OUTPUT RF PHASES FROM THE S-BAND KLYSTRONS USED IN THE KEKB LINAC

S. Michizono, S. Anami, S. Fukuda, T. Matsumoto, K. Nakao, KEK, Tsukuba, Japan

Abstract

Fifty-nine S-band pulsed klystrons and 8 driver klystrons are used in the KEKB linac (8 GeV electron/ 3.5 GeV positron). In this paper, simulation results of rf-phase variations are presented along with the experimental data. The parameters are (1) the temperature of the cooling water, (2) the rf input power and (3) the beam perveance. As for the cooling water, it has been found that the rf phases are delayed along with an increase in the temperature due to detuning of the rf cavities. The phase-delay is greater at the gain cavities where the resonant frequencies are close to the operation frequency. It has also been found that the rf phases are delayed with an increase in the input power at first in the simulation, which agrees with the experimental data. At a higher rf input, the phase is advanced due to a larger bunching formation. For the case that the beam perveance becomes lower (due to poor emission etc.), the phase advances were observed experimentally. Simulation results also agree well with the experimental data.

1 INTRODUCTION

High-power klystrons (2856 MHz, 50 MW in maximum, 4 micro-seconds, 50 pps, 300 kV, 2.0 micro-perveance) are driven by eight driver klystrons (2856 MHz, 60 kW, 4 micro-seconds, 2x50 pps, 28 kV, 2.0 micro-perveance) [1]. A phase stability of less than 1 degree is required for these klystrons; the phase variations are summarized from both operational and experimental aspects [2,3] as follows:

1) It takes about 1 or 2 hours for the output phases to be stable, mainly due to the time constant of the cooling control. The temperature of the cooling water influences the output phases with –0.8 and –2.0 degrees/ degree C at the high-power and driver klystrons, respectively.

Table 1 Cavity parameters of driver klystron [1]

Cavity	Cavity Feq. (MHz)	Q	Gap (mm)	Drift Length (mm)
1	2858	450	5.0	30
2	2860	5000	5.0	35
3	2861	5000	5.0	40
4	2886	5000	5.0	60
5	2891	5000	5.0	35
6	2856	75	5.0	

2) The output phases are varied with the input power.
3) An increase in the output phases was observed at the high-power klystrons along with a decrease in the emission current (perveance) caused by cathode degradation. A 20% reduction in the perveance causes a 15 degree phase-advance at the high-power klystrons.

These experimental results were analysed using JPNDISK[4], which is a one-dimensional klystron simulation code. ANSYS[5] and SUPERFISH[6] were also used for distorting the rf cavity and resonant frequency calculations, respectively.

2 DEPENDENCE ON THE COOLING-WATER TEMPERATURE

Since the output phase varies by only about 0.05 degrees/degree C with the expansion of the drift length (~0.4 m), the changes upon detuning the cavities are considered. The first 2 or 3 cavities, called “gain cavities”, have smaller detuning frequencies in order to induce

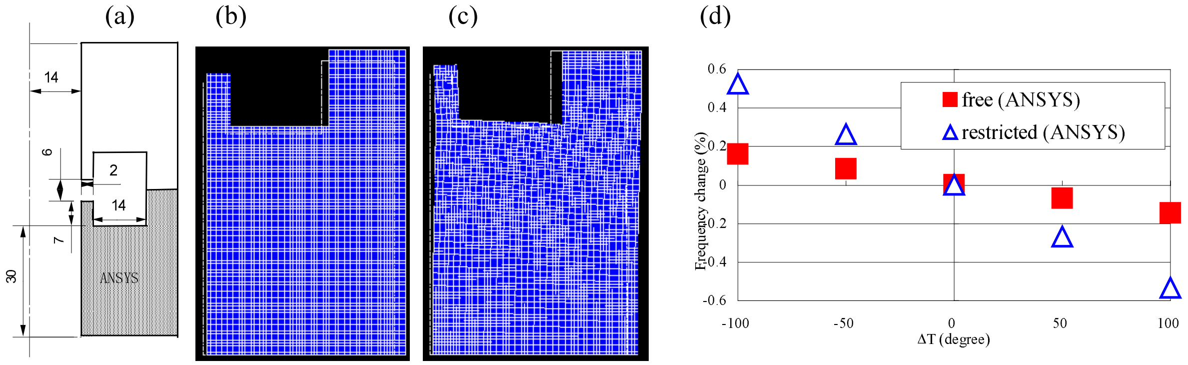

Figure 1 Cavity geometry (a), calculated distortions by ANSYS with free (b) and restricted (c) boundary conditions. (d):Cavity detuning ratio with applied temperatures calculated by ANSYS and SUPERFISH

