WORLDWIDE PROGRESS IN X-BAND POWER SOURCES

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Abstract

The high power klystrons are among the most challenging components in the RF system for linear colliders and their development is indeed critical for all the projects at hand. In the last several years, the emphasis of R&D work for JLC X-Band (JLC-X hereafter) and NLC projects has been on developing PPM (Periodic Permanent Magnet) focusing klystrons to eliminate the expense (power supply, cooling, controls, etc.) and power requirements of focusing solenoids. Recently, the efforts were successfully materialized in PPM-2 and PPM-3 tubes at KEK, which have also met pulse performance requirements of JLC-X and NLC. In this paper, we will present the progress the JLC-X and NLC klystron development programs have made, including the measurement results and simulations. The JLC C-band PPM klystron development will be also described.

1 INTRODUCTION

To deliver the beam energy of 500GeV in the centre of mass, both the JLC-X and NLC projects require roughly 2000 klystrons per linac. Currently, the design goal is to produce 75MW in 1.6 μs pulses with efficiency of 55% at 150Hz (JLC-X) or 120Hz (NLC) repetition rates. The development of the X-band power source has been one of major goals for the JLC-X and NLC R&D program. The actual R&D on these sources began 15 years ago and has been much more difficult than initially anticipated. However now, the design for PPM klystrons is finally converging. Success also comes in large part from the development of new simulation and modelling tools [1].

2 PRE-PPM PERIOD

The initial efforts of JLC-X/NLC focused on the development of solenoid-focused klystrons during the first half (NLC) or most of 1990's (JLC-X). The best outcome was XL-4 tube of SLAC, which met the NLC requirements of that time (1995). The achievement of the XL-4 tube is summarized in Table 1, together with those of the JLC-X XB72K No.10 tube.

Ten XL-4 tubes have been constructed for the NLC Test Accelerator project (NLCTA) and are used as the workhorse X-band power sources to power the NLCTA as well as to produce power for X-band component testing. The XL-4 tubes nominally produce 50MW in pulse length up to 1.5 μs at a repetition rate of 60Hz and an efficiency of 43% in that program.

The solenoids on these tubes consume 24kW apiece, which is more than the average output power of the tubes (14kW) and thus the net efficiency including the solenoid power is too low for JLC-X and NLC.

Table 1: Achievements of SLAC XL-4 and KEK XB72K No.10

	SLAC XL-4	KEK XB72K No.10
Peak power (MW)	75	50
RF pulse length (μs)	1.5	1.5
Repetition rate (Hz)	120	25
Efficiency	43	35
Year	1995	1999

By the middle of 1990's, it became increasingly clear that ultimately a less energy consuming focusing system would be needed to keep the JLC-X/NLC operating costs manageable. A solution was the PPM focusing. In the PPM design, many magnet rings with alternating polarities are interleaved with iron pole pieces to generate a periodic axial field between the gun anode and beam collector. Its pros and cons are summarized below:

Pros:

1. It eliminates an energy consuming solenoid magnet with its associated overhead of power supply, cooling and controls.
2. Smaller and lighter.
3. High efficiency due to a low perveance (a weaker PPM field leads to a klystron design with a higher voltage-current ratio, which reduces the space charge defocusing and increases the klystron efficiency).

Cons:

1. Increased complexity may cause higher construction costs and higher failure rate.
2. A weaker focusing makes a PPM tube more susceptible to instabilities.
3. It requires a higher operating voltage due to a smaller perveance.

The PPM focusing is utilized in Travelling-Wave Tube (TWT) devices for commercial and military applications, but only for kW output power. The development of a 100MW level PPM klystron was a quite challenge.

