# Joint ARIES Workshop on Electron and Hadron Synchrotrons
# “Next Generation Beam Position Acquisition and Feedback Systems”

12 – 14 November 2018

Hotel Exe Campus, Cerdanyola del Vallès

Barcelona - SPAIN

## Contributions Summary

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|  | Monday Nov. 12th | Tuesday Nov. 13th | Wednesday Nov. 14th |
|---|---|---|---|
|  | Session 1 - HADRON BPM ANALOG ELECTRONICS | Session 3 - ORBIT FEEDBACK SYSTEMS FOR HADRON AND ELECTRON SYNCHROTRONS - PART 1 | Session 5 - INSTABILITIES FEEDBACK SYSTEMS FOR ELECTRON SYNCHROTONS |
| 8:30 | Registration |  |  |
| 8:55 | Workshop Welcome, A. Olmos (ALBA) |  |  |
| 9:00 | **Analogue electronics for BPMs at GSI - Performance and limitations**, W. Krämer (GSI) | **Overview from light source – demands, achievements, and future challenges**, M. Böge (PSI) | **Coupled-bunch instabilities and the Anna Karenina principle**, D. Teytelman (Dimtel) |
| 9:30 | **Diode Orbit electronics & performance**, M. Gasior (CERN) | **LIBERA BPM and Closed Orbit feedback systems**, A. Bardorfer (Instrumentation Technologies) | **Longitudinal feedback systems at the lepton collider DAFNE**, A. Drago (INFN) |
| 10:00 | **The SNS Ring BPM system - old and new**, R. Dickson (SNS) | **Fast Orbit Feedback - soft or hard real-time?**, E. Tan (Australian Synchroton) | **Fast kickers for multi-bunch feedbacks**, M. Dehler (PSI) |
| 10:30 | Coffee break | Group Photo & Coffee break | Coffee break |
| 11:00 | **Time multiplexing of BPM signals to avoid channel to channel variations**, M. Wendt (CERN) | **New BPM system and Fast Orbit Feedback for SLS 2.0**, B. Keil (PSI) | **Experience on the integration of Diamond MBF-2 @ ESRF**, B. Roche (ESRF) |
| 11:30 | **BPM systems at BNL**, R. Michnoff (BNL) | **The fast orbit correction scheme of the ESRF EBS storage ring**, E. Plouviez (ESRF) | **Feedbacks against collective instabilities at MAX-IV**, F. Cullinan (MAX-IV) |
| 12:00 | **Performance of the new Logarithmic Amplifier based Electronics for the CERN SPS**, T. Bogey (CERN) | **The new ASTRID2 Fast Orbit Feedback system**, J.S. Nielsen (ISA) | **New SPring-8 Bunch-by-Bunch Feedback Processor for hybrid filling**, T. Nakamura (Spring-8) |
| 12:30 | **The design & progress of bunch by bunch measurement system for HIAF**, M. Li (IMP) | **The Petra 3 fast orbit feedback system**, H. Duhme (DESY) | **Single bunch instabilities with transverse feedback at Diamond Light Source**, E. Koukovini-Platia (CERN) |
| 13:00 | LUNCH | LUNCH | LUNCH |
|  | Session 2 - HADRON BPM DIGITAL ELECTRONICS & DAQ | Session 4 - ORBIT FEEDBACK SYSTEMS FOR HADRON AND ELECTRON SYNCHROTRONS - PART 2 | Session 6 - ORBIT FEEDBACK TOOLS FOR ELECTRON SYNCHROTONS |
| 14:30 | **Data transmission & digitisation - what is state of the art today?**, M. Barros Marin (CERN) | **LHC orbit feedback – architecture & operational experience**, J. Wenninger (CERN) | **Suppression of the injection perturbations using feed-forward techniques**, E. Plouviez (ESRF) |
| 15:00 | **Digital electronics & DAQ for FAIR, algorithms for position calculations and achievable resolution**, A. Reiter (GSI) | **Robustness considerations for a fast orbit feedback at hadron synchrotrons**, S. Mirza (GSI) | **New corrector power supplies for SLS / SLS-2.0**, H. Jäckle (PSI) |
| 15:30 | **A next generation digital BPM system for the LHC**, A. Boccardi (CERN) | **BPM Data Acquisition and Orbit Feedback at BNL**, A. Marusic (BNL) | **Closing remarks**, A. Olmos (ALBA) |
| 16:00 | Coffee break | Coffee break | Coffee break |
| 16:30 | **Digital BPM development for HEPS project**, S. Wei (IHEP) | **The NSLS-II BPM system,** D. Padrazo (BNL) |  |
| 17:00 | **Bunch-by-Bunch position measurement for the CERN-PS: coping with RF-gymnastics**, J. Belleman (CERN) | **BPM and Orbit Feedback System for ALS Upgrade**, G. Portmann (ALS) |  |
| 17:30 | **BPM electronics and orbit feedback system at Sirius**, D. Tavares (LNLS) |  |  |
| 18:00 |  |  |  |

