PERIODIC PERMANENT MAGNET DEVELOPMENT FOR LINEAR COLLIDER X-BAND KLYSTRONS*

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Abstract

The Stanford Linear Accelerator Center (SLAC) klystron group is currently designing, fabricating and testing 11.424 GHz klystrons with peak output powers from 50 to 75 MW at 1 to 2 μs rf pulsewidths as part of an effort to realize components necessary for the construction of the Next Linear Collider (NLC). In order to eliminate the projected operational-year energy bill for klystron solenoids, Periodic Permanent Magnet (PPM) focusing has been employed on our latest X-band klystron designs. A PPM beam tester has operated at the same repetition rate, voltage and average beam power required for a 75 MW NLC klystron. Prototype 50 and 75 MW PPM klystrons were built and tested during 1996 and 1997 which operate from 50 to 70 MW at efficiencies greater than 55 %. Construction and testing of 75 MW research klystrons will continue while the design and reliability is perfected. This paper will discuss the design of these PPM klystrons and the results of testing to date along with future plans for the development of a low-cost Design for Manufacture (DFM) 75 MW klystron and invitation for industry participation.

1 AN INTRODUCTION TO PPM

Periodic Permanent Magnet (PPM) focusing is utilized in 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 are used to reduce operational cost and weight. In PPM focusing the axial field changes polarity with every magnet. If the magnetic period is small enough when compared to the beam plasma wavelength, $\lambda p/L$, then sufficient beam stiffness can maintain the beam profile in the presence of large space charge forces due to the rf bunching.

Due to the high energy-products 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 so particular attention must be paid to the gun design and beam transport issues.

The ratio of the axial field to the Brillouin field, Bz/Br, is shown in Table 1 along with other important parameters for three SLAC solenoidal-focused klystrons and three PPM designs. The Brillouin field is that value of magnetic focusing at which all forces operating on the beam are balanced and it is possible to transport the beam with a constant radius. All of the klystrons have output power levels from 50 to 75 MW except the 150 MW DESY klystron. The cathode-to-beam area convergence, A_c, is approximately 100 for all the X-Band klystrons because of the smaller drift tube dimensions. As can be seen the B_z/B_r ratios for the PPM klystrons are not all that different than those found for the solenoidal-focused klystrons. The loss in axial beam velocity, Δu_z, is higher for the PPM klystrons due to the full reversal of the field as seen by the beam.

Table 1: Comparison of SLAC Klystrons (see above text)

Tube	5045	Desy	XL-4	50XP	75XP	DFM
Beam Focusing	Sol.	Sol.	Sol.	PPM	PPM	PPM
frequency, GHz	2.86	3.00	11.42	11.42	11.42	11.42
Beam kV	350	525	440	464	490	490
uK	1.90	1.85	1.20	0.60	0.80	0.75
A_c	18	40	129	144	98	126
Cathode A/cm^2	6.34	5.04	8.75	7.39	7.71	7.23
B_z confined, T	0.12	0.20	0.45	0.20	0.17	0.23
Flux cath/beam	0.85	0.94	0.92	0.50	0.55	0.75
B_z/B_r, axis	1.90	2.82	2.54	1.15	1.20	1.51
B_z/B_r, drift tube	1.90	2.82	2.54	2.03	2.11	2.66
Δu_z	0.1%	0.1%	0.1%	1.6%	2.5%	4.8%

The drawback with PPM focusing is that the construction complexity of the tube may be increased so construction costs and failure rates could rise. The magnetic circuit is fixed and so there may be no easily accessible "knob" for the operator to turn in case adjustment is required. If the beam voltage is reduced enough, $\lambda p/L$ becomes small and the beam will impact the drift tube. This is known as the "stop-band" voltage. Since the high voltage beam pulse has a finite rise and fall time, then a portion of the beam pulse is below the stop-band and interception occurs. There are also areas of beam instability in PPM focused tubes and the possibility of coupling to modes which grow from an undulating beam.

