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D. Sprehn, G. Caryotakis, E. Jongewaard, R. M. Phillips, and A. Vlieks

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

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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 completed a solenoidal-focused X-band klystron development effort to study the design and operation of tubes with beam microperveances of 1.2. As of early 2000, nine 1.2 μK klystrons have been tested to 50 MW at 1.5 μs. The first 50 MW PPM klystron, constructed in 1996, was designed with a 0.6 μK beam at 465 kV and uses a 5-cell traveling-wave output structure. Recent testing of this tube at wider pulsewidths has reached 50 MW at 55 % efficiency, 2.4 μs and 60 Hz. A 75 MW PPM klystron prototype was constructed in 1998 and has reached the NLC design target of 75 MW at 1.5 μs. A new 75 MW PPM klystron design, which is aimed at reducing the cost and increasing the reliability of multi-megawatt PPM klystrons, is under investigation. The tube is scheduled for testing during early 2001.

Keywords: Klystron, PPM, NLC.

1. INITIAL KLYSTRON DEVELOPMENT PROGRAM

The X-band klystron program at SLAC began with a series of 100 MW klystrons with 1.8 μK gun designs. After several years and 6 tubes tested, it was determined that the peak power requirement was too aggressive for the existing technology. New techniques for coupling the rf power, a more conservative gun design and improved windows were some of the items in need of address. A new klystron parameter set, denoted as the XL series, was adopted which called for a peak power of 50 MW and a 1.2 μK gun design for increased efficiency. A new TE01 window design, the addition of an ion pump located at the gun, lower gun gradients and lower gradients in the output structure were also implemented. Both standing-wave and travelling-wave output structures were tested on four XL klystron designs. A klystron design designated as the XL-4 was chosen for limited production due to its superior performance. The XL-4 has a 1.2 μK beam in a 0.375" diameter drift tube with 6 cavities and a 4-cell traveling-wave output structure. To date, nine XL-4 klystrons have been fabricated and operated for a total of approximately 10,000 hours of use. The klystrons have operated from 50 MW at 2.4 μs up to 75 MW at 1.5 μs. The klystrons are currently being used in the NLC Test Accelerator and the Accelerator Structure Test Area (ASTA) as workhorses of the X-band accelerator and component development programs.

2. PPM DEVELOPMENT PROGRAM

To eliminate the large solenoids in high power klystrons in NLC project, which would add substantial operational cost savings of 10's of millions of dollars per year, an investigation into Periodic Permanent Magnet (PPM) focusing was begun. PPM focusing is utilized on thousands of Traveling-Wave Tube (TWT) devices for commercial and military applications. Instead of a solenoidal magnet with its associated overhead of power supply, cooling, and controls, permanent magnets can be used to reduce operational cost and weight. In the PPM scheme, the axial field changes polarity with every magnet. If the axial magnetic period is small enough compared to the plasma wavelength of the beam, then the beam will be focused with sufficient stiffness to maintain the beam profile in the presence of large space charge forces due to the rf bunching. The rms value of the PPM field on axis is used in the same way that the axial field value is used in solenoidal focusing.

The drawback with PPM focusing is that the construction complexity of the tube may be increased, as is the amount of handling of the assembly in preparation for operation, such that construction costs and failure rates could rise. The magnetic circuit is also fixed and so there is no easily accessible "knob" for the operator to turn in case adjustment is desired except perhaps for a gun coil to alter the cathode flux and control beam size. As previously mentioned, the magnet period must be small compared to the plasma wavelength and since the wavelength reduces as beam voltage is reduced then there exists some level of beam voltage where the magnet period appears large to the beam. Eventually the beam follows the flux lines and impacts into the drift tube and transmission is stopped. This is known as the "stop-band" voltage. Since the high voltage beam pulse has a finite rise and fall time, then part of the edges of the beam pulse are below the stop-band and interception will occur. There also exist areas of instability in PPM beam optics and also possibilities of coupling to modes which grow from an undulating beam. Due to the high energy densities required for the magnets combined with geometrical constraints it is usually not possible to thread as much flux through the cathode as it is with solenoidal focusing. With less field at the cathode and the inability to adjust the field after construction, particular attention must be paid to the gun design and beam transport issues.

The program initially called for the construction of two devices and added a third device after the success of the 50 MW klystron and an altering of accelerator parameters. When testing of the 75 MW device revealed weaknesses in the design an improved design was begun. Since this new design has radically different manufacturing technology and optics, two diodes will be built to test the optics and technology only. These diodes, currently under construction, will compare beam transmission and manufacturing details of the improved 75 MW klystron and will also be used as loads for modulator testing. These new designs, originally designated as Design For Manufacture (DFM), have reduced the parts counts and complexity where possible. The improved 75 MW klystron is scheduled (Table 1) to begin testing in 2001.

Device type	**Goal**	**Test date**
465 kV, 0.6 μK full-scale beam-stick	Test focusing	complete
465 kV, 0.6 μK 50 MW klystron	Test rf	complete
490 kV, 0.75 μK 75 MW klystron (75XP-1)	Higher power	complete
Two 490 kV, 0.75 μK beam-sticks	Test DFM and focusing	Mid 2000
490 kV, 0.75 μK 75 MW klystron (75XP-3)	Test DFM rf	Early 2001

Table 1: Completed and ongoing components of the X-Band PPM effort .

The drift tube and cavity design for the beam-stick and first klystron were patterned from the success of the 50 MW solenoidal focused XL-4 klystron. The perveance was dropped from 1.2 μK to 0.6 μK to increase the efficiency from 50 % to 60 % and increase the plasma wavelength which consequentially makes PPM focusing easier to achieve. The increased efficiency will also save 17 % in operational energy costs of the electron beam. Other factors were considered in choosing the beam microperveance such as reasonable beam voltages, available power, and magnetic field strengths. With a perveance too low the beam voltage becomes unmanageable and so a value of 0.6 μK was settled on for the first diode and klystron.

The 75 MW klystron design 75XP-1 called for an increase in perveance to 0.75 μK in order to increase the total power output without raising the beam voltage beyond 500 kV. As the beam voltage is increased the modulator and electron gun design becomes complicated and the associated costs rise due to the large volumes and electrode sizes involved. But raising the voltage also decreases the perveance and, for a given desired output power, increases the attainable efficiency. The chosen 0.75 μK was a trade-off for this design.

