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Analog Signal Pre-Processing For The Fermilab Main Injector BPM Upgrade

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Abstract. An analog signal pre-processing scheme was developed, in the framework of the Fermilab Main Injector Beam Position Monitor (BPM) Upgrade, to interface BPM pickup signals to the new digital receiver based read-out system. A key component is the 8-channel electronics module, which uses separate frequency selective gain stages to acquire 53 MHz bunched proton, and 2.5 MHz anti-proton signals. Related hardware includes a filter and combiner box to sum pickup electrode signals in the tunnel. A controller module allows local/remote control of gain settings and activation of gain stages, and supplies test signals. Theory of operation, system overview, and some design details are presented, as well as first beam measurements of the prototype hardware

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INTRODUCTION

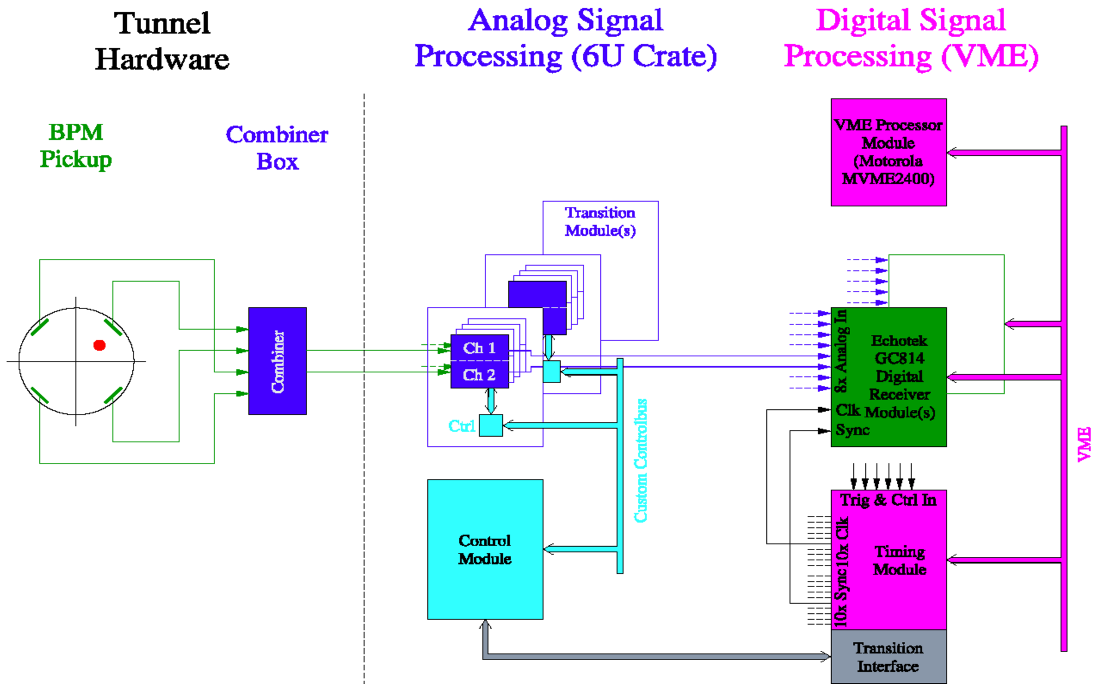

FIGURE 1. Overview of the Main Injector BPM hardware, showing 2 of the total 430 channels.

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The beam position monitor (BPM) system of the Fermilab 8-150 GeV fast cycling p/pbar Main Injector (MI) synchrotron consists out of 201 stripline and 7 electrostatic pickups distributed along the 3320 m circumference. While the majority of the pickups and the cabling remain unchanged, a complete new signal processing schema was developed to provide position detection of proton and anti-proton beams, as well as other enhanced features [1].

Fig. 1 shows an overview of the upgraded system for one pickup station. The central part of the signal processing hardware is a commercial *Echotek* GC814 digital receiver (VME module). The GC814 includes digital downconverters (DDC) to translate the 2.5 MHz antiproton and 53 MHz proton beam signals to baseband. The analog pre-processing section (Combiner Box, Transition Module) adapts the broadband pickup signals in level and frequency content for various Main Injector beam conditions to become manageable by the digital receiver. Eight analog pre-processing channels are located on each “Transition Module”. A “Control Module” is required to remotely change gain, (de)activate gain stages or provide test signals. It is interfaced via a Transition Interface card to the “Timing Module” that resides in the VME 6U chassis with the digital receiver modules. The analog modules are placed in a 6U high crate frame, powered by a linear power supplies.

