Dimtel Digital Low-level RF

LLRF9

D. Teytelman

Dimtel, Inc., San Jose, CA, USA

June 14, 2019

Outline

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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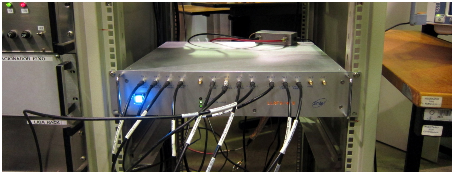
Installations and Demos

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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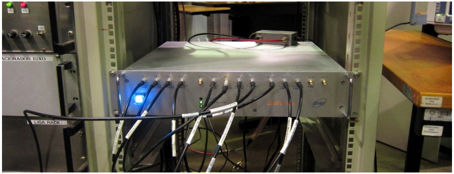

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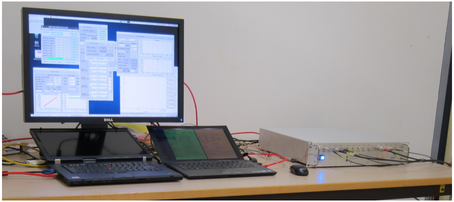

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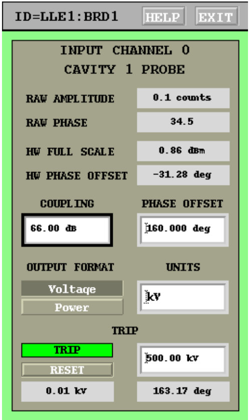
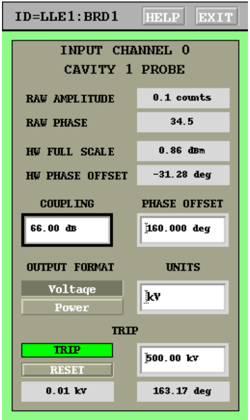
Outline

Calibrated Channels



- 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.

Calibrated Channels



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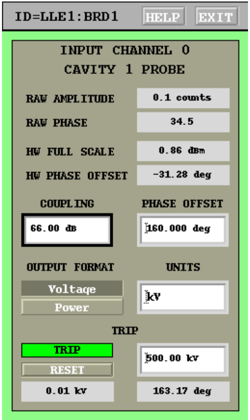

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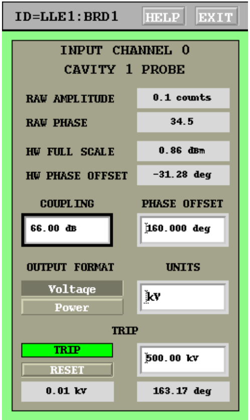

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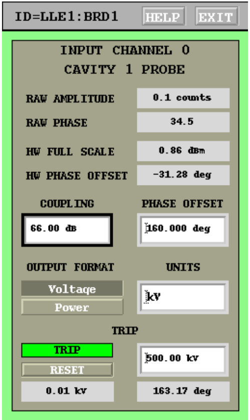

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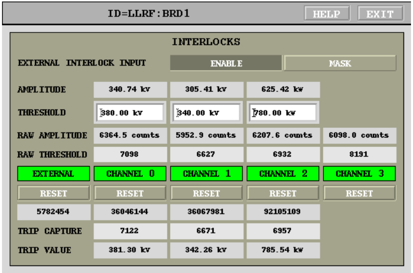
Interlock Chain



- 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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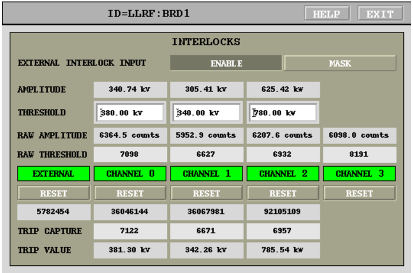

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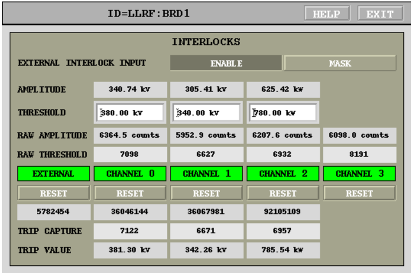

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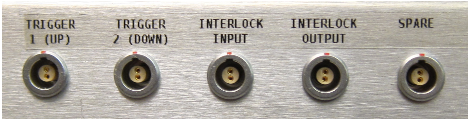
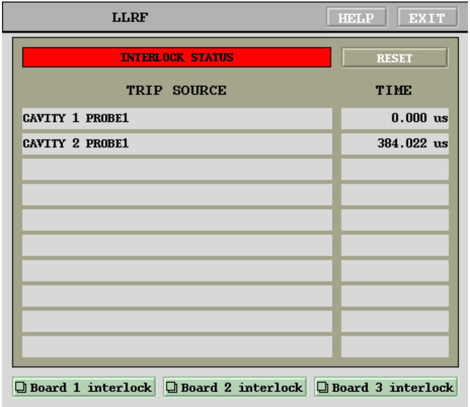
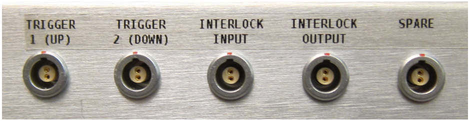
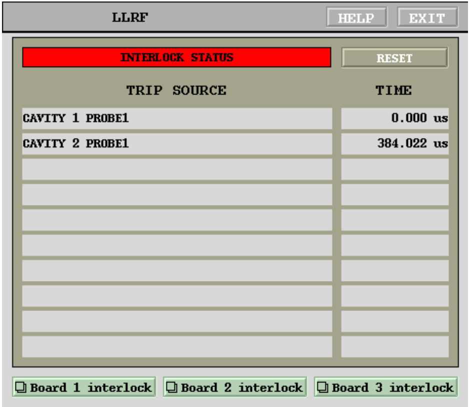




- External interlock enable input and interlock output allow for easy daisy-chaining:
  - Opto-isolated input;
  - 5 volt logic and solid-state relay output.
- All interlock sources are timestamped;
- IOC automatically sorts events to simplify trip diagnostics.

