DESIGN AND TEST RESULTS OF THE LOW ENERGY DEMONSTRATION ACCELERATOR (LEDA) RF SYSTEMS

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Abstract

The Low Energy Demonstration Accelerator (LEDA) being constructed at Los Alamos will serve as the prototype for the low energy section of the Accelerator Production of Tritium (APT) accelerator. The APT accelerator requires over 200 RF systems each with a continuous wave output power of 1 MW. The reliability and availability of these RF systems is critical to the successful operation of the APT plant and prototypes of these systems are being developed and demonstrated on LEDA. The RF system design for LEDA includes three, 1.2 MW, 350 MHz continuous wave (CW), RF systems driving a radio frequency quadrapole (RFQ) and one, 1.0 MW, CW, RF system driving a coupled-cavity drift tube linac (CCDTL). This paper will present the design and test results for these RF systems including the klystrons, cathode power supply, circulators, RF vacuum windows, accelerator field and resonance control system, and RF transmission components. The three RF systems driving the RFQ use the accelerating structure as a power combiner, and this places some unique requirements on the RF system. These requirements and corresponding operational implications will be discussed.

1 LEDA RF SYSTEM DESIGN

The LEDA RF system provides RF power to an RFQ which accelerates a proton beam to a final energy of 6.7 MeV and to a CCDTL which further increases the energy to 10 MeV. To accomplish this acceleration the RFQ requires structure and beam power of 1900 kW and the CCDTL requires structure and beam power of 800 kW. The power to the RFQ is provided by three 1.2 MW klystron amplifiers and the power to the CCDTL is provided by a single 1.0 MW klystron amplifier.

The LEDA RF systems utilize modulating-anode klystrons with individual power supplies to maximize operating flexibility and efficiency. Each klystron has an individual power supply, and the modulating anode voltage is derived from the cathode voltage using a regulator tube. The high efficiency klystrons are protected from reflected power by circulators. The power from a klystron is divided into four equal parts using 3 dB hybrids to reduce the power passed through the accelerating structure vacuum windows. For the RFQ waveguide runs, the power from the three klystrons is carried in three full height WR2300 through a waveguide switch to hybrid splitters. The hybrid splitters divide the power into twelve waveguide feeds that transition to half-height WR2300 and deliver the power to the RFQ through coaxial vacuum windows. The 700 MHz waveguide run for the CCDTL is identical in topology, however, full-height WR1500 waveguide is used throughout.

Because the LEDA systems are, in part, meant to serve as prototypes for the APT plant, the approach to achieving high availability is also being prototyped on LEDA. Only two of the three RF systems connected to the RFQ are required for operation of the RFQ. The RFQ serves as the power combiner. Should any component of any of the RFQ RF systems fail, a waveguide switch is used to isolate the failed system from the RFQ. The waveguide switch also reflects a short circuit at the appropriate phase to the RFQ irises associated with the failed system allowing the RFQ to continue to operate with the two remaining systems.

This approach results in some additional requirements on the RF system. With the RFQ serving as the power combiner, it is necessary to balance the output power and phase of the two or three RF systems connected to the RFQ or unwanted reflected power will result. To accomplish this, local phase control loops are implemented around each klystron and the group of klystrons is treated as if it were a single RF source by the low level control system, which modulates the amplitude and phase of the klystron drive to control the RFQ amplitude and phase. Also, an RF arc in a window or circulator requires that all RFQ RF systems be disabled, not just the system associated with the arc, to prevent the other RFQ systems from continuing to drive the arc through the RFQ. This logic also holds true for a crowbar or interlock trip in any one of the RF systems. The other RFQ RF systems must be disabled to prevent the disabled system from being driven through the cavity by the remaining RF systems.

The low-level RF control (LLRF) system performs various functions. Foremost is feedback control of the accelerating fields within the cavity in order to maintain field stability within $\pm 1\%$ amplitude and $1°$ phase. Other functions of the LLRF control system are implementation of the local phase control loops of each klystron and RFQ resonance condition monitoring. The resonance of the RFQ is controlled by varying cooling water temperature. Because the RFQ will rapidly cool when RF is shut down, drive frequency agility in the main feedback control subsystem is incorporated to quickly restore the cavity to resonance with RF heating.

2 RF COMPONENT DESCRIPTIONS

Details of the design and test results of the major RF subsystems are provided in the following paragraphs.

