DESIGN STUDY OF A HIGH EFFICIENCY KLYSTRON FOR SuperKEKB LINAC

F. Qiu, S. Fukuda, S. Matsumoto, T. Matsumoto, T. Miura, T. Natsui
Accelerator Laboratory, KEK, Tsukuba, Japan

Abstract

The injector linear accelerator (linac) for the SuperKEKB particle accelerator requires a higher efficiency klystron than the currently used 50 MW, S-band, pulsed unit (PV3050/E3730), which operates at the same voltage, to increase the power redundancy. The efficiency is expected to improve from the currently observed 45% to more than 60%. We propose a type of high efficiency klystron using novel bunching mechanisms. The 1-D disk model based code is used for preliminary optimization of the tube parameters; these parameters are further checked by 2-D codes known as field charge interaction (FCI) and MAGIC. In this paper, the design consideration of the high efficiency klystron is presented.

INTRODUCTION

The KEKB electron–positron (e-/e+) collider is being upgraded to the SuperKEKB to achieve a 40-times higher luminosity [1]. As shown in Fig. 1, the linac consists of eight sectors (A–C and 1–5). The black squares in each sector represent the accelerating units that provide an energy gain of approximately 160 MeV each [1-2]. A total of 60 accelerating units are mounted in the SuperKEKB injector.

The klystron drive line for each unit is shown in Figure 2 (left). The low-level radio frequency (LLRF) system generates 4 µs RF pulses at first, and the phase of the RF pulse is reversed by 180° during the last 1 µs. The RF pulse is then amplified by the 600 W solid state amplifier (SSA). In the next step, the output of the SSA drives an S-band 50 MW klystron (PV3050/E3730A). A SLAC energy doubler (SLED) compresses the 4 µs pulse from the klystron output and generates a shorter 1 µs pulse with high peak power, thus powering four 2-m accelerating structures with an accelerating field of 21 MV/m. The picture and specifications of the klystron PV3050 are shown in Figure 2 (right) and Table 1, respectively [3].

High efficiency klystrons have become popular in recent years owing to their benefits of reducing the operating costs of the accelerators as well as increasing the operating margins. In cooperation with MELCO (Mitsubishi Electric Corporation), KEK has a plan to develop a type of high efficiency klystron (PV3064) to replace the current PV3050 tubes [4]. Several methods have been proposed to increase the efficiency of a klystron. These methods can be divided into two main categories: The first kind is a multi-beam klystron (MBK) which has several low perveance beam-lets because lower perveance usually corresponding to higher efficiency [5]. Each beamlet carries a small amount of current, but the total current can be large. The other kind focuses on novel bunching mechanisms. Based on this idea, the core oscillation method (COM) [6], bunching-alignment-collection (BAC) [7], and core stabilization method (CSM) [8] are proposed. It would be useful if we can develop a compatible tube of the existing PV3050 with minor modifications by following the recent trends in efficiency improvement. These techniques can also be extended to other projects such as the international linear collider (ILC). In this paper, based on the existing PV3050, we present a compatible BAC-based tube. To achieve higher efficiency, the cavity parameters are first optimized, and the focusing magnet and tube length are modified slightly. The RF window would need to be redesigned because of the increment in the output power; however, this is not considered in the current work.

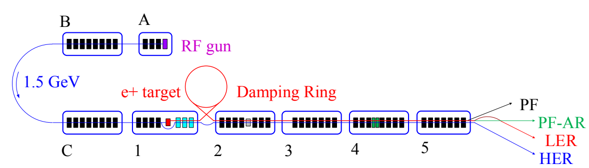

Figure 1: Layout of SuperKEKB injector linac.

