Development of PPM-focused X-Band Pulse Klystron

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Abstract

The status of the development work of 75MW PPM-focused X-Band pulse klystron at KEK is reviewed. R&D of these klystrons, which had been conducted in Global Linear Collider (GLC) project, was started in 1999 FY. So far six prototype tubes have been designed and fabricated. Five of these have been already tested. Some of them successfully produced the RF power required in GLC (75MW, 1.6μs). However, it was found that the performance of the tubes was not stable enough as a GLC tube. Further improvement is required with respects to the stability in RF output and its gun performance. The test of the very last tube, PPM6, has been just started. Following this test, two repaired tubes will be tested successively. The whole R&D work will end up with these tests. Recent test results as well as some simulation and design studies are discussed.

1 PPM TUBE AS GLC POWER SOURCE

GLC project was a pursuit of the high energy frontier with a TeV scale electron-positron collider[1]. Its main linacs were to be a pair of X-band linacs. A PPM (Periodic Permanent Magnet)-focused klystron tube was proposed as the power source of these linacs. The specification of the tube is given in the table below. R&D work of the tube was initiated at KEK in 1999. Since then six prototype tubes, as named PPM1-PPM6, have been built. Among them, PPM2, PPM4 and PPM5 have attained to 75MW 1.6μs simultaneously at their maximum performance.

Table 1: PPM tube design specifications

Frequency	11.424GHz
Peak Power	75MW
Pulse width	1.6ms
Repetition	150Hz
Cathode Voltage	480kV
Cathode Current	266A
Perveance	0.8uK
Efficiency	>55%
Main Focus	PPM
Max B / period	0.32T / 30mm
Magnet Material	NdFeB

In August 2004, the decision was made that all of the worldwide efforts for LC R&D should be integrated into an L-Band based superconducting LC toward the construction of the International Linear Collider. The Linear Collider R&D programs at KEK have been already reorganized along this decision. Our X-Band activities are now concentrated into XTF (X-Band Test Facility, formerly GLCTA), where a series of PPM-klystron tests as well as a series of high gradient accelerator structure (and some RF components) tests continue in parallel. The last prototype tube, PPM6, is now under testing.

2 REVIEW OF PPM TUBE R&D

2.1 Early Efforts: PPM1, PPM2 and PPM3

The first PPM tube, named PPM1, was designed as a 50MW tube and fabricated in 1999 after our solenoid-focused X-band klystron (called XB72K) R&D program as an LC power source for a decade. We did not design our PPM klystron by a simple replacement of solenoid into PPM for XB72K klystrons. We prepared a new design for the gun, for the RF circuit and, of course, for the focusing magnetic field. We adopted some of key concepts developed in XB72K such as a travelling wave output cavity with two output ports for the high power stability. The details are found in Ref 2.

PPM1 showed a very good performance in the test. The beam transmission from the gun to the collector was practically perfect. No parasitic oscillation was observed. The RF design and the magnetic field design of PPM1 are good enough to be the baseline for the next tube. PPM1 was operated below 5pps because of its minimum cooling ability. Most of the permanent magnets are air-cooled.

PPM2 was designed to meet fully GLC specification. The PPM1 output cavity was optimised for PPM2 to produce 75MW. Adequate cooling water circuits were equipped. We redesigned the shape of the permanent magnets while the magnetic field being unchanged.

This tube also showed a very good performance like PPM1. Under 25pps, the tube produced 52MW 1.5μs. The tube eventually could produce 73MW 1.4μs but repetition was low (3pps) because of the RF windows (ceramic) being damaged. This tube has been thought to be the proof-of-existence to a 75MW PPM tube.

PPM2 was repaired after the test. Its RF windows were renewed (replaced). The operation of the repaired tube, PPM2A, was limited by frequent outgassing and breakdown events on the ceramic of the RF windows. The test was terminated due to the damage (crack) to the ceramic disk.

