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DEVELOPING A NEW BEAM POSITION MONITOR ELECTRONICS FOR HIPA, THE PSI HIGH INTENSITY PROTON ACCELERATOR

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Abstract

The High Intensity Proton Accelerator (HIPA) at PSI presently has a radio frequency (RF) beam position monitor (BPM) system based on 20-year-old Xilinx Virtex-2 Pro System-on-Chips (SoC), with application-specific integrated circuits (ASICS) as direct digital downconverters (DDCs). For the planned upgrade of the electronics as well as for new HIPA projects, we started the development of a new HIPA BPM electronics, using a generic electronics platform called "DBPM3" that is already being used for SwissFEL and SLS 2.0 electron BPM systems. In this contribution, first test results of a DBPM3-based HIPA BPM electronics prototype are presented, including a comparison with the present electronics.

INTRODUCTION

The HIPA Accelerator Facility

In the HIPA facility, shown in Fig.1, a proton beam is accelerated in three stages. A Cockcroft-Walton pre-accelerator generates an 870 keV CW beam. Then a 1st cyclotron ("injector 2") accelerates this beam to 72 MeV, followed by a 2nd cyclotron ("ring cyclotron") with 590 MeV final beam energy. Up to 2.4 mA beam current result in a world leading CW beam power of up to 1.4 MW.

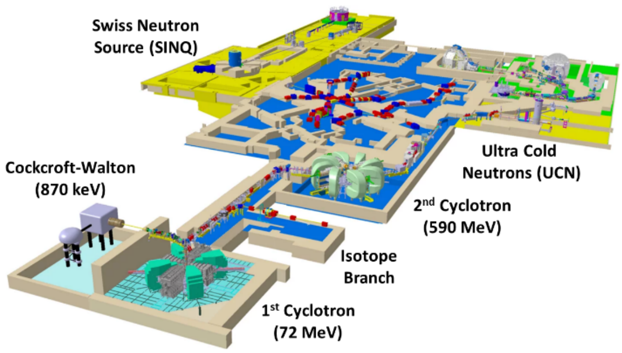

Figure 1: High Intensity Proton Accelerator (HIPA).

The 590 MeV beam passes two rotating targets, where a fraction of the protons is converted to muons and pions that are directed to several experimental beamlines. Most protons pass these targets, finally reaching the so-called SINQ (Swiss Spallation Neutron Source) target, where CW neutron beams for a larger number of beamlines are generated.

The 72 MeV proton beam can also be redirected to a side branch for production of radioactive isotopes, mainly for medical use. Part of the 590 MeV beam can be redirected with a fast kicker to another spallation target for the generation of ultracold neutrons ("UCN") for fundamental particle physics research. The UCN proton beam is usually pulsed with a low duty cycle, where the BPM system records data after an external trigger with multi-kHz data rates (presently 50 kSamples/s) and bandwidth (presently 22 kHz) for sub-millisecond time resolution.

Motivation

The present HIPA BPM electronics was developed at PSI about 20 years ago [1]. In the near future, additional BPMs are required, for new HIPA extension projects like IMPACT [2], as well as for improved monitoring of the HIPA beam especially downstream of the rotating targets. Due to the limited number of spares for our present electronics, we will equip these new BPM pickups with new electronics, based on the so-called DBPM3 platform. This generic BPM platform, developed at PSI, is already used at SwissFEL [3] and the Swiss Light Source [4].

In a 2nd step, we will replace all present HIPA BPM electronics with this DBPM3 based solution. This general upgrade is motivated primarily by maintenance reasons, due to the age and growing maintenance effort for the present system, the limited number of spares, and the growing number of obsolete electronics parts. Furthermore, the radiation-hard RF front-end (RFFE) electronics of the present system is installed in the accelerator bunker not too far from the beam pipe for historical reasons, with short coaxial cables from BPM pickup to RFFE, and long triaxial cables (partly re-used from the previous system) to the technical gallery where ADCs and digital back-end electronics are installed. For the DBPM3 upgrade, this historical topology (from times where HIPA had much lower beam current and radiation levels) will be changed, with new coaxial RF cables from pickups directly to the DBPM3 electronics (including RFFEs) in the technical gallery. This will avoid exposure of maintenance personnel during hardware replacements and repairs of activated RFFEs, in addition to speeding up replacements and reducing accelerator downtime and beam interruptions for accelerator bunker access.

