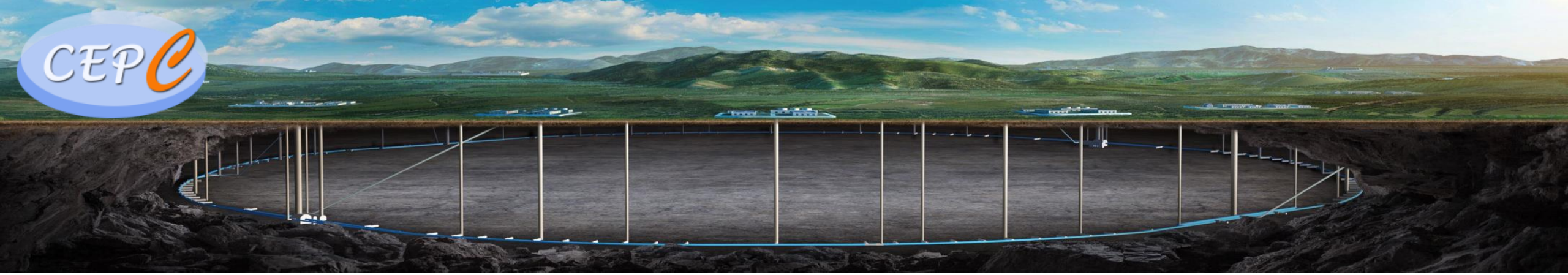


# High Efficiency Klystron Studies and Development for Green Colliders

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- **We are doing**
  - High efficiency and high power klystron R&D
- **Future plan**

# Research background

# Research background

- Large-scale accelerator facilities are consuming increasingly high levels of energy. For instance, during operation, the energy consumption of large-scale accelerator facilities such as CEPC Fcc-ee and CLIC  is up to tens of megawatts and hundred of megawatts power. Therefore, there is an urgent need for **low carbon** and **energy efficient** operation solutions(**Green collider**).

# CEPC power consumption

## CEPC TDR Power Consumption Breakdowns@Higgs with 30GeV injection Linac and 30MW SR/beam

| | Location and electrical demand(MW) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Ring | Booster | LINAC | BTL | IR | Surface building | TOTAL |
| RF Power Source | 96.9 | 1.4 | 11.1 | | | | 109.5 |
| Cryogenic System | 11.6 | 0.6 | - | | 1.1 | | 13.4 |
| Vacuum System | 1.0 | 3.8 | 1.8 | | | | 6.5 |
| Magnet Power Supplies | 52.3 | 7.5 | 2.4 | 1.1 | 0.3 | | 63.5 |
| Instrumentation | 1.3 | 0.7 | 0.2 | | | | 2.2 |
| Radiation Protection | 0.3 | | 0.1 | | | | 0.4 |
| Control System | 1.0 | 0.6 | 0.2 | 0.0 | 0.0 | | 1.8 |
| Experimental devices | | | | | 4.0 | | 4.0 |
| Utilities | 31.8 | 3.5 | 2.0 | 0.6 | 1.2 | | 39.1 |
| General services | 7.2 | | 0.3 | 0.2 | 0.2 | 12.0 | 19.8 |
| RF system | | | 0.8 | | | | 0.8 |
| TOTAL | 203.4 | 18.2 | 18.9 | 1.8 | 6.8 | 12.0 | 261.1 |

**60MW** SR power (e+&e-), RF power demands **109.5MW**, waster power **49.5MW**

# Energy conservation measure

- Klystron efficiency improvement
  - By optimizing klystron beam dynamics with different methods, the efficiency of the klystron itself can be enhanced.
  - From the current technological development perspective, the improvement of RF conversion efficiency of the klystron itself has reached its limit.

