650MHz/800kW Klystron Development at IHEP

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On behalf of HERSC (High Efficiency RF Source R&D Collaboration) in China

Presentation at the IAS Program on High Energy Physics
January 22, 2018, IAS, HKUST

HERSC effort

- IHEP team
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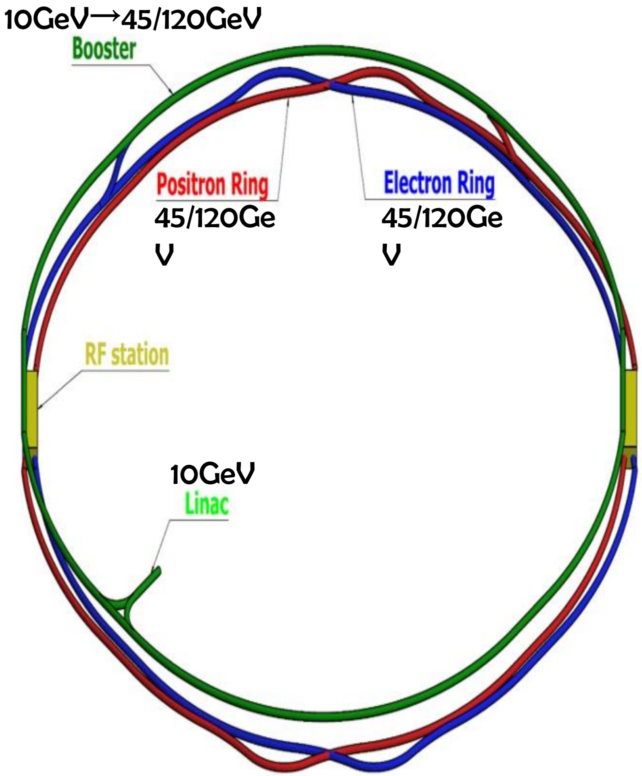
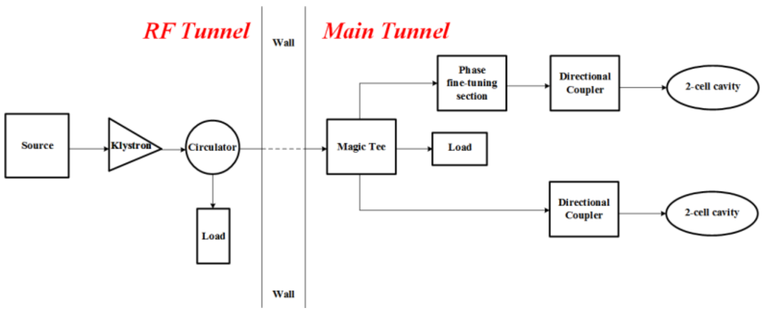
- Collaborators
  - IE (Institute of Electronics, CAS)
    - Xuhua Hu, Xiuxia Li, Yan Li, Yunfeng Liao, Xiaoxia Wang, Long Yao, Xiudong Yang, Jianyong Zhou, Rui Zhang, Zhiqiang Zhang, etc.
  - GLVAC (GLVAC Industrial Technology Research Institute for High Power Devices)
    - Mingkun Cao, Zhiqiang Cai, Hao Huang, Junjie Huang, Ming Lei, Yang Shen, Shaozhe Wang, Jingui Zhang, etc.

RF system for CEPC collider

CEPC schematic layout



RF unit for CEPC collider



Parameters for CEPC collider RF system

Parameters	Goal
Frequency (MHz)	650
Cell number per cavity	2
Input power per cavity (kW)	278
Total cavity number	336
Total input power (MW)	93.4
Cavity number per klystron	2
Klystron number	168

- 800kW saturated klystron output power by taking into account the transmission loss, the power reflection caused by the cavity mismatch and the operation margin for the LLRF system
- The higher the klystron efficiency, the lower the collider operation cost
- >80% ultimate goal for the 650MHz/800kW klystron

R&D plan from 2016 to 2018

- 3 klystron prototypes in 6 FYs
- FY 2016: done
  - Finalize the gun and the collector design of the 1st conventional klystron prototype (UHFKP8001, Ultra High Frequency band Klystron Prototype with 800kW output power)
  - Initialize the dynamics design of the UHFKP8001
- FY 2017: done
  - Finalize the interaction section and coil design of the UHFKP8001
  - Preliminary mechanical design of the UHFKP8001
- FY 2018: being carried out
  - Finalize the mechanical design and fabrication of the UHFKP8001
  - Infrastructure construction for the klystron brazing, baking and testing
  - Finalize the interaction section design of the 2nd high efficiency klystron prototype (UHFKP8002)
  - Design of the new gun and the new collector for the UHFKP8002

R&D plan from 2018 to 2021

- FY 2019
  - High power test of the UHFKP8001
  - Finalize the mechanical design and fabrication of the UHFKP8002
  - Finalize the interaction section design of the 3rd high efficiency klystron prototype (UHFKP8003), reuse the gun and the collector design for the UHFKP8002
- FY 2020
  - High power test of the UHFKP8002 (>75% efficiency to be expected)
  - Finalize the mechanical design and fabrication of the UHFKP8003
- FY 2021
  - High power test of the UHFKP8003 (>80% efficiency to be expected)
  - More klystron prototypes or klystron industrialization

Parameters for UHFKP8001

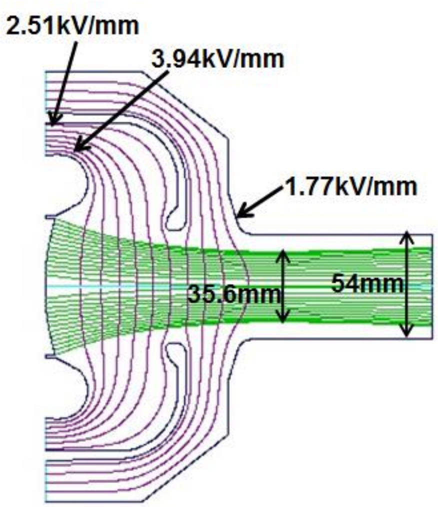
- Conventional method based on 2nd harmonic cavity to investigate the design and manufacture technologies for high power CW klystron

Main parameters	Goal
Frequency (MHz)	650
Vk (kV)	81.5
Ik (A)	15.1
Perveance (μP)	0.65
Efficiency (%)	>60
Saturated gain (dB)	>45
Output power (kW)	800
1dB bandwidth (MHz)	±0.5
Brillouin magnetic field (Gs)	106.7
Reduced plasma wavelength(m)	3.47
N cavities	6
Normalized drift tube radius	0.63
Normalized beam radius	0.41
Filling factor	0.65

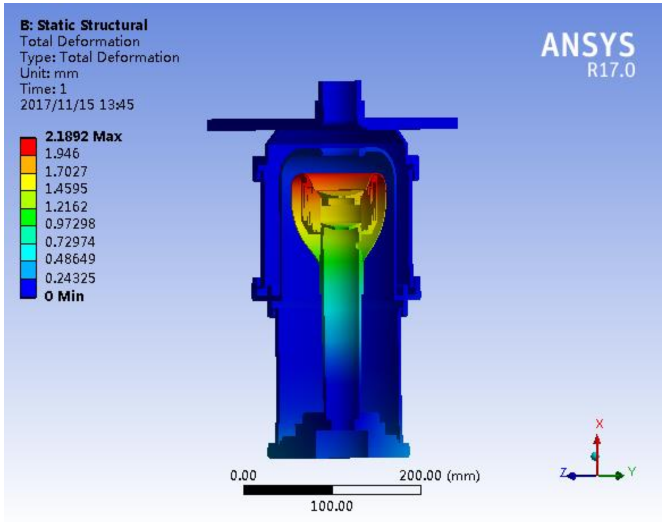
Electron gun for UHFKP8001

- Triode gun with the modulating anode for convenient adjustment of the beam perveance
- Φ10 hole at the cathode center to avoid damage by the ion bombardment

