PIP-II LLRF Introduction and Overview

P. Varghese – L3 LLRF/RFPI
PIP-II LLRF Final Design Review

July 17, 2024

A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST

LLRF FDR Content

- Introduction
- Collaboration
- PIP-II overview and requirements
- System Design, Simulations
- Results from Testing at CMTF and STC
- Status of RFPI, MO/PRL, BPG and WFE upgrades
- Summary

CMTF	- Cryo Module Test Facility
STC	- Spoke resonator Test Cave
RFPI	- RF Protection and Interlocks
MO	- Master Oscillator
PRL	- Precision Reference Line
BPG	- Beam Pattern Generator
WFE	- Warm Front End

About Me:

- **Philip Varghese**
  - L3 Manager for LLRF and RFPI
  - Ph.D. Electrical Engineering
  - 30+ Years Experience, 22 Years in FNAL LLRF Group
  - >7 years of direct involvement with PIP-II
- Relevant Experience
  - Principal Engineer, LLRF Group Leader
  - Lead Engineer: PIP-II IT LLRF System design/testing
  - Lead Engineer: Design of 3 generations of FPGA based LLRF Hardware for SRF cavity control
  - Resonance control studies on LCLS-II cavities
  - FAST/IOTA cryomodule LLRF system design/commissioning
  - Experience working with various collaboration teams for PIP-II and LCLS-II Projects
  - Extensive experience developing various LLRF systems for normal and superconducting cavities
- Previous Relevant Experience
  - 12 years, Embedded Systems, Industrial Controls, Automotive Electronics

DOE LLRF and International Collaborations

LLRF Teams from FNAL, JLab, SLAC and LBNL have been collaborating for the past 9 years in the context of LCLS-II and now PIP-II. We are integrating DAE and TUL into this collaboration.

TUL

DAE LLRF and RFPI systems for 325 MHz and 650 MHz cavities have been Received at FNAL and have completed preliminary testing

DAE Team is arriving at FNAL this year to complete testing with cavities

PIP-II LLRF Collaborations

Fermilab
Philip Varghese(L3)
Shereze Humphrey(CAM)
Shrividhyaa Sankar Raman(SE)
Lennon Reyes(EE)
Dan Klepec(Tech)
Matei Guran(EE)
Ahmed Syed(EE)
Pierrick Hanlet(SE)
Niral Patel(EE)

DAE (LLRF System and RFPI)
Gopal Joshi
BARC LLRF Team

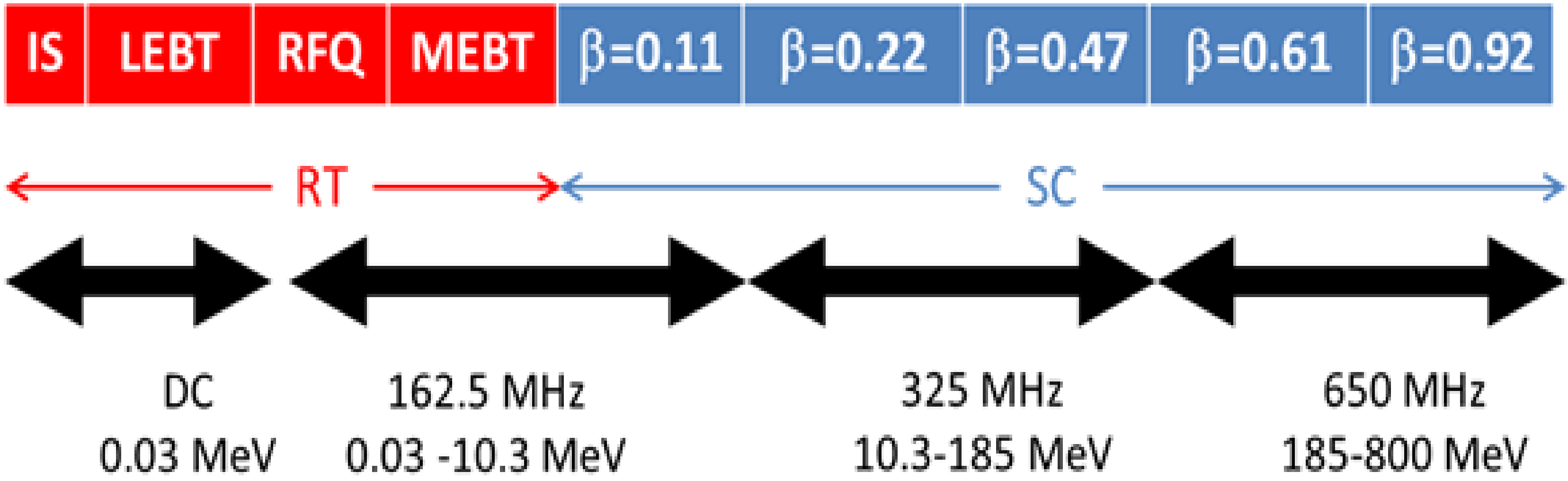
Berkeley Lab (LLRF Controller)
Qiang Du
Larry Doolittle
Shreeharshini Murthy

Jefferson Lab (Resonance Controller)
Curt Hovater
James Latshaw

SLAC (Beam Pattern Generator)
John Dusatko
Daron Chabot

SC Linac - Main Part of PIP-II

- SC Linac consists of
  - Room temperature front end (up to 2.1 MeV)
  - SC (cold) linac
    - 5 types of SC cavities: HWR, SSR1, SSR2, LB650, HB650
- 3 RF frequencies are used for acceleration



IS | LEBT | RFQ | MEBT | β=0.11 | β=0.22 | β=0.47 | β=0.61 | β=0.92

RT

SC

DC
0.03 MeV

162.5 MHz
0.03 -10.3 MeV

325 MHz
10.3-185 MeV

650 MHz
185-800 MeV

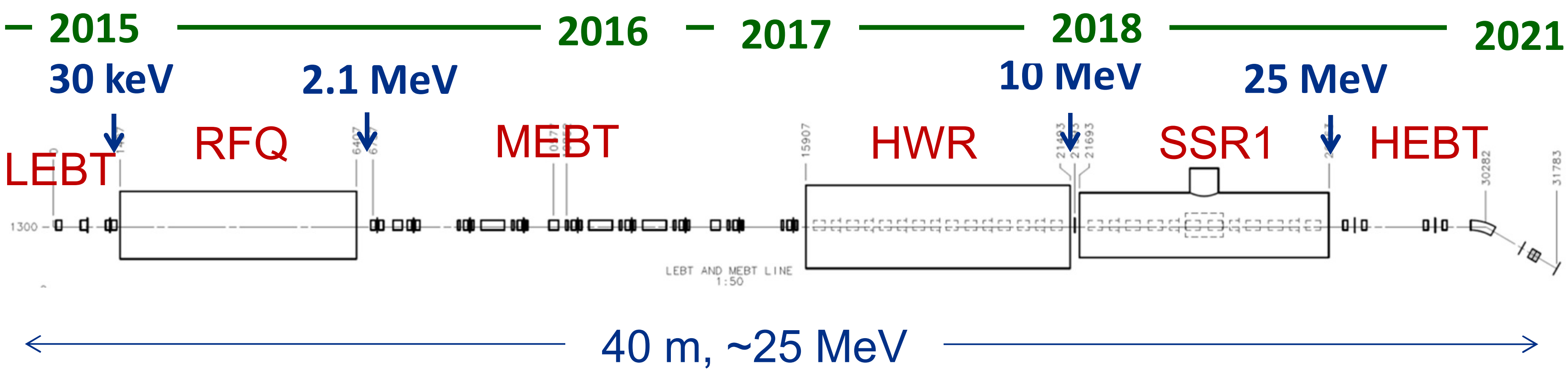
β in the above figure: optimal for HWR, SSR1, SSR2; geometric for LB650, HB650

PIP-II High Level Performance Parameters

Performance Parameter	PIP	PIP-II	Unit
Linac Beam Energy	400	800	MeV
Linac Beam Current (chopped)	25	2	mA
Linac Pulse Length	0.03	0.54	ms
Linac Pulse Repetition Rate	15	20	Hz
Linac Upgrade Potential	N/A	CW	
Booster Protons per Pulse (extracted)	4.2	6.5	10^{12}
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	166	kW
8 GeV Beam Power to LBNF	N/A	83-142*	kW
Beam Power to 8 GeV Program	30	83-24*	kW
Main Injector Protons per Pulse (extracted)	4.9	7.5	10^{13}
Main Injector Cycle Time @ 120 GeV	1.33	1.2	sec
Main Injector Cycle Time @ 60 GeV	N/A	0.7	sec
Beam Power @ 60 GeV	N/A	1	MW
Beam Power @ 120 GeV	0.7	1.2	MW
Upgrade Potential @ 80-120 GeV	N/A	2.4	MW

* First number refers to Main Injector operations at 120 GeV; second number to 60 GeV.

PIP2IT:



Phase 1: retirement of risks associated with operation of the PIP-II linac in pulsed mode as required for neutrino operations and described in the CDR (1% duty factor). The primary risks to be retired during this period (now-2020) include:

- Achievement of required beam characteristics from the ion source through the SSR1 cryomodule
  - Operated 2 mA, 20 Hz, 550 μsec through MEBT ✓
- Demonstration of MEBT chopper operations at a level required for Booster injection
  - Operated 2 prototype kickers with these parameters ✓
- Demonstration of the operation of the HWR cryomodule, with beam, with resonance control, in close proximity to the MEBT beam absorber ✓
- Demonstration of stable beam acceleration in the SSR1 cryomodule, under the full control of prototype RF control systems, including resonance control ✓

Requirements Flow Down

- PIP-II performance goals and physics design flow down from the project Functional Requirements Specification
  - TC: #ED0001222
  - Pip2-docdb 1166
- PIP-II LLRF FRS
  - TC: #ED0004194

Main Physics Requirements

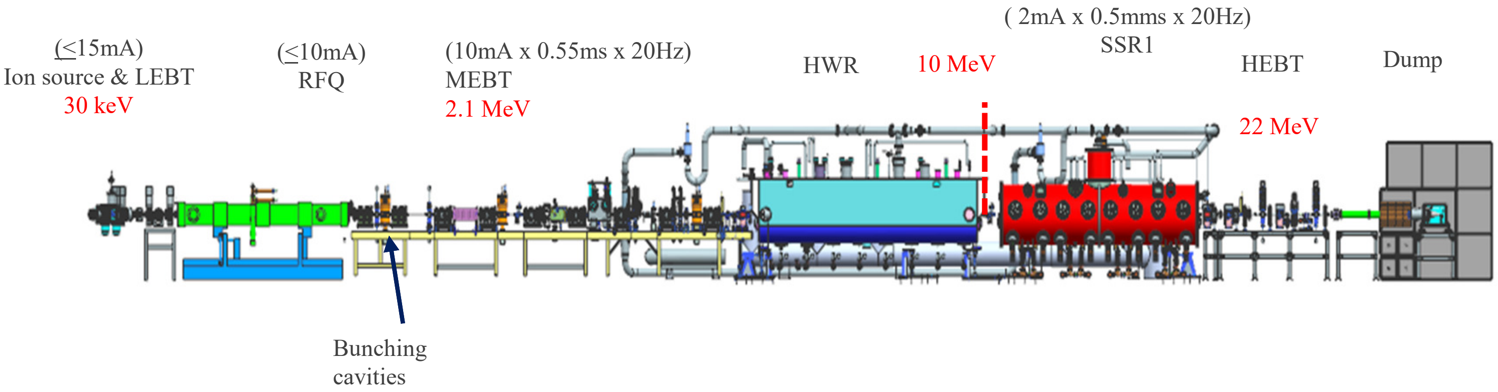
- 0.01% rms beam energy spread
- 0.01 deg. rms beam energy jitter

