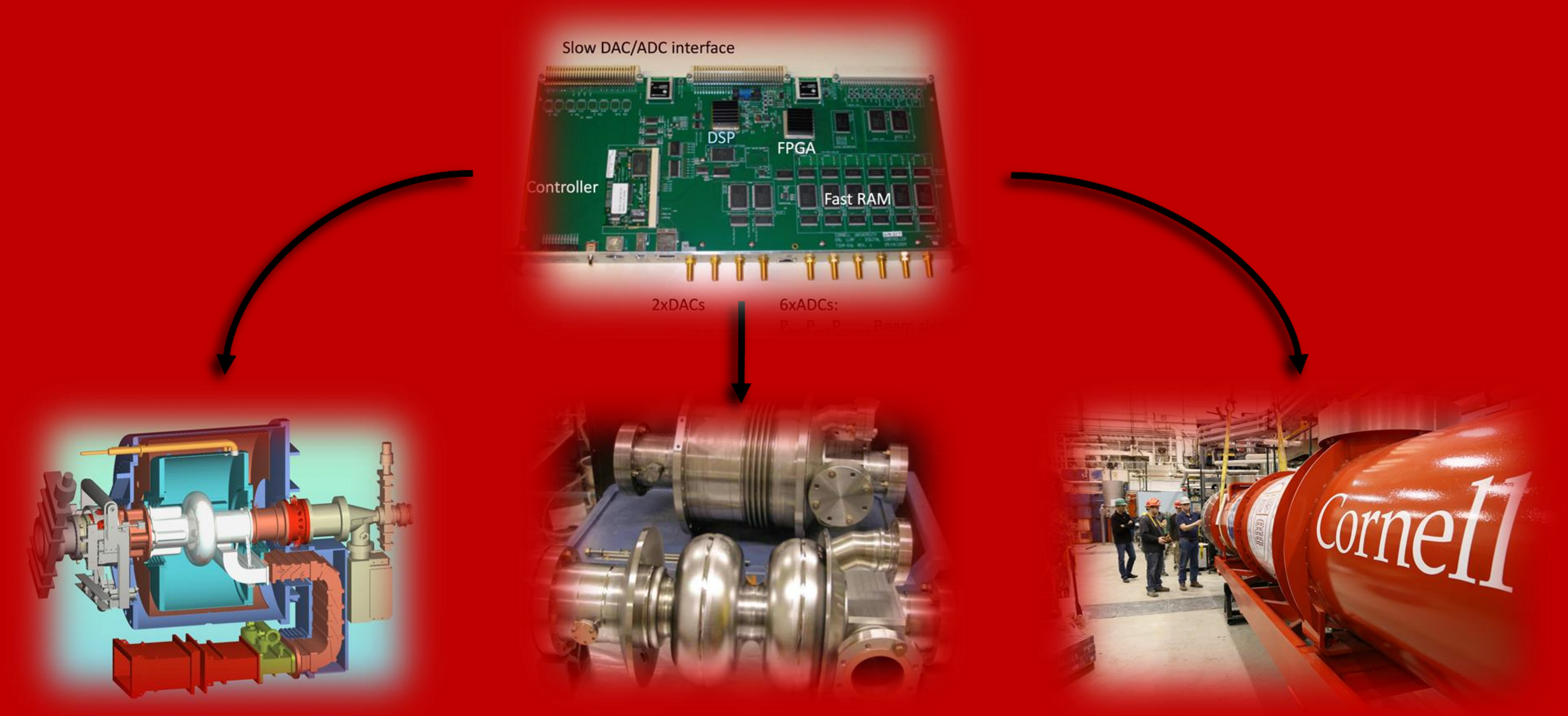


Recent Developments of the Cornell LLRF System

Nilanjan Banerjee
Cornell University

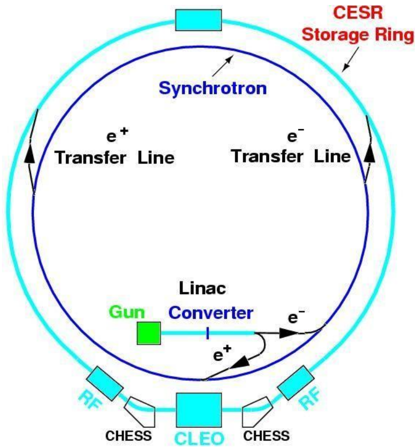
Overview

1. Introduction
2. Cornell LLRF Architecture
3. CBETA Requirements
4. Field Stability
5. Automatic Resonance Control
6. Summary

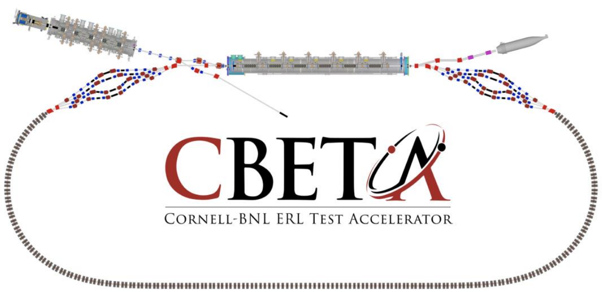
Introduction

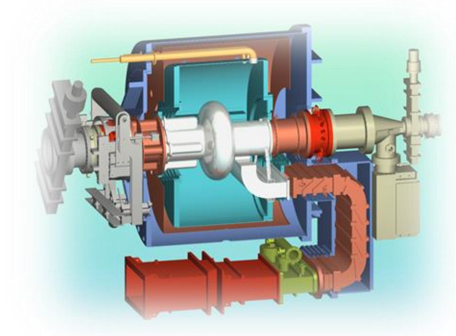
Cornell operates two accelerators:

