

Dimtel Digital Low-level RF

LLRF9

D. Teytelman

Dimtel, Inc., San Jose, CA, USA

June 14, 2019



LLRF9 System



- A single 2U chassis;
- 9 input RF channels;
- 2 output RF channels:
 - Amplified;
 - Filtered;
 - Interlocked.
- Two spare outputs.
- Tuner motor control;
- External interlock daisy-chain;
- Two external trigger inputs;
- Eight opto-isolated baseband ADC channels.

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Installations and Demos

Machines

Ring	Stations	Cavities
ELSA	1	2
ANKA	2	4
ANKA booster	1	1
SESAME	4	4
SESAME booster	1	1
Diamond booster (demo)	1	1
LNLS (demo)	2	2
LNLS booster (demo)	1	1

- System is in daily operation at 3 storage rings and 2 boosters;
- Successfully demonstrated at 3 other rings;
- Commissioning in DELTA later this year.



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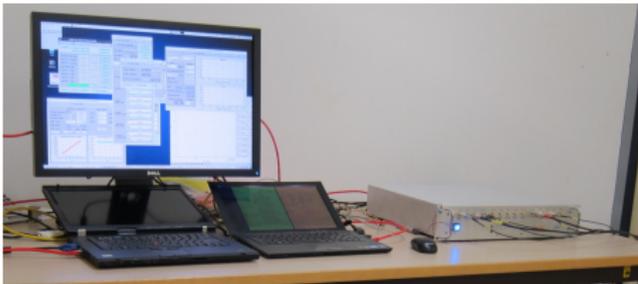


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Outline

- 1 Overview
 - LLRF9 Introduction
 - **Inputs and Interlocks**
 - Feedback Loops
 - Diagnostics
- 2 LLRF Characterization
 - Frequency Domain
 - Time Domain
- 3 Stability Measurements
 - Thermal
- 4 Precision Measurements
 - Tuning Scans
 - Beam-Based Calibration



Calibrated Channels

ID=LLE1:BRD1 HELP EXIT

INPUT CHANNEL 0
CAVITY 1 PROBE

RAW AMPLITUDE 0.1 counts

RAW PHASE 34.5

HW FULL SCALE 0.86 dBm

HW PHASE OFFSET -31.28 deg

COUPLING 66.00 dB PHASE OFFSET 160.000 deg

OUTPUT FORMAT Voltage UNITS kV

TRIP 500.00 kV

RESET 0.01 kV 163.17 deg

- Each of 9 input channels is monitored at 10 SPS;
- Phase measurements are relative to the master oscillator phase reference at the front panel;
- All RF components are mounted on a 10 mm cold plate with active temperature stabilization;
- Each channel can be configured for voltage or power measurements;
- Precision calibration procedures have been developed.

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Interlock Chain

ID=LLRF: BRD1

INTERLOCKS				
EXTERNAL INTERLOCK INPUT	ENABLE		MASK	
AMPLITUDE	340.74 kv	305.41 kv	625.42 kw	
THRESHOLD	<input type="text" value="380.00 kv"/>	<input type="text" value="340.00 kv"/>	<input type="text" value="780.00 kw"/>	
RAW AMPLITUDE	6364.5 counts	5952.9 counts	6207.6 counts	6098.0 counts
RAW THRESHOLD	7098	6627	6932	8191
EXTERNAL	CHANNEL 0	CHANNEL 1	CHANNEL 2	CHANNEL 3
<input type="button" value="RESET"/>	<input type="button" value="RESET"/>	<input type="button" value="RESET"/>	<input type="button" value="RESET"/>	<input type="button" value="RESET"/>
5782454	36046144	36067981	92105109	
TRIP CAPTURE	7122	6671	6957	
TRIP VALUE	381.30 kv	342.26 kv	785.54 kw	

- Fast interlock threshold can be set for each of 9 RF inputs;
- Guaranteed trip in a few hundred nanoseconds;
- Drive outputs doubly protected:
 - On interlock trip, an RF switch is opened;
 - FPGA DAC drive is set to zero.



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INTERLOCKS				
EXTERNAL INTERLOCK INPUT	ENABLE		MASK	
AMPLITUDE	340.74 kv	305.41 kv	625.42 kv	
THRESHOLD	380.00 kv	340.00 kv	280.00 kv	
RAW AMPLITUDE	6364.5 counts	5952.9 counts	6207.6 counts	6098.0 counts
RAW THRESHOLD	7098	6627	6932	8191
EXTERNAL	CHANNEL 0	CHANNEL 1	CHANNEL 2	CHANNEL 3
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Interlock Chain - Continued



LLRF HELP EXIT

INTERLOCK STATUS RESET

TRIP SOURCE	TIME
CAVITY 1 PROBE1	0.000 us
CAVITY 2 PROBE1	384.022 us

Board 1 interlock Board 2 interlock Board 3 interlock

- External interlock enable input and interlock output allow for easy daisy-chaining:
 - Opto-isolated input;
 - 5 volt logic and solid-state relay output.
- All interlock sources are timestamped;
- IOC automatically sorts events to simplify trip diagnostics.

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- **Feedback Loops**
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- Time Domain

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Stability Measurements

- Thermal

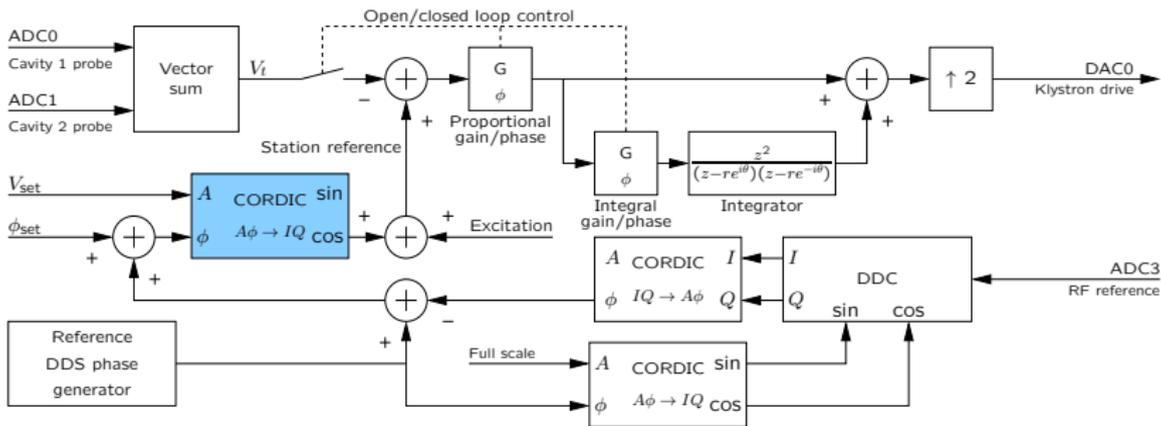
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Precision Measurements

- Tuning Scans
- Beam-Based Calibration



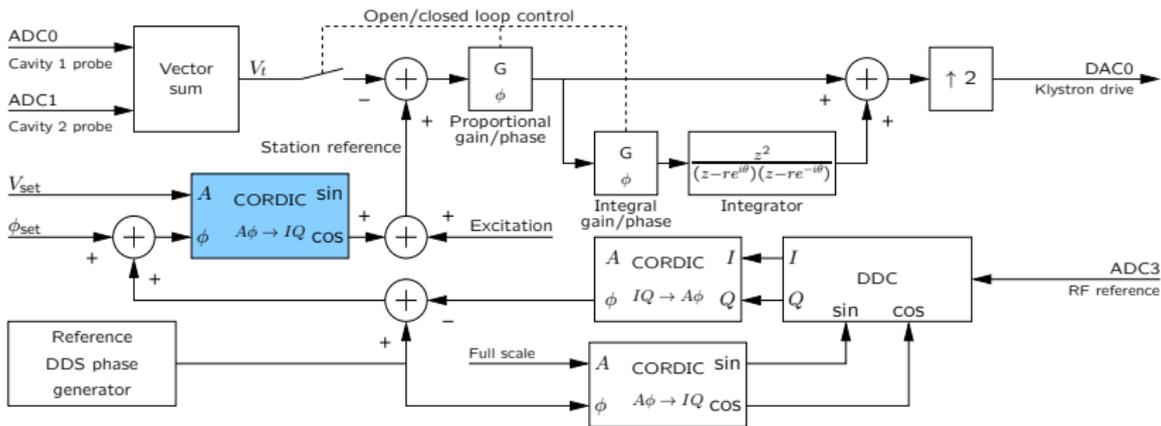
Field Control Loop



- Single cavity or vector sum of two;
- Reference phase is compensated in real-time;
- Proportional and integral loops;
- Double rate DAC drive;
- 512-point amplitude and phase profiles;
- Excitation input for built-in network analyzer.



