OVERVIEW OF THE APT RF POWER DISTRIBUTION SYSTEM*

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Abstract

The Accelerator Production of Tritium (APT) [1] project requires a linac of nearly a kilometer in length. Accelerating potential for the 100-mA CW proton beam is provided by 350 and 700 MHz klystrons. The radio frequency (RF) power distribution for the planned 244 1MW klystrons has a wide range of design requirements and constraints. Efficient transport, control of phase, control of fault events, thermal dissipation and coupling considerations will be discussed. A description of the currently proposed configurations will be presented.

1 PLANT OVERVIEW

The primary purpose of the RF Power Distribution System is to safely and efficiently couple up to 244 MW of RF power to the APT linac in a reliable manner and to respond to fault conditions with minimum impact on beam operations. The APT linac will deliver a 1700 MeV 100mA CW proton beam to a tungsten based target that generates neutrons used in the production of tritium. 3.0 KG of tritium can be produced yearly at this power level. An alternative modular design has been conceived to allow the accelerator to be built in two stages. Stage 1 would produce 1.5 kilograms of tritium yearly, using 160 klystrons rather than 244. Stage 2 could be added while the accelerator is in operation if additional tritium is required. The design issues of this paper are applicable to either schedule, however, where absolute numbers are given, the number in parenthesis is for a 1.5 kilogram system.

APT will be located at the U.S. Government's Savannah River Site (SRS) near Aiken, South Carolina. The entire accelerating portion of the linac is about 1032 (735) meters in length. One MW klystrons provide the RF power that generates the accelerating potential in the cavities along the linac. The klystrons are located in a gallery that runs parallel to the linac tunnel.

The APT linac has three distinct sections with unique power coupling characteristics for the RF power. Power coupling to the linac under full beam (100 mA) conditions is designed to be optimum, i.e., no reflected power. Under off-normal (no beam) conditions, the coupling is inversely proportional to the Q of the cavity. Q is defined as the ratio of energy stored to energy dissipated per RF cycle. The three linac sections with distinct Q's are 1) the Radio Frequency Quadrapole (RFQ), 2) the low energy normal conducting (NC) section and 3) the medium and high-energy superconducting (SC) sections. The amount of reflected power from each section determines the size of the RF load necessary to absorb this power. Under start-up conditions, a three-stage process to bring the beam up to full current (100 mA) requires full RF fields in the cavities continuously.

1.1 RFQ

The RFQ follows the proton injector and its function is to bunch the proton beam while accelerating it to 6.7 MeV. Three 350 MHz klystrons drive the RFQ. It has an unloaded (no beam) match of approximately 2:1 which means about 1/3 of the incident power is reflected when no beam is present. Only two klystrons of the three are required to drive the RFQ. This redundancy allows three klystrons to operate at 67% of maximum power or two at 100%.

1.2 NC Section

Fifty-one 700 MHz klystrons drive the normal conducting section. The NC linac accelerates the beam from 6.7 to 211 MeV. The NC section is composed of one CCDTL (Coupled Cavity Drift Tube Linac) driven by a single klystron and ten 'supermodules' (either CCDTL's or CCL's (Coupled Cavity Linac)) each driven by multiple (up to seven) klystrons. The 'supermodule' technique provides redundancy by allowing beam operation even with a failure of one klystron per module. The phase of the RF power delivered to the cavities in any supermodule must be equal. The Low Level RF (LLRF) system [2] measures the phase at selected linac ports and controls the klystron phase to ensure phase alignment. The unloaded match for this section is approximately 4:1 resulting in reflected power of about 60% when no beam is present.

1.3 SC Section

One hundred fifty four (or seventy) 700 MHz klystrons drive cryomodules containing super conducting (SC) cavities. These boost the beam energy from 211 to 1700 (1030) MeV. The unloaded match is approximately 4000:1. Essentially all of the incident power is reflected when no beam is present. Each cryomodule has two, three, or four SC cavities with a pair of RF ports per cavity. The RF phase of each pair must be identical. As the phase relationship between pairs changes along the length of the linac with increasing beam velocity, the proportion of the reflected power going to RF loads changes. This complicates the placing and sizing of the loads.

