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COMMISSIONING OF THE LCLS-II PROTOTYPE HOM DETECTORS WITH TESLA-TYPE CAVITIES AT FAST *

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Abstract

Experiments at the Fermilab Accelerator Science and Technology (FAST) facility detected electron beam-induced high order mode (HOM) signals from Tesla superconducting cavities. This paper describes some of the signal detection hardware used in this experiment, as well as measurements of the HOM signal magnitude versus beam trajectory. These measurements were made both with a single bunch and with a train of 50 bunches at bunch charges from 400 pC/b down to 10 pC/b. The detection hardware is designed for use with the Tesla superconducting cavities of LCLS-II at SLAC and is based on a prototype already in use at Fermilab. The HOM signal passes through a band-pass filter that is centered on several cavity dipole modes and a zero bias Schottky diode detects its magnitude. Direct comparisons were made between the FNAL chassis and the SLAC prototype for identical beam steering conditions. To support measurements with bunch charges as low as 10 pC, the SLAC detector has RF amplification between the band-pass filter and the diode detector. With this hardware, usable HOM signal measurements are obtained with a single bunch of 10 pC in cryomodule cavities as will be needed for LCLS-II.

INTRODUCTION

Bunch charge passing through a cavity will induce high order mode (HOM) fields. An off axis beam will excite dipole modes with an amplitude that is proportional to the beam offset, charge and coupling impedance value (R/Q) [1]. It has been shown that these beam induced HOMs can alter the bunch shape and displacement of bunches or trains of bunches [2, 3]. This effect is proportionally larger for bunches at lower energies, where the same induced fields will produce a larger effect on the trajectory of beam particles.

Tesla-type cavities have couplers that remove RF at HOM frequencies from the cavities – two couplers for each cavity – that can be used to detect the presence of cavity HOM fields. Since the beam-induced HOM fields are proportional to the offset of the beam and its charge, they provide information about the transverse beam offset [1, 4].

The planned bunch charges for LCLS-II range from 300 pC down to about 10 pC with repetition frequencies of up to 929 kHz and a beam energy at the first Tesla-type cryomodule of 750 keV. For the reasons mentioned above, it is most critical that the HOM fields be minimized in the cavities of this first cryomodule. During commissioning in early 2022, it is expected that both the bunch charge and repetition frequency will be at the low end of their range.

The hardware designed for LCLS-II will be installed on the first cryomodule and must be ready to provide usable signals for tuning during initial commissioning of the injector. So the design choices put a heavy weight on simplicity.

THE FERMILAB PROTOTYPE

At the Fermilab FAST facility, a prototype detector was constructed that consists of a notch filter to remove 1300 MHz, a band-pass filter to select a range of dipole mode HOM frequencies and a diode detector to measure the RF magnitude. This is probably the simplest way to make a measurement. Although it does not give the sign of the offset or resolve the modes, it does give the essential figure of merit – the magnitude of all the beam-induced HOMs within its pass-band. A sketch of the 1750 MHz section of the design is given in Fig. 1. For the February 2020 data, an amplifier was added to an RF monitor output which was recorded on a 4 GHz oscilloscope.

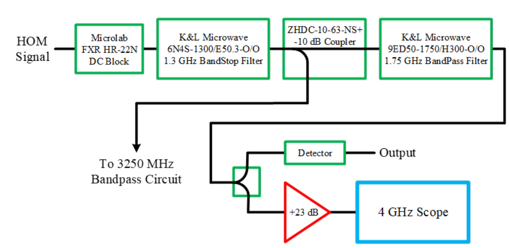

Figure 1: Block diagram of the 1750 MHz section of the Fermilab Prototype. This includes an amplifier (red) added for the February 2020 experiment.

The chassis was connected to the upstream HOM probe of a single Tesla-type cavity, capture cavity 1 (CC1), and the chassis RF output sent to a 4 GHz oscilloscope. A single bunch of 100 pC was sent through the cavity and an upstream vertical steering magnet varied to change the trajectory through the cavity. Figure 2 shows oscilloscope data of the filtered and amplified RF from the signal induced by

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a 100 pC bunch with a displacement of roughly 6 mm. This gives a sensitivity of about 25 mV/mm at 100 pC for the RF signal. The output of the Krytar 201A detector would be about 8 mV/mm according to its data sheet.

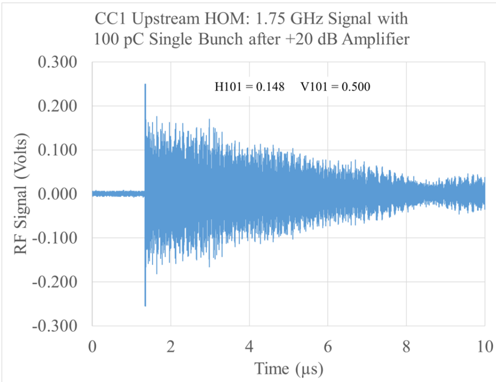

Figure 2: Oscilloscope data from February 2020, showing the 1725 MHz HOM signal level with a single 100 pC bunch and approximately 6 mm of vertical beam displacement.

