WP4: RF systems

Update on the 36 GHz and 48 GHz power sources

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Outline

• Research groups (Strathclyde & UESTC)
• Motivation
• Principles of klystron and gyro-klystron
• 36GHz 2 MW gyroklystron simulation results
  – MIG gun
  – Cavity simulation
• 36 GHz 3 MW gyroklystron simulation results
• 48 GHz 1.5 MW studies
Motivation

- **Accelerator (High acceleration gradient, CERN)**
  - Higher operating frequency
  - Breakdown limit

- **Microwave undulator (WP5)**
  - Smaller period requires higher frequency
  - High power required

- **Lineariser (CompactLight, Cockcroft Institute)**
  - Correct the longitudinal phase space non-linearity from X-band linac
    - compensate for the curvature imposed on the bunch by the fundamental by adding harmonic
  - 3\textsuperscript{rd} (36GHz) or 4\textsuperscript{th} (48GHz) harmonic of X-band (12GHz) LINAC frequency
    - the higher the harmonic, the less amplitude (and thus RF power) required
    - The higher the frequency and power the shorter the lineariser

- **Design targets**
  - Gyro-klystron (amplifier, narrow bandwidth)
  - 36 GHz, >2MW
    - Design for 48 GHz, 1.5MW output power (Laurence Nix)
  - Pulse duration 2 us, PRF 100 Hz.
MW amplifiers

X-band (~12 GHz) klystrons

<table>
<thead>
<tr>
<th></th>
<th>SLAC XL4,5</th>
<th>CPI 8311A</th>
<th>Toshiba E3768B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>11.424</td>
<td>11.994</td>
<td>11.424</td>
</tr>
<tr>
<td>Beam Voltage (kV)</td>
<td>440</td>
<td>410</td>
<td>500</td>
</tr>
<tr>
<td>Beam Current (A)</td>
<td>350</td>
<td>310</td>
<td>270</td>
</tr>
<tr>
<td>Peak Power (MW)</td>
<td>50</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>50</td>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td>Efficiency</td>
<td>40%</td>
<td>40%</td>
<td>55%</td>
</tr>
</tbody>
</table>

Klystrons: Operating frequency determined by the cavity size, difficult to achieve high power at high frequency
Klystrons & Gyroklystrons

- **Conventional klystron**
  - Bunching in axial direction, TM modes
  - Operating frequency determined by the cavity size, difficult to achieve high power at high frequency
  - High beam voltage, high frequency leads to small cavity gap
  - To reduce the space charge effect and get higher power (still small dimensions)
  - Multiple-beam klystron
  - Sheet-beam klystron

- **Gyro-klystron**
  - Bunching in azimuthal direction. TE modes.
  - Lower axial velocity due to the beam alpha results in larger cavity size.
  - Operating frequency determined by the external magnetic field.
  - Open output cavity, high power capability.
## Ka-band gyro-klystron at UESTC

### Medium-power demonstration version

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power (kW)</td>
<td>260</td>
</tr>
<tr>
<td>Beam voltage (kV)</td>
<td>68</td>
</tr>
<tr>
<td>Beam current (A)</td>
<td>11</td>
</tr>
<tr>
<td>Magnetic field (T)</td>
<td>1.32</td>
</tr>
<tr>
<td>Output frequency (GHz)</td>
<td>33.98</td>
</tr>
<tr>
<td>Drive power (W)</td>
<td>40</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>38.8</td>
</tr>
<tr>
<td>Efficiency</td>
<td>40%</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>280</td>
</tr>
</tbody>
</table>

- Dual-anode MIG gun.
- Beam alpha 1.2
- Magnetic field compression ratio 7.8
Ka-band gyroklystron at UESTC

