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FIRST RESULTS WITH A BASE BAND TUNE (BBQ) MEASUREMENT SYSTEM AT SOLARIS

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Abstract

All CERN circular accelerators are equipped with Base Band Tune (BBQ) measurement systems, based on the direct diode detection technique, allowing to measure the tunes of hadron beams by employing their residual betatron oscillations or very small external excitation. In the framework of the Future Circular Collider (FCC) project, a study was launched to optimise such a system for operation with short electron bunches. A prototype system has been recently installed in Solaris light source. The system has immediately allowed an unprecedented detection of residual betatron oscillations, whose amplitudes, estimated to be in the 100 nm range, are more than two orders of magnitude lower than the smallest beam oscillations used for tune measurements with the Beam Position Monitoring (BPM) system. The residual oscillations allowed reliable continuous tune measurements, which have also revealed spectral content never observed before. This paper provides an overview of the installed BBQ system and describes beam measurement results obtained so far. The aim of the paper is to disseminate new results in the light source community and provide information that may help in building and installing similar systems. It is hoped that wider usage of BBQ systems will help in better understanding the observed spectra of electron beam residual oscillations.

HARDWARE

The Solaris BBQ installation, illustrated in Fig. 1 with a block diagram of one of its planes and a photograph, consists of a stripline Pick-Up (PU) with four electrodes whose output ports are connected by short coaxial cables to four Diode Detectors (DD) mounted directly on the inputs of an Analog Front-End (AFE). The coaxial cables act as low-pass filters stretching the lengths and lowering the amplitudes of the short electron beam pulses to values adequate for the detectors.

The diode detectors, illustrated in Fig. 2, are built as high impedance circuits, to minimise the power dissipated in small, high-frequency circuitry. As a result, the incoming beam pulses are reflected and ultimately dissipated in high-power RF terminators connected to the downstream ports of the stripline through short cables.

The diode detector has a simple input high-pass filter (C_{IN}, R_{IN}) blocking potential low-frequency interference. The current limiting resistor (R_{LM}) protects the following RF Schottky diodes (D, HSMS280C) during the first injections of the beam, when the detector parallel capacitors (C_{ST}, C_{FT}) have not yet been charged. With high current beams the capacitors may charge to a hundred

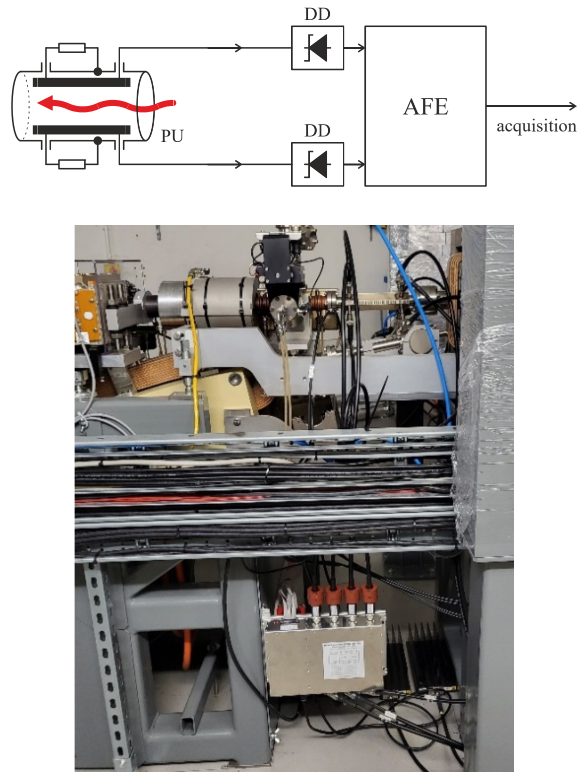

Figure 1: Diagram of one channel (top) and a photograph (bottom) of the Solaris BBQ installation.

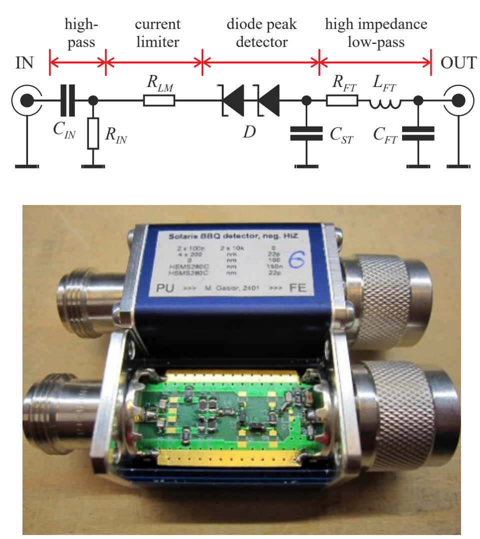

Figure 2: Block diagram (top) and a photograph (bottom) of the Solaris BBQ detector.

