650MHz/800kW Klystron Development at IHEP

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

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HERSC effort

• IHEP team
  – Yuan Chen, Yunlong Chi, Dong Dong, Shigeki Fukuda, Xiang He, Zhijun Lu, Cai Meng, Zaib Un Nisa, Guoxi Pei, Shilun Pei, Guan Shu, Ouzheng Xiao, Shengchang Wang, Fengli Zhao, Ningchuang Zhou, Zusheng Zhou, etc.

• 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.
The RF system for the CEPC collider is designed with a saturated klystron output power of 800 kW, taking into account the transmission loss, power reflection caused by cavity mismatch, and the operation margin for the LLRF system. The higher the klystron efficiency, the lower the collider operation cost. The ultimate goal for the 650 MHz/800 kW klystron is >80% efficiency.
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 2\textsuperscript{nd} harmonic cavity to investigate the design and manufacture technologies for high power CW klystron

<table>
<thead>
<tr>
<th>Main parameters</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>650</td>
</tr>
<tr>
<td>( V_k ) (kV)</td>
<td>81.5</td>
</tr>
<tr>
<td>( I_k ) (A)</td>
<td>15.1</td>
</tr>
<tr>
<td>Perveance (( \mu P ))</td>
<td>0.65</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>&gt;60</td>
</tr>
<tr>
<td>Saturated gain (dB)</td>
<td>&gt;45</td>
</tr>
<tr>
<td>Output power (kW)</td>
<td>800</td>
</tr>
<tr>
<td>1dB bandwidth (MHz)</td>
<td>( \pm 0.5 )</td>
</tr>
<tr>
<td>Brillouin magnetic field (Gs)</td>
<td>106.7</td>
</tr>
<tr>
<td>Reduced plasma wavelength (m)</td>
<td>3.47</td>
</tr>
<tr>
<td>N cavities</td>
<td>6</td>
</tr>
<tr>
<td>Normalized drift tube radius</td>
<td>0.63</td>
</tr>
<tr>
<td>Normalized beam radius</td>
<td>0.41</td>
</tr>
<tr>
<td>Filling factor</td>
<td>0.65</td>
</tr>
</tbody>
</table>
Electron gun for UHFKP8001

- Triode gun with the modulating anode for convenient adjustment of the beam perveance

- $\Phi 10$ hole at the cathode center to avoid damage by the ion bombardment

### Main parameters

<table>
<thead>
<tr>
<th>Main parameters</th>
<th>DGUN</th>
<th>EGUN</th>
<th>CST</th>
<th>Design goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam waist radius (mm)</td>
<td>17.8</td>
<td>17.48</td>
<td>17.64</td>
<td>17.5</td>
</tr>
<tr>
<td>Perveance ($\mu$P)</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.65</td>
</tr>
<tr>
<td>Current density @ cathode (A/cm²)</td>
<td>&lt;0.45</td>
<td>0.39~0.43</td>
<td>&lt;0.5</td>
<td></td>
</tr>
<tr>
<td>Current uniformity @ cathode (%)</td>
<td>9.8%</td>
<td>&lt;10%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Beam optics

Thermal deformation

Electric field distribution
Beam optics for UHFKP8001

- Good laminarity without electron interception along the klystron
- Ripple rate less than 5%
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
Dynamics for UHFKP8001

• 1dB bandwidth larger than $\pm 0.5$MHz, Saturated gain around 48dB
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
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 3.9 kW, cooling capability designed to be 8 kW

Cooling pipes distribution

Temperature distribution
Collector for UHFKP8001

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

<table>
<thead>
<tr>
<th>Duty factor (%)</th>
<th>Max. heat flux (W/cm²)</th>
<th>Max. stress (Mpa)</th>
<th>Max. temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>210</td>
<td>158</td>
<td>187</td>
</tr>
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</table>
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 ± 0.5MHz
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 ($L \times W \times H$: 5.12m $\times$ 0.87m $\times$ 1.56m)
- Discussion on the manufacturing details being conducted
HERSC quarterly meeting

• Physical design report for UHFKP8001 released in October, 2017

• Quarterly meeting held inside HERSC, 1st in November, 2017, 2nd to be in March, 2018
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.
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.

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<th>Goal for UHFKP8002</th>
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<tr>
<td>Efficiency (%)</td>
<td>&gt;60</td>
<td>&gt;70</td>
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<td>800</td>
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<tr>
<td>1dB bandwidth (MHz)</td>
<td>±0.5</td>
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<td>N cavities</td>
<td>6</td>
<td>7</td>
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<td>0.38</td>
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<td>0.41</td>
<td>0.23</td>
</tr>
<tr>
<td>Filling factor</td>
<td>0.65</td>
<td>0.6</td>
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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, $>\pm 0.5\text{MHz}$ 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
Summary

• Based on the current mature technologies (low perveance electron gun and 2\textsuperscript{nd} harmonic bunching), the physical design of the 1\textsuperscript{st} 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. 3\textsuperscript{rd} 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!