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THE SECOND GENERATION SLAC MODULATOR*

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SUMMARY

The Stanford Linear Accelerator Laboratory has undertaken the construction of a single pass electron-positron collider. In order to reach required beam energy 235 new klystrons needed upgraded modulator systems.

The collider will use 50 GeV electrons and positrons. The increase in accelerator energy from the present 30 GeV necessitates the replacement of existing 35 MW klystrons with new 67 MW units. The doubling of klystron output power required a redesign of the modulator system.

The 67 MW klystron needs a 350 kV beam voltage pulse with a 3.7 μs pulse width. A new pulse transformer was designed to deliver the increased voltage and pulse width. Pulse cable design was evaluated to obtain increased reliability of that critical element. The modulator, with the exception of its power supply, was rebuilt to produce the required power increase while enhancing reliability and improving maintainability. An investigation of present thyratron switch tube performance under the new operating conditions resulted in agitation and some warranted panic but these conditions were mitigated after several successful experiments and some evolutionary narrowing of the klystron pulse width. The discussion to follow will cover the upgraded modulator system specifications and some details of the new pulse transformer tank, pulse cable, modulator, and modulator switch tube.

BACKGROUND

The klystron that made the Stanford two mile linear accelerator possible was the XK5.[1] The 30 GeV electron linac used 245 XK5 stations. The XK5 was initially designed for a 250 kV beam voltage but was later successfully operated at 265 kV with a pulse current of 273 A and a 2.5 μs flattop. The XK5 klystron specifications and modulator drive requirements are given in Table 1.

The modulator was of the classic line type with a pair of 10 section pulse forming networks (PFN's) in parallel which were subresonantly charged and thyratron switch discharged at up to 360 pps. The paralleled PFN's resulted from the inability to procure 42 kV, 5000 amp, 3.5 μs equivalent square wave (ESW) switches in 1963 and the consequent use of two smaller thyratrons discharging individual PFN's. Single thyratrons became available in 1964 from Tung-Sol/Wagner (CH1191) and ITT/Kuthe (KU275A) at which time the PFN's were paralleled at the thyratron anode. For the past 20 years these two tube types were successfully used. The average life of the 245 operating tubes has depended upon the accelerator operating regime. Thyratron lifetimes as high as 70,000 hours have been recorded with the accelerator operating at a low duty factor of 60 pps. The lifetimes for operation at 360 pps have averaged 10,000 hours. A program of scheduled ranging of the reservoir voltage has been responsible for the long lifetime and excellent performance (less than one fault or overcurrent per eight hour period).

TABLE 1. COMPARISON OF THE ORIGINAL AND SECOND GENERATION SPECIFICATIONS

KLYSTRON SPECIFICATIONS F = 2856 MHz	THE ORIGINAL	SECOND GENERATION
SLAC model designation	XK5	5045
Beam voltage (kV)	265	350
Beam current (A)	273	414
Microperveance	2	2
RF peak output power (MW)	35	67
RF pulse width (μs)	2.5	3.7
MODULATOR SPECIFICATIONS FOR MICROPERVEANCE=2	**THE ORIGINAL**	**SECOND GENERATION**
SLAC model designation	6575	150MW
Output voltage pulse (kV)	22	23.5
Transformer ratio	1:12	1:15
Maximum peak power (MW)	76	152
Maximum average power (kW)	96 @ 360pps	136 @ 180pps 91 @ 120pps
Thyratron anode voltage (kV)	44.2	46.7
Thyratron current (A)	3280	6225
Power supply voltage (kV)	22.2	23.5
Output pulse ESW (μs)	3.5	5.0
Repetion rates (pps)	60,120,180,360	60,120,180
Rise time (μs)	0.7	0.8
Fall time (μs)	1.2	1.8
PFN impedance (ohms)	7	4
PFN total capacitance (μF)	0.28	0.70

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The original SLAC klystron operated with a 1:12 step-up of the 22 kV modulator output pulse. The pulse transformer used a reset bias to minimize core size and weight. The resultant unit was small enough to be mounted in an oil tank with the klystron high voltage insulator and the assembly handled as a unit.

