# HIGH POWER PULSED KLYSTRON FOR LINACS

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## Summary

Three types of klystrons for linacs are currently produced. These are the PV-2012 (7MW/10kW), PV-2014 (25MW/30kW), and PV-3030A (30MW/12kW), for the S-band. Now two types of klystrons for new demands are under development. These are the PV-3030B (30MW/30kW) for the S-band and PV-9002 (2MW/2kW) for the X-band. Here, the brief explanation of the characteristics and improvements of the production tubes are given. Then, the resonant ring test of the output window for PV-3030B and design study of PV-9002 are described.

## Introduction

Since 1965, we have supplied more than 400 high power pulsed klystrons for linacs and radars. The characteristics of five kinds of klystrons for linacs described in this paper are summarized in Table I. The reliability of the S-band klystrons for modern linacs is mainly related to failure rates of the output window and electron gun. We look back three types of the S-band klystrons to see how we could improve the reliability of these klystrons. Then we measured the power handling capability of our window for PV-3030B using the SLAC resonant ring which can transfer more than 100MW (peak)/108kW (average). High power pulsed microwave sources in the X-band are needed for linacs of the next generation, but are not commercially available. To fill this need, we have started designing a 2MW output X-band pulsed klystron.

## Characteristics and improvements of production tubes

### Characteristics

PV-2014 was developed for the 300 MeV linac of Tohoku University in Sendai, Japan. It has two output waveguides with one each window and pressurization of $SF_6$ gas is utilized in the load side waveguide. These structures enable stable operation at a high average power of 30kW. PV-2012 is a 5 cavity klystron mainly used for medical and industrial linacs, and delivers a peak output power of 7MW. As it has the same structure as PV-2014 except for output waveguide and window, it has enough margine in power handling capability, so that it can be increased to 25kW in average power. Thus, it can be relied on for 40,000 hours of MTTF and it has the same life-span (about 10 years) as linacs. PV-3030A was developed for the 2.5 GeV linac of KEK in Tsukuba. It can be used with either permanent magnet focussing or electromagnet focussing. In order to use PV-3030A with a permanent magnet and to replace it without magnetic field readjustment, these tubes are required to operate in a same distribution of magnetic field. Recent tubes satisfy this requirement with our technology and quality control i.e., improvements of assembly tolerance in gun and body of the klystron. PV-3030A has a single output window operating under high vacuum conditions at both sides of the window. The window consists of a thin alumina disk coated with titanium on both sides to suppress multi-pactor heating.

### Improvements

Table II shows a history of the number of delivered PV-3030A klystrons, failure modes, and cumulative MTTF. Failures are mainly classified into two categories: window puncture and gun arcing.

Window puncture seems to be caused by the following mechanism. If the disk surface of the window in the load side is being contaminated by organic substances and adsorbed gas, local arcing occurres when gases are released from the disk surface by microwave power. The worst case result is a window puncture. Two trials were tested by MELCO and KEK, and both were very effective. The first is to fill the klystron output waveguide with nitrogen gas during storage and transportation in order to keep the load side window surface clean. The second is to carefully increase output power more gradually in order to clean the disk surface of the window. As can be seen in Table II, since 1983 there has been no window failure after these improvement methods were instituted.

The gun arcing problem was the most serious one for the klystron. The gun arcing is a discharge mainly between the anode and focus electrode in the vacuum region. In operations at KEK, klystrons occasionally had heavy gun arcings. Once a heavy arcing occurred, gun arcings tended to occur more

Table I. Characteristics of Klystrons for Linac

| | f (MHz) | V (kV) | I (A) | Ppeak (MW) | Pav. (kW) | width (μs) | gain (dB) | effic. (%) | deliv. tubes | MTTF (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|
| PV-2012 | 2856/2998 | 148 | 114 | 7 | 10 | 5.0 | 50 | 42 | 134 | 40,288 |
| PV-2014 | 2856 | 245 | 242 | 25 | 30 | 4.0 | 50 | 42 | 28 | 18,414 |
| PV-3030A | 2856 | 260 | 278 | 30 | 12 | 4.0 | 50 | 42 | 91 | 14,437 |
| PV-3030B | 2856 | 260 | 278 | 30 | 30 | 3.3 | 50 | 42 | under development | |
| PV-9002 | 9300 | 120 | 42 | 2 | 2 | 5.0 | 60 | 40 | | |

