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PREFACE

FUNDAMENTALS OF KLYSTRON TESTING is a text primarily intended for the indoctrination of new Klystron Group test stand operators. It should significantly reduce the familiarization time of a new operator, making him an asset to the Group sooner than has been experienced in the past.

The new employee must appreciate the mission of SLAC before he can rightfully be expected to make a meaningful contribution to the Group's effort. Thus, the introductory section acquaints the reader with basic concepts of accelerators in general, then briefly describes major physical aspects of the Stanford Linear Accelerator. Only then is his attention directed to the klystron, with its auxiliary systems, and the rudiments of klystron tube performance checks.

It is presumed that the reader is acquainted with basic principles of electronics and scientific notation. However, to preserve the integrity of an "indoctrination" guide, tedious technical discussions and mathematical analysis have been studiously avoided.

It is hoped that the new operator will continue to use the text for reference long after his indoctrination period is completed. Even the more experienced operator should find that particular sections will refresh his understanding of basic principles of klystron testing.

J. William Caldwell, Jr., 1975

ACKNOWLEDGMENTS

Most of this text was prepared in the Klystron Laboratory of the Stanford Linear Accelerator, supported by the Department of Energy.

The uniqueness of high powered klystron testing affords very little recorded information to the individual in search of fundamental concepts. Consequently, the experience of the Klystron Group members proved to be the most vital source of information for this text.

It would have been impossible to complete this endeavor without the help of almost everyone in the Group. In particular, I would like to acknowledge just a few persons who rendered me invaluable assistance:

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SECTION I INTRODUCTION

SO WHAT ARE WE DOING HERE?

Stanford Linear Accelerator, a national experimental facility, is one of several accelerators built since WWII for the study of elementary-particle physics using high energy beams.

At the present time, scientists worldwide have discovered approximately 200 sub-atomic particles, which can be examined in an effort to understand the fundamental properties of all matter. This knowledge can be a powerful tool in solving some of the complex technological problems that face contemporary society. Practical applications of recent studies have already resulted in exciting breakthroughs in a variety of fields, from communications to medical technology. For example, the electron-microscope was one of the earlier inventions that resulted from the initial studies of elementary-particle physics.

HIGH ENERGY BEAMS

Why are high energy beams necessary to study these particles? An oversimplified explanation can be offered. The smaller a particle is in size, obviously the more difficult it is to "see". Thus the instrument used to examine this small particle must have a high resolution ability. This resolution is limited by the wavelength of the "light" which illuminates the particle under study. In other words, the shorter the wavelength of the "light", the smaller the object it will be able to illuminate.

It has been determined that this wavelength is inversely proportional to the illuminating particle's energy. Thus, the higher the energy of the illuminating beam, the smaller its wavelength, and the smaller the object that may be examined.

SO WHAT KIND OF BEAM DOES SLAC USE?

Modern accelerators use two species of illuminating devices, either electrons or protons. These particles are raised to a high

energy level, then shot as a beam at the "target" under study. Figure I-1 illustrates the basic components of a linear accelerator.

Figure I-1: Simplified Accelerator

Both the electrons and the protons interact with their nucleus targets in much the same manner. But the proton (being a nuclear particle itself) causes extra activity involving nuclear forces.

With all else being equal, the net effect is that the proton interaction is more complicated to interpret than the electron interaction. Of course, the advantage of the proton is that it interacts in more variable and interesting ways than the electron. But since the electron interaction is much easier to interpret, the electron beam has been selected for use at Stanford. From an electron, a positron can be generated, and in fact positrons are also utilized as a beam supply in our accelerator.

WHY IS THE ACCELERATOR SO STRAIGHT?

As you probably already know, there are round accelerators, too, called cyclotrons. Both the cyclotron and the linear accelerator have their own inherent advantages. Some considerations involved in deciding that SLAC should be a linear type accelerator were:

1. There are lower energy losses in the electron beam of a linear accelerator, because electrons lose energy when they travel a curved path. Thus, for a given beam, higher energy can be delivered on "target" in a linear accelerator than in a cyclotron.
2. Injection and extraction of the beam is much simpler in a linear accelerator.

One major disadvantage of a linear accelerator, however, is the necessity of duplicating power sources along the entire length of the beam. Only one power source is required in a cyclotron.

Not to be confused with cyclotrons are the SLAC colliding beam storage rings, PEP and SPEAR. These rings siphon off a portion of the linear accelerator beam for their source of high energy particles. The nature of the design of the storage rings enables them to achieve much more forceful collisions than the linear accelerator, which expands the range of possible experiments at SLAC. The very informative SLAC BEAM LINE offers a detailed description of both PEP and SPEAR.

HOW DOES THIS BEAM WORK?

The "accelerating" mechanism of the beam can best be described in terms of imparting energy to the beam, measured in electron volts. A strong electric field is supplied, which applies force to the electron by means of its electric charge. Refer to Figure I-2, which illustrates a cylindrical waveguide, through which an electron beam is traveling. An electric field is injected that travels with the anticipated speed of the electrons, essentially the speed of light.

Figure I-2: Cylindrical Waveguide

If the arrival of the electron is timed to coincide with the crest of the electric field, the electron will be "accelerated"; i.e., the maximum energy will be imparted to the electron. It is apparent that bunching and phasing are important.

The energy imparted to the beam is directly proportional to the number of energy injectors deployed along the waveguide. In our case, SLAC uses approximately 243 klystrons spaced equidistant along the accelerator waveguide. The total beam energy approaches 25 Gev. Remember, the higher the beam energy, the smaller the target particles that may be "seen", and the more elaborate the experiments that the physicists are able to conduct. Thus, the SLAC Klystron Department continuously strives for higher output and more stable klystron tubes.

WHY WAS THE KLYSTRON PICKED AS AN ENERGY INJECTOR?

Other devices could have been used, such as the magnetron or the amplifron, but the Klystron has desirable properties that are especially attractive for accelerator applications. It can generate unusually high voltages at RF frequencies with only a moderate power consumption. Since klystrons can be driven from a common source, phase stability for the entire beam is easier to achieve. Also, klystrons can be pulsed, which results in higher peak power than continuous operation, and this in turn enables a higher electron beam energy to be produced.

PHYSICAL DESCRIPTION OF SLAC

The accelerator complex extends two miles long. It consists of the Accelerator Housing, the Klystron Gallery, the Central Control building and the Beam Switchyard and End Stations. Refer to Figure I-3, and the schematic representation of our linear accelerator in Figure I-4.

The accelerator itself is a disc-loaded, cylindrical copper waveguide, buried 25 feet below the ground to shield the operators from radiation. It is constructed of 960 - 10 ft. sections of waveguide. Spaced along its length at various points are focusing devices and beam monitoring equipment.

The 243 klystrons that power the beam are spaced approximately 40 ft. apart along the accelerator. For maintenance purposes, the

Figure I-3: SLAC Layout

Figure I-5: General Arrangement of a Klystron Hookup

Accelerator Housing and Klystron Gallery are subdivided into 30 "sectors" along its length. Part of a typical sector is shown in Figure I-5.

Each 333 ft. sector is comprised of 8 klystrons and their modulators, and one sub-booster klystron providing the drive power for that sector's power klystrons. This is graphically illustrated in Figure I-6. Each modulator supplies pulsed DC power to its respective klystron. A Master Oscillator located in Sector One generates a 476 MHz drive signal, which is amplified by a main booster amplifier and applied to the 2 mile long main drive line. At each sector, the drive signal is coupled to a frequency multiplier which raises it to 2856 MHz, then amplified by a sub-booster and applied to that sector's eight klystron tubes. The output pulse of the klystron is coupled to the accelerator waveguide as depicted in Fig. I-5.

Note that this particular drive system enables all 8 klystrons in each sector to have the same phase stability, which can be monitored and adjusted by the Central Control station.

Figure I-6: Diagram of One 333 Ft. Sector

SECTION II THE HIGH POWERED KLYSTRON

Now that the role of the klystron in SLAC operations has been defined, perhaps it is time to take a closer look at the tube itself.

The klystron tube is a stable microwave power amplifier which provides high gain at medium efficiency. Depending on the type of tube, klystron power outputs range from a few milliwatts to several megawatts peak power, and over 100 kilowatts average power. Power gains vary from 3 to 90 db. SLAC klystrons have achieved a 40 MW peak power, with about 36 kW average power at approximately 50 db gain.

WHY CAN'T A STANDARD VACUUM TUBE BE USED TO AMPLIFY MICROWAVES?

In a regular triode vacuum tube, the time it takes electrons to cross the tube is on the order of a billionth of a second. This transit time is short compared to the period of a cycle of a radio wave below the microwave range (approximately a millionth of a second). Hence, the electrons are slowed or speeded up by the voltage on the grid at a given instant. The flow of electrons, therefore, can follow the voltage fluctuation on the grid. In the case of microwaves, however, the oscillations are so rapid (i.e., the period of a cycle is so short) that the voltage on the grid may go through several complete oscillations while a particular quantity of electrons travel across the tube. In other words, the grid voltage changes too rapidly for the electrons to follow the fluctuation. There are other reasons why the conventional triode tube fails at microwave frequencies, but the most fundamental reason is that the transit time of the electrons is long compared to the period of one cycle of the microwave signal.

SO THEN HOW DOES THE KLYSTRON WORK?

The klystron tube makes a virtue of the very thing that defeats the triode - the transit time of the electrons. The klystron modulates the velocity of the electrons, so that as the electrons

travel through the tube, electron bunches are formed. These bunches deliver an oscillating current to the output resonant circuit of the klystron. Figure II-1 shows a cutaway representation of a basic klystron amplifier. The klystron consists of three separate sections; the electron gun, the RF section, and the collector.

Figure II-1
Basic Klystron Amplifier

Consider first the electron gun structure. It consists of a heater, cathode, and anode. Electrons are emitted by the cathode and drawn toward the anode, which is operated at a positive potential with respect to the cathode. The electrons are formed into a narrow beam by magnetic focusing techniques (not shown on Fig. II-1).

The electron beam is well formed by the time it reaches the anode. The beam passes through the anode and on to the RF section of the tube, and eventually strikes the collector. The electrons are returned to the cathode through an external power supply. It is evident that the collector of a klystron acts much like the plate of a triode insofar as the collecting of electrons is concerned. However, there is one important difference. The plate of a triode

is normally connected, in some fashion, to the output RF circuit, whereas, in a klystron amplifier, the collector has no connection to the RF circuitry at all.

