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RF Note #069

Status of the Main Injector Mid-Level Radio Frequency (MRF) Project a Run II Main Injector RF Upgrade

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Abstract: *The purpose of this note is to give a general overview of the Main Injector (MI) mid-level RF (MRF) project, document currently achieved operating parameters and performance results, and describe study requests which will be needed to complete the project.*

Introduction

The purpose of the Main Injector (MI) mid-level RF (MRF) project is two-fold:

- Provide global vector regulation (amplitude and phase) of the MI h588 system cavity voltage
- Provide MI state based control of MI h588 voltage requests

The global vector control regulates both the h588 voltage magnitude to a user request and the phase to the low level RF (LLRF) vector reference.

The MI state control of the MI h588 system voltage intimately associates unique user voltage requests to their respective MI state. Currently h588 voltage requests are mapped to 8 curves while there are over 31 MI states (or scenarios). The MRF design provides a means to make unique voltage requests within the existing MI states; thus providing a unique one-to-one mapping.

Many other changes to the high-level RF (HLRF) stations have been made or are proposed that bring the HLRF system closer to a low noise, linear system model. These improvements will increase the MRF closed loop bandwidth and the peak beam loading operation.

Project Stages

The project has been divided into two stages:

- Stage I (2x9)
- Stage II (6x3)

Stage I has provided a smooth transition into the new MRF system by preserving the traditional h588 system's architecture during the MRF development. Stage II offers a novel architecture that can better handle certain abrupt manipulations of the h588 system.

The Stage I vector control design regulates the h588 voltage using the traditional structure of 2 groups (Group A and Group B) of 9 cavities; hence the name 2x9. The MRF vector controller independently regulates each group's resultant voltage in both magnitude and phase. It is during Stage I that a better understanding of the operation of the HLRF stations has been gained and alternative methods of station operation will be explored.

The Stage II (6x3) design rearranges the grouping of the 18 MI HLRF cavity stations by subdividing each group of 9 cavities into 3 subgroups of 3 cavities; hence creating a total of 6 groups of 3 cavities. The traditional Group A becomes 3 groups of 3 cavities. The same happens for Group B. This allows either Group A or Group B to independently produce a resultant voltage of nearly zero by counter-phasing the vectors of the 3 subgroups. This is an extension of the traditional 2x9 architecture which already counter-phases the Group A and Group B vectors to produce a nearly zero resultant h588 voltage. The difference being that in Stage II, each group can now do the same independently. This is useful in many scenarios. Some examples are: during slip-stacking, which uses separate RF frequencies for Group A and Group B, and 2.5 MHz acceleration which requires the h588 voltage to go to zero at one frequency and turn back on at another frequency.

Presently, low or zero voltage operation is obtained by "RF Station Control"; the turning off of HLRF stations. The transients involved in turning on a station that has been off are large and difficult to control. By keeping the cavity stations on and producing voltage, Stage II minimizes the transients. Furthermore, it keeps the cavity station control loops stable during situations in which a frequency change occurs while the request voltage is zero.

Local Station Control Loops

The cavity station control loops are the loops at each of the 18 HLRF cavity stations that regulate a station's individual behavior; such as amplitude, phase, and resonant frequency. These loops ensure that, as an individual, each cavity contributes equally to its group's total voltage while remaining well behaved. These loops also reduce the effect of disturbances to each cavity station; including the disturbance of the beam going through the RF cavity (beam loading).

Beam loading concerns were the impetus for the HLRF solid state driver (SSD) upgrades of 2004. The HLRF SSD upgrade doubled the available RF drive power at each station to counteract the beam induced voltage on an individual cavity basis. The additional drive power is used by both the Direct RF feedback (Direct RF FB) loop and the global RF Feed Forward system. The Direct RF FB loop is one of the individual cavity station loops which contributes to beam loading compensation along with the RF Feed Forward system. The RF Feed Forward system measures the beam current in the MI and provides a RF drive signal to each cavity station which is equal and opposite to the beam current in order to cancel the beam loading at each cavity.

MI h588 System Parameters

A block diagram of the MI h588 system which depicts the architecture for the MRF global vector control is shown in Figure 1 on the following page.

It is extremely important to note that a single HLRF station is a complicated nonlinear system. The parameters quoted here are approximations and do not fully characterize the complex behavior of the system.

