FARADAY CUP AWARD: HIGH SENSITIVITY TUNE MEASUREMENT USING DIRECT DIODE DETECTION

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Abstract

Direct Diode Detection (3D) is a technique developed at CERN initially for the LHC tune measurement system, to reach sensitivity allowing observation of beam betatron oscillations with amplitudes below a micrometre. In this technique simple peak diode detectors are used to convert short beam pulses from a beam position pick-up into slowly varying signals. Their DC components, constituting a large background related to beam offsets, are suppressed by series capacitors, while the small signals related to beam oscillations are passed to the subsequent stages for amplification and filtering. As the demodulated beam oscillation signals are already in the kHz range, their processing is simple and they can be digitised with high resolution audio ADCs. This paper presents the history as well as the adventures of the 3D development and prototyping, along with some technical details. It documents a very efficient collaboration between CERN and Brookhaven National Laboratory (BNL), with contributions from other labs. This paper is also meant as a reminder that for some applications even simple analogue signal processing can be by far more efficient than the presently common "digitise-it-immediately" approach and that old good ideas should not be ever forgotten.

HISTORY OF THE 3D DEVELOPMENT

Initially the LHC tune measurement system was planned to be split into two sub-systems, one general purpose and another for high sensitivity measurements [1]. The general system requiring substantial beam excitation was meant to allow commissioning the LHC with single pilot bunches and operation with various filling patterns. Beam excitations at the 50 µm level were considered necessary, which could cause a significant emittance degradation, excluding the general system from operation with physics beams. For this purpose the second high sensitivity system was required, capable of operating with the beam excitation at the micrometre level. The required sensitivity was considered feasible at the expense of optimising the system to work only for physics beams with the 40 MHz bunch filling pattern. The system was planned to be based on the phase-locked loop (PLL) principle [2], with continuous beam excitation phase-locked to the narrow-band beam response signal. It was believed that the required sensitivity could be achieved by using a beam position pick-up (PU) resonating at a 40 MHz harmonic, put on a motorised support for automatic beam centring to minimise beam offset signals and make the detection of small betatron oscillations possible. The steering feed-back loop of the resonant PU motorisation was supposed to have its own position PU.

Base-band tune measurement at RHIC

The development of the LHC high sensitivity PLL tune measurement system was done in collaboration with BNL within the framework of the LHC American Research Programme (LARP), as at BNL a similar system [3] was already built and operated at RHIC, also a hadron collider. This is why in February 2004 two members of the CERN tune team, Rhodri Jones and Marek Gasior, went to BNL to meet the corresponding BNL group, led by Peter Cameron, to learn about the RHIC PLL system and discuss future developments. After a day of intensive discussions it was agreed that the main limitation of the RHIC system perturbing its smooth operation was the insufficient input dynamic range, leading to saturations during fast beam orbit changes, which cannot be followed by the motorisation of the 245 MHz resonant PU. As a potential remedy it was considered a base-band operation below the RHIC revolution frequency (f_{rev}, ≈ 78 kHz), allowing using low-frequency amplifiers with larger dynamic range than their RF equivalents. This would have implied an extension of the PU response towards lower frequencies by using a high impedance differential amplifier connected directly to the PU output ports. After a suggestion of Peter Cameron, it was decided that the design and construction of such an amplifier would be attempted, with the hope of installing it in the RHIC tunnel during a short access possible the day after. During the following night and morning such an amplifier was designed and built. As seen in Fig. 1 showing the photograph of its original schematic, it contained three operational amplifiers, simple 100 kHz RC low-pass filters and, what turned out later to be very important for the future of the project, a diode clamping circuit for an overdrive protection of the op-amp inputs. Around noon, after quick testing, the amplifier was installed on a free 1 m RHIC stripline PU with its output connected to a surface building housing the RHIC PLL tune system. Once the beam was back, base-band tune spectra popped up on a spectrum analyser. Then Peter Cameron, using his