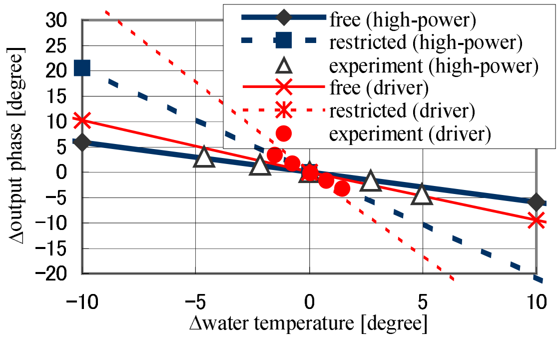

Figure 2 Output phases of high-power and driver klystrons calculated with different applied temperatures.

higher gap voltages. A bunching cavity has a higher detuning in order to maintain the bunching center.

The analytical bunching center (zero-cross-point of cavity voltage) at each cavity is written as

$$\phi = \tan^{-1}(\frac{2Q_l\Delta f}{f_0}) - \frac{\pi}{2} ,$$

where ϕ is the phase advance of the bunching center, f_0, the operation frequency, Δf the detuning (with beam) and Q_l the loaded Q. Although these parameters depend on the beam, cavity detuning is almost same to that obtained without beam and Q_l is dominated by the beam, in general. A change in cavity detuning causes the analytical bunching center to change by

$$\Delta\phi = \phi' - \phi \approx \frac{2Q_l(\Delta f' - \Delta f)}{f_0\sqrt{1+(2Q_l\Delta f/f_0)^2}\sqrt{1+(2Q_l\Delta f'/f_0)^2}} ,$$

where ϕ' and $\Delta f'$ are the phase of bunching center and detuning at a different temperature, respectively. From this equation, it is well understood that the phase changes are higher at the gain cavities due to the smaller Δf, leading to a smaller denominator in the expression. These expressions can explain the phase advance with an increase in the cooling temperature. However, the analytical bunching center is not the same as the real bunching center at the klystron, because the real bunching center depends not only on the phase of the cavity voltage, but also on the drift length and space-charge force. Simulations including these parameters are necessary for a precise study.

The high-power klystrons are based on SLAC XK-5 klystron[7], which has 5 cavities (3 gain, 1 bunching and 1 output cavities). The driver klystron has 6 cavities (3 gain, 2 bunching and 1 output cavities), as summarized in Table 1. Although the numbers of gain cavities are the same between the driver and the high-power klystrons, the detunings from the operation frequency (2856 MHz) are smaller at the driver klystron. The distortions are calculated by ANSYS with two kinds of boundary conditions (free and restricted to the z-direction). Since the cavity-distortion is restricted by a cooling duct made on stainless steel having lower expansion coefficients, the real distortion is intermediate between the free and the restricted conditions. A simplified cavity geometry (Figure 1 (a)) and higher temperatures (-100, -50, 50, 100 degrees) are applied in order to evaluate the resonant frequency easily by SUPERFISH. The distortion of the cavities under free and restricted boundary conditions, calculated by ANSYS, are shown in Figs.1 (b) and (c), respectively. The resonant frequency changes linearly with the applied temperatures, and 3.5-times larger changes are obtained under the restricted condition, as shown in Fig. 1(d). The output phases with these distortions were calculated by JPNDISK. The results are shown in Figure 2. The higher calculated value from the driver klystron is caused by its smaller detunings at the gain cavities. The experimental results of high-power klystron are close to the "free" boundary condition. On the other hand, the experimental results of the driver klystron are close to the results obtained under

