

DESIGN AND PERFORMANCE OF L-BAND AND S-BAND MULTI BEAM KLYSTRONS

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Abstract

Recently, there has been a rising international interest in multi-beam klystrons (MBK) in the L-band and S-band, with active development taking place. These MBKs are developed by industries such as Toshiba, Thales and CPI for the European X-FEL project or at the Naval Research Laboratory for high-power, low-voltage, broadband radar/radio communication systems. Some of them are already in operation at full specification and are commercially available. MBKs have distinctive advantages to conventional single-beam klystrons in their ability to produce high power with high efficiency and large bandwidth at lower voltage in compact body. This paper reviews the design and performance of these multi-beam klystrons, and describes future development plans.

INTRODUCTION

Klystrons have been always the major sources of high power RF in particle accelerators. The development of new types of klystrons has made large and important contributions in achieving significant advances in energy outreach of linear accelerators. The historical growth in klystron power in the past 60 years since WWII shows that the output power increases 10-fold every 14 years. Recent projects and proposals of high-energy superconducting linacs demand high power klystrons with high efficiency (60-70%) and long pulse duration (an order of 1ms). The peak power delivered by a long pulse Single-Beam Klystron (SBK) is limited by the high voltage that its gun can withstand. A lower cathode voltage (more exactly speaking, the maximum surface electric field in the gun region) is desirable to ensure reliable operation without gun arching or voltage breakdown. However, in a single-beam klystron, the simultaneous optimization of output power, voltage and efficiency is nearly impossible, since the perveance determines the relationship of all other operating parameters and even an achievable maximum efficiency of the tube.

When one designs a single-beam klystron for a given output power P_{out} , he first has to choose the perveance, p , given by $p=I/V^{3/2}$, where I is the beam current from a cathode and V is the cathode voltage. The perveance indicates how much beam current comes out of the cathode when the voltage V is applied between the cathode and the anode. There is the empirical relation between the perveance and the achievable highest efficiency, η_{max} , given by [1]

$$\eta_{max} (\%) = 78 - 16 \times p (\mu\text{-perveance}). \quad (1)$$

Figure 1 illustrates this relationship. This figure indicates that a lower perveance beam with weaker space-charge

forces enables stronger bunching and thus consequently higher efficiency.

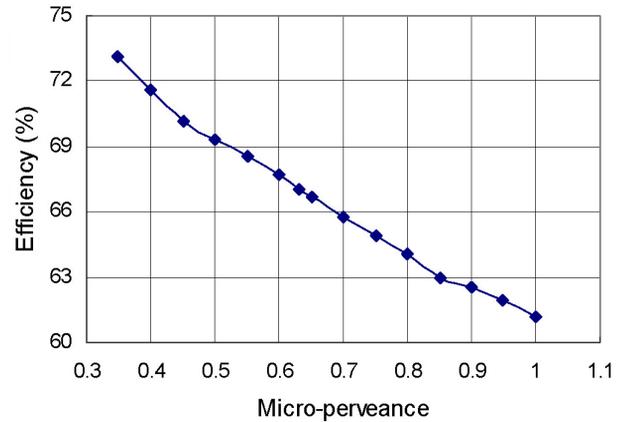


Figure 1: The empirical relation between the perveance and the achievable highest efficiency, η_{max} .

Once the efficiency ($\eta \leq \eta_{max}$) of the tube is assumed, the cathode voltage is determined from the relation

$$P_{out} = \eta IV = \eta p V^{5/2}. \quad (2)$$

In this circumstance, only way to increase the output power without increasing the voltage, or reduce the voltage without reducing the output power, is to increase the perveance, i.e., the beam current. However, a high perveance is strongly undesirable since (1) it provides a lower efficiency (2) it requires a larger cathode current loading resulting in a shorter cathode lifetime (see Fig.2) (3) it requires stronger magnetic fields for beam focusing which can lead higher system volume and weight (4) it has a higher risk of gun oscillation and gun arching. In conclusion, the choice of perveance in a single-beam klystron is always a compromise between high power and efficiency and tube reliability.