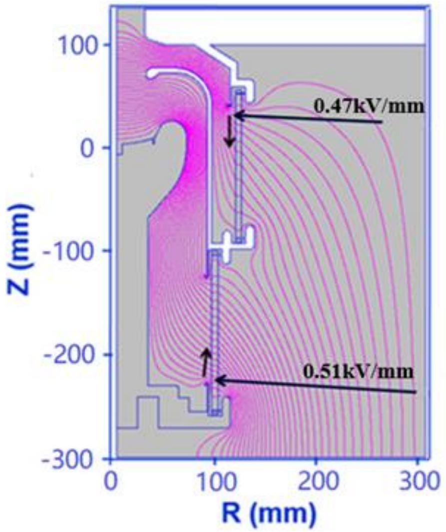
Main parameters	DGUN	EGUN	CST	Design goal
Beam waist radius (mm)	17.8	17.48	17.64	17.5
Perveance (μP)	0.64	0.64	0.64	0.65
Current density @ cathode (A/cm^2)	<0.45	0.39~0.43		<0.5
Current uniformity @ cathode (%)		9.8%		<10%



Beam optics



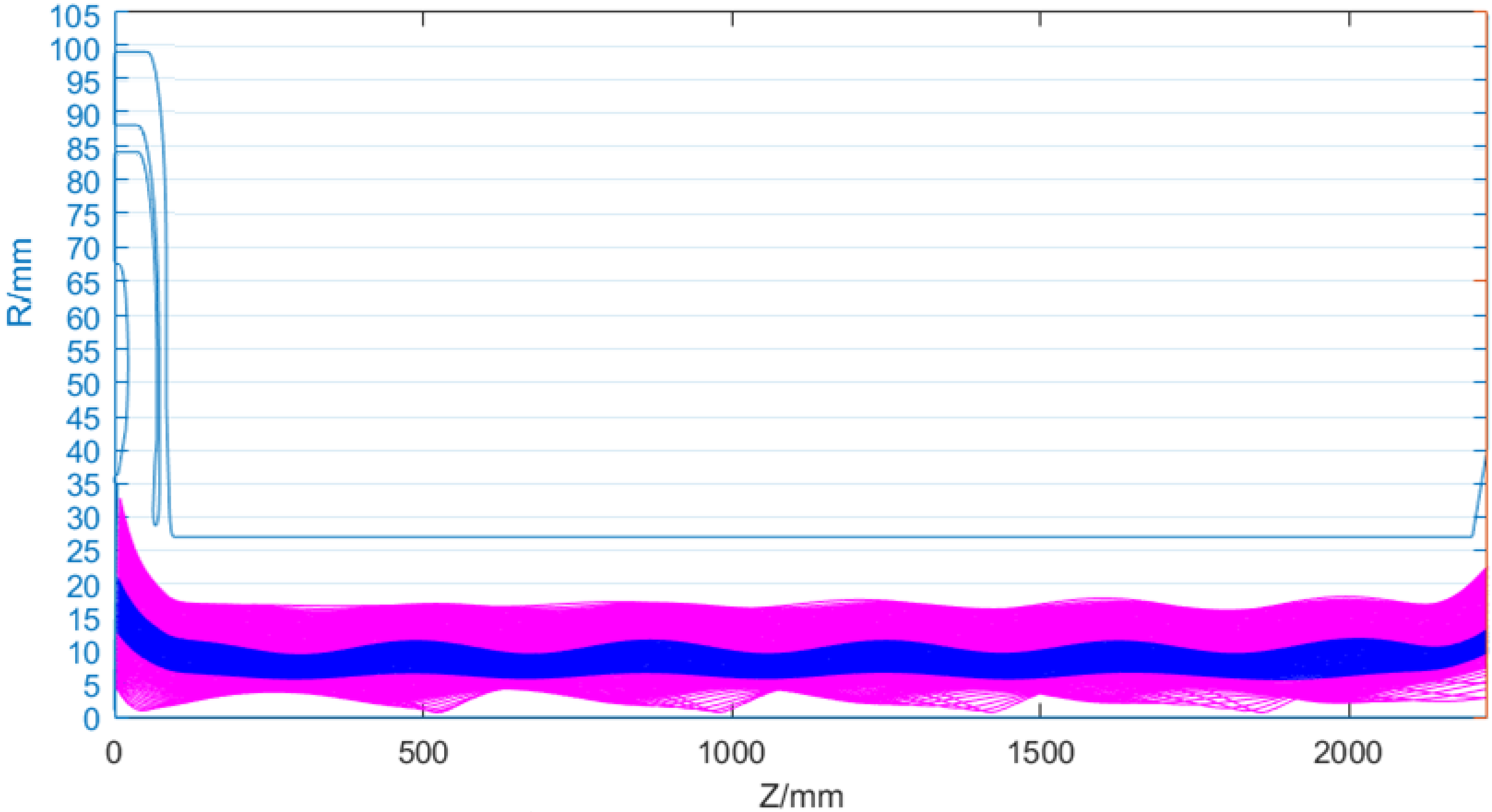
Thermal deformation



Electric field distribution

Beam optics for UHFKP8001

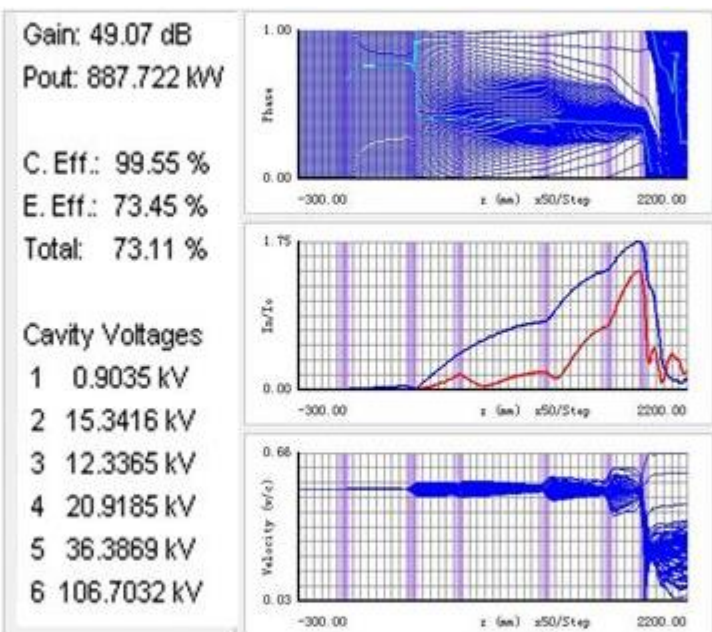
- Good laminarity without electron interception along the klystron
- Ripple rate less than 5%



