The 13th Symposium on Accelerator Science and Technology, Suita, Osaka, Japan, October 2001

Development of PPM-Focused X-Band Pulse Klystron

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Abstract

Development of high power X-band (11.42GHz) klystrons is in progress at KEK, as one of the R&D programs for Japan Linear Collider (JLC) project. Effort has been devoted to develop klystrons with the focusing by periodic permanent magnet (PPM) in recent years, after almost a decade development work of the klystrons with solenoidal focusing. Two prototype PPM klystrons have been built successively and each of them has shown good performance. The second tube produced the output power of 73 MW at 1.4 microseconds pulse length where the RF efficiency was 54%. These values are almost those required in JLC. The design features and high power test results of the two PPM klystrons are reported.

1 POWER EFFICIENCY: THE REASON WE ADOPT PPM KLYSTRONS

Japan Linear Collider (JLC) is a future electron-positron collider machine to accelerate the beam up to TeV energy scale[1]. We have developed at KEK a series of X-band (11.42GHz) klystrons named XB72K[2] as a JLC prototype klystron, which has a strong solenoidal focusing magnet (the maximum field is some 6.5 kGauss). Since a few thousands of klystron tubes would be operated in JLC main linacs, the power efficiency of individual tube is a critical issue in the operational cost of the machine. From this point of view, one cannot neglect the electrical power consumed in the solenoidal magnet. In fact, the magnet of XB72K consumes 35 kW, which is almost the same to the average beam power to produce RF. In order to save this power, use of periodic permanent magnet (PPM) as a focusing magnet had been proposed[3]. Another advantage of the PPM focusing system lies in its compactness and small weight. Soon after the proposal, X-band PPM klystrons were built at SLAC[4].

2 DESIGN OF PPM KLYSTRON

KEK and Toshiba Co. started a two-year project of X-band PPM klystrons to develop a new prototype of JLC klystron[5]. It was planned that two klystron tubes were built in 1999 and 2000 (one tube per year).

We do not build a PPM tube by simple replacement of the focusing system of XB72K since it is not realistic for PPM to make the field equivalent to the strong solenoidal field of XB72K. The beam current (perveance) should be lowered from that of XB72K for good beam transmission. Thus a new gun design was prepared for the PPM tube.

The focusing field and RF circuit were designed based on the new gun. As the specification of the first tube (#1), we adopt 50 MW RF power at the pulse length of 1.5 μs (microseconds) under 450 kV cathode voltage. This design is fairly conservative to be the base design for the successive tubes. To make the magnet design simple, no cooling water channel was equipped for the PPM circuit of #1 tube.

The performance of #1 tube was very good. The second tube (#2) was designed by the optimization of RF circuit to achieve JLC specification: 75 MW RF power at 1.5 μs pulse length (480 kV, 55% RF conversion efficiency). Adequate cooling water was distributed in the tube for the operation under high repetition rate. The shape of the magnets in PPM circuit was redesigned for the water pipes while the field design was unchanged.

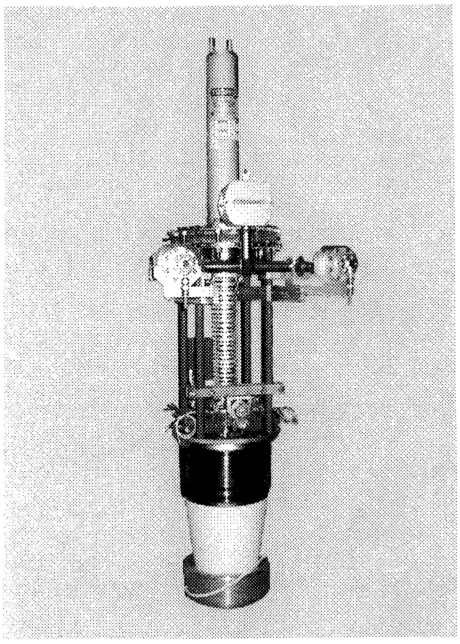

Figure 1: PPM klystron (#2).

2.1 Gun

The perveance of the electron gun is 0.8μK. We used DGUN code[6] as a design tool. The parameter list of the gun is given in Table 1. The two electromagnets for beam tuning are placed in the upstream region of the tube. One is the bucking coil which controls the magnetic field on the cathode. The beam size is tunable by the cathode field as in Table 1. The other is the matching magnet (coil). It consists of a pair of short solenoids in series and produces alternate axial field. It controls the matching of the beam from the gun to the PPM focused region to minimize the beam scalloping in the tube.