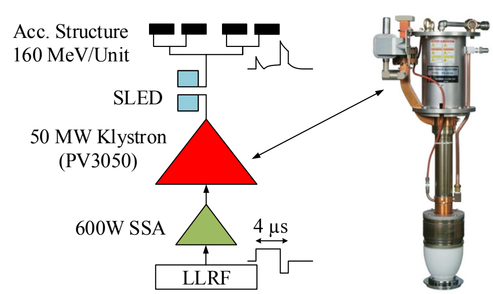

Figure 2: Klystron drive line (left), and the 50 MV klystron PV3050 (right).

Table 1: Specifications of PV3050

	Value	Unit
Frequency	2856	MHz
Peak RF power	50	MW
Repetition rate	50	Hz
Efficiency	45	%
RF pulse duration	4	µs
Beam voltage	310	kV
Gain	50	dB

BAC METHOD

The existing PV3050 klystron has the potential to provide increased efficiency from the present 45% to a higher value owing to introduction of the BAC section. We have tentatively applied four additional BAC cavities, including two second harmonic cavities, to the drift tube. Various codes, such as AJDISK [9], FCI [10], MAGIC, and CST, can be used for klystron design. The one-dimensional (1-D) code AJDISK is used for preliminary optimization of the tube parameters (e.g., cavity detuning and external Q of the output cavity), and the effect of the magnetic field and beam profile are subsequently checked with the two-dimensional (2-D) code (e.g., FCI). Finally, the tube is simulated using a PIC code such as MAGIC or CST.

Figure 3 compares the 1-D AJDISK simulation of the original PV3050 tube and the proposed BAC-based klystron. As mentioned above, we have added four cavities between the 3rd cavity and the penultimate cavity of the PV3050 tube (indicated by the green box). Compared with the original PV3050 tube, more outside bunches are collected by the BAC tubes at output cavity. The predicted efficiency is improved from the original 45% to approximately 69%.

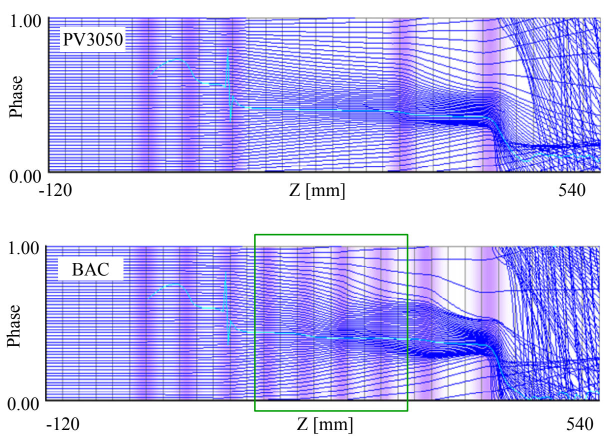

Figure 3: Phase diagrams of PV3050 (top) and proposed BAC-based klystron (bottom) in the AJDSIK simulation. The BAC cavities are indicated by the green box.

SIMULATION RESULT OF 2-D CODE

Because of the limitations posed by the 1-D code (e.g., distribution of the magnetic field and current density), we have to check the parameters obtained from AJDISK with the 2-D code (and the 3-D code as well). The FCI and MAGIC are used to verify the BAC-based design [10]. For the 2-D codes, the electron gun parameters and magnetic field need to be considered first.

Gun and Solenoid

The prototype of the particle gun for the planned BAC klystron is mostly derived from the gun of the PV3050. The trajectories of the gun with an applied voltage of 310 kV are simulated using MAGIC and DGUN code as shown in Figure 4. The simulation results for the current density obtained from MAGIC together with that of DGUN are shown in Fig. 5. Furthermore, the perveances of the gun obtained using these two codes are compared in Table 2. For further confirmation, the simulation results from CST are also presented in the table.