A triaxial cable connected the modulator cabinet to the pulse transformer tank. A plug on the triax connected to a socket on the pulse transformer tank to allow convenient disconnection of the klystron-tank unit for rapid removal and replacement. The cable plug and socket have been one of the less reliable parts of this system.

The system just described was operated essentially unchanged for 20 years. System availability met all requirements with a regular program of maintenance and detail improvement.

SECOND GENERATION REQUIREMENTS

The reconfigured accelerator/collider called the SLAC Linear Collider (SLC) will use 235 new high power klystrons and 13 XK5 klystrons. The 235 new klystrons will be pulse powered by an equal number of upgraded or second generation modulator systems. The second generation column in Table 1 lists the specifications of the new klystron and modulator, and the ensemble is shown in Fig. 1.

The klystron is designated the 5045[2,3] where the 50 referred to 50 MW peak power ability and the 45 refers to the 45 kW average power output. The 5045's were designed to deliver a 5 μs RF output pulse but after serious waveguide window and waveguide vacuum valve problems an investigative program determined that a shorter pulse would minimize or eliminate the problems. The pulse flattop was reduced to 3.5 μs and the output power was increased to 67 MW peak to maintain the required beam energy.

Fig. 1. Overall view of the modulator, pulse transformer tank, and klystron.

The modulator power supply designed in 1963 for a 24 kV maximum output and an average power output of 96 kW for 360 pps has remained virtually unchanged. The power supply cannot produce sufficient average power for operation beyond 120 pps but this pulse rate is sufficient for present requirements and can be increased later with replacement of the power supply transformer and choke. The maximum PFN charge is limited to less than 50 kV by the PFN capacitor rating and the allowable anode voltage of available air cooled thyratrons. Consequently the 100 kV increase in klystron beam voltage could only be obtained by increasing the pulse transformer step-up ratio, which meant not only a new transformer but a completely new pulse transformer tank assembly. It also meant a significant increase in PFN pulse width and in PFN discharge current so new capacitors were needed and an appropriate charging choke. Much consideration was given to the effect of this increased current on the pulse cable and especially the thyratron. Both units had operated satisfactorily with the XK5 klystron and the quantity on hand meant a large savings if they could me made to work with the new system.

THYRATRON INVESTIGATIONS

Historically, SLAC had pushed the operating parameters of the klystrons and hence the thyratrons. Every accelerator advance was followed by an engineered or operational improvement of the thyratron performance. The following discussion will consider the evolutionary path to the present 47 kV, 6500 A, 5 μs. ESW thyratron solution.

As development work proceeded on the pulse transformer and modulator, the thyratron investigations were continuing. The new specifications had placed a severe operating condition on the original thyratrons. As the transformer and modulator work entered the construction stage, the thyratron investigation still had not produced a viable solution.

Table 2 summarizes the operating parameters beginning in 1964 with line one and the arrival of the Wagner CH1191 and the ITT KU275. A few years later the klystron and hence the thyratron were pushed to the parameters shown on line two. In 1979 one sector of eight modulators was modified to produce the line three requirements for thyratron performance. The success with this mode of operation suggested line four and the present upgrading of the modulators.

In 1983 the prototype modulators were first operated with thyratrons that had been in use before the modulators were upgraded. The upgrade to the 6 μs ESW, 46 kV, 5300 A pulse (line four) resulted in thyratron failure within 48 hours. Brand new tube spares which were rated at 45 kV and 5000 A also failed at these operating conditions. The increase in current from 3400 A to 5300 A at that time seemed the obvious problem. Some tubes were capable of survival for several months but the fault rate with the new operating parameters was as high as several per hour. Thyratron operation at the level listed in line four and five Table 2 was difficult to achieve so improved thyratron cooling and state of the art thyratron replacements were suggested to meet these requirements.

Initial attempts to increase the cooling airflow were promising. Increasing the horizontal airflow across the anode was difficult because of the space available in the compartment so vertical airflow was implemented. The tube was mounted over a 150 cfm centrifugal blower and the fault rate was reduced but only with greatly impaired thyratron lead access for servicing or removal. Repackaging the thyratron seemed advisable to enhance thyratron serviceability.

