Australian Synchrotron Booster: LLRF9 Setup Procedure

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Author: Dmitry Teytelman © Dimtel, Inc.

1 Introduction

In this short note I outline the procedure for setting up the low-level RF system in the Australian Synchrotron Booster. This procedure applies to Dimtel LLRF9/500 series 3 hardware with the IOC revision of 9.4.2 and the FPGA gateware revision 1.02.

2 Setup Procedure

Full setup of the LLRF9 system can be completed via the standard set of EDM panels supplied with LLRF9. Figure 1 shows the main control panel that opens when the EDM is launched. All other panels shown in this procedure are accessible from this main control panel.

2.1 Initial Setup

First of all, several settings must be configured as follows:

1. Open the field control loop by selecting "Open loop" in the feedback panel (Fig. 8) or by clicking on the switch symbol in the top level diagram panel (Fig. 2);

2. Open the tuner loop by selecting "Open" on the tuner loop panel (Fig. 7) or by clicking on the switch symbol within the cavity outline in the top level diagram panel (Fig. 2);

3. From the tuner loop panel open the probe balancing loop (Fig. 16) and set the loop control to "Open";

4. Launch the amplifier phase loop panel (Fig. 15) from the feedback panel and set its loop control to "Open loop";

Figure 1: Main LLRF9 control panel.

5. Open the gains and phases panel (Fig. 11, accessible from the feedback panel or the top level diagram panel. Set `VECTOR COMBINER INPUT 1` to a gain of 1 and a phase shift of 0. Set `DIRECT OPEN LOOP` to a gain of 1 and a phase shift of 0. Make sure the gains for the `VECTOR COMBINER INPUT 2` and the `INTEGRAL OPEN LOOP` are set to 0.

6. Clear the latched interlock fault, if any, from the interlock summary panel.

2.2 Tune the Cavity

The first step in configuring the station is to tune the cavity on resonance.

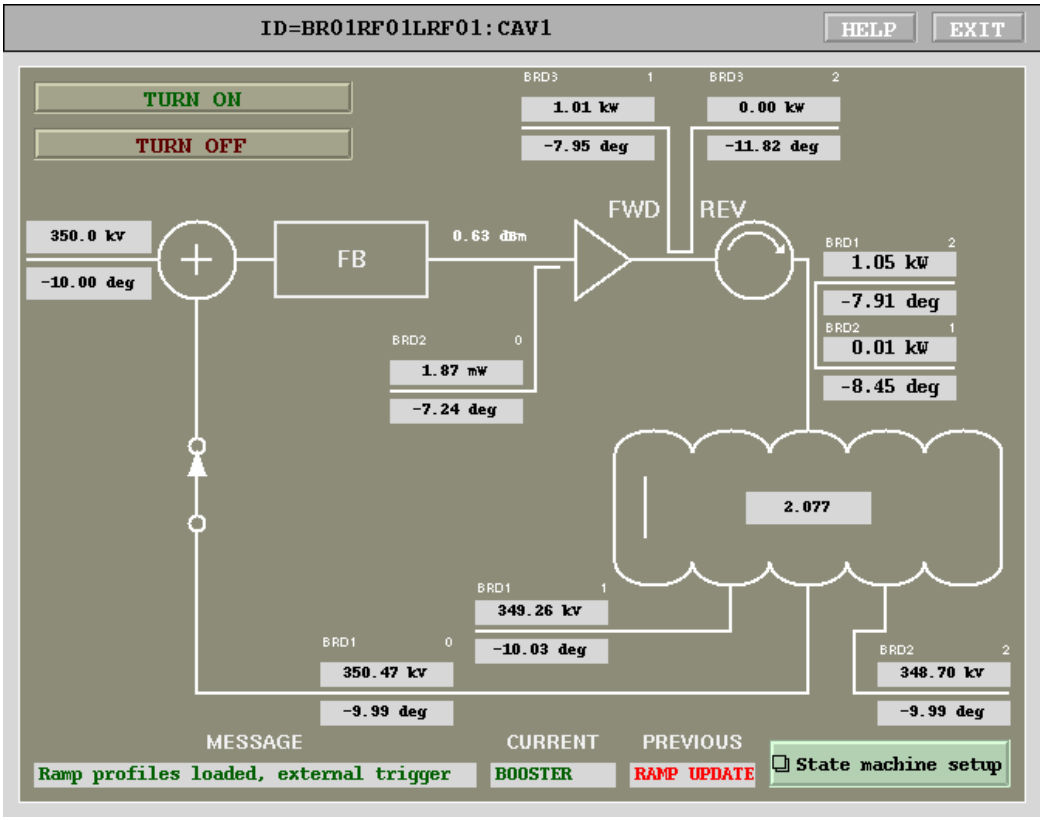

Figure 2: Top level diagram panel for the SLSA booster.

2.2.1 Configure the Built-in Network Analyzer

Open the network/spectrum analyzer panel (the button is labeled "NA/SA"). This panel is shown in Figure 3. Configure the network analyzer settings as follows:

1. Frequency span of 500 kHz;
2. `SETTLE` length of 4096;
3. `SAMPLES` integration length of 8192;
4. `MAX INTEGRATION LENGTH` of 1000000;
5. Set `INPUT` to "Cavity sum";

