DEVELOPMENT OF THE RF FRONT END ELECTRONICS FOR THE SIRIUS BPM SYSTEM

R. A. Baron, F. H. Cardoso, J. L. B. Neto, S. R. Marques, LNLS, Campinas, Brazil
J.-C. Denard, SOLEIL, Paris, France

Abstract

Tight stability requirements for new low emittance light sources, such as SIRIUS being built in Brazil, strongly depend on the BPM RF Front-End performance. Small nonlinearities, uneven temperature drifts and excess noise can spoil the performance of the whole digital BPM system and orbit correction. Calibration and temperature control schemes have been tested in order to suppress position measurement drifts during user beam delivery down to a fraction of micrometer. A method for measuring electronic component nonlinearities at mdB scale is also presented.

INTRODUCTION

SIRIUS is the new third-generation light source under construction at LNLS, the Brazilian Synchrotron Light Laboratory. The 3 GeV machine, has a 518 m circumference with a natural emittance of 0.28 nm.rad.

To fulfil the beamline user's requirements for stability of the small and high brilliance photon beams, a very stable and linear electronics is required to perform the signal conditioning of the electron BPM system. Less than 0.14 µm drift for one-hour and less than 5 µm for one week rms are required. These values comprise all drifts and noise from electronics, BPM mechanics and BPMs support stands. The BPM system requirements are listed in [1].

The BPM electronics is central to beam stability performance. Since an orbit feedback system is going to lock the electron beam onto a well centred golden orbit measured by the BPM system, the stability of the beam is that of the BPMs.

The BPM electronics must achieve the desired resolution and stability in all modes of operation of the light source. To achieve the specifications the SIRIUS RF Front-End (RFFE) is based on a design that ensures linear operation over a broad range of input power and counts on an active temperature stabilization control and a crossbar-switching scheme designed to provide a stable operation.

The entire electronics, not only the RFFE, was designed according to the Open Hardware approach which makes it available to the whole accelerator community [2].

RF FRONT-END OVERVIEW

RF Design

The SIRIUS RF Front-End is made up of four channels, grouped by two. They provide up to 50 dB of adjustable gain for machine commissioning. The specifications of the RF Front-End electronics for SIRIUS are summarized in Table 1. The assembled board without its RF shielding is shown in Figure 1.

Table 1: Sirius RF Front-End Specifications

Parameter	Value
Dynamic Range	40 dB
Noise Figure	10 dB
Crosstalk	< -50 dB
Bandwidth (3 dB)	80 MHz
1 dB Compression Point	> 20 dBm
Long Term Stability (1 week)	$< 5\ 10^{-4}$
RFFE MTBF in user beam delivery	10 years

The RFFE electronics prototype has been designed for the 476 MHz RF frequency of the electron UVX accelerator currently in operation at LNLS [3], but it is easily adaptable for 500 MHz. The main idea is to use the existing 1.37 GeV machine to test some basic parameters of the electronics as well as its reliability for long periods of operation. As the UVX nominal bunch length is not as short as the SIRIUS one, 40 ps versus 10 ps (RMS values), the electronics response for higher bandwidth signals will be more carefully verified by other means. Figure 2 shows the RFFE board schematic diagram.

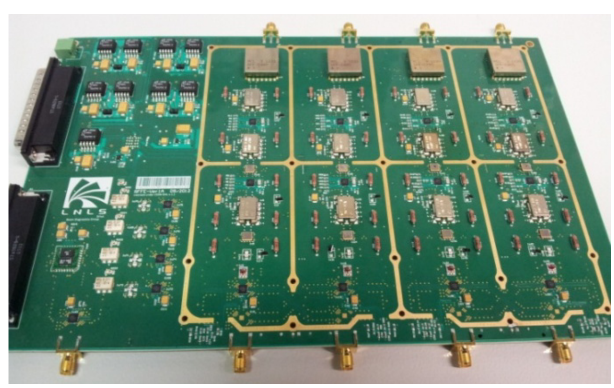

Figure 1: RFFE board. Ten layers of the Rogers RO4350 RF substrate.