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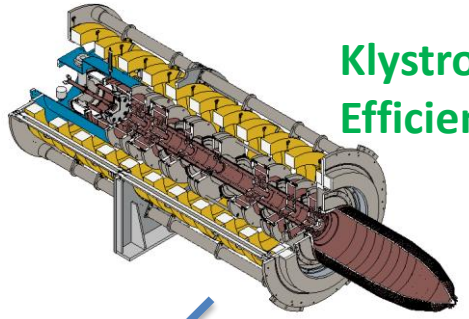
**60MW** SR power (e+&e-), RF power demands **109.5MW**, waster power **49.5MW**

**Very difficult**

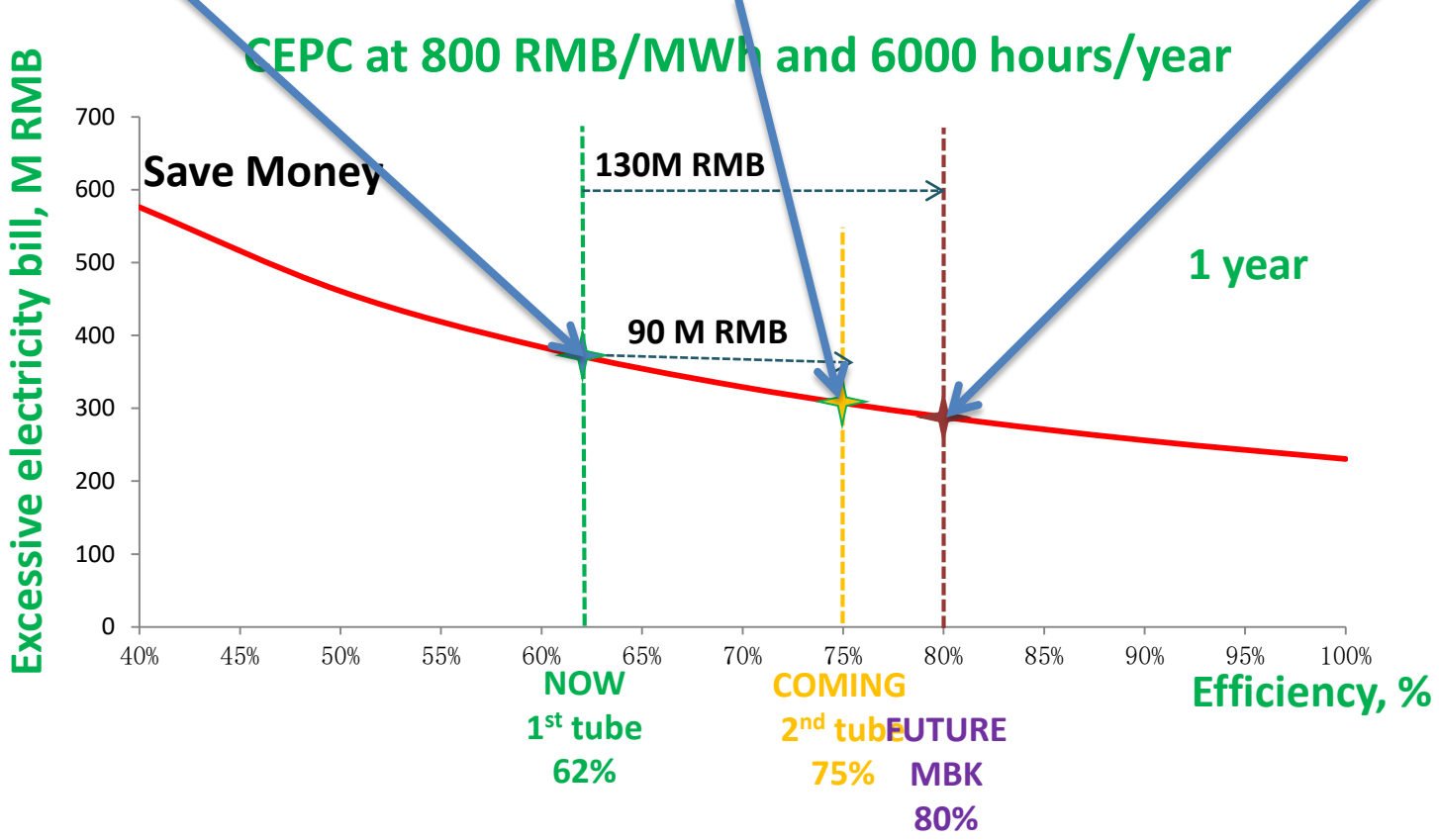
# Efficiency impact on operation cost

Klystron No. 1
Efficiency 62%
(2020)