The two DFM beam-sticks, compared to the 75XP-1, have improved beam confinement, collector and gun designs. Coils at the beam entrance are used and the peak axial field variation has been reduced. The gun is smaller, contains fewer parts, and has lower overall gradients than previous designs. The 75XP-3 uses the same gun and collector as the beam-sticks and uses an rf circuit very similar to the 75XP-1 with slight changes to the output circuit and cavity spacings.

3. A 50 MW KLYSTRON PROGRAM

In order to achieve 50 MW with an assumed efficiency of 56.6% (from simulation), an 88 MW DC beam is required. At 0.6 μK the beam operates at 464 kV and 190 A into a 0.375" tunnel with a 50 % fill factor. In order to keep the cathode current density below an average value of 7.5 A/cm^2, a 2.25" diameter cathode is required which yields an area convergence ratio of 144:1. This value is deemed high for most high power work and led to the conclusion that a beam-stick should be produced to verify gun and drift region optics for the PPM design. The beam-stick (Table 2.) should be robust, operate beyond the expected klystron design parameters, and yield data concerning the beam transport issues without interference from possible gun or collector problems.

The design philosophy of the beam-stick was to eliminate common sources of trouble which could interfere with the study of beam formation and transmission such as voltage breakdown, insufficient vacuum pumping, collector issues, and to allow for testing with both zero and partial flux through the cathode. To accomplish this, many of the parts utilized existing components which served to hasten the program and allowed for operation at higher voltages than the design requires which may prove useful in future research on more powerful PPM designs. Specifically, the gun housing, ceramic, and collector all came from a prior program which allowed operation in excess of 500 kV at more than three times the PPM design current. Furthermore, it was decided not to give up completely on maintaining a focusing "knob" to turn in case of trouble. The field at the gun is controlled by a standard bucking coil and the field in the region from the gun to the beam minimum is controlled by three compact coils closely wound around the drift tube. The same general philosophy and beam focusing is found on the 50 MW PPM klystron.

Beam voltage	464 kV
Beam current	190 A
Beam pulsewidth	1.5 μs
Cathode loading	7.4 A/cm^2 Ave., (8.5 peak)
Cathode convergence	144:1 (2.25" ∅)
RMS focusing field:	
Shielded flow	1690 gauss (Brillouin)
Confined flow	1950 gauss (1.15*Br)
Max rep rate	120 Hz
Max average collector Power	< 60 kW

Table 2. Design parameters for the PPM beam-stick

The beam-tester processing began with a 1 μs beam pulsewidth and proceeded up to 490 kV, 5 % above the design parameters, without incident. The beam microperveance was found to be 12 % higher than the design of 0.6 μK. To improve the reliability of beam transmission data, the pulse width was extended to 2.8 μs and the repetition rate increased to 120 Hz. At 490 kV there was roughly 42 kW dissipated in the collector. The beam transmission at this point was found to be 99.9 %. This rather striking result is in direct contrast to experience with travelling-wave tubes (TWT) which traditionally are operated on a bench with iron shunts placed along the magnetic circuit to improve transmission. Adjustments are not possible with the beam-stick as most of the tube is covered in lead due to several kRads of radiation from the collector.

There were no instabilities or spurious oscillations arising from noise detected at a 2.8 μs pulsewidth. No gas pressure rise other than that considered normal was detected and the collector vac-ion pump was running at about 10^{-8} Torr under full power and rep rate. With a design goal for the klystron of 1.5 μs and 465 kV, the operation of the beam-tester exceeded expectations and demonstrated robustness. The 490 kV level is also required for the 75 MW X-band klystron discussed in section 4.

3.1. A 50 MW klystron design

The PPM klystron, with its lower perveance, lossy materials in the rf circuit, and higher operating voltage will require modifications from the existing XL-4 rf circuit design. For the prototype tube (Table 3) not all the specifications for the NLC klystron such as bandwidth or gain etc. are immediately required; however, the major milestones of 50 MW at 1.5 μs with reasonable efficiency and beam transmission are foremost.

The rf circuit is adapted to the lower perveance and higher voltage beam by increasing the cavity spacing, altering cavity tunings, and adding an extra cell in the traveling-wave output structure for a total of 5 cells. The number of cavities was kept constant and in order to maintain the required gain, the bandwidth was made more narrow than in the XL-4. The loss in gain between the two designs is primarily influenced by the lossy materials used in the PPM design. The drift tube, as in the beam-stick, is made of alternating iron pole pieces and cupronickel spacers except that some of the spacers have cavities machined into them. These cavities have a lower Q_o than copper cavities and suffer more from rf heating. The lossy drift tube material may dampen any trapped oscillations and reduce any coupling between the gun, cavities and collector.

The magnetic field is relatively constant in amplitude up to the last three cavities where it gradually tapers to a peak in the output structure. The tapering confines the beam as space charge forces on the beam increase due to the growing rf current. The field in the output structure is unidirectional, unlike the rest of the klystron where it is periodic, and this forces the magnets to be physically larger than elsewhere. Designs were attempted to continue the periodic field through the output structure or use harmonically related field profiles without complete field reversals but neither of these have proved satisfactory. Instead, the field is modified by the presence of two iron rings inside the output magnet inner diameters, and by several individual magnets with various strengths and sizes. Different magnetic field profiles and focusing schemes will be further investigated on future designs.

The cavity gradients found in this design are no higher than in the current XL-4 klystrons, and the gun gradients and collector power densities are lower. Output hardware such as waveguides, couplers, mode converters (to TE01 for window transmission), windows and loads are all of proven design. The PPM design has two output waveguides which are not combined, differing from the XL-4, which operate at lower gradients and power levels than the XL-4 klystron. The purpose of the klystron test was to verify the beam containment in the presence of large rf bunching forces thus other possible failure modes have been reduced as much as possible in.