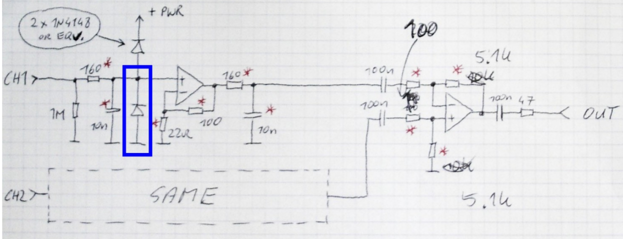

Figure 1: Original schematic of the high impedance amplifier built at BNL, with the marked error, very important for the future development.

experience with the RHIC PLL tune measurement system, quickly built its base-band equivalent. It consisted of a lock-in amplifier tuning the frequency of a signal generator to match the phase of the receiving base-band beam signal, indicating the tune frequency. The generator was sending some 100 mW to another free 2 m stripline PU working as a beam kicker. Once this simple base-band PLL system was set up, it was able to follow a tune change requested from the control room, proving that the measurement loop was indeed closed. This was demonstrated just before the CERN team had to rush to the airport to catch their return flight.

Direct diode detection

The BNL visit was a great success and the feasibility of the base-band PLL tune measurement was demonstrated, but it was not the ultimate solution. The system dynamic range was indeed larger, but the lack of resonating PU required a stronger beam excitation, causing substantial emittance degradation. The remedy came very soon from an unexpected direction.

While discussing improvements to the high impedance amplifier built at BNL, it was noticed that on its schematic, as shown in Fig. 1, one diode, supposed to be in a clamping configuration, was drawn as a parallel diode detector. By consulting the photograph of the built circuit it was confirmed that it was only a schematic error. Fortunately for the whole project, the question "what would happen if it had been indeed a diode detector" was asked and seriously considered.

In both, the base-band and the 245 MHz RHIC tune systems, the beam betatron oscillation signal was detected at a single frequency, while it was repeating in the beam spectrum very many times as the sidebands of every revolution frequency harmonic. It was realised that if the PU beam signal is passed through a diode detector, then a good part of the energy of all those betatron harmonics appears at its output in the base-band, resulting in a large betatron signal gain with respect to the classical "one betatron harmonic" tune measurement. In case of a single short bunch the gain can be orders of magnitude [4]. In addition the diode detector followed by a series capacitor suppresses the beam offset pulses (e.g. saturating the 245 MHz system) by a factor proportional to the time constant of the RC circuit at its output [4]. This was possible without amplifiers, therefore, processing large beam pulses seemed possible, contrary to the classical systems with low noise, small signal amplifiers at the input.

The number of advantages and the simplicity of the diode detector technique were overwhelming and the question "how could such an obvious solution have been overlooked" was asked many times. As it turned out later, diode detectors were used in the past for tune measurements [5], but the idea had just been forgotten to be re-discovered thirty years later. However, this time the diode detectors were followed by a dedicated processing electronics optimised for sensitivity, with high impedance differential inputs and strong active filtering.

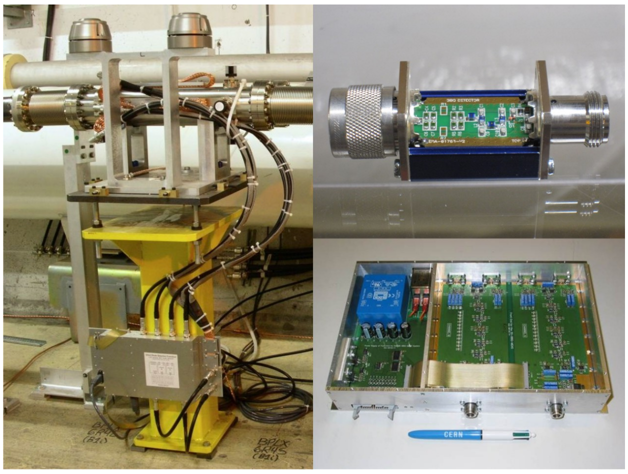

Figure 2: Typical 3D tunnel installation with the diode detector and the analogue front-end (LHC example).

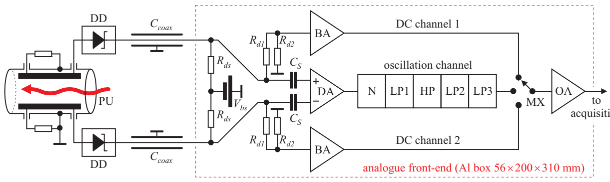

Figure 3: Block diagram of the 3D AFE with detectors.

