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Low-Level RF Control System Issues for an ADTT Accelerator

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Abstract. The RF control system for a charged-particle accelerator must maintain the correct amplitude and phase of the RF field inside the accelerator cavity in the presence of perturbations, noises, and time varying system components. For an accelerator with heavy beam-loading, fluctuations in the beam current cause large perturbations to the RF field amplitude and phase that must be corrected by the RF control system. The ADTT applications require a high-current, heavily beam-loaded, continuous-wave (CW) accelerator. Additional concerns created by the CW operation include system start-up, beam interruption, and fault recovery. Also, the RF control system for an ADTT facility must include sophisticated automation to reduce the operator interaction and support. This paper describes an RF control system design that addresses these various issues by evaluation a combination of feedback and feedforward control techniques. Experience from the high-current Ground Test Accelerator (GTA) is drawn upon for this RF control system design. Comprehensive computer modeling with the Matrix_X software has been used to predict the performance of this RF control system.

INTRODUCTION

The proposed design for the accelerator-driven transmutation technologies (ADTT) requires a high current, heavily beam-loaded, continuous-wave (CW) accelerator. The heavy beam-loading and the CW operation necessitate advanced low-level RF control techniques. With a 200 mA beam, the ADTT accelerator will have greater than 70% beam loading. The RF field control accuracy for an accelerator with heavy beam loading is very sensitive to fluctuations in the beam current. To enable particle acceleration, the RF field control system must be able to maintain the correct RF field amplitude and phase in the presence of strong perturbations caused by beam current fluctuations. Similar problems were addressed by the low-level RF control system for the high-current GTA accelerator [1,2]. Many of the same feedback and feedforward techniques used on GTA apply to the ADTT low-level RF control system. CW operation results in high average RF power levels that cause thermal effects within the RF system. These thermal effects cause large shifts in the resonance characteristics of the coupled-cavity LINAC (CCL) accelerating structures. Consequently, the low-level RF control system must allow efficient, reliable operation in the presence of these resonance shifts. Also, CW operation creates additional concerns regarding accelerator start-up, beam interruption, and fault recovery. It must be possible to turn on and tune up the accelerator from a variety of initial conditions, including first-time commissioning, cold starts after maintenance shutdowns, short interruptions caused by RF station faults, and extremely brief beam absences due to chopping or fast protection aborts. From the perspective of the RF system, there are only two levels of start-up modes: 1) when the beam and/or RF abort momentarily but can return to operation before the temperature changes in the CCL cavity, or 2) when the RF has been off for more than a few seconds and the CCL cavity resonance has shifted. In the first case, the low-level RF system must maintain the correct RF field level while experiencing the transient disturbances of the beam and RF switching on and off. The second case is further complicated by the resonant frequency shift and requires a method to retune the cavity to accept RF power at the design frequency. Automation is a fundamental component to the low-level RF system. Embedded computer programs perform many of the tracking and regulation functions, reducing the need for manual intervention. From the perspective of the low-level RF system, these various concerns reduce down to two basic issues: field control and resonance tracking. Figure 1 shows a simplified block diagram of a low-level RF system. This diagram depicts the fundamental components of the low-level RF system needed to perform the two basic functions. The field control electronics use a sample of the field in the RF cavity along with a beam feedforward signal to maintain the proper amplitude and phase in the RF cavity. The resonance detection electronics use the reflectometer signals to calculate the resonance condition of the RF cavity. This calculated resonance condition is used for both frequency tracking and cavity tuning.