Table II. Failure Mode and MTTF of PV-3030A 1986 March

| Delivered 'FY | '79 | '80 | '81 | '82 | '83 | '84 | '85 | Total |
|---|---|---|---|---|---|---|---|---|
| Number of tubes | 4 | 20 | 20 | 9 | 13 | 13 | 12 | 91 |
| Tubes in use | 0 | 7 | 11 | 4 | 13 | 12 | 12 | 59 |
| Failed tubes | 4 | 13 | 9 | 5 | 0 | 1 | 0 | 32 |
| Failure Mode | | | | | | | | |
| 1. Filament open/short | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 2 |
| 2. Gun insulator puncture | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 2 |
| 3. Output window puncture | 1 | 6 | 2 | 1 | 0 | 0 | 0 | 10 |
| 4. Gun vacuum arcing | 2 | 6 | 5 | 3 | 0 | 1 | 0 | 17 |
| 5. RF output power shortage | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Cummulative MTTF (hrs) | 3,902 | 8,306 | 11,586 | 11,407 | 13,909 | 14,213 | 14,437 | 14,437 |

frequently. In these cases klystrons had to be operated at reduced beam voltage to suppress gun arcings. At the worst case, some of their beam voltages fell below the allowable threshold beam voltage. To solve these problems, we tried to improve the materials, structures, and processes, of the electron guns. For example, the vacuum firing process was reinforced, and heater power efficiency was increased to reduce the focus electrode temperature. Owing to these improvements, the number of gun arcings has been decreased and the fault-rate at operating beam voltage remarkably reduced.

## Resonant ring tests of output windows

PV-3030B was originally planned for the new linac at Tohoku University. The tube can be built by redesigning the PV-3030A window and using other PV-3030A parts. Thus, it was necessary to confirm the power handling capability of the PV-3030A window. With an output waveguide pressurized with $SF_6$ at the load side of PV-3030B, multi-pactor heating can be reduced by half compared with the vacuum output waveguide. In order to verify window power handling capability under the most severe conditions, we tested our windows with both sides of them under vacuum conditions using the SLAC resonant ring which is the most powerful in the world. Figure 1 shows the characteristics of three windows due to their alumina contents: AL-300 (Alumina content is 96%), AD-995 (99.5%), and AL-995 (99.5%). Two windows were coated with TiOx by us and one was coated with $TiN_2$ by SLAC. In the figure, the abscissa is power transmitted through the window and the ordinate is power dissipation of the window. Figure 2 shows window loss due to the coating conditions and coating materials. Here, each window is made from AL-300. The typical SLAC windows coated with TiOx and $TiN_2$ are also shown for comparison. Figure 3 shows window loss vs. average power (not peak power). Following are our conclusions of the test results.

(1) Window loss is determined mainly by the average power through the window.
(2) There is a significant improvement in characteristics between AL-300 and AL-995/AD-995.
(3) The effect of our TiOx coating is not remarkably different from SLAC $TiN_2$ coating.
(4) Our windows appear to have the same characteristics in the 100MW/108kW power range as SLAC windows which operate at more than 30kW in the SLAC XK-5 klystron.

(solid line: MELCO window, dashed line: SLAC window)

