NEW LLRF SYSTEM FOR FERMILAB 201.25 MHZ LINAC

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Abstract

The Fermilab Proton Plan, tasked to increase the intensity and reliability of the Proton Source, has identified the Low Level Radio Frequency (LLRF) system as the critical component to be upgraded in the Linac. The current 201.25 MHz Drift Tube Linac LLRF system was designed and built over 35 years ago and does not meet the higher beam quality requirements under the new Proton Plan. A new VXI based LLRF system has been designed to improve cavity vector regulation and reduce beam losses. The upgrade includes an adaptive feedforward system for beam loading compensation, a new phase feedback system, and a digital phase comparator for cavity tuning. The new LLRF system is phase locked to the 805 MHz reference line, currently used as frequency standard in the higher energy accelerating section of the Linac. This paper will address the current status of the project, present the advancements in both amplitude and phase stability over the old LLRF system, and discuss commissioning plans.

INTRODUCTION

The RF control system that is presently implemented in low energy (LE) Linac was first commissioned in the late sixties. Although it received minor modifications in 1994, it does not meet the present amplitude and phase stability requirements. During the last seven years, the types and number of beam pulses that are being accelerated in the Linac have risen tenfold, resulting in an increase in activation of the Linac enclosure. As a result, the Proton Plan was developed to fund projects that could either improve beam quality or reduce enclosure activation due to beam loss [1]. In order to meet these demands, a new LLRF for the LE Linac system has been designed and prototyped. The design goal for the new LLRF system is to reduce amplitude variations to < 0.2% and to reduce the beam setting time to < 2 µs. The current LLRF system (see Fig. 1) is only able to achieve 2% amplitude stability. During the first 10 µs of beam, both the RF amplitude and phase errors have the largest excursion. These errors cause momentum drift in the beam, which in turn, creates matching problems into the downstream Booster accelerator. A beam drift of 2 mm, both vertically and horizontally was measured at the downstream end of Linac. In order to reduce this mismatch into Booster, the first 10 µs of beam is presently chopped off and sent to a dump line. With the increased repetition rate of the Linac, this wasted beam has steadily increased the activation of both the dump line and the accelerating structure. By reducing the beam settling time from 10 µs to less than 2 µs, and by improving beam loading compensation and regulation, the beam loss and resulting activation can be greatly reduced [2].

LINAC LLRF SYSTEM

In order accomplish the goals of the Proton Plan, a new LLRF system has been designed and implemented to replace the present LLRF system (see Fig. 1). The new system consists of three parts, a slot 0 controller, a multi-channel field control (MFC) module, and an analog RF module (see Fig. 2). The slot 0 controller is used to connect the Fermilab controls network (ACNET) with the

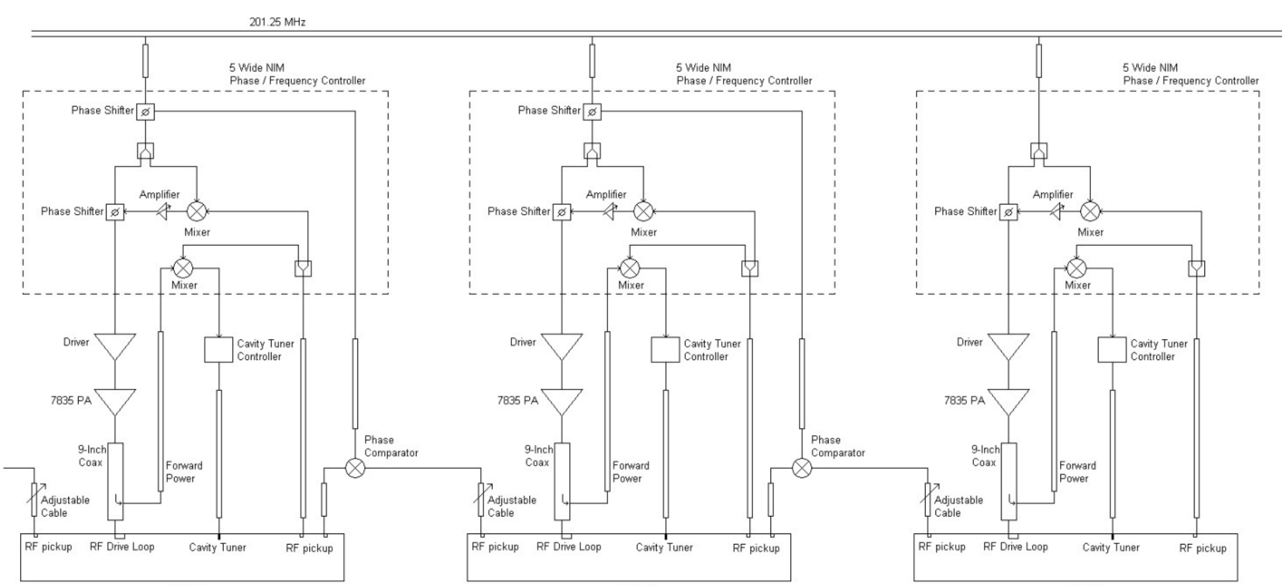

Figure 1: Simplified low energy (LE) linac RF block diagram of the present LLRF control system.