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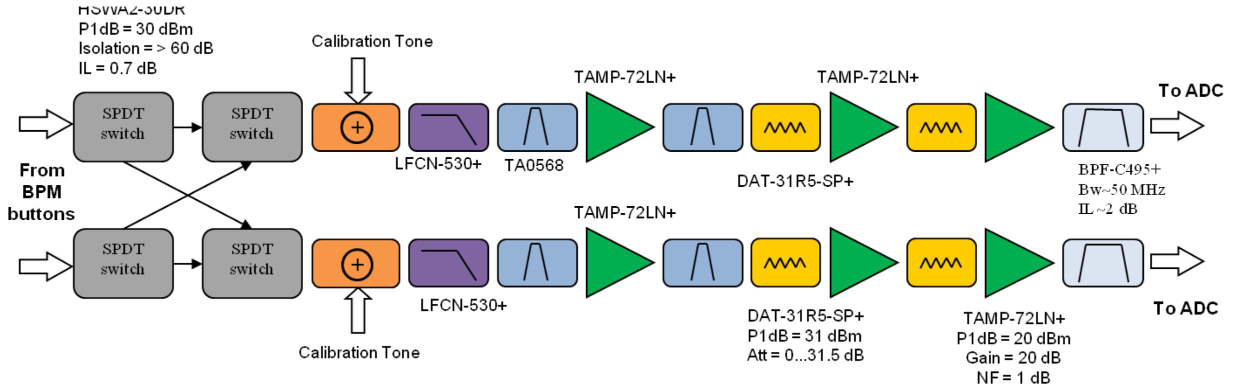

Figure 2: RF chain developed for the SIRIUS RF Front-End of the BPM electronics. Only one pair of channels is shown since the electronics is symmetric.

The crossbar switching scheme was implemented on the first stage of the RF chain, allowing short and long term drift compensations of the whole downstream part of the electronics. As the switches themselves are not compensated, the higher the 1 dB compression point and IP3 are, the better the crossbar switching performance.

The isolation between channels must achieve more than 50 dB in order to keep well below 1 % the horizontal to vertical coupling errors. The electronic compensation method based on an on-line pilot-tone strategy satisfies this crosstalk specification.

For keeping a low beam current dependence (BCD) in a high current single (or few bunch) mode it is necessary to insert a bandpass filter in front of the switches in order to prevent them from saturation.

Considerations on Linearity

The linearity of the RF channels plays an important role in the overall electronics performance. Measuring beam position deviations of the order of one micrometer means to detect relative differences of input signals in the 10^{-4} range. For this reason it is important to keep insertion losses of the channels as similar to each other as possible in several situations. In the commissioning phase usually the beam has low intensity and few variations of the filling patterns. During the first months of operation the top-up injection is not going to be available, and the BPM electronics must work properly with the storage ring in decay mode. Besides that, we also anticipate filling patterns different from the standard uniform multibunch presently foreseen.

The switched-electrode scheme is insensitive to temperature induced gain drifts. Only the relative drifts of the switches and upstream devices and cables have an effect. If these elements have a total attenuation of about 20%, the stability is improved by a factor of 5 with respect to a non-switched scheme. Also, the volume to be stable on the PC board is very small and easier to control if needed. Linearity measurements will be presented in the next sections.

Strategies for Achieving High Stability

The stability of the BPM electronics strongly depends on the RF Front-End drifts. The beam stability requirements for SIRIUS demand a very small temperature dependence of the channels. The long-term (one week) unbalance among the channels gain must be smaller than 5 mdB. Four schemes have been implemented on the RF Front-End board aiming to achieve the long-term stability requirements, two out of the four strategies were extensively tested up to now.

