SLAC–PUB–8410
May 2000

Programmable DSP-Based multi-bunch feedback - operational experience from six installations*

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Abstract

A longitudinal instability control system, originally developed for the PEP-II, DAΦNE and ALS machines has in the last two years been commissioned for use at the PLS and BESSY-II light sources. All of the installations are running identical hardware and use a common software distribution package. This common structure is beneficial in sharing expertise among the labs, and allows rapid commissioning of each new installation based on well-understood diagnostic and operational techniques. While the installations share the common instability control system, there are significant differences in machine dynamics between the various colliders and light sources. These differences require careful specification of the feedback algorithm and system configuration at each installation to achieve good instability control and useful operational margins.

This paper highlights some of the operational experience at each installation, using measurements from each facility to illustrate the challenges unique to each machine. Our experience on the opportunities and headaches of sharing development and operational expertise among labs on three continents is also offered.

Presented at
Beam Instrumentation Workshop
Cambridge, Massachusetts
May 8 – May 11, 2000

*Work supported by Department of Energy contract DE–AC03–76SF00515.

Table 1: Parameters at 6 installations

Parameter	ALS	DAΦNE	PEP-II	SPEAR	BESSY-II	PLS
Bunches	328	120	1746	280	400	468
RF Freq.	499.7 MHz	368 MHz	476 MHz	358 MHz	499.7 MHz	500 MHz
Sampl. Freq.	499.7 MHz	368 MHz	238 MHz	358 MHz	499.7 MHz	500 MHz
Rev. Freq.	1.52 MHz	3.1 MHz	136 kHz	1.28 MHz	1.25 MHz	1.1 MHz
Synch. Freq.	11 kHz	36 kHz	3,6 kHz	28 kHz	6.8 kHz	11.3 kHz
Downsampling	22	14	6	14	31	15
Sampling Rate	68 kHz	214 kHz	22 kHz	91 kHz	40 kHz	71 kHz
e-fold Time	2 ms	200 μs	5 ms	16 ms	2 ms	5 ms
e-fold, Samples	130	42	110	1500	80	350
# of DSPs	40	60	80	40	40	60
Bunches/DSP	9	2	22	7	10	8
Kicker Type	Drift Tube	Cavity	Drift Tube	Stripline	Cavity	Cavity
# of Kickers	4	1	2	1	1	1
Kicker Freq.	9/4 RF	13/4 RF	9/4 RF	RF	11/4 RF	9/4 RF
Output Power	200 W	750 W	1500 W	200 W	220 W	250 W
Amp Type	TWT	GaAs	GaAs	Bipolar	GaAs	GaAs
Filter BW	108%	105%	26%	46%	108%	111%
DSP Gain	25	5	41,25	88	11.3	48

System Summaries

Table 1 summarizes the important machine parameters for the six facilities where the common longitudinal system[1] has been operated. The PEP-II and DAΦNE machines are colliders, with two rings, and the table entries with two numbers reflect any different parameters for the two rings. The ALS, BESSY-II[2] and PLS[3] systems are similar in scale and functional requirements. The range in synchrotron frequencies, revolution frequencies and downsampling factors helps illustrate the advantages of the downsampled processing. The filter bandwidths are specified as fractional bandwidths around the nominal synchrotron frequency. The DSP filter gain is the dimensionless filter gain of the baseband processing. The e-folding times (1/growth rates) are listed for the full design currents (except for SPEAR, where the rates reflect a low-current feedback test configuration).†

†The SSRL SPEAR implementation, shown in Table 1, was used in 1997 as a system testbed, and is interesting in that at that time SPEAR had no broadband longitudinal kicker or cavity structure. Instead, for the testbed purpose a pair of transverse striplines was driven common-mode as a very weak longitudinal kicker. This limited the total ring current that could be controlled, but the SPEAR testing was extremely useful in developing operating techniques for this low kicker gain configuration, and as a test bed for ideas about longitudinal modulation coupling to reduce growth rates[4]. A complete longitudinal system has been constructed for the SPEAR-III project, and will be installed as part of the upgrade. SPEAR-III will use the same 476 MHz RF systems as PEP-II, so the longitudinal system will operate at 476 MHz RF frequency.

