Digital Low-level RF Test at Diamond Booster
LLRF9 demo, March 16–20, 2015

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Outline

1. Setup
   - LLRF9 Introduction
   - Demo Setup and Schedule

2. System Operation

3. Performance Tests
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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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 $\omega_{rf}$;
- Faster than expected gain roll-off above the resonance.
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- Faster than expected gain roll-off above the resonance.
Wider sweep reveals a parasitic mode at 2.8 MHz above the $\pi$ mode;

- Negative feedback for the $\pi$ 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).
Wideband Open Loop Transfer Function

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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.
Proportional Loop Gain and Delay

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Closed Loop Transfer Function

- 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.

![Diagram of closed loop transfer function](image)
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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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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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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 $\pm 0.05$ dB down to $-50$ dBFS;
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IQ Circles: On the Bench

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Frequency offset input, IQ circles, decibel radius scale
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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.
Single Channel Phase Noise

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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 °C/°C.
Performance Tests

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Successfully operated booster RF station with beam;

Demonstrated powerful user interface tools necessary for fast station configuration;

Demonstrated field control at forward power 60 W to 60 kW;

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