Now consider the RF section of a basic klystron amplifier. This part of the tube is quite different from a conventional triode tube. The resonant circuits used in a klystron amplifier are resonant cavities, tuned to a particular frequency.

Referring to Fig. II-1, electrons pass through the cavity gaps in each of the resonators as well as the cylindrical metal tube between the gaps. These metal tubes are called "drift tubes". In a klystron amplifier the low level RF input signal is coupled to the first resonator, which is called the "buncher cavity". On the SLAC tubes, the signal is coupled through a coaxial connection. If the cavity is tuned to the frequency of the RF input it will be excited into oscillation. An electric field will exist across the buncher gap, alternating at the input frequency. For half a cycle, the electric field will be in a direction which will cause the field to decrease electron velocity. This effect is called VELOCITY MODULATION, and is illustrated in Figure II-2. Note that when the voltage across the cavity gap is negative, electrons will decelerate; when the voltage is zero, the electrons will be unaffected; and when the voltage is positive, the electrons will accelerate.

After leaving the buncher gap (Fig. II-1) the electrons proceed through the drift tube region, toward the collector. In the drift tube region, electrons which have been speeded up by the electric field in the buncher gap will tend to overtake electrons which have been slowed down. Due to this action, bunches of electrons will begin to form in the drift tube region and will be completely formed by the time they reach the gap of the last cavity. The last cavity is called the catcher cavity. Figure II-3 illustrates this bunching action.

Figure II-2: Velocity Modulation

Figure II-3: Bunching Action

Bunches of electrons periodically flow through the gap of this catcher cavity, and during the time between bunches relatively few electrons flow through the gap. The time between arrival of electron bunches is equal to the period of one cycle of the RF input signal.

The initial bunch of electrons flowing through the catcher cavity will cause the cavity to oscillate at its resonant frequency, setting up an alternating electric field across the catcher cavity gap. With proper design and operating potentials, a bunch of electrons will arrive in the catcher cavity gap at the proper time to be retarded by the RF field. Thus, energy will be given up to the catcher cavity by the slowed down electrons.

The RF power given up to the catcher cavity will be much greater than that applied by the drive power in the buncher cavity. This is due to the ability of the concentrated bunches of electrons to deliver great amount of energy to the catcher cavity. Since the electron beam delivers some of its energy to the output cavity, it arrives at the collector with less total energy than it had when it passed through the input cavity. This difference in beam energy is approximately equal to the energy delivered to the output cavity.

It is appropriate to mention here that velocity modulation does not form perfect bunches of electrons. There are some electrons

which come through out of phase. These electrons show up in the output cavity gap between bunches. The electric field across the gap at the time these out-of-phase electrons come through is in a direction to accelerate them. This causes some energy to be taken from the cavity. However, much more energy will be contributed to the output cavity by the concentrated bunches of electrons that will be withdrawn from it by the small number of out-of-phase electrons.

THE MULTICAVITY POWER KLYSTRON

In the above discussion, only a basic two-cavity klystron has been considered. This simple type of klystron amplifier is not capable of the high gain, high output power, or suitable efficiency demanded by SLAC applications. With the addition of intermediate cavities and other physical modifications the basic two-cavity klystron may be converted to a multicavity power klystron. This tube is capable of high gain, high power output, and satisfactory efficiency. Figure II-4 illustrates a multicavity power klystron amplifier.

In addition to the intermediate cavities, there are several physical differences between the basic and multicavity klystron. The cathode of the multicavity power klystron must be larger, in order to be capable of emitting large numbers of electrons. The shape of the cathode is usually concave, to aid in focusing the electron beam. The collector must also be larger to allow for greater heat dissipation. In a high power klystron, the electron beam strikes the collector with sufficient energy to cause the emission of X-rays from the collector, and thus requires lead shielding around the collector as protection against this radiation. Most high power klystrons are liquid cooled and must be constructed to facilitate the cooling system. (Klystron cooling will be discussed in greater detail in a subsequent section.) Figure II-5 is a cutaway drawing of a Stanford 2422 High Power Klystron, and readily illustrates these physical characteristics.

Figure II-4: Multicavity Klystron

Figure 11-6: The Stanford 100P Akytron

the output of the amplifier is a function of the input signal. The output signal is a function of the input signal, and the output signal is a function of the input signal. The output signal is a function of the input signal, and the output signal is a function of the input signal.

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Figure 11-7

Curve A of Fig. II-6 shows typical performance for synchronous tuning. Under these conditions the tube has maximum gain. The power output is almost perfectly linear with respect to the power input, up to about 70% of saturation. However, as the RF input is increased beyond that point, the gain decreases and the tube saturates. As the RF input is increased beyond saturation the RF output decreases.

To better understand the reason for this decrease, recall that in the previous discussion, electron bunches were formed by the action of the RF voltage across the buncher cavity gap. This RF voltage accelerated some electrons and slowed down other electrons, resulting in formation of bunches in the drift tube region. Obviously, this speeding up and slowing down effect will be increased as the RF drive power is increased. The saturation point on Fig. II-6 is reached when the bunches are most perfectly formed at the instant they reach the output cavity gap. This results in the maximum power output condition. When the RF input is increased beyond this point, the bunches are perfectly formed before they reach the output gap. That is, they form too soon. By the time the bunches have reached the output gap, they tend to debunch because of the mutual repulsion of electrons and because the faster electrons have overtaken and passed slower electrons. This causes the output power to decrease.

If a multicavity power klystron is stagger tuned, with the next to the last cavity tuned slightly highest, the gain of the amplifier is reduced, but the saturation power output level may be increased. This effect is shown by curves B and C of Fig. II-6. Curve B represents a small amount of detuning of the next to the last cavity, and curve C represents even more detuning. Note that the gain of the tube has been reduced, and that the saturation output power is higher than that obtained with synchronous tuning (curve A). Thus, SLAC power klystrons are operated stagger tuned at the saturation point because of the resulting higher output power capability with the same beam power input.

As might be expected, stagger tuning may be carried too far, at which point the saturation output power will drop, as illustrated by curve D of Fig. II-6.

FOCUSING

One very important item which is required for high power klystron tube operation is an axial magnetic field (i.e., a magnetic field parallel to the axis of the klystron). In SLAC klystrons, which are physically long, it is quite difficult to keep the electron beam properly formed during its travel through the long RF section. The mutual repulsion between electrons causes the beam to spread in a direction perpendicular to the axis of the tube. If this is allowed to occur, electrons will strike the drift tube and be collected there, rather than passing through the drift tube to the collector.

To overcome beam spreading, an axial magnetic field is used. The action of the magnetic field is to exert a force on the electrons which keeps them focused into a narrow beam. The magnetic field may be developed by a permanent magnet or by one or more electromagnets. Most SLAC tubes currently use the permanent magnet arrangement. Alnico 8 permanent magnets are employed with shunts and bar magnets to "fine tune" the beam to approximately .8 inch in diameter.

....AND LET'S NOT FORGET THE WINDOW!

While it would be proper to assume that most of the basic operating principles of the klystron have been discussed, it is impossible not to mention the importance of a component that is just as vital to SLAC applications as the klystron itself; the "window".

The output window is physically located in the RF output waveguide of the klystron, and can be clearly seen on Fig. II-5.

The window performs a function that its name implies; i.e., it acts as a "window" to RF energy, out as a physical barrier between the high vacuum klystron body and the external loads. This enables personnel to keep the vacuum systems of the accelerator separate from the klystrons, which facilitates the ease of maintenance and

installation of gallery systems. On the test stands, the window similarly serves as a boundary between the klystron vacuum and the dummy load vacuum.

In fact, the window is such a critical interfacing component, it could not be an exaggeration to imply that just about as much effort has been spent at SLAC experimenting with windows as with klystrons. Likewise, many of the problems a test stand operator will encounter will most probably be window associated.

Let's examine some of the criteria necessary for satisfactory window performance. The choice of window material is difficult because of the high power densities across the window, and since a vacuum exists on both sides of the window, the usual convection gas cooling process can't be utilized. This subjects the window disc to multipactor heating. Multipactor is produced by secondary emission in a strong electric field, such as the RF field in the output waveguide. It causes prohibitive window heating when secondary electrons strike the window surface. Symptoms of multipactor could be a high window temperature or visible surface illumination, or both.

So the ideal window material would have a high thermal conductivity in order to dissipate the heat, and a high dielectric constant to withstand the large electric fields.

This assumption was confirmed during the testing of materials to determine a suitable type. The testing revealed a general pattern of two modes of window failures. One was due to a dielectric breakdown which resulted when peak power was increased above a critical level. The second type of failure occurred when the average power through the window exceeded a critical value, as would be expected. The window usually failed by cracking or sometimes a puncture was observed. It was noted that during both modes of failure, a glow existed at the surface of the disc, its shape and intensity determined by the particular power level at the time of failure. (This is why we regularly check the window with the periscope during test stand operations.)

After many tests were performed with several types of material, alumina coated with titanium was chosen as SLAC window material. It successfully minimized multipactor effects, and demonstrated an ability to handle twice the power that would be required. The alumina serves to reduce the tendency to multipactor by conducting electrons off the surface of the window.

KLYSTRON AUXILIARY SYSTEMS

In the preceding sections, the basic theory of klystron operation has been discussed. Considerable additional equipment is required for a complete amplifier system. Various power supplies are necessary, to deliver the required voltages and currents. In the SLAC high power systems, a method of cooling is required. Various RF circuit components are required to control and measure the RF output from the tube. A large collection of meters and protective devices are needed to monitor tube performance and protect operating personnel and equipment, in the event of a malfunction or operator error.

A complete amplifier system would include the following major components:

- (1) The Klystron Tube - In SLAC tubes, the anode, RF section, and collector are connected together inside the vacuum envelope. These parts are normally called the TUBE BODY, and are operated at ground potential. This makes it easier to connect the klystron into the rest of the system. In addition, the grounded body eliminates any electrical danger to the operators.
- (2) The Modulator - This is the beam supply that provides the voltage required to accelerate the electrons and form the beam. It must also deliver the required beam current.
- (3) The Sub-booster - Generates the 2856 MHz drive signal, which is applied to the klystron at 360 pps rep rate.
- (4) Filament Supply - This supplies power to the klystron filament, which heats the cathode to create the space charge necessary for beam formation.
- (5) The Load - The accelerator waveguide is the primary load for a klystron in the gallery. However, when tube performance is being checked in the Test Lab, it is necessary to connect a "dummy load" to the tube output to dissipate the RF output energy.