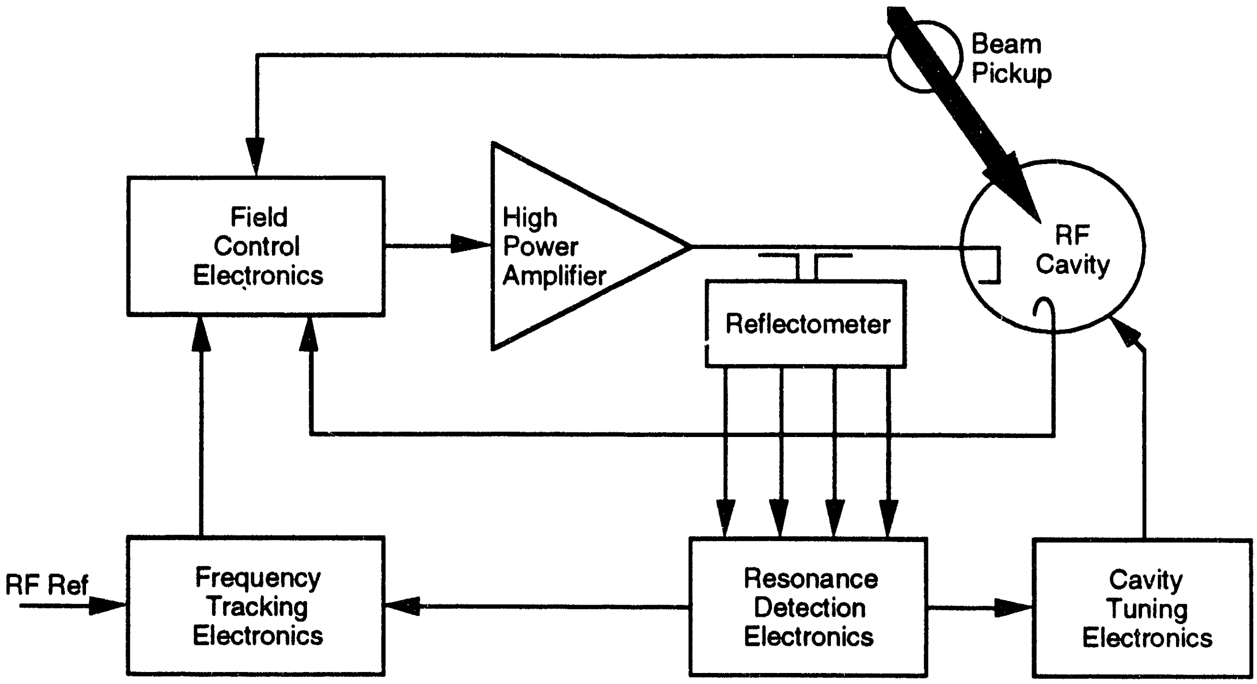

Fig. 1. Simplified block diagram of low-level RF control system for ADTT accelerator

FIELD CONTROL

The field control requirements for the ADTT accelerator address many of the preceding issues. As a fundamental objective, the low-level RF control system must regulate the RF field of each accelerator cavity at a predetermined amplitude level and phase angle. Fluctuations in beam current in the heavily beam-loaded ADTT accelerator adversely affect the cavity RF field. Beam noise and beam chopping are two phenomena that cause these fluctuations in beam current. In addition, fault conditions where the beam and/or RF abort momentarily affect the RF field control system design. The RF field control system must compensate for the transient effects of the beam and/or RF switching on and off. Faults should be resolved quickly enough to prevent the RF accelerator structure from drifting off resonance due to the loss of RF power. This allows the RF to be returned on without having to address the more complicated issue of tracking resonant frequency changes. Frequently, RF field regulation is accomplished with a feedback control system. A feedback system uses the measured RF field parameters to adjust the drive signal and maintain the correct amplitude and phase. Because an error must occur in the field output before a correction can be made, a feedback system always has an inherent bandwidth limitation and corrects low-frequency disturbances only. The modeling results indicate that a typical feedback control system operating on the ADTT accelerator can reject beam-noise disturbances in the RF field for frequencies below 10 kHz. Beam-noise frequencies between 10 kHz and 1 MHz are not completely rejected by the feedback system. The worst-case errors occur between 100 kHz and 200 kHz. Also, during CW operation, any brief beam interruptions cause transient errors in the RF field parameters that require some time for the feedback loop to respond. These transient errors also occur during beam turn-on, beam chopping, and beam-fault recovery.