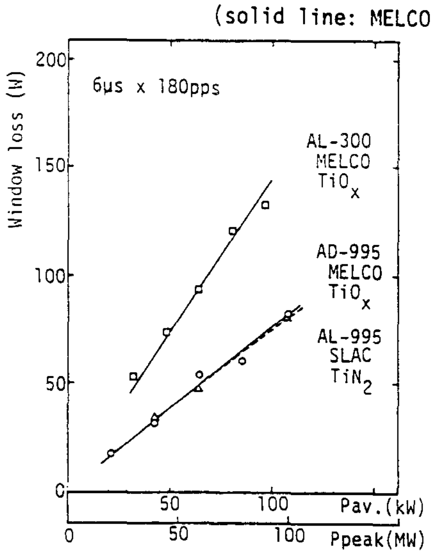


Fig.1 Window loss due to alumina contents

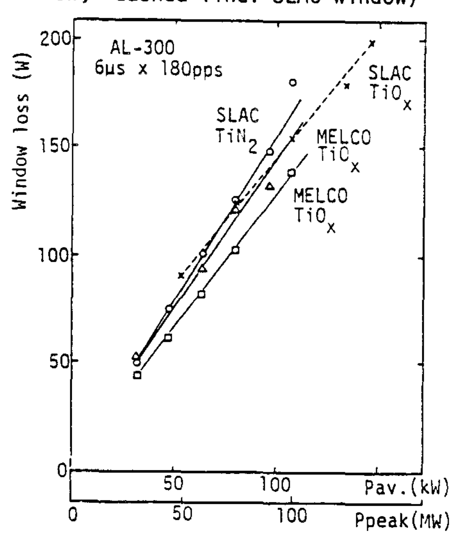


Fig.2 Window loss due to coating materials and conditions

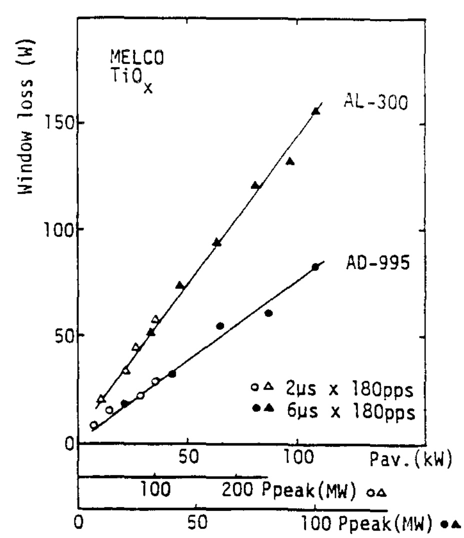


Fig.3 Window loss vs. average power

## Design study of PV-9002

Accelerator tubes of the X-band have not only compact size, but also many other advantages, like higher shunt impedance per unit length, shorter filling time, and a higher RF breakdown limit. Although they are suitable for linacs of medical use and non-destructive inspection, there is no commercial MW-class microwave source for the X-band linacs; magnetrons are not tunable, CFAs are very expensive, and klystrons are not commercially available. We have started some design studies of a 2MW klystron (PV-9002) operated at 9300MHz.

The first step of the design study is a computer simulation of each part of the klystron. We used a one dimensional disk model time stepping large signal code to analyze bunching and energy exchange, Herrmannsfeldt's code to design the electron gun and beam focussing, Superfish code to design the cavity, and the code of finite element method to design the magnetic circuit of focussing magnet. The most important parameter is the microperveance of the electron gun which relates conversion efficiency, beam focussing, and modulator wave shape. This was determined as one micropervcance. Figure 4 shows a result of large signal analysis. If the klystron is composed of six cavities, its saturated gain is more than 60dB, which enables the use of a semiconductor RF driver.

Figure 5 is a conceptual drawing of the klystron and focussing magnet, both of which are installed horizontally in order to be mounted on a rotating pedestal of a medical linac. The klystron is inserted into the solenoid from collector and output waveguide to accommodate the electron gun high voltage insulation dimensions. The klystron and the solenoid can be separated from the modulator and the pulse transformer tank, by using a high voltage cable of X-ray apparatus. In order to prevent high voltage breakdown outside the electron gun, the outside of the envelope is pressurized by $SF_6$ or filled with oil. The output window is a pill box type, using a half-wave length of alumina disk. After some computation of the alumina disk dimensions on ghost mode, we will finally determine the actual dimensions by experimentation.

## Conclusions

(1) PV-2012 and PV-2014 are sufficiently reliable.
(2) The gun arcing failure of PV-3030A has been solved by improving materials, structures, and processes of the electron gun.
(3) The output window of PV-3030B appeared to have about 30kW average power handling capability.
(4) Preliminary designs of PV-9002 have been finished.