During January 1985 a test modulator was set up with two standard SLAC thyratrons in a parallel connection. Each tube switched half of the PFN and both shared a grid driver and a PFN charging circuit. This configuration was run for 300 hours with a very acceptable fault rate at 180 pps and the power level of line six. The decision was made to allow for installation of two thyratrons per modulator with vertical air cooling and install either one or two depending on the success of a search for a commercially available single tube to meet the new specifications.

The 5045 klystrons were designed to deliver a 5 μs RF output pulse but after serious waveguide window and waveguide vacuum valve problems an investigative program determined that a shorter pulse would minimize or eliminate the problems. The pulse flattop was reduced to 3.5 μs but in order to maintain the required beam energy the klystron power was increased to 67 MW peak. The thyratron pulse requirements changed to 47 kV, 6500 A, for 5 μs ESW (line eight, Table 2).

As the pulse width was reduced from 6 μs (line five) to 5 μs (line eight) the prospect of using old tubes or new spares improved. There was a noticeable decrease in the time and effort required to process a tube for the 5 μs pulse width rather than the 6 μs pulse width in spite of the increased anode current from 5300 A to 6500 A. The current increase had a less adverse effect on tube performance than the benefit gained from reducing the pulse width. The overall gain in reliability and stability was significant. Either a single or dual tube solution looked promising and only long term operation of each set up could determine the actual performance advantages.

The search for replacement tubes continued because of the expense associated with dual tubes and the requirement for a better tube should long term tests prove disastrous to the lifetime of on-hand tubes. The search resulted in contact with four suppliers: EG&G, English Electric Valve, ITT and Omni-Wave Electronics. The following tubes are currently being tested: the CX1536A from EEV, the F-241 from ITT, and the 1002 from Omni-Wave (a rebuilt Tung-Sol/Wagner CH1191).

All thyratrons are processed through a receiving test modulator at 180 pps to the specifications of line eight Table 2. An acceptable tube must run at least 8 hours with not more than one high voltage over current fault. Each supplier has had at least one tube pass this test without a single fault. Also each has had more than one tube fail the test. In most cases the tubes were returned for reprocessing and accepted upon retest. There is a distinct possibility that rough handling during shipping is a major cause of failure during test.

The present thyratron situation will be described.

The klystron test stands are operating very favorably with 1 Omni-Wave, 2 ITT, and 7 EEV tubes.

We have 15 EEV tubes operating successfully, eight are in Sector 10 accelerator modulators and 7 are in klystron test stands. There are 41 tested EEV tubes in the uncommitted spares inventory.

The procurement effort with ITT started with the F175 new design. This evolved through F175A, B, C and D. The F175C and F175D tubes were accepted on test and are presently operating in Sector 22. ITT then produced the F241 series. SLAC has purchased 8 prototypes which were accepted and presently we are receiving tubes on a 16 tube purchase. One of the F241 series is in Sector 22 and has been operating since October 1985, and 6 other tubes are running in Sector 19.

The first Omni-Wave tube delivered was accepted and operated 4300 hours in a klystron test stand at the levels shown on lines four and eight, Table 2, it was then moved to an upgraded modulator in Sector 16. We have ordered 10 prototypes and 16 production units and presently 22 have been accepted. Four of these tubes are in Sector 22 and 7 are in Sector 20.

At this time the upgraded requirements are being met with the thyratrons on hand and new units from three suppliers, all with acceptable fault rates when operated at levels shown on line eight, Table 2. With regard to tube lifetime in this service, only with more time at full power will the relative merits of the different tubes be apparent. Presently we have 24 dual tube modulators and 128 single tube units in operation.

