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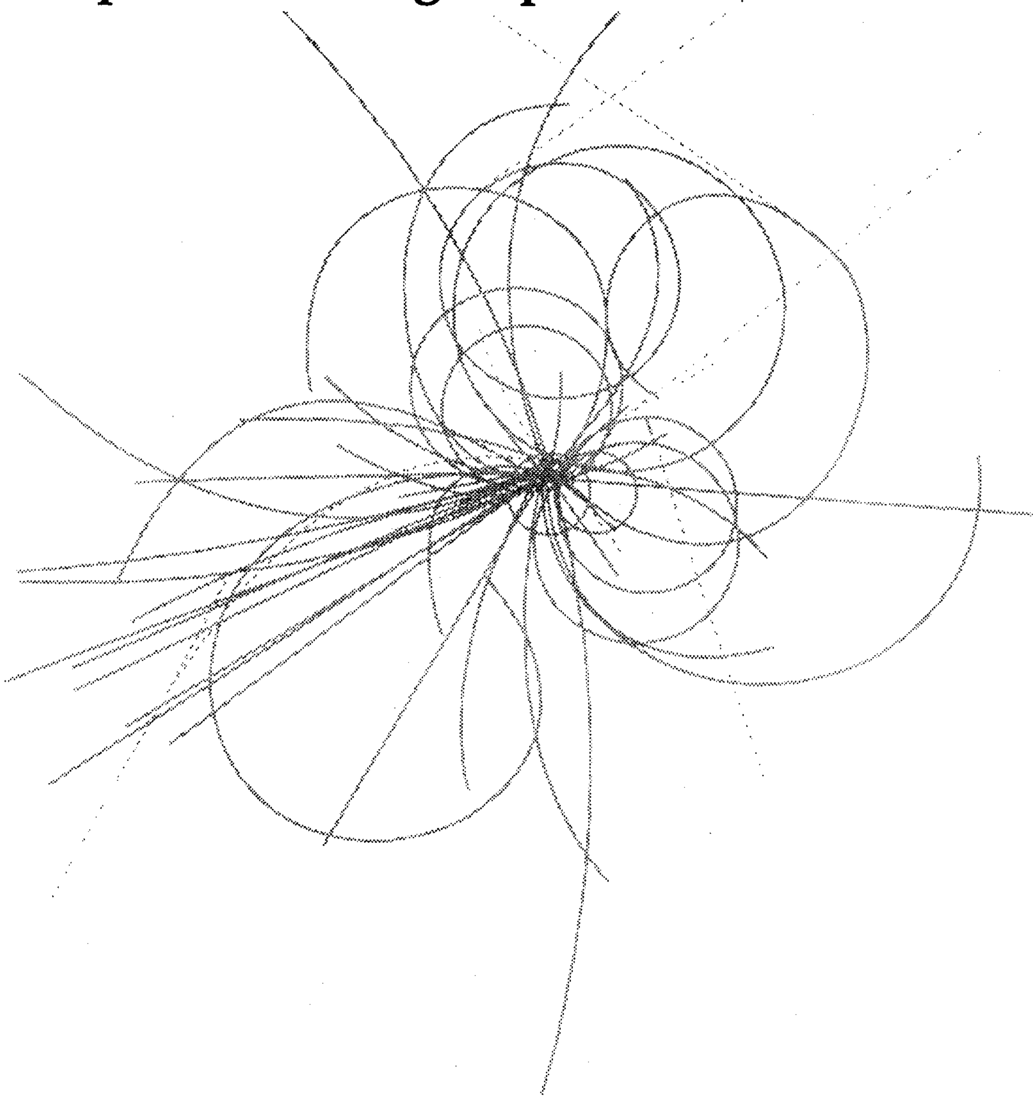
Superconducting Super Collider Laboratory



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Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave.
Dallas, TX 75237

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THE SUPERCONDUCTING SUPER COLLIDER

LINAC RF SYSTEMS

J. Grippe, R. J. Rodriguez
M. Tomek, E. Marsden, J. Mynk
Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave. MS 4010
Dallas, Texas 75237
Telephone: (214) 708-3781

Abstract

The Superconducting Super Collider Linear Accelerator (LINAC) consists of six separate Radio Frequency (RF) Systems which accelerate the H^- beam from 35 keV to 600 MeV. The RF systems consist of the Radio Frequency Quadrupole (RFQ), Drift Tube LINAC (DTL) Input Matching Section, Drift Tube LINAC (DTL), Coupled Cavity LINAC (CCL), Input Matching Section, Coupled Cavity LINAC (CCL), and the Low Energy Booster (LEB) Energy Compressor as shown in Figure 1.