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2 PPM DEVELOPMENT PROGRAM

PPM focusing had never been used successfully on very high-power klystrons and so there existed several unknowns with respect to the outcome of such an attempt. The large area beam convergence of 144:1, no axial field adjustability, possible interactions with an undulating beam, the presence of stop bands, and new materials and construction techniques presented several engineering challenges. It was decided to construct a beam-tester to test the gun optics followed by a 50 MW klystron, and lastly a 75 MW klystron. The 50 MW rf design was patterned closely after the successful solenoid X-band klystrons (XL series) at SLAC after allowances were made to drop the perveance to improve efficiency. The 75 MW klystron design requires a slightly higher perveance than the 50 MW design to keep the beam voltage below 500 kV to reduce modulator costs.

The beam-tester and 50 MW klystron were constructed with Samarium-Cobalt (SmCo) magnets and a gun coil. These magnets were die-pressed individually and a high level of quality control went into the manufacturing process. Inspection of the field on the axis agreed with simulation to within 1 %. To reduce cost, an experiment was performed on the 75 MW klystron by replacing the gun coil with permanent magnets and using Neodymium-Iron-Boron (NdFeB) magnets instead of SmCo. Replacing the gun coil forced large peak-to-peak variations in the field strength design on axis, and switching to bulk NdFeB resulted in a loss of control in material quality. These magnets were fabricated out of large blocks by slicing, core-drilling, and grinding to size. Magnetic, on-axis, field strengths of the individual magnets varied by as much as 20 % from simulation. The 75 MW design has more magnet periods in a plasma wavelength and a higher focusing field to Brillouin field ratio, both of which should allow for better focusing. Design parameters for both the klystrons are found in Table 2.

2.1 Beam-tester and 50 MW gun Design

In order to keep the cathode current density below an average value of 7.5 A/cm^2 for increased lifetime, a 2.25" diameter cathode was required which resulted in an area convergence ratio of 144:1. Since this value is higher than previous SLAC klystrons, a beam-tester was fabricated to prove gun and drift region optics for the PPM design. The design philosophy of the beam-tester was to eliminate all sources of trouble that could interfere with a study of the PPM beam formation and transmission. The issues of gun voltage breakdown, insufficient vacuum pumping, and collector power were addressed by using oversized components from previous klystron designs. This served to hasten the program and allowed for operation at higher voltages than the design required (in the interest of research into more powerful PPM designs). Furthermore, it was decided to control 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. The gun and magnetic circuit were constructed so that operation with and without flux at the cathode was possible. The same general philosophy and beam focusing were used in the 50 MW klystron design.

Table 2: 11.424 GHz PPM klystron Specifications

rf power	50 MW	75 MW
Beam voltage	464 kV	490 kV
Beam current	190 A	257 A
rf pulsewidth	1.5µs @ 60Hz	1.5µs @ 60Hz
Cathode loading	7.4 A/cm^2	7.2 A/cm^2
A_c	144:1	98:1
RMS Gauss	1950	1680
Efficiency	55 %	55 %
Gain	55 dB	55 dB
Max gradients: Cavities	< 700 kV/cm	< 650 kV/cm
Anode	< 250 kV/cm	< 250 kV/cm
Focus electrode	< 220 kV/cm	< 210 kV/cm

The drift tube is constructed of alternating iron pole pieces and monel spacers that are brazed together in subassemblies and then welded together at specially split pole pieces. Each subassembly consists of eight permanent magnets where each magnet produces an axial field opposed in polarity to its immediate neighbor. EGUN[1] simulations were performed (Fig. 1) until the beam scalloping was less than 8 %. The testing began with the confined flow case because the beam is held in check by a larger magnetic field, and continued with the shielded flow case afterward.

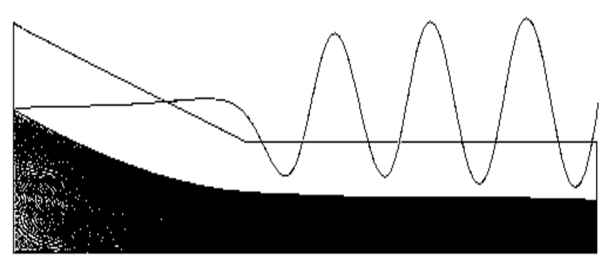

Figure 1: EGUN simulation of the beam as it enters the PPM stack as used for the beam-tester and 50 MW klystron.

