Statement of Work | APS Upgrade

APS-U LLRF Analog Front Ends

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Revision	Date	Reason
0	5/20/2020	Original

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1 Introduction

The APS-U requires low-level radio frequency (LLRF) analog front ends (AFE) in three areas: (1) the Injector LLRF system for Booster, (2) the Injector Timing/Synchronization system for the RF Source, and (3) the Bunch Lengthening LLRF system. The AFEs are used to convert to/from the RF frequency from/to the intermediate frequency (IF) used by the digital LLRF systems with the use of a local oscillator (LO).

Fermilab has existing AFE products that can be used by the APS-U. These products include both an up-converter chassis [1] and a down-converter chassis [2]. The up-converter chassis is used to up-convert an IF signal coming from a Digital-to-Analog Converter (DAC) to the RF signal which drives an RF system. The down-converter chassis performs the opposite operation, it down-converts the RF signal to an IF signal. The IF signal output from the up-converter AFE can then be sampled with an Analog-to-Digital Converter (ADC) in the digital LLRF receiver.

Fermilab has already developed, produced, and used both of these designs for their Proton Improvement Plan II (PIP-II) project as well as a similar version of the designs for the Linac Coherent Light Source II (LCLS-II) LLRF systems. Both designs support an IF of ~ 20MHz which is compatible with the APS-U LLRF frequency plan. The designs are also configurable via component selection to match APS-U RF and LO frequencies.

Through this statement of work, the APS-U will contract the purchase of the PIP-II style AFEs to Fermilab for their use in the APS-U LLRF systems.

Fermilab will be responsible for fabrication, testing, and delivery of the AFEs according to this statement of work.

APS-U will be responsible for contract management, receipt, and final acceptance testing of the AFEs according to this statement of work.

2 Scope of Work

- **Production Quantities**

Fermilab will produce the type and quantities of up converters as listed in Table 2.1 and down-converters in Table 2.2 according to the requirements given in Section 3.

Table 2.1: Up-Converter types and quantity

Type	Qty
Booster LLRF 352MHz up-converter (see Sect. 3.1)	2
Timing/Synchronization 352MHz up-converter (see Sect. 3.3)	2
Bunch Lengthening system 1408MHz up-converter (see Sect. 3.4)	2

Table 2.2: Down-Converter types and quantity

Type	Qty
Booster LLRF 352MHz down-converter (see Sect. 3.2)	5
Bunch Lengthening system 1408MHz down-converter (see Sect. 3.5)	2

- **Addition of Heater Resistors to Up-Converters**

The present Fermilab up-converters do not have heater resistors and a rear panel connection to these resistors like the down-converters do. Fermilab shall modify the thermal plate design for the up-converter and the rear panel to accommodate heater resistors for the up-converters.

- **Parts Selection for Frequency Adjustment**

Fermilab shall be responsible for ordering and acquiring all parts to fabricate the units, except as noted in the below paragraph. Fermilab shall identify any replacement components that are required to tune the PIP-II designs to accommodate the frequencies requirements given in Sections 3 through 5. Fermilab is also responsible for coordinating acquisition and assembly of the printed circuit boards.

Upon Fermilab and APS-U together identifying the output K&L Microwave bandpass filters required for use in the up-converters, APS-U shall be responsible for ordering and acquiring the K&L Microwave bandpass filters for the up-converters. These are the only parts which APS-U will be responsible for acquiring.

- **Fabrication and Testing**

Fermilab shall be responsible for fabricating and testing all units. Measurement reports from both the board check and the chassis check of each unit shall be supplied.

3 AFE Requirements

3.1 Booster 352 MHz Up-Converter

The up-converter fabricated for Booster shall have the specifications listed in Table 3.1.1.

