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Tune Measurement and Correction Systems

Isabella Stevani

Brazilian Synchrotron Light Laboratory, Campinas, Brazil

This document contains information about discussions and experiments done about tune measurement and correction systems. Its intention is to help in the comprehension about these two systems, using as an example the systems from UVX, the current operating particle accelerator at the Brazilian Synchrotron Light Laboratory (LNLS).

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1 Systems

1.1 Signal analyzer system

This is a **measurement** system.

The measurement is done by a signal analyser operating in spectrum mode. Its OUT pin is connected to an amplifier, which is connected to one of the eight connectors available on a stripline. The signal generated by the signal analyzer is a sinusoid with fixed amplitude and variable frequency (generally, this variation follows a sawtooth function).

- An amplifier is needed because the signal from the signal analyzer has not enough power to excite the beam.
- The opposite connector of the stripline is connected with an 50Ω load so the excess power could dissipate (the beam absorb only a few percent of the excitation power).
- To determinate the frequency range of the excitation signal, an initial and a final frequencies should be define. For tune measurement application, those two frequencies should be chosen in a way that the range contains the horizontal and vertical betatron frequencies.
- The amplifier gain could be adjusted remotely, but this is not considered in the measurement loop yet.

The signal received by the stripline excites the beam over a predefined frequency range. But is known that the beam oscillation amplitudes grow at the betatron frequencies, so its frequency response should be something like Figure 1.

The tunes can be obtained by the distance between the betatron frequencies (f_{ν_x} e f_{ν_y}) and their respective revolution harmonic. Dividing that distance by the revolution frequency, you can obtain the tune fractional part.

The beam oscillations are measured by a beam position monitor (BPM), stripline type. One of its connections is connected to the OUT pin of the signal analyzer.

- On both excitation and measurement processes, only one antenna is used. This configuration is sufficient because the antennas inside the striplines are positioned across de major axis (in other words, they're positioned like an X over tha vacuum chamber) in a way that its signal contains both plane information.
- The fact mentioned above is only possible because the bean trajectory oscillations (the ones caused by the betatron and dispersion functions) occurs

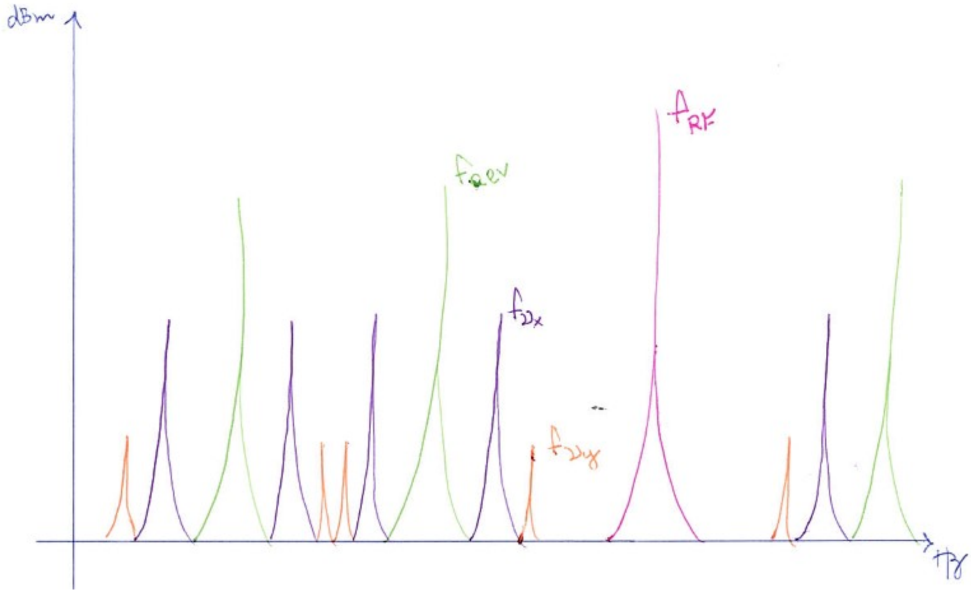

Figure 1: Rough sketch of the beam oscillation frequency response.

in a frequency much smaller than the excitation range of frequencies. Regarding that the excitation signal comes from the signal analyzer, this one knows exactly in which frequency it should analyze the signal, so it filters the measurement only over the predefined frequency range. In other cases, would be necessary collect the measurement from two opposite antennas and subtract their signals to obtain information only from the excitation oscillations.

1.1.1 Notes

It's important to emphasize one characteristic of this system. The excitation signal excites **all bunches**, no exception. But the power absorbed by them is so little that this don't affect the beam dynamics in a significant proportion. Still, it's sufficient to compute the tune measurement due to the great sensibility of the signal analyzer.

1.1.2 Possible issues and solutions

Plane identification

The signal analyzer system from UVX works with both planes at the same time, so both x-axis and y-axis frequency responses are displayed on the screen together. In that configuration, sometimes could be difficult for the tune measurement algorithm to identify which peak belongs to which axis.