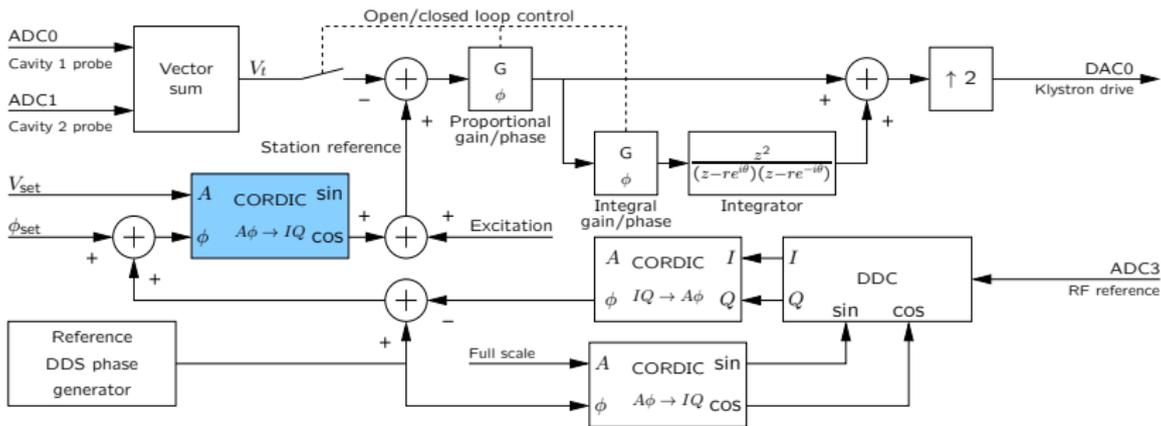
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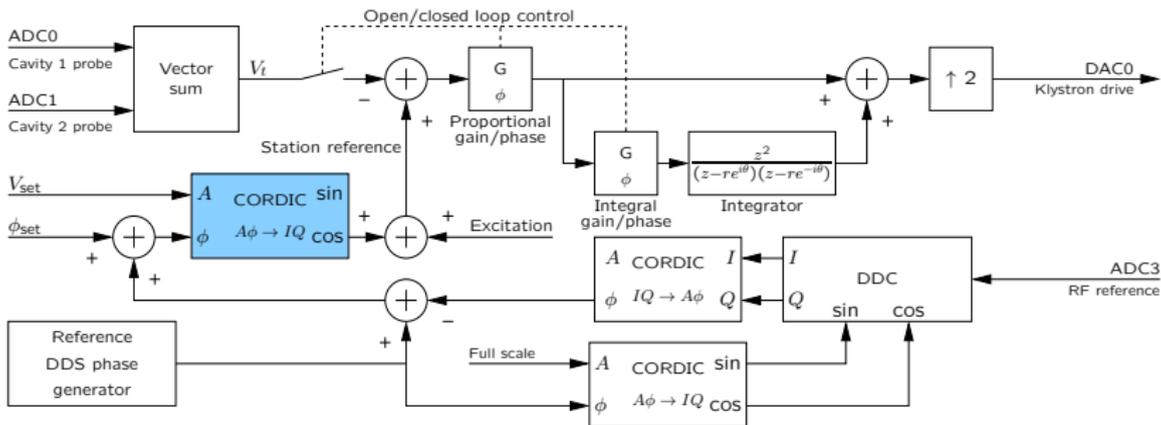


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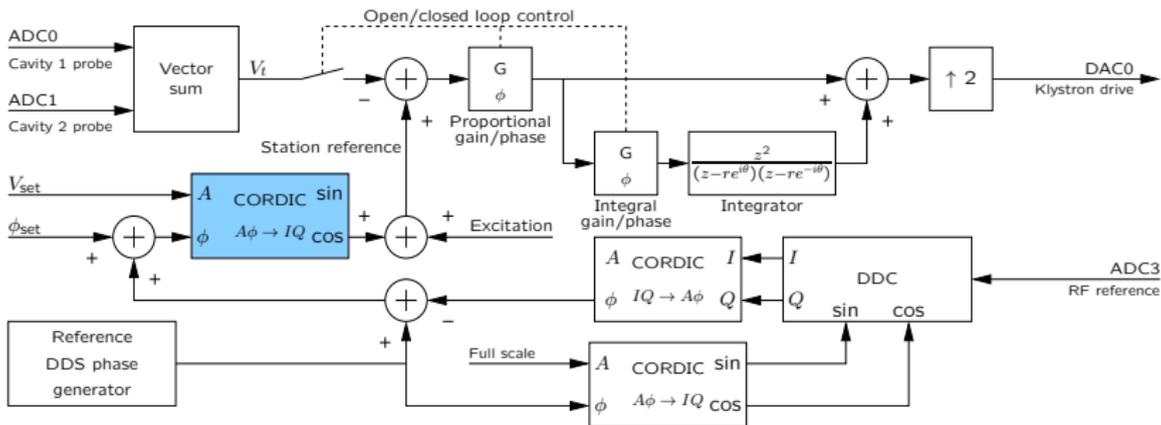
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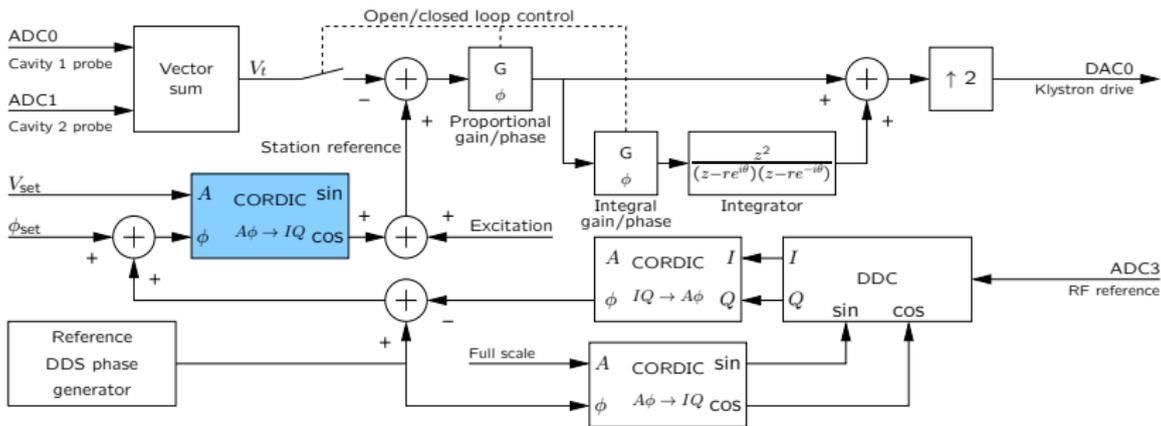
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Tuner Loop

LLRF:TUNER:C1

TUNER LOOP

LOOP CONTROL

PROP	INT	DIFF	ANTI WINDUP
<input type="text" value="5.0"/>	<input type="text" value="1.5"/>	<input type="text" value="0.0"/>	<input type="text" value="-0.1"/>

DEADBAND

MINIMUM FORWARD POWER

LOAD ANGLE OFFSET

LOOP SIGN ERROR

Tuner 1 Motor Control

Tuner 2 Motor Control

Probe balancing loop

- Loop runs in the EPICS IOC at 10 Hz;
- Keeps cavity forward and probe phases aligned;
- Options for one or two motors per cavity, field balancing loop for multi-cell cavities;
- Adjustable deadband to avoid unnecessary mechanical wear.

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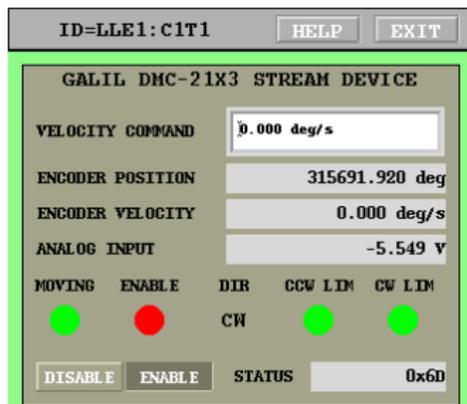
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Tuner Motion Control

- LLRF9 supports a number of off-the-shelf motor controllers:
 - Galil DMC-21X3
stepper/brushed DC/brushless;
 - Schneider Electric Motion Mdrive Plus stepper;
 - Aerotech Soloist brushed DC.
- Interfaces include Ethernet, RS-485, RS-422;
- Plunger position monitoring from analog potentiometer;
- Standard support for limit switches;
- EPICS MotorRecord is supported, not recommended.



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Tuner Motion Control

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GALIL DMC-21X3 STREAM DEVICE

VELOCITY COMMAND

ENCODER POSITION 315691.920 deg

ENCODER VELOCITY 0.000 deg/s

ANALOG INPUT -5.549 V

MOVING ENABLE DIR CCW LIM CW LIM

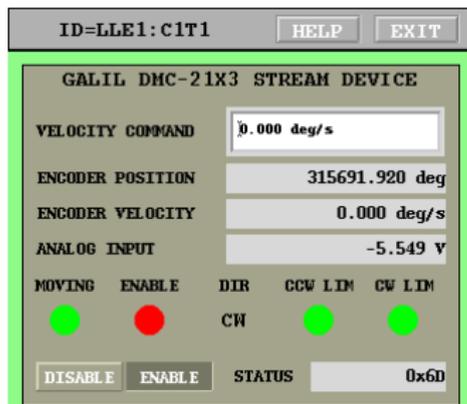
● ● CW ● ●

 STATUS 0x6D

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<input type="button" value="HELP"/> <input type="button" value="EXIT"/>	
MOTOR RECORD	
POSITION (DEG)	<input type="text" value="[-6607.06"/>
RELATIVE VALUE (DEG)	<input type="text" value="0.00"/>
VELOCITY (DEG/S)	<input type="text" value="5000.00"/>
ACCELERATION TIME (S)	<input type="text" value="0.040"/>
DIRECTION OF TRAVEL	<input type="text" value="0"/>
RAW MOTOR POSITION	<input type="text" value="-939567"/>
READBACK VALUE (DEG)	<input type="text" value="-6606.33047"/>
ANALOG INPUT	<input type="text" value="986"/>
DONE MOVING LOW LIM HI LIM <input type="radio"/> <input checked="" type="radio"/> <input type="radio"/> <input type="radio"/>	

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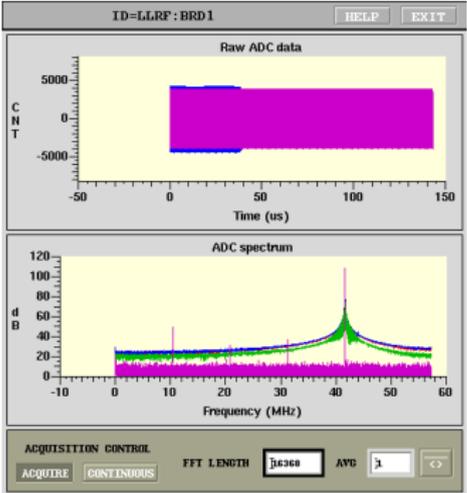
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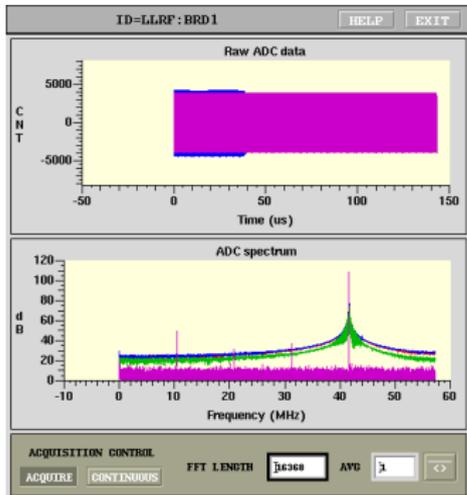
ADC Waveform Capture

- 12 ADC channels sampling IF signals (9 inputs, 3 references);
- 24576 sample buffer;
- 10 updates per second in free running mode;
- Multiple hardware trigger sources:
 - External trigger;
 - Ramp profile start;
 - Interlock.
- Supports pre-trigger acquisition for trip capture.



