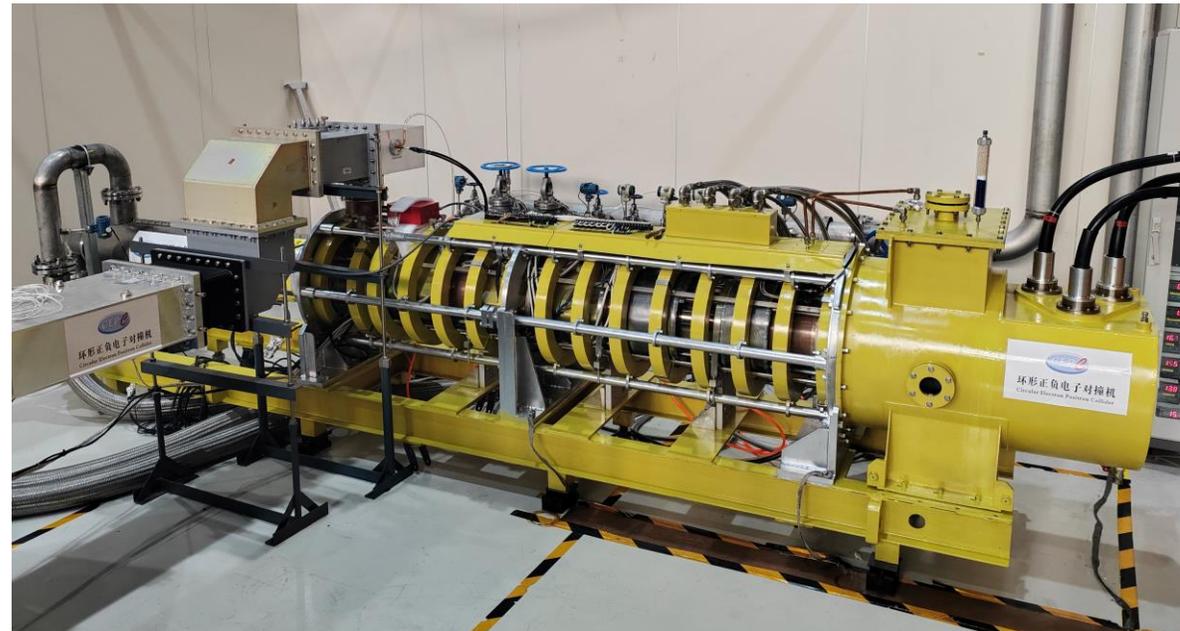
Parameters	Design	Test
Operating frequency (MHz)	650	650
Beam Voltage (kV)	81.5	80
Beam Perveance ( $\mu\text{A}/\text{V}^{3/2}$ )	0.65	0.7
Efficiency(%)	65	62
Saturation Gain(dB)	$\geq 45$	47
Output power(kW)	800	800
1 dB Bandwidth(MHz)	$\geq 1$	1.8



# 2<sup>nd</sup> prototype (HE design)



- Jan. 2021: Prototype manufacture
- Jul. 2022: CW 630kW with Eff. 70.5% (1<sup>st</sup> stage high power test)
- Aug. 2024: CW 803kW with **Eff. 78.5%** (2<sup>nd</sup> stage high power test)



# 3<sup>rd</sup> prototype (MBK)



- Dec. 2021: Klystron beam tester manufacture
- Oct. 2023: Accomplishment of klystron beam tester high voltage conditioning and beam emission.
- Now: Klystron prototype manufacture is in progress.