6. Set `AMPLITUDE` to −48 dB;

7. Set `INTEGRATION MODE` to "Adaptive";

8. Acquisition controls to "CONTINUOUS" and "ACQUIRE" (in that order).

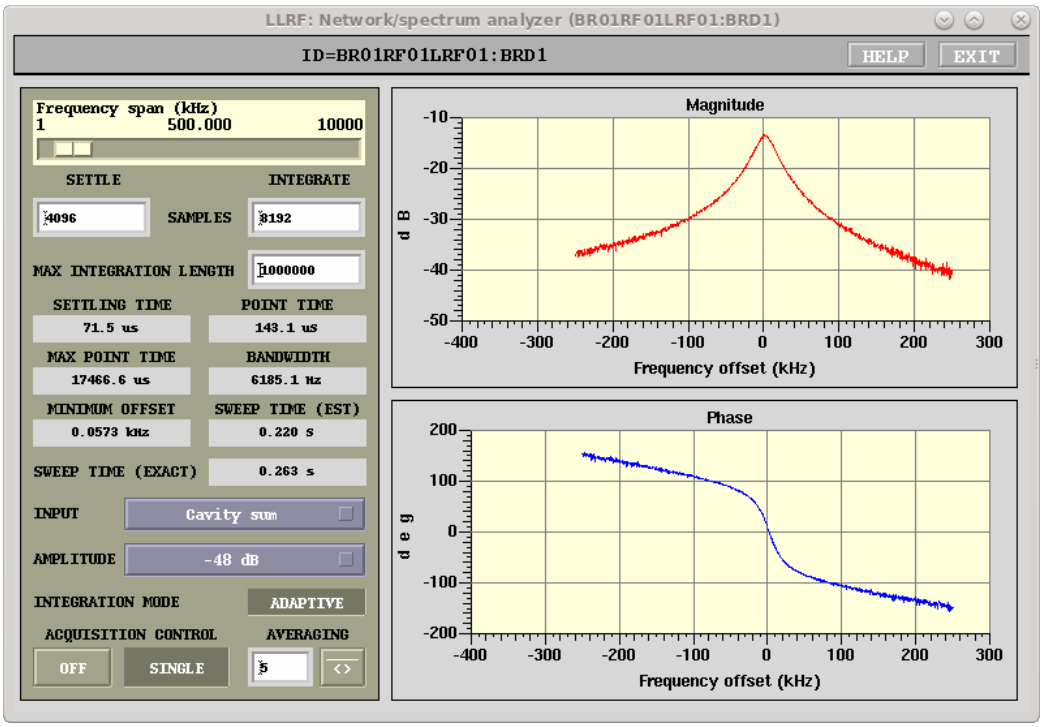

Figure 3: Network analyzer panel, cavity on resonance.

2.2.2 Load the Open-loop Setpoint Value

Next, open the setpoint ramp panel, accessible from the main control panel or the top level diagram. This panel is shown in Figure 4. Set a moderate open-loop setpoint — the goal is to get at least 50 W cavity forward power reading. Typically, a value of 500 kV works well. To set the value it is enough to enter in the `START` field and hit the "Load" button.

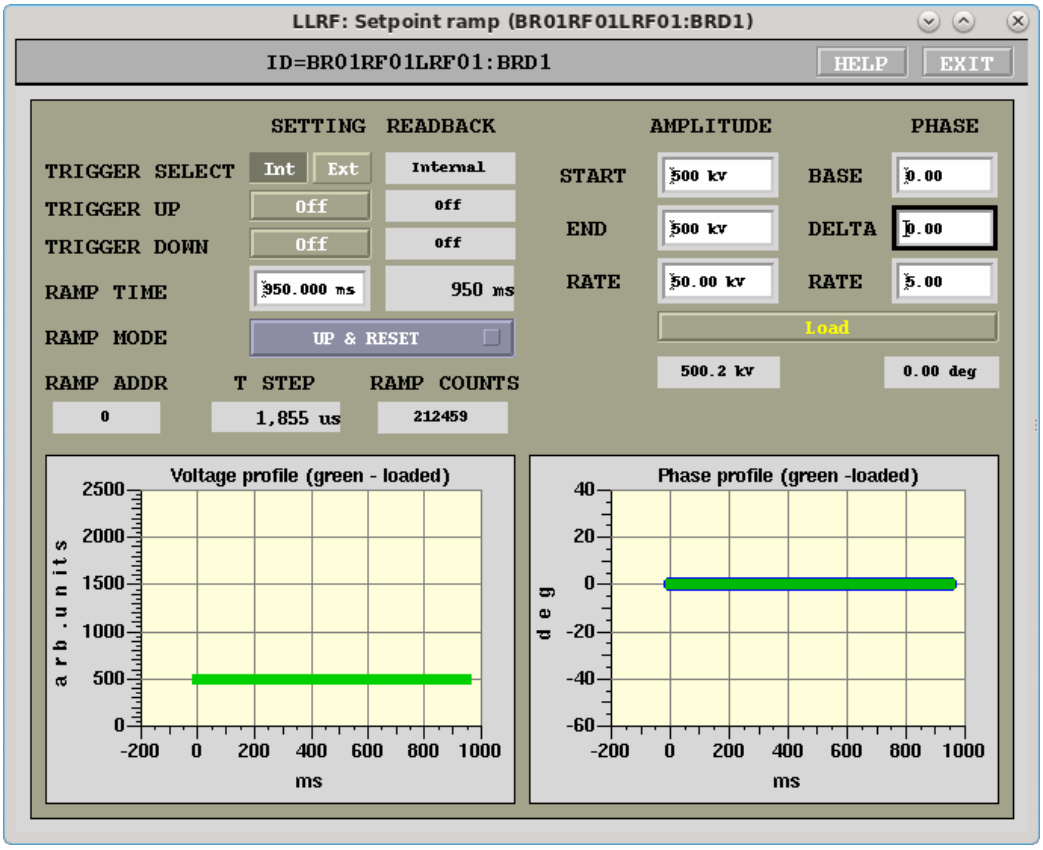

Figure 4: Setpoint ramp panel.

2.2.3 Tune the Cavity on Resonance

Now open the cavity tuner 1 and 2 panels (Figure 5), accessible from the tuner loop panel. While monitoring the cavity transfer function in the network analyzer, set the `VELOCITY COMMAND` field on both to a moderate value of 60°/s. Make sure the motors are enabled. As the tuners move, cavity resonance will either tune closer to the RF frequency or farther away from it. If the cavity resonance is moving in the wrong direction, change the velocity command sign to −60°/s. When the cavity response is centered on resonance set the `VELOCITY COMMAND` to 0 for both tuners.