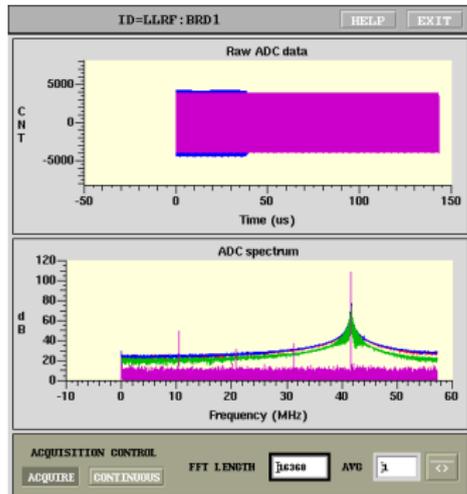
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ACQUISITION CONTROLS

POST-TRIGGER LENGTH

CH2/CH3 WAVEFORM ADC2/ADC3

TRIGGER SELECT

SOFTWARE
HARDWARE

HARDWARE TRIGGER RAMP

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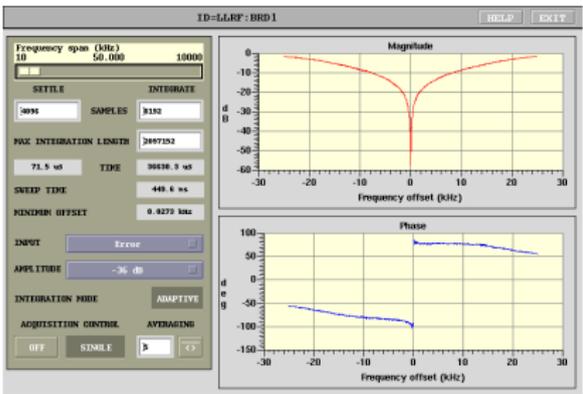
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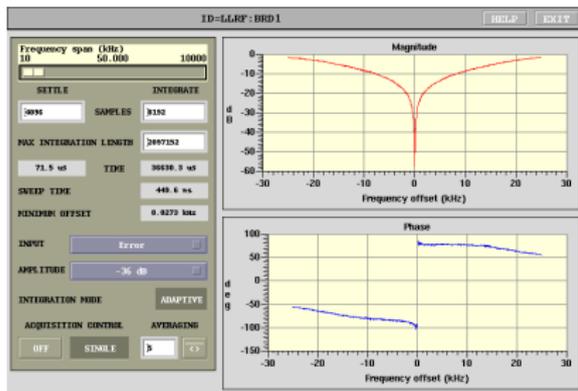
HARDWARE TRIGGER

Network Analyzer

- High resolution (1024 point) swept analyzer;
- Adjustable excitation level;
- Fast sweep times with proprietary carrier suppression algorithm;
- Multiple probe points within the system:
 - Cavity probe;
 - Cavity sum;
 - Error signal;
 - Drive output.
- Spectrum analyzer mode with excitation disabled.



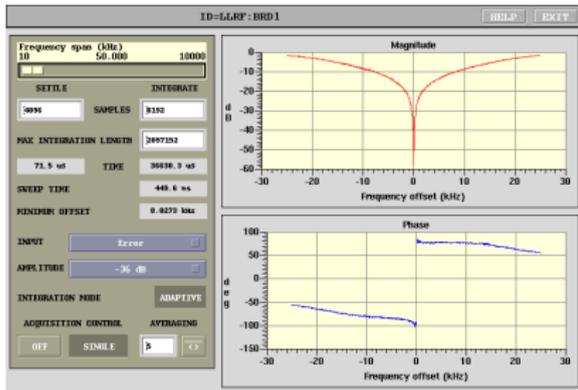
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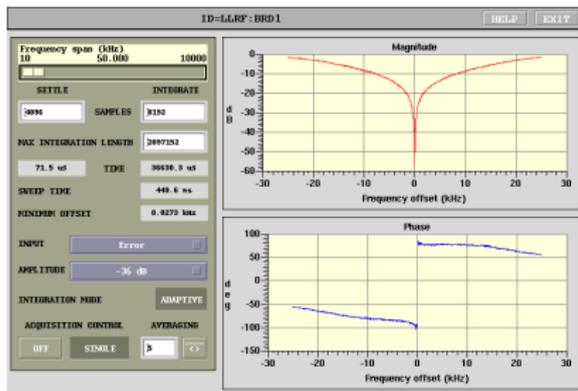
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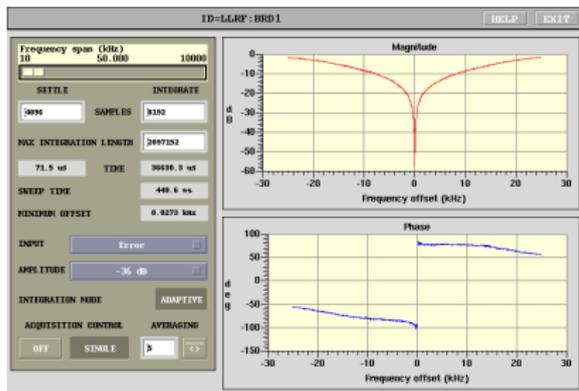
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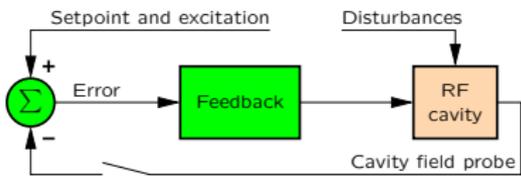


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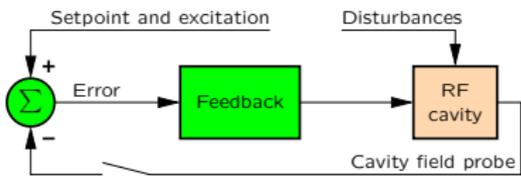
Open Loop Transfer Function



- Measured from setpoint to the cavity probe;
- Feedback block in open loop has no dynamics, just gain and phase shift;
- Open loop cavity response;
- Fit resonator model to extract gain, loaded Q,
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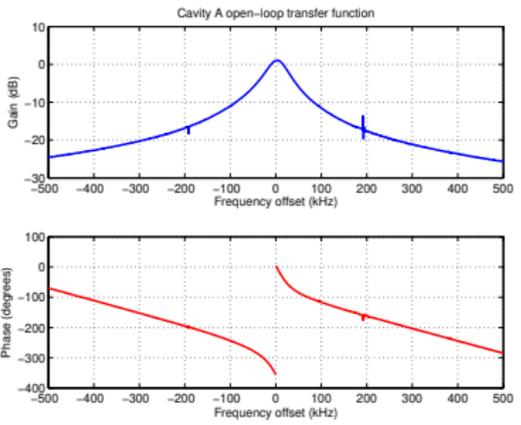


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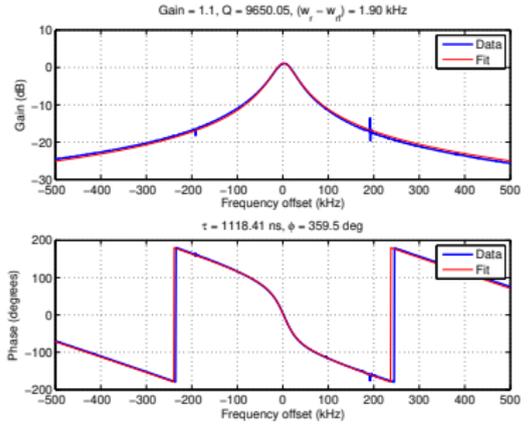
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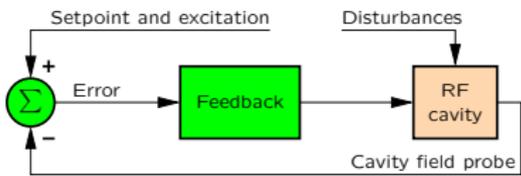