First 3D prototypes

In May 2004 the first prototype of the tune system based on diode detectors was ready and it got installed on a stripline PU in the SPS, just in time to be measured together with the BNL tune team coming in June. The tunnel installation consisted of detectors housed in small boxes put directly on the PU ports. The detectors were connected by ≈ 1.5 m coaxial cables to the analogue front-end (AFE) box, accommodating the signal processing electronics. Such a scheme was kept for all subsequent 3D tunnel installations, shown in Fig. 2 on the LHC example, together with photographs of the diode detector and the AFE box. One AFE houses 2 processing channels, typically used for horizontal and vertical planes of a 4-electrode PU.

As depicted in the AFE block diagram shown in Fig. 3, the capacitance (C_{coax}) of the coaxial cable connecting each diode detector (DD) to the AFE constitutes most of the detector output capacitance. The detector discharge resistors (R_{ds}) are used also to provide small bias currents for the diodes, increasing system sensitivity for small beam signals. The currents are provided from a dedicated carefully filtered bias voltage (V_{bs}).

The DC part of the detector output signals related to static beam offsets are blocked by series capacitors (C_s), while the oscillation signals pass to the differential amplifier (DA), subtracting the signals from the opposing PU electrodes and amplifying the result. This stage provides also a suppression of potential input interference, likely to appear as a common mode signal. The AFE frequency characteristic, shown in Fig. 4, is shaped with the subsequent active filter stages, ordered for the maximal input dynamic range:

– notch filter (N) for f_{rev} (≈ 43 kHz for the SPS), built with an RC 2T bridge and an op-amp;
– low-pass filter (LP) with the cut-off at ≈ 0.5 f_{rev}, built with three Sallen-Key sections LP1, LP2 and LP3, dimensioned for the overall 6th order, 0.5 dB ripple Chebychev characteristic;
– high-pass filter (HP) with the cut-off at ≈ 0.05 f_{rev}, built as a Sallen-Key section.

The AFE is equipped with two simple auxiliary channels for monitoring DC detector voltages [4]. Each channel has a divider (R_{d1}, R_{d2}) with large value resistors lowering the diode detector DC voltage to the level acceptable by the following buffer amplifier (BA). The DC channels can be connected to the AFE output by means of an analogue multiplexer (MX). If the beam orbit changes only slowly, it can be estimated from the voltages of both DC channels measured alternately.

The first SPS diode detectors were very simple, as shown in Fig. 3a. Later they evolved to more complex circuits, with an example sketched in Fig. 4b. It includes:

– an input high-pass filter, suppressing potential low frequency interference, especially from DC loops formed from the stripline electrodes and the downstream terminations;
– a low-pass filter smoothing beam pulse shapes and removing high frequency components which are not tune related;
– a peak detector, built with large signal RF Schottky diodes; if needed, a few diodes can be used in series to increase the maximal acceptable PU electrode signal;
– an output low-pass filter, suppressing residual beam pulses passed through parasitic diode capacitances.

The listed diode detector blocks are realised as high impedance circuits to limit power dissipation in their components, which can be then small and optimised for good RF properties. The detectors are put on the upstream ports if used with stripline PUs, while the downstream ports have RF terminators with adequate power rating. Most of the upstream beam power is then reflected and dissipated in the downstream power terminators.

The 3D prototype built according to the described design allowed observation of betatron oscillations of the SPS beams, to a common surprise, without explicit excitation, with the most problematic f_{rev} component being almost completely suppressed. The f_{rev} attenuation introduced by the diode detectors and the AFE active filtering was in the order of 40 and 100 dB, respectively [4], saving some 23 bits of the ADC dynamic range. Without the diode demodulation the ADCs would have to cope with the ns PU beam pulses.

