THE FERMI@ELETTRA CAVITY BPM SYSTEM: DESCRIPTION AND COMMISSIONING RESULTS

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Abstract

The FERMI@Elettra cavity BPM (C-BPM) system is based on an original implementation of the C-BPM scheme as the pick-up, operating at 6.5GHz, is coupled to a dedicated, self-calibrating electronics based on a novel concept. The system has been developed in-house; both the E-M and the mechanical design of the pick-up have been carried out, including an original frequency tuning scheme. The detector electronics directly obtains the envelope of the sum and difference signals by means of an RF 180° hybrid; no mixer for the RF signal down conversion is used. The detector is based on 3 blocks: an RF front-end, a baseband analogue transmission module and a digital back-end unit, based on a μ-TCA platform. The digital back-end is equipped with a powerful Virtex 5 FPGA and several real-time tasks have been implemented on it, including intra-pulse calibration. Ten C-BPM stations have been installed so far, fully integrated in the FERMI control System, enabling a real-time control of this key FEL diagnostics. Results on performances with beam are also presented; the scale factor of C-BPMs is obtained with beam, as two-axis micrometer translation stages have been installed.

FERMI C-BPM MEASUREMENT PRINCIPLE

C-BPM Pick-Up

The FERMI@Elettra cavity BPM pick-up [3] consists of two mechanically tuneable copper cavities with a 6.5 GHz resonance frequency. One of these cavities generate the monopolar component called *reference* signal. This signal is a damped sine wave at 6.5 GHz with a time constant τ of approximately 300ns. The amplitude of the *reference* signal is directly proportional to the charge. The second cavity generate the two X and Y dipolar components on the four output connectors, two for vertical plane and two for horizontal plane These signals are called the *position* signals and have the same time domain response like the *reference* one. The amplitude of the *position* signal is directly proportional to the charge and to the distance of the beam from the cavity longitudinal axis. A key feature is that if the electron beam is on axis the amplitude of the output signal goes to zero. The phase of the *position* signal on each plane has a 180 degrees jump when passing through the zero. The mechanical tuners fitted to the each cavity on the C-BPM allow the alignment of three frequencies (reference, horizontal and vertical position) within 200 kHz around the nominal value of 6.5GHz.

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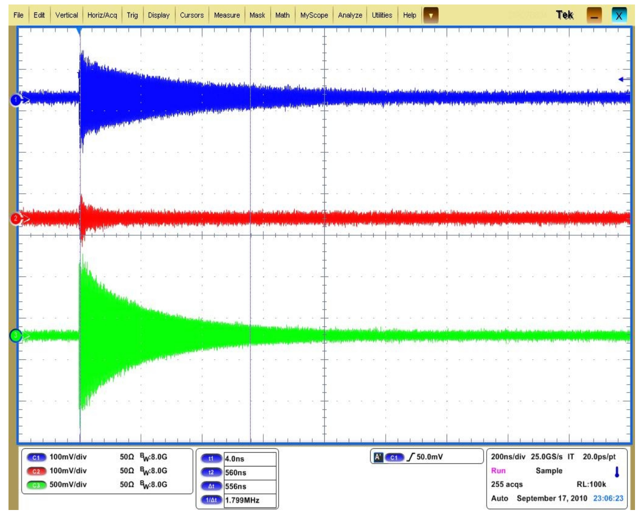

Figure 1: C-BPM signals with 200pC. Trace1: X off center, trace2: Y nearly in center, trace3: Reference.

Each C-BPM is mounted on remotely controlled movers (stepper motors). The motion has an accuracy of about 5 μm. The reading of the position has an accuracy of 1 μm. Through the accurate reading of relative movement we can calibrate very precisely the response scale of the electronics. The first three C-BPM have a simpler two axis mover, with an X and Y range of ±0.8mm. The remaining C-BPM are mounted on larger movers together with the quadrupole magnet. These movers are used both for "Beam Based Alignement" and for the calibration of the response scale of the associated C-BPM.

Signal Detection

To detect pick-up signals (Fig. 1) two possibilities have been investigated. A classical approach consisting of a frequency down-conversion from 6.5 GHz to approx. 40 MHz and a direct analogue to digital conversion, followed by a sophisticated digital signal processing [1] performed by a dedicated FPGA/DSP.

Due to some issues like the availability of a digitizer and the available time and manpower to develop the firmware for IQ demodulation, we decided to directly detect the envelope of the RF signals pre-processed by an RF hybrid.

Detection Block Diagram: RF Front End Box

The RF Front End Box is located in the accelerator tunnel, as close as possible to the pick-up to minimize the RF signal losses from the connection cables. The pick-up signals are filtered by a 50 MHz band-pass filter to avoid any spurious frequencies. Then the *position* signals, phase shifted and an amplified, are combined with the *reference* signal in a 180° Double Arrow Hybrid Coupler. The hybrid coupler is a passive component performing the sum and the difference of its two input signals.

