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Abstract

Performance of high power S-band klystrons focused with permanent magnet is presented. The axial magnetic field distribution and the transverse magnetic field play an important role in the tube performance. Effects of the reversal field in the collector and the cathode-anode region are discussed precisely. It is also shown that the tube efficiency is strongly affected with the residual transverse magnetic field. The allowable transverse field is less than 0.3 % of the longitudinal field in the entire rf interaction region of the klystron.

KEYWORDS: klystron, permanent-magnet focusing, electromagnet focusing, alnico 9, tube efficiency, transverse magnetic field, beam trajectory.

1 Introduction

The KEK 2.5 GeV electron linear accelerator as an injector for the Photon Factory (PF) storage ring and the TRISTAN accumulation ring has been completed and operated successfully since 1982[1]. This accelerator is composed of 162 two-meter-long accelerator guides and accelerates 50 mA electron beam with a 1 μsec width up to the energy of 2.5 GeV[2]. The rf source system has already been reported elsewhere[3]. A high power klystron feeds four accelerator guides with a peak rf power of 30 MW. Forty-one klystrons are used for accelerator guides as well as one for an injector system composed of a prebuncher, a buncher and two accelerator guides.

At the design stage of the 2.5 GeV linear accelerator, possible troubles of the rf source during scheduled operation were taken into consideration and permanent-magnet focusing was chosen. This focusing method led to the great simplification in machine operation introduced by the elimination of the 41 focusing coils, focusing supplies, cooling water interlocks, etc., which would be necessary for electromagnet focusing. Stable operation of a tube was also expected because the focusing field was kept constant after once magnetized and adjusted. How to optimize the focusing field remains a problem in contrast to the electromagnet focusing in which the field is variable to some extent. The permanent-magnet focusing seems to be suitable to a rather large scale accelerator system, if we wish to make the operation simple. In fact it has been reported that permanent-magnet focusing was successfully used in SLAC 2 mile long accelerator[4),5)].

A comprehensive description of the desirable focusing field is not so easy because it depends deeply on design of many factors such as the

electron gun, the rf circuit etc.. The magnetic field distribution around a cathode determines the maximum required field, and also determines whether a Brillioun flow or an immersed flow. Generally an actual focusing field has a following profile: the field increases gradually in a region from the cathode to the 1st cavity and keeps almost constant in the interaction region to have the constant beam size which is roughly determined by the cathode-anode structure. The field falls rapidly beyond the output cavity and the beam diverges uniformly due to its own space charge force in the collector region.

It is known that the rising field near the input cavity characterizes a gain of amplification and the field shape near the output cavity characterizes an efficiency. However, the gain and the efficiency for a realistic klystron are very sensitive to the magnetic field distribution. The most common and simplest way to find the optimum focusing field is to vary the magnetic field of the electromagnet to maximize the efficiency. In permanent-magnet focusing, the "standard" or "optimum" field distribution is necessary and it is experimentally surveyed using the electromagnet at first. An important process for the utilization of the permanent magnet is to obtain the optimum field distribution for focusing from tube to tube. The optimum field distribution noted here is concerened with a proper axial field profile (usually fitted to the vendor's data) and an axisymmetry.

To use the permanent magnet effectively it is important that every tube has same characteristics. Very small differences in tube characteristic are often introduced by various causes such as the changes in tune frequencies of the cavities, manufacturing errors, etc., and require the different magnetic field profile. This situation forces us to have a rather complicated process in which the field profile must be adjusted from tube to tube. In fact it took a long time until the klystron manufacturer delivered the tube with the designated field profile.

2. Description of the permanent magnet

2-1 Specifications of the high power klystron

The linear accelerator in KEK is designed to be able to accelerate electrons to 2.5 GeV at a beam current of 50 mA by about 840 MW of total rf power from 41 klystrons. Required rf output power from a klystron is about 20 MW. Peak power of more than 25 MW was desired from the consideration of the klystron fault rate. In those days the 38 MW XK-5 klystron had already been developed and brought into operation in SLAC[6),7)]. A few time later a commercial tube similar to the XK-5, namely PV-3030A, was developed in MELCO (Mitsubishi Electric Corporation) with reasonable efficiency and cost. General design is based on the XK-5 and the maximum rated output power is 30 MW at the beam voltage of 265 kV. The specifications of this tube are shown in Table 1. Permanent magnet focusing was tested and investigated in KEK.

2-2 Structure, material and specifications of the permanent magnet

The magnets used for the PV-3030A klystron are cylindrically shaped and are designed to have a total length of 478 mm and an inside diameter of about 216 mm, which provides enough clearance for insertion of lead shielding and for easy removal of the tube from the magnet. The maximum outer diameter is 470 mm, and the total weight is nearly 450 kg. The cut-away view of the magnet is shown in Fig. 1.

The klystron manufacturer desired to test the tubes with the electromagnet focusing because the permanent-magnet focusing of the very

high power klystror such as PV-3030A was the first trial in Japan. Therefore general guide lines on the focusing field were discussed and the following specification items are decided: the maximum field available for the tube did not exceed 1 to 1.1 kG so as to be produced by the permanent magnet and the optimum field profile has some allowance with the field distribution to achieve easy fitting of the field. At the first stage of tube developments the resultant required field changed frequently and it took some time to obtain a fixed field profile. Figure 1 shows the axial field profiles of the PV-3030A. The solid line represents the average field calculated from about 80 tubes. The other 2 thin lines indicate a standard deviation from the average field profile.

The field shape in the cathode-anode region is sensitive for the tube perfomance. The permanent magnet produces the strong reversal field on both ends of the magnet while the gun design requires a suitable field shape in the gun region. Field shaping has been made by using a magnetic shield to reduce the reversal field and by incorporating small field shaping bar-magnets or solenoidal coils. The iron skirt shown in Fig. 2 has a function of the magnetic shield. Its dimension and shape are determined after several trials with different dimensions. Field shaping bar-magnets are made of an alnico 5, a ferromagnetic alloy composed of alunminum, nickel and cobalt, for which diameter and length are 10 mm, 50 ~ 100 mm respectively. By careful adjustment of the location and number of the bar- magnets, the desired field for proper electron beam focusing can be obtained. Sometimes the field shaping coils are used to investigate the appropriate field shape. The iron ring 1 shown in Fig. 2 is a ring which is welded between the output cavity and the collector in the tube to shield the main field. The iron ring 2 was later added to modify the field profile near the input cavity.

The magnetic material used is an alnico 9, which is also a ferromagnetic alloy composed of aluminum, nickel and cobalt. This material is manufactured by means of a zone melting method in the atmosphere at high temperature under the external magnetic field. It has a magnetic anisotropy and the magnetization is parallel to the external field. It has residual magnetic flux density Br of 10.5 ∿ 11.5 kG, coercive force Hc of 1400 ∿ 1600 Oe and maximum energy products (BH) max. of 9.0 ∿ 11.0. All of the values are larger than those of an alnico 8. An alnico 9 magnet has a smaller volume than an alnico 8 magnet while producing the same field strength. In those days a rare earth cobalt magnet like a Sm-Co magnet was just coming on the market, however the alnico 9 had a merit on both the price and the performance. The B versus H curve of an alnico 9 is shown in Fig. 3[8]. Generally an alnico material is hard and not easy to be cut precisely, therefore there are some difficulties to make a large magnet with an accurate dimension. To ensure the axisymmetry, the magnets are made by stacking small bar-magnets of which diameter and length are 25 mm and 50 mm respectively. Cylindrical surface of each bar-magnet is grinded mechanically and its cross sections on both ends are carefully finished. It was expected to have a good axisymmetry by averaging the all bar-magnets field. The allowable cross or transverse magnetic field in our specifications was chosen to be of the same value as for the SLAC magnet because we had no reliable data. Table 2 shows the summarized specifications of the KEK permanent magnet.

Finally the stability of the permanent magnet is briefly described. The changing rate of the magnetic field of an alnico magnet is well known and its dependence upon demagnetization is linearly varying with logarithmic scale of the time. Known value of the changing rate for an alnico 8 or 9 is

less than -0.4 % at $10^{8.5}$ sec which is corresponding to about 10 years. Consequently the magnetic field of the magnet is considered to be quite stable during the full life of the klystron.

2-3 Adjustment of the permanent magnet

Figure 1 shows that the axial magnetic field conforming to the klystron has a certain allowance but the field shape of the permanent magnet must be fitted to the test data of manufacturer as close as possible to maximize the output power of the tube. Therefore the adjustment of the axial field profile was the first important step. The procedure is briefly described here.