Interlock Chain - Continued





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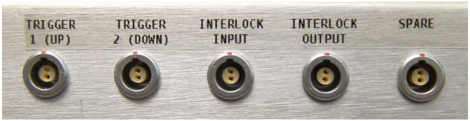

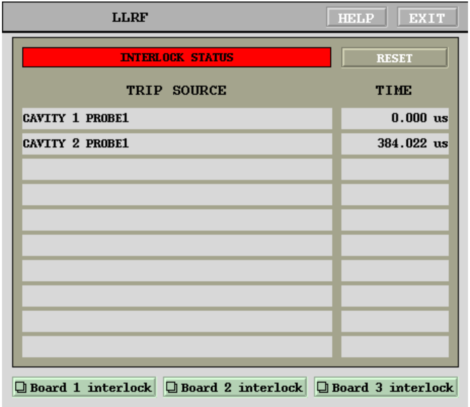

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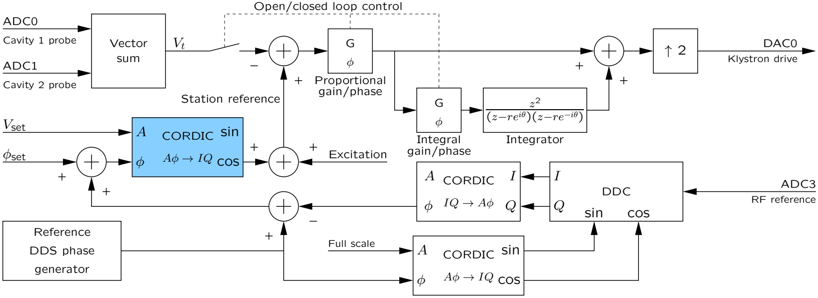

- Single cavity or vector sum of two;
- Reference phase is compensated in real-time;
- Proportional and integral loops;
- Double rate DAC drive;
- 512-point amplitude and phase profiles;
- Excitation input for built-in network analyzer.

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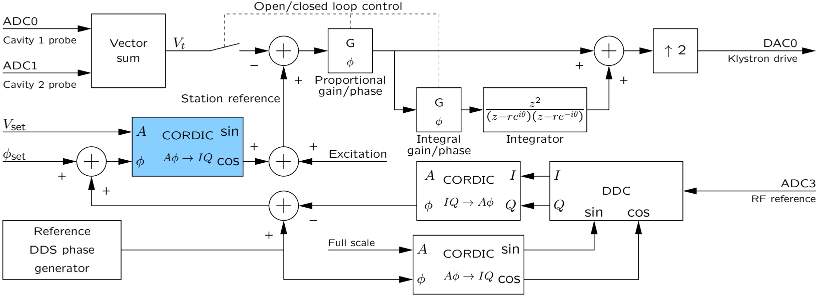

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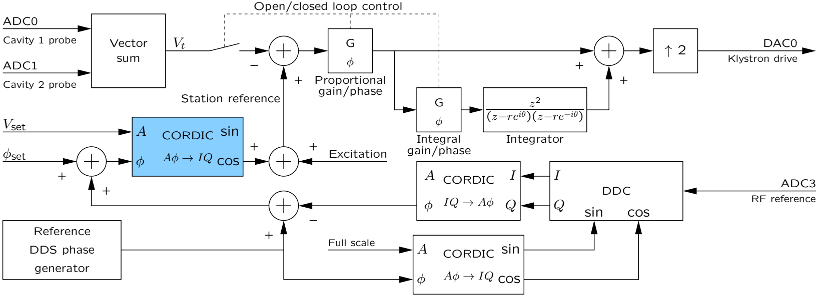

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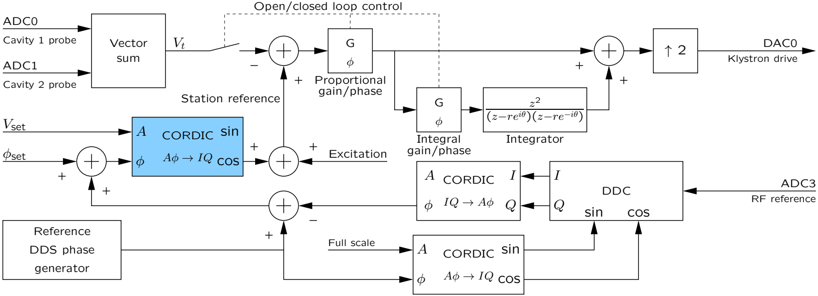

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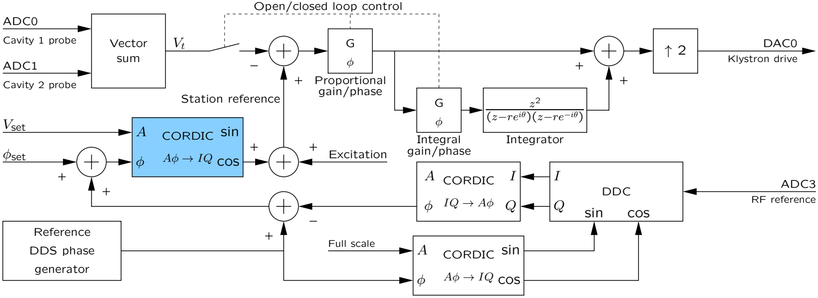

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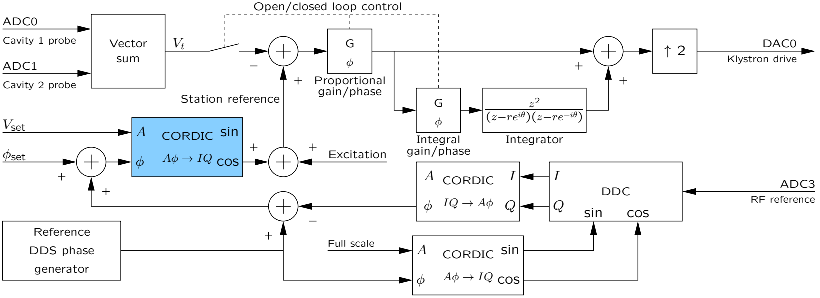