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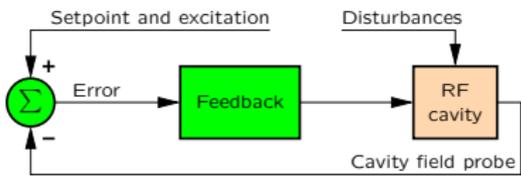
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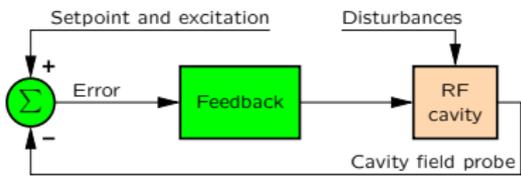
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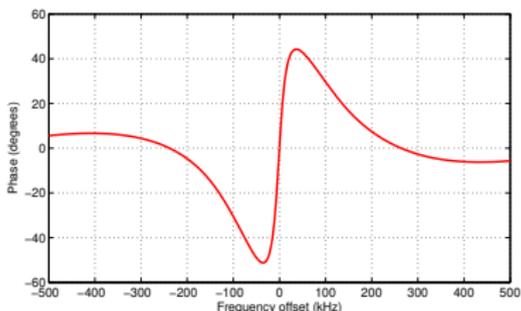
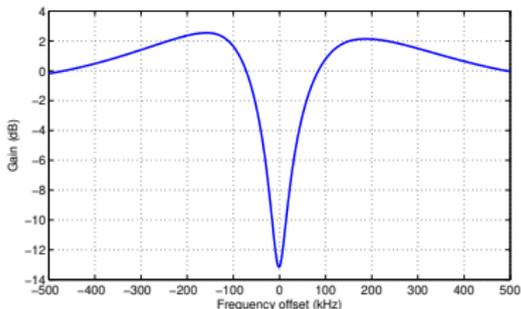
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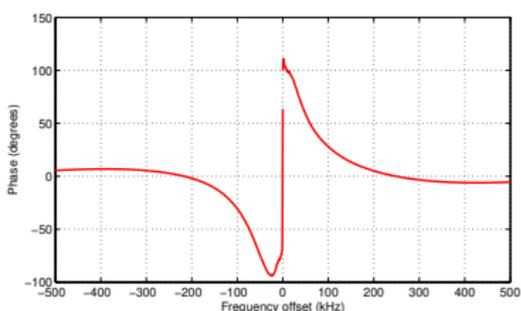
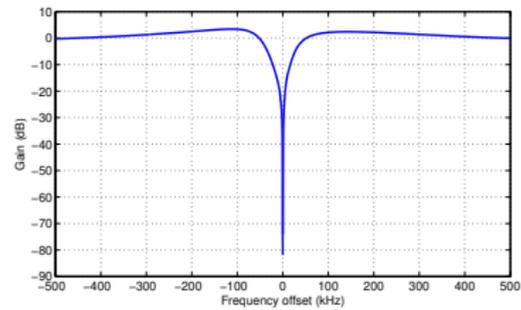
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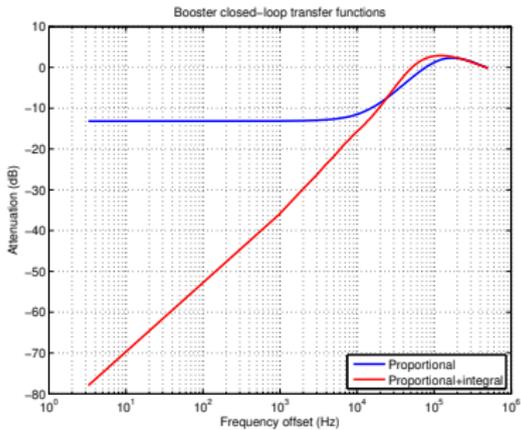
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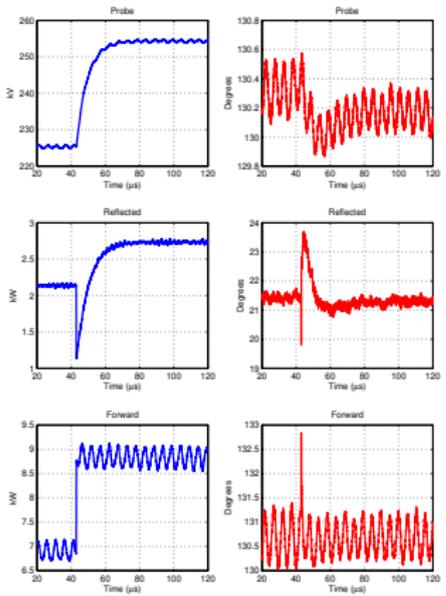


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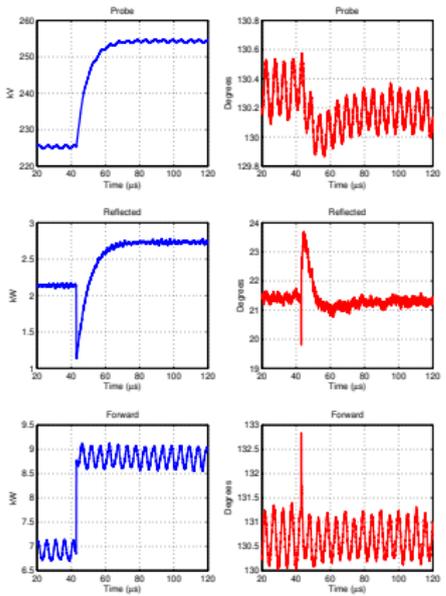
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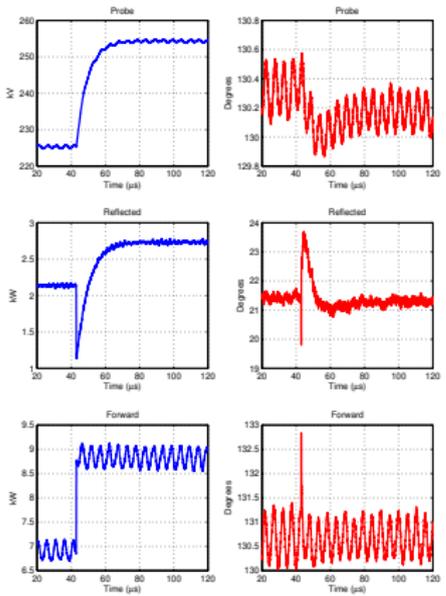
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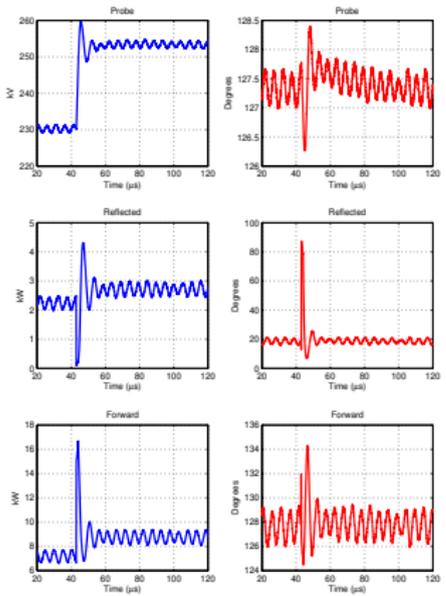
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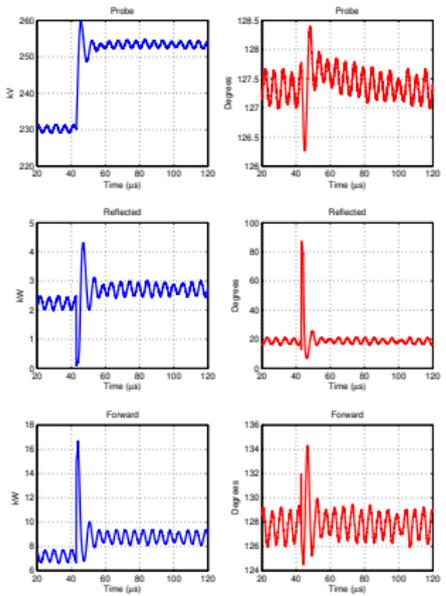
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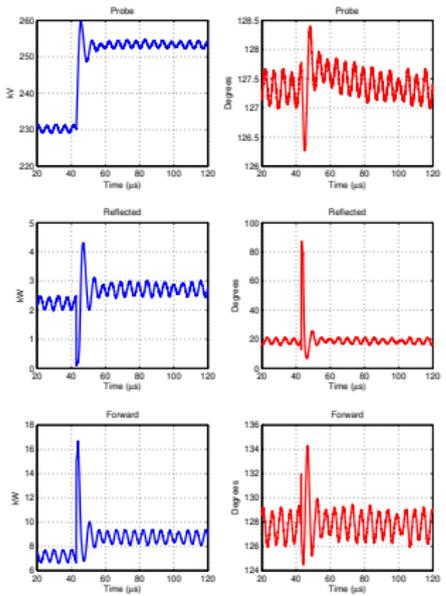
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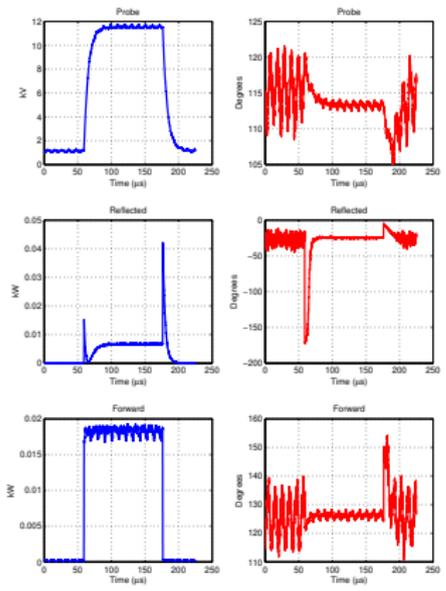
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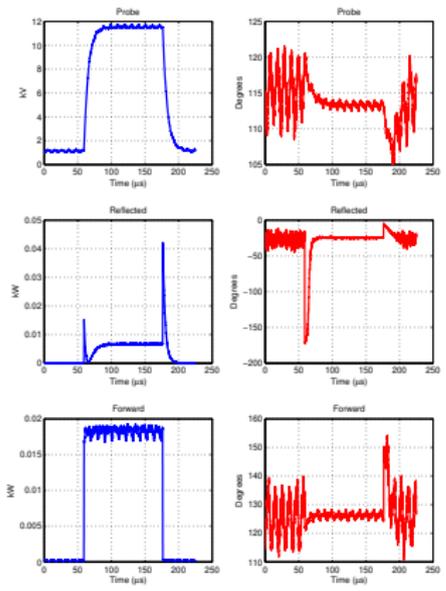
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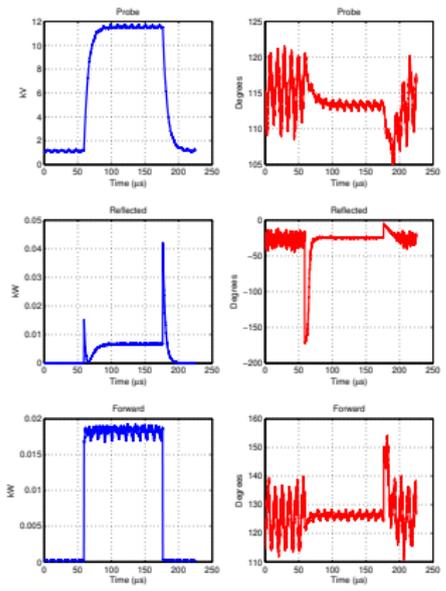
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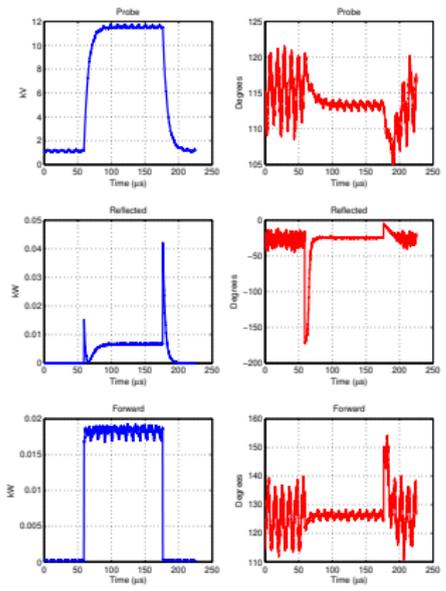
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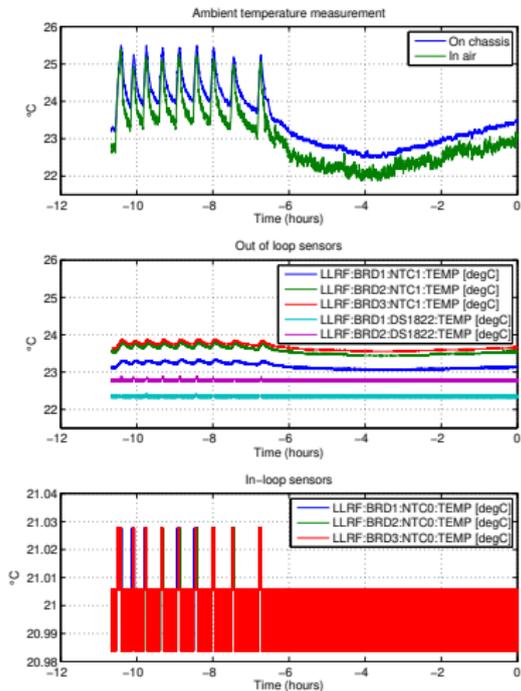