Table 3.1.1: Booster Up-Converter Specifications

Parameter	Value
IF signal input frequency (nom.)	19.6 MHz
RF output frequency (nom.)	351.93 MHz
LO input frequency (nom.)	332.38 MHz
LO input signal level (nom.)	0 dBm
Number of RF outputs	4
Full Scale IF I/Q input signal level (nom.)	-2 dBm each
Full scale RF Output signal level (min.)	+ 10 dBm (+/- 1dB)
Output Linearity	+/- 1%
Channel-to-Channel Crosstalk	< -80dB
Residual Phase Noise (1Hz-100kHz BW)	< 2 mdeg rms
Residual Amp. Noise (1Hz-100kHz BW)	< 0.02% rms

3.2 Booster 352 MHz Down-Converter

The down-converter fabricated for the Booster shall have the specifications listed in Table 3.2.1.

Table 3.2.1: Booster Down-Converter Specifications

Parameter	Value
RF signal input frequency (nom.)	351.93 MHz
IF output frequency (nom.)	19.55 MHz
LO input frequency (nom.)	332.38 MHz
LO input signal level (nom.)	+5dBm
Number of RF inputs and IF outputs	8
Full scale RF Input signal level	+ 10 dBm
Full scale IF Output signal level	+ 5 dBm (+/- 1dB)
Output Linearity	+/- 1%
Channel-to-Channel Crosstalk	< -80dB
Residual Phase Noise (1Hz-100kHz BW)	< 2 mdeg rms
Residual Amp. Noise (1Hz-100kHz BW)	< 0.02% rms

3.3 Timing/Synchronization 352 MHz Up-Converter

The up-converter fabricated for the Timing/Synchronization system shall have the specifications listed in Table 3.3.1. Note this unit has a slightly higher IF frequency from the Booster unit and uses a high-side LO.

Table 3.3.1: Timing/Synchronization Up-Converter Specifications

Parameter	**Value**
IF signal input frequency (nom.)	23.09 MHz
RF output frequency (nom.)	351.93 MHz
LO input frequency (nom.)	375.02 MHz
LO input signal level (nom.)	0 dBm
Number of RF outputs	4
Full Scale IF I/Q input signal level	-2 dBm each
Full scale RF Output signal level	+ 10 dBm (+/- 1dB)
Output Linearity	+/- 1%
Channel-to-Channel Crosstalk	< -80dB
Residual Phase Noise (1Hz-100kHz BW)	< 2 mdeg rms
Residual Amp. Noise (1Hz-100kHz BW)	< 0.02% rms

3.4 Bunch-Lengthening 1408 MHz Up-Converter

The up-converter fabricated for the Bunch Lengthening LLRF system shall have the specifications listed in Table 3.4.1.

Table 3.4.1: Bunch-Lengthening Up-Converter Specifications

Parameter	Value
IF signal input frequency (nom.)	19.6 MHz
RF output frequency (nom.)	1408.2 MHz
LO input frequency (nom.)	1388.6 MHz
LO input signal level (nom.)	0 dBm
Number of RF outputs	4
Full Scale IF I/Q input signal level	-2 dBm each
Full scale RF Output signal level	+ 10 dBm (+/- 2dB)
Output Linearity	+/- 1%
Channel-to-Channel Crosstalk	< -70dB
Residual Phase Noise (1Hz-100kHz BW)	< 10 mdeg rms
Residual Amp. Noise (1Hz-100kHz BW)	< 0.05% rms

3.5 Bunch-Lengthening 1408 MHz Down-Converter

The down-converter fabricated for the Bunch Lengthening LLRF system shall have the specifications listed in Table 3.4.2.