A possible solution to that would be working with each plane separately, exciting and measuring one plane at a time with a switch to do that shift. The benefits would be that x-axis and y-axis measurements would be more isolated from each other, but the shifting process would make impossible to measure both planes simultaneously like the actual system does. Also, the measurement process would became slower.

Another possibility that could have all the benefits of the two listed above would be use two signal analyzers simultaneously, one for each plane. But this solution implies in buy another signal analyzer and develop a system to group the excitation signal from each device in just one that go to the stripline and then do the opposite with the measurement signal.

Peak tracking when operating with low-current

When the machine is operating with low-current, the beam frequency response generated by the excitation process could be so small that, if the tune measurement algorithm is based on a peak tracking logic, it could not be able to distinguish the right peak from noise.

A way to increase the frequency response amplitude is to increase the amplifier gain, transferring more energy to the beam during the excitation process. So, a good solution to this problem would be adding the amplifier gain in a control loop that identifies if the machine is operating with low-current. If it is, the amplifier gain is increased to make the tune measurement possible.

Peak tracking when operating at high chromaticity

At high chromaticity, sidebands of similar amplitude could appear near the betatron frequencies, causing the same peak tracking problem mentioned earlier. While studying the oscillations eigenmodes, an idea to solve this problem occurred.

At each eigenmode, the frequency response amplitudes could be different. That said, could exist an eigenmode where the amplitudes at the betatron frequencies are higher, maybe higher than the sidebands caused by the high chromaticity. If this happens, the peak tracking logic would be able to measure the tune again. To do this, it should be enough measuring the tunes at these higher amplitude harmonics.

1.2 Bunch-by-bunch

This is essentially a **correction** system, but it could be used for **measurement** too.

The oscillations that the bunch-by-bunch (BbB) system wants to correct are the coherent coupled bunch oscillations. In this type of oscillation, all bunches oscillates with same amplitude and frequency. The only thing that can vary from one bunch to another is the phase of their oscillation, but the phase difference between any two consecutive bunches remains constant. This phase difference is described as

$$\Delta\varphi = m\frac{2\pi}{M} \tag{1.1}$$

where M is the number of bunches and m is an integer between 0 and $M-1$ called multi-bunch mode number.

Although the physical explanation about how coherent coupled bunch oscillations occurs it's not the focus here, it's sufficient to say that this type of instability is "excited by the interaction of the particle beam with its surroundings" [1], and this interaction can excite different multi-bunch modes at the same time. In any case, the phase difference $\Delta\varphi$ remains constant.

- Both two transverse planes and longitudinal plane are affected by those oscillations. Therefore, the BbB system acts over all of them.

Differently from the spectrum analyzer system, the BbB system doesn't need to excite the beam. It's already excited by the coherent coupled bunch oscillations. So only a measurement and a correction process are necessary.

The measurement process starts with a BPM. All its four antennas are used, and their signals are carried out to an analogue system called monopulse. The monopulse process these four signals and turn them into three outputs: x, y and z which, for a configuration like the one shown in Figure 2, are essentially given by

$$x = \frac{A+D-B-C}{z} \tag{1.2}$$

$$y = \frac{A+B-C-D}{z} \tag{1.3}$$

$$z = A+B+C+D \tag{1.4}$$

where A, B, C and D are the signals received from antennas A, B, C and D, respectively. A more detailed explanation about how this position calculation is done could be find in [2].

Then, these three analogue signals go to a demodulator unit called front-end which "receives the position error signals modulated around the third harmonic, provides gain and proceeds with analog down-conversion" [2]. Roughly speaking, it prepares those signals so they could be used on the next BbB system stages.

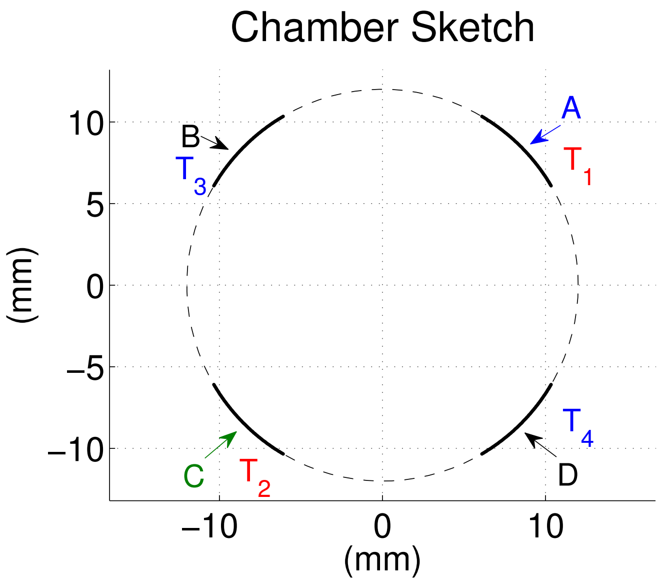

Figure 2: Vacuum chamber illustration showing BPM antennas position. Reprinted from [2].