Once the BNL team came to CERN, more systematics measurements were done during dedicated machine development periods. The "natural" betatron oscillations observed with the diode system with a comfortable ≈ 30 dB signal-to-noise ratio (SNR) were estimated to have micrometre amplitudes, indicating that the new

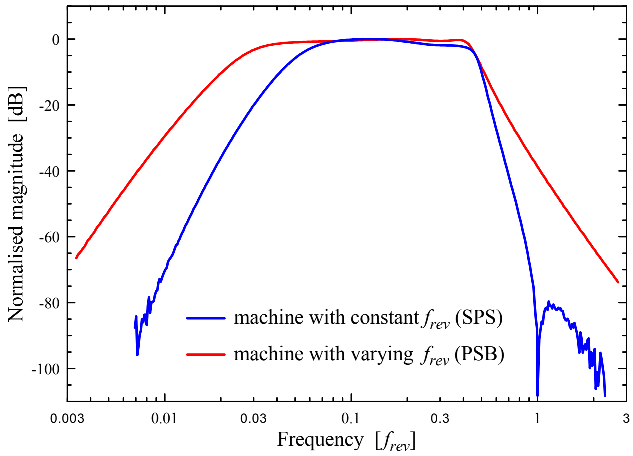

Figure 4: Typical AFE frequency characteristics.

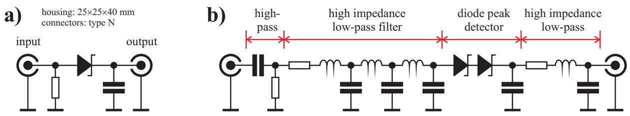

Figure 5: Examples of diode detectors.

diode system could detect the beam motion at the unprecedented 10 nm level. It was agreed that the diode detection technique could be an option to improve the RHIC PLL system and to be used in the future LHC tune diagnostics systems. One 3D AFE optimised for RHIC was decided to be built at CERN and sent to BNL for beam tests.

The second AFE was built for the SPS at the beginning of September 2004 on new printed circuit boards (PCBs) designed to allow its circuitry to be adapted for virtually any accelerator by selecting and soldering adequate components. The new SPS AFE replaced the installed prototype, which then got modified for the PS (max. f_{rev} ≈ 480 kHz) and moved there to test the 3D technique at higher frequency and with a PS shoe box PU. First results obtained with these two prototypes are summarised in [4].

Initially SPS beam spectra had been displayed with a laboratory, low frequency spectrum analyser that lacked the option of longer signal recording. One day its schematics got studied while waiting for the return of the SPS beam and it was noticed that the instrument is based on audio ADCs. This triggered the idea of using a PC sound card for long recording of the SPS 3D signals, having adequate 22 kHz bandwidth. Laptop built-in sound cards were excluded due to their high interference level and an external USB sound card was purchased for some 100 €, i.e. less than 1 % of the price of the used spectrum analyser. Afterwards such sound cards were routinely used for 3D signal recording followed by an off-line Fourier analysis. This approach gave spectra not worse than those with the laboratory spectrum analyser and records of practically an unlimited length were possible.

As the 3D SPS signals were routed to a surface building with deafening noise, headphones had to be used to setup the very first recording session with the sound card. This helped to discover that the SPS 3D signals are quite interesting to listen to and they have much more content than just the tunes. The signals were recorded as PC audio files having a few MB sizes, which at that time was too much to be emailed to share the discovery with the colleagues. For that reason a small website was made with the beam sound audio files and its address was sent around. With time the website was growing and it was used for regular exchange of larger beam sound records with the US colleagues. The website is still operational and contains beam records from the early days of the 3D development [6].

When preparing the website it was realised that the "Direct Diode Detection" with the three "D" abbreviation is a nice name for the technique, but this technique was used in a system, which needed also a name. This is when "BBQ" was first used as the abbreviation of "Base-Band Tune", with "Tune" traditionally denoted by "Q".

"BBQ" was a good name since quickly became popular but soon also brought troubles, when it appeared on shipment documents for the RHIC AFE built in October 2004. The parcel going from CERN to BNL got stopped by custom services to investigate a supposed food exchange between physics laboratories. It took a few weeks to clarify the matter, before the parcel finally got released to go to BNL. Just after construction of the RHIC AFE, another AFE with the diode detectors were quickly built for Tevatron ($f_{rev} \approx 48$ kHz) and shipped to Fermi National Accelerator Laboratory (FNAL), this time with no single "BBQ" reference in the documents.

