SLAC-PUB-10159
September 2003

# SLAC RF Source Research at X-Band

D. Sprehn

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

## Abstract

X-band klystrons capable of 75 MW and utilizing either solenoidal or Periodic Permanent Magnet (PPM) focusing are undergoing design, fabrication and testing at the Stanford Linear Accelerator Center (SLAC). The klystron development is part of an effort to realize components necessary for the construction of the Next Linear Collider (NLC). SLAC has developed a solenoidal-focused X-band klystron which is currently the workhorse of high power component testing for the NLC. A state-of-the-art modulator will drive eight of these tubes which, in turn, will power an rf distribution system referred to as the "8-pack" in order to test these modulators and waveguide components. Eventually, in an interest to save millions of dollars per year in the operational cost of the NLC, these tubes will be replaced by PPM klystrons. The PPM devices built to date which fit this class of operation consist of a variety of 50 MW and 75 MW devices constructed by SLAC, KEK (Tsukuba, Japan ), and industry. These tubes follow from the successful 50 MW PPM design of 1996. Recent testing of this particular tube at wider pulsewidths has reached 50 MW at 55 % efficiency, 2.4 μs and 60 Hz. Two 50 MW PPM klystrons produced by industry have been delivered to SLAC. One of these devices arrived with a vacuum suitable for test. Testing during 2001 revealed a serious, but curious, vacuum response which limited the operation to an rf output of ~40 MW. A 75 MW PPM klystron prototype was first constructed in 1997 and later modified in 1999 to eliminate oscillations. This tube has reached the NLC design target of 75 MW at 1.5 μs though at a significantly reduced rep rate. Two new 75 MW PPM klystrons were constructed and tested in 2002 after a diode was successfully tested in 2001. The new design was aimed at reducing the cost and increasing the reliability of such high-energy devices. The rf circuit and beam focusing for one of these devices was built by industry and incorporated into one of the tubes. Both of these latest devices suffered from a variety of issues concerning gun stability, beam confinement and rf stability. A rebuilt version of this latest design was constructed in early 2003 and completed testing in June. The performance of these various klystrons, particularly during 2002 and 2003, will be presented along with results of studies pertinent to their construction. Design and manufacturing issues of the various klystrons are discussed, along with plans for future modifications and areas of research.

*Presented at the Sixth Workshop on High Energy Density and High Power RF (RF2003) June 22 - June 26 Berkeley Springs, West Virginia*

This work is supported by the Department of Energy under Contract DE-AC03-76SF00515.

# INTRODUCTION

For over a decade X-band research at the Stanford Linear Accelerator Center (SLAC) has been attempting to discern a workable machine technology for achieving TeV-level energies in an electron-positron accelerator known as the Next Linear Collider (NLC). The ~TeV energy is required in order to perform experiments at the frontiers of particle physics. This design consists of room-temperature accelerator cavities, storage rings, pulse modulators, a suitable rf distribution system and ~100 MW-level rf vacuum tubes. Around the world are competing ideas with alternate machine technologies but the X-band effort is currently fixed on the preceding approach.

The rf sources consist of microwave tubes operating at <100 MW and >1μs along with an rf pulse-compression and distribution scheme which results in higher peak powers (100's of MW) and shorter pulses (~100ns range). The exact numbers have been fluid as various technologies are attempted and evaluated for cost, performance and reliability. The tube effort [1], after a foray into cross-field devices and "relativistic klystrons", has settled on the conventional klystron as the basic unit of power. Klystron designs have been considered in some detail and consist of "conventional" solenoid, Periodic Permanent Magnet (PPM), multi-beam, and even sheet beam designs. The specification for the klystron has, for instance, been 50 MW for 1200 ns with SLED II Pulse Compression. The specification later changed to 75 MW for 1525 ns for Single-Mode X 4 DLDS Pulse Compression and was followed by a specification for 75 MW for 3050 ns for Dual-Mode X 8 DLDS Pulse Compression. The most recent specification is shown in Table 1.

**TABLE 1.** June 2003 X-band klystron specifications

| | | |
|---|---|---|
| Peak power | 75 | MW |
| Pulselength | 1.6 | Microseconds |
| Rep Rate | 120 | Hz |
| Gain | 55 | dB |
| Efficiency | 55 | % |
| Bandwidth | 100 | MHz |
| Stability | 2 | Breakup/hour |

## Previous X-Band Klystrons

The main effort of SLAC research in these klystrons has been single-beam solenoid and PPM focused designs. After the brief development using induction linac drivers and X-band "relativistic klystron" technology, the first in a series of conventional solenoid-focused tubes known as the XC-series [2] were created in 1990. The XC's were designed for 100 MW at 800 ns. Gun and window breakdown, internal cavity damage, and rf extraction were some of the major difficulties encountered with these tubes. Five years later, in 1995, the first XL-series klystron was tested. The XL's were designed for 50 MW and 1500 ns. The reason for this 3dB drop in the output power was due to the difficulties encountered during the XC development. A little over a year into the XL program, the first XL4 klystron was constructed and tested.

