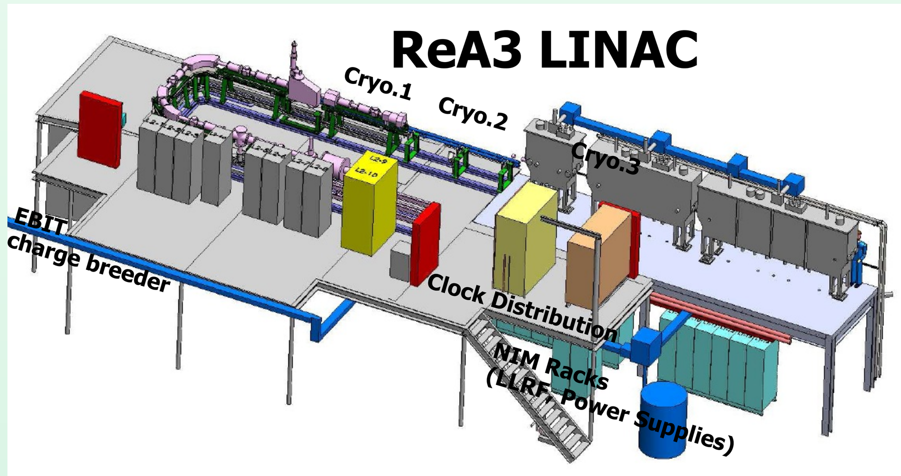
Digital LLRF Improvements at NSCL / FRIB

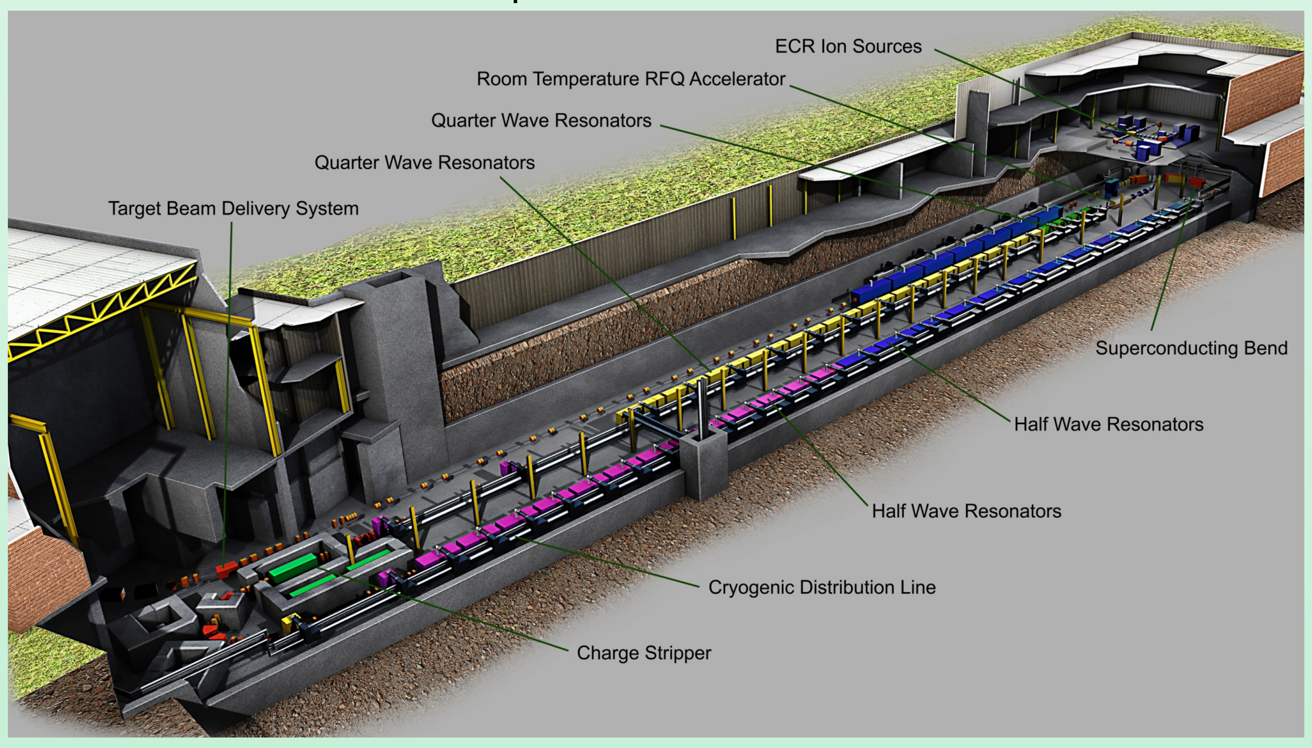
N. USHER usher@nscl.msu.edu, D. MORRIS morrisd@frib.msu.edu
NSCL, Michigan State University, 1 Cyclotron Laboratory,
East Lansing, MI, 48824-1321, USA

