THE RADIO-FREQUENCY SYSTEM GUIDE FOR THE ACCELERATOR TEST FACILITY

1. The Radio-Frequency System

1.1 Introduction

The accelerator RF system operates at 2856 MHz. The internal dimensions of the accelerator cavities, klystron, and waveguide components determine the frequency. Frequency adjustment of about 0.1 MHz is possible by changing the temperature of the components by adjusting the water-cooling set point. The normal water temperature is at 44.60 ± 0.05C.

The choice of operating frequency was due to the 50-year legacy of development and manufacturing at this frequency and availability of standard components developed at Stanford University and SLAC.

Pulsed power is available at up to 6 pulses per second with pulse widths from 2.5 to 10μs. Total peak power of 20 to 70 megawatts is available depending on the klystron(s) used.

The power is distributed as follows:
Electron gun 4-10 megawatts
Accelerating sections 5-30 megawatts (each)

The pulses of RF power are rectangular with rise and fall times of about 400 nanoseconds. Pulse amplitude should be constant to ±0.3% with a pulse-to-pulse repeatability of better than ±0.05%. Noise and FM jitter should not exceed 0.5 degree during the pulse.

The source of RF is a temperature controlled crystal oscillator at 40.8 MHz. The frequency drift is less than 1 part in 10^7 per day. The output of this oscillator is used to provide a synchronizing signal to the laser system and as the input to a frequency multiplier.

The frequency multiplier is used to provide a signal at the 35th harmonic of 81.6 MHz for the klystron system. This 2856 MHz output is also used to provide signals for master timing reference and to power diagnostic equipment.

2. The Amplifier System

2.1 Introduction

This system operates with each stage operating in a non drive-saturated condition in order that the output power of the klystron may be controlled by the input low power drive signal. There is a separate amplifier system for each klystron, though in order to maintain synchronism all systems are driven from the common oscillator

The klystron output power varies with anode voltage and with input drive power. Because changes in anode voltage change the electron beam velocity, it also causes a change in the phase shift across the klystron. In normal operation the klystron has about 1300 degrees of phase shift across it. A 1% change in anode voltage will then result in about 13 degrees of phase shift. For that reason it is desirable to control klystron power output by varying the drive power which has only a small second order effect on phase. Changes in anode voltage are used to control klystron efficiency and maximum power output.

At low anode voltages bunching occurs at frequencies above the cutoff mode of the klystron bore tube and may allow the klystron to self oscillate at frequencies which will cause klystron failure. This requires that anode voltage not be applied below ≈200 kV.

2.2 Amplitude Modulator

The output of the oscillator system is first coupled to a voltage controlled attenuator for each klystron to servo its output and to allow control of the output pulse shape. This allows compensation for energy changes due to beam loading and reduction of energy ripple.

2.3 Solid State Amplifier

The output of the attenuator is fed to a 30-db solid-state amplifier, which will deliver about 1 watt CW at 2856 MHz. Whether this pre-amplifier is used or not depends on the gain of the 1KW Amplifier used (see 2.4 below).

2.4 Cascade Triode Amplifier

The next stage is a 1KW pulsed RF Amplifier consisting of a cascade of 2, 3, or 4 identical vacuum tube tuned triode cavities (depends on amplifier), used to obtain a pulsed power output of up to 1200 watts. These units are grid modulated and are capable of pulses of 15 microseconds at up to 60 pulses per second. The output of this amplifier drives the klystron amplifier. The ATF owns three 1KW amplifiers, 2 used in operations and 1 spare unit. Their gains and input power requirements vary from one unit to another.

2.5 Klystron Amplifier

The klystron is a fixed tuned 5-cavity solenoid magnet focused assembly. The klystron was developed at Stanford University and then at SLAC and has been manufactured at SLAC, and by several U.S., European, and Asian manufacturers. Several versions of the tube exist with power output capabilities of 20 to 65 megawatts. Some of the tubes have been tested at power output of up to 180 megawatts.

The commercial version of the tube produced originally for SLAC had a rated power output of 2 megawatts and was designated as EIA type 8568. This tube and several different improved versions of it were designated as type XK5 and eventually upgraded to 35 megawatts by increasing klystron efficiency.

A new series of high power klystrons was developed at SLAC designated as type 5045 with an initial operating goal of 50 megawatts peak and 45 kilowatts average power. Most present versions of the tube are now capable of greater than 65 megawatts peak power. The tubes presently used at ATF are of the XK5 type. The klystron requires RF drive power of 120 to 400 watts depending on tube type and operating conditions. The drive power may be applied independent of anode voltage.

The RF power is coupled into the tube via 50Ω Heliax cable. Because of high attenuation in the coaxial cable at 2.856GHz the losses in this cable may dissipate as much as 75% of the drive power depending on the distance between the 1KW Amplifier and Klystron. The output of the Klystron tube is carried to the load via a high vacuum waveguide of EIA type WR284 (2.84 by 1.35 inches cross section).

An external solenoid magnet focuses the electron beam in the klystron. On the type 8568 and XK5 tubes this is normally done with a permanent magnet for circuit simplicity and reliability. An electromagnet may be used on these tubes for slightly higher output power if required and is necessary for the type 5045. The XK5 tube requires an anode voltage of about 250 kilovolts at 250 amperes to obtain full power output. These 62.6 megawatts will result in 20 to 35 megawatts of power output depending on tube efficiency. The tube is normally operated with the anode at ground potential and the cathode assembly immersed in a tank of oil for insulation and cooling. A negative voltage pulse of 250 kilovolts is then applied to the cathode.