RF Pulsewidth @ rep rate	1.5 µs @ 120 Hz
RF output power	50 MW
Saturated gain	~ 55 dB
Bandwidth	110 MHz
Efficiency	~ 55 %
Operating frequency	11424 MHz
Max gradients:	
Cavities	< 700 kV/cm
Anode	< 250 kV/cm
Focus electrode	< 220 kV/cm
RMS focusing field:	
Shielded flow	1690 gauss (Brillouin)
Confined flow	1953 gauss (1.15*Br)

Table 3. Design parameters for the 50 MW PPM klystron

Simulation of the klystron design using CONDOR[1] gives an efficiency of 63 % at 55 MW at the full beam voltage of 465 kV. The lowest electron energy levels for electrons at the output are approximately 9 % of the average initial energies and should not reflect in large numbers back down the drift tube. One of the advantages of a PPM klystron is that the transmission stop bands provide a desirable service at the output by stopping any low energy reflected electrons. One of the disadvantages became apparent during simulation as the efficiency and output structure interception were found to be sensitive to the field strength of the magnets immediately preceding the output structure. Tight specifications of the magnets are necessary since while in operation the magnets cannot be varied without turning off the klystron and physically replacing them. Comparisons of the simulated and actual PPM stacks showed that the individual axial magnetic field peaks fell within ±2 % of the design goal, and transverse field strengths averaged about 0.2% of the axial strength. Accurate measurement of the fields has proven quite problematic and an automated computer-controlled 3-D measurement stand has recently been constructed to alleviate measurement error.

Output power and efficiency data at saturation were collected at a 200 ns pulsewidth to avoid breakdown at the higher power levels in excess of 60 MW. At the design current of 190 A, (at 426 kV), the output power and efficiency are approximately 50 MW and 60 % respectively. The perveance of the gun as constructed was 10 % too high and consequently the design voltage and current were not coincident. At the design voltage the efficiency appears to have reached a maximum and perhaps is falling. It appears that the efficiency peak may lie somewhere between the design current value and the design voltage as expected. Also, by turning off the gun focus coils in the beam convergence region, it is possible to gain an incremental improvement in power and efficiency. The power increase is due to a slightly larger beam which in turn increases the interception at the beam pulse edges and probably would reduce klystron lifetime. Despite the initial encouraging results, the operation of the klystron was plagued by what appeared to be multipactor distributed along the tube which would manifest itself by large jumps in gain while the rf drive was increased.

3.2. Testing of the rebuilt 50 MW klystron

To eliminate the jumps in the gain curve, the klystron was opened and the inside of the drift tube coated with a titanium-nitride (TiN) layer roughly 100 Å thick from the input cavity to the output structure. The TiN coating was utilized to reduce the secondary emission coefficient of the surfaces subject to rf fields in the vacuum. After a standard bake, the 50 MW PPM was again processed up to the full specification of 50 MW at 1.5 µs rf pulsewidth. The three main "multipactor" gain steps were replaced by a single step from approximately 3 MW to 10 MW (Fig. 1) which allowed for smoother operation at higher power levels. The location of the step with rf drive appears completely independent of beam voltage and it is hypothesized that the step is due to multipactor at the input cavity. Careful measurements in this series of tests over a 70 dB range of rf drive power shows the small signal gain to be 65 dB, falling by 10 dB at the 50 MW power level.

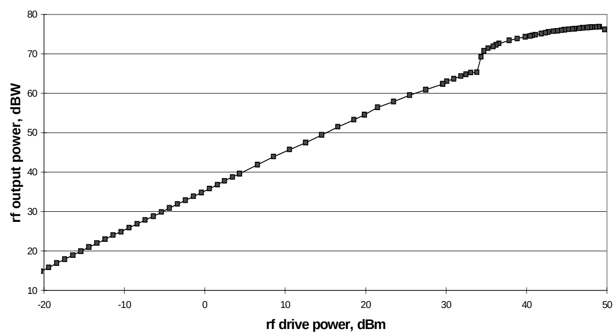

Figure 1. Power output in dBW versus drive power in dBm for the TiN-coated 50 MW PPM klystron operated just below the design current of 190 A (414 kV @ 183 A)

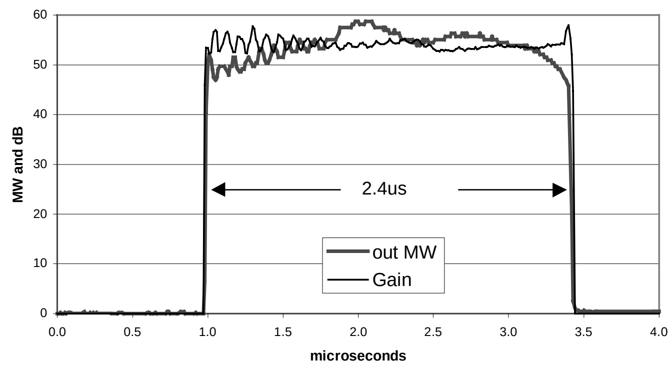

Figure 2. Gain (dB) and power out across the pulse during re-testing of the 50 MW PPM klystron at 2.4 µs.

Recently, an opportunity arose to re-examine the 50 MW PPM device. Testing during early 1999 resulted in klystron operation (Fig. 2) of over 50 MW at 120 Hz with a 2.4 µs rf pulse. The 120 Hz rep-rate operation was limited to 2 minute bursts due to insufficient cooling and high radiation levels. The gain and efficiency measured approximately the same as before even though the magnetic drift tube shunts were removed, eight magnets changed, and one less gun coil assembled.

4. A 75 MW PPM KLYSTRON PROGRAM

Originally, the 1 TeV upgrade of the NLC project required upgrading all the 50 MW klystrons to 75 MW klystrons for powering the rf accelerator. Since then, the most likely scenario has been to construct only 75 MW klystrons A design program based on the SLAC XL-4 and 50 MW PPM klystron technologies was begun to investigate the feasibility of constructing and testing a 75 MW PPM X-band klystron. One klystron has been built and tested and a second design is currently under construction.

4.1. Klystron design

As in the 50 MW program, the gun, collector, waveguide components and vacuum pumping are all over-designed to eliminate possible sources of trouble during experimentation which may interfere with the analysis of the rf performance. This was accomplished by using oversized gun and collector components, dual output waveguide with separate mode transducers, windows and loads, and by using numerous pumpout ports. The design emphasizes achieving 75 MW at a 1.5 µs pulsewidth with an efficiency > 55 % and a gain of at least 55 dB.