Introduction

Reaccelerated beams in the energy range of 0.3-12 MeV/nucleon open the door to a variety of experiments in the area of nuclear structure studies and nuclear astrophysics. NSCL is presently constructing the first phase of such a reaccelerator, named ReA3, which will provide rare isotopes from fast-fragment beams in the energy range of 0.3-3 MeV/nucleon. ReA3 will also serve as a test bed for many systems that will be used in FRIB in much greater numbers.



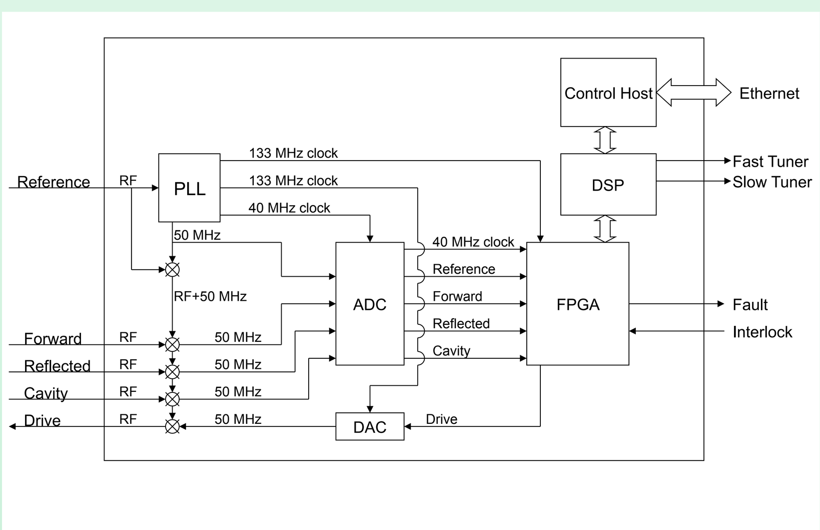
The FRIB driver linac will contain approximately 350 RF systems. The accelerating cavities in the linac will be primarily superconducting quarter-wave or half-wave resonators. The RF system for each of the SRF cavities will consist of an LLRF controller and a solid state amplifier.



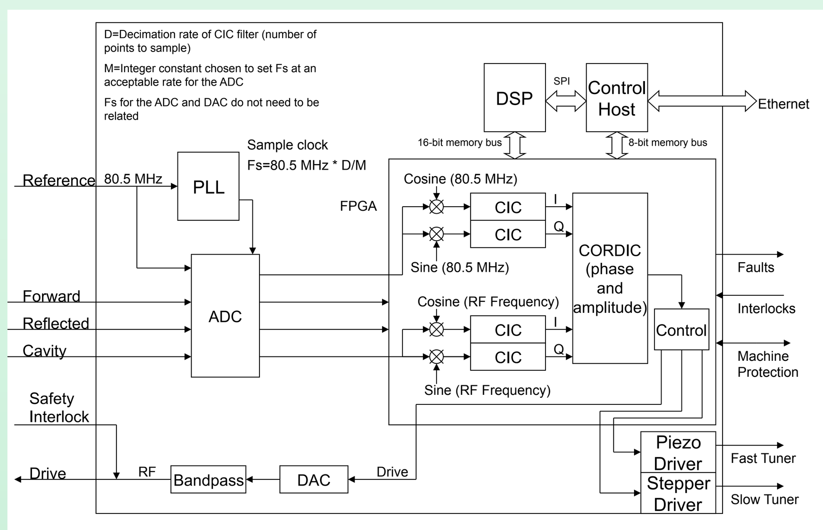
Installed ReA3 Hardware vs. New Design

The current ReA3 LLRF system design consists of 3 separate modules per cavity which are installed in a NIM crate: Turn On / Spark Detector, Digital LLRF Controller and Piezo / Stepper Controller. Prototypes are being tested for a redesigned system that adds several improvements while also lowering the production and maintenance costs of the system and simplifying the reference clock design.