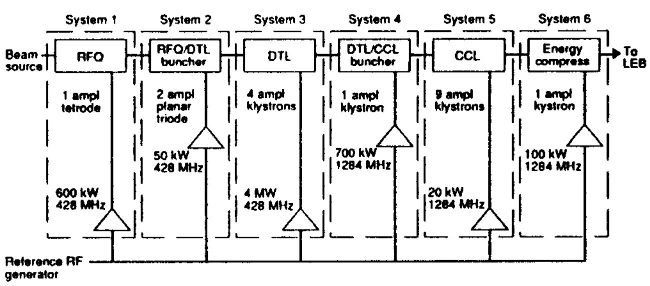

Fig. 1. Block diagram showing the six RF systems used in the LINAC

The voltage in each cavity is a function of the peak power provided by the individual RF amplifier stations, the cavity shunt impedance and the voltage generated by the beam passing through the cavities. The LINAC requirements dictate that the accelerating cavity voltage and phase be maintained within 0.5% of the desired voltage and within 0.5 degrees of the desired synchronous phase. In order to meet the voltage and phase requirements, the RF amplifier subsystem must exhibit low RF amplitude and phase modulation and include a closed loop feedback system. As shown in Figure 1, each cavity system may contain more than one RF amplifier. The design requirements of each RF amplifier are such that the amplifier's contribution to the amplitude and phase noise is minimized. The DTL, CCL, CCL Input Matching Section and the LEB Energy Compressor use klystron amplifiers, cathode driven by a line-type modulator. The Pulse Forming Network in the modulator is tuned to have a rising characteristic during the pulse to compensate for transformer droop.

The RF amplifier control system will be designed to allow full remote control of modulator parameters that would affect the proper acceleration of the H^- beam. Therefore, synchronization of all RF systems is critical and performed from a centralized location. During subsystem testing and maintenance, each RF station can be operated from an 'extended local' control system.

Introduction

The purpose of the individual RF systems is to provide voltage of the desired synchronous phase and proper amplitude to accelerate the negatively charged hydrogen ions (H^-) provided by the beam source from 0.00864 the speed of light to 0.792 the speed of light, for entry into the low energy booster (LEB). The energy in the beam increases from an initial value of 35 keV as the beam enters the RFQ to 600 MeV as it leaves the LINAC and enters the LEB. A typical RF system is shown in Figure 2.

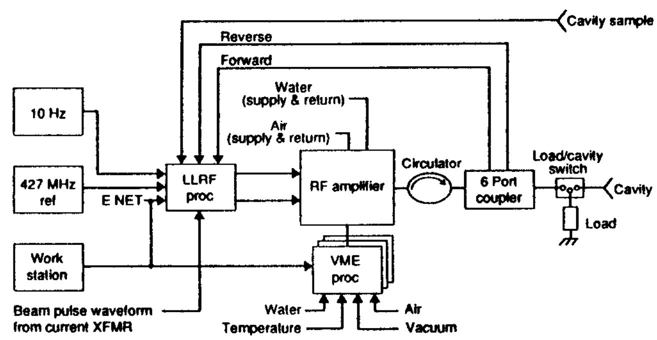

Fig. 2. Typical RF system

To accomplish the preceding task the Superconducting Super Collider LINAC is being constructed with six major RF systems. The Radio Frequency Quadrupole (RFQ) increases the velocity of the beam to 0.0729 the speed of light and the energy to 2.5 MeV. The DTL matching section shapes the geometrical and momentum properties of the beam so that it may be efficiently accepted by the Drift Tube LINAC (DTL). The DTL increases the velocity of the beam to 0.3661 the speed of light and increases the energy to 70 MeV. The DTL to Coupled Cavity LINAC (CCL) matching section again changes the geometrical and momentum properties of the beam so that the shape of the beam is acceptable to the CCL which operates at a higher frequency. The CCL increases the velocity of the beam to 0.792 the speed of light and the energy of the beam to the final LINAC energy of 600 MeV. The LEB energy-compressor again shapes the beam characteristics to make them acceptable to the LEB. The design explanation for each of the six RF systems follows.