Table 3.4.2: Bunch-Lengthening Down-Converter Specifications

Parameter	Value
RF signal input frequency (nom.)	1408.2 MHz
IF output frequency (nom.)	19.6 MHz
LO input frequency (nom.)	1388.6 MHz
LO input signal level (nom.)	+5dBm
Number of RF inputs and IF outputs	8
Full scale RF Input signal level	+ 10 dBm
Full scale IF Output signal level	+ 6 dBm (+/- 2dB)
Output Linearity	+/- 1%
Channel-to-Channel Crosstalk	< -70dB
Residual Phase Noise (1Hz-100kHz BW)	< 10 mdeg rms
Residual Amp. Noise (1Hz-100kHz BW)	< 0.05% rms

4 Acceptance Testing

Test reports for all units shall show evidence that all channels meet the requirements in Sect. 3 except for the phase and amplitude noise which will be measured at Argonne per Sect. 4.1 and 4.2 below.

4.1 Down-Converter Testing

4.1.1 Down-Converter Phase Noise Test

The general setup of Fig. 1 will be used at Argonne to measure the residual phase noise of the down-converters. Since the down-converter is a frequency translation device, the residual phase noise is measured between two channels of the down-converter. The LO and RF signals will originate from a common frequency source. A phase shifter is used on one of the RF input signals to adjust for quadrature conditions at the mixer used to compare the IF outputs from the down-converter. The output of the mixer is fed through a low-pass filter (LPF) which is then amplified using a Wenzel BPAA-1000 audio amplifier. The output of the audio amplifier is then fed to a Stanford Research Systems SR785 which estimates the power spectral density through fast fourier transform (FFT) analysis.

All channels will be measured. The integrated phase noise of each channels over a 1Hz to 100kHz bandwidth shall be less than 2mdeg rms for the 352MHz units and less than 10mdeg rms for the 1408MHz units.

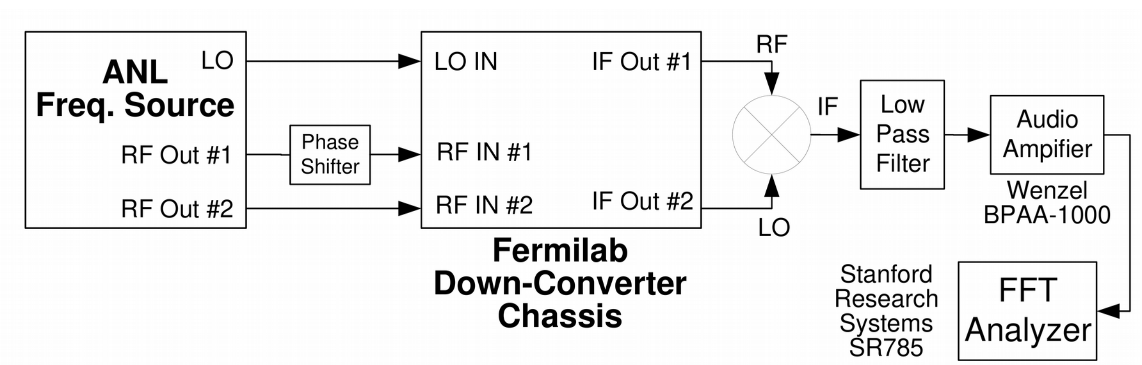

Figure 1: Down-converter residual phase noise measurement test setup

4.1.2 Down-Converter Amplitude Noise Test

The general setup of Fig. 2 will be used at Argonne to measure the amplitude noise of the down-converters. The LO, RF, and clock (CLK) signals will originate from a common frequency source. The down-converter will convert the RF signal to the IF signal which will then be measured with a digital LLRF receiver based upon the Vadatech DAQ523 MicroTCA module. The integrated amplitude noise of this setup for each channel over a 1Hz to 100kHz bandwidth shall be less than 0.02% rms for the 352MHz units and less than 0.05% rms for the 1408MHz units.