The permanent magnets delivered to KEK were usually demagnetized for safety. At first the magnet is full magnetized by a magnetizer which is the solenoid whose outer diameter, inner diameter and height are 1200 mm, 550 mm and 710 mm respectively. This is enclosed with thick iron cylinder to raise the inner field up to more than 8 kG. The central field of 6 kG with about 600 A exciting current is enough to full-magnetize the alnico 9 within a few minutes. Field shaping is performed using the solenoid coil array composed of 12 independent coils. The power supply has many capacitors and the charges stored in them are discharged through one of the solenoid coils for a short time. Resultant strong reversal field demagnetizes the axial field locally and field shaped approximately to the desired profile is achieved after several trials. Figure 4 shows the example of the full magnetization curve (solid line), the fitted field shape (broken line) and of the optimum profile for the tube, i. e. the factory test data (dash-dotted line). The first power test is made with the constitution of the permanent magnet with a field shaping solenoid to realize the field profile which gives the maximum output power and efficiency. Then the solenoid is replaced by the field shaping permanent bar-magnets described in the Section 2-2 to reproduce the results. Once the configuration of the field shaping magnet is determined, no longer change is necessary when the following adjustment is made for the new tube.

Another important procedure for the field adjustment is so called "magnetic shunt adjustment" which reduces the transverse magnetic field and makes the field as axisymmetric as possible. The adjustment is performed to maximize the output power during the power test of a tube. The details on this will be described in the Section 3-3.

The measurement of the magnetic field is made in every step mentioned above; an axial field profile and a transverse magnetic field are recorded. The instrument used in the field measurement is composed of 2 Hall probes; one is for the longitudinal field (Bz) and the other is for the transverse field (Br). The Hall probes are moved along the axis by a step motor and their positions are outputted by DAC through a rotary encoder. Whole field profiles are plotted by a X-Y recorder. There are two ways to measure the transverse magnetic field. One is the successive measurements of the transverse field at the fixed position of Z by rotating the Hall probe for Br. Another is the successive measurements that the Hall probe for Br surveys longitudinally at the fixed angle. It takes a few hours to obtain the useful information about the transverse field.

3. Performances of the klystron focused with the permanet magnet

In this section some problems associated with the permanent-magnet focusing and the performance of the klystron are discussed. Sometimes

comparison with the electromagnet is made to understand the difference between both types of focusing. The electromagnet mentioned here is used in the positron generator in KEK and its structure is basically the same as the manufacturer's one. The computer simulations are sometimes helpful to discuss the effects of the magnetic field on the beam quantitatively. Full simulations including the interaction between a cavity and a beam are difficult, so our simulations in this section are limited to the beam trace in the magnetic field under no drive rf power. The beam trace is analyzed using the electron trajectory program of Dr. Herrmannsfeldt[9]. The magnetic field analyses are made by using the PANDIRA code in the POISSON group program[10]. For the permanent magnet problem, the PANDIRA code is not available for the alnico magnet whose B versus H curve is not linear in the second quadrant. Furthermore slight demagnetization due to the profile fitting involves some difficulties to solve the problem exactly. Therefore our calculations are made for the equivalent rare-earth cobalt magnet which has the same field profile as our measured data.

Figure 5 shows the axial magnetic field profiles and the magnetic force lines of both the permanent magnet and the electromagnet. The lines of the magnetic force near the axis where the klystron beam passes are drawn precisely. This figure indicates that the permanent magnet produces reversal field at both ends of iron pole pieces: Arrows in Fig. 5-2 show these reversal fields. Location of the electron gun of the PV-3030A on the axis is 56 cm apart from the top pole piece so that the field shaping is necessary in this case. In the main body region both distributions of the magnetic force lines are almost the same and parallel to the axis. In this region the small transverse magnetic field gives the large effects on the tube performances. In the Section 3-1 the beam behavior in the collector region is discussed. The relations between the klystron performances and the magnetic field shape in the gun region are discussed in the Section 3-2. The effects of transverse field on the tube are described in Section 3-3.

3-1 The effects of the reversal field in the collector region.

Electrons which have passed the output gap enter the collector and their energy are converted to the thermal energy and dissipated there. Under a condition of no drive rf power, all of the beam energy fed by the power supply are dissipated in the collector and the dissipation power becomes maximum. For instance the dissipated power reaches the peak power of 84 MW when the beam voltage is 270 kV. Usually the collector is located beyond the magnet and the beam diverges uniformly by its own space charge forces. While the permanent magnet produces a high reversal field in this region as shown in Fig. 5-2: the uniform dispersion of the beam is possibly unexpected. There are some possibilities that a local temperature rise could occur due to the re-focused beam. In fact there were some troubles associated with the collector overload at the beginning of this project. Phenomenally the tube failures due to the arcing between the cathode and the anode were observed. The inspections after disassembling of the tubes showed that small copper balls were on the cathode. Furthermore melted surface was found near the tip of the collector (Fig. 6). It was thought that the copper balls came from the melted surface of the collector and gave the serious damages to the gun. Collector design was considered to be unadequate to the permanent-magnet focusing. A magnetic shield of the reversal field was the easiest way and no significant modifications were required to the tube. The iron cylinder with 10 mm thickness and 100 mm long was insterted outside of the collector as the magnetic shielding. This

geometrical size was determined by the field profile measurements. Measured and calculated axial field profiles are drawn in Fig. 7. It was confirmed that an iron shield reduced the reversal field satisfactory except for the entrance of the collector, as shown in Fig.7. The effect of the iron shield on the beam trajectory is calculated and shown in Fig. 8. In these calculations, the incident beam to the collector is assumed to be a laminar flow which has the kinematic energy of 270 keV and passes in the maximum magnetic field of 1 kG. This condition corresponds roughly to the maximum collector loading without drive rf power. Figure 8-1 shows the beam trajectory in the electromagnet field which is almost zero in the collector region. (see Fig. 5-1) In this case an uniform divergence by the space charge effect is achieved. Figure 8-2 and Fig. 8-3 show the beam trajectories in the field with and without an iron shield respectively. The magnetic field used in these calculations corresponds to the fields shown in Fig. 7-1 and Fig. 7-2 respectively. Figure 8-2 indicates that most of the beam can reach the tip of the collector and local overheating of the copper wall seems to occur. On the contrary, Fig. 8-3 shows that the proper divergence of the beam is achieved despite that the beam was once re-focused by the narrow and strong reversal field. The magnetic shield leads to the very similar beam trajectory as in the electromagnet case.

The iron shield could remove the phenomenon of the collector melting but furthermore the following protection sequence was introduced for safety: the rf drive power is always fed before the high voltage is applied to the tube. In this case it is obvious that the collector dissipation decreases to (100-η) % of the total beam power, where η denotes the tube efficiency in the percent unit.

3-2 The effect of reversal field in a cathode-anode region

Generally the klystron gun is designed assuming the Brilloun flow or the confined flow to focus the beam with a finite field strength, such as 1 kG[11),12)]. In the Brilloun flow scheme, an axial magnetic field is applied in the interaction region of the tube but not in the cathode-anode region, which is magnetically shielded from the field. While the confined flow or the partially immersed flow allows the magnetic field in the cathode-anode region but requires nearly zero on the cathode surface. These initial conditions for the magnetic field are very important and sensitive to the tube operation because the velocity of the electrons on the cathode is nearly zero in the space-charge-limited condition. The optimum field of the klystron PV-3030A allows a weak magnetic field in the cathode-anode region: the design of its gun was based on the assumption of the confined flow or the partially immersed flow. However the accurate magnetic field distribution on the cathode is practically uncertain because the cathode of the PV-3030A has a large diameter of 80 mm and a spherical shape. The magnetic field measurements were made only along the axis and the off axis field at the cathode might not be same as on the axis.

In the electromagnetic focusing main magnetic field is generally changed to maximize the output power since the field in the cathode-anode region is fixed to the shape determined by the iron skirt. Sometimes a backing coil is used but its effect is generally small. Whereas in the permanent-magnet focusing, the main field is fitted to the test data of the electromagnet, even though it is impossible to fit completely. (see Fig. 4) The possible fine adjustment to maximize the output power is to change the field shape slightly in the cathode-anode region. This fine adjustment is made at first with a small solenoid mounted in the vincinity of the gun

since the reversal field there is shaped roughly by the iron shield. However the diameter and the length of this shield are different from those of the electromagnet due to the various limitations, therefore the resultant field shape is also different. Figure 9 shows the field dependence on the tube performances. Figure 9a shows the field shapes in the cathode-anode region when the current of field shaping coil is changed. The field of the electromagnet is also shown on the same figure. It has a quite different shape from that of the permanent magnet due to the different shapes of the shield as mentioned above. The relation between the tube parameters such as the output power and the gain, and the current of the field shaping coil is shown on Fig. 9c, which indicates that the tube performances are very sensitive to the field shape. There are two peaks which give the maximum output power when the field is varied: one peak leads to the field slightly positive (this means the same polarity as the main field) as large as + 10 ∿ 20 Gauss on the cathode and another leads to that slightly negative as large as - 20 ∿ - 30 Gauss. The performances of a tube become unstable when the coil current is out of these peaks and finally result in a fault due to the arcing inside the tube. On the other hand, an amplification gain stands at its maximum on the boundaries where the instability occurs. Operating points of the electromagnet and the permanent magnet are ploted by an open circle and a double circle respectively in Fig. 9c.

