LLRF REQUIREMENTS FOR APT *

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Abstract

As part of the Accelerator Production of Tritium (APT) program, a normal conducting (NC) - superconducting (SC) 100 mA continuous wave (CW), 1030 MeV accelerator is being designed. Maintaining the RF cavities in this linac at their proper resonant frequency, rf field amplitude and phase during commissioning (low duty factor pulse mode) and operation (high current continuous beam) is the function of the Low Level Radio Frequency (LLRF) system. This paper describes the linac characteristics that determine the LLRF system requirements with the corresponding control functions, and an overview of the techniques proposed to meet these requirements.

1 INTRODUCTION

APT uses a 350 MHz radio frequency quadrapole (RFQ) structure immediately after the injector to boost beam energy from 75 keV up to 6.7 MeV. From 6.7 MeV up to 211 MeV is considered the low energy (LE) linac. A trade study is being conducted to determine the relative merits between using normal conducting and superconducting cavities for the LE linac. The NC linac consists of 700 MHz coupled-cavity drift-tube linac (CCDTL) and coupled-cavity linac (CCL) modules. The SC structures under consideration are 350 MHz spoke resonators and 700 MHz β=0.48 (where β is the beam velocity relative to the speed of light) elliptical cavities. The APT high energy (HE) design uses β = 0.64 and β = 0.82 elliptical cavities from 211 MeV up to the final design energy of 1030 MeV.

1.1 Availability Requirements

The calculated availability for the rf system on APT is 98% to achieve a total linac availability of 81.4% necessary to meet the tritium production goals [1]. This necessitates the ability of the rf system to quickly respond to failures by isolation and replacement of individual rf stations. A rf station consist of a rf generator and its associated power supply, controls and waveguide. Since the APT design is for a production facility, a 'factory' mindset must be assumed. This means not troubleshooting and repairing equipment in place, but isolating and replacing it quickly. Much emphasis has been placed on designed-in safety and ease of maintenance in the rf system layout.

The NC LE linac uses 23 multi-cavity modules, each supplied with up to 1680 kW of 700 MHz rf power from two klystrons, or 46 LE rf stations active at one time. To meet the availability requirements, a hot-spare rf station is provided for every four active stations. A failed rf station is isolated by using WR1500 waveguide switches to short the failed rf station waveguide and connect a hot-spare to the module. The hot-spare is always running at minimum power into a 1 MW water-cooled rf load. When called upon, its high voltage power supply (HVPS) ramps up to full voltage within a few milliseconds. The LLRF system must allow for the difference in waveguide lengths and cable delays that translate to different phase values of the generator and cavity rf fields. It must take control of the spare rf station seamlessly and bring the NC module back to resonance quickly. This rf station replacement must occur as quickly as possible with a goal being the time taken for the waveguide switches to actuate.

If the LE linac design is chosen to be superconducting, isolating the rf station is much simpler and even quicker (<300 milliseconds) than the NC scenario. Upon recognizing a rf station failure, the LLRF shuts down the rf power from the rf station, shuts off the linac beam, and mechanically de-tunes the SC cavity(ies) associated with the failed rf station. At this time, new set-points are down-loaded into the succeeding rf stations from look-up tables generated during commissioning. These set-points are the new field amplitude and new phase relative to a reference signal running the length of the LE linac. This is the SC technique to maintain availability.

As an example, if after a de-tuned cavity, each of the succeeding cavities had its field amplitude boosted 5%, then after twenty cavities the beam would be back to its original energy. As long as the change in field amplitude isn't severe, the beam focussing will still be adequate. The magnet currents can then be gradually optimized over time for the new field levels. If several cavities had to be taken off-line concurrently during a run period, the resulting new phase and amplitude settings will get fairly complicated. This technique of raising the cavity field above nominal requires a higher rf power margin than just isolating and replacing the rf station.

1.2 Cavity Field Perturbations

The control of the electric fields in a CW heavy particle linac such as APT is simpler than that of a pulsed linac. The CW linac cavity field has time to stabilize before the beam arrives. For the APT NC LE linac, the cavity bandwidth (F_0/Q_L) is comparably large (~44000 Hz). With the narrow bandwidth (1400 Hz) SC structures, however, perturbations causing small cavity resonance shifts can drive the cavity significantly off resonance. Because the linac beam is continuous, microphonics induced by the onset of rf power have time to settle out and chronic microphonics induced by coupled vibrations from surrounding equipment such as vacuum pumps will be

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attenuated by design (vibration isolation) and compensated for by the LLRF feedback system. Lorentz force de-tuning can be compensated by offsetting the natural cavity resonance from the design frequency and using the predictable Lorentz force to bring the cavity to the design frequency. LLRF feedback will control fine tuning of the cavities either thermally (water-cooling for NC) or mechanically (SC) to compensate for dynamic shifts in the cavity resonance during rf operation.

