# BREAKING NEW GROUND WITH HIGH RESOLUTION TURN-BY-TURN BPMS AT THE ESRF

L.Farvacque, R.Nagaoka, K.Scheidt, ESRF, Grenoble France

*Abstract*

This High-Resolution, Turn-by-Turn BPM system is a low-cost extension to the existing BPM system, based on the RF-multiplexing concept, used for slow Closed-Orbit measurements. With this extension Beam Position measurements in both planes, at all (224) BPMs in the 844 m ESRF Storage Ring, for up to 2048 Orbit Turns with 1 micrometer resolution are performed.

The data acquisition is synchronised to a single, flat 1 uS, transverse deflection kick to the 1µs beamfill in the 2.8µs revolution period. The high quality of this synchronisation, together with the good reproducibility of the deflection kick and the overall stability of the Closed Orbit beam allows to repeat the kick & acquisition in many cycles. The subsequent averaging of the data obtained in these cycles yields the 1um resolution.

The latter allows lattice measurements with high precision such as the localisation of very small focussing errors and modulation in Beta values and phase advances. It also finds an unique application to measure, model, and correct the (H to V) Betratron coupling which recently showed successfully the reduction of coupling and vertical emittance below respectively 0.3% and 12picometer.rad. This method takes full benefit from 64 BPM stations situated around 32 straight-sections (no focussing elements) of 6m length allowing the phase-space measurements in their centers.

## 1 EXTENSION TO THE EXISTING CLOSED-ORBIT BPM SYSTEM

### *1.1 The 'slow' BPM system for Closed Orbit*

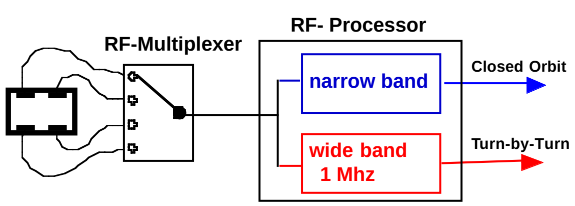



fig.1 the BPM RF-Mux concept with fast & slow output

The C.O. BPM system measures the electron beam Closed Orbit position in the Storage Ring at a slow rate of 1Hz at 224 individual BPM stations evenly distributed in the Storage Ring. This measurement is an average of many turns and taken on all the beam filling i.e. all bunches & electrons. This C.O. BPM system is at the heart of the slow Global Orbit correction scheme that attains the objective of serving the beamlines with a stable positioned beam over time periods of a few seconds to hours, days, weeks and longer [1].

The requirements of notably high reproducibility, low drift and low dependency on beam fill were fulfilled using the concept of RF-Multiplexing. [2,3] Each BPM station scans the 4 signals from the electrode buttons by an RF-Multiplexer device and performs all the signal conditioning operations (filtering, amplification, detection, digitization) on the 4 time-multiplexed signals by a single RF Processor. (see fig.1) This offers the advantage of high immunity to variations of characteristics (gain, linearity, offset) of the Processor electronics (since it affects the 4 signals equally). However, the drawback is that the slow scanning (millisec) does not allow to measure a beam position on a single beam turn (microsec).

Nevertheless, the Processor possesses 2 channels of signal conditioning : 1) a narrow band, low noise channel, and 2) a wide band (1MHz) for fast signals (1µs). With the latter a single turn can be detected, but only on one electrode at a time. Consequently a position measurement needs 4 separate cycles. It is in this way that First-Turn BPM measurements after injection have been performed to satisfaction with the existing system.

After careful analysis of the applications that the Turn-by-Turn BPM system would fulfil it was concluded that in a similar way the position data on a large number of turns could be obtained.

