Digital Low-level RF Test at Diamond Booster

LLRF9 demo, March 16–20, 2015

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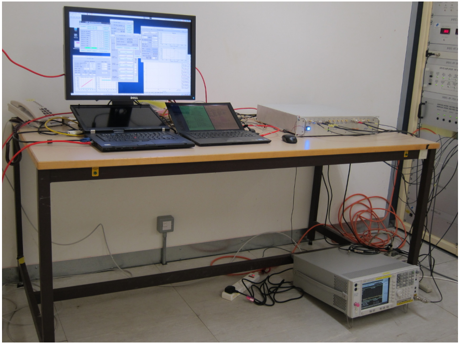
April 15, 2015

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;
- External interlock daisy-chain;
- Two external trigger inputs;
- Eight opto-isolated baseband ADC channels for slow interlocks.

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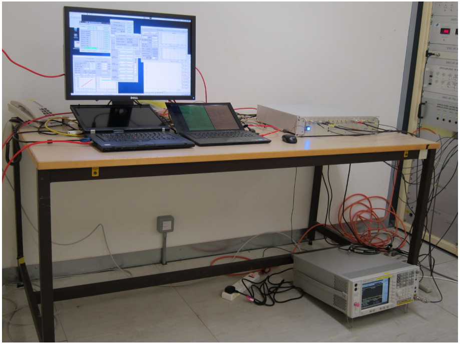

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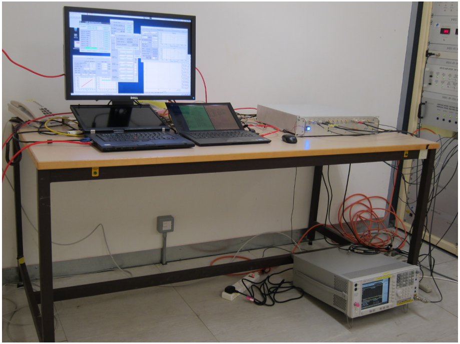

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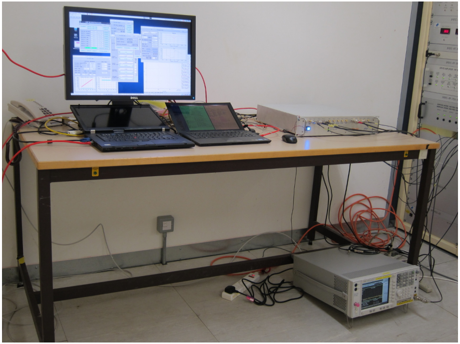

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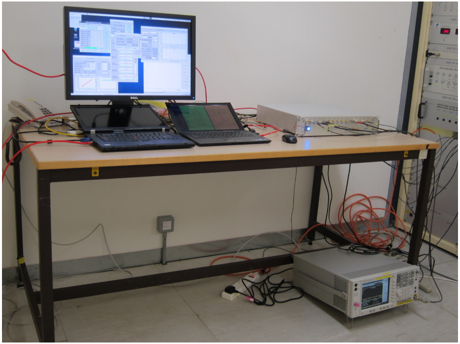

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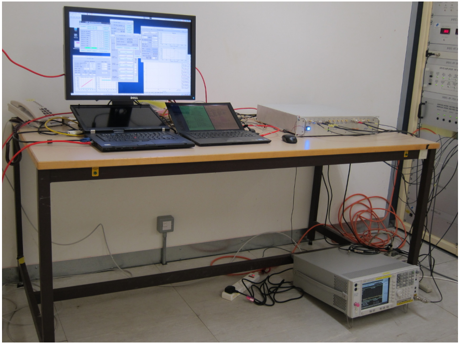

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Outline

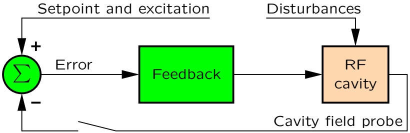
Demo Setup

- Set up LLRF9 to run the booster RF with the following signals:
  - RF reference (500 MHz)
  - Three cavity probe signals (500 MHz)
  - Cavity forward signal (500 MHz)
  - Cavity reflected signal (500 MHz)
  - Drive output (500 MHz)
  - Interlock input (TTL)
  - Ramp trigger (TTL)
- Used EPICS interface to control cavity tuning;
- LLRF9 drive was connected to RF Safety Crate (113S) to maintain interlocks;
- Bypassed existing LLRF chain, RF Safety Crate output connected directly to preamplifier (222S).