The major changes in the rf design are due to a higher gun perveance, a larger diameter drift tube, a stainless steel drift tube, and the elimination of the gun focus coils. The perveance was increased to 0.75 µK in order to increase the available output power while keeping the efficiency high but still maintaining the beam voltage below 500 kV. It was calculated that 75 MW could be accomplished at 490 kV with a 5-cell TW output circuit. The 13 % larger drift tube reduces the beam current density but also reduces the efficiency of the beam-cavity interaction and thereby forces the inclusion of an extra gain cavity. The larger drift tube also raises concern in the possible coupling to additional modes which can now propagate along the drift tube. These other modes include the second harmonic in a TM01 mode (f_c = 21.26 GHz), which prior to opening the drift tube could only propagate in the TE11 mode. The construction of the PPM magnetic circuit differs in that the drift tube is a semi-continuous stainless steel structure punctuated by the cavities with the iron pole pieces and non-magnetic spacers placed outside of the vacuum envelope. This design addresses three separate issues; the possible source of multipactor seen in the 50 MW klystron, the eventual low-cost design of a production klystron using a clamp-on magnetic circuit, and the added loss in the drift tube to increase the start-oscillation currents of the various parasitic modes which may arise. The coils were also eliminated to see if it is possible to remove their complexity and associated power supplies from the eventual production design.

The large drift tube opening makes possible a lower beam area convergence and lower current density in the beam, which in turn reduces the Brillouin field required hence reducing the magnet strength. Conversely, opening the drift tube and moving the pole pieces outside of the vacuum envelope increases the magnet strength required and the overall effect was a slightly higher energy product required for the 75 MW design. Previously, Samarium-Cobalt magnets had been used which are highly resistant to radiation and temperature. The 75 MW design uses Neodymium-Iron-Boron (NeFeB) magnets which have higher energy products available but are more susceptible to temperature variations. The radiation effects do not appear to be an issue over the projected lifetime of the magnets but the temperature increase due to beam interception and rf heating is an issue. NeFeB material is less susceptible to fracturing (although rust can occur if the magnets are left unplated), is much easier to machine and costs roughly one-fifth that of SmCo. For these reasons we are planning to use NeFeB in our designs provided that the temperature of the magnets can be maintained to levels below approximately 80 °C.

An experiment at SLAC addresses the long-term loss of magnetization of NeFeB (Table 4) by exposure to a cesium source (^{137}Cs) at 661 keV and exposure to bremsstrahlung from a spent klystron beam with photon energies approximately from 100-600 keV. The magnets under test have mechanical dimensions approximating those used in our designs. Two 35 MG*Oe energy-product materials were chosen with different intrinsic coercivity values of about 12 kOe (35-#) and 22 kOe (SH-#). It is thought that the lower intrinsic coercivity material is more susceptible to radiation and so a change in field should appear in these magnets first. With a desired magnet assembly lifetime of at least 100,000 hours and an exposure during operation assumed to be 100 R/hr, one would expect a dose of 10 Mrad over the magnet assembly lifetime. Four of the magnets have already exceeded this level of exposure with 661 keV photon energies. To date, no change in field within our measurement error has been detected for any of the test magnets. Tests will continue indefinitely since it only requires a simple measurement every few months.

Magnet No.	**Exposure Method**	**Gauss on Nov. 98**	**Gauss on Feb. 99**	**Exposure MRad**
35-1	^{137}Cs	4935	4940	10.5
35-2	^{137}Cs	4916	4950	10.5
SH-1	^{137}Cs	5090	5092	10.5
SH-2	^{137}Cs	5003	5004	10.5
35-3	Klystron	4346	4283	2.69
35-4	Klystron	4625	4570	2.69
SH-3	Klystron	4737	4701	2.69
SH-4	Klystron	4615	4570	2.69
35-5	Klystron	4695	4621	2.68
35-6	Klystron	4696	4678	2.68
SH-5	Klystron	4280	4242	2.68
SH-6	Klystron	4665	4610	2.68

Table 4. NeFeB radiation test data reveals no change in field strength to date.

Klystron simulations produced approximately 80 MW at the design beam power (Fig. 4) while maintaining low gradients in the output structure. There is a curious dip in the beam profile as electrons lose energy to the circuit, and also a fair amount of interception after the structure; both will be studied in future design work. A plot of momentum space (Fig. 5) shows most of the slowest electrons with energies of about 11 % of their initial energy and a few stragglers falling as low as 5 % which could be cause for concern. The slowest electrons in the 50 MW PPM klystron simulations were roughly at 9 % of their initial energy.