BPM PICKUPS

The 72 MeV and 590 MeV cyclotrons in HIPA both use 50.63 MHz as working frequency for their main RF accelerating cavities, thus bunching the initial CW beam of the Cockcroft-Walton pre-accelerator at this frequency. The HIPA RF BPMs measure the position of this bunched beam with coils (having a single winding) rather than button electrodes as RF pickups in the beam pipe.

Measurement Frequency

As shown in Fig. 2, the HIPA BPM pickup coils have a broadband response, where the present HIPA RF BPM electronics uses the 2nd harmonic at 101.26 MHz for position measurement, instead of 50.63 MHz. This choice avoids systematic measurement errors that may be caused

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by power of the ring cyclotron main RF cavities (with several MW RF power) leaking into the BPM electronics and cables, where the BPM electronics should work at beam signal levels ~180 dB below the power levels of the ring cyclotron high-power RF system.

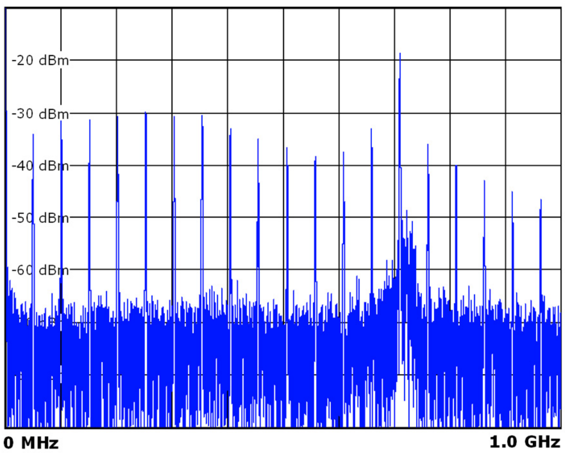

Figure 2: Beam signal level of a HIPA BPM pickup after the 2nd cyclotron (vertical scale) vs. frequency, with 50.63 MHz bunching frequency and harmonics.

Some future new BPMs will be located very close to profile monitors (wire scanners), where the profile monitor housing and mechanics generates higher order modes (HOMs). Simulations show that the mode frequencies are significantly higher than 101.26 MHz, but closer to some higher main RF harmonics. Therefore, we decided to keep the 101.26 MHz working frequency also for the future DBPM3 system, thus minimizing the risk that such HOMs have impact on BPM readings when they couple to the BPM pickup electrodes.

REQUIREMENTS

The HIPA RF BPMs are used by a global orbit feedback, where a larger number of magnets used for orbit correction have iron cores that are not laminated. As a result, the correction bandwidth and correction rate of the feedback is rather low, presently using BPM data decimated to 10 Samples/s with a -3 dB bandwidth of about 4 Hz.

Due to the high CW beam power of up to 1.4 MW, it is important to avoid a mis-steering of the HIPA beam at higher beam currents, since larger beam loss can result in reduced lifetime or damage of accelerator components. For this reason, tuning of machine parameters, including orbit, is usually done at low beam current to minimize losses, before the current is then ramped up to ~2 mA. Thus, the BPM system should be able to measure beam currents from several mA down to ideally ~1 µA, corresponding to ~72 dB dynamic range.

In contrast to machines like SLS 2.0 with micron-level beam sizes and sub-micron stability requirements, HIPA has typical proton beam sizes of several mm, with comparatively large beam pipe apertures typically ~100 mm upstream of the rotating targets, and ~150 mm downstream.

However, for HIPA it is vital to minimize beam loss, where the dynamics of the lost particles in the halo of the beam is rather complex due to their large transverse offsets, and where the amount and spatial distribution of the losses depend on the beam orbit. Moreover, a stable orbit is also important for the reproducible acceleration of the beam in the cyclotrons, for reproducible beam quality, and for a safe and reproducible temperature distribution in the SINQ target, where ~1 MW beam power must be dissipated 24/7 safely and reliably.