A breakthrough solution to this gridlock is to use multiple low perveance beamlets in parallel in the same vacuum envelop. The number of beamlets introduces a new degree of freedom in parameter space. In a Multi-Beam Klystron (MBK), a high current electron beam is separated into multiple parallel beamlets,

- each with a sufficiently low current density (perveance) to ensure efficient electron bunching and a high efficiency,
- while the high total perveance of beam current provides the required high output power.

The co-existence of these two different perveances in the same device is the great advantage of MBK to SBK, which allows simultaneous optimization of efficiency and output power. Each beamlet propagates in individual drift tube, paralleled to, but isolated from each other and are allowed to interact only in common RF cavities. Schematic presentation of MBKs is shown in Fig.3

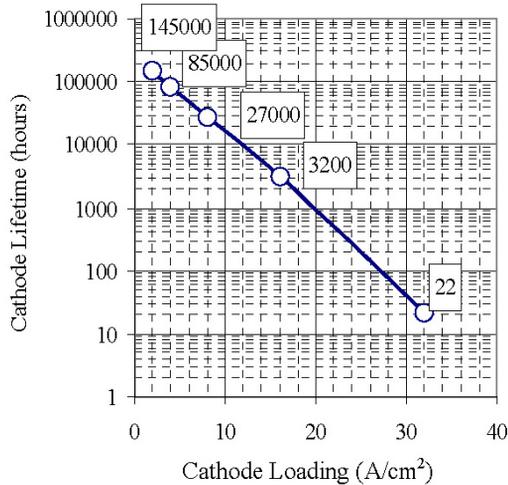


Figure 2: Empirical relation between the cathode loading and expected lifetime of the cathode.

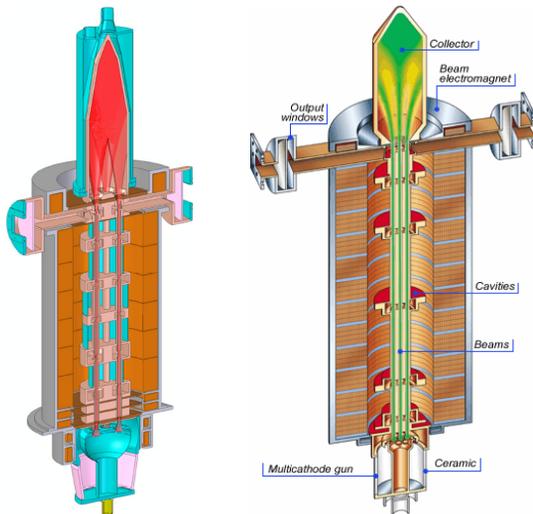


Figure 3: Schematic presentation of MBKs (Toshiba E3736: left and Thales TH1801: right).

For a given output power, a lower cathode voltage is required in a MBK compared to a SBK. The combination of high total beam current and lower beam-induced voltage in a common output cavity makes it possible for a lower external Q-factor, facilitating higher bandwidth operation.

HISTORICAL BACKGROUND

The concept of multi-beam klystron is not new. It was proposed as early as the middle of the 20th century in both the Former Soviet Union and France. MBK development in the US all but ceased after the early 1960s,

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since it was thought that potential benefits of MBK technology did not outweigh the added device complexity and associated cost [2]. In the last three decades, MBK development has occurred primarily in the Former Soviet Union for mobile ground-based, airborne and space-based radar and radio-communication systems because of its advantages in high power, efficient, broadband operation capability at lower voltage in compact and lightweight body. Few details were published to outside world before the end of Cold War, as they were developed primarily for military applications. Recently, other countries have revived their activities in MBK for similar applications.

Under the renewed interest in US, Naval Research Lab recently built a broadband (6%), S-band, 600kW, 8-beam MBK for shipboard radar/communication systems [2]. Table 1 summarizes its parameters and measurement results. They employ the typical design of MBK for a large instantaneous bandwidth, with eight clustered beamlets around the geometric axis, interacting with four common TM₀₁₀ cylindrical cavities (see Fig. 4).