THE DESIGN FOR LCLS-II

The design for LCLS-II is based on the Fermilab design, using a diode detector after analog filtering. Other methods that involve down-converting the RF can give additional information about the sign of the displacement and separate individual modes [1,5], but these methods will be considered as a future upgrade path.

Figure 3 is a block diagram of the SLAC prototype front end used in experiments at FAST beginning in November 2020. It is similar to the Fermilab design, but in order to increase the range of measurable signals, a 31 dB controllable attenuator and two cascaded +23 dB amplifiers have been added. The second amplifier was added to obtain a usable signal with a bunch charge of 10 pC. The amplifiers are followed by a zero bias Schottky diode detector. The state of attenuators and amplifiers is controllable through chassis front panel switches, with four channels in each chassis.

The amplifiers have an enable input so that the RF is bypassed with minimal attenuation when amplification is disabled. Cascading these two amplifiers carries the risk that the output of the first amplifier can damage the second. So care must be taken in their use.

EXPERIMENTAL RESULTS

Comparison of the Fermilab and SLAC Prototypes

A direct comparison was made of the signals from the Fermilab prototype and the newly constructed SLAC prototype detector under the same beam conditions. This was done as a final check to ensure that the two newly constructed SLAC chassis were functioning properly. We used the HOM signals coming from CC1 in the FAST injector. A vertical steering magnet upstream of the capture cavities was set to 0.5 A to give an offset of about 6 mm at CC1.

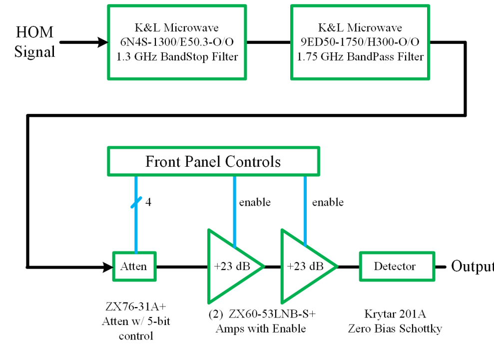

Figure 3: Block diagram of the SLAC prototype channel. There are four channels per chassis

The electron beam consisted of a train of 50 bunches at about 125 pC/bunch with a 3 MHz repetition frequency – this pattern repeats at 1 Hz. Signals from the Fermilab chassis were recorded first, then the same HOM signals were connected to the SLAC chassis without changing the state of the accelerator. For each chassis, 300 traces of 2048 points were taken. Figure 4 shows a comparison of the output of the two chassis with no amplifiers enabled. The SLAC chassis output is a little higher than that of the Fermilab chassis. This is probably due to the 4 dB insertion loss of the coupler in that chassis.

Figure 4 also shows the resonant buildup of energy in the mode(s) over the train of 50 bunches. This gives an enhancement of the signal since bunches are spaced less than the damping time of the mode. For LCLS-II, the highest bunch frequency is less than 1 MHz, with much lower frequencies anticipated during commissioning. So it was important to obtain some data with only a single bunch to be able to estimate the sensitivity during commissioning.

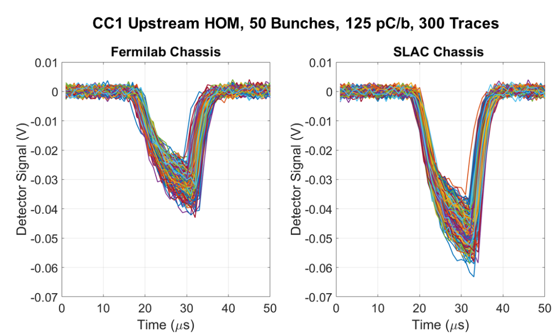

Figure 4: Overlay of 300 traces of CC1 data taken under the same beam conditions with the Fermilab and SLAC prototypes. The electron beam is 50 bunches at about 125 pC/bunch with a spacing of 333 ns.

Connection to the 8-Cavity Cryomodule

The two SLAC chassis of 4 channels each were connected to the HOM signals coming from the 8-cavity cryomodule (CM) at FAST, which is several meters downstream of the capture cavities [6–8]. Figure 5 shows the configuration with

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the two SLAC chassis connected to all eight up(down)stream HOM probes of the CM. Two chassis of a newer design of the Fermilab prototype were connected to the cavity 1 (c1) and cavity 8 (c8) down(up)stream HOMs. A vertical steering magnet V125, which is 4 m upstream of the CM, was used to vary the trajectory for different sets of measurements.