# C band klystron

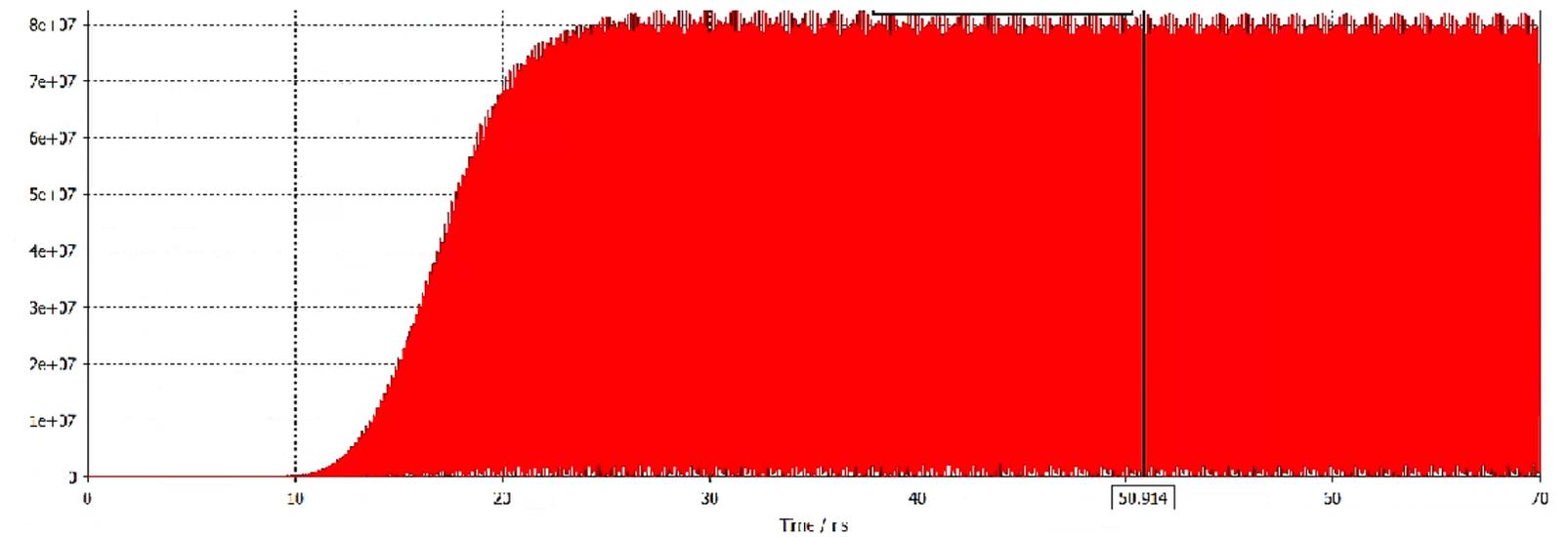
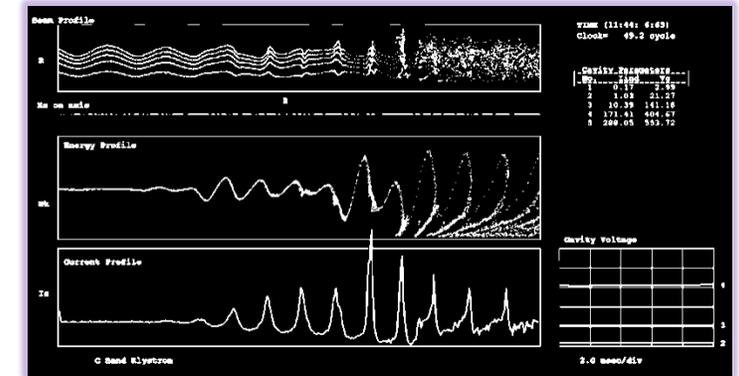
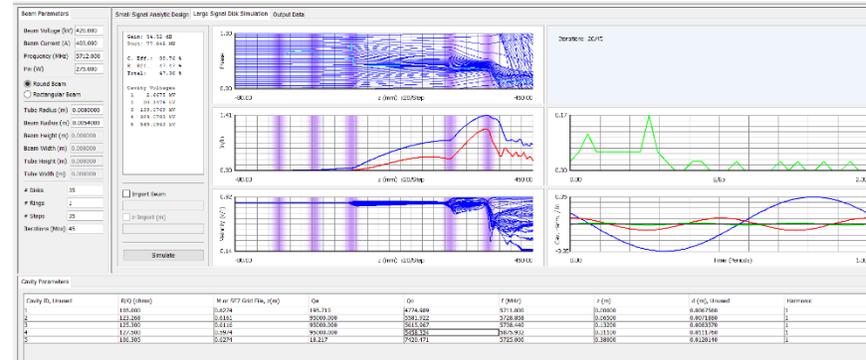
# Design progress