The HLRF system feedback loop parameters are currently (as of 5/5/2005) as follows:

- Direct RF FB loop delay: ~ 423 nsec.
- Direct RF FB Gain : 2 – 4.5 V/V
- Local Phase Delay Line: ~ 431 nsec.

Note: The operational Direct RF FB Gain is a complicated function of anode bias, grid bias, RF drive level, and frequency. The numbers quoted here were determined from "small signal" measurements during the HLRF SSD upgrade at a fixed Anode Bias, Grid Bias, and RF Drive level. The range was due to station to station variations and the 300kHz operating frequency sweep.

Cavity Parameters:

- Q at injection (52.8114MHz): ~ 3000
- Q at flat top (~53.104MHz): ~ 4400-5000
- Anode to Gap Voltage Step-Up Ratio: ~ 12.3
- R/Q: ~ 100

Note: The Q quoted here was based upon small signal NWA measurements of a single cavity at the test station. The Anode to Gap Voltage Step-Up Ratio was based upon large signal conditions at the test station using the assumption of calibrated gap and DC anode voltage monitors. It assumed a peak RF anode voltage based upon the anode bias, screen bias, and screen current. The R/Q value is that which is usually quoted from various sources.

MRF system feedback loop parameters:

- Global Phase Delay Line: ~ 1.17 usec.
- Amp & Phase feedback parameters – See 'Completed Studies' for parameter values used thus far during studies.

h588 Voltage Request Dynamic Range

- Vmin: 0 kV (for coalescing and 2.5MHz accel.), 550 kV (30.6 kV per station) during Tclk 2A and 2B cycles
- Vmax: 3.7 MV (205.6 kV per station) during typical stacking cycles

HLRF Station Gain:

- Total Variation: ~ 17dB

Note: The HLRF station gain is a complex function of anode bias, grid bias, RF drive level, and frequency. The range quoted here was taken from test station measurements. The lowest gain of ~99dB was measured at 52.8114MHz, 20 kV cavity gap voltage, –275V grid bias, 2.37 KV anode bias, and 200mA screen current. The highest gain of ~116 dB was measured at 53.104 MHz, ~ 221 kV cavity gap voltage, –275V grid bias, 20 kV anode bias, and 200mA screen current.