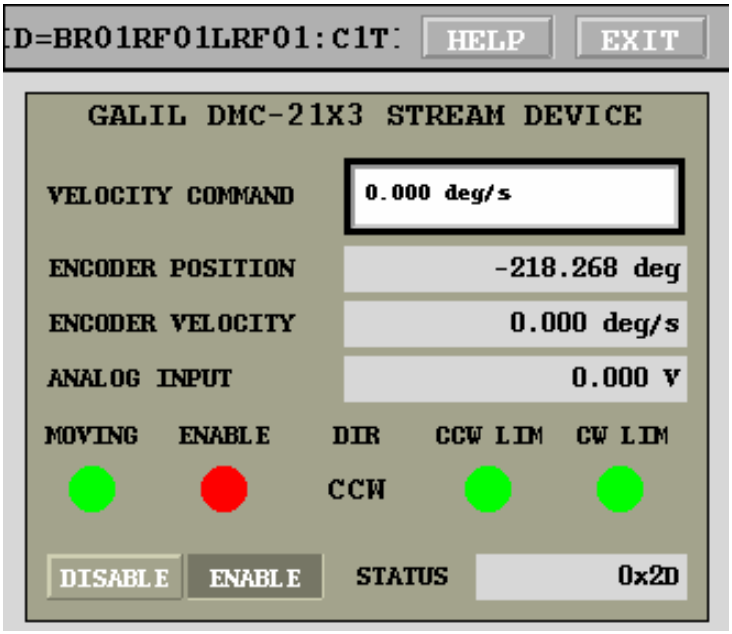

Figure 5: Tuner motor control panel.

2.3 Configure the Tuner Loop

With the cavity tuned on resonance it's time to configure the tuner loop. Make sure the setpoint phase is 0° and adjust the phase offsets for the cavity centre probe and the forward to produce a zero reading. From the top level diagram panel, click on each channel to bring up its configuration panel (Fig. 6). Adjust the `PHASE OFFSET` field so that the corrected phase reading at the bottom of the panel is zero.

Once both centre probe and forward signals have been adjusted, tuner loop error displayed inside the cavity outline on the top level diagram should be close to zero. Click on that error to open the tuner loop panel, shown in Figure 7.

Set integral, differential, and anti-windup gains to zero. Proportional gain should be set to a positive number. During commissioning a value of 40 was determined to be a good choice for fast and stable tuner loop response. The deadband is typically configured to 5° in operation. Temporarily set it to 0.1° to test the loop operation. Minimum forward power for loop operation should be set to 20 W. Load angle offset should be zero. Open tuner 1 and

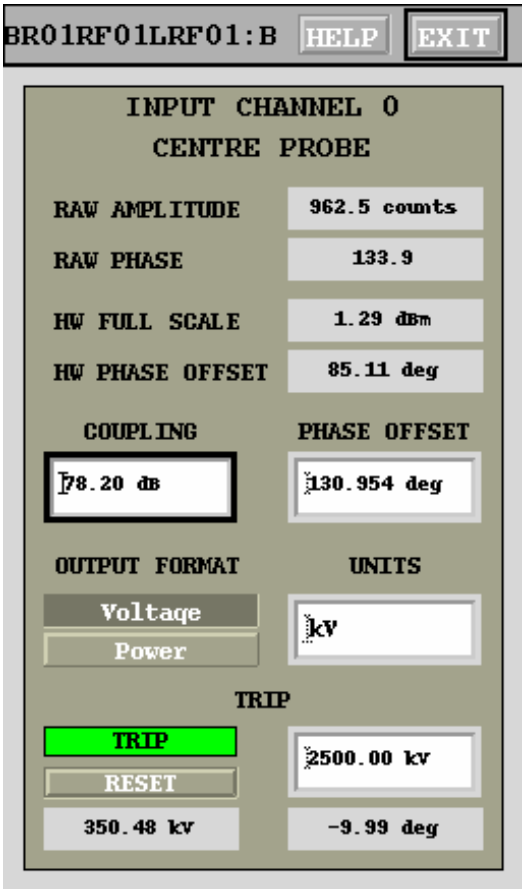

Figure 6: Channel configuration panel.

2 panels and make sure the motors are enabled. Now close the tuner loop. If the loop sign is correct, the absolute value of the tuner loop error should be reduced below the 0.1°. If the error increases with the tuner loop closed, invert the loop sign.

Once the loop configuration is done and the error is within the deadband, the deadband can be relaxed to 5°.

2.4 Parasitic Mode Phase Equalization

5-cell PETRA cavities typically have a parasitic mode around 2.7 MHz above the main accelerating mode (typically at 499.654 MHz). Wideband propor-

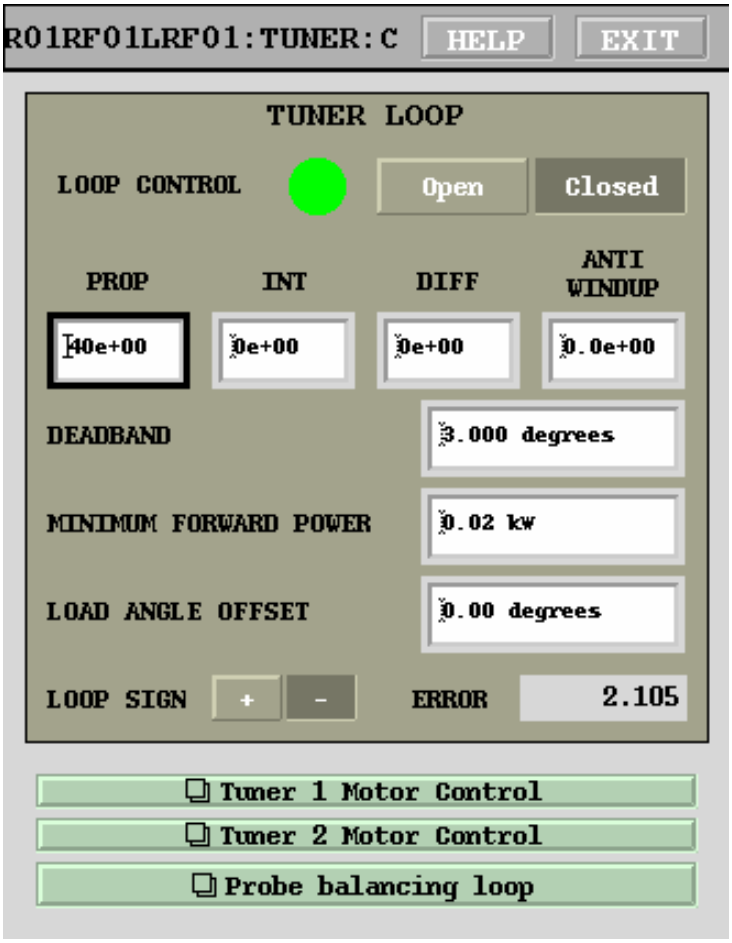

Figure 7: Tuner loop panel.