RFQ RF System

The RFQ cavity requires 225 kW of power at each of two RF input ports at a frequency of 427.617 MHz. To provide this power with an adequate amount of safety margin and enough overdrive to ensure a fast cavity fill time, a joint venture was entered into with Los Alamos National Laboratory to design and build a 600 kW amplifier. The requirements placed upon the amplifier are as shown in Table 1.

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Table 1

RFQ amplifier requirements

Operating Frequency	427.617 MHz
Bandwidth	300 kHz minimum
Power Output	600 kW peak
Gain	77 dB nominal
Pulse Length	100 microseconds
Pulse Repetition Rate	1-10 Hz
Pulse Droop	1% maximum
Linear Range	15% to 85% of peak-power rating
Amplitude Stability	<0.5 dB within any one-hour period
Phase Stability	<10 deg. within any one-hour period

The amplifier consists of three stages of RF amplification. The first stage is a solid-state amplifier which takes the input RF and amplifies it by approximately 48 dB. The intermediate amplifier consists of a cathode-modulated Eimac 8938 Triode, cavity, and a high-voltage power supply. The tube is air cooled and has a gain of approximately 15 dB. The final power stage consists of a Burle 4616 tetrode and its associated cavity, a 25 kV anode power supply rated at 2 kW average power output, and the necessary grid supplies. The tetrode operates in class AB with approximately 5 mA of bias current from the high-voltage power supply. At the 600 kW output power level, the efficiency is at the 60% level. Acceptance testing completed at the Los Alamos National Laboratory was favorable.

The rest of the RFQ system consists of a high-power circulator to prevent high VSWR from damaging the amplifier, high-power couplers (forward and reverse power) for monitoring and controlling the output RF, a high-power transfer switch for transferring the output power to a dummy load during test and a 3 dB power divider to split the power between the cavity inputs. Rigid coax, 3 1/8 in. (7.93 cm), is used in all high-power areas. The coax contains SF_6 gas to increase the breakdown characteristics.

DTL Matching Section RF System

The purpose of the RF systems in the DTL matching section is to provide voltage of proper amplitude and phase to the buncher cavities to longitudinally match the output of the RFQ to the input of the DTL. Two buncher cavities are used for matching. Therefore, two individual RF systems are used, one for each of the cavities since the cavities have a high Q and are very sensitive to variations. Table 2 lists the requirements placed on the RF amplifiers.

Table 2

Matching section amplifier requirements

Operating Frequency	427.617 MHz
Bandwidth	10 MHz minimum
Power Output	50 kW peak
Pulse Length	100 microseconds
Pulse Repetition Rate	1 - 10 Hz
Linear Range	<0.5 dB from 10 kW to 42 kW
Amplitude Stability	<0.5 dB
Phase Stability	<10 degrees

This RF power amplifier is currently in the proposal stage, therefore little is known about its makeup. The amplifier probably will consists of at least two stages, a driver and a power stage. The power stage will most likely be a tetrode or a triode in a cavity arrangement since klystrons at this power level are virtually nonexistent. A total solid-state amplifier has not not been ruled out and, if proposed, will be considered. The major goal in this area is to use an off-the-shelf amplifier, or at least one that has a proven design, in the RF section — one that poses little schedule risk.

The additional pieces that make up the matching section system consist of a power circulator to prevent damage to the amplifier under high VSWR conditions, and forward and reverse power couplers for RF monitoring and control. Rigid 3 1/8 in. (7.93 cm) coax will be used throughout the high power output section to couple the amplifier and the associated components to the cavity. Since the power is relatively low for this coax, it will not be pressurized. Therefore, no switch is used between the cavity and a dummy load for testing. When testing of the amplifier is required, a piece of coax will be removed and the dummy load attached.

Drift Tube LINAC (DTL) RF Systems

The Drift Tube LINAC (DTL) RF systems power the cavities of the drift tube linear accelerator, accelerating the H^- Ion beam from 2.5 MeV to 70 MeV. Each of the four drift tube tanks will have different input power requirements, which will vary from 2.1 MW on tank #1 to 3.2 MW on tank #4. In order to meet this varying power requirement, each tank will be connected to an independent RF system, consisting of a klystron modulator, a low-level RF, front-end processor (remote operation), vacuum system, and other necessary peripheral systems to operate and diagnose an accelerator cavity system.

The DTL klystron modulator system consists of a klystron tube, a modulator, input and output RF systems, and all the auxiliary power supplies required for the operation of the klystron tube. Table 3 lists the DTL Klystron Modulator System technical requirements.