Table 1 shows the specifications for the HIPA BPMs. The HIPA BPM coil pickup electrodes A, B, C, D are at the right, top, left, and bottom of the beam pipe, in contrast to the diagonally arranged button pickups of SLS. The geometry factors k for the calculation of the horizontal (X) and vertical (Y) HIPA beam position are also rather large, with typical values ranging from k=37 mm to k=43 mm (where V represents the pickup signal voltage amplitude)

$$X = k * (V_A - V_C) / (V_A+V_C)$$
$$Y = k * (V_B - V_D) / (V_B + V_D).$$

Table 1: HIPA BPM Specifications

Parameter	Specification
Beam Current Range	1-4000 µA
Pos. Noise < 5 Hz	< 0.1 mm (1-10 µA) < 0.03 mm (0.01-2 mA)
Pos. Noise < 20 kHz	< 0.2 mm (0.1-2 mA)
Pos. Dependence on Beam Current	< 0.5 mm (ramp from 5 µA to 2 mA)

The beam signal level at 2 mA beam current is about -28.5 dBm directly at the BPM pickup electrode and -32 dBm at the end of a newly installed coaxial cable to the technical gallery where we tested the DBPM3 prototype electronics, in addition to lab tests with an RF generator as beam signal source.

HIPA DBPM3 PROTOTYPE

For the DBPM3 based HIPA BPM electronics, we use the same digital back-end as for SLS 2.0 and SwissFEL, where three HIPA-specific RFFE modules with four RF channels each are plugged into the back-end from the rear side. Figure 3 shows a DBPM3 unit from the front side, Fig. 4 the RFFE schematics.

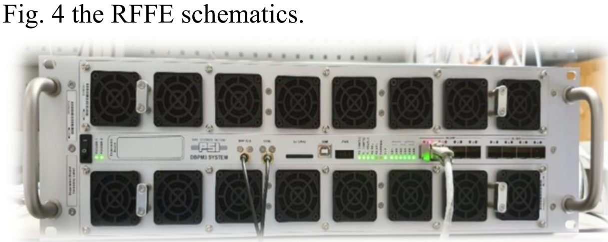

Figure 3: DBPM3 electronics.

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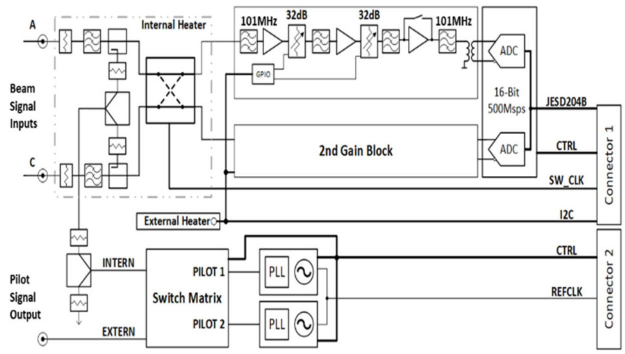

Figure 4: HIPA DBBPM3 RFFE: Simplified Block Schematics, only two of four beam signal channels shown.

Each RFFE contains the analog/RF part of the beam signal processing chain, as well as ADCs with multi-gigabit (JESD204B) serial interface to the back-end. On the digital DBPM3 back-end, a Xilinx/AMD Zynq UltraScale+ MultiProcessing System-on-Chip (MPSoC) receives the ADC signals. A DDC implemented by PSI in the programmable logic (“PL”) of the Zynq MPSoC filters and decimates the ADC data, providing signal amplitudes and beam positions at three different data rates. Bandwidth and data rate can be programmed and changed during operation. For the first tests, we used 1 MSamples/s (500 kHz bandwidth), 20 kSamples/s (3 kHz bandwidth), and 20 Samples/s (3.7 Hz bandwidth).

The Zynq MPSoC also has two multi-core ARM CPUs on the same chip, where a 2-core 32-bit CPU (“RPU”) is used for real-time data processing and control, while a 4-core 64-bit CPU is running Linux and the EPICS control system.

To speed up the prototyping and to preserve the latest RFFE version for SLS 2.0, we modified an older pre-series SLS 2.0 RFFE for HIPA that only had a single pilot tone PLL and no external pilot output. On this RFFE, we replaced frequency-specific components for the SLS 499.654 MHz beam signal frequency with parts suitable for the 101.26 MHz HIPA beam frequency, including:

- Input lowpass filter
- Two bandpass filters
- Transformer before ADC

Figure 4 shows a simplified schematics of the proposed final version of the HIPA RFFE that is identical to the SLS 2.0 one except the lower frequency.

For the bandpass filters, all commercially available solutions were slightly too large to fit on the unmodified SLS 2.0 RFFE PCB, therefore we designed a bandpass filter with suitable size ourselves. Figure 5 shows a measurement of the bandwidth, where suitable components with low production tolerances were used to obtain a sufficiently reproducible center frequency. Figure 6 shows the schematics of the filter.

