IOT RF POWER SOURCES FOR PULSED AND CW LINACS

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Abstract

For many years, klystrons have been the preferred RF power amplifiers for both pulsed and CW linacs at UHF and higher frequencies. Their properties have earned them that position. But in recent years, in UHF terrestrial television transmitters, the earlier predominant klystron has been replaced by the Inductive Output Tube (IOT) because the IOT provides higher efficiency and , due to its excellent linearity, can handle the simultaneous amplification of both the vision and the sound signal. Its robustness and life expectancy equals that of a klystron, and it more than compensates its lower gain by a lower price and a smaller size. Pulsed operation of an IOT can be achieved without the help a high-voltage modulator. Since the beam current is grid-controlled it is sufficient to pulse the drive power. For linac operation, derivates of UHF TV IOTs, capable of up to 80 kW CW output power, are already available and operating. In L-Band, they are presently joined by recently developed 15 to 30 kW CW IOTs. HOM-IOTs are expected to extend the CW range in UHF to 1 MW and beyond.

LINAC RF SOURCE REQUIREMENTS AND BASIC IOT PROPERTIES

Every linac has certain requirements regarding its RF power source. The most common ones are (not necessarily in this order): high efficiency, reliability and ruggedness, long-term stability, low pushing factors (AM/AM and AM/PM), long life, and all that at a price that does not jeopardize the project. For many years, klystrons have provided most of these properties, and they still do so. So, why and when use IOTs instead?

In now almost two decades of TV operation the IOT has developed into a device that equals the klystron in terms of reliability and ruggedness, long-term stability and life. That by itself is remarkable, but it would not serve as a prudent reason for a change. However, there are areas where the IOT shows significant superiority compared to the klystron.

Efficiency and Linearity

The IOT, also known as a klystrode*, is by its nature a special tetrode. The bunches in its electron beam are generated by means of a control grid and not by velocity modulation, as in a klystron. This results in several advantages. The first one is basic efficiency. Like a tetrode the IOT can be operated in class C mode, providing efficiency figures in the order of 73 % and higher. The second advantage is that the IOT's high basic efficiency can actually be fully exploited.

* Klystrode® is a trademark of CPI

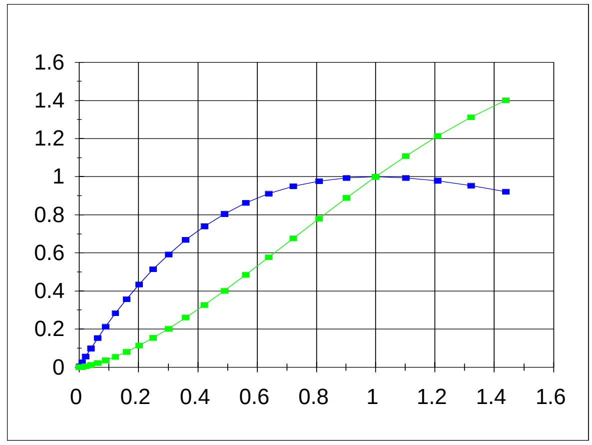

Figure 1: Normalized characteristics of output power (vertical axis) vs. drive power (horizontal axis) for klystrons (blue, saturating) and IOTs (green, not saturating).

Figure 1 highlights this very important feature for accelerator operation. In order to apply fast feedback control when using a klystron, a back-off in the order of 10 % of output power from the point of maximum efficiency (1/1 in the figure) is necessary, due to the change of slope in the characteristic at that point. An IOT, on the other hand, does not require a back-off; full use of its already higher basic efficiency can be made since its characteristic does not saturate at its nominal output power level.

A third advantage is superior linearity, resulting in low pushing factors. The characteristic in Figure 1 already reveals the lower AM/AM conversion in the vicinity of the operation point, compared to that of a klystron. AM/PM conversion is likewise much more benign in an IOT.

Costs

IOTs are simple devices. Basically, they contain only one RF circuit (the so-called input circuit is merely an impedance-matching device between the input line and the low-impedance cathode-grid structure). The whole tube is considerably shorter than a comparable klystron, resulting in a significantly lower price for both the IOT proper and the assembly hardware, including the focusing magnet.