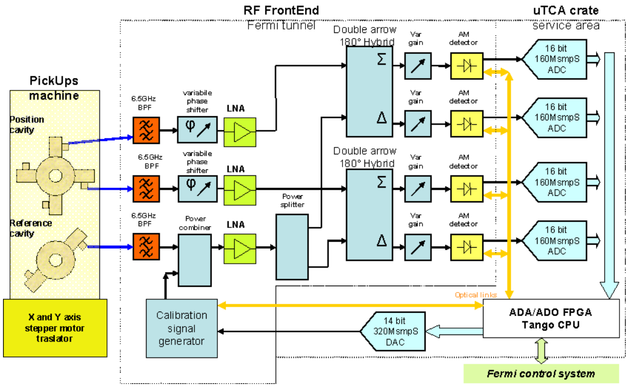

Figure 2: C-BPM system Acquisition Block Diagram.

The sum and the difference output signals from the hybrid pass through a digital 64 step attenuator. Finally the amplitude envelope is detected by a precision RF Detector with 12MHz baseband bandwidth. The linearity of the circuit has been measured: in the range from 100mV rms input (-7dBm) to 1000mV (+13dBm) the linearity resulted better than 1% (Fig. 3) which corresponds to a 20 dB detection window for the position range of ±2mm.

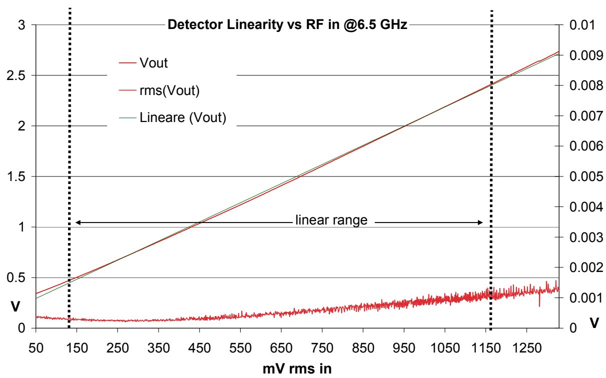

Figure 3: RF detector linearity.

The purpose of the digital step attenuator is to follow the signal dynamic range for different beam charges. The specifications for the C-BPM system are from 200 to 800pC. The resulting signals are then coupled through a transformer with 70KHz-200MHz band to isolate the masses. The signals are sent in analog form through a biaxial pair cable outside the Fermi machine tunnel until the Fermi Service Area where all the processing units are located. The signals (Fig. 3) are received and transformed from balanced to unbalanced. Then the signals from the tunnel electronics are acquired by the ADO digitizer board housed in the μ-TCA crate.

The Detection Block Diagram, μ-TCA Part

In the Fermi Service Area four μ-TCA crates have been located managing all the C-BPMS installed in Fermi FEL1. Three crates are stuffed with two ADA boards, three ADO boards, three OPTO-IO boards and one MiTich each managing three C-BPM each. The fourth μ-TCA crate is stuffed with one ADA board, one ADO board, one OPTO-IO board and one MiTich board to manage the tenth C-BPM.

The ADA Board [2] is an Analog to Digital and Digital to Analog converter board equipped with one FPGA Xilinx Virtex-5 SX50T, two ADC Linear Technology LTC2208, two DAC Maxim MAX5890, one Ethernet service interface (Lantronix), two SFPs for gigabit communications and is backplane gigabit communication enabled. The ADA board is used to generate the calibration signals (see Fig. 2, Block Diagram).

The ADO Board is an Analog to Digital Only converter board equipped with one FPGA Xilinx Virtex-5 SX50T, four ADC Linear Technology LTC2208, one Ethernet service interface (Lantronix), two SFPs for gigabit communications and is backplane gigabit communication enabled. The ADO board is used for fast signal data acquisition (see Fig. 2, Block Diagram).

The OPTO-IO board is used to interfaces the different digital control signals from Xilinx Virtex5 FPGA to the RF Front end in the Fermi tunnel.

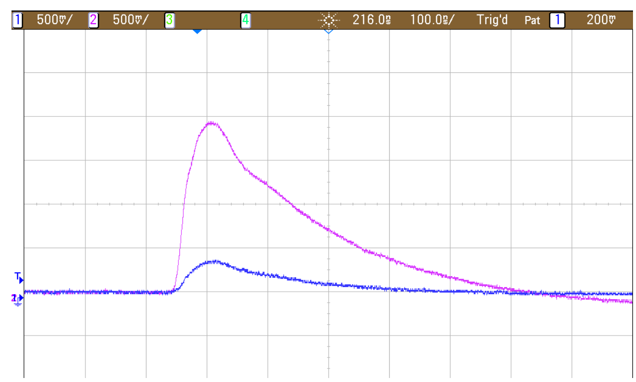

Figure 4: C-BPM X axis envelope signals with 50pC off axis Beam.Ch1:envelope Σ signal, Ch2: envelope Δ signal.