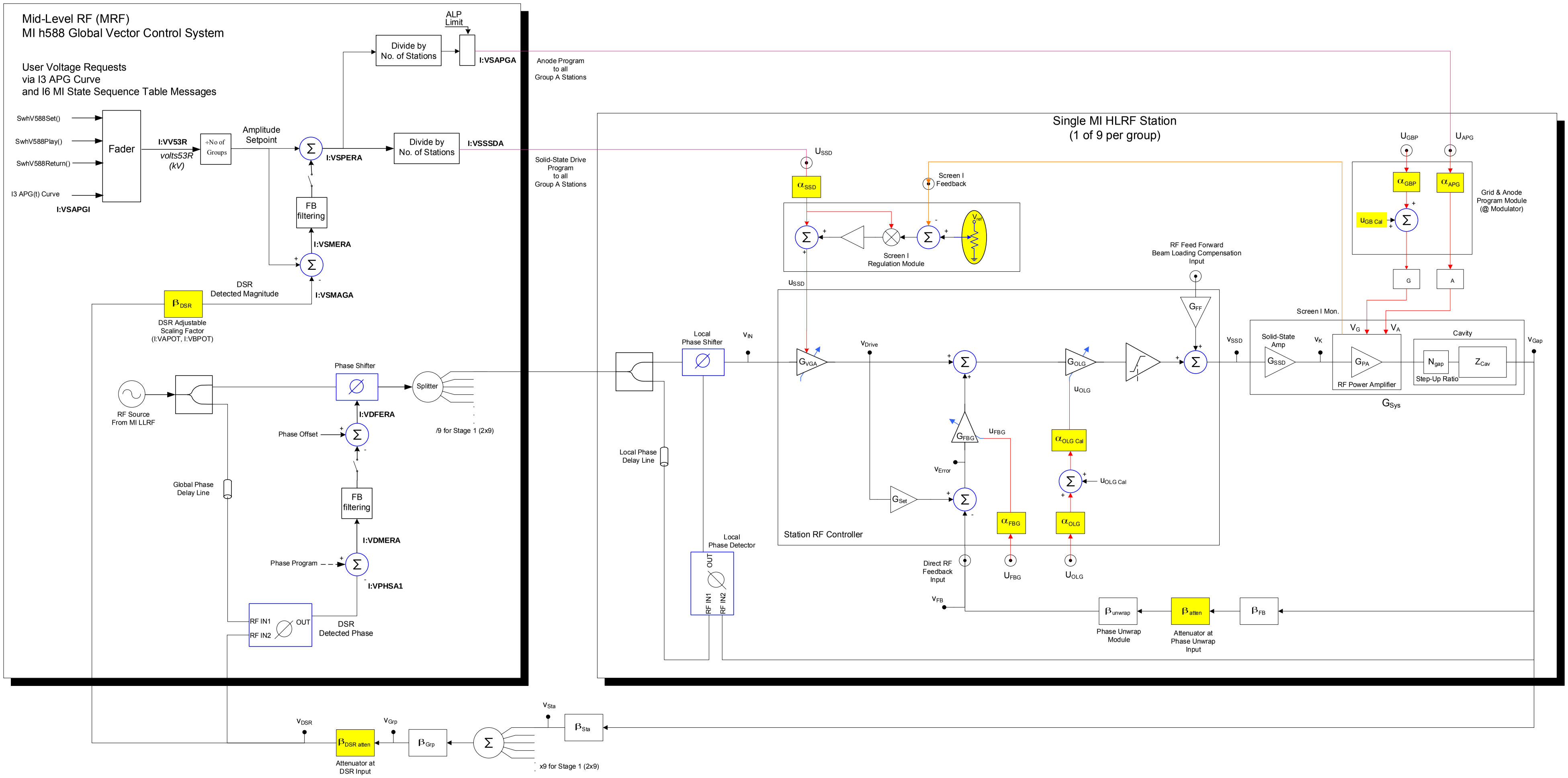

Figure 1: MI h588 System Block Diagram

MI HLRF Station Improvements

By studying the system architecture of the entire MI h588 HLRF system during the MRF project, it was determined that improvements could be made to some of the MI HLRF station hardware in order for the system as a whole to operate more effectively. The following HLRF station modules were chosen for modifications or upgrades:

- Screen Current Regulation Module modifications – DONE
  - To reduce station overshoot and
  - To allow operating without screen current
- VGA (Variable Gain Amplifier) upgrade – IN PROGRESS
  - To increase the range of linear amplitude control
- Phase Unwrap Module – IN PROGRESS
  - To reduce the spurious content of the SSD RF drive signal due to down-converting and up-converting the cavity gap signal for the Direct RF FB loop

The Screen Current Regulation Module was historically used to force the final RF power amplifier (PA) tube to always draw screen current. This purpose was twofold: (1) in combination with anode programming, it served as an approximate amplitude control, and (2) it ran the PA tube efficiently. With the installation of Direct RF FB and with the MRF amplitude control, it is not necessary to force screen current for amplitude control anymore. Furthermore, it may prove to be better to run the PA tube away from the screen current region during periods of increased feed-forward beam loading compensation. Operating away from the screen current region provides increased headroom and linearity for the feed-forward drive signal.

The Screen Current Regulation Module was modified so that it would minimally increase the RF drive, but would still be able to reduce it. This reduces its ability to force screen current so that stations can be run with no screen current if desired. It also greatly reduces the station turn-on overshoot and noise during low voltage operation.

The VGA upgrade replaces the historic VGA with a new VGA that has an increased linear range, flat phase response, and reduced noise. The VGA resides in the Station RF Controller and is used to program the station cavity voltage request. By increasing its linear range, the control efforts of the MRF amplitude and phase loops are minimized.

The Phase Unwrap Module is used to provide a phase shift on the cavity gap monitor used as the direct RF FB signal. This is to counteract the natural phase shift during the h588 frequency sweep caused by the total station loop delay. The phase shift is realized by down-converting and up-converting the cavity gap monitor signal. These processes are imperfect and add mixing products or spurious spectral components to the direct RF FB signal. Unlike the fundamental component, these spurious components do not subtract from anything at the direct RF FB error summing junction; thus, depending on the direct RF FB gain, they can reach the same level as the fundamental component of the PA drive signal. The amplified spurs waste large amounts of real power in the PA and can create new mixing products that may excite cavity modes. Modifications to the Phase Unwrap Module are planned in order to reduce the spurious content.