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volts, which requires using a few diodes in series to prevent them from going into the Zener regime.

The large-signal diodes used in the system exhibit significant parasitic parallel capacitance, which causes a fraction of beam pulses to pass through to the storage capacitor (C_{ST}). To prevent saturation of the AFE inputs, which have a relatively small dynamic range, these pulses are filtered by the output high-impedance low-pass filter (R_{FT}, L_{FT}, C_{FT}).

The Solaris detectors are built on Printed Circuit Boards (PCBs) originally designed for proton machines, with the low-pass filter omitted. In this configuration the detector bandwidth extends to a few GHz.

The one-channel diagram and a photograph of the AFE are shown in Fig. 3. In the front-end the large DC detector voltages are blocked by series capacitors (C_S) passing only signals with frequencies above the cut-off frequency of the high-pass C_S, R_{LNA}. The resulting signals are amplified by the subsequent Low Noise Amplifiers (LNAs) based on a JFET (BF862) and a PNP transistor (BFT92) in a folded cascode configuration. The LNAs provide 20 dB gain, which is set by a noiseless transformer feedback.

Signals from two LNAs corresponding to opposing PU electrodes, are subtracted in a Differential Amplifier (DA) employing three operational amplifiers (op-amps, THS4032) in the classic instrumentation amplifier scheme. The DA gain can be switched to 6 or 26 dB.

The DA output signal passes through a series of active filters, whose sequence is optimised for the dynamic range:

– a 2T notch filter (N) blocking the Solaris revolution frequency ($f_r \cong 3.123$ MHz);
– three low-pass, 2nd order Sallen-Key sections (LP1, LP2, LP3) forming a 6th order, 1 dB ripple Chebyshev filter with the cut-off at $0.5\,f_r$;
– a 2nd order Sallen-Key, 1 dB ripple Chebyshev high-pass (HP), with the cut-off around $0.03\,f_r$.

All filters are built with op-amps (THS4032) and have the total gain of approximately 27 dB. The filters do not contain any adjustable elements to avoid temperature drifts and assure adequate long-term stability. The notch filter frequency is fine-tuned within 0.1 % of the Solaris f_r by soldering correction components with the values calculated to compensate for any deviation in the initially measured notch frequency.

The filtered signal goes through an intermediate amplifier (IA, THS3001), which has a selectable gain of 0 or 30 dB. The signal then passes to the output amplifier (OA, THS4031), where the gain can be optionally increased by 5, 10 or 15 dB. An output 14 dB attenuator limits the output voltage to a maximum of 2 V_{PP} and provides a 50 Ω back-matching. If the following acquisition system has a larger dynamic range, then it is never saturated, as all clamping of excessive beam signals is done in the AFE.

The minimum gain of the AFE is about 40 dB and can be increased to approximately 105 dB in 5 dB steps. All switches (reed relays) can be controlled using a parallel bus foreseen to be driven by optocouplers providing a galvanic isolation.

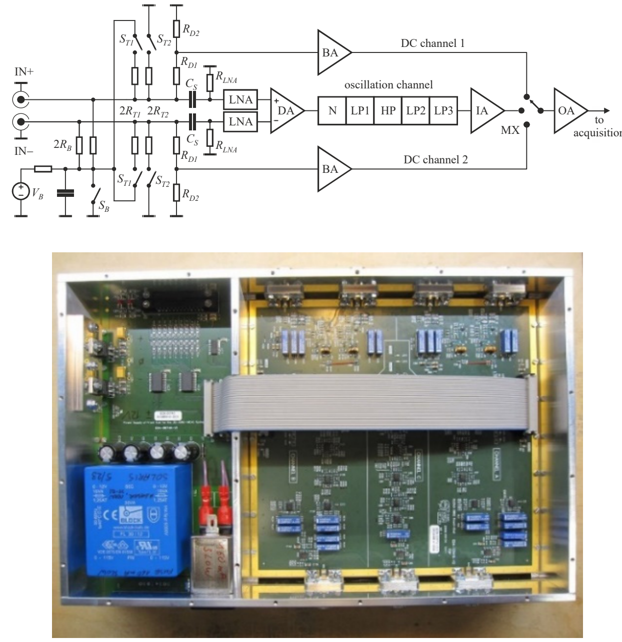

Figure 3: Block diagram of one channel of the Solaris BBQ analog front-end (top) and its photograph (bottom).