During most of 1990's, the design efforts for the JLC-X program were centred at BINP in Russia. This collaboration yielded a series of solenoid-focused, 80MW klystrons (the XB72K series) that improved over the years but did not converge on a fully functional design. In 1998, KEK has revamped its klystron design program by improving its klystron modelling capability using the MAGIC code as reported at Linac98 conference [1]. The first original design and the last solenoid-focused klystron at KEK, the XB72K No.10, was built in 1999 with limited success: the maximum power of 50MW in 1.5μs pulses with efficiency of 35% at 25 Hz repetition rate. The performance was limited by the RF oscillation (tube instability) at 11.6GHz. The XB72K solenoid-focused klystron program was terminated in 1999 and all design work has shifted to PPM tubes.

3 X-BAND PPM KLYSTRON PROGRESS (IN HISTORICAL ORDER)

3.1 SLAC 50MW PPM Klystron 50XP

The first SLAC 50MW PPM klystron was built in 1996 with great success. The design parameters and the actual measured values are tabulated in Table 2 [2]:

Table 2: Design parameters and actual values for the SLAC 50MW PPM klystron 50XP.

SLAC 50XP	Year 1996-1999	
	Design	Achieved
Output power (MW)	50	50
Pulse length (μs)	1.5	2 (1997) 2.4 (1999)
Repetition rate (Hz)	120	120
Efficiency (%)	55	57

The beam transmission was 99.9% with no RF. It was reduced to 93% when RF is turned on. Neither gun nor tube oscillation was observed. The drift section was fabricated from brazed stacks of alternate iron pole pieces and Monel spacers. These stacks were welded together at the end pole pieces to form the complete drift tube. The magnets were high quality individually die-pressed Samarium-Cobalt SmCo. It was decided to control the magnetic field in the gun with a standard bucking coil and the field in the region from the gun to the beam minimum with three compact coils closely wound around the drift tube. This tube has no cooling system for the body or PPM stacks.

The excellent result gave confidence that a magnet structure could be designed and built with no allowance for shunting or adjustment. Recently (1999), the 50MW klystron was re-tested to explore longer pulse operation, where 50MW at 2.4μs and 60Hz with 55% efficiency were achieved.

3.2 SLAC 75MW PPM Klystron 75XP-1

Next, the first SLAC 75MW PPM klystron was designed and constructed in 1997. In comparison to the 50MW design, a number of major changes were made in the design, including an enlarged stainless steel drift tube for higher beam current and the elimination of the gun focus coils. The construction of the 75MW PPM magnetic circuit differed in that the drift tube is a semi-continuous stainless steel structure interrupted by the cavities, with the iron pole pieces and non-magnetic spacers placed outside the vacuum envelope. The stainless steel tube adds loss in the drift space to increase the start-oscillation current of the various parasitic modes, which may arise. The 75MW design used NdFeB magnets that have higher energy-products, and easier to machine and less brittle, but have a lower Curie temperature and are more sensitive to radiation damage. The tube has no body cooling like the 50MW design.

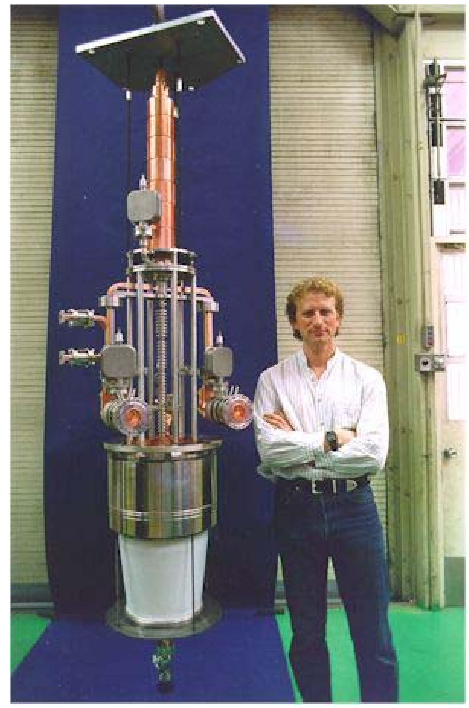

Figure 1: Photo of SLAC 75MW PPM klystron, 75XP-1.