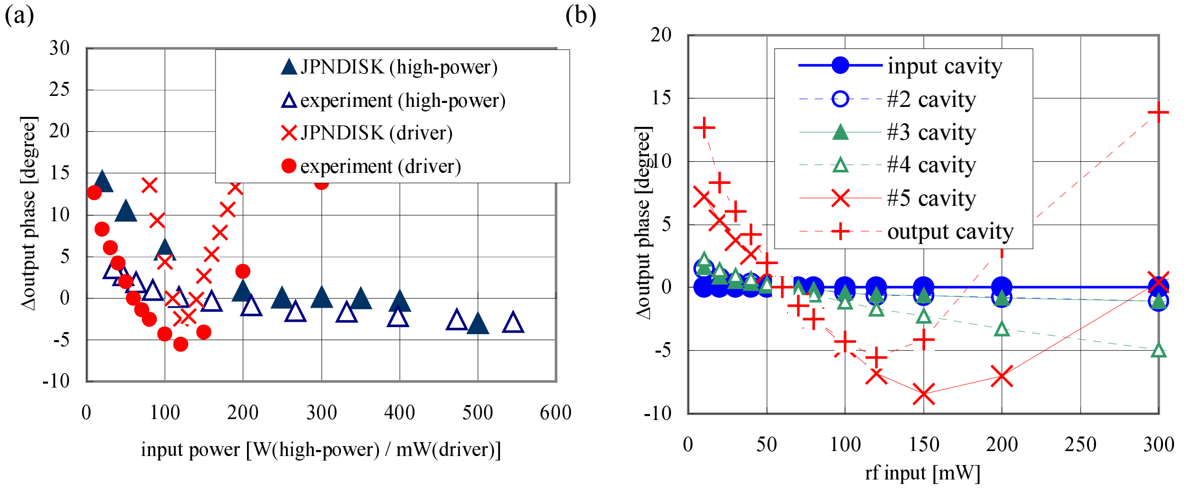

Figure 3 Output phase changes with rf input. (a):driver klystron and high power klystron. The experimental data are also shown. (b): calculated output phase at each cavity of driver klystron.

"restricted" boundary condition. This is considered to be due to the smaller radius of the beam ducts at the driver klystron, where the restriction is larger.

It is found that a smaller detuning of the gain cavities and/or larger restriction condition induces a higher output-phase coefficient.

3 RF INPUT AND PERVIANCE DEPENDENCE

The output phase dependence on the rf input power was calculated. Figure 3 (a) shows the results for the driver and high-power klystrons. The output-phase increases at a higher input power, which is similar to the experiments. Although the phases at the gain cavities vary linearly, the phase changes nonlinearly at the bunching cavities of the driver klystron (Fig.3 (b)), where the beam has higher space-charge forces. Since the number of bunching cavities is larger compared to the high-power klystron, larger phase changes are obtained at the driver klystron. The difference between the experiment and the simulation is considered to be due to the one-dimensional code, where the beam diameter is constant, even when the space-charge-force becomes higher.

The output phases were calculated for different perveances of the high power klystron. In the calculations, the beam radius was kept at 10 mm (design beam radius), and only the beam currents were varied. The results are almost the same as the experimental results, as shown in Figure 4 (a). Phase changes occur mainly at the gain cavities (Figure 4 (b)), which is considered to be due to lower rf voltages, by the lower beam current. Periodic phase measurements will enable us to detect any degradation of the cathode.

4 SUMMARY

Output phase changes were calculated for the driver and high-power klystrons used in the KEKB linac. It has been confirmed that the output phases change with the cooling temperature due to the changes in the detuning frequency, especially at the gain cavities. It is found that the highly restricted cavities show a higher detuning, leading to higher temperature dependences. It is also found that the changes in the rf-input power and perveances result in phase changes. The phase advances at a higher rf input-power result from the non-linearity at the higher space-charge forces. Since these phase changes with temperature, input-power, and perveances agree well with experiments, phase measurements are expected to be good diagnostics for stable linac operation.

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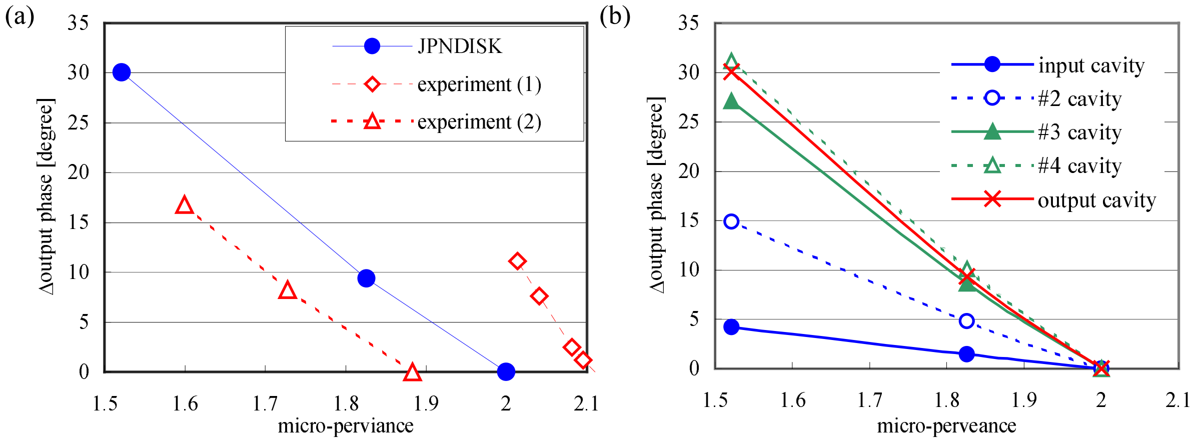

Figure 4 (a): Phase changes calculated for high-power klystron with different beam current. In this calculation, beam radius is kept to 10 mm. Experimental results are also shown. (b): Phase changes at each cavity. The changes occur at the gain cavities probably due to lower beam loading.