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CURRENT STATUS OF THE NEXT LINEAR COLLIDER X-BAND KLYSTRON DEVELOPMENT PROGRAM[*]

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Abstract

Klystrons capable of driving accelerator sections in the Next Linear Collider (NLC) have been developed at SLAC during the last decade. In addition to fourteen 50 MW solenoid-focused devices and a 50 MW Periodic Permanent Magnet focused (PPM) klystron, a 500 kV 75 MW PPM klystron was tested in 1999 to 80 MW with 3 µs pulses, but very low duty. Subsequent 75 MW prototypes aimed for low-cost manufacture by employing reusable focusing structures external to the vacuum, similar to a solenoid electromagnet. During the PPM klystron development, several partners (CPI, EEV and Toshiba) have participated by constructing partial or complete PPM klystrons. After early failures during testing of the first two devices, SLAC has recently tested this design (XP3-3) to the full NLC specifications of 75 MW, 1.6 µs pulse length, and 120 Hz. This 14.4 kW average power operation came with an efficiency of 50%. The XP3-3 average and peak output power, together with the focusing method, arguably makes it the most advanced high power klystron ever built anywhere in the world. Design considerations and test results for these latest prototypes will be presented.

PREVIOUS KLYSTRON TECHNOLGIES

Solenoidal focusing

SLAC's X-band klystron development began with a series of tubes designed to produce 100 MW of peak output power. After study of several design approaches, the peak power goal was deemed too high for the existing technology. After a series of six prototypes it was decided to reduce the design goal to 50 MW peak output power for the next series of experimental tubes. This series of klystrons utilized a lower perveance (1.2 µK), a TE_{01} output window and improved vacuum pumping. After initial implementation of standing wave output structures, a final design was arrived at which utilizes a four-cell traveling wave output structure. This design, known as the XL4, powers the NLC Test Accelerator and other test facilities at SLAC. These klystrons have operated from 50 MW at 2.4 µs pulse length up to 75 MW at 1.5 µs pulse length.

The challenge of PPM focused klystrons

With 1000's of klystrons required for the NLC design, operational costs can be drastically reduced by elimination of the solenoid power requirement of 20kW per klystron. PPM technology for low power microwave devices is a fairly mature technology but had never been successfully implemented in a high power klystron. Figure 1 shows the essential construction of a PPM klystron drift region in a rotationally symmetric sketch.

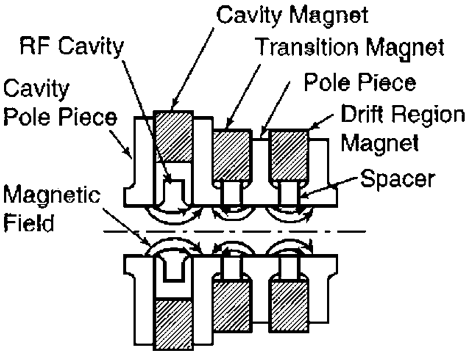

Figure 1: Drift tube construction for a PPM klystron.

In our high power designs, interception of the electron beam can cause failure by destroying the integrity of the vacuum envelope. To improve beam transmission and rf performance on lower power PPM devices, manual tuning of the focusing structure is performed. Manual tuning, or shunting as it is known in the industry, is performed by placement of either magnets or iron pieces directly on the focusing structure of an operating device in order to reduce transmission losses due to manufacturing and design errors. Industrial PPM devices are not strong

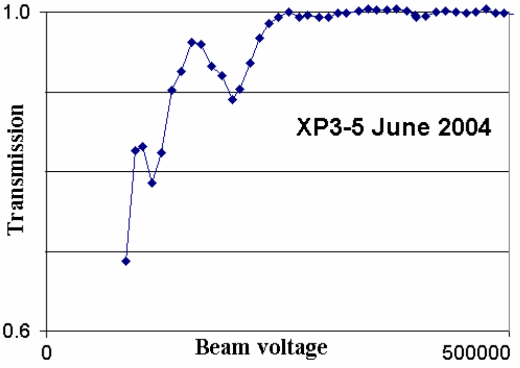

Figure 2: Typical PPM klystron beam transmission data.

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sources of gamma radiation as they typically operate much lower than 100 keV. With the ~500 keV electron beam and hundreds of amperes in our high power klystron, manual tuning of the beam transmission is not possible. Because shunting is not possible, much attention is placed in the design, construction and testing of the various components and sub-assemblies. Additionally, a high power beam-stick is usually constructed and tested when major modifications are made to the devices which could affect the beam transport system. Figure 2 shows beam transmission data typical of these devices. Due to selection of the PPM magnet period the transmission is not perfect for all voltages hence the modulator pulse rise and fall time leads to a certain amount of unavoidable interception. Even so, the total transmitted beam pulse power at a 2.8 μs FWHM pulsewidth is greater than 99 % measured calorimetrically when operating at 500 kV.

