Precision Low-level RF System for Short-Pulse X-Ray in the APS Upgrade*

Hengjie Ma, Tim Berenc, Alireza Nassisri,
Ned Arnold, Frank Lenkszus, Sinisa Veseli, Tom Fors **
** Argonne National Laboratory

Lawrence Doolittle, Gang Huang, John Byrd ++
++Lawrence Berkeley National Laboratory

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Abstract

A precision digital Low-level RF control system(LLRF) with embedded drift calibration loops has been developed for The Short-Pulse X-ray R&D (SPX0) in the Advanced Photon Source Upgrade (APS-U) at Argonne National Laboratory. As a major capability in APS-U, SPX/SPX0 imposes a set of stringent requirements on the rf stability in the deflecting cavities, among which the is the very tight differential phase error budget of a total 0.038-degree RMS for the differential phase between the two deflecting cavities in two sectors. The solution to meet this challenge is a joint-system of the Low-level RF and a Timing-synchronization. The development of this system has been a collaborative effort between Argonne National Laboratory and Lawrence Berkeley National Laboratory. At this time, a prototype system has been built, and tested in field with high-power SRF, and produced good results.

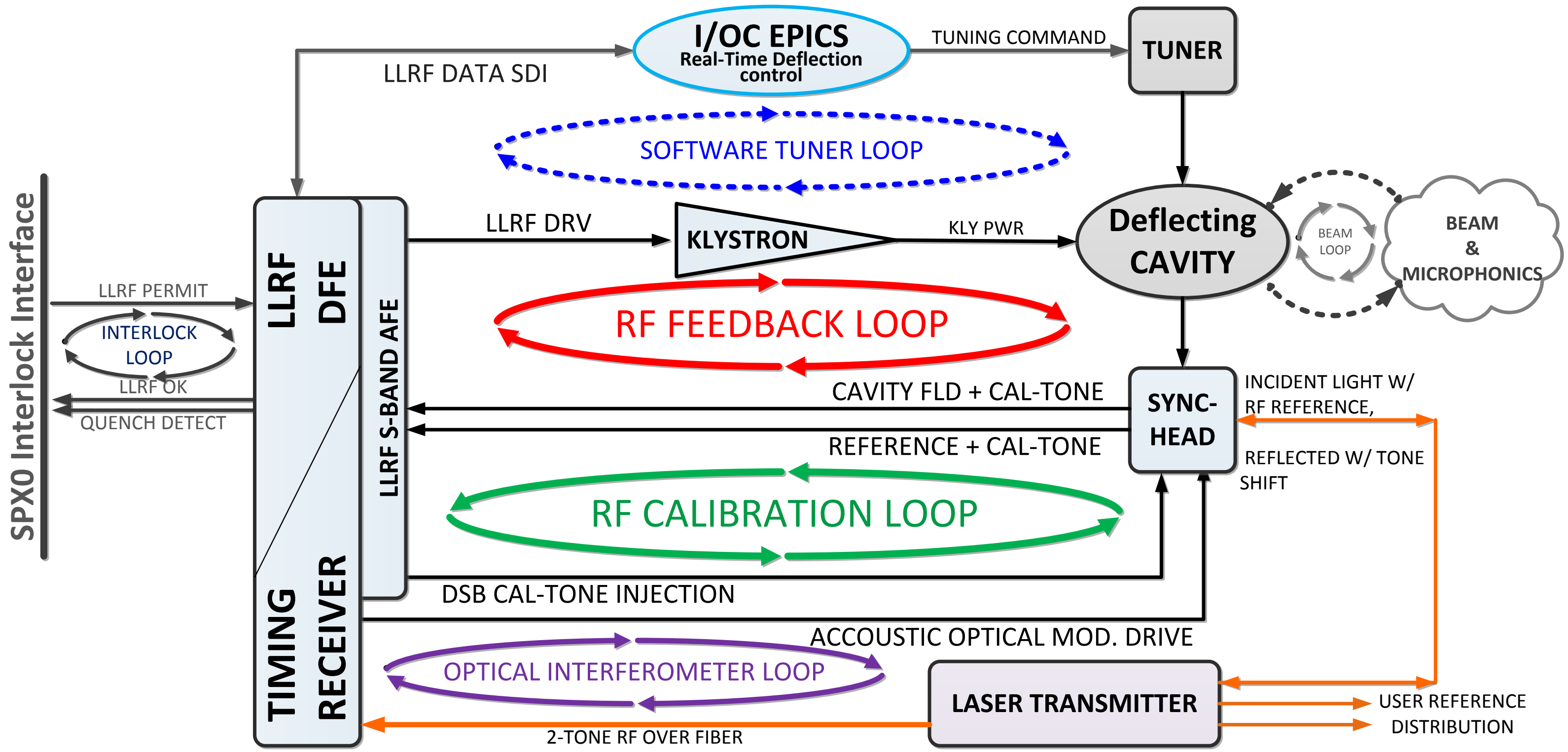
SPX RF Phase Stability Requirement

Specification Name	RMS Value	Bandwidth	Driving Requirement
Common-mode phase Variation	< 10 deg	0.01 Hz – 271 kHz	Keep intensity variation under 10% rms
Differential mode phase variation between sectors	< 0.038 deg[a]	0.01 Hz – 200 Hz	Keep rms beam motion outside of SPX within beam stability requirements
Differential mode phase variation between sectors	< 0.077 deg[a]	0.01 Hz – 1 kHz	Keep rms beam motion outside of SPX within beam stability requirements
Differential mode phase variation between sectors	< 0.28 deg	1 kHz – 271 kHz	Limits effective emittance growth to below 1.5 pm
