Development of MW-level Ka-band Gyroklystrons

Liang Zhang

on behalf of research teams of
Department of Physics, SUPA, University of Strathclyde, Glasgow, UK
Electronic Engineering department, UESTC, Chengdu, China
Outlines

• Research groups (Strathclyde & UESTC)
• Motivation
• Principles of klystron and gyroklystron
• Simulation results
  – MIG gun
  – Cavity simulation
ABP group, Physics department, University of Strathclyde, Glasgow, UK

- Founded in 1978 by Prof. Alan Phelps
- **Group member**
  - 5 academic staff
  - 10 research staff
  - 6 PhD students
  - 1 technician

Successful high-power microwave sources built include FEL, CARM, gyrotron, gyro-TWA, BWO, Cherenkov maser & superradiant sources.

Accelerator relevant projects: DATA (dielectric and THz acceleration, CI), UK XFEL (Microwave Undulator, CI), MICE (Muon Ionisation Cooling Experiments, RAL), CompactLight project, WP4).

Present interests range from 200MHz to 1THz
High power millimetre wave technology group, Electronic Engineering department, University of Electronic Science and Technology of China, ChengDu, China

- **Lead by Prof. Yong Luo**
- **Group member**
  - 4 academic staff
  - 12 research staff
  - 11 PhD + 40 master students
  - 30 technicians

**Research covers:**
Millimeter and sub-millimeter high power microwave sources, including gyrotron, gyroklystron, gyro-TWT. High efficiency, compact sources. Reliability and stability testing. Digital control and online diagnostics systems. Modulation power supplies for vacuum electron devices.
Capabilities of Both groups

INTEGRATED CAPABILITY from IDEA to DEMONSTRATOR

- Theory & New concepts
- Modelling & Simulations
- Design Construction & Experiments
- Effects Tests & Applications
- Technology Transfer to Industry & Manufacturability

- Cathode & Electron gun
- High Voltage Power Supply
- Beam voltage & current diagnostics
- Guide magnetic field
- Beam/wave interaction region
- Output window & antenna
- Vacuum
- Guide magnetic field

INTEGRATED CAPABILITY from IDEA to DEMONSTRATOR
Motivation

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

- **Microwave undulator (Design for UK-XFEL)**
  - Smaller period requires higher frequency
  - High power required (0.3 GeV/m ~ 1T).

- **Lineariser (Cockcroft Institute, CompactLight)**
  - Correct the longitudinal phase space non-linearity from RF acceleration
  - 3\textsuperscript{rd} or 4\textsuperscript{th} harmonic of X-band RF LINAC frequency

- **Design targets**
  - Gyroklystron (amplifier, narrow bandwidth)
  - 36 GHz and 48 GHz, 2 MW or 1.5MW output power.
  - Pulse duration 2 us, PRF 100 Hz.
Microwave sources

- Oscillators:
  - Backward wave oscillator (GW-level)
  - Gyrotron (ITER)
  - Magnetron (industry heating)

- Amplifiers:
  - TWT (wide bandwidth, lower gain, communications)
  - Klystron (narrow bandwidth, high gain for accelerators and radars)
  - Cyclotron Autoresonance Maser (CARM, high frequency)
# Commercial klystrons

- **S-band (3 GHz)**
- **C-band (6 GHz)**
- **X-band (~12 GHz)**

<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><strong>50</strong></td>
<td><strong>50</strong></td>
<td><strong>75</strong></td>
</tr>
<tr>
<td>RF Pulse width (us)</td>
<td>1.5 @ 60Hz</td>
<td>1.5</td>
<td>1.6</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

- 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 lead to small cavity gap.
  - To reduce the space charge effect and get higher power. (still small dimensions)
  - Multiple-beam klystron
  - Sheet-beam klystron

- Gyroklystron
  - 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.

![Klystron Diagram](image1)

![Gyrolystron Diagram](image2)
Ka-band gyrokystron at UESTC
Low-power demonstration version

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power (kW)</td>
<td>300</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 gyrokystron 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.
Improvements required

- From kW to MW
  - Higher beam voltage
  - Higher beam current
  - Energy recovery
  - Thermal stress
  - Quasi-optical mode converter