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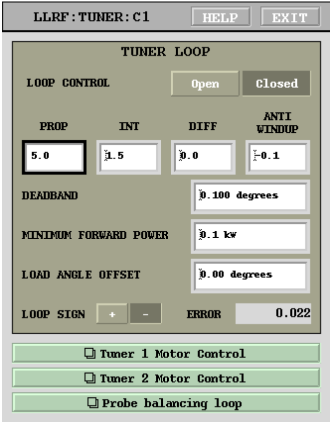
Tuner Loop



- 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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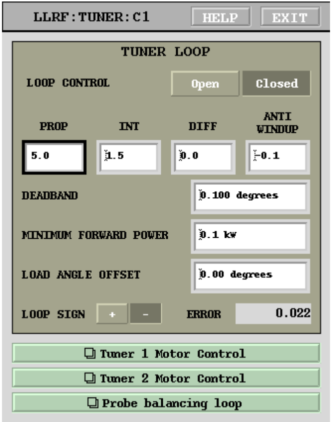

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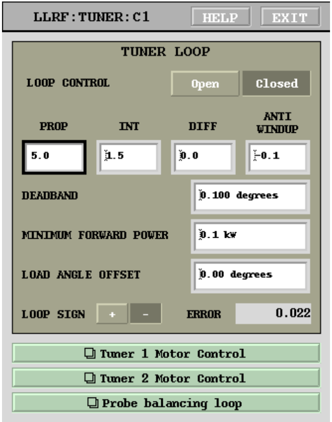

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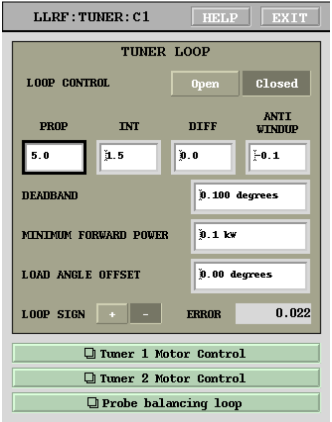

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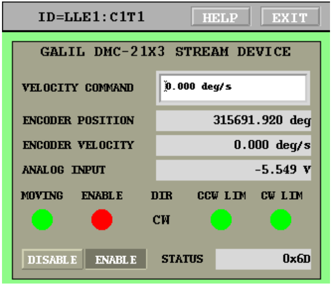

- LLRF9 supports a number of off-the-shelf motor controllers:
  - Galil DMC-21X3 stepper/brushed DC/brushless;
  - Schneider Electric Motion Mdrive Plus stepper;
  - Aerotech Soloist brushed DC.
- Interfaces include Ethernet, RS-485, RS-422;
- Plunger position monitoring from analog potentiometer;
-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

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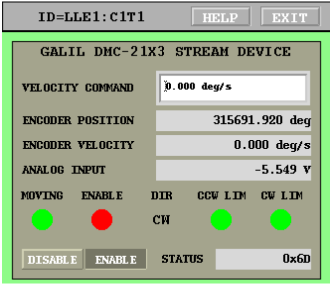

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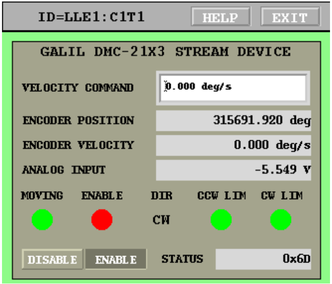

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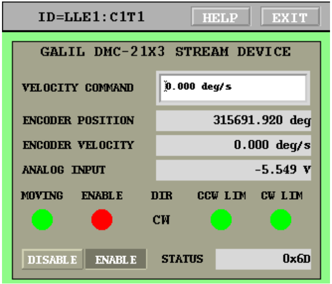

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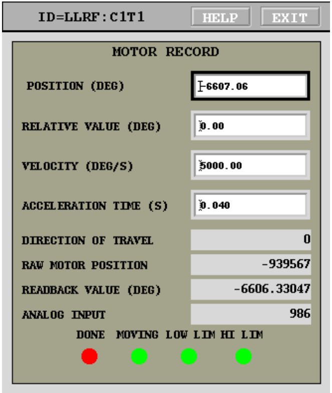

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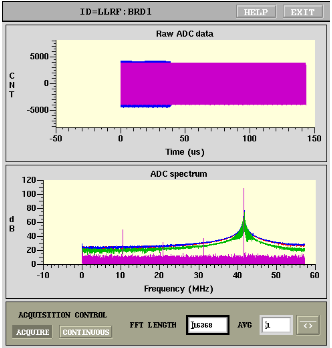
ADC Waveform Capture



- 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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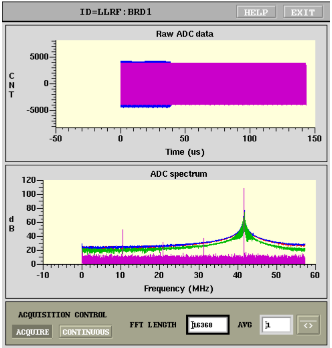

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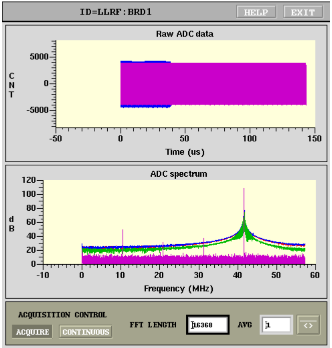

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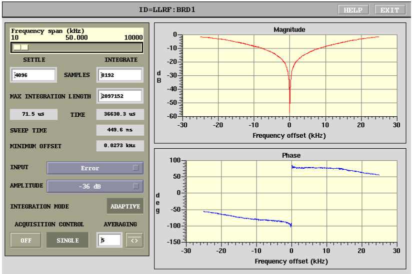
Network Analyzer



- 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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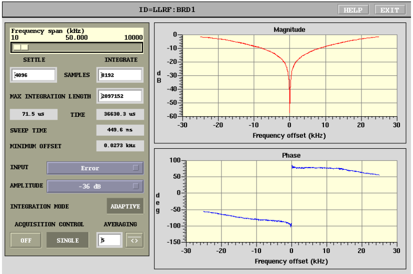