Klystron No. 2
aiming at
efficiency 77%

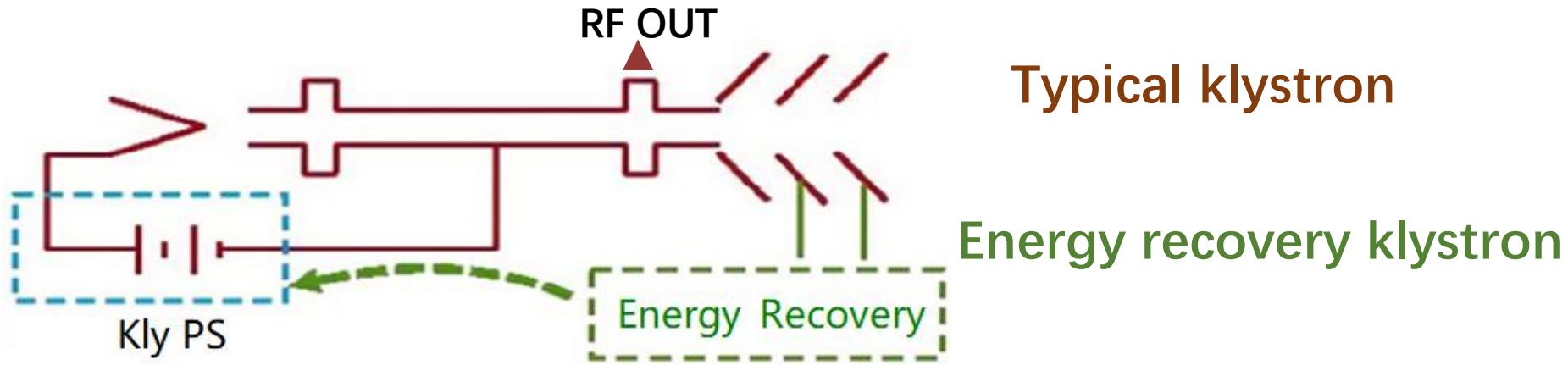


Klystron No. 3
Efficiency 80.5%



# Energy conservation measure

- Energy recovery klystron
  - 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.



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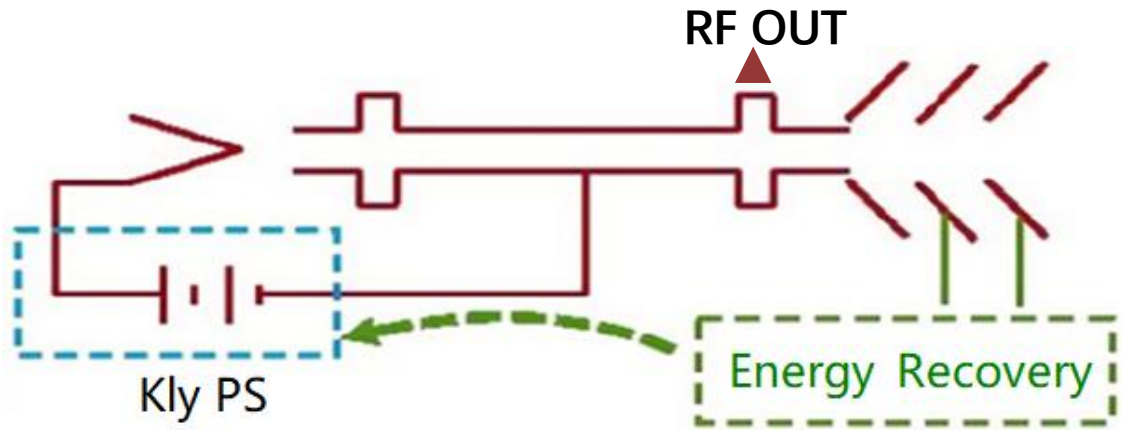



