THE 120 MW X-BAND KLYSTRON DEVELOPMENT AT KEK

Y. H. Chin, K. Takata, S. Fukuda, H. Mizuno, S. Michizono, S. Yamaguchi, S. Matsumoto,
S. Tokumoto, and H. Tsutsui, KEK, 1-1, Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan
S. Kazakov, BINP, 142284, Protvino, Moscow, Russia

Abstract

In this paper, we summarize our activities on X-band klystron development for the Japan Linear Collider (JLC) project. Our goal is to produce a 120-MW class klystron at 11.424 GHz with a pulse length of 1.5 μs and with an efficiency better than 47%. For this end, we have advanced three programs simultaneously. First, we adopted the particle-in-cell (PIC) code, MAGIC, for a realistic simulation of klystron and for a better design of Traveling-Wave (TW) output cavity. Simulation results for the XB72K No. 8 and No. 9 klystrons and the SLAC XL-4 klystron show excellent agreements with measurements. A new solenoid-focused klystron, XB72K No.10, is the first klystron designed by using the MAGIC code. Its predicted performance is 126 MW output power (efficiency 48.5%) with peak surface field of about 77 MV/m, low enough to sustain a 1.5 μs long pulse. It is now in manufacturing and the high power testing is scheduled to start from November 1998. Second, new RF windows with 100-MW power-handling capability have been designed and the cold model test is about to start. They utilize TW mixed modes (TE11 plus TE12 modes, or TE11 plus TM11 modes) to reduce the surface field at the brazing edge of the ceramic, instead of a single TW TE01 mode window that needs expensive mode converters. Third, the Blumlein modulator is upgraded to produce a pulse with 2 μs flat top and 200 ns rise time at 550 kV output voltage. Details of the klystron development are presented.

1 ACTIVITY HISTORY

The 1-TeV JLC (Japan e^+e^- Linear Collider) project[1] requires about 3200 (/linac) klystrons operating at 75 MW output power with 1.5 μs pulse length. The main parameters of klystron are tabulated in Table 1. The X-band klystron program at KEK, originally designed for 80 MW peak power at 800 ns pulse length, has already produced 9 klystrons with solenoidal focusing system. The first five klystrons in this XB72K series employed a single-gap output cavity. They repeatedly showed RF discharge at the output structure due to the high electric field there. A output power of 90MW could be sustained only for a short pulse of about 100 ns (only 30 MW at 200 ns). To reduce the maximum surface field in the output cavity, the traveling-wave (TW) multi-cell structure has been adopted since the XB72K No. 6. The design of TW output structure has complex tasks: a high efficiency requires a good synchronization between the traveling-wave and the beam for an extended period of interaction. The electromagnetic energy density in the output structure must be also distributed as uniformly as possible among cells (quasi-constant gradient) to minimize the field gradient. Four TW klystrons have been built and tested. All of them share the same gun (1.2 micropeaveance and the beam area convergence of 110:1) and the buncher (one input, two gain and one bunching cavities). Only the output structures have been redesigned each time at BINP. XB72K No.8 (5 cell TW) attained a power of 55 MW at 500 ns, but the efficiency is only 22%. The last tube, No. 9 (4 cells), produced 72 MW at 520 kV for a short pulse of 200 ns so far. The efficiency is increased to 31% and no sign of RF instability has been observed. The limitation in the pulse length attributes a poor conditioning of the klystron. Testing for a longer pulse is still in progress. MAGIC simulations predict that No.9 will sustain 75 MW at a longer pulse length (1-1.5μs). A newly designed XB72K No.10 and its predicted performance are described in detail in Section 3.

Table 1: Specifications of solenoid-focused X-band klystron for JLC.

Operating frequency	11.424 GHz
RF pulse length	1.5 μs
Peak output power	75MW
Repetition rate	120 pps
RF efficiency	47%
Band-width	100 MHz
Beam voltage	550 kV
Perveance	1.2 μ
Solenoidal focusing field	6.5 kG (max.)
Gain	53-56 dB

Apart from the solenoid-focused XB72K series, a PPM (periodic permanent magnet) focusing X-band klystron was designed and build by BINP in the collaboration with KEK. It has a gun with beam area convergence of 400:1 for the micropeaveance of 0.93. The PPM focusing system with 18 poles (9 periods) produces the constant peak magnetic field of 3.8 kG. The field in the output structure is still periodic, but tapered down to 2.4 kG. There are two solenoid coils located at the beam entrance for a smooth transport of a beam to the PPM section. It achieved 54 MW at 430 ns, but there is a clear sign of RF instability at higher frequencies. The DC current monitor in the collector shows about 20% loss of particle when RF is on. MAGIC simulations indicates a large amount of particle interception in the output structure and thereafter due to a lack of focusing for particles that drop to the stop-band voltage after losing energy to the traveling-wave. A more detail of BINP PPM klystron and measurement results will be published somewhere.