Table 1: Parameters and Measurement Results of Naval Research Lab’s S-band, 600kW, 8-beam MBK

Parameter	Measured	Unit
Central Frequency	3.2	GHz
Peak Output Power	600	kW
Beam Voltage	45	kV
Beam Current	32	A
RF Pulse Duration	5	μs
Efficiency	39	%
Bandwidth	6	%
Gain	30	dB

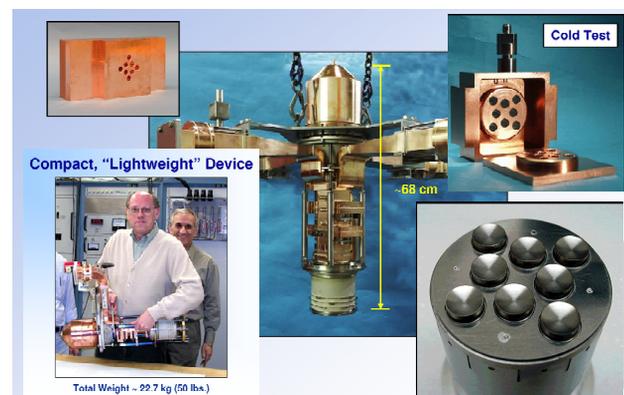


Figure 4: Naval Research Lab’s S-band, 600kW fundamental-mode, 8-beam MBK.

L-BAND 10MW MBK FOR TESLA

Recently, there has been a rising international interest in MBK for applications in particle accelerators, with active development taking place, in France, US, and Japan. That began about 10 years ago, when DESY

started its efforts to develop an L-band 10MW MBK with Thales (France) for the TESLA [3] (now XFEL [4] and ILC) project. Thales started the design work in late 1990, and the full power test of the first MBK was done successfully at DESY in May 2000 [1]. CPI joined this effort with its own design in 2001 [5] and the test of the first CPI MBK was done at DESY in September 2005. At last but not least, Toshiba joined the worldwide effort of MBK development with its own design in 2002. Although it was late start, they built and successfully tested the vertical MBK at DESY in June 2006 [6]. They then built the first horizontal MBK for XFEL and the full power test was done successful at DESY in February 2008 [7].

The major challenges to design and operation of L-band (1.3GHz) MBK for TESLA are (1) “super-high” peak (10MW) and average (150kW) power requirements (2) a high efficiency ($\geq 65\%$) required at this power level (3) multiple and uniform beam cathodes that stably sustain long beam pulse operation (1.7ms at 115kV at 10Hz repetition rate) with long tube lifetime ($>60,000$ hrs). However, the required instantaneous -1dB bandwidth is only 3MHz unlike a broadband MBK for radars. At acceptance test at DESY, a tube has to satisfy all requirements for operation parameters. Transfer curves (RF output power vs. RF drive power) need to be smooth without any discontinuity, meaning no sign of multipactoring or parasitic oscillation. 24 hours continuous operation without fault by gun or window arching is also required at the end of test.

DESIGN AND PERFORMANCE

Development of “super-high” power MBKs is relatively new area, and there is no standard design model yet. In fact, the all three MBKs (Thales, CPI and Toshiba) have different designs with their own pros and cons. Success of any MBK among them will greatly help to establish a design model for future MBKs in a centimetre-wavelength band. The following assessments are based on the author’s analysis of pros and cons of different design approaches when he made the basic design of the Toshiba MBK in 2002, which later became Toshiba E3736.

