# *Specification Document of a RF Front-End for the Beam Position Monitor Electronics*

*In this text we summarize the specification of the RFFE (RF Front End) electronics which will be used in the SIRIUS EBPM (Electron Beam Position Monitor) design. The main purpose of this document is to provide companies with basic information to design and manufacture prototypes for the Brazilian Synchrotron Light Laboratory*

**Brazilian Synchrotron Light Laboratory**
*Beam Diagnostics Group (DIG)*

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**Centro Nacional de Pesquisa em Energia e Materiais (CNPEM)**
**Laboratório Nacional de Luz Síncrotron (LNLS)**
Rua Giuseppe Maximo Scolfaro, 10000, Polo II de Alta Tecnologia
Campinas, São Paulo, Brazil
CEP 13083-970 – Caixa Postal 6192

# Document history

| Date | Revision | Description | Authors |
|---|---|---|---|
| 12/06/2012 | 0.1 | Initial draft. | Rafael A. Baron, |
| 28/07/2012 | 0.2 | Revision of the specifications | Jean-Claude Denard,<br>Sergio R. Marques,<br>Rafael A. Baron |
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# 1. Introduction

The BPM (Beam Position Monitor) is a system dedicated to monitor the electron beam that "circulates" on a vacuum chamber of a particle accelerator. It is composed by an electronics that processes the analog signals coming from 4 small antennas inside this vacuum chamber and calculate the beam position. This electronics has an analog RF Front End (RFFE), which must be designed to accomplish some requirements that are described on this document.

Some of RFFE specs are very hard to be satisfied, mainly when we are dealing with the system stability over long time periods and nonlinearity. On this project, the stability and high resolution design are priority instead of power efficiency and low cost.

This document specifies a BPM analog RF Front End (RFFE) to be supplied to LNLS by a third-party partner. It describes the system requirements, system interfaces and all necessary information to explicit the needs of LNLS to the third-party partner. This document is intended to serve as a base for discussion of service conditions and project planning.

**1.1** The following procedures, documents and product must be generated and delivered to LNLS:

- **1.1.1** Perform the circuit design of the RFFE according to the specifications presented on this document;
- **1.1.2** Provide a documentation explaining the functionalities of the system;
- **1.1.3** Three prototypes of the RFFE board designed, fabricated and tested by the contracted company;
- **1.1.4** Provide all the documents and files related to the schematic and PCB files to LNLS, and according to the Open Hardware approach[1] ;
- **1.1.5** Altium designer is not mandatory, but it's preferred to be the design tool.

## 1.2 Project Schedule

On Figure 1 we show a milestone of the project schedule and the expected delivery date. On the following sections we explain each part of the design schedule:

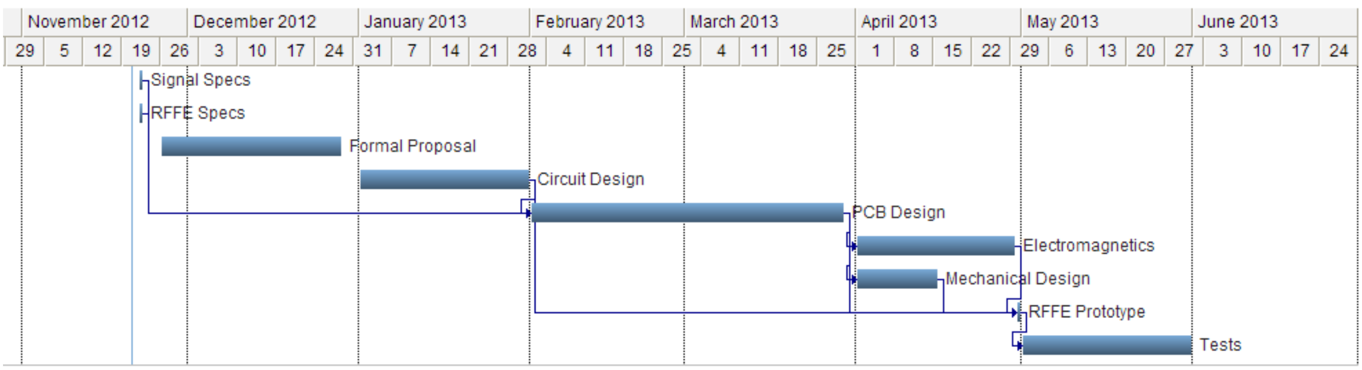


Figure 1: Milestone for the RFFE design.