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Thermal Stability: Lab Measurements

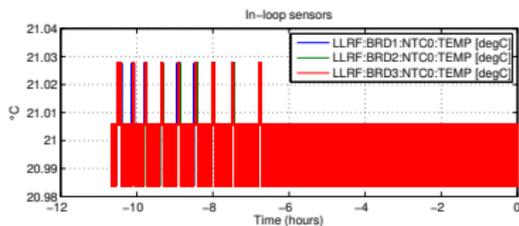
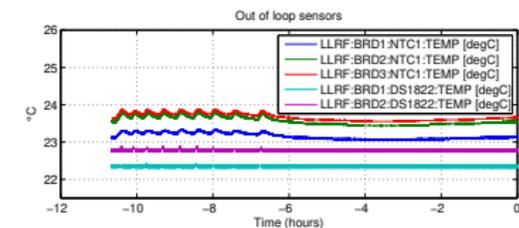
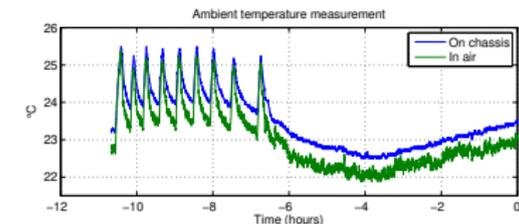


- 9 internal sensors on cold plate: 6 NTCs, 3 DS18B20 digital sensors;
- Three temperature stabilization loops using thermoelectric coolers;
- Two external sensors, in air and attached to chassis;
- Tight stabilization of in-loop sensors;
- Residual sensitivity of out-of-loop sensors is 0.09–0.12 °C/°C.

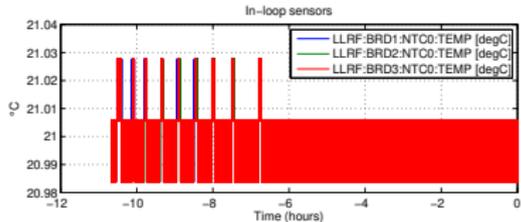
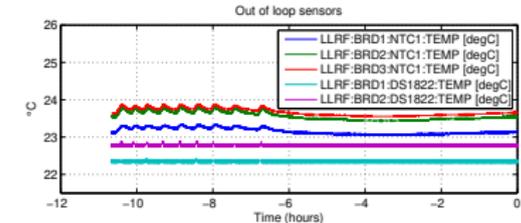
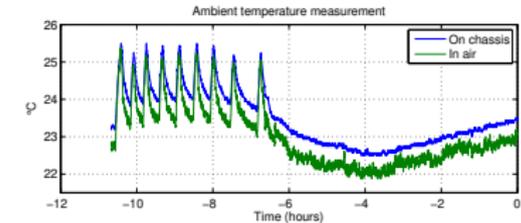


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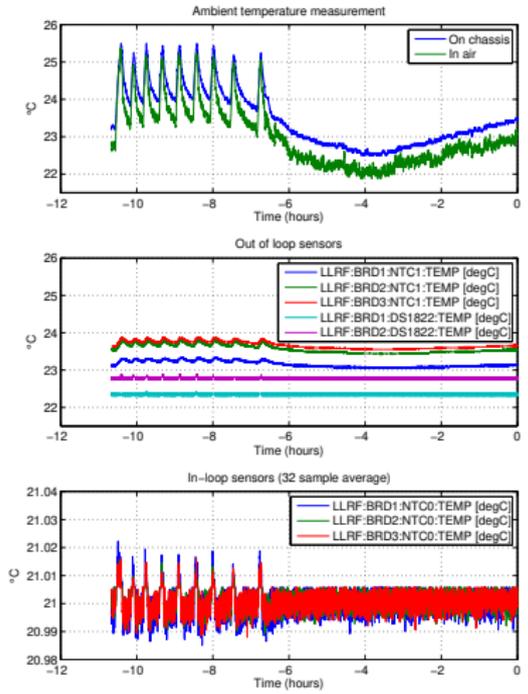
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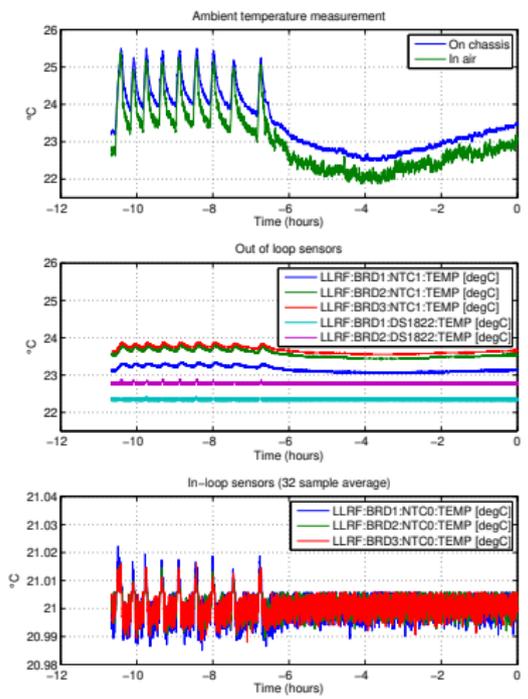
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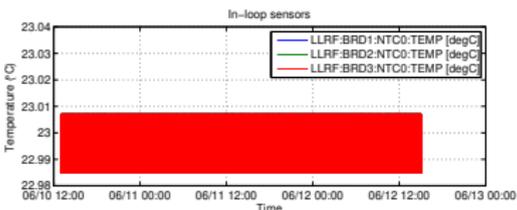
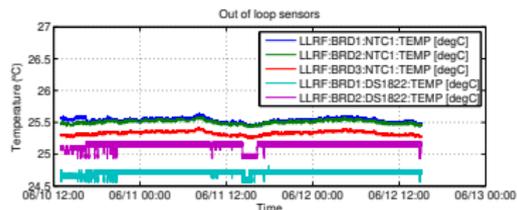
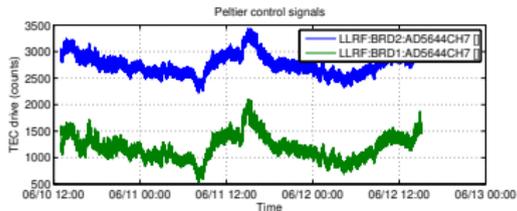
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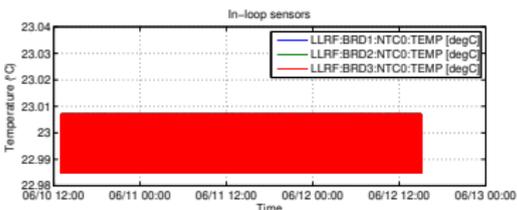
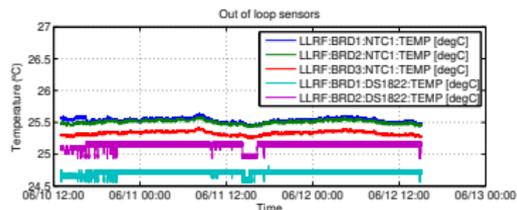
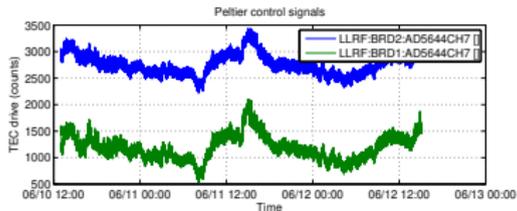
Thermal Stability: LNL5 Measurements



- Recorded over 2 days;
- Diurnal temperature variation clearly seen in out of loop sensors and Peltier control signals;
- Out of loop NTC sensors show 0.22 °C peak-to-peak variation.