- (6) The Vac-Ion System - A high quality vacuum system designed to maintain vacuum integrity on the load side of the window. Some older tube designs employ a vac-ion system to maintain tube body vacuum.
- (7) Cooling Water - LCD (low conductivity, deionized) water is used to dissipate the heat generated by absorption of beam power in the collector, and RF energy absorbed by the load. The pulse transformer tank insulating oil is also cooled by this system.
- (8) Pulse Transformer Tank Oil - High impedance oil insulates the HV components of the pulse transformer tank and dissipates the heat generated by the pulse transformer.
- (9) Test and Measuring System - Various measuring devices and standard test equipment are used to observe and record tube parameters both in the gallery and in the Test Lab.

A more detailed description of these systems is the topic of the next section.

SECTION III TEST STAND SYSTEMS

Prior to installation in the gallery, new and reworked klystrons are sent to the Klystron Test Lab for performance checks. Special test stands have been constructed in the lab to measure and evaluate the performance of the high power tubes. The test stands are capable of delivering the maximum design power of the tubes at various pulse repetition rates.

A functional diagram of a typical test stand is illustrated in Figure III-1. Note that the test stand is comprised essentially of the klystron auxiliary systems mentioned earlier.

This section will describe each test stand system and how it interrelates with the other systems and the klystron tube. Perhaps the most logical subject to first pursue is the power source required by these high powered systems.

TEST LAB POWER DISTRIBUTION

Refer to Figure III-2 for the Test Lab AC power distribution to the test stands (TS1 - TS 9 only).

PG&E provides 220 kV power to the SLAC master substation. There is also 60 kV standby power available in emergencies. The SLAC substation steps down the 220 kV to 12.6 kV, which is delivered to the Test Lab substation. This substation steps the voltage down again, from 12.6 kV to 480 VAC, 3 phase.

Note on Figure III-2 that there are essentially three 480 VAC busses in the building that power the klystron test stands. Only the active stands are pictured.

There are basically two types of test stand loads on the bus ducts. One is a 480 VAC supply to the variac or variable voltage transformer (VVT) that powers the modulator HV power supply. The other load is a 480 to 208/120 VAC step-down transformer that services the test stand systems. A typical test stand AC power distribution is shown on Figure III-3.

Figure III-1: Test Stand Block Diagram

Figure III-2: AC Power Distribution

Figure III-3: Test Stand Power Distribution

Figure III-4: Modulator Block Diagram

THE MODULATOR AND SUB-BOOSTER

Each klystron tube, whether in the gallery or in the Test Lab, is powered by a modulator. Although gallery modulators are almost identical in construction, this discussion will concern the test stand modulators only.

The modulator can be considered the heart of the test stand systems. It produces accurately timed high voltage pulses of the proper width, amplitude, and polarity to pulse the klystron tube. The sub-booster supplies the RF drive that velocity modulates the beam pulse. Figure III-4 is a functional diagram of this system.

The modulator furnishes the beam pulse to the klystron via a pulse transformer. The modulator's output pulse has a peak power rating of about 84 MW (on the new test stands), a duration of 3.5 microseconds, and a repetition rate variable in steps from 60 to 360 pps. The power level and repetition rate can be varied from the test stand control panel. The pulse duration and its shape is preadjusted by tuning the inductors of the modulator's pulse forming network.

Now let's take a closer look on how the modulator works. The klystron modulator used at SLAC is a line type modulator, as opposed to a hard tube type modulator that can be found in other applications. A block diagram of the line modulator is shown below on Figure III-5.

Figure III-5

The line pulsing modulator consists of the following components:

- (1) SOURCE - provides high voltage to the storage element in the modulator.

- (2) Z_{ch} - The total impedance in the storage network charge path.
- (3) SWITCH - allows the storage network to charge when open; allows the storage network to discharge when closed.
- (4) PULSE FORMING NETWORK (PFN) - Stores the high voltage provided by the source. Also determines the shape and width of the high voltage applied to the load.
- (5) LOAD - Primary winding of the pulse transformer. (The klystron is connected to the secondary.)

Now relate the block diagram of Fig. III-5 to a simplified schematic of the same circuit:

Figure III-6: Simplified Modulator Schematic

When the modulator is turned on, the pulse forming network (PFN) capacitors charge to twice the DC power supply voltage (SOURCE) due to the DC resonance charging characteristics (Z_{ch}) of the charging choke and the total PFN capacity. The charging current flows from power supply ground, through the primary of the pulse transformer (LOAD), the PFN inductors, the charging diode and choke, to the positive side of the HV DC power supply. Because of the low value of inductance of the pulse transformer primary and the PFN inductors at this charging rate, they have a negligible effect on the charging cycle.

The PFN capacitors retain the voltage level of twice the DC power supply. Now some method of switching must be provided to allow the pulse forming network to discharge through the load. The switch must be able to handle a high pulse repetition frequency and pass a current flow which may exceed 4000 A. In this case, a hydrogen thyratron tube is used as a switching device. When the 5 kV driver triggers the thyratron (SWITCH), the thyratron is driven into conduction, allowing the PFN to discharge into the load. The PFN capacitors will discharge through the primary of the pulse transformer, the thyratron, and the PFN inductors. Since the reflected impedance of the klystron into the pulse transformer primary is approximately equal to the PFN impedance, half the voltage of the PFN capacitors appears across the load, and half is dropped across the PFN. But for a matched load, in principle, all of the power is transferred from the PFN to the load. The total time for discharge is approximately 3.5 microseconds. Note that if it were not for the charging diode (Fig. III-6), the charge on the PFN capacitors would discharge back into the power supply. Since this charge cannot return to the power supply, it remains on the PFN until the thyratron is triggered, allowing discharge through the load.

Now that the basic operation of the modulator has been discussed, let's examine some of its major components. These components are all illustrated on Fig. III-4.

One of the requirements demanded by the specifications of the accelerator beam is that the magnitude and phase of the injected klystron RF energy be constant during the entire pulse width. In fact, this stability is mandatory for each and every klystron pulse applied to the accelerator beam. The triggering circuit of the modulator is the first step towards achieving this pulse stability.

The klystron will deliver its maximum peak output power only if its beam pulse and drive pulse are synchronized. This insures optimum velocity modulation of the beam pulse. The master pulse generator performs this synchronizing function. It sends a 360 Hz signal to the sub-booster, so that the 2856 MHz drive pulse is applied

to the buncher cavity of the klystron at a 360 pps rate. Simultaneously, the master trigger fires the thyratron, and a voltage pulse is applied to the klystron cathode at a 360 pps rate. Thus, the two pulses arrive at the same time in the klystron tube and generate the velocity modulated beam. However, it is sometimes desirable to vary the klystron power output for a given beam voltage, so the firing rate of the thyratron can also be adjusted to either 180, 120, or 60 pps (all multiples of 60 pps). Remember, even though the thyratron is being triggered by multiples of 60 pps, the drive signal is continuously applied at 360 pps, so there will always be a drive signal available to modulate the beam pulse, no matter which beam pulse repetition rate is selected. Because both pulses are generated by the same trigger generator, they will always be synchronized. The delay network in each line compensates for the physical characteristics of the circuits to insure synchronization of the pulses at the klystron.

The master trigger generator is located in the RF rack by the sub-booster along the side of Test Stand #9. It sends 60, 120, 180, and 360 pps pulses to each test stand. A selector switch on each test stand is provided to trigger that test stand and oscilloscope at any of the applied pulse repetition rates. One trigger signal is applied to the modulator delay unit mentioned above. This delay allows the modulator to be placed in sync with the drive pulse. This adjustment is required due to the distance the RF must travel from the sub-booster to the high power klystron. From this delay unit, the trigger is sent to the 5 kV amplifier, which amplifies the trigger so it is large enough to fire the thyratron. The trigger to the delay chassis of the oscilloscope is necessary to present the pulses on the center of the oscilloscope screen.

The pulse transformer is a critical section of the modulator. It must faithfully reproduce the modulator output pulse while stepping up its voltage to the several hundred kV required by the klystron cathode. It also acts as an impedance matching device between the

modulator and the klystron. This characteristic was illustrated earlier during the charge/discharge sequence of the modulator.

Pulse transformer design is critical because of the high frequency components present in the output pulse. The core is composed of thin laminations of ferromagnetic material, usually silicon steel. Close coupling between primary and secondary reduces leakage inductance to preserve the steep leading edge of the input pulse (modulator output pulse). Low intervening capacitance is desired to prevent high frequency oscillations. To minimize these effects, close coupling is attained between the primary and secondary by winding the primary closely to the secondary, and by using the same leg of the core for both windings. The secondary is called a BIFILAR winding.

Basically, the bifilar secondary winding is made up of two insulated conductors, wound side by side so that exactly the same voltage is induced in each. The bifilar winding acts as two secondaries which have equal and inphase voltages induced in them. This arrangement permits the use of a filament secondary without high voltage insulation. The pulse transformer is wound to step up the modulator pulse by a factor of twelve.

SLAC pulse transformers are the biased core type. This means that a DC current is fed through the primary winding in such a direction to allow full use of the hysteresis curve during pulsing. This allows a smaller core transformer. The source of bias current is the core bias power supply seen on Fig. 11F-4. If the pulse transformer is run at less than 12 amps core bias, the core will saturate and cause excessive heating, which will result in failure of the pulse transformer.

A capacitive voltage divider divides the output pulse voltage (klystron cathode voltage) by a factor of 5000 for viewing and monitoring purposes. More on this later.

For space and cost reasons, the pulse transformers must use a dielectric of high breakdown strength such as high impedance oil.

Since the klystrons are also designed for oil immersion of the cathode end, it is highly advantageous to locate both klystron and pulse transformer in the same oil tank to eliminate the need for a high voltage transmission line between these two. Thus, the pulse transformer tank is mounted on the bottom of the klystron, and contains the pulse transformer, filament transformer, klystron cathode socket, capacitive voltage divider, and assorted bypass capacitors.

In order to gain a further understanding of the operation of the modulator, there are a few remaining components that will be briefly discussed.

