LESSONS LEARNED FROM PEP-II LLRF AND LONGITUDINAL FEEDBACK*

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Abstract

The PEP-II B-Factory collider ended the final phase of operation at nearly twice the design current and 4X the design luminosity. To highlight the evolution from the original conceptual design through to the 1.2E34 final machine we choose one example each from the broadband feedback and from the LLRF system. They illustrate the original design estimation missed some very significant details, and how in the course of PEP-II operation unexpected difficulties led to significant insights and new approaches which allowed higher machine performance. We present valuable ”lessons learned” which are of interest to designers of next generation feedback and impedance controlled LLRF systems.

BROADBAND COUPLED BUNCH FEEDBACK - UNDERSTANDING THE IMPACT OF NOISE IN THE PROCESSING CHANNEL

A multi-lab collaboration developed a reprogrammable digital processing architecture to control coupled-bunch (HOM driven) instabilities in both light sources and factory colliders. The system designers used modelling [1][2] and machine measurements [3] to develop estimates of the required noise floors, gains and output powers required for the various installations. The DSP control filters estimated were FIR bandpass (typically with 4 - 16 coefficients), specified to implement a 90 degree phase shift at the synchrotron frequency with zero DC gain. The expense of the broadband 1-2 GHz kicker power amplifiers led to every effort to minimize the installed output power. The design placed the system noise floor (RF receiver + A/D converter noise) to not saturate the kicker amplifiers at the operating gain. Care was taken to develop low phase noise oscillators and receivers so that the controlled damped beam would damp down to the noise floor of the processing channel (roughly 2% of the cm bunch length).

The initial PEP-II commissioning measurements revealed the ”noise” in the processing channel was much greater than anticipated. This was due to signals in the LLRF system and RF cavities driving the beam longitudinally. The spectrum of this ”noise” shows features including the 6.3 kHz synchrotron resonance, klystron HV power supplies at 720 Hz with harmonics, noise within the LLRF system processing channels and phase reference distribution systems. Figure #1 presents the receiver power spectrum of a controlled damped 1700 mA HER beam.

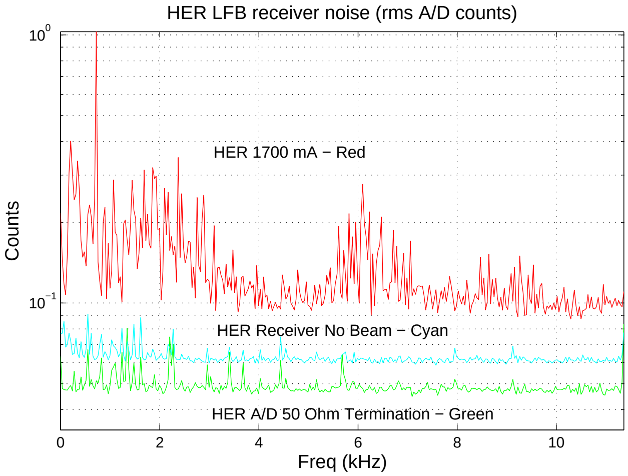

Figure 1: Power Spectrum of detected closed-loop controlled HER beam motion (rms A/D Counts). A/D Quantizing noise is 0.4 counts rms and the combined noise with the phase detector receiver (no beam) is 0.6 counts rms. The quantization noise from the 8 bit A/D is negligible compared to the signals on the beam (a 6 bit A/D system would provide the same performance).

While these signals are filtered through the bandpass DSP control filters, (reducing out of band power away from ω_s), the overall impact of the low-frequency signals from the RF system was problematic. Narrowing the FIR filter helped but the output still had significant power at low frequencies (high-Q filters with large phase slope also impact the group delay limit). In high current (2100 mA) HER operation the system began to reach an effective gain limit due to saturation effects in the power stages from 720 Hz impulsive noise on the beam from RF power supplies.

Figure #2 shows an interesting fault file where an impulsive 720 Hz low frequency transient saturates the feedback, leading to loss of HOM control and eventual loss of the beam. This sort of beam loss was very hard to diagnose as the measured growth and damping rates always showed excellent margins. The transients which would randomly saturate the system occured infrequently and appeared and disappeared over time. The original designers never anticipated that the control limits of the system would be reached from impulsive noise generated in the RF systems, and it was only in the last year of operations that this mechanism was finally seen and understood from fault file data.