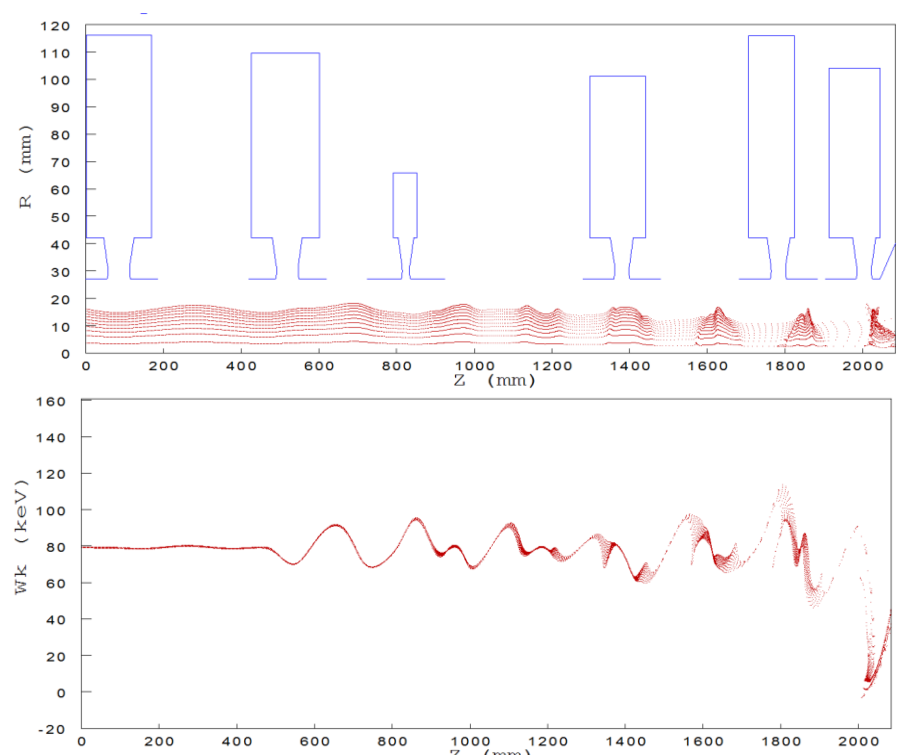
Electron beam trajectory without RF drive

Dynamics for UHFKP8001

- 1D optimization on the dynamics and crosschecked by 2D&3D
- 73%/68%/65% efficiencies for 1D/2D/3D respectively
- 888kW/827kW/790kW output power for 1D/2D/3D respectively



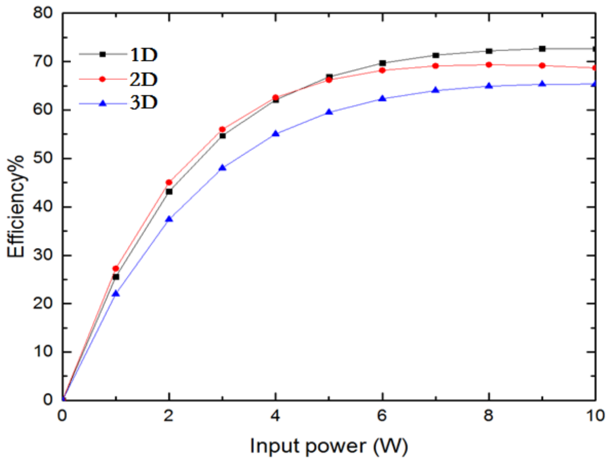
1D dynamics



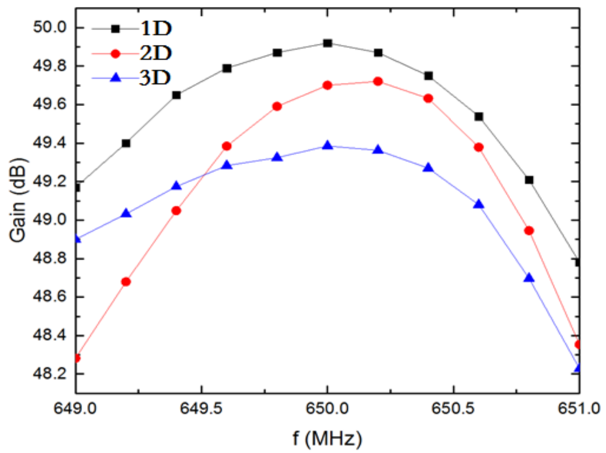
2D dynamics

Dynamics for UHFKP8001

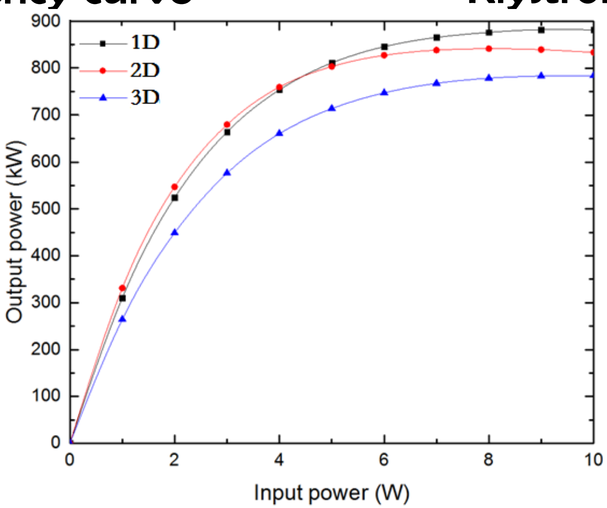
- 1dB bandwidth larger than ±0.5MHz, Saturated gain around 48dB