2.1 Klystrons

The LEDA RF systems utilize 1.2 MW CW klystrons at 350 MHz and 1.0 MW CW klystrons at 700 MHz. The 350 MHz klystron is based on the CERN klystron with one major design modification. The LEDA 350 MHz klystrons are designed to dissipate the full beam power (1.85 MW) in the klystron collector in the steady state. This design requirement is driven by the size of the APT plant and the impact that turning off all klystrons would have on the local power grid. The 700 MHz klystron is a new design for APT. It is being developed by two vendors, English Electric Valve (EEV) and Communication and Power Industries (CPI).

The design requirements for the 350 MHz and 700 MHz klystron are summarized in Table 1. The 350 MHz klystrons and the EEV 700 MHz klystron have demonstrated all design requirements in the acceptance tests. The CPI 700 MHz klystron is yet to be tested. A picture of the CPI 700 MHz klystron is shown below in Figure 1.

Table 1: Klystron Requirements

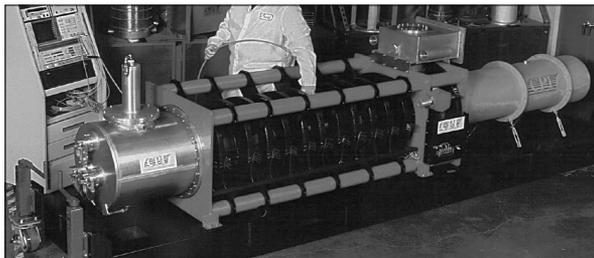| Requirement	350 MHz	700 MHz
Voltage (Max)	95 kV	95 kV
Current (Max)	21 A	21 A
Output Power (Min)	1.2 MW	1.0 MW
Efficiency (Min)	65 %	65 %
Gain (Min)	40 dB	40 dB
Operating VSWR (Max)	1.2:1	1.2:1
1 dB Bandwidth	.7 MHz	1.4 MHz
Collector Power	1.85 MW	1.54 MW

Figure 1: Picture of CPI 700 MHz klystron.

2.2 Power Supplies

LEDA is prototyping two power supply topologies that are under consideration for the APT plant: a Silicon Controlled Rectifier (SCR) center point controlled power supply and a solid state modulator power supply using Insulated Gate Bipolar Transistors (IGBTs). Both topologies must provide a klystron beam voltage of up to 95 kV and a maximum beam current of 21 A. They must protect the klystron from excessive energy deposition in the event of a tube arc.

The SCR power supplies utilize two SCR bridges with filter inductors at the center tapped transformer primaries to produce 12 pulse rectification as shown in Fig 2. In the event of a klystron arc, the crowbar circuit protects the klystron from the filter capacitor stored energy. These power supplies must have an efficiency of ≥95%, a power factor of ≥0.93 at full power and the harmonic distortion at the input must meet IEEE Std 519-1992 requirements. Three of these power supplies have been delivered by Maxwell Labs and have met all performance requirements.
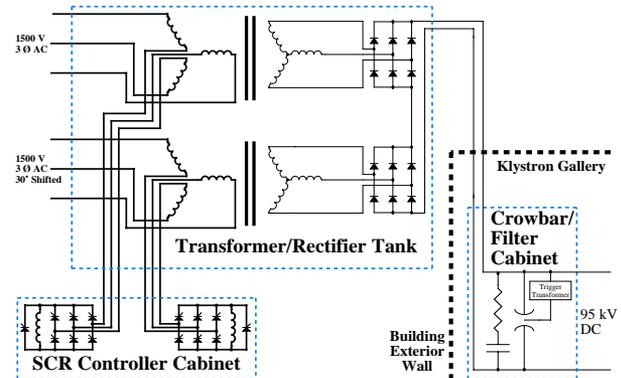

Figure 2: SCR bridges are in the center of the primaries.

The IGBT power supplies utilize 96 separate rectifying modules stacked in series. Each module is fed from an isolated secondary winding on one of four transformers. The primary windings of each transformer are phased for 24 pulse rectification at the series output. Each module uses an IGBT for current control, eliminating the need for a crowbar. Failed modules are bypassed by the control system to provide graceful degradation of operation. These power supplies must have an efficiency of ≥97%, a power factor of ≥0.98 and meet IEEE Std 519-1992 requirements. Three of these power supplies are on order from Continental Electronics but have not yet been tested.