Feedforward control is an enhancement to feedback RF field regulation. For a pulsed accelerator, many of the disturbances to the RF field repeat with each pulse of the accelerator. This allows adaptive feedforward techniques to be used where the past error information is used to predict the current feedforward correction function [3,4]. For a CW accelerator, disturbances do not repeat in any definable pattern. A more direct feedforward approach must be used where a measured system input is used to predict errors in the output. For the ADTT accelerator, beam-current fluctuation is the dominant disturbance to the RF field. Consequently, the amplitude and phase of the beam current are measured and used to derive feedforward correction functions that negate any errors in the RF field parameters before they occur. The system topology for such a beam feedforward implementation requires that a single beam diagnostic sensor just after the beam source be used to derive the feedforward signals for all of the RF cavities in the system. This feedforward concept relies upon the fact that the charged-particle beam is non-relativistic at the beginning of the accelerator. Because the beam travels at less than the speed of light and the measurement signals are transmitted near the speed of light with air-core cables, the measured beam feedforward signals arrive before the beam does. This allows a correction function to be applied at the RF generator such that the beam fluctuations and a corrected RF field occur concurrently. Because the beam causes both amplitude and phase disturbances, the feedforward correction signal must include both amplitude and phase information. This requires that the amplitude and relative phase information be available from beam diagnostic sensors with bandwidths of at least 10 kHz to 1 MHz. Also, the absolute phase at each insertion point must be determined to compensate for the propagation phases within the system.

Feedforward systems tend to require frequent manual adjustments due to drifts in the gain parameters that are determined in an empirical manner. The feedforward signal levels must be consistent with the effects of the beam on the RF field parameters. If a device in the system changes (like the gain of the RF amplifier or the sensitivity of the beam diagnostics), there is no mechanism to automatically correct the feedforward signal level. As a result, feedforward systems typically require frequent manual gain adjustments. As an alternative to manual adjustments, a cross-correlation algorithm can be used to automatically adjust the feedforward signal levels. The cross-correlation algorithm uses a time-averaged product of the RF field error and beam signals. The goal is that an RF field error resulting from a beam fluctuation causes an adjustment of the feedforward signal level. Figure 2 shows a simplified block diagram of the implementation of the automatic gain adjustment. The first delay aligns the measured beam and the measured RF field error corresponding to that beam. The two aligned signals are multiplied together and the product integrated. The integrator output provides the feedforward gain function that varies over time. This gain is multiplied by the original beam signal to give a feedforward signal with the correct signal level. The feedforward signal is delayed to compensate for any excess advance resulting from the different propagation speeds between the beam and the feedforward signal and, thus, aligns the feedforward signal with the corresponding beam.

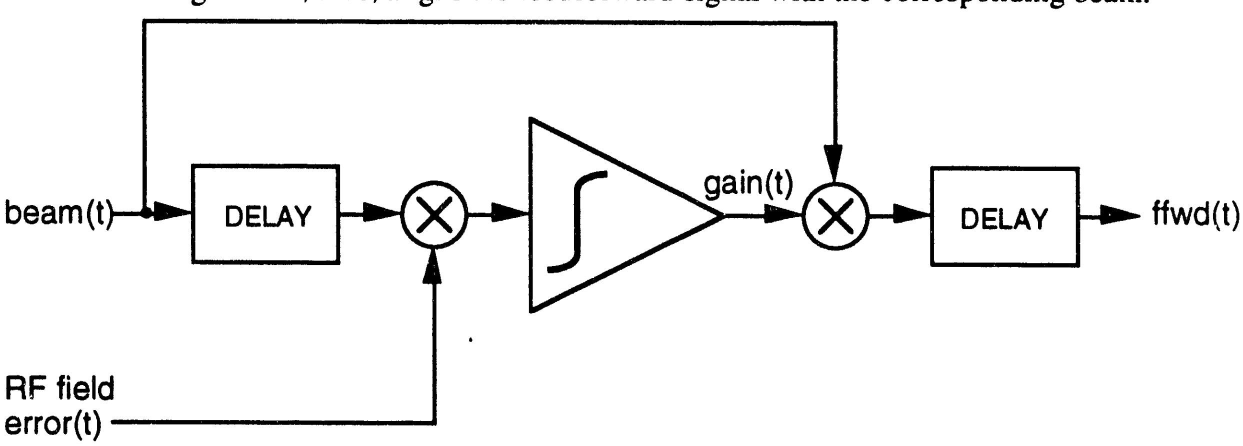

Fig. 2. Simplified block diagram of automatic beam feedforward correlation algorithm