RHIC, Tevatron and SPS beam measurements

The test BBQ systems got installed at RHIC and Tevatron and first beam spectra were observed at the beginning of 2005 [8]. Both prototypes were sensitive enough to operate with natural beam oscillations. The number of details found in the beam spectra was a common surprise at both laboratories, to the extent that some of them were believed to be instrumentation artefacts. The largest astonishment made mains ripple harmonics visible in the beam spectra, which had not been observed before in the 22 and 4 year of operation history of Tevatron and RHIC, respectively. The effect was observed already on 4 accelerators (including CERN SPS and PS [4]), however always with the BBQ diode systems, raising the question whether this is due to the unprecedented sensitivity of the technique or rather a defect of the BBQ hardware built at CERN.

At FNAL the question was more or less academic with no serious implications, especially that Tevatron was approaching the end of its operation. After putting the Tevatron AFE on batteries replacing its original power supply and making dedicated beam studies it was concluded that the mains ripple are indeed real [6].

At BNL the observation of the mains harmonics in the RHIC beam spectra had larger consequences, as they were an obstacle to use the full sensitivity of the 3D technique, which started being introduced into the RHIC PLL tune measurement system [9]. Finally the mains harmonics were proven to be real by comparing the "suspicious" BBQ spectra to the corresponding spectra from the 245 MHz resonant PU, another development system with homodyne detection and a BPM system using a million turn acquisition. By choosing adequate beam conditions it was possible to observe similar mains harmonics in beam spectra from each of these systems [10]. At that occasion the sensitivity of the RHIC development BBQ was estimated to about 10 nm.

A considerable effort was invested to understand the source of the RHIC mains harmonics, with the hope of decreasing their amplitude, allowing in turn decreasing the necessary beam excitation for the PLL tune measurement [11]. Eventually the RHIC PLL tune measurement system based on the 3D AFEs built at CERN became operational and used for continuous coupling and tune feed-back [12-14].

At CERN the BBQ studies first concentrated on the SPS system. In October 2004, just a month after its installation, the system was used for very important measurements of the impedance of an LHC collimator prototype. The impedance, considered to be a potential limit of the LHC performance, was measured as a small tune shift induced by collimator jaws put close to the beam. The measurement required tune resolution in the order of 10^{-5}, which was achieved with small natural beam oscillations and long acquisitions, not possible with the regular SPS tune meter [15].

The performance demonstrated during the collimator measurements earned at CERN first important credits to the 3D technique and a request to install an operational BBQ system on the SPS. This was also a good opportunity to install a complete prototype of the LHC tune measurement system, which then could be handed over to the operation team for permanent testing under different beam conditions.

BBQ acquisition and signal processing

For the operational SPS and LHC BBQs it was necessary to design and build an acquisition system optimised to take full advantage of the 3D performance and fitting well into the VME world of the CERN control system (with no place for PC sound cards). The first system block is a 24-bit ADC/DAC NIM module [16], based on an audio codec. Its design permitted achieving a 160 dB dynamic range in the frequency domain and very clean reception of kHz band signals, even when the signals were sent over coaxial cables hundreds meters long. The DACs are used to generate harmonic excitation signals, optionally applied to the beam using the power parts of the SPS or LHC transverse damper systems.

The ADC/DAC NIM module is connected over a serial LVDS link to a VME Digital Acquisition Board (DAB), accommodating a large FPGA chip and memory, being the standard processing board in the CERN Beam Instrumentation (BI) Group. The FPGA was used to implement a low frequency Fast Fourier Transform (FFT) spectrum analyser optimised for BBQ signals. The PLL tune measurement was also programmed inside this

FPGA, with the beam driving signals produced with the 24-bit DACs.

The FPGA signal processing algorithms and their implementation are essential parts of the BBQ tune diagnostics systems and they have contributed significantly to the success of the project. They required a few years of intense development work of Andrea Boccardi, resulting in a very elegant and powerful system [17]. The FPGA processing allows beam spectra FFT computation with a 180 dB dynamic range, requiring a real-time calculation of the sine and cosine functions in integer arithmetic. The PLL tune system features quadrature demodulation, allowing measurements of betatron coupling module and phase, according to the formalism developed also within a collaboration between CERN and BNL [18].