1. Cornell Electron Storage Ring (CESR)
   Storage ring operated as a light source.
   RF System: 500 MHz CW
   Beam Current: 130 mA



2. Cornell BNL ERL Test Accelerator
   4-turn energy recover Linac.
   RF System: 1300 MHz CW
   Injector Current: 40 mA
   Main Linac Current: 320mA

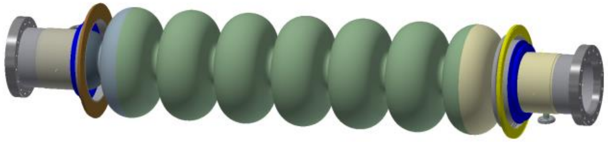




CESR B-cell

CBETA Injector 2-cell

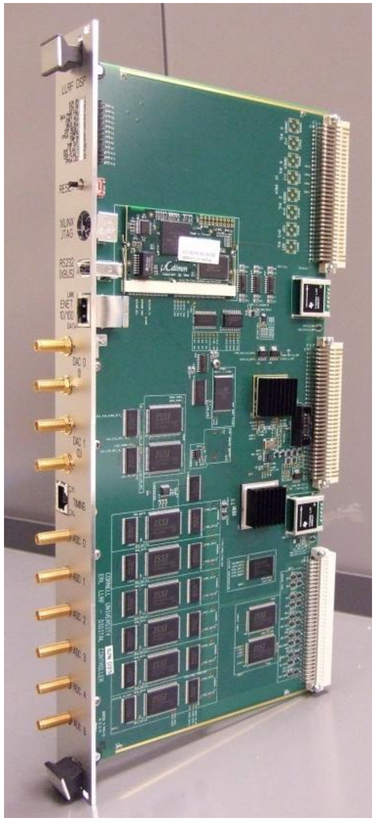
TESLA 9-cell

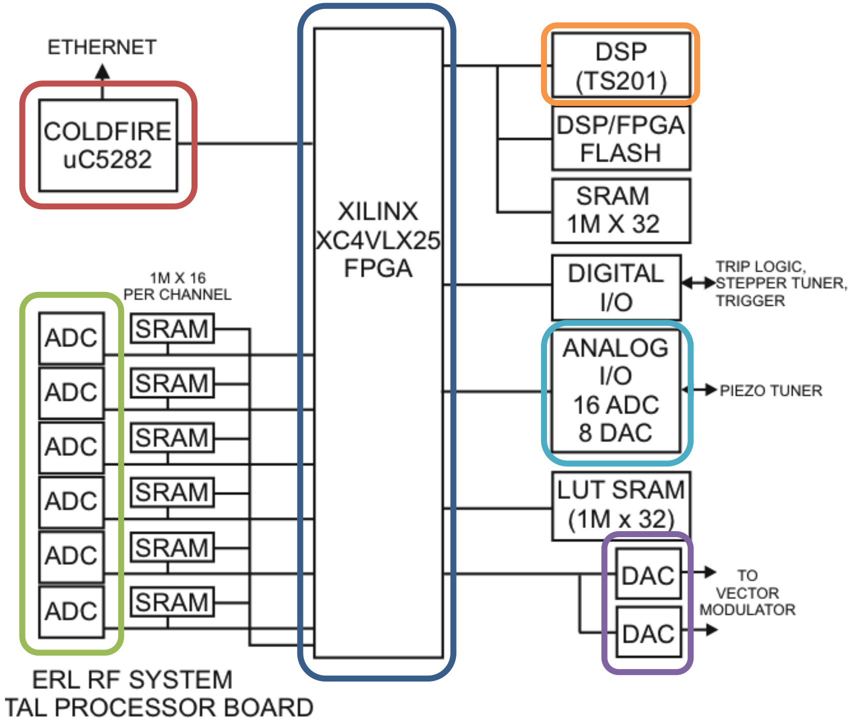


CBETA Main Linac 7-cell

And copper cavities, including a buncher and a deflector cavity for CBETA!

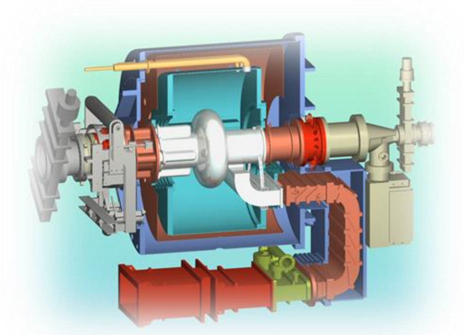
Cornell LLRF Architecture

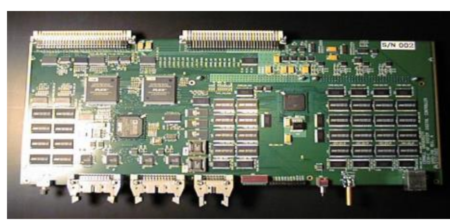




FPGA: (Loop latency < 0.1µs)
Field Control
DSP: (Fast loop: ~ 10µs, Slow loop: ~ 100 µs)
Tuner and piezo control
Coldfire:
Talks to the outside world.

