SLAC-PUB-13741
July 2009

X-BAND KLYSTRON DEVELOPMENT AT SLAC

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Abstract

The development of X-band klystrons at SLAC originated with the idea of building an X-band Linear Collider in the late 1980's. Since then much effort has been expended in developing a reliable X-band Power source capable of delivering >50 MW RF power in pulse widths >1.5 µs. I will report on some of the technical issues and design strategies which have led to the current SLAC klystron designs.

INTRODUCTION

The X-band klystron program at SLAC began as a result of the need of a new Linear Collider envisioned at SLAC and other Institutions. The first set of source parameters called for a 100 MW Klystron operating at 11.424 GHz. (i.e. Four times the existing SLAC Collider frequency) and was to begin with a scaling of the successful SLAC S-band Klystron, the 5045. There were naturally uncertainties and risks in this approach. Since the output power requirement for the new design was higher than the 5045 one would expect the voltage across the output cavity to be somewhat higher. Since the frequency is also 4 times higher, the output cavity gradient could be at least 4 times higher.

In addition, the proposed gun was not scaled but remained the same as the 5045. As a result, the areal beam compression became significantly higher than the 5045 due to the smaller drift tube size. Finally, the thin output window design was uncertain because of the high power being passed through it .

These were the principle issues to be investigated as the X-band Klystron design began.

One can divide the development program into three distinct series of klystrons. The XC, the XL, and the PPM series. The XC series investigated the main weaknesses in developing a Klystron, and found solutions. The XL series sought to demonstrate and "fine-tune" a reliable design. The PPM series modified this design to make it more suitable for use in a future collider. This latter program addressed cost efficiency issues and simplicity of construction

XC SERIES

The XC series began with the XC1**.** This Klystron was roughly a scaled up version of the 5045. It was a 5 cavity klystron with a single cell output cavity. It used extremely thin windows (0.8 mm) for maximum bandwidth and no ghost modes. It's basic parameters are listed in table 1. It was able to deliver 65 MW at 30-40 ns but suffered from RF breakdown at wider pulse widths[1]. In order to reduce the peak fields in the output cavity, two new klystrons were designed, the XC2 and XC3. These klystrons were similar to the XC1 except the output cavity was replaced with a pair of inductively coupled output cells. The coupling was accomplished by an iris between the two cells. In addition, after several failures of the ceramic windows, a new 3.7 mm window was employed which greatly improved reliability.[2]

Table 1. XC design Parameters

Frequency	11.424 GHz.
Pk. Output Power	100 MW
Rf Pulse Width	1 µs.
Beam Voltage	440 KV
Beam Current	520 A
Beam areal Compression	190:1
Max. Gun Surface Gradient	308 KV/cm
Cathode diameter	8.9 cm (3.5")
Focusing Field	≈ 6kG

The XC2 was able to demonstrate 72 MW output power at 100-200 ns but rf breakdown and beam erosion in the output cavities prevented reasonable performance at wider pulse widths, XC3 showed similar performance. See figure 1.

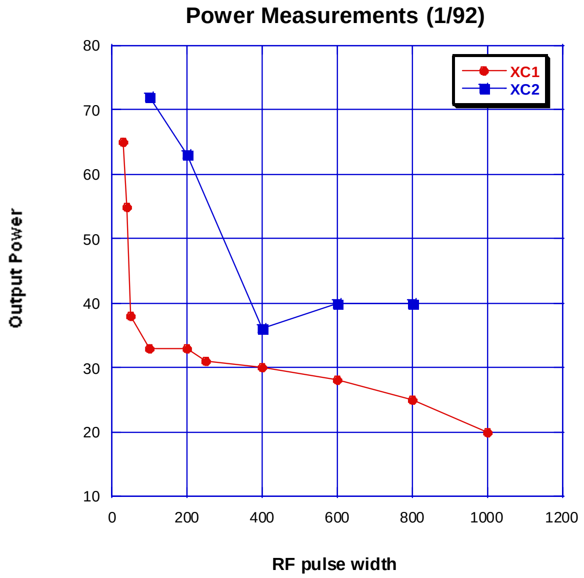


Figure 1. Measurements of XC1 and XC2

Although these klystrons were limited in output performance they were useful in testing other new components and systems proposed for the Next Linear