EARLY PPM FOCUSED KLYSTRONS

XL-PPM

Concurrent with the development of the solenoid focused series of XL klystrons, a 50MW PPM klystron was constructed and tested. This klystron was preceded by a beam stick, which was tested for a week at 120Hz and 2.8 μs pulse width. The successful operation of the beam stick and its associated 99.9% average beam transmission was followed by testing of the 50MW klystron. After an initial rebuild to address an issue with multipactor, the klystron exceeded the design specifications. The original design specifications of 465 kV, 190 A, 60 Hz and 1.5 μs rf pulse width at 11.424 GHz was later altered to a 2.4 μs pulse width and the tube was subsequently operated at the new specification. Two similar devices were built by industry and delivered to the SLAC Klystron Test Laboratory but unfortunately both devices suffered from manufacturing related vacuum problems. However, with the initial success of a possible replacement device for the XL series of klystrons and parameter space selections for the NLC in mind, it was decided to attempt a 75MW PPM klystron.

XP-1

Considering a modulator limitation of approximately 500 kV it was decided to increase the perveance of the gun design from 0.6 to 0.75 μk [1]. This allows the device to theoretically produce the 75 MW of rf output power at a reasonable efficiency of ~55 %. Klystron parameters, which are also applicable to the XP3 design, are shown in Table 1. Note that the rf pulse width has changed several times during the program while the NLC rf scheme has continued to evolve. To design the XP1 klystron we started with the XL-PPM design and then added a gain cavity, a stainless steel drift tube, and made alterations to the output circuit and gun. An attempt to reduce construction costs led to the use of NdFeB magnets instead of the SmCo magnets used on the XL-PPM, along with the elimination of the anode focus coils. These latter two changes sacrificed beam quality and thermal stability enough such that subsequent XP3 designs include the anode coils and have more stringent quality control checks of the NdFeB material. Due to a gun oscillation at 1.4GHz and a 20 GHz oscillation at the output, the XP1 required a retrofit of additional loss material. The tube was re-tested and was then able to produce over 75 MW at 2.8 μs pulse lengths. At this output level the pulse rep rate was limited to 10 Hz due to inadequate cooling of the tube body.

Table 1: 75MW Klystron Parameters.

Beam V	490 kV	Rf Pulse	1.6 – 3.2 μs
Beam A	257 A	Average rf	14 - 29 kW
Perveance	0.75 μK	Gain	~55 dB
PRF	120 Hz	Efficiency	~55 %
Peak rf	75 MW	Bandwidth	120 MHz

RECENT PPM KLYSTRONS

XP3 DFM versions

The SLAC klystron department is currently testing the next devices in the series, the XP3. This tube is meant to address the lessons learned so far while pushing for full duty operation with a lower cost, simplified design [2]. Aside from a simplified electron gun, simplified gun coils and other cost-cutting measures, the principle design change from the XP1 is a drift tube without pole pieces brazed to it as in Figure 3. Instead, a magnet structure which is clamped on after bake during the tube dress assembly is employed. This structure takes the form of clam-shell halves containing all the field-forming components that can be built and tested apart from the klystron vacuum envelope. Additionally, the magnet structure can be transferred to another tube and reused as the klystrons reach end of life. These simplifications

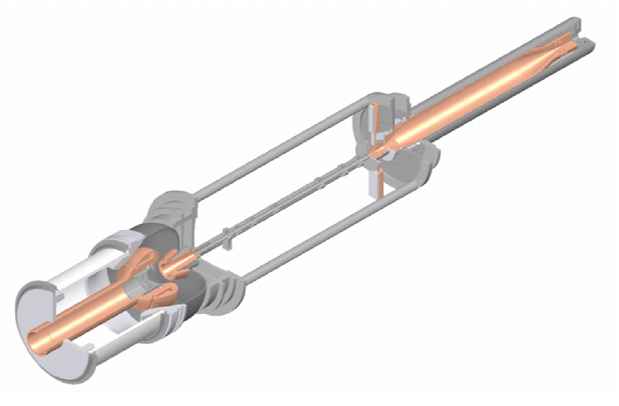

Figure 3: An XP3 DFM Klystron.

allow cost reductions and represent our first attempt to Design for Manufacture (DFM). The first of these klystrons suffered from an output oscillation as a result of a manufacturing oversight and the second from a gun oscillation due to an attempt to use new material in the gun. Both tubes were disassembled and a new tube, the XP3-3, was constructed from their components. The result was our first full-spec operational klystron tested in July of 2003. Thus tube operated at 75 MW, 120 Hz at 1.6 µs pulse length.