Once the DAB BBQ acquisition was finished with the corresponding real-time software, the SPS system was delivering data, which could be displayed by standard BI applications. However, to profit fully from the BBQ advantages, control tune calculation algorithms and the parameters of the acquisition system, a dedicated application was needed. The program was planned to be universal and also used in the future for the LHC tune measurement system, including the control of the tune feed-back, so its writing was considered as an important task. At that time a lot of urgent software was being prepared for the LHC start-up, so the tune application was put in the waiting queue. Fortunately at that time Ralph Steinhagen was already a member of the LHC tune team and, to advance the project development, took things into his hands and during a few days wrote a prototype Java application optimised for visualisation of BBQ data and deriving tune values from beam spectra. Initially the program was meant to be an expert tool, allowing the full control over settings of the FFT and PLL sub-systems, AFEs, acquisition, tune fitting algorithms and data visualisation. It has a modest name “TuneViewer”, but over time it accumulated a lot of powerful features, based on the large control room experience of its author. Today the TuneViewer is one of the most complete applications in the CERN control room, with many features beyond its main tune measurement capabilities, such as single and continuous chromaticity measurement, trimming beam parameters and performing data post-processing. It is used as the standard tune measurement application for all CERN BBQ systems. Its screenshot, illustrating a very small fraction of its capabilities used in everyday operation, is shown in Fig. 7 on the LHC example.

LHC BBQ

For the LHC start-up in 2008 the machine was equipped with quite mature FFT BBQ systems being copies of the SPS BBQ, which had already been in service for about 3 years [19]. This time was used for its extensive optimisation as well as for the development of the LHC BBQ PLL tune measurement system, with beam tests carried on the SPS [20]. The LHC FFT BBQ systems were essential for the LHC commissioning from its first

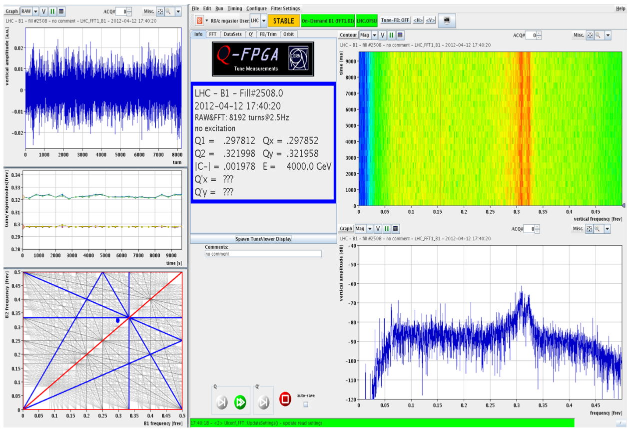

Figure 7: TuneViewer operated for the LHC.

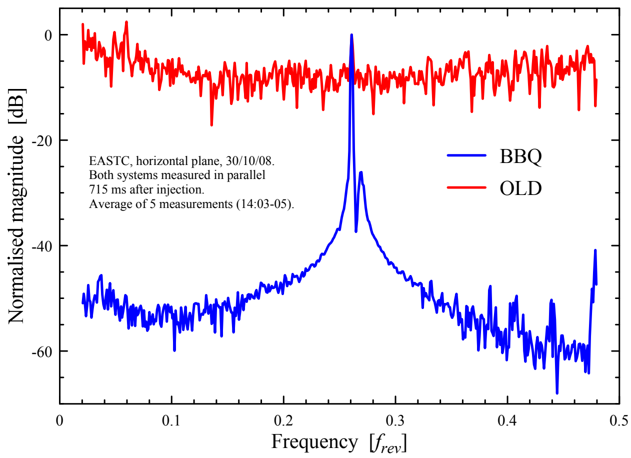

Figure 8: Comparison of the PS BBQ and OLD systems.