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2 RF SECTIONS

2.1 Klystron Gallery

The physical spacing of the klystrons in the gallery lines up closely with their respective coupling ports on the linac in the tunnel. Klystron garages house the klystron tubes and shield the gallery from klystron generated X-rays. The garage mechanically supports the five electric power and five water-cooling connections to the klystrons. Breaking these connections is all that is required to remove and replace a defective klystron. The water connections are at the front of the garage, the electrical connections at the rear. A trough in the concrete floor near the front of the garage contains supply and return water pipes that provide cooling water for the klystrons. This keeps the pipes short and unobtrusive.

A mezzanine running above the garages supports the control racks for the klystrons, linac magnet supplies, diagnostics and the 'transmitter' unit of the high voltage power supply (HVPS). This close proximity reduces cable length with a corresponding reduction in stored energy and enhances maintenance and troubleshooting. An HVAC duct hung under the mezzanine will connect with short spur ducts to each garage to provide cooling for the klystron solenoid coils and the garage in general. The HVPS for the klystrons sit in groups of four just across a maintenance access way and outdoors, behind the gallery building. A 95 kVDC cable from each HVPS runs through conduits in the concrete floor and up to the transmitter on the mezzanine.

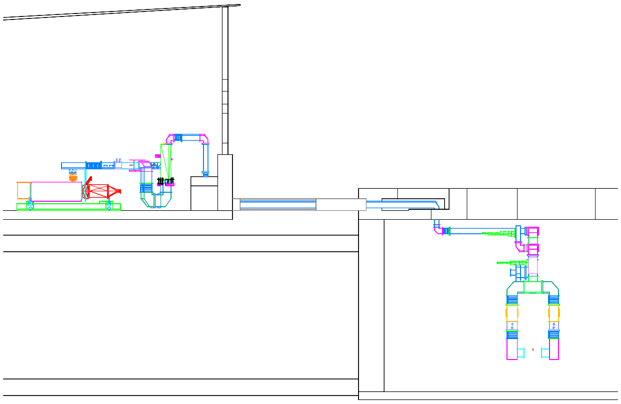

Figure1: Waveguide run between gallery and tunnel.

2.2 Waveguide System

Aluminum WR-1500 waveguide (15"x7.5") transports the 1 MW RF power from each klystron in the gallery to the linac couplers in the tunnel. A typical WG run from klystron includes the following:
1) Harmonic filter; absorbs higher order harmonics from the klystron to prevent harmful feedback. 2) Circulator; directs RF energy to the linac and routes RF energy reflected from the linac to a water load to protect the klystron. 3) Directional Couplers; detects the level of forward and reverse RF power in the waveguides, used for fault detection and phase balancing. 4) Loads: absorb incident RF power without significant reflection. 5) Magic-tees and hybrid splitters: divides RF power into two legs. 6) WG switches (remotely controlled); selects a different waveguide path. 6) Bellows; compensates for thermal expansion. 7) Linac Couplers: Air to vacuum transition between the waveguide and linac incorporates an alumina window [4]. Several waveguide components have been developed and tested [5] on the Low Energy Demonstration Accelerator (LEDA) at LANL with direct applicability for APT.

The waveguide run between the circulator and the gallery wall contains a loop which serves two functions: 1) Provide a clear walkway on the tunnel side of the gallery and 2) Provide a mechanism for equalizing the lengths of the waveguides on a supermodule by shimming. For reliability and efficiency the waveguide (WG) runs are as short, straight, and simple as feasible.

