DEVELOPMENT OF A 10-MW, L-BAND, MULTIPLE-BEAM KLYSTRON FOR TESLA*

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Abstract

A high-efficiency, Multiple-Beam Klystron (MBK), designated the VKL-8301, is being manufactured for the DESY Tera Electron volt Superconducting Linear Accelerator (TESLA) in Hamburg, Germany. There are a number of excellent reasons for using an MBK for this application. The primary reasons are reduced size and lower operating voltage with respect to the conventional, single beam counterparts. Once this decision has been made, the class of MBK must now be selected. MBK's can be divided into two categories: Fundamental Mode (FM) and Higher-order Mode (HM) devices, distinguished by the interaction mode of the cavity resonators. Each class has inherent advantages and disadvantages dependent upon end-user requirements. For the 10 MW, 1.3 GHz TESLA application the HM-MBK is the clear choice. The primary factor influencing this choice was operational life, since the accelerator will require approximately 600 MBK's. The advantage of the HM approach is low cathode loading. Our cathode loading design goal of 2 A/cm^2 or less has been achieved. For this application the HM-MBK cathode loading is a factor of four lower than competing FM-MBK designs and a factor of three lower than the SLAC 5045 design. The VKL-8301 will use six off-axis electron beams interacting with a combination of TM_{010} and hybrid TM_{020} cavities. These six beams are equally spaced on a diameter of approximately 25 centimeters. Because of the large beam-to-beam separation, individual high-area convergence guns can be utilized versus the single multi-emission-site gun used in FM-MBK's. This solution requires a sophisticated focusing system that is relatively difficult to realize, compounded by our use of confined-flow focusing. Newly developed, state-of-the-art three-dimensional electromagnetics codes have been used to design the novel electron-beam-focusing system and microwave cavity geometry. Modeling and simulation results will be presented, hardware will be shown, and a description of the FM- versus HM-MBK selection process will be discussed.

BACKGROUND

Last year we reported on the progress developing the TESLA MBK and provided a description of the CPI approach [1]. This paper is intended to supplement the original, updating our progress, and more importantly describe the thought process involved when selecting the HM-MBK for this application. All of the large, next-generation linear colliders considering the use of klystrons as their high-power rf source should consider, as DESY has, the FM-MBK approach. The merit of the approach is a result of one of the most important parameters for a practical system, LIFE.

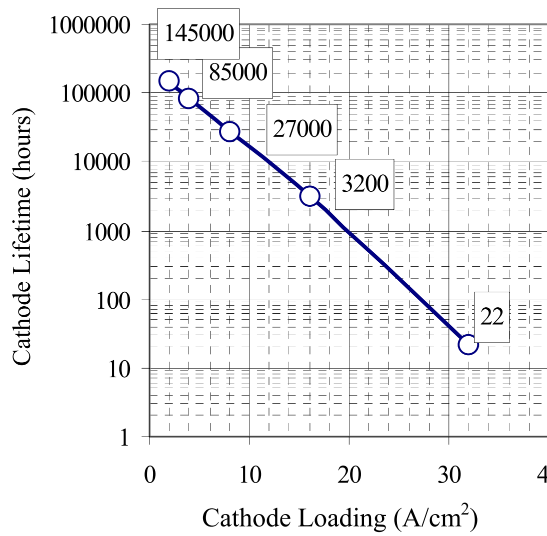

Figure 1. Life versus loading for an M-type dispenser cathode, space charge limited operation, 40 ^oC above the knee.

For any mature, well-designed tube the primary mode of failure is cathode end-of-life, a result of barium depletion. So, what factors influence cathode life? There are primarily two: Temperature and Pressure. Today's manufacturing techniques provide products operating with exceptionally low pressure, so for a well-designed product this is no longer a major issue. What's left is temperature. However we will use current density, rather than temperature, because most tube engineers can readily quote cathode loading for a given design.

Cathode lifetime as a function of cathode current density can be seen in Figure 1, and is based on a compilation of measured data taken within the past 30 years. This curve is in excellent agreement with measured average lifetimes for klystrons and CCTWT's installed in mature systems, with current densities in the 2 A/cm^2 to 8 A/cm^2 range. This curve plays a pivotal role in selecting the appropriate class of MBK for this application, as will be shown.

* This work supported by Deutsches Elektronen-Synchrotron , DESY

MBK DESIGN

Classification

There are two classes of MBK's, differentiated by the rf cavity mode used: FM- and HM-MBK's [2][3]. These can be further subdivided by the proximity of neighboring electron beams and the number of cathodes used.

Clustered Emitters (CE) are single-cathode guns with multiple emission sites designed to form clusters of electron beams in close proximity to one another. The primarily advantage of this approach are the large instantaneous bandwidths that can be achieved with the use of single gap or inductively coupled, multiple gap TM_{01} resonator. All large instantaneous bandwidth FM-MBK's use this approach, however narrow bandwidth FM- and HM-MBK's equally benefit. The disadvantage of this approach is the cathode current density is constrained, proportional to the square of frequency, as will be shown.