Klystron efficiency curve



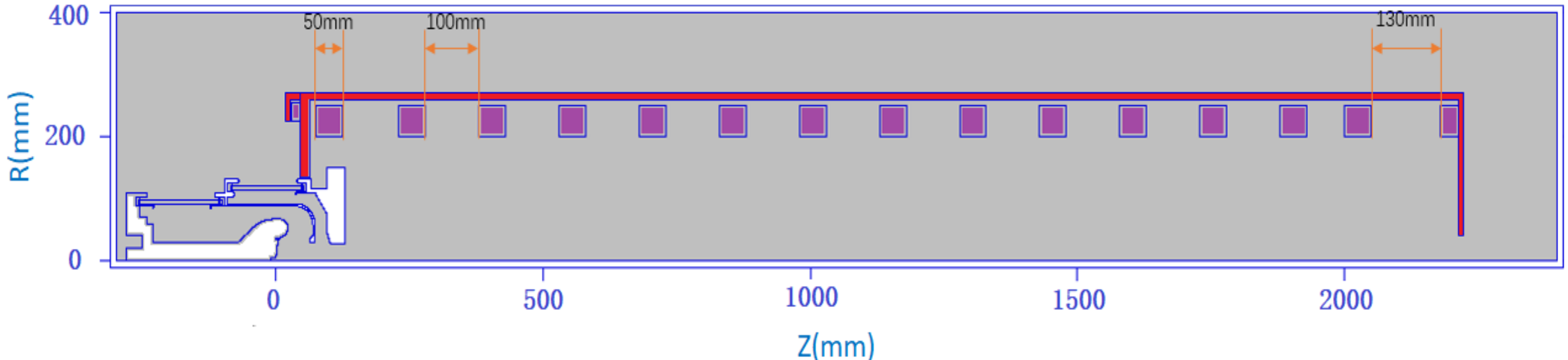
Klystron gain curve



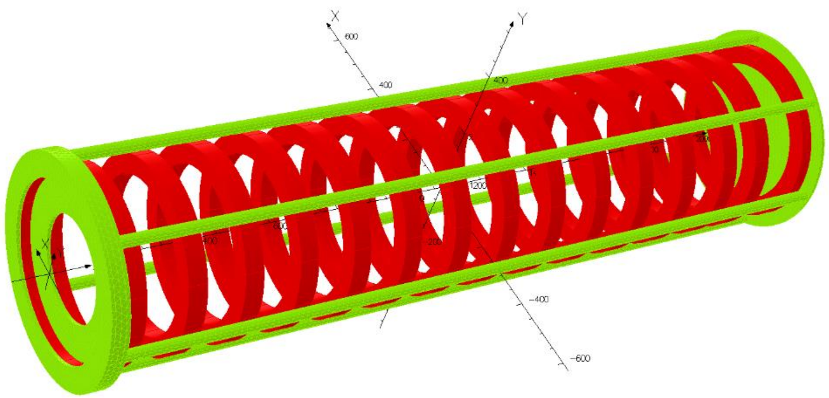
Klystron transfer curve

Coils for UHFKP8001

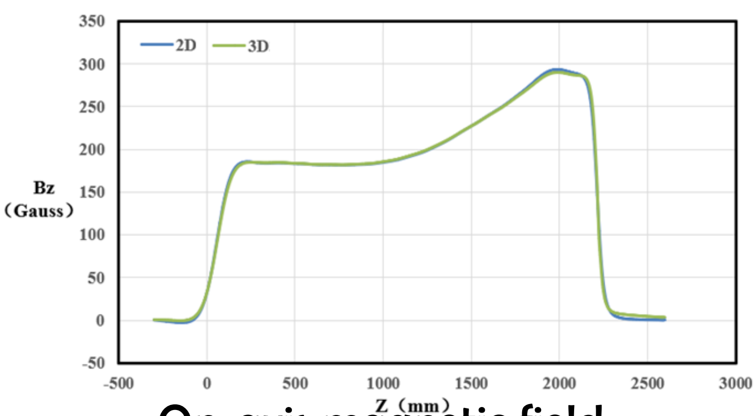
- Designed by 2D and crosschecked by 3D, very good consistency
- 15 regular coils with 1 bucking coil near the gun
- Cathode: 32 Gauss, Gain cavity: 180 Gauss, Output cavity: 270 Gauss



2D solenoid model



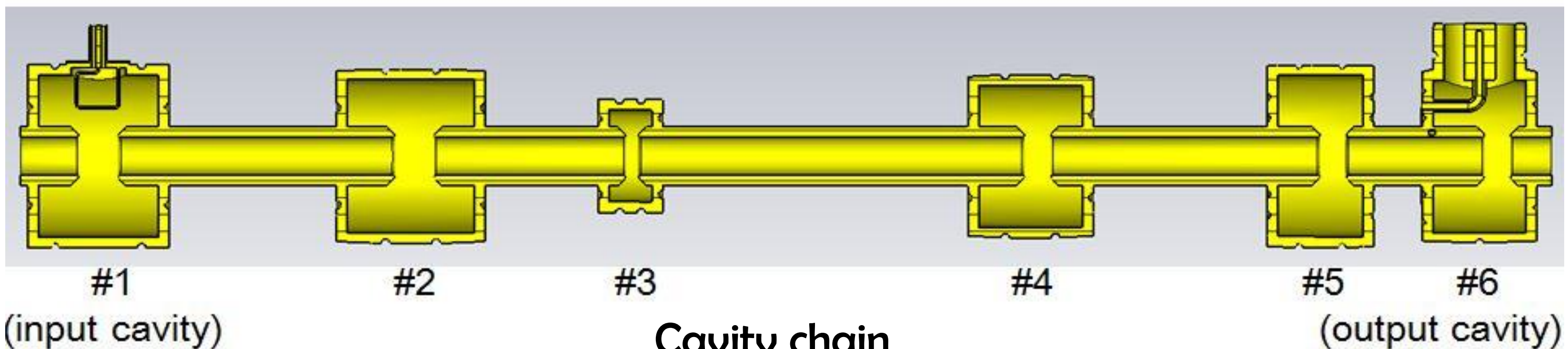
3D solenoid model



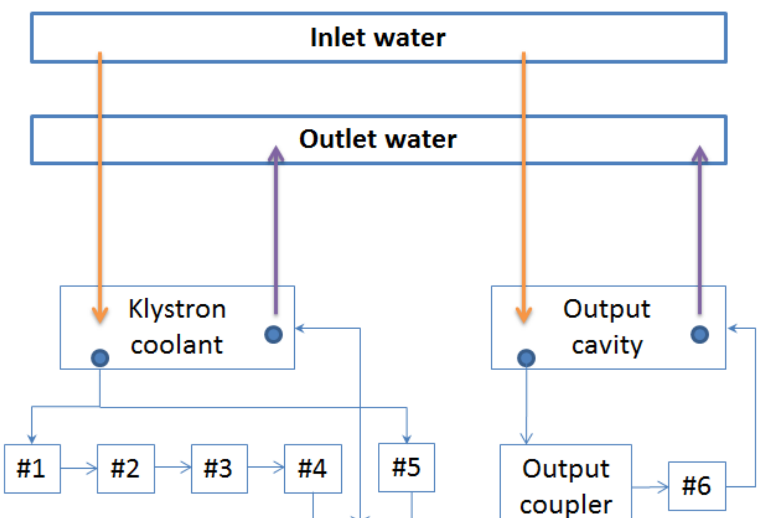
On-axis magnetic field

Cavity chain for UHFKP8001

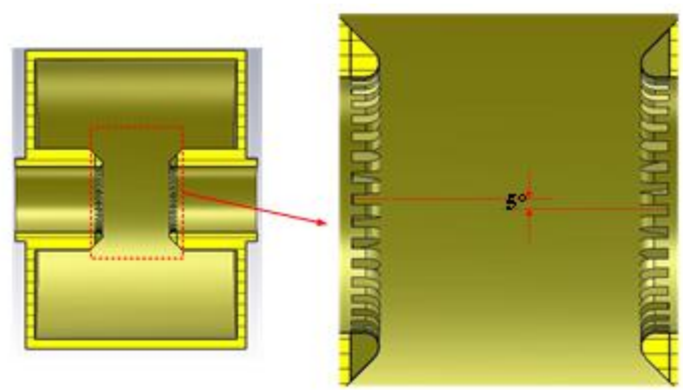
- RF design and cooling analysis conducted
- Grooved nose cone for each cavity to suppress the multipacting effect