**20:00 - Bus from Hotel to restaurant**

**20:30 - Workshop Dinner**

# Session 1 - HADRON BPM ANALOG ELECTRONICS (R. Jones)

## Analogue electronics for BPMs at GSI - Performance and limitations (W. Krämer – GSI)

Three amplifier designs were presented:

- **Low noise Cryamp** whose main features include a bandwidth from 10 kHz to 40 MHz, a near constant gain (40 dB or 60 dB +/- 0.05 dB) over the entire range, an input/output impedance of 1 MΩ / 50 Ω and an equivalent input noise of only 2.3 nV / $\sqrt{Hz}$. A BPM linked to such an amplifier was shown to be much better than an ICT for measuring the intensity of low current (10nA) beams.
- **High dynamic range (110 dB) 50 Ω amplifier/attenuator** whose main features include a selectable gain in the range -50 dB to 60 dB (10 dB steps), a bandwidth from 40 kHz to 55 MHz and an equivalent input noise of 1.6 nV / $\sqrt{Hz}$.
- **Phase matched amplifier** for time of flight measurements. This has a bandwidth from 325 MHz to 3.25 GHz, a gain from 0 dB to 40 dB (in 10dB steps) and phase matching delay lines to achieve 0.1° phase accuracy at 325 MHz.

## Diode Orbit Electronics (M. Gasior – CERN)

A new concept for **high-resolution position measurement** based on compensated diode detectors was presented. In this system the forward voltage across the diodes, which would otherwise introduce a significant position error, is compensated using two operational amplifiers. Such a system has been constructed for use in the embedded collimator BPMs of the LHC and for the directional BPMs near the LHC interaction points. While the system works very well for the centred beams in the collimators, **reaching sub-micron resolution**, it is a challenge to make it work as a normal beam position system. For non-centred beams, the limited linear dynamic range of the detector leads to a dependence of the measured position on the signal amplitude. This can be mitigated by the use of variable gain amplifiers, but complicates the system and still results in errors some two orders of magnitude larger than the system resolution. The design also **includes cross-bar switching** to eliminate systematic gain and offset errors in the parallel processing chains used for opposite electrodes.

## SNS Ring BPM System – Old and New (R. Dickson – ORNL)

The main motivation to move to a new system was obsolescence of hardware and software, the limitation of 1Hz acquisition (60Hz required) and an increased dynamic range from the original $5\times10^{10}$ - $2\times10^{14}$ to $6\times10^{9}$ - $6\times10^{14}$ protons per pulse. A custom analogue front-end is built, but the DAQ solution was chosen to be an industrial platform due to the limited availability of experienced digital engineers - **NI PXI system (NI PXIe-8880 CPU, NI PXIe-7971 FPGA, NI 5751B ADC)**. Two jitter reduction algorithms were presented – one using linear interpolation to combat phase slip of the RF frequency with respect to a free running ADC, and one to cope with jitter on the acquisition trigger. The final application software now displays turn-by-turn position, orbit, bunch centroid and peak phase, and position evolution within a given turn.

## BPM Signal Processing using Time-Multiplexed Electrode Signals (M. Wendt – CERN)

The presentation was focussed on techniques for **minimising time varying asymmetries** between electrode acquisition channels that result in uncontrollable position offsets – one of the major limitation of any BPM system's performance. The main emphasis was on single channel receivers using time-multiplexing of the input signals. Such systems eliminate asymmetries by design, but **only work for beams where the time between bunches is long compared to the bunch signal**. The case of the LHC was cited as an example with 1ns bunches spaced by 25ns. However, it was pointed out that this could also work for picosecond electron bunches spaced by a few nanoseconds. The components needed for such a scheme are a **high isolation power combiner** and a **delay line filter** (comb bandpass filter). Examples of both, adapted to a 500MHz operating frequency, were presented.

### BPM Systems at Brookhaven National Laboratory (R. Michnoff – BNL)

The presentation gave an insight into the many BPM systems developed for the various accelerators at BNL. Most of these are now based on an in-house designed **V301 VME DAQ module**. Its main features include a **Xilinx Zynq gate array running Linux** in its Arm processor (bootable from an on-board microSD card), 400 MSPS 14-bit ADCs, 1GB DDR3 memory, and 2 ethernet connections, one for controls communication and the other for custom use (e.g. high speed position distribution). This can be adapted to a variety of acquisition techniques – oversampling, undersampling and single sample on bunch peak. In addition it includes an **RF section with selectable gain and filtering stages**, which can be **adapted to work with ion, proton and electron beams**.