TABLE 2. HISTORICAL PROGRESSION OF THYRATRON OPERATING CONDITIONS AS A FUNCTION OF THE KLYSTRON PULSE SPECIFICATIONS

	DATE & OPERATION	KLY. BEAM VOLT (kV)	PULSE FLAT-TOP (μs)	PULSE ESW (μs)	THY. ANODE VOLT (kV)	PEAK ANODE CURRENT (A)[1]	PEAK ANODE CURRENT (A)[2]	PEAK POWER (MW)[2]	PULSE XFMR RATIO
1.	1963 Original	250	2.5	3.5	41.7	3000	3150	65.7	1:12
2.	1967 Pushed	265	2.5	3.5	44.2	3276	3438	75.9	1:12
3	1975 Wide Pulse	265	5.0	6.2	44.2	3276	3438	75.9	1:12
4.	1983 Test Stand	315	5.0	6.2	46.4	5188	5447	126.0	1:14
5.	1983 2nd Gen.	315	4.6	6.0	45.7	5166	5321	121.6	1:14
6.	1985 Dual Thy (1:14)	315	4.6	6.0	45.7	2583[3]	2661[3]	60.8[3]	1:14
7.	1985 Dual Thy (1:15)	350	3.7	5.0	46.7	3115[3]	3250[3]	75.8[3]	1:15
8.	1985 2nd Gen.	350	3.7	5.0	46.7	6225	6500	151.6	1:15

[1] 2.0 MICROPERVEANCE KLYSTRON

[2] 2.1 MICROPERVEANCE KLYSTRON

[3] PER THYRATRON

PULSE TRANSFORMER TANK UPGRADE

The previous pulse transformer tank design had performed well over the 20 years it had been in use, so the basic concept was not changed but almost all components had to be redesigned due to the increased energy to be handled. The pulse transformer nearly doubled in size and weight so a much larger tank was needed (see Fig. 2). A more efficient tank cooling system was required to deal with the increased heat from pulse transformer losses and increased filament dissipation. The previous filament had required up to 400 W but the new klystron design called for 1000 W to be available, and most of this heat would be dissipated through the tank cooling system so a copper coil was designed to be attached to the tank lid and contain circulated deionized water.

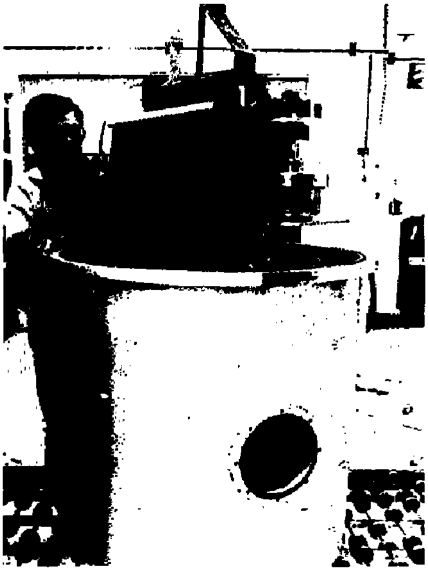

Fig. 2. The pulse transformer with base plate and tank.

The increased filament power meant a much larger filament transformer. In order to minimize the current in the bifilar windings of the pulse transformer the ratio was changed from 5:1 to 10:1 so current would be limited to 5 A to keep resistive loss to a minimum. The filament current had been conducted to the base of the klystron by four pressure contacts but the new higher secondary current would have required as many as nine contacts and space was restricted so it was decided to attach the filament transformer to the base of the klystron, allowing bolted secondary connections. A handhole was added to the tank design to allow connection of the filament primary leads to connectors on top of the pulse transformer secondary windings. These leads and connectors only had to handle 5 A instead of 50 A, with all high current carried through bolted connections.

The handhole for filament connection had several additional benefits. By making the cover out of thick polycarbonate a window was provided to allow tank inspection and aid in troubleshooting. Previously a rupture disk had been used to prevent excessive tank pressure due to arcing in the oil, but units that would withstand a vacuum inside the tank but blow out under as little as five psi had been quite fragile and expensive. By securing the window with spring assemblies a very large area was made available for release of pressure pulses. The window seals quite well under vacuum, and is less expensive and less fragile than the rupture disks previously used. The window also reseals itself after a pressure pulse after releasing only a minimum amount of oil but the rupture disk, once used, remains open and makes a real mess.