## Main parameters

Parameters	Value
Frequency	5720 MHz
Output Power	<b>80MW</b>
Pulsed width	<b>3us</b>
Repetition rate	<b>100Hz</b>
Gain	54 dB
Efficiency	47%
Beam voltage	420 kV
Beam current	403 A

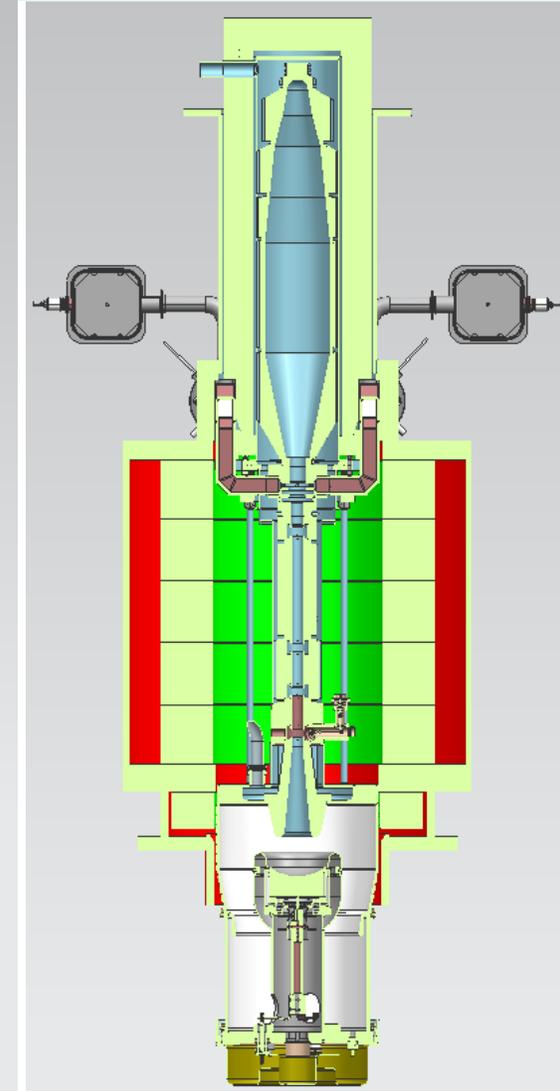
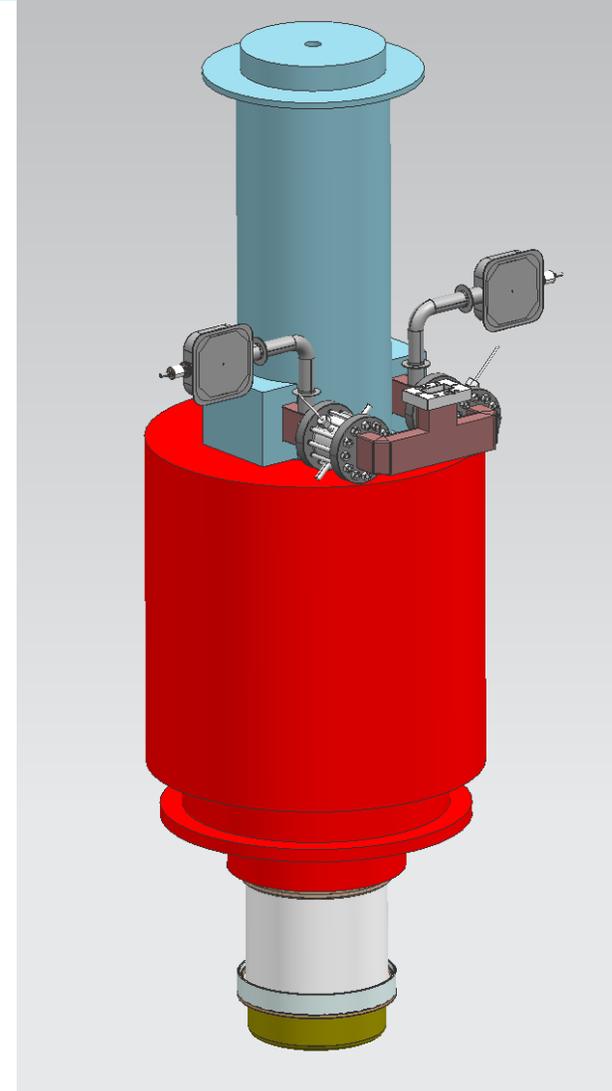
## Beam dynamics