Progress

- Monday
  - Connected LLRF9 to inputs only, established signal levels and transferred calibrations;
  - Connected drive output, configured feedback loops;
  - Established closed-loop operation in CW mode.
- Tuesday
  - Interfaced LLRF9 tuner control loops to booster motor control;
  - Established closed-loop operation of tuner and field balance loops.
- Wednesday
  - Transitioned to closed-loop operation with ramping and beam;
  - Characterization of open and closed-loop spectra.
- Thursday
  - Step response measurements;
  - System set up from scratch by Alun Watkins.
- Friday
  - Performance testing;
  - Discussion.

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, detuning, delay, phase shift at ω_{rf};
- Faster than expected gain roll-off above the resonance.

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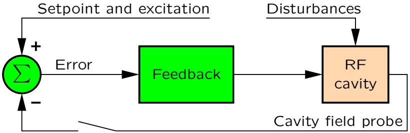

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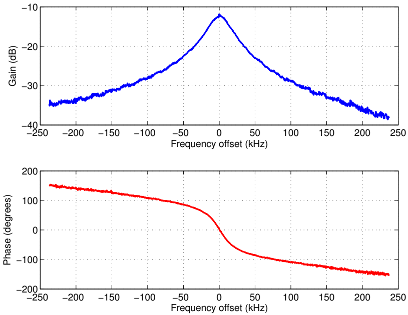

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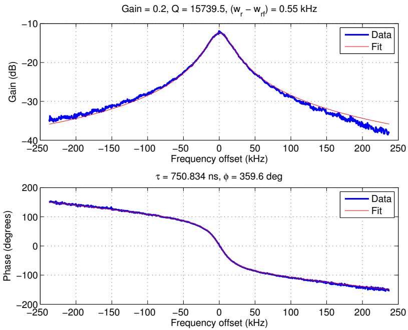

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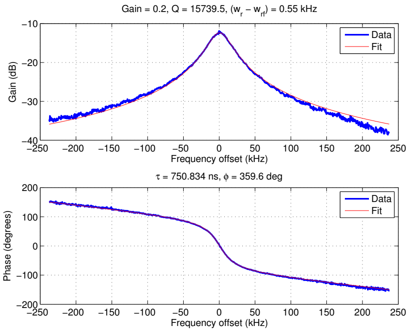

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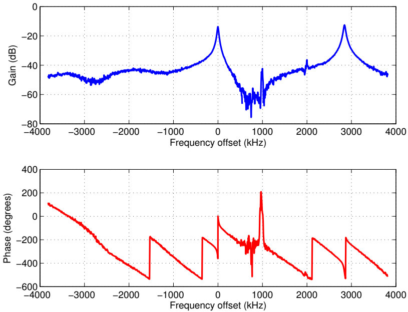
Wideband Open Loop Transfer Function



- Wider sweep reveals a parasitic mode at 2.8 MHz above the π mode;
- Negative feedback for the π mode is positive for the parasitic mode;
- This positive feedback limits direct loop gain;
- The simplest way around the issue is to use digital delay to equalize the modal phase shifts (230 ns).

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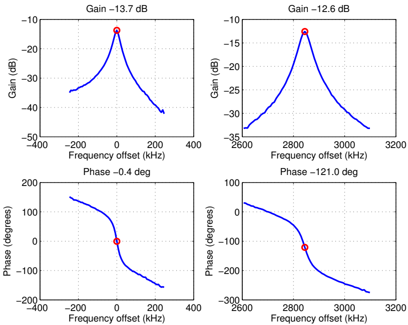

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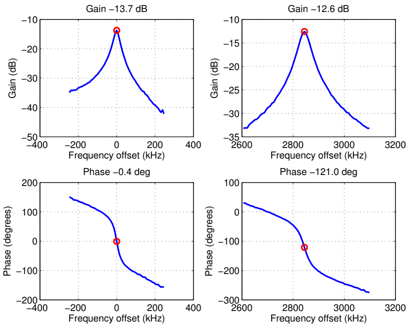