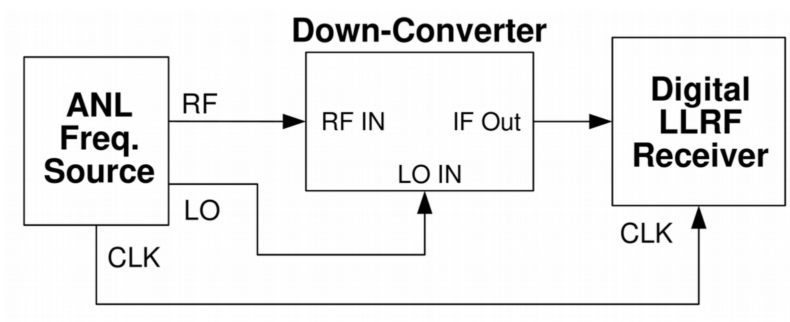

Figure 2: Down-converter amplitude noise measurement test setup

4.2 Up-Converter Testing

4.2.1 Up-Converter Phase Noise Test

The general setup of Fig. 3 will be used at Argonne to measure the residual phase noise of the up-converters. Since the up-converter is a frequency translation device, the residual phase noise is measured between two channels of the up-converter. The LO and IF signals will originate from a common frequency source. A phase shifter is used on one of the IF output signals from the up-converter chassis to adjust for quadrature conditions at the mixer used to compare the phase of the IF outputs. The output of the mixer is fed through a low-pass filter (LPF) which is then amplified using a Wenzel BPAA-1000 audio amplifier. The output of the audio amplifier is then fed to a Stanford Research Systems SR785 which estimates the power spectral density through fast fourier transform (FFT) analysis.

All channels will be measured. The integrated phase noise over a 1Hz to 100kHz bandwidth shall be less than 2mdeg rms.

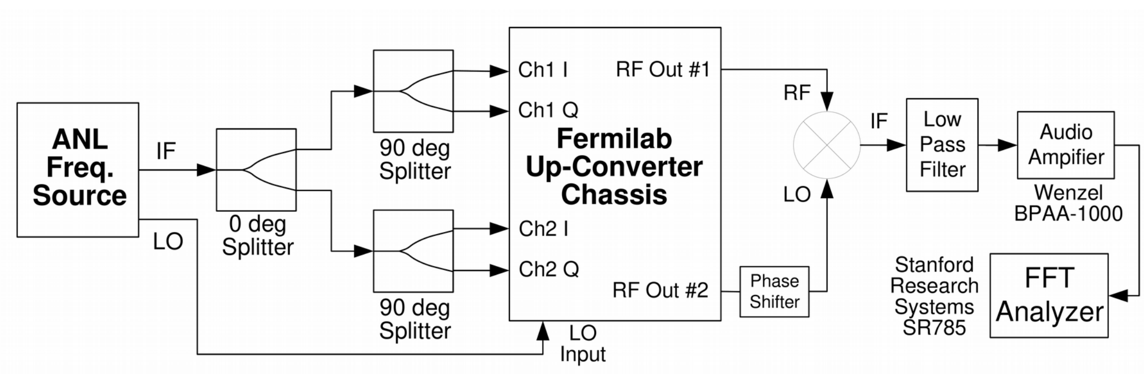

Figure 3: Block diagram of up-converter residual phase noise measurement test setup

4.2.2 Up-Converter Amplitude Noise Test

The general setup of Fig. 4 will be used at Argonne to measure the amplitude noise of the down-converters. The LO, IF, and clock (CLK) signals will originate from a common frequency source. The up-converter will convert the IF source signal an RF signal which will then be down-converted back to an IF signal which will then be measured with a digital LLRF receiver based upon the Vadatech DAQ523 MicroTCA module. The integrated amplitude noise of this setup for each channel over a 1Hz to 100kHz bandwidth shall be less than 0.03% rms for the 352MHz units and less than 0.07% rms for the 1408MHz units. For the 352MHz units the 0.03% rms is greater than the 0.02% rms of Table 3.1.1 and Table 3.3.1 since a down-converter is used in the test setup. Hence we allow the noise of the combination to be less than the rms sum of the two devices. Similar logic gives the value for the 1408MHz units.