Typical klystron

Energy recovery klystron

**60MW** SR power (e+&e-), RF power demands **109.5MW**, waster power **49.5MW**

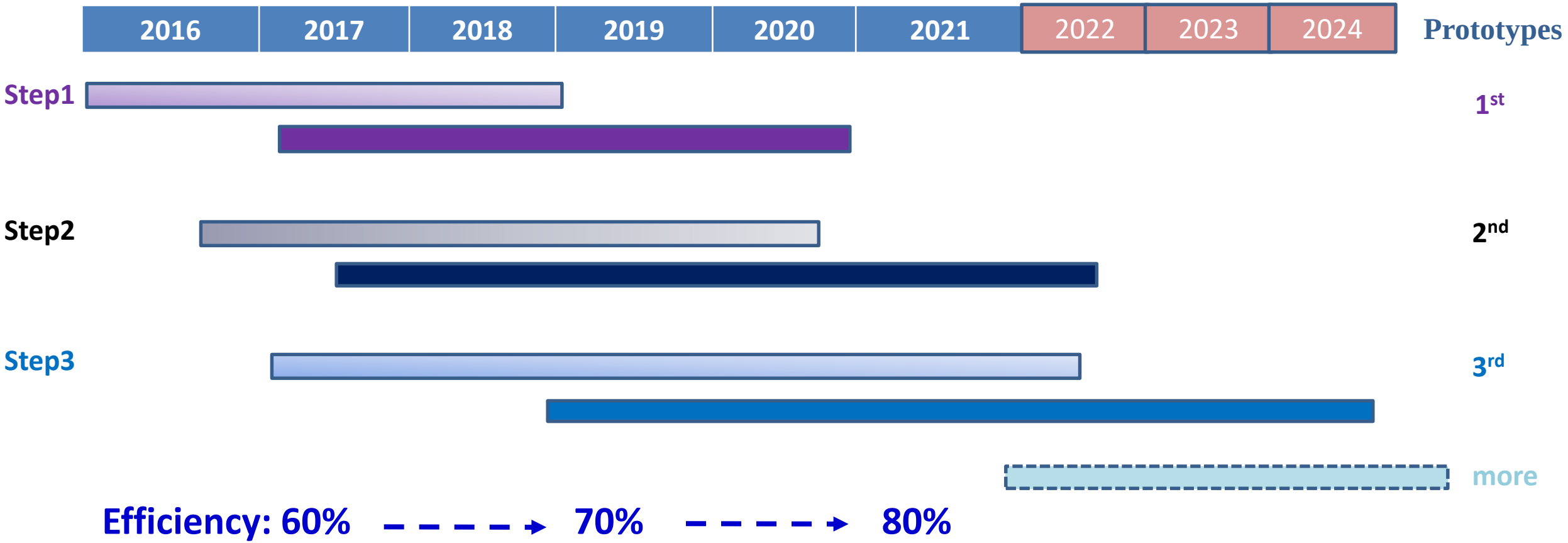
**Also difficult, but great possibility**