Thales MBK TH1801

Thales design is the conventional “clustered-beam approach” for a radar requiring a large instantaneous bandwidth. This design uses 7 beamlets (6 on a circle and 1 at the center), each with 0.5μ -perveance [1]. They enter the center of cylindrical common cavities operating in the fundamental (TM_{010}) mode through individual drift tubes. Figure 5 shows the photograph of the multi cathode gun (left) and the cross sectional view of TM_{010} cylindrical cavity. This design provides the most compact and lightweight MBK. The primary drawback to this design is that clustered beamlets are closely packed near the center of the tube. The consequent small cathodes and poor beam area compression (9:1) lead to high cathode loading ($5.5A/cm^2$), which in turn results in the relatively short

cathode lifetime (36,000hrs). Use of recent long-life, high emission current density cathodes may ease this concern.

In reality, the lifetime of a tube is likely to be determined by, not the cathode loading itself, but deposition of Barium, evaporated from cathodes, on focus electrode or anode. For this reason, lower operating temperature of cathodes (lower cathode loading), and larger deposition area of Barium (larger focus electrode and larger anode) help to significantly extend the arc-free lifetime of a tube. In this sense, the Thales design may inherit the typical problem of relatively short lifetime of MBK for radar/radio-communication systems.

Another characteristic of Thales design is the conflicting role of the center beamlet. If only off-axis beamlets are used, the pervenace of each beamlet will be 0.58μ -perveance, and the achievable highest efficiency is 68.7%, according to the relationship (1). Addition of the center beamlet helps to reduce the single beam pervenace to 0.5μ -perveance, and increase the achievable highest efficiency to 70%. The current loading of each cathode is also reduced, benefitting longer cathode lifetime. On the other hand, the center beamlet experiences a larger voltage across the gap of a cavity than the off-axis beamlets due to the field shape, and the R/Q of the center gap is 40% higher than those of the off-axis gaps. Therefore, the center beamlet will develop different bunching from other beamlets, which will perturb coherent excitation of TM_{010} modes at the cavities, in particular at the output cavity. As will be seen soon, the measured efficiency of Thales TH1801 is 65%, 5% lower than the achievable highest efficiency of 70%. A challenge of this design is to find methodology for improvement of efficiency and peak power.

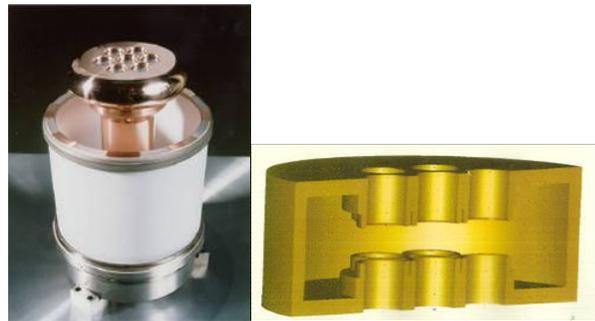


Figure 5: The multi cathode gun (left) and the cross section of TM_{010} cavity (right) of Thales TH1801.

Eight Thales TH1801 tubes have been built and successfully tested (except #2) at DESY. Figure 6 shows its photograph. The typical test results are summarized in Table 2. The early two TH1801 tubes showed gun arching problems. The small cathodes and the large cathode loading were suspected as the causes. However, thoroughly investigation at Thales revealed that the cause was a gun oscillation and the problem was fixed. Since then, no sign of degradation has been observed. The horizontal version, which fits in the accelerator tunnel, is almost ready to be delivered for testing at DESY in fall 2008.

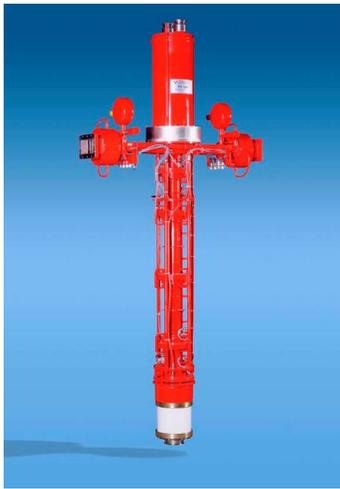


Figure 6: Thales TH1801.

Table 2: Typical test results of Thales TH1801 at DESY.