1.3 Other Perturbations

Two other expected perturbations to the cavity fields are klystron HVPS ripple that modulates the rf output of the klystron and longitudinal beam bunch modulation. The beam bunch modulation, caused by injected beam density fluctuations, will be relatively slow (<1kHz) while the HVPS may have ripple up to 100 kHz depending on the type (linear/chopper) of HVPS selected.

2 COMMISSIONING & CONDITIONING

During commissioning the accelerator will be operated in the pulsed mode. This mode is not the same as a true pulsed system in the sense that for APT the rf power is *continuously* applied to the cavities and the beam is pulsed at the injector and by gating the rf drive to the RFQ klystrons. However, conditioning of the cavities and windows (no beam) will require the LLRF to have the programmable ability to modulate the pulse-width and amplitude of the applied rf field.

3 PERFORMANCE REQUIREMENTS

The APT beam dynamics [2] requires the cavity fields to be held to tolerances as shown in table 1.

Table 1: APT Steady State Cavity Field Tolerances

Linac Section	Cavity Parameter	% error allowed
NC	Amplitude	+/- 0.5 %
NC	Phase	+/- 0.5 degrees
SC	Amplitude	+/- 2.5 %
SC	Phase	+/- 2.5 degrees

3.1.1 Loop Bandwidth Requirements

Control of amplitude and phase requires two control loops. The first, an inner control loop, keeps the rf power output from the klystron tracking the rf input, effectively eliminating the HVPS induced ripple. A chopper type HVPS may have fifth harmonics as high as 100 kHz. A bandwidth that limits the error yet doesn't add excessive noise is desired. Because the ripple is consistent and sinusoidal, an additional delay can be built into the loop error signal to generate an odd multiple at 180° and therefore the loop bandwidth doesn't have to significantly exceed the ripple frequency.

The second (outer) loop controls the phase and amplitude within the accelerating cavities. The cavities' resonance is expected to change at a *rate* determined by their thermal drifts or less than 10's of Hertz. For SC cavities, microphonics will be less than 300 Hz [3] and beam loading fluctuations less than 1 kHz. A control response of >10 kHz should be sufficient. However, a planned adjustable loop filter will allow a LLRF bandwidth in excess of the cavity bandwidth.

3.2 Cavity Fill-Time Effects

The cavity fill-time acts as a time constant that impedes changes in cavity fields. This limits the loop bandwidth requirement due to perturbations on the incident rf field, from beam current fluctuations, or other sources of field change. The field in the cavity responds like a low-pass filter with a time constant of fill time = $2Q_L/\omega_o$ [4].

For a NC linac with a Q_L of 16000 and ω_o of 700 MHz, the fill time is 7.3 μs: the cavity response is limited to 137 kHz. For a SC linac, with a Q_L of 5E5 and ω_o = 350 MHz, the fill-time is about 455 μs and the cavity response is limited to 2.2 kHz. Thus for the NC structures, 100 kHz ripple on the incident rf power will be transferred to the cavity field. This same ripple would be greatly attenuated in the superconducting structures. Compensating for the klystron HVPS ripple should first be done at the power supply itself. The effect of the remaining output ripple can be attenuated with a LLRF inner loop that negatively feeds the ripple detected on the klystron rf output (by a waveguide directional coupler) back to a gain control on a solid state pre-amp.

4 CONTROL SCENARIOS

To maintain the electric field in the cavity at the proper amplitude, the field is measured using a pick-up probe in the cavity and the voltage on the pick-up is compared to the set-point. Conceptually, this could be performed by having a comparator output control an attenuator in-line with the solid-state amplifier to maintain a constant cavity field voltage (figure 1).