In order to understand these tendencies, the beam simulations were made for the different magnetic field on a cathode. The beam traces were calculated from the cathode to 1st cavity, because the beam diameter was thought to be the most important parameter in the interaction region in the 1st approximation. Of course the beam scallops must be taken into consideration in the more precise analysis. Figure 9b shows the relations between the beam size and the field on a cathode. Numbers in the parentheses in Fig. 9a correspond to the same numbers as in Fig. 9b. The beam trajectory analyses indicate that the beam size at the input cavity is the minimum when the field on the cathode is nearly zero and increases when the field is not zero. Solid and broken lines in Fig. 9b denote the beam size at the input cavity and at the point where the locus becomes minimum respectively. These analyses show that the optimum interaction occurs at a relatively large beam diameter which is determined by the magnetic field whose strength is not zero on the cathode. Larger coupling coefficients between beam and cavity are expected when the beam diameter is larger. Unstable region in Fig. 9c comes from the beam interception at the drift tube due to too large beam diameter or the beam scallops. Beam trajectories corresponding to the realistic operation are shown in Fig. 10. Figure 10-1 is the trajectory in electromagnet focusing and corresponds to the operating point of an open circle shown in Fig. 9c. Figure 10-2 is that in the permanent-magnet focusing and corresponds to a double circle point in Fig. 9c. The magnetic force lines near the cathode surface are also drawn in these figures. The resultant beam diameters and envelops are almost the same in spite of the quite different feature of the field. That's the reason why the two peaks of the maximum output power are obtained. More precise analysis may be possible if the interaction between the beam and the cavity is taken into account.

Another problem associated with a magnetic field in this region is pointed out. It is a magnetron oscillation which is induced by some electron clouds around the gun housing[13]. Similar electron movements like in a magnetron occur in the residual magnetic field and finally give damages to the anode. Possible way to eliminate this is to set the field shaping

magnet array irregularly not so as to synchronize with the magnetron frequency. Fortunately this oscillation has not been observed in the KEK klystrons because the configuration of the field shaping magnets is chosen to prevent this oscillation with the field shape as shown in Fig. 9a.

3-3 Effects of the transverse fields on klystron performances

Figure 5 shows that the magnetic field lines are almost parallel to the axis in the interaction region for both the electromagnet and the permanent magnet. In other words, the transverse magnetic field in this region is zero or very small. In the actual cases the main problems remaining with the permanent magnets are those of cross or transverse magnetic field. Their effects on tube performances are discussed in this section.

First, the transverse magnetic field of the electromagnet is considered. Main components of electromagnet are coils and iron structures which form a part of magnetic circuit. Coils are wound cylindrically with a winding machine and iron structures are machined with a lathe. Therefore the electromagnet is easily made axisymmetric and its transverse magnetic field in the interaction region seems to be very small. In fact a measured Br/Bz is less than 0.3 %, where Br and Bz denote the transverse and longitudinal magnetic fields respectively. An example is shown on Fig. 11. On the other hand, the permanent magnets which were manufactured carefully as mentioned in Section 2-2, have sometimes a large Br/Bz value from 1.5 % to 2.0 %. Possible causes of transverse magnetic field are thought to be as follows: (1) inferior mechanical error of the magnet itself, (2) the effect of axially asymmetric shape of the iron pole piece which locates near an output waveguide, (3) a slight misalignment of bar-magnets or their assemblies which form the main magnet, (4) the influence of magnetic materials which are placed near the magnet, and (5) the local demagnetization on the surface caused by contact of magnetic objects with the side of the magnet. The first one may be ignored because with the initial inspections of the magnet it is possible to exclude the inferior quality. Next is also out of question because such an asymmetric shape is inevitable and is same for both the permanent magnet and the electromagnet. Some attentions must be paid to the last because even an initially well-behaved magnet produces a transverse magnetic field due to the local magnetization. Steps of the degaussing and the magnetization are repeated again if the magnets are accidentally out of the tolerable range of magnetic fields. Causes of (3) and (4) seem to be important in our case. The cabinet of the pulse modulator made of iron is placed beside the magnet at a distance of 700 mm. The magnetic field is possibly affected by the magnetic materials because the permanent magnet makes an open magnetic circuit; i.e. its magnetic fluxes spread out in the wide area. (see Fig. 5) A value, Br/Bz $\doteq$ 0.5 % is estimated as the effect due to the iron cabinet from the transverse field measurement. Thus it is considered that the main sources of the transverse magnetic field come from the causes (3) and (4).

It must be made clear what is the allowable transverse magnetic field to focus a klystron properly. In the confined flow condition the orbits of electrons in the axisymmetric magnetic field are spiral wound tightly around the magnetic field line and in the Brillouin flow condition they spin around the axis with constant angular velocity. Let's consider the simplest case in which the beam is confined within the diameter of 2b and the axis of the uniform axisymmetric field is tilted with an angle of θ about the axis of the klystron. In this case, the beam passes through along the cylindrical surface around the tilted axis with a same diameter, where it is assumed

that there are no scallops in the beam. Complete transmission is necessary for normal operation of the klystron. Simple geometrical consideration leads to $\theta \doteq 0.83°$ or Br/Bz $\doteq$ 1.45 % for the beam passing through the drift tube without interception, where the tube design value is taken into account; i.e., the beam diameter, 2b = 20 mm, the maximum drift tube diameter, 2a = 31.8 mm and the distance between the input and output cavities, d = 400 mm. This Br/Bz value is consistent with that listed in Table 1. Actually required value of Br/Bz must be smaller than the obtained value because the beam diameter near an output cavity is possibly larger than the initial 2b due to the scallop of the beam under the non-linear large signal behavior of the tube. Also off-centered beams are likely to induce an instability due to the axial asymmetric interactions between cavity and beam, even if there are no interceptions in the drift tube. Above simple discussion shows that the practically required Br/Bz should be chosen to be small enough compared with 1.5 %. The practical minimum is probably 0.3 % which is obtained in our electromagnet.

The transverse field can be reduced by magnetic shunts which consist of thin steel plates parallel to the main field axis. This procedure, which is called "an adjustment of iron shunt", is made at the final test so as to maximize the output rf power. This magnetic shunt changes the local magnetic resistivity in the open magnetic circuit of the permanent magnet and leads to the local concentration of the magnetic flux. Proper adjustment with the iron shunts reduces the transverse field without significant changes in the main field. Examples of the measurements of the transverse field with and without magnetic shunts are shown in Fig. 12 and Fig. 13. In these figures 4 lines indicated by angles are measured transverse field shapes with iron shunts, which are obtained by rotating the

Hall probe azimuthally in every 90° step. Dotted areas indicate the maximum envelops of 4 lines which are measured without magnetic shunts. Dushed curve is the line of Br/Bz = 1.5 % and gives the rough guide lines. Figure 11 shows the transverse field of an electromagnet, which is less than 0.3 % of a longitudinal field except for both sides. Figure 12 is one of the examples for the permanent magnets. The characteristics of the output power vs. the beam voltage are also shown in the figures. Predominant phenomenon without iron shunts are the existence of a limit for the output power at high beam voltage. The tube performance becomes unstable at the beam voltage of more than 240 kV and the vacuum pressure inside becomes high. It is probably due to the interception of the beam in the interaction region. The magnetic shunts increase the output power drastically and the result is shown in the right of Fig. 12. The transverse field is reduced to about 0.5 % in the region from the 1st cavity to the 4th cavity. Fig. 13 shows an another example, in which the maximum output power of 22 MW without the magnetic shunts is larger than that of the previous examples. The output power increases to 28 MW with the magnetic shunts. In this case the transverse field in the region from the 1st cavity to the 3rd cavity is reduced to 0.5 %, whereas in the output cavity region the field is increased. It is generally found that reduction of the transverse field in the region from the 1st cavity to the 3rd cavity leads easily to the maximum output power of 27 ~ 28 MW. The transverse field is about 0.5 ~ 0.7 % in these cases. However it is too complex to discuss the transverse field effect quantitatively. Figure 14 shows the characteristics of the output power and the efficiency in both the electromagnet and the permanent-magnet focusing. Input drive power difference is not important because the slightly different field shape in the gun region gives a large effect on the

gain of amplification as mentioned in Section 3-2. Comparing results in both types of focusing, the efficiency at the beam voltage of 260 ~ 270kV is decreased in the permanent-magnet focusing. This comes probably from the remaining transverse field in the regions of the output cavity and of the 4th cavity. Empirical adjustment by the magnetic shunt is not perfect to reduce the entire transverse field and it remains certain amount in the output cavity region as shown in Fig. 12 and Fig. 13. The beam behavior near the output cavity is thought to be very complex, because the transverse field due to the asymmetric iron pole piece is inevitable. Furthermore rf field in the region is possibly asymmetric due to the coupling window iris in the output cavity. Figure 15 shows the summary for the tube characteristics; i. e. the output power vs. the beam voltage, which have been measured during a year. Closed circles denote the data in the permanent-magnet focusing and open circles in the electromagnet focusing. Fluctuations of the data in the permanent-magnet focusing show that there is some way to improve the transverse field. The goal is the reduction of the transverse field in the entire region below 0.3 %, which was achieved in electromagnet. It must be stressed that some causes of the data fluctuations in Fig. 15 come from the different characteristics from tube to tube.

