Commissioning Plan

PXIE RFQ System – Amplifiers

Prepared by: J. Steimel	Fermilab	steimel@fnal.gov
Approved by: R. Pasquinelli		
Approved by:		
Approved by:		
Approved by:		
Approved by:	Fermilab	

Revision History

Revision	Date	Section No.	Revision Description
0	5/15/14	All	Initial Release.

TABLE OF CONTENTS

1. Introduction:

The purpose of this document is to define a plan for commissioning the RFQ power amplifiers and RF power distribution system. The plan will verify that the amplifiers and circulators meet design specifications and will be reliable components for RFQ operation. The plan will also verify protection interlocks work properly and that remote controls and monitors work properly as well.

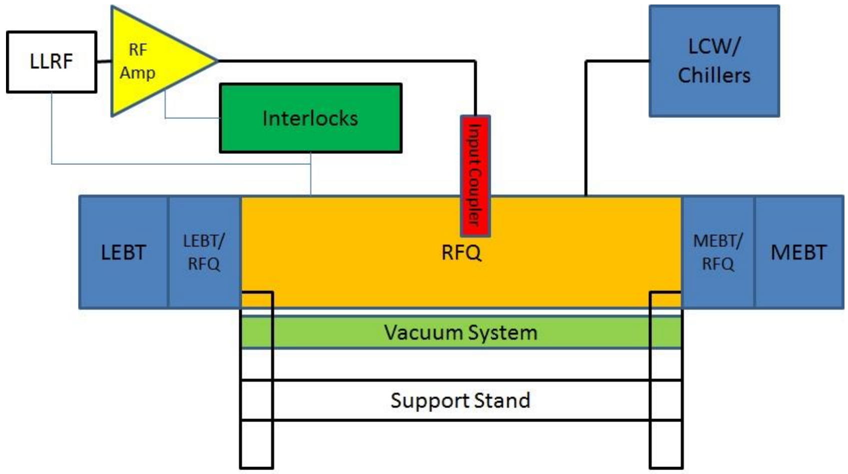

Figure 1: RFQ System block diagram.

2. Description:

The RFQ design incorporates two RF input couplers to provide the total power required for beam acceleration, and each coupler has a dedicated RF amplifier power source. The purpose of the amplifier system is to amplify and transport RF from the LLRF system to the RFQ input couplers. The transmission line is specified to handle the full amplifier power, at full reflection, without external cooling. The only components in the distribution that require interlock protection, besides the amplifier itself, are the circulator and the circulator load.

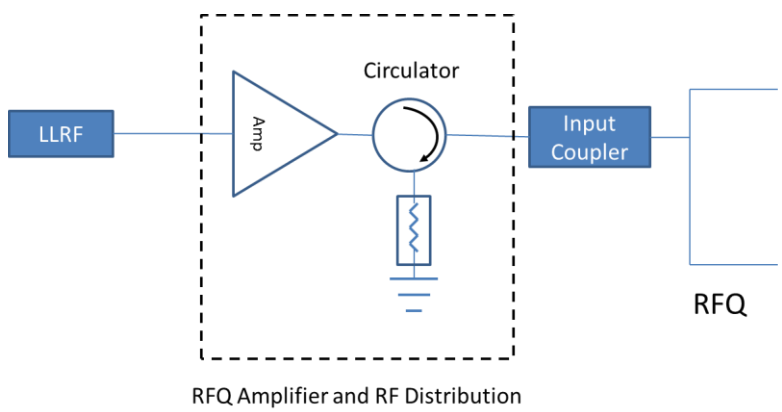

Figure 2: Schematic of amplifier and RF distribution within RFQ system.

3. Summary of Amplifier and RF Distribution Specifications

The following table summarizes the specifications for the RFQ amplifier and RF distribution. These specifications will be verified in the following procedures.