This tune has suffered from a series of problems. When delivered, most of magnets failed to meet specifications. A very strong 1.5 GHz gun oscillation was revealed. A lossy collar of BeO-SiC ceramic was designed and fabricated, and placed in the gun region to damp the gun oscillation. Re-testing confirmed a strong parasitic oscillation at 20 GHz in the transition region from the output cavity and collector. A replacement transition was designed to damp the RF energy in the 20GHz range. This device was installed in the klystron and the klystron was again re-tested. The 20GHz oscillation was found to be effectively suppressed, allowing operation of the tube at 79MW at 2.8μs in 1999. The measured values in re-testing in 1999 are summarized in Table 3. A large number of particle interception was observed when RF on, and the operation was limited to 1Hz repetition rate due to heating of the un-cooled magnet stack.

Table 3: Design parameters and actual values for the SLAC 75MW PPM klystron 75XP-1.

SLAC 75XP-1	Year 1997-1999	
	Design	Achieved
Output power (MW)	75	79
Pulse length (μs)	1.5	2.8 (1999)
Repetition rate (Hz)	120	1
Efficiency (%)	55	62

3.3 KEK 50MW PPM Klystron PPM-1

In 1999, KEK has launched a two-step program with Toshiba to build a 50MW PPM tube first, followed by a 75MW version in two years [3]. Figure 2 shows photos of the KEK PPM-1 (left) and PPM-2 (right) klystrons. The main emphases of the KEK PPM-1 klystron are to test a new gun design and to study the design and manufacturing of the PPM circuit. The damping structure of parasitic modes was adapted by using the stainless steel beam pipes and the Monel cavities, and by tilting the output couplers slightly to break the symmetry in the output cavity to damp TE_{01} modes. The NdFeB magnets are used for stronger magnetic field and easier fabrication. The clamp-on type matching-coil was installed around the anode region for a smooth transition of the magnetic field from the gun to the PPM regions. No body cooling was adopted to avoid complicated geometry design for the first PPM tube. The high power testing was done successfully in 2000. It achieved the output power of 68MW with efficiency of 47%. It also produced 56MW power at standard 1.5 μs pulse length. Neither oscillation of parasitic mode nor gun oscillation was observed. The particle transmission was found to be 98% even with RF on.

Figure 2: Photo of KEK PPM klystrons, 50MW PPM-1 (right) and 75MW PPM-2 (left).

The gain cavities were mistakenly fabricated at wrong frequencies by the manufacture. It was expected to cost 2-3% on the efficiency. PPM-1 klystron was sent back to the manufacture and it was returned to KEK as PPM-1.5. Re-testing revealed that the efficiency was increased to nearly 50%. The performances of PPM-1 and PPM-1.5 are tabulated in Table 4. Due to time constraints, testing was terminated at 5Hz repetition rate, but the temperature rise in the tube body suggested that the repetition rate up to 25Hz was operational even with the present insufficient cooling system.

Table 4: Design parameters and actual values for the KEK PPM-1 and 1.5 klystrons.

KEK PPM-1 & 1.5	Year 2000-2001	
	Design	Achieved
Output power (MW)	50	67.5
Pulse length (μs)	1.5	1.5 (at 56MW)
Repetition rate (Hz)	50	5 (25Hz possible)
Efficiency (%)	50	50

3.4 KEK 75MW PPM Klystron PPM-2

After good start with the PPM-1 klystron, the first KEK 75MW PPM klystron, PPM-2, was built and tested in 2001. The main emphases of the PPM-2 klystron are full satisfaction of JLC specifications and refinement of the design and manufacturing process for future mass production. To meet these goals, the PPM-2 introduced the water-cooling system of the PPM klystron body and the PPM circuit. At the same time, the water-cooling system of the output cavity was improved for a higher repetition rate. Some revisions of resonant frequency of the penultimate cavity and design of the output coupler were also applied for a higher efficiency. The PPM-2 klystron produced 73.2MW at the 1.4 μs pulse length. Oscilloscope traces are shown in Fig. 3. At 70MW, the standard 1.5 μs pulse was attained with the efficiency of 55%. The maximum efficiency reached 56% at the specified cathode voltage. The performance of PPM-2 klystron is tabulated in Table 5.