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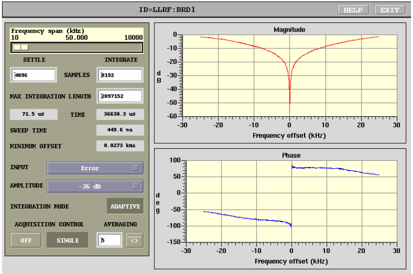

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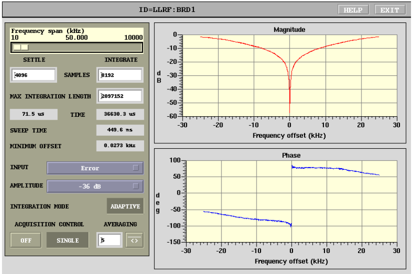

- High resolution (1024 point) swept analyzer;
- Adjustable excitation level;
- Fast sweep times with proprietary carrier suppression algorithm;
- Multiple probe points within the system:
  - Cavity probe;
  - Cavity sum;
  - Error signal;
  - Drive output.
- Spectrum analyzer mode with excitation disabled.

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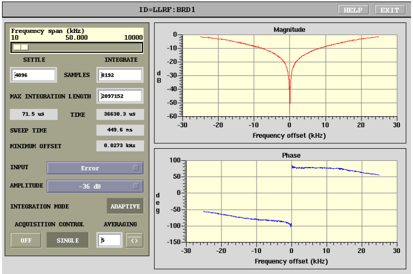

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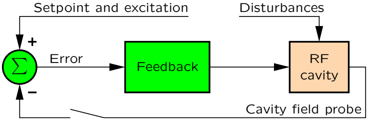
Outline

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*,
- Extremely useful for configuring the feedback loops, tuner loops, general diagnostics.

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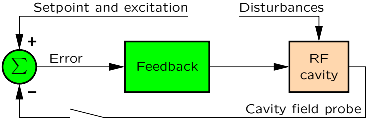

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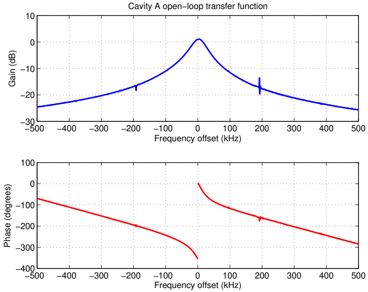

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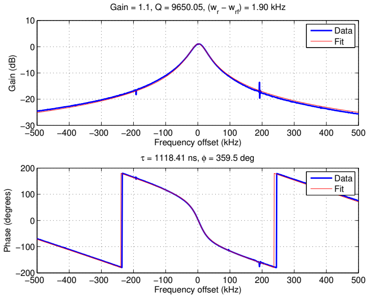

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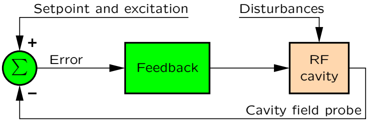
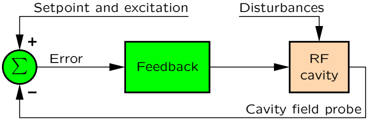


- Measured from setpoint to the error signal;
- Shows attenuation at frequencies where feedback has gain;
- Perturbations at the input of the cavity are rejected with the same transfer function;
- Proportional only;
- Proportional and integral, much higher rejection at low frequencies;
- Easier to see with the logarithmic frequency scale.

Closed Loop Transfer Functions



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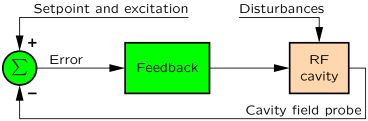

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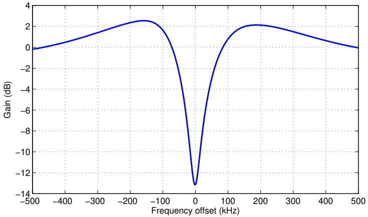

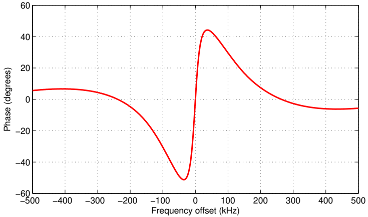

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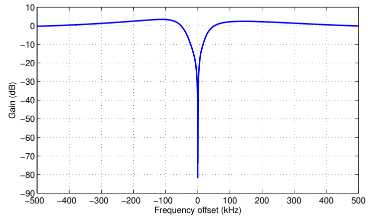

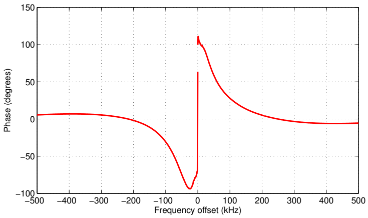

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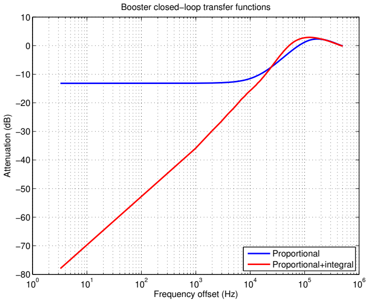

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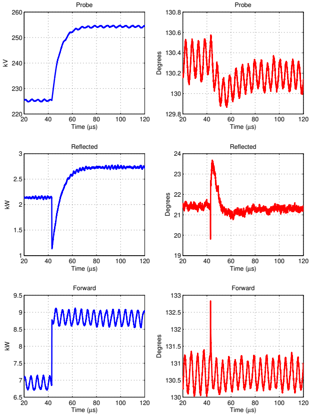
Outline

Step Response



- Ramp start triggers waveform acquisition;
- Ramp profile loaded with a 10% amplitude step (230 to 253 kV);
- Open loop: phase shift (AM-PM in power stage), setpoint error;
- Closed loop response is much faster, as expected;
- A bit too much gain, overshoot seen;
- Prominent ripple due to SSA power supply switching at 190 kHz.

