COMPARISON OF KLYSTRON AND INDUCTIVE OUTPUT TUBES (IOT) VACUUM-ELECTRON DEVICES FOR RF AMPLIFIER SERVICE IN FREE-ELECTRON LASER

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ABSTRACT

The MIT X-Ray Laser project, to produce output in the 0.3 to 100 nanometer range, is based on a super-conducting 4 GeV linear accelerator, using 24 cryo-modules, each with its own RF amplifier, operating at 1.3 GHz. The CW output of each amplifier is nominally 15 kW. Although nothing precludes consideration of any RF amplifier type, including solid-state or conventional triode or tetrode, the most appropriate technology includes the Klystron and the IOT. The mechanisms by which these devices convert DC input into RF output are discussed. The devices are then compared with regard to availability (developmental status), efficiency, means of pulse-modulation, gain, phase and amplitude stability (pushing factors), and acquisition and life-cycle costs.

INTRODUCTION

A means of providing 1.3 GHz power to the super-conducting cavities of a Free-Electron Laser is to provide a separate RF amplifier for each cavity, at 15 kW CW, with an optional pulse-modulation mode of 100 millisecond pulses at one pulse per second (10% duty factor). The most appropriate technology, at this frequency and power level, comprises the Klystron and the IOT.

A cross-section of a typical Klystron is shown in figure 1. It uses a magnetically-focused cylindrical electron beam, accelerated to a velocity determined by the beam voltage. The beam passes through a beam-tunnel, having periodic gaps, surrounded by annular resonant cavities, tuned to frequencies close to or at the operating frequency. The RF fields in the cavities are such that the maximum voltage appears across the gaps, in the direction of electron flow. RF drive power is coupled into the first cavity. The electric field produces velocity modulation of the constant-density beam. As the beam progresses, faster electrons from one RF cycle catch up with slower electrons from a previous one, producing density modulation enhanced by voltage induced into subsequent cavities, spaced by a length that maximizes the conversion, typically ¼ plasma wave-length. The last cavity is the output cavity, where density modulation has been maximized. The electrons give up energy to the RF field at the output gap and RF power is coupled out. The “spent” electron beam terminates on the inner surface of a beam-collector electrode.

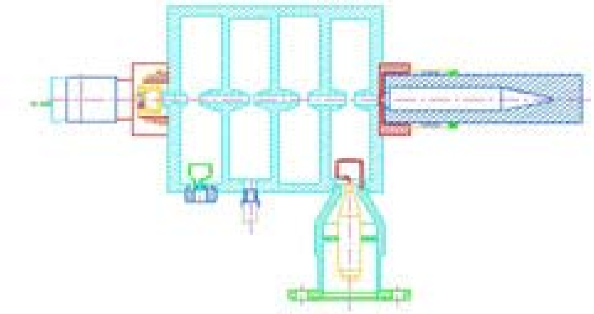
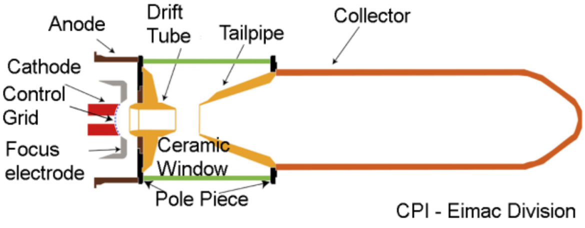


Figure 1: Cross-section of typical multi-cavity klystron.

The IOT, shown in figures 2 and 3, also uses a cylindrically shaped stream of magnetically-focused electrons. The input cavity, however, has a cathode where the leading-edge of a gap would be and a grid where the trailing-edge would be. The RF voltage between grid and cathode determines the amplitude of the emitted current, as in a triode. The discs of electrons are accelerated through a “tailpipe” by the beam voltage to an output gap and resonant cavity, like that of a Klystron, where the bunches give up their energy to the RF gap voltage. The grid has a negative DC bias, so that there is no quiescent cathode current. Current leaves the cathode only for grid voltage exceeding cutoff, having a maximum conduction angle of 180 degrees. It is already “bunched”.



CPI - Eimac Division

Figure 2: Cross-section of typical IOT.

DEVICE AVAILABILITY

A klystron, type VKL-7811ST, rated at 10 kW CW at 1.3 GHz, is available from CPI. This power rating is not an upper limit, however. It is likely that 15 kW power output could be obtained by operating at higher beam voltage and current.