[1] More details can be found at http://www.ohwr.org/projects/cernohl/wiki

# 2. Project description

## 2.1 Analog Front-End Specs

The Figure 1 shows the signal path from the BPM until the output of the RF Front-End. On this block diagram we included the Band-Pass filtering, the gain stage and the gain control that must be used for each of the four channels of the RF Front-End.

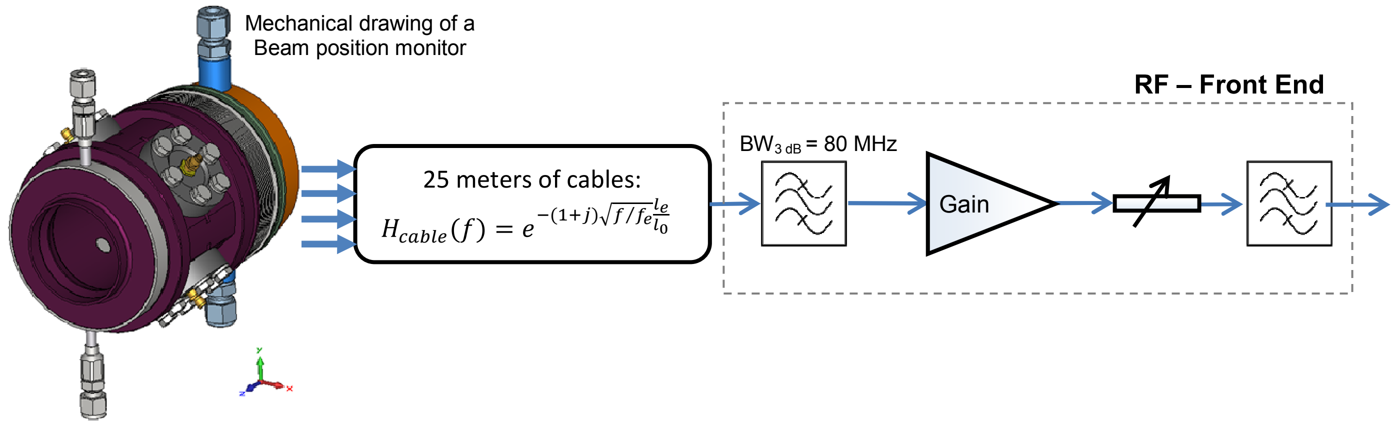


Figure 2: General block diagram that describes each of the four channels of the RFFE.

There are two modes of operation on the particle accelerator. The first one is called Single-Bunch, and the other one is called Multi-Bunch, which means that the machine can operate since 1 until 864 small electrons bunches running inside the vacuum chamber. On what follows we will show the time and frequency domain of the signals on the input of the electronics for each operation mode.

### 2.1.1 Single-Bunch operation

On single bunch there is just one electron bunch stored in the machine. On this case, the signal on the antennas will have the time signal characteristics as showed in Figure 3. This signal was obtained from an electromagnetic simulation, using a specialized toolbox for particle accelerators. For the complete simulation we used the cable LMR-400 from Times Microwave, and just considered the skin effect, resulting in a transfer function as presented on Figure 2.