This then drives the cavity regulation requirements

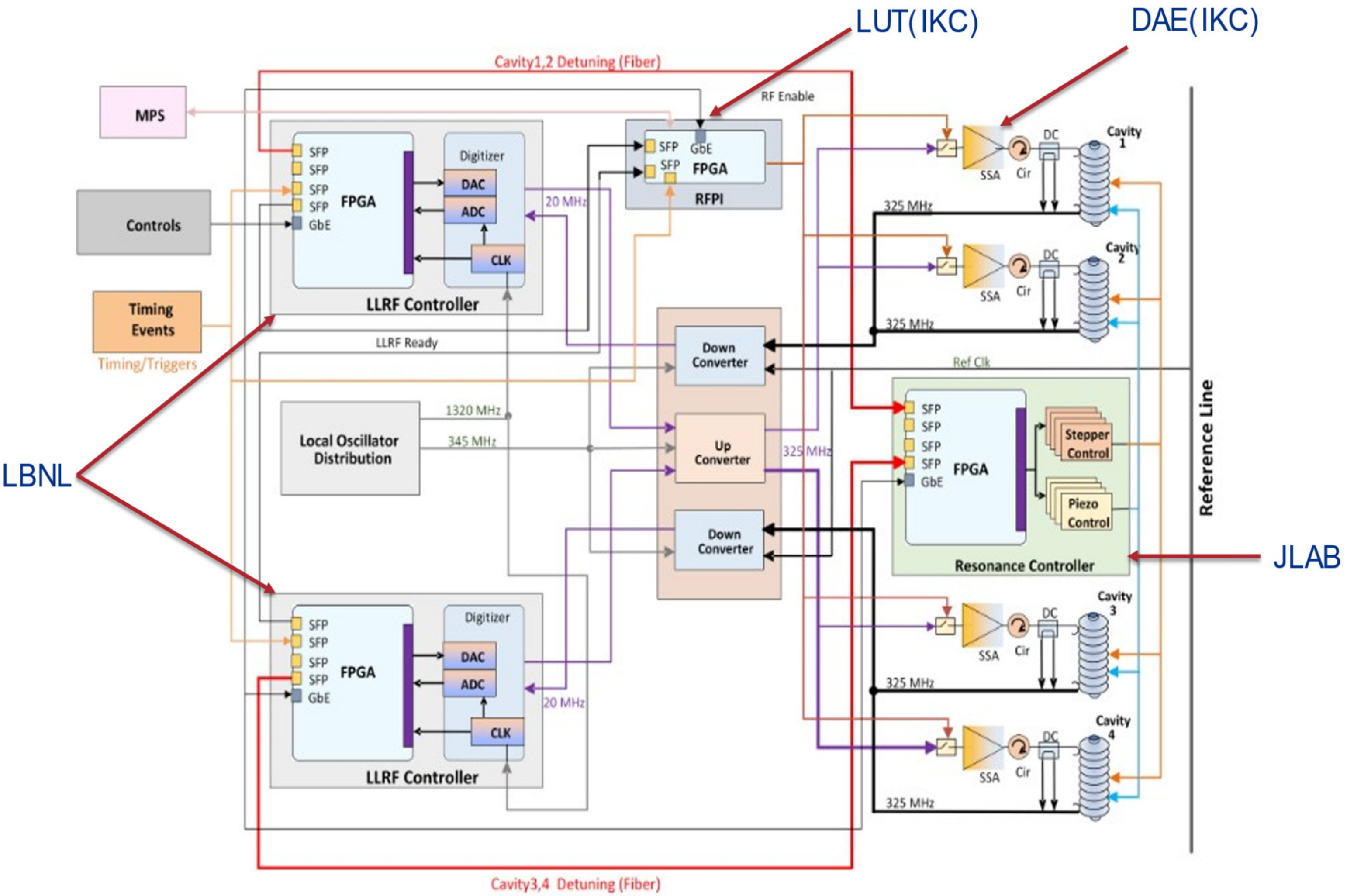
- 0.06% rms amplitude
- 0.06 deg rms phase

Proton Improvement Plan–II Injector Test

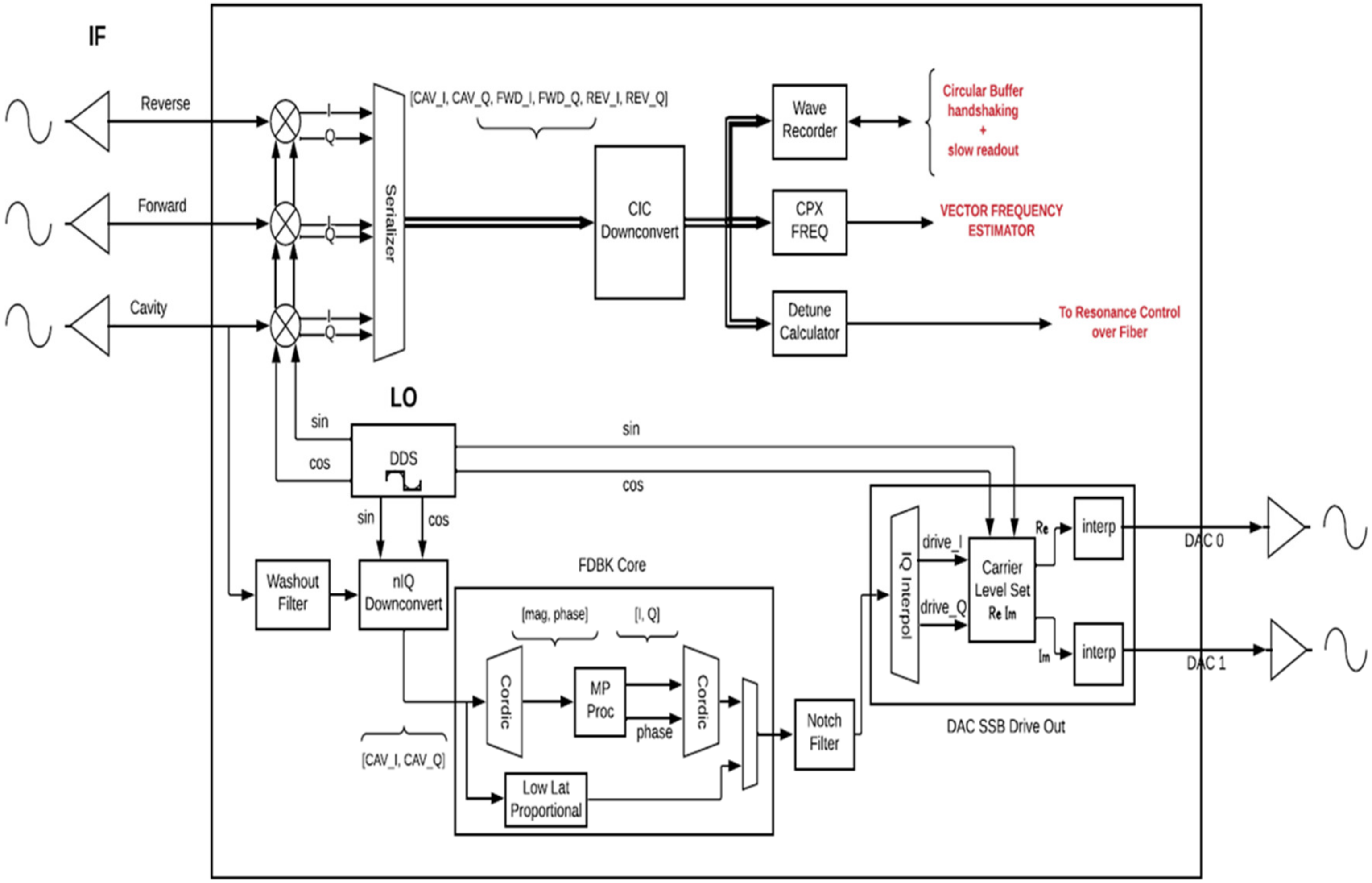
- LLRF System Prototypes Successfully Tested with beam
  - Field Controllers, Up/Down Converters (162.5,325,650 MHz)
  - Resonance Controllers - thermal, pneumatic and stepper/piezo
  - RF Protection and Interlocks
  - Beam Pattern Generator
  - Limited but highly successful operation of Berkeley(LCLS-II) system with EPICS interface