### Performance of the Log Amp based Electronics developed for the SPS at CERN (T. Bogey – CERN)

The choice of technology was driven by the desire to **cover a large dynamic range without gain switching**, minimising the complexity of the gain setting per beam type and the associated calibration factors. It was shown that a single log amp (Analog Devices **ADL5519 dual-channel** logarithmic amplifier) could only provide a **linear response over a dynamic range of 40 dB**, which was not sufficient. Three parallel channels, spaced by 20dB, have therefore been implemented to cover a total dynamic range of 70dB. Despite residing in the same IC package, the two log-amps within the ADL5519 were shown to have gains that could be mismatched by a few %, leading to intensity dependent position drifts. This problem is overcome by acquiring the channels individually rather than using the in-chip difference output. In this way each channel can be calibrated and corrected. As all three gain stages are acquired in parallel the optimised choice of gain can be made in the processing FPGA or software layer. Use of a **hairpin band-pass filter** to stretch the response for single bunches was also presented.

### The design & progress of the bunch-by-bunch measurement system for HIAF (M. Li – IMP)

The presentation gave an overview of the HIAF facility, with its ion Linac, booster ring, fragment separator and spectrometer ring. The booster ring contains 39 elliptical, ceramic, diagonally cut BPMs, based on a GSI design, that will be linked to a system that needs to provide **10 kHz data for orbit feedback**. To implement the fast orbit feedback three data communication protocols have been studied: **reflective memory, remote direct memory access and commercial (NI) protocols**. Two possible architectures for the HIAF closed orbit feedback system were then presented. The first based on Libera Hadron, similar to what is being implemented for GSI, and the second on a commercial DAQ system (NI or MicroTCA). It was commented that the **physics-driven MicroTCA.4 standard could be of interest** because of its flexibility, modularity, redundancy in key components, and advanced crate management system, with Rapid I/O the preferred choice for backplane communication.

# Session 2 - HADRON BPM DIGITAL ELECTRONICS & DAQ (P. Fork)

### Data transmission & digitalization – What is state-of-the-art today? (M. Barros Marin – CERN)

For the long term perspective of LHC a new BPM system must be implemented. In this contribution the main focus is related to ADC chip and digital data transmission. For the existing installation those components were developed at CERN in connection with groups form the high energy physics detector. This included a radiation hard layout for some components installed in the tunnel. The properties of the used AD41240 are given and the application of the LHC BPM amplitude-to-time conversion chain is depicted. For LHC run 3 (starting in 2021 after the long shutdown LS2) the usage of COTS ADCs is foreseen for any new installations. The optical data link realization is discussed.

### Digital Electronics & DAQ for FAIR - Algorithms for position calculation and achievable resolution (A. Reiter – GSI)

The digital signal processing of the BPMs at GSI's SIS18 and for FAIR was presented. The bunch length at those synchrotrons and storage rings ranges from 50 ns to some 1 µs and, after broadband amplification the digitalization rate is 125 or 250 MSa/s. Different methods for the digital treatment of such oversampled bunches were discussed and compared concerning their accuracy and numerical stability: The 'classical' method comprises the integration of the bunch-signal, which requires firstly the generation of an window to distinguish between the bunch signal and the pause to enable an adequate baseline reconstruction as the second step followed by a difference-of-sum position calculation. The usage of the signal power, i.e. the square of the electrode followed by the position proportional difference calculation, is usage as a second method. As a novel alternative, a least-square fit of opposite plate signals was realized; the slope of the curve is related to the beam position. The achievable properties concerning resolution, noise and offset immunity of the three methods are compared in detail. The advantages of the latter methods was demonstrated. One advantage is that a bunch recognition isn't required and closed orbit determination can be done with a long, user-defined time window. As an 'exotic' application a position reading even for dc-beams could be achieved by using the 'Schottky-like' signals.

### A next generation digital BPM system for the LHC (A. Boccardi – CERN)

At present the BPM position evaluation proceeds via time-multiplexed signal chain as designed more than 20 years ago, see the talk by M. Wendt during this workshop: The four electrode signals are individually delayed and transmitted via one cable with the advantage of systematic drift compensation. The general properties of several position evaluation algorithms (Delta-over-sum, linear displacement dependence and rms power evaluation) are compared. The requirements of the ADC resolution for those algorithms are given e.g. for nominal LHC currents with $10^{10}$ protons/bunch an 9.6 effective bit ADC delivers about 0.1 mm resolution for the broadband signal. These results are weight in terms of accuracy for an interlock generation. The foreseen hardware design (ADC and FPGA) is shown.

### Brief Introduction to the Digital BPM development for HEPS project (S. J. Wei – Chinese IHEP)

For the High Energy Photon Source HEPS in total 693 BPM locations are planned with 576 stations in the 1300 m long storage ring. The design criteria for the BPM digital electronics and the decision using home-made boards were discussed. The hardware realization of the analogue and digital front-end were shown and test results are shown. Beam-based tests will be done at existing BEPCII facility, first results are promising. As a form-factor µTCA4.0 is realized. The suitable algorithms where simulated in Matlab extensively and their firmware is now implemented. Some optimizations for the hardware remains, e.g. methods related to the temperature influence and the calibration method have to be implemented.