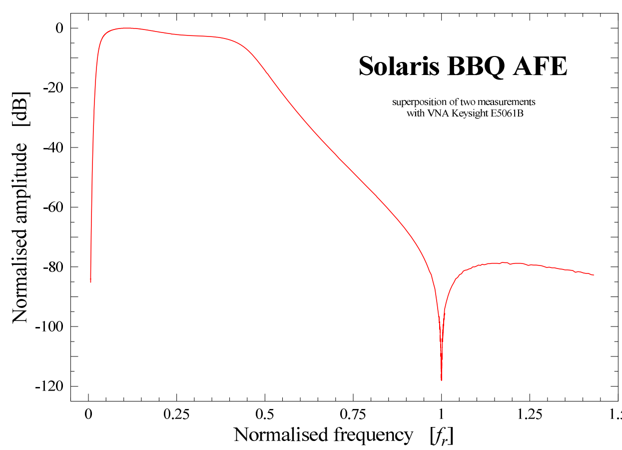

Figure 4: Frequency characteristic of the Solaris BBQ analog front-end.

The AFE contains two DC channels, which allow connecting the output to a fraction of the DC voltage of either detector (dividers R_{D1}, R_{D2}) through high-impedance buffer amplifiers (BA, OPA2140). These channels are used to monitor detector DC voltages and estimate the beam position in the PU.

The filtered bias voltage V_B is utilised to provide an optional (S_B switch) microampere diode bias current by R_B resistors, which, in conjunction with R_{D1} and R_{D2}, set the largest time constant for the peak detectors. Optionally, the detector time constant can be decreased, and the bias current increased, by connecting R_{TC1} resistors (S_{T1} switches). Two resistors R_{T2} allow further time constant reduction (S_{T2} switches).

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The frequency characteristic of an AFE oscillation channel is presented in Fig. 4. Please note that the f_r component is attenuated by approximately six orders of magnitude. Equivalent filtering in the digital domain would consume around 20 bits of the dynamic range of the acquisition system. This estimate does not take into account an important f_r attenuation provided by the diode detectors [1].

The AFE accommodates two oscillation channels, connected to two pairs of the system's PU. The PU planes are rotated by 45° with respect to the machine planes, ensuring that each plane is equally sensitive to both, horizontal and vertical beam oscillations. This configuration allows one AFE channel to serve as a reference while testing hardware changes implemented in the second channel.

The Solaris BBQ AFE is built on PCBs designed for CERN proton machines, with only different components soldered, optimised for the Solaris electron beam parameters and the signals from the stripline PU used.

BEAM MEASUREMENTS

In the initial BBQ setup two-diode detectors were connected to the stripline via coaxial cables of approximately 2 m long on both AFE channels. Shortly after installation in October 2023, the system began yielding tune spectra with around 10 - 15 dB Signal-to-Noise Ratio (SNR) at the top energy, as observed on a conventional RF spectrum analyser. However, the spectra were either degraded or completely absent during the beam filling process and the energy ramp. The detector DC voltages exceeded – 50 V with high intensity beams at the top energy, which was still far from putting the detectors into the Zener mode.

Subsequently, the coaxial cables in one of the AFE channels were shortened to about 1 m and the detectors were upgraded to a four-diode version. This modification resulted in a few dB increase in tune signals at the top energy, however, there was little improvement during the filling process and the energy ramp. A large progress was achieved when BBQ signals were observed in the time domain on an oscilloscope. This led to a discovery that during these challenging conditions the inputs of the LNAs were saturated by large low frequency content, probably related to the longitudinal beam dynamics. The situation improved drastically after rising the cut-off frequency of the high-pass C_S, R_{LNA} (see Fig. 3) by about two orders of magnitude on one of the AFE channels. This changed the optimisation of this channel from SNR to dynamic range. With this modification, the spectra were observed through the entire machine cycle, except a brief period at the end of the energy ramp when the bunch length is manipulated. Further studies are foreseen to overcome this limitation.

