RF SOURCES FOR 3RD & 4TH GENERATION LIGHT SOURCES

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Abstract

The growing number of third and fourth generation light sources has resulted in an increase of the available rf sources to power them. Single beam klystrons are the traditional power source, but the development of IOT's and multiple-beam klystrons (MBK's) in L-Band have increased the options for these machines. The Eimac division of CPI has recently built and tested a prototype L-Band IOT, which delivered 30 kW CW at 1.3 GHz. Future work includes the building of an IOT at 1.5 GHz. Meanwhile the MPP division of CPI is currently testing the prototype 10 MW peak, 1.3 GHz MBK for the TESLA x-ray free-electron laser (XFEL). Test results for these new products as well as information on all CPI products at 500 MHz, 1.3 GHz, and 1.5 GHz will be presented.

INTRODUCTION

CPI, formerly the Electron Device Group of Varian Associates, has a long history of building high-power pulsed and CW klystrons for many applications. For many years, klystrons have been the preferred RF power amplifiers for both pulsed and CW linacs at UHF and higher frequencies. Their high power capability, reasonable efficiency, stability, robustness and long life expectancy have earned them that position. Recent developments are encroaching into the klystrons dominant position. Advancements in Inductive Output Tubes (IOT) and Multiple-Beam Klystrons (MBK) make these devices very attractive in a growing number of applications.

Operation at 500 MHz provides many options at power levels below 60 kW CW. This frequency is in the UHF-TV broadcast band and can often utilize existing devices with little or no modification. Devices for L-band tend to be specifically designed for a given application, but then become available to others interested in using the developed hardware.

KLYSTRONS

Klystrons have been the traditional device for accelerators for many years. They come in a variety of power levels and frequencies. Modern design tools and the plethora of existing designs make this device easily adaptable to the needs of the accelerator community. Klystrons at 500 MHz, 1.3 GHz, and 1.5 GHz are available in many power levels, both pulsed and CW. Beam conversion to rf efficiency can exceed 65% and rf gain ranges from 40 to 55 dB.

UHF Klystrons

At 500 MHz, CPI has klystrons up to 800 kW CW. The lower power tubes are the VKP-7953 series klystron. The device is based on our UHF-TV klystron that has many years of proven service. The VKP-7953A is a slightly modified version of our UHF-TV klystron and rated for 70 kW CW and the VKP-7953B is rated for 100 kW CW. The "A" version has been in service at Taiwan's Synchrotron Radiation Research Center (SRRC) for the past 10 years. The first of higher power "B" version is presently being built. These tubes have a 5-cavity rf circuit, mod anode gun, and a single output window.

At 800 kW CW CPI has built the VKP-7957A for the Cornell Electron Storage Ring (CESR) at Cornell University and the VKP-7958A for the HERA ring at DESY. These tubes share the same rf circuit, have a single output window, and an electron gun with a modulating anode. The VKP-7957A operates horizontally with the gun in oil; the VKP-7958A operated vertically with the gun up and in air, see Figure 1.

Figure 1: VKP-7958A Klystron for DESY

Additionally there are a number of klystrons at other UHF frequencies. The VKP-7952A was developed for the APT Project and produces 1 MW CW at 700 MHz. At 805 MHz, the VKP-8291A is in production for the Spallation Neutron Source project at Oak Ridge National Lab. CPI is building 81 of these 550 kW peak pulsed devices with a beam conversion to rf efficiency in excess of 65% [1]. Additionally there is the VKP-7955 which operates at 200 kW pulsed at 1 msec at 805 MHz.

L-Band Klystrons

In this frequency band CPI has a series of low power klystrons that have been in service for a number of years. The VKL-7811 series have been reliable klystrons for a number of facilities around the world. These compact devices use diode guns, liquid cooling, and permanent magnets for focusing. The VKL-7811W was developed in the early 1990's for the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson

National Accelerator Facility. These tubes are rated for 5 kW CW at 1.497 GHz. Approximately 380 units were made in the original production run to populate the accelerator. Next came the VKL-7811M (5 kW CW at 1.3 GHz) for an application in Japan. Finally the VKL-7811ST (10 kW CW at 1.3 GHz) was developed for Stanford University and Forschungszentrum Rossendorf (FZR).

The VKL-7966A is a 100 kW CW klystron at 1.497 GHz that was recently built to drive the cryogenic cavities in the injector stage of the FEL Driver Accelerator at TJNAF [2]. These units were used in their experiment that achieved 10 kilowatts of infrared laser light, making it the most powerful tunable laser in the world.

In addition to these klystrons that were specifically designed for accelerator applications, CPI has tubes designed for radar that are available as well. The VA-963A is rated for 6.5 MW peak power and 10 kW of average power. It's a pulsed device that can provide 5 μseconds pulses at 1.3 GHz. The VKL-7796 is rated for 4 MW peak and 300 kW average with pulse lengths up to 130 μseconds.