# Fabrication progress



- Prototype manufacture is started from August 2024.
- The processing is scheduled to be completed in July this year.



# Energy recovery klystron

# 3<sup>rd</sup>-Energy recovery

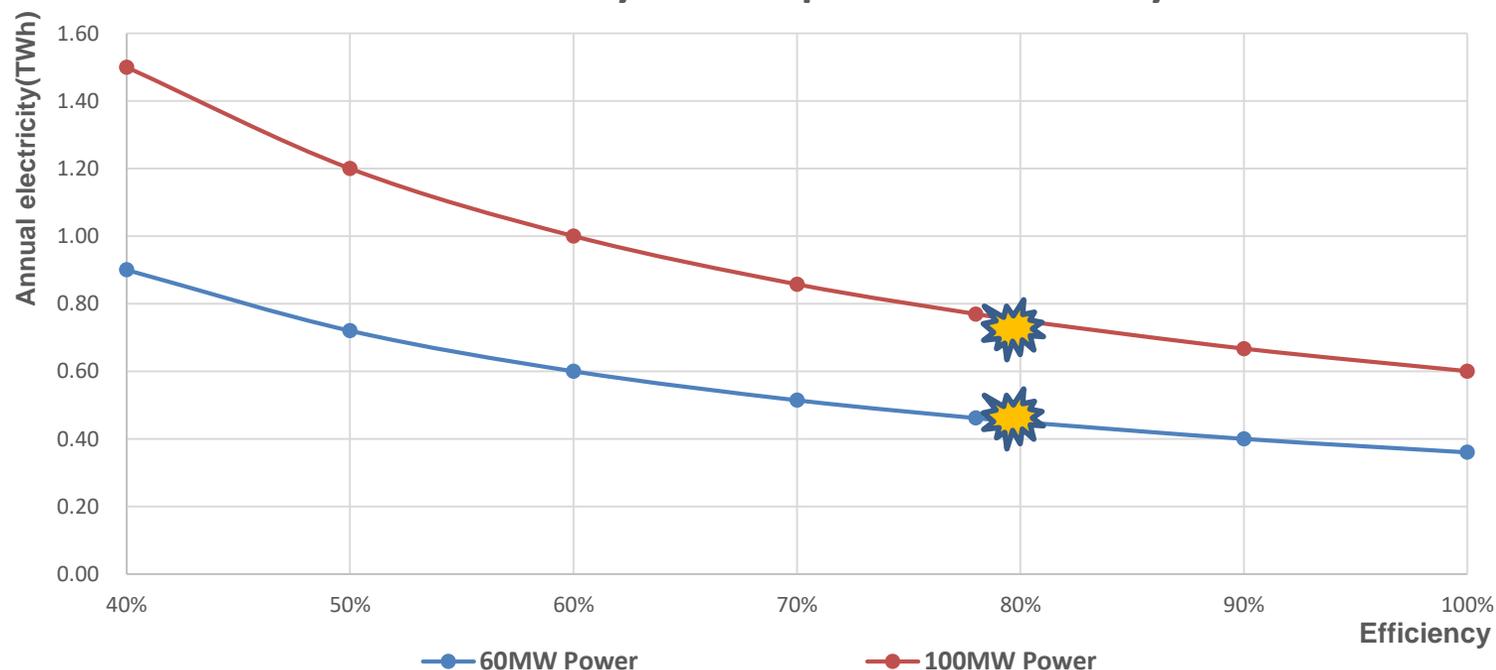


- Higher efficiency
- Less power consumption

*Assuming klystron efficiency is up to 80%.*