All BPM crates with analog and digital signal processing hardware are located outside the accelerator tunnel in seven above-ground buildings. Each building accommodates approximately 60 BPM signal processing channels (for 30 pickups). The pickup signals are transferred through 300…1300 ft long RG-8 type coaxial cables. To reduce cable installation, the signals of four stripline electrodes are combined in the tunnel, using a passive “Combiner Box”, to provide only horizontal or vertical only displacement signals from each stripline pickup.

ANALOG SIGNAL PRE-PROCESSING SCHEMA

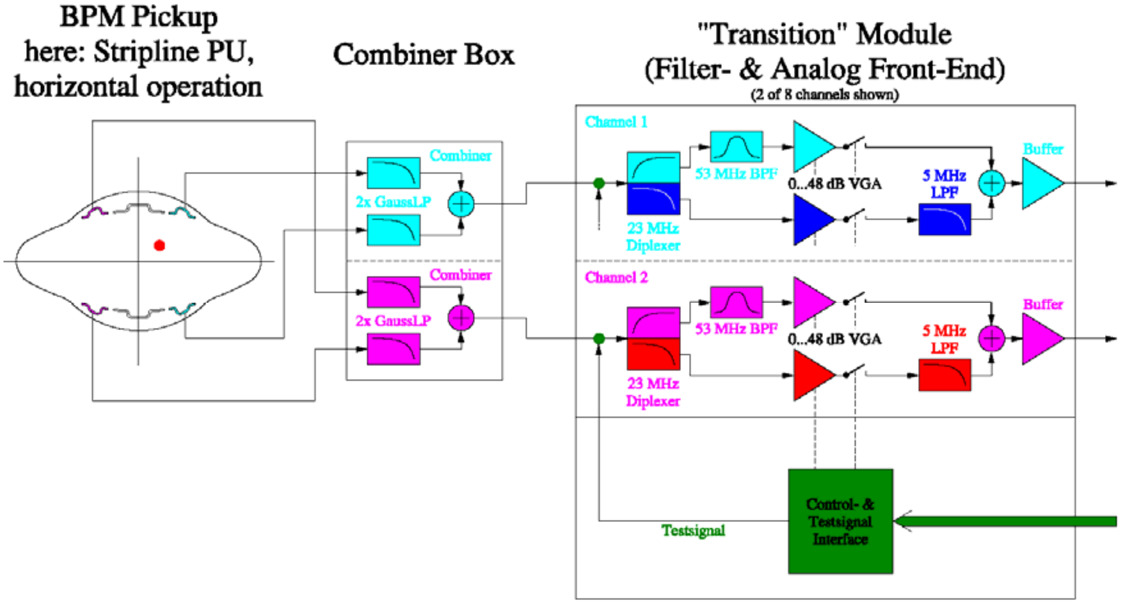

FIGURE 2. The analog signal pre-processing schema of the Fernilab Main Injector BPM system (2 channels shown).

Fig. 2 gives an overview of the MI-BPM analog signal pre-processing schema. This is based on the design principle of the Fermilab Rapid Transfer-line beam position monitors (RT-BPM) [2]. Broadband pulse signals from the four 28 cm long electrodes of the stripline pickup are low-pass filtered in front of a 3-dB hybrid combiner using an absorptive 100 MHz quasi-Gaussian network. Separate, frequency selective gain stages are used for the amplification of proton (53 MHz bunched) and antiproton (2.5 MHz bunched) signals. The central component of the gain stages is an *Analog Devices* AD8332 dual-channel low-noise variable gain amplifier (VGA). It offers a remotely controlled variable gain (total range: 0…60 dB), while keeping the gain mismatch between the two channels < 0.1 dB. This gives the required precision and flexibility to operate the BPM system under a broad range of Main Injector beam conditions and intensities. The “power-down” functions of the post-amplifiers (*Analog Devices* AD8129/30 differential receiver) are used to remotely (de)activate frequency selective gain stages, i.e. operating at 2.5 or 53 MHz, or at both frequencies simultaneously.