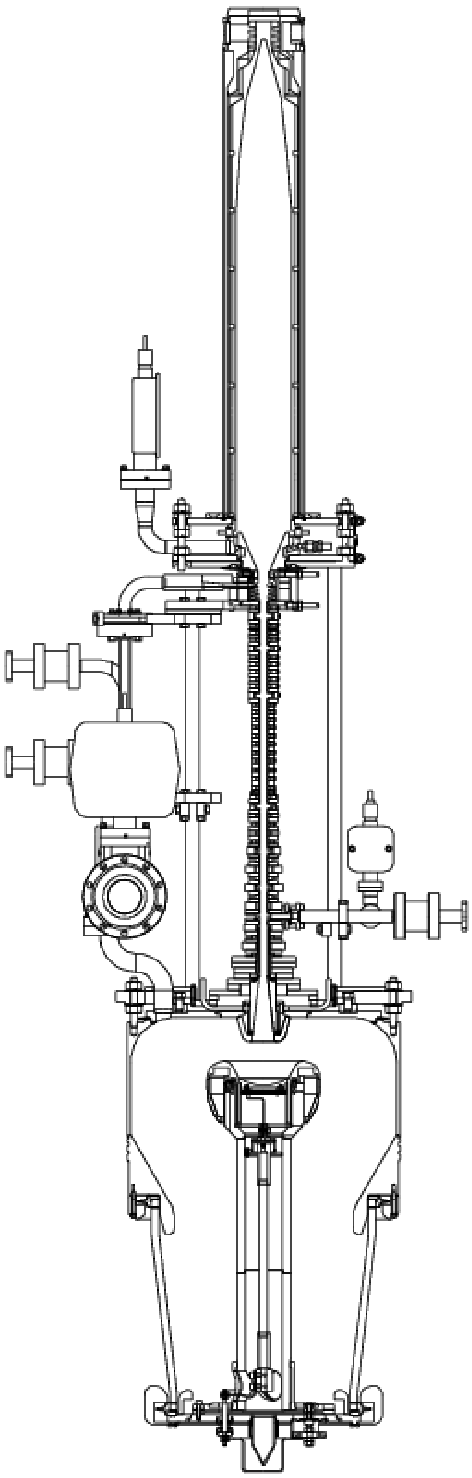

Figure 3. 75 MW PPM Klystron

Beam voltage	490 kV
Beam current	257 A
RF Pulse @ rep rate	1.5 µs @ 60 Hz
Cathode loading	7.2 A/cm^2 Ave.
Cathode area convergence	84:1 (2.65" ∅)
RF output power	75 MW
Saturated gain	~ 55 dB
Bandwidth	75 MHz
Efficiency	~ 55 %
Operating f	11424 MHz
Max gradients:	
Cavities	< 650 kV/cm
Anode	< 250 kV/cm
Focus electrode	< 206 kV/cm
RMS field:	
Shielded flow	1250 G (Brillouin)
Confined flow	1600 G (1.15*Br)

Table 5. Design parameters for the PPM klystron

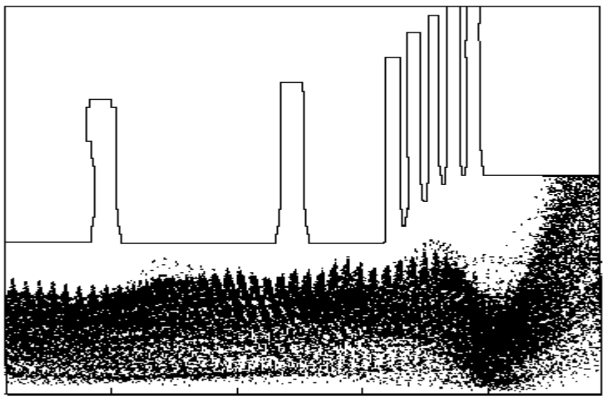

Figure 4. Simulation showing the beam envelope for the 75 MW klystron design at 490 kV and approximately 80 MW rf output power.

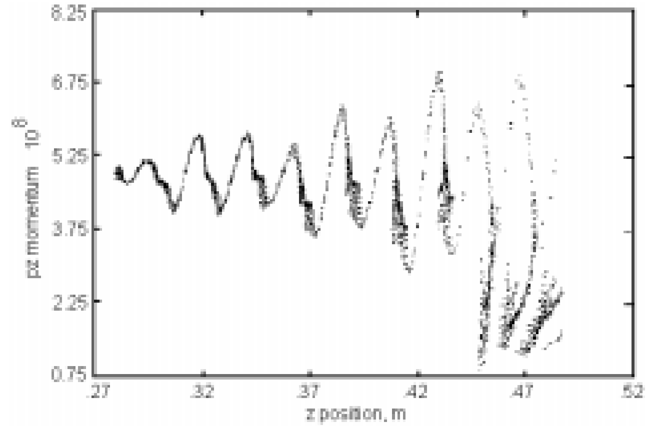

Figure 5. Simulation showing particle momentum through the buncher and output structure of the 75 MW klystron design at 490 kV and approximately 80 MW rf output power.

4.2. Preliminary experimental results

As the beam voltage was increased an oscillation appeared (Fig. 6) which could be damped by increasing the bucking coil current, but too much bucking current caused the beam to impact unpredictably on the vacuum envelope. Increasing the rf drive would also dampen the oscillation but overdriving most klystrons will often produce another set of instabilities. However, by combining the two methods it was possible to raise the voltage peak to 463 kV (design is 490 kV) and attain 71 MW peak at a very narrow pulsewidth. Due to the irregular and short beam pulse, the tube was driven into hard saturation at the peak of the beam pulse which gave a rounded (Fig. 7) rf pulse shape. A rough estimate of efficiency can be found by taking the peak power waveforms with the most pessimistic number using the gun power. The gun power yields 69/130 = 53 %, and using the collector power gives 63 %. The true efficiency is probably close to 60 % since the gun power has an inherent error due to charging the capacitance of the pulse transformer and the rf pulse is flat for some distance as the beam waveforms are falling.

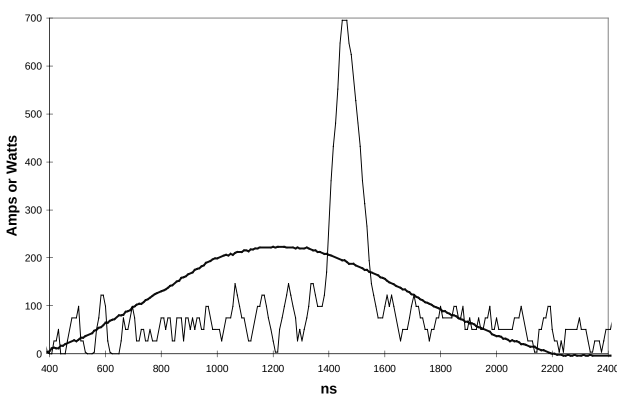

Figure 6. Reflected rf drive signal shows large spike (700 W uncalibrated) on the falling edge of the beam pulse and believed to be ~20 GHz. Collector pulse is shown above, 223 A peak.

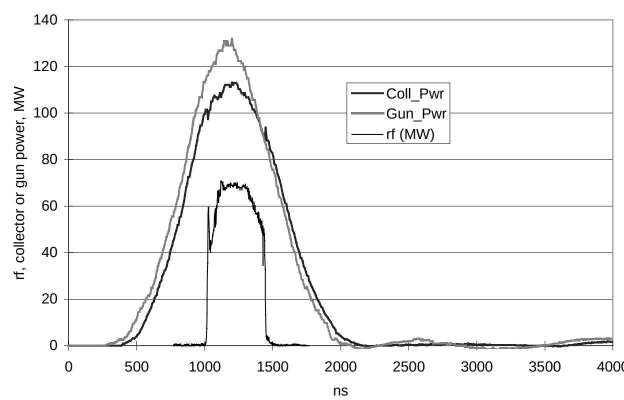

Figure 7. Collector, gun, and rf power waveforms used for finding efficiency (70 MW rf out, 463 kV beam voltage).

