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PPM Focused X-Band Klystron Development at the Stanford Linear Accelerator Center

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Abstract. X-band klystrons capable of 50 MW and utilizing Periodic Permanent Magnet (PPM) focusing are undergoing design and fabrication 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). The first klystron to be tested this year has a 0.6 μK beam at 465 kV, a 5-cell traveling-wave output structure and a predicted efficiency of 63%. A 465 kV, 190 Abeam-stick with 12 periods of PPM focusing has recently operated to verify the gun optics and transmission of the beam in the absence of rf bunching. Beam transmission greater than 99.8%. has been measured. Design and simulation of the beam-stick and klystron are discussed along with performance of the beam-stick under confined-flow and shielded conditions.

INTRODUCTION

Periodic Permanent Magnet (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, a permanent magnet can be used to reduce operational cost and weight. Single polarity permanent magnets have large amounts of leakage flux and so PPM focusing is used to reduce the size and weight of the magnets. In the PPM scheme, the axial field changes polarity with every magnet thus the field on axis may approach a sinusoid. If the magnetic period is small enough when compared to the plasma wavelength of the beam then the beam will be focused with sufficient stiffness to maintain the 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. Due to the high energy densities required for the magnets it is usually not possible to thread as

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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 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. The magnetic circuit is also fixed and so there is no easily accessible "knob" for the operator to turn in case adjustment is desired. 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. At some point the beam essentially 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 are also areas of instability of beam optics in PPM focused tubes and also possibilities of coupling to modes which grow from an undulating beam.

The major advantage with PPM focusing is in the cost savings of DC power. With 4000 klystrons each consuming 10 kW, the operational energy bill is 10's of millions per year. The lightweight structure poses additional advantages as do the initial costs and the ability to tailor the field down close to the beam tunnel.

The Next Linear Collider (NLC), as currently envisioned by the physics community in the United States, requires several thousand high power X-band klystrons operating at approximately 50 MW at 1.2 μs pulsewidths. The 1 TeV upgrade to the NLC may require 75 MW klystrons of the same pulsewidth. Because of the prohibitive cost of operating solenoids, the complexities with superconducting magnet systems, and the attractiveness of PPM focusing, an investigation into the merits of PPM focusing was begun. Since increasing the efficiency of the klystron from 50% to 60% will save 17% in operational energy costs of the electron beam, and the fact that PPM focusing works better at low beam microperveance, the first PPM klystrons built will have microperveance of

TABLE 1. Design parameters for the PPM klystron

Beam voltage	465 kV
Beam current	190 A
RF Pulsewidth @ rep rate	1.2 μs @ 180 Hz
Cathode loading	2:1 (10 A/cm^2 max)
Cathode convergence	144:1 (2.25" dia.)
RF output power	50 MW
Saturated gain	55 dB
Efficiency	60 %
Operating frequency	11424 MHz
RMS focusing field	1600 gauss (1.25*Br)

0.6. Other factors weigh into the chosen beam microperveance such as reasonable beam voltages, available power, and realizability of the magnetic circuit. There exist points of diminishing returns and a value of 0.6 μK was settled on for this program. A design for a prototype PPM klystron is shown in Table 1.

PPM DEVELOPMENT PROGRAM

PPM focusing has not as yet been used successfully on high power klystrons and so there exist several unknowns with respect to the final outcome of such an attempt. In the SLAC design, the following areas of concern are:

1) Beam area convergence of 144:1
2) No immersion and partial immersion of the cathode
3) Cooling of, or lack thereof, the circuit
4) Cost of the circuit
5) Transmission at high rf efficiency
6) Spurious oscillations
7) rf circuit design for high efficiency

Items 1 through 4, and perhaps some answers to item 6, can be addressed by first building a beam-stick. Items 5 through 7 follow testing of an eventual prototype klystron. Thus the program begins with the design and construction of a full power beam-stick to prove the first four elements. In parallel with that development will be design and construction of the first klystron with design changes possible after testing of the beam-stick. The klystron design is based on the highly successful X-band klystron development at SLAC. A 50 MW klystron operating at 1.5 μs and 60 Hz and using a 4-cell traveling-wave output circuit is installed in the NLC test accelerator at SLAC. This design is used for 4 more klystrons under construction at SLAC and the rf circuit for the PPM klystron is based upon the successfull design of the solenoidal focused klystron. A beam-stick with 12 periods of PPM focusing (24 magnets) was constructed and testing performed from January to March of 1996. Testing of the first klystron is to begin in June 96.