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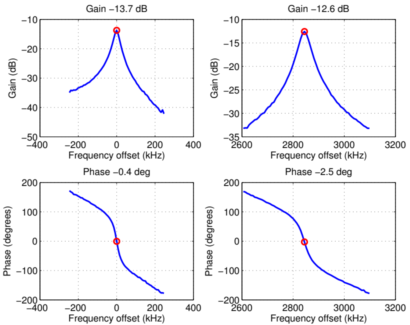

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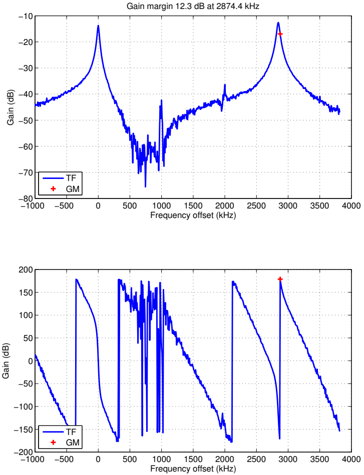
Proportional Loop Gain and Delay



- Set up minimum delay and equalized transfer functions for identical 3 dB closed-loop peaking.
  - Minimum delay: peak gain at RF is -9.2 dB, gain margin 12.3 dB
  - Equalized: peak gain at RF is $+8$ dB, gain margin 11.8 dB, phase margin 88 degrees
- More sophisticated parasitic mode suppression methods can improve the performance only slightly, around 2-3 dB.

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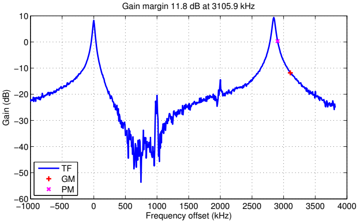

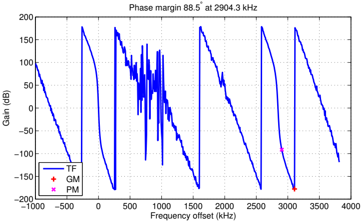

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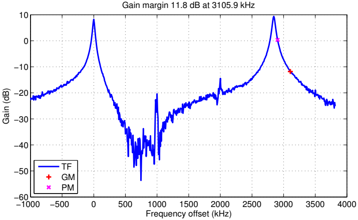

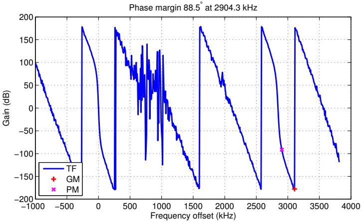

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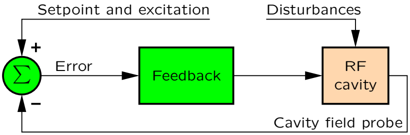
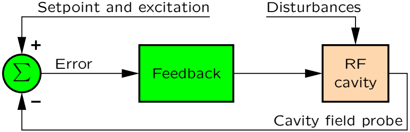


- Measured from setpoint to the error signal;
- Quantifies closed-loop disturbance rejection vs. frequency offset from f_{RF};
- Proportional and integrator loops produce high rejection at low frequencies;
- Magnitude on log-log scale, field setpoint of 1 MV.

Closed Loop Transfer Function



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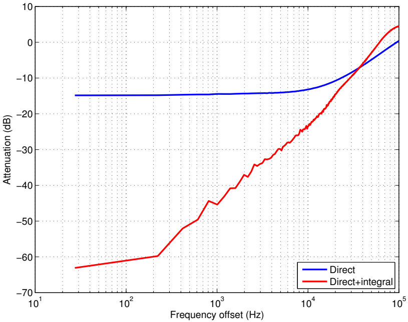

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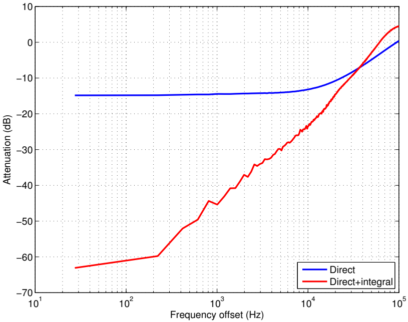

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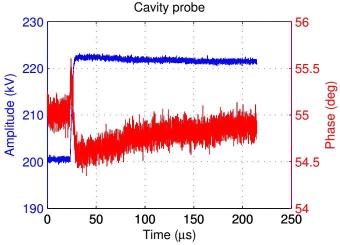

- Use ramp start signal to trigger waveform acquisition;
- Ramp profile loaded with a 10% amplitude step (200 to 220 kV);
- Some coupling between amplitude and phase;
- All input channels are captured on the same trigger, observing reflected power here;
- Characterized a 5 degree phase step as well.