MRF Hardware/Software

The hardware that was necessary for the MRF project is listed below:

Available Hardware Installed for Stage I:

- MRF VXI system with:
  - DSR (Digital Signal Receiver)
  - DDS x2 (Direct Digital Synthesizer)
  - SWH (Switch)
  - XFR (Transfer Sync Module)
  - Reflective Memory Module
  - I/O100 (Digital I/O Module)
  - V152 Power PC Processor
  - Interface panels

New Hardware/Software design for Stage I:

- MRF DAC Line Driver – DONE
  - replaces the HLRF CAMAC 465 modules and Anode Program Combiner electronics
- New Software Libraries
  - MRF, SWH, XFR, DDS, DSR libs

New Hardware designs for Stage II

- 6x3 Fan Out module – IN PROGRESS
- 6x3 Fan Back module – IN PROGRESS

Completed Studies in Main Injector

- 4/1/2005: MRF test at MI HLRF Station 2 - NO BEAM.
    - This study demonstrated MRF amplitude control only of a single operational station. The MRF phase control was not yet completed for testing.
    - The single station calibration procedure was successfully tested. This procedure assumes 'calibrated' gap monitors. It is NOT a beam based method.
    - The Direct RF FB loop was run approx. 12dB higher than current operational levels. Simultaneously, the MRF amplitude loop was run with a 80Hz pole at a gain of 10.

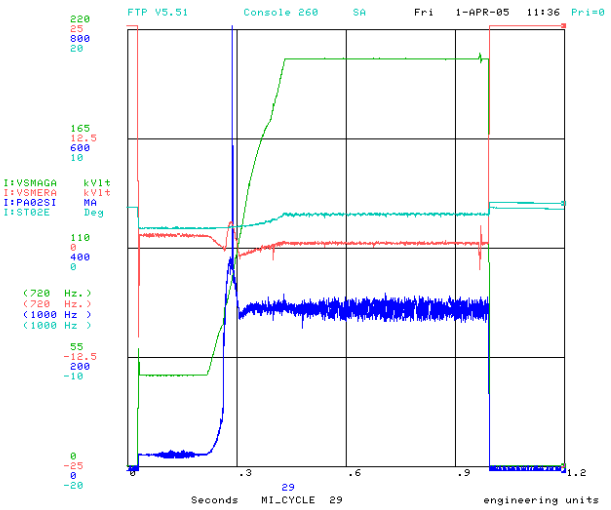

Figure 2: MRF amplitude control at Sta 2 without beam

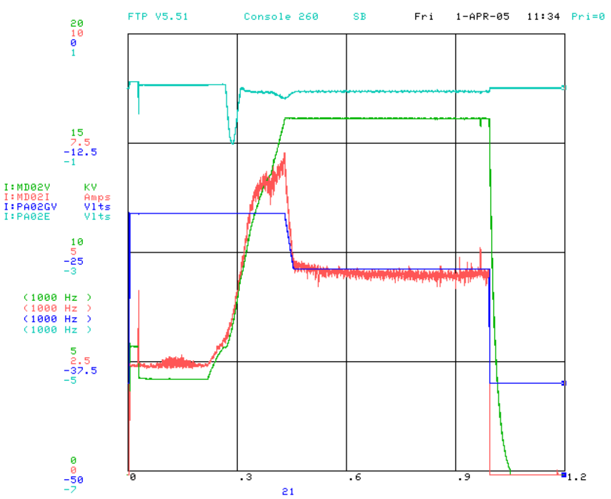

Figure 3: MRF amplitude control at Sta 2 without beam

- 4/4/2005: MRF test at MI HLRF Station 2 - WITH BEAM.
    - This study successfully demonstrated MRF amplitude control only of a single station WITH BEAM.
    - Station 2 was run during a typical MI State 28, Tclk29 slip stacking cycle with the operational Direct RF FB gain and with an MRF amp gain of 10 with an 80 Hz pole. Higher Direct RF FB gains were used but time did not permit determining causes of station SSD FWD power trips. Feed Forward was also active on this station during the tests.

