Review of Available Power Sources

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ABSTRACT

Klystrons and triodes have been the accepted choice for particle accelerators because they produce high power RF and offer high gain (60 dB) with efficiencies of ~50%. Although fairly new to the market, IOTs have become available at L-band frequencies and have maintained their high efficiency. The development of Superconducting RF at the L-band frequency allows IOTs to become the choice for future accelerator programs. Due to the operational nature of SRF technology in energy recovery mode, there is no longer the requirement for large amounts of RF power from single sources. This report reviews some of the developments in RF power sources suitable for ERLs.

Keywords: Klystron, Inductive Output Tube, IOT, Power Sources, Radio Frequency.
1. KLYSTRONS

Invented in the late 1930’s by the Varian brothers, Klystrons contain three separate sections, the gun region, the RF interaction region, and the collector (figure 1). A typical klystron would contain a thermionic gun, several RF cavities and a collector to retrieve the spent electrons.

A DC electron beam is emitted from the gun, and in the absence of RF the electrons travel through the drift tube and would disperse in the collector. The electron beam is magnetically focused to counter the effect of space charge growth through the drift tube section.

A typical klystron is a Class A amplifier, this is defined as one which is biased to a point where beam current flows for the entire 360 degrees of an input cycle, at the full, unclipped output of the amplifier. This is the least efficient method of amplification, because the output devices are dissipating maximum power with no input signal.

When RF is applied to the input cavity the RF fills the cavity and produces an electric field between the cavity noses. This field resonates at the designed frequency of the cavity.

The electrons that pass the input cavity 180 degrees out of phase of the electric field are retarded, whilst those that pass in phase with the electric field are accelerated. The electrons that pass when the field is at a minimum are unaffected. This momentum transfer causes the electrons to bunch together, an effect called velocity modulation. Neglecting the effects of space charge, the bunching effect is described by the applegate diagram (figure 2)

As the beam passes through each cavity the current density of the bunches increases. The bunches then pass through the output cavity at a phase such that the field is in the opposite direction to the direction of motion. This causes the electron bunches to lose energy into the cavity where the amplified RF power is extracted. The gain of the RF signal is dependant upon the number of RF cavities, typically about 20 dB’s per bunching cavity.
2. Inductive Output Tubes (IOTs)

Inductive output tubes (IOTs) are a hybrid tube, partly based on the resonant circuit technologies of cavities, but also using the grid modulation techniques used in tetrodes and triodes (figure 3). They were invented in the late 1930’s but the technology available for the manufacturing of such a device has only become available since the early 1990’s.

Like triode technology, when the plate is at a positive potential electrons travel from the cathode to the plate (anode) and a current is measured. A grid is introduced to regulate the potential profile along the cathode and thereby to control the current from the cathode. The RF is applied directly to the electron gun setting up a RF voltage between the grid and the cathode. When the voltage across the gap is zero or negative, no electrons are emitted, when the voltage goes positive, electrons are emitted. This type of bunching effect is called density modulation. This is typical of class B operation, where the grid bias is set at cutoff, i.e., no plate current flows in the absence of an input signal. Plate current only flows when a signal is present, and only flows for exactly half, or 180 degrees, of the input cycle.

An IOT gun is heavily based on this principle utilizing a control grid to regulate the flow of electrons through the tube and class B operation is inherently more efficient. However, class B operation suffers from cross-over distortion and harmonics as the beam is triggered.

IOTs can also be operated in a class AB mode, where the grid bias is set so that the plate current flows for between half and 360 degrees of the input cycle. This increase in idle bias current over class B operation keeps the tubes on a small amount at all times, resulting in reduced crossover distortion, because it keeps the tubes out of the highly nonlinear region. Unless the idle bias is set too close to class A operation, efficiency gains similar to class B operation can be maintained.
An IOT operates in such a way that RF power is removed from the beam by passing it through a resonant cavity. The beam is bunched at the cathode by applying an RF voltage to the control grid.

As the beam passes through the output gap, the resonant cavity induces an oscillating voltage and current in the cavity. RF power is then extracted from the resonant cavity similar to that of the Klystron output cavity.

Due to having a single resonant cavity the IOT is much shorter than the Klystron. For this reason, the beam is generally much wider than that for the klystron and the beam can be controlled to pass the cavity at the point of highest field. Therefore, the interaction to the cavity is much greater than with the klystron and the overall efficiency is much higher. Observations have recorded IOT efficiency as high as 80%.

Although there are considerable advantages in efficiency, IOTs also suffer from a much lower gain, due to only having one cavity, therefore they require a much higher drive power.