Sometimes too much transverse field causes an instability. One of these examples is the instability due to the harmonic frequency. It is easily found when the transverse field increases intentionally with too many magnetic shunts. This is the phenomenon when the 3rd harmonic (8.6 GHz) of the fundamental frequency (2.8 GHz) is observed at the 1st cavity. In this case 2nd harmonic is not obtained because it is below the cut-off frequency of the drift tube. The mechanism is not clear but the higher order harmonics are induced in the output cavity region by the off-center beam.

This instability disappears and the foundamental output power increases if the transverse field is reduced by the proper magnetic shunt. This indicates the importance of the transverse field reduction in the focusing field in an indirect way.

The computer simulation on the large signal behavior of the klystron including an actual focusing magnetic field might be a powerful tool for us to understand the complex phenomenon mentioned above. It is difficult to make an analysis including the transverse field because it needs the three dimensional analysis, and there are no studies about it. Recently simulation using the particle-in-cell code for the XK-5 klystron which has almost similar structure with the PV-3030A has been made[14),14)]. They assumed an axially symmetric condition but interesting results were presented. Good agreement with the experimental data was obtained from the simulation using the magnetic field which was empirically obtained by maximizing the efficiency of the tube. Also the results showed the well-known feature that the maximum efficiency was achieved by allowing a beam to pass the output gap as close as possible to the wall without hitting it. The effect of the magnetic field was shown to be very sensitive to the efficiency and this scheme agrees well with our results.

4. Conclusion

It has been passed 5 years since the initial operation of the klystron using the permanent-magnet focusing in the Photon Factory linear accelerator. Stable operation has been continued without any troubles leading to the permanent magnet failures. The initial purposes to adopt the permanent-magnet focusing were staisfied. The axial magnetic field profile

and the transverse field play an important role in the tube performance. Particularly, reduction of the transverse magnetic field has large effects on maximizing the tube efficiency. The allowable transverse field is required to be less than 0.3 % of the longitudinal field in the entire rf interaction region of the tube. As it is planned to improve the field measuring instrument which is composed of multi-Hall probes, the adjustment with the magnetic shunts will be performed completely in short time before the power test. The measurement of beam interception in the interaction region is also important. This is generally difficult for the pulsed high power tube because the tube body and the collector are welded together. One possible way is to measure the temperature difference of cooling water at the body and the collector. The measuring instrument is under preparation.

Recently more stable operation of the tube in the permanent-magnet focusing became possible because the newly produced tubes became to have more uniform quality. If tube to tube performances are different, it is difficult to operate them stably with the permanent-magnet focusing. There are many improved items including the tube processing but the most significant progress seems to be the stability of the emission property.

In the future, development of the higher output power tube will come into our stage and this will increase the importance of the focusing field. More detailed studies for the permanent-magnet focusing are being carried out.

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References

1) J. Tanaka, "Construction of Photon Factory 2.5 GeV Injector Electron Linac", Nucl. Instr. Method., 177, pp.101, 1980.

2) I. Sato, "Accelerator Structure and Beam Transport System for the KEK Photon Factory Injector", Nucl. Instr. Method., 177, pp.91, 1980.

3) S. Anami et al., "The rf System of the Photon Factory Injector Linac", Proc. 1981 Linear Acc. Conf., Santa Fe, pp.177, 1981.

4) R. Neal, "The Stanford Two Mile Accelerator", W.A. Benjamin INC, New York, 1968.

5) G.K. Merdinian and J.V. Lebacqz, "High Power Permanent Magnet Focusing S-band Klystron for Linear Accelerator Use", 5th Int. Conf. On Hyperfrequency Tubes, Paris France, September, pp.14, 1964 / SLAC-Pub-48, 1964.

6) J.V. Lebacqz," RF Sources Developments", 1979 Linear Accelerator Conference, Upton, New York, September, pp.10, 1979.

7) G.T. Konrad, "High Power RF Klystrons for Linear Acceleators", 1984 Linear Accelerator Conference., Seeheim/Darmstadt, West Germany, May, pp.7, 1984.

8) Data Sheet of Sumitomo Co.

9) W.B. Herrmannsfeldt, "Electron Trajectory Program", SLAC-226, 1979.

10) K. Halbach and R.F. Holsinger, to be published.

11) C. Süsskind, "Electron Guns and Focusing for High-Density Electron Beams", Advances in Electronic and Electron Physics Vol. VIII, ed. L. Marton, Academic Press, 1956.

12) G.R. Brewer, "High Intensity Electron Guns", in "Focusing of Charged Particles", Vol.II, ed. by A. Septier, Academic Press, New York, 1967.

13) C. Greenfil, Private Communication.

14) K. Eppley, S. Yu, A.Drobot, W.B. Herrmannsfeldt, H. Hanerfeld, D. Nielsen, S. Brandon and R. Melondez, "Results of Simulations of High Power Klystrons", IEEE Trans. on Nuclear Science, NS-32, No.5, pp.2903, 1985.

15) S. Yu, "Patricle-in-cell Simulation of High Power Klystrons", SLAC/AP-34, 1984.

Table 1. Specification and operation condition

	specification	*operation*
Max. beam voltage	270 kV	
Max. beam current	297 A	
Pervience	2.1±0.1 $A/V^{3/2}$	
Average beam power	30 kW	
Beam pulse width	< 4 μs	3.5 μs
RF pulse width	< 4 μs	3.5 μs
Pulse reptition rate	100 pps	10-50 pps
RF frequency	2,856 MHz	2,856 MHz
Peak output power	30 MW	20-30 MW
Efficiency	40 %	35-40 %
Gain	51 dB	45-52 dB
Focusing magnet	electromagnet	permanent magnet

Table 2. Specifications of the permanent magnet

Material	Alnico 9, bar-magnet
Shape	ϕ470 × 478, including iron pole pieces ϕ215 for inner diameter
Maximum field	more than 1,100 gauss in full magnetization
Axial field profile	see Figure 1 0 cross point in the gun region locates between 550 mm and 570 mm from the top iron pole piece.
0 cross point	Field shaping bar-magnets enable to move the 0 cross point between 550 mm and 570 mm.
Transverse field	Transverse field not to exceed 1.5 % of the longitudinal field or 2 gauss, whichever is greater.

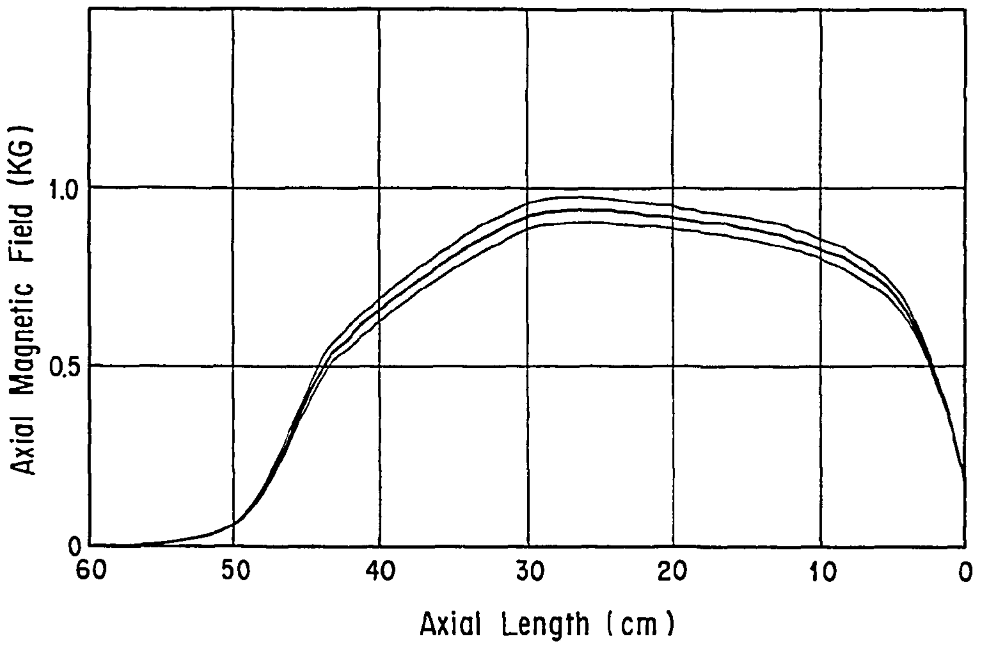

Fig 1 Axial magnetiic field profile on the axis.