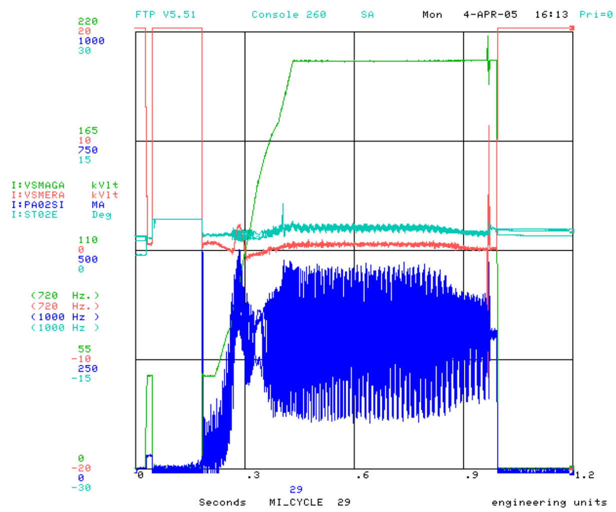

Figure 4: MRF amplitude control at Sta 2 with beam

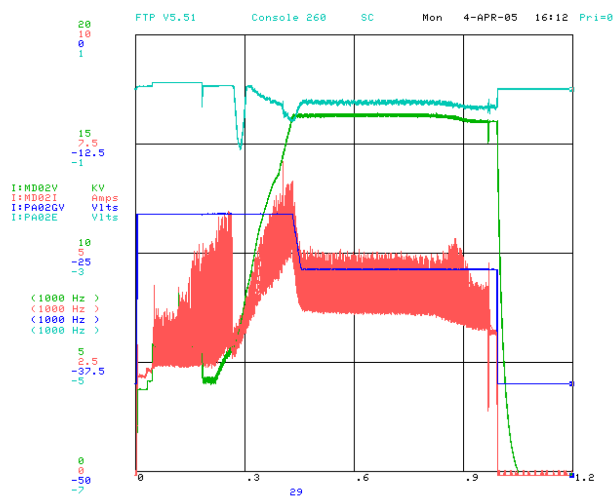

Figure 5: MRF amplitude control at Sta 2 with beam

- 5/4/2005: MRF Stage 1 (2x9) Test - NO BEAM
    - This was the first test of the MRF system on all 18 MI HLRF stations. It included both MRF amplitude and phase control of the h588 voltage via individual Group A and Group B control.
    - Cycles studied were the MI State 28 / Tclk 29 slip stacking cycle and the MI State 4 / Tclk 2B cycle.
    - The Direct RF FB Gain was run ~ 6dB higher than the normal value used for operations. The MRF amp gain was run at a gain of 5 with an 80Hz pole and on a separate occasion at a gain of 10 with a pole of 20 Hz. The MRF phase gain was run at gains of 50 and 70 with a 40Hz pole.

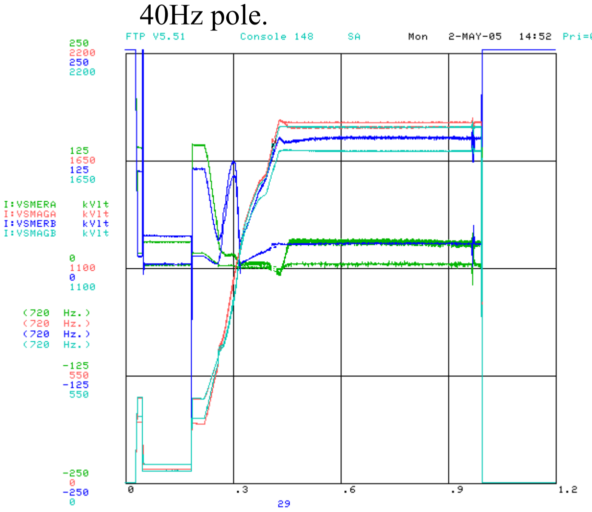

Figure 6: MRF amp. control on all stations (no beam Tclk29)
MRF FB is off for large error and on for small error

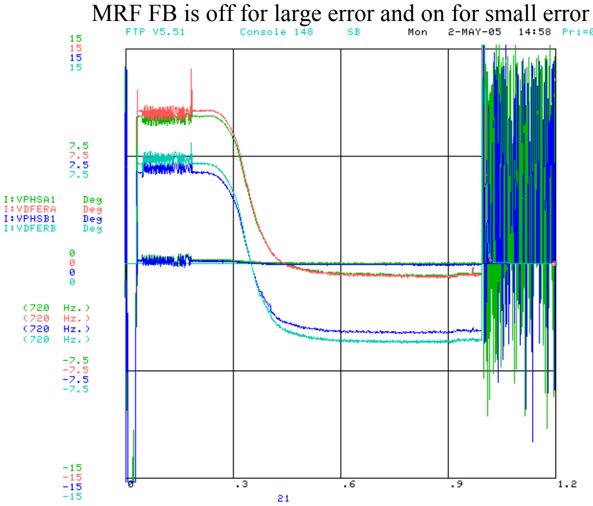

Figure 7: MRF phase control on all stations (no beam Tclk29)
MRF FB is off for large error and on for small error

