RF Control System – Low Level RF

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10.7.1 Overview

Low Level RF encompasses the programming and regulation of the cavity field vector, as well as the control and protection of other parts of the RF system. *The cavities in the Main Linacs are operated in pulsed mode at gradients of 35 MV/m with each klystron driving 24 cavities. The pulse repetition rate is 5 Hz and the rf pulse length is 1370 μs from which 420 μs are required for cavity filling while the remaining 950 μs with constant gradient (flat-top) are necessary for the acceleration of the beam. During the beam pulse the fluctuations of the accelerating field - defined as the vector- sum of the fields in 24 cavities - must be kept small. The major sources of field perturbations, which have to be controlled by the low level RF system, are caused by fluctuations of the resonance frequency of the cavities and by fluctuations of the beam current. Fluctuations of the resonance frequency are a result of deformations of the cavity walls induced by mechanical vibrations (microphonics) or the gradient dependent Lorentz force (also referred to as radiation pressure or ponderomotive force). Slow changes in frequency, on the time scale of minutes or longer, are corrected by a frequency tuner, while faster changes are counteracted by fast amplitude and phase modulation of the incident RF power.*

10.7.2 Functions

LLRF programs and regulates the cavity vector; provide resonant control of the cavity, program control of the modulators and machine protection. The system must diagnose fault conditions and handle fault recovery. It is also the primary data acquisition system for the overall performance of the RF system and provides information such as RF heat load to cryogenics and LCW systems. Each LLRF station will part of the interlocks and beam inhibit and aborts. *Fast amplitude and phase control can only be accomplished by modulation of the incident wave that is common to the 24 cavities. The incident wave may be adjusted on a slower time scale with motor driven three stub tuners.*

10.7.3 Key parameters

The regulation specifications of the bunch compressor sections of 0.08% and 0.03 degrees are the tightest requirement for a single station. The rest of the Linac requirements are somewhat relaxed at least for non-correlated errors. Error in the cavity phase has many sources that sum, including the master oscillator, RF reference distribution, local oscillator, cavity probe, cable, ADC clock, modulator ripple, Klystron etc. These errors are composed of drifts and noise terms and must be understood fully in both time and frequency domains. Fast resonant control is implemented with piezo actuators that are programmed to cancel the Lorentz detuning and to damp microphonics. The required travel and bandwidth of the actuators are a function of the cavity and cromodule design.

10.7.4 Description

Fast amplitude and phase control can only be accomplished by modulation of the incident wave which is common to the 36 cavities. The modulator for the incident wave is designed as an I/Q modulator to control the in-phase (I) and quadrature (Q) component of the cavity field. This scheme minimizes coupling between the loops and guarantees control in all four quadrants. The overall scheme of the rf control system is shown in Fig.2. ??? The detectors for cavity field, and incident and reflected wave are implemented as digital I/Q detectors. The rf signals are mixed with a local oscillator to down-converted to an IF frequency in the range of 50 MHz and sampled at a rate that harmonically related to the 1300 MHz RF. The exact frequency will be based on the state of the art digitizers and will be optimized for signal quality. Present 14 bit digitizers are operating up to 105 MSPS. The digitized signal is then down-converted to baseband to produce I and Q data streams that describe the cavity field. The IQ analytic signal for each cavity is multiplied by a 2x2 matrix that calibrates the magnitude and phase for each cavity probe. The vector-sum is calculated and corrected for systematic measurement errors. Finally the set point is subtracted and the compensator filter is applied to calculate the new actuator setting (I and Q control inputs to a vector modulator). Feed forward is added from a table in order to minimize the control effort. The feed forward tables are adaptively updated to reflect slowly changing parameters such as average cavity detuning, changes in klystron gain, phase shift in the feed forward path, and general changes in

10.7.5 Automation

The operation of the more than 560 linac rf systems will be highly automated by the implementation of a finite state machine finite state which has access to high level applications including the adjustment of the loop phase, vector-sum calibration, frequency and waveguide tuner control, and exception handling. The area of automation is viewed as a major area of R&D needed for the successful operation of the accelerator complex. The needs of RF system automation will help to define the structure and complexity of the control system.

10.7.6 Present State of the art

As in much of the instrumentation electronics, LLRF is benefiting from the wireless telecom industry. The core components of ADC, DACs and FPGAs have seen dramatic advancements in the last 10 years. While there may be a flattening of the rate of advancement in the foreseeable future, one can only make a general guess what will be available in the next several years. While the requirements for stability and regulation are quite stringent and much R&D is needed we believe that the technology is currently available to realize a design. In order to be ready for a final design, a robust continuous design effort must be in place.

10.7.7 Path to Specification

1. More complete modeling of longitudinal plane for the damping rings and main linac will provide a better idea of the full regulation requirements. This model must include both the systematic and stochastic errors and noise of the ground motion, cryomodules and RF system.
2. Identify bunch compressor feedback loop requirements.
3. Identify any additional beam-based control loops required from gun to IP.
4. As new technologies are developed for modulators, such as Marx Generators, new specification for both modulator spectral content and LLRF bandwidth requirements need to be spelled out.
5. Error budgets that span many systems are needed. This must cover areas that are sources of disturbance as well as the regulation performance of the LLRF control loops.

10.7.8 Required R&D

There are many aspects of R&D for LLRF for a machine on this scale. Many present LLRF systems need careful and time consuming calibration and adjustment by experts. Fault diagnosis is often time consuming and can generate significant down time. Key improvements are needed for installation and commissioning, fault diagnosis and recovery.

Beam based energy and phase global controllers need to be developed and studied on existing machines. “Variations in beam intensity creates systematic errors for both the damping rings and Linac. However, because the individual bunch intensities are known while in the damping ring, feedforward information can be passed up the Linac before beam extraction. Also because most of the cavity errors are within 100kHz of bandwidth, uncorrected errors from individual LLRF controllers may be accumulated and passed on to other station controllers. This approach has the potential to increase overall Linac performance by more than 5% as klystrons could be operated closer to the true required power level with less overhead for feedback.

Platforms are a major concern for instrumentation, controls and LLRF. It would be idea if there is a single platform for all systems. One the other hand standardization must not compromise individual system performance. There are many approaches within the LLRF community to this issue which includes standard instrumentation crates like VXI, Cpci and PXI, to crateless systems with Ethernet interface. As mixed signal IC technology advances and the total electronic circuit footprint is reduced, the value of a crate based system is reduced. Crates may keep there advantage especially if multiple systems are able to share crates and even processing modules.

R&D with the current state of the art components in ADCs, DACs, FPGAs, DSPs and analog processing must be an ongoing process. Keeping up with current computer science advances is equally important. Because of the large effort involved, it is imperative that this work span many institutions in open collaborations

10.7.9 References:

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10.7.11 Alternate Configuration

No alternates under active consideration at this time.