LLRF system. The MFC Board uses a modern Digital Signal Processor (DSP) and Field Programmable Gate Arrays (FPGA) to implement the phase loop, perform feed-forward calculations, and execute other digital control loops. The RF module is responsible for all of the analog RF signal processing and control. Working together, the new VXI based LLRF system provides the following features:

- Digitally controlled phase feedback system that replaces the present analog RF phase feedback
- Adaptive feed-forward for both amplitude and phase control to improve beam loading compensation
- 201.25 MHz RF reference generated from the HE Linac 805 MHz reference line
- Phase loop regulation from the reference line replacing the present inter-tank phase reference
- Digital phase detection for the cavity resonant control system

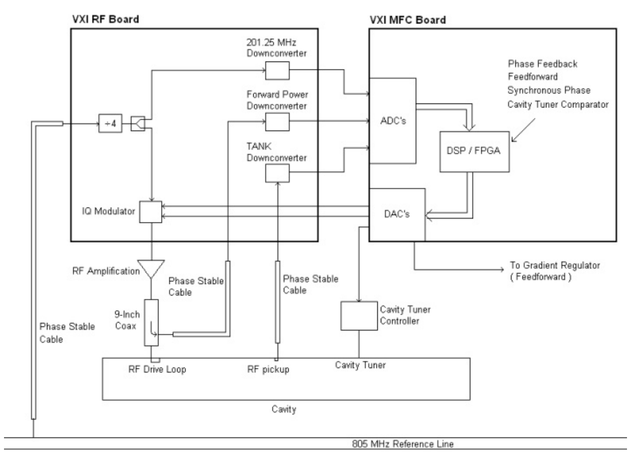

Figure 2: Block diagram of the new VXI LLRF system.

Multichannel Field Control Module

The MFC is modern Low Level RF Controller designed to handle from one to 32 cavities driven from a single RF power amplifier. This allows it to be used in many applications such as Project X or the International Linear Collider (ILC). The MFC module has 32 12-bit ADC's that can operate up to 65 MHz, one 14-bit ADC that can operate up 105 MHz, four 14-bit DAC's that operate up to 240 MHz, an Altera Cyclone II FPGA and a 400 MHz SHARC Digital Signal Processor (DSP). The clock distribution is programmable and there is 64 Mbytes of DDRAM as well as ample flash memory. It is packaged in a one wide VXI module. The Altera Cyclone II FPGA (EP2C70F672C6) functions as the primary signal processor [3].

RF Control Module

Unlike the MFC module, the VXI RF control module was designed specifically for the Linac LLRF upgrade (see Fig. 3). The RF module down converts RF signals to an intermediate frequency (IF) of 12.578 MHz for processing by the MFC module. This module also takes the 805 MHz reference line and divides it by 4 to generate the 201.25 MHz reference at each accelerating cavity. This 201.25 MHz reference signal provides the RF drive for the cavity. An in-phase/quadrature (IQ) modulator on board allows vector control of the magnitude and phase of the RF drive. The module also performs analog RF signal processing tasks, such as RF gating, clock division, phase comparison, and other signal conditioning.

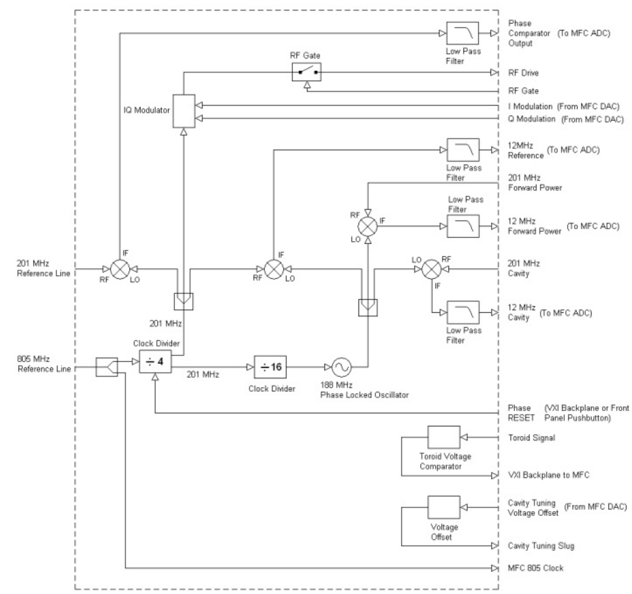

Figure 3: Block diagram of VXI RF module.

RF Phase Reference

The main reason for using the 805 MHz reference line in the new LLRF system is to provide an independent, phase stable RF drive for each accelerating cavity (see Fig. 4). This new system allows the phase of each cavity to be adjusted independently. The present LLRF system uses an inter-tank phase comparator that holds the cavity phase constant relative to each other (see Fig. 1).