Table 1. RFQ Amplifiers, Circulators, and Loads Specifications [1][2]

Amplifier			Test Section
	Center Frequency	162.5 MHz	4-e-*ii*
	Minimum Bandwidth	+/- 1 MHz at -1dB compression	4-e-*ii*
	Minimum Saturated Output Power	75 kW	4-f-*i*
	Minimum 1 dB Compression Output Power	60 kW	4-e-*i*
	Minimum Gain	69 dB for full saturated output power	4-e-*i*
	Maximum VSWR - Input	1.5:1	
	Maximum Input Drive Power	10 dBm for full saturated output power	4-f-*i*
	Maximum Output Harmonics	-30 dBc	4-f-*ii*
	Maximum Spurious Signals	-50 dBc	4-f-*ii*
	Maximum Amplitude to Phase Conversion	10° saturation to half power	4-e-*i*
	Maximum Noise Figure	15 dB	4-f-*iii*
Circulator			
	Center Frequency	162.5 MHz	5-e-*i*
	Minimum Bandwidth	1 MHz	5-e-*i*
	Maximum Forward Power	75 kW	5-f
	Maximum Insertion Loss at Center Frequency	0.3 dB	5-f
	Maximum VSWR (with matched load on reflected port)	1.2:1	5-f
	Minimum Isolation	20 dB	5-f
Load			
	Maximum Drive Power	75 kW	
	Maximum VSWR	1.1:1	

4. Amplifier into Load Only Test:

a. Test Setup:

The primary purpose of this test is to measure the amplifier specifications without interference from downstream components. The amplifier is driven by a network analyzer or signal generator, depending on the particular test. The output goes through a high power directional coupler to a fixed load. The load is specified to handle the full power of the amplifier with a reflection coefficient well below the maximum output VSWR limit of the amplifier. Figure 3 shows a block diagram of the test configuration. Forward powers from the signal generator and amplifier output are continuously monitored through the RF detectors. These detectors also provide RF pass-through for monitoring RF levels directly with a scope or spectrum analyzer.

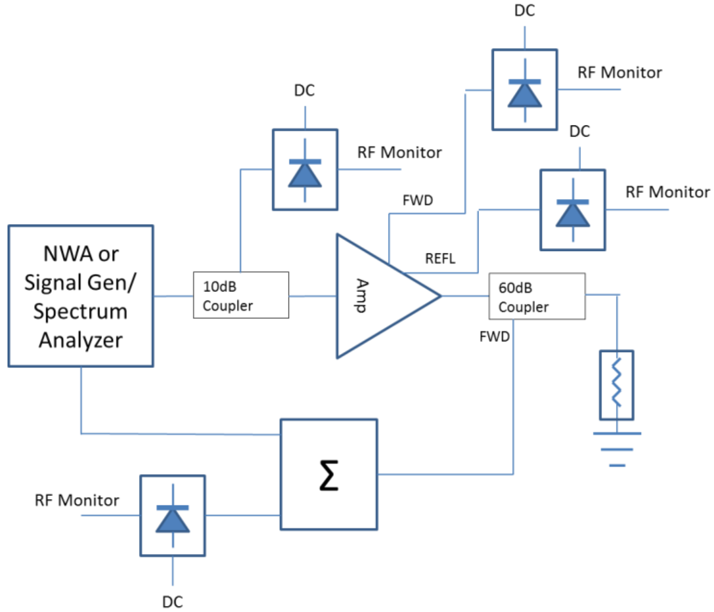

Figure 3: RF block diagram of amplifier test setup.

b. Utilities:

i. Wall Power

Each power amplifier requires a 480V, 3-phase line power input capable of 150kW minimum power. Control power for the amplifier is derived from the 480V line power. Each amplifier has a dedicated line power breaker located close to the amplifier (DS1-DHP-NL-15D1-3 and DS2-DHP-NL-15D1-3). This makes them qualified for standard LOTO procedures when performing maintenance on the amplifiers or RF distribution.