tional loop of the LLRF9 acts on both modes. If the phase shift of the main accelerating mode is significantly different from that of the parasitic mode, negative feedback for one can correspond to positive feedback for the other. In this step we adjust the `FB DELAY` setting on the feedback panel to equalize the loop phase shifts at the two resonances. Feedback panel is shown in Figure 8.

First, we will measure the loop transfer function over a wide span by setting the frequency span in the network analyzer panel to 6000 kHz. Such a measurement is shown in Figure 9. Now we need to determine the phase shift value at the two resonances. Use EDM zoom function to zoom in around

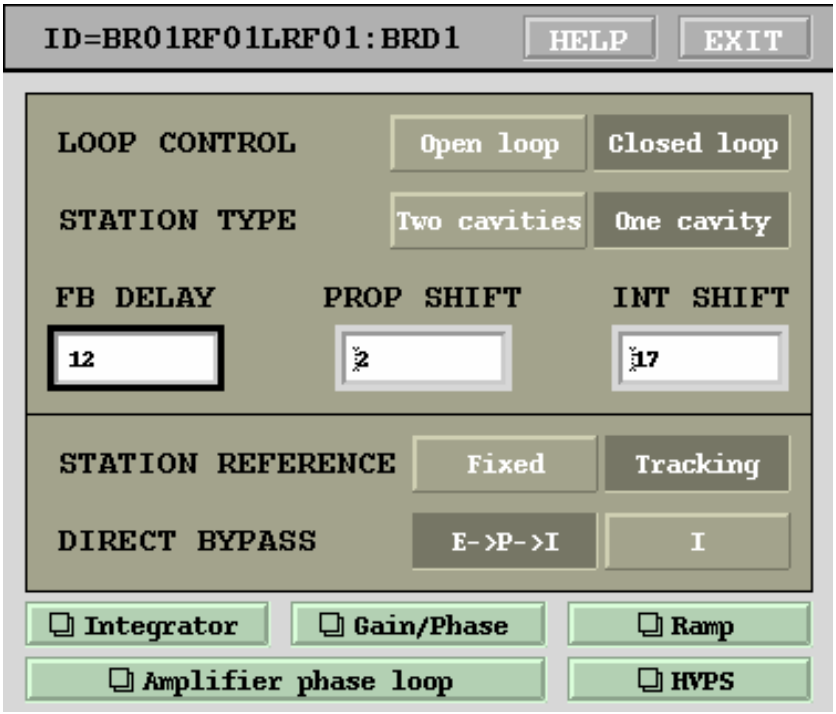

Figure 8: Feedback control panel.

each peak, first in magnitude to get the frequency offset, then in phase to read out the phase shift at that offset. Figure 10 shows the same data set as Fig. 9, but analyzed and plotted in Matlab. Such offline analysis is not mandatory for the setup procedure and is used here for clarity.

Transfer function in Fig. 10 has $148 - (-111) = 259^\circ$ of phase shift between the two resonant modes separated by 2721 kHz. In order to equalize the phase shifts we should increase the loop delay to add 101° of additional phase rotation over the measured separation[1]. The required delay change can be calculated as follows:

$$\Delta\tau = \frac{360 - \Delta\phi}{360\Delta f} \tag{1}$$

Where $\Delta\phi$ is the measured phase shift between the two modes (259°) and Δf is the frequency separation of the resonances (2721 kHz). Substituting

[1]Additional delay steepens the phase slope. With an extra 101° of phase shift overall difference becomes $259 + 101 = 360^\circ$.

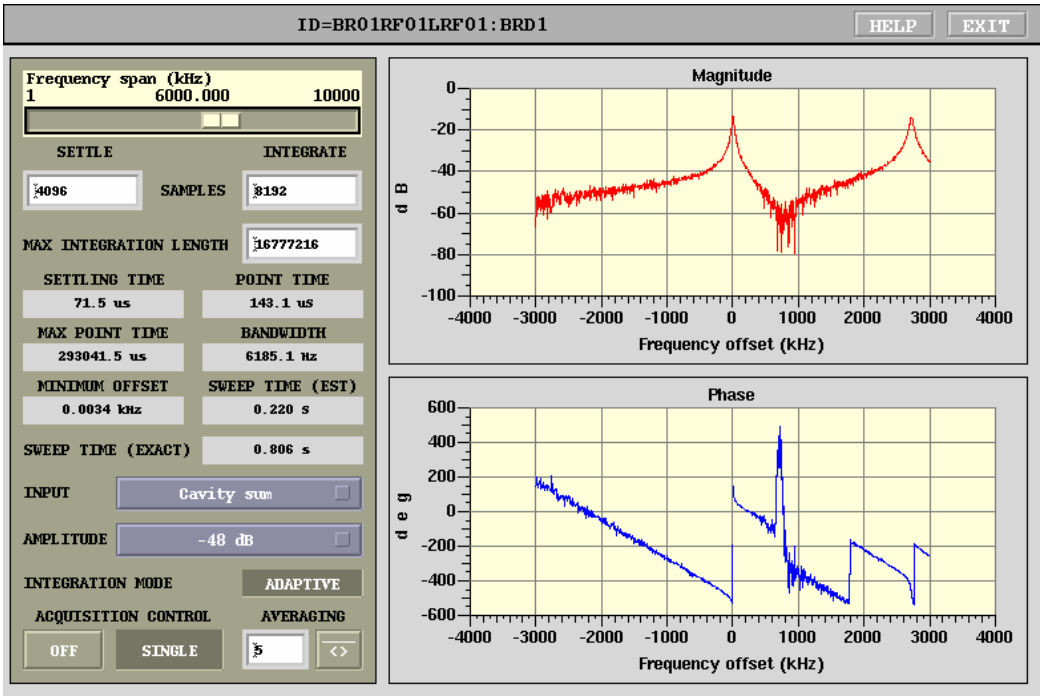

Figure 9: Loop transfer function measured over a wide frequency span.

the values we obtained previously into Equation 1 we calculate $\Delta\tau = 103$ ns.