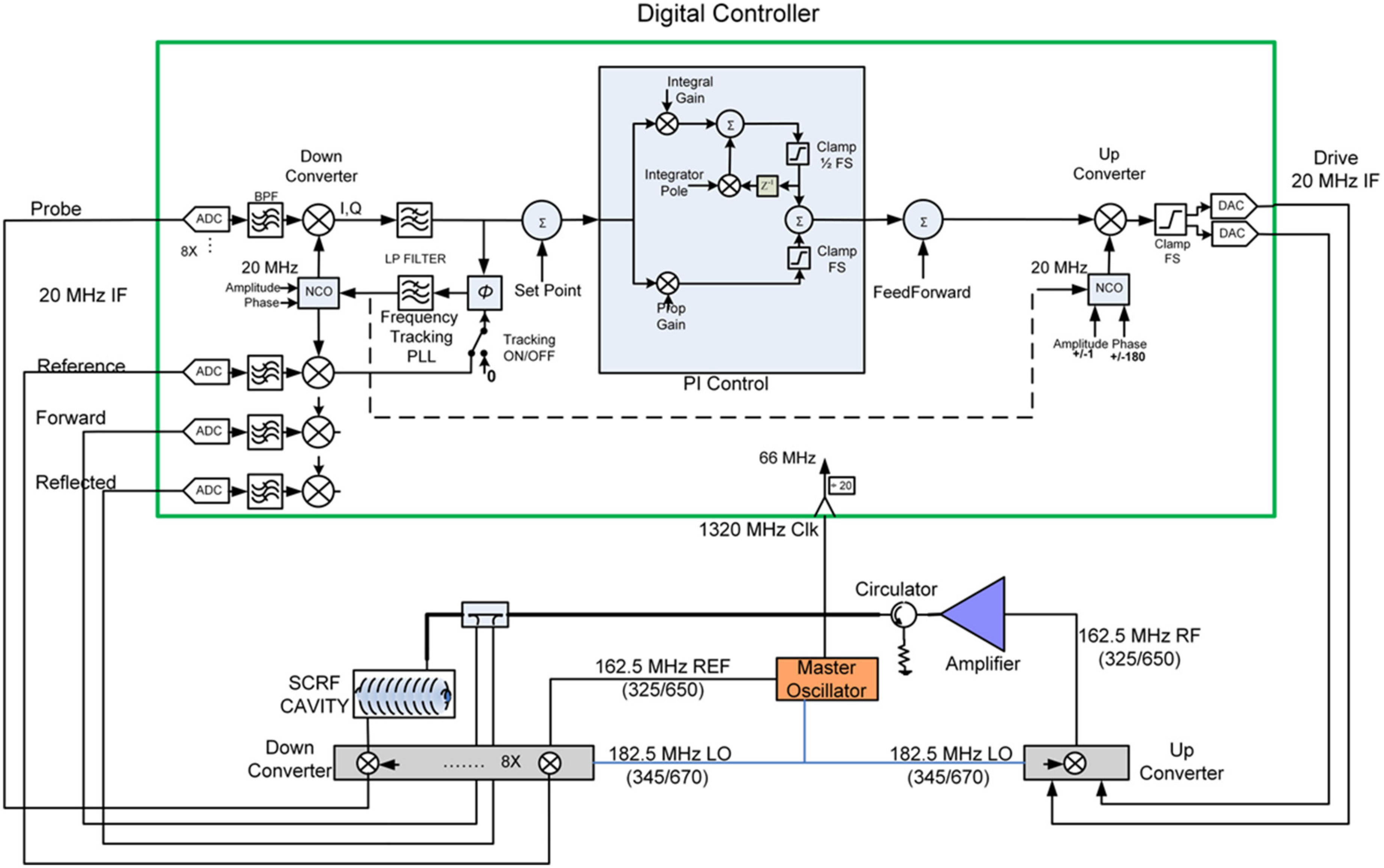
LLRF Systems Diagram



LLRF Control Architecture1 – Amplitude/Phase

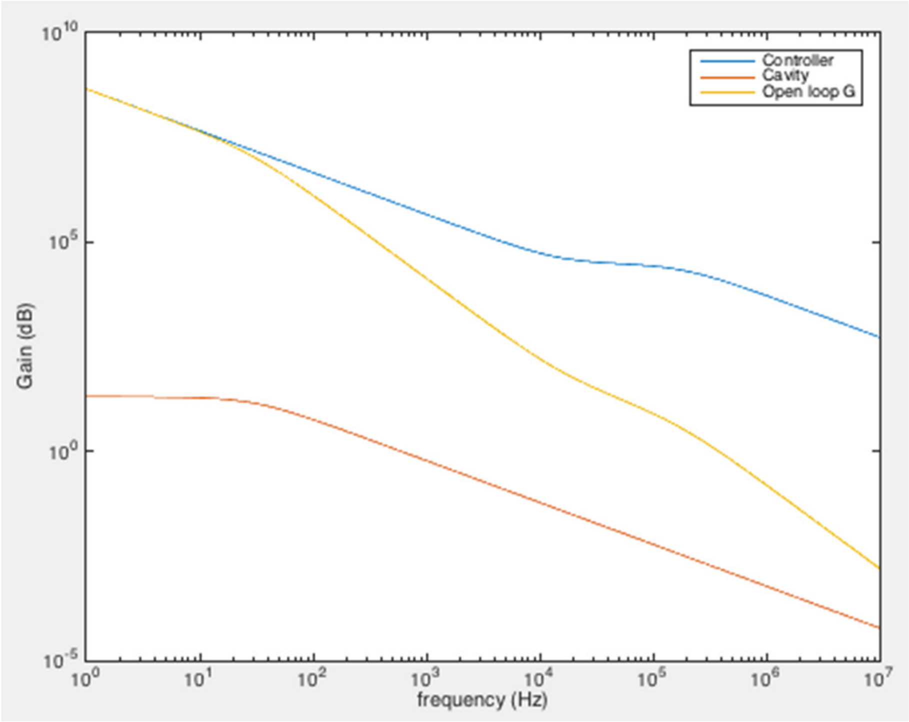


LLRF Control Architecture2 – I/Q Control

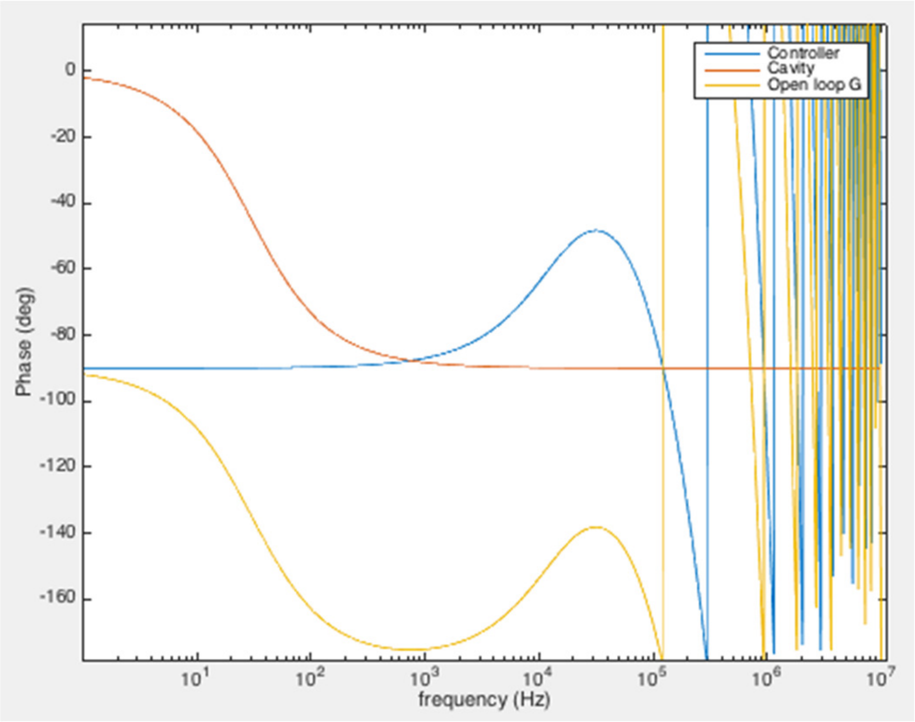


Open loop transfer function of cavity and controller

Magnitude



Phase



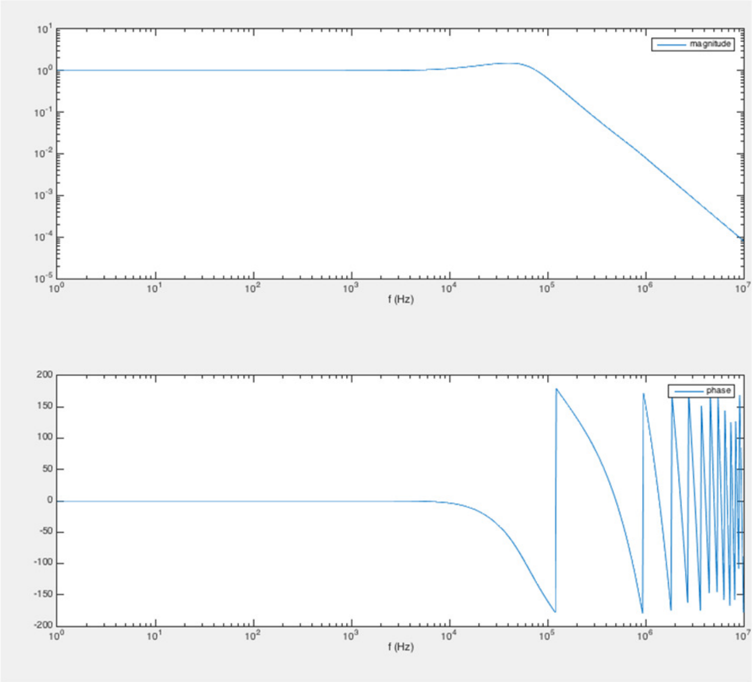
Max gain

Closed-loop bandwidth: ~50 kHz
Control system zero: 15 kHz
Proportional gain: 1500
Integral gain: 1.44e+08

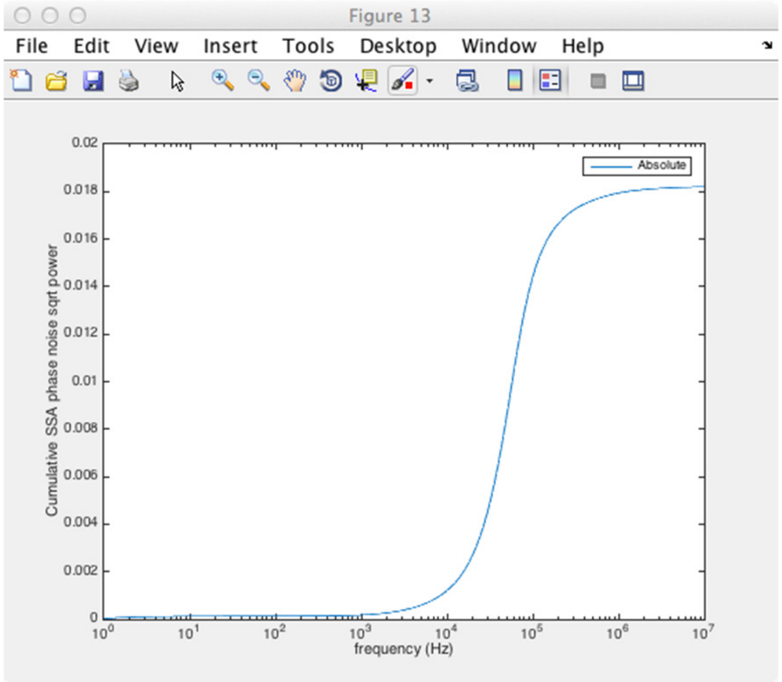
Nominal gain

Closed-loop bandwidth: ~25 kHz
Proportional gain: 750
Integral gain: 7e+07

Total phase noise to SSA from controller and oscillator



Closed loop response



Cumulative SSA phase noise voltage

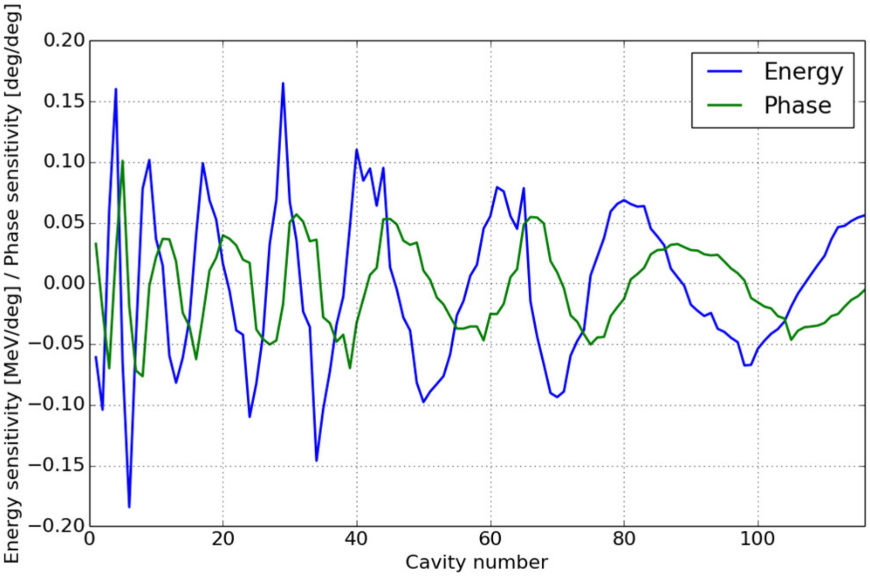
Careful attention to noise terms will allow high controller gains

- Cavity: 0.00078° rms
- SSA: 1.04°
- SSA from ADC noise 0.96°

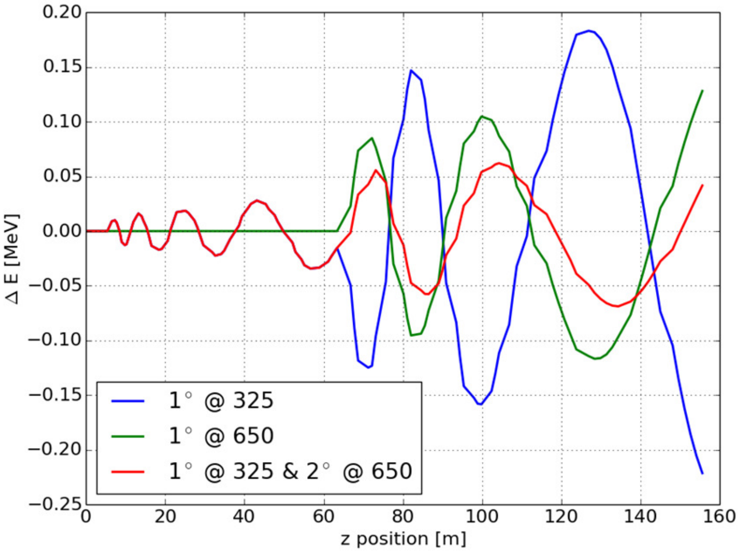
Code developed for LCLS-II
Larry Doolittle LBNL and FNAL

Phase-energy Stability Simulations

- Studying the amplitude and phase regulation requirements and their impact on the LLRF system
  - Study effects of perturbations on the cavities through beam simulations
  - Develop code that performs basic beam dynamics calculations as well as RF feedback simulations to study the interaction between the RF system



Linac output energy sensitivity to single cavity phase errors

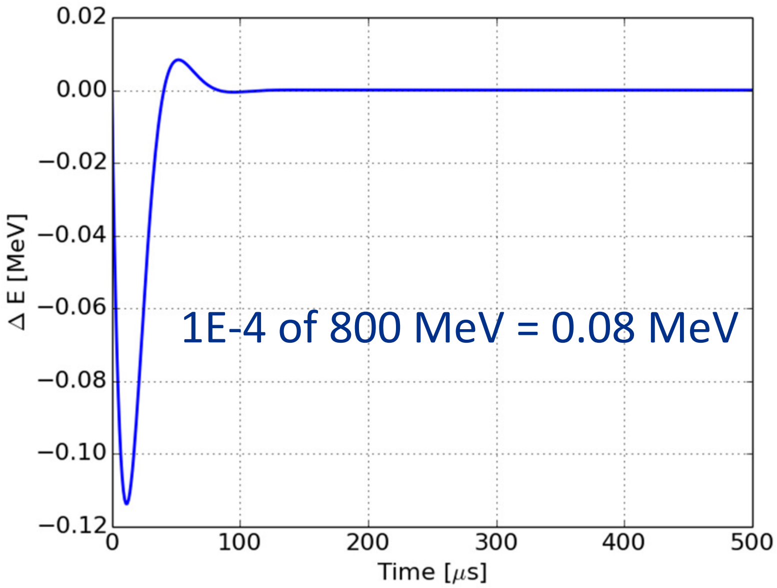


Linac output energy sensitivity to phase reference line phase errors at frequency transitions

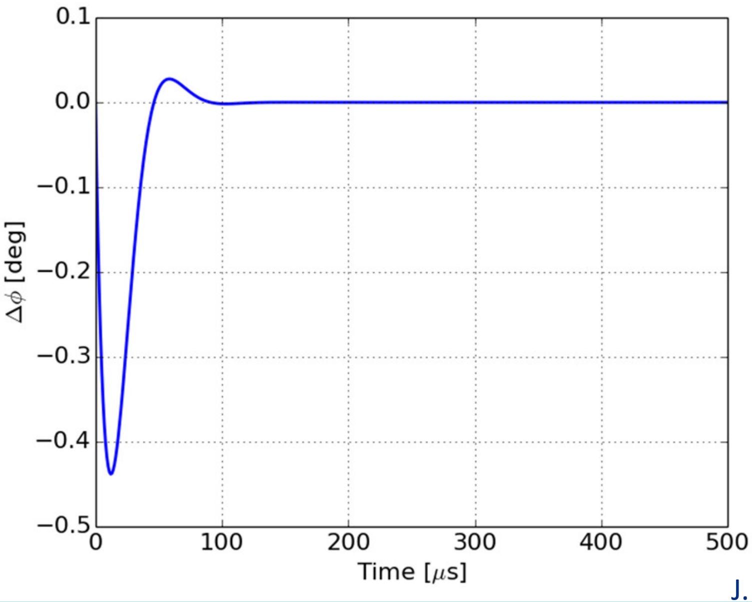
J. Edelen

Simulating the impact of RF transients due to beam-loading on the beam-parameters

- The feedback model for the RF cavity is done in python (and compared with existing MATLAB models)
- The energy gain for each cavity was calculated using simulation results from PARMELA and TraceWin
- The phase advance during drift spaces was calculated using analytic models
- The beam current was assumed to be 2mA average during the pulse
- Left: Change in energy along the beam pulse due to uncompensated transients in the RF system
- Right: Change in phase along the beam pulse due to uncompensated transients in the RF system