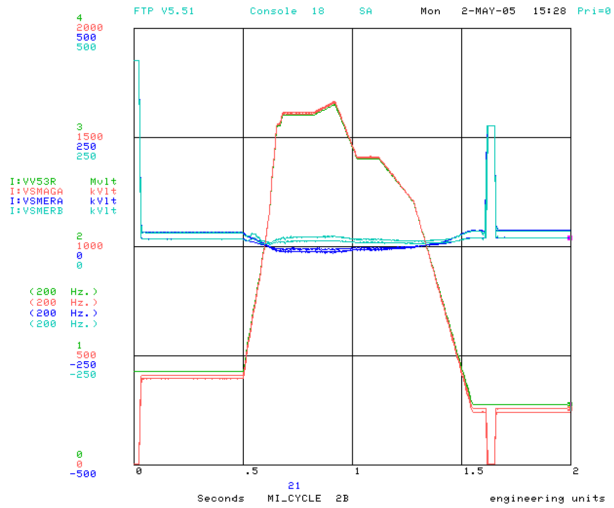

Figure 8: MRF amp. control on all stations (no beam Tclk2B)
MRF FB is off for large error and on for small error

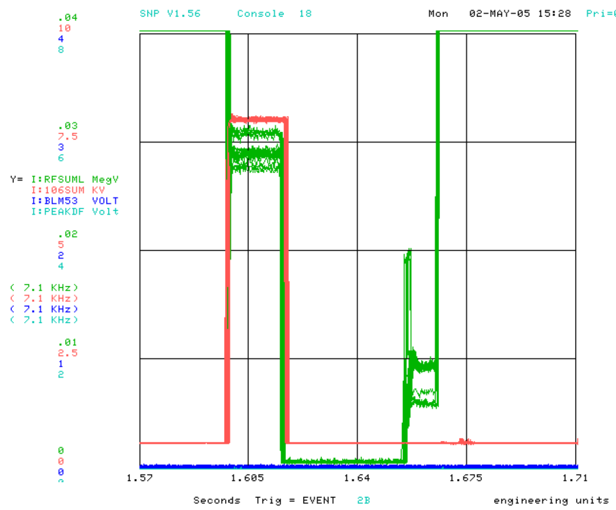

Figure 9: MRF phase control on all stations (no beam Tclk2B)
MRF FB is off for large error and on for small error

ACNET Device Description:
I:VSMAGA = Group A DSR detected magnitude,
I:VSMAGB = Group B DSR detected magnitude,
I:VSMERA = Group A magnitude error,
I:VSMERB = Group B magnitude error,
I:VPHSA1 = Group A DSR measured phase,
I:VSPHSB1 = Group B DSR measured phase,
I:VDFERA = Group A DDS filtered error which drives the DDS Group A phase shifter,
I:VDFERB = Group B DDS filtered error which drives the DDS Group B phase shifter.
I:PAxxSI = RF Power Amplifier Screen Current
I:STxxE = Local Station Phase Error
I:MDxxV = Station RF PA DC anode bias
I:MDxxI = Station RF PA DC anode current
I:PAxxGV = Station RF PA DC grid bias
I:PAxxE = Station RF PA screen current error

Test Station Studies

The MI-60 Test Station has been used to perform extensive studies of both a typical HLRF station and the MRF system. Some of the important work tasks which were accomplished using the test station were:

- MRF VXI system design and development of amplitude and phase feedback control algorithms as well as I6 sequence table messages,
- Measurements of HLRF station gain variations as a function of anode bias, grid bias, RF drive level, and frequency,
- Development of a station calibration procedure to minimize the control effort of all control loops including the MRF system; This involved a detailed study of HLRF station parameter scalings.
- Modification of the HLRF station Screen Current Regulation Module,
- Development of the station VGA Upgrade,
- Station ON/OFF gating response as well as system response and timing latencies
- Direct RF FB gain studies without beam,