Cavity chain



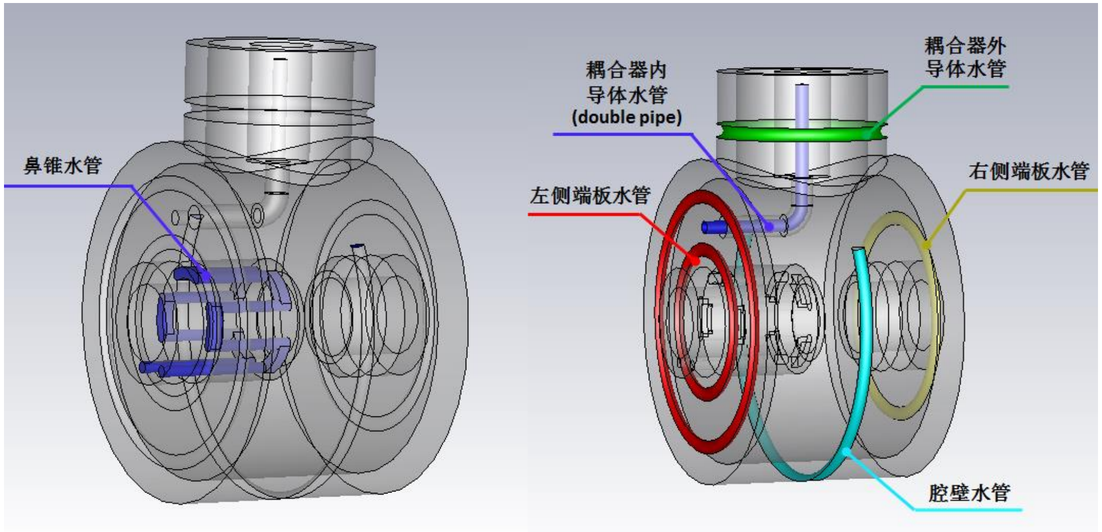
Klystron cavity chain cooling scheme



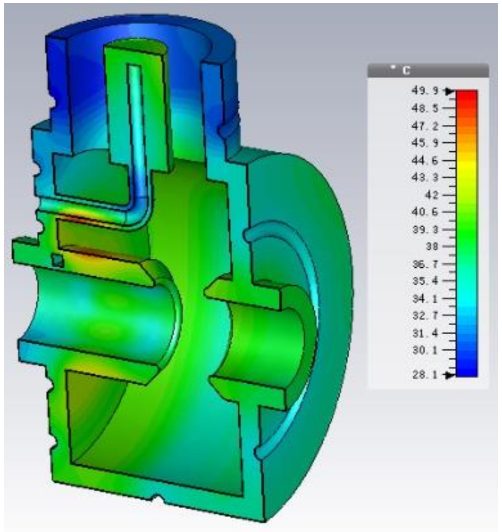
Grooved nose cone for each cavity

Output cavity cooling

- 87% of the total power loss for the cavity chain located at the output cavity
- Efficient cooling needed to guarantee the klystron operation stability
- Theoretical power loss around 3.9kW, cooling capability designed to be 8kW



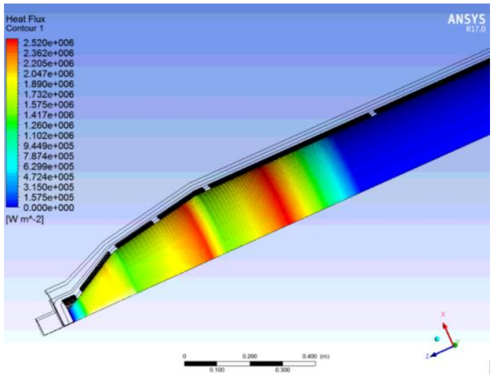
Cooling pipes distribution



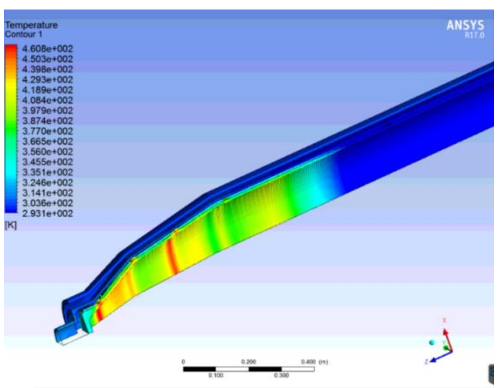
Temperature distribution

Collector for UHFKP8001

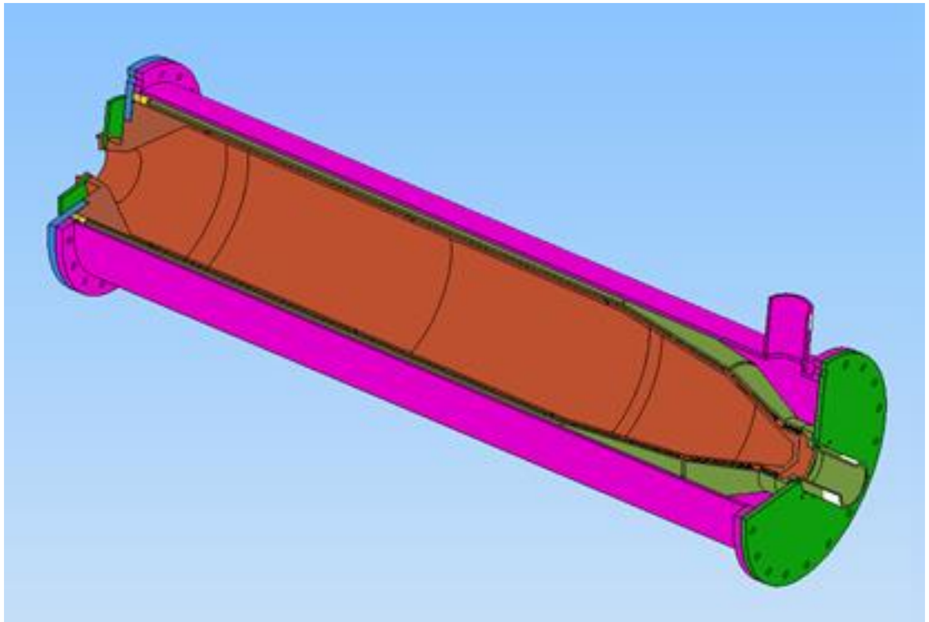
- ~2m long collector to sustain 1.23MW full beam power