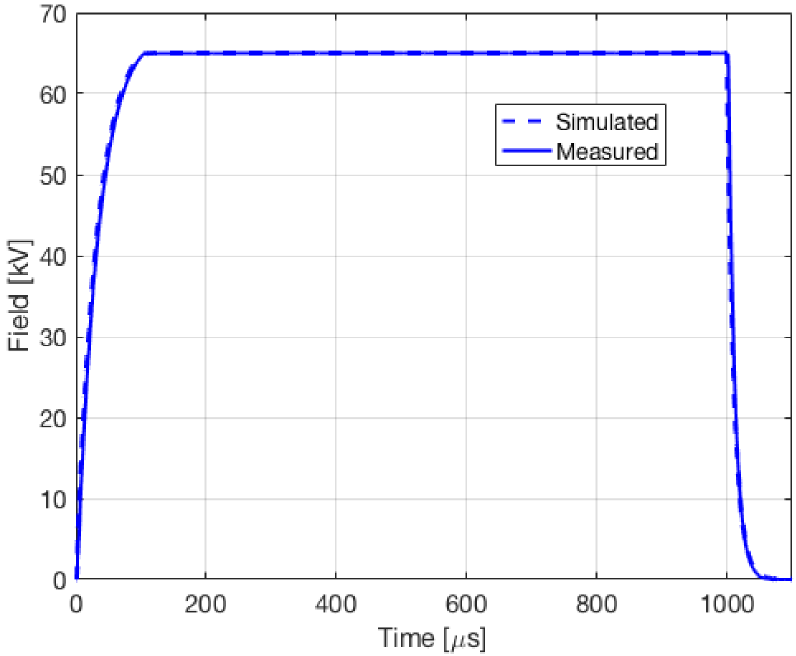


1E-4 of 800 MeV = 0.08 MeV

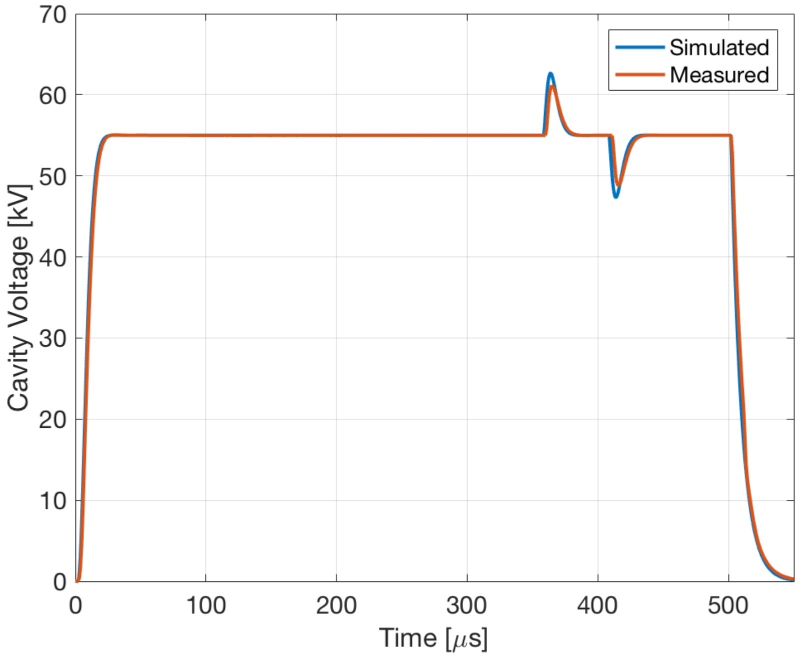


J. Edelen

RFQ and Buncher pulsed response



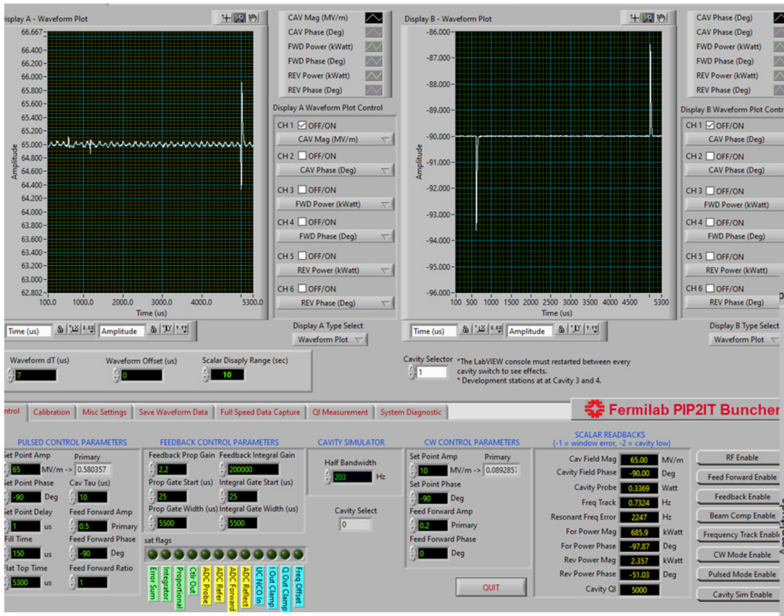
RFQ Pulse measured vs. simulated (Proportional and integral gains were 9.0 and 8.0e5 respectively)



Buncher simulated vs. measured (kp 3.5, ki 6.0e5, Ql ~5000)

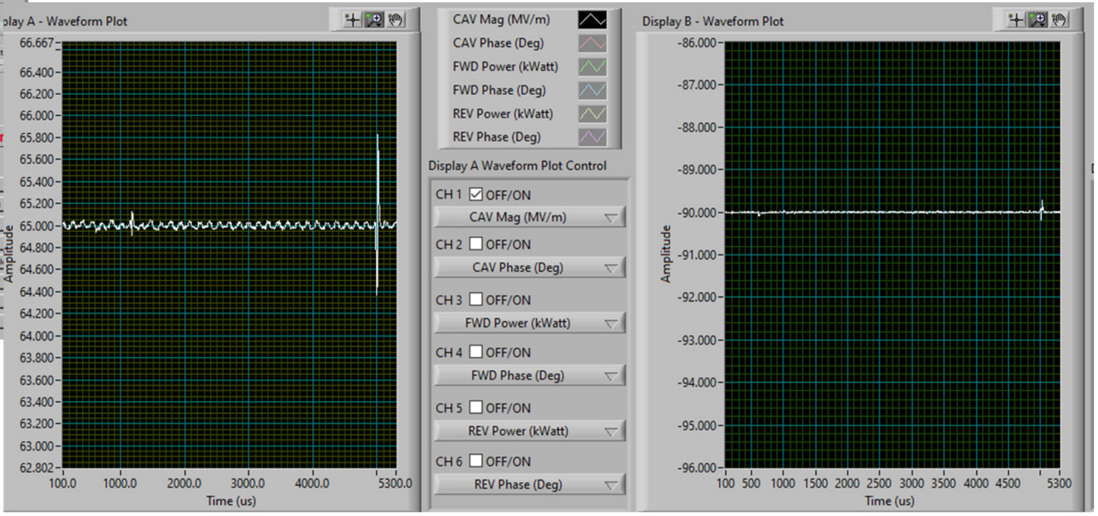
J. Edelen

Transient Response and Beam Loading Compensation Bunching cavity 2



- BLC works well and meets spec
- BLC learning system is not automated in this code version

BLC ON



BLC Tuning was focused on minimizing phase excursion at leading edge

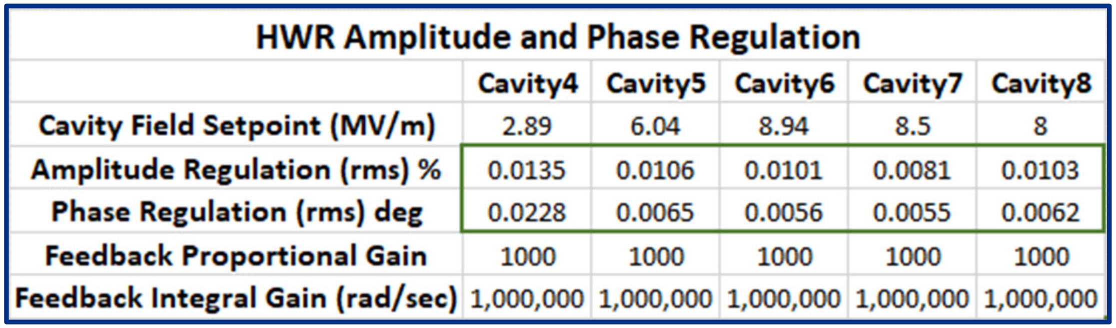
Phase disturbance reduced from -3.5 deg to < 0.2 deg

Performance of LLRF Systems at PIP2IT - 1

REGULATION (In Loop Measurements)

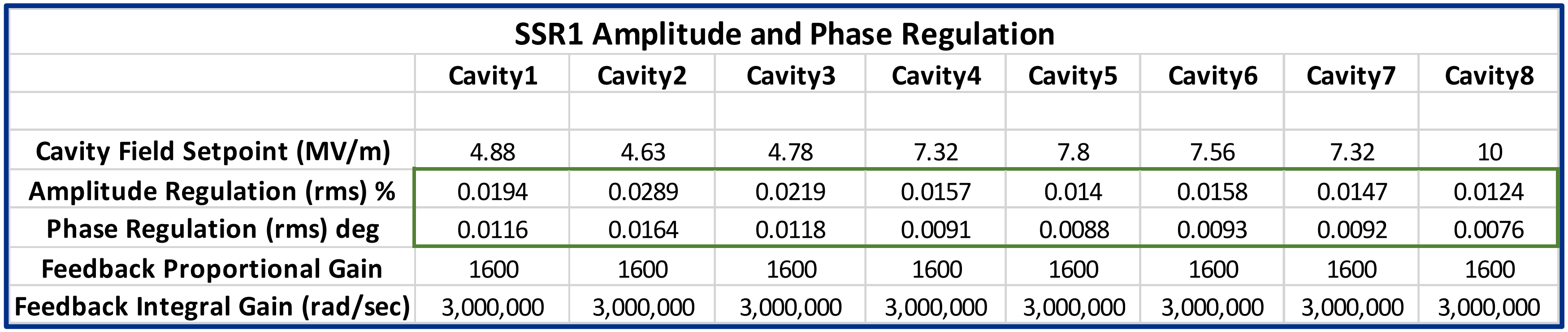
PIP-II Specifications

- Energy Stability (Linac) < 0.01%
- Phase Regulation < 0.065 deg rms
- Amplitude Regulation (individual cavity) < 0.065% rms



HWR Amplitude and Phase Regulation

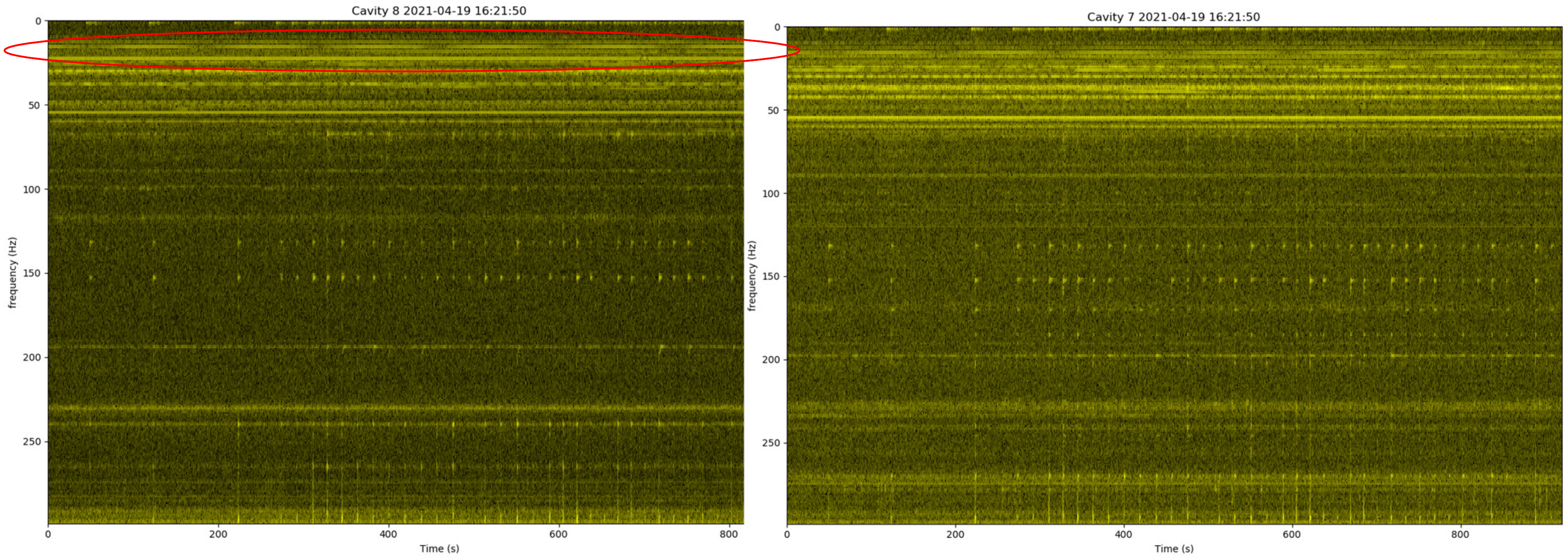
	Cavity4	Cavity5	Cavity6	Cavity7	Cavity8
Cavity Field Setpoint (MV/m)	2.89	6.04	8.94	8.5	8
Amplitude Regulation (rms) %	0.0135	0.0106	0.0101	0.0081	0.0103
Phase Regulation (rms) deg	0.0228	0.0065	0.0056	0.0055	0.0062
Feedback Proportional Gain	1000	1000	1000	1000	1000
Feedback Integral Gain (rad/sec)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000



SSR1 Amplitude and Phase Regulation

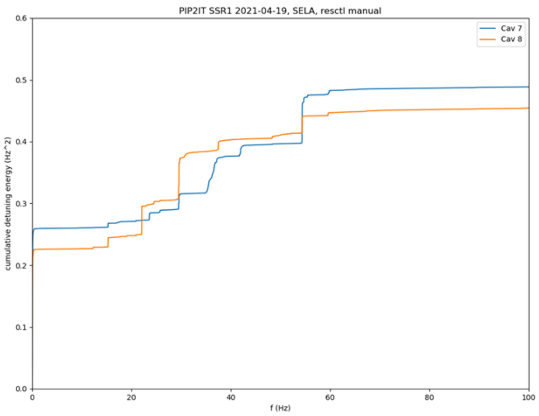
	Cavity1	Cavity2	Cavity3	Cavity4	Cavity5	Cavity6	Cavity7	Cavity8
Cavity Field Setpoint (MV/m)	4.88	4.63	4.78	7.32	7.8	7.56	7.32	10
Amplitude Regulation (rms) %	0.0194	0.0289	0.0219	0.0157	0.014	0.0158	0.0147	0.0124
Phase Regulation (rms) deg	0.0116	0.0164	0.0118	0.0091	0.0088	0.0093	0.0092	0.0076
Feedback Proportional Gain	1600	1600	1600	1600	1600	1600	1600	1600
Feedback Integral Gain (rad/sec)	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000

Spectrograms of Frequency Modulation of cavity detuning(7&8)