The tank circuitry as shown in Fig. 3 was not greatly changed. In the past the filament circuit had been connected to the bifilar pulse transformer with one side grounded and the other side grounded through capacitors. The new tank circuit has both sides grounded through capacitors at the bottom and pulse current connected to the klystron cathode through capacitors in a symmetrical manner at the top of the pulse transformer. The filament transformer primary is center tapped to allow for discharge of these capacitors. Additionally, a current transformer was added at the bottom of the pulse transformer secondary to allow more accurate monitoring of pulse current than the previously used primary current transformer in the modulator allowed.

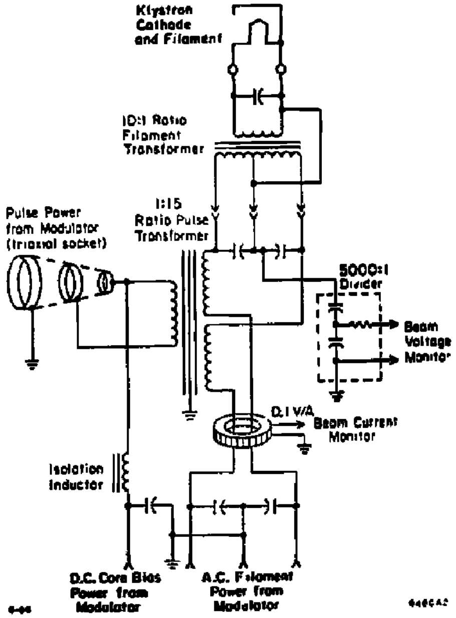

Fig. 3. Pulse transformer circuit.

The only component salvaged from the old pulse transformer tanks was the voltage divider. It had been designed to operate at 250 kV but when fitted with a smaller center electrode proved to be usable at the proposed new level of 320 kV. When the klystron operating voltage was increased to 350 kV by changing from 1:14 to 1:15 pulse transformer ratio, a new voltage divider was needed and a unit was eventually procured that would mount in the available space and withstand up to 400 kV.

TRIAX PULSE CABLE

The pulse transformer tank, and therefore the klystron, is connected to the modulator by a short flexible triaxial cable with a plug at the tank and to allow convenient disconnection for klystron changes. Since the cable is short it must be quite flexible to allow the plug end to be withdrawn from the socket on the tank, yet carry pulse current of over 5 kA at over 25 kV. The characteristic impedance must be low and the cable must withstand as much as 10 kV from inner to outer shield, so selection of the cable is not easy. Two types have been used, one is a silicone rubber insulated construction that is no longer made, the other has an insulation made up of layers of polyethylene tape impregnated with thick silicone oil. This cable is not widely available. Over the last 20 years both constructions had been used, supplied by three different assemblers. Some units had lasted over 15 years, but later units of a slightly different design had an average service life of about six months.

Despite these disadvantages, it appeared the cable would be usable at the new higher energy level. Cables had been run at the new current level in the past, and at the higher voltage level, but not under both conditions simultaneously. It was decided to use the existing design in the klystron development program and see how it held up. Results were encouraging so the design was retained.

It was eventually determined that the basic cable design would be usable with the new klystron, but the design flaws of the recent units must be avoided. A new specification was written concentrating more on required performance of the cable assembly, leaving selection of cable and connector design to the vendor. The cables eventually received are very similar to units previously supplied with minor mechanical design changes only (Fig. 4, bottom).

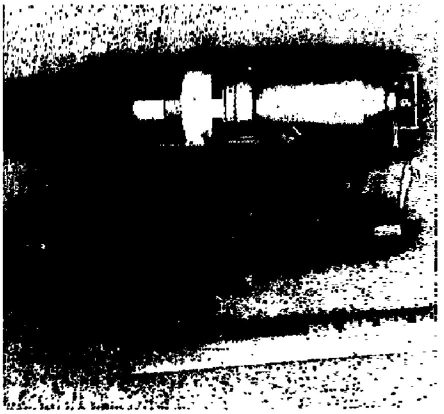

Fig. 4. Pulse cable plugs and a cross sectioned socket.