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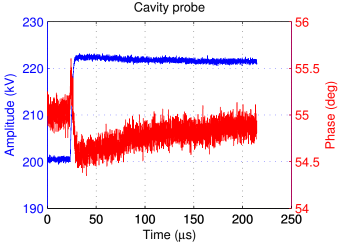

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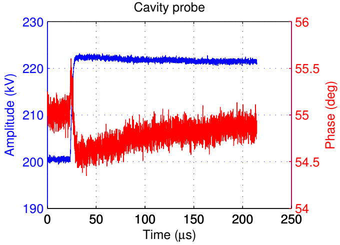

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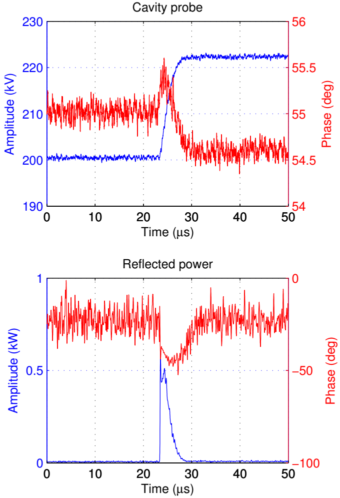

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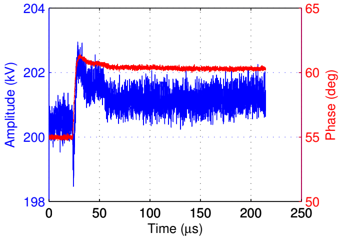

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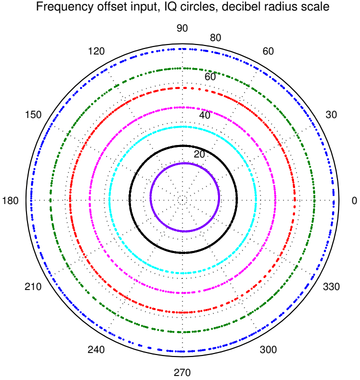
IQ Circles



- Input signal at -60 to 0 dBm in 10 dB steps, $\approx$ 1 Hz offset;
- Log scale polar plot ($r = 20\log_{10}|x|$);
- Center offset, more prominent at low amplitudes, is due to RF feedthrough (coupled from the reference channel);
- Can numerically remove the offsets;
- Good linearity (uncorrected for synthesizer errors), consistent offsets at -73 dBFS.

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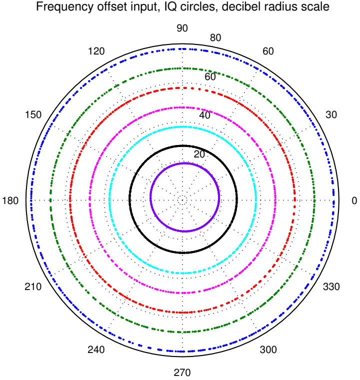

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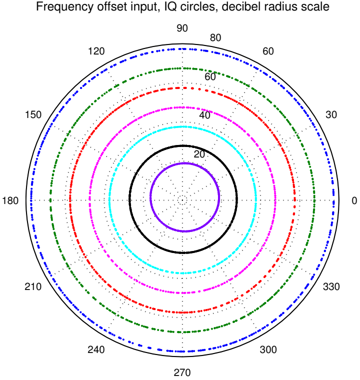

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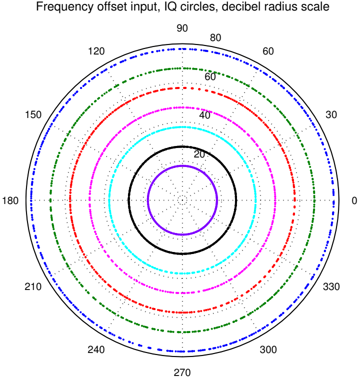