Beam Line Laser Synchronization to X-ray pulse	< 0.27 psec	0.01 Hz to 1 kHz	Limit increase in effective pulse duration to < 10%

1. System Design for Stabilization

To achieve the required rf stability, four primary feedback loops have been implemented in this joint-system of LLRF and Timing ;

1) A fast rf feedback loop of the digital LLRF controller stabilizes the cavity field with respect to the rf phase reference distributed to the Sync-head at the cryo-module in Storage Ring tunnel by the Timing-synchronization system via. Fiber optics.
2) The Timing-synchronization system monitors and calibrates the phase drifts along the fiber cables through its optical interferometer loop,
3) The LLRF controller monitors and calibrates the phase drifts along the rf signal transmission coaxial cables between the sync-head and the LLRF controllers with its rf calibration loop, and
4) The LLRF monitors the cavity resonance, and provides the tuning error data to the EPICS I/OC which in turn tunes the cavity.

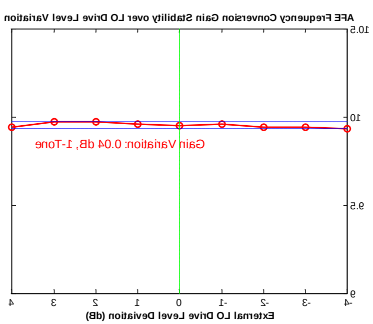


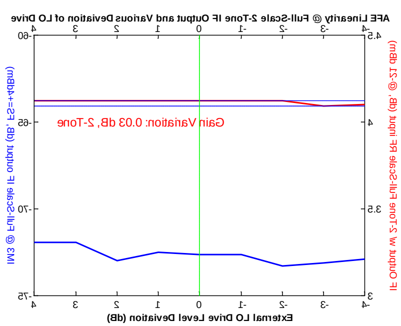
2. RF Measurement Precision Begins in AFE

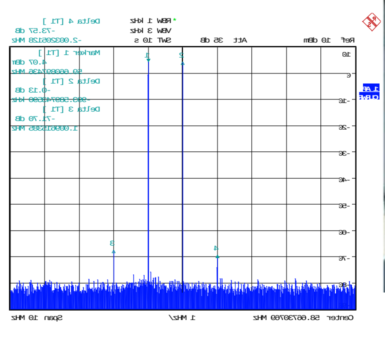
The elaborated feedback loops effectively address the stabilization of rf phase. However, this scheme requires an ultra-linear S-band analog front-end with the lowest IM3 term in the IF output, so that the spectral components of the three frequencies in each channel (rf carrier and two pilot tone sidebands) do not get mixed by the inter-modulations, and thus an accurate phase measurement can be made for the phase-drift correction computation.

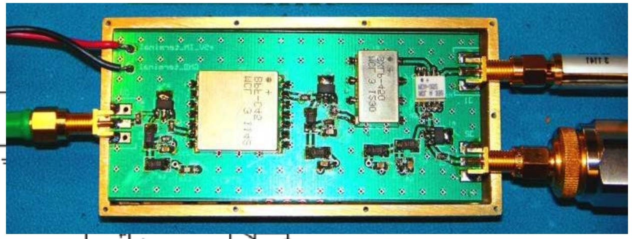
Furthermore, the gain of the frequency down-conversion in the AFE also needs to be stabilized against the inevitable deviation in LO drive power over time, so that an accurate rf amplitude measurement can be made for the rf amplitude stability requirement.