Delay adjustment in the LLRF9 feedback panel is in ADC clock cycles[2]. Dividing the required delay change of 103 ns by the 8.73 ns clock cycle time we get 11.8 cycles. Rounding that to 12 cycles results in 104.8 ns and 102.7° of additional delay and phase rotation respectively. With such adjustment we expect the phase shift at two resonances to differ by only 1.7°. Eq. 1 can be modified to calculate the delay change directly in ADC clock cycles:

$$N = \frac{360 - \Delta\phi}{360\Delta f}\frac{11 f_{\mathrm{rf}}}{48} \tag{2}$$

Set the delay value, as calculated, on the feedback panel and re-measure the transfer function[3]. Verify that the phase shifts at two resonances are close to each other.

[2]ADC clock is 11/48 of the RF frequency or 114.504 MHz.

[3]Network analyzer can be left in continuous sweep mode during these adjustments.

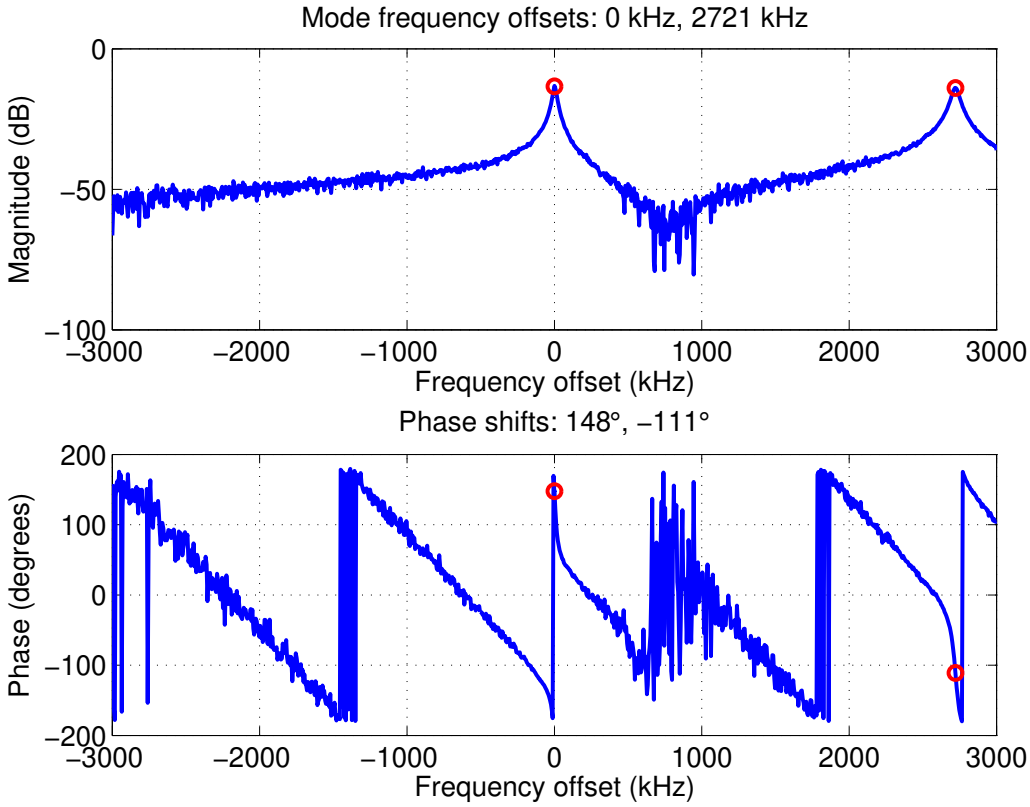

Figure 10: Loop transfer function — Matlab analysis plot.

2.5 Proportional Loop Setup

In this step we will adjust the gain and phase of the proportional — often referred to as direct — feedback loop. First, we will set up the network analyzer for the 500 kHz span and measure the accelerating mode response. Read out the phase shift on resonance and adjust the `DIRECT OPEN LOOP` phase shift setting to zero that phase shift. Measured phase shift value should be subtracted from the setting to achieve zero phase shift. Once the phase shift is properly corrected, you should see a transfer function very similar to that in Figure 3.

Now, check that the proportional bit shift[4] on the feedback panel (Fig. 8,

[4]Bit shift values act as a coarse gain setting, adding 6 dB of gain at each step. Gain for the bit shift value of m is given by 2^m.