Invited talk presented at the 44th ICFA Advanced Beam Dynamics Workshop: X-Band RF Structure And Beam Dynamics, 12/01/2008 -- 12/04/2008, Warrington, United Kingdom

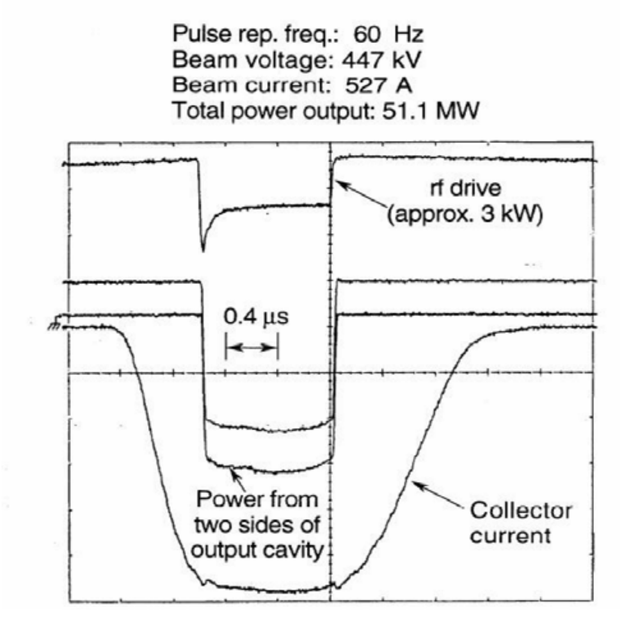
Work supported in part by US Department of Energy contract DE-AC02-76SF00515

Collider program. These include the testing and verification of pulse compression schemes and window/window coating tests.

In order to improve performance it was decided to design a new gun with a lower areal compression ratio. To verify the new design, a beam diode was built. The body of the diode consisted of 4 electrically isolated sections with decreasing drift tube diameters. The measured results showed that 0.5 % of the beam current was lost in the output tailpipe with virtually no other losses.[3] The measured perveance was 1.93 μP compared to the design of 1.90. (Microperveance may be defined as $\mu P=10^{-6}$*Amperes/Volts$^{3/2}$)

Using this new gun, XC4, was built to study RF breakdown in the output cavity. In order to reduce other sources of breakdown, the klystron was built with no windows (Loads were installed during bakeout) and with the addition of Beryllium beam scrapers to reduce beam erosion in the input and output cavities. During testing, rf breakdown occurred in the output cavity. Autopsy revealed that asymmetric breakdown occurred in the output cavity coupling iris. This result led to the redesign of the output cavity for almost all future Klystrons to incorporate either symmetric standing wave or traveling wave structures.

Two klystrons, XC5 and XC7 were built with a 4 –cell, $\pi/2$ traveling wave output structure designed using the simulation code CONDOR[4]. They successfully generated 51 MW with a 1μs pulse width. See figure 2.



Both tubes however suffered from low efficiency, ≈30% and eventually failed due to broken output windows. Gun arcs were also a problem. These results led to a markedly different Klystron design- the XL series [5]

Figure 2. XC-5 pulse shapes.

XL SERIES [6]

It was clear that the XC klystrons were limited in performance by fragile windows and excessive beam interception in the output cavity.

A more efficient, more reliable klystron could be developed if the perveance and output power were lowered and if the operating mode for the windows was changed to circular TE01 rather than theTE11 mode. One of the problems with the TE11 mode was that the electric fields crossed the ceramic/metal periphery, which often had rough, sharp edges due to a braze fillet. A new family of Klystrons was begun with the parameters shown in table 2.

Beam Voltage	440 KV
Beam Current	350 A
Peak Output Power	50 MW
RF Pulse width	1.5μs
Cathode Diameter	71.4 mm
Beam areal compression	125:1
Peak Cathode loading	12.8 A/cm2
Magnetic field	0.47 T
μPerveance	1.2

Table 2. XL Series design Parameters

A beam tester was first built to verify the new gun design.