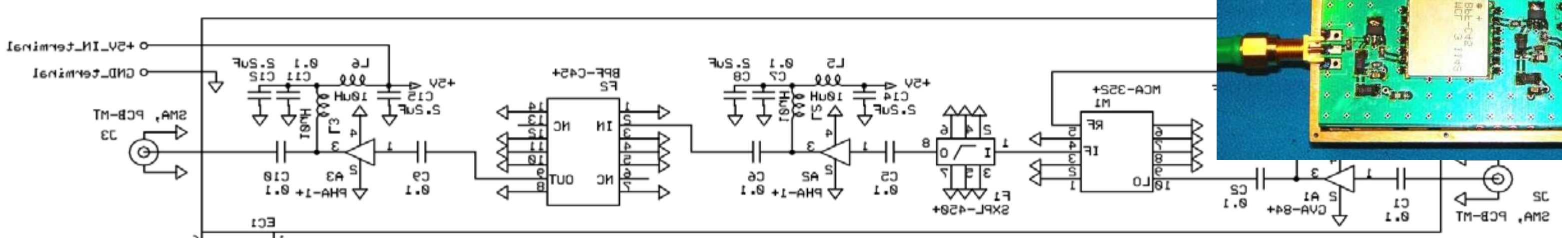
To meet this requirement, two SPX AFEs of using different high-performance components have been design, constructed, and tested. One design uses all connectorized components, while the other uses the SMD/PCB components. Both use high-IP3 frequency mixers to allow to operate at higher RF input level, while maintaining the lowest IM3 in the IF output, and both employ the saturated LO driver amplifiers to make the frequency mixer gain insensitive to the change in LO power. The test results show that both designs are successful. The IM3 term is below -70dBc at the full-scale 2-tone output level, and <u>the frequency conversion gain stays practically constant</u> when the LO drive power deviates as much as +/-4dB from the nominal +10dBm.









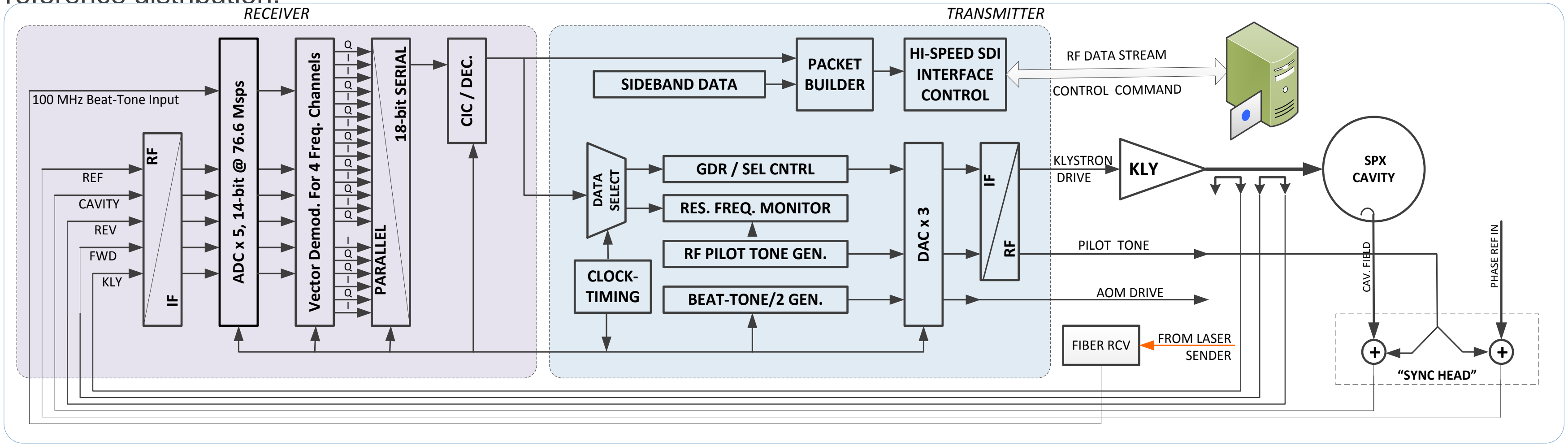


3. Implementation

The key electronics technology for this system is the advanced FPGA implementation of a four-frequency demodulation digital receiver on which the critical functionality of a simultaneous rf cable phase drift calibration with a rf pilot-tone (Calibration loop) as well as the fiber optics drift calibration with an interferometer beat signal is realized. The 6-channel digital vector signal receiver demodulates and processes the following four frequencies;

1)The rf carrier of cavity field, forward and reflected power, as well as the phase reference,
2)The double-sideband rf pilot tone ("CAL-TONE") with +/-1.6MHz frequency offset, and
3)The 100MHz beat-tone from the optical interferometer,

The multi-frequency digital receiver also generates the rf drive to the klystron, and transmit the DSB pilot tone for rf cables, and a 50.51MHz AOM (acoustic optical modulator) drive to produce the 101.02 MHz beat-tone in the fiber link for the reference distribution.