Fast ADC board:
6 Channels 16-Bit ADC @ 50 Msps
Fast DAC board:
2 Channels16-Bit DAC @ 12.5 Msps
Medium ADC/DAC board:
Additional 10 to 100 ksps channels for frequency control…





CESR ported to new version last year!

CBETA Requirements

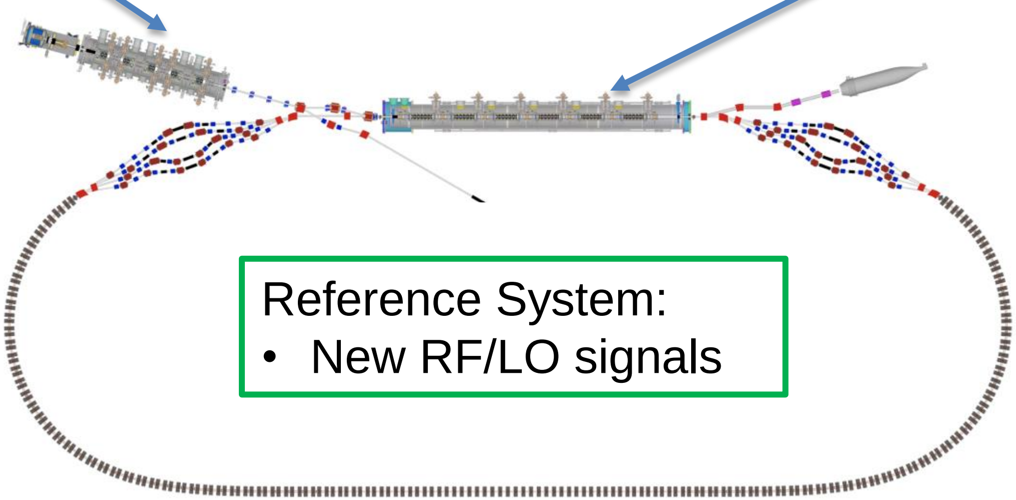
CBETA is a prototype for a bigger ERL, the specifications are chosen keeping in mind the requirements of a light source where bunch compression can be used.

Injector SRF:

- High beam loading (40mA)
  - Small $Q_L \sim 5 \cdot 10^4$ to $4 \cdot 10^5$
  - *Large bandwidth $\Delta f \sim 2$ to 13 kHz*
- Field stability requirements:
  - $\sigma_A/A \sim 1 \cdot 10^{-3}$
  - $\sigma_\Phi \sim 1$ *deg*

Main Linac SRF:

- No (almost) beam loading (~0mA)
  - High $Q_L \sim 6 \cdot 10^7$
  - *Small bandwidth $\Delta f \sim 25$ Hz*
- Field stability requirements:
  - $\sigma_A/A \sim 2 \cdot 10^{-4}$
  - $\sigma_\Phi \sim 0.1$ *deg*



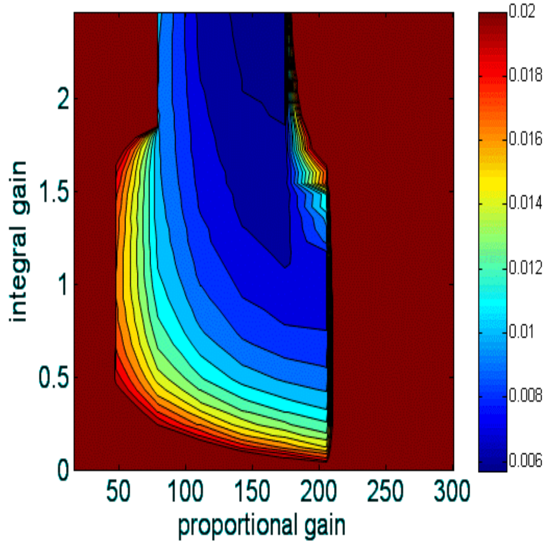
Reference System:

- New RF/LO signals

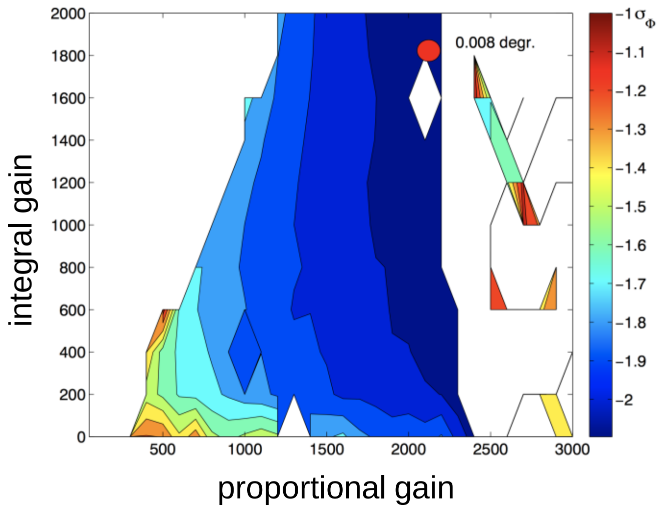
Field Stability

- Field controlled by a Proportional Integral feedback loop.