There are no mechanical switches in the signal path. A 23 MHz diplexer at the input is used for the 2.5/53 MHz signal separation. The 53 MHz gain stage is equipped with a commercial 3-stage Bessel-type band-pass filter (f_{center} = 53 MHz, BW = 5 MHz), matched in pairs. The 2.5 MHz gain stage uses a single-pole Tchebycheff-like low-pass pulseformer ($f_{3\mathrm{dB}} \approx 5$ MHz) to fix the frequency response. The two gain stages are operated in parallel: the output signals are added – again using the AD8130 differential amplifier – and further buffered.

A programmable logic based control section manages the control signals and can provide 2.5 or 53 MHz test signals supplied through a 3 dB 180^0 hybrid at each channel input. The test signals may be CW or a trigged sine-wave like burst signal. A remote controlled attenuation option allows to simulation of a centered (A=B) or off-centered beam (A>B, A<B).

MAIN INJECTOR BEAM SIGNALS

The different beam operating modes of the Main Injector are described in detail elsewhere in these proceedings [1]. The analog signal processing design has to satisfy the broadband BPM operation, capable to acquire individual batches of four 2.5 MHz or eighty-four 53 MHz bunches. A ~ 5 MHz bandwidth was chosen for each path, resulting in a ~ 70 ns response time. A detailed analysis (theoretical and measurement-based) of the Main Injector beam conditions and the pickup characteristic provides an estimation of the levels along the signal path.

Main Injector BPM Pickup Characteristics

The analysis of the output voltage of a BPM pickup electrode is twofold:

- Analysis of the transverse beam-to-electrode coupling $s(x,y)=\phi_{elec}$, and the resulting position characteristic.
- Analysis of the frequency dependent transfer impedance $Z_{elec}(\omega)$.

$$V_{elec}(x,y,\omega) = s(x,y)\; Z_{elec}(\omega)\; I_{beam}(\omega) \qquad (1)$$

Main Injector Pickup Position Characteristic

The position characteristic was analyzed in 2D on the cross-section of the Main Injector stripline and electrostatic BPM pickups. The electrostatic solver of *MAFIA* was used to numerically solve the Laplace equation

$$\Delta\Phi = 0 \quad \Rightarrow \quad \phi = f(x, y) \qquad (2)$$

for each of the four electrodes. Combining the resulting scalar potentials yields the horizontal and vertical position characteristics (shown here for the stripline electrodes, which are not arranged along the x- and y-plane):

$$\frac{\Delta}{\Sigma}(hor) = \phi_{hor} = \frac{(\phi_{ur} + \phi_{dr}) - (\phi_{ul} + \phi_{dl})}{\Sigma\phi} \qquad \frac{\Delta}{\Sigma}(vert) = \phi_{vert} = \frac{(\phi_{ur} + \phi_{ul}) - (\phi_{dr} + \phi_{dl})}{\Sigma\phi} \qquad (3)$$

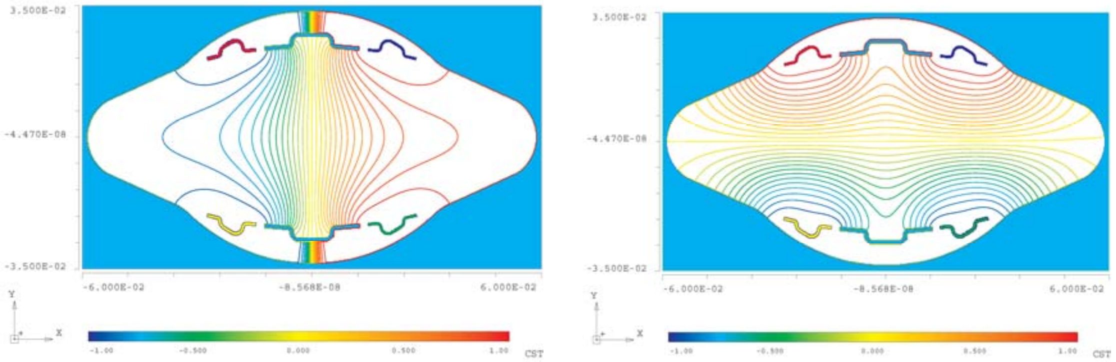

FIGURE 3. Normalized horizontal and vertical difference equipotentials of the stripline pickup (2D).

