Digital Low-level RF Demonstration at LNLS UVX

LLRF9 demo, June 8–12, 2015

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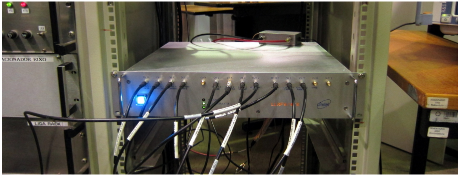
July 20, 2015

Outline

LLRF9 System



- A single 2U chassis for one- and two-cavity RF control;
- 9 input RF channels, 2 RF outputs;
- Tuner motor control via RS-485/Ethernet/EPICS/analog output;
- External interlock daisy-chain;
- Two external trigger inputs;
- Eight opto-isolated baseband ADC channels for slow interlocks.

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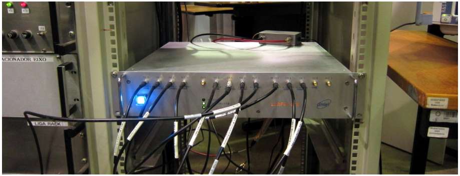

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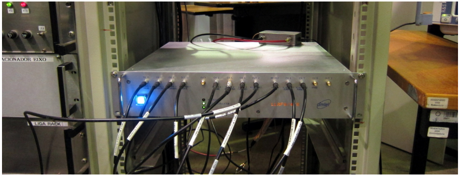

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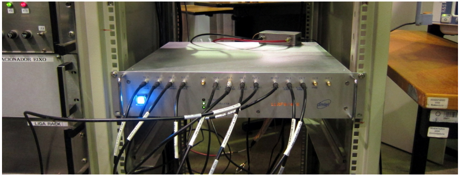

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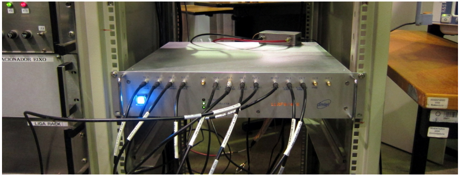

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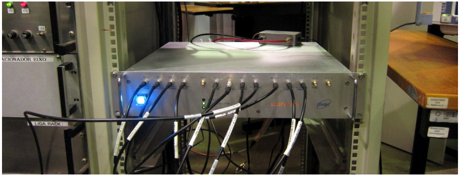

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Outline

Demo Setup: Booster

- Set up LLRF9 to run the booster RF with the following signals:
  - RF reference (476 MHz)
  - Cavity probe signal (476 MHz)
  - Cavity forward signal (476 MHz)
  - Cavity reflected signal (476 MHz)
  - Drive output (476 MHz)
  - Ramp trigger (TTL)
  - Tuner speed control ($\pm$7.5 V slow DAC)
  - Tuner position potentiometer (0–10 V slow ADC)

Demo Setup: Storage Ring

- Set up LLRF9 to run both storage ring RF stations with the following signals:
  - RF reference (476 MHz)
  - For each RF station:
    - Cavity probe signal (476 MHz)
    - Cavity forward signal (476 MHz)
    - Cavity reflected signal (476 MHz)
    - Cavity probe monitor (476 MHz)
    - Drive output (476 MHz)
    - Tuner speed control ($\pm$7.5 V slow DAC)
    - Tuner position potentiometer (0–10 V slow ADC)

Progress

- Monday, June 8th
  - Booster setup: inputs first to establish signal levels;
  - Connected drive output, configured feedback loops;
  - Established closed-loop operation in CW mode.
- Tuesday, June 9th
  - Interfaced LLRF9 tuner control loops to booster motor control;
  - Established closed-loop operation of the tuner loop;
  - Ran booster with beam, adjusted for maximum efficiency;
  - Started storage ring setup, configured station A.
- Wednesday, June 10th
  - Completed storage ring configuration;
  - Tried operation with beam, some dynamic difficulties;
  - Left RF stations operating overnight (no beam) to collect stability data.

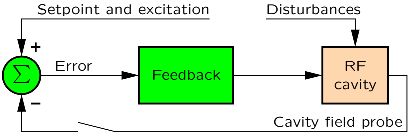
Progress (Continued)

- Thursday, June 11th
  - Analyzed LLRF setup and found proper configuration for operation with beam;
  - Training (Station A setup by Felipe Santiago);
  - Injected beam around 17:00, left to coast overnight.
- Friday, June 12th
  - Synchrotron tune tracking exploration;
  - Time and frequency domain characterization;
  - Phase noise studies;
  - Switched back to analog LLRF;
  - Injected beam around 19:00, left to coast overnight.
- Saturday, June 13th
  - Hardware removal;
  - Bunch-by-bunch feedback experiments.

Outline

1. Setup
   - LLRF9 Introduction
   - Demo Setup and Schedule
2. LLRF Characterization
   - Frequency Domain
   - Time Domain
3. Stability Measurements
   - Thermal
   - Without beam
   - With beam
4. Precision Calibrations
5. Phase Noise

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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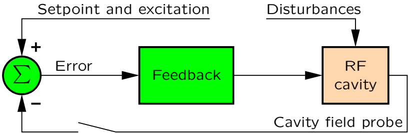

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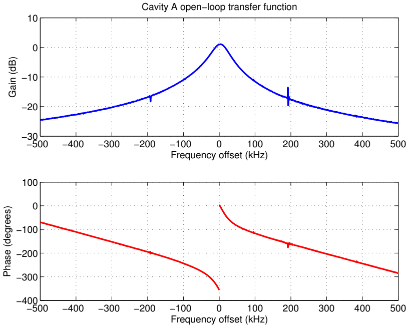

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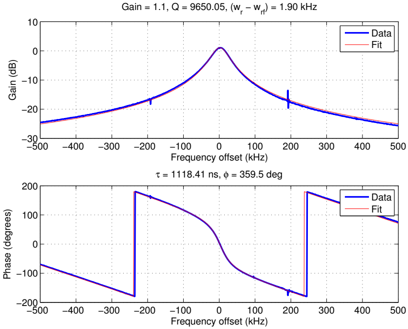

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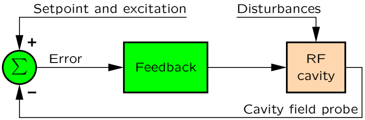

- Measured from setpoint to the error signal;
- Shows attenuation at frequencies where feedback has gain;
- Perturbations at the input of the cavity are rejected with the same transfer function;
- Proportional only;
- Proportional and integral, much higher rejection at low frequencies;
- Easier to see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

