A Brief History of the MI 53MHz RF System Run II Upgrades

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9/15/2005

Introduction: *The purpose of this note is to give a general overview of the Main Injector (MI) 53MHz radio frequency (RF) system upgrades associated with the Run II Luminosity Upgrade project and to introduce the Mid-Level RF (MRF) system.*

SSD Upgrade for Slip-Stacking

As part of the Run II Luminosity Upgrade project, the Main Injector (MI) 53MHz radio frequency (RF) system went through a series of upgrades to provide increased beam loading compensation during slip-stacking for pBar production. Beam loading compensation attempts to completely counteract the effect that a particle beam has on itself from its interaction with the RF accelerating cavities as it traverses them. The specific beam loading compensation techniques employed in the MI are Direct RF Feedback and RF Feed-Forward. Perfect cancellation is achieved only by delivering to the cavity a generator current which is equal and opposite to the beam current.

Since the method of slip-stacking ideally doubles the batch intensity in the MI, the amount of generator current needed for perfect cancellation also doubled. For the beam intensities associated with pBar production slip-stacking, the final power amplifier (PA) that sits on each RF cavity is adequate for delivering the necessary generator current. However, due to the cathode driven PA configuration, the solid-state driver (SSD) which is upstream of the PA and provides the cathode drive had to be upgraded. Thus, the number of SSD amplifiers was doubled from 4 to 8 at each of the 18 RF stations. The doubling of the SSD amplifiers was completed during the Fall 2004 shutdown.

The SSD amplifier upgrade also required a review of the SSD driver combiner network. The combiner network combines all of the 8 SSD amplifier outputs into a unified cathode drive signal for the final PA. It was decided to simply add another 4-way combiner identical to the existing combiner and double the number of cathode drive cables going to the PA cathode. This configuration is inherently only optimized for increased tube biasing under which the PA cathode impedance is reduced. It is not optimized for all conditions.

With the addition of 4 SSD amplifiers, the SSD control unit and the SSD metering chassis needed to be upgraded. The SSD control units monitor the SSD amplifiers and provide the on/off controls and interlocks for the amplifiers. The SSD metering chassis provides monitoring points and front panel visual meters of the SSD amplifiers' operation.

Furthermore, due to space limitations in the SSD metering chassis, a new device called the Station RF Controller was designed to house the low-level RF electronics that sum the Direct RF Feedback and the RF Feed-Forward signals at each station and provide the RF drive signal to the SSD amplifiers. One controller is installed at each station. The electronics within this device were redesigned to properly handle the RF power levels needed for the RF stations.

The Birth of the Mid-Level RF System

It was during the course of the SSD amplifier upgrade that the RF Department had the chance to review the entire MI 53MHz RF system architecture. An immediate observation was that the original system was not designed with beam loading compensation systems and required that the new Station RF Controller properly configure some of the historic RF control points. These RF control points are used to dynamically (during an operation cycle) compensate for natural changes in the system that occur within an operation cycle; i.e. a system gain change due to the cavity Q which is a function of frequency. Additional dynamic control points were also added; such as a dynamic control of the Direct RF Feedback gain so that it could be changed during an operation cycle.

Next, it was observed that the signal generators that supply the actual signals to these control points were not mapped to MI states. The MI has many modes of operation, called MI states; i.e. pBar production slip-stacking or pBar production slip-stacking with multibatch protons to NuMI. For a given state, the MI has to sequence through a set of instructions which are unique for that particular state. Currently there are 31 MI states and only 8 signal generator mappings. As an analogy, it is similar to a car which 31 people want to drive with their individualized car seat position to their unique destination of choice; yet the car has only 8 settings for seat positions and only 8 destinations to choose from. Obviously, all 31 people will not get to have an individualized experience.

Furthermore, it was observed that the MI 53MHz RF system does not have a global vector regulation system. In other words, it does not have a means to regulate both the amplitude and phase of the 53MHz RF accelerating voltage to a specified user request. It only has a crude balancing system that tries to maintain a balance between two groups of cavities designated as ‘A’ and ‘B’ group cavities. It only attempts to make the A voltage equal to the B voltage without regulating either A or B to a specific voltage. And currently there is no means of regulating the global phase of the A group or B group to a phase reference; there is a local phase loop at each station that regulates individual station phase but not the resultant of all stations.

Acting upon these observations, the Mid-Level RF (MRF) system was proposed. It is called the ‘Mid-Level’ because it essentially is a bridge between the low-level RF (LLRF) system which already contains MI state information and the high-level RF (HLRF) system which needs to deliver the user requested 53MHz RF accelerating voltage for each MI state. Its purpose is two-fold:

1. Provide slow global vector regulation (amplitude and phase) of the MI 53MHz RF system voltage

2. Provide MI state based control of end-user 53MHz RF system voltage requests.

The LLRF system determines which MI state is requested to be played and provides the sequence of instructions. The MRF system interprets the instructions and delivers a voltage amplitude and phase request to the HLRF system. The HLRF system produces a voltage which is then detected, in both amplitude and phase, and regulated by the MRF system.

The benefits of incorporating a MI state mapped global vector regulation system with the MRF include:

- A repeatable, consistent, and regulated 53MHz RF system voltage

- A tool to facilitate studies that explore new and/or optimal operating points of the system

- New digital control knobs for calibrations; i.e. an A group and B group magnitude and phase calibration knob for paraphasing.

The MRF system offers for the first time global regulation and true MI state mapping of the HLRF system operations. This is important for a system which has to dynamically span a range of 90kV to 3.7MV as well as having to be gated off or paraphased to produce near 0 volts. A specific example where MI state control can be employed is for the $23 MI reset event which is currently used for 2 separate MI states, the NuMI only cycle and the pBar+NuMI cycle. Currently the same control signals are played out for both scenarios which have a different sequence of instructions and which have different beam intensities.

The MRF system is not intended to be a panacea for all MI performance issues; only those that would benefit from better vector regulation. And as a MI state controlled system, it is intended to be a digital tool which facilitates studies and explorations of new control techniques; i.e. addressing the anode modulator power dissipation issues at low cavity voltage, an issue for the Proton Plan Project.

The MI 53MHz RF system will continue to be studied and upgraded to ensure performance for the increased beam intensities expected for the Proton Plan Project.

References

[1] T. Berenc, B.Chase, “Status of the Main Injector Mid-Level Radio Frequency (MRF) Project- a Run II Main Injector Upgrade”, Fermilab RF TechNote #069, http://www-rfes.fnal.gov/global/technotes/TN/TN069.pdf