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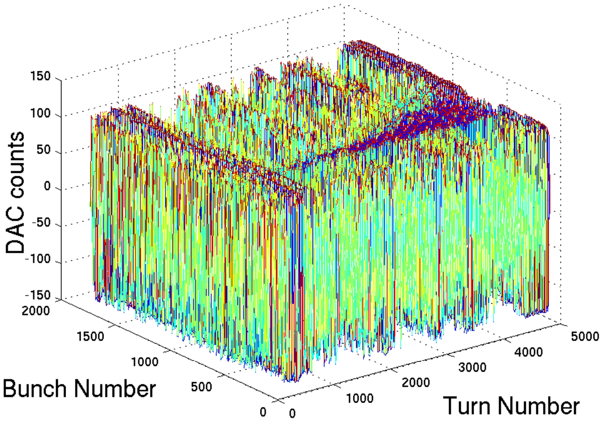

Figure 2: Time-domain fault file of kicker drive signal showing low-frequency noise in the RF systems saturating the kicker. While the impulsive transient is at 720 Hz rate, and does not couple strongly to the 6.5 KHz synchrotron frequency, the transient is significant enough to pass through the control filter and saturate the power stage. Once HOM control is lost for a few bunches (near bunch 500) from power stage saturation at +127/-128 counts, the runaway HOM at mode 800 grows exponentially and eventually drives all bunches to beam loss.

THE IMPACT OF NON-LINEAR ELEMENTS IN THE LLRF FEEDBACK PATHS

The PEP-II LLRF system design used linear and non-linear (time domain) simulation to study the direct and comb loop stability, the limits on group delay, the basic structure of the 2nd order Comb IIR notch filter, the required direct loop gain, etc. It was understood that a non-linear element in these loops would have a significant impact on the impedance control. The power klystron was an obvious candidate for non-linear behavior. [4][5]

PEP-II commissioning revealed the HER and LER low-mode growth rates were much faster than expected from either model. The very fast low mode instabilities led to development of a ”Low Group Delay Woofer”[6]. A ”Klystron Linearizer” was developed to force the large signal and small-signal Klystron gains to a fixed value [7]. Surprisingly, experiment in the real machine showed the linearizers did not have the full effect predicted. There were also issues with direct and comb loop stability as the loop operating points moved with Klystron power. The system dynamics change with operating point was not anticipated by the designers. The operational difficulties and continual trade-off between station stability and instability growth rates became a difficult issue as currents increased and margins were lost.

These concerns drove re-investment in a 2nd generation non-linear time domain model[8]. This focus in conjunction with Klystron test stand measurements revealed some subtle deviations in the small-signal frequency response between model and physical systems. The deviations were utimately found within a medium power solid-state RF amplifier. At design it was specified (spurious harmonics better than -60 dBc) and the amplifier was uneventfully tested for gain uniformity and frequency response.

The entire LLRF processing chain must faithfully provide linear response for small modulation signals which can be 60 or 90 dB below the high power fundamental(Fig.#3).The modulation signals provide the impedance control feedback. For the initial 7 years of operation this driver amplifier had never been a source of any trouble or curiosity (the focus was the power Klystron). However, when the amplifier is tested using a large signal power carrier in conjunction with a small test signal, the small signal gain distortion is obvious and very significant.(Fig.#4)[9]

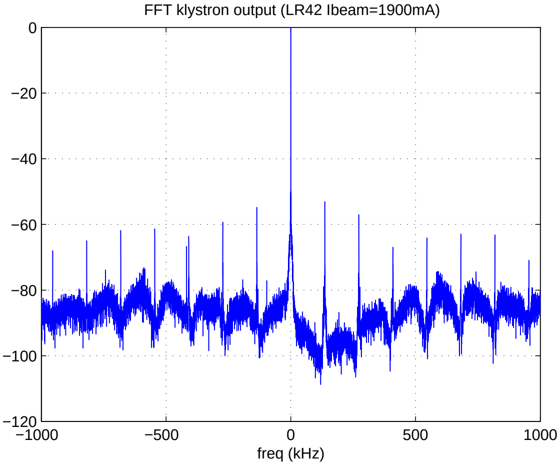

Figure 3: Power spectrum of signals in the Klystron output during closed-loop operation of LER Station 4-2. +/- 7 revolution harmonics are visible around the 476 MHz carrier.