After attempts were made at altering the magnetic field by purchasing new magnets, degaussing existing magnets, applying shunts and additional magnets there was little success at boosting the klystron performance. The oscillation was investigated with more vigor and it was determined that there was a gun oscillation present at approximately 1.423 GHz. The first solid clue came from a probe inserted in the oil tank which showed multiple frequencies (Fig. 8) separated by 1.423 GHz. The 8th harmonic is roughly the klystron design frequency of 11.424 GHz and the 14th harmonic is coincident with a ~20 GHz frequency seen in earlier testing. When observed at other ports, the continuous band of harmonics is not observed.

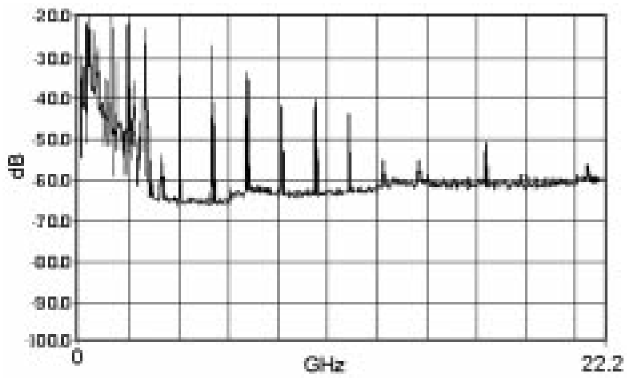

Figure 8. Harmonics found in the oil tank displayed a separation of 1.423 GHz

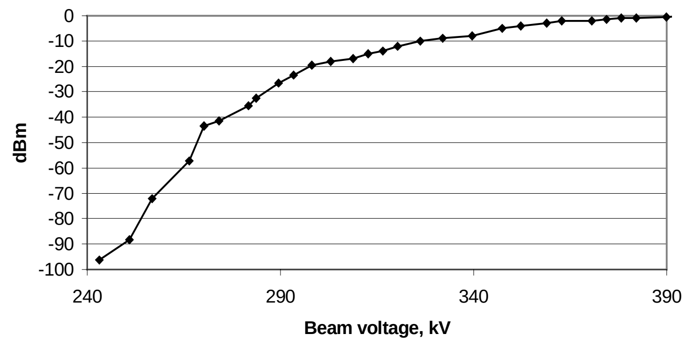

Figure 9. Growth of the 1.423 GHz gun oscillation vs. beam voltage.

By using a calibrated series of pads, couplers and a spectrum analyzer it was possible to plot the growth of the oscillation (Fig. 9) with an increase of beam voltage. The signal was observed to increase over a 100 dB range. Operation over 390 kV at the pulsewidth used in these measurements was not possible but looking at the data it appears that the oscillation saturated at that level. The measured Q of the 1.423 GHz signal was on the order of 500.

Using SUPERFISH[2] to model the gun produced a mode at 1.423 GHz. This mode, consistent with the measured frequency, appears to be able to couple strongly to the beam. By performing a static field solver and an EGUN[3] simulation, the instantaneous electron velocity vector could be calculated and folded into the static fields to get an idea of the beam-loaded Q. This was calculated to vary from about -2000 to -200 as the beam voltage varied from 100 kV to 500 kV. A calculated Q of -400 to -600 corresponded to the measured value of 500 across the beam voltages from 240 kV to 390 kV. It was found using the complex field solver CFISH (Fig. 10) that a lossy collar around the gun stem could lower the Q substantially and probably eliminate the oscillation. The gun was further analyzed across a band from 300 MHz to 3 GHz without any obvious signs of trouble with other possible modes. A BeO loss collar was designed and constructed for the klystron gun stem.

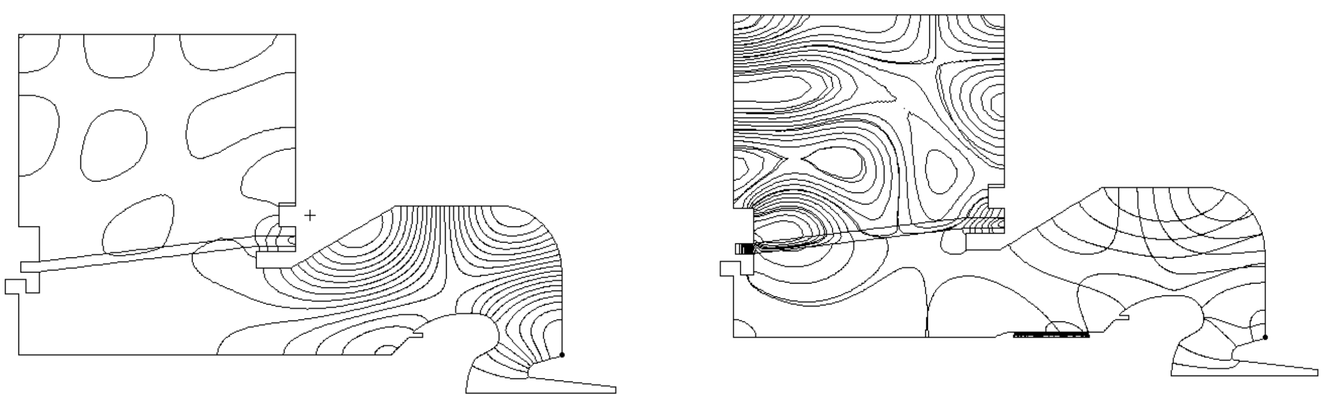

Figure 10. The 1423 GHz oscillation in the 75XP-1 gun before (left) and after (right) insertion of a lossy ceramic collar around the gun stem to lower the Q and eliminate the 1423 MHz oscillation. The two modes were found to correspond by incrementally increasing the loss tangent of the ceramic.