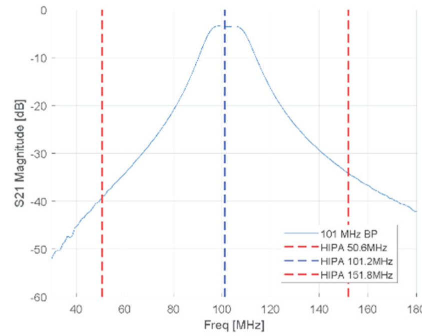

Figure 5: HIPA DPBM3 RFFE 101.26 MHz bandpass transmission measurement.

The final HIPA BPM RFFE version will have an external SMA pilot output and two pilot tone PLLs like the latest SLS 2.0 version, see Fig. 4. For the planned upgrade of all HIPA BPM electronics, we intend to have a passive RF combiner close to the beam pipe, where the pilot signal coming from the RFFE in the technical gallery is split, combined with the beam signals, and then going back to the RFFE in the technical gallery. The DBPM3 electronics then uses the pilot tone to monitor the integrity of the beam signal RF cables and connectors and suppress cable-induced position drift.

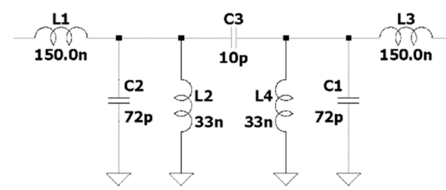

Figure 6: HIPA DBPM3 prototype RFFE 101.26 MHz bandpass schematics.

DBPM1 LAB MEASUREMENT RESULTS AND COMPARISON WITH PRESENT ELECTRONICS

Figure 7 shows a measurement of the RMS position resolution of the new HIPA DBPM3 electronics prototype and of the present 20-year-old “pDBPM1” electronics, for the 10 Samples/s (3.7 Hz bandwidth) data stream used by the orbit feedback.

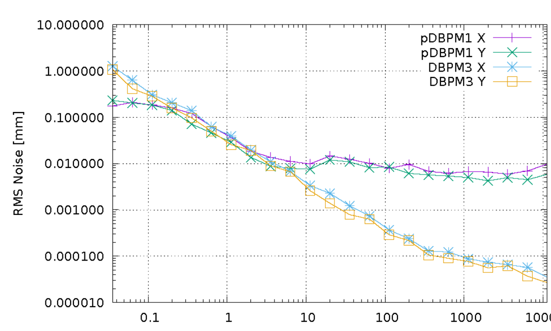

Figure 7: Beam position noise vs. beam current of present “pDBPM1” HIPA BPM electronics, and DPBM3 prototype. Date rate was 20 Samples/s, -3 dB bandwidth ~4 Hz.

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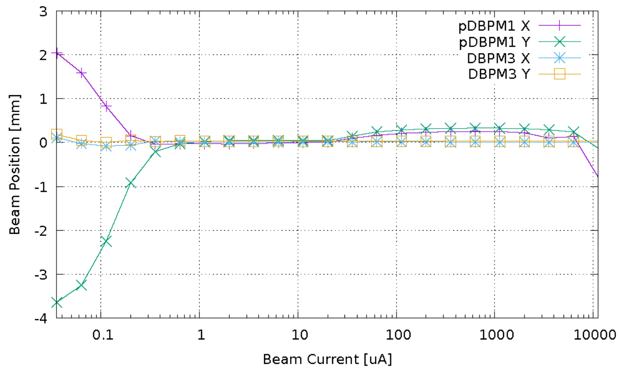

Figure 8: Beam position vs. current of present “pDBPM1” HIPA BPM electronics, and DPBM3 prototype.

Figure 8 shows the dependence of the BPM readings on the beam current, where the position offset around 10 µA beam current was subtracted from each curve to better visualize the changes of the curve at lower and higher beam current.

The present HIPA BPM electronics [1] uses two ASICs of type ISL5126 from Intersil as DDCs. Each ISL5126 has four DDC channels, thus the BPM electronics processes four beam signals and four pilot tone signals simultaneously, normalizing beam to pilot tone signal amplitudes for compensation of gain imbalances and drift. The DDC output data rate is 50 kSamples/s, the -3 dB bandwidth is set to ~22 kHz. The decimation to lower data rates of 1 kSamples/s, 10 Samples/s and 1 Sample/s is then done in software in a PowerPC CPU on a Virtex-2 Pro FPGA. This decimation is applied to the BPM electrode signals, and then the beam positions are calculated from the resulting decimated signal amplitudes. Since the ADCs of the present system are free-running not synchronized to the main RF frequency, this scheme provides robust readings in the presence of kHz-range production tolerances of the ADC sample rate and pilot tone frequencies.