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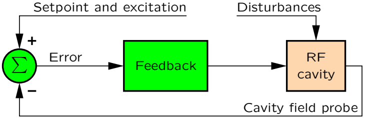

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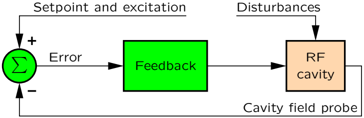

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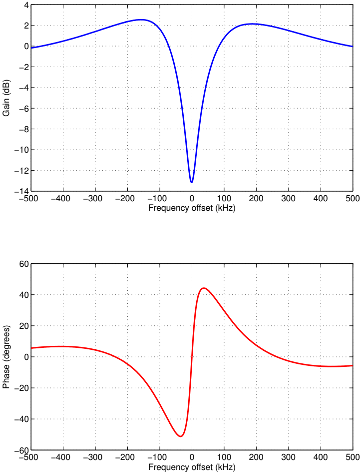

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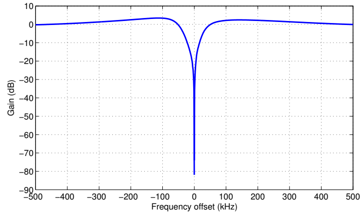

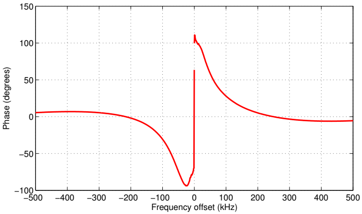

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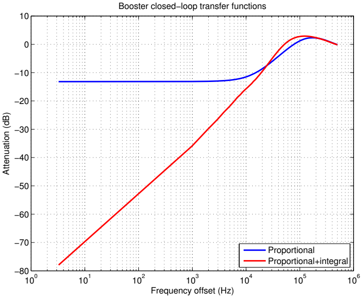

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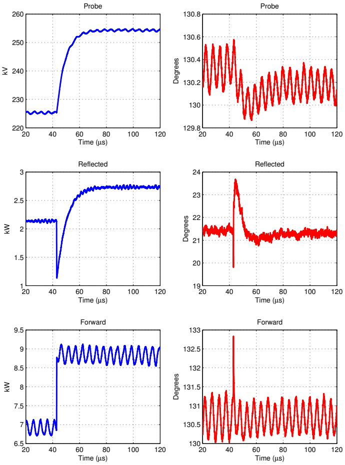
Step Response



- 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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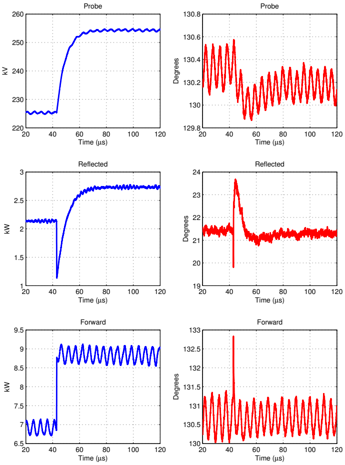

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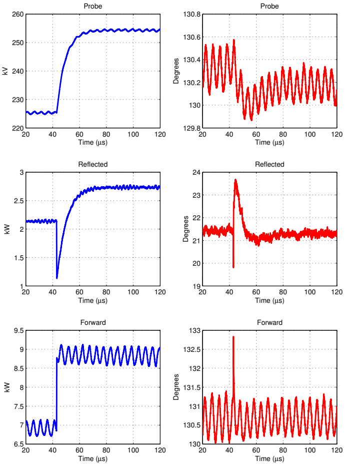

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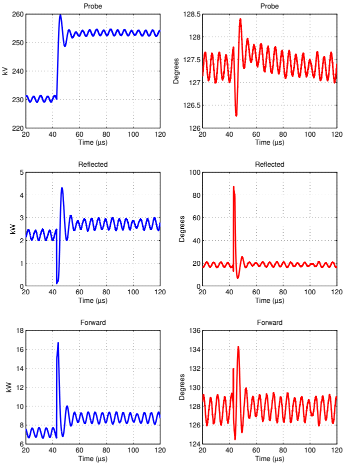

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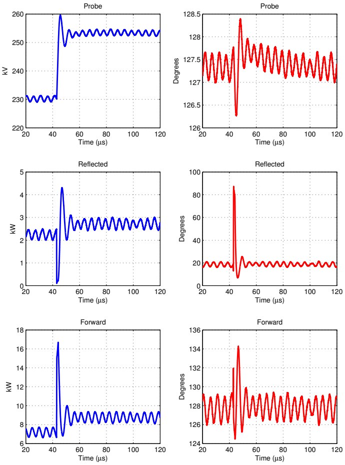

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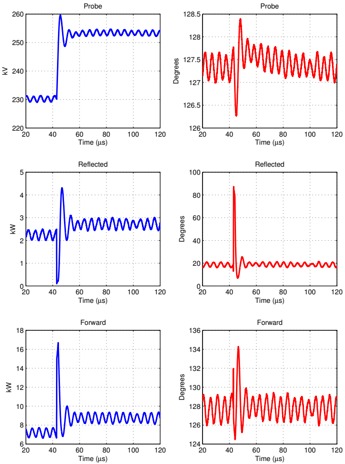

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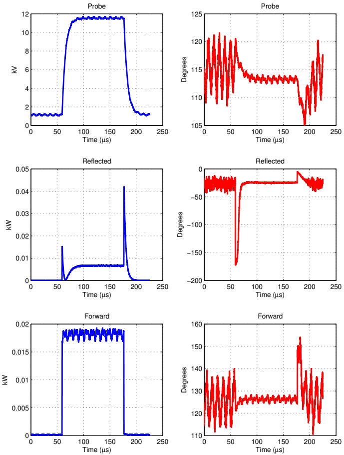
Pulse Response



- 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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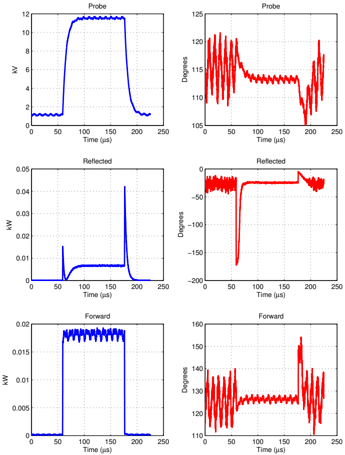