3. AVAILABLE TUBES

Due to the compact nature of the IOTs they are considerably cheaper to purchase than the conventional klystron. More significantly there have been many developments of 1.3 GHz IOTs suitable for particle accelerators.

A constraint from going to high (10’s GHz) frequencies is that the cathode-grid spacing is inversely proportional to the frequency, it is also essential that the grid and cathode spacing has to be equidistant. Manufacturing tolerances therefore prohibit the building of devices operating at frequencies much higher than a few gigahertz. The gap size is such that the grid would be at serious risk of breakdown and from migration of barium from the cathode to the grid.
Through simulations using the existing electron gun designs it is theoretically possible to obtain high levels of beam current at frequencies up to 3 GHz (figure 4). These are latest results from CPI based on their 1.3 GHz IOT gun operating at 22 kV (class B).

The cathode and grid configuration of modern IOTs has been developed considerably over the past years and is becoming well proven. Typically fewer IOTs report failures due to grid manufacturing reliability. For this reason there is an increase in support for choosing the less expensive IOT technology.

The IOT designs that have been used for transmitters have been adopted for particle accelerator designs, benefiting from the experience obtained from the IOT manufacturers.

The main difference being, for transmitters the devices are broad band. Only a small modification is required to the output circuit to operate at a single frequency.

It has also been considered that the output circuit can be altered to operate at L or C band. Simulations of the IOTs operating in this manner have not been conclusive, and therefore require further research.

A comparison of IOTs operating at the fundamental frequency and at second harmonic can be seen in table 1. The calculations were performed by CPI with the hope of achieving similar levels of efficiency for the second harmonic IOTs.

Table 2 gives the latest test results of the CPI development tubes operating in the principle mode of 1.3 GHz. As seen from the data, the high frequency IOTs have maintained the high levels of efficiency as seen with a typical broadcast tube, however, they have shown signs of degradation in gain.
It is expected that these tubes will, through further development, operate with efficiencies up to 60% with a gain of 24 dB at power levels of 20 kW or more as required for ERL operation in order to be considered as an alternative to Klystron technology.

Table 3 shows the latest results of the e2v technologies 1.3 GHz IOT prototypes. Again these tube developments have shown significant decrease in gain, for a moderate efficiency (50%). By varying the operation of the tube, it is possible to trade between efficiency and gain as can be seen from this data.

4. SENSITIVITY

Operational data made available from e2v technologies shows that the sensitivity of the phase to both grid voltage (figure 5) and beam voltage (figure 6) is both linear and small when compared to that of a klystron. The phase shift as a function of grid voltage has been shown to be ~0.25 degrees per volt. As a function of beam voltage the phase shift is ~8 degrees per kilovolt.

5. DISCUSSION AND CONCLUSIONS

IOTs are being developed at L-band frequencies which may prove to be key components in new ERL designs. At present though there is not enough evidence to suggest that they would replace klystron operation, however they have many advantages in contrast to Klystrons:

- Efficiency (also maintained at reduced output power)
- Higher gap voltage
- Density modulation direct from the cathode (shorter devices)
- Cost

However the limiting factors for IOTs are:

- Lower gain
• Cathode-grid gap inversely proportional to the frequency, therefore limited to below a few gigahertz.
• Higher harmonic IOTs calculations do not guarantee performance.
• Typically lower power than klystrons.

Manufacturers are producing IOTs suitable for ERL operation, and although higher order mode designs may not be solved, there is sufficient research taking place to develop these for higher frequencies.

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FIGURE CAPTIONS

Figure 1. Klystron Schematic.

Figure 2. Applegate Diagram (ignoring space charge effects)

The green line represents electrons entering the cavity at zero phase and hence no acceleration. The blue line represents the electrons that enter the cavity when the voltage is negative and hence are decelerated. The red line represents the electrons passing at the peak electric field and are accelerated. The point at which the lines cross is where maximum bunching occurs.

Figure 3. IOT schematic

Figure 4. Beam Current versus Frequency

Figure 5. Grid Voltage Sensitivity

Figure 6. Beam Voltage Sensitivity

Table 1. Comparison of IOT's operating in the fundamental and secondary mode.

Table 2. CPI 1.3 GHZ IOT Development results

Table 3. e2v technologies 1.3 GHz IOT Development results
REFERENCES


Figure 1

Figure 2
Figure 5

Phase - Grid Voltage Sensitivity

Figure 6

Phase - Beam Voltage Sensitivity
### Table 1

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<th>Principle</th>
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### Table 2

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<td>Gain</td>
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### Table 3

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