ii. Water Cooling

Both the amplifier and load require water flow for heat removal. Each 75kW amplifier unit has two, independent cooling circuits. The amplifier requires a minimum of 20gpm of cooling flow, while the load requires a minimum of 10gpm. These are the only components that require water cooling for this test. The CMTF water system has about 90gpm capability with 120psi of head pressure and should be able to handle the amplifier tests.

c. Interlocks:

i. Instruments and Logic

Amplifier temperature, water flow, water temperature, forward power, and reflected power are monitored internally to the amplifier system. The amplifier will trip off if any of these values are out of range. The amplifier is also equipped with external interlock inputs. The external signals that will trip the amplifier for this test are the load water flow switch, and the RF leak detector.

Table 2. Amplifier Interlock Parameters[3]

Parameter	Instrument	Trip Point	Signal Path
Drive Power	Amplifier Detectors	13 dBm max	Internal Amplifier Logic
Forward	Amplifier Detectors	75+ kW max	Internal Amplifier Logic

Power			
Reflected Power	Amplifier Detectors	~15 kW max	Internal Amplifier Logic
Inlet Water Temperature	Amplifier Detectors	10-40° C	Internal Amplifier Logic
Amp Water Flow Rate	Amplifier Detectors	20 gpm min	Internal Amplifier Logic
Load Water Flow Rate	External Flow Meter	8 gpm min	External logic to amplifier external interlock input
RF Leakage	Tuned Antenna with RF detector	0.5 mW/cm^2 max	External logic to amplifier external interlock input

ii. Testing

There will be a series of tests to verify the power amplifier interlocks. The first set of tests requires amplifier wall power but no drive. With the amplifier active but driveless, water flow will be interrupted to the amplifier and then the load to verify a trip. Amplifier temperature and water temperature interlocks will not be tested.

The input of the RF antenna module will be driven with a low level RF signal to verify that the RF leak detector system trips the amplifier.

Once these tests are complete, RF power from the amplifier can be sourced to the external load. The power level of the amplifier will be gradually increased to full, saturated power (75kW). Then, the drive power will be increased slowly until the forward power trip interlock is activated. The final interlock test will require that a RF short is placed on the output of the amplifier. The drive power will be slowly increased until the reflected power interlock is activated (~15kW).

d. Calibration:

Calibration of the 60dB coaxial power coupler was completed earlier. For the amplifier power measurements, we assume that the power coupler, coupling factor is a known, fixed quantity.

There will be three permanent RF-DC power detectors associated with each amplifier. These detectors will measure forward drive power, forward output power, and reflected output power. There will also be a temporary power detector measuring the forward output power from the 6” coaxial coupler. This coupler will not remain close to the amplifier during operations.

Each power detector’s reading will be compared to measurements from a calibrated power meter, capable of accurate power readings at 162.5 MHz. The forward drive power can be calibrated independent of the power amplifier. Power from the signal generator can be measured by the power meter at the point just before it enters the amplifier. The readings from the power meter can be correlated to the voltage levels measured by the detector.

Forward output power detectors will be calibrated using the 60dB coaxial coupler. With the amplifier driving power into the load, a power meter measures the power in the forward power port of the coupler. This is compared to the voltage measured by the RF detector connected to the forward power monitor of the amplifier. Reflected power will be measured by placing a short on the output of the coaxial coupler. A power meter will measure the power from the reflected port of the coupler and compared to the voltage measured by the RF detector connected to the reflected power monitor of the amplifier. This will be verified up to 10kW or the power amplifier trip, whichever comes first.

e. Network Analyzer Measurements

The following measurements are performed with a network analyzer, calibrated through the 10dB coupler up to the amplifier input. Amplifier net gain and net phase are calculated using the 60dB coupler measurements.