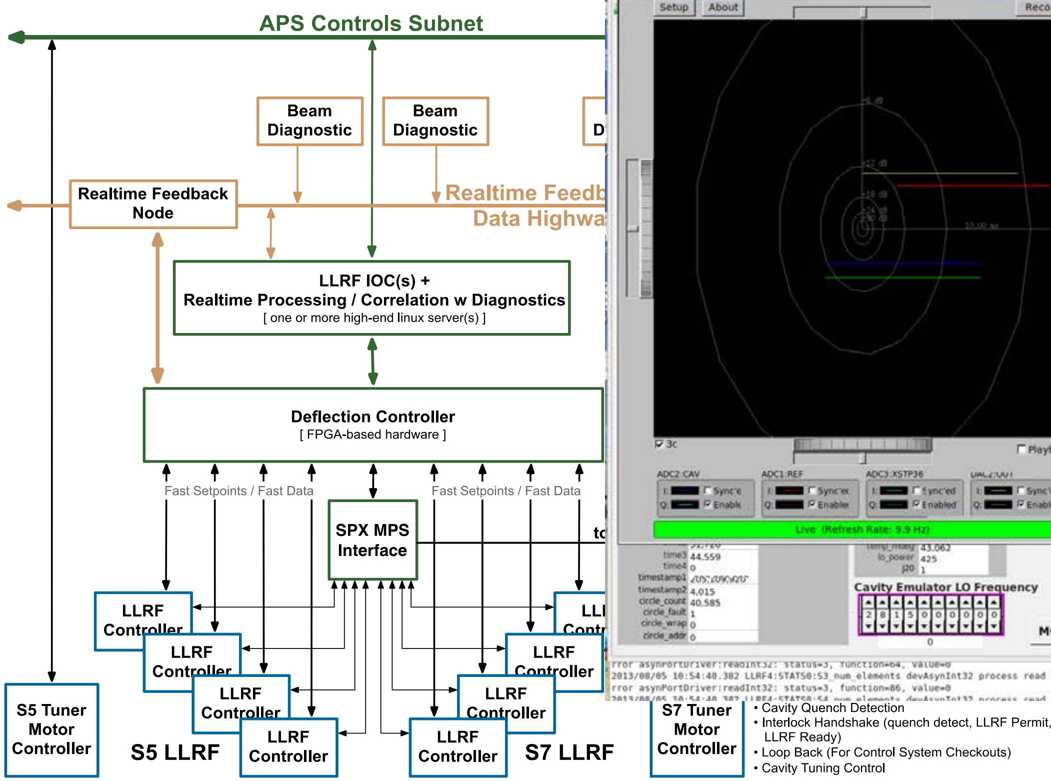


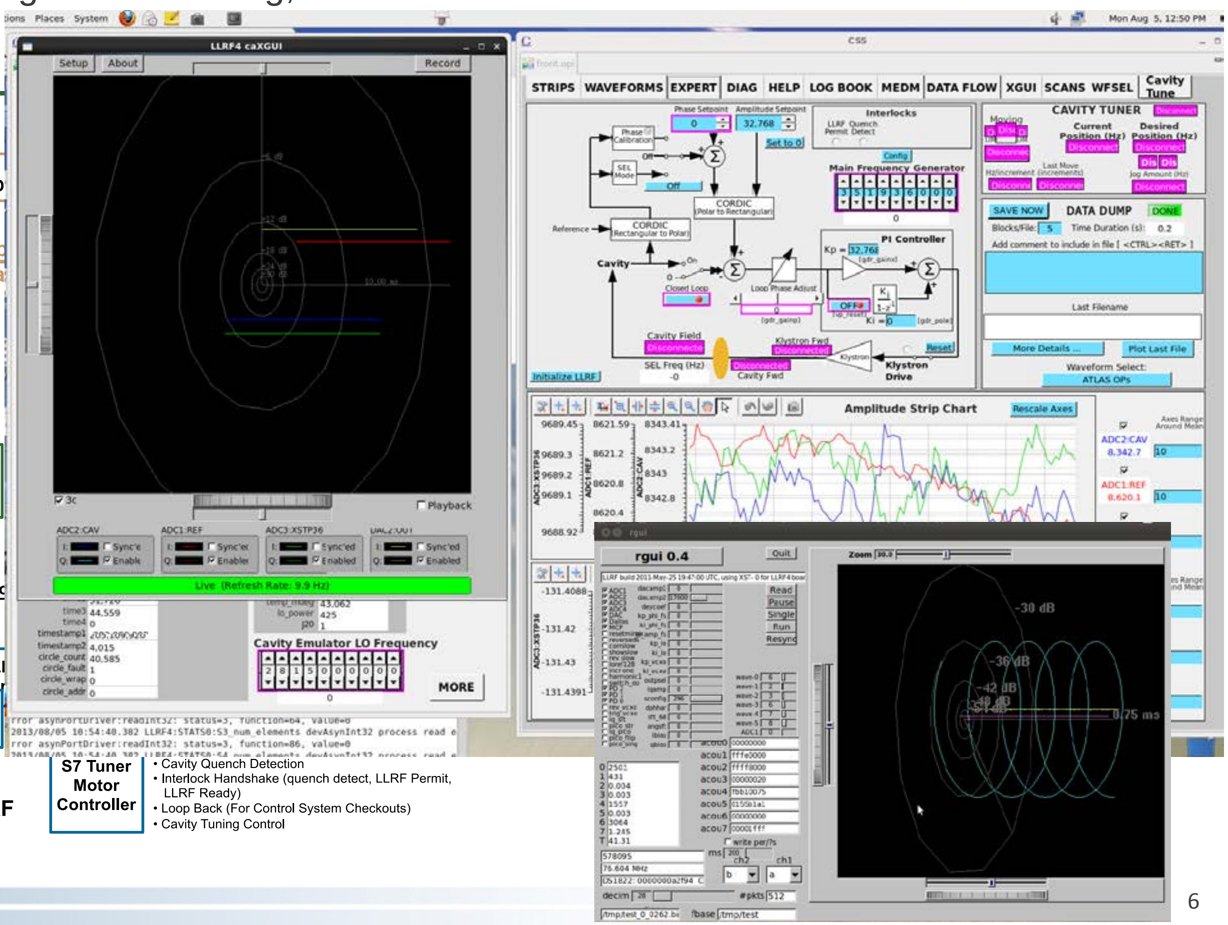
The implemented essential LLRF functionalities in FPGA also include
•GDR rf feedback P-I control, and Self-Excited Loop (SEL) control w/ hardware set-point ramping,
• Feed Forward Control (FFWD) for facilitating a jitter-free transition during switching between the open to closed-loop control mode,
•Output rf frequency agile either by DDS or SEL, w/ a frequency counter,
•Interlock logic with output rf drive limiting.
•High-speed rf data stream to EPICS I/OC host.