## CEPC annual electricity @6000 hours/year

Annual electricity consumption vs. Efficiency



# 3<sup>rd</sup>-Energy recovery

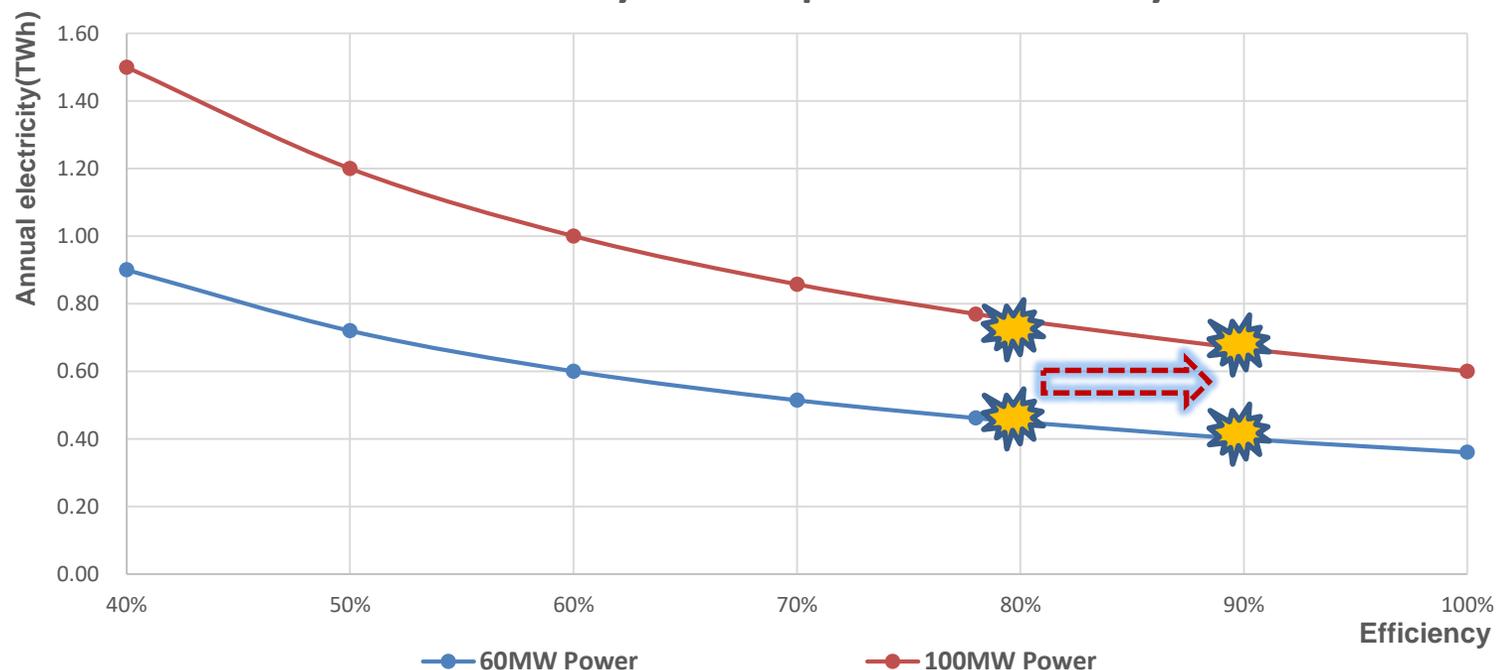


- Higher efficiency
- Less power consumption

*It is difficult to increase RF conversion efficiency of the klystron itself from 80% to 85 or 90%? So we need other methods to achieve a leap in efficiency.*