## Bunch-by-Bunch position measurement for the CERN-PS: coping with RF-gymnastics (J. Bellemann – CERN)

The technical layout of the CERN PS system comprises of 43 BPMs for trajectory determination was discussed in detail. The analogue signal chain comprises of hybrids to generate difference and sum followed by variable gain amplifiers. Signals are digitized by 125 MSa/s ADCs on a commercially produced cPCI crate-based board. The creation of windows for the bunch-synchronous signal integration is locked to the revolution frequency by a Numerical Controlled Oscillator PLL and a look-up table for a possible variation of the relative phase realized on an FPGA basis. The bunch repetition frequency as a higher harmonics of the revolution is generated by this cycle- and time-dependent look-up table. The technical system realization was discussed in detail and the properties were demonstrated with relevant examples. As several steps of bunch merging and splitting are performed during the PS cycle, the system flexibility was discussed and it was shown that a pause-free trajectory display can be achieved. The large flexibility of the chosen digital processing was demonstrated for the system which works in a stable manner since several years in particular for the display during the bunch gymnastics within the PS cycle.

## BPM Electronics and Orbit Feedback Systems at SIRIUS (D. Tavares – LNLS Sirius)

The requirement of the BPM system for the Brazilian Synchrotron Light Source was presented for turn-by-turn and closed orbit determination in terms of resolution and stability. The main part of the contribution was attributed to the hardware realization.  In contrary to many other light sources, the electronics is partly home-made and based on the design published at an open hardware repositories and the related codes are available at: http://github.com/lnls-dig and https://www.ohwr.org/projects/afc.  The layout and the achieved properties of the analogue front-end are discussed. Generally, the design of the digital components is based on µTCA4.0 carrier boards and FMC extensions using open hardware and commercial products. The digital processing is based on a standard digital radio receiver method. A modified difference-of-sum algorithm is used to provide higher resolution for the typical booster BPM electrode orientation. The achievements concerning resolution and stability obtained at a test bench were presented and the solution of commissioning problems was discussed. The design considerations of the fast Closed Orbit Feedback were given; the commissioning of the entire system is expected for spring 2019. Generally, the experiences using open hardware design and its production were quite positive.

# Session 3 - ORBIT FEEDBACK SYSTEMS FOR HADRON AND ELECTRON SYNCHROTRONS - PART 1 (N. Hubert, G. Kube)

**Overview from light source – demands, achievements, and future challenges (M. Böge - PSI)**
**LIBERA BPM and Closed Orbit feedback systems (A. Bardorfer - Instrumentation Technologies)**
**Fast Orbit Feedback - soft or hard real-time? (E. Tan - Australian Synchrotron)**

The demands and requirements for the Beam Position Monitor (BPMs) and Orbits FeedBack (OFB) systems for future low emittance light sources are already almost fulfilled on current machines, in term of resolution and stability. Nevertheless they are still ways for improvements:

- BPM better resolution in turn by turn for better optics measurement.
- BPM higher bandwidth and sampling rate could provide bunch by bunch position measurements.
- Increase (in frequency) the fast orbit feedback 0 dB point. This is not so much the perturbations at higher frequencies that need to be suppressed, as the perturbations at low frequency that could be damped higher with this increase.
- Integrate in the FOFB more actuators (skew quads, quads…) and sensors (beam size monitors, photon BPMs…) for coupling, lifetime and optic control at higher rate.

Currently the main limitation to increase the FOFB bandwidth (0 dB point) is generally the latency in the feedback loop. This latency comes from 2 main contributions: BPM filtering (group delay) and magnet bandwidth (except for air coil correctors) whereas the FOFB computation contribution is rather small (few µs) thanks to the massive parallelism provided by FPGAs or GPUs.

AS-ANSTO demonstrates the viability of a FOFB processing, based on real-time Linux on COTS PCs. The main drawback is the additional processing delay that reduces the bandwidth. Nevertheless, it is a way to develop rapidly a solution when you miss specialized FPGA developers.

**New BPM system and Fast Orbit Feedback for SLS 2.0 (B. Keil - PSI)**

Boris Keil (PSI) reported about the SLS-2 upgrade and the renewal of the RF BPM and fast orbit feedback system. Specifications for this new system are a position noise of < 50 nm (rms @ BW 1 kHz) resp. < 1 µm (rms @ BW 0.5 MHz) and a position drift (electronics only) of < 100 nm/hour, all values taken at nominal beam current. In order to make the BPM electronics simpler, cheaper and more performant, it is planned to use latest technologies (Xilinx Zynq UltraScale+ MPSoC and JESD204B ADCs with multi-gigabit link), using a newly developed BPM specific housing with hot pluggable BPM RF front-end/ADC modules. In 2017 the development of the new “DBPM3” BPM platform started which shall have much lower hardware complexity and points of failure compared to the former DBPM systems. SLS-2 will require 31 DPPM3 units (incl. spares) for the RF BPM system with 3 BPMs per unit, and 27 units for the FOFB with 16 SFPs per unit. For the new FOFB system a tree topology will be used with centralized feedback algorithm.