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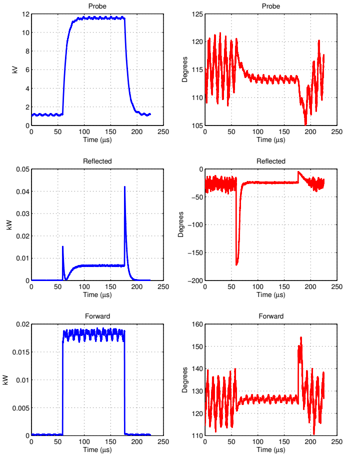

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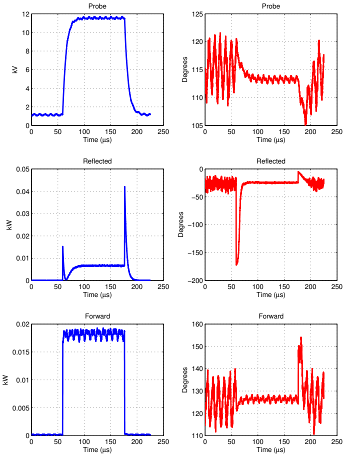

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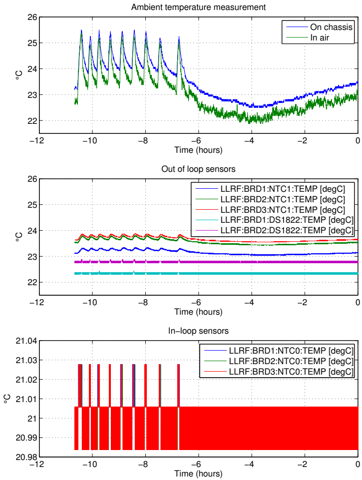
Thermal Stability: Lab Measurements



- 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 $°C/°C$.

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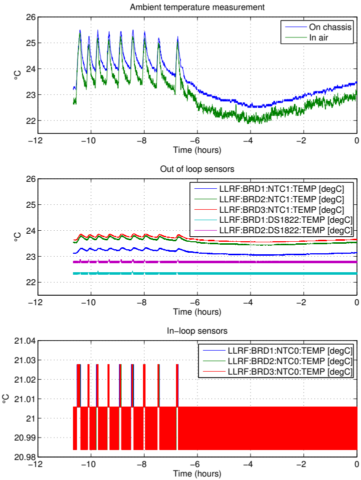

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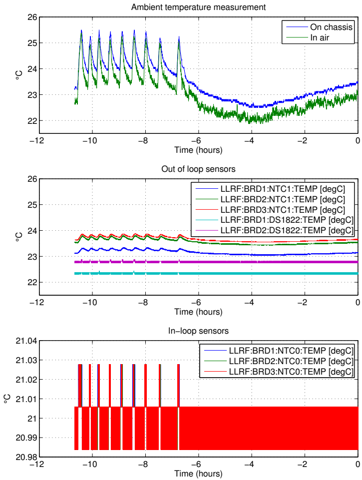

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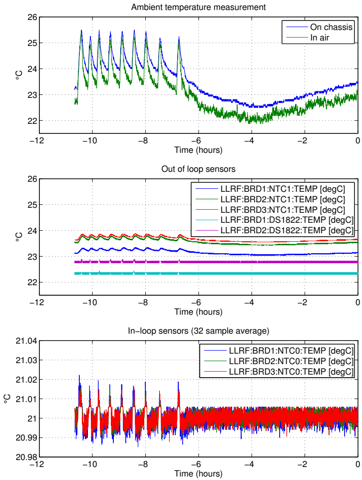

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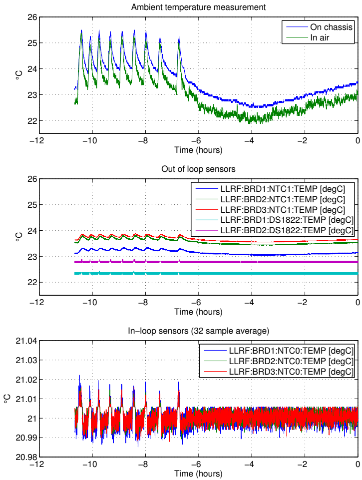

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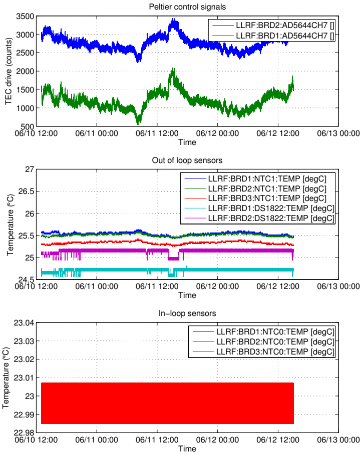

- Recorded over 2 days;
- Diurnal temperature variation clearly seen in out of loop sensors and Peltier control signals;
- Out of loop NTC sensors show 0.22 $^\circ C$ peak-to-peak variation.

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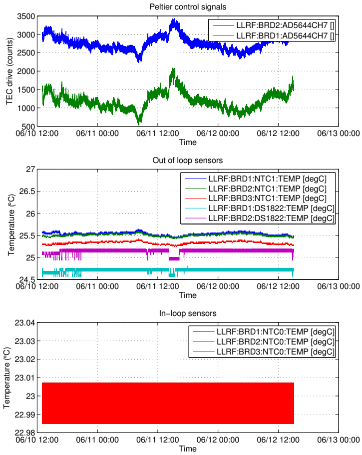

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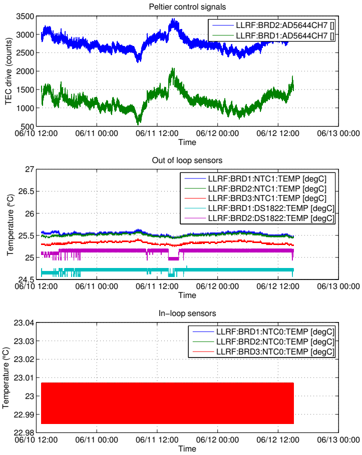

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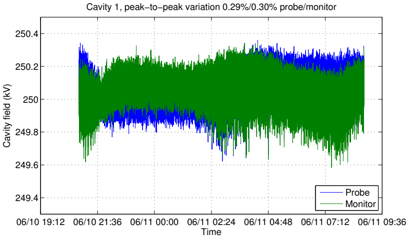

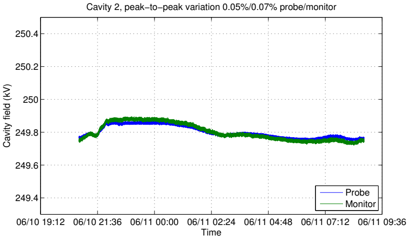

- Overnight run of two RF stations, no beam;
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- Monitor channels show more variation than feedback channels, as expected.