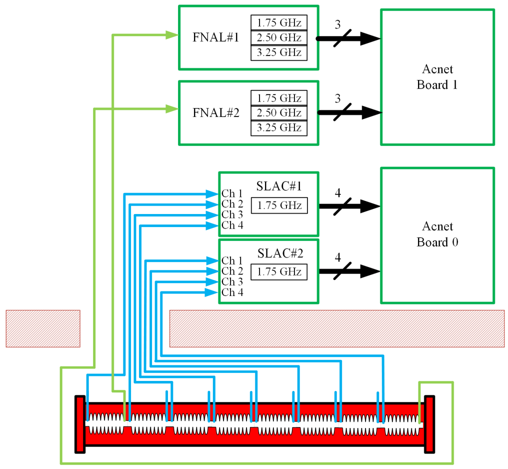

Figure 5: Block diagram of the cryomodule with its connections to the Fermilab and SLAC chassis and Fermilab's ACNET data acquisition system.

An important test for the SLAC prototype is its ability to detect offsets with a single bunch of 10 pC. Figure 6 shows the signals obtained from all sixteen HOM probes with a single 10 pC bunch without changing the accelerator magnet settings. This data was taken after roughly minimizing the upstream signals by hand adjustment of steering magnet settings. The estimated beam offset is about 1 mm. For this measurement, both cascaded amplifiers are enabled in all channels with no added attenuation.

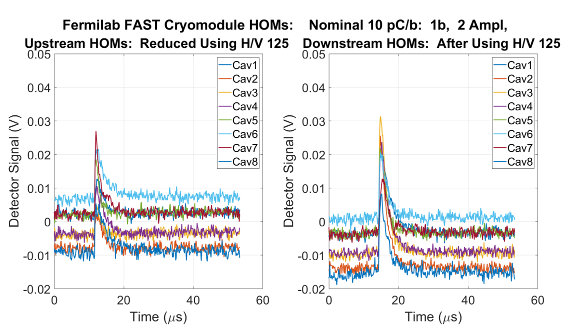

Figure 6: Output of the SLAC chassis with a single bunch of 10 pC and the beam approximately on axis (see text). Both cascaded amplifiers are enabled in all channels.

With higher bunch charge, data was also taken of the signal from the CM HOMs versus the setting of an upstream steering magnet. The electron beam has an energy of 25 MeV and the V125 steering magnet is about 4 meters upstream of the CM. With a current of 1 A, V125 gives an angle of 2 mrad, for a displacement of about 8 mm at the entrance to the CM (the cavity 1 end). Figure 7 shows the peak HOM signal for each cavity versus magnet current with a 50 bunch train of 400 pC/bunch. One amplifier is enabled in each channel and for larger beam offsets, 10 dB of attenuation was inserted to keep the signal on scale. The attenuated data was scaled to make it consistent with the other data in the set.

The signal from c1 is about 800 mV for a 1.0 A setting, which should correspond to a displacement at c1 of about 8 mm. So the rough calibration is 100 mV/mm at 400 pC. The minimum of the c1 signal in Fig. 7 is about 125 mV, or a little more than 1 mm displacement. At 10 pC this would be 2.5 mV/mm, but the second amplifier (23 dB) could be enabled at this low bunch charge to give 35 mV/mm.

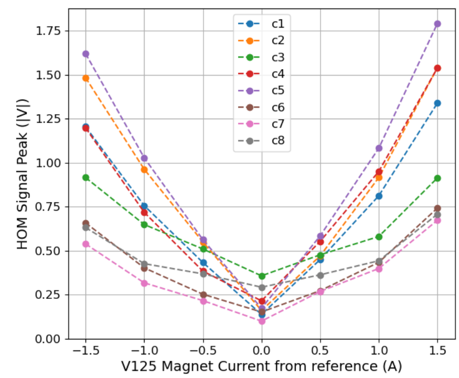

Figure 7: Plot of the SLAC chassis output versus steering magnet current with one amplifier enabled in each channel. The electron beam was 50 bunches at 400 pC/bunch.

SUMMARY AND FUTURE WORK

The SLAC HOM measurement front end hardware has been tested with electron beam at Fermilab's FAST facility. With two cascaded amplifiers, data show a usable signal with a single bunch of 10 pC and beam offsets of roughly 1 mm. The controllable attenuator allows finer control of the signal level – 31 dB in 0.5 dB steps. The combination of amplifiers and attenuator gives a sensitivity that can be varied over 77 dB.

The analog front ends used in these experiments need data acquisition for their use at SLAC. The present plan is to use a digitizer and FPGA for HOM measurement and for remote control of the amplifiers and attenuators. Data from the experiments at Fermilab are also being used at SLAC for ongoing work in machine learning [9].

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