**The fast orbit correction scheme of the ESRF EBS storage ring (E. Plouviez - ESRF)**

Eric Plouviez (ESRF) reported about the new fast orbit correction scheme of the ESRF EBS storage ring. Each new EBS Hybrid MBA cell (in total 32 cells) includes 10 BPMs (6 equipped with Libera Brillance and fast ouputs, 4 with Libera Sparks without fast ouputs) and 9 correctors (3 fast correctors @ 500Hz BW and 6 slow correctors embedded in the sextupoles). He demonstrated that small and fast orbit distortions without DC component can be corrected with the subgroup of 32x6 = 192 BPMs and 32x3 = 96 correctors without spoiling the correction quality such that in principle a reuse of the former orbit correction system is possible. The remaining 128 BPMs equipped with Libera Sparks and the 192 slow correctors will be used for slow orbit control such that the entire orbit control system will consist of a hybrid slow/fast configuration. Tests performed at the present ESRF storage ring with only 5 BPMs and 2 correctors per cell for fast corrections (and 7 BPMs/ 3 correctors per cell for slow corrections) indicate a perturbation on the horizontal beam position which could be identified as leaking of the septum pulse and compensated by a feed forward correction.

**The new ASTRID2 Fast Orbit Feedback system (J.S. Nielsen - ISA)**

Jørgen S. Nielsen (ISA, Aarhus University) presented the new ASTRID2 fast orbit feedback system. The ring has 24 BPMs equipped with Libera Electron, 12 HV window frame correctors, and additional 12 H correctors. Up to now only a Labview-based slow orbit feedback was implemented based on the 12 HV correctors, and a lot of orbit disturbances could be observed in the beam spectrum (caused by several reasons). A new cheap and simple fast orbit feedback system was installed based on a standard PC running with the Labview real-time environment and performing the orbit calculations. Input data are the 10 kHz FA data of the Liberas, and for the output the digital values from a FPGA enabled DAQ card are fed to 4 DAC chips via SPI-like lines. Two software loops are in operation, one for high priority (10 kHz) and one for low priority (1-10 Hz), data are transferred between the loops via real time FIFOs. Based on this setup a clear improvement was observed in the beam spectrum below 100 Hz.

**The Petra 3 fast orbit feedback system (H. Duhme - DESY)**

Hans-Thomas Duhme (DESY) gave an overview over the PETRA-III fast orbit feedback system which is successfully in operation since the machine commissioning in 2009. Main tasks are to stabilize the orbit to ±0.5 µm in the vertical plane over 24 h, the damping of orbit distortions from DC up to 200 Hz, the compensation of 50 Hz disturbances and higher harmonics, a feed forward during injection, and the interaction with the slow orbit control and beamline via the control system. The system architecture is based on star topology, it processes turn-by-turn data from 246 BPMs to the power supplies while using a custom-made TbT data output from Libera Brilliances. The correctors consist of air coils mounted over stainless steel chambers and powered by fully digital current source power supplies. The system has no frequency gap, the reference orbit of the feedback is determined by slow orbit corrections, and the DC current of the fast correctors is removed by transferring it to the slow corrector magnets. The 3dB cut-off frequency is 390 Hz, however the system is bandwidth limited by filters to 150-200 Hz for better noise performance. Higher frequencies are processed with 50 Hz compensation and adaptive injection feed forward.

# Session 4 - ORBIT FEEDBACK SYSTEMS FOR HADRON AND ELECTRON SYNCHROTRONS - PART 2 (G. Rehm, V. Schlott)

### LHC orbit feedback – architecture & operational experience (J. Wenninger - CERN)

Jorg presented a talk providing the link bridge for Orbit FB on Hadron synchrotrons and light sources. He emphasised the need for orbit control in hadron machines to be more connected to collimation systems and interaction points.

Due to the superconducting nature of many magnets, LHC is inherently a slow machine, so orbit feedback aims a close loop BW of 0.1-1 Hz. A commercial PC server acts as the controller for all 2000 monitors and 1100 actuators, at an update rate of 25Hz.

Monitors are affected by some systematic errors which can be removed by calibration, and mainly temperature drift of 20-50um.

Optics are corrected by AC excitation and BPM turn-by-turn data. Response matrices for orbit feedback are precalculated from a model, and inverted using SVD with clipping of higher singular values. Stability is adequate for achieving good collisions, however, even small earthquakes or large building activity push the OFB to its limits. For the future, a faster OFB (~30Hz BW) is under consideration.