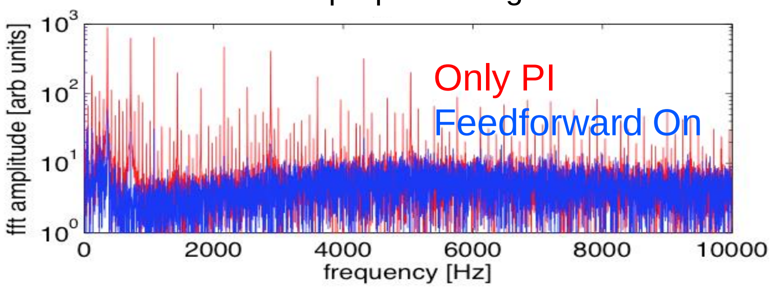
Injector Cavity Phase Stability



TESLA Cavity Phase Stability*



- Feedforward compensation
  1. Klystron High Voltage
  2. Beam Pulse



Cavity	Q_L	σ_A/A	σ_Φ(deg)
2-cell	$5\cdot10^4$	$2\cdot10^{-5}$	0.01
TESLA	$5\cdot10^7$	$1\cdot10^{-4}$	0.008

*A. Neumann et al., CW Measurements of the Cornell LLRF System at HoBiCaT, MOPO67, Proceedings of SRF 2011

Automatic Resonance Control

Detuning of the **main linac** cavities pose a major challenge in field control.

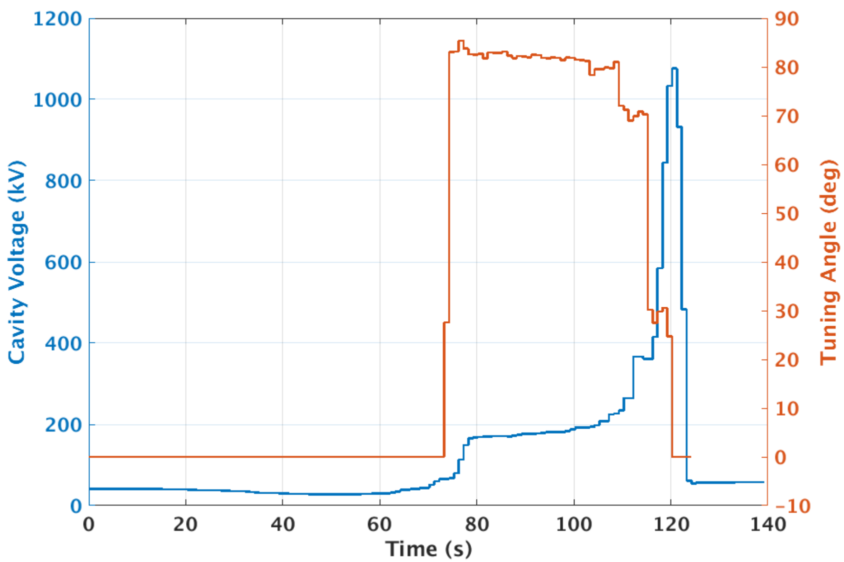
1. Coarse Tuner Control

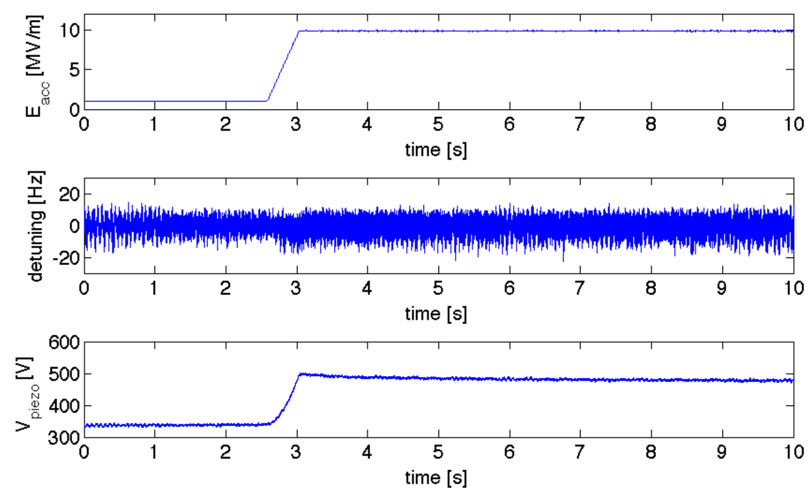
   A simple automatic tuning algorithm was designed based on a set of rules, drawing from experience of manually tuning cavities. Steps:

   1. Turn on constant forward power into the cavity.
   2. Determine direction of tuning.
   3. Tune until a certain field is reached.