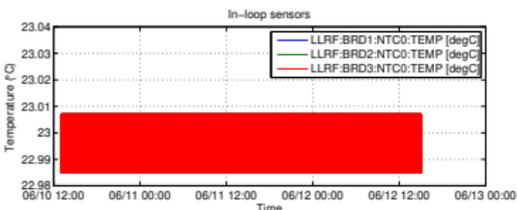
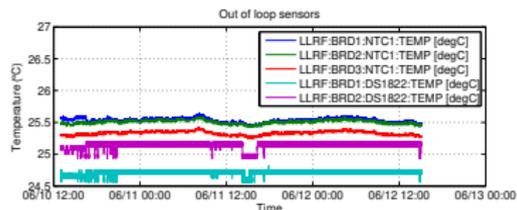
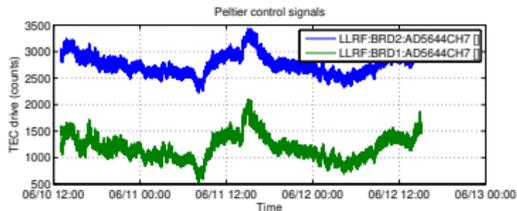
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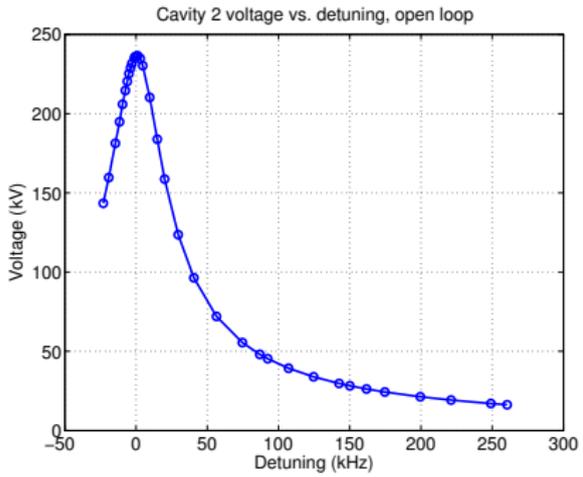


Tuning Scan at SESAME

- Run the station in open loop, fixed setpoint;
- Move the cavity from limit switch to limit switch;
- At multiple points record:
 - Probe voltage and phase;
 - Forward and reflected power and phase;
 - LLRF9 output power meter;
 - Tuner potentiometer;
 - **Open-loop transfer function.**
- A lot of interesting plots!



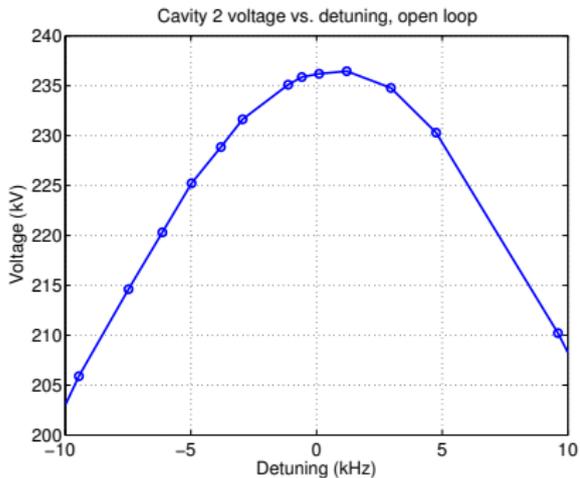
Cavity Voltage vs. Detuning



- Cavity voltage peaks around 0;
- Zooming in we see an interesting effect — peak voltage is around 650 Hz;
- Likely due to imperfect match at the SSA output.



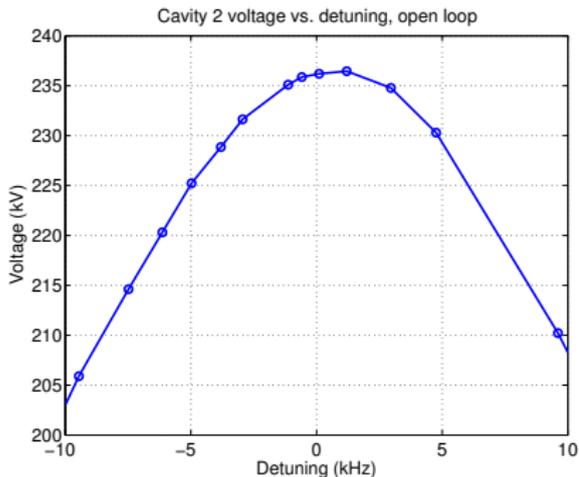
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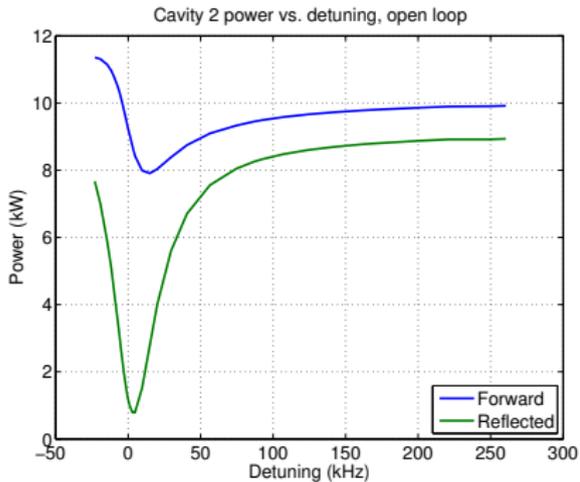
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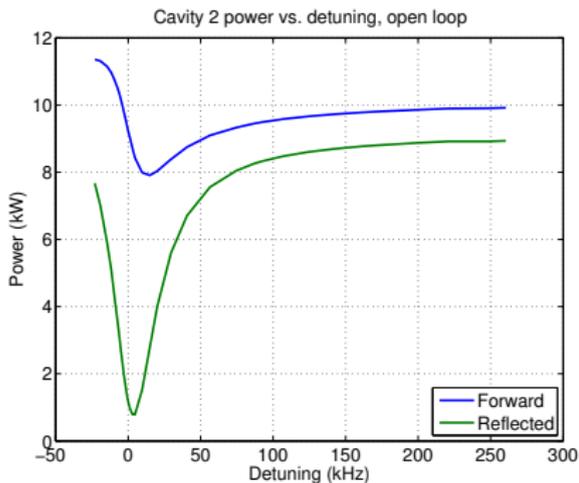
Waveguide Power vs. Detuning



- Reflected power minimum near 0;
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- Peak field and minimum reflected are offset;
- Offset minimum of reflected power is expected, directivity again.