Between the klystron and the first power splitter in the tunnel, each aluminum waveguide carries 1MW with an expected loss of 250 W per foot. Waveguide temperatures of 80-100 C have been measured at English Electric Valve Ltd., in a test garage with little ventilation. In the gallery, where personnel are present, exposed waveguide should not exceed 60 C. A physical shield will envelop the guide and water-cooling is being considered. In the concrete conduit between the tunnel and gallery, the temperature may not exceed 65 C to prevent long term damage from excessive drying. An air cooling scheme forces HVAC tunnel air under and over the waveguide to keep the guide well within limits. In the tunnel, the RF power is typically divided into four equal legs before mating with the couplers. This reduces the power to the individual vacuum windows and couplers to no more than 250 KW under normal conditions. The tunnel HVAC system will be expected to handle the heat deposited such that the ambient temperature doesn't rise above 37 C. Circulating air is expected to uniformly cool individual waveguide legs such that they don't differ in temperature by more than 5 C. This last requirement ensures that differential temperatures don't contribute to significant differences in waveguide length from thermal expansion and hence RF phase differences between coupler pairs.

2.3 Phase Control

Magic-tees are four port waveguide splitters that have the characteristic of equally dividing incoming RF power between two output legs. These devices will be used to divide the RF power in the tunnel. The RF phase at each coupler pair should be equal within ± 0.5 degree. To minimize phase discrepancy, the legs to the couplers will be as short as feasible and the length of each leg uniform within ± 0.015" (standard EIA tolerance).

3 OFF-NORMAL CONDITIONS

The linac is designed such that if any klystron in a NC supermodule goes off-line, the remaining klystrons can be boosted in power to compensate. The SC linac also compensates for an RF system failure by adjustment of the RF phase and amplitude. This function is performed by the LLRF system.

The three most likely RF system faults are klystron or HVPS failure, waveguide arcs and window failure.

3.1 Klystron or HVPS failure

The klystron or HVPS is taken off line. The beam is shut off for approximately six seconds while a waveguide switch is thrown which presents the proper impedance to the cavity. If the failed klystron drives a supermodule, then the power on remaining klystrons on the supermodule is raised. If the failure is in a cryomodule, the offending cryomodule's cavity is de-tuned (no beam interaction) and the power on the remaining downstream klystrons is raised and rephased.

3.2 Waveguide arcs

An arc in the waveguide is effectively a short that will cause 100% reflection in that particular leg. This usually occurs near a window or discontinuity. The fiber optic arc detector system (part of the Low-Level RF system) shuts down the klystron and beam momentarily (<150 ms) then brings them back on. If the arc persists, the associated klystron is shut down and the waveguide switch thrown. During the arc, the klystron power is reflected into the local magic-tee load.

3.3 Window failure

Impending window failure can usually be detected by a temperature excursion at the thermal sensors. RF power to the window is shut down. If the window can be isolated and power can still be sent to other couplers driven by the same klystron, then only a coupler pair (rather than a klystron) will be taken out of service. In the event of an actual vacuum window leak, the RF and beam will be shut down. If the window is in the NC section, a vacuum gate valve may be incorporated to separate the window from the linac, and operations would resume. If the window is in the SC section, a double window is employed. The volume between the windows is evacuated, the RF is removed from the defective window, and the associated cavity is detuned (no RF from the beam will couple to the window). Beam operation can then begin with that cryomodule cavity off line.

4 SAFETY

Safety is a main driving force in the APT design. All systems must pass a rigorous safety review. A concerted effort is being made to incorporate safety by design rather than add on. Physical access, for both safety and maintenance, thermal surfaces, electrical procedures, RF and radiation, noise and ambient temperature are all factors in the overall plant safety design.

For radiation shielding purposes, the gallery is broken into three sections along its length. At the low energy (injector) section of the linac, up to 211 MeV, the distance between the gallery and the tunnel is 7' of soil. Between 211 and 471 MeV, the gallery is 12' from the tunnel. And above 471 MeV to the end of the accelerator at 1700 (1030) MeV, the separation is 17' of soil. The waveguide run is imbedded in the four-foot thick tunnel ceiling resulting in a tenfold reduction of neutron streaming. Borel lined shield blocks form an igloo around the aperture where the waveguide enters the gallery from the tunnel. This attenuates neutrons streaming through the waveguide into the gallery [6] to a level below requirements. An air block between gallery and tunnel prevents potentially activated tunnel air from permeating the gallery. The waveguides and klystrons are shielded physically and electrically. Dual redundant RF and radiation detection systems are planned.

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