Table 1: Various UHF and L-Band Klystrons

Model	Frequency	Output Power, kW	Duty
VKP-7953A	500 MHz	70	CW
VKP-7953B	500 MHz	100	CW
VKP-7957A	500 MHz	800	CW
VKP-7958A	500 MHz	800	CW
VKP-7952A	700 MHz	1000	CW
VKP-8291A	805 MHz	550	.09
VKP-7955	805 MHz	200	.002
VKL-7811M	1.3 GHz	5	CW
VKL-7811ST	1.3 GHz	10	CW
VA-963A	1.3 GHz	6500	.001
VKL-7796	1.3 GHz	4000	.075
VKL-7811W	1.497 GHz	5	CW
VKL-7966A	1.497 GHz	100	CW

MULTIPLE BEAM KLYSTRONS (MBK)

MBK technology can be separated into two categories: Fundamental Mode (FM) and Higher-Order Mode (HM) MBKs [3]. The differences between the two are the proximity of neighboring beams and the proximity of neighboring cavity modes. The primary drawback to the FM-MBK is that the clustered electron beams are constrained to fall within a circle of approximately $\lambda_0/4$ for optimum cavity interaction. The FM-MBK are generally used for applications requiring large instantaneous bandwidth. The HM-MBK electron beams can be widely separated from each other operating into higher-order-mode cavities. The HM-MBK is selected when relatively narrow bandwidths are acceptable, as with conventional single-beam klystrons, at high average power. However, for this geometry, the cathode loading is not constrained by the circuit and is instead limited by the skill of the beam-optics designer.

An equally important factor is that as a result of beam interception with and without rf, the cavity thermal loading is distributed along a relatively large surface area, increasing the average power handling capability of the HM-MBK versus the FM-MBK. A comparison of MBKs to single-beam klystrons can be seen below.

Advantages

- Lower operating voltage for a given rf power level
- Lower x-ray level due to lower operating voltage
- High efficiency vs. microperveance
- Large instantaneous bandwidths (FM-MBK)
- Compact, lightweight
- Low Noise

Disadvantages

- Difficult to focus the electron beams
- Lower average power (FM-MBK only)
- High cathode loading (FM-MBK only)

1.3 GHz MBK for TESLA

The first opportunity for CPI to build an MBK was for the TESLA project at DESY. The CPI-DESY engineering team agreed to use the HM-MBK approach. The primary reason for doing so is discussed above and worth repeating: low cathode loading combined with distributed thermal loading of the rf circuit. This HM-MBK uses six off-axis electron beams emitted from six individual cathodes. Table 2 lists the essential design parameters for this device.

Table 2: TESLA MBK Typical Operating Parameters

Parameter	Value	Units
Peak Output Power	10	MW
Average Output Power	150	kW
Beam Voltage	114	kV
Beam Current	131	A
Efficiency	65-67	%
Frequency	1300	MHz
Pulse Duration	1.5	ms
Saturated Gain	47	dB
Number of Electron Beams	6	- - -
Number of Cavities	6	- - -
Cathode Loading	~2.1	A/cm^2
Solenoid Power	4000	W, max.
Cathode Loading	~2.0	A/cm^2

TESLA MBK Prototype Test Results

Initial testing of the device has validated the basic design approach [4]. Six 120 kV electron beams of measurably identical currents of 22.9 A each have been successfully propagated through the klystron circuit with 99.5% DC beam transmission at full operating video duty and with 98.5% saturated RF transmission. A peak power of 10 MW at 1.3 GHz with 60% efficiency and 49 dB of gain have been measured. The output power versus input power curves for varying beam voltages is shown in Figure 2. As can be seen, the curve characteristics for the MBK are substantially the same as a conventional klystron. A photo of the device is shown in Figure 3.

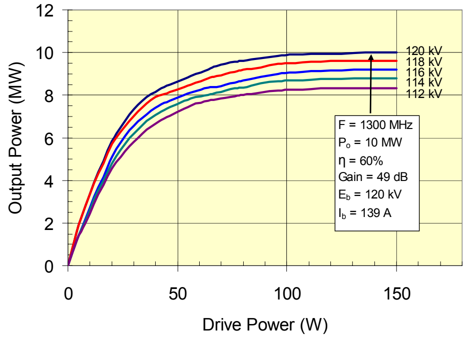

Figure 2: Measured output power versus drive power for five beam voltages

Figure 3: Prototype MBK for TESLA

Unfortunately testing was stopped due to a problem with one of the two output windows. During long pulse, high-average power testing several gas bursts were experienced, along with severe rf pulse shortening. The average power capability of the MBK degraded after these events. The problem with the window was verified. The klystron is in the process of being repaired with the target of shipping it to DESY by the end of the year.

INDUCTIVE OUTPUT TUBES (IOT)

Since the late 1980s the Inductive Output Tube (IOT) has established itself as a useful device for broadcast, applied science and industrial applications in the UHF range. Compared to a klystron, the IOT compensates for its lower gain with both superior efficiency and linearity, and it outperforms the tetrode, its next of kin, with regard to power capability and gain. However, it has long been thought that transit time effects limit the useful frequency range of IOTs to the VHF and UHF bands; 1 GHz was considered a threshold beyond which the performance of IOTs as fundamental frequency amplifiers would fall off rapidly.