### *1.2 a 'pseudo' Turn-by-Turn beam position measurement system*

A wealth of information can be obtained on the beam characteristics and machine parameters by measuring the beam position on a turn-by-turn basis after the application of a single deflection kick. [4-15]

Note that the measurement is to be synchronised with this deflection kick. If this synchronisation is precise and if this kick is of good reproducibility then the measurement can be performed in 4 distinct cycles (1 for each of the 4 electrodes). Moreover, each cycle may itself be repeated a large number of times. The individual measurements can be averaged which then improves the resolution of the results. It is essential that the beam is otherwise stable during the whole measurement sequence. It is obvious that the system is a 'pseudo' turn-by-turn system since the data is acquired over many cycles during a time much longer then N x revolution time. However, this has no effect on the information that the system yields, i.e. turn-by-turn beam position after an applied beam excitation, since the beam excitation and the data acquisition are intimately synchronised, and therefor reproducible & repeatable.

### *1.3 Hardware & Software additions :*

The extension had to be realised without interfering with the existing BPM system that permanently serves the slow orbit correction. Since the RF electronics would be untouched the main hardware additions are :

- a data acquisition card (32 units) that digitises pulsed signals at 355Khz rate (upto 2048 turns) and performs an internal averaging (up to 4096).
- a synchronisation / timing network between the beam, the kick and 32 data-acquisition cards.

The software for driving and reading these devices was added with full compatibility with the existing system. A user-level application permits the setting of the parameters like number of turns and averaging.

The quality (stability) of the synchronisation is about 50ns. Also, due to difference in RF cable lengths, relative time delays (up to 120ns) exist between the 7 BPMs in one cell (digitised by the same card). Avoiding the slightest impact on the precision (and resolution) of the system by these time differences and timing (in-)stability implied the following conditions :

a) The beam-fill is partial up to a maximum duration of 1µs. b) The beam-kick is flat and uniform over the whole of the beam-fill. c) The data acquisition card incorporates a track & hold function of the peak input signal.

### *1.4 The Beam Deflection Kick*

For the deflection kick in the horizontal plane one of the four injection kickers could readily be used. They offer the advantage of delivering a flat & clean single kick of 1µs that is adjustable in strength with a maximum >10mm rms. These kickers have a negligibly small component in the vertical plane and equally negligible parasitic kick on the next beam passage (2.8µs). The injection kickers however are limited in repetition frequency to 10Hz.

For kicks in the vertical plane a HV pulser was implemented to an existing fast ferrite shaker (used for tune measurements). Its kick amplitude is limited to 0.5mm rms but the repetition frequency can be > 100Hz.

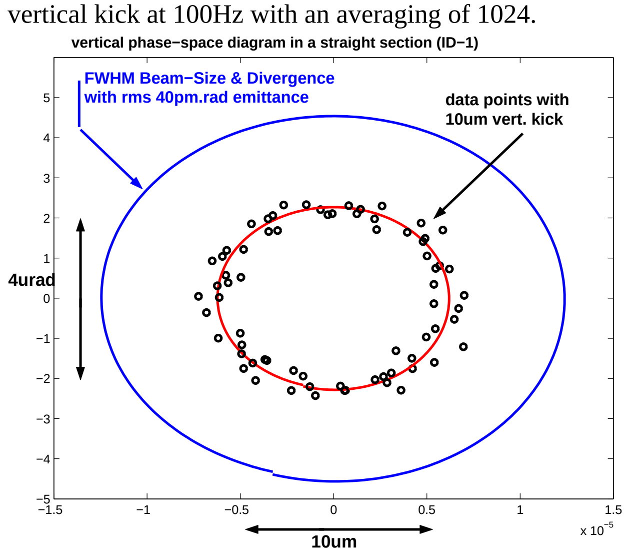
## 2 RESULTS : HIGH RESOLUTION

### *2.1 Resolution vs. acquisition-time and current*

The measurement time of the system is obtained by multiplying the number of averages with 4 (for the 4 electrodes) and dividing by the repetition frequency. For a beam current of 10mA (in 1µs beamfill) a resolution of 2µm is reached for an averaging of 256 (typically used). This value can easily be assesed by analysing the standard deviation of the position measurements on a number of turns (typically 16) before the kick is applied to the beam. The measurement time here is 103sec for a 10Hz repetition freq. (with injection kicker) or 10sec at 100Hz (with vertical shaker device).