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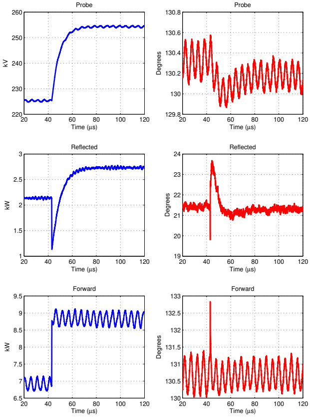

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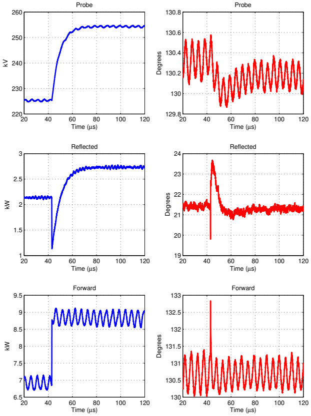

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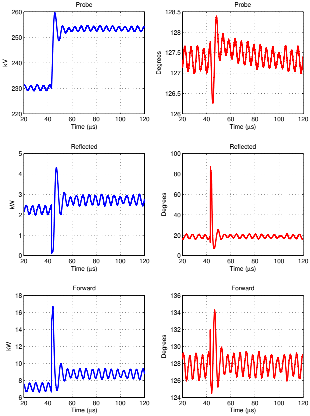

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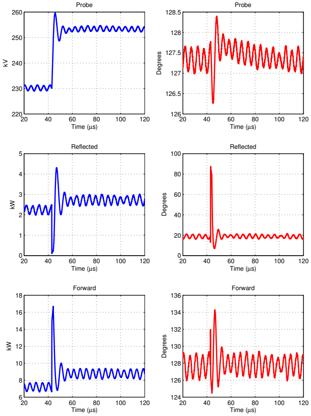

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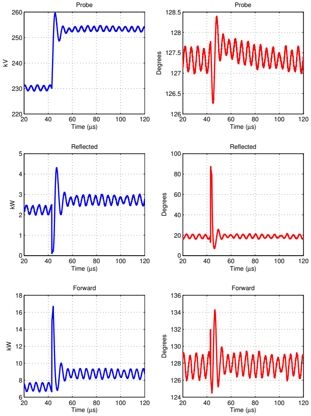

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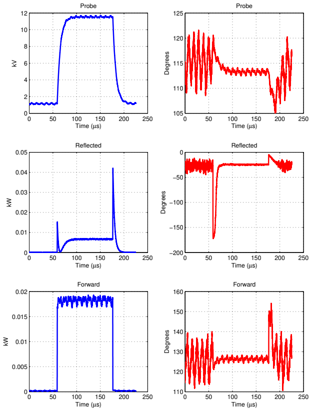

- Open-loop pulse response, cavity A;
- Base 2 kV, pulse 20 kV;
- Larger reflected power peak at the falling edge, expected for coupling factor $\beta > 1$;
- Phase slope during pulse decay indicates the cavity is slightly detuned.

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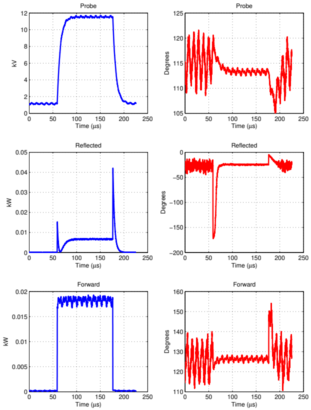

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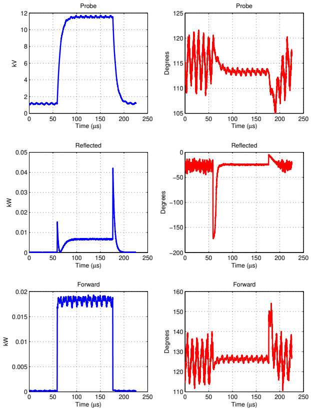

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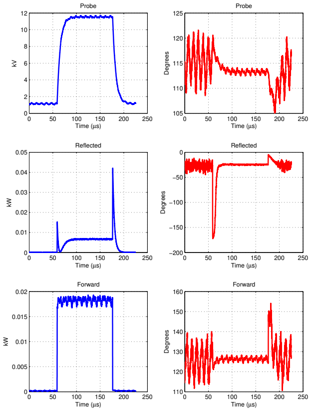

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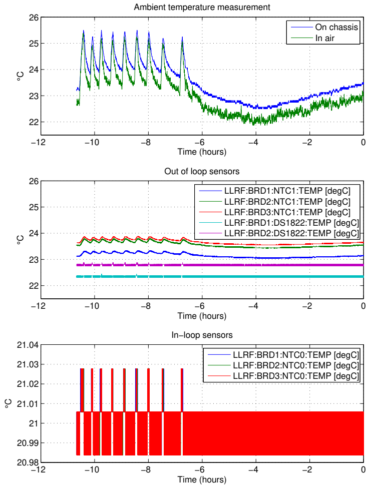
Thermal Stability: Lab Measurements



- 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 $^\circ C/^\circ C$.

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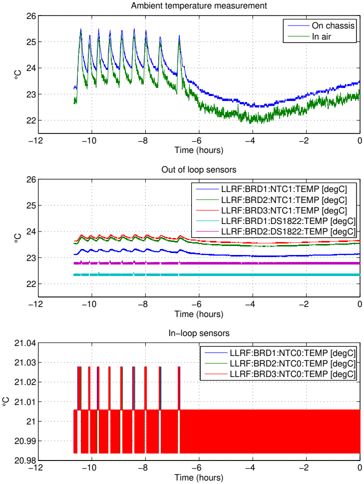

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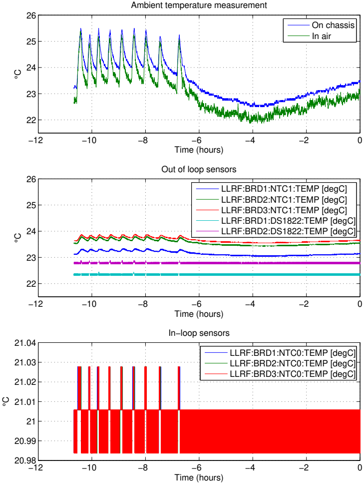