2. Lorentz Force Detuning Compensation

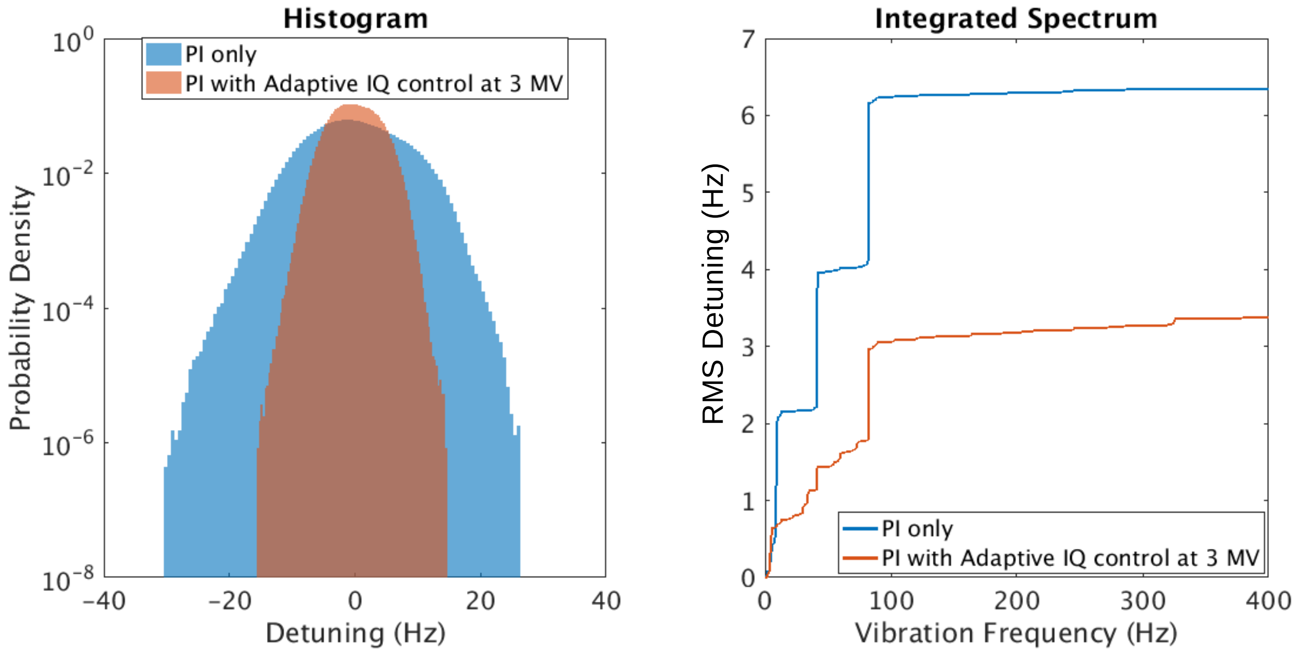
   - Piezo based feedforward on proportional to field square
   - Allows fast changes in cavity field.
   - Works very well!





Automatic Resonance Control: Microphonics

2. Microphonics Compensation
   - Proportional Integral feedback for low frequency vibrations
   - Frequency domain Least Mean Square technique for discrete lines in the frequency spectrum. – Very effective for high Q vibration peaks!



Algorithm is stable! Reduced peak detuning from 30.2 Hz to 15.5 Hz.

Summary

- The Cornell Low Level Radio Frequency system is an universal architecture used for controlling a wide variety RF cavities including superconducting and copper cavities.

- The processing is divided among a Xilinx FPGA (loop latency < 0.1 μs) which controls data acquisition and executes field control loops, and an Analog Devices DSP which handles the state machine, trip processing and fast tuner control.

- CBETA puts very strict limits on cavity field stability in situations of high beam loading(~ 40 mA) and also in cavities having high Q_L(~ $6 \cdot 10^7$).

- Tests on 2-cell cavities developed for the Cornell ERL injector and in TESLA cavities at HoBiCaT demonstrate that the system is indeed capable of reaching these requirements.

- Fast tuning for Lorentz force and microphonics compensation along with automatic coarse tuning have been demonstrated and is actively under development for the CBETA project.

Acknowledgements

People who contributed to this work.

1. John Dobbins
2. Prof Georg Hoffstaetter
3. Roger Kaplan
4. Peter Quigley
5. Prof Matthias Liepe
6. Charles Strohman
7. Vadim Vescherevich

Thank you!

References

1. CESR Web pages. https://www.classe.cornell.edu/Research/CESR/WebHome.html

2. G.H. Hoffstaetter et al., CBETA Design Report, Cornell-BNL ERL Test Accelerator, arXiv:1706.04245 [physics.acc-ph], 2017

3. ERL LLRF Web Page https://www.classe.cornell.edu/~jad/erl_llrf_docs/ERL_LLRF_Controls.html

4. Status of the Cornell ERL SRF Cryomodule https://www.classe.cornell.edu/~liepe/webpage/docs/TU303.pdf

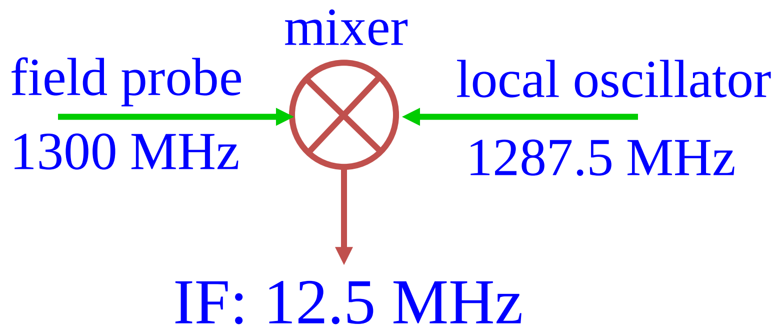
5. A. Neumann et al., CW Measurements of the Cornell LLRF System at HoBiCaT, MOPO67, Proceedings of SRF 2011