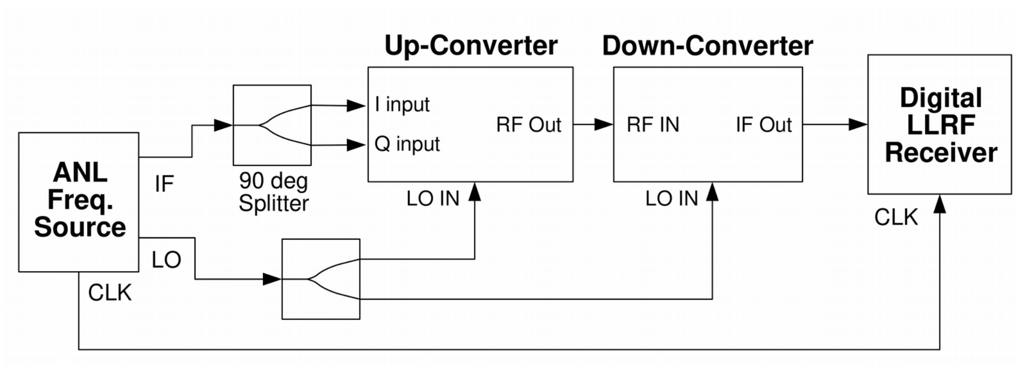

Figure 4: Up-converter amplitude noise measurement test setup

5 Deliverables

1. A total of 6 up-converters of the following types:

    - Qty 2: Booster LLRF 352MHz up-converter per Sect. 3.1
    - Qty 2: Timing/Synchronization 352MHz up-converter per Sect. 3.3
    - Qty 2: Bunch Lengthening system 1408MHz up-converter per Sect. 3.4

2. A total of 7 down-converters of the following types:

    - Qty 5: Booster LLRF 352MHz down-converter per Sect. 3.2
    - Qty 2: Bunch Lengthening system 1408MHz down-converter per Sect. 3.5

3. Test reports for each unit according to the below:

    - For the up-converters the reports shall include
        i. RF out vs. IF input for all channels
        ii. Output linearity
        iii. monitor levels for all channels
        iv. channel-to-channel isolation between all channels
        v. current draw at +6V.

    - For the down-converters the reports shall include
        i. IF out vs. RF input for all channels
        ii. Output linearity
        iii. monitor levels for all channels
        iv. channel-to-channel isolation between all channels
        v. current draw at +6V.

4. Schematics

5. PCB files

6. Parts Lists

7. Chassis Drawings

6 Schedule

Table 6: Schedule

Item	Description	Quantity	Earned Value	Due Date
Up-Converter Heater Resistor Modification	*Modify up-converter thermal plate drawings to accommodate heater resistors and rear panel drawings to accommodate a connector to them*	*N/A*	*10%*	*3 weeks ARO*
Parts Selection	*Identify all drop-in replacement parts for frequency selectivity*	*N/A*	*10%*	*3 weeks ARO*
Order all Parts	*Place orders for all parts except for the K&L filters which APS-U is responsible for*	*N/A*	*10%*	*4 weeks ARO*
Fabricate and Test: Timing/Synchronization up-converter, first article	*Fabricate and test the first article Timing/Synchronization 352MHz up-converter*	*N/A*	*N/A*	*14 weeks ARO*
Ship: Timing/Synchronization up-converter, first article	*Ship first article Timing/Synchronization 352MHz up-converter*	*1 Timing/Synch Up-Converter*	*10%*	*15 weeks ARO*
Fabricate and Test: Booster down-converter, first article	*Fabricate and test first article Booster 352MHz down-converter*	*N/A*	*N/A*	*15 weeks ARO*
Ship: Booster down-converter, first article	*Ship first article Booster 352MHz down-converter*	*1 Booster Down-Converter*	*5%*	*16 weeks ARO*
Fabricate and Test: Booster up-converter, first article	*Fabricate and test the first Booster 352MHz up-converter*	*N/A*	*N/A*	*16 weeks ARO*
Ship: Booster up-converter, first article	*Fabricate and test the first Booster 352MHz up-converter*	*1 Booster Up-Converter*	*5%*	*17 weeks ARO*
Fabricate and Test: BLS up-converter, first article	*Fabricate and test first article Bunch-Lengthening System (BLS) 1408MHz up-converter*	*N/A*	*N/A*	*17 weeks ARO*
Ship: BLS up-converter, first article	*Ship first article Bunch-Lengthening System (BLS) 1408MHz up-converter*	*1 BLS Up-Converter*	*5%*	*18 weeks ARO*
Fabricate and Test: BLS down-converter, first article	*Fabricate and test first article Bunch-Lengthening System (BLS) 1408MHz down-converter*	*N/A*	*N/A*	*18 weeks ARO*