The crossbar switching technology was first used by the I-Tech digital BPM electronics [4] and its effectiveness in improving the long-term stability is well known everywhere. In the case of the SIRIUS BPM electronics, this scheme works by forcing the diagonal input signals to be subjected to the same gain drift. In other words, each diagonal signal cyclically passes through two different signal paths; the digital post-processing is responsible for unscramble the data. This scheme improves the stability performance with the drawback of adding spectral lines on the signals spectra and provoking a small power loss in the RF harmonic as the digitized RF signals must be discarded during the switching process. With that in mind, it is easy to verify that slow switches degrade the performance of the BPM system by reducing the signal to noise ratio. For the SIRIUS RFFE the attenuation of the carrier is less than 3 dB if the switching frequency is below approximately 100 kHz. Figure 3 shows a measurement on how the switching speed affects the RF signal attenuation.

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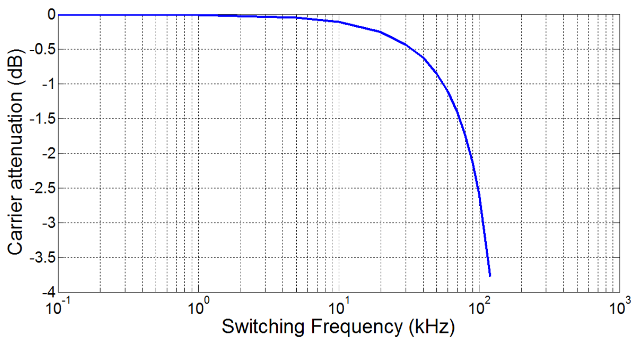

Figure 3: Switching speed effect on the RF signal attenuation. The switches used in the test have 2 µs stabilization time (10 - 90 % specification).

An onboard temperature control is also present in the RFFE board and can achieve ± 0.05 ºC peak-to-peak stability using heating elements. This feature also reduces the thermal stabilization time of the circuits by a factor of 6 (15 minutes against 90 minutes). The disadvantage of this solution is the reduction of the theoretical MTBF, as the average temperature is 40 ºC with the control turned on, 10 ºC higher than normal temperature. After computing the MTBF data provided by the electronics component vendors we estimated the MTBF degradation for each board from 15 years to 10, applying the reliability theory described in [5].

The temperature dependence of each RF channel is around -22 mdB / °C for a wide range of temperatures and the channels' behaviours are roughly identical. The RFFE board has been divided into 8 mechanical regions by a shielding enclosure that creates small environments inside the board. Each environment has one temperature sensor as input variable for the control loop and four resistors distributed through the RF channel as heating elements. The loop has been implemented and optimized into the control board as a PID controller based on eight transfer functions.

Online and offline calibration tones are the last two strategies implemented for reaching high stability rely on calibration tones, both were not tested yet. The on-line strategy is based on coupling the external calibration tone to the beam signals. A circuit based on cascaded hybrid couplers guarantees the high isolation (better than 50 dB) among the beam signals with the online pilot circuit activated. The offline pilot tone has been developed to inspect the general behaviour of the electronics. In this scheme the beam signals are disconnected of the signal chain and a reference tone is injected in each channel, allowing the determination of parameters like the channels S21 and crosstalk among channels. The offline pilot generator was implemented in a separated board which is also responsible for communication, temperature, switches and attenuators control.

LINEARITY BENCH TESTS

All the tests described hereafter were performed without RF channels swapping; the input RF switches were kept static.

The key to achieve high linearity is to keep the operation point of all the devices in the signal chain around 30 dB below the 1 dB compression point (P1dB). In other words, the circuit must operate below the 0.001 dB compression point as much as possible. This approach, combined with the crossbar switching scheme provides a good performance for both, linearity and long-term stability.

Figure 4 shows the block diagram of a test bench developed to measure the nonlinearity of each RFFE channel and to determine the safe operating range of input power (beam current) that affects the position measurement less than approximately 1 µm.

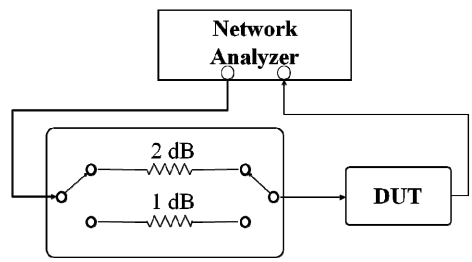

Figure 4: Block diagram of the setup used for measuring nonlinearity of RF electronics.