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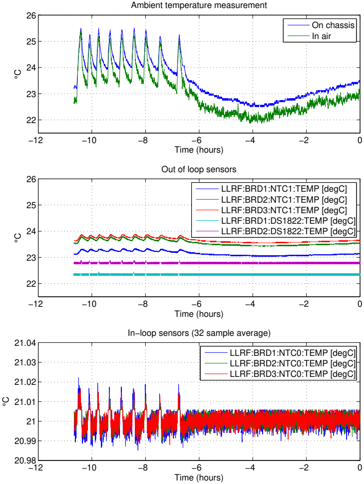

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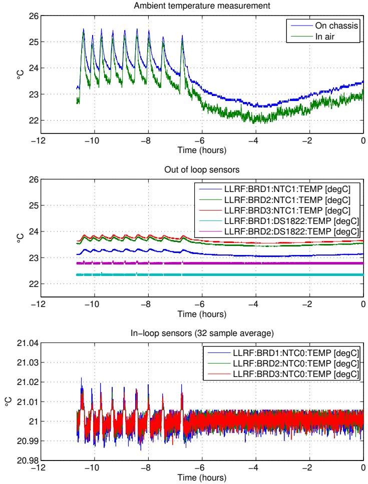

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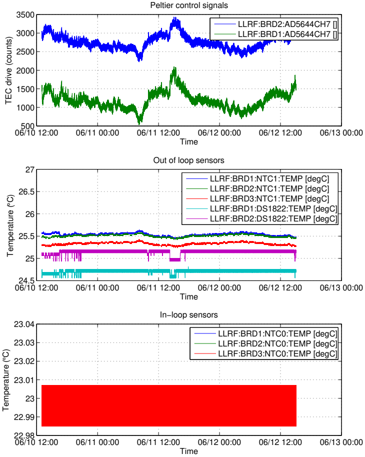

- Recorded over 2 days;
- Diurnal temperature variation clearly seen in out of loop sensors and Peltier control signals;
- Out of loop NTC sensors show 0.22 $^\circ C$ peak-to-peak variation.

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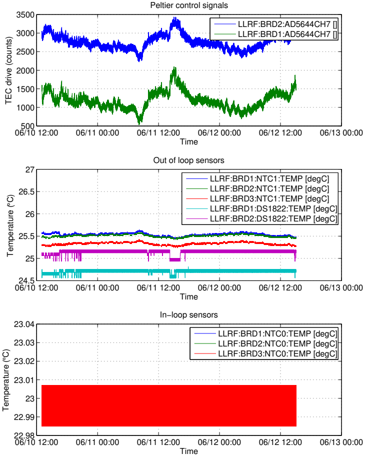

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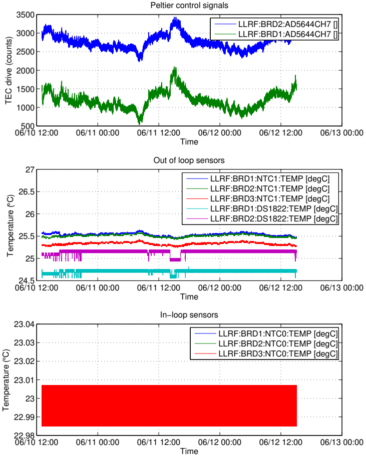

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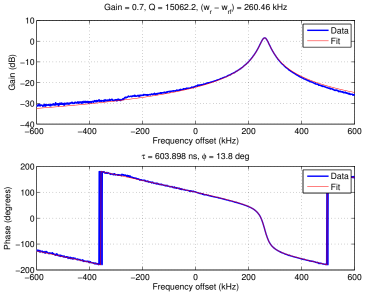
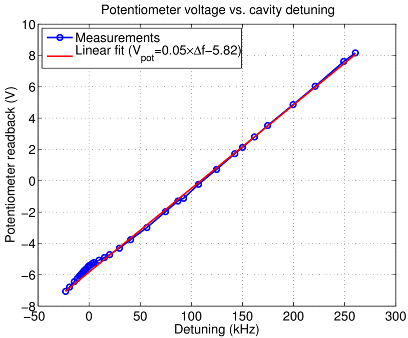
Tuning Scan at SESAME



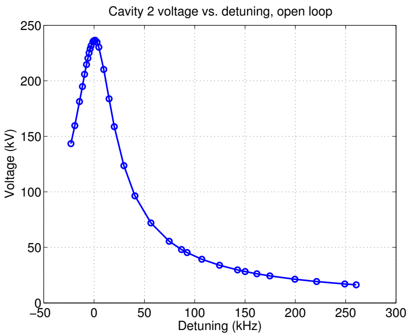
- Run the station in open loop, fixed setpoint;
- Move the cavity from limit switch to limit switch;
- At multiple points record:
  - Probe voltage and phase;
  - Forward and reflected power and phase;
  - LLRF9 output power meter;
  - Tuner potentiometer;
  - Open-loop transfer function.
- A lot of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

Tuner Position Potentiometer vs. Detuning



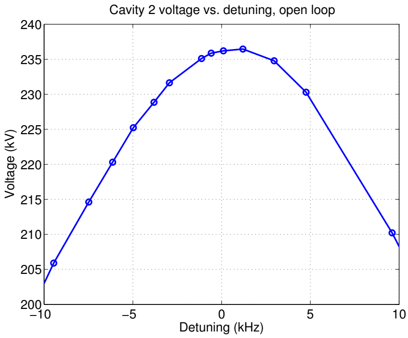
- Nearly linear;
- A deviation near zero detuning is caused by wall heating;
- Slope should be consistent, offset shifts with temperature.

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.

