Klystron development in X band
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R&D Thales Electron Devices
### Applications

<table>
<thead>
<tr>
<th>Medical radiology</th>
<th>Space</th>
<th>Defense</th>
<th>Science</th>
<th>Industrial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiography, radiology</td>
<td>Telecom</td>
<td>Radars</td>
<td>Fusion</td>
<td>NDT-Security</td>
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<tr>
<td>Angiography, urology</td>
<td>Broadcast</td>
<td>Countermeasures</td>
<td>Light Sources</td>
<td>Laser</td>
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<td>Dental 3D imaging</td>
<td>Earth observation</td>
<td>Missiles</td>
<td>Large accelerators</td>
<td>Industrial heating</td>
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<tr>
<td>Vet exams</td>
<td>Navigation....</td>
<td></td>
<td></td>
<td>Sterilization</td>
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</tbody>
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### Subsystems and products

- **Digital flat detectors**
  - X-Ray Imaging Units
  - X-Ray Image Intensifiers
  - CCD cameras
  - Associated sub-systems

- **Traveling Wave Tubes**
  - Amplifiers
  - Power Grid Tubes
  - Associated sub-systems

- **Traveling Wave Tubes**
  - Transmitters
  - Klystrons
  - CFAs
  - Associated sub-systems

- **Klystrons**
  - Gyrotrons
  - Diacrodes
  - Associated sub-systems

- **Power grid tubes**
  - X-Ray Tubes
  - X-Ray detectors
  - Associated sub-systems
From Components to Subsystems - Science

Klystrons, gyrotrons, IOTs & tetrodes

Energy storage
Mega Joule Laser

RF amplifier

X Band Workshop - Components & Subsystems
Klystron technology for X band

A single beam 9.3 GHz / 4 MW Klystron

Alternative technologies
  - PPM focusing
  - Multi-Beam Klystron
Klystron source for medical and industrial applications
The klystron, a high-gain amplifier

Klystron is a high-power, high-gain amplifier providing:

- More peak power than magnetrons
- Stability of output power
- Reliability: theoretical long lifetime even at high frequencies
- Output power versatility

Signal from 9.3 GHz oscillator → Input ~10 W → Isolator/circulator → Output ~ MW
… but in field of industrial and medical applications, some others parameters have strong importance:

- Compactness of the source as a whole: klystron + (oil tank) + HV modulator
- Availability of passive components
- Power consumption
- Cost
Single beam 4 MW Klystron
Electromagnet focusing
### RF source characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (f)</td>
<td>9.3 GHz</td>
</tr>
<tr>
<td>Pulsed output power</td>
<td>4.0 MW</td>
</tr>
<tr>
<td>Average output power</td>
<td>4 kW</td>
</tr>
<tr>
<td>RF pulse duration</td>
<td>5 µs</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>0.001</td>
</tr>
<tr>
<td>-1 dB bandwidth</td>
<td>&gt;30 MHz</td>
</tr>
<tr>
<td>Pervaneance (K)</td>
<td>1.0 μA / V^{1.5}</td>
</tr>
<tr>
<td>Efficiency</td>
<td>49 %</td>
</tr>
<tr>
<td>Expected lifetime</td>
<td>&gt; 30 000 hours</td>
</tr>
</tbody>
</table>

### Operating conditions

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode voltage (V)</td>
<td>152 kV</td>
</tr>
<tr>
<td>Cathode current (I)</td>
<td>60 A</td>
</tr>
<tr>
<td>X ray shielding</td>
<td>integrated</td>
</tr>
</tbody>
</table>
Interaction structure

- 6 cavities including 1 harmonic
- Interaction length (cavity 1 to 6) = 270 mm
- Output cavity carefully shaped to reduce electric field below 60 MV/m (at the expense of coupling factor…)

Simulation of klystron operation: electron beam interaction with cavities’ RF field
animation period = $1 / (9.3 \text{ GHz})$
Calculation result at nominal cathode voltage:
- Saturation gain = 51.5 dB
- Output power = 4.3 MW
- Efficiency = 49%
Wide instantaneous bandwidth compared to magnetron

Calculated bandwidth at −1 dB: 60 MHz (at nominal cathode voltage)
The challenges of X band for standard klystron

- **RF electric field in output cavity**
  - Directly limits the **pulsed output power**

- **Power loss in output window**
  - Directly limits the **average output power**

Calculation of window’s temperature
Klystron & electromagnet interfaces

- **Output waveguide**
  - WR112 flange
  - SF$_6$ pressurization (3 bars)

- **Water cooling**
  - Total flow ~ 26 L / min

- **Electromagnet**
  - Power consumption ~ 4 kW

- **Electron gun power supply**
  - 152 kV / 60 A / 9.2 kW modulator
  - Oil tank insulation
  - Heater voltage 15 V, current 13 A

- **Input driver**
  - Input power = 30 W at saturation
Footprint and weight

- **Klystron**
  - Height = 0.9 m
  - Weight ~ 60 kg
  - Output flange at 400 mm from axis

- **Electromagnet**
  - Outer diameter = 500 mm
  - Weight ~ 350 kg
Klystron length = 87 cm + HV connector

- **Sub element**
  - \( L(\text{collector}) = 30 \text{ cm} \)
    - Electron collector
  - \( L(\text{interaction}) = 27 \text{ cm} \)
    - Drift tubes & cavities
  - \( L(\text{gun}) = 30 \text{ cm} \)
    - Electron gun
**Gun ceramic length**:  

$L(\text{gun}) \propto V$
Interaction structure length:

$L(\text{interaction}) \propto \lambda_q$

$\lambda_q : \text{reduced plasma length}$

$\lambda_q \propto V.K^{-0.5}.f^{-1}$
Collector length (empirical):

\[ L(\text{interaction}) \propto K^{-0.5} \cdot (V \cdot I)^{0.42} \]

K dependence due to natural beam expansion
- System size scales more with power and voltage than with frequency.
- Focusing solenoid is a major contributor to weight, size and power consumption.
Alternative technologies

Dealing with:

- weight
- size
- high voltage
Single beam klystron with PPM focusing allows reduction of size, weight and power consumption.
Multi Beam Klystron (MBK) technology

Perveance \( K = \frac{I}{V^{1.5}} \)

Peak power \( P = V I \)

A number of beams interacting together in cavities:

\( K(\text{total}) = \sum K(\text{beam}) \)

- **Lower voltage** (goal: under 50 kV for operation in air)
- Better efficiency
- Wider bandwidth (less sensibility to cavity frequency)

For medical and industrial systems:

⇒ klystron length and modulator size reduced
⇒ oil tank suppressed
1.3 GHz, 116 kV, 10 MW
1.5 ms RF pulse @ 10 Hz
7 electron beam-structure

Current status:
- 7 serial tubes under operation at DESY. Stability at every voltage.
- Currently operating under saturation on FLASH machine.
- Full output power for conditioning and optimization of future photo-injector of European XFEL.

7 beam electron gun
Choice of cavity and operating mode:

- Compatibility with spatial arrangement of beams
- Good beam-field coupling (high R/Q)
- Sufficient mode separation or damping possibilities to avoid mode competition
- Manufacturing aspect

Example: coaxial cavity

Courtesy of C. Lingwood, Lancaster U.

Fundamental mode:

- High order mode:

![Graph showing frequency vs. azimuthal index for different modes](image)
Thales klystron & gyrotron development team:

- Armel Beunas
- Christophe Lievin
- Rodolphe Marchesin
- Jean-Christophe Bellemere
- Sébastien Berger