Table 3

DTL modulator system requirements

Operating Frequency	427.617 MHz
RF Peak Output Power	4.0 MW
RF Peak Input Power (nominal)	1.0 W
Klystron Peak Beam Voltage	125 kV
Klystron Peak Beam Current	64 A
HV Pulse Flat-Top Width (100%)	90 microseconds
HV Pulse Top Ripple, including overshoot	<0.5%(p-p)
HV Pulse Droop	<1.0%
Klystron Voltage Rise Time	<10.0 microseconds
Klystron Voltage Fall Time	<20.0 microseconds
Pulse Repetition Rate	1 to 10 Hz
Klystron Duty Cycle	0.00105 max
Recharge Time	95 mseconds
Klystron Peak Beam Voltage Time Jitter	10 nanoseconds
Klystron Peak Beam Voltage Pulse-to-Pulse Amplitude Variations	0.2%

The Thomson Tubes Electroniques TH-2140 is a cathode-pulsed klystron capable of delivering 4.0 MW peak, 5.0 kW average @ 427.617 MHz with RF pulsewidth of up to 100 microseconds. The tube is 321.5-cm long, 105-cm wide and weighs close to 1500 kg. A lead structure 316.5-cm high, 122-cm wide, 122-cm deep and weighing close to 1850 kg will surround the tube to attenuate the x-ray radiation generated by the klystron tube.

The modulator will provide the required power to the klystron tube cathode as specified in Table 3. In order to meet the reliability and maintainability requirements, the modulator will be designed with a major emphasis on modularity and interchangeability between the modulators. The modulator pulse is generated by discharging a Raleigh-type pulse forming network (PFN) of up to 20 sections through a high-voltage step-up pulse transformer to the required 125 kV. The PFN will be manually tuned by adjusting the individual section inductance. Tuning will help compensate for the pulse transformer droop and reduce PFN ripple.

One or more high-efficiency, full-bridge, switching power supplies will be used to charge the PFN. The power supply will operate as a constant current source, charging the pulse forming network capacitors up to the desired voltage. When the capacitors have reached the required voltage, the supply will precisely regulate the voltage on the PFN capacitors. During the PFN discharge cycle the power supply will be inhibited thereby preventing "hang-fire" of the discharge switch from follow-on current.

All modulator parameters will be monitored through the remote control interface (RCI) by a front-end processor (FEP). The remote control interface will collect all the interlock/fault/monitoring information from the individual modulator assemblies and route the individual signal to the appropriate VME module in the SSC front end processor crate. Control functions to the individual modulator assemblies will be limited to a few selected signals through the remote control interface. Protection against computer and/or operator error will be provided by the hardware protection circuits built into the modulator. The hardware protection circuits will inhibit any command signal issued out of sequence or out of range, thus protecting the modulator from a possible catastrophic operator or computer error.

The solid-state driver amplifier assembly will control the input drive to the klystron tube by amplifying the drive signal generated by the feedback loops of the low-level RF system. This assembly will consist of standard off-the-shelf components such as couplers, -3dB splitters, DC block, filters, isolators, PIN switch and diode detectors as shown in Figure 3.

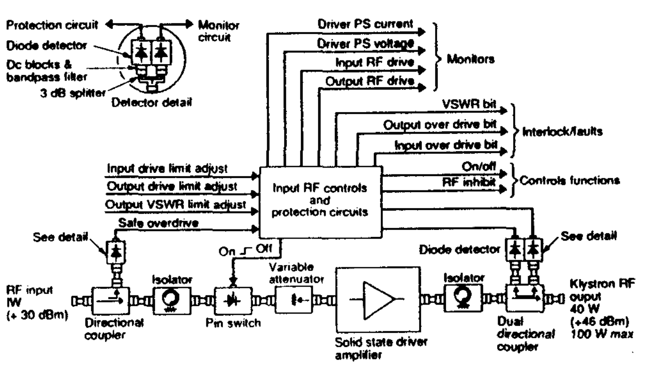

Fig. 3. Solid state driver amplifier assembly block diagram

The output of the klystron tube will be connected to the drift tube tank through the output waveguide assembly, which averages 60 feet (18.3 m) in length. This assembly consists of standard off-theshelf WR-1800 waveguide components, which include arc detectors, miter elbows, waveguide switch, full power dummy load, and various straight sections, as shown in Figure 4. A high power isolator/circulator will be incorporated between the klystron tube and the drift tube tanks. In the current configuration, the DTL RF system is located above ground in the LINAC building and the drift tube tanks are located below in the tunnel. The tunnel is approximately 20 feet (6.1 m) below and approximately 25 feet (7.6 m) away from the LINAC building. Waveguide penetration will be provided at specific locations along the length of the LINAC building to coincide with the input power feeds of the drift tube tanks.The DTL waveguide system will be pressurized with sulphur hexaflouride (SF_6) at 0.25 psig.