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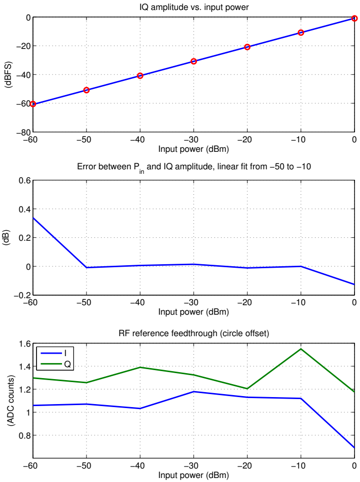

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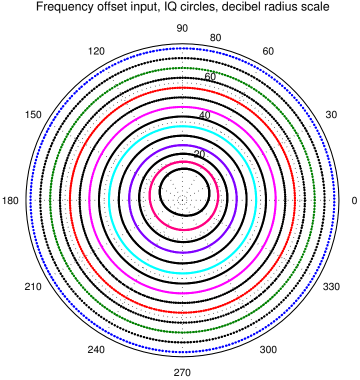

- Similar to the test at DLS with several modifications:
  - Reference level at $+10.5$ dBm vs. $+8$ dBm at DLS;
  - Input power level monitored by a spectrum analyzer;
  - 5 dB steps.
- Center offset correction;
- Linearity good to ± 0.05 dB down to -50 dBFS;
- Offsets/feedthrough at -72 dBFS.

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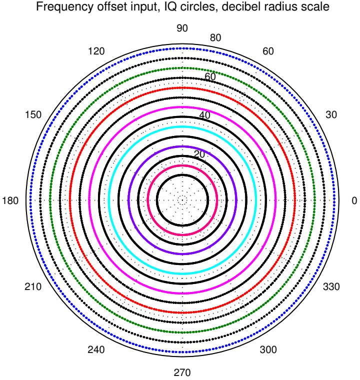

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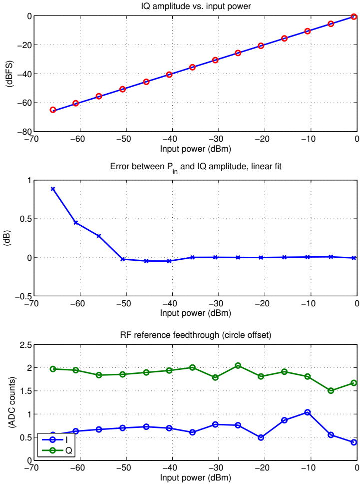

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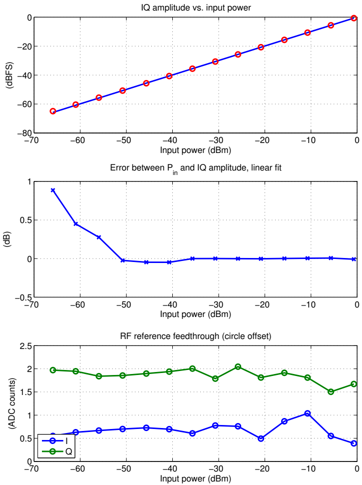

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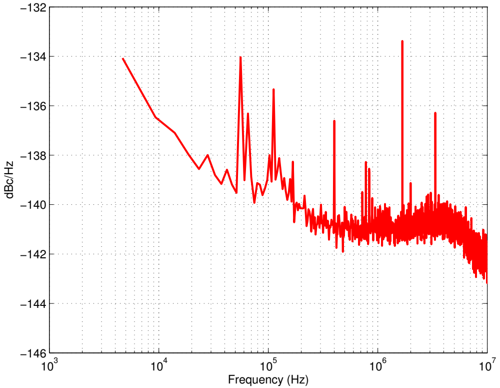

- Reference channel at DLS, $+8$ dBm input level;
- Sources of lines at 65.2 and 111.8 kHz are known, already fixed;
- Same channel measured on the bench, HP8664A at $+11.5$ dBm.