Results of the diode tests showed that the gun had a microperveance of 1.2 and that beam transmission was 99.5%

The first tubes in this series, the XL-1and XL-2, were designed with 3 gain cavities, 3 “penultimate” or buncher cavities and a 3-cell output cavity operating in the π mode. The number of buncher cavities was increased to 3 to reduce the high penultimate cavity voltages. XL-1 showed improved performance over its XC predecessors. In the first set of tests, XL-1 was able to reach 58 MW at 250 ns. At wider pulse widths, however, a 17 GHz oscillation appeared. This could be removed by squeezing the beam to a smaller diameter. It reached its design power of 50 MW, with a 1.5 μs pulse width for a beam voltage of 413 KV. The 17 GHz. oscillation was attributed to a TE11 trapped mode in the equal gap-width penultimate cavities. This was modified in XL-2, Otherwise, XL-2 was the same as XL-1. At narrower pulse widths, 200 ns. XL-1 attained a power output of 58 MW and XL-2, 67 MW. Simulations using “CONDOR” predicted 62.5 MW.

XL3 and XL4

These tubes were designed with a 4 cell traveling wave output structure operating in the $\pi/2$ mode.

In the XL-3, some higher order instabilities were observed. To remove this problem, the last two drift tunnels in XL-4 were made from Stainless steel rather than copper**.** This resulted in a klystron which was unconditionally stable. Results of measurements of the first two XL-4 klystrons can be seen in figure 3.

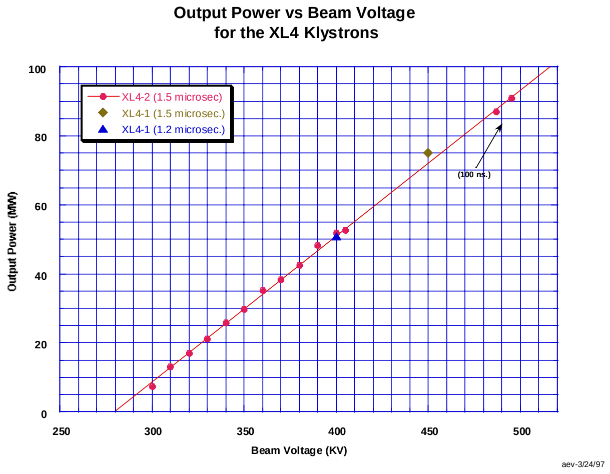


Figure 3. Output Power vs. Beam Voltage.

The XL-4 has been the workhorse of X-band tests over the last 12 years.

It has been used in:

- evaluating accelerator performance for the NLC program,
- the testing of window designs,
- generating ≈ 500 MW RF in conjunction with a SLED-II pulse compressor.
- It is currently being used to study breakdown limits on a variety of RF components. Four test stands in the Klystron Test Lab. are performing these tests. Two test stands are being used in the NLCTA.
- a 5 ½ cell RF gun Photoinjector program for several years.(2 XL-4's)
- LCLS uses one XL-4 to linearize its electron beam profile,

Thus far, 15 XL4's have been built.

PPM SERIES [7][9]

Despite the success of the XL-4 klystron, it has two characteristics that make it marginally useful for a future Collider. Its efficiency is somewhat low and its solenoid magnet requires approximately 20 kW of average power. To ameliorate these problems a klystron was developed which was focused using periodic permanent magnets and which had a lower perveance gun. The type of focusing is shown in figure 4. It consists of permanent magnets, alternating in axial field direction and sandwiched between iron pole pieces. Non-magnetic spacers are located between the pole pieces.

The first klystron, XL-PPM, in this series maintained most of the properties of the XL-4 except its perveance was lowered to 0.6 μP and the Solenoid magnet was replaced by periodic permanent magnet (PPM) focusing. Also, an extra cell was introduced into the output cavity.