2 MAGIC SIMULATION

After a series of disappointing performance of XB72K series, several lessons had been learned. First, KEK should have its own team to specialize the klystron design and overhaul the design process. Second, a new klystron simulation code was needed for a more realistic design of klystron, particularly, that of a TW output structure. The one-dimensional disk model code, DISKLY, had been used by BINP for design of the TW structure from XB72K No.5 till No.9. This code uses an equivalent circuit model (port approximation) to simulate a TW structure and tends to predict the efficiency much larger (nearly twice larger) than the experimental results. For the design of a new klystron, XB72K No.10, we have developed a technique to use the MAGIC code[2] to simulate a klystron. MAGIC is the 2.5-D or 3-D, fully electromagnetic and relativistic particle-in-cell code for self-consistent simulation of plasma. It solves the Maxwell equations directly at particle presence by the finite difference method in time. It requires only the geometrical structure of the cavity and assumes no model for the beam-cavity interaction. In 2.5-D simulations, two-arm output couplers are approximated by a conductor which has the same complex scattering matrix with the actual 3-D ones. Advantages of MAGIC are its accuracy and generality. Even an electron gun can be simulated with results in good agreements with those of EGUN. Simulation results can be imported/exported from one section of klystron to another, allowing a consistent simulation of the entire klystron without loss of physics. Only disadvantage is that it is time consuming.

Figure 1 shows the simulation result of MAGIC and the experimental data for the saturated output power vs. beam voltage for SLAC XL-4 klystron[3]. Excellent agreements can be seen. Similar agreements were obtained between the MAGIC simulations and the measurements for XB72K No.8 and No.9. For XB72K No.8, see Fig. 2.

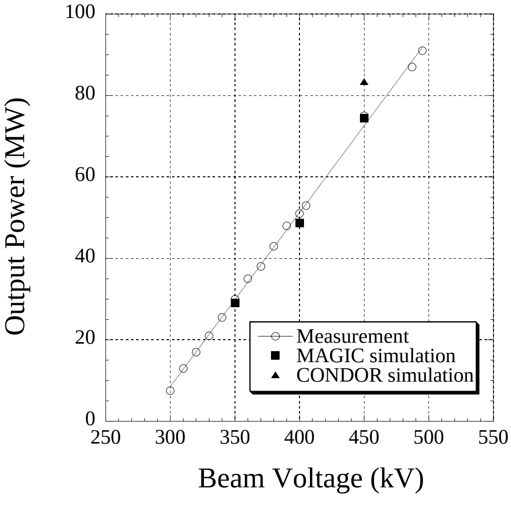

Figure 1: Simulation results of MAGIC and the measurement data for SLAC XL-4 klystron.

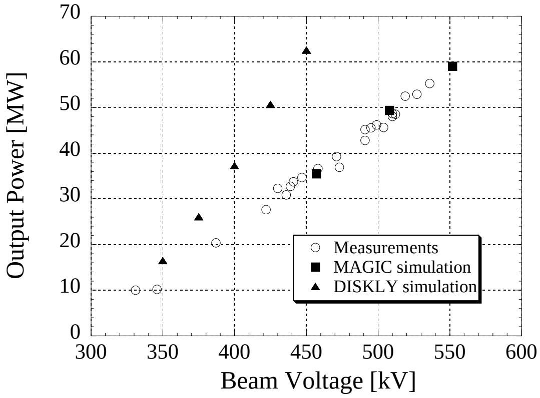

Figure 2: Simulation results of MAGIC and DISKLY and the measurement data for XB72K No.8 klystron.

3 XB72K NO.10 DESIGN

XB72K No.10 is the last solenoid-focused klystron in the XB72K series. The electric power of several 10 kW necessary for the magnetic field of 6.5 kG is prohibitively high for JLC. The next klystron to be developed would be PPM focused.

Main changes from the previous XB72K klystrons are the buncher section and the TW output structure. The operational experience with the previous klystrons proved that the gun portion of XB72K has sufficient performance (1.2 microperveance at 2µs pulse length) and no interception of particles has been observed. The old buncher has two gain cavities and only one bunching cavity. The short drift space prevents capturing of the second harmonic component of RF current in the bunching cavity. As the result, it has a poor RF power generation capability: the RF current /DC current is only 1.2 at the entrance of the output structure. In XB72K No.10, one more bunching cavity was added and the drift space was lengthened to 16cm. The stagger tuning of gain cavities was also adopted to increase the band-width to the current specification of 100 MHz. Figure 3 shows the frequency response of the RF current at the entrance of the output structure. It stays almost constant (≈1.58 x DC current) in the range of ±50MHz around the operating frequency.

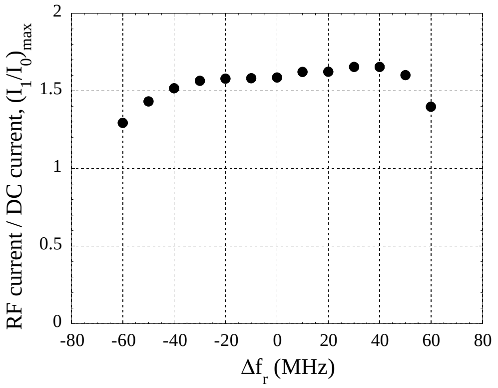

Figure 3: Frequency response of the RF current at the entrance of the output structure in XB72K No. 10.