### Robustness considerations for a fast orbit feedback at hadron synchrotrons (S. Mirza - GSI)

Sajjad presented on considerations and first experiments for Closed Orbit FB at FAIR, where OFB is required due to the multitude of fast cycles for acceleration if different ion species. Disturbance come not only from hysteresis errors in magnets, but also through EMI due to very thin walled chambers. For the Orbit FB during the ramp, deliberate misfit of the actual ORM and the factual ORM of the machine have been considered. Sajjad went on to compare approaches of harmonic correction using Fourier decomposition with singular value decomposition, and highlighted the weakness in human interpretation in the SVD approach. He found that due to the frequent symmetry in ORMs, they can be expressed as circulant matrices, with comes with beneficial effects for decomposition. Even when the lattice is not fully symmetric, it can be shown that a close circulant matrix can still be used as a proxy, and might have certain advantages. Finally, light was cast at model mismatch due to betatron tune shift, and a methodology to assess this was drawn out. This was concluded with a comparison of prediction and experiment at COSY.

### BPM Data Acquisition and Orbit Feedback at BNL (A. Marusic - BNL)

Al provided an entertaining talk with lots of anecdotes from RHIC, where OFB was only introduced during the 11th year of operation. Orbit in RHIC is measured at 167 locations, but 117 are considered enough to the orbit. Other BPMs are for special purposes and for redundancy. Consequently, there are 117 corrector magnets. Using OFB, the beam can be steered to desired orbits, and these are easily programmable, including ramps. Updates of the orbit progress slowly, with individual changes taking up to 1 second to complete.

Actual offsets of BPMs to quads were measured at installation and found to be RMS ~0.5mm. Later these are re-measured using Beam Based Alignment.

### The NSLS-II BPM system (D. Padrazo - BNL)

Although the performance of the present NSLS-II BPM system fulfills the original (and present) specifications / requirements:

- 1 µm (rms) turn-by-turn resolution
- 200 nm (rms) resolution @ the fast orbit feedback sampling rate of 10 kHz
- 200 nm / 8 hrs (@ 10 kHz) long term stability

hardware obsolescence of 9+ years old technology as well as a number of reliability issues and short-comings such as poor network performance and inconvenience with non-standardized operating system and software development environment motivates a presently ongoing BPM electronics upgrade program at NSLS-II.

The NSLS-II BPM electronics upgrade comprises a new digital front end unit called zDFE and a new RF front end called AFE. The major improvements and new / advanced features of the zDFE are:

- Hard dual-core ARM A9 processor with > 500 Mbit/s throughput (25 x performance increase as compared to the present NSLS-II BPM system)
- Runs standard Debian-7 based Linux operating system and provides embedded IOC
- DMA Kernal driver for large waveform access (up to 300 Mbyte)
- Standardized DFE and SW development platform (similar to standard Linux server) allows the inclusion of multiple sub-systems such as RFBPMs, bunch-by-bunch BPMs, X-ray BPMs, controller for fast orbit feedback etc.
- Advanced / improved FPGA resources for digital signal processing may even support bunch-by-bunch position calculation
- Integrated 10 Gbps transceivers allows interfacing of fast (500 MSPS) ADCs

Prototype tests of the new zDFE BPM module with beam have shown that the NSLS-II performance requirements (see above) can be fulfilled.

A number of upgrade considerations for the BPM analog frontend (zAFE) are mainly focusing on noise reduction and improvement of the long-term stability. Features like active temperature control to 1°C, 2-way diagonal switching of RF signals from the pick-ups (A/C, B/D) using a mobile cell RF switch (external switch box for prototype beam tests in collaboration with the Brazilian LS) were applied, while the successful implementation of a (out-of-band) pilot tone was prevented by the temperature dependent pass-band response of the existing SAW filters on the present RFBPM AFE. Beam tests (over 24 hours) show that the new AFE features improves the position resolution from presently 130 nm (rms) to < 20 nm (rms) with the main noise reduction (PSD plot) below 1 kHz (further averaged display on the control room panel show even 2 nm BPM position resolution for the operators indicating the performance level and BPM system health).

In addition to upgrading the present NSLS-II BPM electronics (turn-by-turn and orbit feedback modes), a bunch-by-bunch zAFE is under consideration utilizing improved ADC technology (e.g. 14/16 bit ADCs like ADS54J66 or ADS54J69 from Texas Instruments) and latest advances in FPGA technology (e.g. 1st or 2nd generation Xilinx RFSoC FPGAs with 8 channel, 12 bit or 14 bit, 4 or 5 Gsps). First prototype hardware tests with beam (325 mA, 1000 bunches) show very promising results: ~ 5 µm (rms) bunch-by-bunch and ~ 0.6 µm (rms) turn-by-turn position resolution.