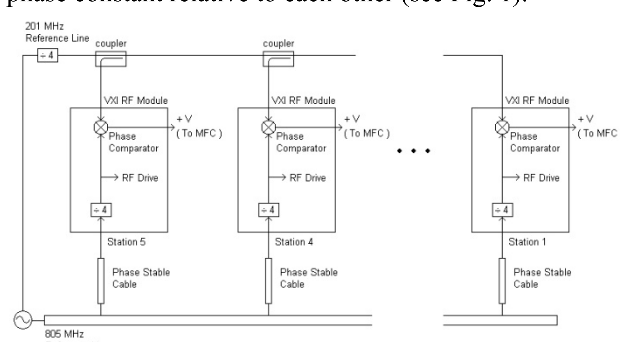

Figure 4: Block diagram of synchronous phase system.

To maintain phase stability of the new LLRF system, phase matched, phase stabilized 3/8" Heliax cable have been installed for each LLRF station. The new cables carry the 805 MHz reference line, the cavity pickup, and the forward power from the accelerator tunnel to each respective RF system. These cables are bundled together so that temperature drifts do not affect the RF system phase. Phase drift problems are very noticeable in the present LLRF system and need constant accelerator tuning to keep beam losses to a minimum.

RF Phase Feedback Control

RF phase modulation is done using the IQ modulator on the RF Board, controlled by the MFC. The IQ modulator is capable of providing both phase and amplitude modulation. Since the main power amplifier, the Burle 7835 power triode, operates in saturation, the amplitude of the cavity vector is controlled by the modulator voltage, not the LLRF drive amplitude. The IQ modulator amplitude is used to adjust the proper output level for the driver amplifier stage.

To control the phase of the LLRF system, the 201.25 MHz reference and the 201.25 MHz cavity pickup signals are both down-converted to an IF of 12.578 MHz. These signals are sent to the analog-to-digital converters (ADC's) on the MFC board (see Fig. 3). The 201.25 MHz reference is generated by dividing the 805 MHz reference input by four on the RF board. The 12.578 MHz IF reference and cavity signals are then digitally down converted to baseband on the MFC board. Using the IF of 12.578 MHz eliminates the problems associated with down converting to baseband in the analog domain.

After down conversion to baseband, the MFC board performs phase feedback calculations which are sent out to the IQ modulator on the RF Board to modulate the RF drive phase. This configuration allows for a complete 360° of phase rotation on the RF drive. This phase modulation is used to regulate the phase of the RF relative to the reference line and uses RF phase feedback to keep the phase of the RF drive consistent throughout the pulse. Using digitally phase feedback also allows the user to easily control the feedback gain of the system.

RF Amplitude Feed-Forward Control

Since the LE Linac RF amplifiers run in saturation, amplitude control cannot be done effectively using direct RF feedback. Instead, amplitude of the RF is controlled by regulating the modulator voltage applied to the anode of the Burle 7835 power amplifier. There are two loops that are presently used to regulate the field in the cavity. The first loop, coded into the Fermilab computer controls network, is used to keep the overall RF field strength consistent on a pulse-to-pulse basis by sampling the field during beam time and making amplitude adjustments to the modulator waveform. This modulator waveform is then input into a second feedback loop to control the overall shape and amplitude of the RF gradient (see Fig. 5). If only the modulator waveform pulse is used as input to this loop, when beam enters the cavity, significant beam loading occurs, dropping the accelerating field in the cavity by more than 10%. The present system compensates for this beam loading by adding the beam toroid pulse into the feedback loop along with the modulator waveform pulse. The problem with using the beam toroid pulse is that it arrives to the LLRF system after beam has already started loading down the cavity. Although adding the beam toroid pulse to the feedback loop reduces the beam loading down to 2%, it still does not meet the proton plan design criteria. In the new LLRF system, instead of using the beam toroid pulse, a feed-forward pulse is added to the modulator amplitude control loop. By summing in this feed-forward input pulse, amplitude stability of 0.1% has been accomplished, which exceeds the design goal of 0.2% beam loading amplitude stability. The vast improvement is a result of the ability for the new LLRF system to precisely control the timing of this feed-forward pulse before beam loading occurs and the ability for precise waveform shaping. Both the modulator and toroid pulse system can add up to 9 µs and 1 µs of delay respectively, which can then be compensated for by timing the feed-forward pulse up to 10 µs before beam arrives [2].

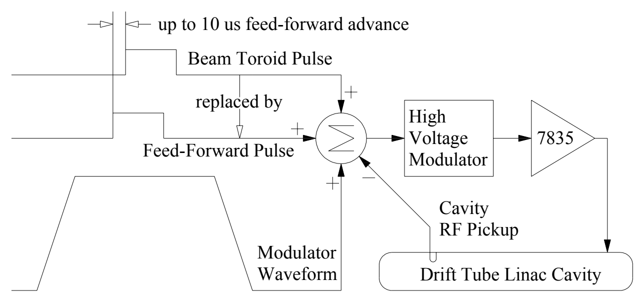

Figure 5: Modulator control system.

COMMISSIONING PLANS

This new LLRF design was prototyped and installed at the LE Linac RF end station. After extensive fine tuning on phase and amplitude control parameters, the design goals of the Proton Plan where exceeded, with amplitude variations < 0.2% and beam setting time < 2 µs. The plan is to have the prototype LLRF system in operation by the end of the year, with full implementation by mid 2009.

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