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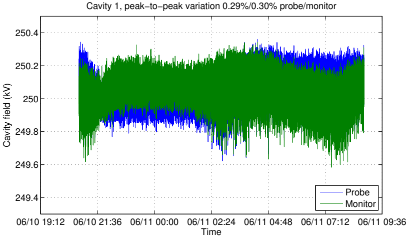

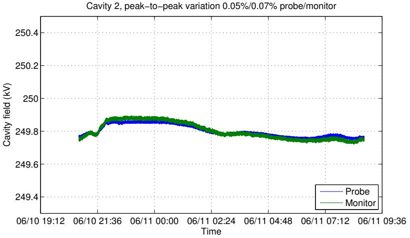

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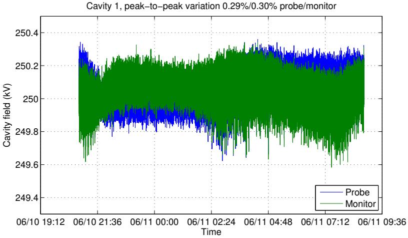

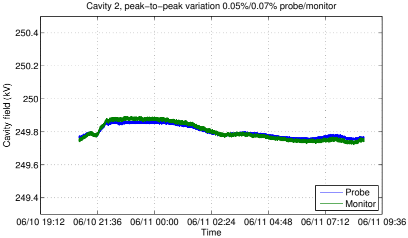

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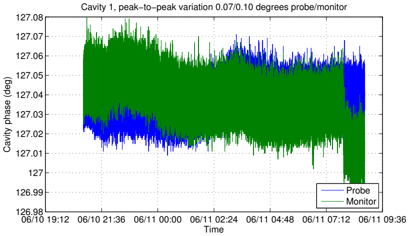
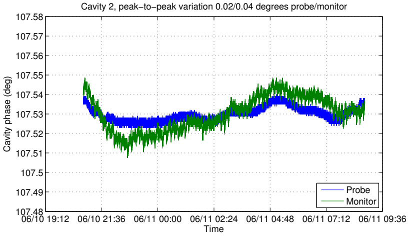
- Average amplitude scale and phase offsets removed, identical vertical scales;
- Station B had significantly higher feedback loop gains, better field stability;
- Monitor channels show more variation than feedback channels, as expected.

Field Stability 1: LLRF9 without beam





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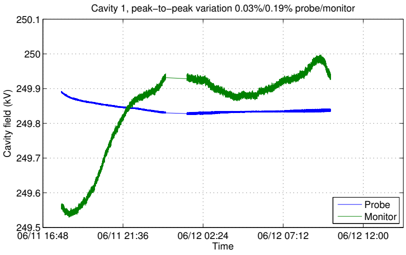
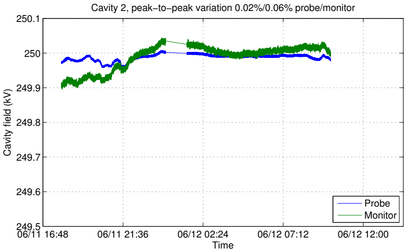
Outline

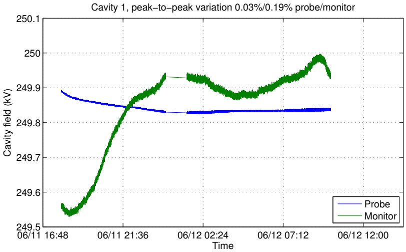
Field Stability 2: LLRF9 With Beam

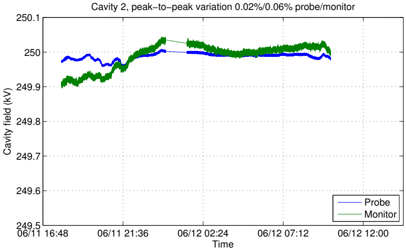




- Overnight run, beam current decaying from 250 mA, 1.37 GeV;
- Masked data between 0:00 and 1:26 corresponds to longitudinal tune tracking studies;
- Similar stability of in-loop signals;
- Monitor channels show significantly more variation than feedback channels;
- Worst-case peak-to-peak range is 0.2% and 0.06°.

Field Stability 2: LLRF9 With Beam





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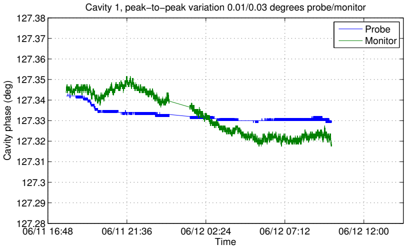

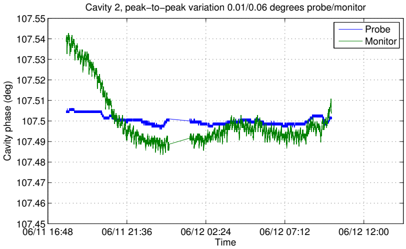

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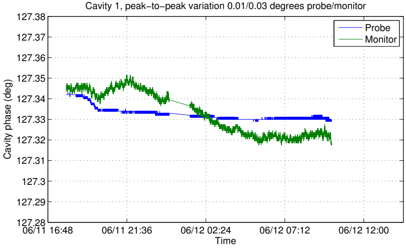

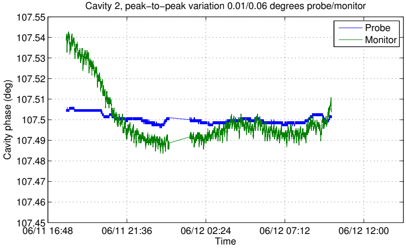

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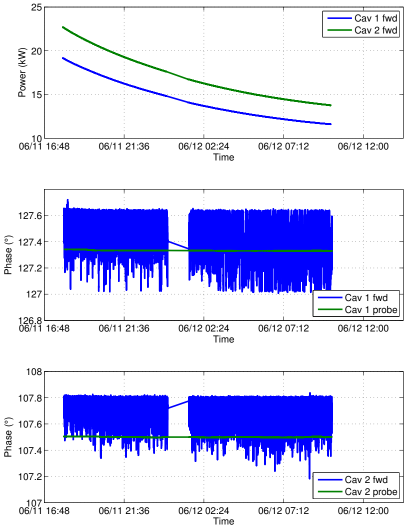

- Cavity probe and forward phases during coasting;
- Field control loops hold probe phases constant;
- Tuner loop is adjusting cavity frequency to keep forward in phase with the probe;
- Dead band of 0.3° is evident.