Proceeding, all front-end outputs go to the processing unit, the core of the BbB system. It receives those signals and split them to various processors, one for each bunch. In that way, each processor can work independently with its respective bunch signal and all bunches signals are processed simultaneously. In this process, all the correction signal calculus is done. In a few words, when the BbB system starts, the processor waits until it has enough samples to compute a wave signal that models the original one. When it does, since the oscillation frequency is almost constant, it could generate an opposite signal (one with a phase difference of 180 degrees) to correct the oscillation just by waiting the exact time the original signal takes to advance its phase in 180 degrees. Doing that spares the processor from generating an opposite wave signal, which would cost some important processing time. Finally, it brings all bunches signals together to compute its output.

- The number of samples needed to model the original signal is defined by the number of taps of the output FIR filter. Those samples fill a buffer used to compute the correction signal. This buffer starts empty and, as the samples are arriving, it substitutes the last sample for the new one. So, after this minimum number of samples is achieved, the measurement is always computed with the newest samples.

At UVX, "the transverse system implemented (...) is based on Instrumentation Technologies processors. Dimtel's iGP processor for controlling longitudinal instabilities were also evaluate at UVX storage ring" [3].

After the processing stage, the signal pass through an amplifier and goes to the control system actuator, which is a stripline kicker for both transverse systems and a longitudinal kicker (overloaded cavity) for the longitudinal one.

- An amplifier is needed because the signal from the processing unit has not enough power to excite the beam.
- At UVX, only one stripline kicker is used to correct both transverse planes. But use one kicker per plane has some important advantages such as avoiding cross-talk between planes and enabling the usage of larger striplines, which would increase the field strength.

Figure 3 presents a general topology of the BbB system.

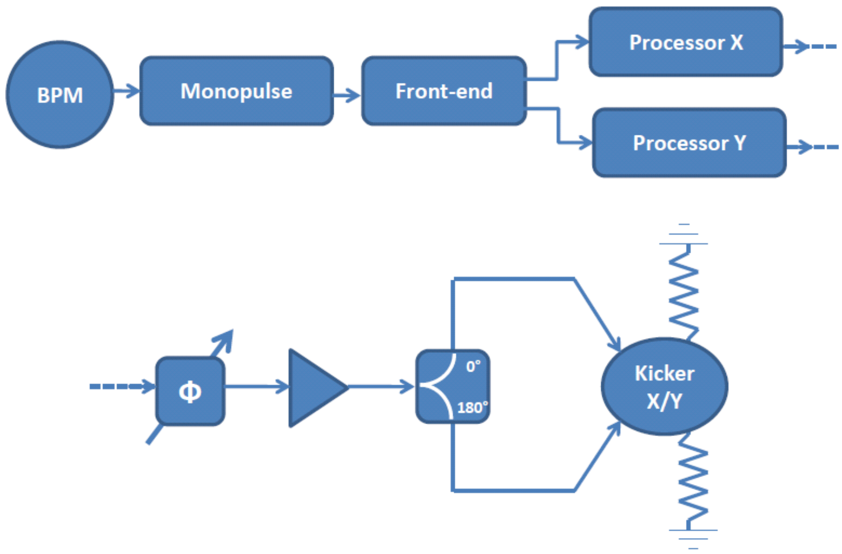

Figure 3: Bunch-by-bunch feedback system general topology. Reprinted from [3].

To turn this into a measurement system, it's possible to modified the BbB system so its output be in phase with the original signal. This would change the configuration of the control loop from a negative feedback to a positive one, exciting the beam instead of damping its oscillation. Then it's only necessary to convert the signal from time domain to frequency with a Fast Fourier Transform (FFT). Fortunately, each bunch is processed separately and one bunch is sufficient for measuring the tunes. So the BbB system could be configured to work with one bunch in positive feedback and the others in negative feedback, measuring the tunes and still correcting the coherent coupled bunch oscillations.

1.2.1 Notes

There are some important differences between signal analyzer and BbB systems that should be emphasized.

First, the signal analyzer system works in frequency domain, while the BbB works in time. Frequency domain analysis are characterized for its high sensitivity and slow response. On the other hand, time domain analysis are exactly the opposite: characterized by low sensitivity and fast response. So, if something with little and periodic variation needs to be observed, a frequency domain system is more suitable. But if it's something with big and momentary variation instead, a time domain system is required. Which are exactly the cases of the signal analyzer and BbB systems, respectively.

Second, when the BbB system is operating with one bunch in positive feedback, a common question would be if this affects the beam stability or something else. The answer is no. When only one bunch is outside the control loop, neither the beam stability or the machine emittance are significantly affected.

1.3 UVX devices

Here are described some characteristics of the devices from UVX used in any of the systems presented in this document.

1.3.1 Signal analyzer system

- **Excitation device**
  Device: Stripline
  Name: AEX08
  Available connectors: 8
  Length: 15 cm

- **Measurement device**
  Device: BPM Stripline type
  Name: AMP11B
  Available connectors: 4 (4 others internally short-circuited)
  Length: 6 cm

References

1 LONZA, M. **Multi-bunch feedback systems**. 2013. Elettra Synchrotron Light Laboratory.

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3 DIG-LNLS. **Beam Diagnostics and Feedback System**. ⟨https://wiki-sirius.lnls.br/mediawiki/index.php/Machine:Beam_Diagnostics_and_Feedback_System⟩. Accessed: 2016-07-19.