A 465 kV PPM FOCUSED BEAM-STICK

The design philosophy of the beam-stick is to eliminate all sources of trouble which could interfere with a study of the beam formation and transmission such as breakdown, insufficient vacuum pumping, and collector issues, and to allow for testing with both zero and partial flux through the cathode. To accomplish this,

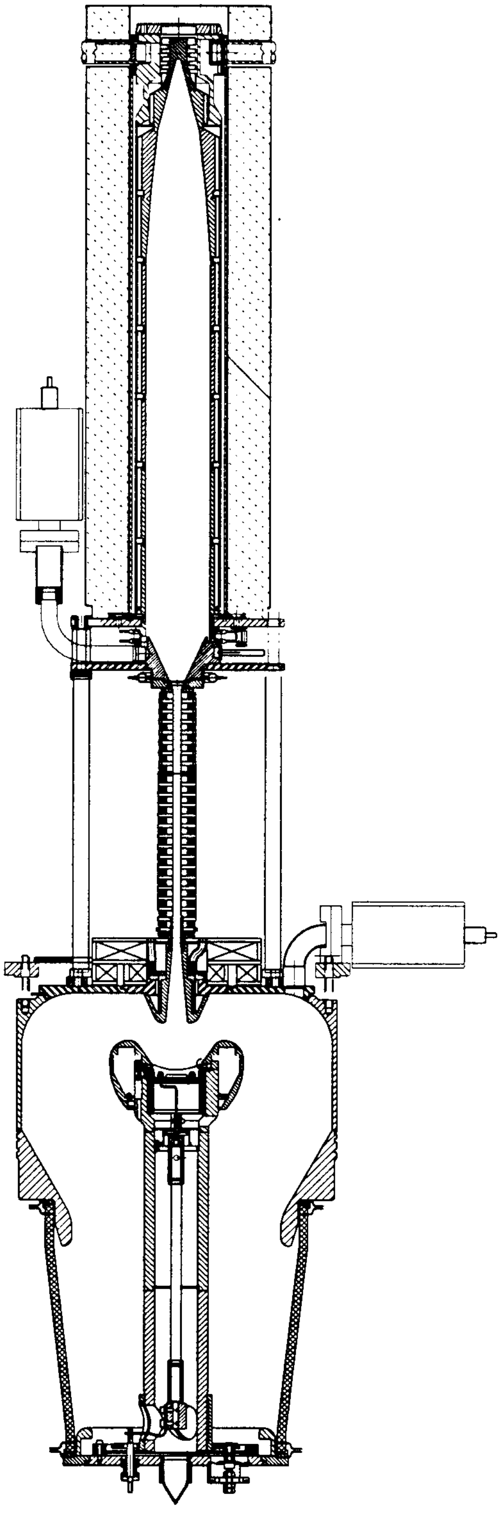

Figure 1. PPM-Focused Beam-Stick

most of the parts utilize existing designs which serves to hasten the program and allow for operation at much higher voltages than the design requires (in the interest of future research into more powerfull PPM designs). The newly designed areas are (Fig. 1) the drift tube/PPM circuit and transition to the collector, the anode nose and anode focus coils, and the gun stem assembly.

General design of the Beam-Stick

The anode housing and ceramic insulator (Fig. 1) are capable of supporting at least up to 550 kV and are well suited to operation at the design levels. The cathode stem is made from a thick copper support tube and mounts to the gun baseplate via a copper heat exchanger. This method is calculated to keep the focus electrode at less than 300 °C. The focus electrode cavity is shorted by insertion of fingerstock at the gap between the focus electrode and gun stem to eliminate coupling to the cavity formed inside the focus electrode. The gun assembly is mounted on an adjustable platform for final alignment of the cathode to anode spacing and concentricity. A vacuum pump out port is located above the cathode, not usually accessible with solenoidal focusing due to the presence of the magnet, to maintain high vacuum in the gun area. While preprocessing the gun assembly in a vacuum belljar, the thermal motion of the cathode and focus electrode was measured along with the absolute temperatures of 10 points on the gun surface. Data collected during preglow helped determine the thickness of an alignment shim placed under the focus electrode and the amount of adjustment in cathode-to-anode spacing before the complete assembly was welded together.

The cathode is supported between the focus electrode and support cup by a temperature compensating molybdenum and stainless steel sleeve to self-compensate thermal motions. An M-type cathode with a 2.25 inch diameter was chosen to reduce emission current density, and hence temperature, for long life. The anode beam entrance is copper with a molybdenum sleeve which serves to intercept the rising and falling edges of the beam pulse, which exist below the stop band voltage, and protect the iron pole pieces and cupronickel spacers. The molybdenum sleeve is brazed to the anode and allows for measuring the intercepted current.