Fourteen of these devices have been produced to date and are the backbone of X-band component development testing at SLAC. The success of these devices is due not only to the reduced power goal, but an improved gun, improved TE01 window, a better understanding of the rf circuit and a multiple-gap traveling-wave output structure. As a result of these improvements some XL klystrons eventually were tested to >70 MW at 1.5μs and 90 MW at 0.1μs to demonstrate engineering overhead.

At the time of the XL development, a program to produce a PPM-version of the XL device was initiated [3]. The same year that the XL4 was tested, the first PPM device also came on test. The high area convergence (120) of the gun coupled with the PPM beam-transport issues led many to believe that such a device was not possible. No other successful attempts of such a high power PPM device had ever been documented in the literature. The design does not allow for tuning the beam-transport during operation and the total magnetic field confinement is considerably less than that of the XL klystrons. Detailed simulations of the transport and beam interaction, an adjustable gun coil assembly, attention to tolerances and inspection of components were strictly relied upon as the only controls over tube performance. Fortunately, after coating the inside of the drift tube to eliminate multipactor, this device was able to operate beyond the existing specification. Stability, average power, peak power and breakdown were not issues in this first high-power PPM X-band klystron.

A program to look at 75 MW PPM devices was begun in 1997 to investigate technological limitations. Late into this effort known as the XP1 program, and into the subsequent XP3 program, the specified pulselength was increased and eventually reached 2.82 μs. After constructing an XP1 device and making repairs over a two-year period, the new 75 MW and 2.82 μs specification was reached. Due to a lack of any cooling on the drift tube, the XP1 had limitations with average power and a new design known as the XP3 was implemented to address this issue and questions concerning manufacturability. The first XP3 klystron was tested in October 2001. Recent testing of the latest XP3 has reached the full NLC specification as listed in the preceding table except for the final stability criterion. A new design, known as the XP4, will be constructed early next year to address this stability issue. Both of these latest devices will be discussed in more detail.

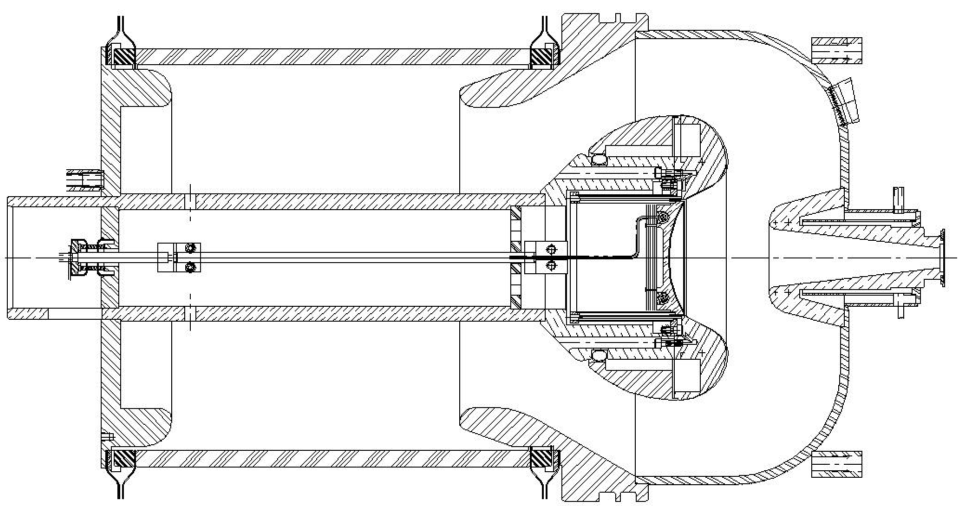

**Figure 1.** Electron gun outline as implemented in the XP3 klystron devices.

## XP3 DESIGN AND TESTING

The XP3 design is a 490 kV gun operating at 260 A with an area convergence less than 100. This gun is designed for a 1.6 μs beam pulse and uses the minimum electrode sizes possible while still maintaining the gradient limitations known for this class of device. As seen in Fig. 1, special shaping of the upper and lower electrodes of the main ceramic seal is used to isolate triple-point junctions from strong electric fields. The focus electrode gradient is restricted to 200 kV/cm. The construction eliminates many of the parts normally encountered in SLAC klystron guns.