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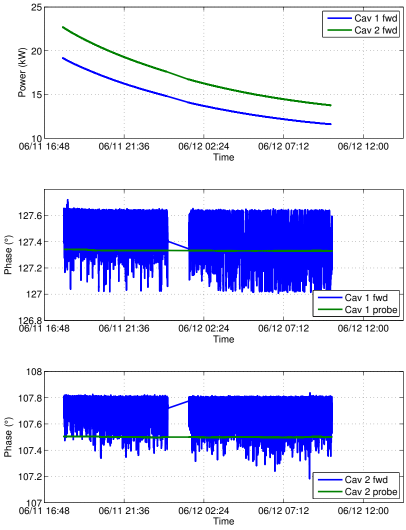

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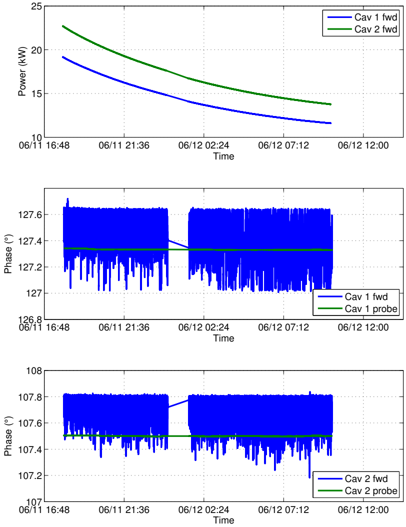

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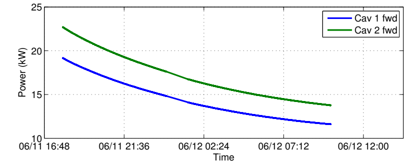

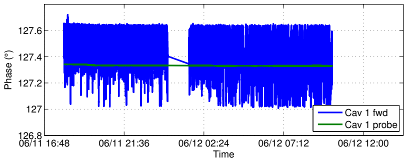

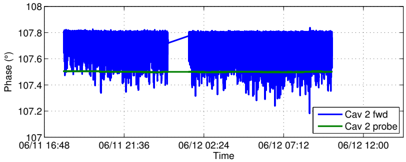

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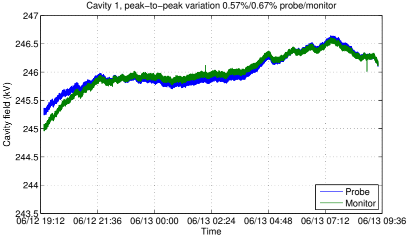
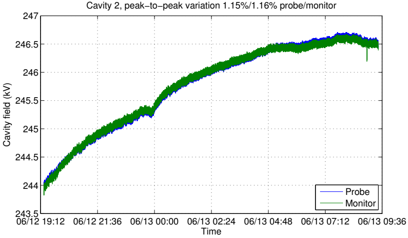
Field Stability 3: Analog LLRF





- Overnight run, beam current decaying from 250 mA, 1.37 GeV;
- Normal LNLS LLRF setup;
- LLRF9 is only monitoring;
- Quite a difference between stations A and B.

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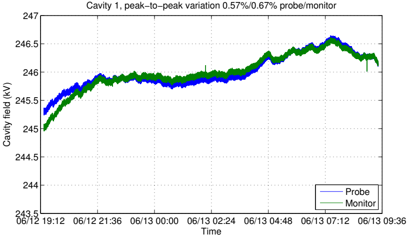

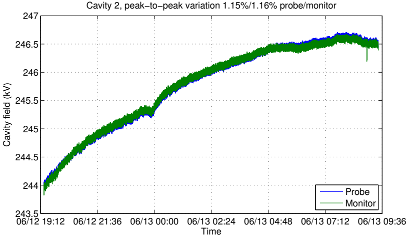

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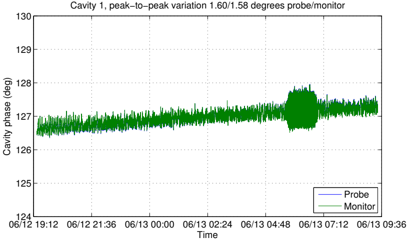

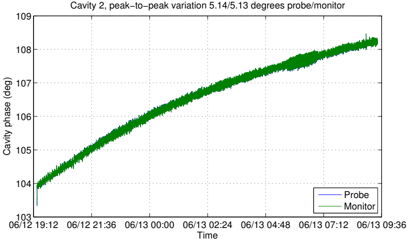

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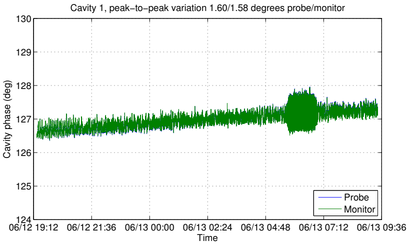

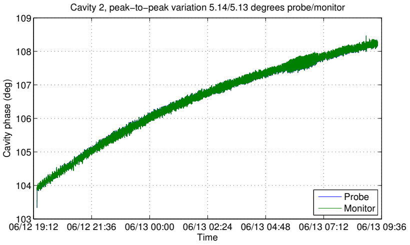

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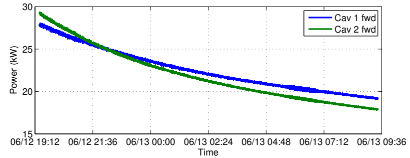