Several key advantages of the IOT make them desirable for accelerator use. The salient parameters in this case are:

1. Most particle accelerator applications do not require high linearity. The IOT can be operated in class C and thus provide efficiency levels far beyond the reach of klystrons, see Figure 4.
2. The IOT does not saturate at the point of its highest efficiency like the klystron. The device does not require power back-off from optimum efficiency to allow fast feedback.
3. Since the beam current in an IOT is grid-controlled, a HV modulator is not required for pulse operation. It is sufficient to pulse the drive power.

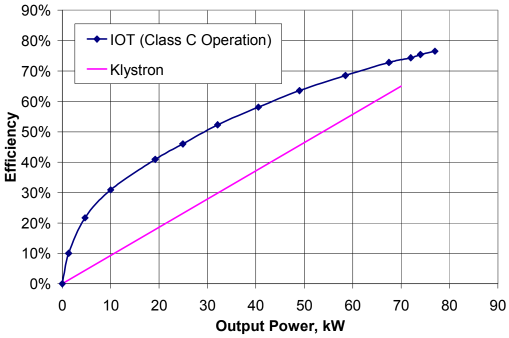

Figure 4: IOT Efficiency vs. Typical Klystron

The existing UHF-TV IOT, EIMAC K2 series, is well suited for use at 500 MHz, or anywhere within the UHF-TV operating band (470-810 MHz) and has a very positive track record in TV broadcast service (up to 130 kW peak in digital or up to 75 kW peak sync in analogue operation, respectively), as well as a CW amplifier for scientific purposes (up to 80 kW CW) with the addition of some cooling.

UHF IOTs are in CW operation in the 5 MeV CW Microtron at MELCO in Kobe, Japan. Two IOTs are combined to generate 100 kW of RF power at 500 MHz. At the FEL at the Japan Atomic Energy Research Institute, Tokai, Japan, two IOTs are used independently as RF sources for the pre-acceleration super conducting cavities (499.8 MHz). See Table 3.

Table 3: Eimac K2 IOT Operation at 500 MHz

Power Level (kW)	50	60	67	80
Beam Voltage (kV)	30	30	35	35
Beam Current (A)	2.14	2.67	2.6	2.98
Grid Current (A)	0.14	0.24	0.14	0.22
RF Drive Power (W)	190	267	275	380
Power Gain (dB)	24.2	23.5	23.9	23.2
Efficiency (%)	77.9	74.9	73.6	76.7

Eimac has delivered 15 IOTs for pulsed operation in a US government project. Each IOT delivers 80 kW peak power and operates at a different frequency in the UHF range.

The First L-band IOT design

The fundamental-frequency IOT seemed to be the single solution to maintain the well-appreciated IOT properties for an L-band version [5]. It was decided to modify EIMAC K2 as little as needed only to arrive at a 1.3 GHz version. To replace the external-cavity UHF output section with an internal 1.3 GHz resonator was a straight-forward development step. The output section consists of a standard 1-5/8 inch coaxial line, which contains an alumina window of the same type that is in use in numerous L-band klystrons. The cavity is water-cooled which serves to remove the loss energy from the cavity and provide stability against de-tuning.

Much more concern was spent on the input circuit. The input impedance of an IOT is of the order of 10 Ω only; thus the input circuit has to transform the impedance downward from that of the input line, instead of upward like in the case of a klystron. Beyond that, the input signal has to be transferred safely and reliably from ground level to the high-voltage DC potential of the electron gun. High-voltage-safe dimensions and low impedance are not easily married, but it was possible to find an elegant solution to the problem.

Apart from these two segments, almost all other elements are identical with those of the UHF version. The 1.3 GHz prototype is shown in Fig. 5.

Figure 5: 1.3 GHz IOT

L-Band Prototype Test Results

The first prototype was slightly off frequency; the second unit was slightly overcoupled. Prototype 3 was on frequency and measured data shown in Table 4.

Table 4: Prototype 3 Test Results at 1.3 GHz

Beam Voltage (kV)	Beam Current (A)	Drive Power (W)	Output Power (kW)	Gain (dB)	Effi-ciency (%)
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

Even at almost 30 kW CW the body of the IOT and its output section did not show signs of meeting any limitations. The thermal output power measurements are believed to be pessimistic because the power-absorbing bricks of the load were operating at very high temperatures and reflected a considerable part of the power back into the waveguide in the form of infrared radiation.

It is believed that these tests, performed in December of 2003 and January of 2004, mark the first time that an IOT has been operated at a frequency beyond the UHF band. The encouraging results have driven the development of a 1.5 GHz, 15 kW CW version, which is scheduled for testing in early 2005, and a 300 kW long pulse IOT at 1.3 GHz.

SUMMARY

CPI has expanded its catalogue of vacuum electron devices with the addition of the MBK and IOT. The particle accelerator community has more options in types of devices to power their machines in UHF and L-band. The klystron will remain the workhorse with the ability to cover virtually any power need. The MBK provides high efficiency at lower operating voltage while the IOT provides high efficiency over a wide range of power level. These newcomers will provide system designers lowering procurement and operating costs.

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