The plug and socket were modified slightly to increase dielectric strength between inner and outer shield circuits. Voltage as great as 10 kV had been measured and breakdown was causing socket damage and premature cable failure. Some changes were also made in the connections at the modulator end to allow easier cable installation and to replace a section of braid in the return circuit with copper sheet to reduce inductance and thus reduce voltage drop between tank "ground" and modulator ground.

MODULATOR UPGRADE

The first element in the modulator upgrade to undergo analysis was the D.C. charging supply. Table 1 indicates the original supply was capable of producing 96 kW of average power. The new klystron requires a 30% increase in average power for 180 pps and no power increase for 120 pps operation. The 30% increase would require the replacement of the a.c. switchgear, transformer, filter choke, and capacitors. Rework or replacement of the power substations which supply 3 phase voltage to the 235 modulators would also be required.

With the above work and expense contrasted to what it would take to operate the klystrons at 120 pps, the decision was made to direct the funding toward replacement of the PFN capacitors, charging chokes, and pulse transformers. These costs and the effort required to implement them are about one third of the total modulator and power supply upgrade costs. The power supply upgrade hence awaits further funding and depends upon the success of a completely reconfigured accelerator and the desire of its designers to increase the duty cycle.

The increase in pulse width and decrease in load impedance meant a total replacement of the PFN capacitors. The original PFN used 20 capacitors for a very smooth and finely tunable flattop. The new klystrons will operate into the SLED cavities[4] which don't demand perfect flattops, but some accelerator applications will still require modest flattop smoothness. As a consequence, 16 capacitors are used in the second generation modulator with a 20% cost savings and some future flexibility. The four empty PFN positions could be filled later for a longer pulse.

The total PFN capacitance was increased from 0.28 μF to 0.70 μF to increase the pulse width and decrease the characteristic impedance. Two vendors supplied the specified 0.044 μF capacitors. The incoming units were tested at 180 pps with a 48 kV, 6500 A, 5 μs ESW pulse width. One vendor's units failed because of an internal lead that was insufficiently protected from high voltage stress. This vendor responded with improved units which are operating satisfactorily.

A simplified schematic of the modulator is shown in Fig. 5 indicating the values of the major components and the layout of major circuits. This diagram illustrates the paralleled PFN's and possibility of separate thyratrons discharging the individual PFN's. Each PFN capacitor bushing is topped with an adjustable coil. PFN pulse tuning is accomplished with these coils.

The photograph of Fig. 6 shows two of the three modulator cabinet compartments. The left compartment holds the thyratron, thyratron chassis, charging components, deq'ing circuit, and end of line clipper circuit. The PFN is in the right compartment. Each capacitor is installed on a shelf in a totally enclosed structure supported on four insulators. The d.c. power supply is in the third compartment.

The increase in PFN capacitance combined with the reduced pulse rate (360pps to 180pps) dictated the charging choke specifications. The 2.4 H choke has three times the inductance of the original and will handle 30% more current, consequently it doubled in size. The slower charging time also benefits the

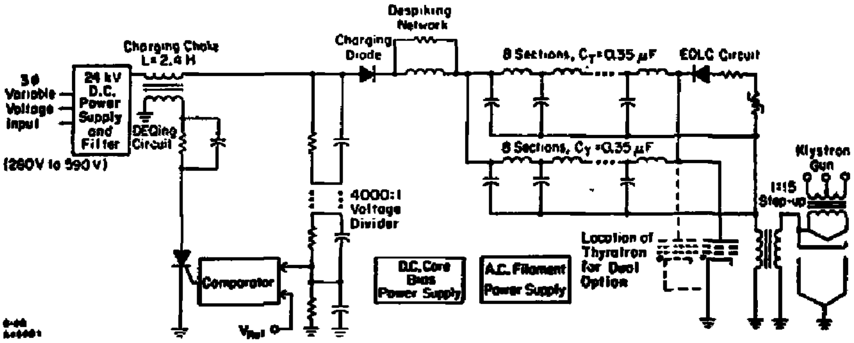

Fig. 5. Simplified modulator schematic.