6. Z. A. Conway et al., Fast Piezoelectric Actuator Control of Microphonics in the CW Cornell ERL Injector Cryomodule, TU5PFP043, Proceedings of PAC 2009

7. N. Banerjee et al., Microphonics Compensation for Low Bandwidth SRF Cavities in the CBETA ERL, O-19, LLRF 2017

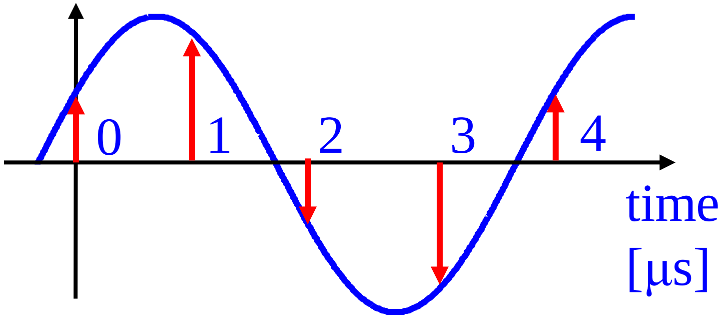
Appendix 1: Digital I-Q Detection

1.



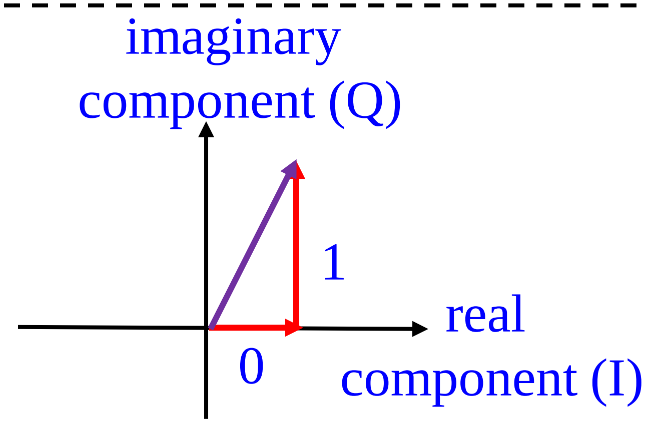
down-conversion of cavity field probe signal; complete amplitude and phase information is preserved

2.