The resolution varies square-root with the number of averaging and the beam current. Because of the use of switchable attenuators in the RF processors the resolution in the 0.5mA to 10mA beam current range is about the same as for the 10 to 200mA range.

However, this assesment only quantifies the noise (or resolution) of the data acquisition system, and not the contribution of fluctuations or imperfections of the beam deflection kicker. A way to estimate the resolution of the whole system is to construct phase-space diagrams and to compare the individual measurement points to a fitted phase-space ellips. The BPM distribution in the Storage Ring has 64 BPMs situated at the extreme ends of the 32 straight-sections (see figure 3). Separated 6.1meters they offer the possibility of drawing phase-space plots in the middle of these sections and to compute the optical functions. If the Storage Ring is operated at low chromaticity then a sufficient number of turns (e.g. >30) can be measured at a practically constant oscillation amplitude (i.e. negligible damping). The figure 2 here below shows a typical example in one of these straight sections of 70 phase-space points obtained with a 10µm vertical kick at 100Hz with an averaging of 1024.




The comparison of these points to the (red) ellips fitting indicates a resolution of about 1µm. Note that the large (blue) ellips represents the ESRF vertical beam-emittance (FWHM) with the standard operation of 1% coupling (40pm rms). This clearly shows that the system is capable of measuring phase-space plots that are a fraction of the ESRF's small vertical beam emittance.

The calibration errors of the BPMs was assesed by comparing the 32 invariants that can be computed in the straight sections, and found to be less than 2%.

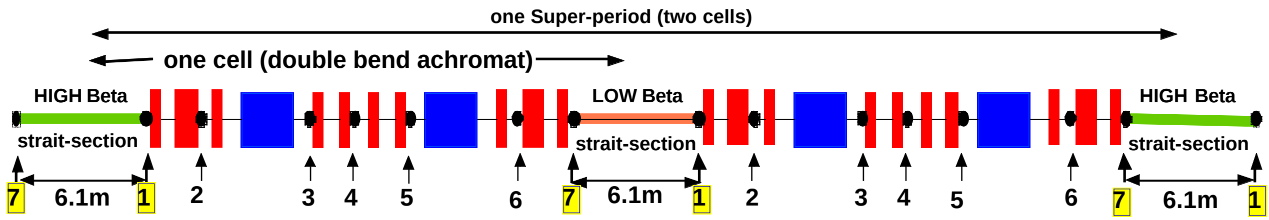



fig.3: the position of 14 BPMS in a 2-cell super-period with 2 BPMs at the extreme ends of all the straight-sections

# 3 APPLICATIONS AND RESULTS

## *3.1 Linear Optics*

The first use of the Turn-by-Turn BPM system is to study the linear optics of the machine. This requires a small excitation of the beam so that the non-linearities of the motion are negligible. Given the resolution of ~2 µm of the BPMs, this is usually done with an rms. beam excitation of 200 to 300 µm.

**Phase advance**

The phase advance $\varphi$ between BPMs is obtained by computing for each BPM the spectral amplitude and phase of the motion on the tune frequency. The average phase advance $\overline{\varphi}$ is computed by taking the average of the phase advances per superperiod. and the phase modulation is defined as $\Delta\varphi = \varphi - \overline{\varphi}$.

**β-functions**

The layout of the BPMs is such that in the 32 straight sections of the Storage Ring, we have 2 monitors, separated by 6.1 m without any intermediate magnetic element (fig.3). In such conditions, we can obviously get a phase-space plot of the beam trajectory in the middle of the straight section, from which we extract the Twiss parameters $\alpha$ and $\beta$, and the invariant of the motion of the kicked beam. This is independent of any calibration of the BPMs and kicker. The comparison of the 32 invariant values from the different straight sections shows the calibration errors in the different monitors. [16] Another method for extracting the $\beta$-functions is to scale the spectral amplitude of the motion on the tune frequency. This may be applied on each BPM. Combining both methods by adjusting the scaling factor to match the phase-space values gives the $\beta$-function on each BPM. The $\beta$-modulation is defined as $\Delta\beta = \left(\beta - \overline{\beta}\right)/\overline{\beta}$, with $\overline{\beta}$ is the average over all superperiods.