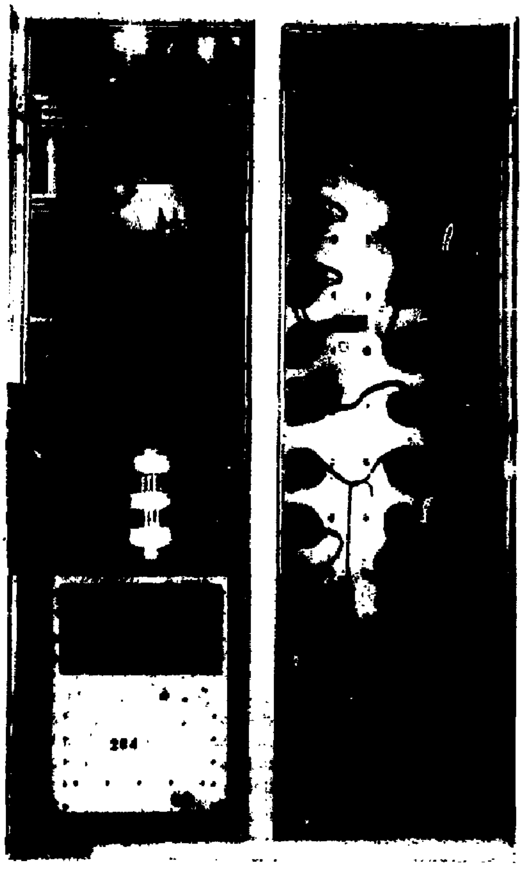

Fig. 6. The thyratron and PFN compartments in the modulator cabinet.

thyratron recovery time. A deq'ing secondary is incorporated into the design and shown in Fig. 5 with associated circuitry.

The bigger choke required a total rearrangement of the thyratron compartment and hence forced a reevaluation of the circuits and components within the compartment. The energy dissipating resistor in the deq'ing circuit was moved outside the cabinet to a spot over the PFN enclosure exhaust fan. The remaining deq'ing parts were arranged together on a panel above the choke with the components placed in the airstream of an exhaust fan. Either the panel or individual parts can be easily replaced.

The end of line clipper (EOLC) circuit was also rearranged but redesigned as well to accommodate the choke. The redesign reduced the circuit area and inductance by employing Carborundum type resistors, large surface conductors, and improved packaging of the thyrite disc clipper. Overall inductance has been reduced by two thirds. The thyratron and PFN capacitors benefit from this improvement since reverse voltage excursions are clipped in a shorter time and the EOLC interlock reacts more quickly than was originally possible.

Improving the thyratron cooling offered an opportunity to improve the system of thyratron installation and service. The thyratron is permanently attached to an aluminum can which functions as an air duct, connector mount, and provides a flat bottom on which to stand the thyratron. The can attaches to the bottom of a slotted flange which supports the tube on the top plate, makes the cathode connection to the chassis, and passes cooling air to the anode fins via the slots. The flange uses four spring clips to locate an acrylic chimney that directs cooling air along the tube body and past the grid and anode cooling fins. The can and flange were designed to accept thyratrons from a variety of manufacturers. Figure 7 shows the final packaging of three thyratrons.

A new thyratron chassis equipped with a centrifugal blower rated at 250 cfm is mounted below the top plate. The canned thyratron, as it is called, is lowered into the chassis top plate and fastened with four bolts which also mount the spring clips. The chimney is slipped over the tube prior to making the anode connection. Holes in the chimney allow the grid connections to be made with plugs pushed into sockets on each grid. A high current socket was used for the common lead and plugs were used for the heater lead and reservoir lead. The cables that supply power from the appropriate transformers are connected

Fig. 7. Canned thyratrons from various manufacturers.

to the can by mating connectors which are sized and polarized to prevent misconnection. A banana plug and socket are used to supply a keep-alive voltage and a two pin connector is used to connect interlock circuitry to the over temperature thermostat mounted on the thyratron flange.