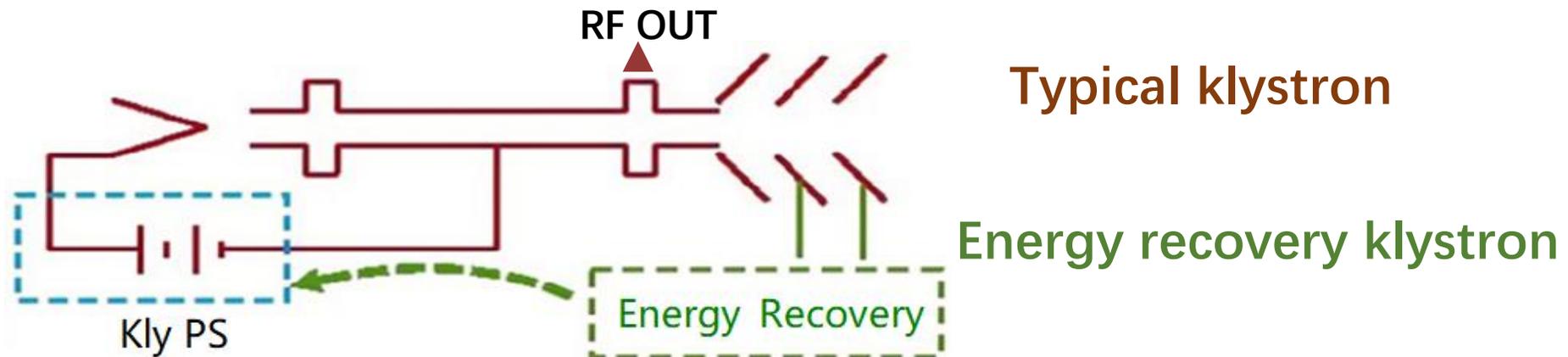
## CEPC annual electricity @6000 hours/year

Annual electricity consumption vs. Efficiency



# Energy recovery klystron(ERK)

- 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



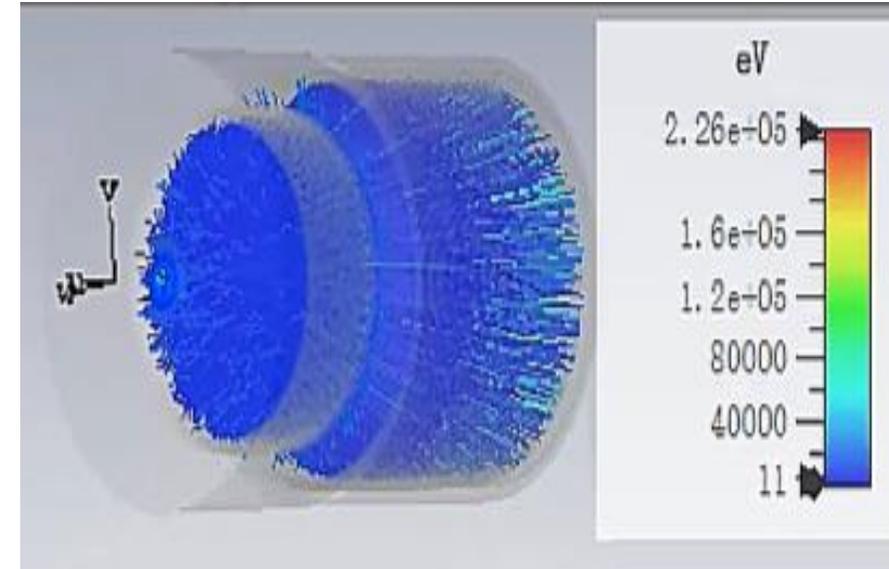
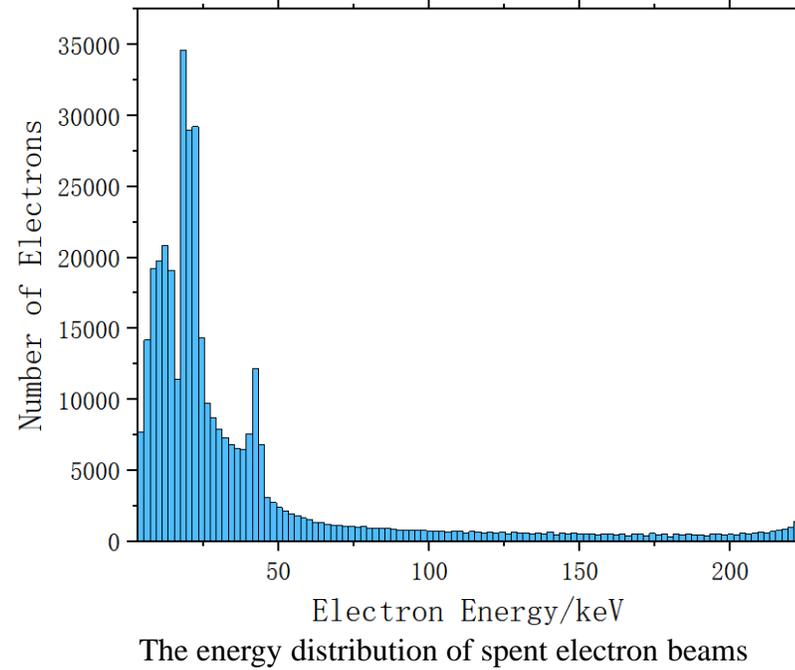
Based on high efficiency klystron design  
**Final efficiency** is the whole efficiency of ERK