The drift tube is constructed of alternating iron pole pieces and cupronickel spacers which are brazed together in subassemblies and then welded together at specially split pole pieces. Each subassembly houses 8 permanent magnets where each magnet produces an axial field opposed in polarity to its immediate neighbor, and is held on by beryllium-copper retaining rings.

Lead shielding for the collector, “squirrel cage” support, and bucking coil components were already in existence so additional savings were realized. The collector diameter is more than Sufficient to absorb the average power and pulse energy of the electron beam and the ratio of drift tube to collector diameter is large such that the possibility of returned electrons is minimized. An actual production tube will have a much shorter collector and smaller gun assembly.

Beam-Stick Magnetic Circuit

Because of the uncertainty of focusing such a highly convergent gun into a PPM stack without flux through the cathode (shielded gun), an approach was settled on whereby the gun could operate shielded and flow into a Brillouin field, or operate partially confined and flow into a field greater than Brillouin. This was accomplished by constructing a complete set of pole-piece “shunt-rings” which can be put on the beam-stick and reduce the field on axis to Brillouin without replacing all the magnets. Additionally, three adjustable coils are located at the beam entrance to attain the correct field for confined-flow operation. The first 8 magnets in the stack along with the first pole-piece are also replaced when switching between the two designs. EGUN[1] simulations, using a 7.62 x 10^{-3} cm mesh, were performed until the scalloping in both designs was less than 8%.

The situation under Brillouin flow in the PPM circuit is not the same as with Brillouin flow in a solenoid. In a solenoid, the maximum field is on the axis but in the beam-stick, the field increases away from the axis so that at the beam edge the RMS field is 30% greater than on axis and 60% greater at the drift tube diameter. This gives an advantage in that the futher the beam strays the more focusing force it experiences. In the confined flow gun where the field on axis is only 1.15 x Brillouin, the field at the drift tube diameter is more than 1.8 x Brillouin.

Beam-Stick Test Results

The beam-stick testing began at 1 μs pulsewidth and processed up to 490 kV without incident. Microperveance was measured at 12% too high (0.67) which was surprising given the level of detail which went into gun simulation. Beam transmission appeared to be in the high 99$ range.

When the pulse was extended to about 2.8 μs (measured at the 95% level of beam voltage) the data becomes much more reliable and at 120 Hz operation there is roughly 42 kW in the collector at 490 kV. This allows for very accurate beam transmission information and was found to be 99.9% regardless if the raw data is in error by as much as 10%.

The pulse was extended in width (Fig. 2) not only to check for transmission but also for instabilities on the beam. No instabilities or spurious oscillations arising from noise were detected at 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. Note that the pulsewidth flat-top

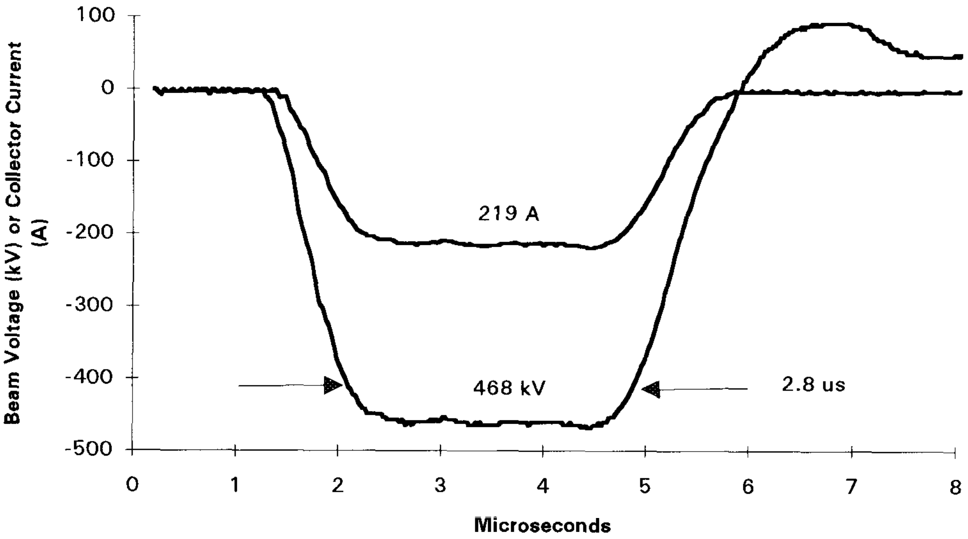

FIGURE 2. Beam voltage and collector current of the PPM-Focused Beam-Stick at 120 Hz.

is at least 1.5 times the requirement for the klystron and the voltage of 490 kV is 5% higher. The 490 kV level is one design value required for a 75 MW X-band design currently under consideration.