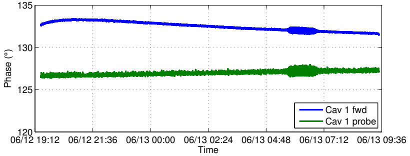

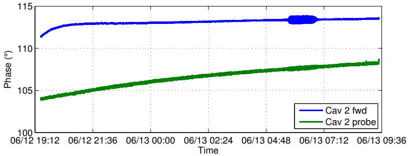

- Cavity probe and forward phases during coasting;
- Phase loop should keep forward phase constant;
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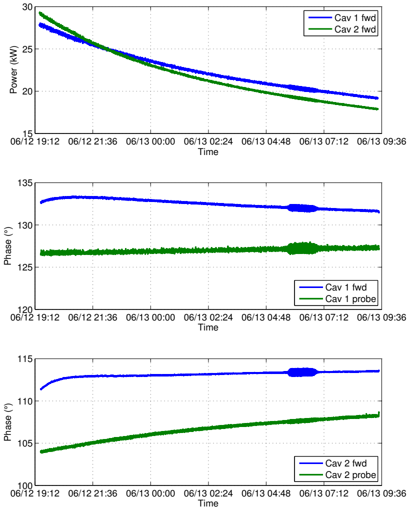

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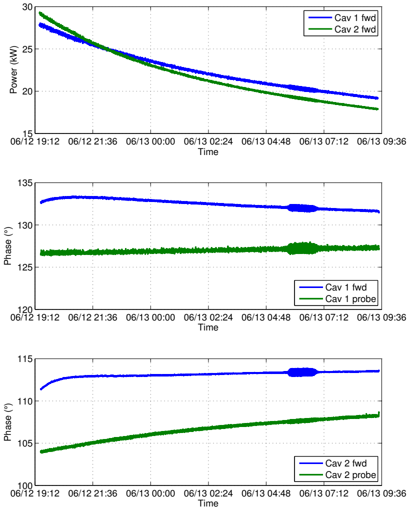

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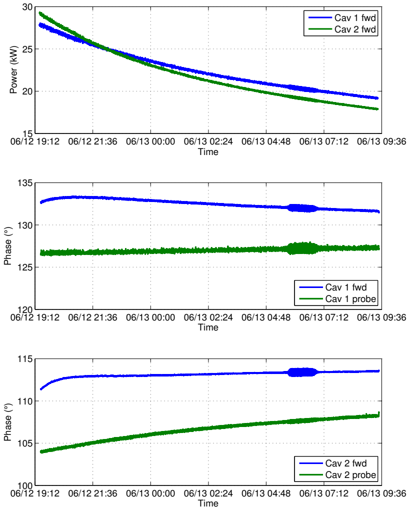

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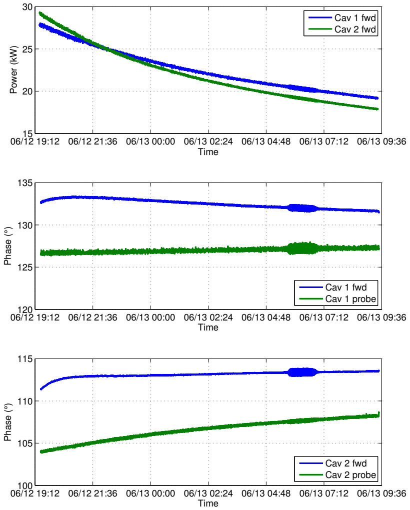

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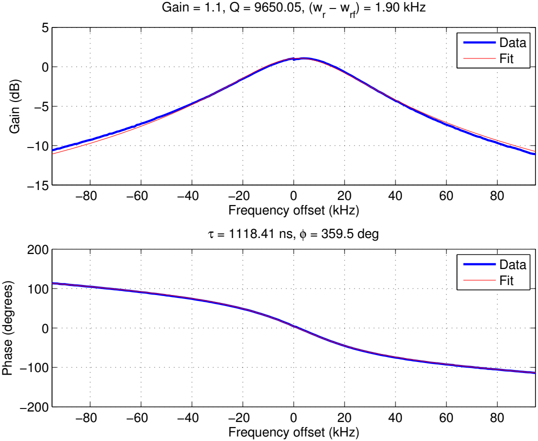
The Plan

- Use open-loop transfer functions to determine Q_l for each cavity;
- Use design R/Q values, known unloaded quality factors;
- From ω_s vs. V_c studies establish precise probe calibrations;
- Use zero current and beam data to calibrate forward power channels;
- For proper reflected power calibration need to quantify coupler directivity.

Cavity Parameters



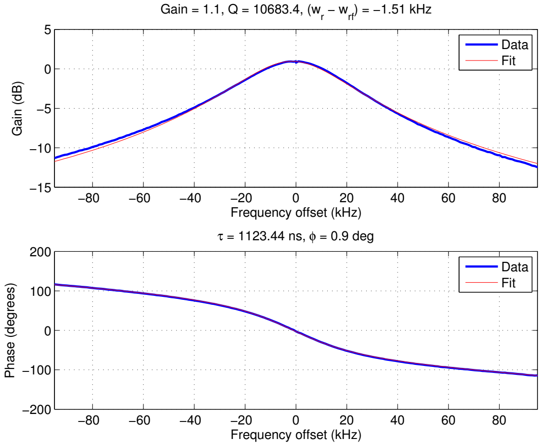
Cavity 1

Q_0	40000
Q_l	9650.0
β	3.1415

Cavity 2

Q_0	43000
Q_l	10683.4
β	3.0249

Cavity Parameters



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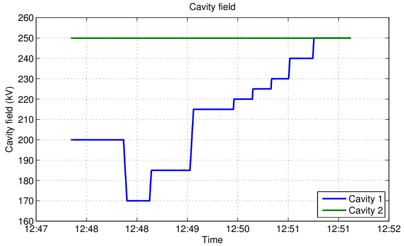
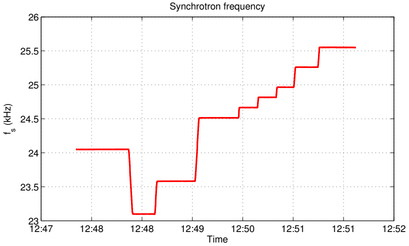
Probe Calibration





- 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 as published.
- Obtain scaling factors for existing calibrations.