THE SOFTWARE

The signals coming from field are digitized at 160 MHz sampling clock. The duration of the ringing signal is approx 500ns. The repetition rate is 10 Hz, the current FERMI@Elettra injection rate. The signal processing is based on 256 points acquired for each Fermi shot and it computes the signal's area. The area computation is performed by searching the ADC mean value preceding the signal. Then the area is computed until the signal goes back down to the mean value. In this way only the positive part of the signal is considered: we noticed that the negative part, introduced by AC coupling of the signal transmission to the ADC, is affected by noise and certain non-linearities caused by slight impedance mismatches (less than 1%). In between every machine shot, a calibration signal is generated by the Calibration Signal Generator which is acquired in the same way as the beam signals. The ADA board generate an 80MHz signal with emulating the Cavity ringing. The Calibration Signal Generator Unit (CSGU), emulating to the RF Front end, up-converts this signal to 6.5GHz. With this method we simulate a perfectly centred beam. In fact, the on axis beam signature is characterized by signal presence only from the *reference* signal (see Fig. 1). With this signal applied all of the electronics drifts, offsets and mismatches are compensated and a very high absolute position accuracy is achieved. With this method the absolute position accuracy is equal to the system resolution. An important task performed by ADO board consists in a programmable frequency generator control. The CSGU is equipped with a 16 bit DAC, a VCO and a divide by 256 prescaler. The firmware checks the frequency generated by the VCO and divided by the prescaler, through the optical interface. It keeps the VCO frequency at the set value by setting the VCO's DAC value. The frequency range is 6.38 GHz to 6.52 GHz and covering all of the possible requirements; its nominal value is 6.420 GHz.

Position Computation

At each shot, eight waveforms of 256 points for each C-BPM are sent to a Control system CPU that uses these data to calculate the position. The eight waveforms are: HorPos Σ, HorPos Δ, VertPos Σ, VertPos Δ , HorPosCal Σ, HorPosCal Δ , VertPosCal Σ, VertPosCal Δ. The Cal signals are used to compensate on a shot by shot basis any difference between all of the acquisition chains, including programmable attenuator, envelope detect or signal conditioning and transmission and ADC. ADO boards transmit data to the Equipment Controller (EC) through a dedicated 100Mbit ethernet network by means of udp packets. The EC, which runs Linux with Xenomai realtime extension and a modified ethernet driver, acquires and process data at the kernel level by a Xenomai realtime thread. The position computations follow these formulas,

$$\mathrm{Gain}\Sigma = \mathrm{AreaCal}\Delta \,/\, (\,(\,\mathrm{AreaCal}\Sigma + \mathrm{AreaCal}\Delta\,)\,/\,2\,)$$

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$$\mathrm{A}\Sigma = \mathrm{AreaBeam}\Sigma * \mathrm{Gain}\Sigma$$

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$$Pos[mm] = k\,\frac{(A\Sigma - A\Delta)}{(A\Sigma + A\Delta)}$$

where k is the conversion factor from arbitrary units (areas) to mm, and it is obtained from precisely known movement performed by a mechanical movers [4]. This calibration method is necessary because of the C-BPM measurement principle: the measurement principle is to detect an absolute value that comes from the pick-up. This absolute value is directly proportional to the position of the beam, but this value may vary in different pick-ups and mainly from the signal detection electronics. Of course a stable electronics is required to avoid k values drifts in time. Also a stable beam is required. For that reason we repeated the k values computation several times in different conditions and in different times and we found always the same results in a 10% range performing movements of ±0.5mm [4] .

THE RESULTS

The C-BPM system for FEL1 is fully operational with 10 of 10 C-BPM. Acquisition data and position computation with 10Hz repetition rate is done in realtime and is fully integrated in Fermi Control System. The measured resolution from 50 up to 350 pC beam charge is 4µm rms. During first steering through the undulator section the beam charge has been lowered to 50pC without loosing resolution which made FERMI@Elettra FEL commissioning possible. C-BPM system performs best resolution with on axis beam. No position drifts has been noticed during the operations. The calibrations factors (k) calculated with the mechanical movers are constant in different times and conditions.

THE FUTURE IMPROVEMENTS

1. Update µ-TCA power supplies with low noise's one
2. Reduce the ADO RF input transformer bandwidth to increase the positive signal area.
3. Decrease the *reference* signal amplifier gain to add more weight to *position* signal but loosing in sensitivity al lower charges.

CONCLUSIONS

The Cavity BPM system has been successfully built, installed, tuned and commissioned on FERMI@Elettra FEL 1. The system is in stable operation and all of the electronics proven to be highly reliable: there was only one hardware fault due to a defective tantalum capacitor. The FPGA firmware never crashed and the realtime control software is very stable (only few malfunctions caused by external events).

ACKNOWLEDGEMENTS

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