Axial length is the distance from the top iron pole piece.

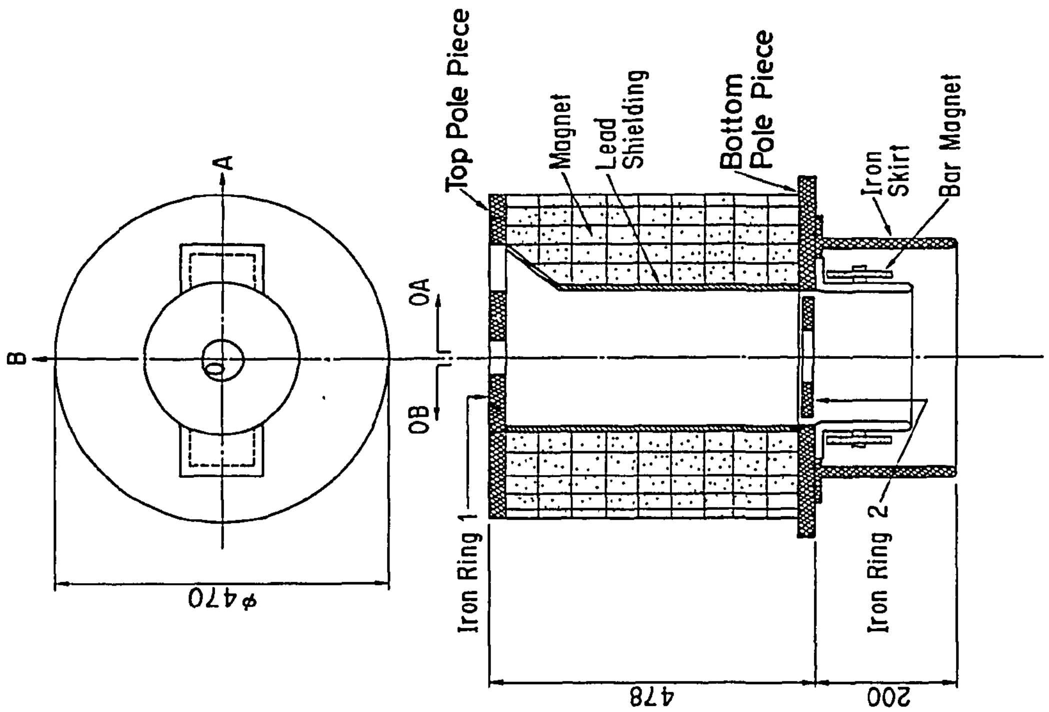

Fig. 2 Cut-away view of the permanent magnet.

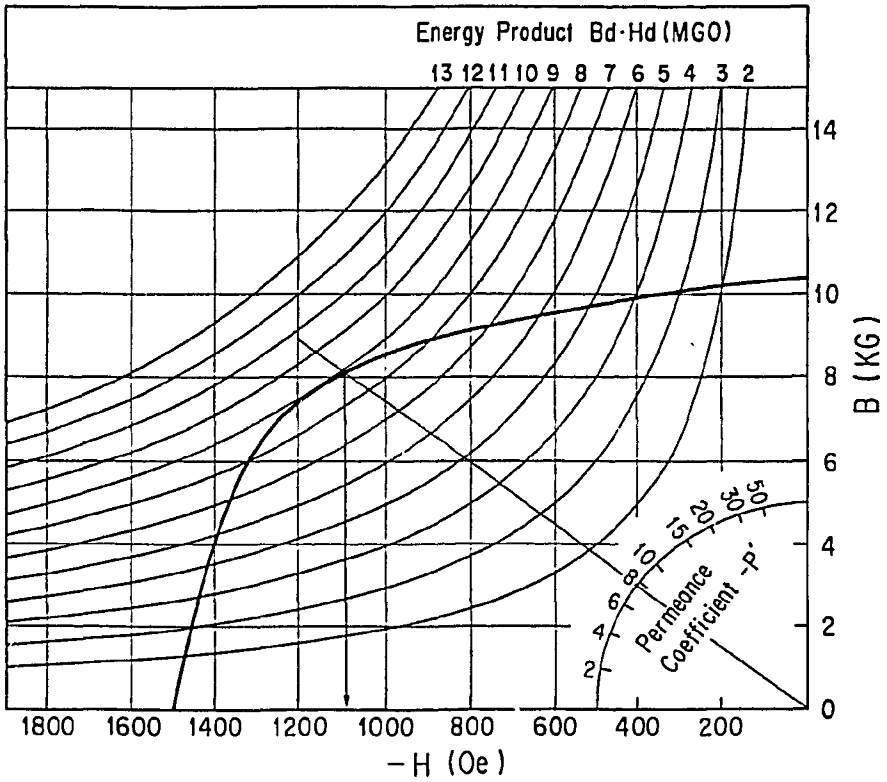

Fig. 3 B versus H curve of the alnico 9 magnet.

Permeance coefficient line corresponds to the geometry of KEK magnet.

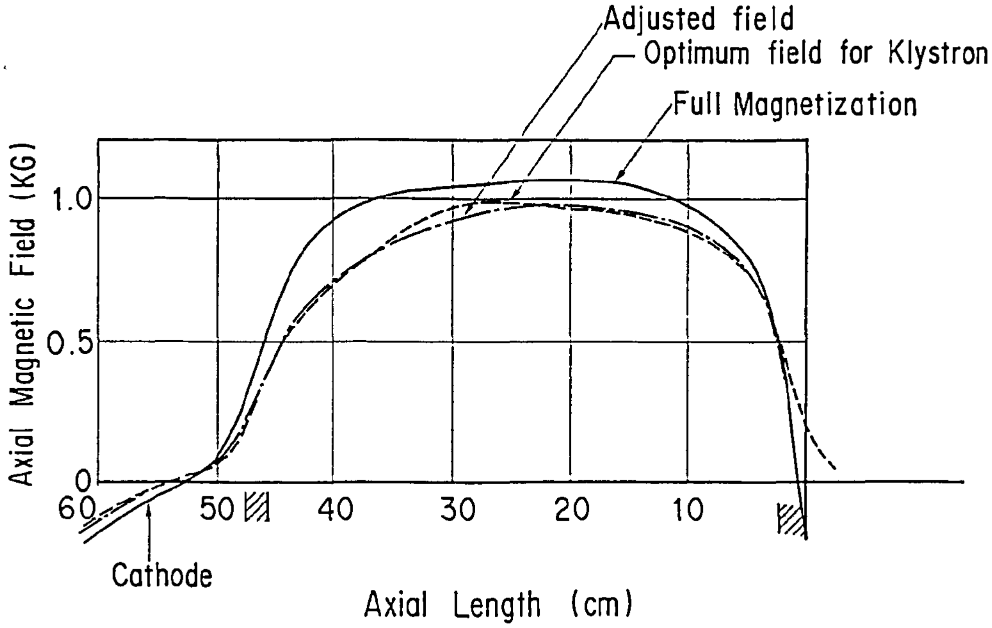

Fig. 4 Axial magnetic field measured in the each adjusting step.

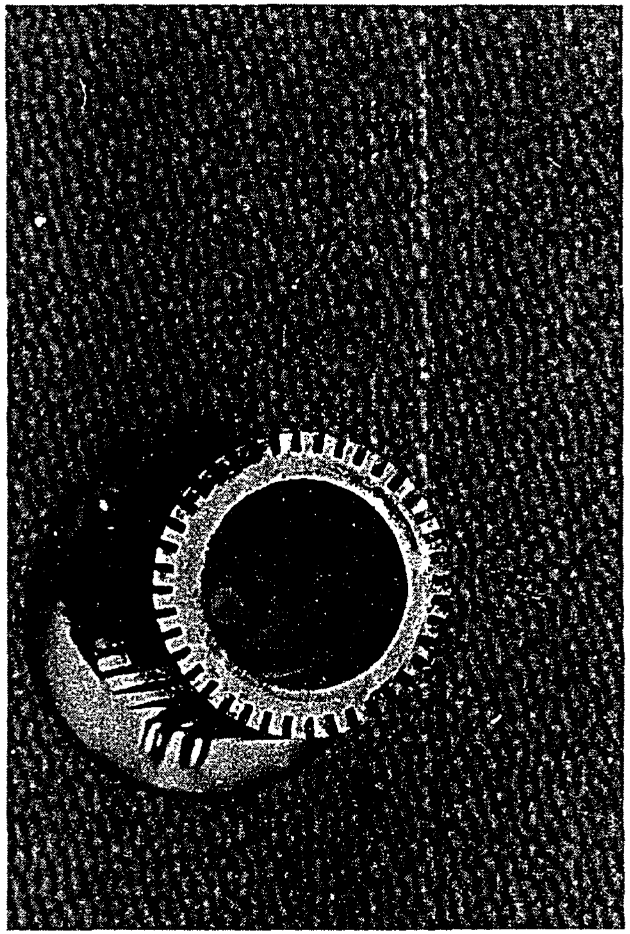

Fig. 6 Photograph of melting point at the tip of the klystron collector.