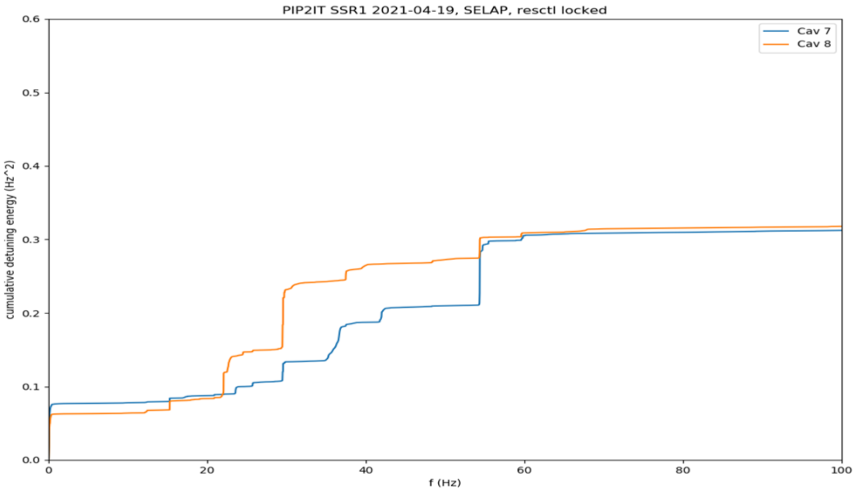
These spectrograms give insight into both external and internal noise and vibration sources
-Note strong continuous lines and 15 Hz line with 180 second beat period

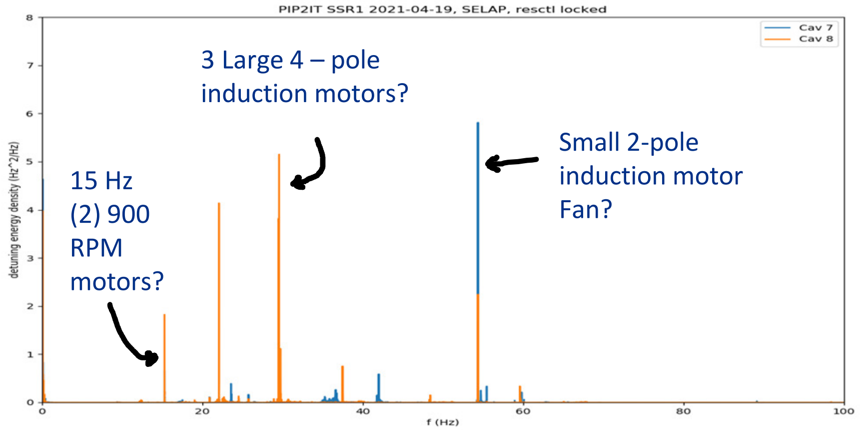
Microphonic Spectra SSR1



<-Resonance control feedback off – higher low frequency component

Rescon FB On ->





3 Large 4 – pole induction motors?

15 Hz (2) 900 RPM motors?

Small 2-pole induction motor Fan?

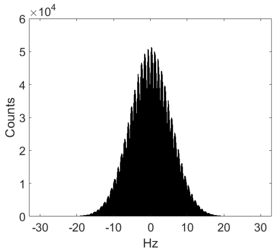
Identification of vibration sources is the first step to reducing microphonics

Microphonic levels were not bad enough to warrant investigation in PIP2IT

SSR1 Cavity Detuning Histograms

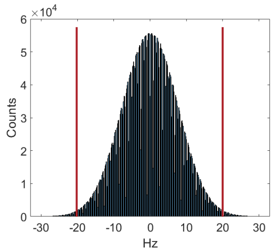
Cavity 2 exceeded the 20 Hz limit , there is a large power overhead for this cavity. This is not the case for all cavities in PIP-II

Some cavities show strong resonance lines seen in the non-gaussian histogram

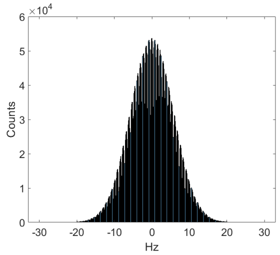


Cavity1

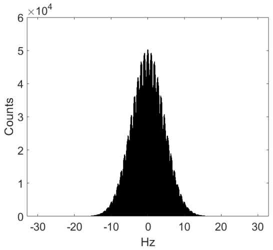
+- 20 Hz detune limits



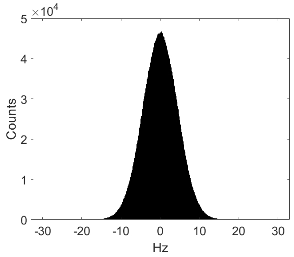
Cavity2



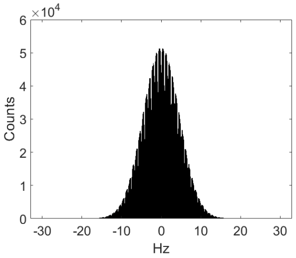
Cavity3



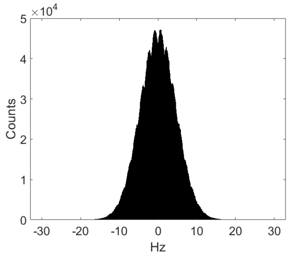
Cavity4



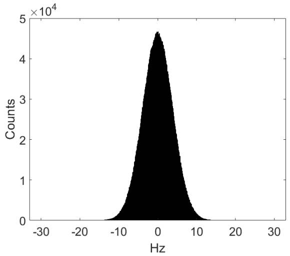
Cavity5



Cavity6

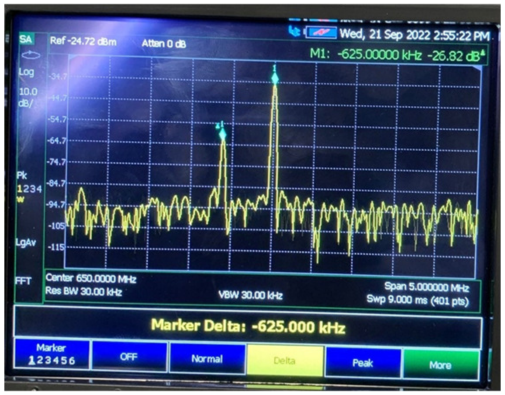


Cavity7

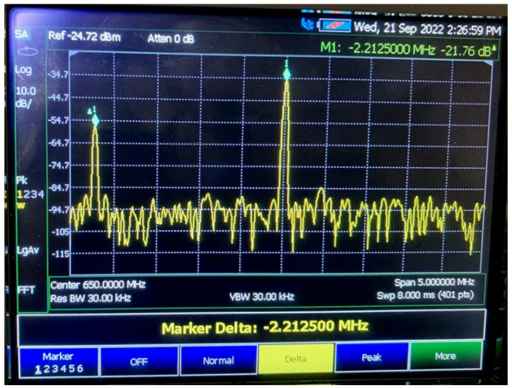


Cavity8

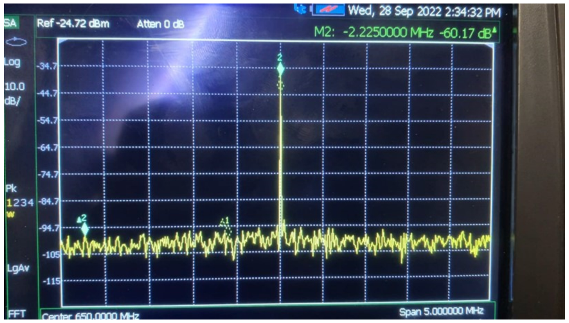
LB650 Cavity Measurements



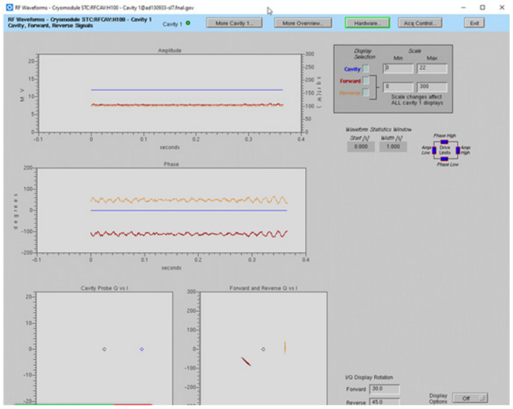
4/5π Mode, 625 kHz



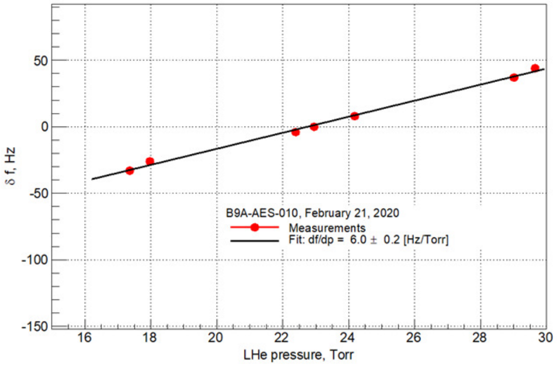
3/5π Mode, 2.125 MHz



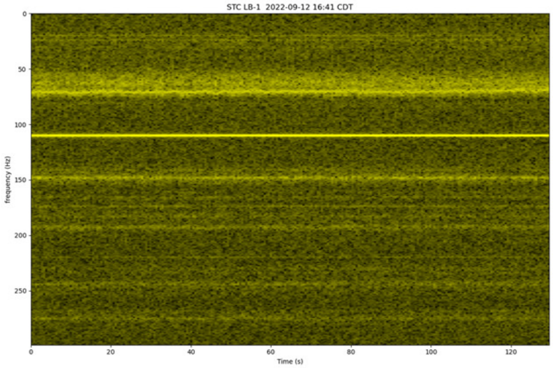
Suppression with notch filters



GDR Mode at 17 MV/m



LFD Coefficient = 2.4

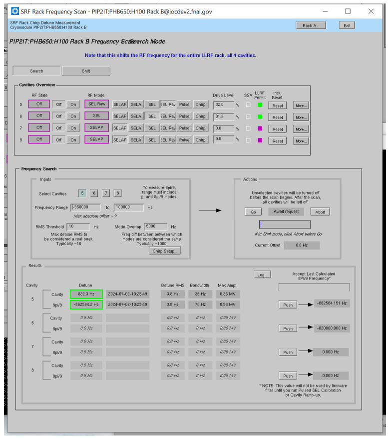


Detuning Spectrogram

Prototype HB650 Cryomodule Testing at CMTF

pHB650 Cryomodule

40 kW SSA



SRF Rack Frequency Scan - PIP2IT:PHB650:H100 Rack B@iocdev2.fnal.gov

SRF Rack Chirp Detune Measurement
Cryomodule PIP2IT:PHB650:H100 Rack B

PIP2IT:PHB650:H100 Rack B Frequency ScaSearch Mode

Note that this shifts the RF frequency for the entire LLRF rack, all 4 cavities.

Cavities Overview

	RF State			RF Mode							Drive Level	SSA	LLRF Permit	Intlk Reset	
5	Off	Off	On	SEL Raw	SELAP	SELA	SEL	SEL Raw	Pulse	Chirp	32.0 %	☐	🟩	Reset	More...
6	Off	Off	On	SEL	SELAP	SELA	SEL	SEL Raw	Pulse	Chirp	31.2 %	☐	🟩	Reset	More...
7	Off	Off	On	SELAP	SELAP	SELA	SEL	SEL Raw	Pulse	Chirp	0.0 %	☐	🟪	Reset	More...
8	Off	Off	On	SELAP	SELAP	SELA	SEL	SEL Raw	Pulse	Chirp	0.0 %	☐	🟪	Reset	More...

Frequency Search

Inputs

Select Cavities: 5 6 7 8

To measure 8pi/9, range must include pi and 8pi/9 modes.

Frequency Range -950000 to 100000 Hz

Max absolute offset ~ ?

RMS Threshold 10 Hz

Max detune RMS to be considered a real peak. Typically ~10

Mode Overlap 5000 Hz

Freq diff between between which modes are considered the same Typically ~1000

Actions

Unselected cavities will be turned off before the scan begins. After the scan, all cavities will be left off.

If in Shift mode, click Abort before Go

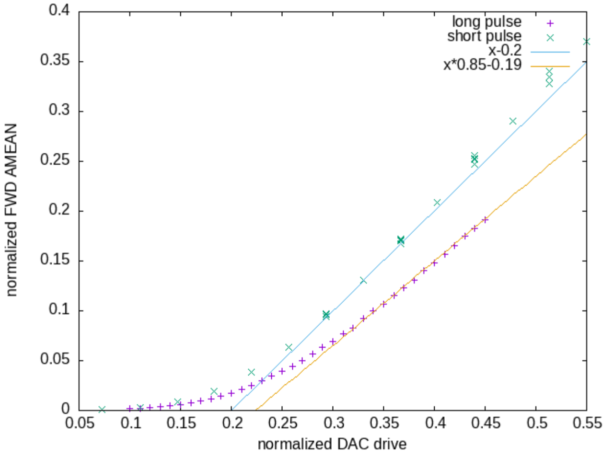
Current Offset 0.0 Hz

Results

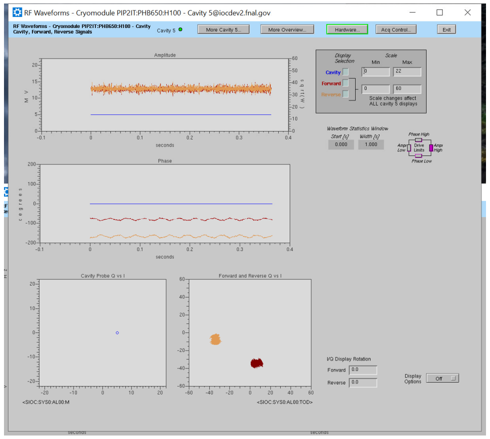
Cavity		Detune		Detune RMS	Bandwidth	Max Ampl	Accept Last Calculated 8PI/9 Frequency*
5	Cavity	832.3 Hz	2024-07-02-10:25:49	3.8 Hz	38 Hz	0.36 MV	
	8pi/9	-862564.2 Hz	2024-07-02-10:25:49	3.8 Hz	70 Hz	0.53 MV	Push → -862564.151 Hz
6	Cavity	0.0 Hz		0.0 Hz	0 Hz	0.00 MV	
	8pi/9	0.0 Hz		0.0 Hz	0 Hz	0.00 MV	Push → -820000.000 Hz
7	Cavity	0.0 Hz		0.0 Hz	0 Hz	0.00 MV	
	8pi/9	0.0 Hz		0.0 Hz	0 Hz	0.00 MV	Push → 0.000 Hz
8	Cavity	0.0 Hz		0.0 Hz	0 Hz	0.00 MV	
	8pi/9	0.0 Hz		0.0 Hz	0 Hz	0.00 MV	Push → 0.000 Hz

* NOTE: This value will not be used by firmware filter until you run Pulsed SEL Calibration or Cavity Ramp-up.