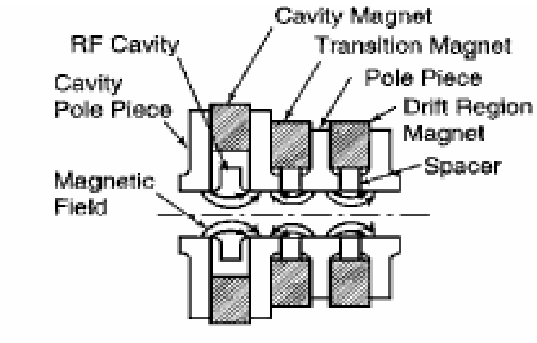


Figure 4. Periodic Permanent Magnet configuration.

To verify the new design**,** a beam diode was first built. It consisted of the new gun and 20 magnetic periods, which was approximately the number used in an actual ppm klystron. Samarium Cobalt magnets (peak fields of ≈ 3000 Gauss) were used.

It was operated up to 550 KV and had a beam transmission of ≈99.9%. It was operated for a week at 120 pps and at a beam voltage of 490 KV with the same transmission. The measured microperveance was 0.66

CONDOR was used to design the first klystron. It predicted an efficiency of 62%.

The design characteristics are the following:

- 50 MW @1.5 μs -> 2.4 μs
- Beam Voltage-464 KV
- Beam Current-190 A
- μPerveance 0.60
- Cathode Loading 7.4 A/cm2
- Integral Pole piece design-drift tube constructed from subassemblies of alternating iron pole pieces and monel spacers brazed together and then subassemblies welded together.
- In gun area, three anode magnet coils and a bucking coil were used to optimized beam minimum for best transmission.
- Output cavity magnetic field is unidirectional

The tube operated as designed, verifying the PPM capability. No oscillations were observed. The only quirk

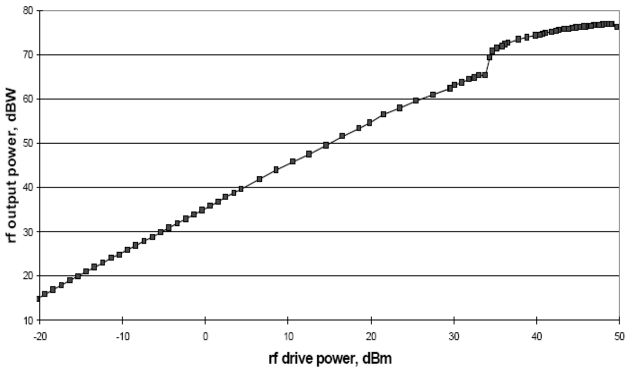


Figure 5. XL-PPM Gain Curve.

observed in its performance was some sudden changes in gain at different drive conditions. These "jumps" were attributed to multipactor in the drift tube. The tube was opened and approximately 100 A of TiN was evaporated on the drift tube from input cavity to output. This resulted in eliminating all but one of the gain jumps. This can be seen in figure 5.

Because of the success with XL-PPM, it was decided to design a higher power Klystron to reduce costs to the NLC program.

Since 500 KV modulators were available, it was determined that at least 75 MW could be generated if the perveance was raised to 0.75 µP. Simulations with CONDOR, suggested that 80 MW was possible.

Several changes were made to the PPM design.

- Drift tube was enlarged slightly because of higher beam current.
- An all stainless steel drift tube was employed. Iron Pole pieces, magnets and spacers were external to vacuum envelope. This required an additional gain cavity because of lossy SS.
- NdFeB magnets were used. NdFeB has a higher energy product, is less brittle, is less expensive in large quantities, but has a lower Curie temperature compared with Samarium Cobalt.
- Anode coils were removed from design.

The first tube, the 75XP-1 was built and tested with these changes.

During initial operation, two oscillations were observed at 1.4 and 20 GHz.

The 1.4 GHz gun oscillation was removed by adding lossy ceramics to the gun stalk and the 20 GHz. oscillation was removed using lossy ceramics in the collector near the output cavity exit. After these modifications the tube was retested and successfully reached 79 MW at 2.8 µs.

The tube was limited to 10 Hz. operation because of inadequate cooling of the tube body.

A second 75 MW tube was designed. The 75XP3 was designed with the help of simulations using the code MAGIC[8]. A representative simulation is shown in figure 6.