The biggest functional change is the switch from IQ sampling with an IF of 50 MHz to non-IQ direct sampling of the input RF as shown below.



ReA3 design block diagram



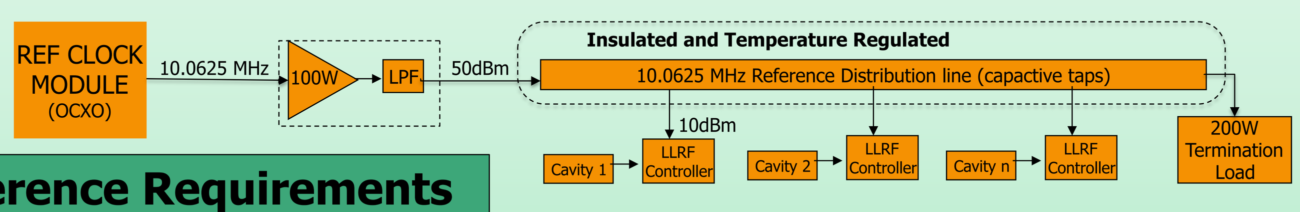
New design block diagram

Major Design Changes

	ReA3	FRIB
Form Factor	3 NIM modules	2U rack-mount chassis
RF Input Frequency	must match reference frequency	can be any harmonic of the reference frequency
Intermediate Frequency	50 MHz	Direct-sample
Sampling	IQ	non-IQ
Input Filters	analog	digital (CIC)

Other RF Design Changes

The ReA3 LLRF design required a reference clock at the same frequency as the cavity. Since FRIB has systems at multiple frequencies, this required multiple sections of the RF reference line at different harmonics of the base frequency. The new LLRF design removes this requirement, allowing a single reference clock to be used for all systems.



1. Harmonics can be derived from reference w/o phase ambiguities.
2. Can use 10 MHz REF INPUT for test equipment.

Reference Requirements

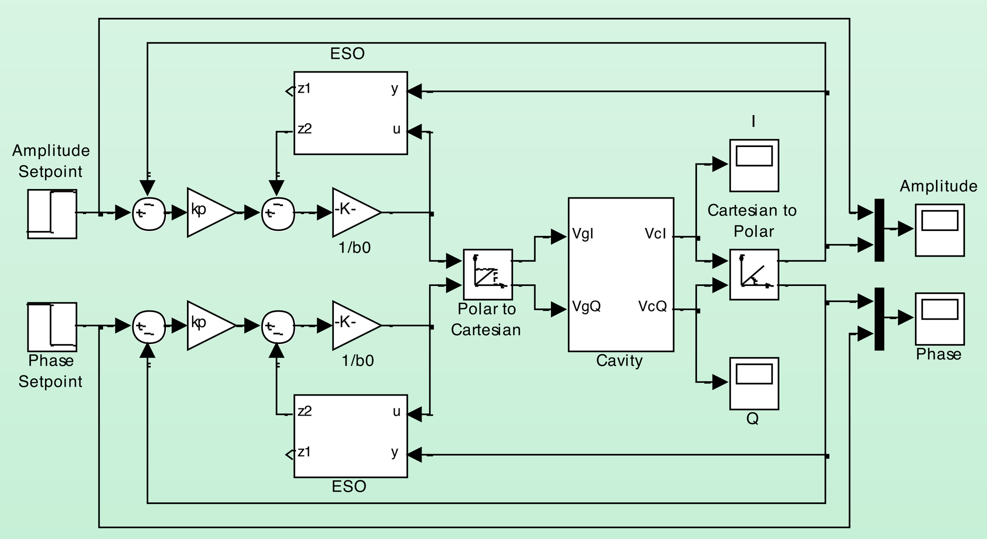
Phase Jitter	1.75 ps rms
Phase variation (First tap to last tap)	±10 ps

Active Disturbance Rejection Control

The installed ReA3 controllers have been upgraded from the standard PID phase and amplitude RF control to an active disturbance rejection control (ADRC) developed at Cleveland State University (Z. Gao). A self-excited loop mode has also been added to the startup sequence to raise the cavity field to the setpoint before moving the cavity tuner. The ADRC controller uses an extended state observer to estimate the external disturbances and any unknown internal dynamics of the cavity.