Parameter	Measured	Unit
Peak Output Power	10.2	MW
Beam Voltage	117	kV
Beam Current	131	A
RF Pulse Duration	1.5	ms
Repetition Rate	10	Hz
Efficiency	65	%
Bandwidth	>10	MHz
Gain	48.2	dB

CPI MBK VLK-8301

CPI takes a unique approach [5]: Their MBK has six weakly-coupled single-beam klystrons in parallel, sharing the same modulator, but with its own cathode, collector and individual cylindrical TM_{010} cavities except for input and output cavities. They are coupled by large common input and output cavities operating in the higher-order (TM_{020}) mode. The beamlets are set on a large bolt circular diameter (26.7cm) and interact with the second radial peak of the axial electric field in the TM_{020} cavities.

The advantage of this design is the ability to use large cathodes with small cathode current loading ($2.2A/cm^2$) and resulting long cathode lifetime (>100,000hrs).

The disadvantage is an increase of the complexity of the tube, in particular, in design of proper focusing system to provide minimum radial fields for 13.4cm off-axis beamlets. The tube has high volume (a major diameter of 53cm) and is heavyweight: the tube weights 900kg, three times heavier than Thales TH1801 (300kg). Use of large TM_{020} cavities also increases a number of parasitic modes and a risk of their undesirable oscillation.

Use of intermediate individual cavities raises concern on efficiency degradation. In a klystron, the beam-induced voltages in cavities amplify the bunching in beams. The induced voltage is a function of the cavity characteristics (R/Q, resonant frequency, etc.) and the

beam characteristics (beam current, size, etc.). In a MBK, the currents and sizes of individual beamlets will not in general be exactly balanced. Therefore, even if all the cavities are exactly same, the beam-induced voltages at each individual TM_{010} cavity will differ, depending on the characteristics of each beamlet. As a result, each beamlet will develop slightly different bunching, and this difference will be amplified as they interact with successive intermediate individual cavities. If the cavities are not balanced either, say, due to deformation during bake-out or heating during operation, the synergy effects of unbalanced beamlets and unbalanced individual cavities will further deviate the synchronous bunching of beamlets. When all beamlets meet at the common output cavity, a loss in synchronization of bunching in amplitude and phase will degrade the efficiency. In Thales and Toshiba designs, they use only common cavities where all beamlets excite the same TM_{010} modes together and receive the same voltages together. Therefore, they are less susceptible to unbalance in beamlets and cavities.

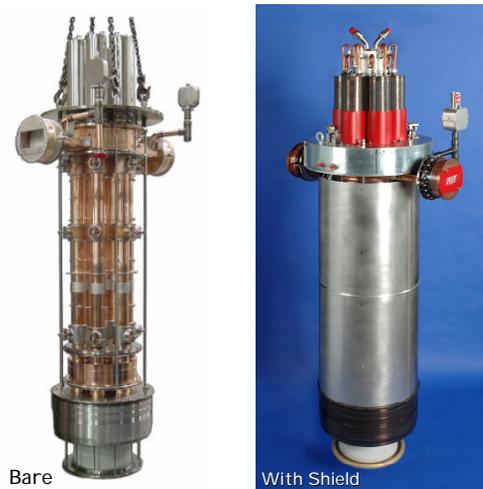


Figure 7: CPI VLK-8301. Bare (left), shielded (right).

VLK-8301 was tested at DESY in September 2005. It did not make full 10MW peak power at full pulse length. The best result was 8.1MW peak power at 1.3ms pulse length at 10Hz repetition rate with efficiency of 53.5%. It attained 9MW peak power at a short pulse length of 0.3ms. The test results are summarized in Table 3. The tube is now in use at DESY for the cryomodule test stand.

Table 3: Test Results of CPI VLK-8301 at DESY in 2005.