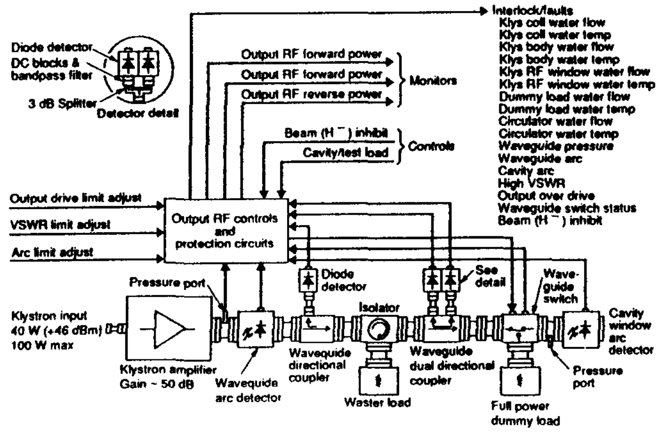

Fig. 4. Output waveguide assembly block diagram

DTL/CCL Matching Section RF System

The purpose of the DTL/CCL Matching Section (bunchers) Amplifier is to provide voltage of proper phase and amplitude to the buncher cavities for the purpose of changing the geometrical and momentum properties of the beam so that the shape of the beam is acceptable to the CCL which operates at a higher frequency. Table 4 lists DTL/CCL matching section amplifier requirements.

Table 4

DTL/CCL Matching Section Amplifier Requirements

Operating Frequency	1282.851 MHz
Amplifier Bandwidth (-1 dB)	5 MHz
Peak RF Output Power	700 kW min
RF Pulse length	60 microseconds
Repetition Rate	1 to 10 Hz

A CCL Amplifier (CCL line-type modulator and CCL klystron) will be used for this amplification stage because of its availability and suitability for the requirements. The difference is that the peak power required to drive the matching sections is on the order of 700 kW rather than 20 MW which means the CCL klystron will be operated 14.5 dB below its full power capability (well within the linear control capabilities of the tube). Even though a CCL Amplifier will be used for this function, some of its unneeded components (HVPS capacitor-charging supplies) may be removed and used here at SSCL for spares support because of an average power reduction of 1300 W (2 kW down to 700 W).

Since two buncher cavities are required, the RF power budget will be approximately 260 kW for the first buncher and 430 kW for the second. To accomplish this from a single 700 kW source, a WR 650 power divider and mechanical phase shifter will be employed. In addition, an RF dummy load will be included for high power amplifier testing.

CCL Amplifier System

The Coupled Cavity LINAC (CCL) RF systems will be used to power the cavities of the drift tube linear accelerator, accelerating the H^- Ion beam from 70 MeV to 600 MeV. Each of the ten drift tube tanks will have different input power requirements, which will vary from 15.9 MW on tank #1 to 16.2 MW on tank #10. In order to meet this varying power requirement, each tank will be connected to an independent RF system consisting of a klystron modulator, a low level RF, front-end processor (remote operation), vacuum system and other necessary peripheral systems to operated and diagnose an accelerator cavity system.

The configuration of the CCL klystron modulator system is identical to the DTL system. The technical requirements of the CCL Klystron Modulator System are listed in Table 5.