The emission curve data for the beam-stick (Fig. 3) shows the sharp knee associated with the M-type cathode (perveance roughly doubles over a ±5 % change in current). The interception was strongly coupled to operation above the knee on the curve (which represents the transition between space-charge-limited and temperature-limited operation). As the heater power was reduced, the

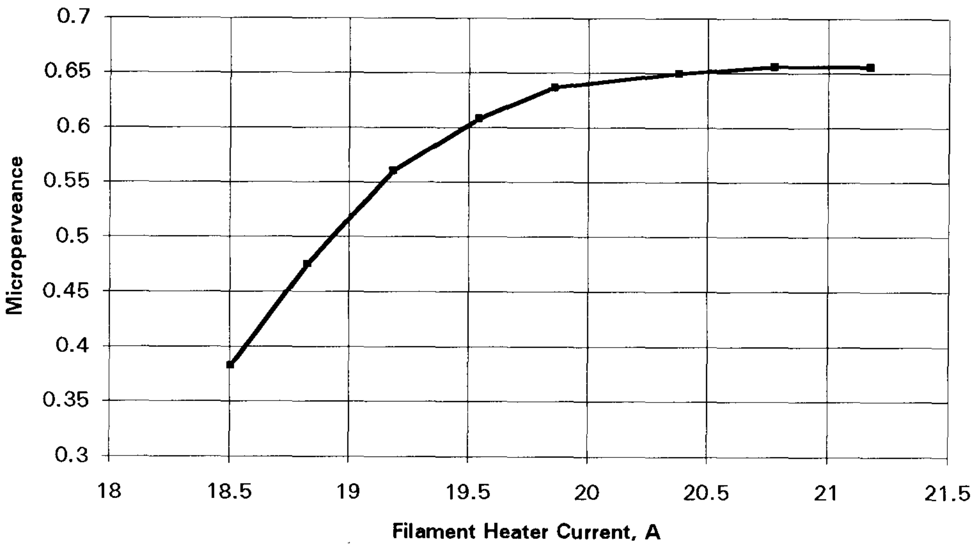

FIGURE 3. Emission curve at 465 kV for the PPM-Focused Beam-Stick.

interception rose and fell dramatically as the beam would focus and defocus due to the changing current density profile. The high convergence gun design will not operate on or below the knee satisfactorily and operation below the knee cannot be used as a way to increase stability if problems are encountered in the klystron.

With most PPM-focused devices it is necessary to manually place iron or magnetic shunts along the drift tube to arrive at acceptable beam transmission values. No shunting of the drift tube was necessary in the beam-stick test. Furthermore, the 3 adjustment coils near the anode had negligible effect on the transmission data but it was seen that 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. The next step will be to test a klystron with PPM focusing.

A 50-MW RF PPM FOCUSED KLYSTRON

The design of the rf circuit of the klystron is based on experience with the SLAC “XL-4” series. The rf circuit is adapted to the lower perveance beam by increasing cavity spacings, altering tunings, and adding an extra cell in the output structure for a total of 5 cells. 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 (Fig. 4) machined into them. The drift tube material may serve to dampen possible trapped oscillations. The magnetic field is the same as the beam-stick until the last three cavities are reached where the field gradually tapers up to finally peak in the output structure at about 4.5 kg. The tapering serves to confine the beam further as the 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.

The cavity gradients found in the design are no higher than in the current XL klystron. The gun gradients and collector power density are also lower than in the current XL klystron. Output hardware such as waveguides, couplers, mode converter (to TE01 for window transmission and water loads), windows and loads are all of proven design. The purpose of the klystron test is to verify the beam containment in the presence of large rf bunching forces thus other failure mode possibilities were reduced as much as possible.

Simulation of the klystron using **CONDOR**[2] gives efficiency of 63% or 55 MW at full beam voltage of 465 kV. Testing of the device will begin in June 1996.

SUMMARY

A PPM-focused beam-stick with a 144:1 area convergence beam has been tested with both shielded and immersed flow conditions. The 465 kV, 190 A beam design has been operated at 120 Hz at 2.8 **μs** pulsewidth. A 50 MW klystron using the same focusing design will be tested in June 96.

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Chris Pearson
Bob Phillips

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