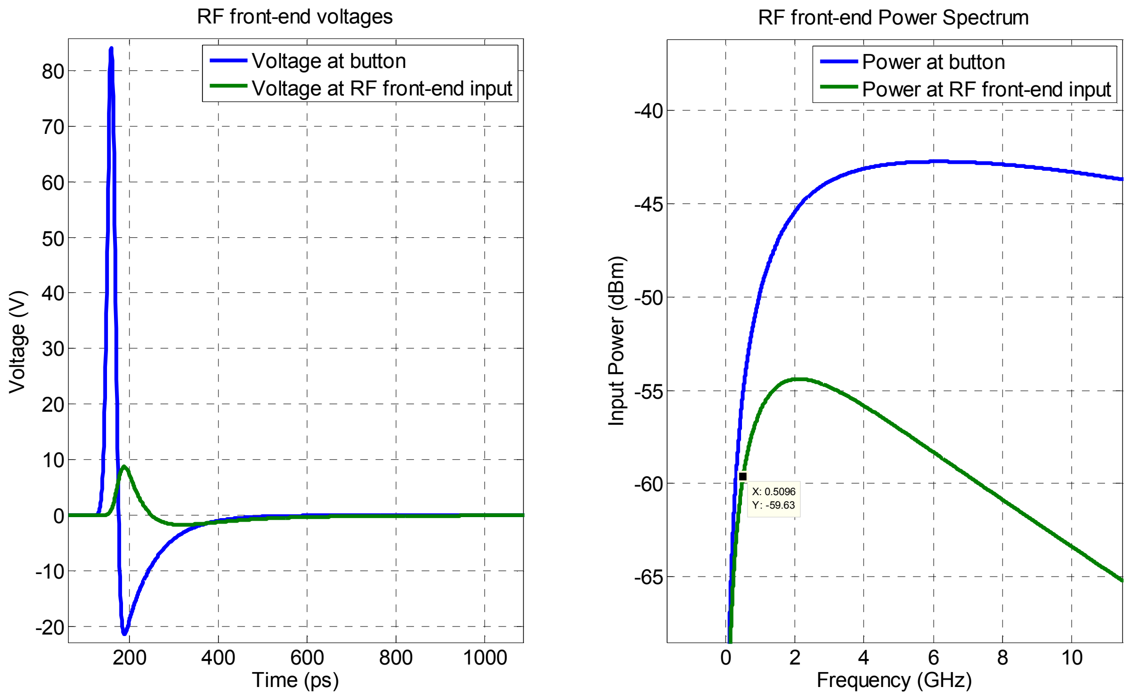


Figure 3: Time and frequency domain signal characteristics for the single-bunch mode of operation. The green curve is the signal after 25 meters of cables.

From Figure 3 we verify that the power spectrum has a wide bandwidth and low amplitude in each frequency component, but in time domain, the peak voltage is very high, and this effect could result in a nonlinear operation of the RF devices. This must be avoided in order to not saturate the filters, and all other active devices.

### 2.1.2 Multi-Bunch operation

On *multi-bunch* operation, 864 electron bunches are stored in the particle accelerator and they are separated in time by 2 ns, resulting in an information of beam position that will be extracted from the 500 MHz signal. The peak voltages are almost the same as shown in Figure 3, but the power of the 500 MHz signal will be different. We show in Figure 4 the power on the input of the electronics for a wide range of operation of electron beam current @ 500 MHz[2]. The single bunch mode operates from 1 mA to 10 mA and the multi-bunch operates at 500 mA.

[2] Electron beam current – the current stored on the particle accelerator as function of the amount of charge on the bunches stored on the accelerator.

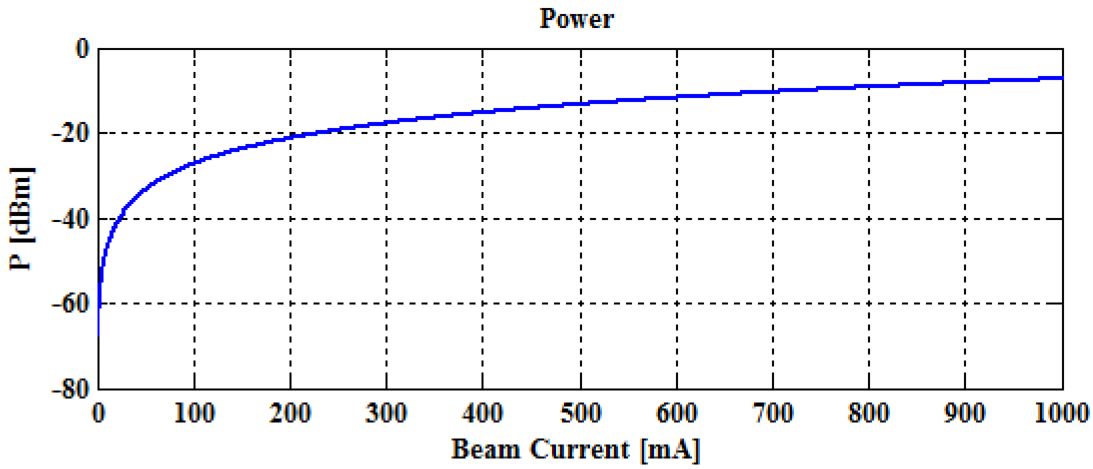

Figure 4: Signal characteristics on the input of the RFFE electronics as function of beam current for 500 MHz.

The signal shown on Figure 3 is the convolution of a few picoseconds Gaussian pulse with the BPM system response, which is composed basically by a few picoFarads capacitor in series with 25 meters of RF cables and terminated in 50 Ω.

The desired information on antennas is on the central RF frequency of 500 MHz. Other frequency components are present on the spectrum and must be filtered out to prevent from non-expected behavior of the devices (for example, heating and nonlinearities). We suggest that the RF chain follows the scheme of the Figure 2.