With this non-linear behavior in the simulation, the model predicted the machines’ rapid growth rates. With this insight all the nonlinear driver amplifiers were replaced in the RF systems. The LER instability growth rates reduced and agreed with the model predictions.[8]

The simulation model also inspired the development of new ”comb rotation” RF configurations[8]. The growth rates vs. current are shown in figure #5 for the the last three years of LER configurations. The final configuration, which ran at 3100 mA in the LER, had excellent agreement with the model predictions.

SUMMARY

The PEP-II longitudinal feedback designers did foresee the essential requirements, among them transient-domain diagnostics used to quantify modal growth/damping rates. Major unforeseen surprises included thermal management of the beam induced power in the kicker structures, coaxial feedthroughs, power cables and connectors. The limit of

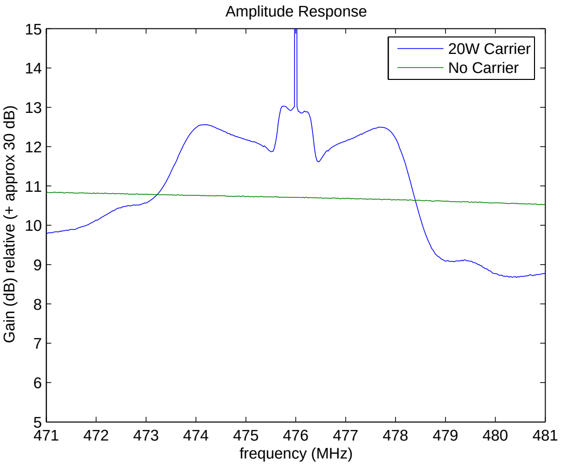

Figure 4: Large and Small-signal Transfer Function measurement of the original LLRF driver amplifier. The large-signal response is a single swept test frequency, the small signal a swept signal -30 dB below a fixed 476 MHz carrier.

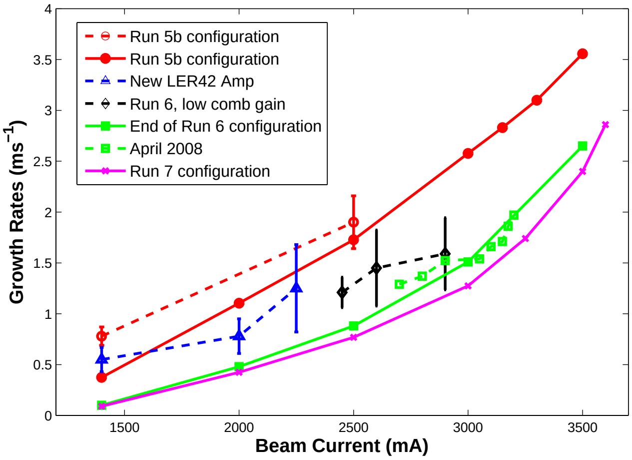

Figure 5: Modeled (solid) and Measured (dashed) LER low mode instability growth rates for various operating configurations. The 30% reduction in cavity fundamental driven growth rates from run 5 through to run 6 is due to replacing nonlinear drive amps and implementing comb rotation configurations. The final LER configuration developed (run 7) was estimated to reach 3600 mA.

high-current instability control in the HER was understood in the last year of operation to be due to low frequency noise in the RF systems driving the beam. This effect was never anticipated in the system design phase.

There are many ”lessons learned” in the LLRF experience. The fast low mode growth rates were not understood for many years. The linearizer development and the second generation nonlinear model together provided critical insight. The LLRF effort also revealed the difficulties in configuration management and the complexity of individual station dynamics with station by station unique configurations. We could not figure out what was happening from machine measurements and fault file data without the simulation models to gain understanding. It took multi-year investment of skilled people to understand the complex dynamics.[10]

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