Ship: BLS down-converter, first article	*Ship first article Bunch-Lengthening System (BLS) 1408MHz down-converter*	*1 BLS Down-Converter*	*5%*	*19 weeks ARO*
Fabrication: Booster down-converters final build	*Fabricate and test the remainder Booster 352MHz down-converters*	*N/A*	*N/A*	*24 weeks ARO*
Ship: Booster down-converters final build	*Ship the remainder Booster 352MHz down-converters*	*4 Booster Down-Converters*	*20%*	*25 weeks ARO*
Fabrication: Booster up-converters final build	*Fabricate and test the last article Booster 352MHz up-converter*	*N/A*	*N/A*	*25 weeks ARO*
Ship: Booster up-converter final build	*Ship the last article Booster 352MHz up-converter*	*1 Booster Up-Converter*	*5%*	*26 weeks ARO*
Fabrication: Timing/Synchronization up-converter final build	*Fabricate and test the last article /Synchronization 352MHz up-converter*	*N/A*	*N/A*	*26 weeks ARO*
Ship: Timing/Synchronization up-converter final build	*Ship the remainder Timing/Synchronization 352MHz up-converter*	*1 Timing/Synch Up-Converter*	*5%*	*27 weeks ARO*
Fabricate and Test: BLS up-converter final build	*Fabricate and test last article Bunch-Lengthening System (BLS) 1408MHz up-converter*	*N/A*	*N/A*	*27 weeks ARO*
Ship: BLS up-converter, final build	*Ship last article Bunch-Lengthening System (BLS) 1408MHz up-converter*	*1 BLS Up-Converter*	*5%*	*28 weeks ARO*
Fabricate and Test: BLS down-converter, final build	*Fabricate and test last article Bunch-Lengthening System (BLS) 1408MHz down-converter*	*N/A*	*N/A*	*28 weeks ARO*
Ship: BLS down-converter, final build	*Ship last article Bunch-Lengthening System (BLS) 1408MHz down-converter*	*1 BLS Down-Converter*	*5%*	*29 weeks ARO*

7 Special Instructions

Until parts are ordered, Argonne reserves the right to call regular weekly meetings via teleconference for technical discussions and to track progress including requesting effort hours spent on the tasks listed in Sect. 6.

Fermilab will give a bi-weekly update via email, including work status and effort hours spent on the tasks listed in Sect. 6. Once a month, Fermilab will provide a total of M&S and efforts spent on the tasks listed in Sect. 6. To accommodate timing of month end accounting, these monthly totals may require a 1 to 2-week forecast.

Fermilab shall not continue with fabricating remainder items after respective first article units until acceptance and approval of first article units by APS-U.

If any re-work is required to pass Fermilab internal tests, Fermilab shall discuss with Argonne before proceeding. If the units do not pass APS-U acceptance tests and are found to be unacceptable, Fermilab shall remedy the situation under APS-U direction.

8 References

[1] Fermilab PIP-II 325 MHz 4-Channel Up-Converter Rev D Datasheet
[2] Fermilab PIP-II 325 MHz 8-Channel Down-Converter Rev D Datasheet
[3] Fermilab Technical Note for Operating at 1408 MHz