IOTs at 1.3 GHz and 20 kW CW have been developed by THALES (TH 713) and CPI (CHK-1320W). L3 Corp. also produces IOTs for UHF TV service and has interest.

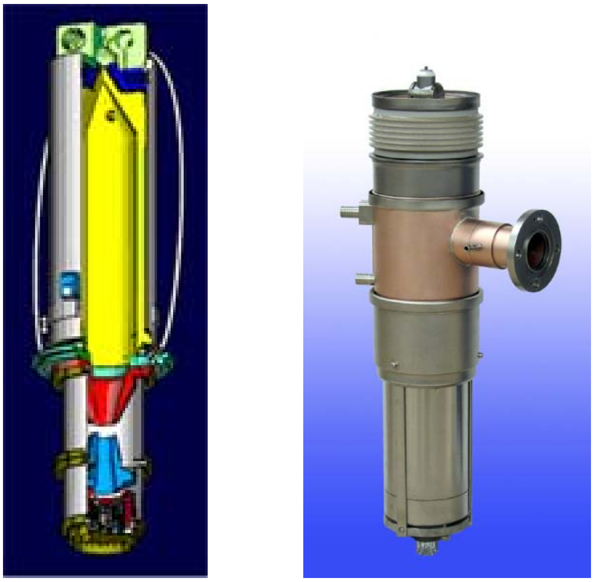


Figure 3: Prototype 1300 MHz IOTs (left Thales, right CPI).

CONVERSION EFFICIENCY

The VKL-7811ST Klystron requires DC input of 30 kW for 10 kW RF output, an efficiency of 33%. If 15 kW can be obtained by raising beam voltage, the efficiency can increase as well. RF output is proportional to the square of the beam current, which varies as the 3/2 power of voltage. RF output, therefore, varies as the cube of the beam voltage, and DC input as the 5/2 power of beam voltage. Efficiency, therefore, varies as the ½ power of voltage. Increasing power from 10 kW to 15 kW requires a 14.5% increase in beam voltage, and a 22.5 % increase in beam current. The DC beam input increases by 40%, to 42 kW. Efficiency would be 15 kW/ 42 kW = 35.5%. Such efficiency, however, is low for a modern Klystron. In a system using hundreds of klystrons, the penalty in total DC input and waste heat is great. The maximum Klystron efficiency is 100%, the same as a Class C amplifier. Achieving it requires that all electrons traverse the output gap in bunches of infinitesimal duration, coincident with the negative peak of the RF gap voltage, and that the gap voltage decelerates each electron to zero velocity. Each electron gives up its kinetic energy to the output RF signal.

This is impossible to achieve, but not to approach. Klystrons have shown over 80% efficiency. Bunching is maximized by adding cavities along the drift tube, including harmonic resonators. Klystrons producing 500 kW CW at 1.3 GHz have efficiency of 55%. The VKL-7811ST has four cavities. The de-bunching influence of space-charge is mitigated by increasing the "stiffness" of the beam, the ratio of beam voltage to beam current, by minimizing the electron-gun "perveance". The perveance of the VKL-7811ST is 1.2 micropervs. Reducing it and adding cavities, with optimized spacing, could increase efficiency to greater than 50%. This, however, requires development.

The maximum efficiency of an IOT is also 100%, the limit of a Class C RF amplifier. In this case cathode current is in the form of zero-length spikes, one per RF cycle. Unfortunately, the output power approaches zero, unless the cathode is capable of infinite emission, and the gain becomes negligible, or even negative, as the required input voltage must be large enough to exceed the negative grid bias for only a few electrical degrees. For these reasons, practical IOTs are operated near Class B, approaching conduction angle of 180 degrees, and a maximum theoretical efficiency of 78.5%. UHF IOTs have demonstrated efficiency above 70%. The THALES and CPI 1.3 GHz IOTs have demonstrated efficiency of 65% and 55%, respectively, at 20 kW output.

The importance of efficiency, especially in a system, using 200 RF amplifiers, extends beyond primary power input. Also important is heat load. A 15 kW amplifier with efficiency of 1/3 requires a DC input of 45 kW, 30 kW of which is heat. A device with efficiency of ½ requires input of 30 kW, 15 kW of which is heat. A device having efficiency of 2/3 requires beam input of 22.5 kW, only 7.5 kW of which is heat load. Doubling efficiency, from 1/3 to 2/3 reduces input power to ½, but heat load to ¼.