Distributed Emitters (DE) are multiple cathode guns with single emission sites from each of the cathodes, are used when large beam-to-beam separation is desired, and are only used for HM-MBK's. The HM-MBK is a narrow band device due to the proximity of neighboring resonator modes, perfectly suited for high-power scientific applications. One key advantage to this approach is the cathode loading is unconstrained. The system designer needs to be aware that this tradeoff exists when developing MBK based systems, particularly those intended for high-power scientific applications requiring a large number of MBK's.

FM-MBK Cathode Loading

When a single-cathode, multi-emission site gun is proposed for a given design, cathode loading must be considered. As such, we need a way of estimating the cathode loading, which in turn can be used to determine tube life. Conversely, one can approach the problem from the other direction: What life/loading is considered acceptable?

$$J_C = \frac{576}{7\pi c^2} I_o f^2 \qquad (1)$$

In order to keep the rf interaction within the cavity uniform, in-general the diameter of the beam cluster must fall within $\lambda_o/4$, or less. This condition forces the individual cathode emitters to follow suit, i.e. they must be concentric to their respective drift tubes. One can readily see there is a connection between cathode loading and frequency. Let's explore this. Assume there are seven emission sites with close-packed hexagonal geometry (or choose a number of emitters suitable for your specific application). Individual emitters would have one third the total interaction diameter, or $\lambda_o/12$. Computing the area of these seven emitters and dividing the total beam current by that value will give you the best-case current density for a given frequency of operation (1); the value obtained is best case because it assumes zero thickness separating the individual emitters. A plot of this function for the cathode loading values given in Figure 1 can be seen in Figure 2.

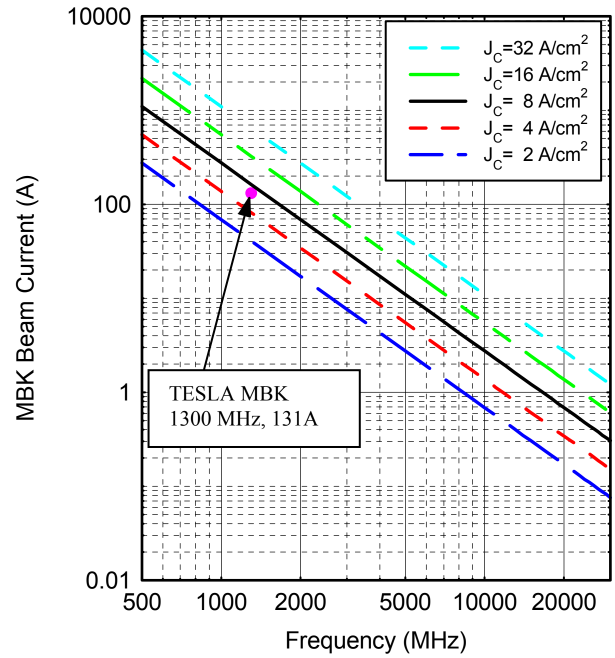

Figure 2. Total current versus frequency for the CE gun geometry.

Table 1: Klystron 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	<2.5	A/cm^2
Solenoid Power	4000	W, max.

The TESLA MBK

The operating parameters for the TESLA MBK can be seen in Table 1. For this analysis the key parameters are the operating frequency of 1300 MHz and the total device current of 131 Amperes. This data point has been placed on the graph, Figure 2. For this application the CE-gun average cathode loading is 7 A/cm^2, minimum. For practical gun designs, i.e. a gun with separation between adjacent emitters, this value is at least 8 A/cm^2. From the graph of Figure 1 we estimate the average lifetime of the CE-gun to be approximately twenty seven thousand hours, or less than three years.

Figure 3. Aluminum output cavity model during rf cold testing.

CPI has recommended the HM-MBK base primarily on the increased life these products would have due to their use of the DE-gun. Since the HM approach imposes no restrictions on cathode loading, we can select a value suitable for long-life operation. We selected 2 A/cm^2 because this value will provide average lifetimes of 145,000 hours (or sixteen years!) and also for ease of manufacture.

This may seem like we're getting something for nothing, which is certainly not the case. An HM-MBK will be more expensive to produce than an equivalent FM-MBK. However when these units are mass-produced the difference in price will be small, on the order of 15% to 30% more. However the long-term benefit resulting from reduced life-cycle costs are orders of magnitude greater than this difference. For this particular application the FM-MBK is the desired approach. Let say the desired frequency were halved, or 650 MHz. At 131 A of total current, either approach would provide excellent life.

PROGRESS UPDATE

We have entered into the build phase of this program. All the material, except for the input and output cavities, has been issued to the assembly floor and manufacturing has begun. The raw material for the higher-order mode TM_{020} input and output cavities has been received, however we have additional rf cold test to perform to fine-tune these resonators before we start the final machining. Full-size aluminum cold test cavity models have been received for the input and output, Figure 3. We have spent considerable time cold testing these cavities measuring frequency, Q-factors, and gap-to-gap electric field (intensity) and phase uniformity. We will finish these tests by the end of May 2003.

Another important milestone will be reached when we receive the magnet in early June 2003. At that time the critical step of measuring, verifying, and fine-tuning the magnetic field will begin. Once this step is complete the MBK will be sealed in, exhausted, dressed and tested. Testing is schedule to start the beginning of August 2003.

REFERENCES

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