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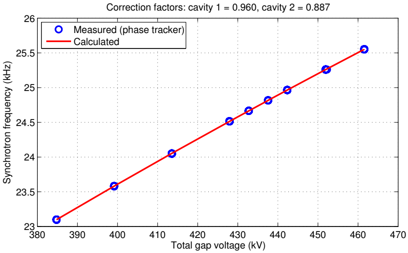

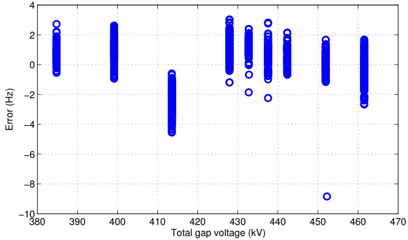

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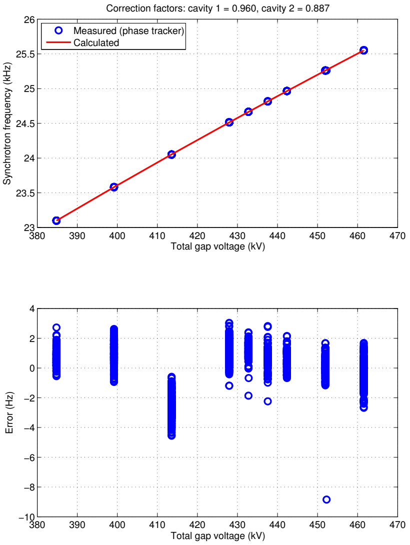

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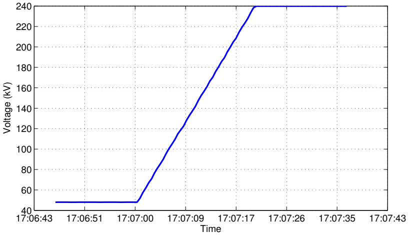
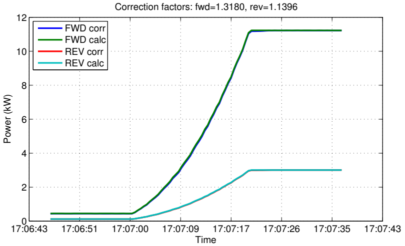
Power Calibration Without Beam





- Calculate cavity operating point from freshly calibrated probe signal
- Assuming on-resonance tuning here, could include transient detuning;
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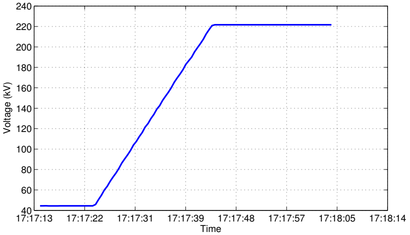

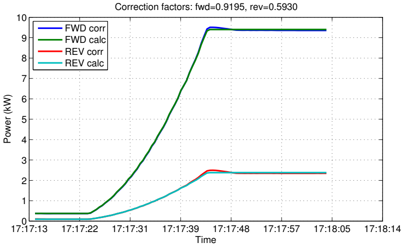

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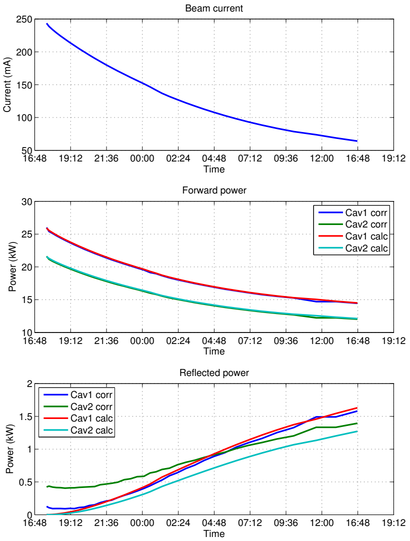
Power Calibration Check With Beam



- Calculate operating points based on cavity fields and phases, beam current, all other accelerator parameters;
- Machine setup: EPU and 2T wiggler @ 22 mm, SCW @ 4 T;
- Matching forward power requires:
  - Offsetting station phases by 2 degrees;
  - Reducing energy loss per turn by 13 keV (132.33 keV).
- Reflected power is skewed by finite coupler directivity.

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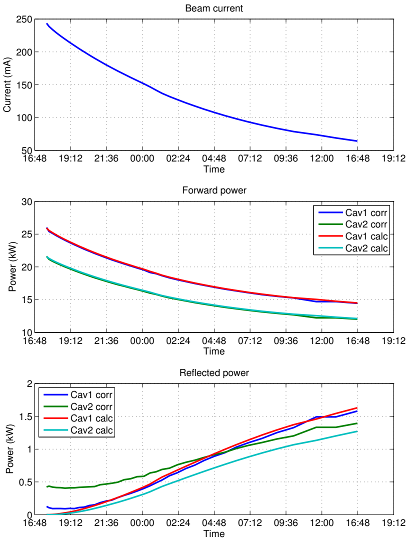

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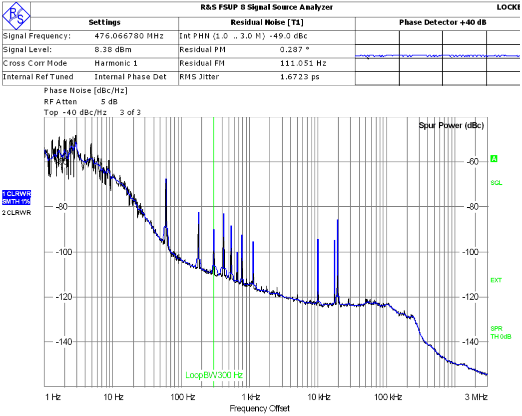
Standard Master Oscillator



- Absolute phase noise measurements with Rohde&Schwartz FSUP
- Master oscillator reference, −123 dBc/Hz @25 kHz;
- Cavity 1, 250 kV, fb optimized, −121 dBc/Hz @25 kHz;
- Cavity 2, 250 kV, fb optimized, −122 dBc/Hz @25 kHz.

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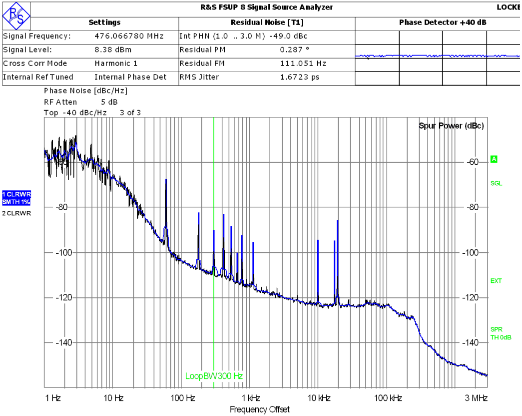