The ongoing thyratron difficulties made the old concept of using individual thyratrons for each PFN half appear very attractive. The dual thyratron idea used the original tubes but required careful layout and repackaging of auxiliary circuits to fit both tubes into the space available. The control grid circuit was redesigned and a new two resistor gradient grid divider replaced the original 100 resistor divider to save space. The redesigned dual grid circuit uses a slightly different pi filter, thyrite overvoltage limiter, and new control grid voltage divider. This modular assembly is in contrast to the former circuit which was scattered across the top plate. As has been mentioned, the present thyratron chassis is designed to accept either one or two thyratrons.

PRODUCTION

Production of the pulse transformer tanks began with creation of specifications for the major components. The pulse and filament transformer, current transformer, and the tank itself were bought to specifications and with delivery scheduled to meet the production schedule and vendor capability.

As previously mentioned, almost nothing was used from the existing pulse transformer tanks. Some of the triaxial cable sockets were reused after reconditioning and the hermetic seal connectors for filament and core bias connection were reused where possible. The new pulse transformers are assembled to an aluminum baseplate with all other circuit components except the filament transformer, then the baseplate is installed in the tank and a test lid with water load is installed. The tank is filled with oil under vacuum and run at full power into the water load to check circuit function under voltage and for final calibration of the voltage divider. The filament transformer is tested separately for proper connections and ratio. Then the tank is emptied, sealed with a shipping lid and placed under vacuum, and sent out with a boxed filament transformer for installation of a klystron.

Even before the beginning of modulator rebuilding, pulse cables were in short supply as the most recently received shipment had an unexpectedly short operating life. A program was established to rebuild the failed cables and return them to service as rapidly as possible. Almost all failures were with the plug part of the cable. At first there was damage between the inner and outer shield portions of the plug because of incompatibility between plug and socket. All plugs were immediately modified to provide more clearance and that problem disappeared. Refer to Fig. 4 where the plug modification is shown in the sectioned socket. Extensive deterioration of the high voltage insulation on the plug was and still is the primary failure mode with these cables. This insulation attaches to the internally threaded body of the plug and high electrical stress around these threads leads quickly to complete destruction of the insulating material. The plugs are readily repaired by removing all of the insulating and stress grading material down to cable insulation, then replacing it with a layer of heat-shrink tubing of high dielectric constant to provide improved stress distribution and a layer of exterior shrink tubing for environmental protection. Before installation of the tubing, the inner shield contact assembly is removed, the internal threads are machined out and the edge is finished to a smooth radius. New contact fingers are fitted if needed and the part is reinstalled. The finished cables are tested for continuity and insulation resistance, then returned to service. Service life of the assemblies as originally supplied was about six months, rebuilt units were first put in service about 14 months ago and are still in use.

A process has been developed to upgrade the modulators in place in the accelerator gallery. The conversion crew disassembles the original modulator, retaining components used in the reconstruction. Then the cabinet and components are steam cleaned. The reused and new parts are reassembled, installed, numerous wiring changes made and then the converted unit is carefully inspected. When the upgraded modulator passes the visual, mechanical, and electrical inspections it is operated for three hours into a transformer coupled dummy load. The 5045 klystron is then installed and powered up.

OPERATING EXPERIENCE

Thyratron experience at the upgrade power level 47 kV, 6500 A, and 5 μs ESW has been gained with five operational sectors, The five Sectors 18, 19, 20 and 22 have run an average of 300 hours at 60 pps and 400 hours at 120 pps. During this time no tube failures occurred. Sector 21, which is one of the dual tube sectors, has the longest running time with an average of 2400 hours at 60 pps and 600 hours at 120 pps at the same level. During this time one tube failed but it had previously logged 18,000 high voltage running hours, an acceptable lifetime.

In June of 1986, 152 upgraded modulators are operating. It is very rare to experience modulator problems after the testing process. The most serious problem with the operational modulators was a failure of the PFN capacitors at the 120 pps rate. This problem was discovered after about 600 hours of operation at 120 pps in four sectors. Our acceptance tests had been performed at 180 pps but were limited to 500 hours using only one test modulator. The vendor has apparently solved this with a completely redesigned capacitor.

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