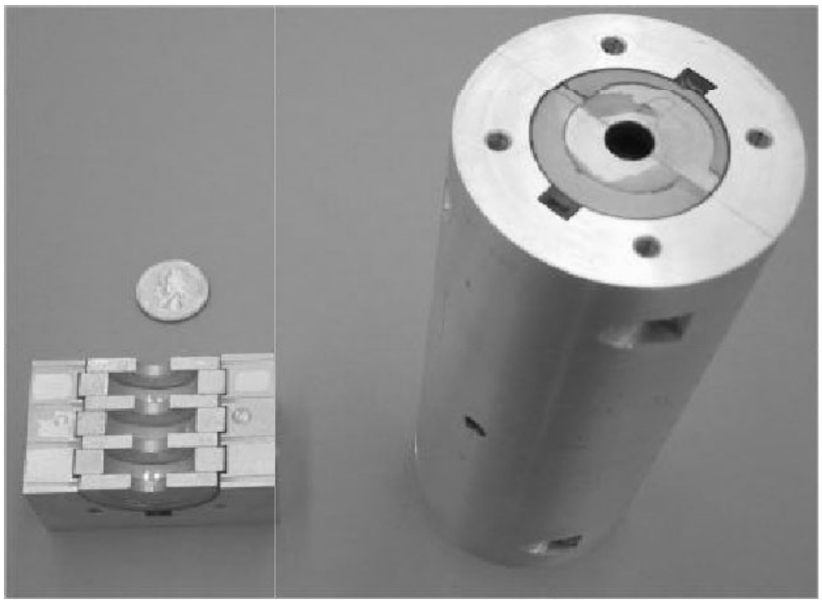

**Figure 2.** Sample clamp-on magnet showing magnets and pole pieces attached with epoxy into a water-cooled aluminum housing.

Other changes from previous X-band klystrons include an integrated gun coil assembly, a stepped drift tube diameter and a new output mode converter design. The most significant change is represented in Fig. 2 where a "clamp-on" magnet assembly is shown. The clamp-on contains all pole pieces and magnets whereas the klystron contains the drift tube punctuated by rf cavities. This form of construction enables testing of the magnet stack separately from the tube and the possibility of using the stack on different tubes once the original tube has reached the end of its useful life. There are several engineering challenges which make the clamp-on design a risky venture such as the uneven drive of the split pole pieces and alignment issues concerning the two halves. One must have excellent quality control at the component level prior to assembly as the clamp-on components are cemented together with epoxy and cannot easily be unmade.

## Initial XP3 Tests

A diode was first constructed which suffered from a trapped mode that coupled strongly to the electron beam traversing the anode gap. After slipping a ceramic collar onto the gun stem this oscillation was suppressed and the device tested to full power at 120 Hz for one week. Beam interception was less than 0.1 % as indicated by a calorimetric measurement. Pulsed operation of the device at full duty and without rf bunching on the beam was successful however this diode did not use a clamp-on structure. Though the magnetic field profile was made to approximate the XP3 klystron design the field was created using prior technology where pole pieces were brazed to a stainless steel drift tube. In this respect the diode did not qualify the clamp-on technology.

The first XP3 tube (XP3-1) suffered from an oscillation in the output structure and did not attain full power operation. This oscillation was actually well-known but an oversight in fabrication led to the misplacement of a reflective loss cavity designed to load the offending mode to a safe level. Testing later that year with the XP3-2 klystron resulted in a gun oscillation and an eventual gun arc that damaged the ceramic gun seal. The gun oscillation was attributed to the change in loss material on the gun stem from the XP3-1 and diode materials. The gun arc occurred while operating the gun at 3.2 μs, which is double the design pulsewidth for the gun. In addition, both the XP3-1 and XP3-2 klystrons had beam transmission issues. Whether these issues were from the split pole pieces and clamp-on alignment was impossible to discern. Since any quick-turnaround rebuild would have to use one of the existing clamp-on structures the only possible change would be to replace the split gun pole pieces to alter the transmission. Each of these issues, except for the clamp-on issue, could be dealt with rapidly in a rebuild version of these tubes. Fortunately there were enough parts between the two tubes to rebuild them into a new klystron dubbed the XP3-3.

## XP3-3 Tests

The XP3-3 used the same gun, collector and waveguide design from the XP3-1 and XP3-2 klystrons and many of the same parts. To fix the gun oscillation, the loss ceramic from the XP3-1 was used. To eliminate the possibility of gun arcs, a 1.6 μs pulsewidth limitation was enacted. This 1.6 μs pulsewidth was the original specification for the design. To eliminate the possibility of an output oscillation, the loss cavity on the output waveguide was moved to the correct location and the penultimate cavities were retuned to reduce gain near the troublesome mode. In an attempt to improve the beam transmission, a continuous rather than split pole piece was used at the beam entrance. Upon testing of the klystron in June of 2003 some rf breakup of the output pulse was noted but full power operation was reached. Thus all of the NLC klystron specification was reached except for the stability criterion. While the stability criterion is extremely important it is the first time that both peak and average power specifications have been met in the NLC klystron specification.

