RF Power Generation II

Klystrons, Magnetrons and Gyrotrons

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and

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Scope of the lecture:

• The output of an IOT is limited to around 30 kW at 1.3 GHz by the need to use a control grid
• At higher frequencies and higher powers the beam must be bunched in another way
• Klystrons
• Multipactor discharge
• Other high power sources
  – SLAC Energy Doubler
  – Magnetrons
  – Gyrotrons
• State of the art
• An un-modulated electron beam passes through a cavity resonator with RF input
• Electrons accelerated or retarded according to the phase of the gap voltage: Beam is velocity modulated:
• As the beam drifts downstream bunches of electrons are formed as shown in the Applegate diagram
• An output cavity placed downstream extracts RF power just as in an IOT
• This is a simple 2-cavity klystron
Multi-cavity klystron

- Additional cavities are used to increase gain, efficiency and bandwidth
- Bunches are formed by the first (N-1) cavities
- Power is extracted by the N\textsuperscript{th} cavity
- Electron gun is a space-charge limited diode with perveance given by
  \[ K = \frac{I_0}{V_0^{3/2}} \]
  - \( K \times 10^6 \) is typically 0.5 - 2.0
  - Beam is confined by an axial magnetic field
Typical Applegate diagram

- Distance and time axes exchanged
- Average beam velocity subtracted
- Intermediate cavities detuned to maximise bunching
- Cavity 3 is a second harmonic cavity
- Space-charge repulsion in last drift section limits bunching
- Electrons enter output gap with energy $\sim V_0$

Image courtesy of Thales Electron Devices
Output saturation

- Non-linear effects limit the power at high drive levels and the output power saturates.
- Electrons must have residual energy $> 0.1V_0$ to drift clear of the output gap and avoid reflection.
- RF beam current increases as bunch length decreases.
  - Theoretical maximum $I_1 = 2I_0$ when space-charge is low.
  - Maximum $I_1$ decreases with increasing space-charge.
- Second harmonic cavity may be used to increase bunching.
- Maximum possible efficiency with second harmonic cavity is approximately
  $$\eta_e = 0.85 - 0.2 \times 10^{-6} K$$
- Efficiency decreases with increasing frequency because of increased losses and design trade-offs.

\[ P_{\text{out}} \text{ (dB)} \]
\[ P_{\text{in}} \text{ (dB)} \]

Gain compression $3 - 5 \text{ dB}$

Saturation

\[ \begin{array}{c}
\text{Frequency (GHz)} \\
\text{Efficiency (\%)}
\end{array} \]
Effect of output match

- Reflected power changes the amplitude and/or phase of the output gap voltage
- **Rieke diagram** shows output power as a function of match at the output flange
- Shaded region forbidden because of voltage breakdown and/or electron reflection
- Output mismatch can also cause:
  - Output window failure
  - Output waveguide arcs
- A Circulator is needed to protect against reflected power

Image courtesy of Thales Electron Devices
### UHF TV klystrons

- **Frequency**: 470 - 860 MHz
- **Power**: 10 - 70 kW
- **Gain**: 30 - 40 dB
- **Efficiency**: 40 – 50%
- **Beam control by modulating anode**
- **4 or 5 tunable internal or external cavities**

**Photos courtesy of Phillips**

**CERN SPS 450kW 800MHz amplifier**
Collector depression

\[ P_{DC} = I_C (V_0 - V_C) + I_b V_0 = I_0 V_0 - I_C V_C \]

\[ \eta = \frac{P_{RF}}{I_0 V_0 - I_C V_C} \]

- Efficiency increases with number of stages: realistic maximum is 4 – 5
- Adds to the complexity and cost of the tube
- High voltage electrodes are difficult to cool
- Can also be used with IOTs
**Accelerator klystrons**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>508 MHz</td>
</tr>
<tr>
<td>Beam</td>
<td>90 kV; 18.2A</td>
</tr>
<tr>
<td>Power</td>
<td>1 MW c.w.</td>
</tr>
<tr>
<td>Efficiency</td>
<td>61%</td>
</tr>
<tr>
<td>Gain</td>
<td>41 dB</td>
</tr>
</tbody>
</table>