A drawback is the lower gain of the IOT (in the order of 23 dB) which requires a more powerful driver, but this is usually more than compensated by reduced costs for power supplies and cooling devices, due to the higher efficiency. And, naturally, there are considerable savings in the power bill, especially in CW operation.

In pulsed operation, the power bill savings may not be that attractive. But in this case, another IOT feature that is based on grid control can save a considerable amount of capital costs: no expensive high-voltage modulator is required; a simple PIN modulator placed at a low level in the driver will serve the purpose.

EXAMPLES OF UHF IOTS

Already in Use in Accelerator Operation

Aided by intensified cooling (water-cooled anode and output cavity, improved air-cooling of the output window), TV-IOT derivates like the CPI/Eimac K2H80W shown in Figure 2 are able to provide CW output power up to 80 kW at efficiencies between 70 and 76 %.

Figure 2: K2H80W, an 80 kW CW UHF IOT with complete hardware assembly.

The double-tuned output circuit provides an additional feature: The almost flat top of the frequency-response curve permits an offset between operating and central frequency, which leads to a further increase in efficiency.

Maintaining High Efficiency when Modulating

Adding two or more collector stages that are operated at potentials lower than the IOT's body potential (with respect to the cathode) permits to slow down considerable portions of the spent beam before it hits a collector surface. This saves energy. The IOT depicted in Figure 3 (CPI/Eimac K3130WC) features 3 collector stages, those at high voltage potential being oil-cooled.

The improvement in efficiency due to Multi-Stage Collector Depression (MSDC) is especially high at power levels lower than the nominal power, as shown by the graph in Figure 4 (efficiency levels presented are relatively low because they represent a TV transmitter application). Collector depression therefore becomes useful in applications with varying power levels, while the additional effort may be wasted for the small efficiency gain in CW operation close to nominal output power.

Figure 3: 3-Stage Depressed Collector IOT K3130WC.

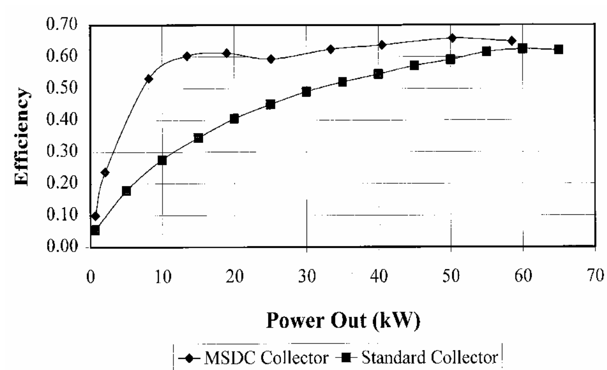

Figure 4: Characteristics of efficiency vs. output power. Top: 3-stage MSDC. Bottom: standard collector.

High-Power and Super-Power Options

For output power levels exceeding 80 kW, and for higher frequencies than UHF, internal cavities replace the external ones. Shown in Figure 5 is the CPI/Eimac (Varian/Eimac) 2KDW250PA, the so called "Chalk River Tube", which provides 250 kW CW output power at 267 MHz with 73 % efficiency.

But there is an IOT option for even higher power levels. The Higher-Order Mode IOT (HOM-IOT) uses multiple beams (or large electron beams with quasiannular cross-section) that interact with the outer voltage maxima in TM_{0n0} mode cavities. The advantage: low beam voltages, low emission densities, low energy densities on surfaces and in cavities.

Figure 5: 250 kW CW “Chalk River” IOT.

Table 1 compares the capabilities of an HOM-IOT and a klystron, both for 1 MW CW output power in UHF.

Table 1: Comparison of HOM-IOT and klystron properties at 1 MW CW output power in UHF

Property	HOM-IOT	Klystron
Effective efficiency	**73 %**	**60 %**
Rel. power consumption	**82 %**	**100 %**
Assembly volume (approx.)	**30 cbf**	**200 cbf**
Assembly weight (approx.)	**1,000 lbs**	**5,000 lbs**
DC voltage	**45 kV**	**90 kV**

Figure 6 shows the first (and so far only) HOM-IOT in test. It has been developed by CPI for Los Alamos National Laboratories for their abandoned APT (Accelerator Production of Tritium) project and has been moth-balled together with it. Its target specification: 1 MW CW at 700 MHz.