When operated in the confined-flow condition the high-convergence gun design has 50 % of the beam flux threading the cathode (as measured at the axis). This is low for typical high-power klystrons. Ratios for other high-power klystron designs range from 80 to 95 %, which yield 1.7 to 3.2 times the Brillouin field condition. It is difficult to get large confinement ratios with PPM focusing because the pole pieces eventually saturate and magnetic materials have finite strengths. There also exists a stability limit to the amount of field that may be applied because the axial velocity is reduced due to the large spin on the beam when the field is reversed from the direction of the field in the cathode. A value of 50 % yields 1.15 times the Brillouin field on the axis (Fig. 2) which increases to 2 times at the drift tube. This is an advantage because the further the beam strays from its radial position, the more focusing force it experiences. PPM focusing, as opposed to solenoidal focusing, increases as distance from the axis increases, which leads to a preference for focusing somewhat hollow beams. As such, hollow beams are a direct result of the gun design parameters in most high-power klystrons due to limitations in the possible emission current density of today's cathode materials for long-life.

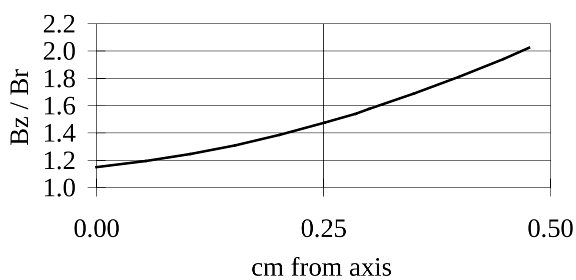

Figure 2: Variation of RMS magnetic field vs. radial distance from the axis for the PPM beam-tester and 50 MW PPM klystron.

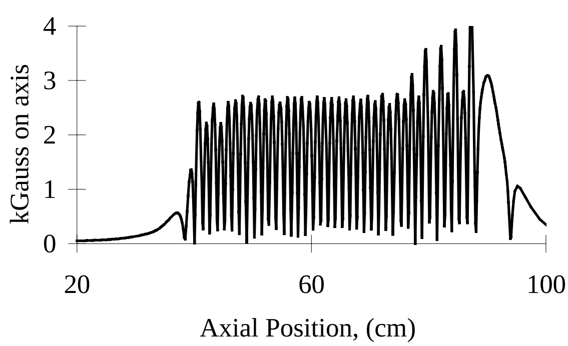

Figure 3: Axial field (Gauss) vs. axial distance (cm) for the 50 MW PPM klystron.

The 50 MW PPM klystron rf design was based on the highly successful XL-4 klystron development at SLAC. The PPM klystron, with its lower perveance, lossy materials, and higher operating voltage requires some modifications in the existing XL-4 rf circuit design. The rf circuit is adapted to the lower perveance beam by increasing the cavity spacings, altering 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 the bandwidth was reduced in order to maintain the required gain. This loss in gain between the two designs was primarily influenced by the lossy materials used in the PPM design. The PPM cavities have a lower Q_o than copper cavities and therefore suffer more rf heating. The lossy drift tube material may serve to dampen possible trapped oscillations and any coupling between the gun, cavities and collector. The magnetic field is very similar to the beam-tester until the last three cavities are reached where the field gradually tapers up to eventually peak (Fig. 3) in the output structure. Tapering serves to confine the beam as the space charge forces 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 larger.

2.2 Beam-tester and 50 MW Experimental Results

The beam-tester processing began with a 1 μs beam pulsewidth and proceeded up to 490 kV, 5 % above the design point, without incident. The beam microperveance was found to be 12 % higher than the design of 0.6 μK. The reason for this discrepancy is not fully known, although a full autopsy is scheduled to occur in October. 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 and iron shunts are placed along the magnet circuit to improve transmission. Such adjustments are not possible with this high-power device as most of the tube is covered in lead due to several kRads of radiation from the collector.

No instabilities or spurious oscillations arising from noise were detected at a 2.8 μs pulsewidth. No gas pressure rise other than that considered normal was seen 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 the robustness of the design. The 490 kV level also happens to be that which is required for the 75 MW X-band klystron discussed later.

The three adjustment coils near the anode had negligible effect on the transmission data but one of the coils had a visible effect on the rising and falling edges of the collector current pulse. Most importantly of all, the shielded-gun operation and the confined-flow operation were essentially identical. Thus the formation and transport of the 144:1 area convergence beam into a shielded or an immersed PPM-focused drift tube for a high-power device has been proven feasible and robust.