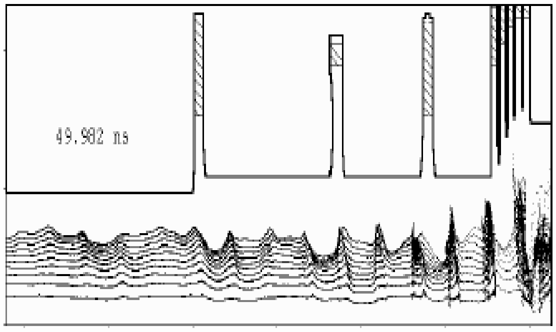


Figure 6. MAGIC simulation of 75 XP3

This was the first tube with design changes to reduce costs of manufacturing.

The major change was the introduction of "Clam-Shell" magnet assemblies. This permitted testing prior to installation on the klystron.

The "clam-Shell" design consisted of constructing two halves of a pole-piece/magnet assembly on a drift tube mandrel in aluminum housing. The components were then epoxied in position after the magnetic field profile was verified. One half of a clam-shell can be seen in figure 7.

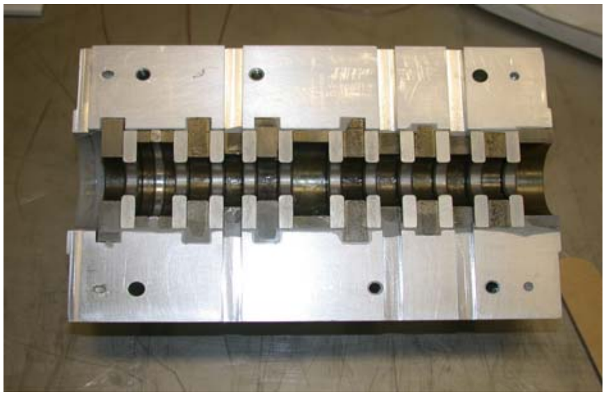


Figure 7. Section of "Clam-Shell magnet assembly

In addition, the gun design was simplified by removing alignment fixturing and using tighter tolerances.

After fixing a gun oscillation in the Beam diode, the 75XP3 was successfully tested to full power (75 MW) at 1.6 µs and 120 pps. No evidence of oscillations was observed.

Despite the success of 75XP3-3, there were still some mechanical issues to improve upon. Measurements of beam transmission showed excessive interception. In addition, It was not possible to measure magnet heating during operation using "clam-shell" design. This in fact resulted in one of the magnets overheating. Because of this, the "clam-shell" design was abandoned and an integral pole piece design was re-initiated in the 75XP3-4.

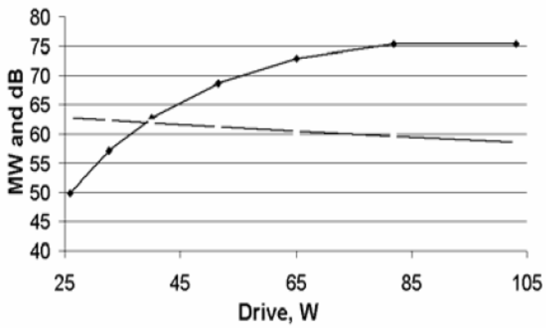


Figure 8. Gain curve of 75 XP3-4

The 75XP3-4 was operated at 506 KV and successfully delivered 75 MW at 1.6µs. repetition rate was 120pps. It was operated using air cooling rather than water cooling.

Results of measurements may be seen in figure 8.

At this point further testing ceased due to the termination of the NLC program.

CURRENT PROGRAM

A new klystron, XL-5 is currently being designed for use at other Laboratories.

It will be very similar to the XL-4 except the operating frequency will be 11.99x GHz rather than 11.424 GHz.

In addition, tests will be made to XL-4 to study its performance under a variety of mismatch conditions. (XL-4's are often used to test components which can have considerable reflected RF power)

ACKNOWLEDGEMENTS

It should be obvious that many people played roles in Klystron development at SLAC. Chief among these are:
Ed Wright, Sami Tantawi, Daryl Sprehn, Richard Schumacher, Chris Pearson, Terry Lee, Erik Jongewaard, Andrew Haase, W.R. Fowkes, Ken Eppley, George Caryotakis, Richard Callin

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