## The Next XP3 Design: XP3-IPP

In an attempt to help stabilize the rf output pulse, the XP3-3 klystron is undergoing reassembly with a spring located in a suspected weld-flange joint to short out possible arcs. That a small arc is responsible for the XP3-3 rf breakup is somewhat unlikely and a new version of the XP3 is under construction which will address the suspected root cause. There is reason to believe that the beam quality with the existing clamp-on configuration is insufficient. This poor transmission is responsible for too much interception during rf bunching conditions and leads to breakup of the rf pulse. To address this issue we will construct an XP3 which differs from previous XP3's only in that the clamp-on structure will be brazed to the drift tube and none of the pole pieces will be split. This type of construction is known as an Integral Pole Piece (IPP) construction and has previously been used on our 50 MW PPM, the XP1 klystron and the XP3 diode designs. Thus we are returning to a design scheme which existed prior to the implementation of the clamp-on structures. The XP3-IPP will be the same as the previous XP3-3 except for the magnet circuit implementation, a slight change to some cavity radii to reduce gradients, and springs in all the possible arc locations.

## After the XP3 Series

The clamp-on structure designs of the XP3 series have been an interesting sideshow in the quest for an NLC klystron. We may see a return of them in the near future but the current effort will be focused on IPP designs for several reasons. The most important reason is that the NLC klystron is a research effort and as such should have a variability of the beam focusing scheme. The clamp-on system locks the design geometry well before the geometry is tested adequately. Secondly, our ability to diagnose any problems is made easier with access to the pole pieces and magnets. One can look for X-rays, acoustic signals, and thermal effects with an enhanced efficiency in an IPP design, and can alter the shape and strength of the magnetic field to test simulation quality.

To move far away from any chance of gun arcing and oscillations, a larger gun housing will be used. Since this housing was previously used on the 50 MW PPM and the XP1, it is an inexpensive solution to attain engineering overhead on the gun. Along with the new gun will come a new coil design and a new magnetic stack design. This new stack will use a much simpler PPM implementation than either the XP1 or XP3 with fewer magnets and magnet strengths. With all these changes the new tube will be called the XP4 klystron. One may notice that this new klystron is somewhat of a hybrid between the XP1 and the XP3 and indeed was originally conceptualized as such well before the design of the XP3 began. Note that an XP2 klystron was never built and was cut for budgetary constraints.

## CONCLUSION

It is believed that the XP3-IPP klystron will help us answer whether the rf output stability is one of beam interception due to poor beam quality or not. Experience with the 50 MW and XP1 PPM devices indicates that a good beam allows for saturated operation without rf breakdown. With a more robust and versatile design, it is hoped that the XP4 design will be able to operate at the full specification for an extended period of time, supply some hints concerning lifetime issues, and be a useful device to instrument and study. We are reasonably sure that the NLC klystron specification is attainable in a reasonably long-lived device but there is no example in industry to support this claim. Only with sufficient engineering overhead will we be able to have the confidence to submit such a design for high-volume production.

## ACKNOWLEDGMENTS

Over one hundred individuals have made contributions in the design, fabrication, assembly, processing and testing of these devices. The majority of these individuals are still within the klystron department at SLAC. The author's own work primarily centered on the PPM devices. Many of the personnel involved with the XC and XL klystron development have since retired from or left SLAC. It is impossible to list and sort these personnel in any reasonable order to do them justice. Special credit should go to Dr. George Caryotakis for his knowledge, perseverance and guidance in linear-beam technology, Robert M. Phillips for his championing of and knowledge of PPM technology, and Chris Pearson for his knowledge and management of the mechanical design and fabrication of SLAC klystrons. This work is supported by the Department of Energy under Contract DE-AC03-76SF00515.

## REFERENCES

1. W.R. Fowkes *et al*., "RF Power Generation for Future Linear Colliders" Presented at BEAMS '90' 8th Int. Conf. on High Power Particle Beams, Novosibirsk, USSR, Jul 2-5, 1990. SLAC-PUB-5282.
2. A.E. Vlieks *et al*., "100-MW Klystron Development at SLAC" Contributed to IEEE Particle Accelerator Conf., San Francisco, CA, May 6-9, 1991. Published in Particle Accel. Conf: IEEE 1991:0798-800. SLAC-PUB-5480.
3. D. Sprehn *et al*., "X Band Klystron Development at the Stanford Linear Accelerator Center" Presented at 7th SPIE Microwave Intense Pulses, Orlando, Florida, 24-26 Apr 2000. Published in Proc. SPIE Int. Soc. Opt. Eng. 4031:132-143,2000. SLAC-PUB-8346, Mar 2000.