2.3 RF Vacuum Windows

The window design we have selected is a coaxial geometry. The 350 MHz window is illustrated in Figure 3. The air side is a half-height WR2300 waveguide. A T-bar is used to transition to a coaxial line. A high-purity alumina coaxial window separates the air and vacuum side of the window assembly. Another T-bar is used to transition back to half-height WR2300 which is then connected to ridge loaded waveguide to drive the iris coupled RFQ. Each RFQ window has been tested under vacuum in a back-to-back configuration to 1.0 MW of CW RF power for a minimum of four hours. In the RFQ the windows are utilized at a maximum nominal power of 300 kW. Prior to the 1.0 MW acceptance test, the windows must be conditioned to this power level. The conditioning time for each of the RFQ windows and

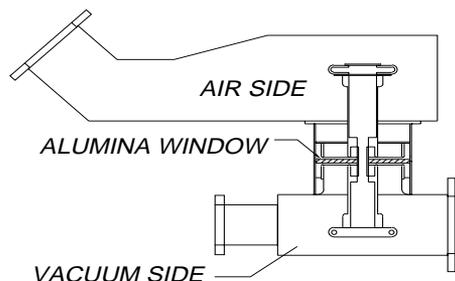spares is indicated in Figure 4. The average time was 18.5 hours.

Figure 3: RFQ coaxial window.

The CCDTL window is also a coaxial geometry. The air side of the window is full-height WR1500 and the vacuum side is half-height WR1150. These windows are currently in production and have not been tested.
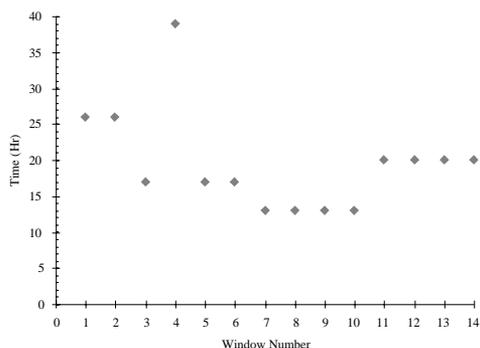

Figure 4: RFQ vacuum window conditioning time.

2.4 Cavity Field Control

The cavity field control system controls the in-phase and quadrature (I/Q) errors of the cavity field. It consists of three VXIbus modules. The Clock Distribution Module receives a phase-stable 10 MHz reference and produces coherent frequencies needed for field signal downconversion and I/Q sampling. The Field Control Module (FCM) houses all of the digital and analog electronics, which perform the high-precision I/Q detection and control. The Amplifier Control Module serves as an interface between the control system and the multiple klystrons driving the cavity. It takes the control signal from the FCM, splits it, and then individually modifies each output leg to compensate for the aberrations of each particular klystron. The closed-loop bandwidth of the field control system is approximately 200 kHz. A block diagram of the entire LLRF system is shown in Figure 5.

2.5 Resonance Control

The resonance condition of the RFQ will be determined by monitoring a sample of its forward, reflected, and transmitted signals. The signals will be run through a simple algorithm in a digital signal processor on board the Resonance Control VXIbus Module to calculate the RFQ's resonant frequency. Should the resonance frequency differ from the fundamental, an error signal will be sent to the RFQ's water-cooling system indicative of the need to increase or decrease the cooling water temperature. This module also implements the frequency agile function, based on direct digital synthesis mentioned earlier. This frequency agility will be utilized only when the cavity is far from nominal resonance, not during normal operation.
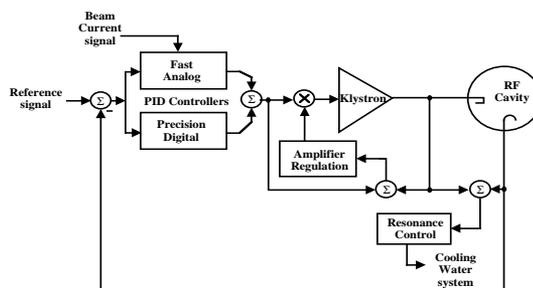

Figure 5: LLRF control system.

2.6 RF Protection

A flexible RF Protection function has also been built into the LLRF VXIbus Control system. The RF Protect Module monitors the HPRF transmission system and turns off the drive to the klystrons should a fault occur anywhere within the system. The RF Protect function protects against arcs in the waveguide, klystron, or RFQ; high reflected power at the RFQ ports, loads on the circulator, and waveguide splitters; crowbars; and bad VSWR at the klystron output. All power measurements are made in duplicate channels, with operator-defined trip levels. All arc inputs have user defined counters, so one may specify the number of arcs within a certain amount of time that can occur before a fault is indicated.

3 CONCLUSIONS

The RF systems for the LEDA accelerator have been installed at Los Alamos and are ready to provide RF power to the RFQ in early October. These systems have been designed as prototype equipment for the APT plant and will be used to demonstrate not only the reliability of RF equipment, but also the redundancy concepts for the APT plant that will allow for very high RF system availability. The individual RF system tests on the equipment have demonstrated that each system meets the design requirements. The integrated testing with the RFQ in October is the next step in the validation of the APT RF system design.