Stage No.	Linear region	Saturation region
Without stage	65%	77.5%
Single stage	72.9%	84.3%
Two stages	79.4%	88.1%
Three stages	83.0%	90.1%

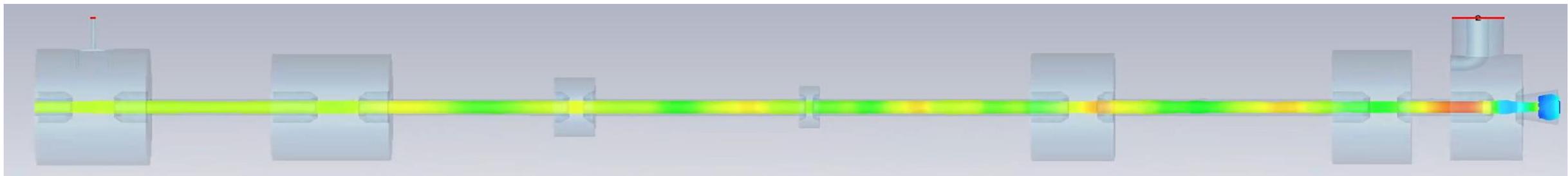
# Design progress



Parameter	Value
Operating frequency	650 MHz
Beam Voltage	113 kV
<b>Efficiency</b>	<b>77.5%</b>
Output power	800 kW
Beam perveance	0.25 $\mu\text{P}$
Beam current	9.5A
<b>Efficiency</b> <b>(one-stage depressed collector)</b>	<b>84%</b>