Feedback Filter Choices

The DSP processing functions are general purpose, and a variety of control filters and diagnostic codes have been developed. The original control filters were all FIR band-pass filters, with the gain maximized near the synchrotron frequency, and the filter phase selected to provide the resistive (90 degree) damping. For the ALS, PLS and BESSY-II the control filters were developed as 6 tap filters, with approximately 100% fractional bandwidth around the nominal synchrotron frequency. The broad pass-band and phase characteristic makes the filter insensitive to variations in machine tune and RF configuration. In the PEP-II machine these filters are made deliberately very narrow (typically 12 tap filters with 25% fractional bandwidth) to reject the broadband noise in the processing channel. The PEP-II installations have effectively the lowest kicker voltage compared to the cavity RF voltage, and so end up running at high filter gains to control high-current growth rates. As a result, the PEP-II systems are the most sensitive of the group to the detector signal/noise ratio. This is shown in figure 1, where the ideal (linear) and implemented (including DSP saturation) processing output is shown for the LER at 1363 mA. For this nominal operating gain the noise within the filter bandwidth is almost enough to saturate the processing - if the gain were increased by a factor of 2 or 4 the processing would be essentially saturated. The DAΦNE and initial ALS installations were based on a relatively broad 6 tap FIR filter, and the noise floor in these machines was not a significant factor in specifying the filter fractional bandwidth. The SPEAR, BESSY-II and PLS systems were also commissioned with the FIR bandpass filter algorithm.

In the last year the ALS and BESSY-II have installed harmonic passive RF cavities, which are intended to increase the Touschek lifetime by lengthening the bunch [5]. These cavities also influence the longitudinal dynamics significantly and a family of IIR based control filters has been developed for use in these machines [6].

Unstable Modes and effects of Damped RF systems

The PEP-II and DAΦNE machines implement special damped RF cavities, which act to lower the HOM impedances and growth rates, but spread out the remaining impedance over many revolution harmonics. In these machines broad bands of unstable modes exist, and any study of the growth rates and unstable modes becomes a complicated task. Phase-space tracking techniques were developed to identify unique eigenmodes from uneven fill aliased modes in the unstable band [7]. The BESSY-II, PLS, ALS and SPEAR machines, in contrast, have high-Q HOM resonances in the RF systems, which lead to unstable modal patterns where a few discrete modes typically are unstable at any instant, though exactly which modes are unstable is a strong function of the cavity tuning and temperature.