The most challenging part of XB72K No. 10 design is a high efficiency and low gradient TW output structure. SLAC has already developed a successful XL-4 klystron which produces 75MW at 450 kV, but the pulse length can go only upto 1.2 µs before the RF breakdown in the output cavity. MAGIC is quite useful for getting an accurate estimate of klystron performance, but the design of an effective TW structure is another matter. A systematic design method was needed to avoid getting lost in the freedom of too many parameters.

For this end, we have developed a simple-minded theory of a constant group/phase velocity TW structure. The idea is to let the power flow with a constant group velocity throughout the structure, while evolving due to merge of the extracted power from a beam. The Q-value at the output port is matched to this group velocity so that the power exits at the same speed as it flows in the structure. This smooth flow of power prevents congestion at local spots and thus the electromagnetic energy density is more equally distributed in the structure

It is also better to keep the phase velocity constant (approximately equal to the average beam velocity) from the first to the last cell, rather than being matched with the declining beam velocity. When the perfect synchronization of traveling-wave and the beam is tried, the beam loses energy too quickly to the wave, and its velocity becomes too slow to be matched with the wave after a few cells (XB72K No. 10 has four cells). The beam then moves to the acceleration phase of the wave and starts to get energy back. The energy extraction efficiency of each cell does not have to be too good. Only the total efficiency of all cells matters. It is more important to keep the beam in the deceleration phase of the wave all the time. In our method, the traveling-wave travels behind the beam at first, and catches it up with in the middle of the structure. It then moves ahead of the beam, but exits from the output port before the beam slips into the acceleration phase of the wave.

We also demand that each cell is operated in $2/3\pi$ mode at 11.424 GHz. The cell length is also constant except the last cell (slightly longer to reduce the field gradient). As the result, the cells become almost identical. We then tapered up the iris aperture slightly to equalize the field gradient among the cells. In this method, once the group and the phase velocities are chosen, the geometry of the structure are almost uniquely determined. The structure of output port can be adjusted to control the reflection of power to maximize the output power.

Figure 4 shows the MAGIC simulation of XB72K No. 10 at the output structure. The predicted performance is summarized in Table 2. Figure 5 shows comparison between XB72K No.10 and SLAC XL-4 for the saturated power versus the maximum field gradient in the output structure. Both have similar efficiencies of about 48%, but the maximum gradient of XB72K No.10 is about 20% lower than that of XL-4, though the power is 67% larger. In XB72K No.10, the fairly constant gradient is achieved in the output structure. This comparison indicates that the XB72K TW output structure can attain 120 MW power at a longer pulse than XL-4 at 75 MW without cavity breakdown. At 75MW, XB72K can tolerate an even longer pulse. It is now in manufacturing and testing will begin in November 1998.

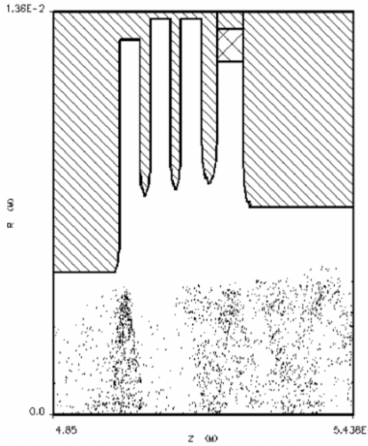

Figure 4: MAGIC simulation of XB72K No. 10 at the output structure.

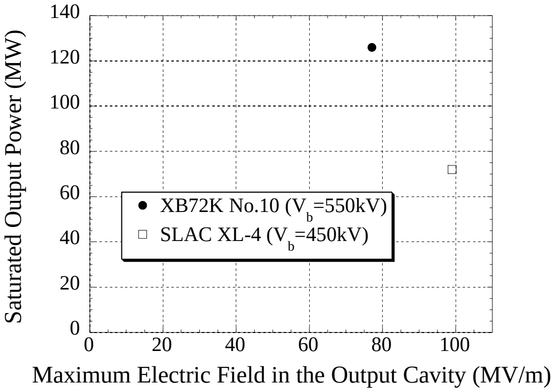

Figure 5: Saturated power versus the maximum field gradient in the output structure for XB72K No.10 and SLAC XL-4.

Table 2: Predicted performance of XB72K No. 10.

Peak output power	126 MW
Beam voltage	550 kV
Efficiency	48.5%
Maximum field gradient in TW	77 MV/m
Pulse length	1.5 µs or longer
Band-width	100 MHz
Gain	53 dB

REFERENCES

[1] JLC Design Study, KEK, April 1997.
[2] MAGIC User’s Manual, Mission Research Corporation, MRC/WDC-R-409, 1997
[3] G. Caryotakis, in Proc. of RF96, KEK Proc. 97-1.