4. EPICS Support and Operator Interface

The strong EPICS software support has also been developed to operate the high-performance, versatile digital LLRF hardware, providing the access to all its control functions at the low level. The software support performs the high-level controls and data processing of

- User-friendly CSS/BOY-based Operator and Expert control screens,
- Operation automation sequencers for setting up control configruations,
- 3-D signal waveform plotting/display at a real-time like update rate,
- Tuner control algorithms,
- Full-speed data buffering and long-term archiving,
- Online data analysis tools



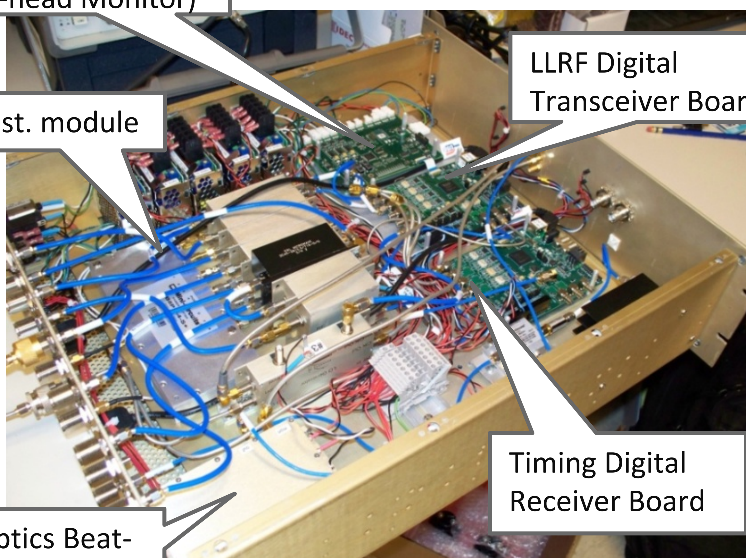


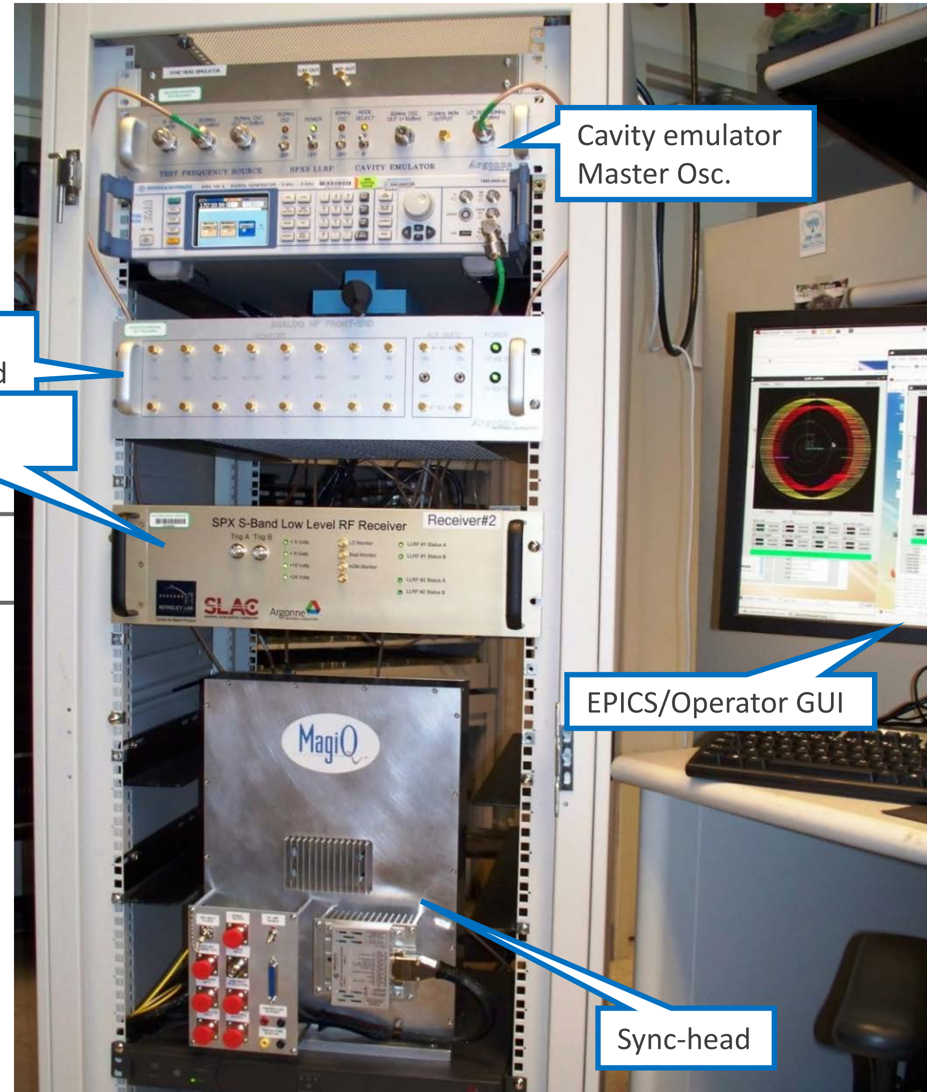