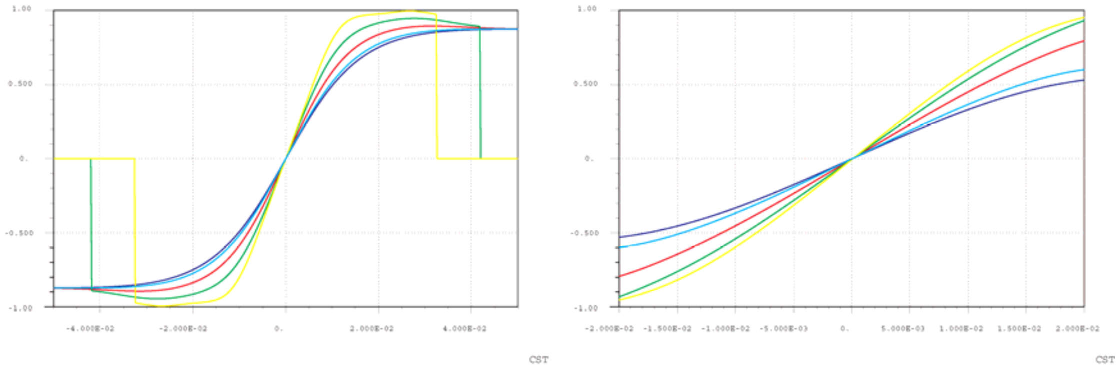

FIGURE 4. Normalized horizontal and vertical position characteristic Δ/Σ with displacement parameter at 0, ±5, ±10, ±15 and ±20 mm in the orthogonal plane.

Fig. 3 and 4 plot the results for the stripline pickup. They exhibit a strong non-linear effect at beam displacements > |~10 mm| (outside most Main Injector applications), and are in good agreement with stretched wire measurements [3]. At x=0, y=0 the coupling is found to be $\phi_{elec} = k = 0.084$. The characteristic impedance of the electrodes was determined from the field energy: Z_0 = 50 Ω (measured: 43…48 Ω).

Rearranging the results in the form of the signal ratio of opposite electrodes gives:

$$\frac{R}{L}(hor) = \phi_{hor} = 20\lg\left(\frac{\phi_{ur} + \phi_{dr}}{\phi_{ul} + \phi_{dl}}\right) \qquad \frac{U}{D}(vert) = \phi_{vert} = 20\lg\left(\frac{\phi_{ur} + \phi_{ul}}{\phi_{dr} + \phi_{dl}}\right) \qquad (4)$$

At x=0, y=0 the position sensitivities of the pickup are found to be 0.96 dB/mm (hor.), 0.61 dB/mm (vert.).

A similar analysis was performed for the electrostatic pickup with circular cross-section of 120 mm diameter. These “Extra Wide Aperture” pickups are installed at 7 injection/ejection locations in the Main Injector and are read-out in both planes (no signal combiner). The position non-linearities are minimized by orientating the pickup electrodes along the x- and y-planes (0^0, 90^0). The pickup electrodes span ~ 60^0 of cross-section aperture, which gives a strong beam coupling: $\phi_{elec}= k$ = 0.218. The electrode capacitance was estimated from the field energy (~ 10 pF), the position sensitivity is ~ 0.5 dB/mm.

The non-linear position characteristic is approximated in the plane of interest by a 5th-order polynomial used in the computation of the read-out software[4].

Main Injector Pickup Transfer Impedance

The transfer impedance was calculated for the stripline electrode (length l, beam coupling k, characteristic impedance Z_0), assuming a Gaussian longitudinal distribution of n particles:

$$i(t) = \frac{ne}{\sigma\sqrt{\pi}} e^{-\left(\frac{t}{\sigma}\right)^2} \qquad I(f) = \pi e\, e^{-(\pi f \sigma)^2}$$

$$Z_{elec}(t) = \frac{kZ_0}{2}\left[\delta(t) - \delta(\frac{2l}{v} t)\right] \qquad Z_{elec}(f) = kZ_0 e^{-j\frac{\pi}{2}} e^{-j\frac{2\pi fl}{v}} \sin\frac{2\pi fl}{v} \qquad (5)$$

$$v_{elec}(t) = \frac{kZ_0 ne}{2\sigma\sqrt{\pi}}\left[e^{-\left(\frac{t}{\sigma}\right)^2} - e^{-\frac{(4\pi l/v - 2\pi t)^2}{4(\pi\sigma)^2}}\right] \qquad V_{elec}(f) = nekZ_0 \sin\left(\frac{2\pi fl}{v}\right) e^{j\frac{\pi}{2}} e^{-j\frac{2\pi fl}{v}} e^{-(\pi f\sigma)^2}$$