4.3. Repair #1 and experimental results

After filling the klystron with N_2, opening the gun weld flange, inserting the collar onto the gun, closing the tube and baking with heat tape at 120 °C over a weekend, the klystron was operated up to 500 kV. The output rf was measured at 75 MW, but only at a 1 μs pulsewidth, with approximately the same gain and efficiency as previously observed. The operation was again limited by an oscillation but this time it was at 19.96 GHz while the 1.423 GHz oscillation had disappeared. By physically moving the collector away from the output cavity during operation it was found that this frequency would shift by 0.19 MHz for every 0.001" of movement. SUPERFISH calculations showed a mode at 19.977 GHz with a shift of 0.23 MHz for every 0.001" of movement. A lossy ceramic scheme was devised to reduce the Q of this mode and most of the nearby modes from values ranging from 10,000's to a few thousands. This scheme used a series of 3 lossy rings (Fig. 11) made from SiC loaded AlN ceramic inserted into the drift tube taper to the collector. In addition, four waveguides with 17 GHz cutoffs were coupled at the exit of the output structure, terminated in lossy BeO wedges, and tuned to 19.96 GHz. These provided for a single-pass loss of about 40 % which, depending on the phase of the reflected signal, should drastically reduce the Q of the mode. The overheating caused by coupling of the second harmonic power to the ceramics was addressed by brazing all the ceramics to the copper transition.

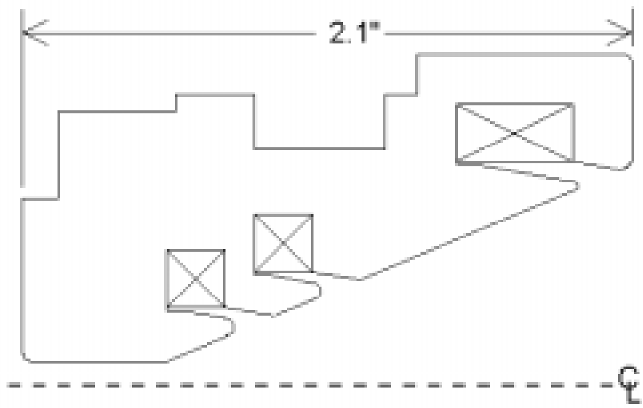

Figure 11. Lossy ring structure for suppressing the 19.96 GHz oscillation is made from a solid copper water-cooled component with lossy ceramic rings inserted (4 BeO-loaded waveguides not shown).

The ceramic loss assembly was inserted into the klystron and the tube was retested. The klystron was able to reach over 500 kV without serious instabilities. Instead of a 1 µs pulsewidth limitation, the tube could reach 2.82 µs (Fig. 12) with over 75 MW of output power. At this longer pulsewidth, the peak power is actually closer to 100 MW while the integrated average pulse power is 79 MW. The efficiency of the klystron at these levels is 50 % average and 67 % peak. The peak power of the tube, not surprisingly, depended upon the pulsewidth (Fig. 13) where shorter pulses could reach higher voltage and power levels. A 1 µs rf pulse could be reached with beams as high as 548 kV at 305 A with 5 capacitors in the PFN line. It required 13 capacitors (the limit of the modulator) to attain a 2.82 µs rf pulse. This allowed for an average 107 MW across 280 ns of the rf pulse, down to a minimum of 79 MW at the longer pulse.

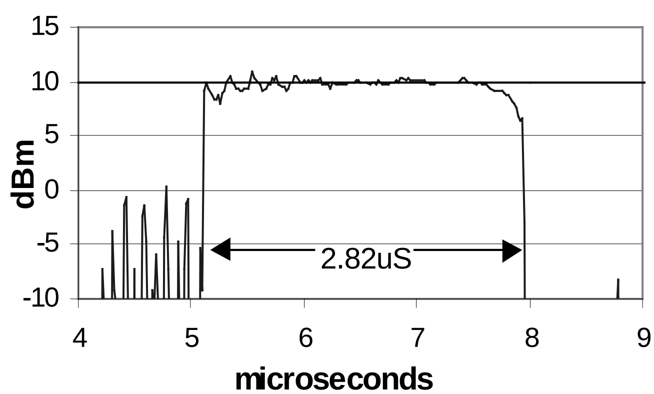

Figure 12. RF output of the 75 MW klystron at 2.82 µs, 1 Hz, 534 kV, peak is 104 MW, average= 79 MW, eff=50 % to 67 %

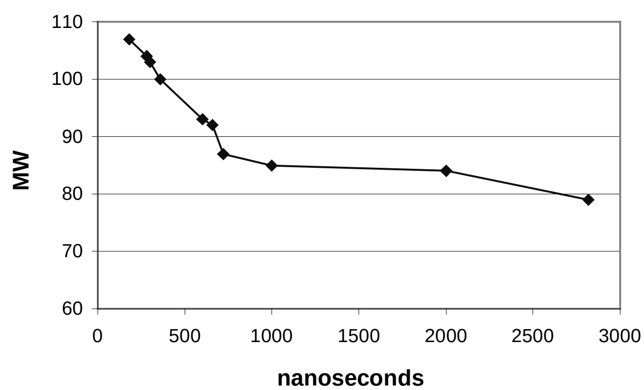

Figure 13.Peak average power integrated across the rf pulse for various time widths.

Because of insufficient cooling along the klystron drift tube structure, beam interception at any appreciable rep-rate led to fast heating of the drift tube and magnets. The magnets on the stack were not heat-treated above 50 °C and so their temperatures were monitored with 15 thermocouples and were not allowed to exceed 40 °C. This constraint made high average power operation problematic. An attempt was made to alleviate this operational constraint with compressed air and leaking in boil-off from a nitrogen tank to maintain a temperature at the stack exterior near freezing. Even with the additional cooling it was only possible to run for extended periods of time at 10 Hz due to overheating. Bursts of 120 Hz were performed but for a maximum of one minute. This constraint will be lifted with the next 75 MW design which includes a clamp-on cooling structure with good thermal contact to the pole pieces.

4.4 Conclusions and future work

The operation of the 75 MW klystron at full power moved the target for an NLC klystron into more difficult territory by extending the pulse duration from 1.5 μs to 3 μs. This extension has not been proven by any means, as the long-term effects of breakdown and fatigue on the surfaces have not been addressed. Full average power operation has not yet been attained nor has the required bandwidth been attained. Oscillations still exist in the 75XP-1 at low drive levels (Fig. 14), although the main sources of concern at 1.4 GHz and 20 GHz have been practically eliminated. Oscillations are not currently a cause for concern in the next klystron design because it has substantially different geometries (smaller gun, smaller drift tube) and better beam focusing.