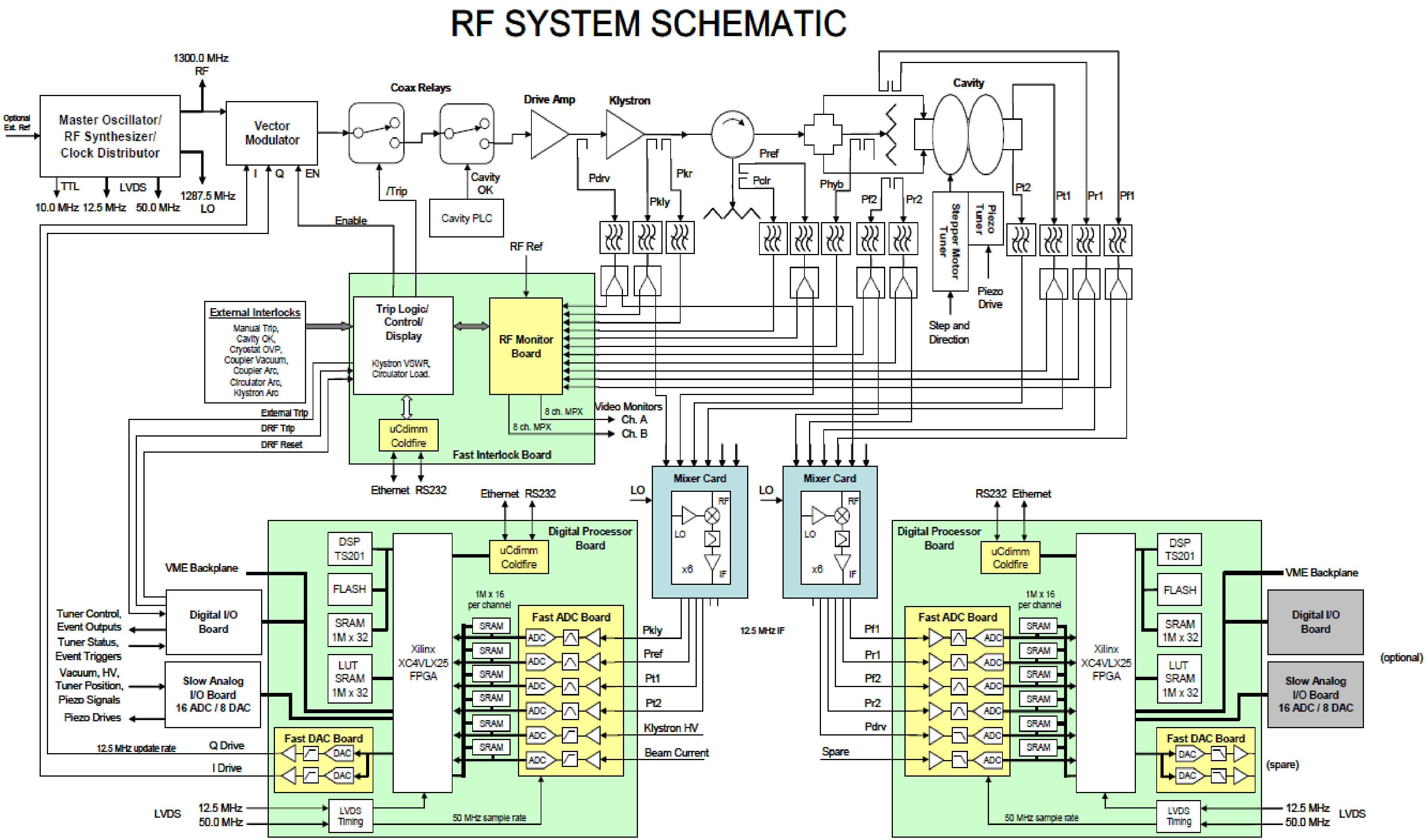
IF signal is sampled at 4*12.5 MHz rate

3.

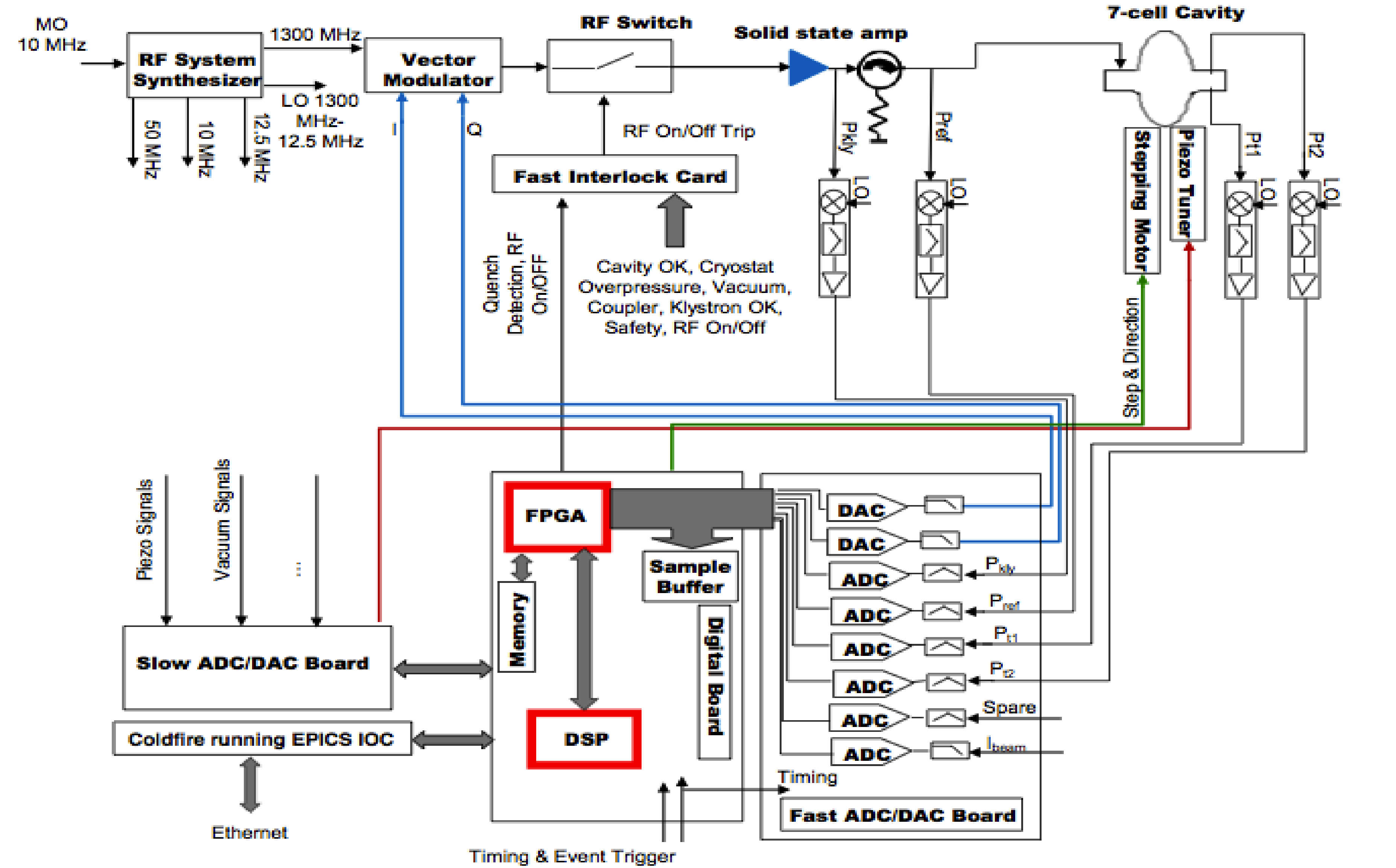


consecutive data points describe real and imaginary part of cavity field (I&Q)