**Focusing errors.**

Focusing errors such as quadrupole length or gradient errors, or sextupole horizontal misalignment result in a modulation of the phase advances and $\beta$-functions. This appears on the results of MT-BPM analysis. [17] The method was tested by introducing arbitrarily a single focusing error with a quadrupole corrector magnet. The resulting tune shift was 0.006, and the error represents $2.10^{-3}$ of gradient error in the strongest quadrupole. Fig.4 shows the difference in phase advance with and without the error: such an error is well within the sensitivity of the method.

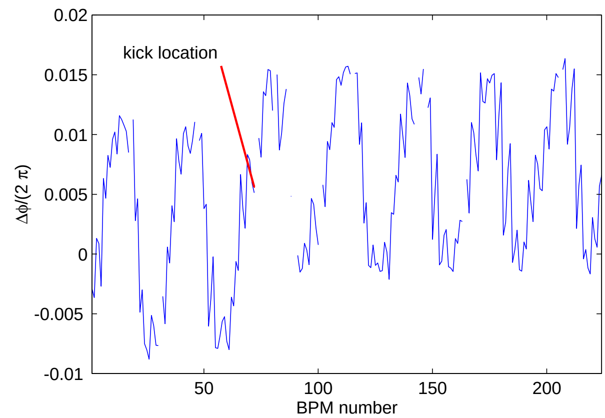



Fig.4: difference in phase-advance with a single focusing error

This was applied to draw the phase modulation with and without the resonance correction applied: Fig.5 shows that the resonance correction is indeed effective. The comparison with a similar data coming from the analysis of the response matrix of the Storage Ring shows an excellent agreement.

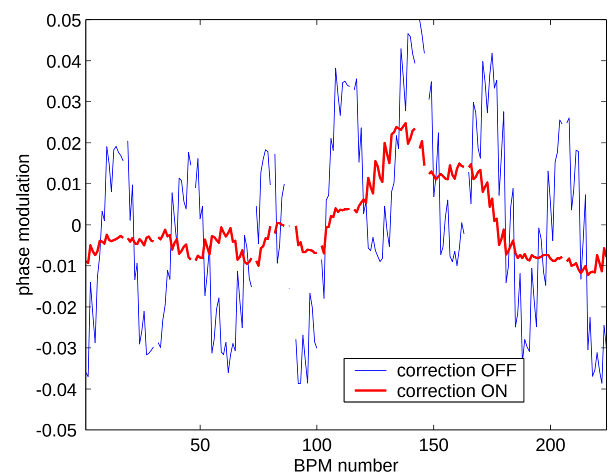



Fig. 5: phase modulation with and without correction

This was also used to try and identify the sources of multibunch detuning as a function of beam current.

**Betatron coupling**

By making full use of the excellent measuring accuracy provided by the system, an attempt was made to measure the betatron coupling through the normal mode decomposition [18]. The advantage of this method is clearly in its comprehensive description of the betatron coupling as opposed to those due to particular resonances, which has been found to be of great importance at the ESRF in achieving ultimately low couplings [19]. Although the quantity of interest for a light source such as the ESRF is the emittance coupling rather than the betatron coupling, it has been found that the latter counts for the major part of the former at the ESRF. The developed steps for the decomposition are as follows: For each straight section that has no focusing element in between two BPMs, 1) Construct the phase space (x, x', z, z'). 2) Fit the phase space data to extract a 4×4 one turn matrix. 3) Perform the normal mode decomposition to obtain the normal modes as well as the rotation matrix that transforms the geometric modes to the former.