## Acknowledgement

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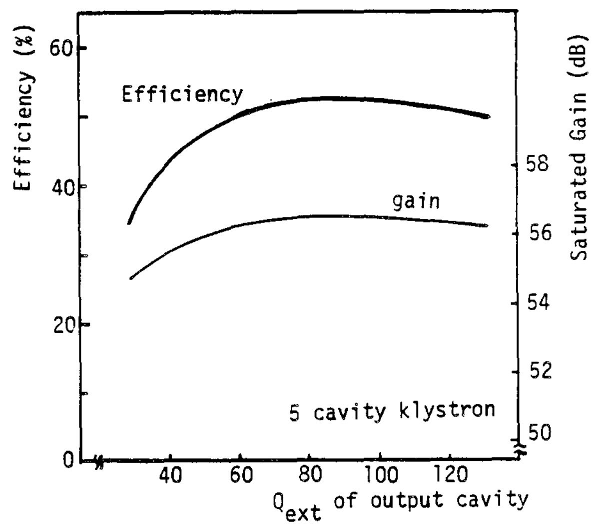


Fig.4 Efficiency and saturated gain vs. $Q_{ext}$ of output cavity (calculated)

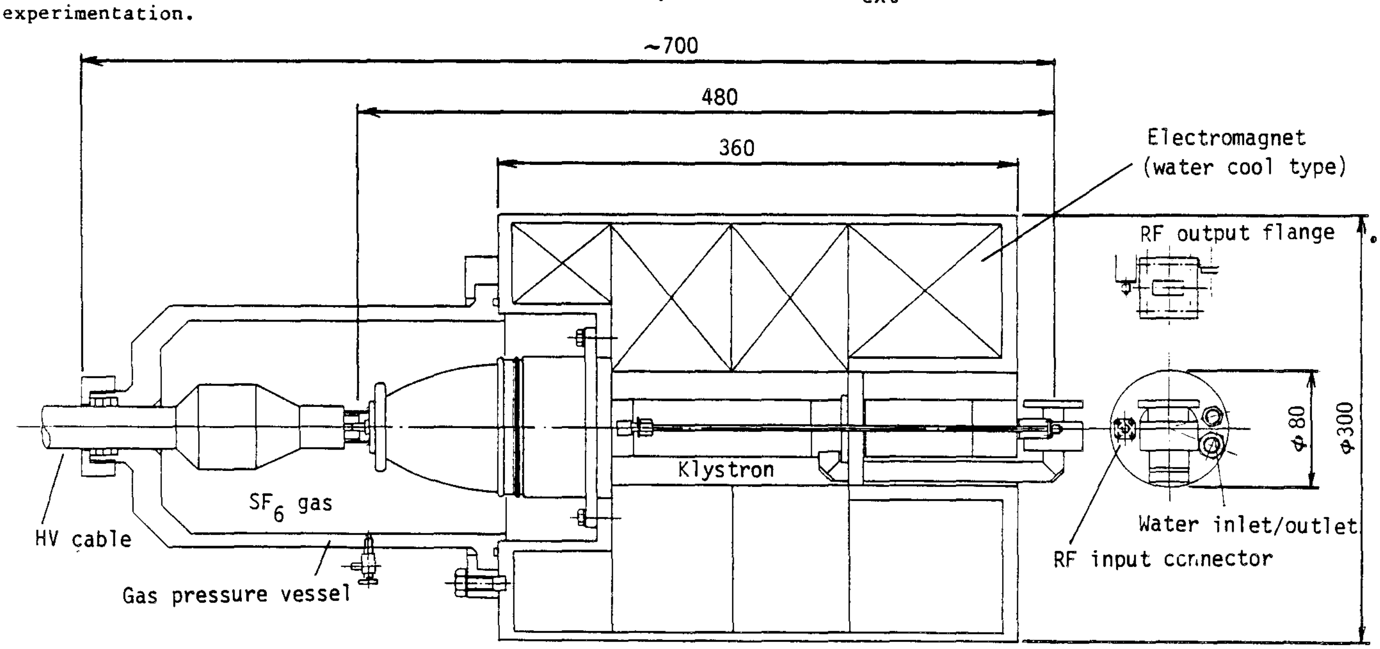


Fig.5 Conceptual drawing of PV-9002