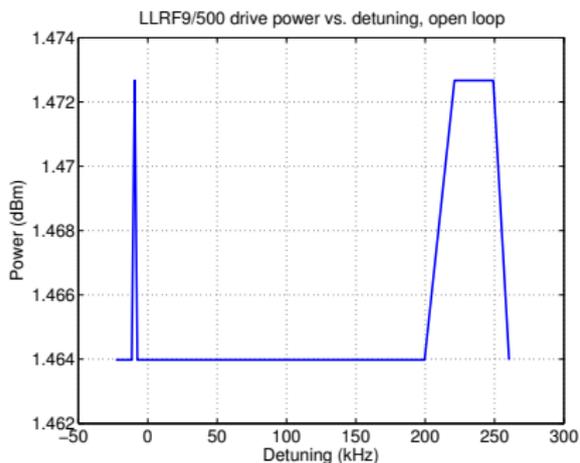
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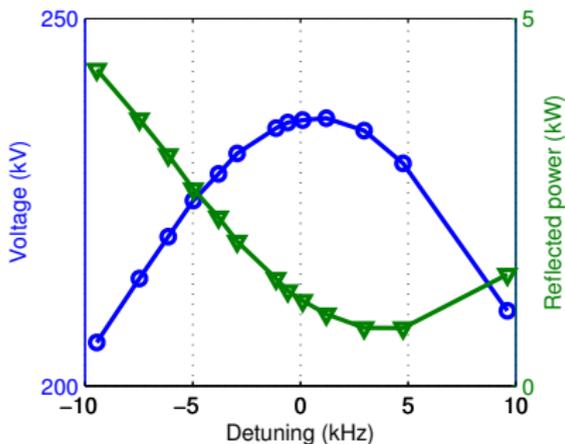
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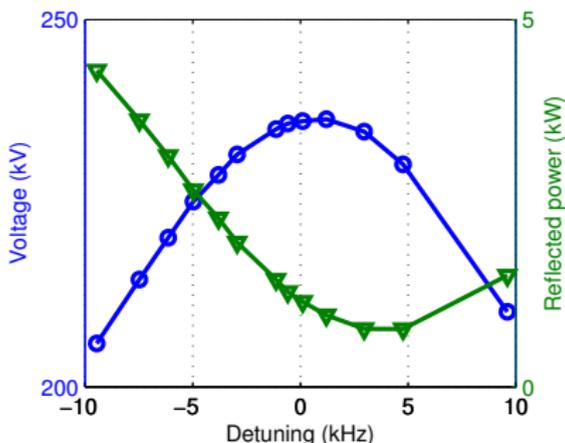
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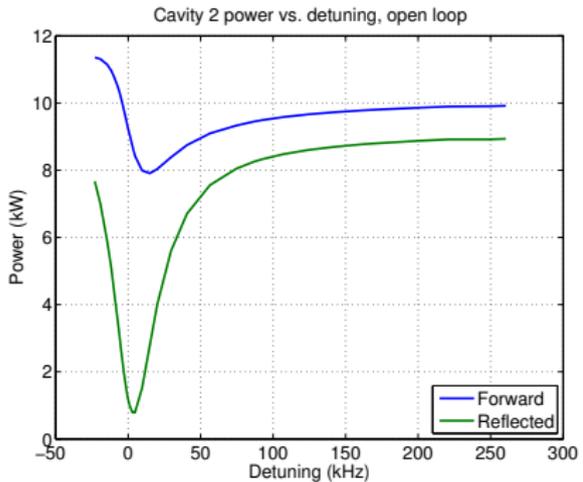
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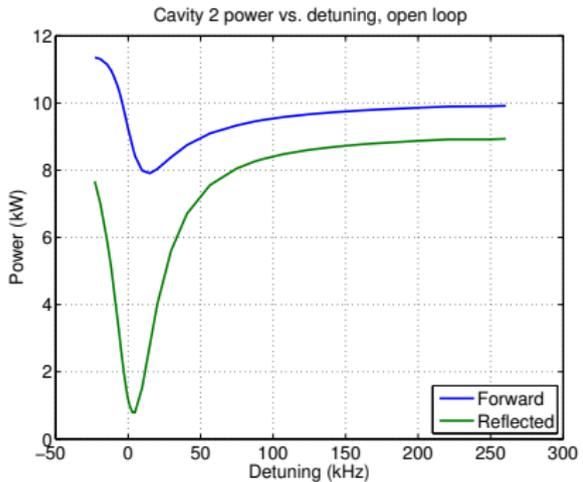
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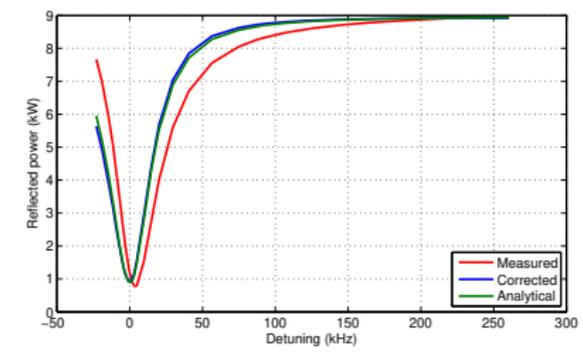
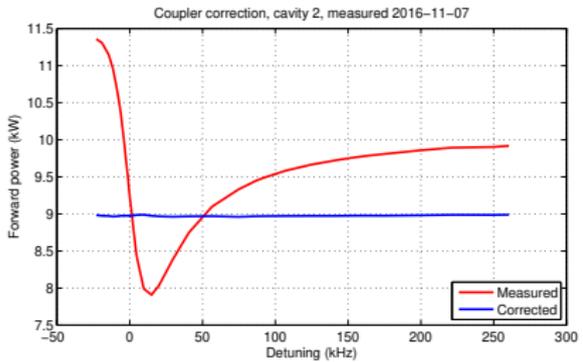
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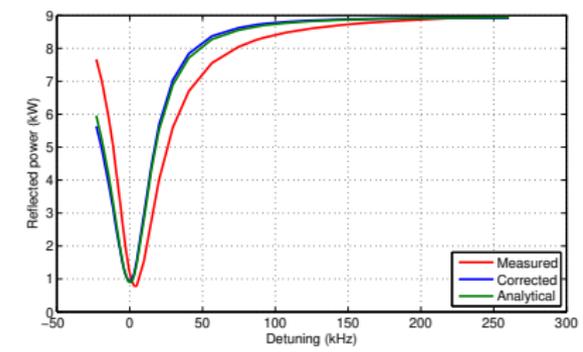
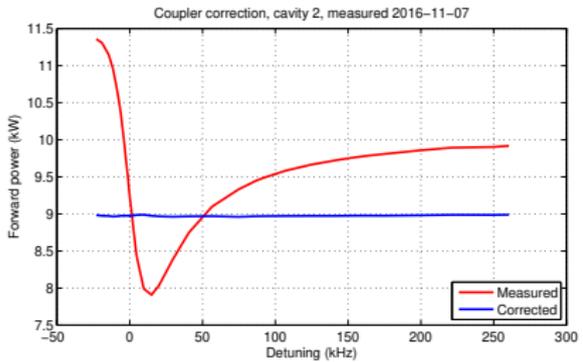
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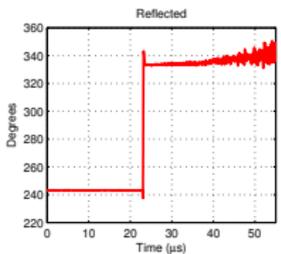
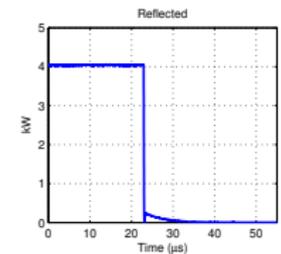
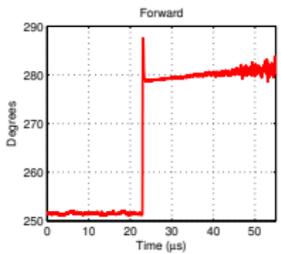
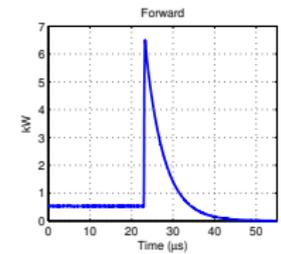
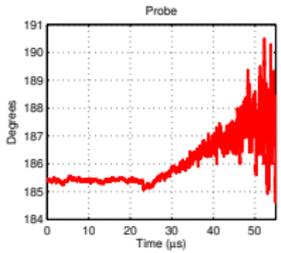
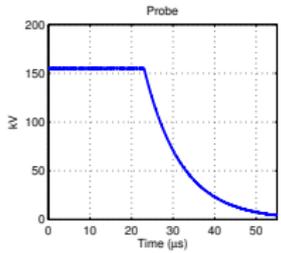
Coupler Directivity Correction



- Assuming power source is matched, we compute the coupler directivity correction matrix;
- At each point, we compute the expected reflection coefficient at RF from cavity transfer function fit;
- Matrix elements are then adjusted to:
 - Remove variation in forward power;
 - Match measured and computed reflection.



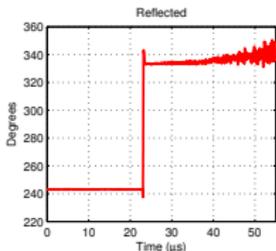
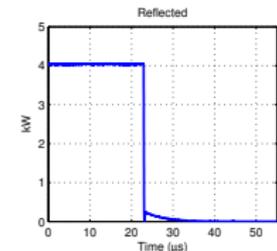
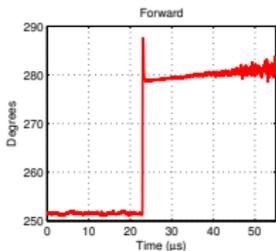
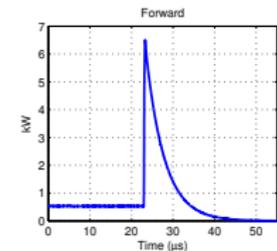
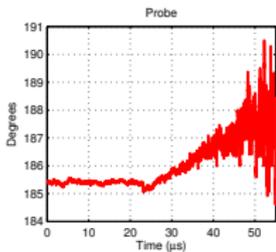
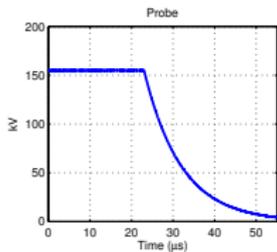
Time Domain Cavity Response



- Step drive to 0;
- Natural cavity response;
- Can extract quality factor and detuning;
- At the same tuning point collected 20 transfer function measurements;
- Roughly 300 Hz offset between frequency and time domain.