The results of RF system simulations demonstrate that beam feedforward does enhance RF field regulation and that automatic gain adjustments are possible. Figure 3 shows the effects of beam current fluctuations of 20% on the RF field of a typical ADTT accelerator cavity. Three control system configurations are shown: open-loop operation without a control system, regulation with a feedback control system, and combining both feedback and feedforward control systems. Notice that for beam-noise frequencies below 10 kHz, the RF field parameters are well regulated by the feedback control system. For beam-noise frequencies above 1 MHz, the damping of the narrow-band accelerator cavity negates any effects of the beam on the RF field. Beam-noise frequencies between 10 kHz and 1 MHz are not completely rejected by the feedback system, with the worst-case errors occurring between 100 kHz and 200 kHz. Also, notice that a beam feedforward system does reduce the RF field errors caused by beam fluctuations for the frequency range over which feedback does not function adequately (10 kHz to 1 MHz). With both feedback and feedforward, the RF field amplitude and phase errors could be maintained at less than 0.5%/0.5° in the presence of beam current fluctuations of 20% at any frequency. In the presence of a pulsed beam (simulating beam turn-on and interruption), the RF field fluctuations were maintained at less than 0.5%/0.5°. This indicates that the beam feedforward concept could be used to significantly improve the performance of the RF field control system.