An example of the Solaris BBQ performance is shown in Fig. 5. The top plot presents an oscilloscope record of 15 625 samples with beam oscillations induced by the smallest tune excitation allowed by the Solaris hardware. With such an excitation the tune signals are barely seen on the standard Solaris tune meter, based on BPM signals,

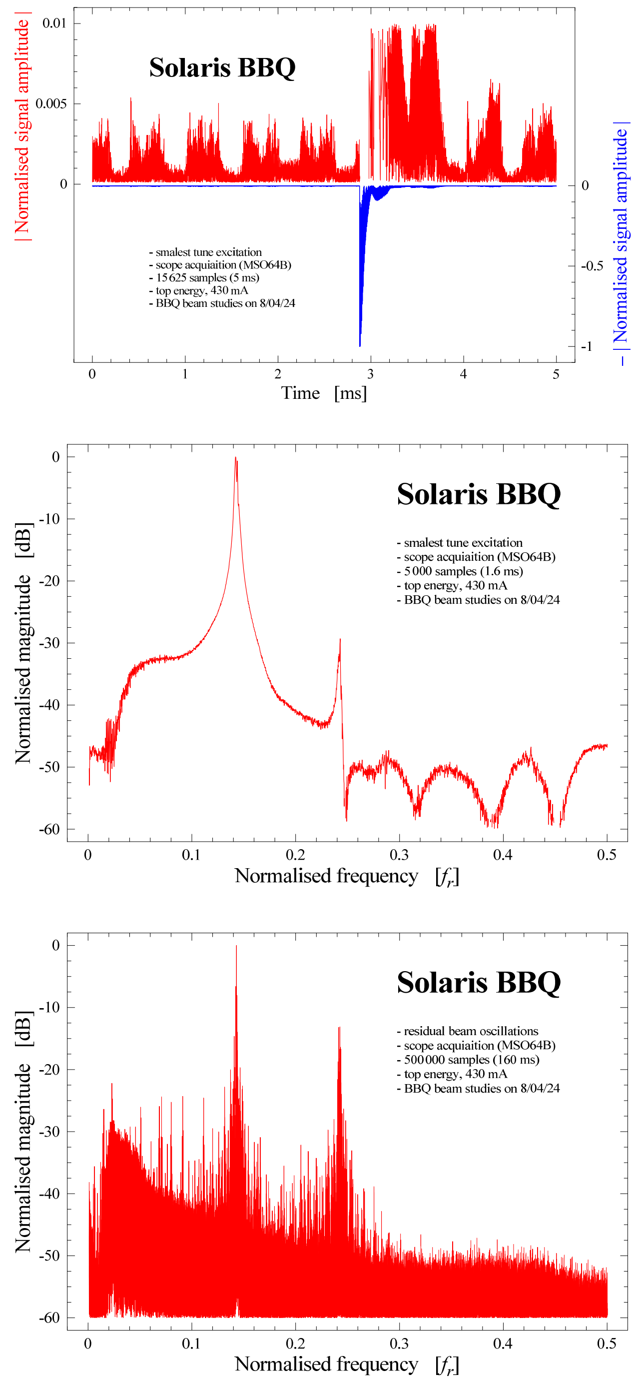

Figure 5: Top: An oscilloscope record of the smallest tune excitation showing the whole rectified signal (blue) and the lowest 1 % of the rectified signal, revealing the residual beam oscillations. Middle: spectrum of the excited beam oscillations shown in the top plot. Bottom: spectrum of the residual beam oscillation prior to the beam excitation in the top plot.

therefore for operational tune measurements much larger excitation is used. On the other hand, beam oscillations induced by the smallest excitation nearly filled the entire BBQ dynamic range when operated with the minimal gain.

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The maximal amplitude of the excited beam oscillations was estimated to be about 20 µm, as assessed from similar measurements performed with the BPM system, which is scaled in absolute units, contrary to the BBQ. From this comparison the amplitude of the presented residual beam oscillations is estimated to be in the 100 nm range.

The middle plot of Fig. 5 shows beam spectrum based on 5 000 samples containing the excited tune oscillations, while the bottom one shows the spectrum of residual beam oscillations calculated upon 500 000 samples acquired prior to the kick. The spectra reveal that the SNR of the lower frequency vertical tune peak is comparable in both cases. However, the higher frequency horizontal tune peak exhibits improved quality in the residual oscillation spectrum. This suggests that employing small but continuous residual beam oscillations acquired for long periods may yield better tune spectra than using large excited oscillations, which decay rapidly.

Figure 6 shows the complexity of the vertical tune spectra. In proton machines studies of such spectra helped in improving beam quality [2, 3], therefore, similar studies may be worth considering in Solaris.