# We are doing

## High efficiency 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) |

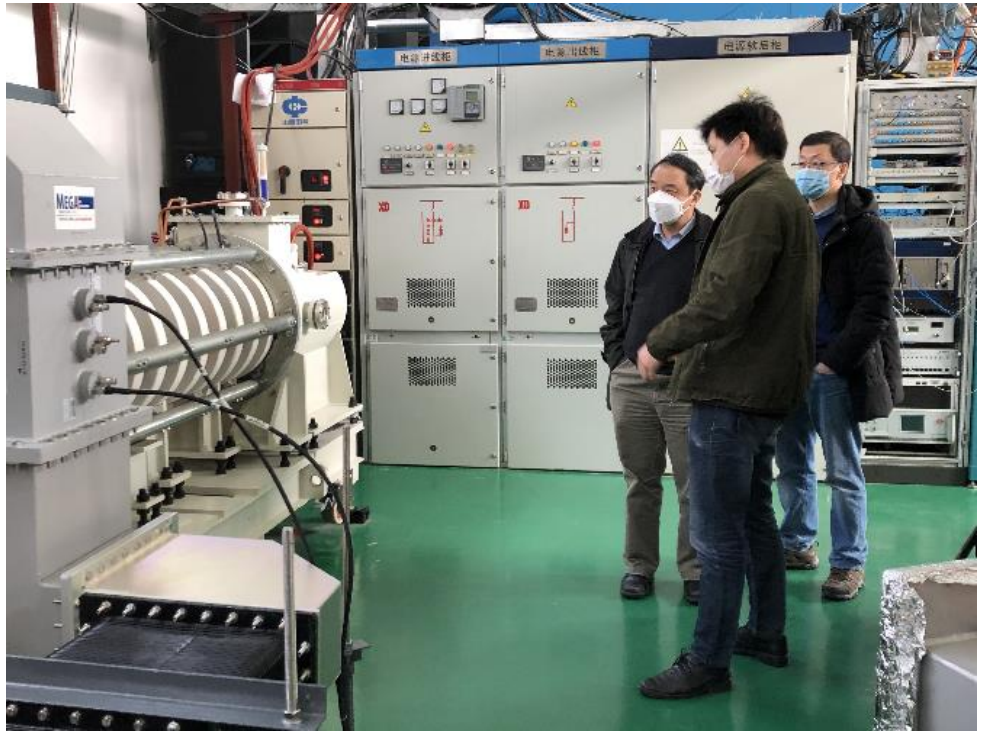
# 1st prototype milestone

- Oct. 2017 Design report
- May 2018 Mechanical design review
- Mar. 2019 Window fabrication
- Apr. 2019  Collector brazing
- Sep. 2019 Prepressing of electron gun
- Oct. 2019 Klystron bake out
- Dec. 2019 Delivered to IHEP
- Mar. 2020 High power test at IHEP

# 1st prototype high power test results

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

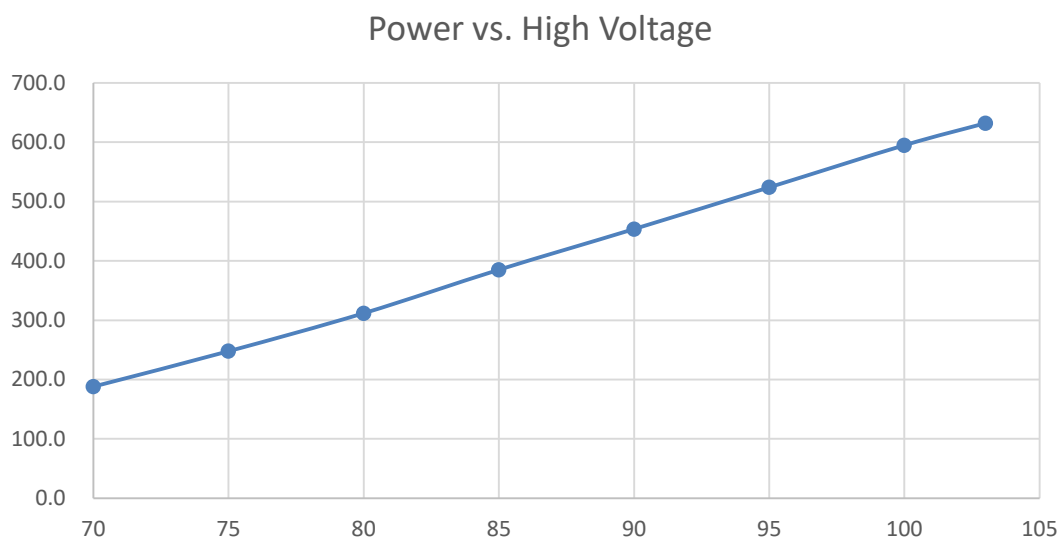
| Parameters | Design | Test |
|---|---|---|
| Operating frequency (MHz) | 650 | 650 |
| Beam Voltage (kV) | 81.5 | 80 |
| Beam Perveance ($\mu A/V^{3/2}$) | 0.65 | 0.7 |
| Efficiency(%) | 65 | 62 |
| Saturation Gain(dB) | ≥45 | 47 |
| Output power(kW) | 800 | 800 |
| 1 dB Bandwidth(MHz) | ≥1 | 1.8 |