### BPM and Orbit Feedback System for ALS Upgrade (G. Portmann - ALS)

ALS-U beam parameters and stability goals define the BPM requirements:

- different fill pattern (single to multi-bunch) determine the full dynamic range
- beam stability needs to be provided over a large frequency range, translating into 200 nm (rms) position resolution (and drift) from a few days to 10 kHz

ALS-U will need 192 BPMs in the storage ring (16 per sector), 72 BPMs in the accumulator ring (6 per sector) and ~ 20 BPMs in the transfer lines. The ALS BPM development team (Gregory Portmann, Eric Norum, Jonah Weber, Mike Chin and Rick Lellinger) is closely collaborating with the NSLS-II BPM experts and uses the NSLS digital front end (DFE), while a number of modifications / optimizations were made to the analog front end (AFE) regarding the ALS parameters.

- pilot tone generation has been put on a separate system
- each analog chain has its separate power regulation
- reference clock generation comes from the FPGA
- increased number of temperature monitors (8 instead of 2)
- monitoring voltages and currents for 3 supplies
- the backside of the PCB is thermally connected to the case
- each DAT is individually controlled
- SAW band-pass filters have been replaced by thermally more stable ceramic filters

For online calibration and drift compensation of the ALS BPM electronics a pilot tone at ± 2 MHz from the 500 MHz BPM carrier signal has been fed in through a combiner stage in the ALS tunnel (to improve the temperature stability). However, the ALS BPM team has found out that this correction mechanism suffers from a strong temperature dependency of the SAW filter pass band behavior, resulting in different transfer function for the RF carrier and the pilot tone. Comparative studies of ceramic filters to the original SAW filter indicate that a mono-block ceramic filter (from CTS) shows the best (temperature) behavior, leading to this important design change in the AFE.

While the NSLS-II digital front end board (DFE) could be taken over without any hardware modifications, the firmware and EPICS software was changed / adapted completely for the ALS BPM system. BPM noise floor measurements (one button signal was split four ways to the BPM inputs) show that the ALS BPM electronics remains below the specified 200 nm (rms) noise floor between 0.4 to 5 kHz, with a very efficient pilot tone noise correction up to 1 kHz (only 75 nm rms noise). This new BPM electronics performance will thus strongly improve the ALS fast orbit feedback system, where most of the beam disturbances occur between 10 and 200 Hz (as shown in an integrated PSD plot). The long term drift (over days) is strongly improved from presently 8 – 10 µm to 0.2 µm with pilot tone compensation. Turn-by-turn resolution (important for beam commissioning and beam optics studies) is below 1 µm (rms) at 500 mA multi-bunch filling and below 10 µm for low bunch charges (beam currents during injection studies and commissioning).

An “expert panel” was presented, which allows BPM health monitoring and maintenance from the control room. It monitors all relevant system parameters (e.g. temperatures, voltages and clock signals) and allows switching to the pilot tone for diagnostic checks of BPM electronics.

For the APS-U, the following (main) features (wish list) should be implemented in a new BPM system:

- Faster ADCs (> 125 MHz sampling rate or 77 samples per storage ring turn)
- Improved components like e.g.: band-pass filters, DAT and amplifiers
- Cleaner pilot tone (mainly above 1 kHz)
- 4 channel ADCs

Plans were shown to stepwise improve the orbit stability at ALS by upgrading the fast orbit feedback (FOFB) with a large number of the new ALS BPM electronics (making the transition in 2019 from Bergoz electronics), new CAEN power supply controllers (CAEN fast-PS-Series operating at 10 kHz) and implementing the ALS Cell Controller for the FOFB communication. With the replacement of the Al vacuum chambers by higher bandwidth stainless steel chambers at the location of the fast correctors, a closed loop bandwidth of 500 – 1000 Hz is anticipated.

# Session 5 - INSTABILITIES FEEDBACK SYSTEMS FOR ELECTRON SYNCHROTONS (U. Iriso, M. Lonza)

**Coupled-bunch Instabilities and the Anna Karenina Principle (D. Teytelman - Dimtel)**

Dimitry showed us how under proper feedback control, all storage rings look more or less alike. But after his presentation, we saw that each accelerator presents unique set of challenges for feedback stabilization. The frequency spectra of machines with properly working feedback systems shows clean notches at the horizontal and vertical planes. But each small undamped instability needs its own special treatment, and Dimitry went through a variety of (exotic) instabilities seen by different accelerators: from ion instabilities (Bessy-II) to resistive wall resonances produced only at certain In-Vacuum Undulators gaps (Australian and Aichi Light Sources), or the coupling between longitudinal and transverse planes (ANKA). In order to properly damp all instabilities, feedback systems need first to become an efficient tool to diagnose them and understand their origin. For future machines, it was mentioned that new light sources and colliders are going become more and more sensitive to residual dipole motion in the transverse plane, low-noise techniques in RF front end and digitizer design are required.

**Longitudinal feedback systems at the lepton collider DAFNE (A. Drago - INFN)**

In the longitudinal plane, A. Drago went through the Front-End requirements to acquire for each bunch the longitudinal oscillations respect to the synchronous phase (phase detector). Using powerful models of FPGA, it was possible to implement very compact version of feedback systems in the digital/analog part of the back-end. While for the acting device, cavity kickers are preferred wrt to stripline-type-kickers to avoid instabilities.