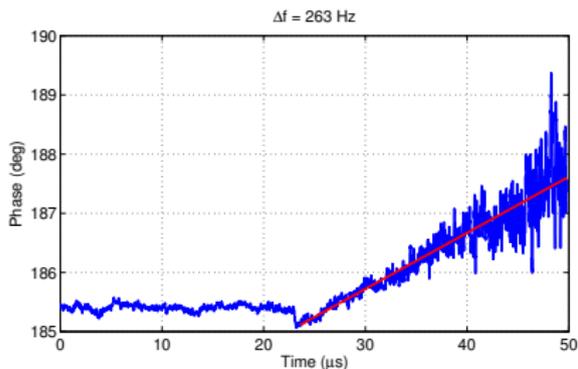
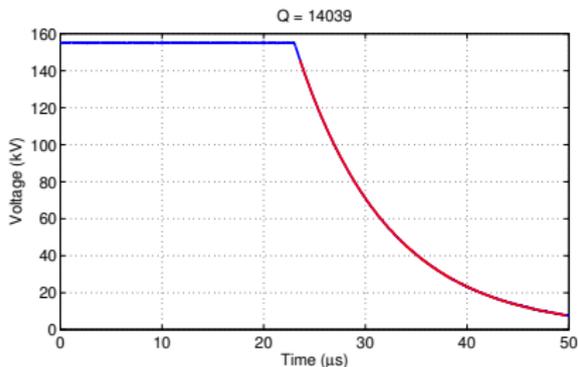
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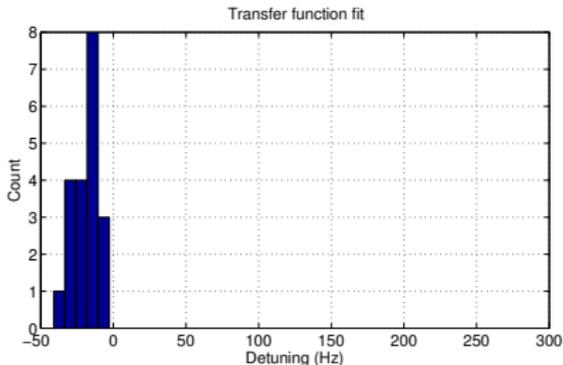
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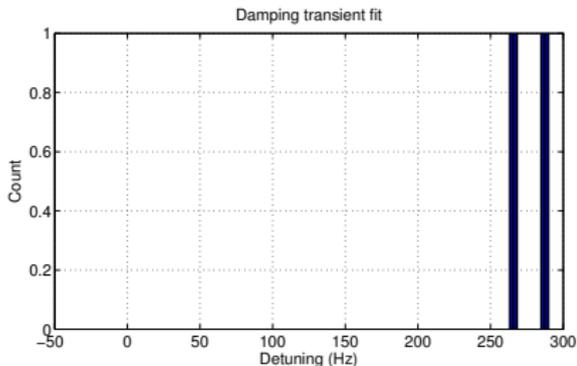
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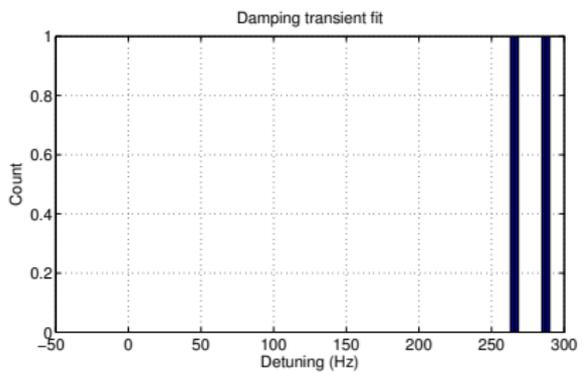
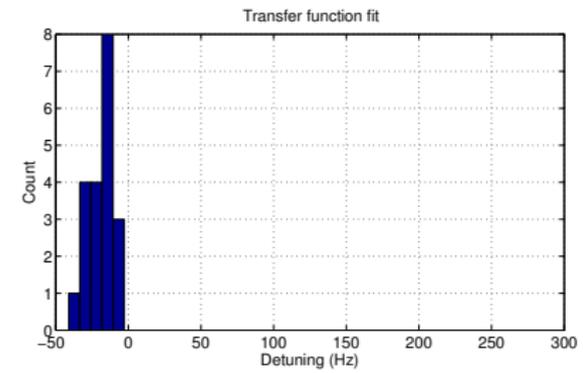
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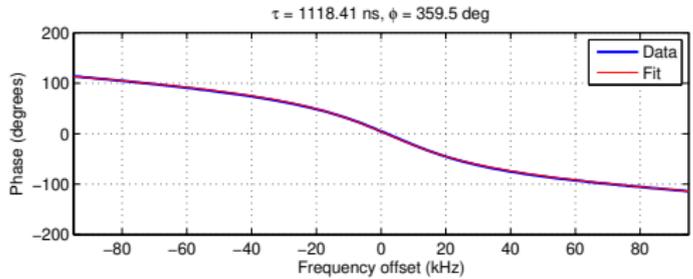
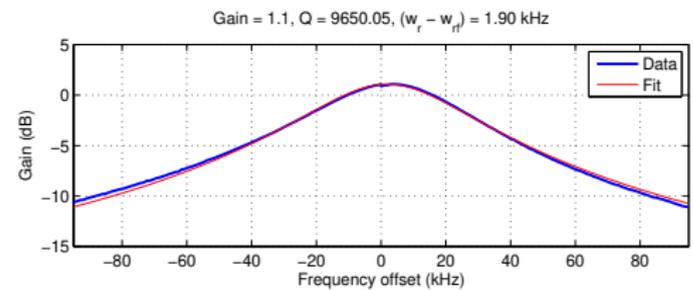


Outline

- 1 Overview
 - LLRF9 Introduction
 - Inputs and Interlocks
 - Feedback Loops
 - Diagnostics
- 2 LLRF Characterization
 - Frequency Domain
 - Time Domain
- 3 Stability Measurements
 - Thermal
- 4 Precision Measurements
 - Tuning Scans
 - Beam-Based Calibration



Cavity Parameters at LNL5



Cavity 1

Q_0 40000

Q_l 9650.0

β 3.1415

Cavity 2

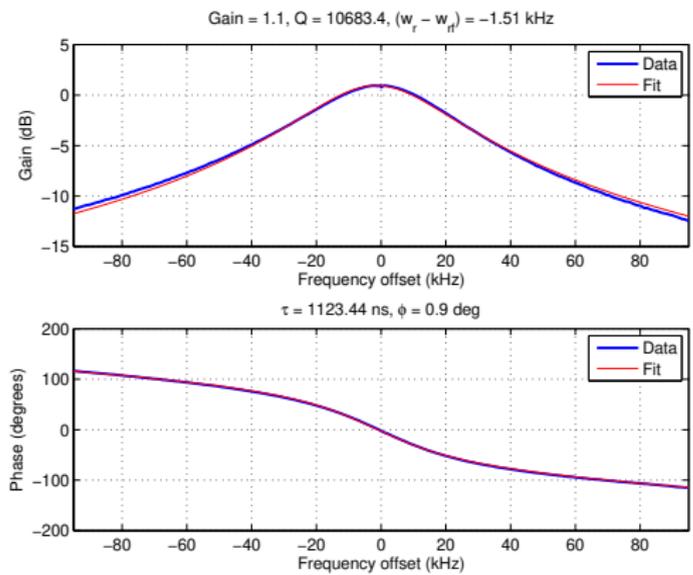
Q_0 43000

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β 3.0249



Cavity Parameters at LNL5



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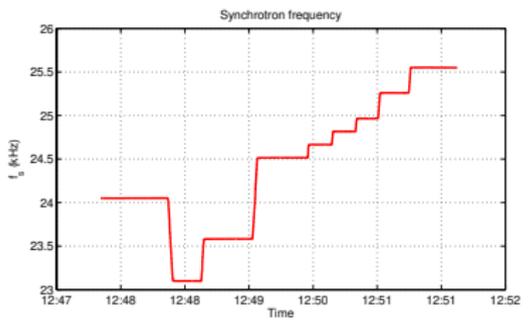
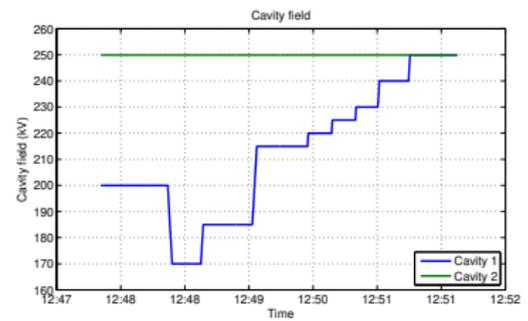
Q_0 40000
 Q_I 9650.0
 β 3.1415

Cavity 2

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 Q_I 10683.4
 β 3.0249



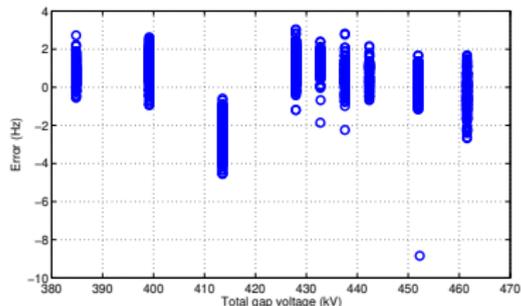
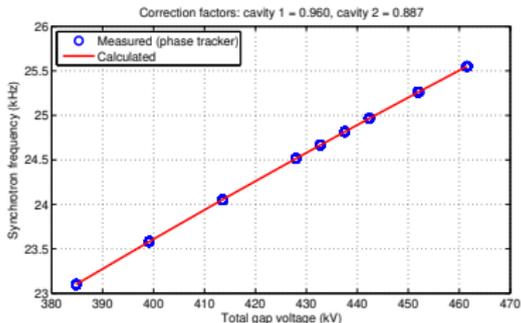
Probe Calibration



- Scanned cavity 1 field down to 170 kV, captured synchrotron tune using LFB tune tracking;
- Fit ω_s to total voltage V_g assuming:
 - Stations are in phase (phased earlier to maximize ω_s);
 - Momentum compaction, beam energy, energy loss per turn are as published.
- Obtain scaling factors for existing calibrations.



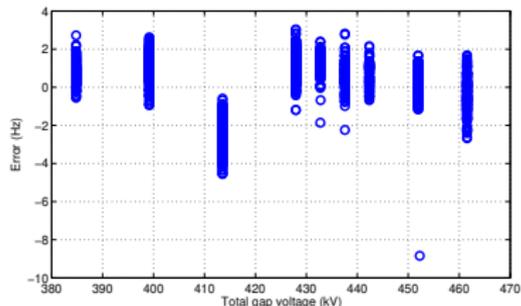
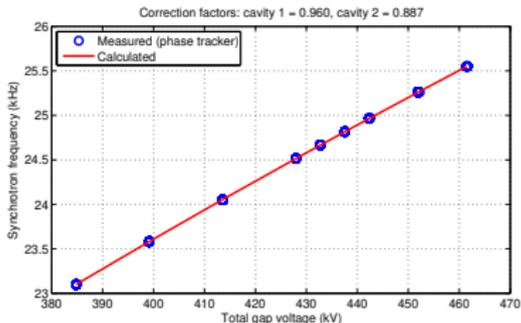
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- LLRF9 integrates a lot of functionality in a single unit;
- Used with normal conducting cavities at a number of machines;
- Powerful diagnostic features to simplify tuning and operation;
- Enables precision measurements of accelerator parameters.

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