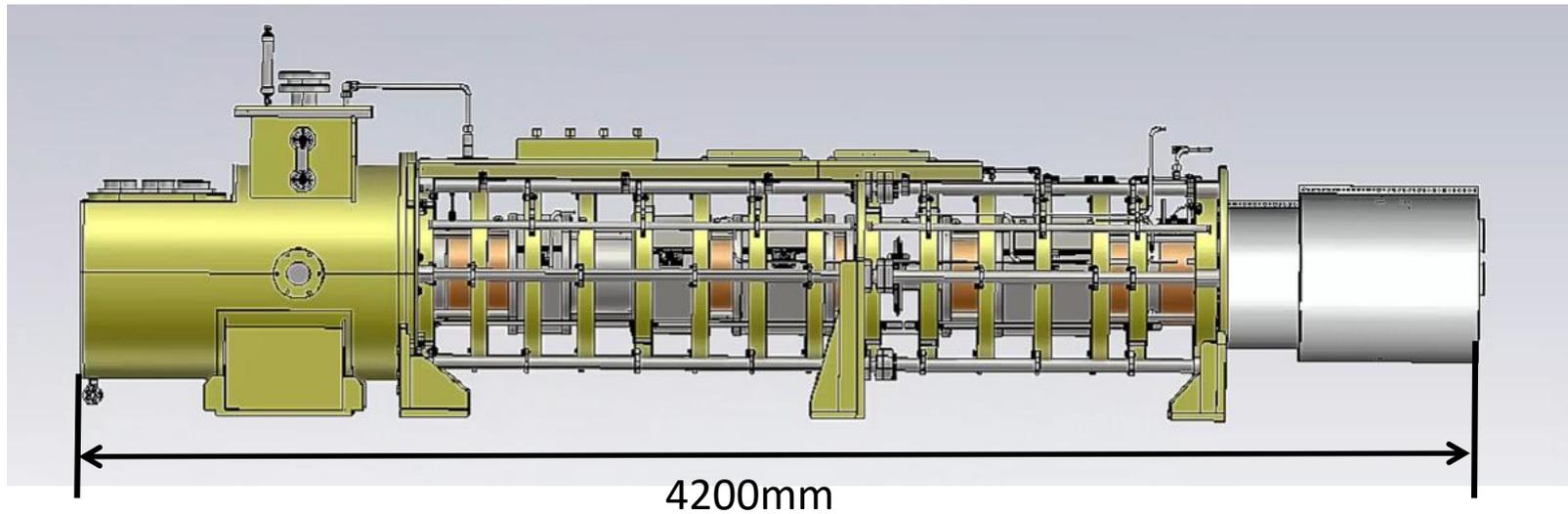
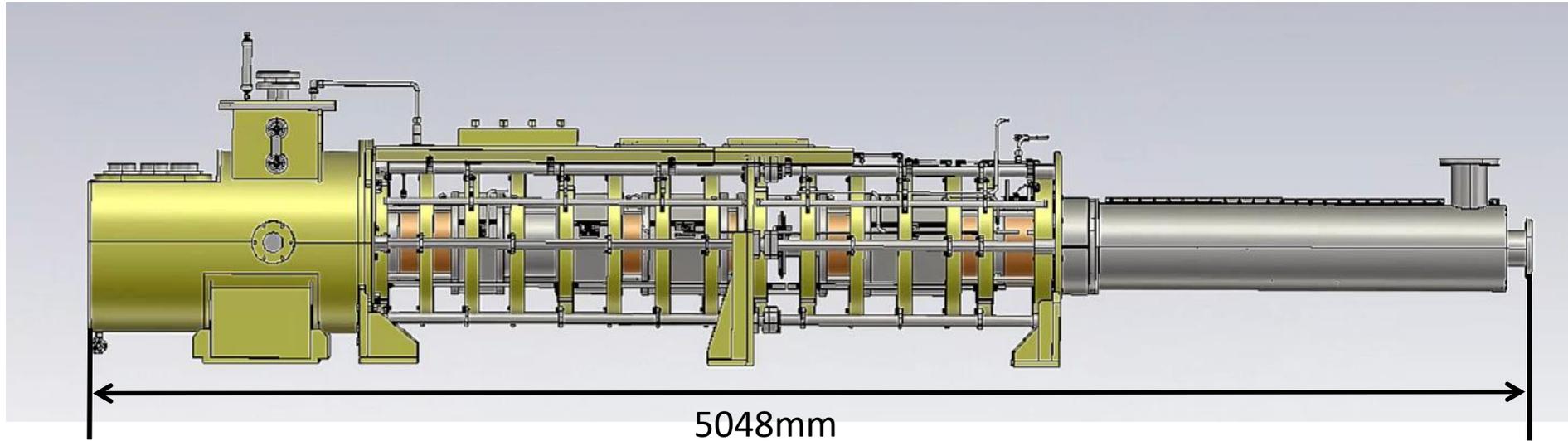


One-stage depressed collector



PIC (Particle-In-Cell) beam simulation

# Preliminary mechanical design



# Conclusion



- The high power test of high-efficiency klystron prototype has been successfully completed, achieving a continuous wave (CW) output of 803 kW and an efficiency of 78.5%.
- The processing of C band 80MW klystron is under progress.
- Processing and high-power test of the MBK will be conducted in the near future.
- Development of an energy recovery klystron based on high efficiency klystron technologies is progressing.

**Thanks for your attention!**