As klystron efficiency increases, another concern arises. Klystrons are Class A amplifiers. The DC input is independent of the RF drive. With zero drive, there is zero output, but full DC input. Collector dissipation of a 50% efficient klystron is twice as great as it is with full RF output (unless the collector is a multi-stage, velocity-sorting voltage-depressed design). The DC input must be interlocked with RF drive to prevent this situation. The IOT operates Class B. With its control grid DC-biased to cathode-current cut-off, there is no collector current unless there is RF drive. Collector dissipation can never exceed the value at maximum RF output.

RF POWER GAIN

An advantage of the klystron is high gain. The VKL-7811ST, achieves 10 kW output with 4 Watts in, a gain of 34 dB. Gain can be traded for other characteristics, such as bandwidth and efficiency. Typical klystron gain is between 40 and 50 dB. Higher gain can make a klystron susceptible to RF feedback from a DC-isolated collector to RF input, affecting RF phase stability or even causing self-oscillation.

The input cavity of the IOT directly produces a bunched beam. There are no "gain" cavities, as in the klystron. Power gain is typically 23-24 dB. A 15 kW IOT requires RF input of 60-75 W. Even the existing 1.3 GHz klystron has an advantage of more than 10 dB. The gain differential can be overcome by a solid-state RF driver, having 100 Watt nominal output. Its expense is small enough to be invisible in the total economics of the RF system.

PHASE AND AMPLITUDE STABILITY

The main contribution to unwanted klystron output results from variations in externally-supplied operating voltages, predominantly beam voltage. The "phase-pushing factor" is related to electrical length and is typically 10deg per 1% change in beam voltage. Phase deviation can then be related to DC input variation. Incremental RF output is approximately 3 times incremental beam voltage, assuming that RF drive is saturated. Phase is related RF drive variation, at saturation by the "AM-to-PM conversion factor".

The IOT is electrically short, having no "gain" cavities. As a result, its phase-pushing factor is approximately 1/10 that of a klystron, making it 20 dB less sensitive to power supply voltage variations. Amplitude sensitivity to beam supply variation is also different. The fundamental-frequency value of cathode current is directly determined by the RF input, and is relatively independent of beam voltage. For a given value of RF output there will be an optimum beam voltage. Less than optimum voltage saturates the output, leading to excessive body current (an effect also seen in klystrons). Excessive beam voltage produces higher collector dissipation. Small voltage variations around the optimum value have much less effect on RF power output than comparable variations in a klystron. Sensitivity to drive-power variations is greater in an IOT than in a saturated klystron. As for the contribution of the solid-state driver amplifier, the supply-voltage to phase and amplitude coefficients of a solid-state RF amplifier are even smaller than those of an IOT.

ACQUISITION AND LIFE-CYCLE COSTS

A major acquisition cost driver for a system based on the existing klystron, having an efficiency of 1/3, is that each klystron requires a 45 kW DC power supply and a 30 kW collector cooling system. In a comparable IOT system, with efficiency of 2/3, each IOT would require 22.5 kW DC input and 7.5 kW collector heat removal. The cost differential, for a system using 200 devices each, is substantial. Production costs of the klystron and IOT amplifiers should be similar. The RF cavities of the klystron are part of the vacuum envelope, whereas the IOT typically has external RF circuits, except for the CPI IOT, which has an integral output cavity, making the part enclosing the vacuum possibly less expensive than a klystron. The IOT also requires the solid-state driver amplifier.

Life-cycle costs of the two systems are a different matter. The primary power demand of the klystron system is 2-3 times that of the IOT system. The only fair competition would come from a new klystron design with efficiency comparable to that of the IOT. Such an approach would reduce the acquisition-cost differential but must include the development cost differential. A second-order life-cycle cost difference could attend the fact that a replacement IOT is less expensive than the original because not all RF circuits have to be replaced.

CONCLUSION

At 15 kW output and 1.3 GHz operating frequency, the IOT, even though it is approaching what many consider to be its absolute upper frequency limit of 2 GHz, has a number of advantages over the klystron. These include efficiency, lower sensitivity of phase and amplitude to supply-voltage variation, and Class B rather than Class A operating mode, which eliminates concern about collector over-heating resulting from loss of RF drive. Acquisition and life-cycle costs are also likely to be lower.

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