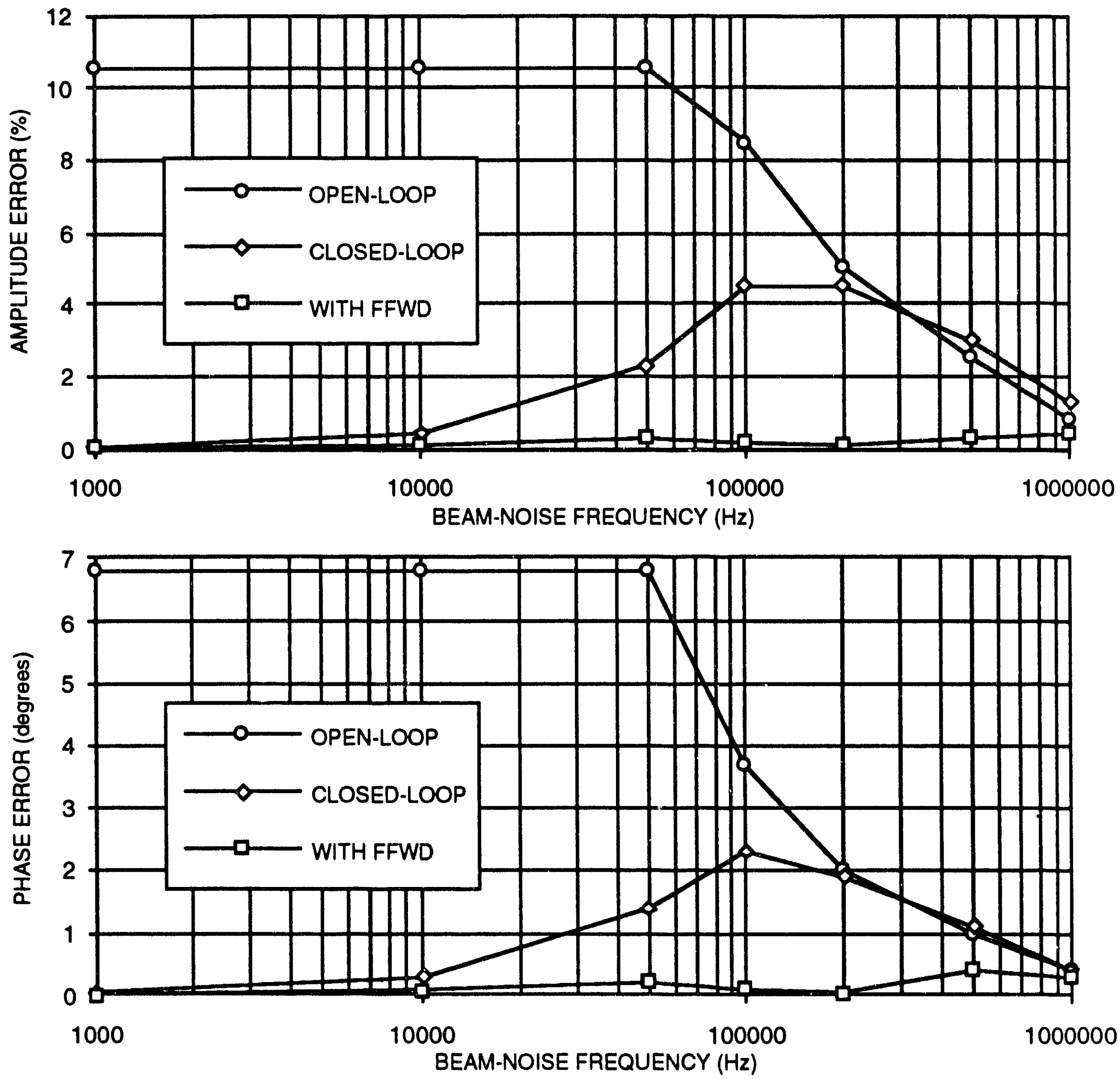

Fig. 3. RF field errors cause by 20% beam fluctuations at various frequencies.

RESONANCE TRACKING

The CW nature of the ADTT accelerator results in high average RF power levels dissipated in the accelerator structures during operation. The high-average power levels cause significant thermal changes to the RF cavities, which affect their mechanical dimensions, which in turn affect their resonant characteristics. Because an accelerator cavity has a high quality factor (Q), it accepts RF power over a narrow frequency range only. A thermal change may cause a resonant frequency shift that prohibits the cavity from accepting RF power at the fundamental machine RF frequency. The low-level RF control system must provide a resonance tracking mechanism that retunes the cavity to accept RF power at the machine frequency.

The proposed ADTT accelerator consists mainly of coupled-cavity LINAC (CCL) accelerating structures. A CCL cavity cannot be easily tuned by disrupting the fields with an external tuning mechanism like a paddle or slug. Consequently, resonance is typically maintained by regulating the temperature of the cavity, and thereby its physical dimensions and resonant frequency. The temperature is typically regulated by applying cooling water to the structure to offset the heating effects of the RF field inside the cavity. Maintaining the proper temperature in the presence of the large thermal transients at turn-on and fault shut-down has not been demonstrated to be feasible. The mixing chambers, flow valves, and other mechanical devices associated with a water cooling system respond very slowly. When the RF drive is shut down for more than a few seconds, a high Q cavity drifts off resonance due to its immediate cooling. This prevents the cavity from accepting RF power at the fundamental machine RF frequency and makes it difficult to heat the cavity back to its nominal temperature. Without an alternative heating mechanism, the system will experience long delays in achieving the proper operating temperature and frequency. Using water heating is inadequate for the same reasons that cooling water is inadequate: the response time is too slow. Also, the mechanical devices associated with water systems tend to require on-going maintenance. Consequently, another means to quickly heat a CCL cavity must be used to resolve the problems with turn-on and fault-recovery. One option is to drive the RF cavity with an alternative frequency source so that it will accept power when its resonance condition has drifted from the machine frequency. This resonance tracking system requires a swept frequency source that can search out and track the resonant frequency of the CCL cavity as its temperature changes. Once the cavity is heated to its nominal operating conditions in temperature and frequency, it can be driven at the machine frequency with the normal RF reference source. The swept frequency source is only used for structure heating and a fixed low-noise freq\ency source is required for accelerator operation. Figure 4 depicts the resonance tracking system.