Direct RF FB Studies at Test Station

In order to contribute to a better understanding of the limitations on the amount of Direct RF FB that can reliably be used, Direct RF FB gain studies were performed at the MI-60 test station. The following plots show the step response of the test station system for various Direct RF FB gain settings. The common conditions for all plots were: (1) initial condition of ~90KV cavity gap voltage, (2) 52.8114MHz operating frequency, (3) Direct RF FB only (MRF FB turned off)

Figure 10 depicts the step response without any Direct RF FB. The natural cavity decay/rise time is measured to be ~18.3usec; corresponding to a quality factor (Q) of 3036.

Figures 11 and 12 depict the step response for various Direct RF FB gain settings. Note the change in time scale from Fig. 10 to Figs. 11 and 12. The Direct RF FB gain setting that is typically used in day-to-day operations in the MI system is shown in Fig. 11.

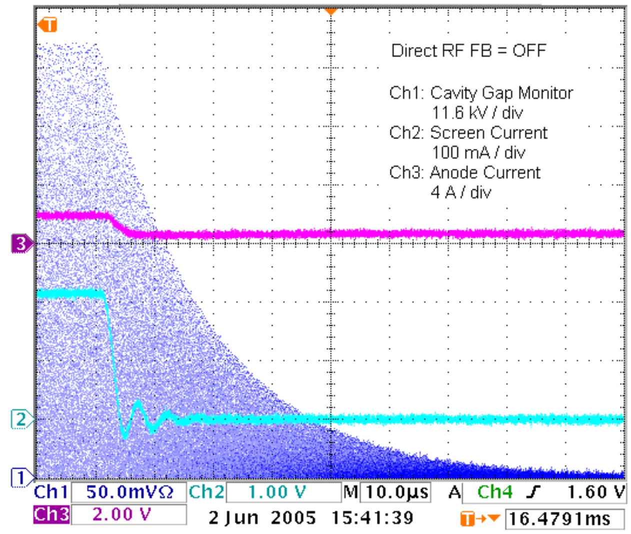

Figure 10: Step Response with Direct RF FB OFF

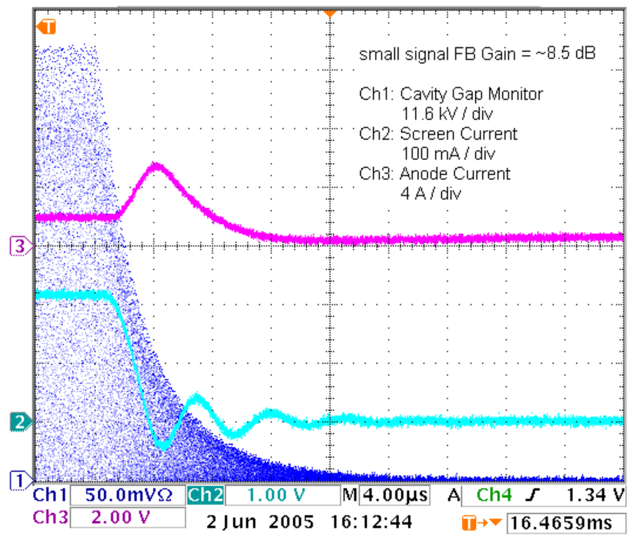

Figure 11: Nominal operating Direct RF FB Gain

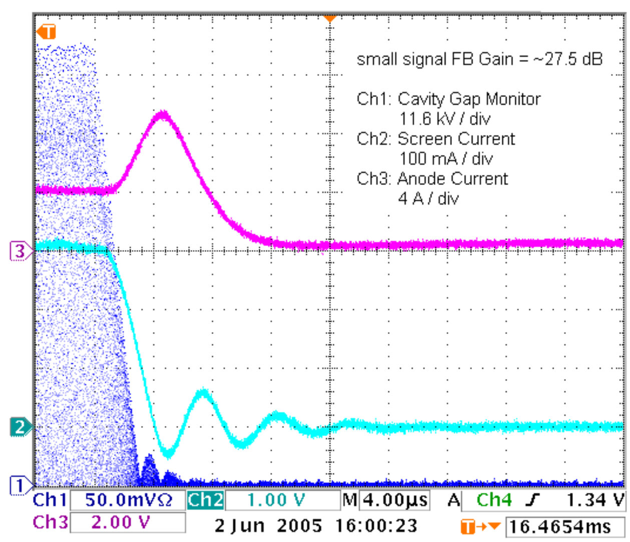

Figure 12: Maximum Direct RF FB Gain setting

Future Studies for Stage I

- **Study MRF Stage I (2x9) with beam during a typical stacking cycle**.
  - This test will be used to confirm MRF operation with beam. It will also be used to verify proper operation of the MI LLRF beam phase lock loop during operation of the MRF phase loop.
  - Study MRF feedback ON/OFF/HOLD transitioning and station overshoot.
  - Test the MRF negative electrical delay line which compensates for the physical fanout delay added to the system by MRF.
  - Check for proper bunch rotation and transfer phase at extraction
- **Study MRF Stage I (2x9) for coalescing**. Study amp and phase offset adjustments for proper coalescing operation on 2A and 2B 150 GeV cycles.
- **HLRF Station Delay Line Tuning** – Tune the Direct RF FB phase unwrap delay lines and the forward RF drive path delay. These tunings must make provisions for the installation of the new VGA which will add approximately 11 nsec to each station.
- **Install new VGA's** into the Station RF Controllers. These can be done 3 stations at a time.
- **HLRF Station Amplitude Calibrations** – NO BEAM - Calibrate each MI HLRF Station with respect to the MRF system. This includes a calibration of the SSD and APG program adjustment knobs and the Direct RF FB loop amplitude response.
- **Run MRF Stage 1 (2x9)** for normal stacking with NuMI multi batches.
- **Confirm MRF operation during all operational cycles**
  - Modify sequence tables to include new MRF V588 messages
  - Confirm tuning of all curves for all cycles
  - Confirm tuning of APG curves and calibration of VSMAGA and VSMAGB for all cycles.

Future Studies for Stage II

- **Install 6x3 FanOut System** – The new 6x3 fanout and fanback modules will be installed independently in order to preserve the system phasing. The original fanback module will be used to verify proper installation of the new 6x3 fanout system.