Initial observations of the 50 MW klystron behavior revealed that the gun behaved identically to the beam-tester performance. An unusual gain curve containing several jumps was believed to be due to multipactor in more than one location in the drift tube and/or cavities. The gain steps would decrease as beam voltage, drive frequency, or bucking coil setting was increased which means that the multipactor was not only a function of the rf drive but also of the rf current present on the beam and hence was located downstream of the input cavity. To eliminate these discontinuities, the tube was opened and the drift tube was coated with a titanium-nitride (TiN) layer roughly 100 Å thick to reduce the secondary emission coefficient of the surfaces subject to rf fields in the vacuum. After testing a second time, only one gain step remained.

Looking in the various coupling ports of the rf drive and rf output, and with a small antenna probe at the collector ceramic insulator, revealed no oscillations higher than 50 dB below the fundamental, which can easily be ignored. Small signal bandwidth was measured at 40 MHz, which closely agrees with the predicted value of 35 MHz. Measurements over a 70 dB range of rf drive power showed the small signal gain to be 65 dB at the design current, falling by 10 dB at the 50 MW power level.

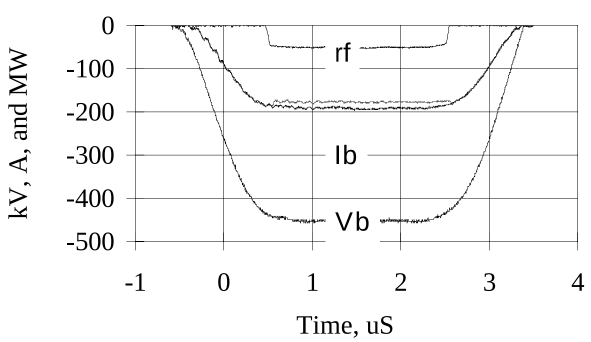

Figure 4: 50MW rf out, beam current (with and without rf present), and beam voltage vs. time for the 50 MW PPM klystron.

After removing the gun coils, replacing the first eight magnets, reducing the output magnet field, and applying prefabricated shunts along the whole magnet stack, the tube was tested in the shielded flow condition. The klystron reached 50 MW with essentially the same gain and efficiency with a 2 % increase in beam interception.

Despite the remaining step in the gain profile (believed to be in the input cavity due to an insensitivity to beam voltage) the PPM klystron reached the full operational specification (Fig. 4) of 50 MW at 2 µs. The efficiency at 50 MW was well over 55 %, and over 60 % at 60 MW, using calorimetric diagnostics. The intercepted beam power at 50 MW was about 1 % of the total beam power, but the beam current lost about 7 % while passing through the tube. This means that the energy of the electrons lost in the tube must be about 66 keV on average.

2.3 A 75 MW Experimental Design

In designing the 75 MW klystron, major changes made were enlarging the drift tube due to a higher beam current, a stainless steel drift tube, and the elimination of the gun focus coils. It was calculated that using a 5-cell travelling-wave output circuit would extract more than 75 MW. Opening the beam tunnel by 13 % to 0.425 inches reduced the efficiency of the beam-cavity interaction and thereby forced the inclusion of an extra gain cavity. This also allows more modes to propagate within the drift tube, including the second harmonic TM mode. The construction of the 75 MW 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. This design change addresses three separate issues; avoiding the multipactor seen in the 50 MW klystron, taking a step toward the eventual low-cost design of a production klystron using a clamp-on magnetic circuit, and adding loss in the drift tube to increase the start-oscillation currents of the various parasitic modes which may arise.

The large drift tube opening resulted in a lower beam area convergence and lower current density in the beam, which in turn reduced the necessary magnet strength. On the other hand moving the pole pieces outside of the vacuum envelope increased the magnet strength required and the overall affect was a slightly higher energy-product required for the 75 MW design. Previously, SmCo magnets had been used that are highly resistant to radiation and temperature. The 75 MW design used NdFeB magnets which have higher energy-products, are easier to machine, are less brittle, but have a lower Curie temperature. However, at 500 keV photon levels, radiation effects do not seem to be an issue over the magnets projected lifetime. Furthermore, NdFeB magnets are less expensive in bulk quantities. Procurement of the NdFeB magnets presented many difficulties, as the vendor was unable to meet the required specifications. This material has been used in applications where the absolute value of the magnetic energy-product is not tightly held. This issue will be studied over the next few months and a decision will be made on the magnetic materials to be used in future designs.