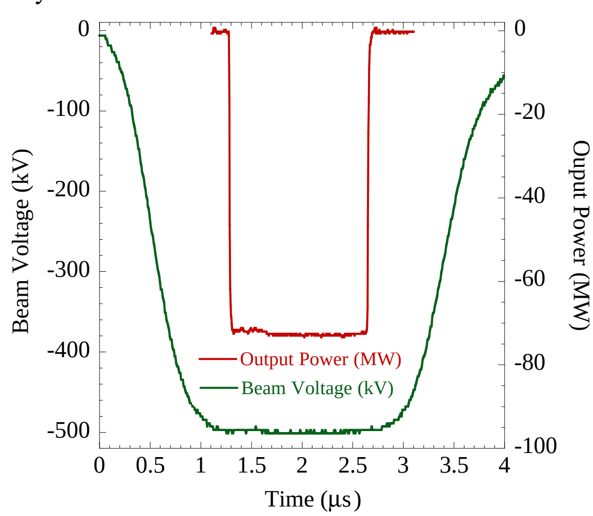

Figure 3: Oscilloscope traces of the output power and beam voltage of PPM-2 klystron for 73.2MW output power at the 1.4 μs pulse length with 54% efficiency.

Table 5: Design parameters and actual values for the KEK PPM-2 klystron.

KEK PPM-2	Year 2001	
	Design	Achieved
Output power (MW)	75	75.1
Pulse length (μs)	1.5	1.5 (@70MW) 1.4 (@73.2MW)
Repetition rate (Hz)	150	25
Efficiency (%)	55	56

Due to time constraints and the failure of the pulse transformer, the testing was forced to terminate when these performance was achieved. In respect of output power, efficiency and pulse length, the PPM-2 tube almost achieved its goals. Testing has been generally limited to 25Hz repetition rates because of the simple cooling systems employed in this prototype design. The operation at a higher repetition rate remained to be a challenge for the next PPM tube, PPM-3.

3.5 KEK 75MW PPM Klystron PPM-3

Following the success of those two klystrons, the development plan was expanded to the next two years. In FY 2001, the PPM-3 klystron was built and high power tested. The main goal of this klystron was to achieve the high repetition operation (limited to 50Hz by the specification of the modulator) to prove that the PPM klystron is ready for use at JLC. For this end, the refining and remodelling of the water-cooling system and the RF windows were made. Two 2^{nd}-harmonic cavities were also installed to increase the efficiency. Before the testing was terminated in July 2002 due to the window failure, the output power of 65MW was attained at 1.5μs pulse length with 53% efficiency. The repetition rate was 50Hz.

Table 6: Testing results of the PPM-3 klystron.

KEK PPM-3	Year 2002	
	Design	Achieved
Output power (MW)	75	65
Pulse length (μs)	1.5	1.5
Repetition rate (Hz)	150	50
Efficiency (%)	55	53

The quest for higher efficiency was temporarily rested at 56% and efforts were directed toward operation at 150Hz repetition rate. The PPM-4 klystron, a mass production version with improved cooling system, was built in 2002 and high power testing is under way since March 2003.

3.6 SLAC75MW PPM Klystron 75XP-3

A lower-cost design of 75MW PPM klystron, known as DFM (Design For Manufacture) klystron or 75XP-3, was built at SLAC in 2002, one by SLAC (XP3-1) and another by CPI (XP3-2). Figure 4 shows the photo of "naked" (without the PPM magnets) XP3-1. This tube design was intended to address the lessons learned so far, while pushing for full duty operation with a lower cost, simplified design. The klystron design is very similar to that of the 75XP-1 with refinements to reduce part count, complexity, size and cost. The electron gun was simplified with critical alignment accomplished through precision part machining, eliminating many complex adjustment features found in other SLAC klystrons. Electrode gradients in the electron gun have been designed to be lower than the earlier tubes in an effort to improve reliability. Experience with the fabrication and operation of the prior PPM focused tubes has lead to the conclusion that the ability to test the complete magnetic circuit before tube operation is highly desirable. To accomplish this, the design of a completely separable magnetic structure was done. This structure takes the form of clamshell halves containing all the field-forming components that can be built and tested apart from the klystron vacuum envelope. Additionally, the magnet structure can be transferred to another tube and reused as the klystrons reach end of life. Simulations and a test structure have demonstrated that precise fabrication and alignment can control the transverse fields introduced by splitting the magnet structure.