5. System Hardware

All the necessary component modules for a LLRF system have been designed and constructed, which is comprised of

- The digital LLRF controller,
- Precision AFE,
- Crystal emulator of SPX SC cavity,
- Sync-head, and
- Coherent frequency/clock generator.

A lab system with these components was integrated, which has successfully supported the development effort to the date.

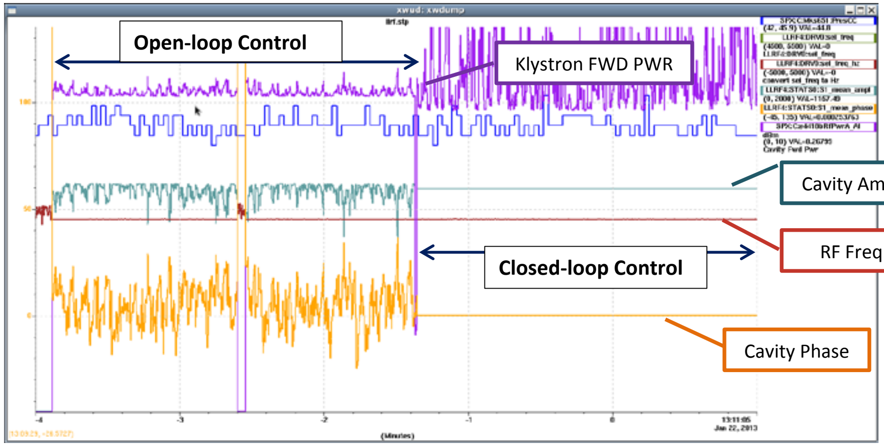




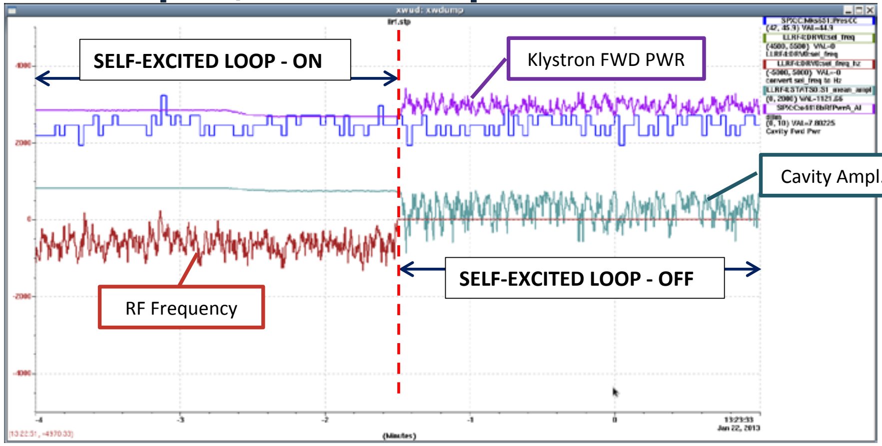
6. Tests

While being developed and tested in the lab, the integrated system was also used to support the high-power tests of the superconducting deflecting cavity in the field with the klystron at ATLAS. Various LLRF functions were verified;