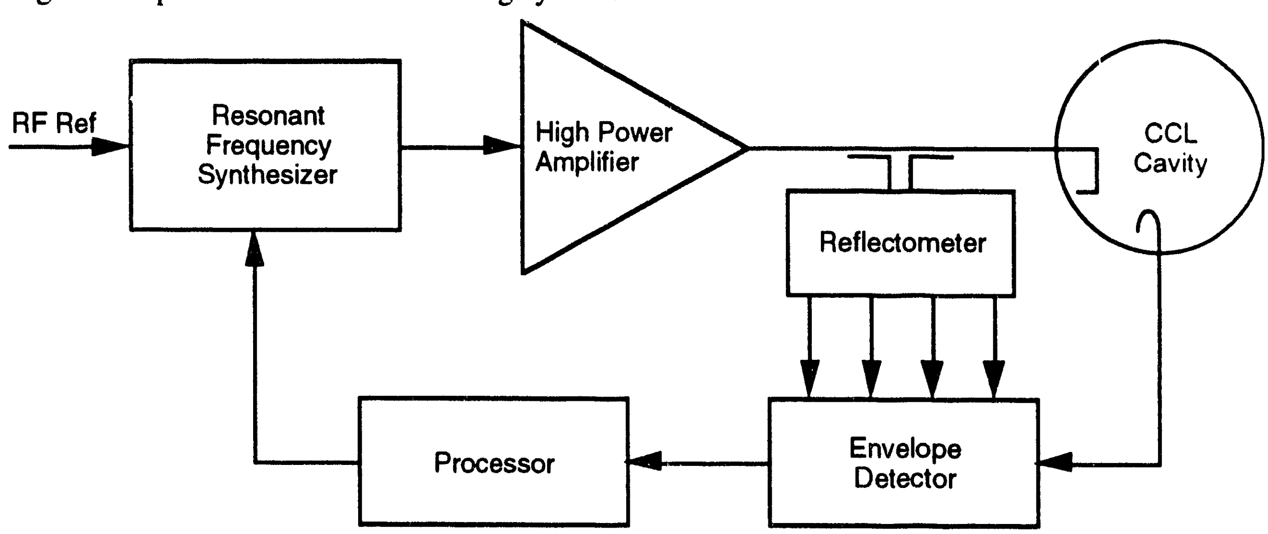

Fig. 4. Resonance tracking system block diagram.

The resonance tracking system uses a reflection analyzer to monitor the match condition between the high-power RF amplifier and the CCL cavity by measuring the incident and reflected waves in the transmission line connecting the two. The reflection analyzer is based upon an RF device called a reflectometer that enables precision transmission line measurements. The magnitudes of the reflectometer output signals are detected and converted to digital values by the envelope detector electronics. These digital values are used by the processor in an error-correction algorithm to compute the resonance condition of the CCL cavity. The resonant frequency synthesizer uses the calculated resonance condition to adjust the frequency of its output to track the resonant frequency of the CCL cavity when its temperature varies during start-up and fault-recovery situations. During normal accelerator operation, the cooling water system maintains the CCL at its nominal temperature and frequency, and the frequency-tracking functionality is disengaged.

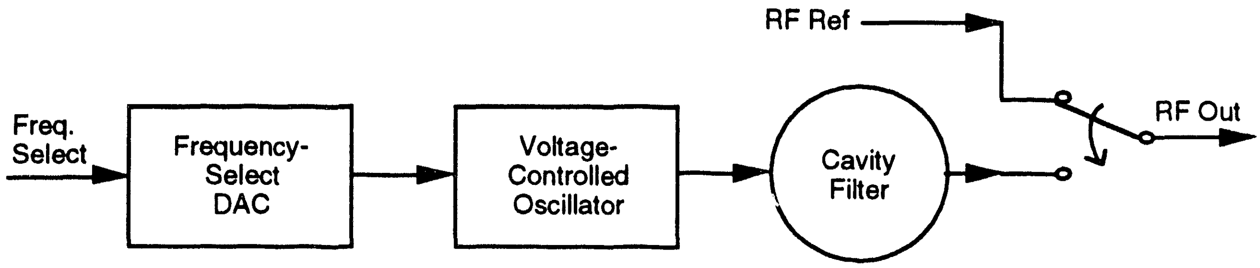

Fig. 5. Detail of VCO-based resonant frequency synthesizer.

Figure 5 shows the details of a possible Resonant Frequency Synthesizer based upon a voltage-controlled oscillator (VCO). The VCO provides a second RF source that can be switched in to replace the machine RF reference. This approach has been demonstrated on the accelerators for the Beam-Experiments-Aboard-a-Rocket and the National Institute of Standards and Technology Racetrack Microtron. The VCO would be operated in a frequency-locked loop configuration with filtering for stability and noise reduction. This configuration requires a conversion step to convert the digital processor output to the analog input needed by the VCO. Due to the noisy nature of the VCO, a stored-energy device like a resonant cavity can be used to filter out the phase noise of the VCO output. This adds size and physical complexity to the design. Also, switching between the VCO and the machine RF reference would cause a transient disturbance due to the phase discontinuity.