Frequency Tune Calibration



SSA Calibration



RF Waveforms - Cryomodule PIP2IT:PHB650:H100 - Cavity 5@iocdev2.fnal.gov

RF Waveforms - Cryomodule PIP2IT:PHB650:H100 - Cavity
Cavity, Forward, Reverse Signals

Display Selection	*Scale* Min	Max
Cavity ☐	0	22
Forward ☐	0	60
Reverse ☐		

Scale changes affect ALL cavity 5 displays

Waveform Statistics Window

Start [s] 0.000

Width [s] 1.000

I/Q Display Rotation

Forward 0.0

Reverse 0.0

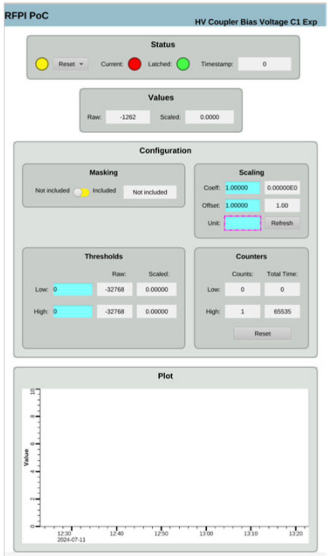
Display Options Off

SELAP Mode at 5 MV/m

RFPI Final Prototype Testing at CMTF

4 Cavity RFPI Module

SSA communication lattice error



Timestamp: 0

Raw: -1262 Scaled: 0.0000

Masking: Not included

Coeff: 1.00000 0.00000E0

Offset: 1.00000 1.00

Unit:

	Raw:	Scaled:
Low: 0	-32768	0.00000
High: 0	-32768	0.00000

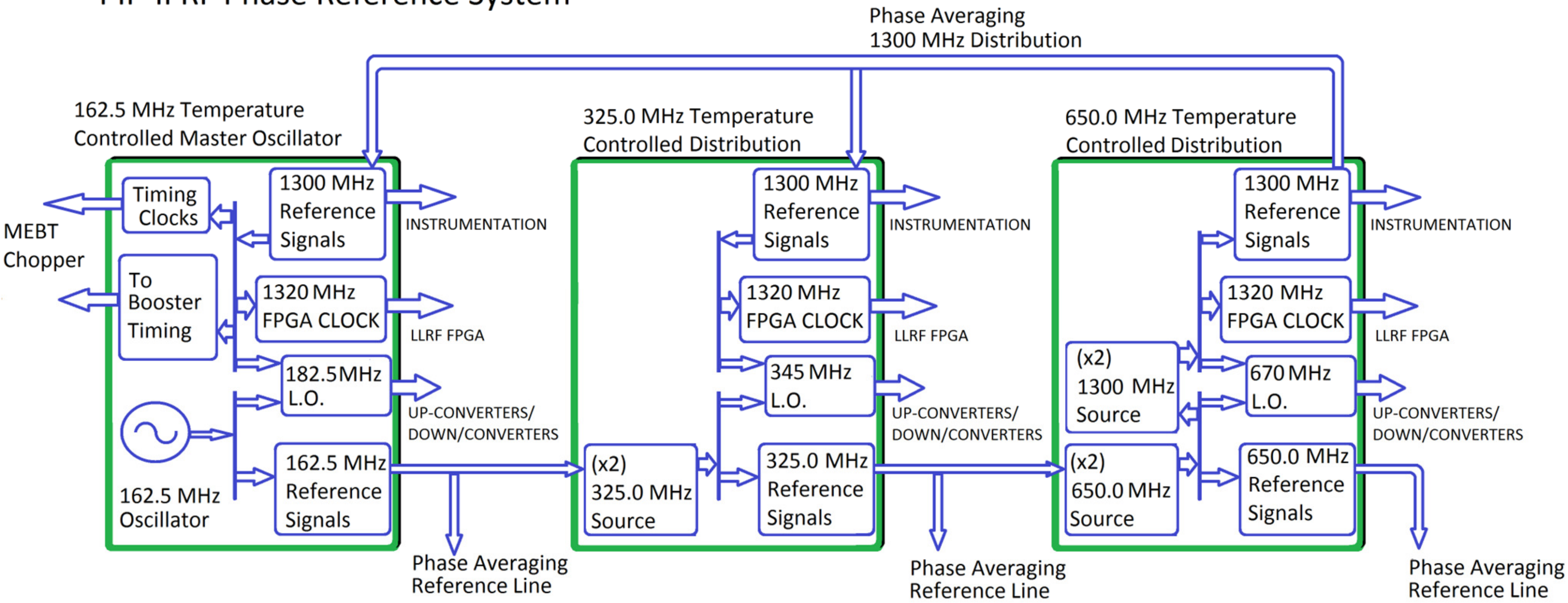
	Counts:	Total Time:
Low:	0	0
High:	1	65535

EPICS Interface

- A single cavity prototype was tested with a cavity at CMTF last year
- New 4-cavity RFPI chassis was installed at CMTF last month.
- Testing is continuing with remote participation of LUT
- RFPI FDR was completed in June 2024

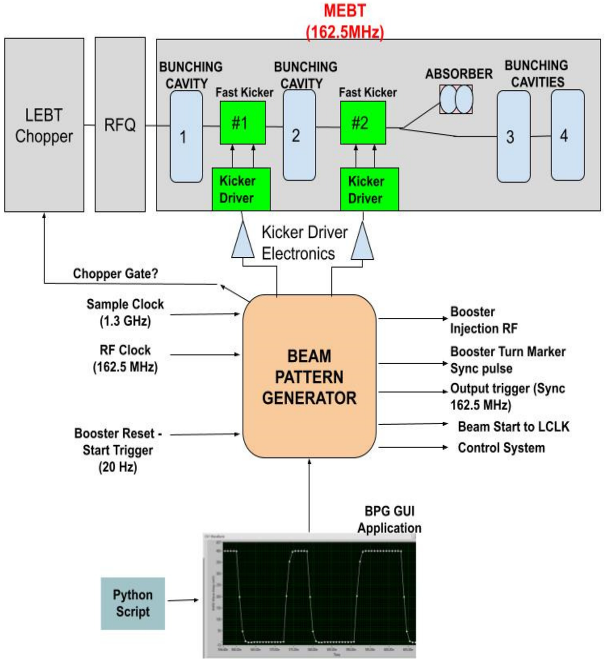
Master Oscillator and Reference Line - Status

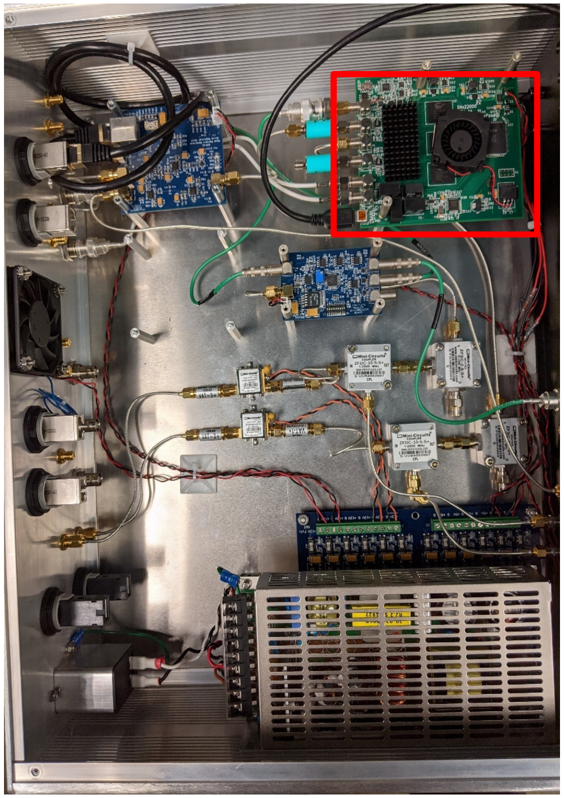
PIP-II RF Phase Reference System



- System block diagram complete.
- Reference line RF simulations nearly complete.
- Building locations and line lengths determined.
- Bill of material complete - parts have been ordered for testing.
- Lab space ready for full system assembly and testing.
- Master Oscillator source is in the process of being measured.
- FDR planned for mid 2025

Booster Injection –Beam Pattern Generator

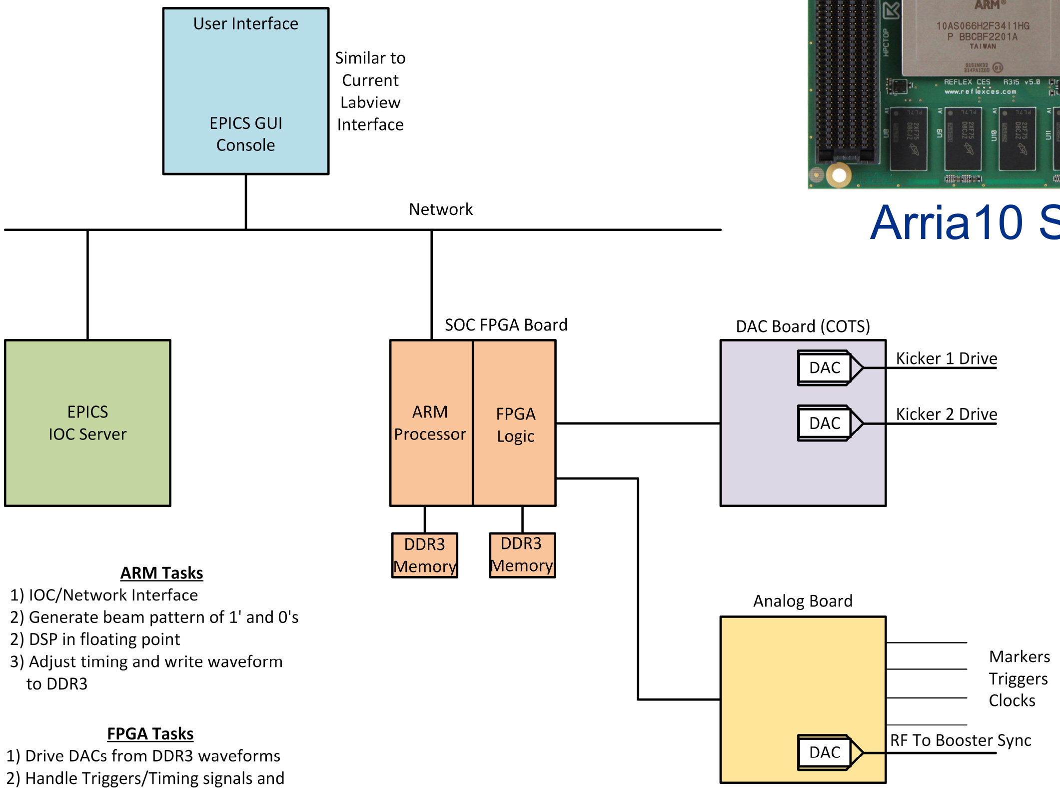




- Prototype Tested at PIP2IT
- Final design replaces obsolete AWG and replaces Labview interface with EPICS

Beam Pattern Generator Upgrade

Final Design Architecture



User Interface

EPICS GUI
Console

Similar to
Current
Labview
Interface

Network

EPICS
IOC Server

SOC FPGA Board

ARM
Processor

FPGA
Logic

DDR3
Memory

DDR3
Memory

DAC Board (COTS)

DAC — Kicker 1 Drive

DAC — Kicker 2 Drive

Analog Board

Markers
Triggers
Clocks

DAC — RF To Booster Sync

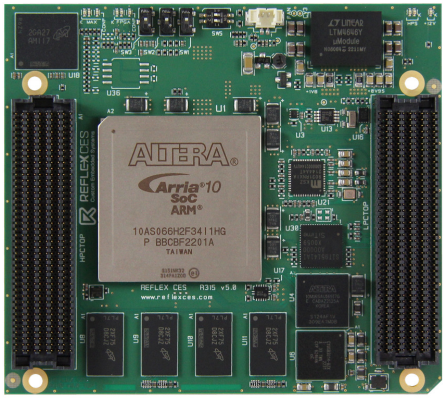
ARM Tasks

1) IOC/Network Interface
2) Generate beam pattern of 1' and 0's
2) DSP in floating point
3) Adjust timing and write waveform
   to DDR3