turns [21] and they were operated with the natural micrometre beam oscillations found to be also present at the LHC. The beam experience gained in the short LHC operation in 2008 was used to further optimise the LHC BBQ systems for the 2009 start-up, which was done with the FFT BBQs, followed by PLL BBQ commissioning [22]. Tune variations during the LHC energy ramps quickly became critical and therefore they were addressed by a fast commissioning of the tune feed-back [23]. Initially the tune feed-back was planned to use the PLL BBQ readings as the input, however, the natural beam oscillations and the BBQ sensitivity made the FFT BBQ system more optimal for this application [23]. The FFT BBQ smaller natural frequency resolution, defined by the FFT binning, was increased by using Gaussian interpolation of the tune spectral peaks [2]. With this method in practice the tune frequency resolution gain is proportional to the frequency domain SNR [24]. Results from the LHC BBQ system operation during the 2011 run are summarised in [25].

BBQ systems of the LHC injectors

Another branch of the 3D development was the tune measurement systems for the LHC injectors. The performance and simplicity of the SPS BBQ system made the 3D technique a good candidate for the tune

Table 1. Operational and test direct diode detection tune measurement systems. Species: $p+$ = protons, $p-$ = anti-protons, $e-$ = electrons, $e+$ = positrons, i = ions. AFE types: A = for constant f_{rev}, B = for varying f_{rev}. AFE sections: LNPA = low noise pre-amplifier, N = notch filter, HP = high-pass, LP4 = 4th order low-pass, LP6 = 6th order low-pass.

Machine (species)	Location	max f_{rev} [kHz]	f_{rev} ratio max / min	Pick-up type	AFE type (stages)	AFE units (built)
LHC ($p+$, i)	CERN	11.2	1.00	stripline	A (N, HP, LP6)	6 (2007)
SPS ($p+$, i)	CERN	43.4	1.01	stripline	A (N, HP, LP6)	2 (2004)
PS ($p+$, i)	CERN	477	1.09	shoe box	B+ (LNPA, N, HP, LP6)	1 (2006)
PSB ($p+$)	CERN	1750	2.92	electrostatic	B (LNPA, HP, LP4)	4 (2006)
LEIR (i)	CERN	1420	3.94	high imp. stripline	B (LNPA, HP, LP4)	1 (2005)
RHIC ($p+$, i)	BNL	78.2	1.00	stripline	A (N, HP, LP6)	2 (2004)
CNAO ($p+$, i)	CNAO	2760	5.86	shoe box	B (LNPA, HP, LP4)	1 (2007)
CesrTA ($e-$, $e+$)	Cornell	390	1.00	button	A (N, HP, LP6)	1 (2009)
Tevatron ($p+$, $p-$)	FNAL	47.7	1.00	stripline	A (N, HP, LP6)	1 (2004)
SIS-18 (i)	GSI	1360	6.34	electrostatic	B (LNPA, HP, LP4)	1 (2011)

measurement system of the newly constructed LEIR ion machine, commissioned in 2006. However, since the LEIR f_{rev} changes from 360 kHz to 1.4 MHz, i.e. by a factor of 4, this new application needed a dedicated version of the AFE and the acquisition system, optimised for smaller signals, higher frequency operation and varying f_{rev}. From the very beginning the LEIR BBQ system was built with the view of copying it also for the PSB and PS and unifying all CERN tune meters to use very similar hardware and almost identical software.

Optimal operation of the LEIR/PSB/PS AFEs at higher frequency required a few changes with respect to its SPS/LHC predecessor. The most important is a low noise JFET 20 dB pre-amplifier (LNPA) with the input referred noise of about 0.8 nV/√Hz, inserted before each input of the differential stage. At the SPS and LHC frequencies the input amplifier built even with 5 nV/√Hz op-amps is not the limiting factor for the overall noise performance [4] and it has the advantage of a larger input dynamic range. In addition due to the varying f_{rev} the notch filter was removed and the cut-off of the low-pass filter, now built as a 4th order, is set to 0.5 of maximal f_{rev}. As an example, the frequency characteristic of the PSB AFE is shown in Fig. 4.

The LEIR/PSB/PS acquisition system was built with 16-bit ADCs and 12-bit DACs for beam excitation, realised as DAB mezzanines. The FPGA data processing was done in such a way that both, the SPS/LHC and LEIR/PSB/PS systems appeared the same for the real-time applications, reducing the necessary controls software integration effort and allowed to re-use the same TuneViewer GUI for all CERN BBQ systems.