Photos courtesy of Phillips
Accelerator klystrons

Second harmonic cavity

Output cavity and coupler

Window components

Photos courtesy of Phillips
Klystrons: State of the art

<table>
<thead>
<tr>
<th>Frequency</th>
<th>352</th>
<th>700</th>
<th>3700 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam voltage</td>
<td>100</td>
<td>92</td>
<td>60 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>19</td>
<td>17</td>
<td>20 A</td>
</tr>
<tr>
<td>RF output power</td>
<td>1.3</td>
<td>1.0</td>
<td>0.7 MW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>67</td>
<td>65</td>
<td>44 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency</th>
<th>2.87</th>
<th>3.0</th>
<th>11.4 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam voltage</td>
<td>475</td>
<td>590</td>
<td>506 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>620</td>
<td>610</td>
<td>296 A</td>
</tr>
<tr>
<td>RF output power</td>
<td>150</td>
<td>150</td>
<td>75 MW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>51</td>
<td>42</td>
<td>50 %</td>
</tr>
</tbody>
</table>

Note: Breakdown voltage is higher for short pulses than for DC
Multiple beam klystrons

- To deliver high power with high efficiency requires low perveance
- High beam voltage is not desirable
- Several low perveance klystrons combined in one vacuum envelope as a multiple-beam klystron

<table>
<thead>
<tr>
<th>Frequency</th>
<th>1300 MHz</th>
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</thead>
<tbody>
<tr>
<td>Beam</td>
<td>115 kV; 133 A</td>
</tr>
<tr>
<td>Power</td>
<td>9.8 MW peak</td>
</tr>
<tr>
<td>Efficiency</td>
<td>64 %</td>
</tr>
<tr>
<td>Gain</td>
<td>47 dB</td>
</tr>
<tr>
<td>Pulse</td>
<td>1.5 msec</td>
</tr>
</tbody>
</table>

Images courtesy of Thales Electron Devices
Klystron performance limited by:

- Voltage breakdown
  - Electron gun
  - Output gap
- Cathode current density
- Output window failure caused by
  - Reflected power
  - Vacuum arcs
  - Multipactor discharge
  - X-ray damage
- Heat dissipation
Multipactor discharge

- Resonant RF vacuum discharge sustained by secondary electron emission
- One or two surfaces involved
- Multiple modes
- Signs of multipactor:
  - Heating
  - Changed r.f. performance
  - Window failure
  - Light and X-ray emission
- Multipactor on dielectric surfaces does not require RF field
- Multipactor can sometimes be suppressed by
  - Changing shape of surface
  - Surface coatings
  - Static electric and magnetic fields

<table>
<thead>
<tr>
<th>Secondary electron emission constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Copper</td>
</tr>
<tr>
<td>Platinum</td>
</tr>
<tr>
<td>Carbon black</td>
</tr>
<tr>
<td>Aluminium Oxide</td>
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</table>
The SLAC Energy Doubler (SLED)

- a) Power transmitted by the cavities ($E_T$)
- b) Power re-radiated by the cavities ($E_e$) (antiphase)
- c) Sum of transmitted and radiated power

Note: No power is reflected to the klystron
Magnetrons

- Interaction in crossed electric and magnetic fields
- Free-running oscillator: Efficiency up to 90%
- Frequency
  - Is not stable enough for use in most accelerators
  - Coarse control of frequency by controlling the current
  - Frequency locked by injecting radio-frequency power \( \sim 0.1\% \) of output power
- Locked magnetrons could be suitable for use in accelerators

June 2010  CAS RF for Accelerators, Ebeltoft
Magnetron for medical linacs

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>2.855 GHz</td>
</tr>
<tr>
<td>RF Power</td>
<td>5.5 MW peak</td>
</tr>
<tr>
<td>Anode</td>
<td>51 kV; 240 A</td>
</tr>
<tr>
<td>Pulse</td>
<td>2.3 μs</td>
</tr>
<tr>
<td>Duty</td>
<td>0.00055</td>
</tr>
<tr>
<td>Efficiency</td>
<td>45%</td>
</tr>
</tbody>
</table>

Photos courtesy of e2v technologies
Gyrotrons

- Interaction between a relativistic hollow electron beam and a waveguide TE mode
- Use of fast wave allows electrons to be further from the metal than in a klystron
- Cyclotron resonance requires strong axial magnetic field
- Chiefly developed for heating plasmas for fusion

\[ \omega = s \omega_c \]
\[ s = 1, 2, 3, \ldots \]
TH1506 Gyrotron Oscillator

Frequency: 118 GHz
$V_0$: 85 kV
$I_0$: 22 A
Power: 500 kW peak
Efficiency: 30%
Pulse: 210 sec

Photo courtesy of Thales Electron Devices
Gyro-TWT Amplifier

Output power (TE_{11}) 1.1MW
Efficiency 29%
3 dB bandwidth at 9.4GHz 21%
Saturated gain 37dB
Small-signal gain 48dB
State of the art

- Gridded tubes
- IOTs
- CW Klystrons
- Pulsed Klystrons
- Pulsed magnetron
- Solid state devices
- Solid state amplifiers

Power (MW) vs. Frequency (GHz) graph