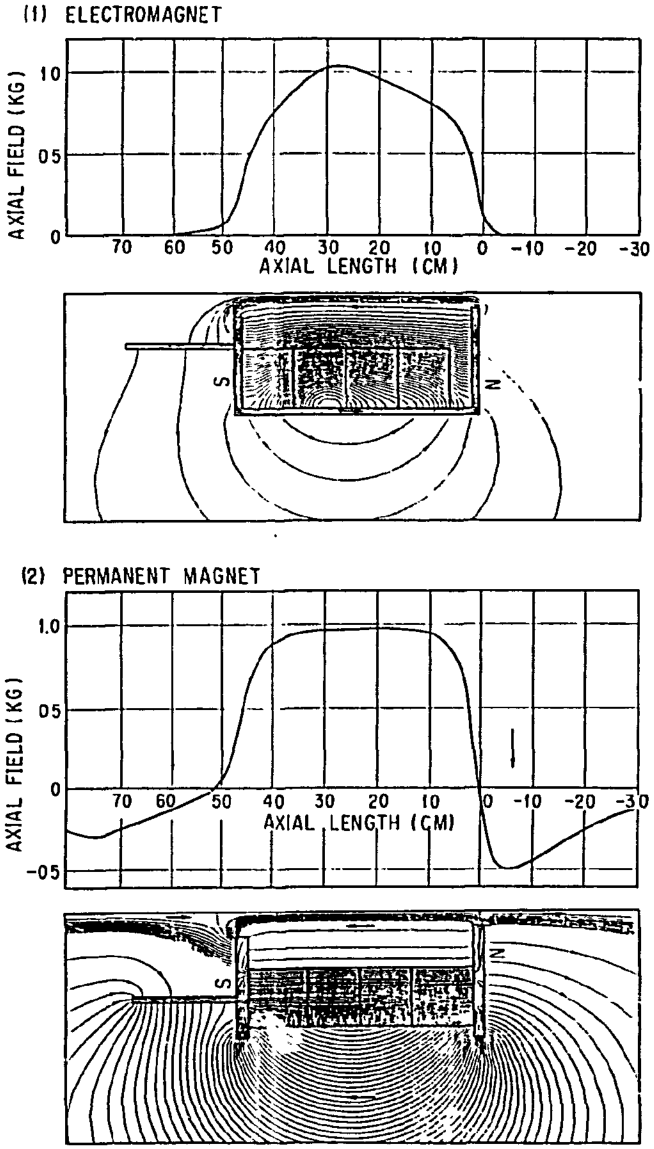

Fig. 5 Calculated lines of magnetic force and axial field profiles

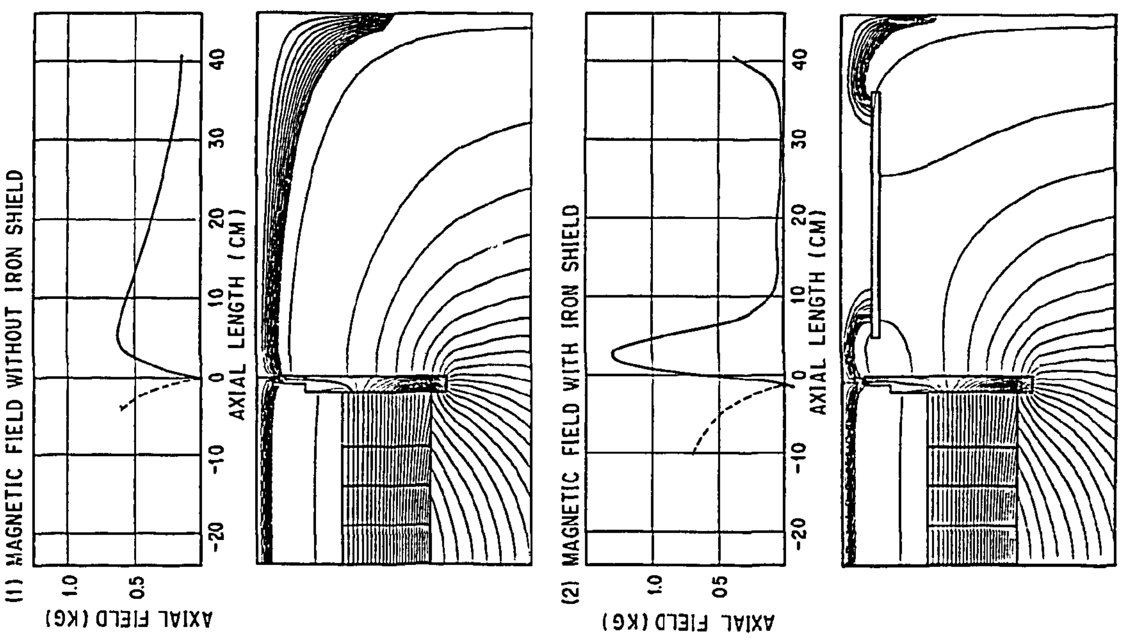

Fig. 7 The magnetic field profiles and the distributions of the magnetic force lines with and without the iron shield in the collector region.

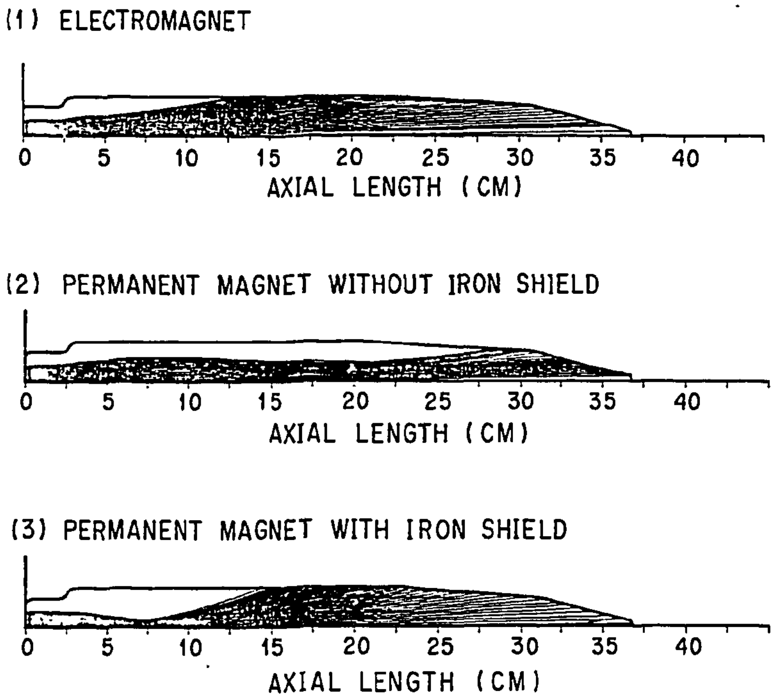

Fig. 8 Electron trajectories in the collector region.

(1) corresponds to the electromagnet focusing of which field is the same as that of fig. 5-(1). (2) and (3) corresponds to the permanet magnet focusing of which fields are the same as those of fig. 7-(1) and fig. 7-(2) respectively.

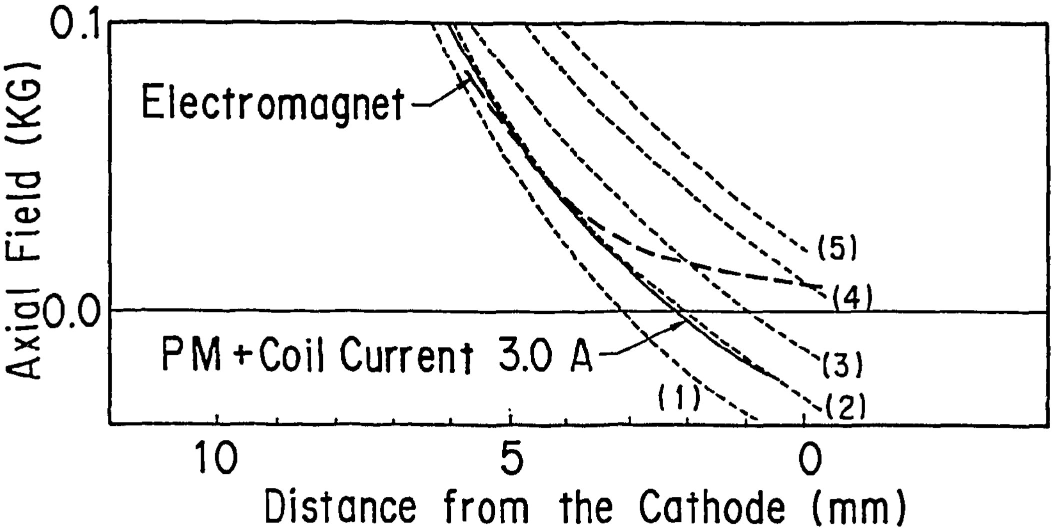

Fig. 9a Axial magnetic field distributions near the cathode. 0 mm denotes the cathode position. Solid line is the measured field with 3.0 A of the field shaping solenoid coil current. Dotted lines are calsulated fields with the different coil current. Broken line is the measured field of the electromagnet.