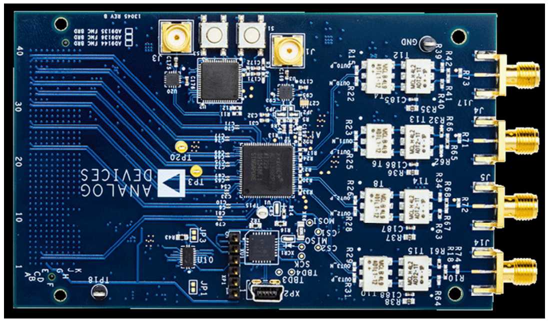
FPGA Tasks

1) Drive DACs from DDR3 waveforms
2) Handle Triggers/Timing signals and
markers

COTS Hardware Components



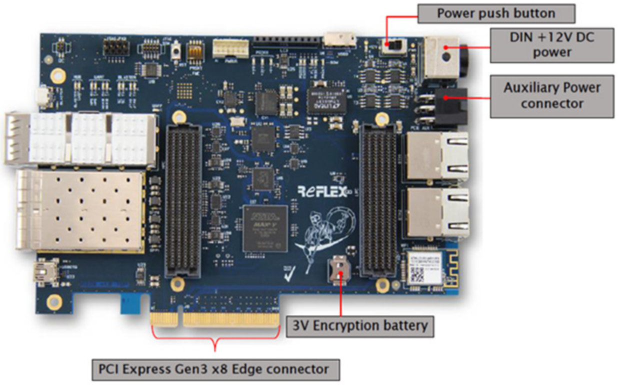
Arria10 SOM



2 ch HS DAC Board

AD9136-FMCEBZ

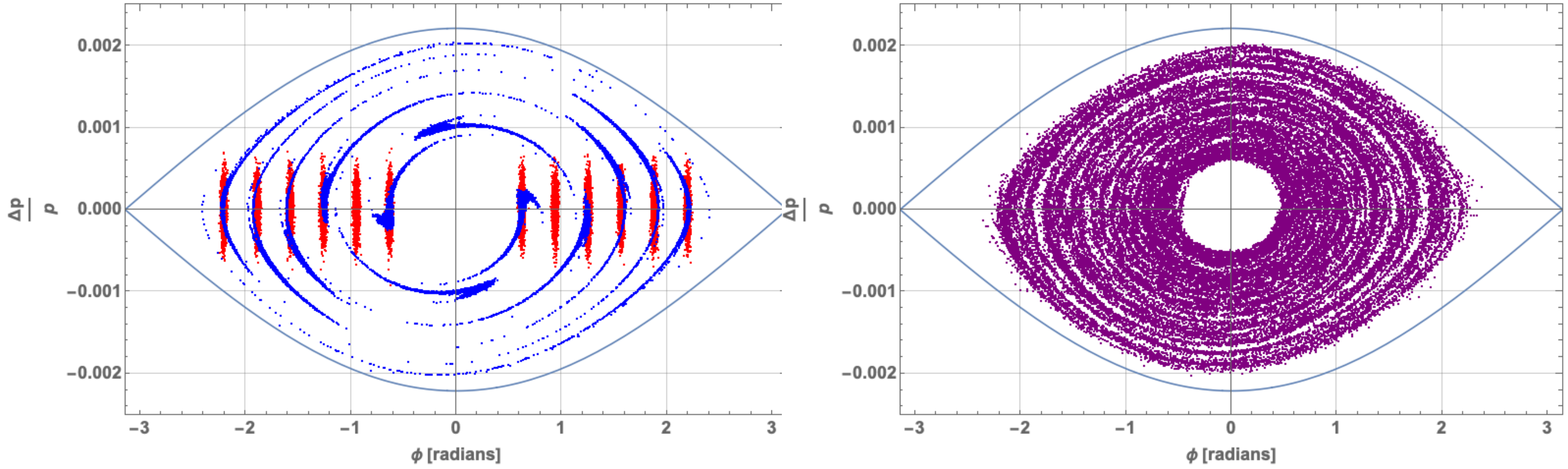
16-bit, 2.8 GSPS, Ext Clk Input



Carrier Board

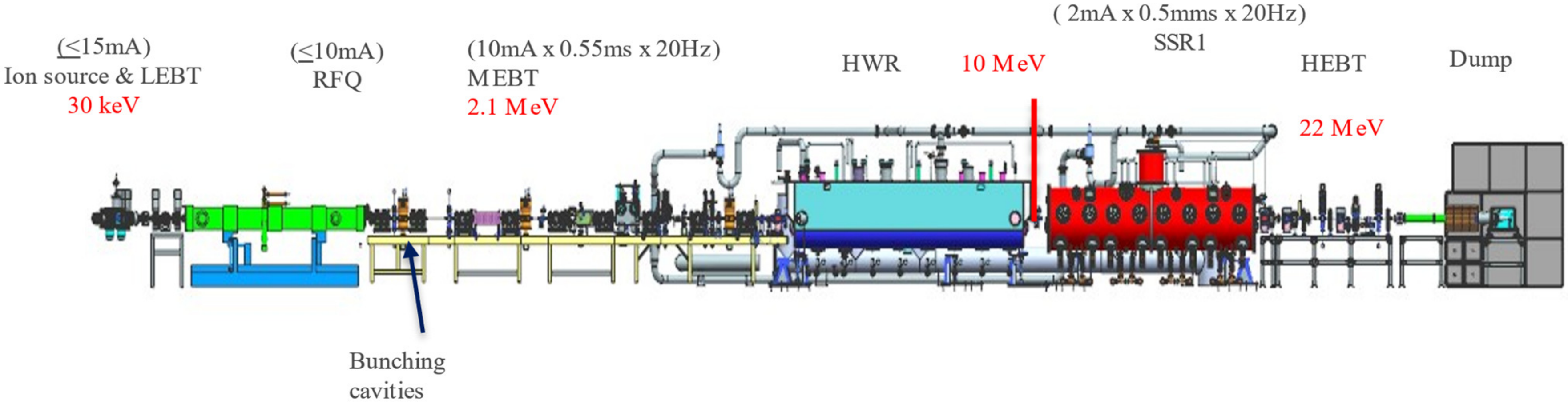
On Momentum Booster Injection Scheme for PIP-II

- Proposed overlap area for beam injection. The red dots are representative of beam in the incoming Linac buckets, the green dots are after 292 turns. Linac bucket centroids are are chosen to be in the range {−0.7π, −0.15π} or {0.15π, 0.7π}



PIP-II Document 4023-v1

WFE and HWR LLRF Controller Upgrade



RFQ,B1

B2,B3

HWR

- VXI Crate System is obsolete
- Cyclone V SOC board is limited in resources - EPICS needs to be added
- Arria 10 based FPGA board will be used to upgrade LLRF controllers
- BCR in process, FDR Planned for 2025

12 Months Look ahead

- pHB650 Cryomodule testing at CMTF provided the opportunity to test pre-production hardware/software components for LLRF and RFPI(IKC)
- LLRF Final Design Review – July 17, 2024
- STC single cavity testing provides additional testing opportunities.
- Beam Pattern Generator upgrade will start this month with an FDR in mid 2025
- EPICS control software and LLRF hardware can be tested with available cavity emulators
- LLRF system firmware/software documentation project is progressing well and will continue till FNAL team is fully trained in maintaining the code base
- Starting warm front end LLRF controller upgrade this year

Summary

- A number of LLRF hardware components have been tested and verified to meet project specifications
- Firmware, Software and EPICS interfaces are heavily leveraged from LCLS-II
- Detailed documentation of the LLRF system firmware/software is making good progress
- Cryomodule testing will be a continued test bed for LLRF development where we will work with all cavity types, further reducing risks.
- We have a strong DOE collaboration in place with the depth to carry us through the completion of the project (Fermilab, LBNL, Jefferson Lab and SLAC)
- Expect key contributions from International partners

Thank you for your attention!

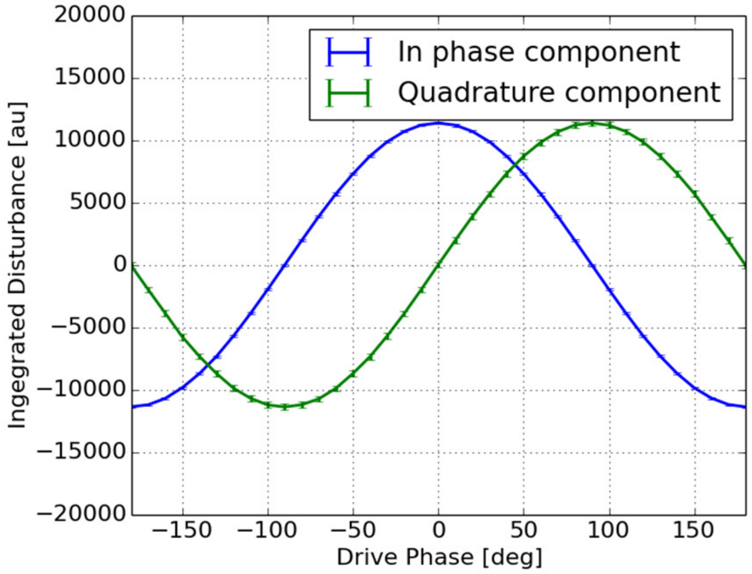
Backup Slides

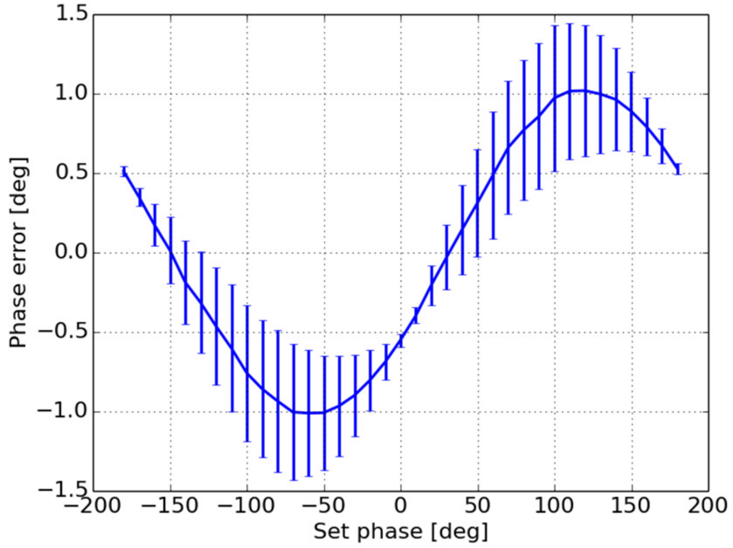
Beam-based Phase Calibration

- In theory the average beam phase can be computed from cavity field due to beam-loading

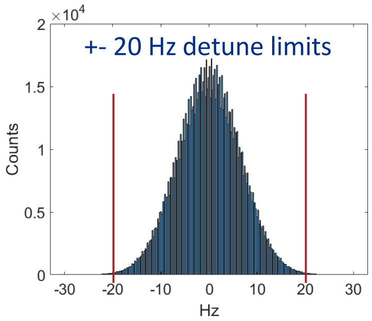
$$\phi_{\rm b} = \tan^{-1}\left(\frac{\int_{t_0}^{t_1} V^{Q}_{\rm cav-beam}(t)dt}{\int_{t_0}^{t_1} V^{I}_{\rm cav-beam}(t)dt}\right)$$

- However this relies on proper background subtraction and some, albeit minor, assumptions about the profile of the beam
- First test is to try and reconstruct the phase of an ideal disturbance that is driven by the LLRF system
  - Some unexpected behavior is still under investigation
- Top: Integrated cavity voltage due to the ideal disturbance as a function of phase
- Bottom: Difference between reconstructed phase and drive phase as a function of the drive phase