Thermal load distribution



Temperature distribution

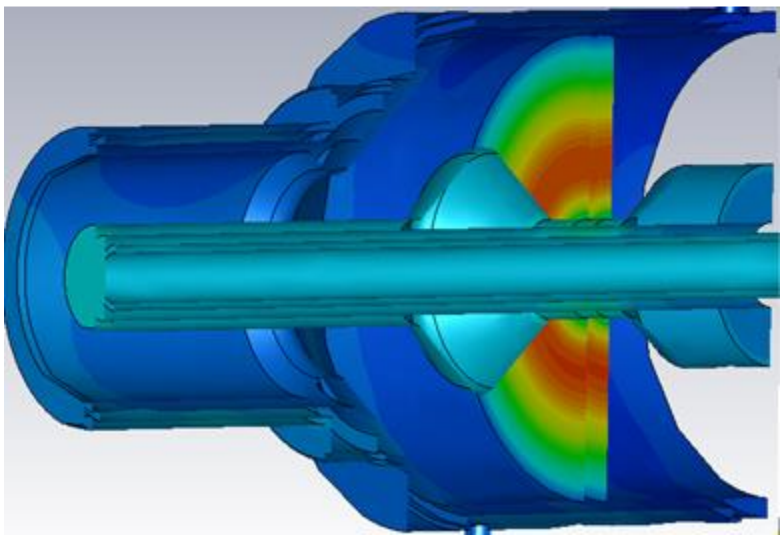


Mechanical design

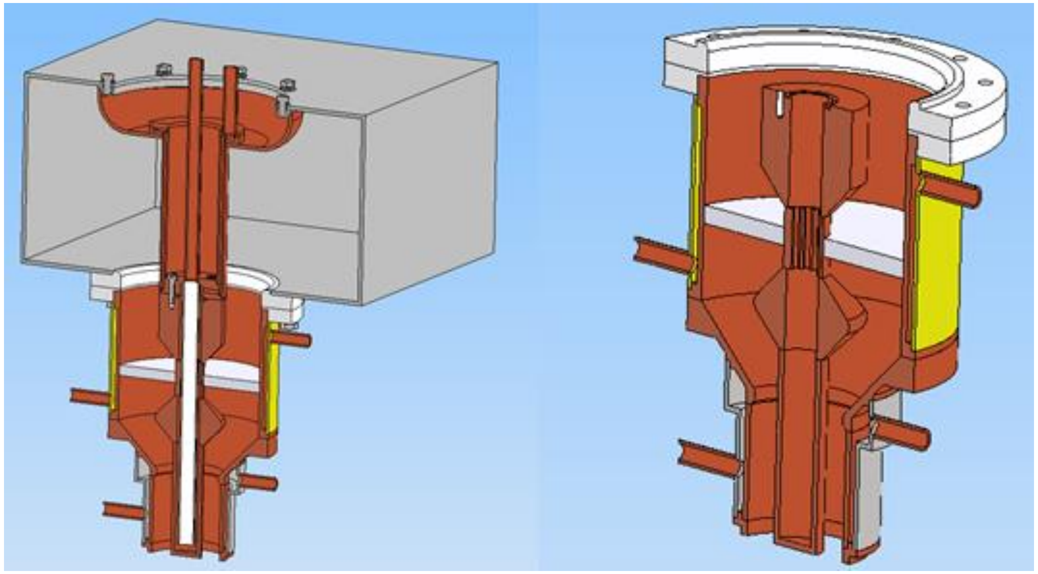
Duty factor (%)	Max. heat flux (W/cm²)	Max. stress (Mpa)	Max. temperature (°C)
100	210	158	187

Output window for UHFKP8001

- Relatively simple design with door knob to facilitate the fabrication
- >800kW capacity of CW RF power @ 650MHz
- <1.05 VSWR @ 650 $\pm$ 0.5MHz



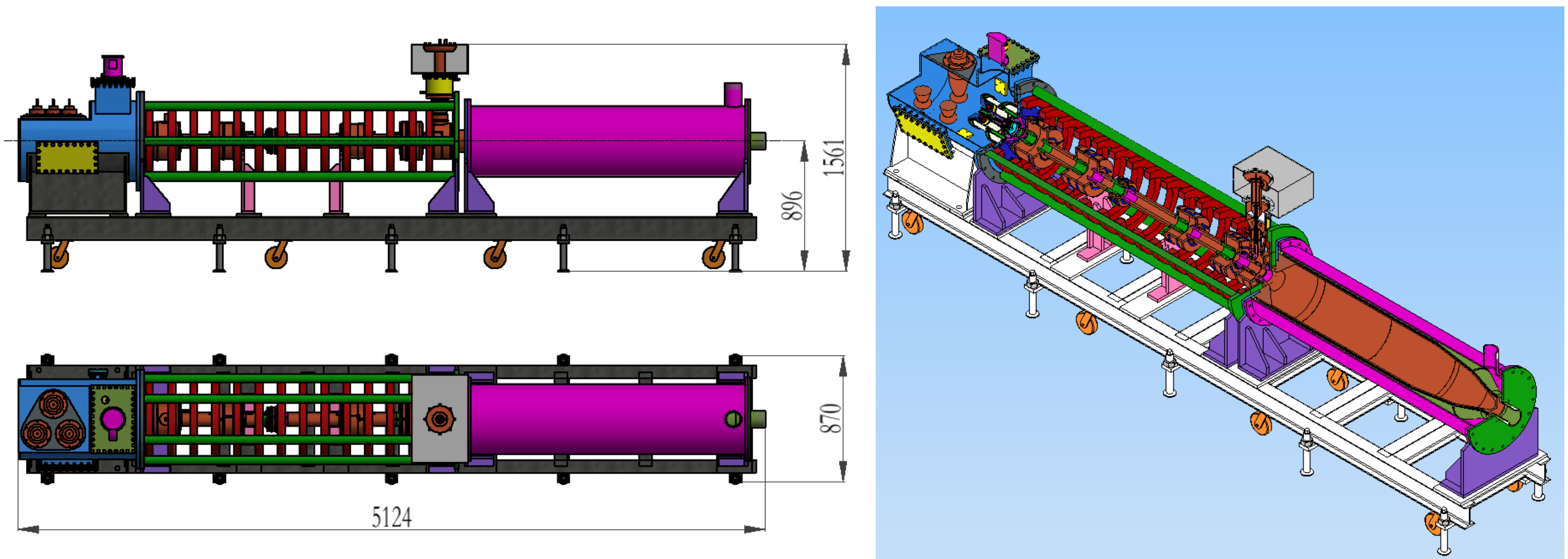
Temperature distribution



Mechanical design

Mechanical design for UHFKP8001

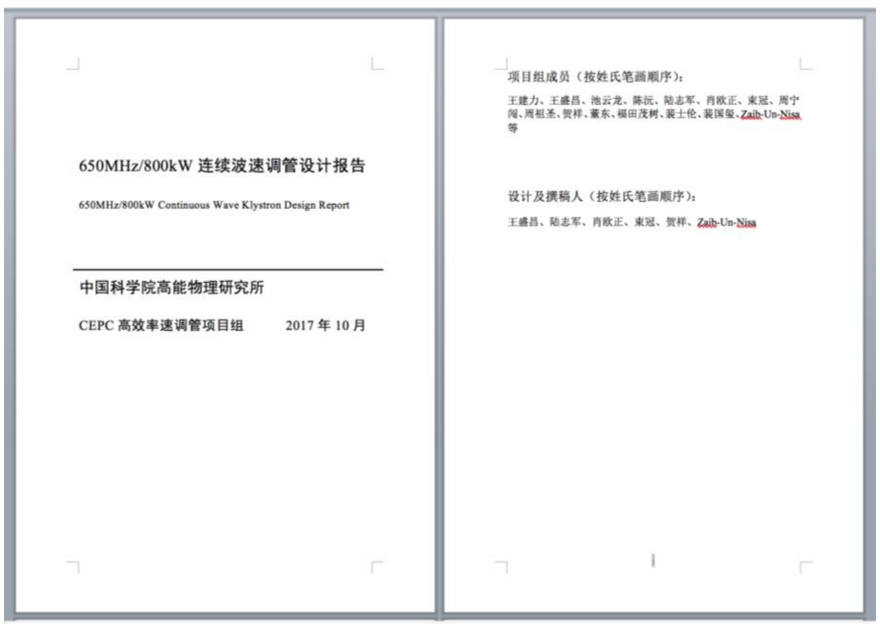
- China consortium HERSC (High Efficiency RF Source R&D Collaboration) established in 2017 for 650MHz/800kW klystron design and fabrication
- Preliminary mechanical design achieved (L×W×H: 5.12m×0.87m×1.56m)
- Discussion on the manufacturing details being conducted



Preliminary mechanical design for UHFKP8001

HERSC quarterly meeting

- Physical design report for UHFKP8001 released in October, 2017
- Quarterly meeting held inside HERSC, 1^{st} in November, 2017, 2^{nd} to be in March, 2018