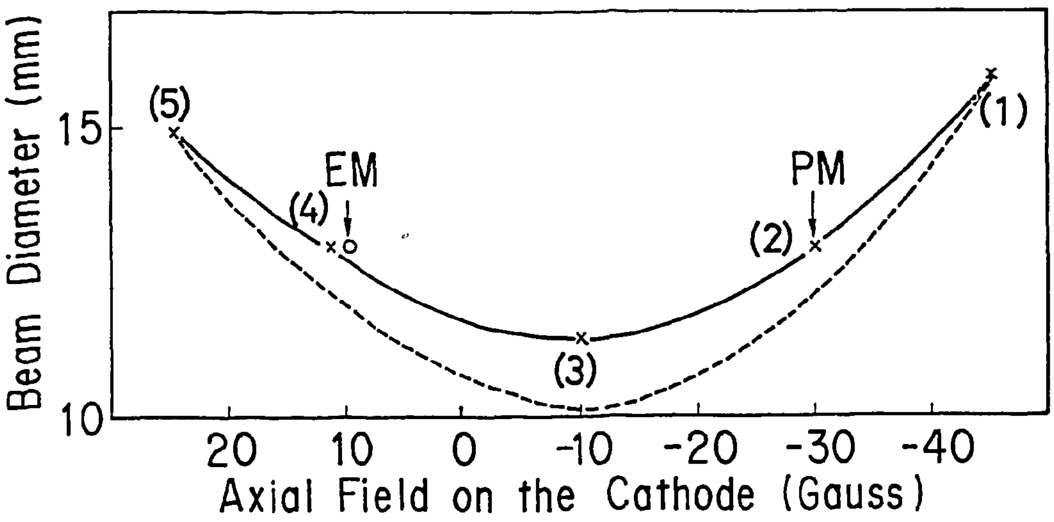

Fig. 9b Calculated beam diameter with the different axial field on the cathode. Solid line and dotted line are corresponding to the size at the 1st cavity gap and at the minimum locus point respectively.

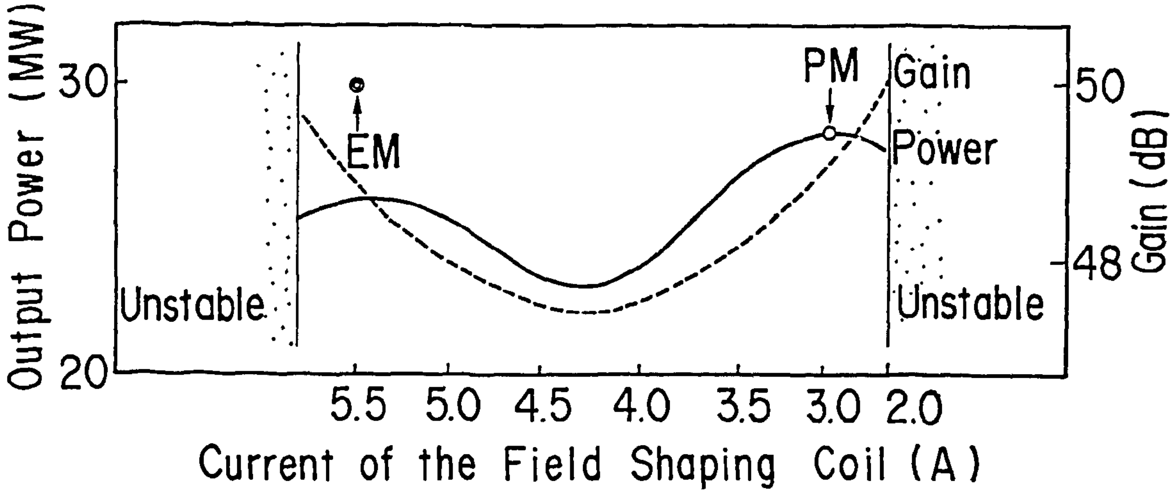

Fig. 9c The measured performance of the tube as the function of the current of the field shaping coil. Solid line and dushed line are corresponding to the output power and the gain respectively.

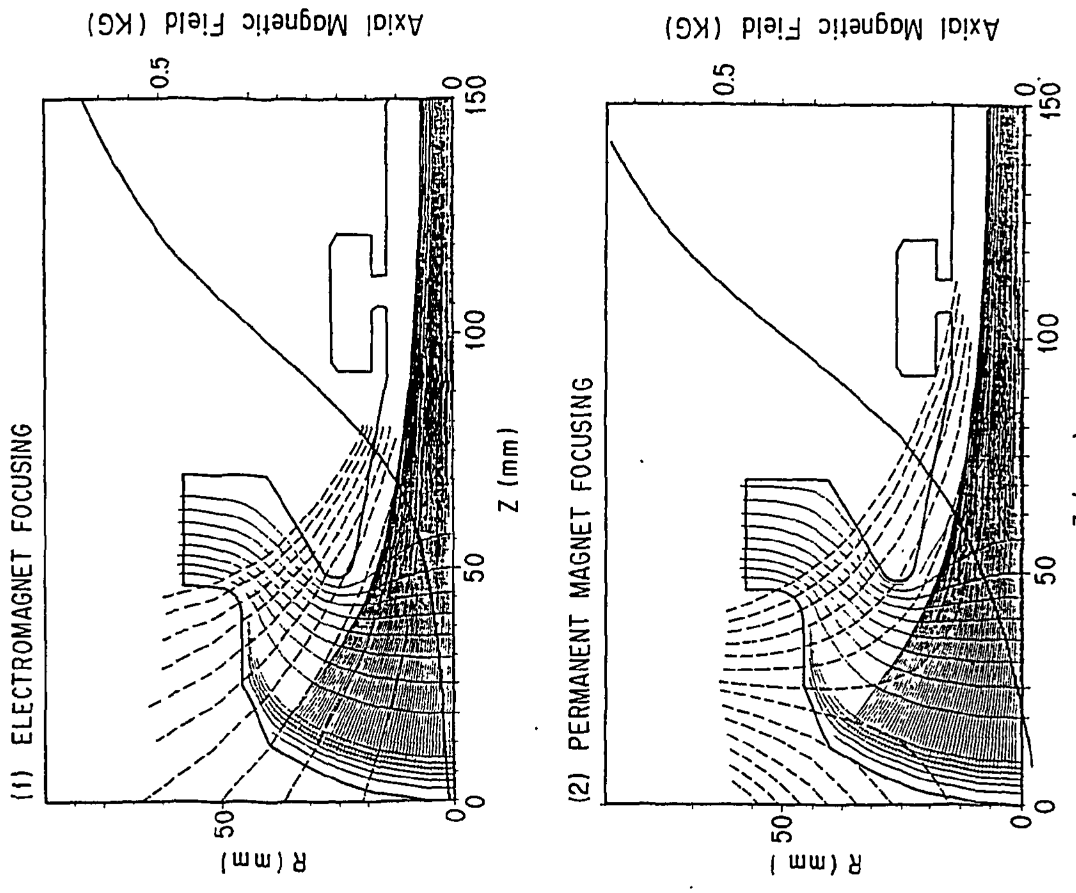

Fig. 10 Beam trajectories of the actual operations. Broben lines show the lines of magnetic force in the vincinity of the cathode.

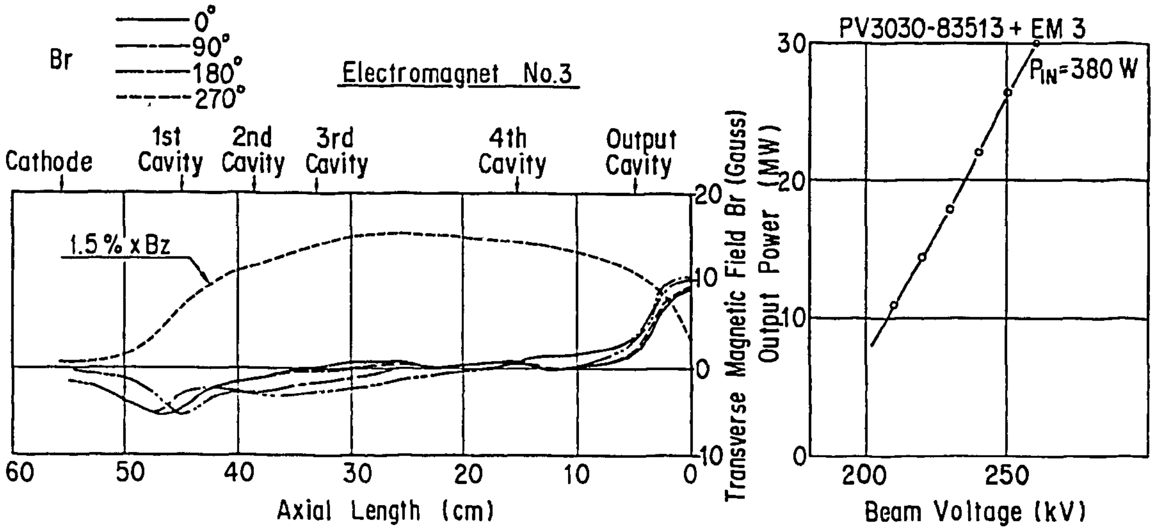

Fig. 11 Transverse field of the electromagnet and the output power charcteristics.