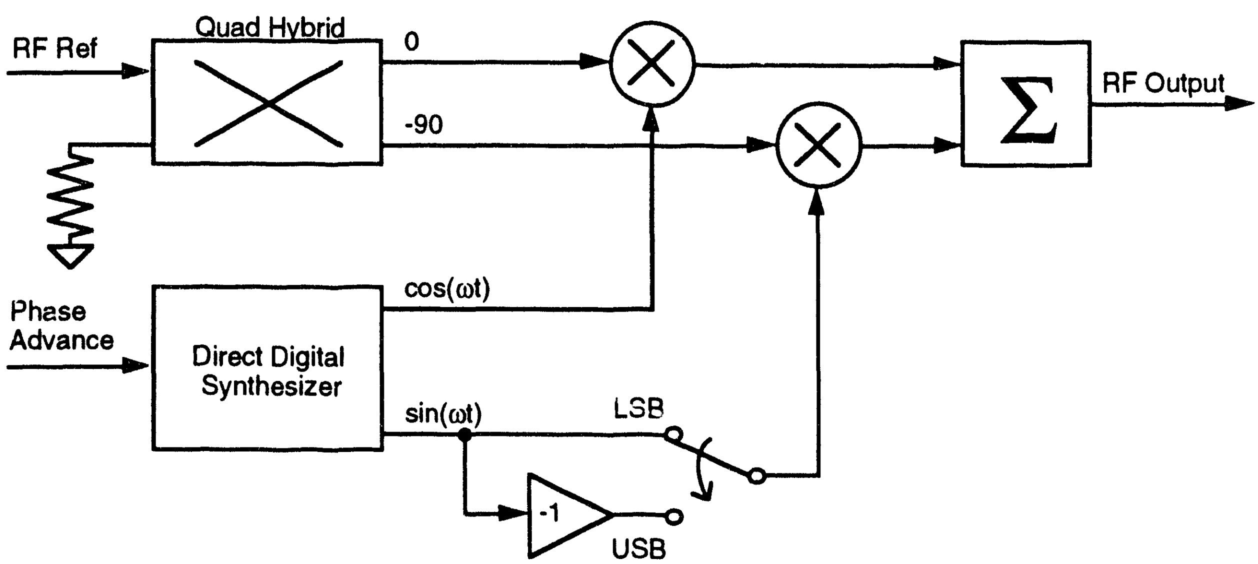

Fig. 6. Detail of DDS-based resonant frequency synthesizer.

Figure 6 shows the preferred design for the Resonant Frequency Synthesizer which is based upon a direct digital synthesizer (DDS). The DDS uses a digital phase advance value from the processor to create two sinusoidal analog IF outputs that are in phase quadrature. These IF signals are used in a single-side band heterodyne modulator to adjust the frequency of the RF output. Notice that the RF output is derived directly from the machine RF reference source. The switch allows the modulator to perform both upper and lower side-band modulation. If the phase advance is set to zero, the RF reference input passes through the Synthesizer without being affected. The DDS configuration is preferred for its simplicity and because it provides phase-continuous switching.

The entire resonance tracking system consists of electronic devices. This provides many inherent advantages including reliability, automation, and flexibility. The mathematics for the resonance tracking are accomplished using a digital processor, allowing flexibility in the resonance tracking algorithm. The algorithms could be modified for transmission measurements instead of reflection measurements. Empirical data could be added to the control algorithms. Undesired operating conditions (frequencies that excite other cavity resonance modes) could be strictly avoided. As a result, this frequency tracking system enables an ADTT accelerator to be turned on and tuned up as quickly and automatically as possible.

CONCLUSION

The low-level RF system implementation for a ADTT accelerator is feasible with little technical risk. The concepts and designs that were developed for the GTA accelerator could be modified slightly for application to an ADTT accelerator. The RF field control can be accomplished with a combination of feedback and beam feedforward. The frequency tracking can be accomplished with a reflection analyzer and an off-line RF source heating the RF cavity during turn-on and fault recovery. The implementation for this equipment should be accomplished entirely with electronic circuitry to provide the most reliable system possible. Automation should be designed into the system to take advantage of modern digital processing capabilities that will eliminate the costly hands-on operator intervention. It is not surprising that the Los Alamos Meson Physics Facility (LAMPF) is experiencing similar issues with high beam currents and quick fault recovery. The next step in this development would be to build a proof-of-principle prototype of the low-level RF equipment. This prototype should be used within experiments at LAMPF to verify and refine its functionality.

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