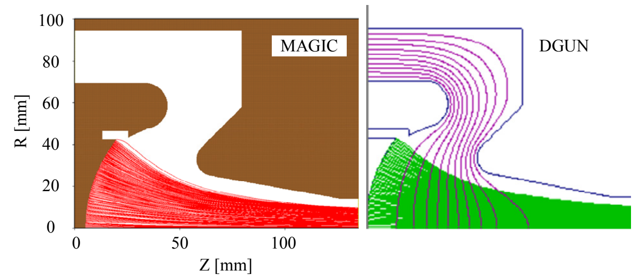

Figure 4: Simulation result of electron gun. Left: Magic, right: DGUN.

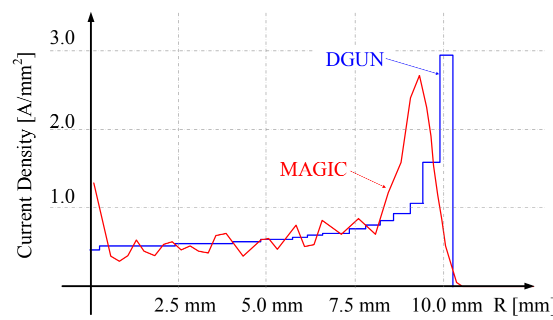

Figure 5: Current-density distribution of the electron gun 120 mm away from the cathode.

Table 2: Performance of the GUN Simulation

	DGUN	MAGIC	CST
μPerveance	1.86	1.88	1.87
Mesh size[mm]	0.25	0.25	0.25

The solenoids in the BAC are primarily based on the PV3050 klystron as well. A total of eight solenoids is used in the klystron PV3050. The focusing magnet is then simulated using POISSON SUPERFISH code [11]. We have compared the simulated magnetic field with the measured value of the PV3050 (indicated by the blue and red lines in Fig.5). The results show that the simulated field is in good agreement with the measured field.

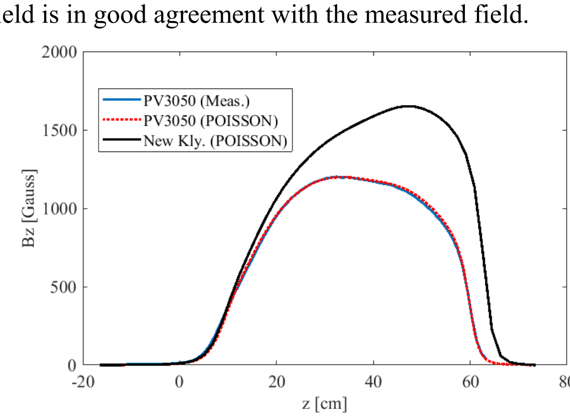

Figure 6: Comparison of the magnetic field on axis.

For the BAC klystron, because we have extended the length of the klystron tube to obtain a higher efficiency (see Figure 7), it is necessary to have a longer magnet that has a stronger field at the output cavity to suppress the scalloping effect. The new magnetic field obtained is thus shown as the black line in Figure 6.

Tube Simulation

The electron gun parameters shown in Figure 4 and the corresponding magnetic field are used in the 2-D code. The FCI code is applied first because it is faster compared to the MAGIC code. Figure 7 shows the comparisons of the FCI simulations of PV3050 and proposed BAC tube. It should be noted that the distances of the penultimate cavity and output cavity were increased by approximately 5-cm because it was found that the efficiency could be further improved under this condition. As seen from the beam profile of these two cases, compared with PV3050, more particles are bunched by the BAC tube at the output cavity. The FCI code predicted the maximum efficiencies of PV3050 and BAC klystron as 44% and 68%, respectively. The efficiency of the BAC tube predicted by FCI is shown in Figure 8.