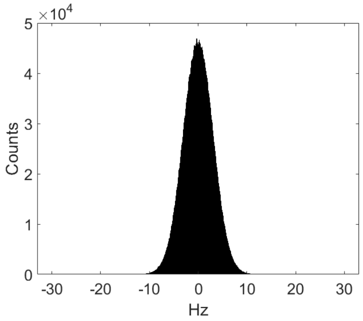




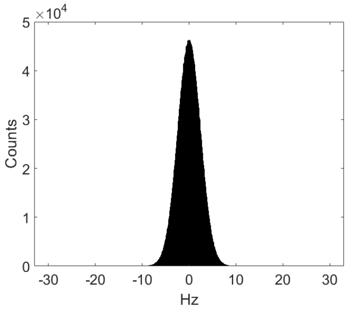
HWR Cavity Detuning Histograms


+- 20 Hz detune limits

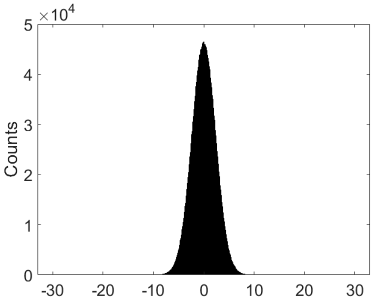
Cavity 4



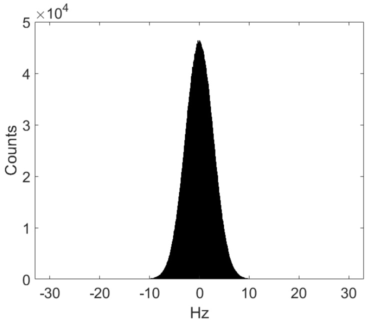
Cavity 5



Cavity 6

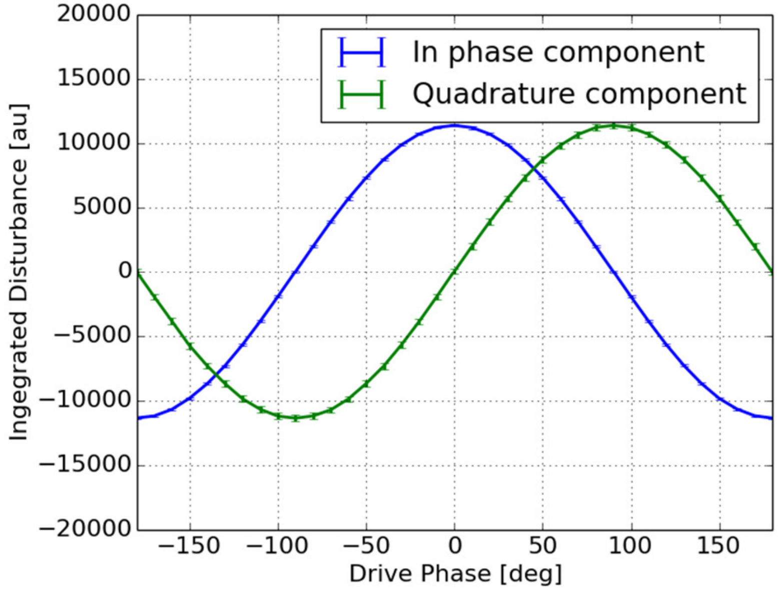


Cavity 7

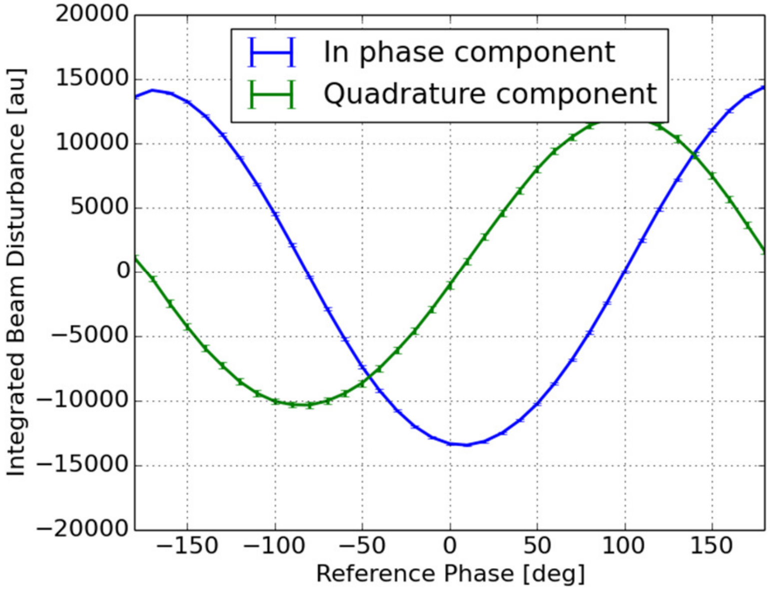


Cavity 8

Beam-based Phase Calibration



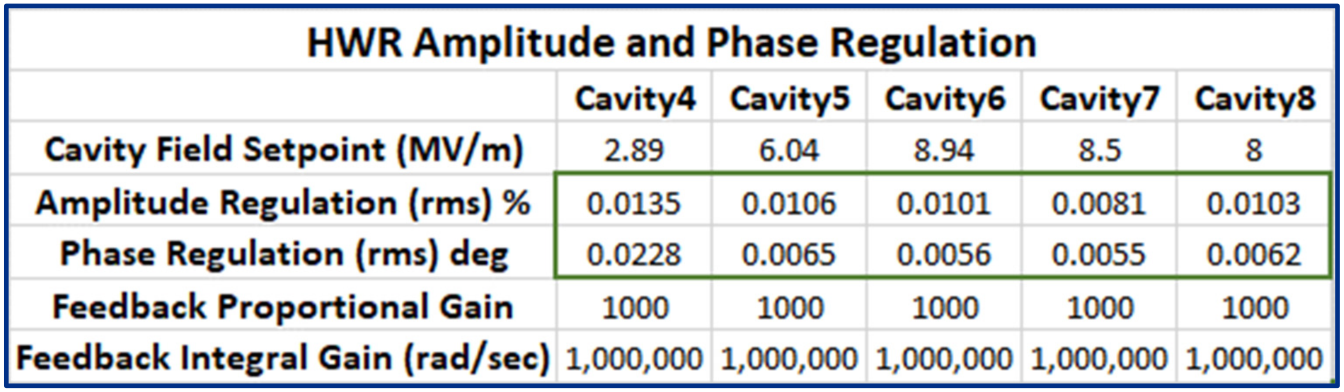
Integrated cavity field due to beam loading as a function of the drive phase for an ideal disturbance driven from the LLRF system



Integrated cavity field due to beam loading as a function of the drive phase for a 4.9mA beam in the PI-Test bunching cavity. Note the I and Q components are not symmetric.

J. Edelen

HWR Amplitude and Phase Regulation Short Term(5 min) In Loop Measurements (No Beam)

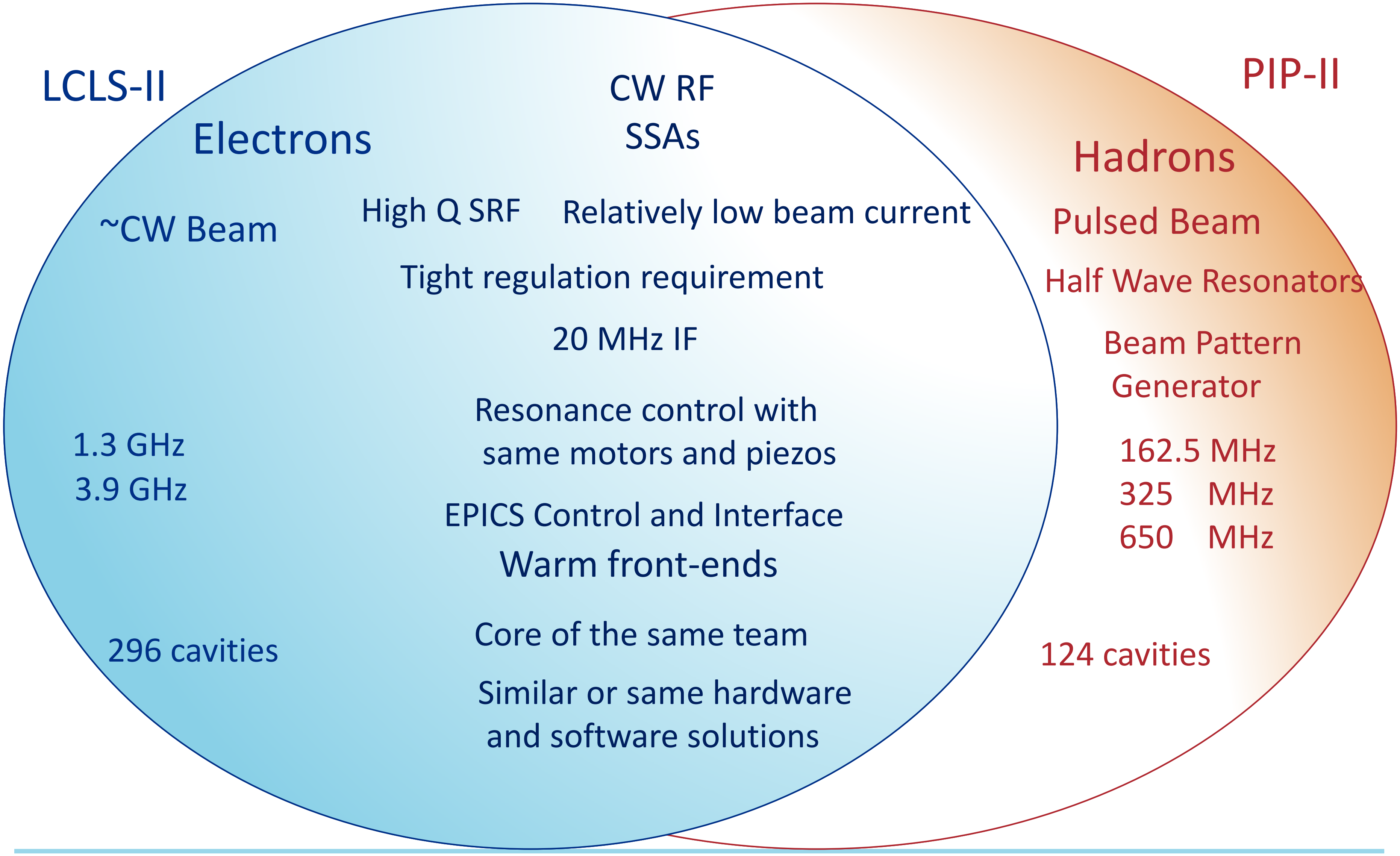


HWR Amplitude and Phase Regulation					
	Cavity4	Cavity5	Cavity6	Cavity7	Cavity8
Cavity Field Setpoint (MV/m)	2.89	6.04	8.94	8.5	8
Amplitude Regulation (rms) %	0.0135	0.0106	0.0101	0.0081	0.0103
Phase Regulation (rms) deg	0.0228	0.0065	0.0056	0.0055	0.0062
Feedback Proportional Gain	1000	1000	1000	1000	1000
Feedback Integral Gain (rad/sec)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000

PIP-II Specifications

- Amplitude Regulation (individual cavity) < 0.06%
- Energy Stability (Linac) < 0.01%
- Phase Regulation < 0.06 deg

LCLS-II and PIP-II Overlaps



LCLS-II

Electrons

~CW Beam

1.3 GHz
3.9 GHz

296 cavities

CW RF
SSAs

High Q SRF

Relatively low beam current

Tight regulation requirement

20 MHz IF

Resonance control with
same motors and piezos

EPICS Control and Interface

Warm front-ends

Core of the same team

Similar or same hardware
and software solutions

PIP-II

Hadrons

Pulsed Beam

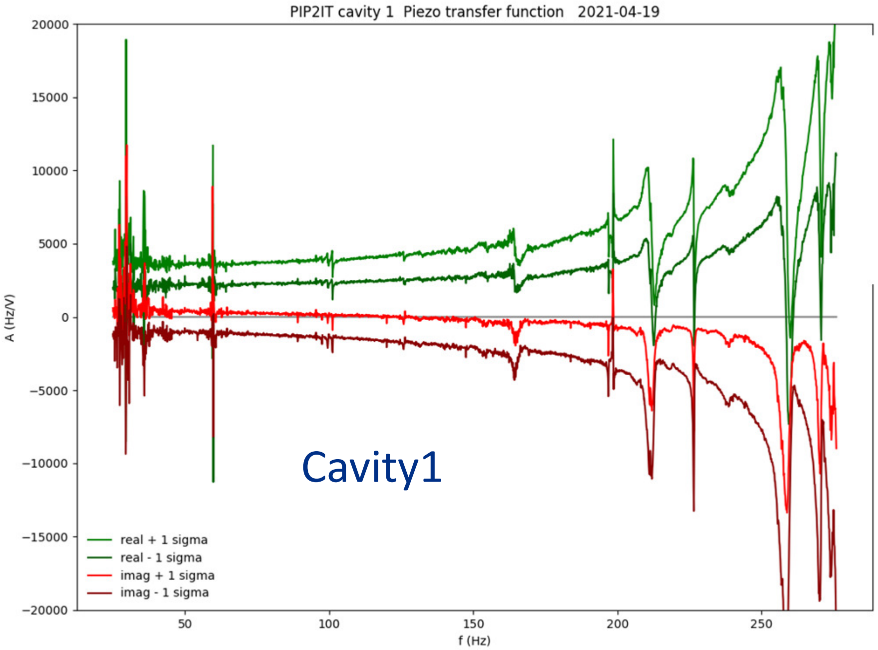
Half Wave Resonators

Beam Pattern
Generator

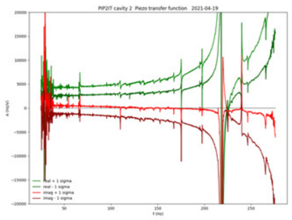
162.5 MHz
325 MHz
650 MHz

124 cavities

SSR1 Piezo Transfer Functions

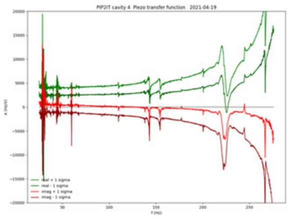


Cavity1

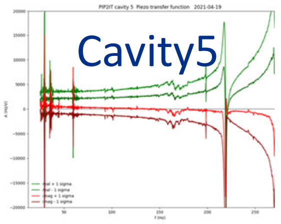


Cavity2

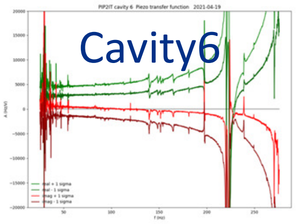
Cavity3



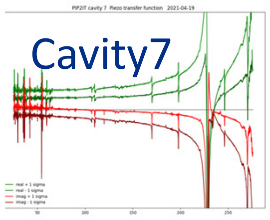
Cavity4



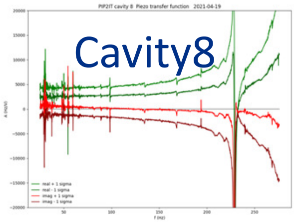
Cavity5



Cavity6



Cavity7



Cavity8

Swept sinusoidal excitation of the tuner piezo actuators and response of cavity detuning depth

Response Peaks are mechanical resonances which make broadband feedback a challenge