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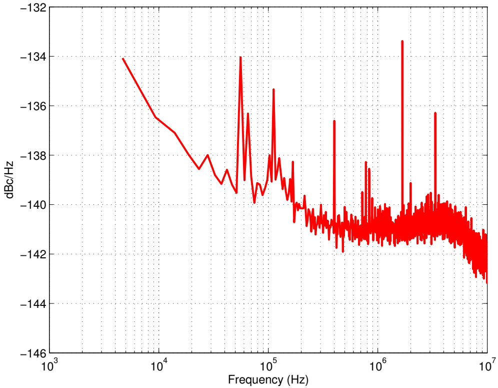

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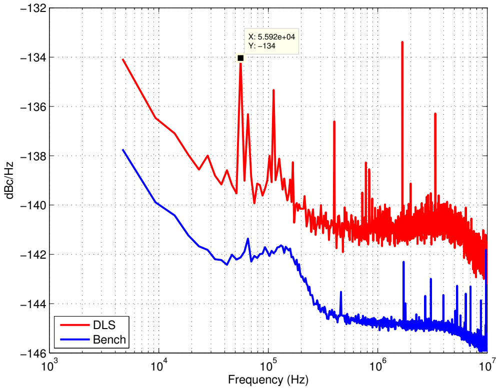

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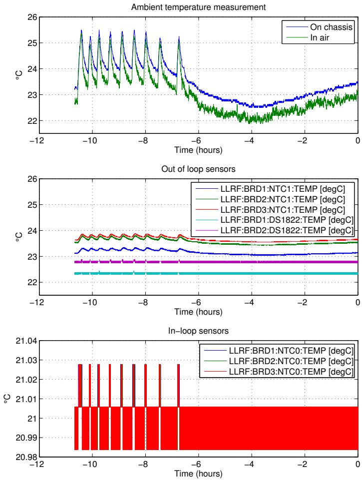
Thermal Stability



- 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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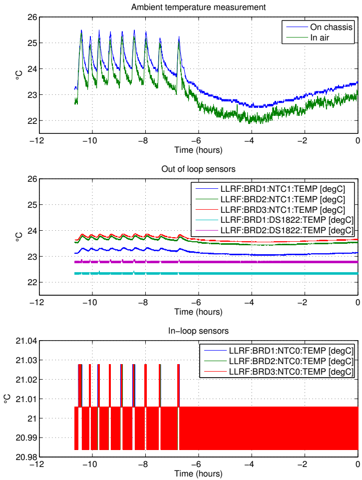

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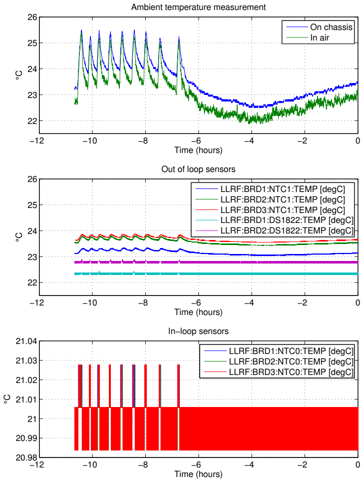

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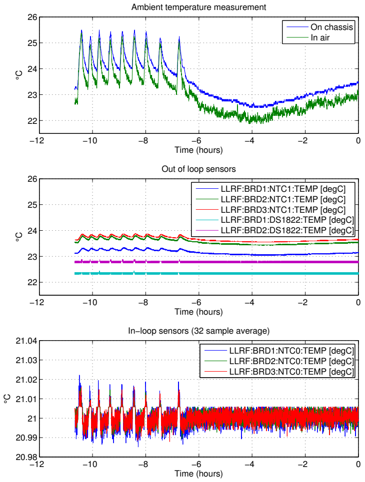

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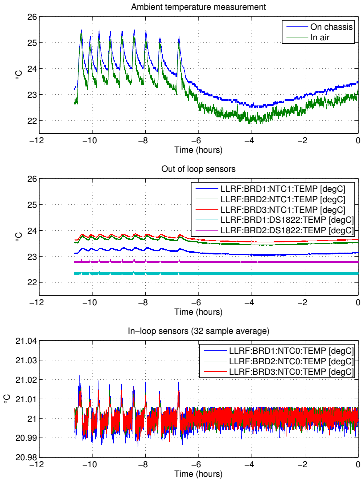

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