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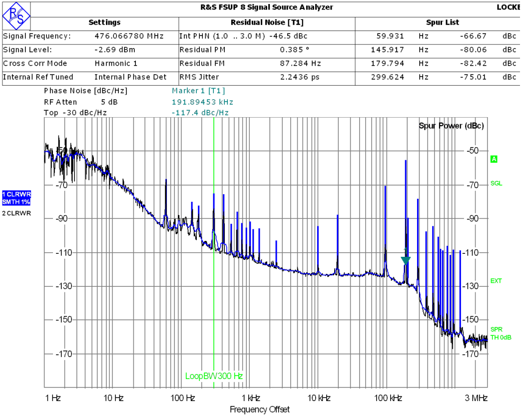

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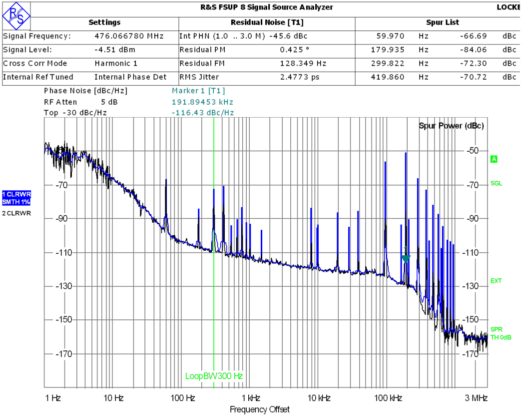

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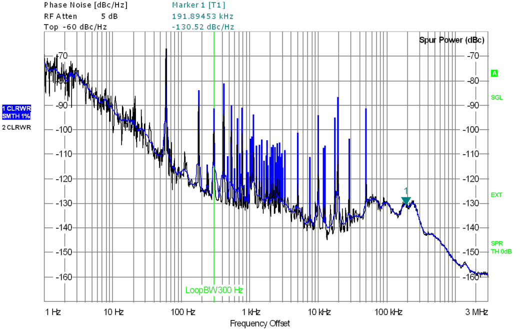
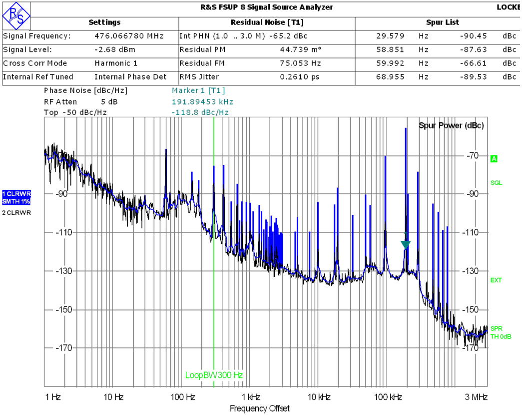
Quiet Master Oscillator

R&S FSUP 8 Signal Source Analyzer							LOCKE
Settings		Residual Noise [T1]		Spur List			
Signal Frequency:	476.066780 MHz	Int PHN (1.0 .. 3.0 M)	-70.3 dBc	21.140	Hz	-91.42	dBc
Signal Level:	8.22 dBm	Residual PM	24.872 m°	59.963	Hz	-66.90	dBc
Cross Corr Mode	Harmonic 1	Residual FM	71.818 Hz	179.888	Hz	-83.75	dBc
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.1451 ps	239.856	Hz	-114.08	dBc



- Much quieter reference, 145 fs vs. 1.67 ps, -137 dBc/Hz @25 kHz;
- Cavity 1 probe, 250 kV, fb optimized, -134 dBc/Hz @25 kHz;
- Cavity 2 probe, 250 kV, fb optimized, -132 dBc/Hz @25 kHz.

Quiet Master Oscillator



- Much quieter reference, 145 fs vs. 1.67 ps, -137 dBc/Hz @25 kHz;
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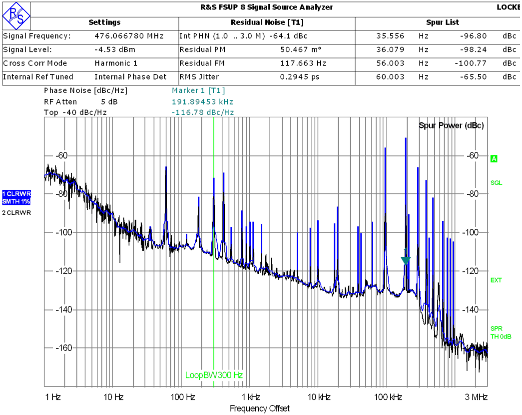

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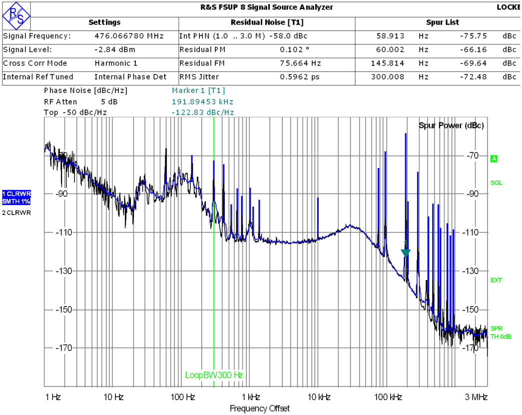
Quiet Master Oscillator, Analog LLRF



- Cavity 1 probe, -107 dBc/Hz @25 kHz;
- Cavity 2 probe, -105 dBc/Hz @25 kHz.

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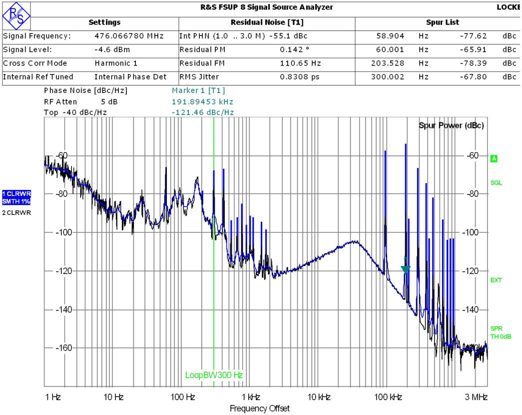

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Summary

- Successfully operated booster RF station with beam;
- Operated two storage ring stations using one LLRF9/476 unit;
- Demonstrated stable operation through full machine cycle from injection to ramping, ID closure, and coasting;
- LLRF9/476 has much lower (27 dB) cavity field phase noise in the vicinity of the synchrotron frequency;
- Modulation capabilities of LLRF9 were used to apply quadrupole modulation to stored beam;
- Precise measurements of cavity signals enable better RF calibrations and determinations of accelerator parameters.

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