The function of the keep alive power supply on Fig. 11F-4 is to furnish a constant current of around 325 ma to the pre-trigger electrode of the hydrogen thyatron. The thyatron is simply a gas-filled triode tube. It is employed in many applications as an "electronic switch". The thyatron switch is normally in the "off" mode until a large enough voltage pulse is applied to its control grid. The "switch" will stay on for the duration of the pulse. This current "keeps alive" the thyatron by maintaining some measure of ionization within the tube when the tube is in its quiescent (turned off) state. This ionization region helps considerably to reduce the tube anode delay time, which leads to a sharper modulator output pulse.

The end-of-line clipper consists of a series combination of diodes, power resistors, and thyrites. The entire assembly is connected across the last (farthest removed from the thyatron) PFN capacitor. Its function is to remove any negative voltage that may be present on the PFN capacitors because of a momentary shorted or low impedance load caused by a klystron fault. If the klystron shorts, the stored PFN energy still has to be dropped somewhere. Without the end-of-line clipper, the excess energy on the PFN inductors would be transferred as an inverse charge to the PFN capacitors. Such a negative charge on the capacitors would have two adverse effects. The thyatron tube could be damaged by reverse a-c-through and the PFN capacitors could be over voltage during the next charging cycle.

The despiing network protects the charging transformer from excessive voltage spikes and the charging diode from excessive peak current when the thyratron fires. It consists basically of a parallel inductance-resistance network in series with the charging choke.

DUMMY RF LOAD

The RF energy generated by the klystron tube must be dissipated or the tube will suffer severe damage. This presents no problem during Gallery operations, because the RF energy is normally coupled to the accelerator waveguide to provide beam power. At the test stands, however, an artificial means of power absorption must be employed. A device that performs this function well is called an RF load, also known in some circles as a "dummy load". The load is designed to have the same electrical characteristics as the accelerator waveguide, so as far as the klystron is concerned, there is negligible difference in operating behavior. Thus, the klystron is really the dummy, because it can't tell the difference between the load and the accelerator.

The load also performs an important secondary function for the test stand operator. It has a connection that enables the operator to measure the RF output power of the klystron tube.

Simply speaking, the load is a microwave device that is bolted to the output waveguide of the klystron, and absorbs and dissipates the RF energy produced by the klystron under test. The electrical characteristics of the load are "matched" as closely as possible to the tube characteristics, so there is a maximum power transfer between the tube and the load. The load converts the RF energy to heat energy, which is then removed by the test stand cooling water

system. The RF energy is actually dissipated in the LCD water flowing through one or more glass tubes within the load. Figure III-7 is a functional diagram of the energy conversion process at a typical test stand.

Figure III-7

There are currently two models of SLAC designed loads in use at the test stands. The HP model is a tapered load. The TP (twin-pipe) model is pictured in Figure III-8.

Recall that the "window" in the klystron output waveguide acts as a physical barrier between the tube's internal high vacuum, and any external connections. After the load is connected to the output waveguide, the volume between the window and the load must also be pumped down to a high vacuum. This insures proper operation of the waveguide and preserves the integrity of the load. Once the load is bolted into place, it is "roughed down" to a vacuum of approximately 10^{-4} Torr. Then a Vac-Ion® pump is connected to the load, which increases the vacuum to about 10^{-7} Torr. The Vac-Ion controls are located on the operator's console.

*A registered trademark of Varian Associates.

Figure III-8: TP Load

If a load air leak occurred during tube operation, the load and the window could become damaged if there were no automatic protection available. The Vac-Ion control has a feature that automatically removes high voltage from the klystron if a high pressure excursion occurs when the tube is operating. Also, the load cooling water is interlocked to de-energize the high voltage if a cooling water failure should occur.

A viewing port has been installed in the load waveguide so that the window can be visually monitored for any aberrations. Also installed in the load waveguide is an RF connector that samples the klystron RF output.

VACUUM SYSTEMS

Like most electron tubes, the klystron cannot operate efficiently unless its interior is under an extremely good vacuum. A rise in pressure in the klystrons or in the output waveguides and accelerator sections could result in internal electrical breakdown. First, a poor vacuum means a decrease in breakdown strength, and hence increases the chance of arc-over. Secondly, this electrical breakdown causes a release of adsorbed gas from surfaces of the region of the arc which elevates the pressure. The internal electrical arc, if prolonged, will cause local melting of the structure. Moreover, in some instances of arcing inside the klystrons, the large ceramic seal which holds and insulates the cathode assembly has been cracked. To protect an expensive tube from damage due to poor vacuum, it is important that the operator be familiar with vacuum systems in general and klystron vacuum systems in particular.

A vacuum is produced by removing gas molecules from a vessel by means of a pump. The gas flows from the vessel through the connecting passages to the pump, where it is either held or ejected into the atmosphere, depending on the type of pump. The remaining gas in the container is of low density and consequently low pressure. The container to be exhausted is referred to as a vacuum vessel, and the gas is removed by means of a vacuum pump. A pump and vessel, together with the necessary "plumbing" and vacuum-measuring equipment, are referred to as a vacuum system.

Any vacuum system must have certain basic parts which are common to all systems regardless of pumping methods employed. These are:

- (1) A gas-tight vacuum vessel with gas-tight closures where entrance can be made at some phase of the operating cycle. In our applications, the klystron tube and/or its associated dummy load would be considered the vacuum vessel. Vacuum valves serve as closure mechanisms.
- (2) A rough-pumping system which will reduce the pressure from atmospheric to a level where low-pressure systems can be used.
- (3) A high vacuum pumping system which is capable of reaching the ultimate pressure the system must attain, with sufficient

pumping speed to handle the outgassing and leaks, if any, which result from materials used and work carried out within the vessel.

- (4) A system of vacuum gauges and read outs to enable the pressure to be measured both during the roughing stage and during the high-vacuum stage.

A typical test stand vacuum system is shown in Figure III-9.

Before examining the details of the test stand vacuum system, let's review some basic concepts of vacuum technology.

The word "vacuum" has Greek origins, and means "empty". In practice, it is the absence of gas from a vessel. Since air, like any gas, exerts a pressure on its surroundings, the removal of air from a container would lower the pressure within the vessel. Clearly various degrees of vacuum can be obtained, depending on how much air is removed from the enclosure. Practically, a vacuum vessel that is free of all matter can never be attained. If this were possible, the vacuum would be called perfect or absolute. However, even at ultra high vacuums, molecular densities in the system are greater than 10^6 molecules/cm³.

Vacuum can be measured by several different pressure standards, depending on the degree of vacuum attained. A vacuum gauge, such as a mercury manometer, will read vacuum in "millimeters of mercury", where 1 atmosphere = 760 mm mercury. This standard was determined from an early experiment by a man named Torricelli. He found that if a closed tube is immersed in a container of mercury at sea level, atmospheric pressure would push the mercury up the tube to a height of 760 mm.

Figure III-9: Test Stand Vacuum System

The pressure is caused by the $\sim 10^{19}$ molecules/cm³ of air pushing against the surface of the mercury. As the air pressure drops, for instance if the pan were taken to a higher altitude, then the column of mercury would fall. This happens because the air is less dense, and it would exert less pressure on the surface of the mercury. At an altitude of 8,000 ft., for example, the mercury column would travel only 560 mm up the tube. This relationship is illustrated below:

10^{19} molecules/cm ³	1 Atmosphere (760 Torr)	760 mm mercury
3.25×10^{16}	$1/760$ Atmos	1 Torr
3.25×10^{13}	10^{-3} Torr	10^{-3} mm mercury
3.25×10^{10}	10^{-6} Torr	10^{-6} mm mercury
3.25×10^7 molecules/cm ³	10^{-9} Torr	10^{-9} mm mercury

It can be readily seen that as more air molecules are removed from a vessel by a vacuum pump, less pressure is exerted on the walls of the vessel, and the higher the vacuum becomes. The Klystron Group frequently works with high vacuums, so more practical units of measurement are employed. Recall that a standard of vacuum measurement is 1 Atmosphere = 760 mm mercury. Other units based on this standard are:

$$1 \text{ mm Hg} = 1 \text{ Torr (so that } 1 \text{ Torr} = \frac{1}{760} \text{ Atmosphere)}$$

$$10^{-3} \text{ Hg} = 1 \mu\text{Hg} = 1 \text{ millitorr}$$

"Hg" is the chemical symbol for mercury. " μ " means micron, or 10^{-3} mm Hg.

EXAMPLE (1): The pressure in a vacuum system is read as $10^{-2} \mu$. What is the pressure in Torr?

Answer: Recall that 1 Torr = 1 mm Hg = 1000 μ

$$1 \mu = \frac{1}{1000} = 10^{-3} \times 10^{-2} = 10^{-5} \text{ Torr}$$

EXAMPLE (2): The pressure in a vacuum system is read as 2×10^{-4} Torr. What is the pressure in microns?

Answer: 1 Torr = 1 mm Hg = 1000 μ

$$\begin{aligned} 2 \times 10^{-4} \text{ Torr} &= 2 \times 10^{-4} \times 1000 = 2 \times 10^{-1} \times 10^{-3} \\ &= 2 \times 10^{-1} \\ &= 0.2 \mu \end{aligned}$$

Routine operations in the Klystron Group measure pressure as low as the 10^{-9} Torr range. To appreciate the implications of this small number, let's examine a vessel that has been evacuated to 10^{-8} Torr. If it weren't for the walls of the vessel, a molecule at 10^{-8} Torr vacuum would drift randomly for 3 miles before touching another molecule. In practice, of course, it collides with the system walls. On the other hand, it must be pointed out that in this same vacuum, the density of gases is still 5×10^9 molecules/cm³.

Here are some degrees of vacuum and their pressure ranges:

Rough vacuum - 760 to 10^{-3} Torr (i.e., 1 Atmos. to 1 micron Hg)

High vacuum - 10^{-3} to 10^{-6} Torr

Very High vacuum - 10^{-6} to 10^{-9} Torr

Ultra High vacuum - 10^{-9} Torr and less

The two vacuum vessels that will be of primary interest to the test stand operator are the klystron tube and its RF load.

You might recall from a previous section that between the output of the klystrons and the input to the accelerator (or RF load), there is a vacuum tight "window" in the connecting waveguide through which RF energy passes. One purpose of this window is to permit the klystron to be moved from one station to another without destroying its vacuum. SLAC built klystrons are pumped down, baked, and sealed off under a very high vacuum in the 10^{-9} Torr range. Before the klystrons are delivered for testing, the tubes are baked at 400°C for several days and at 600°C for approximately one day, for outgassing the tube body. The gassing gradually decreases and the vacuum of close to 10^{-9} Torr is achieved. Once the tube is outgassed and the cathode activated, it is not desirable to expose the interior to air

since the cathode would become poisoned. SLAC tubes have their interiors permanently "pinched off". There are a few remaining RCA tubes, however, that require a vacuum pump connection to maintain tube vacuum.