A maximum transfer impedance of 4.2 Ω can be achieved at 267.7 MHz. At the nominal operation frequencies, the transfer impedances are substantial lower: 1.3 Ω @ 53 MHz (-10.3 dB), 0.062 Ω @ 2.5 MHz (-36.7 dB). In case of 2.5 MHz pbar operation, the signal levels suffer also from low beam intensities and long bunches.

On the other hand, the output signal power of a proton bunch of $n = 10^{11}$, $\sigma = 0.25$ ns reaches 3.6 W requiring RF-resistors with sufficient power rating in the absorbing low-pass pulseformer of the Combiner Box.

The Range of Beam Signal Levels

Applying the previous analysis on the different Main Injector beam conditions, results in an estimation of signal levels at the input of the first active element – the

VGA – of the analog electronics. In addition to the analytical computations, a transient simulation of pickup electrodes, Combiner Box circuits (Gaussian low-pass, 3 dB hybrid combiner), long RG-8 coaxial cables, and the passive input circuits of the Transition Module (diplexer and 53 MHz band-pass) was performed. This was done using *Agilent* ADS software and verified on a test-setup at the Main Injector.

TABLE 1. VGA input signal levels

		53 MHz
min. level	0.7 mV_{pp}	single coalesced pbar bunch, $10x10^9$ pbar/bunch, $\sigma \approx 5.8$ ns, 12 dB att.
max. level	1.5 V_{pp}	> 20 p bunches, $200x10^9$ p/bunch, $\sigma \approx 0.4$ ns, 2 dB att.
		2.5 MHz
min. level	0.6 mV_{pp}	single coalesced pbar bunch, $5x10^9$ pbar/bunch, $\sigma \approx 55$ ns, 1.5 dB att.
max. level	83 mV_{pp}	single coalesced pbar bunch, $150x10^9$ pbar/bunch, $\sigma \approx 14$ ns, 0.5 dB gain

Tab. 1 lists minimum and maximum input signal levels. At 53 MHz they span a range of 67 dB, at 2.5 MHz the range is 43 dB. Up to 1 dB/mm beam displacement has to be added to estimate the total required dynamic range of the system. The input level of the *Echotek* digital receiver is limited to 1.1 V_{pp}, so reasonable signal levels should range 100…600 mV_{pp}. Thus, the required gains ranges from -8…+54 dB (53 MHz) and +15…+60 dB (2.5 MHz). 53 MHz proton signals typically have high levels, only anti-proton signals may have low levels at 53 MHz.

DESIGN DETAILS

Combiner Box

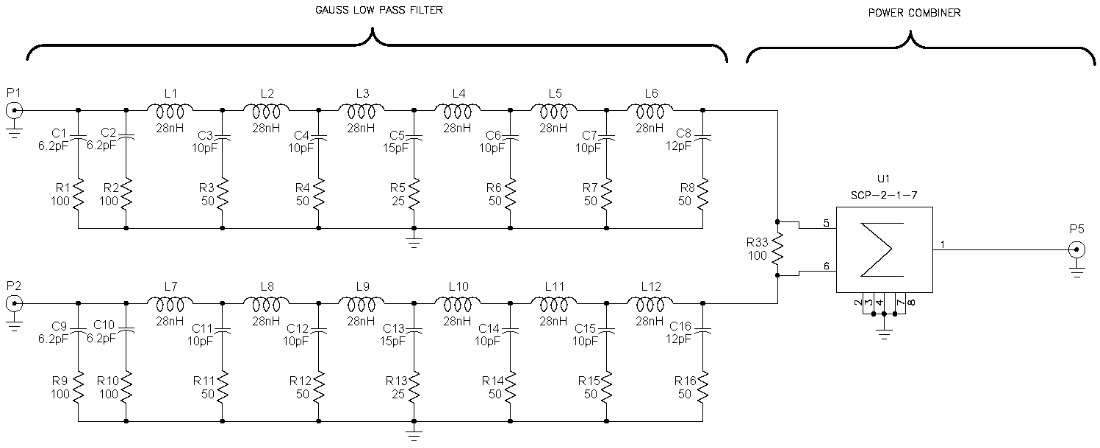

FIGURE 5. Schematics of the "Combiner Box" (1-of-2 channels).