3. The Modulator

3.1 Introduction

In order to make a practical pulse modulator it is necessary to generate the pulse at a lower voltage and use a step up transformer to transform the voltage to the correct level. The transformer is located in the oil tank below the klystron cathode assembly. It has a step-up turns ratio of 1:12. This requires the modulator to deliver a primary voltage of 21 kV at 3000 amperes.

The cathode is heated by passing filament power up two parallel secondary windings of the step-up transformer. The tube requires about 300 watts of filament power.

To reduce the size and rise time of the pulse transformer it is designed with a minimum amount of magnetic core material. This requires that it be supplied with a D.C. priming current to preset the operating point on the core saturation curve and allow sufficient pulse length without core saturation.

The modulator cabinet contains the following items:

3.2 Klystron Filament Power Supply and Regulator

The klystron filament power supply provides a current regulated source of power to a filament transformer located on the cathode/filament terminals in the oil tank. This source must be regulated to ensure long cathode lifetime and to prevent destructive inrush current during power turn on.

3.3 Core Bias Supply

The core bias power supply provides 9 amperes D.C. to the primary winding of the pulse transformer to back bias the core to saturation. Its setting is not critical.

3.4 A.C. Power Distribution

The modulator uses 208VAC 3 phase power which is supplied to the modulator as two separate systems. The first is used to power the filaments and all low voltage auxiliary supplies. Power to these is interlocked by the sub-systems that they serve. For instance, a loss of cooling water to the klystron filaments will turn off all filament-related equipment in the modulator.
The second system provides power to the high voltage power supply that charges the pulse forming network (PFN). Power supplied by the second system is controlled in one of three ways: by a Safety Switch by means of which power to the modulator can be locked out, by an external security logic fault that prevents operation of the klystron if electrical or radiation safety systems are not satisfied, and last by an interlock fault in the first power system. Both power systems also contain primary over current protection and transient protectors.

3.5 Energy storage pulse forming network

The pulse-forming network consists of an array of capacitors and inductors connected as an artificial delay line. The line is normally charged to about 42 kilovolts. If we use the total capacitance and inductance of the line we get.

$$T = \sqrt{(LC)} \quad \text{and} \quad Z = \sqrt{(L/C)}$$

where T is the one way propagation delay time of the line and Z is the line impedance. Adding more selections to the line increases T without changing Z.

The pulse transformer in the klystron tank requires 21 kilovolts at 3000 amperes. Setting Z equal to this transformer input impedance and T = 2.5 microseconds. We get:

$$C = 0.357\ \mu F \quad \text{and} \quad L = 17.4\ \mu H$$

Since the complete PFN discharge requires the wave to travel down and back on the unit the actual discharge time = 2T. The PFN capacitors must be charged to twice the required discharge voltage. This requires a stored energy per pulse of $1/2CV^2 = (0.357/2) \times (42)^2 = 315$ joules. About 30 to 45% of this shows up as RF output energy.

3.6 High Voltage Power Supply and Regulator

The PFN is charged by a Maxwell CCDS 50KV 10KJ/s positive polarity high efficiency capacitor charging power supply. Between the power supply and the PFN there is a protection circuit which consists of a 100KV rated diode and two 100Ω power resistors. The power supply is connected to the cathode of the diode through one of the resistors. The PFN is similarly connected through the second resistor. The anode of the diode is connected to ground. This results in a charging time constant of 107 milliseconds. It will take 1.44 time constants to charge the PFN to 42 kV at which time the thyristor servo system will regulate the PFN voltage until the discharge pulse takes place. The servo system senses the PFN voltage to regulate the charge and runs at full output during the beginning of each charge cycle. With the above time constants the system is capable of running up to 6 pulses per second (pps). In conventional SLAC type modulators the PFN is charged through a resonant charging choke and has a practical lower repetition rate of about 10 pps. Resonant charging also results in the final PFN voltage being affected by the residual charge on the PFN from the proceeding pulse. This limits the accuracy and stability of the output pulse at low repetition rates. While high repetition rates may be desirable for some linac operations it would require a large increase in electrical power, cooling and radiation shielding.

3.7 Pulse Monitoring System

The power supply current and voltage, the PFN charge voltage, the PFN discharge voltage and current the klystron cathode voltage are monitored with calibrated sensors.

3.8 Hydrogen Thyratron Switch Tube Assembly

The PFN is discharged by effectively grounding the high voltage side of the end capacitor of the network. The low voltage side of the network is connected to the primary of the pulse transformer and delivers the resulting 21 kV pulse to the transformer.

A multi-grid hydrogen thyratron is used as the switch and requires a 2 kV trigger pulse to its second grid. The first grid is held at a small voltage, which continually supplies a hydrogen plasma in the tube. Mainly the amplitude of the trigger pulse to grid #2 controls the discharge rise time and delay. The third grid is used to control the voltage gradient in the tube. In operation a drift and pulse jitter of less than 2 nanoseconds is required.

3.9 Interlock and Overload Protection Circuits

Interlocks are provided to prevent application of high voltage if access doors are open or if appropriate auxiliary voltages and time delays are not correct.