PPM3 installs two harmonic cavities in order to enhance the efficiency. However, the basic performance

Table 2: Summary table of the early PPM prototype tubes.

Tube	**1**		**1A**		**2**		**2A**		**3**	
test started (m/y)	7/ 00		2/ 01		4/ 01		11/ 01		3/ 02	
test ended (m/y)	11/ 00		3/ 01		6 /01		2/ 02		10/ 02	
Power (MW)	54	63	55	61	73	73	53	65	54	62
Pulse width (μs)	1.5	0.3	0.5	0.4	1.4	1.0	1.0	0.5	1.5	1.0
Voltage (kV)	476	514	480	500	504	500	454	490	487	495
Rep rate (pps)	5	2	5	2	2.94	3.6	17	17	25	50
Window type	Otake Taper[3]		Mixed-Mode		Mixed-Mode		Mixed-Mode		Mixed-Mode	
Features	Baseline model for followers. 50MW tube.		Both windows renewed from PPM1.		Adequate Cooling ability. 75MW tube.		Both windows renewed from PPM2.		Harmonic Cavities.	
Comment	Very Good performance.				75MW Proof-of-existence.				Parasitic oscillations.	
Why test ends?	Failure in window.		Scheduled.		Failure in window.		Scheduled. (Failure in window.)		Failure in window.	
Current status	Repaired to 1A.		Exhibition.		To 2A.		To 2B.		Disassembled.	

of PPM3 was very similar to that of PPM2. Parasitic oscillations of 27.2 and 27.9GHz were seen when the cathode voltage stays at between 420kV and 450kV. The test was terminated due to an accidental leakage of the tube because of the one of the windows being damaged. This tube was disassembled after the test.

Most of the failures in the early tests appeared in the RF windows. The early tubes installed the TE11-TM11 Mixed-Mode (MM) windows [4](except PPM1). The high power test of the window demonstrates the MM window could run up to 80MW 1.6μs [5]. However, in our earlier tube tests, we have suffered serious damage on the ceramic several times.

In our processing procedure, photomultiplier to monitor the light emission from the window ceramic is an essential tool. The light emission is commonly seen when RF is on. Sometimes we have the stationary light emission with slight vacuum pressure increase due to a continuous multipactoring. It is believed that a *regulated* multipactor process makes the TiN coated ceramic surface optimum for the RF transmission. We have learned a lot about the properties of MM window including the processing technique for it.

Our recent tubes install the newest windows, called TE01 window, which uses the circular TE01 as the transmission mode[6]. We have confirmed the robustness of this kind of window in the recent klystron tests. Therefore, in our recent tube tests, we have no window failure (except PPM4).

2.2 Recent tubes PPM2B, PPM4 and PPM5

PPM2B is a repaired tube from PPM2A. This tube was a candidate power source for 8-pack project [7] and it was sent to SLAC for the test. It has attained 75MW however, gun breakdowns occurred more and more in the end. The tube has got leaked in an accident and was sent back.

PPM4 is almost the same to PPM2. The changes are minor, e.g., the output cavity tuning was reviewed to improve frequency response. This is the first tube that we did intensive conditioning to pursue the GLC specification under 50pps. We introduced a fast RF interlock system, "Vogel Module", which shuts out the input RF to the klystron within the RF pulse duration when the klystron RF output gets lost. This is a fast protection system from the RF breakdowns in the output cavity.

Since the window problem has practically gone, the "hidden" problem of the tube came out. The "RF pulse shortenings", which were already observed in the test of PPM1, arouse. This phenomenon is characterized as a loss of output power that develops over several hundreds ns. We will discuss it following section in some detail. We have encountered the first pulse shortenings in PPM4 at 55MW 750ns. Beyond this point, either more power or longer pulse width, the pulse shortenings are common.

The rate of the events increases as higher output power and/or longer pulse length. With the help of Vogel Module, we could run the tube even if the pulse shortenings occurred. However, the pulse shortenings are not likely to be gone completely by usual processing techniques.