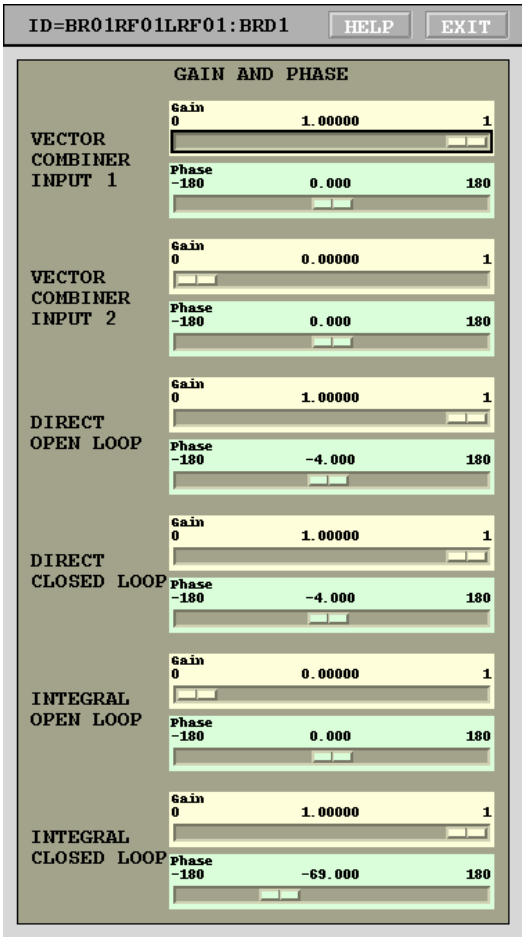

Figure 11: Field control loop gains and phases panel.

field `PROP SHIFT`) is 2. Verify also that `DIRECT CLOSED LOOP` gain setting is 1 and that the closed loop phase shift matches the open loop setting. Since we are only configuring the proportional loop here, `INTEGRAL CLOSED LOOP` gain setting should be at zero.

Adjust the station setpoint to zero, close the feedback loop, then go to the setpoint of 500 kV.

Change the network analyzer input setting to "Error" and measure the closed-loop transfer transfer function. You should observe a response similar to that shown in Fig. 12. Adjust proportional gains (`DIRECT CLOSED LOOP` on the gains and phases panel and `PROP SHIFT` on the feedback panel) to

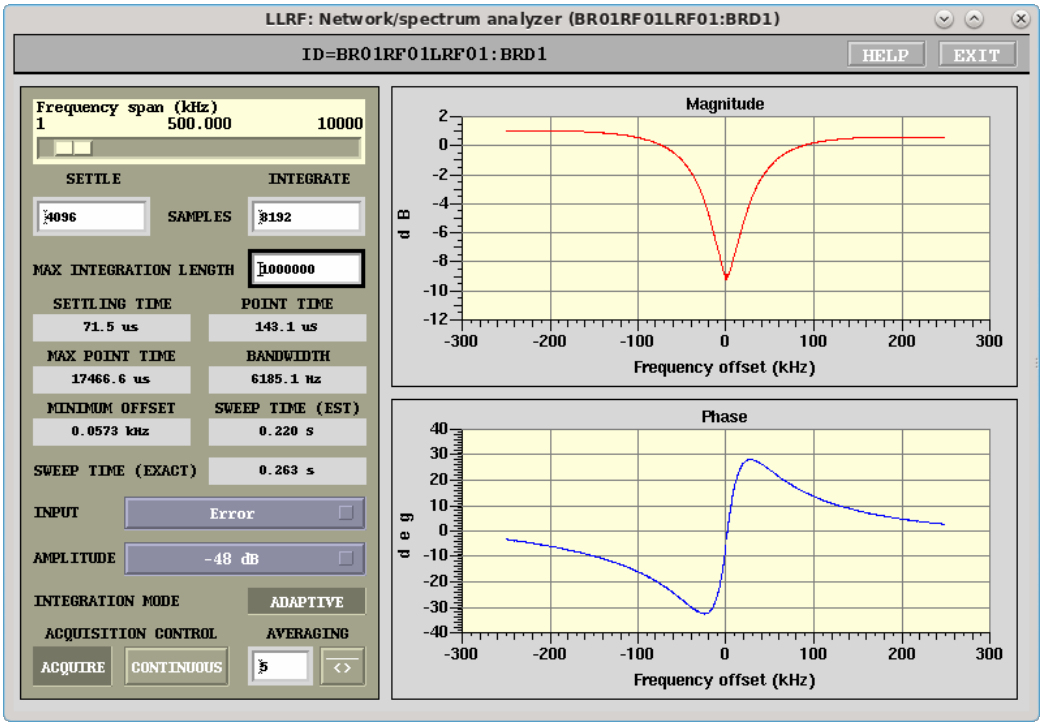

Figure 12: Closed-loop transfer function, proportional loop only.

achieve roughly 10 dB minimum on resonance and no more than 2 dB of peaking at 100–250 kHz offsets.

2.6 Integral Loop Setup

At this point we are ready to close the integral loop. The first step is to ensure that the closed-loop integrator coefficient in the integrator panel (Fig. 13, accessible from the feedback panel) is set to -524288.

Integral loop input signal is taken after the proportional loop's gain and phase block. As a result, phasing of the integral loop is fixed at $-69°$. The gain may need to be adjusted, but commissioning experience suggests that leaving `INTEGRAL CLOSED LOOP` setting at 1 and `INT SHIFT` at 17 works well for the SLSA booster operation. Sample closed-loop response with both proportional and integral loops is shown in Figure 14.

At this point, select "SINGLE" acquisition mode to stop the network analyzer sweeping.

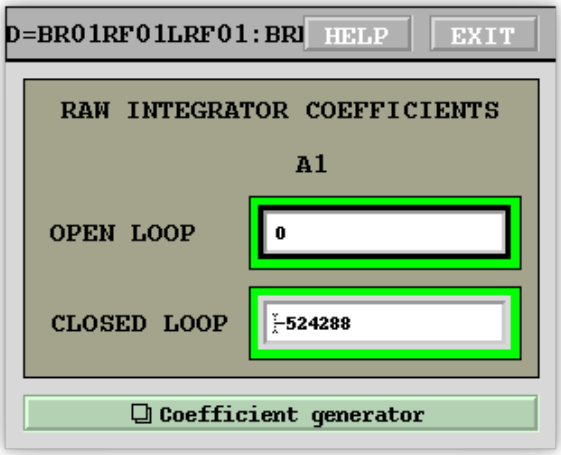

Figure 13: Integrator coefficient configuration panel.

2.7 Adjustment of Phase Readouts

Next, we will adjust the phase readings of the RF channels to be in agreement with the setpoint. Temporarily set the tuner loop deadband to 0.1 degrees.