Appendix 2: Injector LLRF Layout



Appendix 3: Main Linac LLRF Layout

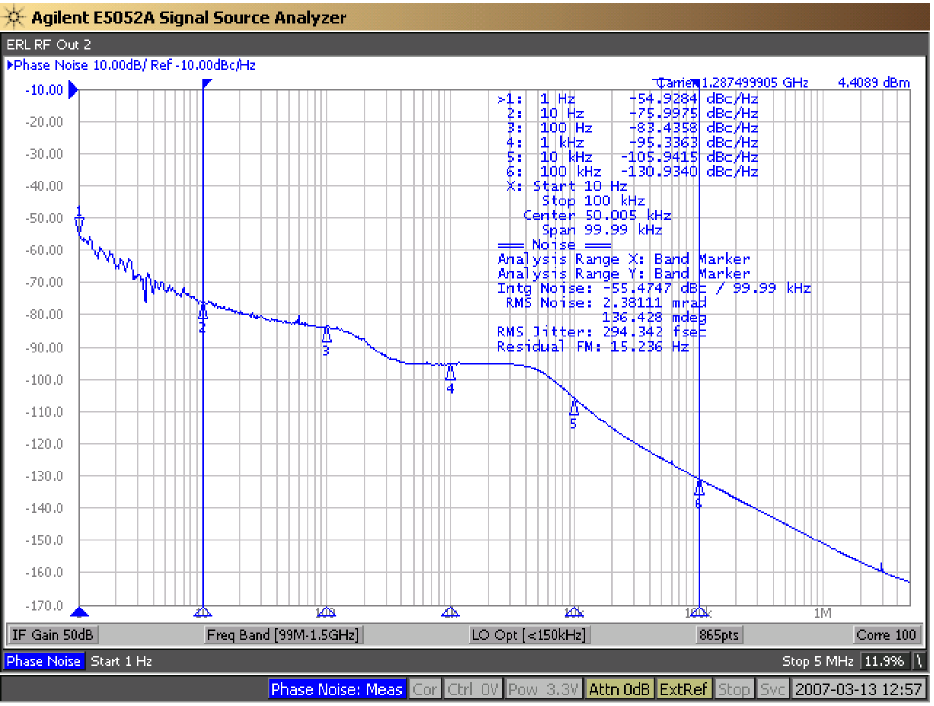


Appendix 4: RF Reference System

Need phase noise <<300 fs for 0.15deg phase stability at 1.3 GHz

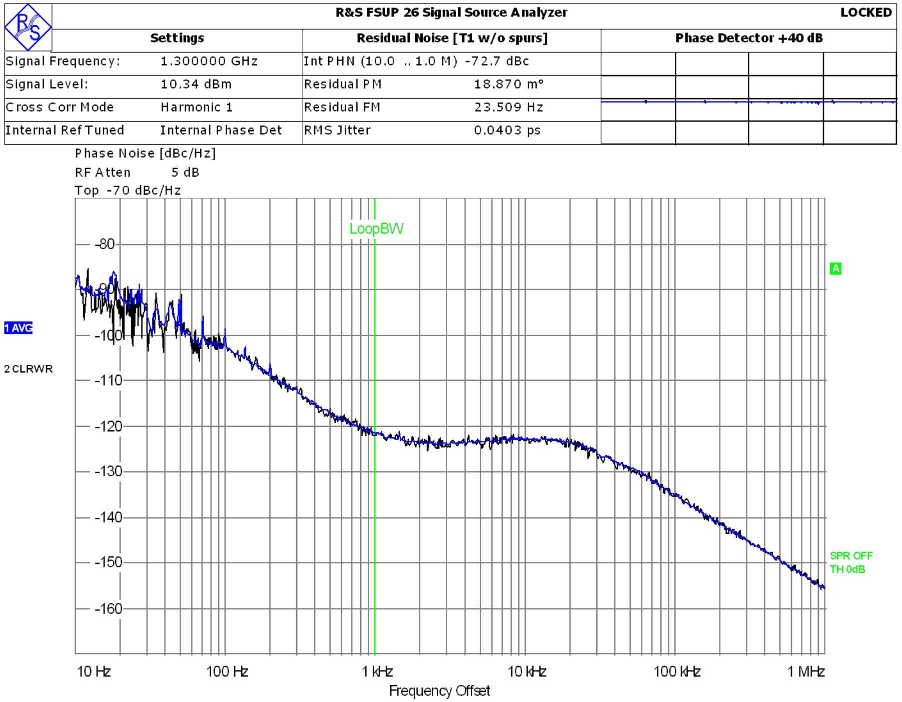
ERL injector master oscillator

- ~300 fs rms jitter



Test system master oscillator

- ~40 fs rms jitter



New MO system based on test system will be designed and fabricated for CBETA.

Appendix 5: Field Uncertainty

Injector Cavity Phase Stability