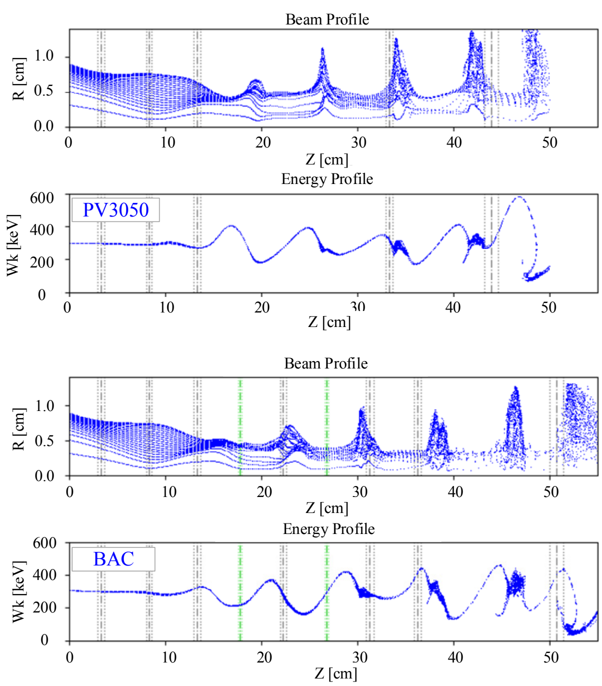

Figure 7: Beam and energy profiles from FCI simulation. Top: PV3050, bottom: BAC tube.

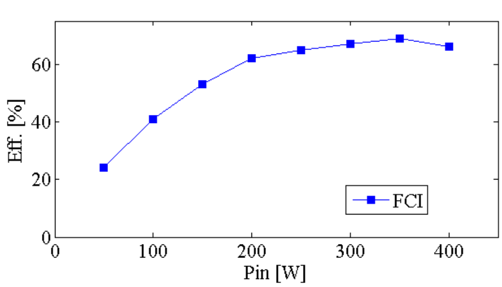

Figure 8: Predicted efficiency curve of the BAC tube.

It is possible to realize an all-in-one simulation with the MAGIC code, which means the gun, focusing magnetic field, and cavity tubes can be simulated at the same time. However, in our simulation, owing to limited time, we record the beam information of the GUN outlet region first and then import this beam information from the inlet of the klystron tubes. We expect that we can achieve a high efficiency as according to FCI predictions. However, for MAGIC, the predicted efficiency at the saturation point is approximately 52% (~15% lower than those of FCI and AJDISK). As shown in Figure 9, the currents of MAGIC and FCI were not in good agreement. Noted that we have modified the position of the output cavity for the MAGIC code to achieve the highest efficiency. It can be seen that the two codes are in agreement before the second 2nd harmonic cavity. However, the currents show disagreement after the pre-penultimate cavity. We attempted to reduce the mesh size of the MAGIC code, but the result did not improve significantly. Furthermore, we attempted to change the detuning of the 2nd harmonic and penultimate cavities by some extent, but we could not achieve high efficiency as expected. The reason for this is not understood thus far, and further simulations with other codes may be required in future studies.

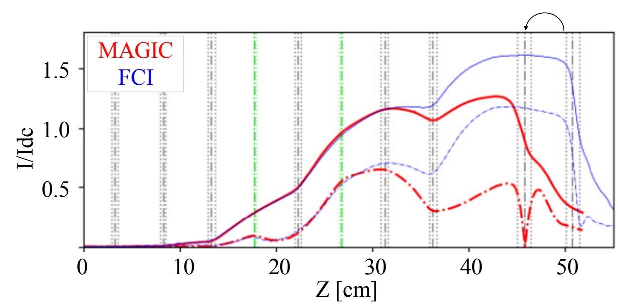

Figure 9: Current comparison of MAGIC and FCI code.

CONCLUSION

Recently, interesting methods based on the novel bunching mechanism are proposed for the high efficiency klystron. KEK is planning to develop a high efficiency klystron to improve the operating margin of the SuperKEKB project. We present our work at developing a compatible tube for the existing PV3050. By adding four BAC cavities, the efficiencies predicted by the AJDISK and FCI codes are improved by more than 20% at the saturation point. However, disagreements are observed for simulations with the MAGIC code, and the reason for this is not well understood thus far. Further simulations are required to address this in the future.

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