The second step was found to be the most non-trivial, especially as the number of available turns is severely limited by the strong decoherence of the beam, which comes from tune shifts with amplitude, with momentum (chromatic modulation), as well as from the head-tail damping. To minimise them, measurements were made with a low beam current in 1/3 filling, a small oscillation amplitude given by a horizontal injection kicker, and a sextupole setting that gives zero chromaticities and minimal tune shift with amplitude. It turned out nevertheless that measured readings are sufficiently free from the decoherence effects only in the first few tens of turns. Since the matrix can be obtained using only 4 independent turns, the data over the first 20 turns were used to increase the precision through averaging. It was also found important in many cases to impose the symplectic condition to be fulfilled by the one turn matrix, to extract more ambiguous off-diagonal elements due to smallness of the vertical amplitudes.

The correctness of the results can be readily seen in the decoupling of the two normal modes (Figs. 6), as well as in constancy of the normal mode ellipses around the machine. The application was successful over the entire range of coupling, surprisingly down to the lowest coupling, where the vertical emittance of 8 pm.rad (~0.2% emittance coupling) was measured with a pinhole camera. Note that the corresponding normal mode phase space ellipse (Figs. 6 lower) measured has even a smaller magnitude than the vertical emittance. In fact, it was found that the decomposition at the ultimately low coupling requires a perfect machine stability and fails as soon as the beam is perturbed by external noises.

Although the ratio of the two normal mode ellipses in most cases closely followed the measured emittance coupling, it depends on the initial condition. The magnitude of off-diagonal elements in the rotation matrix, instead, represents the local coupling of the machine. The present scheme thus opened a new possibility of coupling correction with two advantages, one that the coupling can be measured at all ranges, and the other that it enables a global correction. At the ESRF, the response matrix approach, despite offering an accurate model of the coupling, could only measure the initial large coupling, and smaller couplings had to be measured with pinholes, which are located at only two positions in the ring. The first tests showed positive results, managing corrections in both high and low coupling regimes.

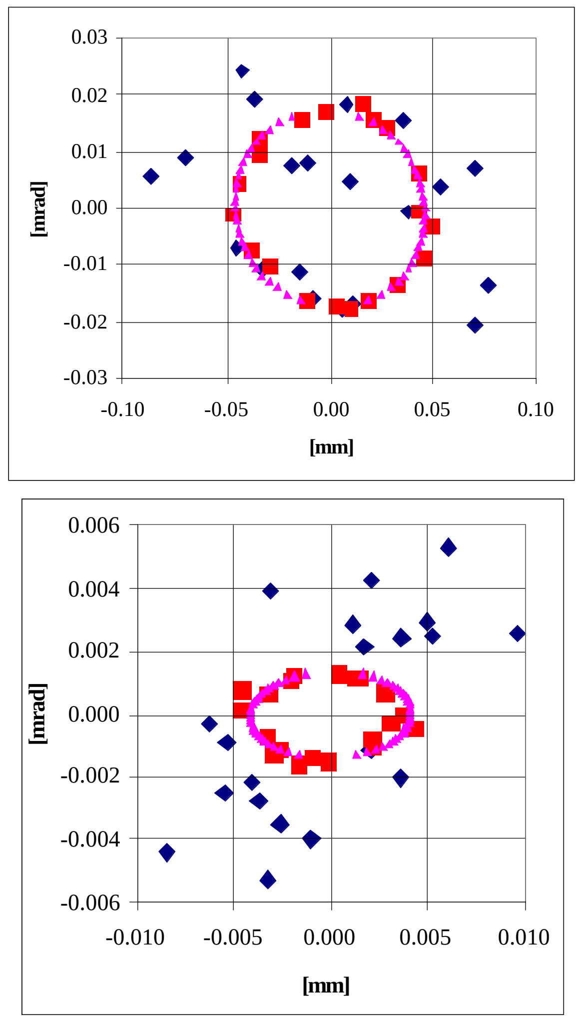



Fig.6: Two examples of decomposition showing the transformation from the vertical phase space (blue) to the normal mode (red), and triangles (pink), the fit of the normal mode. Upper: The standard operation setting (30 pm.rad vertical emittance). Lower: The lowest coupling (8 pm.rad vertical emittance).