Simulations of the klystron using CONDOR[2], a 2.5-D particle-in-cell code, show approximately 80 MW at the design beam power while maintaining low gradients in the output structure.

2.4 75 MW Experimental Results

Most of the completed magnets delivered to SLAC failed to meet the specification. Specifically the magnets at the beam convergence area near the gun, the gain cavity magnets, the penultimate cavity magnet, and the output magnets were all below specification. Due to time constraints it was decided to test the klystron and testing began with a 1 µs flattop beam pulse. Upon reaching 280 kV, an oscillation was noticed at the end of the beam pulse. The beam pulse was reduced to zero flattop, approximately 1 μs FWHM pulse, and the voltage was raised to 360 kV until the oscillation was again seen. A spectrum analyzer was used to carefully search for all frequencies between 11 GHz and 26.6 GHz and found only the fundamental, the second harmonic, and a signal at 20 GHz.

As the beam voltage was increased the oscillation could be damped by increases of the bucking coil, which tends to make the beam smaller, but the method has the limitation that too much of an increase and the beam impacts unpredictably on the vacuum envelope. Increasing the rf drive would also damp the oscillation but overdriving most klystrons will usually produce another set of instabilities. However, by combining the two methods it was possible to raise the voltage peak to 463 kV and attain 71 MW peak at a 200 ns pulsewidth. Despite the difficulties, gain was found to be between 55 and 60 dB and efficiency measured 60 % at the saturated rf output level of 70 MW.

The magnets have been removed from the klystron and are inserted on a full-scale model of the klystron circuit so that the field can be shunted on the bench to a desired profile. After simulation, theory, and measurement agree on the required field, the newly shunted stack will be installed on the klystron and testing will resume. It is expected that this will occur late in 1998.

2.5 A Low Cost Klystron

A low-cost design of a 75 MW klystron known as the Design For Manufacture klystron (DFM) has been under investigation for the past three years and seeks to minimize parts count, decrease complexity, reduce construction labor, and increase reliability of the klystron. A smaller gun and collector with reduced parts count, better output waveguide hardware such as mode converters and windows, and a simplified drift tube and magnet structure are the main areas of scrutiny. Industry participation will be solicited with several contracts awarded to build 50 MW klystrons. Close cooperation between industry and SLAC will be required for the successful construction and operation of several thousand 75 MW PPM klystrons. One key to the lower cost will be the development of a clamp-on magnet structure, which can be used repeatedly as klystrons reach the end of their useful lifetime. A clamp-on structure for evaluation purposes is currently under fabrication at SLAC and will be tested in the next few months.

Automated processing of the cathode activation, tube bake and rf processing must be implemented in order to keep up with the demand that will be an order of magnitude greater than any similar effort to date. It is currently planned that one or more factories on site will continuously build and repair klystrons while the accelerator is under construction and operation.

Eventually, the DFM klystron and the research prototypes along with industry efforts will merge in a single design using the best technologies from each.

3 CONCLUSIONS AND FUTURE WORK

The results of the 50 MW klystron testing exceeded the design goals in terms of output power, pulsewidth and efficiency, and provide a proof-of-principle for high-power PPM klystrons. The magnetic field difficulties with the 75 MW design can most likely be overcome by returning to a magnetic circuit similar to the 50 MW klystron. Further study is required to fully explore the failures and possible solutions concerning the 75 MW magnetic circuit. By early next year, a new design will be tested which relies on lessons learned from the previous 75 MW klystron. Furthermore, smaller gun and collector designs, elimination of some vacuum pumps, simpler output waveguide structures, and overall cost-reduction schemes will continue development.

Despite the requirement for further engineering work, this program has shown that a high-power PPM focused klystron is not only feasible, but has demonstrated to function in good agreement with simulation and engineering analysis. The elimination of the focusing solenoids for high-power accelerator sources is a major cost reduction in both the procurement and operational costs of such sources. It is likely that any future large-scale, linear electron accelerator constructed will be driven by PPM focused klystrons.

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