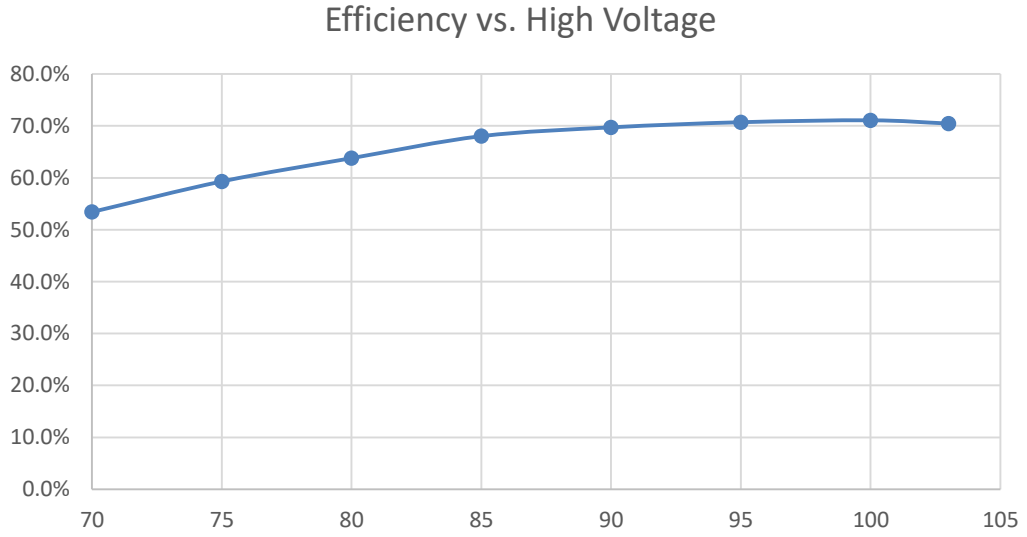


# HE Klystron Milestone

- 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
  - Cold high voltage conditioning
  - Cathode activation
  - High voltage conditioning
  - RF Conditioning(Pulsed and CW)
- Jul., 2022: CW 630kW/Eff. 70.5% of first stage high power test
- **Jan. 2024: Second stage high power test startup**