Measurement setup
PRF 220 Hz

The TE01 output mode pattern captured on film

Successfully verified the design, further improvements on the electron gun and collector are required.
### 36 GHz, 2 MW gyro-klystron design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (kV)</td>
<td>95</td>
</tr>
<tr>
<td>Current (A)</td>
<td>45</td>
</tr>
<tr>
<td>Velocity ratio</td>
<td>1.3</td>
</tr>
<tr>
<td>Drive power (W)</td>
<td>200</td>
</tr>
<tr>
<td>Beam guide radius (mm)</td>
<td>2.3</td>
</tr>
<tr>
<td>Magnetic field (T)</td>
<td>1.33</td>
</tr>
<tr>
<td><strong>Result</strong></td>
<td></td>
</tr>
<tr>
<td>Power (MW)</td>
<td>1.9</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>0.3%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>44%</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>39 (max 42)</td>
</tr>
</tbody>
</table>

- MIG-type electron gun
- Three-cavity structure
- TE01 mode for input and intermediate cavity
- TE02 for output cavity
Electron gun and cavity

- Three-cavity structure
- The operating mode of input and buncher cavity are TE01. The mode of output cavity is TE02, to have larger power capability.

\[ B_0 (T) = 1.34 \, T \]

① is the input cavity, ② is the 1\textsuperscript{st} drift tunnel, ③ is the bunching cavity, ④ is the 2\textsuperscript{nd} drift tunnel, ⑤ is the output cavity and ⑥ is the collector.

<table>
<thead>
<tr>
<th>Structure</th>
<th>F</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity 1</td>
<td>35.25</td>
<td>52.6</td>
</tr>
<tr>
<td>Cavity 2</td>
<td>34.58</td>
<td>23.5</td>
</tr>
<tr>
<td>Cavity 3</td>
<td>35.79</td>
<td>78.6</td>
</tr>
</tbody>
</table>
PIC simulations results

Output cavity
Gain curves in simulations

- Output power $P_{out}$ vs. Input power $P_{in}$ (W)
- Gain $G$ (dB) vs. Voltage $V_0$ (kV)
- Output power $P_{out}$ vs. Current $I_0$ (A)
- Efficiency $E_f$ vs. Frequency $f$ (GHz)
### 36 GHz 3 MW gyroklystron design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (kV)</td>
<td>150</td>
<td>Current (A)</td>
<td>45</td>
</tr>
<tr>
<td>Velocity ratio</td>
<td>1.4</td>
<td>Drive power (W)</td>
<td>400</td>
</tr>
<tr>
<td>Beam guide radius (mm)</td>
<td>2.3</td>
<td>Magnetic field (T)</td>
<td>1.46</td>
</tr>
</tbody>
</table>

**Result**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>3.0</td>
<td>Bandwidth</td>
<td>0.3%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>44%</td>
<td>Gain (dB)</td>
<td>39 (max 42)</td>
</tr>
</tbody>
</table>

- Similar configuration but with a higher operating voltage
  - it is challenging to increase the current using an MIG, it will reduce the beam quality, reducing the interaction efficiency
36GHz simulation results

Current $I_0$ (A) 45
Anode voltage $V_0$ (kV) 150
Modulating anode voltage $V_m$ (kV) 38.5
Magnetic field @ gun exit $B_0$ (T) 1.34
Magnetic compression ratio $f_m$ 10.5
Velocity ratio $\alpha$ 1.32
Axial velocity spread $\Delta \beta_z$ (%) 2.25
Mean guiding center $r_{g0}$ (mm) 2.5
Collector design

Electron beam power 6.75 MW;
Output microwave power 2.77 MW;
Power loss 100 kW;
Power in the spent beam 3.88 MW;
The designed collector power density is 85W/cm².
48 GHz 1.5 MW Gyroklystron

PhD student: Laurence Nix

• Higher frequency, smaller dimensions has limit in the beam current due to the space charge effect
• Higher operating voltage up to 300 kV is being investigated
• Higher operating mode than the $\text{TE}_{02}$ is being studied.
• Improved inverse-MIG gun for the gyrokystron
Preliminary results

• TE01 mode in an example gyro-klystron cavity ready for further design work to determine optimal frequency and properties

Configuration of MIG and IMIG. An example from KIT for 2MW coaxial-cavity gyrotron. Inverted MIG allows a larger emitter ring to have larger beam current and is able to produce a high quality beam.
Acknowledgement

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Thank you for your attention!