Table 5

CCL modulator system requirements

Operating Frequency	1282.851 MHz
RF Peak Output Power	20.0 MW
RF Peak Input Power (nominal)	1.0 W
Klystron Peak Beam Voltage	230 kV
Klystron Peak Beam Current	200 A
HV Pulse Flat-Top Width (100%)	60 microseconds
HV Pulse Top Ripple, including overshoot	<0.5% (p-p)
HV Pulse Droop	<1.0%
Klystron Voltage Rise Time	<10.0 microseconds
Klystron Voltage Fall Time	<20.0 microseconds
Pulse Repetition Rate	1 to 10 Hz
Klystron Duty Cycle	0.00075 max
Recharge Time	95 mseconds
Klystron Peak Beam Voltage Time Jitter	10 nseconds
Klystron Peak Beam Voltage Pulse-to-Pulse Amplitude Variations	0.2%

The Thomson Tubes Electroniques TH-2143 is a cathode-pulsed klystron capable of delivering 20.0 MW peak, 20.0 kW average @ 1282.851 MHz with RF pulsewidth of up to 100 microseconds. The tube is 187.5-cm long, 57.1-cm wide and weighs close to 160 kg. A lead structure 160-cm high, 72.5-cm wide, 72.5-cm deep and weighing close to 950 kg will surround the tube to attenuate any x-ray radiation generated by the tube.

All the discussions concerning the klystron modulator and the input and output RF subassemblies are identical to those in the drift tube LINAC.

LEB Energy Compressor RF System

The LEB Energy Compressor RF system is the final stage of the LINAC system and provides the voltage necessary for the compressor cavities to perform the final shaping of the H^- ions before entering the booster rings. Table 6 lists compressor RF system requirements.

Table 6

Compressor RF system requirements

Operating Frequency	1282.851 MHz
Bandwidth	5 MHz
Peak Power	100 kW min
RF Pulse Length	60 microseconds
Repetition Rate	1-10 Hz

A narrow band, cathode-pulsed klystron, meeting the amplifier design requirements and having a minimum of 45 dB of gain, will be pulse driven from a line modulator. It may be Periodic Permanent Magnet (PPM) or Electromagnetically (EM) focused. The PPM provides the cost savings of the focusing power supplies and associated Built-In Test (BIT) Circuits but there could be a cost advantage to an EM tube because of availability or other reason.

A DTL line-type modulator will be used to pulse the klystron cathode. The cathode pulse transformer, heater supplies, PFN sections, and possibly magnet supplies, will change somewhat from the DTL design because of a decrease in the cathode voltage requirement and a reduction in the RF pulse width. This klystron will emit in the area of 100 kW rather than the 4 MW of the DTL tubes resulting in a decrease in the klystron cathode voltage of from 125 kV to 37 kV. In addition, the RF pulse width is 60 rather than 100 μsec because of the location along the collider beam line. Also, there will not be as great a demand on the capacitor chargers of the high voltage power supply and fewer will be required.

Standard CCL RF components will be used except for the RF output circulator and dummy load. These components will be unique to this RF system because of the significantly lower power requirements.

Low Level RF System

The low level RF system includes the RF Reference Line and one Cavity Phase and Amplitude Control subsystem provided with each of the LINAC RF amplifier systems. The primary purpose of low level RF is control of the cavity RF phase and amplitude. The RF fields in the LINAC cavities are to be maintained within 0.5 degree of the desired phase and 0.5 percent of the desired amplitude.

The RF Reference Line actually is two lines, one operating at 427.617 MHz and a second line operating at 1282.851 MHz. The 427.617 MHz line length will be 100 feet (30.48 m) with a 100 W input power and the 1282.851 MHz line length is 1100 feet (335.28 m) with a 400 W input power. It is imperative that the RF reference line be more stable than the cavity field requirements, since the phase of the RF accelerating voltage in each cavity is controlled by comparison against the reference RF.

To overcome the temperature-related phase problems of long transmission lines, the reference lines will be thermally insulated and maintained at 120 deg F (+/- 0.05 deg F). Directional couplers will be used at various points along the reference lines to provide RF reference samples for cavity field control and diagnostics use.

Each Cavity Phase and Amplitude Control subsystem interfaces with its associated RF system as shown in Figure 2. It compares a cavity field sample to a Reference Line sample to generate inphase (I) and quadrature (Q) error signals. Each of these I & Q error signals is used in conjunction with a proportional, integral, derivative (PID) controller to create an I and a Q control voltage which, through an I & Q modulator, controls the phase and amplitude of the cavity RF field.

The Cavity Phase and Amplitude Control subsystem is a collaboration with Los Alamos National Laboratory and is based on the Ground Test Accelerator (GTA) design. The design uses downconversion to 20 MHz where I & Q detection is followed by baseband PID controllers and then a 20 MHz I & Q modulator. The modulator output is then upconverted back to 427.617 MHz (DTL) or 1282.851 MHz (CCL). This RF subsystem is VXI based with extensive control and monitoring capability available through a processor located in the VXI crate.

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