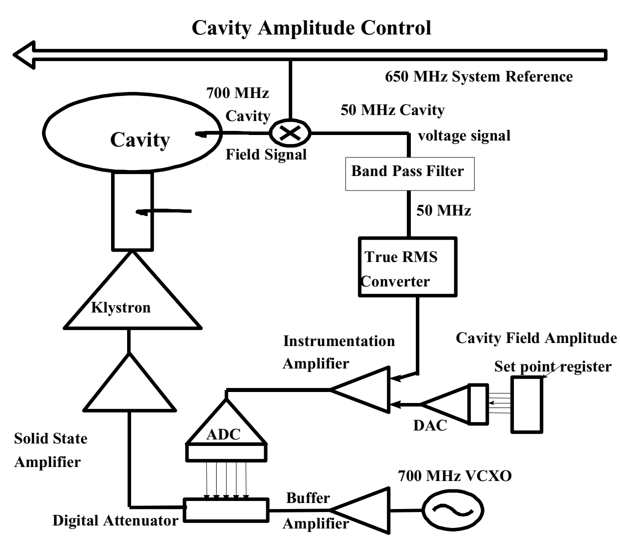

Figure 1. Cavity Field Amplitude Control

Likewise, the cavity phase can be measured with a pick-up and compared with the rf incident field phase in a phase detector. Both of these signals are mixed with a reference in the linac tunnel to produce 50 MHz signals for processing. The phase detector output adjusts a phase shifter that could drive the error signal from the phase detector back to zero. A digital I&Q phase detection and control LLRF system is planned [5].

5 REFERENCE CLOCK SYSTEM

The RF reference signals in the above discussion must be highly accurate signals with very little variability over time. The choice of frequency for the reference signals is driven by practical considerations such as cable thermal expansion/contraction effects on phase as a function of frequency, available sampling rates for digital systems and filter roll off rates. The current APT plan is to use a 650 MHz reference signal in the tunnel and distribute the master 10 MHz signal to each LLRF (that would synchronize the local 50 MHz signal) chassis in the gallery. A $3^1/8$" coaxial distribution line was selected for best compromise between drive power and cost [6].

Since the relative (with respect to the beam bunch) phase error requirement for the cavity field is ± 0.5 degrees, the rf reference that this is based upon must be finer. It is believed that ± 0.05 degrees is achievable and provides a margin of error due to component deterioration over time. The phase accuracy can never be better than the reference and will be worse by the amount of phase error in the calibration and the loss in response due to bandwidth limitations.

6 HIGH POWER PROTECT

The requirement for 98% availability translates to maximum reliability. The second function of the APT LLRF system is to protect the rf system from faults. Typical faults envisioned are arcs, HVPS trips, klystron and other major component failures.

6.1 Waveguide or Cavity Arcs

An arc in the waveguide or cavity effectively causes a short that results in 100% rf power reflection in that particular leg. This usually occurs near a window or discontinuity. A fiberoptic arc detection system picks up the flash of light from the arc and shuts down the associated klystron. To temporarily interrupt the beam (nominally 50 μs), the three rf drives to the RFQ klystrons are shut down. If the arc persists upon reapplication of rf power, the associated klystron is shut down and the beam is turned off for 150 ms to ensure that the arc is extinguished. During the actual arc, the klystron high power RF is reflected into the klystron circulator load.

During the time the drives to the RFQ klystrons are off, the linac cavities are not beam-loaded. The cavity field is still maintained by the feedback loop, however, the rf power required to maintain this field is reduced. When the beam comes back on, the lag in the response of the feedback loop from the cavity fill time delay will result in less than optimum accelerating potential. A feed-forward feature is employed to begin to boost the rf field in the cavity just prior to beam turn-on such that the field achieves its nominal level at beam arrival.

7 FAST PROTECT INTERFACE

Anytime the beam must be shut off because of a rf station failure, the LLRF notifies the Fast Protect system to disallow the injector 'beam permit' signal. The Fast Protect System tells the plant Instrument Control System (ICS) of this action. There will be a Fast Protect connection to each of the rf stations. This Fast Protect interface will coordinate the disabling of the RFQ klystron drive signals within 10 μs during a rf fault and will notify each rf station at beam turn-off. Prior to beam turn-on each rf station will be notified as part of the feed-forward cavity field control function.

8 INSTRUMENT CONTROL SYSTEM

The LLRF system contains the interface in each rf station that communicates with the ICS. Communication covers items such as:

1) Field set-points and adjustments to compensate for a failed rf station.
2) Trending information about rf equipment performance for maintenance purposes.
3) System status to be available in the control room.
4) Isolating and enabling individual rf stations for local test.

The communication port will physically be a module in the LLRF VXIbus crate with an Ethernet type link to the ICS IOC (Input-Output Controller). This is a relatively slow communication link, considering that all 160 rf stations must be serviced by the ICS. All real time control and fault response will be performed by the rf station controls and reported to the ICS.

9 CONCLUSION

The requirements for the LLRF system are driven by the APT linac beam dynamics, rf power architecture, physical layout and the tritium production needs. The LLRF hardware design considerations such as loop gain and bandwidth, digital vs analog techniques and modularity will be based on these requirements.

10 REFERENCES

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