Figure 7 illustrates the evolution of the detector DC voltage during bunch length manipulations at the end of the energy ramp. These detector DC signals are essential for optimising the BBQ system and monitoring bunch length variations during critical phases of the Solaris cycle. As shown in the plot, the detector DC voltages double within a few seconds, indicating significant and rapid changes of the bunch length. Notably, this is the only period in the entire machine cycle where residual tune signals vanish from the beam spectrum. Further studies are planned to gain a deeper understanding of this phenomenon, with the goal of implementing hardware modifications that would enable continuous tune measurements based on residual oscillations also during this period of the machine cycle.

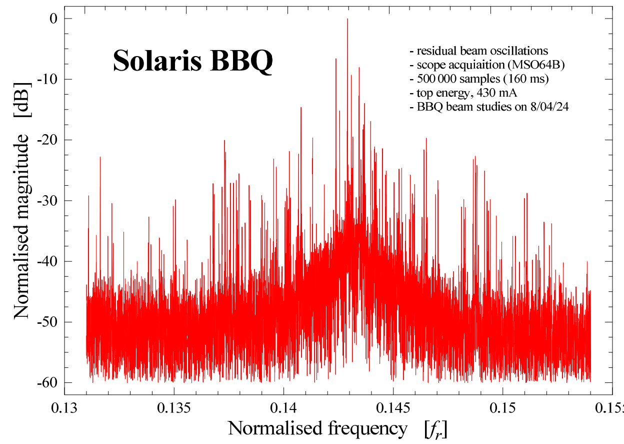

Figure 6: A part of the beam spectrum of Fig. 5, zoomed on the vertical tune region.

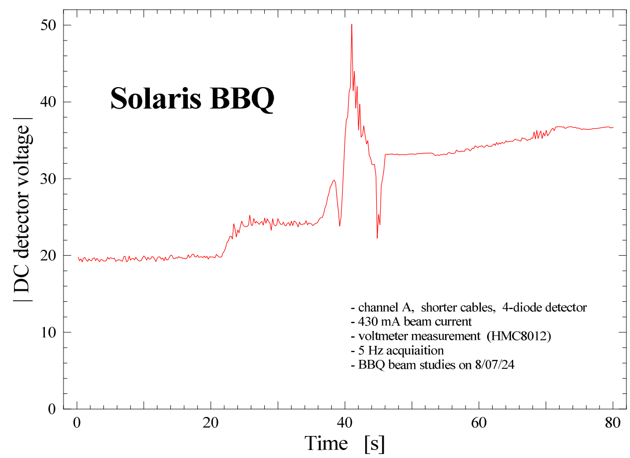

Figure 7: An evolution of the detector DC voltage during bunch length manipulation at the end of the energy ramp.

SUMMARY AND OUTLOOK

The Solaris BBQ system installed in October 2023 immediately enabled tune measurements at top energy using only residual beam oscillations, whose amplitudes are in the 100 nm range. Following the hardware optimisations described in this paper, tune measurements without explicit beam excitation can now be reliably conducted throughout the entire machine cycle, with the exception of a brief period during bunch length manipulations at the end of the energy ramp. The obtained results and details of the Solaris BBQ hardware described are hoped to encourage the building and installation of similar systems in other accelerators.

The presented measurements have been made using an oscilloscope, with the acquired data processed offline. However, in an ongoing project a dedicated BBQ acquisition system is being built, based on 24-bit ADCs (ADS1675) and a system-on-chip (Zynq 7020). The acquisition system will enable real-time computations of long beam spectra, which will be accessible and logged in the Solaris control system. The new BBQ acquisition should help in further optimisations of the system.

To date, the DC detector voltages have been acquired at a 5 Hz rate using a laboratory voltmeter. Given that the bandwidth of these signals extends to several kHz it is crucial to acquire them at a higher rate to effectively study the large, low frequency variations of the detector DC voltages, which currently challenge the AFE input dynamic range.

Further studies will investigate the implementation of high-impedance low-pass filters before the diode detectors, aiming to mitigate the effects of bunch length variations, which may influence the system dynamic range. Such filters have been successfully used in BBQ systems of proton machines.

The Solaris AFE also includes a third channel used in proton machines for frequency domain observations of beam quadrupolar oscillations [4]. Signals from the quadrupolar channel have not yet been studied at Solaris, as this requires symmetry between the two system planes. Once the system is fully optimised for tune measurements, the two planes will be made identical and the quadrupolar channel signals will be analysed.

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