Parameter	Measured	Unit
Peak Output Power	8.1	MW
Beam Voltage	115	kV
Beam Current	131	A
RF Pulse Duration	1.3	ms
Repetition Rate	10	Hz
Efficiency	53.5	%
Bandwidth	>5	MHz
Gain	48	dB

CPI is currently developing a second-generation, horizontal version of MBK, VKL-8301B. In this new design, they utilize 7 ring-shaped cavities operating in the fundamental TM_{010} mode, just like the Toshiba design, instead of TM_{020} cylindrical cavities used in the first generation. The horizontal VKL-8301B is expected to be delivered to DESY in fall 2008.

Toshiba MBK E3736 and E3736H

Toshiba approach is a “simple and symmetric” design [6]. They use common ring-shaped cavities for all cavities, operating in the fundamental TM_{010} mode, to ensure sufficient beam separation (spaced on a diameter of 12cm, not 26.7cm like CPI), while still keeping the overall size small to reduce cost and complexity. The 6cm separation of beamlets allows to use large cathodes (a diameter of 38mm), and the cathode current loading is $2.1A/cm^2$, as small as CPI VLK-8301 for long lifetime (>100,000hrs).

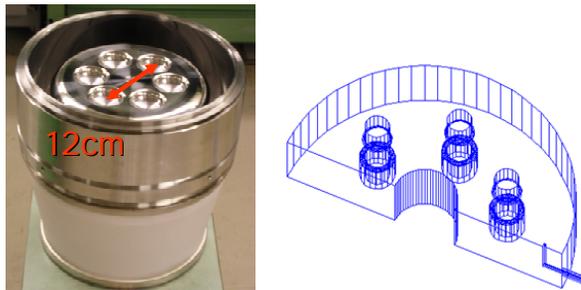


Figure 8: The multi cathode gun (left) and the ring-shaped TM_{010} cavity (right) of Toshiba E3736 and E3736H.

The distinctive advantage of this design is the ability to optimize the cavity structure, the beam separation, the cathode diameter and the number of beamlets for optimum operational performance of the tube, by adjusting the overall sizes of ring-shaped cavities: the diameter of ring is a relatively free parameter, while the width of ring is constrained by the operation frequency of 1.3GHz. Despite of great benefits of the sufficient beam separation and the large cathode size, the tube weights only 340kg, 13% heavier than Thales Th1801. An added advantage of the fundamental mode operation is to make the tube more tolerant to manufacturing errors and cavity deformation due to bake-out or heat deposition.

The first tube, the vertical E3736 (Fig. 9 left), was successfully tested at DESY in June 2006 to full peak and full average RF power at full pulse length [6]. The second tube, the horizontal version, named E3736H (Fig. 9 right), was also tested successfully at DESY in February 2008[7]. Their test results are summarized in Table 4.

Toshiba E3736H was the first horizontal MBK for the XFEL project, delivered, successfully tested and accepted by DESY. The vertical version has been operated for more than 750 hours at the full power in about 80% of time. The horizontal version has been operated for more than 850 hours, in use for investigation of RF behaviour such as temperature stability, harmonic level, and phase stability, etc., which will be of great help for XFEL operation.

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Figure 9: Toshiba vertical E3736 (left) and horizontal E3736H (right).

Table 4: Test Results of Toshiba E3736 and E3736H Measured at DESY in 2006 and 2008, Respectively

Parameter	E3736	E3736H	Unit
Peak Output Power	10.2	10.1	MW
Beam Voltage	115	118	kV
Beam Current	134	130	A
RF Pulse Duration	1.5	1.5	ms
Repetition Rate	10	10	Hz
Efficiency	66	65.4	%
Bandwidth	3.5	3.5	MHz
Gain	49	48	dB

CONCLUSIONS

The good performance of the Thales and Toshiba L-band MBKs operating in the fundamental modes of cylindrical cavities (Thales) or ring-shaped cavities (Toshiba) demonstrates that their design approaches are sound and valid in this wave-length band. The Toshiba design is more advantageous in a shorter wave-length, because of greater flexibility in design of the gun region. In a longer wave-length, Thales design is an attractive choice, since it provides a compact and low-cost tube. The MBK technology and its distinctive advantages over SBK will greatly benefit and advance linear accelerators.

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