According to what was described on the previous sections, and other assumptions, we have the general specs of the RFFE, on Table 1.

| Parameter | Description | Value |
|---|---|---|
| Dynamic Range | | 40 dB |
| Input power | | -60 dBm to -10 dBm |
| Delta-over-Sum | [3] | $<10^{-4}$ |
| Adjustable Gain | Variable gain to accomplish 5 dBm at output | 0 to 50 dB (range) |
| Noise Figure | [4] | As low as possible |
| Central frequency | | 500 MHz |
| Crosstalk | [3] | < -50 dB |
| System Impedance | | 50 Ohm |
| Bandwidth (3 dB) | | 80 MHz |
| 0.1 dB Compression Point | [4] | >10 dBm input power |
| Long term stability | | Better than 2 mdB |

Table 1: RF Specs for the Sirius Analog Front End.

[3] More details can be found on the "Calibration specifications" section and on "Tests Specifications" section.
[4] Considering the electronics operating on a standard operation (attenuators adjusted for 5 dBm at output with a -15 dBm at input).

On Table 2 we show the information related to the circuit.

| *Parameter* | *Description* | *Value/range* |
|---|---|---|
| *In/Out RF connectors* | *Gold finish SMA* | |
| *Output connector* | *DB-62 sub-male* | |
| *Temperature sensors* | *Monitor the temperature near the critical RF devices* | |
| *Environment Temperature* | | *20 °C to 30 °C* |
| *Environment humidity* | | *20 % to 70 %* |
| *Input DC supply* | *High stability for the RF passive/active devices* [5] | *9 Volts* |
| *Boards Qty* | *Prototype* | *3* |
| *Board Finishing* | *ENIG* | |
| *Mechanical* | | *19" rack, height: 2U* |

Table 2: Specs for the Sirius Analog Front End.

### 2.2 Block diagram of the RFFE

On Figure 5 we show a simplified block diagram of the RFFE, including the interface between the RF block, digital control and a calibration circuit. This is a general configuration that we suggest and can be changed.

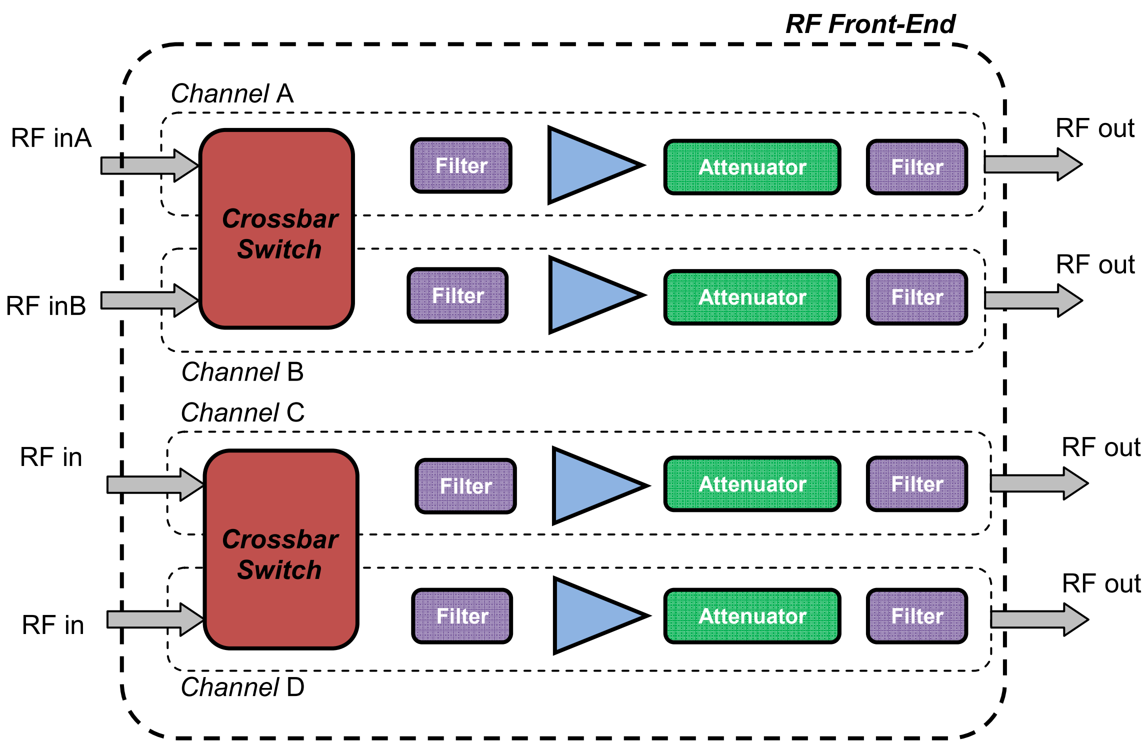


Figure 5: Diagram of the RFFE electronics.