The BBQ systems built according to the described architecture were installed on LEIR, PSB and PS. A measurement example from the PS system is shown in Fig. 8, displaying a comparison of the spectra from the new BBQ system and its predecessor (OLD). It demonstrates that the BBQ SNR can be more than two orders of magnitude better in favourable beam conditions, even for longer PS bunches. Another nice surprise was that the LEIR BBQ is sufficiently sensitive to measure tunes of un-bunched, low intensity ion beams with only small excitation.

CONCLUSIONS

This paper summarises about 8 years of the direct diode detection (3D) development, launched initially to address challenges of the LHC tune measurement. It documents a very good collaboration between CERN and BNL, with important contributions from other laboratories, resulting in a valuable technique optimised for processing the oscillation part of BPM signals. It was exploited in base-band tune (BBQ) measurement systems allowing unprecedented sensitivity with relatively simple and easy to operate hardware. On many machines the BBQ systems are run with micrometre beam oscillations, discovered to be naturally present. An example of such a system is the LHC BBQ, which contributed significantly to the success of the LHC start-up and operation. As listed in Table 1, to date the 3D technique has been used on 10 accelerators in 6 laboratories with the 3D analogue front-ends built at CERN. The experience gained from operating the BBQ systems on different machines, BPM types and in many beam conditions was an important part of the 3D development. Other key ingredients of the success of the 3D project are the large BNL experience with the original RHIC PLL system and the multidisciplinary team of experts in the domains of beam dynamics, analogue and digital electronics, digital signal processing, programming. A large advantage was the assigned comfortable development time, allowing to investigate even small details, which, as described here, often were very important for the whole project.

Significant studies with 3D technique continue [26].

The 3D LHC tune project triggered a number of developments. The most important whose results have been already published are the following (historical order):

- Continuous beta-beat [27]: 3D technique if deployed on many BPMs can be used for optics monitoring by measuring the phase-advance of small driven beam oscillations from one BPM to another.

– Observation of sub-nanometre beam motion [28]: dedicated 3D AFEs and 24-bit ADC/DAC modules were built to observe electron beam motion in the 5 - 1000 Hz bandwidth. Sensitivity in the order of 0.01 nm_{RMS} was achieved with acquisitions lasting a few minutes.
– Diode ORbit (DOR) measurement [29]: allows achieving sub-micrometre beam orbit resolution with standard non-resonating BPMs. The development was triggered by the exceptional simplicity and potential resolution of the AFE DC channels followed by a laboratory voltmeter.
– Observation of LHC Schottky signals [30]: 3D hardware was optimised for operation at 4.8 GHz and processing signals up to 2 f_{rev}.

ACKNOWLEDGMENTS

The development of the 3D technique and its implementation in BBQ systems were possible only due to the large contribution of the four persons already mentioned earlier, namely (historical order) Rhodri Jones (3D conception, beam dynamics, beam measurements, continuous help throughout the whole development), Peter Cameron (PLL tune measurement, 3D conception, beam dynamics, BBQ prototyping on RHIC, beam measurements), Andrea Boccardi (FPGA programming, design and implementation of digital signal processing algorithms, acquisition system design, LabView test software, lab and beam measurements), Ralph Steinhagen (TuneViewer author, design and implementation of data processing, data visualisation, tune peak detection algorithms, tune feed-back, design and implementation of chromaticity measurement, 3D development, beam dynamics, beam measurements, publication of results).

During years of 3D development an important help was provided by (historical order) Jeroen Belleman (analogue signal processing, low noise JFET amplifier design, PS beam measurements, grounding and shielding issues), Christian Boccard (design of the LHC stripline tune pick-ups), Krzysztof Kasiński (LabView and FPGA programming), Lars Jensen (real time software), Peter Karlsson (SPS and LHC real time software), Stephen Jackson (real time software).

Evaluation of the 3D technique outside CERN was done with the help of C.Y. Tan (3D AFE testing at FNAL on Tevatron) and Rahul Singth (3D AFE testing at GSI on SIS-18);

The 3D development has been continuously supported by all members of the BE-BI-QP section as well as the CERN operators.

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