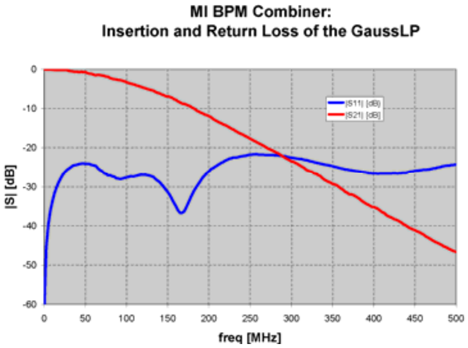

FIGURE 6. S-parameter measurement results of the Gaussian low-pass filter.

A Gaussian-like low-pass filter is used prior to the actual power combiner to absorb all unwanted high frequency energy > 100 MHz. Its RF-resistors are rated at 0.75 W. A custom modified 3 dB combiner (*Mini Circuits* SCP-2-1-7) is used to allow an external an higher power rated RF-resistor (Fig. 6). The filter design is based on a double-symmetric network, empirically synthesized using a frequency domain optimization with *Agilent's* ADS statistical design package. Fig. 6 plots the S-parameter measurements of a prototype, indicating a return-loss > 20 dB over a wide frequency range.

Transition Module

The first component of the Transition Module is a 3 dB 180^0 hybrid, used to input signals from the pickup/combiner or from an internal test signal amplifier. It outputs the signals to a diplexer circuit and to a monitor output routed to the front panel.

The diplexer network with 23 MHz cross-over frequency is used to frequency select the input signals for 2.5 or 53 MHz gain stage processing. In order to minimize reflections, the commercial 53 MHz band-pass filter had to be impedance-matched to the high-pass portion of the diplexer. A total of 1100 filters where characterized (S_{21} measurements of the pass-band) and matched in pairs for minimizing "electronic" offset effects. All other frequency selective stages of the circuit are equipped with low tolerance (1…2 %) RF components.

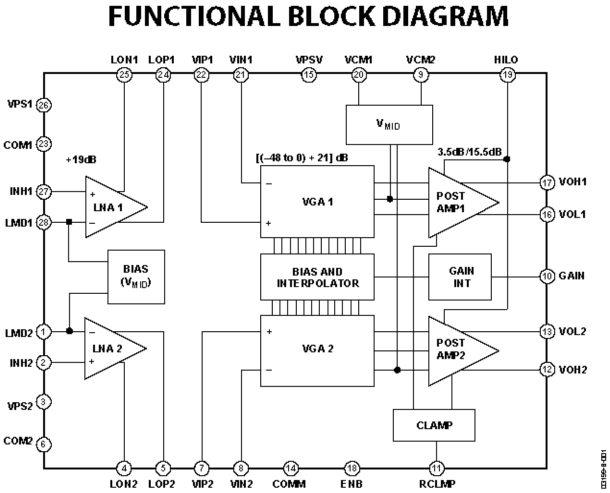

FIGURE 6. *Analog Devices* AD8332 block diagram, the component features:

- Low-noise preamplifier: 0.74 nV/$\sqrt{\text{Hz}}$, 2.5 pA/$\sqrt{\text{Hz}}$
- 120 MHz bandwidth (-3 dB)
- Two 48 dB gain ranges :
  LO: -4.5 dB…+43.5 dB
  HI: +7.5 dB…+55.5 dB
- Typical channel-to-channel gain error (mismatch): ±0.1 dB

Fig. 6 shows the internal block diagram of the Analog Devices AD8332 dual-channel low-noise VGA which serves as central gain component in the analog signal processing path. For any common gain setting, the gain of the two channels is matched < 0.1 dB this minimizes unwanted electronic BPM-offsets in the system. Two AD8332 amplifiers are required for the signal processing of a pickup, one in the 2.5 MHz, another in the 53 MHz gain stages. The low-noise amplifier (LNA) is used only in the 2.5 MHz gain stages, as its saturation level cannot accomplish high level 53 MHz signals. I/O of the VGA and post-amplifier stages have to be differentially driven. This is incompatible with the single-ended signal processing in all the other subsystems. At the VGA input a RF-transformer, at the output a differential receiver (*Analog Devices* AD8129/30) are used for adoption. The 0…48 dB gain variation is adjusted with a voltage control signal

(0…1 V), supplied from an 8-bit DAC. The AD8332 post-amplifier features a high gain setting (+12 dB) which results is a total gain variation range of 0…60 dB.