Once the tuner loop error is within the deadband, adjust the phase offsets for the following channels:

1. Cell 4 probe (VC14)
2. Cell 2 probe (VC12)
3. Amplifier drive (DRV)
4. Circulator input forward (CIRCFWD)

Turn off the tuner loop before adjusting the offsets for the following two channels:

1. Centre probe (VC1)
2. Cavity forward (FWD1)

Once the adjustment is completed, turn on the tuner loop and return the deadband setting to the normal value.

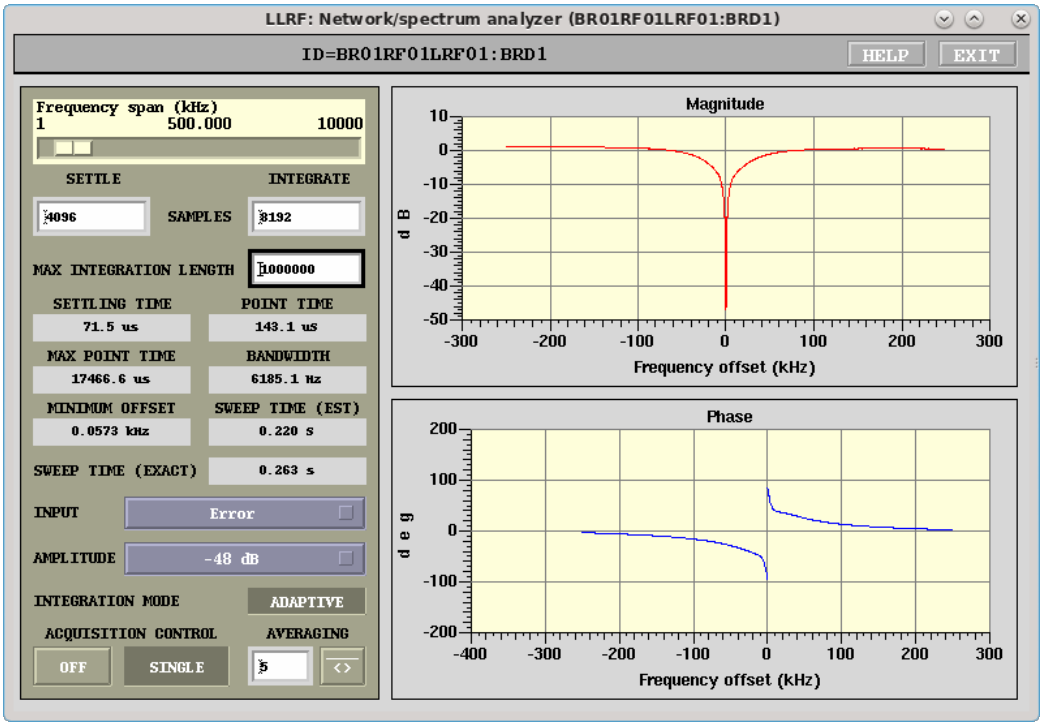

Figure 14: Closed-loop transfer function, proportional and integral loops.

This step can also be performed from Matlab by issuing the following commands:

```
>> null_phases('BR01RF01LRF01', 'BRD1');
>> null_phases('BR01RF01LRF01', 'BRD2');
>> null_phases('BR01RF01LRF01', 'BRD3');
```

In this case only the tuner deadband needs to be adjusted, there is no need to open the tuner loop.

2.8 Amplifier Phase Loop

This EPICS control loop compensates for the phase shifts in low-, medium-, and high-power output chains by first computing the phase shift from the LLRF9 internal drive monitor to the cavity forward signal. That value is compared to an appropriate setpoint and the direct closed loop phase is

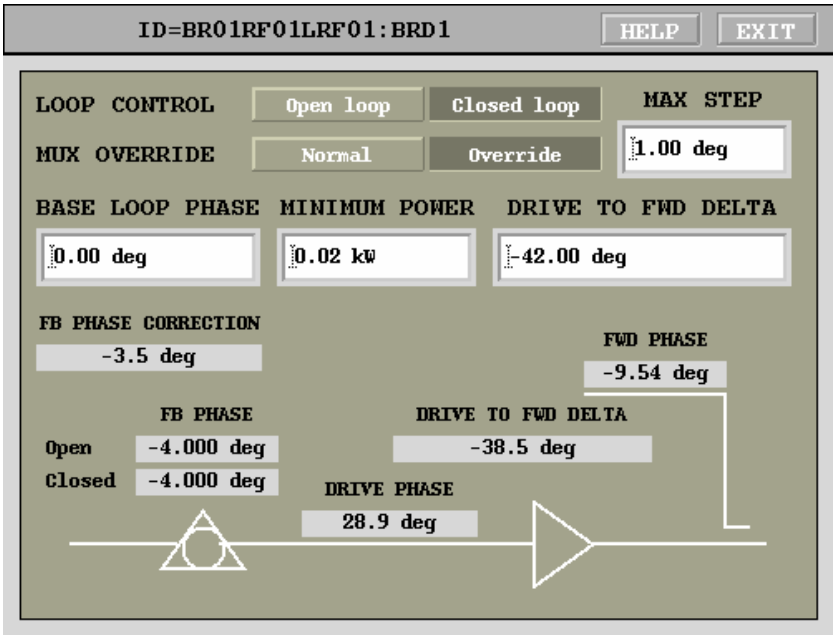

Figure 15: Amplifier phase loop panel.

adjusted to maintain a constant phase shift from the loop error signal to the cavity forward signal. The control panel for the amplifier loop is shown in Fig. 15.

The first step is to turn on the `MUX OVERRIDE` control — this guarantees that the diagnostic DDC channel is monitoring output drive. Set the maximum step to 1° and the minimum forward power to 20 W — these work well for the SLSA booster.

Next, read out the measured drive to forward delta value and set it as the `DRIVE TO FWD DELTA` setpoint. Finally, set the `BASE LOOP PHASE` to the proportional closed loop phase, determined in the step 2.5. Toggle the `LOOP CONTROL` to "Closed".