[5] The power supply design must accomplish high noise rejection, fast transient response and temperature stability. The efficiency requirements are not priority.

**2.2.1** Requirements for the devices and configurations of the RF chain:

- **1.2.1.1** Low noise amplifiers with low noise figure, high linearity (for example, NF < 1.5 dB, Input power at P1dB > 25 dBm @ 500 MHz for amplifiers and P1dB > 30 dBm @ 500 MHz for switches and other active devices).
- **1.2.1.2** Filters, switches, amplifiers, couples and others with low drift over the temperature (consider the devices with lowest drift possible)
- **1.2.1.3** A shielding enclosure for the RF electronics is mandatory. It must shield each channel of the electronics.
- **1.2.1.4** The power supply has a significant impact on the performance of the RF chain. Consider low noise power supplies and minimize Crosstalk between channels through it.
- **1.2.1.5** Noise and crosstalk between channels must be carefully avoided.
- **1.2.1.6** The circuit must be designed for a central frequency of 500 MHz, but it must be easily adapted for the central frequency of 476 MHz. The reason is that the RF frequency of the accelerator determines it. For the LNLS-UVX particle accelerator this frequency is 476 MHz and for LNLS-Sirius[6], this frequency will be 500 MHz.

## 2.3 Digital specifications

The RFFE is being designed to interface with a digital electronics that will control all the RF devices with digital interfaces, like switches, digital attenuators and other that could be necessary. The digital circuit is being designed at LNLS and is not concern of the third party company.

**2.3.1** No digital design must be made. All the digital interfaces must be connected to the pins of the interface connector.

**2.3.2** Provide documentation with all the functions of the digital pins of the interface connector.

**2.3.3** Design the PCB minimizing the Electromagnetic interference of the digital lines on the RF signals.

**2.3.4** Design carefully the PCB in order to separate digital and RF ground planes.

**2.3.5** No special design must be made in order to have high speed digital signals. A maximum data clock frequency should be around 10 MHz.

**2.3.6** Separate all the digital supplies from the RF supplies, minimizing the crosstalk through the power supply.

## 2.4 Calibration specifications

It was included a calibration stage to correct the non-linearity and long term drifts in order to fulfill requirements. The following topics must take into account on the design of the RFFE.

**2.4.1** Take into account a special calibration stage, called a *Crossbar Switching scheme,* as described in this section.

[6] LNLS-UVX is a particle accelerator that is working since 1997 in Campinas, SP, Brazil. LNLS-Sirius is the new particle accelerator that is in the design stage and will be built near the LNLS-UVX.

**2.4.1.1** Switching scheme – In order to accomplish the non-linearity requirements a special calibration was proposed by *Jean-Claude Denard*[7] and first implemented by *Instrumentation Technologies* in a commercial Beam Position Monitor system[8]. This calibration was called crossbar switching, and must be designed to accomplish the scheme showed on Figure 6

**2.4.1.2** The crossbar switch is not commercial and must be designed using SPDT switches.

**2.4.1.3** The switching time (50% Control to 90/10% RF) must be better than 1 µs.

**2.4.1.4** Use switches with the highest 0.1 dB compression point. As the switch will be the first active device on the RF chain, we suggest that it has P0.1dB for an input power higher than 30 dBm.

**2.4.1.5** The crosstalk between channels on the switch must be better than 50 dB.

**2.4.1.6** The symmetry on the *Crossbar Switching scheme* is mandatory. It is one of the most important blocks of the electronics.

**2.4.1.7** The temperature must be controlled on the switches of the *Crossbar Switching scheme*.

**2.4.1.8** PCB design must be made in order to have almost same impedance on the 4 channels. We suggest the same electrical length and symmetrical placement of devices for all the channels.

**2.4.1.9** The effect of the temperature variations on the devices performance is important, for example, for some SAW filters, the temperature coefficient was measured around 0.01 dB/ºC, and this effect may disturb the long-term stability of the system.