Three AD8129/30 differential amplifiers in each channel are used for:

- Differential to single-ended signal conversion from the AD8332 output.
- Fixing the maximum total gain in 2.5 and 53 MHz gain stages.
- Activation/deactivation of the 2.5/53 MHz gain stages, using it's "power down" function.
- Summing 2.5 and 53 MHz signals to a single output.

A buffer amplifier (*Texas Instruments/Burr-Brown* OPA692) is used to drive the output signal to the following *Echotek* digital receiver.

Control Module

The Control Module is a custom designed board used to control the BPM Transition Module subrack. The module is double wide and sits in the leftmost slots of the transition modules' subrack.

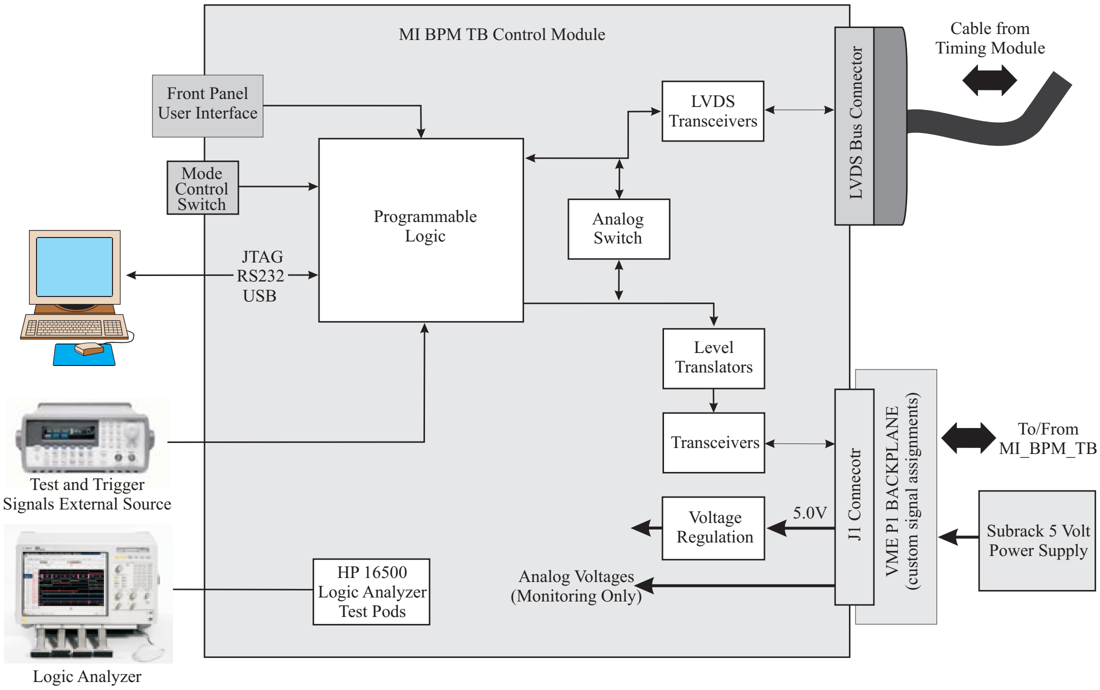

FIGURE 7. Main Injector BPM Control Module.

Timing Module Interface

The Control Module receives data and commands from the Timing Module over a bi-directional 32-bit wide Low-Voltage-Differential-Signaling (LVDS) bus. The link is implemented using a SCSI 68-signal connector and cable.

The Timing Module and the Transition Modules subracks are physically close. This allows the cable used for the LVDS bus to be only 1 meter [3.28 feet] long.

Backplane and Transition Board interface

Data and commands received from the timing module are translated to 5V TTL and sent to the Transition Modules over a backplane. The backplane used is a VME P1 backplane with custom pin and voltages assignments. Mechanically the backplane is positioned to occupy the lower half of the subrack, in what usually is the VME P2 backplane location.

During the system design it was verified that a VME type backplane would meet the system requirements. The use of an off-the-shelf backplane allowed for lower system design time and costs.