The heat expansion of the cathode and its neighbors was estimated by ANSYS code. We measured the displacement of the cathode by a CCD laser displacement sensor. We found the measurement agreed well to the result of ANSYS. The cathode stem was shortened for compensating the expansion. The measured perveance of the gun was very close to the design value.

Table 1: Parameters of the gun.

Cathode	Voltage	480 kV
	Current	266 A
	Loading	< 10 A/cm^2
	Diameter	61 mm
Max. Field on	whole electrode	< 230 kV/cm
	cathode	192 kV/cm
	anode	224 kV/cm
Cathode Field		$0 \sim 20$ Gauss
Beam Radius		$\phi 4.8 \sim 6.8$ mm

2.2 *Permanent Magnet Circuit*

The material of the magnets is Nd-Fe-B (Sumitomo Special Metal Co. NEOMAX 35SH, 39SH). The period of the PPM is 30 mm and the maximum field strength on the beam axis is 3.2 kGauss. The *stopband* voltage of this PPM focusing structure[7] is about 30 kV.

Figure 2 shows the observed beam transmission rate from the gun to the collector under the design matching coil current. The rate is 100% above the *threshold* voltage of ~250 kV, which is much higher than the stopband voltage. Simulation shows that below the threshold, the beam particles are lost due to large scalloping (the beam mismatches to the PPM field).

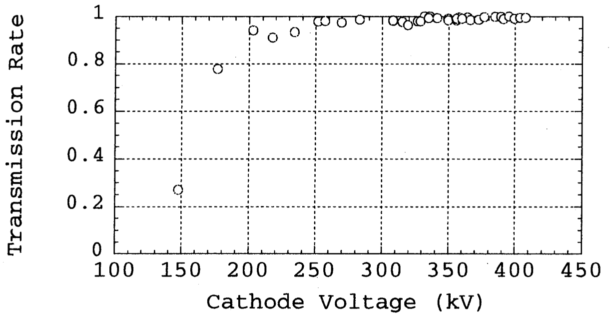

Figure 2: Observed beam transmission rate.

As the modulated beam is bunched in the downstream of the tube, the beam tends to expand in the radial (r) direction. The magnetic field is gradually increased in (about 1/3 of) the downstream to focus the bunched beam well.

The uni-directional magnetic field along z direction is located over the output cavity. The magnet surrounding the output cavity needs two cuts since two output waveguides stick out in opposite directions. The field is not cylindrically symmetric due to the cuts. We designed the magnet as the radial component, B_r, to be zero on z axis. Otherwise the beam should be deflected in a transverse direction and this may trigger off a parasitic oscillation.

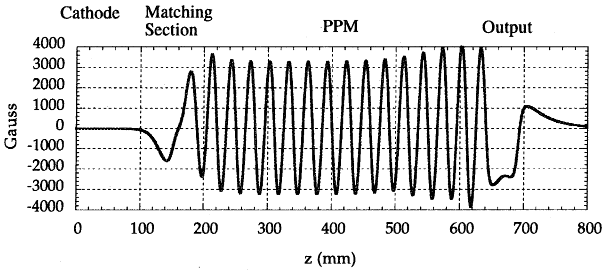

Figure 3: The design focusing magnetic field on the axis.

2.3 *RF Circuit*

The klystrons have five cavities between the input and output cavity: Two gain cavities upstream and three bunching cavities downstream. In order to obtain a robust structure against the parasitic oscillations, all these five cavities are made of lossy metal to damp out effectively the higher order modes in the cavities (Monel = Ni-Cu alloy for #1 while stainless steel for #2). The drift tubes are stainless steel to damp the trapped modes between the cavities.

The output cavity of the PPM tubes is a traveling wave type. We modified the design of traveling wave structure installed on #10 of XB72K[8] for the PPM tubes. The shape of the coupling ports to the output waveguides was redesigned to increase the output power. The original structure is characterize as its relatively low surface electric field and TE111(-like) mode is detuned away from the operation frequency for the suppression of the parasitic oscillation. The modification of the couplers does not spoil these characters.

The output cavity is copper-made. The higher order modes in the output cavity, other than the TE111-like, are damped by the output waveguides. The two waveguides are connected to the cavity not aligned to each other but slanted. The field of higher order modes runs away into the waveguides.