i. 1dB Compression Power Output

The network analyzer is configured to measure the gain of the amplifier through the 60dB coupler. The gain of the amplifier will be measured at 162.5 MHz with the NWA setup for power sweep mode. The output power will be measured up to the maximum specified saturation power (75kW). The point where the gain of the amplifier drops 1dB due to output saturation will be recorded. The gain of the amplifier at the maximum specified saturation power will also be recorded. The change in relative phase will also be recorded over the power sweep.

ii. Center Frequency and Bandwidth

The NWA is set up for frequency sweep mode and low power (~15kW) out of the amplifier. The center frequency is set to 162.5 MHz while the measurement bandwidth is increased until the ½ power points are revealed. The NWA can be recalibrated with the amplifier full bandwidth, and the measurement can be repeated. Precise bandwidth measurements may involve deconvolving the 60dB coupler response. The bandwidth measurement will be repeated at the 1dB compression power and the saturated power.

f. Signal Generator Measurements

The following measurements involve a low noise, high purity 162.5 MHz RF signal generator. Power levels are adjustable and measured with calibrated RF detectors. These measurements will also involve a spectrum analyzer connected to the forward power output of the 60dB coupler.

i. Saturated Output Power

With the signal generator frequency set to 162.5 MHz, the power level will be set to get low power out of the amplifier (~5kW). The power level will be slowly increased until saturated power is achieved (75 kW). The input power level from the signal generator that provides saturated power will be recorded. Power can be increased slowly (0.1dB steps) until the forward power interlock trips. This power level will be recorded.

ii. Output Harmonics and Spurious Signals

This measurement uses the same setup for measuring saturated output power, except it includes a spectrum analyzer on the forward power output of the 60dB coupler. The spectral purity of the signal generator will be verified before it drives the amplifier to its maximum saturated power. The spectrum analyzer will measure signal levels of the next 3 harmonics relative to 162.5 MHz (up to 650 MHz). Signal levels of other non-harmonic frequencies that appear above the noise floor will also be noted. These levels will need to be deconvolved with the 60dB coupler response.

g. Noise Figure

This measurement is performed with the amplifier powered on, but no RF drive. Using a calibrated excess noise source, the noise power at the amplifier output with the noise source turned on is measured by the spectrum analyzer and compared to the noise power with the noise source turned off.

5. Amplifier into Circulator Test

a. Test Setup:

The primary purpose of this test is to measure the circulator specifications without interference from downstream components. The amplifier is driven by a network analyzer or signal generator, depending on the particular test. The amplifier drives the circulator directly, with a temporary matched load on the forward output and a permanent matched load on the reflected output. Each load is specified to handle the full power of the amplifier with a reflection coefficient well below the maximum output VSWR limit of the amplifier. Figure 4 shows a block diagram of the test configuration. Forward and reflected power from the amplifier output is continuously monitored through the RF detectors. Forward power through each of the circulator outputs is also continuously monitored.