The only knowledge of the system required is the order of the system and an estimate of the b value of the cavity. Below is a simulation model and discrete time equations for an ADRC control for a first-order cavity. T is the sampling rate of the system. ω_c and ω_o are tuning parameters.

Simulation Model



Discrete-time Control Equations

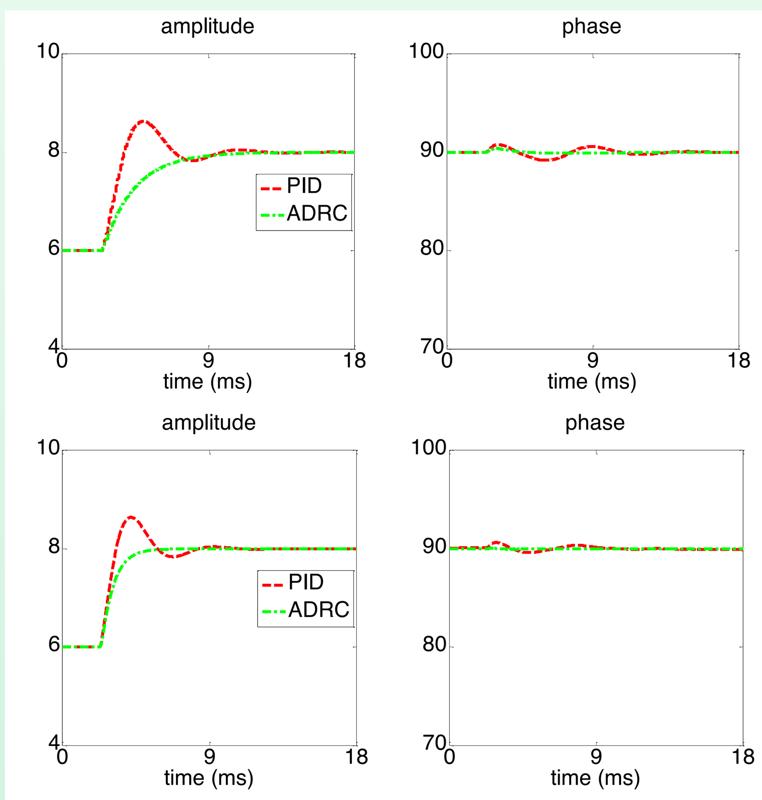
$$\hat{x}_1[k] = \bar{x}_1[k-1] + T\left(\bar{x}_2[k-1] + bu[k-1]\right)$$
$$\hat{x}_2[k] = \bar{x}_2[k-1]$$
$$\bar{x}_1[k] = \hat{x}_1[k] + l_{c1}\left(y[k] - \hat{x}_1[k]\right)$$
$$\bar{x}_2[k] = \hat{x}_2[k] + l_{c2}\left(y[k] - \hat{x}_1[k]\right)$$
$$u[k] = \frac{\left(\omega_c * r[k] - \bar{x}_2[k]\right)}{b}$$

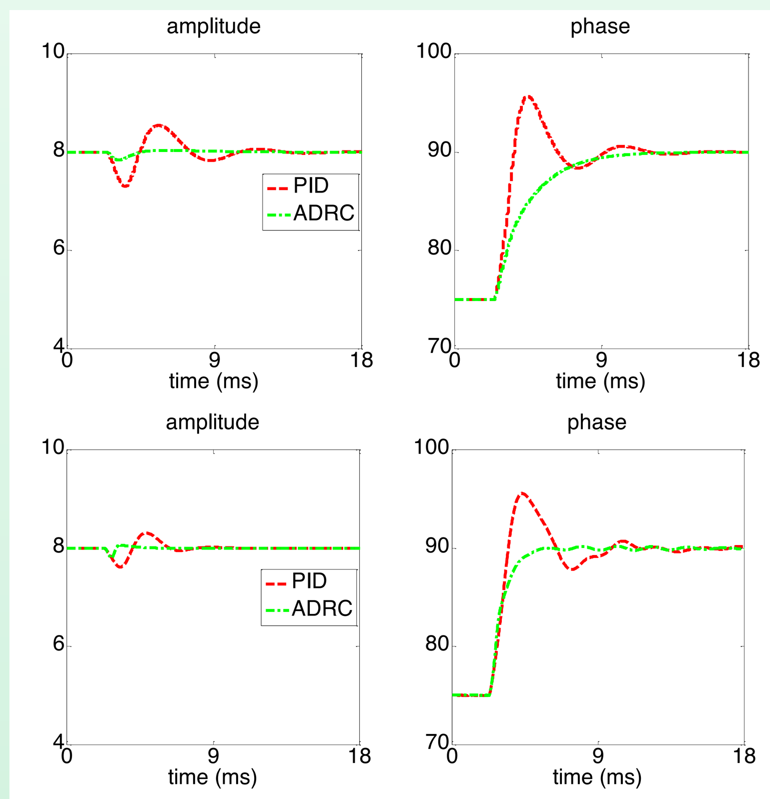
$$\beta = e^{-\omega_o T}$$
$$l_{c1} = 1 - \beta^2$$
$$l_{c2} = \frac{(1-\beta)^2}{T}$$