3 HIGH POWER TEST

The high power test was done at #3 station of KEK AR-South Experimental Hall. The modulator produces the maximum voltage of 550 kV at 1.7 μs flat-top pulse. The maximum repetition rate is 50 Hz.

The #1 tube was tested form July to September 2000. The test was done under low rate (> 5 Hz) due to the limit of cooling ability of the tube. We have never seen any signal of parasitic oscillation during the test. The tube produced the maximum power of 68 MW at 514 kV.

After the 3-month test, the tube got modified to improve its RF performance. The "Taper" RF windows[9] were replaced to the "Mixed-Modes"[10] for the run with long RF pulse. The gain cavities were replaced and the frequency of output cavity was tuned properly to improve the efficiency. The modified klystron, #1A, was tested from January to March 2001. We confirmed the efficiency was improved from #1. No parasitic oscillation was found either. Table 2 summarizes the results of #1 and #1A.

Table 2: High power test result of #1 and #1A.

	Design	#1		#1A
Power (MW)	> 50	54	68	66
Efficiency (%)	> 50	44	47	49
Pulse Length (μs)	1.5	1.5	0.3	0.4
Rep-Rate (Hz)	—	5	2	5

The #2 klystron was tested from April to June 2001. We operated the tube under 25 Hz most of the time. It was confirmed soon by a pilot run with short RF pulse that the efficiency was improved by about 5% compared to #1A. We have found no parasitic oscillation. After the pilot run, we started the run with full RF pulse (1.5 μs). We reached 50 MW at the full pulse length. The ceramic in the RF window was damaged on a way from 50 to 75 MW output. The rate was down to 3.6 Hz and we reached 73 MW at 1.4 μs. The test result of #2 tube is shown in Table 3.

Table 3: High power test result of #2 and JLC specification.

	JLC / Design	Achieved	
Power (MW)	75	52	73
@ Voltage (kV)		(443)	(503)
Efficiency (%)	55	52	54
Pulse Length (μs)	1.5	1.5	1.4
Rep-Rate (Hz)	150 / 50	25	3.6

4 SUMMARY

We have built two PPM klystrons during 1999 to 2000. The performance of these PPM tubes was very good. In Figure 4, we summarize the measured output power and efficiency of #1, #1A and #2 vs. the cathode voltage. The performance is improving from tube to tube, although we have not reached to a JLC klystron yet. We will restart the test of #2 tube after the RF window gets repaired.

Photos and descriptions on the X-band klystron tubes developed at KEK are found at [11].

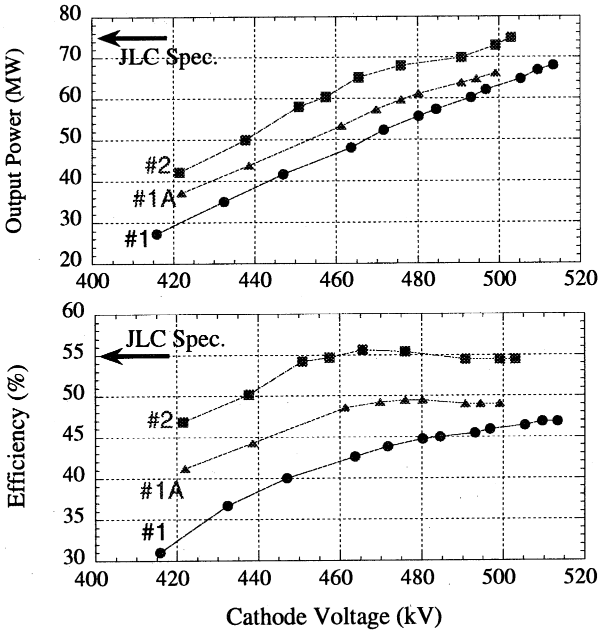

Figure 4: Power and efficiency of #1, #1A and #2.

5 ACKNOWLEDGMENT

The authors would like to acknowledge to H. Nakayama for his help in designing of magnets. We are grateful to T. Kohda of Sumitomo Special Metal Co. and K. Ogata of Tokin Co. for their special efforts in design and fabrication of the permanent magnets and the electromagnets respectively. Thanks are also to K. Takata, V. Balakin, M. Akemoto and N. Toge.

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