SLAC-PUB-15809

A 4.2 GS/s SYNCHRONIZED VERTICAL EXCITATION SYSTEM FOR SPS STUDIES — STEPS TOWARD WIDEBAND FEEDBACK*

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Abstract

A 4.2 GS/sec. beam excitation system with accelerator synchronization and power stages is described. The system is capable of playing unique samples (32 samples/bunch) for 15,000 turns on selected bunch(es) in the SPS in synchronism with the injection and acceleration cycle. The purpose of the system is to excite internal modes of single-bunch vertical motion, and study the bunch dynamics in the presence of developing Electron cloud or TMCI effects. The system includes a synchronized master oscillator, SPS timing functions, an FPGA based arbitrary waveform generator, 4.2 GS/sec. D/A system and four 80W 20 -1000 MHz amplifiers driving a tapered stripline pickup/kicker. A software GUI allows specification of various modulation signals, selection of bunches and turns to excite, while a remote control interface allows simple control/monitoring of the RF power stages located in the tunnel. The successful use of this system for SPS MD measurements in 2011 is a vital proof-of-principle for wideband feedback using similar functions to correct the beam motion.

OVERVIEW

The high-current operation of the SPS for LHC injection requires mitigation of possible Ecloud and TMCI effects [1]. To control these intra-bunch instabilites via feedback techniques will require wideband signal processing, while the specification of control techniques requires complete beam dynamics information. We have developed a wideband beam excitation system useful to explore single-bunch dynamics as well as a testbed for the back-end and power stage functions of a intra-bunch feedback system. The project is a component of the overall instability control effort, which also includes numeric simulation models [2], system estimation tools and a machine measurement (MD) program [3]. A key element of this program is the validation of the beam dynamics simulations and models needed to design and optimize the feedback controller via beam measurements. While there is interesting dynamics in measurements of unstable beams, another approach to validate models is to make beam excitation-response measurements as currents and conditions are increased from the stable regime to the threshold of instability.

The excitation system (Figure 1) requires synchronization of a waveform generator to the stored and accelerating beam via a programmable sequencer that can count turns and bunches after an injection trigger, a digital memory and fast 4.2 GS/sec. D/A system. The low-level signal drives power stages through a kicker structure. Associated software systems configure the memory sequences and allow operation. Operational needs require that the timing of the kick signal be repeatably and consistently phased to the selected bunch, so that the excitation must track the RF frequency acceleration cycle.

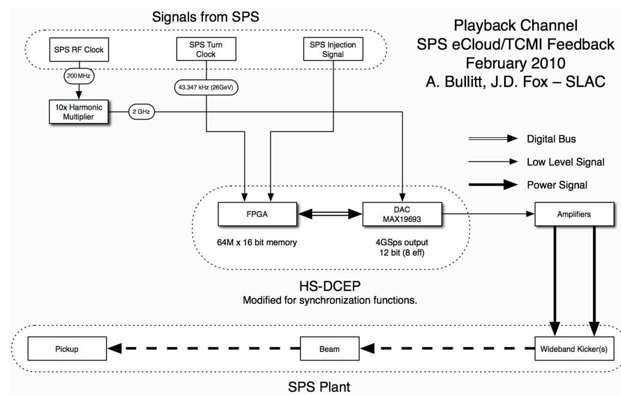

Figure 1: Block diagram of the excitation system developed for use at the SPS. The timing functions are synchronized with the machine RF, so that the excitation can be specific for a selected bunch, and the digital memory stores up to 15,000 turns of user-defined excitation signals.

The heart of this system is the bunch-synchronized sequencer, which selects a particular bunch or sequential bunch train in the SPS, and plays a turn-specific 16 or 32 sample data stream at high rate across the selected bunch(es) for up to 15,000 turns. The excitation sequences are created in MATLAB, and can be tailored to excite a particular bunch mode, or a group of modes via band-limited random excitation. The resulting beam motion is sensed via a pickup and wideband receiver system, and digitized synchronously with the excitation. Offline processing of the data can then reveal the beam dynamics and variation in dynamics as beam intensity and Ecloud parameters are varied [3].

EXCITATION SYSTEM IMPLEMENTATION

The digital functions are implemented on a commercial FPGA hardware fixture originally designed for frequency-domain characterization of D/A circuits [4]. We use this hardware platform with our own FPGA codes and

* Work supported by the U.S. Department of Energy under contract # DE-AC02-76SF00515 and the US LHC Accelerator Research Program (LARP).

additional synchronization inputs to implement the sequencer [5], with the Maxim 19693 D/A converter evaluation board for the fast analog output.