XP3-4 and XP3-5

Due to the beam transmission, rf and thermal issues discovered with the previous DFM versions we decided to temporarily return to a design with pole pieces brazed directly to the drift tube. This new version of the XP3 was constructed and two tubes are currently under test on different test stands. The first tube, the XP3-4 was built and tested with air cooling rather than water cooling while the water cooling components were still under fabrication. The XP3-4 operated full-spec at 120 Hz, 506 kV, 75 MW, 1.62 µs rf, 50 % efficiency with 60 dB gain. Most surprising was the excellent beam transmission of 98.7 % during the full saturated rf pulse. Output linearity of the rf versus beam voltage is shown in Figure 4.

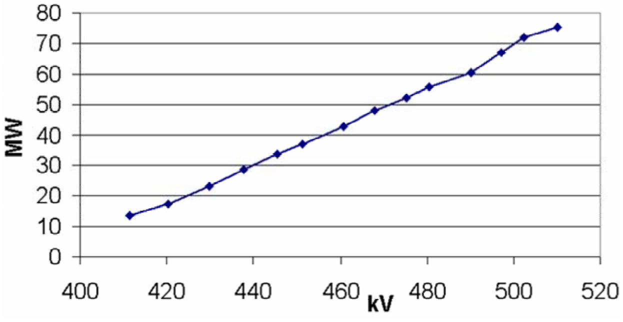

Figure 4: XP3-4 Saturated output power vs. voltage.

The spectral information from both klystrons shows no spurious frequencies at full power within 35 dB of the fundamental as seen in Figure 5. We have probes which look at the rf from: the output waveguides; a high-frequency coupler; the collector isolation ceramic; and the oil tank. The XP3-4 does have a gun oscillation below 500 kV due to insufficient loss material which was addressed in the XP3-5 during construction.

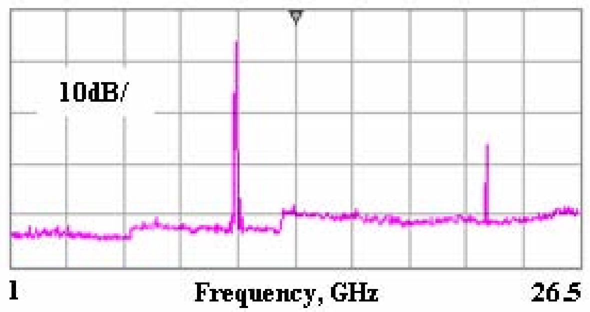

Figure 5: XP3-4 and XP3-5 spectral information.

Both XP3-4 and XP3-5 show a ~100 MHz 3 dB bandwidth as shown in Figure 6 which is deemed more than sufficient for accelerator operations. The XP3-4 is currently under test at full power and has accumulated 60 hours at 120 Hz full-spec operation. The XP3-5 is still processing up to the full pulse width and has reached 75 MW at 1 µs and 120 Hz

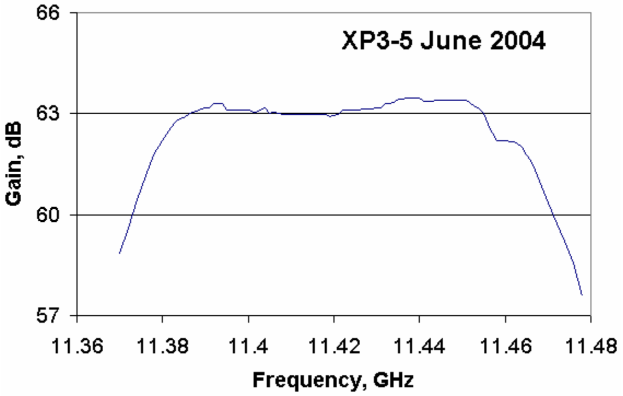

Figure 6: 3 dB bandwidth at a constant 10 MW.

FUTURE WORK

Work continues at SLAC to further optimize the RF power sources for high-energy collider designs. The successful operation of PPM klystrons is a major milestone in the improvement of overall efficiency of these systems. RF breakdown however, currently exceeds our design goal of 1 incident every half hour. Other considerations include reducing the cost of the high voltage pulse modulator for the klystron by lowering the operating voltage. This reduction of operating voltage can be accomplished through the use of multi-beam klystrons where several lower voltage beams are combined in parallel. Other possibilities include the sheet-beam klystron. In this latter device a broad rectangular beam is focused with permanent magnets through a series of high aspect ratio RF cavities. Advantages of a sheet-beam design include very high current capability allowing for high output powers at reasonable beam voltages. This arrangement may prove to be most cost effective due to simplicity of the mechanical design.

REFERENCES

[1] D. Sprehn, et al, “X-Band Klystron Development at the Stanford Linear Accelerator Center”, SPIE 2000 AeroSencse Symposium, Orlando, Florida, April 2000.

[2] E. Jongewaard, et al, “The Next Linear Collider Klystron Development Programr”, LINAC 2000 Monterey, California, August 2000.