# High power conditioning and test



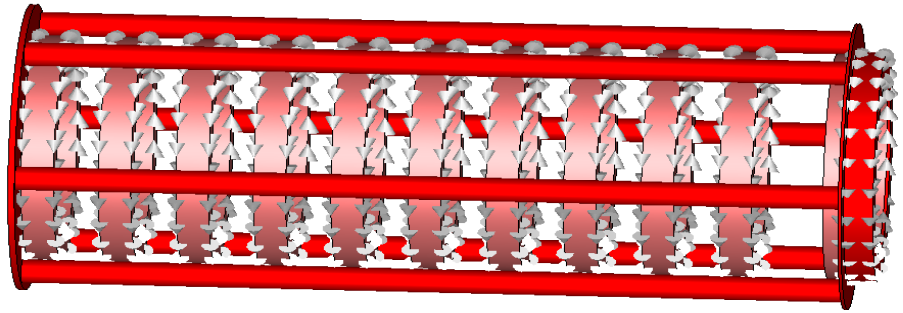

On Jul.5, 2022 for first stage test

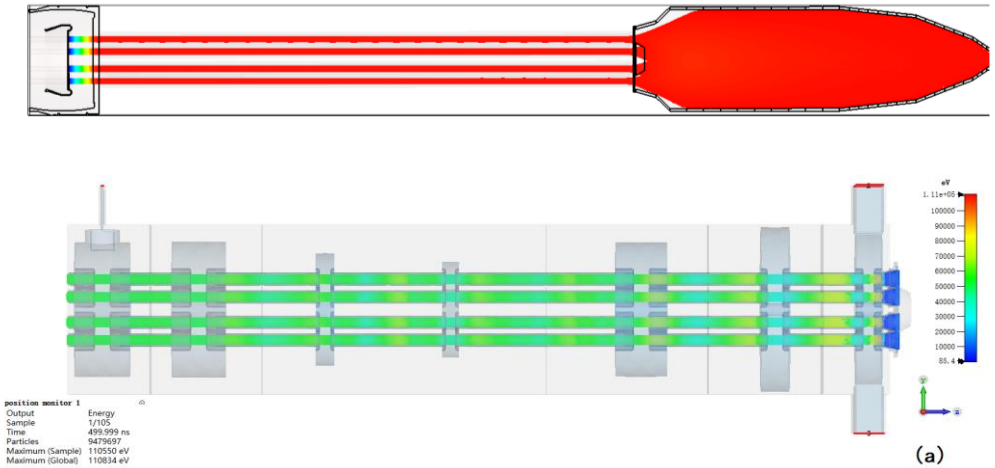
CW power: 630kW

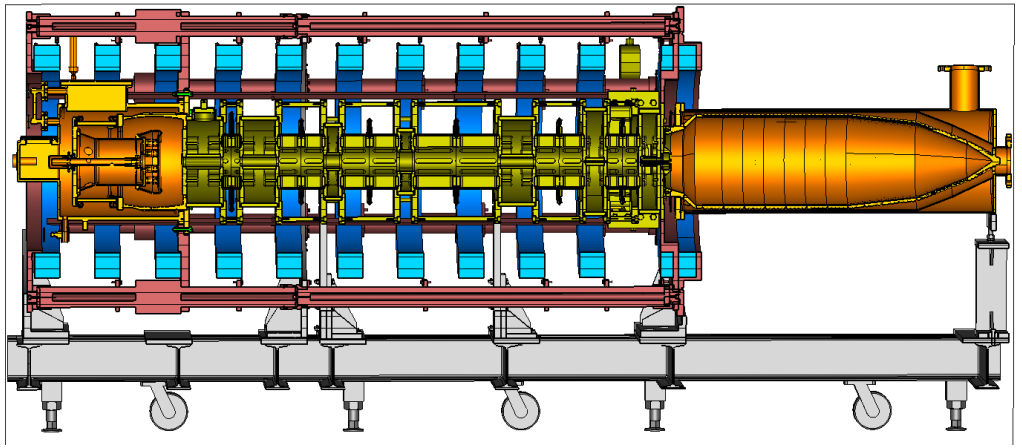
Eff. : 70.5%

# MBK design and fabrication status

| 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 Beam tester

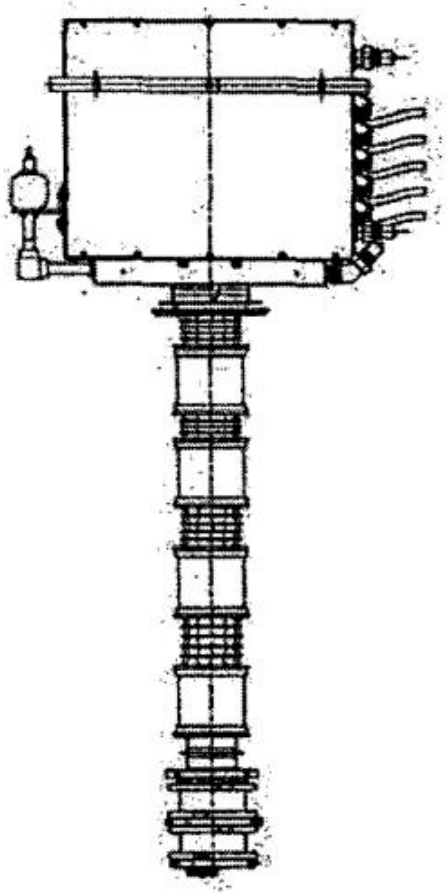
- Fabrication of MBK beam tester is completed(including electron gun, collector, focusing coil) and has been delivered to IHEP March of 2023. Accomplishment of MBK beam tester is at the end of 2023.