The system includes a synchronized master oscillator and a digital FPGA sequencer with turn and injection fiducial signals from the SPS timing system. The SPS RF clock (nominally 200 MHz) is multiplied via a step-recovery-diode harmonic converter to generate a $n{*}200$ MHz system clock which is filtered by a tunable bandpass filter to select the operating harmonic. For $n = 10$ the 2 GHz signal results in a 4 GS/sec. data rate, though any harmonic can be used, and for ease of synchronization in these measurements the $n = 8$ harmonic is used, which generates a 3.2 GS/sec. data stream. During the SPS acceleration cycle the RF frequency changes by several kHz, and this multiplier technique keeps the digital clocks in phase synchronism with the circulating beam. A fast turn fiducial identifies the beginning of each turn, so that the logic of the system can count RF buckets and identify particular bunches (the SPS typically fills bunch trains on a 40 MHz or 5 RF bucket pattern), while an injection fiducial provides a means to synchronize the 15,000 turn data sequence to the accelerating cycle.

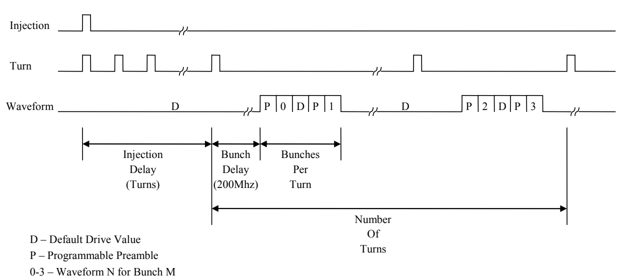

Figure 2: Timing diagram showing the injection trigger, turn fiducial and excitation. A programmable holdoff delay in turns allows positioning of the excitation at arbitrary points in the acceleration cycle, while the sequencer uses the RF clock to count buckets and position the excitation signal on the selected bunches.

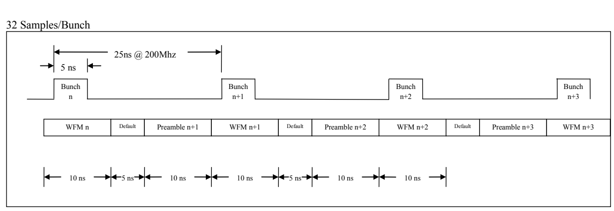

Figure 3: Timing detail of a single turn with several bunches, and the sequence of preamble, WFM data which is applied to the target bunch(es). The excitation memory is 512K, allowing up to 15,000 unique turns with 32 samples per bunch.

POWER AMPLIFIER ARRAY

The excitation signal needs to be converted to a differential set of paired signals to drive a 4 element stripline kicker. A set of low-power hybrids is used to generate 0 and 180 degree signal pairs, these are further split with in-phase power dividers to generate the 4 paired excitation drive signals. Four 80 W 20-1000 MHz amplifiers drive the individual stripline electrodes, each with a high-power termination. These wideband amplifiers are commercial products [6] intended for communications purposes, but for our purpose the time response of the amplifiers is quite important. The amplifier is a multi-stage design with both type A and type AB stages, and in our testing we worked with the manufacturer to increase the output stage bias to improve the transient response, though with the concomitant derating of the amplifier power to 80 W. Figure 4 shows the frequency response of the modified amplifier, while Figure 5 shows the time-domain input and output signals for a 1 cycle 500 MHz RF signal. The amplifiers are packaged with power supplies, cooling, and a dual directional coupler to monitor the forward and reverse RF power. A diode detector and level comparator circuit is implemented to trip off the RF drive if excessive reverse power is sensed (such as from a damaged termination).

In the SPS installation the amplifiers and low-power phasing/splitting networks are placed in the accelerator tunnel to avoid cable power loss and dispersive effects. To control and monitor the amplifiers a simple hardware interface allows via opto-coupled logic signals remote on/off of each amplifier, sensing of any amplifier trip, reset of tripped amplifiers, and measurement of the temperature of each amplifier assembly. A general purpose RF multiplexer allows 1 of 4 signals (such as amplifier coupler signals, beam induced signals, etc.) to be sent back to the control room for study. This simple interface requires 2 high-bandwidth cables in conjunction with low-bandwidth twisted pairs, and allows external operation and verification of state of the drive system. For these initial experiments an existing exponential tapered pickup electrode array has been used as a kicker, though the response of this structure is rolling off above 200 MHz. [7] A high-bandwidth kicker system is in design for fabrication and installation in a future SPS shutdown [8].