A second purpose of the window is to separate the klystron and accelerator vacuum systems. The klystron vacuum is, in general, equal to or better than that of the accelerator. A good vacuum in the klystron is desirable to prolong cathode life.

It is not practical to maintain a permanent vacuum on the RF load. Therefore, after a klystron is connected to the test stand and a load is bolted to its output, a vacuum system must be connected to evacuate the load and connecting waveguide structure. A block diagram of this system is illustrated in Fig. III-9. More correctly, it is actually two systems: A rough-pumping system and a high vacuum pumping system.

The rough-pumping system reduces the pressure from atmospheric to about 10^{-4} Torr, then the high vacuum pumping system can be energized.

The rough-pumping vacuum system is mounted on a portable trolley so that it can be made readily accessible to any test stand. An oil sealed, rotary vacuum pump is employed as the means of evacuation. The roughing system is connected to the load by a length of non-collapse plastic hose. The rotary pump evacuates the air from the load and discharges it to the atmosphere. When the load has been "roughed down" to approximately 10^{-4} Torr, a valve is closed that isolates the roughing system from the load. The high vacuum pumping system is started, the isolation valve is closed, then the roughing system is disconnected.

Fixed piping connects the rotary pump with other components of the roughing system. The molecular sieve trap acts to trap oil vapor molecules from the pump to prevent them from migrating to the load and contaminating window and waveguide surfaces. A liquid nitrogen trap serves the same purpose, and is considered the "last line of defense" to prevent oil contamination of the klystron output sections.

The level of vacuum attained by the roughing system can be read on two meters mounted on the roughing system cart. The system uses two methods of measuring vacuum, one more sensitive than the other. The coarse range (1 Torr to 10^{-3} Torr) utilizes a multi-junction thermocouple device to sense the vacuum. A thermocouple is attached to a heated wire and measures the voltage produced by the thermocouple, which depends on temperature. The temperature increases as the vacuum increases, because there are fewer gas molecules available to cool the wire. As the temperature of the heated wire changes due to pressure changes, the thermocouple's voltage varies. The resulting current flow is measured by a meter calibrated in microns of mercury. The significant advantage of this method is the rapid response due to pressure changes, and its simple, rugged construction. It is also relatively insensitive to contamination.

At lower pressures, a different measuring method must be used. In this particular rough-pumping system, a cold cathode ionization gauge is employed. Basically, this device measures the positive ions produced from the collision of gas molecules with cathode-produced electrons. The resulting current is directly proportional to the system pressure. The meter for the discharge ionization gauge is calibrated in mm of Hg.

Now, let's consider the high vacuum pumping system. It is capable of evacuating the load to its ultimate operating pressure, about 10^{-9} Torr. The fine-pumping system consists of a sputter ion pump, a magnet, and the control unit. The pump is sometimes referred to as the Vac-Ion pump, or Getter-ion pump.

The Vac-Ion pump operates by taking gas molecules and atoms out of circulation by the formation of chemically stable compounds and by ion burial. The pump consists of an enclosure containing an anode grid sandwiched between two cathode plates.

Figure III-10: Vac-Ion Pump Operation

Pumping is initiated by a suitable voltage between the anode grid and cathode plates. Electrons, tending to flow to the anode, are forced into a spiral path by the presence of a strong magnetic field. The greatly increased electron path length results in a high probability of collision between free electrons and gas molecules. These collisions produce gas ions and more free electrons. As can be seen in Figure III-10, positively-charged gas ions then bombard the titanium cathode plates. In this process, titanium atoms are knocked out of the plate (sputtered). The sputtered titanium atoms are deposited on the anode grid, forming chemically stable compounds with the active gas atoms such as oxygen, hydrogen and nitrogen. Chemically inert gases are removed by ion burial in the cathode and by entrapment in the anode. Each collision produces free electrons with long effective path lengths and pumping action is possible down to very low pressures.

Pump current bears a linear relation to the density of the gas molecules, ionic current flow being proportional to the rate of electron-atom collisions. Rather than reading directly in pressure, the Vac-Ion control unit is calibrated to read current flow. When the klystron is operating, the interlocked Vac-Ion control unit selector switch must be placed in the "log" position. This provides an automatic HV cut-off feature that protects the tube window from severe damage and puncturing during load gas bursting. The meter is calibrated from 0 - 3 ma in the "log" position.

THE COOLING WATER SYSTEM

Like any other high power system, the klystron produces heat which must be removed to protect the tube. Low conductivity deionized water (LCD) is provided to the Test Lab by the Plant Engineering Department. LCD water is used as a cooling medium for the klystron and its subsystems. The water is delivered at the rate of 400 gallons per minute at 110 psig.

Cool water is delivered to the Test Lab, where it is heated up by the klystron systems. This warmer water is then pumped back to a cooling tower. It is thus a closed loop system. The cooling water system is filtered and deionized prior to entering the Test Lab. The filtering and deionizing is necessary to minimize the loss of copper from equipment operating at high voltages. It also inhibits the deposit of scale on heat transfer surfaces and prevents plugging of small flow passages. Refer to Figure III-11 for an illustration of a test stand cooling water system.

Since the collector output water temperature specification is $\leq 70^{\circ}\text{C}$, the collector cooling water flow at the test stand must be maintained at 13-14 GPM flow rate, with a supply water temperature of 40°C . Load cooling water flow is kept at a minimum of 9 GPM.

Figure III-11: Test Stand Cooling Water System

Figure III-12: Test Stand Oil Cooling System

The pulse transformer tank oil is heated up during the course of klystron operations, so it also requires some method of heat dissipation. The relatively simple oil cooling system is pictured in Figure III-12.

The klystron collector and body, dummy load, and the transformer tank oil are presently the major cooling loads for the LCD water system. Earlier test stand systems, however, required both focusing magnet and Vac-Ion pump cooling capabilities. These features are rarely utilized anymore, because of the prolific use of the permanent magnets and newer Vac-Ion pump design. The cooling installations still exist, so for the sake of completeness, are included in the system drawing.

A salt water dummy load is periodically used to calibrate the modulator high voltage circuit. Valves for its cooling water connections are also located on the LCD water manifold.

It should be pointed out that both the klystron body and the klystron collector are cooled by the same connections. Thus the frequently used term "collector cooling water" is just an abbreviated expression for the more accurate "klystron body and collector cooling".

Figure III-13 shows the regenerative heat exchanger employed in the collector cooling water system. While most heat exchangers are designed to remove heat from a system (such as your car radiator), a "regenerative" heat exchanger is designed to put heat back into the system, usually to improve overall thermal efficiency. For example, if the incoming water was too cold for the efficient operating conditions of a device, then the warmer output water could be used to preheat the cooler incoming water. This is the case for SLAC klystrons.

Because the Gallery supply water temperatures run higher than the Test Lab supply water temperatures, it was discovered that the Test Lab tube data did not reflect actual operating conditions. This is because the cooler Test Lab supply water changed slightly the thermal operating characteristics of the klystrons, which in turn affected the

THIS IS A FLOW DIAGRAM OF THE REGENRATIVE HEAT EXCHANGER

In this diagram the 2-way valve is in the "Hot Water" position. This means that the hot return water from the collector is cycled thru the heat exch. to pre-heat the incoming supply water.

This diagram shows the 2-way valve in the "Cold Water" position. Note that the hot water from the collector bypasses the heat exchanger with no effect on the cooler incoming supply water.

Figure III-13: Collector Cooling Water Heat Exchanger

data taken from the test runs. Since the Test Lab data is used as a reference by the Gallery in establishing operating potentials, it is important that the tube data be recorded under the same operating conditions.

The regenerative heat exchanger was installed in the Test Lab to preheat its supply water. This duplicates the temperature of the Gallery supply water. That way, data measured in both places would be recorded under the same thermal conditions. The regenerative heat exchanger merely takes heat from the output of the klystron (which would normally be wasted) and adds it to the incoming water, thereby raising its temperature a few degrees. In some phases of klystron testing, it is not desired to do this, so a two-way air-operated valve was installed. This allows the collector cooling water system to be used in the regenerative mode, as just described, or the heat exchanger can be bypassed completely so that the supply water temperature is unaffected.

Several thermocouples were placed at various points in the cooling system so that input and output temperatures could be monitored. These can be read at the test stand operator's console.

These monitoring points are important not only in preventing dangerously high temperatures on the Klystron, but also in performing a calorimetric power balance. A calorimetric check is a heat balance that is determined by the cooling water flow and the differences between the input and output temperatures. It is an accurate measurement of the total power being delivered to the klystron. This number can be compared with the power determined by the parameters measured on the electronic test equipment to check the accuracy of the measuring equipment. The power measured by the calorimetric method must agree with the power as measured by installed test equipment to within 5%.

TEST STAND INTERLOCKS

Interlocks are provided at various points in the system to protect personnel from hazardous potentials and to prevent equipment damage. Water interlocks are included to prevent operation in case of inadequate water flow to either the klystron or its load or the oil cooling system. Vacuum interlocks prevent klystron window damage in case of inadequate vacuum in the output waveguide system. Over-voltage and over-current interlocks are necessary to avoid damage to the modulator, pulse transformer tank, or the klystron in case of malfunction.

Some interlock functions can be cleared in a few seconds, and some are not expected to clear rapidly (for instance, the water interlock). For those functions which expect to clear rapidly, the system is designed to try again within a few seconds of the fault and to stop trying after a predetermined number of tries. This "fault counter" can be pre-set at the operator's control station.

The interlocks can be classified into two categories. The external interlocks insure that the auxiliary systems are operating at design parameters prior to energizing the high voltage. The internal interlocks (i.e., internal to the modulator) prevent tube and modulator damage during operations when the high voltage is applied to the klystron.