- **GDR open, closed-loop control,**



- **SEL open, closed loop control,**



6. Tests (continues)

- **Effectiveness of cavity microphonics noise suppression by rf feedback with a strong integral term.**

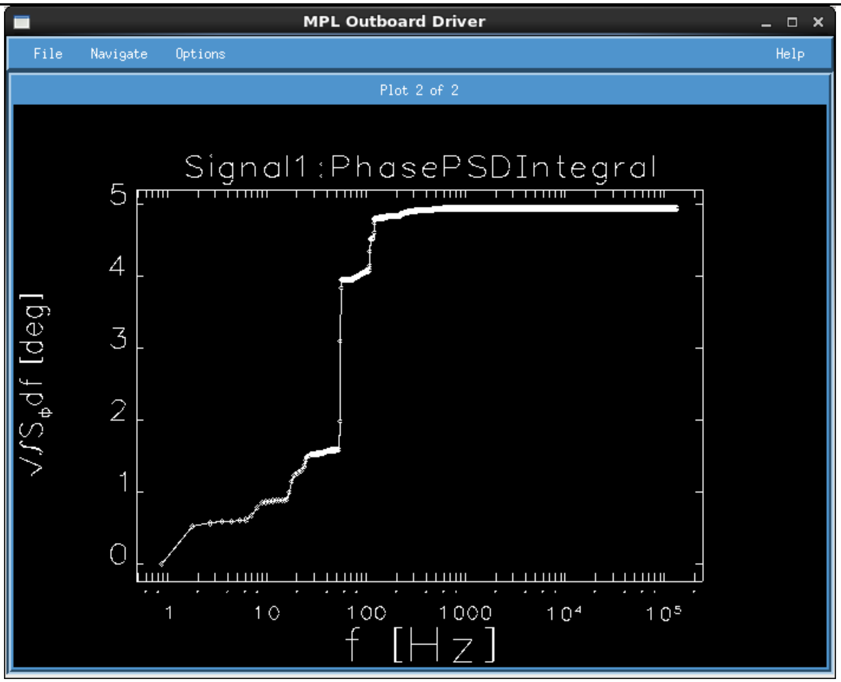


Figure 1 Integrated phase error of cavity rf field over 130kHz bandwidth, under open-loop LLRF control, at 7~10W RF power level. Over this bandwidth, the total phase error amounts up to ~5 degrees, RMS, of which the major contributing component seems to be a ~ 55Hz mode, presumably from the SRF system.