The high power testing revealed the output cavity oscillation at 11.7GHz (SLAC XP3-1), and the gun arching and mysteriously low efficiency (CPI XP3-2). They severely limited the performances of these tubes as summarized in Table 7. The remodelled version, XP3-3, is now under high power testing, followed by another remodelled version XP3-4 and a totally new XP4 in 2003.

Table 7: Design parameters and actual values for the SLAC 75MW PPM klystron 75XP-3.

SLAC 75XP3	Year 2002		
	Design	Achieved	
		XP3-1	XP3-2
Output power (MW)	75	70	40
Pulse length (μs)	3.2	0.3	0.5
Repetition rate (Hz)	120	120	60
Efficiency (%)	55	55	31

Figure 4: Photo of SLAC "naked" 75XP3-1.

4 C-BAND KLYSTRON PROGRESS

The C-band klystron development started in 1996, and it also focused on the solenoid-focused klystrons initially. Three C-band solenoid-focused klystrons were designed and built, and they made steady progresses as shown in Table 8. The E3746 #3 tube achieved more than 4,000 hours of accumulated operation without major failure. Similar to the X-band solenoid-focused tubes, the solenoid power of the C-band tube reduces the net efficiency by 18%. Thus the C-band program was also turned to the development of a PPM tube since 2000.

Table 8: Design parameters and actual values for the KEK C-band solenoid-focused klystron E3746.

JLC-C E3746	Year	97	98	99
	Design	#1	#2	#3
Output Power (MW)	50	46	53	53
Pulse length (μs)	2.5	2.5	2.5	2.5
Repetition rate (Hz)	100	25	50	50
Efficiency (%)	50	42	44	47

The first C-band PPM klystron, E3747#1, was built and tested in 2000 [4]. In order to minimize the required R&D items, it was decided to upgrade the existing design of the C-band klystron (TOSHIBA E3746#3-tube, solenoid focus). The same design in the electron gun, the output cavity (travelling-wave structure) and the beam collector were used. Only the drift tube part was renewed in order to implement the PPM focusing scheme. Hot isostatic pressing (HIP) technique was applied to fabricate a magnetic circuit in a PPM klystron. The first C-band PPM klystron generated 37-MW output power at the beam voltage of 350-kV, pulse width of 2.5μs and repetition rate of 50 Hz. A parasitic oscillation was found when the gun-voltage exceeded 320-kV. The frequency of the parasitic oscillation is around 5726-MHz, which is within the gain-bandwidth. It is believed that the cause of the oscillation is the back streaming electrons from the beam collector, which supports the positive feedback of rf-signal from the output cavity to the input cavity. The second C-band PPM klystron is now under development for completion in 2003. A new PPM klystron for 70MW output power and 70% efficiency is also being planned.

Table 9: Design parameters and actual values for the first KEK C-band PPM klystron, E3747#1.

JLC-C E3747#1	Year 2000	
	Design	Achieved
Output power (MW)	50	37
Pulse length (μs)	2.5	2.5
Repetition rate (Hz)	100	50
Efficiency (%)	50	34

5 CONCLUSIONS

The development of X-band PPM klystrons has been an arduous learning process requiring much patience and foresight due to the year-long development cycle needed to produce each new version of a tube. It certainly has been a bumpier road than initially anticipated. But, many lessons have been learned in the process of getting over many difficult problems. Now we start to see that the design is finally converging. The reliability and the system integration issues will be addressed next.

6 REFERENCES

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