The external interlocks are connected in series so that all the relays must be picked up before the high voltage relay will energize. Conversely, if one interlock relay drops out at any time during test stand operations, the high voltage relay will deenergize, removing high voltage from the tube. The operator can easily determine the status of the interlock relays by observing the lights on the interlock status board at his control station. When an interlock condition is satisfied, a relay picks up to energize its respective light on the status board. After all the interlock relays are picked up, a green "interlocks complete" light illuminates, and allows the "high voltage start" relay to be energized. The operator then merely

has to push the "high voltage start" button to energize the klystron. This system is versatile in that five bypass toggle switches are provided that permit certain interlocks to be bypassed in special circumstances. These conditions depend on the type of tube under test and the type of test being conducted. For instance, SLAC uses very few klystrons anymore that require electromagnet focusing. Consequently, the interlocks associated with the test stand electromagnet focus supplies are usually bypassed at the interlock panel when permanent magnet klystrons are under test.

Remember, external interlocks are those which must be completed prior to energizing the high voltage relay. Any interruption of these interlocks will return the modulator to the "modulator start" condition:

- (1) COLLECTOR WATER FLOW - set for minimum of 11 GPM.
- (2) LOAD WATER FLOW - set for minimum of 7 GPM.
- (3) OIL COOLING WATER - 2 GPM "sure flow" limit switch.
- (4) VACUUM PUMP WATER - set for minimum of .5 GPM.
- (5) COLLECTOR WATER TEMPERATURE - 75°C max set point.
- (6) ELECTROMAGNET FOCUS WATER ON
- (7) OIL TEMPERATURE - "square tank", 65°C max in transformer side.
- "round tank", bypassed in connector, not used.
- (8) LOAD VACUUM - 15 liter power supply on, toggle switch in "protection" position, selector switch on "log" scale.
- if 5 liter supply on, selector switch on "50 uA".
- (9) RECTIFIER AIR - ceiling fan in cabinet #3.
- (10) THYRATRON AIR - cooling fans on wall of cabinet #5.
- (11) THYRATRON UNDERCURRENT - set at 75% of current drawn by thyatron at 6.5 volts.
- (12) CORE BIAS UNDERCURRENT - 10 amps minimum.
- (13) FOCUS SUPPLY - energized when using electromagnets.
- (14) THYRATRON AND 5 KV DRIVEN TUBE DELAY - set for 15 minutes.

The high voltage overcurrent protection feature is necessary to protect the power supply against current excursions caused by thyatron misfiring, shorts, and capacitor or charging choke failures. The inverse voltage protection function protects the modulator and pulse circuit from an arcing klystron tube or shorted secondary winding of the pulse transformer.

TEST STAND INSTRUMENTATION AND CONTROL

The complex experiments conducted at the accelerator demand an extremely stable RF power source. To insure the reliability of the high power klystrons, each tube is subjected to a series of thorough tests prior to Gallery installation.

These performance checks require an extensive array of electronic and mechanical monitoring devices. Figure III-14 is a block diagram of the test stand measuring and monitoring system.

Figure III-14: Test Stand Measuring and Monitoring System

Several parameters are measured and recorded for each klystron at the test stands. An oscilloscope located at the operator's console is used to measure beam pulse voltage and current, as well as various output pulse characteristics. Power meters sample the RF output pulse, and the incident and reflected drive signals. An X-Y recorder provides a graphical record of the RF output pulse stability. Critical klystron temperatures are monitored by thermocouples that have been mounted in the cooling system.

As previously mentioned in the Cooling Water section of this text, these temperatures are also used in conjunction with flow data to calculate a calorimetric power output.

Other control and instrumentation devices necessary for test stand operation are also located in the operator's console:

- (1) Variac and modulator control panel.
- (2) Interlock panel.
- (3) Vac-Ion control panel.
- (4) RF drive delay modules.
- (5) Klystron filament voltage and current control chassis.
- (6) High and low voltage power supply breakers and meters.
- (7) RF drive attenuator.
- (8) Oscilloscope voltage comparator panel.
- (9) Electromagnet power supply (not all test stands).

In order to realistically test the klystrons, the tube installation facilities at the test stands are designed to simulate Gallery connections. In the Gallery, the cathode end of each klystron is bolted to a "round tank" full of oil. Besides oil, the round tank also contains the components necessary for interfacing the klystron with the modulator; pulse transformer, filament connections, and a capacitance voltage divider (5000:1 ratio) for beam pulse viewing. This arrangement eliminates the need for a high voltage transmission line between the pulse transformer and the klystron. The oil serves both as a cooling medium and an insulator between all high voltage round tank components.

In the Test Lab, however, initial testing is done with the klystron connected to the permanently installed "square tank" at a test stand. This square tank electrically and physically simulates

the round tank. It contains a pulse transformer, voltage divider, and filament connections. In addition, an installed current transformer senses the beam current pulse. The square tank is also filled with oil. The square tank installation is convenient for the operator, because he can use the same measuring standards for multiple numbers of tubes. Once the square tank's voltage divider is calibrated, it remains a fixed constant for subsequent performance checks on any klystron. This enables the operator to develop a standard calibration chart on his voltage comparator that does not require recalibration each time a new tube is installed at a test stand.

The pulse voltage viewing divider is one of the most critical components of the test stand measuring system. Located in the pulse tank, it is a highly accurate 5000:1 capacitive voltage divider. It is connected across the output of the pulse transformer. (Refer to Fig. III-14.) The signal is brought out of the tank by a coax cable via a cable tray to the control console. A secondary pulse current transformer, connected between the cathode circuit and the pulse transformer secondary winding, provides a beam current signal to the control console.

All tube performance checks, up to and including the acceptance tests, are performed with the klystron installed in the square tank. (For more detailed information on testing procedures, see Section IV.) Just prior to release for Gallery operations, the klystron is removed from the square tank, and then attached to its round tank. This combination is then reconnected to the test stand so that a final test can be run to insure the satisfactory operation of the tube with its mated pulse transformer (round) tank. This test also checks the round tank's voltage divider for calibration. Figure III-15 is a pictorial sequence that illustrates the major square tank/round tank configuration changes.

The connections from the test stand to the round tank are necessarily similar to the square tank hookups. The filament and

Figure III-15: Klystron Testing Sequence

voltage pulse viewing connections are basically the same. But since the round tank does not have a beam current pulse viewing capability, some method of viewing the current pulse at the test stand had to be devised. This was accomplished by installing a current transformer on the PFN output in cabinet #5 of the modulator. Electrically, it is connected in the round tank pulse transformer primary. Since the round tank's oil is cooled by the klystron body cooling system, the test stand oil cooling interlock is bypassed on the round tank test cable.

SECTION IV

TUBE CONSTRUCTION AND TESTING PROCEDURES

This section introduces the major phases of Klystron testing. It will trace the path of a new tube from its construction through the various performance measuring processes that are necessary prior to releasing the tube for service.

At one time SLAC purchased Klystron tubes from commercial vendors to supplement its own inventory. Now, however, SLAC is the sole supplier of its Klystrons. Completely self-supporting machining, assembly, and testing facilities produce about two to three tubes per week.

The construction of a klystron tube entails many intricate and detailed procedures that obviously can't be judiciously presented here. But perhaps a brief sketch of the construction process will enlist the appreciation of the reader for the effort and craftsmanship that has gone into a tube before the operator sees it for the first time.

First, design changes are incorporated into current drawings. Then the various components and subsections of the tube are machined to exacting tolerances. After that, they are sent to another facility to be cleaned.

After the parts have been meticulously cleaned, they are collected together in the Tube Shop for assembly. The Tube Shop normally assembles four tubes at a time.

The partial body assembly is "stacked" (cavities 2-4) and "cold" tested. During cold testing, an RF signal is injected into the cavities to check for the proper frequency response. Slight deviations from the expected frequency can be corrected by mechanical tuning. Concurrently with this building step, other sub-assemblies are readied; collector, output waveguide, and window assembly.

Next, the partial stacked body is brazed, then once again cold tested to insure the brazing process didn't interfere with the cavity frequencies.

After brazing and leak checking the sub-assemblies, the entire tube, except for the cathode, is assembled. Then the tube is brazed, and cavity dimensions are checked. Also, a final cold test of cavities 1-5 is conducted.

Simultaneously, the cathode has been coated and the electron gun has been assembled. In this process, the cathode spends many days in a high vacuum environment, then the whole gun is placed in an RF induction heated vacuum bell jar in an effort to rid it of gaseous impurities. This is one of the more critical aspects of tube construction.

Finally, the gun structure is heliarced into the tube, and the completed tube is placed in a bake station oven. Highly sophisticated turbine vacuum pumps lower the tube vacuum to around 10^{-9} Torr. The tube is baked for 5 days, again to outgas impurities and to insure proper conversion of the cathode coating material. Then the tube is "pinched off", or sealed. Afterwards, an emission check of the cathode is made.

Now the finished Klystron is ready to leave the Tube Shop. It is sent over to the Mechanical and Vacuum Group where the auxiliary connections are affixed to the tube. Here, the water lines and RF drive cables are attached, and the lead shielding is put in place. Also, the entire assembly is leak checked. Finally, the Klystron is sent to the test stands for performance checks.

Just like a new car, the new Klystron requires a "breaking in" process before it will effectively operate at full power levels. Also, it cannot be released for service until its operating parameters are determined to be within design tolerances. The test stand operator performs these services.

After the tube has been declared mechanically sound and mated with its permanent magnet, it is wheeled to a test stand and placed in a square transformer tank. Electrical and water connections are made, and the lead bolted on. After the proper administrative remarks are entered in the test stand log, the tube is initially energized at 50 kV, with no drive power applied.

The operator increases the applied HV in prescribed increments at certain time intervals. After a gradual voltage increase, drive power is eventually applied. In this way, residual gases and contaminants are gradually burned off. This procedure is really a continuation of the "aging" process that was started in the bake station. In fact, this first major test stand evolution is called processing. Processing is the first assessment of tube performance of the new klystron.

At first, the cold water mode of the collector heat exchanger is selected. This is because of the frequent faulting a tube usually experiences at this stage. "Faulting", the automatic turning off of the HV applied to the tube, is caused by tube arcing and other transients routinely encountered while breaking in a new tube. The cold water minimizes the thermal transients, and thus stress, when the tube experiences several faulting episodes. Later on, as the faulting rate decreases, hot water is cut in to give more meaning to the measured data. (For an elaboration on this point, refer to the Cooling Water section.)

After successful operation at 360 Hz, and 270 kV (or whatever the max rated voltage of the tube), the klystron then enters the preparation phase of testing. This could also be termed the "dry run" phase, because the tube is being readied for acceptance. Basically, the preparation phase works out any bugs discovered during processing, such as break-up or excessive faulting. The preparation step also serves to document a detailed analysis of any encountered problems in case the tube is eventually rejected and sent back for reworking. In any event, the mechanical procedures for preparation and the parameters that are subsequently recorded are much the same as the processing phase.