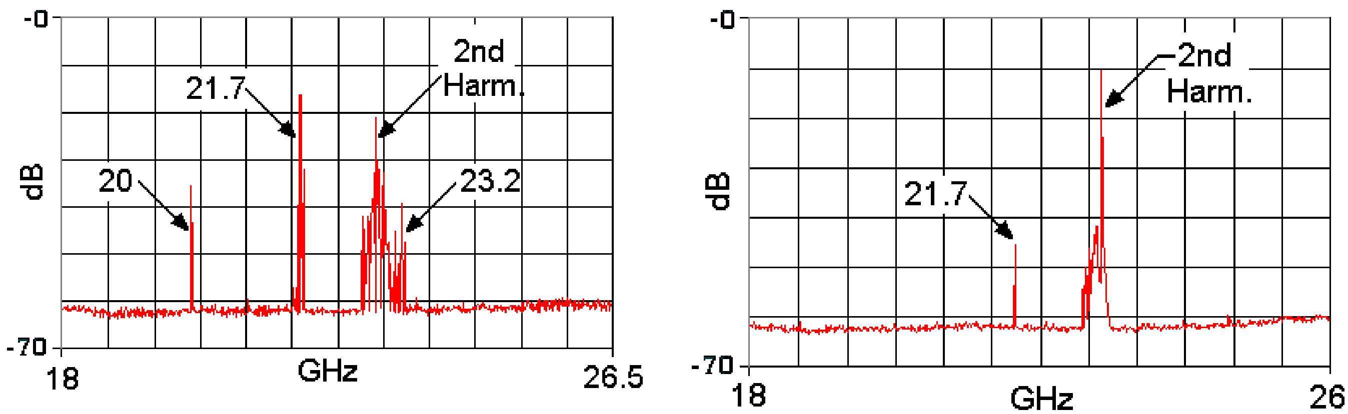

Figure 14. Unsaturated (left) and saturated (right) output of the 75 MW klystron at 1.5 μs, 5 Hz, 500kV shows suppression of higher frequency oscillations at saturated drive condition.

5. THE NEXT X-BAND KLYSTRON: 75XP-3

An effort is underway to construct a lower-cost 75 MW klystron (75XP-3) using advanced manufacturing techniques which limit the parts count and minimize human intervention. In addition, a long-life robust design for the NLC may include new windows, a different cathode, and elimination of the ion pumps. All of these options are currently under study. Automated processing of the cathode activation, tube bake and rf processing must be implemented in order to keep up with the demand for klystrons which will be an order of magnitude greater than any similar effort to date. One or more factories on site will continuously build and repair klystrons while the accelerator is under construction and operating. A final version of the robust, low-cost NLC klystron is at least two years away.

5.1. General mechanical design

The 75XP-3 klystron borrows heavily on the 75XP-1 design with refinements to reduce part number, complexity, size and cost. The electron gun is simplified from previous SLAC designs in that the traditional mechanical alignment adjustments have been eliminated. The new gun design has eliminated many screws and feed-through diaphragms, thereby increasing yield and reliability. The critical alignment of the gun stem to the anode is maintained by precision machining of gun sub-assemblies so that the parts stack-up and proper alignment is established automatically. The gun gradients at the focus electrode, anode, and high voltage seal are by SLAC standards very low. The tube body is significantly simplified compared to earlier designs with the use of a new magnet structure.

Through the experience gained from the fabrication and operation of the XL, 50 MW PPM and the 75XP-1 tubes we have come to the conclusion that the ability to test the complete magnetic circuit before tube operation is highly desirable. This has led to the idea of a clamp-on magnetic circuit where all the magnetic field forming components are integrated into a single (or small number of) clamshell assembly which can be placed around the vacuum envelope of the klystron. The advantages of this design are numerous; the complete magnetic circuit can be built and tested apart from the klystron, the magnet structures can be re-used when a klystron is no longer serviceable, a virtually unlimited magnet lifetime, and the magnet assemblies can be produced by vendors of magnetic assemblies in large quantities at reasonable cost. The disadvantages of such a scheme arise from the need to split the structure longitudinally to allow assembly around the klystron vacuum envelope. This can give rise to various magnetic field defects ranging from quadrupole field components from the split in the magnetic pole pieces to dipole field components arising from a shearing between the halves of the clamshell structure. These defects can be minimized through the use of precision fixtures to fabricate the clamshell structure halves. A test structure has been constructed and tested at SLAC with very promising results. Axial fields measured agreed well with simulations and the transverse field was found to be a respectable 0.5 % of axial field.

Sources of heating present in the klystron include the interception of electrons along the drift tube and ohmic heating of the cavity walls. Since the 75XP-3 utilizes stainless steel cavities, this heating is more severe than that found in more conventional klystrons with copper cavities. Since the drift tube and cavities are poor thermal conductors, the design relies upon using the clamp-on magnet structure as a heat sink to conduct heat from the klystron. To reduce exposing the sensitive NeFeB magnets to temperatures beyond their capability, special heat sink straps were designed to be placed beneath the magnets at critical high thermal flux locations. ANSYS simulations of this scheme have shown that magnet temperatures can be maintained at 75°C or below with the anticipated average power losses for 75 MW operation at 1.5 µs and 120 Hz. Further work is underway to push the cooling capability up to the new operation point of 75 MW operation at 3 µsec and 120 Hz.

The 75XP-3 collector has been designed to reduce parts count and complexity as compared to previous SLAC high peak power tube collectors. Simulations were conducted using an electron scattering and transport code (EGS4) to determine the electron energy deposition pattern within the collector. The peak flux was found to be $5x10^6$ W/cm^2 which corresponds to an average flux of 900 W/cm^2 (1.5 µs at 120 Hz). The spacial average fluxes are a factor of five lower which is acceptable for long term operation.

SUMMARY

X-Band klystrons have been constructed and tested at SLAC as possible rf sources for the NLC. Elimination of the large focusing solenoids in high power klystrons has been realized. A PPM-focused beam-stick with a beam area convergence of 144:1 has been tested with both shielded and immersed flow conditions. The 465 kV, 190 A PPM beam design has been operated at 120 Hz at 2.8 µs pulsewidth. A 50 MW PPM klystron using the same focusing design was tested and exceeded output power and efficiency expectations. A 75 MW PPM klystron was constructed and test results exceeded the power output and pulsewidth requirements for the NLC parameters then in use. New specifications for the NLC include a 3 µs rf pulsewidth and will be addressed in a new (75XP-3) design. The 75XP-3 is scheduled for testing in early 2001.

ACKNOWLEDGMENTS

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