Transition Module interface

The Transition Modules are individually addressable allowing for module-specific parameter settings and for module status readback. In this way individual gain settings can be used to compensate 53 MHz signal attenuation effects due to the different lengths of the coaxial cables.

Operating Modes and Diagnostics

Control Module diagnostics is an important component of the MI BPM system.

The Control Module can operate in three modes:

Off Mode.

During normal operations most of the logic on the Control Module is powered down. The powered components provide a transparent interface between the Timing Module (LVDS bus interface) and the Transition Modules (backplane interface).

Monitoring Mode.

The Control Module diagnostics provide a real-time system status through the front panel user interface. This interface consists of LED displays and multifunction switches providing access to each individual Transition Module and allows monitoring of both the LVDS bus (Timing Module interface) signals and the backplane (Transition Modules) signals.

Local Mode.

In this mode the Control Module isolates the backplane bus from the LVDS bus and directly controls the Transition Modules.

During Monitoring and Local Mode operations, the diagnostics are fully accessible from the Control Module's RS-232, USB and front panel user interfaces. The diagnostics are also accessible by the Timing Module.

The Control Module's Local Mode diagnostic capabilities allow a user to operate a "Transition Module" subsystem independently from the other BPM system components. Such a subsystem has been extensively used for development and production testing of the Transition Modules.

MEASUREMENTS

A 2-channel prototype board was assembled and extensively analyzed with measurements in the time and frequency domains on the bench and beam measurements in connection with the other subsystems. The overall gain ranges are measured as:

- -17.5…+42 dB for the 53 MHz gain stages
- +6.5…+65 dB for the 2.5 MHz gain stages

The channel-to-channel gain mismatching was verified to be < 0.1 dB (typically). The 1 dB compression point of the 53 MHz gain stages was measured at +22 dBm input level, sufficient to handle highest proton signal levels at larger beam displacements. The isolation of the AD8129/30 in disable (off) was measured to be 75 dB at 53 MHz, and > 100 dB at 2.5 MHz. Switching times are: < 10 ns (off-to-on), < 100 ns (on-to-off).

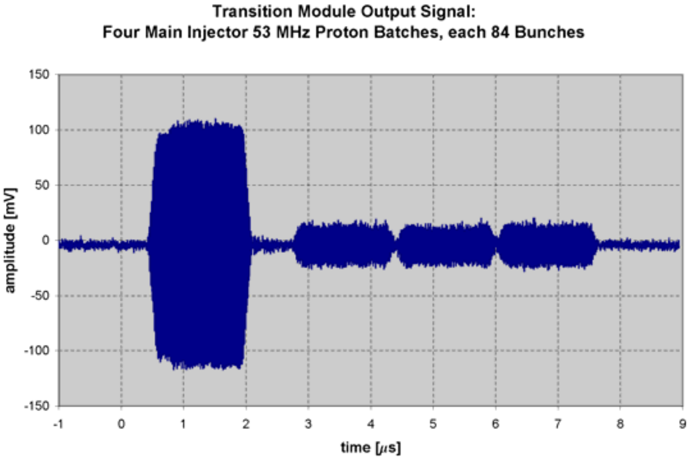

FIGURE 8. Measurement of the Transition Module output signal on a Main Injector beam.

Fig. 8 shows the output signal of the Transition Module applying beam signals from the Main Injector stripline pickup. The measurement was taken during a ramp cycle of four 53 MHz proton batches, each 84 bunches. The first high intense beam batch is followed by three batches of lower intensity. A rise time < 100 ns can be identified, allowing turn-by-turn position measurements of individual batches.

The noise levels measured on the Transition Module is dominated by the AD8332 post-amplifier. It is almost independent of the gain setting and measured to be approximately -40…-46 dBm (~6…12 mV_{pp}) at the output. This corresponds to a turn-by-turn resolution in the range 50…150 µm (RMS): variations are due to the pickup characteristics, signal levels, operation frequency and gain settings.

ACKNOWLEDGMENTS

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REFERENCES

1. B. Banerjee, et. al., these proceedings
2. N. Eddy (private communications)
3. J. Fitzgerald and J. Crisp, *Proc. of the 1997 Particle Acc. Conf.*, Vancouver, B.C., Canada, 1997, pp. 2072-74
4. L. Piccoli, et. al., these proceedings