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650MHz/800kW 连续波速调管设计报告

650MHz/800kW Continuous Wave Klystron Design Report

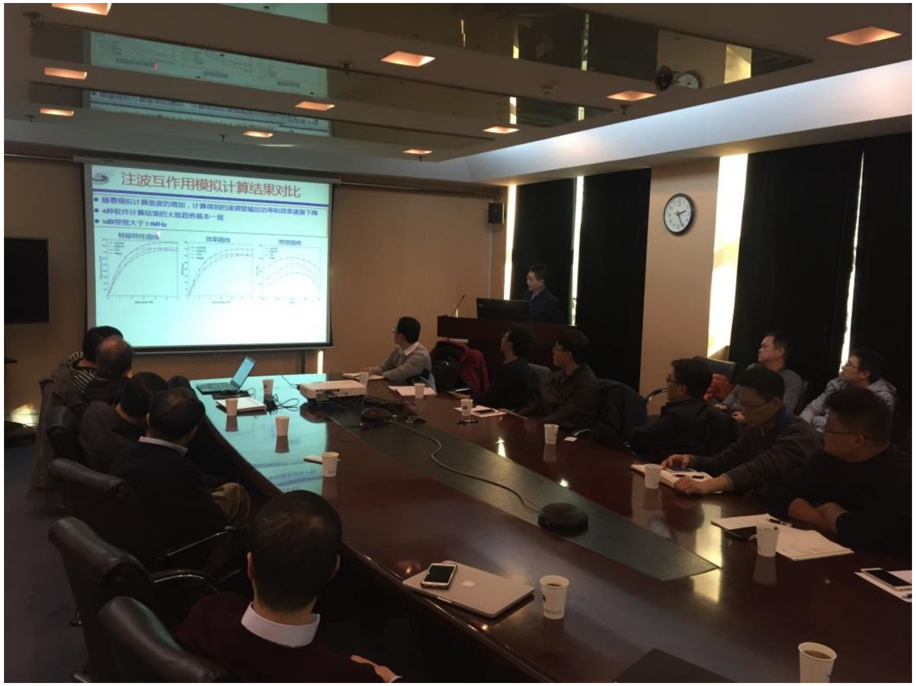
中国科学院高能物理研究所

CEPC 高效率速调管项目组 2017 年 10 月

设计及撰稿人（按姓氏笔画顺序）：

王盛昌、陆志军、肖欧正、東冠、贺祥、Zaib-Un-Nisa

Physical design report for UHFKP8001

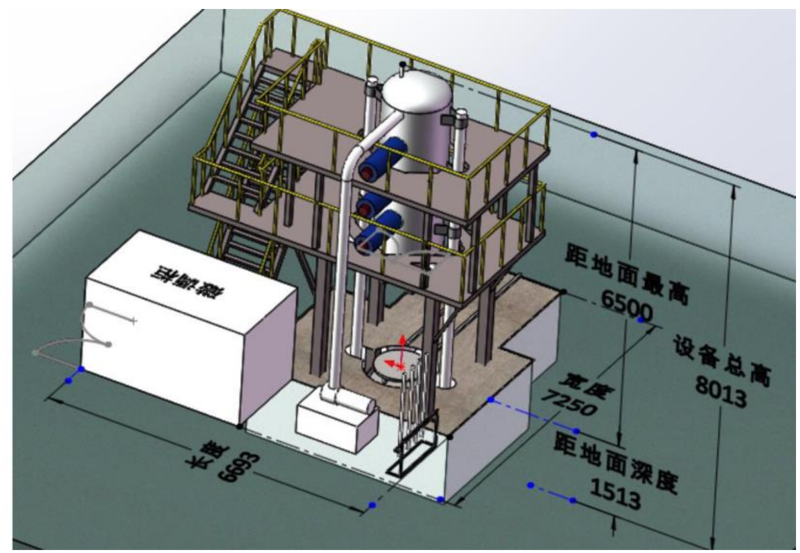


1^{st} HERSC meeting

Infrastructure construction

- GLVAC Industrial Technology Research Institute established in 2016 for large baking furnace construction (expect to put into use at end of 2018), supported by local government
- Klystron high power testing stand construction being conducted, supported by the PAPS project in Beijing

PAPS project being constructed



Sketch for the large baking furnace

Parameters for UHFKP8002

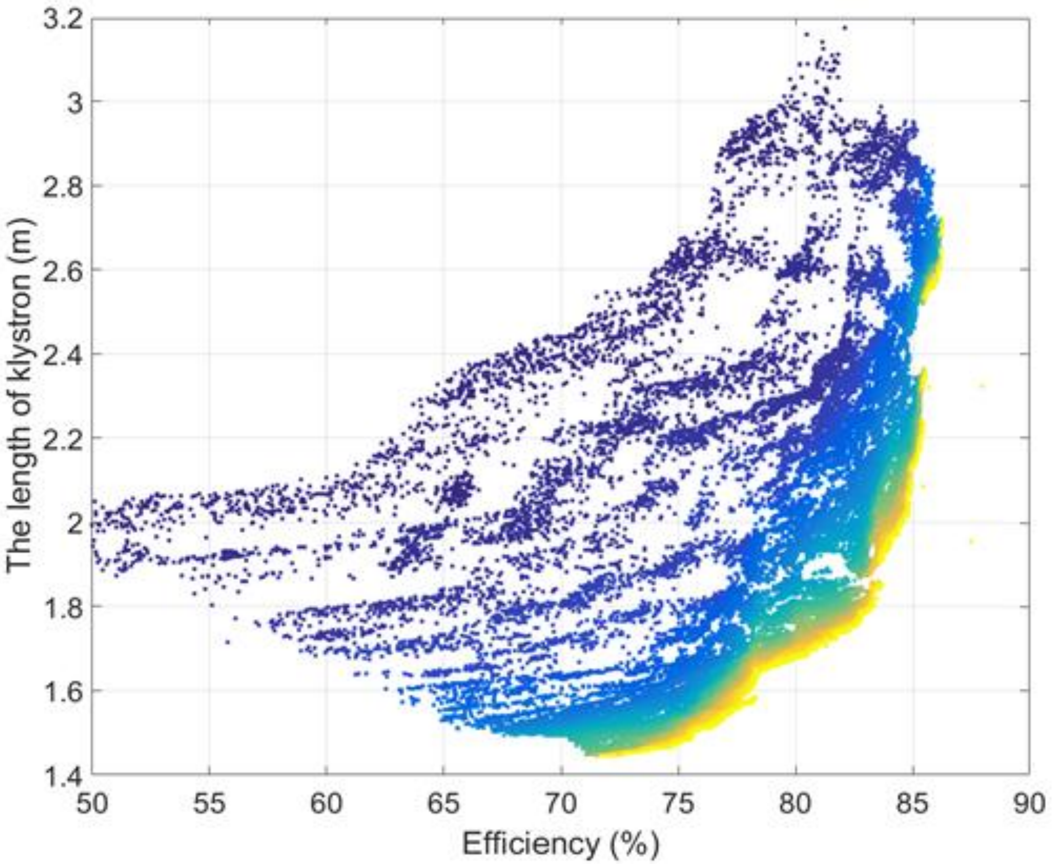
- To get higher efficiency than UHFKP8001, 3rd harmonic cavities were introduced, and the perveance was further lowered by increasing the gun voltage and reducing the beam current.