Cavity Voltage vs. Detuning



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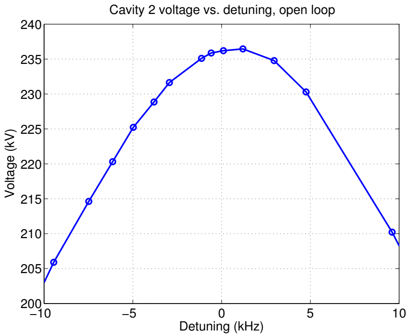

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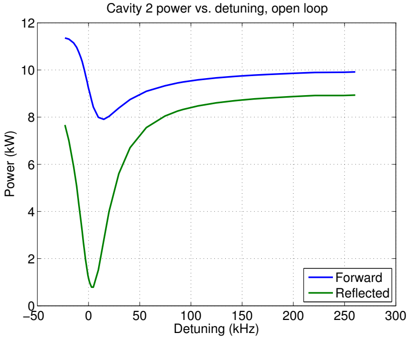
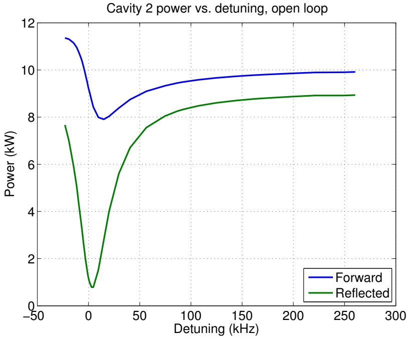
Waveguide Power vs. Detuning



- Reflected power minimum near 0;
- Forward power reading changes due to finite directivity of couplers;
- Drive level is constant;
- Peak field and minimum reflected are offset;
- Offset minimum of reflected power is expected, directivity again.

Waveguide Power vs. Detuning



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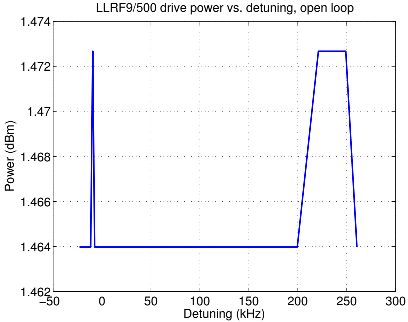

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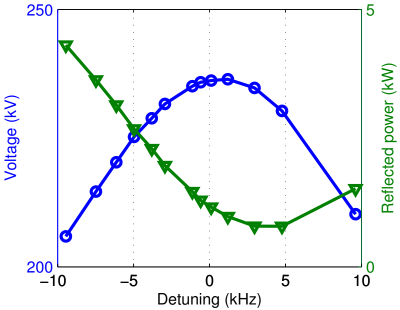

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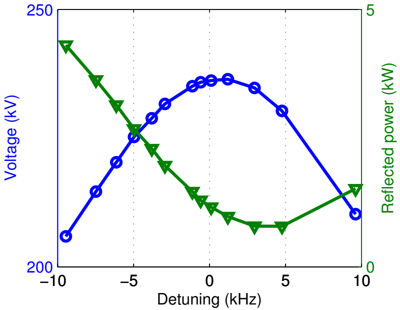

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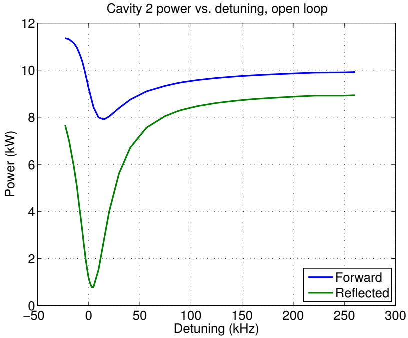
Coupler Directivity Correction



- 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;
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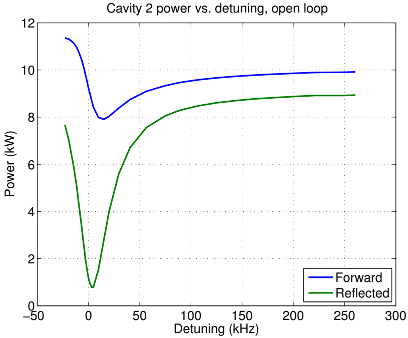

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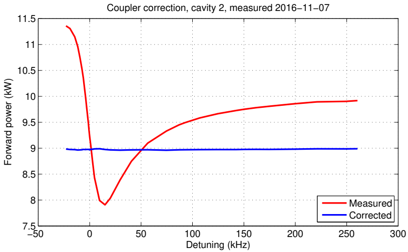

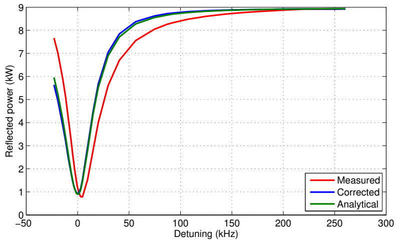

- Assuming power source is matched, we compute the coupler directivity correction matrix;
- At each point, we compute the expected reflection coefficient at RF from cavity transfer function fit;
- Matrix elements are then adjusted to:
  - Remove variation in forward power;
  - Match measured and computed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

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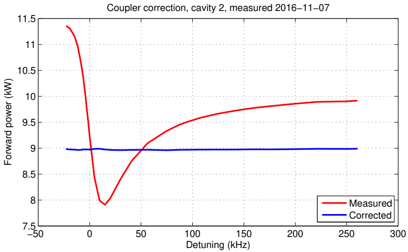

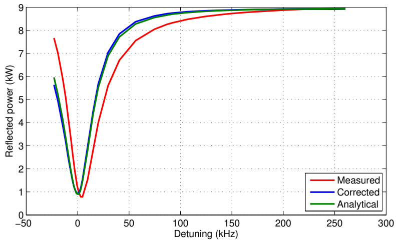

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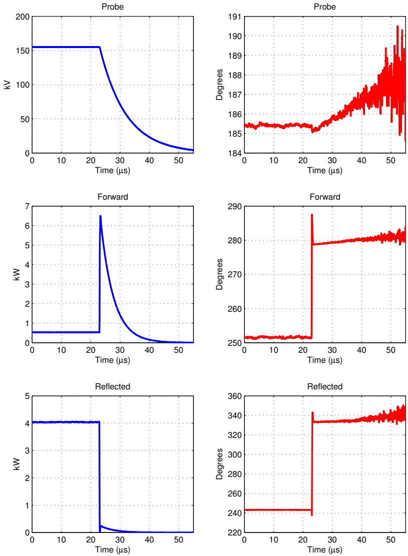
Time Domain Cavity Response