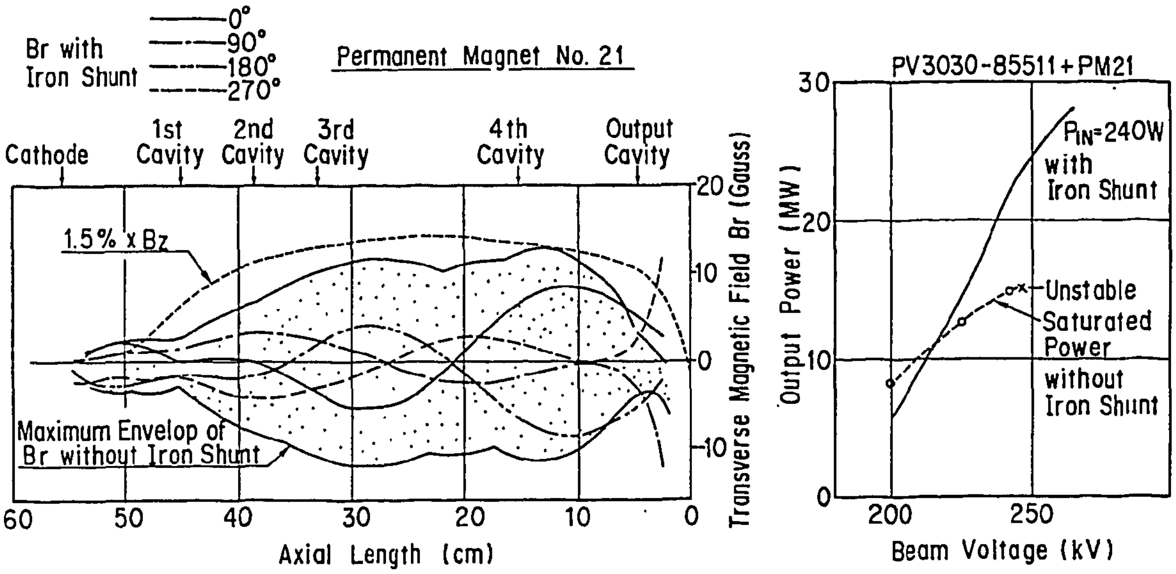

Fig. 12 The example of the transverse field of the permanent magnet and the output characteristics (I)

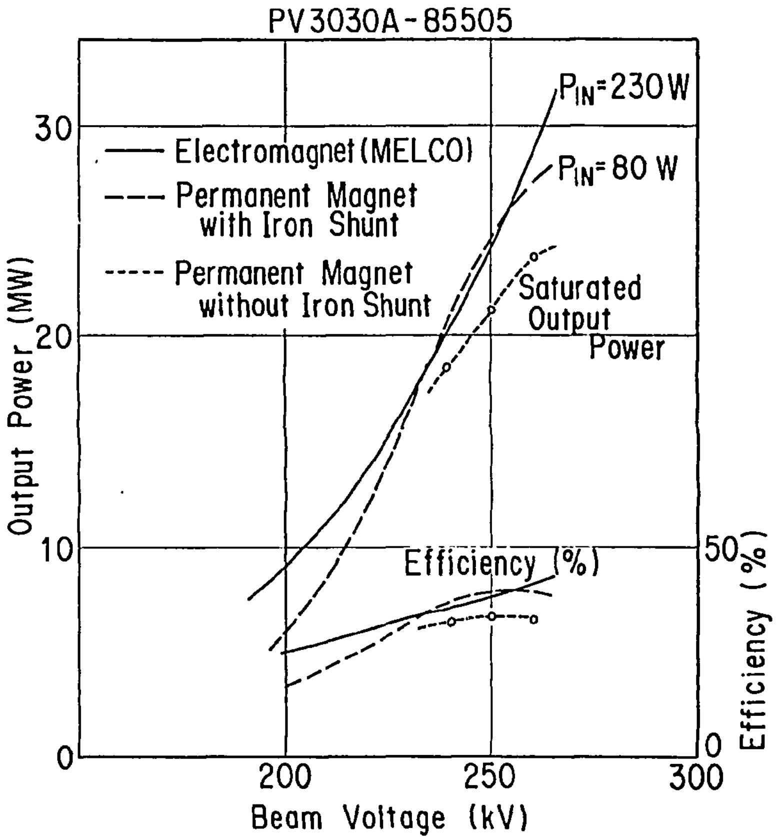

Fig. 14 The output power and the efficiency as the function of Beam valtage.

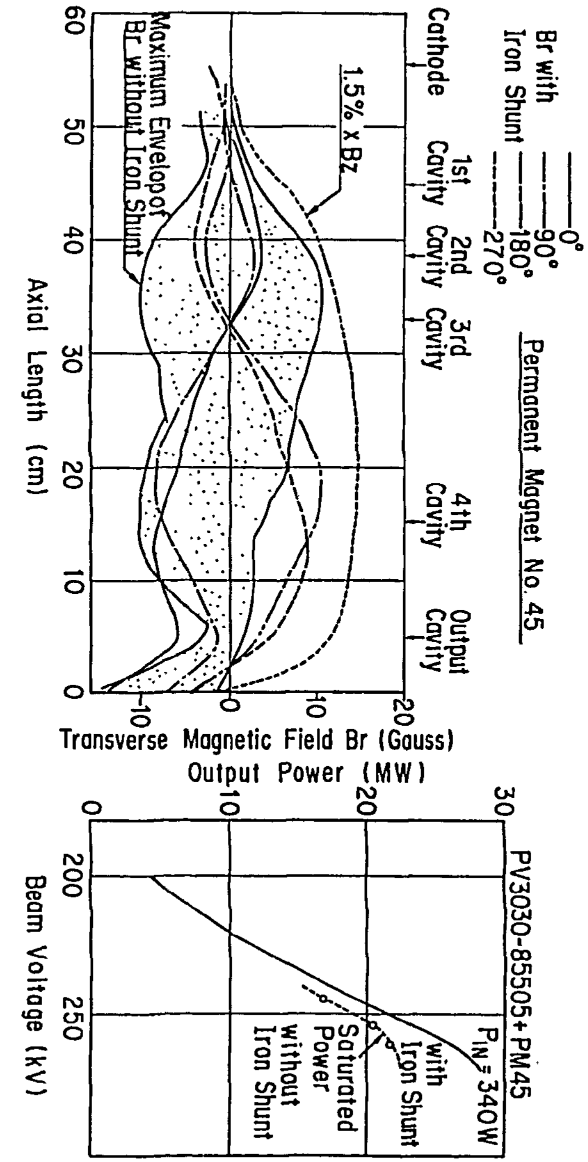

Fig. 13 The example of the transverse field of the permanent magnet and the output characteristics (II)

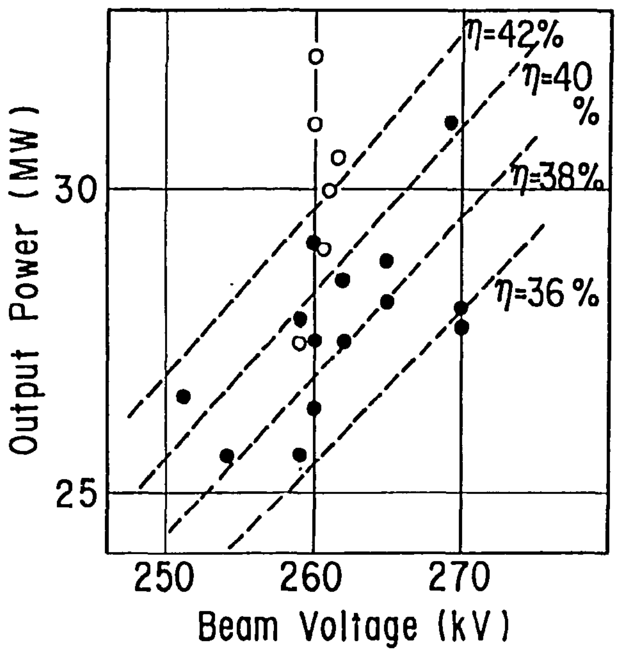

Fig. 15 Summary of the test data for a year.
Open circles and closed circles correspond to the electromagnetand the permanent magnet focusing respectively.
η denotes the efficiency of the tube.