- **Install 6x3 FanBack module** – The new 6x3 fanback module must preserve the calibration of the detected Group A and B fanback signals.
- **Study MRF Stage II 6x3 control** with and without beam.

Suggested Studies for MI h588 System

- **Install modified phase unwrap modules**.
- **Perform a beam based calibration of the h588 detected voltage**. This study can be used to develop beam based calibration methods. Ideally the 6x3 fanback system should be installed before this calibration.
- **Study Fanout-to-FanBack phase cavity tuning control**. The justification for this was proven during Matlab simulations. Current cavity tuning control is derived from anode-to-cathode phase
  - Reason: Cathode sees only feed-forward, FB, and RF drive while the Anode sees beam, feed-forward, FB, and RF drive
- **Study increased anode voltage at low cavity volts** during and immediately after slipping within a slip stacking cycle. Compare the resultant beam loading compensation achieved in the time domain to current performance. Compare the required RF drive power requirements including Feed Forward

Conclusion

The MRF Stage I (2x9) control algorithms, hardware, and software have been tested on both the MI-60 test station and the actual MI h588 system without beam. The MRF project is now ready for Stage I (2x9) studies with beam.

Acknowledgements

The manifestation of this project is due to the dedication of those who have done the hard detailed work. In particular the LLRF group has provided extensive efforts: Philip Varghese has been responsible for the SWH and DDS software code design and development that provide the real-time MRF control algorithms; Paul Joireman has been responsible for I6 sequence table messages and Slot0 code which provide the user interface and control of the MRF functionality; Barry Barnes has been responsible for MRF software code as well as hardware and software infrastructure and support; Keith Meisner provided big picture software architecture design and guidance as well as the pathway for parallel operation of MRF with I3; Dan Klepec has provided invaluable assembly and documentation support.

The HLRF group is also to be commended for support of this project. John Reid and Joe Dey provided information on the existing operation of the HLRF system as well as resource support for installing modified modules and performing system studies. Tom Kubicki is acknowledged for the VGA upgrade design and development. Rick Zifko has provided invaluable assembly, calibration, and installation efforts. John Holm provided MI-60 test station support.

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Ralph Pasquinelli, as RF Department head, is thanked for bringing together the HLRF and LLRF groups in order for this project to truly be a collaborative HLRF group and LLRF group RF Department project.