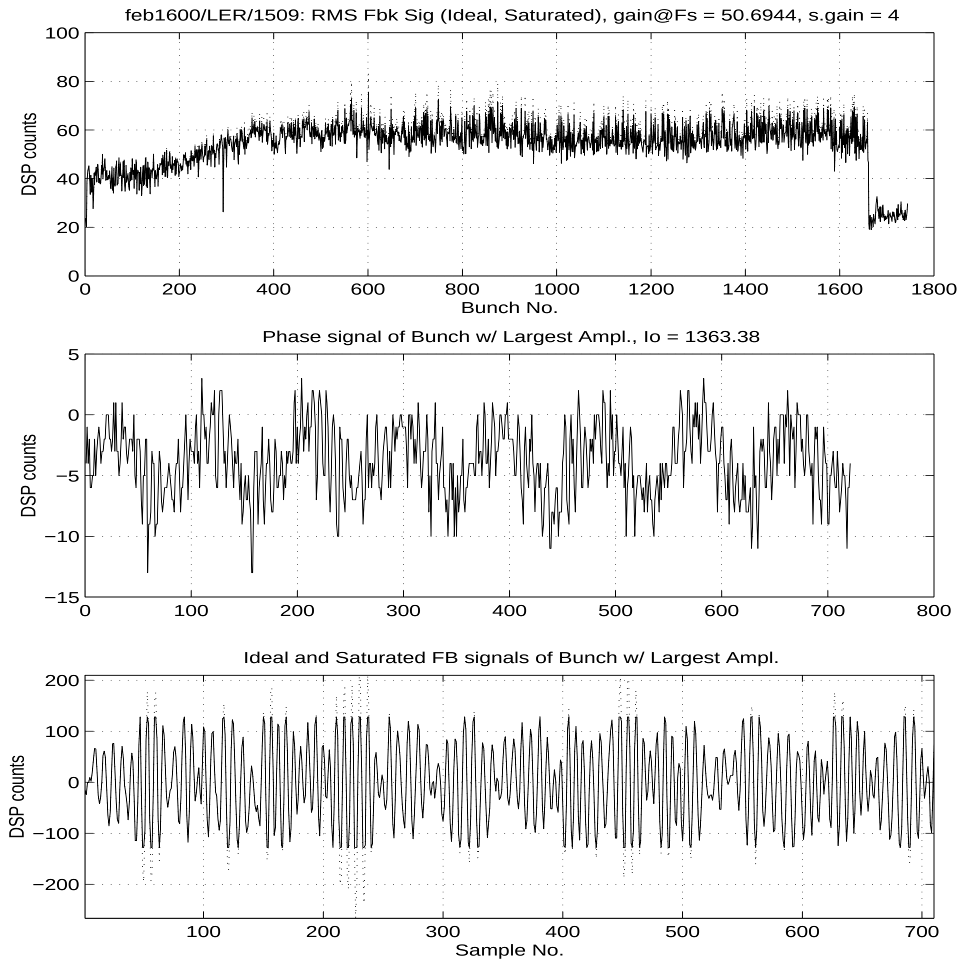

Figure 1: Measurements from a closed-loop record of stabilized PEP-II LER at 1363 mA. The middle figure shows the raw amplitude vs. time for the largest amplitude bunch. The third figure shows that the bunch with largest amplitude is saturating the DSP processing roughly 5 - 10 % of the time. The gap transient at this current causes the first 320 bunches in the turn to have significantly less gain, as seen in the lower detected rms bunch motion (first figure). The narrow 12-tap control filter removes the low-frequency modulation seen in the raw bunch motion - the calculated output only contains the motion at the synchrotron frequency.

Mode Zero Control

The PEP-II system uses a special low-mode woofer via a digital data path through the RF system for extra gain at the 10 lowest modes in the RF system bandwidth [8]. DAΦNE has implemented a separate analog mode zero feedback loop to help stabilize mode zero at the high operating currents where the Robinson damping from the RF cavity detuning becomes less effective. The other systems do not have special treatment of mode zero, and any motion at mode zero is controlled by the broadband system.

Effects from RF systems with Harmonic Cavities

The original system designers were most concerned with gap transient effects for the PEP-II collider, and the importance of the gap transient and tune spreads resulting from the variation in synchronous phase across the turn were studied in PEP-II [9][10]. However, the addition of harmonic cavities in the ALS make the longitudinal feedback processing more difficult. As there are multiple operating modes, depending on the tuning of the cavities, several operating configurations need to be available for the feedback system. One important effect from the bunch-lengthening mode of operation, with the cavities strongly coupled to the beam, is an increase in the gap transient from partially filled rings. This effect, which is a result of the gap in the beam modulating the cavity RF voltage, means that the variation in synchronous phase from the start to end of a filled turn can become a significant fraction of the operating range of the system front-end. All of these systems operate at 6*RF (2998 MHz for ALS) so that greater than 30 degrees of gap transient (at the 500 MHz fundamental) invert the sign of the feedback gain - practical constraints limit the gap transient to something around 20 degrees. To allow operation in these cases we are constructing an alternate ALS front-end detector at 4*RF, to allow 50% greater range. Of course, this greater range has a concomitant reduction in sensitivity, which then needs to be made up in the DSP processing gain.