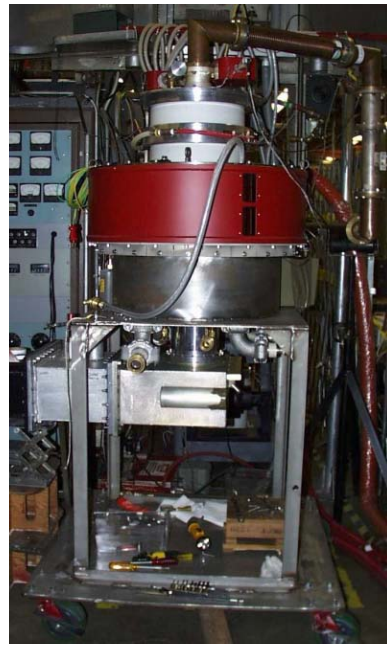

Figure 6: 1 MW / 700 MHz HOM-IOT in test.

IOTS IN L-BAND

Basic Considerations

The cathode-grid configuration of modern IOTs is well proven. There have been scarcely any grid failures reported. Thus there are good reasons to maintain this configuration when designing an IOT for higher frequencies. That these well established assemblies are well-suited for L-Band operation is documented by the simulation of the fundamental-frequency currents versus operation frequency of an existing IOT electron gun in class B operation at in this case 22 kV, as shown in Figure 7.

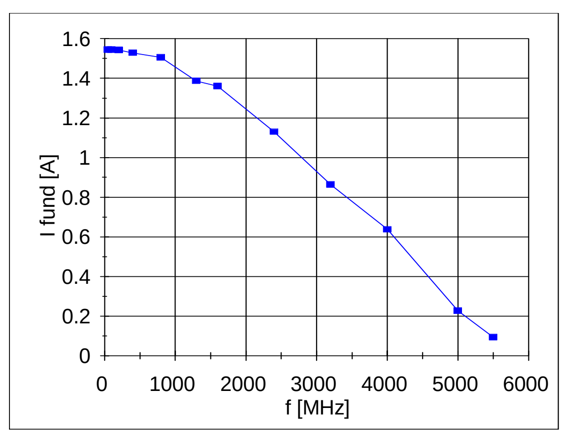

Figure 7: Simulated fundamental frequency current of existing IOT gun vs. frequency at 22 kV (Class B).

The characteristic proves that reasonable operation results can be expected using such a gun up to 2 or even 3 GHz.

Birth of a New IOT Generation

A 1.3 GHz IOT has been developed at CPI / Eimac, based on considerations like those explained above. Figure 8 depicts the tube.

Figure 8: 30 kW CW L-Band IOT by CPI / Eimac.

The following table 2 lists the test results of the third prototype tube at 1.3 GHz.

Table 2: L-Band IOT test results

Voltage(kV)	Current(A)	Drive(W)	Output(kW)	Gain(dB)	Eff(%)
24	0.79	208	10.0	17	52.7
25	1.10	203	15.1	19	54.9
26	1.46	183	20.6	21	54.3
32	1.35	192	25.7	21	59.5
34	1.39	253	30.2	21	63.8

The test results confirm the computer simulations: the almost 64 % efficiency, achieved at 30 kW CW output power, are in good agreement with the about 10 % of predicted loss in fundamental current at 1.3 GHz, compared to UHF. This power range is well positioned to satisfy the requirements of fourth-generation light sources.

Figure 9 shows the L-Band IOT in its hardware set, in this case equipped with a coax-waveguide transition at the output.

Figure 9: 30 kW L-Band IOT in hardware set.

CONCLUSION AND OUTLOOK

Less than twenty years after the design of the first modern IOT the device has established itself as a reliable and very efficient amplifier for medium power levels in UHF, and it is on the verge of expanding its area of use into the UHF super-power range and into medium- and high-power L-band applications, especially in fourth generation light sources.

ACKNOWLEDGEMENTS

The authors wish to thank all members of the CPI / Eimac IOT team for their inventiveness and their dedication to the task, and many of the present and future IOT users for lots of suggestions.