**2.4.1.10** Another calibration schemes could be proposed.[9]

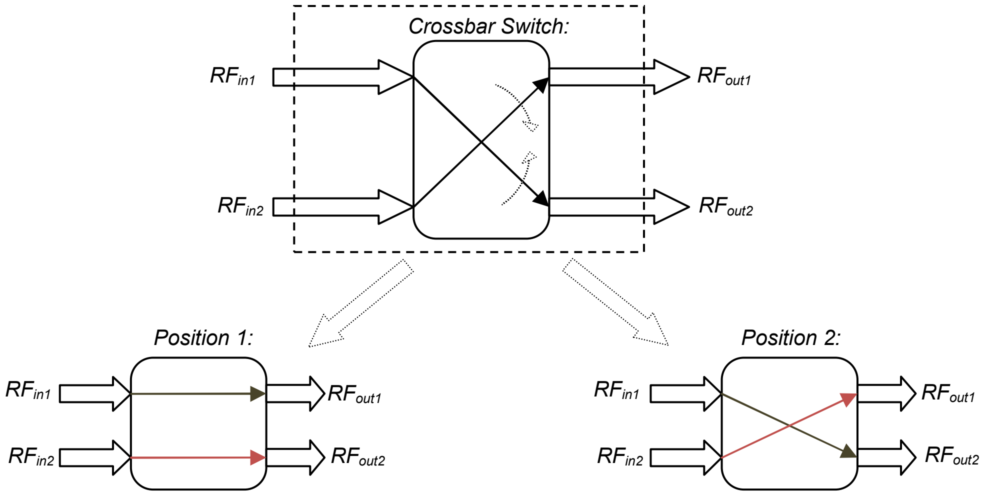


Figure 6: Crossbar switching scheme. The post-processing will correct the non-linearities from the measured signal using this *Crossbar switching scheme*.

[7] Electrical engineer Consultant.
[8] Commercial Beam Position Monitor system – Libera Brilliance +: http://www.i-tech.si/
[9] Another synchrotrons and commercial BPM electronics use different calibration and compensation schemes to correct the nonlinearities and drift over temperature. More details could be found in [1], [2] and [3].

# 3. Tests Specifications

On this section we specify the tests that the RFFE must be subjected in order to fulfill the requirements listed on Table 1.

## 3.1 Test procedures and documents

The following procedures and documents must be generated from the tests and delivered to LNLS:

**3.1.1** Test Documentation

**3.1.2** Test Raw Data

**3.1.3** Prepare and discuss with LNLS all system specific test plans

**3.1.4** Perform tests in accordance with test plans, satisfying the requirements and specifications of this document.

## 3.2 Position Measurement

The procedure to measure the position of the electron beam on the vacuum chamber and to increase the sensitivity of the measurements considers in calculating what we call the *Delta-over-Sum,* which will be used for the specification of some parameters of the electronics. This calculation is related to the beam position measurement which relates the RF outputs to the beam stored on the ring. Considering that $Va, Vb, Vc \text{ and } Vd$ are the output voltages on each of the four channels, the Delta-over-Sum is calculated by the following expression:

$$\Delta/\Sigma = \frac{Va + Vb - Vc - Vd}{Va + Vb + Vc + Vd} \qquad \text{Eq 1}$$

## 3.3 General and RF specifications

### 3.3.1 Test name: General characteristics

This test must show the RF characteristics of each of the four channels of the electronics:

**3.3.1.1 Test 1**: Noise Figure[10]

- Measured in the bandwidth: 0.4 - 0.6 GHz

**3.3.1.2 Test 2**: Dynamic Range

**3.3.1.3 Test 3**: 0.1 dB Compression point

- Measured for 500 MHz and for 476 MHz.

**3.3.1.4 Test 4**: DC Power consumption[6]

[10] During the test, all the attenuators need to be fixed, and no changes can be done on its values. The standard operation considers the attenuators values in a such way to provide 5 dBm at output with a -15 dBm at input

### 3.3.2 Test name: S-parameters

The isolation between channels and frequency response must be satisfied, following the specified data on table 1. The S-parameters that must be measured are listed below:

**3.3.2.1 Test 1**: Gain and impedance matching: $S_{11}$, $S_{22}$, $S_{33}$, $S_{44}$, $S_{15}$, $S_{26}$, $S_{37}$, $S_{48}$, $S_{55}$, $S_{66}$, $S_{77}$, $S_{88}$

**3.3.2.2 Test 2**: Crosstalk: $S_{16}$, $S_{17}$ $S_{18}$, $S_{25}$, $S_{27}$, $S_{28}$, $S_{35}$, $S_{36}$, $S_{38}$, $S_{45}$, $S_{46}$, $S_{47}$, $S_{12}$, $S_{23}$, $S_{34}$, $S_{56}$, $S_{67}$, $S_{68}$, $S_{78}$

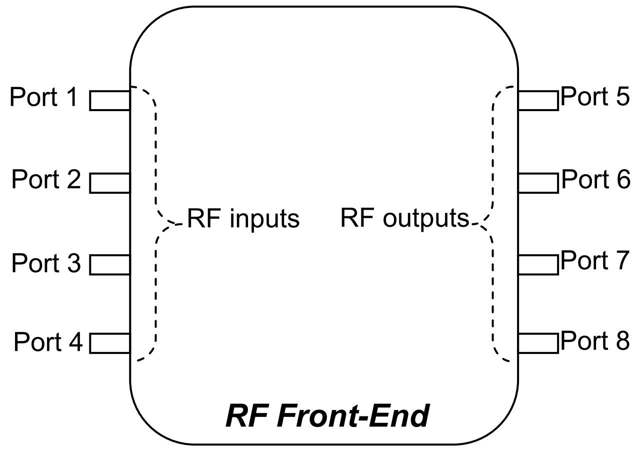


Figure 7: Reference number for the ports of RFFE.