The MM windows of PPM4, which were actually damaged at the final stage of the test, were replaced to TE01 windows. The tube was reborn as PPM4A. PPM4A showed frequent gun breakdowns like PPM2B, however if the high voltage pulse is short, these breakdowns are gone. PPM4A is now working at XTF accelerating structure test stand as a workhorse where the tube is required at most 0.4μs pulses.

PPM5 was got an intensive conditioning over one and half months. However, we had frequent gun breakdowns in the final stage of the test. This behaviour looks similar

to that of PPM2B or PPM4A. This tube has already been disassembled for inspection.

PPM4G1 is a replica of PPM4, built for the XTF accelerating structure test stand. We have confirmed that the performance of this tube is enough to be used in the stand and it is now operated at XTF within 50MW 0.5μs without the pulse shortenings.

3 DISCUSSION

So far we have tested 10 tubes as we listed in the tables. We can do processing those tubes well up to 50MW 0.5μs. Beyond this point, though the boundary is not strict, every tube will fall in the operation with the pulse shortenings (PS).

By the observation with X-ray monitors and acoustic sensors, the output cavity is the most suspicious place. Usually we have a burst of higher frequency at the same time although we do not know whether the burst is the origin of the PS or it is simply the result of PS. We conclude PS is surely owing to some breakdown event in the output cavity.

We have observed various phenomena associated with PS. Each of these listed below has appeared if we continue running the tubes with PS.

1) Decrease of beam transmission occurred. Beam loss increased likely at input cavity region where the temperature raise and increase of X-ray were observed.

2) Emission from the gun decreased. It is not recovered soon even though we stop operation. In the most case we need to increase the cathode heater power to recover the previous emission. This may indicate some contamination occurs in the gun.

3) Increase of gun faults. We have never succeeded to condition this type of gun faults. Usually the fault occurs near to the tail of the high voltage pulses.

Although we have accumulated the data on the PS, we do not get any definite explanation for the phenomena.

On the other hand, by the inspection of the disassembled tubes, we found recently various parts of the tube got damaged. One of the remarkable damage was found on the surface of the beam pipe located slightly upstream of the input cavity. Both PPM2B and PPM5 got this damage. The damage is likely caused by the pulse heating from the beam loss due to the stopband of PPM. Although PPM5 has improved cooling circuits around the region, it does not help for the pulse heating. Since the loss is inevitable in the pulse operation of a tube, all of our latest tubes are with Molybdenum sleeve to cover this "hot region".

PPM6, the latest tube, get some modifications related with PS. We replaced its output cavity in order to check how the PS depends on the structure. Its test has just started and we expect the useful results to solve the issue of stability of our PPM tubes. As for long-term performance, or lifetime issues, we expect that PPM4G1 or PPM4A, which intensively runs at XTF, will give us the idea about them.

REFERENCES

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Table 3: Summary table of recent tubes.

Tube	**2B**		**4**	**4A**	**5**	**4G1**
test started test ended	2/ 03 11/ 03		4/ 03 8/ 03	12/ 03 8 /04	3/ 04 12/ 04	9/04 2/05
Power (MW)	75	67	77	73	70	50
Pulse width (μs)	1.7	1.7	1.6	1.6	1.6	0.4
Voltage (kV)	510	490	515	515	515	460
Rep rate (pps)	60	120	50	25	25	50
Window type	Mixed-Mode		Mixed-Mode	TE01	TE01 (SLAC)	Mixed-Mode
Features	Used to be a candidate to power 8-pack. Tested at SLAC.		Each ion pump for each window.		cooling at input and penultimate cavities enforced. TiN Coated drift tube.	PPM4 Replica. For XTF accelerating structure test stand.
Why test ends?	Frequent Gun breakdown.		Failure in Windows.	Scheduled.	Frequent gun breakdowns.	Scheduled.
Status	Disassembled. Recycled to 2C.		To 4A.	XTF workhorse.	Disassembled.	XTF workhorse.