**Fast kickers for MultiBunch Feedbacks (M. Dehler - PSI)**

Kickers in transverse multibunch feedbacks are stripline-type, with the goal of producing strong and homogenous kicks, with load broad-band impedance and negligible contributions from HOMs. This presentation went through the main concepts to achieve these goals. In particular, maximizing the stripline kick (or the stripline shunt impedance) consists on choosing the appropriate shape and location of the electrodes. Nevertheless, even though electrodes are relatively well thermally isolated, there have been some cases where the beam power distribution has damaged the electrodes due to HOM heating (Diamond and Petra-III, the latter including water cooling system in the electrodes).

After the first part of the session characterized by speakers with long experience in the field of multi-bunch feedback systems, the second part was dedicated to new implementations and recent machine physics studies using feedback systems.

**Experience on the integration of Diamond MBF-2 @ ESRF (B. Roche - ESRF)**

Benoît Roche presented the new ESRF bunch-by-bunch digital processor based on a Diamond Light Source design. At ESRF multi-bunch feedbacks are not used during users operation but only in particular cases to increase the maximum current both in multi and single bunch mode. In the future, they plan to use the feedbacks and their diagnostic capabilities to speed up the commissioning of the accelerator after the forthcoming upgrade (ESRF-EBS). The new processor is based on a μTCA platform and commercial boards with software and firmware developed by Diamond. After a smooth work of integration into the ESRF control system, the commissioning with beam has been fast and successful.

## Feedbacks against collective instabilities at MAX-IV (F. Cullinan - MAX-IV)

MAX-IV features two storage rings at 1.5 and 3 GeV, both of them equipped with longitudinal and transverse bunch-by-bunch feedback systems employing Dimtel hardware. The interaction between harmonic cavities used for bunch lengthening and the feedbacks is quite challenging due to the effect on the synchrotron frequency and energy spread. The talk presented the studies and experience gained in operating them at the same time. Mode-0 and quadrupole instabilities were also discussed as well as the remedies adopted to control them.

## New SPring-8 Bunch-by-Bunch Feedback Processor for hybrid filling (T. Nakamura - Spring-8)

The talk was another example of sharing a common project among different laboratories, being a development carried out by Spring-8 in collaboration with SOLEIL and PLS. Takeshi Nakamura presented a different approach of implementing the feedback processor based on an original idea aimed at solving the problem of managing storage-ring hybrid filings with single high-charge bunches. The processor features multiple ADCs dedicated to different bunches and a digital selector to recombine the calculated digital kick signals. The presentation also included other interesting approaches for kick pulse-length stretching, multiple BPMs feedback, beam size feedback control and head-tail feedback for single bunch instabilities.

## Single bunch instabilities with transverse feedback at Diamond Light Source (E. Koukovini-Platia - CERN)

Eirini presented a study carried out at the Diamond Light Source on single bunch instabilities. The multi-bunch feedback system has been used as a powerful instrument to perform machine physics studies thanks to the built-in diagnostic functionalities implemented in its firmware. The instability current threshold in single bunch has been measured in different conditions of chromaticity and feedback settings. Thanks to this studies, with the use of the feedbacks it is now possible to store twice the single bunch current with the same chromaticity, which is particularly useful during users operations in hybrid filling mode.

# Session 6 - ORBIT FEEDBACK TOOLS FOR ELECTRON SYNCHROTONS (A. Olmos)

**Suppression of the injection perturbations using feed-forward techniques (Eric Plouviez - ESRF)**

The recent top up operation at the ESRF showed up the interest to cope the beam position perturbations due to the injection system. Eric showed that the position oscillations are due to the none perfect closing of the kickers bump (sextupoles) and some leakage of the septum field. Orbit and Instability feedback systems are limited because of their bandwidth, but correctors bandwidth (500Hz) is enough to correct such perturbation. The use of feedforward techniques allows to get profit of the higher correctors bandwidth and acts more efficiently over the correctors strength in order to reduce the effect of the septum leakage. Eric explained that the effect of the sextupoles in the bump is being addressed by passive cancellation (shaping the kickers filed and adding an octupole to the bump) and active correction with a shaker plus a stripline.

**New corrector power supplies for SLS / SLS-2.0 (Hans Jaeckle - PSI)**

Hans started his contribution doing a review about power supplies, their main components, current measurement methods and their principle of operation. Then he jumped into the different generations of power supplies controllers @ PSI, analyzing the design of the controllers based on the nature of the signal to control (strength and bandwidth) and the noise and ripples sources to face. Finally he showed the different types of power supplies expected for SLS2 machine and commented about the design process and constrains for the new power supplies, explaining in detail the plan of building a power supply prototype.