With highly linear switches it is possible to measure the nonlinearity of the DUT in the mdB range. The network analyzer must have about 0.001 dB resolution in the amplitude scale. It is not necessary to know the insertion loss of the switches and attenuators with high precision; it only needs to be constant over input power. For the tests performed with the RF components as well as the RFFE board, the so called linearity box, the DUT and the network analyzer were installed in a temperature chamber with a ± 0.1 ºC stabilized temperature.

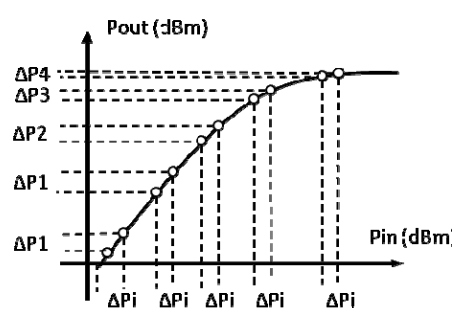

Figure 5: Main idea of the linearity test setup. It is possible to determine the linearity of the response of an RF device by measuring the difference in the output power for a known difference in the input power. If the difference between adjacent points on the output power remains constant, this determines the range of input power within which the system is linear.

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The scheme showed in Figure 4 is based on the principle of determining the slope of the saturation curve of the RF chain. Figure 5 shows the main idea of the measurement.

Automated test bench have been developed to measure the nonlinearity of the electronics. This procedure was repeated several times to allow for a statistical data analysis. As mentioned, all the instruments and electronics have been installed in a climatic chamber to avoid coupling thermal drifts to the nonlinearities under analysis. A typical result of linearity test is presented in Figure 6.

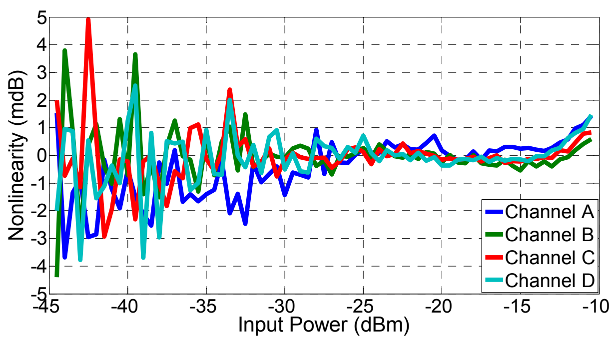

Figure 6: Nonlinearity measurements with the SIRIUS RFFE electronics.

CONCLUSION AND FUTURE WORK

The SIRIUS RF front-end electronics has been presented. A method for measuring nonlinearity with mdB precision was used with excellent results.

The Sirius RFFE is part of a digital BPM electronics being developed at LNLS that consists on a MicroTCA.4 platform using ADC mezzanine cards in ANSI/VITA 57.1 FMC form factor and standalone RFFE boards. It has been developed for the new Brazilian low emittance third generation machine which has tight requirements in terms of linearity and stability. For beam currents from 100 mA to 500 mA the input power will change from -31 to -17 dBm at RFFE input; in this range the RF channels are linear within ±1 mdB, even without the switching scheme.

The first prototype of the Sirius BPM electronics has been tested. The more general results such as beam current dependence, filling pattern dependence and stability are presented in [1].

Some improvements are being planned for future prototypes. Tests with the complete BPM system showed there is still room to enhance the performance: the noise floor can be reduced and the linear range can be extended, however the switching scheme, not completely explored up to date, can overcome the differences among the channels. The modifications for a possible second version of the board are well understood, the RF chain linearity range can be improved by upgrading the output RF amplifiers for highly linear ones, faster RF switches can improve the resolution and the stability can be improved even more by including input bandpass filters before the crossbar switching scheme.

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