BESSY-II has recently commissioned operations with the harmonic cavities tuned passively (parked to reduce interaction with the beam) and is just starting commissioning of the ring with tuned harmonic cavities. We expect that the IIR filter techniques developed at ALS will be directly applicable to BESSY-II as well.

System and Kicker Timing Issues

The broadband systems act as bunch-by-bunch damping systems, and there are several important timing and phasing adjustments necessary to commission the systems. The required precision of the back-end phasing is set by the operating frequency of the kicker structures - figure 2 shows the measured kicker drive vs. time delay for the 1125 MHz ALS kicker acting on the beam. To get the maximum gain, the bunch passage must fall on a voltage maximum of the kicker response, and so the effective gain falls off like $cos(\delta\phi)$, where $\delta\phi$ is the phase difference between the arriving particle and the voltage maximum on the kicker at the kicker center frequency. A $\pm$ 45 degree arrival offset($\pm$ 111 ps) drops the gain by 3 dB, and an offset of 90 degrees ($\pm$ 222 ps) drops the gain to zero.

This gain variation exists for mis-timing of the kicker structure, as well as variations in synchronous phase across a turn from gap transient effects. Adjusting and maintaining the group delays in the amplifiers and cable assemblies at this level requires care in operation.

Our initial experiences with the first ALS system led us to develop a suite of tools, techniques and MATLAB codes for efficient commissioning, and these tools were used and expanded at PEP-II, DAFNE, SPEAR and BESSY-II. The timing techniques center on measurements of a single bunch while the feedback system is programmed to drive a selected bunch at the synchrotron frequency. An automated process sweeps selected delay line(s)

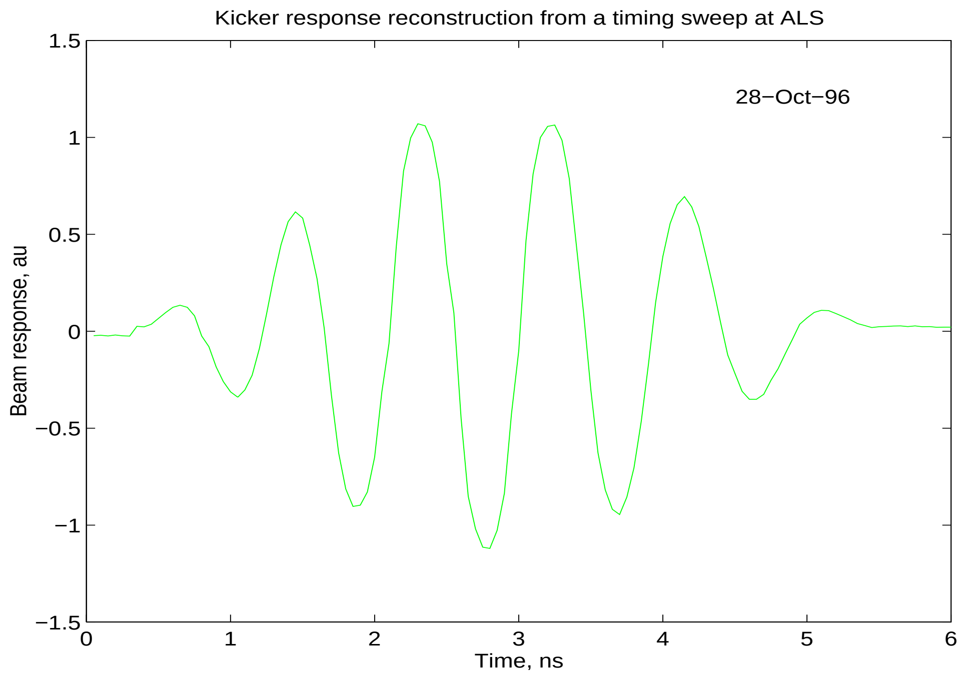

Figure 2: Kicker impulse response for the 1125 MHz drift-tube kicker at the ALS. The beam must traverse through the kicker at one of the voltage maxima for effective use of the drive power.

through a timing range while measuring the detected motion at the synchrotron frequency. The PEP-II system requires extra commissioning steps, as it has multiple output amplifiers and kickers, which must be synchronized to each other and to the beam.