2.9 Probe Balancing Loop

5-cell PETRA cavities have two independent tuner plungers. Common mode[5] motion of these plungers adjusts the central frequency of the fundamental mode. Differential motion affects the field distribution between the individual

[5]In the same direction.

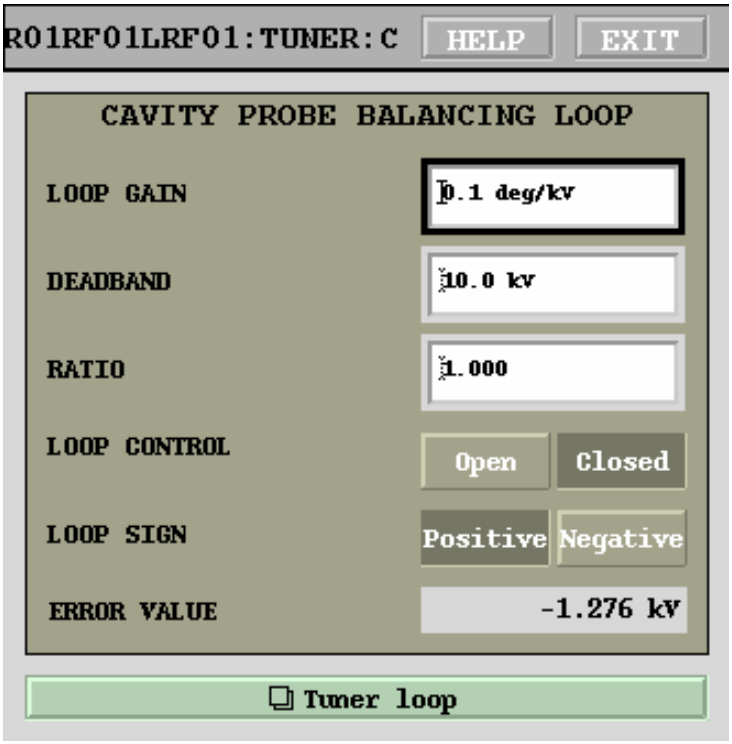

Figure 16: Probe balancing loop panel.

cells. LLRF9 includes a probe balancing (also known as field flatness) loop. There are three field probes in the cavity — in cells 2, 3, and 4. These are monitored by the LLRF9 with the labels `CELL 2 PROBE`, `CENTRE PROBE`, and `CELL 4 PROBE` respectively. Probe balancing loop compares the voltages in cells 3 and 4 and adjusts the tuners differentially in order to achieve the desired ratio.

Probe balancing loop control panel is shown in Figure 16. Start from setting the `LOOP GAIN` to 1 deg/s/kV. Next, set the `DEADBAND` to 1 kV. `RATIO` setting defines the goal that the loop tries to maintain. Calibration factors have been adjusted during commissioning to achieve a balanced temperature distribution among the individual cells. Such a balanced distribution is achieved with the `RATIO` set to 1. Now, close the loop. If the loop sign is set correctly, the absolute error should decrease and the probe voltages should come into balance. Invert the loop sign if the error increases upon loop closure.

To finalize the loop setup raise the DEADBAND to 10 kV.

2.10 State Machine Setup

Figure 17: State machine control panel.

In this final step of the setup procedure we will configure the state machine. Station TURN ON and TURN OFF controls operate through a sequencer state machine which handles all the necessary tasks in the turn on/turn off process. During the turn on process the state machine sequence is as follows:

1. Synchronize the clocks in LLRF9;
2. Reset the interlocks;

3. Load the open loop tuning setpoint;

4. Wait for the tuning loop to tune the cavities on resonance (within the specified tuning error);

5. Set the field amplitude to zero and close the field control loop;

6. Set the operating voltage and phase, wait for the station to ramp up;

7. Load the configured amplitude and phase profiles, switch to the external trigger.

Appropriate settings for the SLSA booster are documented in Figure 17. Make sure that the booster mode is enabled, vector sum servo and dump window — disabled. Set the `RAMP TIME` in the setpoint ramp window (Fig. 4) to 950 ms and the `RAMP MODE` to "UP AND RESET".

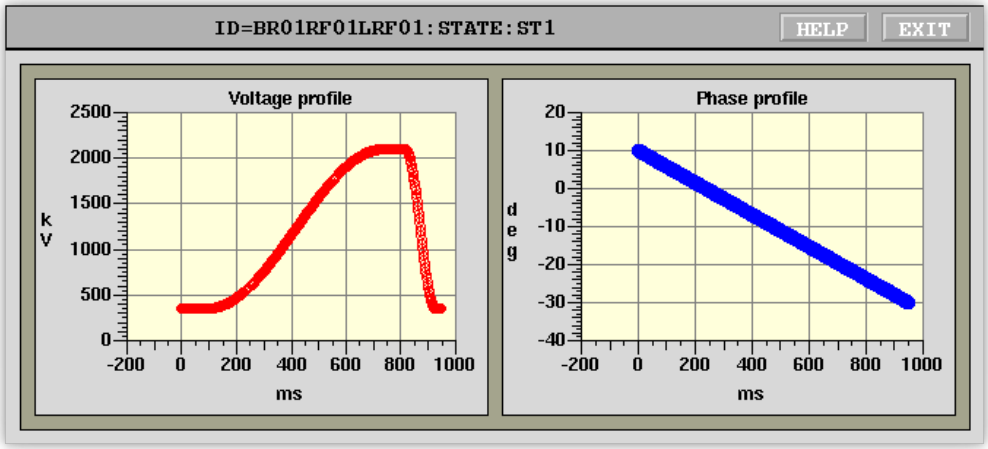

Figure 18: Booster profiles panel.

Booster amplitude and phase ramps can be examined in the booster profiles window, illustrated in Figure 18. These profiles are generated in Matlab and then loaded into the appropriate EPICS PVs. To update the profiles one can use the following Matlab function:

```
>> asp_ramp(v_inj, v_top, ph_inj, ph_top);
```

Here injection and top voltages and phases can be adjusted as needed.