Main parameters	Goal for UHFKP8001	Goal for UHFKP8002
Frequency (MHz)	650	650
Vk (kV)	81.5	110
Ik (A)	15.1	9.1
Perveance (μP)	0.65	0.25
Efficiency (%)	>60	>70
Saturated gain (dB)	>45	>45
Output power (kW)	800	800
1dB bandwidth (MHz)	±0.5	±0.5
Brillouin magnetic field (Gs)	106.7	115.8
Reduced plasma wavelength(m)	3.47	6.46
N cavities	6	7
Normalized drift tube radius	0.63	0.38
Normalized beam radius	0.41	0.23
Filling factor	0.65	0.6

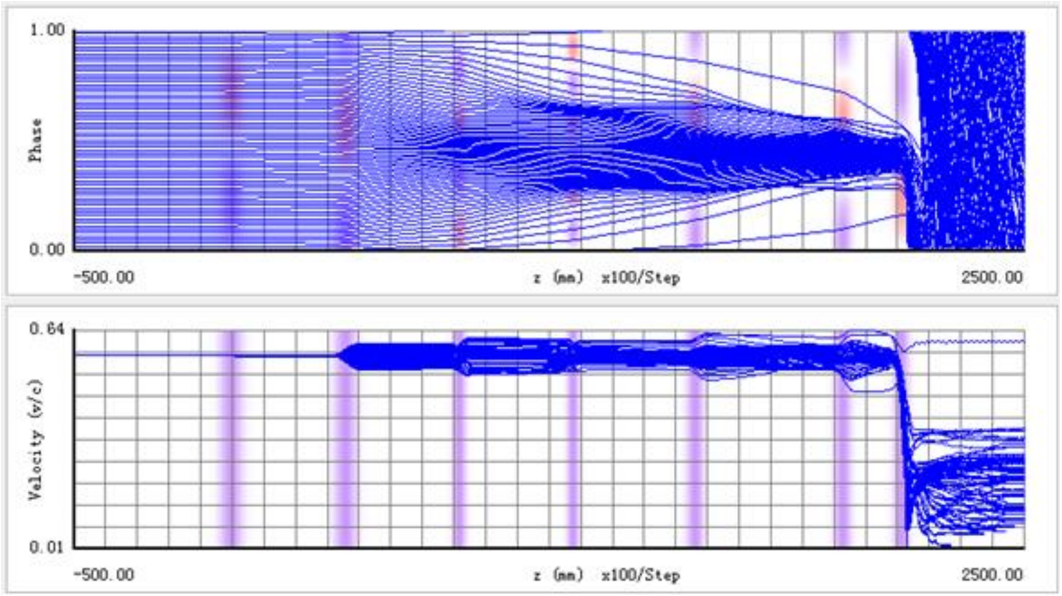
Automatic klystron optimization

- 1D automatic klystron optimization
  - MOGA, appropriate setting of the initial conditions and the final selection mechanism being deeply studied

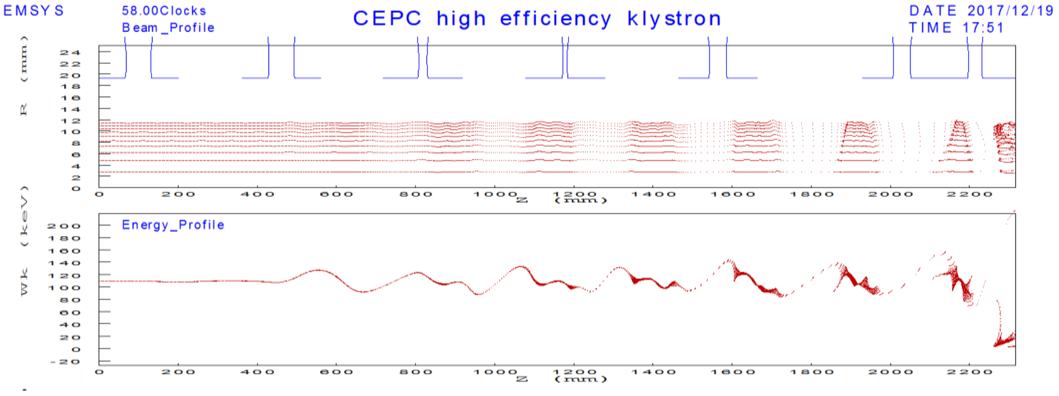
Typical example for klystron automatic optimization result (15 variables: 7 cavity frequencies, 6 cavity distances, 2 Qe; Targets: efficiency to be high as possible, total length to be short as possible; Constraints: positive minimum velocity, >±0.5MHz bandwidth)



Dynamics for UHFKP8002



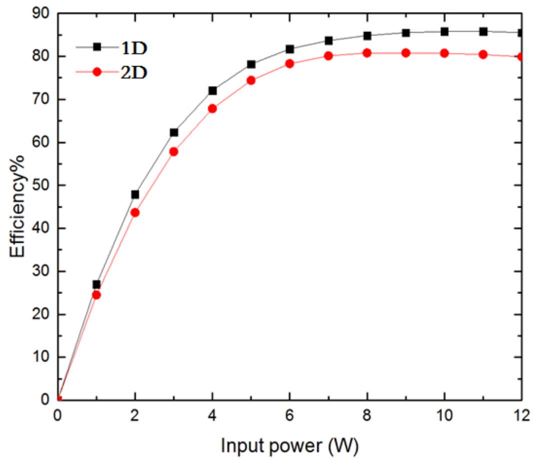
1D dynamics



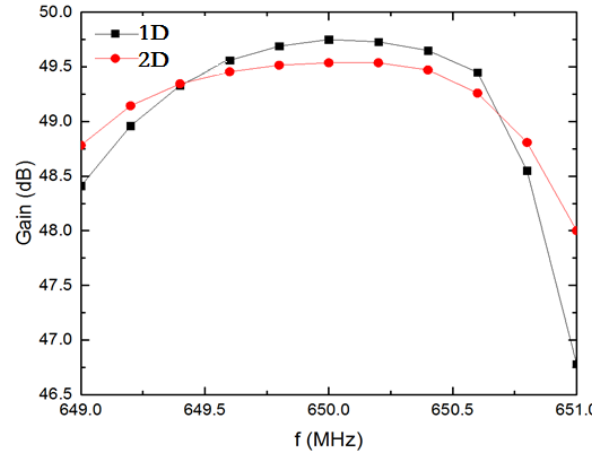
2D dynamics

Dynamics for UHFKP8002

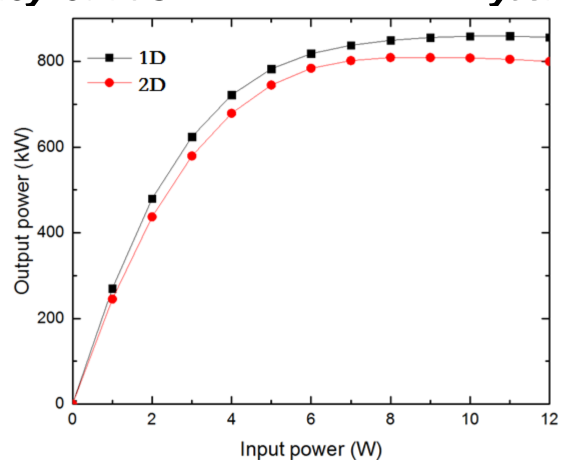
- 86%/81% efficiencies for 1D/2D respectively
- 859kW/809kW output power for 1D/2D respectively



Klystron efficiency curve



Klystron gain curve



Klystron transfer curve

Summary

- Based on the current mature technologies (low perveance electron gun and 2nd harmonic bunching), the physical design of the 1st klystron prototype UHFKP8001 has been finalized, the mechanical design is being carried out, the high power test is expected to be in 1 year later.
- The physical design of the high efficiency klystron prototype UHFKP8002 is being conducted, the electron gun perveance is lowered further by increasing the gun voltage and reducing the beam current. 3rd harmonic bunching is being studied.
- Automatic klystron optimization is being carried out.
- China consortium HERSC was established, infrastructure for UHF band klystron brazing and baking is being constructed.

Thanks for your attention!