These techniques were not applicable to BESSY-II, which did not not originally have a single-bunch injection capability. This created some initial difficulties in commissioning while a new procedure was developed. To time the BESSY-II system the feedback system was programmed to have non-zero gain for only a single bucket, and the overall filter phase set for positive feedback. A search through the various bucket patterns allowed the coarse overall digital offset delay, quantized in units of RF buckets, to be found as the timing where some bucket stood up above the others due to the action of the positive feedback. A subsequent second sweep, using the precision back-end delay lines, allowed the kicker timing to be properly set.

Common Hardware and Software

The systems were developed around flexible hardware, and were designed so that the modules of the system (downsamplers, DSP boards, back-ends, etc.) would be identical for each installation and therefore easier to produce and maintain as a group. It is also desirable, in terms of system spare components, to have interchangeability allowing a common spares pool. This common hardware goal has been achieved, though there are RF frequency system-specific filters and phase shifter components in some of the RF modules and the system master oscillators. The baseband and DSP functions are easily interchangeable.

The commonality goal was an important part of the system software design. Having common operating software and analysis tools allows the labs to share the amortization of the development efforts, and has allowed each lab to get the benefit of special codes written at another lab. The set of MATLAB analysis codes is directly portable, and has been one of the most successful components of the system package [4].

The operating codes are EPICS based, and are common codes, as are the DSP system functions (the filters, grow-damp recorders, drive programs, and the like). However, this commonality has come with an unpleasant amount of system software development interaction with experts at each installation. We have discovered that despite our best efforts to use a common software distribution that is sent as a single package to each lab, it seems there are always installation-specific details (involving central servers, networks, availability of various UNIX system tools, etc.) which require care and expertise to bring up a new installation - the messy details of which then need to get incorporated into the master source to avoid the problems on the next revision and distribution cycle. Maintaining and ensuring that new software features work properly across the various installations has been a bigger task than anticipated - in retrospect it might have been less work for the system designers to enforce a higher degree of host hardware and software commonality than was allowed. Another unanticipated effort involved the network security measures that each lab implemented over the last several years, as each security approach interfered either with the core system functions themselves (the ability of the VME and VXI controllers to rlogin to their host servers, for example) or the ease that an outside expert could remotely operate and commission the system (the SLAC team hands-on involvement with the PLS and BESSY-II systems was entirely remote, yet we were able to help with commissioning and even do machine physics measurements via the internet).

Summary

Our experience commissioning the PLS and BESSY-II systems has been that the tools and techniques we developed over a long ALS/PEP-II/DAΦNE commissioning period were extremely helpful in rapidly bringing up the later installations. The initial installations required many months of commissioning to optimize filter and timing parameters, and considerable effort went into understanding the various noise floor limits and gain limits of the system components. While commissioning the BESSY-II and PLS systems were important non-trivial tasks they were each commissioned in a period of weeks, not months, showing the benefit of the ALS/PEP-II/DAΦNE operating experience.

With the five installations commissioned and in operation (and the SPEAR-II system ready for installation) we now see this effort moving away from a SLAC-based development effort towards a shared expertise collaboration. To encourage this transition, a User's Group workshop was held in October, 1999 at the LNF - INFN (Frascati). The workshop included progress reports from the labs, a tutorial covering some of the most recent data analysis tools, and provided a forum to bring the various lab efforts together. We see great benefits to this collaborative sharing of expertise, and are very pleased that this design goal of common hardware and transportable software tools has been established as a working model for the joint development of accelerator technology.

Acknowledgements

The authors thank the operations groups and laboratory staff at the Advanced Light Source, PEP-II, DAFNE, SPEAR, BESSY-II and the PLS for their continual opportunities to develop these systems, and their help and operational expertise. We thank C. Limborg and J. Sebek for their collaboration and interest on the SPEAR measurements. We especially thank the DAFNE team at LNF-INFN for their enthusiasm as our hosts for the Feedback Workshop.

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