Considerations:

**3.3.2.3** When measuring the S-parameters between 2 ports, all the other ports must be matched at 50 Ohms.

**3.3.2.4** All the S-parameters must be measured for two bandwidths. From 0.01 to 1 GHz and 0.4 to 0.6 GHz.

## 3.4 Stability

### 3.4.1 Test name: Long term stability - Temperature dependence

The RFFE electronics will be installed on an environment where the temperature will change between 20 ºC to 30 ºC. So, some performance tests must be realized at a climatic chamber to verify the electronics dependence as a function of environment changes.

**3.4.1.1 Test 1**: The temperature inside the climate chamber must be changed between 20 ºC to 30 ºC in 2 ºC steps.

3.4.1.1.1 The output power of the generator must be *splitted* by 4 and the input power on each channel must be -15 dBm[11] for 500 MHz.

3.4.1.1.2 The *Delta-over-Sum* must be monitored during this test and must be less than $2.10^{-5}$.

3.4.1.1.3 Each step must be maintained long enough for thermal stabilization.

3.4.1.1.4 The humidity must be controlled within 10% of the initial value.

**3.4.1.2 Test 2**: The temperature of the environment must be controlled in 30 ºC +/- 1 ºC for 24 hours.

3.4.1.2.1 The output power of the generator must be *splitted* by 4 and the input power on each channel must be -15 dBm[7].

[11] Care must be taken to the Power Splitter. Temperature variations in this device can lead to uneven power division. Ideally the Power Splitter should be kept in a controlled environment.

3.4.1.2.2 The *Delta-over-Sum* must be monitored during this test and must be less than $2.10^{-5}$.

3.4.1.2.3 The humidity must be monitored and controlled between 20% to 90% RH during the test.

### 3.4.2 Test name: Temperature distribution

**3.4.2.1 Test 1:** This test must show the temperature distribution on the board when working on the standard condition of input power -15 dBm and in a stabilized environment of 20 ºC +/- 0.2 ºC.

Considerations:

**3.4.2.2** This test must show if some devices in the board are heating excessively and if the temperature gradients on the board could determine some correlation between temperature and a nonlinear behavior measured before. We show in the example of figure 7 a picture of the temperature distribution in an electronic board.

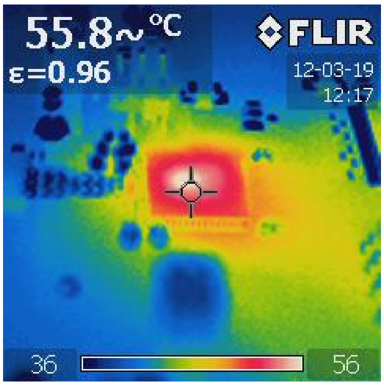


Figure 7: Temperature distribution in an electronic board.

## 3.5 Fine-Tune Tests

### 3.5.1 Test name: Linearity as function of input power.

The linearity of each RF channel must be measured using a special circuit and method. This method was proposed and patented by Jean-Claude Denard and implemented at LNLS with good results. On this scheme we measure a well known difference between two signals applied to the DUT. A combination of two SPDT RF switches and two attenuators were used to measure the signal through two paths with a known attenuation. The scheme is presented on Figure 8.