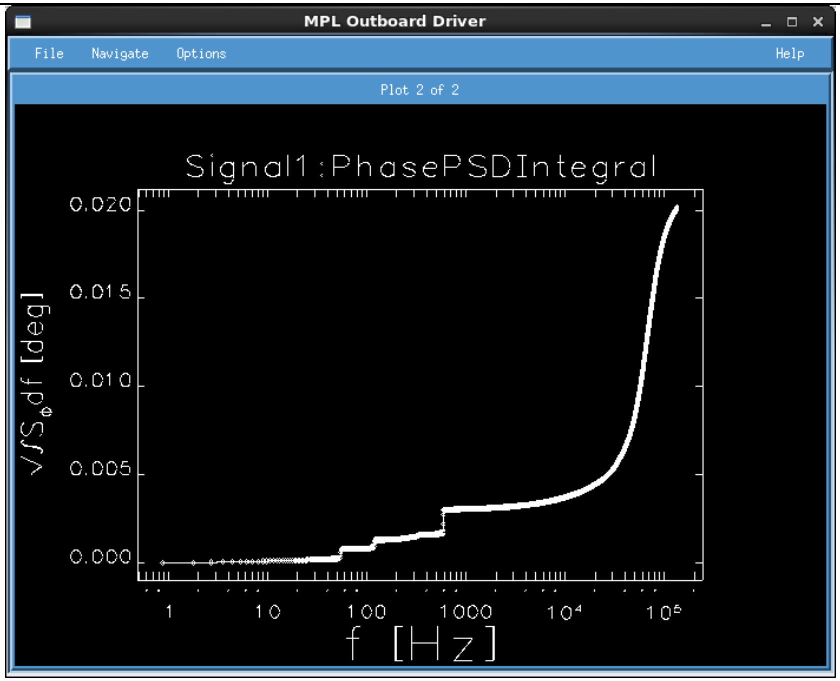
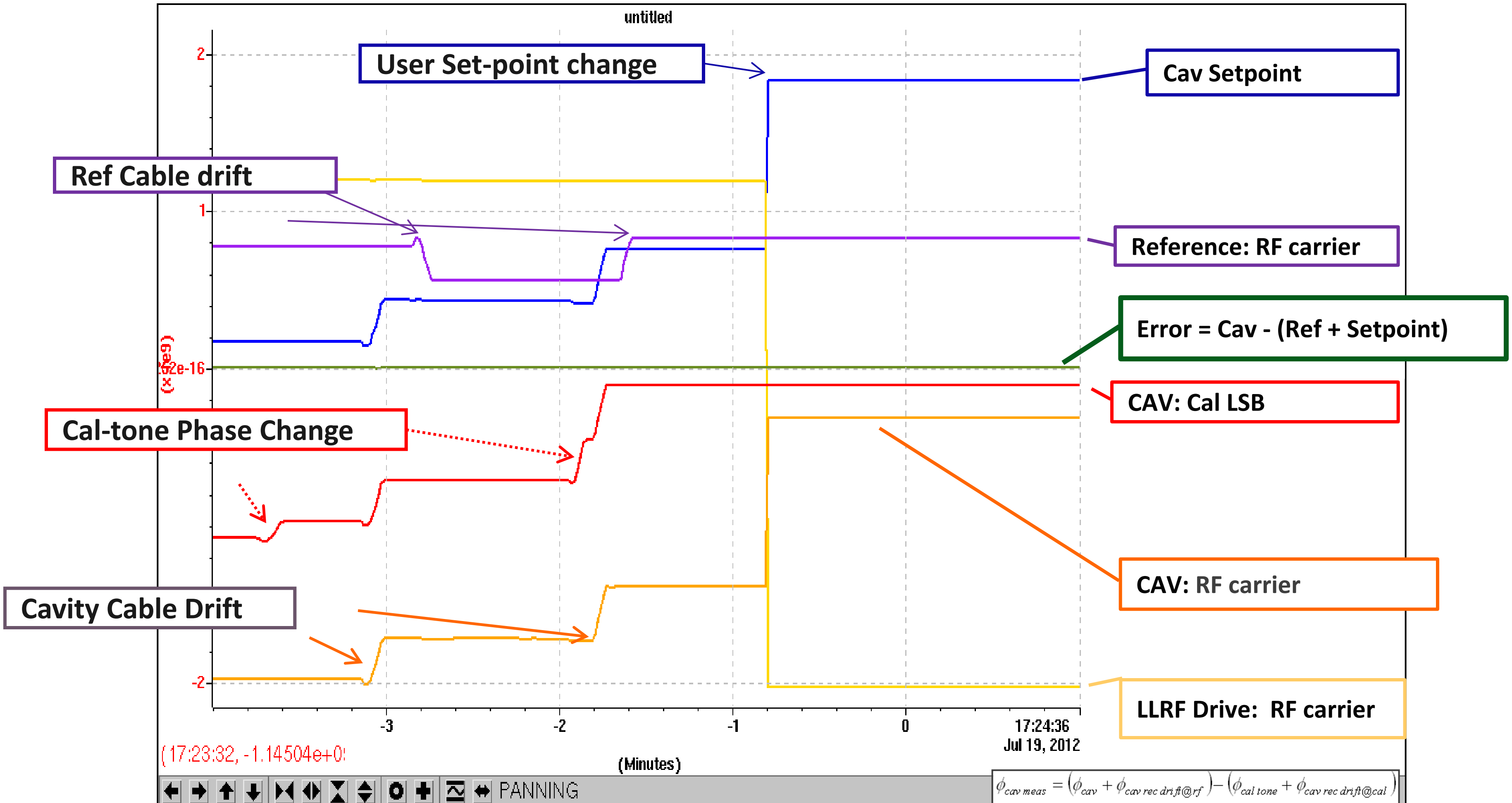


Figure 2 Integrated phase error of cavity rf field over 130kHz bandwidth, under closed-loop LLRF control, at 7~10W RF power level. The amount of phase error by the previously observed ~ 55Hz mode has been largely suppressed by the feedback control. Notice that the scaling of the Y-axis has been changed by auto-scaling.

6. Tests (continues)

- **Successful lab test for rf calibration loop function**
- **The functionality was implemented in July 2012, and tested in lab soon after at LBNL**
- **Cable drift in the test was simulated with phase shifters inserted in input channels.**



$$\phi_{cav\ meas} = (\phi_{cav} + \phi_{cav\ rec\ drift@rf}) - (\phi_{cal\ tone} + \phi_{cav\ rec\ drift@cal})$$

$$\phi_{ref\ meas} = (\phi_{ref} + \phi_{ref\ rec\ drift@rf}) - (\phi_{cal\ tone} + \phi_{ref\ rec\ drift@cal})$$

7. Looking Ahead

The developed LLRF system for SPX0 has successfully gone through a number of field tests, and supported high-power SRF test programs. The great deal of key LLRF technology gained from SPX0 will not only enable the targeted application - SPX, but with no doubt will also benefit greatly the other APS accelerator upgrade projects in future.