# Future plan

## Energy recovery klystron

# Current status

- CPI (USA) has developed multiple models of TV energy recovery klystron; NASA has also collaborated with CPI to develop satellite communication klystrons.
- There are also research institutions in Japan, the UK, and Russia do R&D on energy recovery klystrons, but klystron power level is very low(from several kW to tens of kW.



CPI klystron

NASA Klystron

# Roughly theoretical analysis

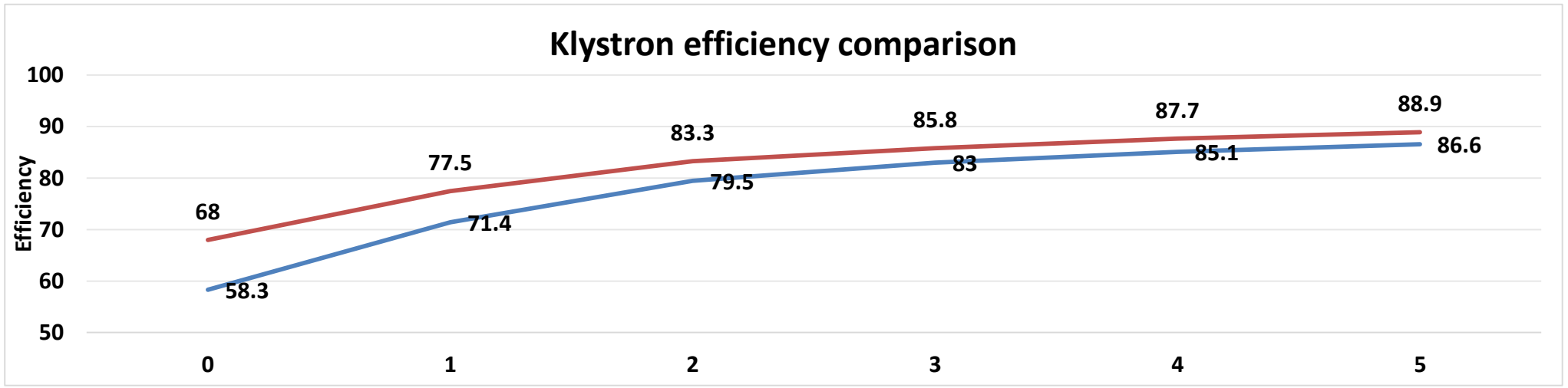
- Based on 1st and 2nd prototype, the efficiency on line region is 58% and 68% respectively (15% lower of saturation power level).

| Parameter | 1st prototype | 2nd prototype |
|---|---|---|
| Freq. (MHz) | 650 | 650 |
| Voltage (kV) | 82 | 110 |
| Current (A) | 16 | 9.1 |
| Beam No. | 1 | 1 |
| Perveance (μP) | 0.65 | 0.25 |
| **Saturation efficiency (%)** | **65** | **~80** |
| Power(kW) | 800 | 800 |

# 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% |



# Summary

- Research on high efficiency klystron is still undertaking for much higher efficiency.
- High power energy recovery klystron is being conducted for klystron efficiency improvement and operation cost decreased of large accelerator facility.
- This is expected to increase the current 68% linear efficiency to over 85%, even reach 90% with energy recovery klystron.

# Thanks for your attention!