OPERATION AT THE SPS

The FPGA system is configured and controlled via a USB interface from a host PC, which allows the core gate array configuration to be loaded. Software GUI tools allow the selection of a particular bunch to drive, the synchronization method, the specification of the type of excitation, etc. The system supports the use of frequency chirps and random noise bursts in addition to steady-state narrowband excitations targeted to a single mode.

The phasing adjustment of the 16/32 sample output burst relative to the passage of the selected bunch in the kicker is critical. To excite barycentric (mode zero) motion, all

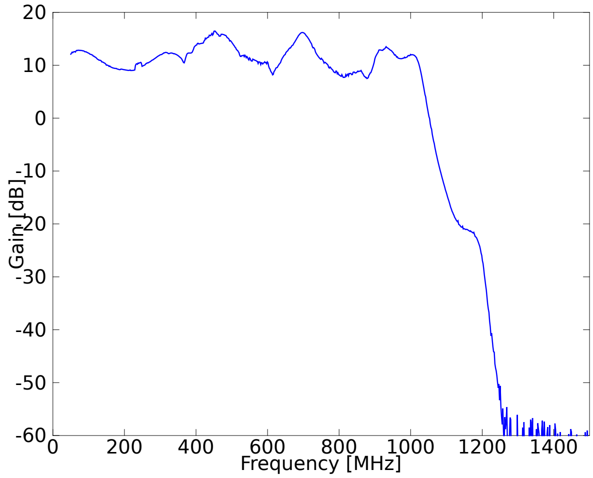

Figure 4: Full-power frequency response for the modified 20-1000 MHz amplifier as installed.

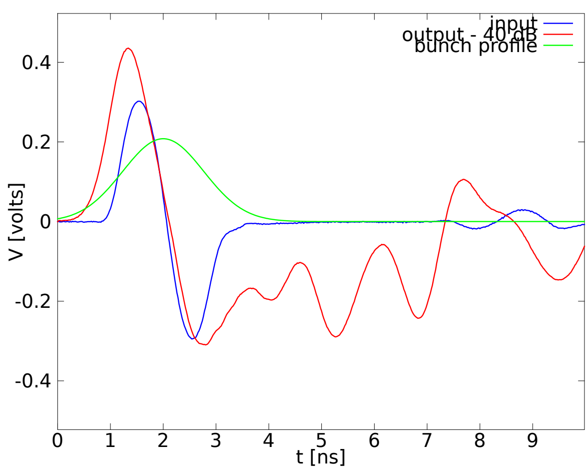

Figure 5: Time domain signals for a 500 Mhz single-cycle burst, with a 2 ns gaussian bunch shown for time scale. The amplifier response has significant ringing, but in this application the majority of the kick signal applied to the bunch is free from the ringing response.

the individual samples in the burst are in phase, though the kick waveform is amplitude modulated at the betatron frequency over the turn sequence. To excite mode 1 (head-tail) motion the individual drive signals are calculated to drive head and tail oppositely (again the entire waveform is amplitude modulated at the betatron tune +/- synchrotron tune). However, if a mode zero (barycentric) chirp signal is slighly mis-phased, so that it only overlaps the beginning or the end of the bunch, a higher-frequency mode with head tail differential motion can be excited. As the bunch is roughly 2 ns long, this requires careful timing on the sub-nanosecond level for consistent and repeatable mode-specific excitation at full amplitude.

SUMMARY

This system was installed in the SPS in July 2011, and has been used to study the beam motion in August, November 2011 and April 2012. Even with the limited bandwidth kicker, we are able to selectively excite up through mode 4. To date these measurements have served to verify the response of the beam against theoretical expectations, and we are now preparing to study as we increase the beam current, and go to multiple bunch trains. With these conditions the system dynamics from Ecloud and TMCI effects will start to be evident via the beam response measurements. This excitation system with associated beam motion sampling then becomes a beam diagnostic, capable of measuring small tune shifts in parts of the beam. The system development is also a vital test-bed to prove system functions for a future feedback system.

ACKNOWLEDGEMENTS

We thank the CERN operations teams for providing and setting-up the beams necessary for this study, and the AR Modular RF (Kalmus) company for their ideas and help in modifying the amplifier bias to improve the transient response. We thank the SLAC ARD, CERN AB RF departments and the US LHC Accelerator Research program (LARP) for support.

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