At beam currents <0.3 µA however, the beam signal is getting so small that the decimated electrode signal amplitudes converge to beam-independent constant values, representing the remaining thermal noise level. As a result, the present system does not provide usable beam position readings below ~0.1 µA, where the “constant” RMS noise in Fig. 7 is thus not the noise of usable beam position readings, but of the remaining constant noise. This is indicated to the operator and orbit feedback by a “position valid” flag that is only raised when the beam signal levels are large enough for reliable position readings.In contrast, the new DBPM3 system is locked to the accelerator main RF frequency, where the multi-stage DDC can thus decimate the beam signal amplitudes to sub-Hz bandwidths around the 101.26 MHz beam signal frequency, thus enabling position measurements well below 0.1 µA.

Wideband Position Noise

In addition to the position measurements at ~4 Hz bandwidth shown above, we also measured the position noise of the DBPM3 prototype for higher bandwidths. The requirement of 0.2 mm RMS resolution from 0.1 mA to 2 mA specified in Table 2 is not only reached up to 20 kHz bandwidth, but even up to 500 kHz bandwidth.

Table 2: DBPM3 Wideband Position Noise at 0.1 mA and 2 mA Proton Beam Current

Frequency Range	RMS Position Resolution
0.005 - 0.5 MHz (@1 MSamples/s)	<0.15 mm (0.1 mA) <0.03 mm (2 mA)
0.003 - 3 kHz (@ 20 kSamples/s)	<0.012 mm (0.1 mA) < 0.003 mm (2 mA)

CONCLUSION AND OUTLOOK

We successfully tested a first prototype of a new BPM electronics for HIPA, based on the PSI DBPM3 platform. By adapting a number of passive components of an SLS 2.0 BPM RFFE to the lower HIPA beam frequency, the prototype hardware already meets HIPA requirements. The new electronics reaches similar performance like the present one for lower beam currents in the few µA range, where thermal noise is limiting improvements. At higher beam currents up to ~2 mA, the resolution of the new system is up to two orders of magnitudes better, thanks to better ADCs and multi-stage DDCs. Their synchronization with the accelerator main RF frequency enables a reduction of the slowest stage of the multi-stage DDC to 10 Samples/s and 3.7 Hz DDC filter bandwidth used for test in this paper, resulting in usable beam position readings even at lowest beam currents <0.1 µA, where the present system does not provide usable readings anymore.

While we re-used the same PCB layout as the SLS 2.0 RFFE for our first HIPA DBPM3 RFFE prototype, we intend to redesign the RFFE PCB for the next version, such that we have more PCB space for the bandpass filters and thus could accommodate larger commercially available bandpass filters. The new DBPM3-based HIPA BPM electronics will be used at first for newly added BPMs of the IMPACT project and for improved target beam monitoring in 2026-2027. In a 2nd step, we will upgrade all existing HIPA BPMs to DBPM3 electronics, also replacing all long-range triaxial RF cables with new coaxial cables.

REFERENCES

[1] B. Keil, P.-A. Duperrex, U. Mueller, “Commissioning of a New Digital BPM System for the PSI Proton Accelerators”, in *Proc. EPAC’06*, Edinburgh, Scotland, Jun. 2006, p. 1128. doi:10.18429/JACoW-EPAC2006-TUPCH092

[2] D. Kiselev, “High-Power Targetry and the IMPACT Initiative at the Paul Scherrer Institute”, in *Proc. HB’23*, Geneva, Switzerland, Oct. 2023, p. 30. doi:10.18429/JACoW-HB2023-MOA3I3

[3] B. Keil *et al.*, “First Application of a Multiprocessing System-on-Chip BPM Electronics Platform at SwissFEL”, in *Proc. IBIC’22*, Krakow, Poland, September 2022, pp. 245-248. doi:10.18429/JACoW-IBIC2022-TUP12

[4] B. Keil *et al.*, “Development of the SLS 2.0 BPM System”, in *Proc. IBIC’23*, Sascatoon, Canada, Sep. 2023, pp. 15-18. doi:10.18429/JACoW-IBIC2023-MO3C03