Reference: On active disturbance rejection based control design for superconducting RF cavities; J. Vincent, D. Morris, N. Usher, Z. Gao, S. Zhao, A Nicoletti, Q Zheng; **Nuclear Instruments and Methods in Physics Research A 643 (2011) 11–16**

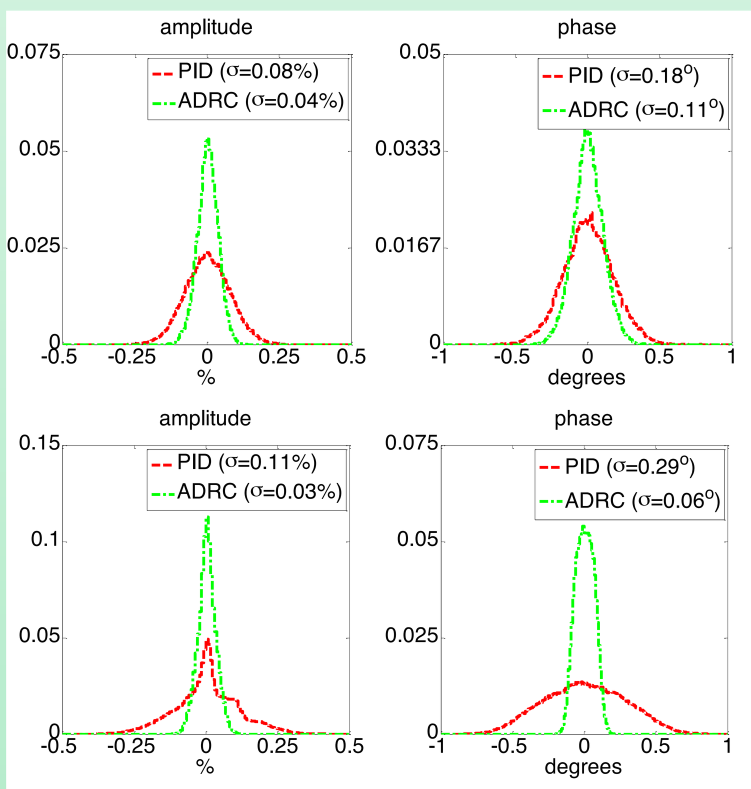
Control Results

The switch from PID to ADRC control yielded significant improvements in both the step response of the systems as well as the steady-state behavior. Below are the step responses for an amplitude step (left image) and a phase step (right image). The top plots in each image are the simulated response and the bottom plots are the measured response.





Below is the probability density function of the cavity control for both PID and ADRC. The top plots are simulated and the bottom plots are measured. The measurements were made simultaneously on adjacent cavities within a single cryomodule to ensure the microphonics were the same for both controls during the measurement period.



SRF Control Requirements

	ReA3	FRIB
Phase Regulation	0.5° σ	0.25° σ
Amplitude Regulation	0.5% σ	0.25% σ
Max Frequency	80.5 MHz	322 MHz

Material Cost

	ReA3	FRIB
LLRF controller	$1650	$2304
Turn On module / spark detector	$250	built into LLRF
Piezo / Stepper driver	$1250	built into LLRF
Hardware and cables (10 meters)	$1850	$1659
Total system cost / cavity:	**$5000**	**$3963**

Acknowledgements

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