- 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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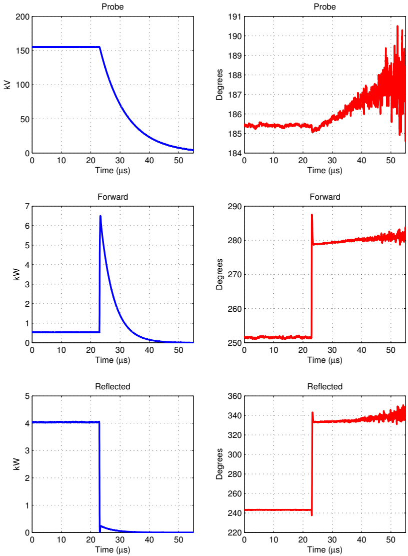

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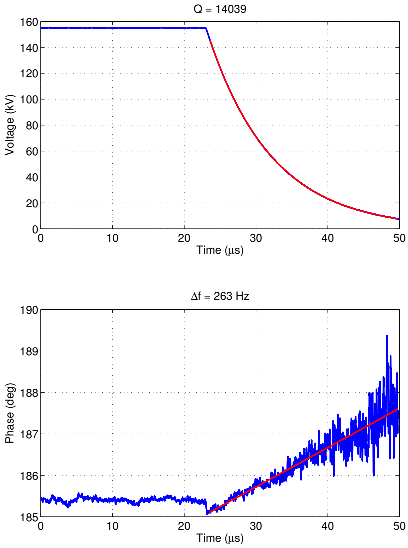

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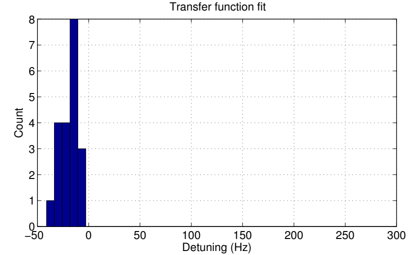

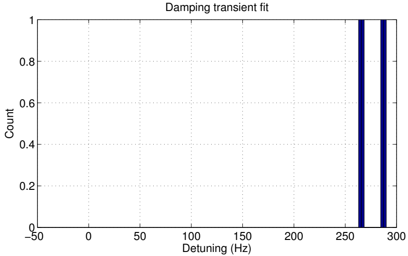

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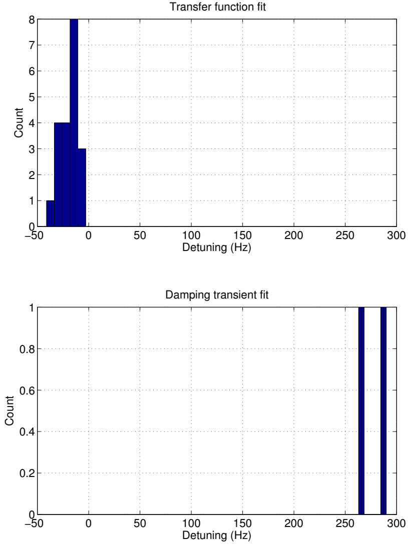

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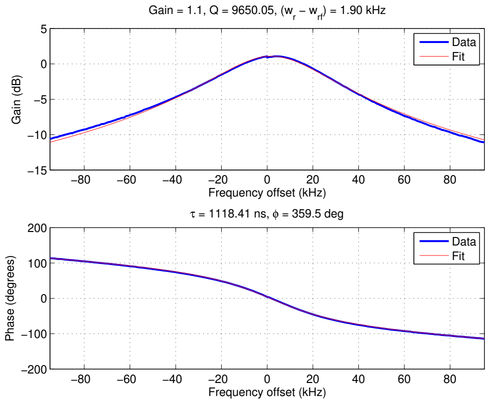
Outline

Cavity Parameters at LNLS



Cavity 1

Q_0	40000
Q_l	9650.0
β	3.1415

Cavity 2

Q_0	43000
Q_l	10683.4
β	3.0249

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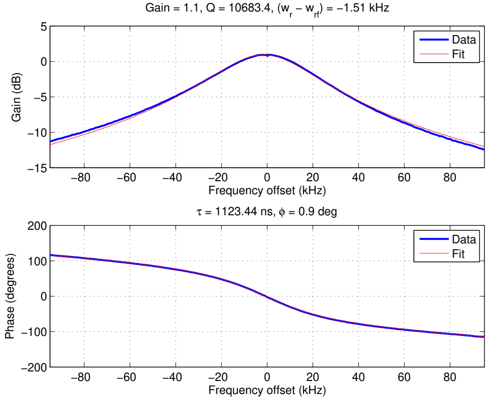

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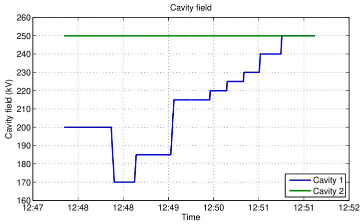
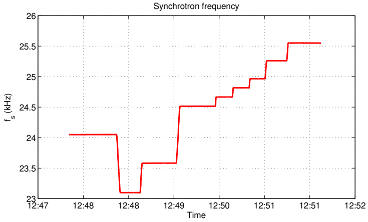
Probe Calibration





- 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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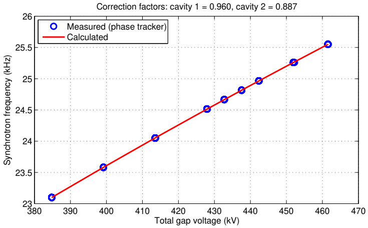

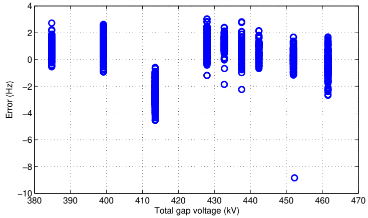

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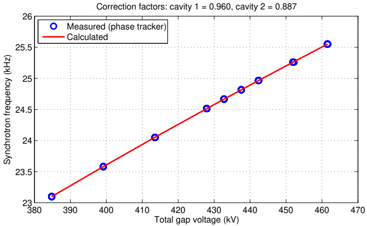

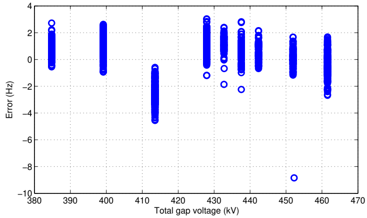

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Summary

- LLRF9 integrates a lot of functionality in a single unit;
- Used with normal conducting cavities at a number of machines;
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