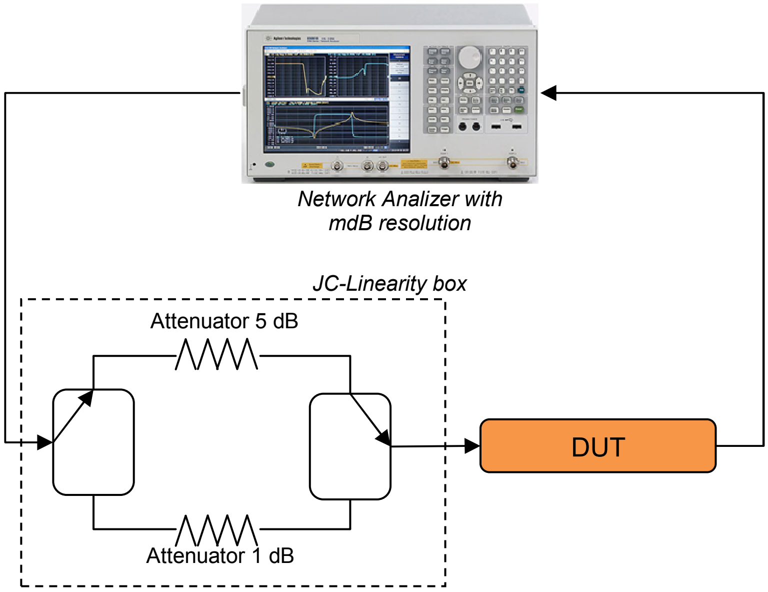


Figure 8: Scheme used to measure the linearity of active devices.

The procedures to measure linearity consist in fixing an input power on the JC-linearity box and switch this signal through one attenuation path. After measured the $S_{21}$ parameter, we change the two switches, so that the signal pass through the other attenuation path and then measure the $S_{21}$ parameter for this case. Making the difference of the $S_{21}$ parameter between the two attenuation paths, we know the slope of the power response of the DUT because we know the power difference between the two signals. This procedure is made for a wide range of input power, for example, from -45 dBm to 10 dBm in 2 dBm steps. By this way, we can evaluate the characteristics of the device.

Considerations:

**3.5.1.1** This specific test must be discussed with LNLS.

**3.5.1.2** The non-linearity tests must be made on each of the four channels and the results must be provided in a plot of $S_{21\_5dB}$ - $S_{21\_1dB}$ as function of input power.

**3.5.1.3** During the test all the attenuators need be fixed and no changes can be done on its values. The variation of the input power must be made carefully because nonlinearities in the order $10^{-4}$ can be easily inserted by the generator.

**3.5.1.4** Tests performed for the specified range of input power established on table 1 in steps of 2 dB.

**3.5.1.5** The *JC-linearity box* can be provided by LNLS.

**3.5.1.6** The Network analyzer must have more than 1 mdB resolution.

**3.5.1.7** The *JC-linearity box* must be inside a climatic chamber. The box must not even be touched during the tests.

**3.5.1.8** This procedure can be used to evaluate the linearity of each active device used on the RFFE.

### 3.5.2 Test name: Attenuator performance

**3.5.2.1** **Test 1:** Off-set variations: This test accomplishes variations between two fixed nominal values of attenuation, 0 dB and 15 dB, for a defined number of 20 repetitions. With this test it's important to determine the variations on the off-set of the attenuator in a scale of 0.001 dB.

**3.5.2.2** **Test 2:** Stabilization time: This test verify the switching time of the attenuators. It must determine the switching speed between 50% control to 10/90% of RF[12].

### 3.6 Digital Interfaces

#### *3.6.1* Test name: Digital control

On this test, all the digital interfaces must be tested to verify the correct behavior of the devices, accomplishing the specifications of the Table 1.

**3.6.1.1** The correct behavior of all the digital devices must be verified. For attenuators all the range of attenuation of each one must be tested.

**3.6.1.2** For switches, verify all the positions of each one.

### 3.7 General test suggestions:

**3.7.1** Climatic test chamber to realize the tests over temperature.

**3.7.2** High stability waveform generator. The drift over temperature must be at maximum 0.001 dB over 25 ºC +/- 2 ºC.

**3.7.3** Stable and high resolution spectrum analyzer for the specified measurements. The drift over temperature must be at maximum 0.001 dB over 25 ºC +/- 2 ºC.

**3.7.4** Stable and high resolution network analyzer for the measurements of general RF specifications. The drift over temperature must be at maximum 0.001 dB over 25 ºC +/- 2 ºC.

## 4. References

[1] B. N. Kosciuk, "Optimizing the Thermal Management of NSLS-II RF BPM Electronics," *Procedings of BIW12, Long Island, New York, US,* 2012.

[2] K. Vetter, "NSLS-II RF Beam Position Monitor," *Procedings of BIW10, Santa Fe, New Mexico, USA,* 05 2010.

[3] I. Technologies, "Libera Brilliance Plus," [Online]. Available: http://www.i-tech.si/accelerators-instrumentation/libera-brilliance-plus/benefits_1. [Accessed 07 2012].

[4] P. Forck, P. Kowina, D. Liakin, "Beam Position Monitors," Gesellschaft f¨ur Schwerionenforschung GSI, Darmstadt, Germany.

[12] Time plots of the RF signal must be documented, using -15 dBm input power at 500 MHz.