After preparation, the tube enters the acceptance sequence. It must successfully complete this check before the tube can be accepted for Gallery operations. During this phase, the tube must experience less than 10 faults per 8 hours run time. Also, over 30 performance

parameters are measured, and the klystron must meet each specified tolerance. Once again, everything is recorded in detail.

If the tube passes the acceptance criteria, it enters the final test phase. During this sequence, the tube is removed from the square tank, and placed in the same round transformer tank that will accompany it to the Gallery. Then various checks are conducted to insure the compatibility of the klystron with its respective transformer tank.

This completes the summary of the testing sequence of a new klystron. However, not all klystrons sent to the test stands for tests are new tubes. Some are "Gallery returns", tubes that have been sent back from the Gallery for one reason or another. Perhaps a Gallery operator noticed that a particular klystron was experiencing an intolerable number of overcurrent faults, or had too high a reflected energy, or maybe was leaking oil or water. Tubes with these types of problems are returned to the Test Lab for corrective action. All tubes returned, no matter for what reason, and having more than 20,000 hours run time on their round tanks, are automatically sent to the test stand square tanks. Once again, a complete set of performance checks are made on the tube, first on the square tank, then on its new round tank. Returned tubes with less than 20,000 hours running time on their round tanks are normally checked at the test stands with the same round tank.

SECTION V TUBE DYNAMICS

The SLAC klystrons have been designed to be able to operate at beam voltages between 150 and 270 kV, corresponding to peak power outputs of approximately 4 to 40 MW. The test stand operator must be intimately familiar with the capabilities and limitations of the particular klystron tube at his stand. In addition, he must possess basic skills in measuring techniques and data interpretation, for it is his responsibility to either certify satisfactory tube performance, or identify trouble symptoms as early in the testing sequence as possible. This section is intended to acquaint the new operator with typical klystron specifications, and to introduce some basic tube monitoring techniques employed at the test stands.

A partial list of the objective specifications of a SLAC XK-5 klystron tube is as follows:

Operating Frequency (f)	2856 MHz
Filament Voltage (E_f)	13-18 volts
Filament Current (I_f)	13-18 amps
Peak Forward Beam Voltage (e_{pv})	270 kV
Peak Beam Current (i_k)	295 amps
Peak Input Beam Power (P_i)	72-80 MW
Pulse Length RF Output (t_{rpf})	2.4-2.7 μ s
Pulse Repetition Frequency (prf)	60-360 pps
Peak Drive Power (p_{dr})	240 watts
Peak RF Output Power (P_{out})	38 MW
Average RF Output Power (P_{out})	42.2 kW
Efficiency $\frac{P_{out}}{P_i}$	47%
Gain	52.5 dB

Since the SLAC klystron is a pulsed amplifier, the most graphic representation of tube performance is an oscilloscope display of the input and output pulses. Many of the tube parameters recorded at the

test stands are derived from these pulse measurements. Let's review some of the basic concepts of pulse dynamics.

The modulator generates RF energy in the form of extremely short pulses with comparatively long intervals of rest time. The useful power of the modulator is that contained in the pulses and is termed the peak power of the system. This power is normally measured as an average value over a long period of time. Because the modulator is resting for a time that is long with respect to the pulse time, the average power delivered during one cycle of operation is relatively low compared with the peak power available during the pulse time. The number of pulses transmitted per second is called the pulse repetition frequency (prf) or pulse repetition rate (prr). The time from the beginning of one pulse to the beginning of the next pulse is called the pulse repetition time (prt). The prt is the reciprocal of the prf ($prt = 1/prf$). The duration of the pulse, the time the modulator is "on", is called the pulse width.

A definite relationship exists between the average power over an extended period of time and the peak power developed during the pulse time. The overall time of one cycle of operation is the reciprocal of the pulse repetition frequency. Other factors remaining constant, the greater the pulse width the higher will be the average power; and the longer the pulse repetition time, the lower will be the average power. Thus,

$$\frac{\text{average power}}{\text{peak power}} = \frac{\text{pulse width}}{\text{pulse repetition time}}$$

These general relationships are shown in Figure V-1.

The operating cycle of the klystron can be described in terms of the fraction of the total time that the RF output pulse is generated. This time relationship is called the duty cycle and may be represented as:

$$\text{duty cycle} = \frac{\text{pulse width}}{\text{pulse repetition time}}$$

High peak power is desirable in order to deliver maximum power to the accelerator beam at the optimum timing cycle. Conversely, low average power enables the modulator and the klystron tube to be made smaller and more compact, entailing obvious economic benefits. Thus, it is advantageous to have a low duty cycle. The peak power that can be developed is dependent upon the interrelation between the peak and average power, and the pulse width and prf, or, in other words, the duty cycle.

Figure V-1: Relationship of Peak and Average Power

For example, the duty cycle of a klystron having a pulse width of 2.00 μsec and a pulse repetition frequency of 360 pps is:

$$\frac{2.00 \times 10^{-6}}{2.78 \times 10^{-3}} = .720 \times 10^{-3} = 7.2 \times 10^{-4}$$

(Remember that prf equals the reciprocal of prf.)

For the convenience of the operator, the test stand log book contains a chart that has the pulse width vs. prf already computed. A correction factor is included for power conversions.

A ratio between the average power and peak power may be expressed in terms of the duty cycle. In the following example it is assumed that the peak power is 30 MW, and the pulse width is 2 microseconds. Therefore, for a period of 2 microseconds, a peak power of 30 MW is generated by the klystron amplifier, while for the remaining 1998

microseconds the klystron output is zero. Because the average power equals peak power times duty cycle, the P_{ave} equals:

$$(3 \times 10^7) \cdot (7.2 \times 10^{-4}) = 21.6 \text{ kW}$$

There is another important klystron parameter called "perveance" that is frequently calculated by the test stand operator. This property defines the relationship between the voltage and current of the tube as determined by tube geometry. To gain an intuitive understanding of perveance, let's review the basic operating characteristics of a vacuum diode tube. The operator should recall that the cathode-anode components of the klystron exhibit the same DC properties of a diode tube.

Every vacuum tube must have at least two elements; a cathode and an anode. The anode is the element toward which the electrons emitted by the cathode are attracted. The material, shape, size and location of the elements vary with the type of tube. In particular, the type of cathode coating determines its electron emission properties.

In any purely resistive circuit, Ohm's Law dictates that the current flow is directly proportional to the applied voltage. This relationship, however, does not hold true in a diode vacuum tube, and therefore, not the klystron. Experiments with diode vacuum tubes indicate that the amount of current which flows from the cathode to the anode depends upon two limiting factors--saturation and space charge. In a diode, these factors cause $I \propto V^{3/2}$. Let's see why.

When an emitter (in this case, the cathode) is heated to the required temperature, electrons gain sufficient energy to be liberated from the cathode. If these emitted electrons are not drawn away by an external field, they will form a space charge. This can be described as a cloud of electrons moving about the cathode with different velocities. One factor that affects the size of the space charge is the filament temperature, which in turn is a function of filament voltage. A test stand procedure exists that determines the proper

filament voltage for SL/C klystrons. Obviously, the cathode-anode potential also affects the space charge. Under steady-state conditions, a current equilibrium is reached by electrons flowing from the cathode to the space charge, then from the space charge to the anode.

Saturation of a tube occurs at high cathode-anode potentials when the anode strips away all the electrons emitted by the cathode. When this occurs, the electrical field is so strong that a space charge does not form.

Figure V-2 illustrates the space-charge limited and saturation limited characteristics of a diode tube:

Figure V-2: Saturation Characteristics of a Diode Tube

SLAC does not operate its klystrons in the saturation region of this curve. The klystrons are operated only in the non-linear space-charge limited region.

A man named Child studied this space-charge limited region and determined a relationship between the tube current, anode-cathode potential, and the tube geometry. This relationship is now called Child's Law:

$$I_k = \frac{KV^{3/2}}{x^2}$$

where I_k = beam current

V = beam voltage

x = distance between electrodes

K = constant, depending on geometry of tube

Since the spacing between the electrodes is not adjustable except during manufacture, this expression can be simplified to:

$$I_k = K'V^{3/2}$$

$$\text{where } K' = \frac{K}{x^2}$$

We can transpose this equation to get: $K' = \frac{I_k}{V^{3/2}}$

K' is called the perveance of the tube. Frequently microperveance (μk) is used because the denominator is larger than the numerator in our applications. Thus $K'\mu = \frac{I_k}{V^{3/2}} \cdot 10^6$

Typical values of microperveance range from 1.7 - 2.1, depending on the age of the tube.

Because perveance is an expression of the tube current-voltage relationship in the space-charge region, it is a useful parameter to monitor tube performance. Any abnormalities affecting the electron beam would be reflected in a change of the expected value of perveance for that particular tube.

For example, a failure in an electron-gun structure weld could change the tube geometry, thereby altering beam performance. While the operator would readily observe an abnormal beam presentation on his oscilloscope, he couldn't be certain whether the problem originated in the modulator or the tube. He needs to examine other tube parameters for more information. Since the value of perveance

would deviate from normal values because the tube geometry changed, the operator could immediately presume a malfunctioning tube,

This section is concluded with Figure V-3, which shows some normal and abnormal beam and output pulse shapes that have been observed on test stand oscilloscopes. Some of the problems are tube related, and some of the abnormal shapes are modulator induced.

Figure V-3A: Beam Pulse Wave Shapes

Normal Drive Pulse
Scope .5 usec/cm
20 mv/cm

"Glitch", causing pulse flutter in amplitude only. It may jump between two discrete levels with drive power variation.

Reduced pulse amplitude, with flutter in both time and amplitude. This also may jump between two discrete levels with drive power variation.

Increased pulse amplitude with flutter in both time and amplitude components of pulse.

Trailing edge flutter.

"Indian" type glitch on trailing or leading edge of pulse. May also be visible on beam voltage pulse.

Typical "glitch". May move along length of pulse. Sometimes affected by variations in RF drive power.

Pulse droop, due to drop in power output during duration of pulse.

RF output pulse ripple. Can be affected by a magnetic field.

NOTE: Any combinations of the above instabilities may occur.

Figure V-3B: RF Pulse Wave Shapes, Cont.