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.
### MIG-type electron gun

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter width $L_s$ (mm)</td>
<td>5.23</td>
</tr>
<tr>
<td>Emitter average radius $R_c$ (mm)</td>
<td>6.85</td>
</tr>
<tr>
<td>Anode angle $\phi_a$ (deg)</td>
<td>66.9</td>
</tr>
<tr>
<td>Current density $J_s$ (A/cm$^2$)</td>
<td>20</td>
</tr>
<tr>
<td>Current $I_0$ (A)</td>
<td>45</td>
</tr>
<tr>
<td>Anode voltage $V_0$ (kV)</td>
<td>95</td>
</tr>
<tr>
<td>Modulating anode voltage $V_m$ (kV)</td>
<td>38.5</td>
</tr>
<tr>
<td>Magnetic field @ gun exit $B_0$ (T)</td>
<td>1.34</td>
</tr>
<tr>
<td>Magnetic compression ratio $f_m$</td>
<td>10.5</td>
</tr>
<tr>
<td>Velocity ratio $\alpha$</td>
<td>1.31</td>
</tr>
<tr>
<td>Transverse velocity spread $\Delta\beta_t$ (%)</td>
<td>2.31</td>
</tr>
<tr>
<td>Axial velocity spread $\Delta\beta_z$ (%)</td>
<td>4.09</td>
</tr>
<tr>
<td>Mean guiding center radius $r_{g0}$ (mm)</td>
<td>2.25</td>
</tr>
</tbody>
</table>

![Magnetic field](image1.png)

![Beam trajectories](image2.png)
MIG-type electron gun

Simulated by Egun, MAGIC and CST PS.

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>EGUN</th>
<th>MAGIC</th>
<th>CST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity ratio $\alpha$</td>
<td>1.32</td>
<td>1.32</td>
<td>1.32</td>
</tr>
<tr>
<td>Velocity ratio spread $\Delta \alpha$ (%)</td>
<td>7.99</td>
<td>5.74</td>
<td>7.12</td>
</tr>
<tr>
<td>Transverse velocity spread $\Delta \beta_t$ (%)</td>
<td>3.06</td>
<td>2.17</td>
<td>2.78</td>
</tr>
<tr>
<td>Guiding centre radius $R_{g0}$ (mm)</td>
<td>2.36</td>
<td>2.42</td>
<td>2.41</td>
</tr>
<tr>
<td>Modulating anode voltage $V_m$ (kV)</td>
<td>43.2</td>
<td>46.6</td>
<td>45.45</td>
</tr>
</tbody>
</table>
Simulation of the 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.

The normalized coupling coefficient as the function of the normalized size of beam radius

<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>
Nonlinear simulation model

Beam-wave interaction

$$\frac{dp}{dt} = -e(E + v \times B)$$

$$\frac{d\varepsilon}{dt} = ev \cdot E$$

The normalized motion equation

$$\frac{dp}{dz} + \frac{i\omega}{c u_z} \left(\gamma - \frac{\Omega_0}{\omega}\right) p = \frac{i\eta p}{2\Omega_0} \frac{dB_0}{dz} + \frac{i\eta}{2 u_z} C_{mp} k_{mp} V_{\max} \left(\frac{f_{mp}(z)}{(s-1)!}\right) \times J_{m-s} \left(k_{mp} R_e\right) \left(\frac{ck_{mp} p^*}{2\Omega_0}\right)^{s-1}$$

$$\frac{du_z}{dz} = -\left(\eta c u_z r_L\right) \frac{dB_0}{dz}$$

Ignore the axial momentum of the helical electron beam

$$\frac{dp}{dz} + \frac{i\omega}{c u_z} \left(\gamma - \frac{\Omega_0}{\omega}\right) p = \frac{i\eta}{2 u_z} C_{mp} k_{mp} V_{\max} \left(\frac{f_{mp}(z)}{(s-1)!}\right) \times J_{m-s} \left(k_{mp} R_e\right) \left(\frac{ck_{mp} p^*}{2\Omega_0}\right)^{s-1}$$

interaction efficiency

$$\eta = \frac{\langle \gamma_i \rangle - \langle \gamma_f \rangle}{\langle \gamma_i \rangle - 1} = \frac{\gamma_0 + 1}{2\gamma_0} \frac{\alpha_0^2}{\alpha_0^2 + 1} \eta_\perp$$

Fast and quickly estimate the interaction efficiency.

Not accurate enough.
Nonlinear simulation results

**Input cavity**

**Middle cavity**

**Output cavity**

Efficiency curve

E-field amplitude
PIC simulations on the beam-wave interaction
Gain curves in simulations

Output power and gain
Acknowledgement

- This work is supported by the European Commission Horizon 2020 Project Compact light (777431-XLS), and the State Scholarship Fund from the China Scholarship Council.

Thank you for your attention!