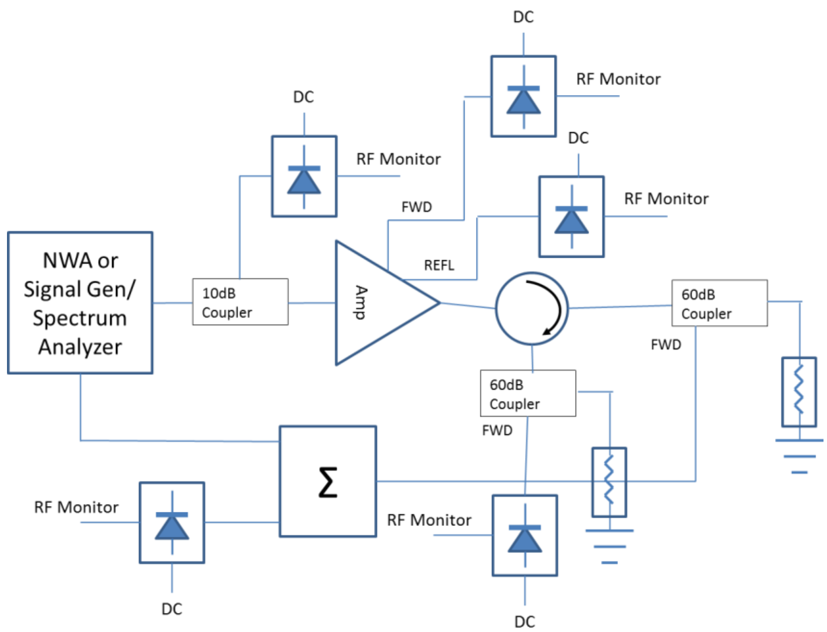

Figure 4: RF block diagram of circulator test setup

b. Utilities:

This test setup uses the same utilities required to operate the amplifier plus extra utilities required to operate the circulator. This includes an extra 8gpm of water for the circulator and an extra 10gpm for the permanent load on the reflected port.

c. Interlocks:

It is assumed that all critical amplifier interlocks were tested during amplifier commissioning and the amplifiers are considered operational.

i. Instruments and Logic

All interlocks for this test will trip the power amplifier off, either through the amplifier's internal interlocks or through the amplifier's external interlock input. Forward and reflected power interlocks will be handled directly by the amplifier. The interlocks added to the system are the load water flow switches and the circulator water flow meter with temperature.

ii. Testing

With the amplifier on but no drive power, water flow will be interrupted to the circulator and loads to verify that the amplifier trips off.

Table 3. Circulator Interlock Parameters

Parameter	Instrument	Trip Point	Signal Path
Input Forward Power	Amplifier Detectors	75 kW max	Internal Amplifier Logic
Input Reflected Power	Amplifier Detectors	~15 kW max	Internal Amplifier Logic
Inlet Water Temperature	Flow Meter with Temperature	25-30° C	External logic to amplifier external interlock input
Water Flow Rate	Flow Meter with Temperature	6 gpm min	External logic to amplifier external interlock input

d. Calibration

These measurements will continue to use the calibrated forward and reflected power signals from the amplifier and the calibrated 60dB coaxial couplers. The response of the RF detectors will need to be calibrated with power readings from the 60dB couplers during high power testing.

e. Network Analyzer Measurements

The following measurements are performed with a network analyzer driving the input of the amplifier and measuring the output power of the circulator through the 60dB coupler. Since all of these measurements involve relative gain and phase, network analyzer calibration is not necessary.

i. Center Frequency and Bandwidth

The NWA is set up for frequency sweep mode and low power (~15kW) out of the amplifier. The center frequency is measured and the measurement bandwidth about the center frequency is increased until the ½ power points are revealed. Precise bandwidth measurements may involve deconvolving the 60dB coupler response.

ii. Center Frequency vs. Water Temperature

The center frequency is measured as a function of water temperature over a 5°C range at low power (~15kW).

iii. Forward Power, Insertion Loss, VSWR, and Isolation

Due to the potential for drifting center frequency vs. water temperature, the following measurements will be performed with a network analyzer set to the center frequency. Power levels are adjustable and measured with calibrated RF detectors. With the network analyzer frequency set to the measured center frequency (~162.5 MHz), the power level will be set to get low power out of the amplifier (~5kW). The power level will be slowly increased (5kW steps) until maximum specified input power is achieved (75 kW). At each step, the forward power from the forward and reflected ports of the circulator will be recorded. Also, the power reflected back to the amplifier will be recorded. This will verify the maximum forward power, maximum insertion loss, maximum VSWR, and minimum isolation specifications at the center frequency.

6. References:

[1] Specifications for RFQ Drive Amplifier for Project X/PXIE at Fermilab, Ralph J. Pasquinelli, March 9, 2012.

[2] Instruction Manual: Liquid-Cooled Coaxial Load Resistor Model 57200B, Altronic Research Inc., Yellville, AR, October 25, 2006.

[3] Maximum Ratings PXIE RFQ System – Amplifiers, J. Steimel, Project X Doc #1234, February 19, 2014.