Figure V-3B: RF Pulse Wave Shapes

SECTION VI RADIATION HEALTH PHYSICS

One of the unfortunate side effects of high power klystron operation is that they produce ionizing radiation in the form of X-rays. All ionizing radiation is injurious to the human body. As the radiation passes through tissue, some of it is absorbed. It becomes absorbed by ionizing the cellular structure, which upsets the delicate chemical balance of the cell, thereby causing cell damage. All humans are constantly exposed to natural background radiation, but the dosage level is so low that the body easily repairs the damage.

Physically, X-rays are similar to radio waves, infrared waves, visible light waves, and ultra-violet waves except that they have a much shorter wave length. This shorter wavelength enables them to have much greater penetrating power than the other waves, so they are much more difficult to reflect or detect. The denser the substance they pass through, the greater the absorption that takes place. That is why lead is such an effective shield.

WHERE DO X-RAYS COME FROM?

Different types of ionizing radiation cause biological damage to human beings in varying degrees, but their significant difference lies in their source. For example, X-rays and gamma rays share almost identical characteristics. Gamma rays are emitted from the nucleus of an unstable atom. X-rays result from the collision of high energy electrons with atoms. The electron is traveling with so much kinetic energy that when it is suddenly stopped, the energy is released from the electron in the form of an X-ray.

In our applications, the X-rays result from the collision within the klystron tube of its electron beam and the collector structure and tube body. The amount and intensity of radiation produced is dependent upon the velocity and number of electrons within the beam, and so is a result of the beam voltage level and the modulator repetition rate.

For instance, a 270 kV rated tube would generate the most X-rays when it is operated at 270 kV with a 360 pps repetition rate.

Since the successful operation of klystrons requires that the amount of beam energy lost to the body be at a minimum, the largest percentage of the beam electrons impinges on the collector. And so it is the collector that is the most heavily shielded. The tube body area and the oil tank are also shielded with lead.

When the klystrons are properly shielded and properly monitored, the test stand operator should normally have no reason for concern for his health. Federal standards have been set to limit the exposure of radiation workers to levels that will cause little or no harm to the individual. SLAC is even more conservative and has established its maximum permissible radiation levels at less than one-third that allowed by the Federal Government. The maximum exposure permitted at SLAC is 1.5 rem per year. Individuals who might accrue 375 mrem per quarter are monitored for further exposure on a special program. However, the klystron test stands have many long hours of run time that attest to the fact that test stand operators rarely even receive the minimum detectable amount of radiation over a long period of time. In fact, one would probably receive a higher radiation dosage lying out in the sun all day than he would sitting at a test stand.

The major reason why operators have such low exposure levels in the Test Lab is because of the strictly enforced safety standards. All operators must carry a TLD (thermal-luminescence-detector) that is periodically checked for exposure. Calibrated radiation detectors are provided to survey the klystrons. (They are calibrated in "mrem", which is 10^{-3} rem. A rem has the same biological effect as the deposition of 100 ergs of ionizing radiation per gram of human tissue.) The maximum permissible radiation level from the klystron is 3 mrem at 3 feet. A flashing magenta light at each test stand warns personnel of the radiation hazard. A yellow and magenta rope surrounding the klystron acts as a radiation barrier to minimize personnel exposure. A supply of lead is kept on hand to shield any local "hot spots" that might be detected on a particular tube.

Minimizing X-ray radiation isn't just a question of additional lead shielding or keeping one's distance, but may also require adjustment of the klystron for optimum operating conditions.

Radiation can also occur around the klystron RF load system, because high RF energy can create fields capable of accelerating electrons into collisions with each other and the waveguide structure.

It is the responsibility of every operator to survey the radiation level in the area of an operating klystron under the following conditions:

- (1) Beginning operation
- (2) A change in beam voltage level
- (3) A significant change in RF drive power (doubled or halved)
- (4) A significant change in electromagnet focus currents
- (5) An increase in the modulator pulse repetition rate
- (6) At least twice every shift regardless of the above

SECTION VII SAFETY PRECAUTIONS

Nothing at work can be more important to the individual than his own personal safety and the safety of his coworkers. Operation and maintenance of the test stands obviously involves dangerous voltage potentials. By virtue of the fact that they're still alive, most technicians have demonstrated a familiarity with commonly practiced electrical safety precautions. But human nature breeds complacency, and many of us sometimes lose respect for the hazards of a voltage potential. You might recall that it takes only .1 amp from a 115V source to kill a man. That "close call" you had today might very well have been the "last call". So it's necessary that we all review some of the "basics" from time to time, both for personal protection and the well being of fellow workers. This section will review some common electronics safety precautions.

PERSONAL PROTECTION

The technician must not work on electrical or electronic equipment when his hands or clothing are wet. Never wear loose or flapping clothing, or clothing with exposed zippers or metal fasteners when working on electronic equipment. The same is true for rings, wrist-watches, bracelets, and similar metal items. Another very important item is shoes. Never wear thin-soled shoes and shoes with metal plates or hobnails when working on electronic equipment. There are shoes on the market that have insulated soles, and were designed specifically for the electrical worker.

Work should never be done on live circuits where the voltage potential exceeds 30 volts except in dire circumstances. Under these conditions when work must be performed on live circuits, every precaution must be taken to prevent accidental grounds. Wear rubber gloves and use properly insulated tools and make sure that at least one other person is present at all times. All persons should be thoroughly familiar with approved methods of rendering first aid and artificial respiration.

Danger signs and suitable guards must be provided to prevent personnel from coming in accidental contact with high voltages.

There are other special precautions against electric shock that should be taken. Certain items (for example, brushes, dusters, brooms) not generally considered to be conductive can be dangerous, and the necessary precautions should be taken. Sufficient illumination is important, and so is keeping one's attention directed to the work being done. Do not trust equipment insulation to protect you from high voltage when work is to be performed, and keep alert to the possibility of accidental grounds or shorts. When working on live circuits, exercise as much care with low voltages as with high voltages; and never take a shock intentionally from any voltage regardless of how small it may be.

Capacitors are potentially dangerous. Before touching a capacitor which is connected to a deenergized circuit (or even disconnected entirely), short-circuit the terminals to make sure that the capacitor is completely discharged. The Klystron Lab provides suitably insulated shorting sticks for this purpose.

The primary function of the shorting stick is to pass the discharge current from a capacitor through the ground wire to ground, NOT through the body of the person discharging the capacitor. The hook enables the technician to fasten the stick to the high voltage terminal so that it can serve as an added protection while work is in progress. Connect the ground clamp to ground BEFORE using the hook. There are shorting sticks placed permanently inside each modulator high voltage cabinet. Take precautions against flash from high power sources.

When removing a capacitor from a circuit for any reason, short the capacitor terminals with wire to prevent its ability to recharge while not in use.

COMMON SAFETY FEATURES IN ELECTRONIC EQUIPMENT

The technician should be aware of the safety features that are generally included in electronic equipment. He should also remember that safety devices cannot always be counted upon to function (refer to the applicable Murphy's Law). Some of the common safety features are interlock switches, bleeder resistors, insulated controls, and power line safety devices.

The interlock switch is ordinarily wired in series with the power line leads to the power supply unit, and is installed on the lid or door of the enclosure so as to break the circuit when the lid or door is opened. A true interlock switch is entirely automatic in action; it does not have to be manipulated by the operator. Naturally, it is dangerous practice to bypass an installed interlock.

Multiple interlock switches, connected in series, may be used for increased safety. This is the type installed in the modulator cabinets.

A bleeder resistor is often connected across the output terminals of high voltage DC power supplies. It is used to bleed the dangerous charges off the filter capacitors because a high-grade filter capacitor can maintain its charge for a long period of time. In some equipment where large, high voltage capacitors cannot be effectively shunted by bleeder resistors (such as the modulators), the technician must resort to the shorting bars to discharge them.

The technician must keep in mind the possibility that the bleeder resistor may burn out and thus become useless as a protective device. For this reason, filter capacitors must be discharged as a matter of routine when repair work is to be done. Do not depend on the bleeder; it is merely an added protection.

POWER LINE SAFETY MEASURES

Only line cords in good condition should be used. Such cords must be protected with insulating grommets at the point where they pass through the chassis or panel.

All portable tools usually have a distinctively marked ground wire in addition to the conductors for supplying power to the tool. The end of the ground wire (usually green) within the tool must be connected to the tool's metal housing. The other end must be connected to a positive earth ground. In all cases, the terminal connections must be soldered to insure positive continuity. A properly grounded tool or piece of equipment will have a small fraction of an ohm resistance measured from the metal case to the ground prong on the power plug.

Extreme care must be exercised to see that the ground connection is made correctly. If the grounding conductor, which is connected to the metallic casing, is connected by mistake to a line contact of the power plug, a dangerous potential will be placed on the equipment casing. To guard against this danger, the connections must be tested after they have been made and prior to energizing the equipment, to make certain that the leads are connected properly and that a good ground is assured.

RADIOACTIVE ELECTRON TUBES

The Klystron Group maintains voltage regulators that utilize electron tubes coated on the inside with a radioactive material, such as Cobalt 60. These tubes must be handled delicately and disposed of properly to prevent the possibility of ingestion of a radioactive substance. Poisoning from radioactive materials contained in these tubes may be of three types:

1. ASSIMILATION - Eating, drinking, or breathing radioactive substances or absorbing them through cuts. Radium-bearing dust, which may be present in certain tubes, is dangerous in this respect.
2. BREATHING RADON - Radon is a tasteless, odorless, colorless gas that is given off by radium at all times. When this or cobalt particles are breathed into the lungs, severe injury might result.
3. RADIATION - All radioactive materials emit radiation (similar to X-rays) that can cause invisible, but detrimental effects.

A SUMMARY OF SOME SAFETY RULES TO REMEMBER:

1. Do not rely on safety devices such as interlocks and high voltage relays.
2. Do not work alone on energized circuits. If you must, have another individual standing by who is trained in first aid and qualified to secure the power in an emergency.
3. Remember that cleaning solvents are potentially toxic. While most cleaning solvents used in the electronics group are not dangerous, check with your supervisor prior to using an uncommon variety.
4. Use a shorting stick for discharging capacitors, and wear a face shield.
5. Use approved fuse pullers with a face shield.
6. Remember that personnel may be killed or injured by high voltage equipment that is assumed to be off. Take NOTHING for granted. Make sure that the power is secured by PADLOCKING the power breaker in the OFF position. When securing knife switches, insure prompt and positive motion in the off direction.
7. The use of properly grounded equipment cannot be overemphasized.

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