### *3.2 Non-linear optics*

The MT-BPM system was also used to measure tune shifts with amplitude [20]. We need here larger kicker excitations. The oscillation is then damped in a shorter time because of the decoherence resulting from the tune dependence with amplitude within the bunch. The amplitude is measured by the invariant coming from phase-space analysis, the tune is given by the spectral analysis, both being taken over the first 20 turns only. The figure 7 shows a typical measurement for 3 different sextupole tunings.

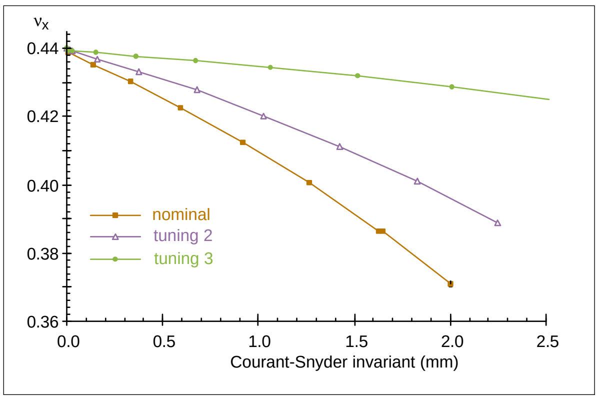



Figure 7: tune shifts with amplitude

## 4 CONCLUSION & FUTURE

The high resolution Turn-by-Turn extension has been implemented at a minimum cost and without any interference with the existing Closed Orbit BPM system. The system concept takes full advantage of the good reproducibility of the beam deflection kick and the stable synchronisation between this kick, the beam and the data acquisition system, allowing to repeat individual measurement cycles and to achieve micrometer resolution by averaging.

This has been used to study with precision and in detail the linear optics of the SR Machine and to model the betatron coupling to very small values. It is also a valuable tool for measurements of non-linear optics and the studies of injected beam conditions for which its application is planned in the near future.

## ACKNOWLEDGEMENTS

The authors would like to thank J.Cerrai and Ph.Chappelet for the digital hardware developments and M.C.Dominquez and J.L.Pons for the writing of the device-servers and application software.

## REFERENCES

[1] L.Farvacque "Beam Stability" CERN Accel. School on synchrotron radiation source and FELs, Grenoble 1996
[2] K.Scheidt, F.Loyer "Electron Beam Position Monitors : Performance Considerations", DIPAC-93, Montreux, May 1993
[3] G.Vismara "The Comparison of Signal-Processing for Beam Position Monitors", DIPAC-99, Chester UK, May 1999
[4] A.Hofmann "beam diagnostics and applications", BIW-98, Stanford,C.A. May 1998
[5] J.Borer et al.,"Harmonic Analysis of Coherent Beam Oscillations in LEP", EPAC-92, Berlin 1992
[6] A.Burns et al., "Betatron Function Measurment at LEP using the BOM 1000 Turns Facility", PAC-93, Washington D.C. 1993
[7] G.Morpugo, "The BOM 1000 Turn Display : a tool to visualise transverse Phase-Space Topology at LEP", EPAC-98, Stockholm
[8] P.Castro, "Applications of the 1000-turns Orbit Measurement System at LEP", PAC-99, New-York, 1999
[9] J.Klem et al., "Multiturn measurements at the CERN SPS", EPAC-2000, Vienna, June-2000
[10] J.Klem and G.Morpugo "a method to measure the Beta-beating in a 90 deg. phase-advance lattice", EPAC-2000, Vienna, June-2000
[11] K.T.Hsu et al., "functionality enhancement of the multiplexing BPM system in the storage ring of SRRC", this DIPAC-2001 proceedings Grenoble May-2001
[12] M.Lamont, G.Morpugo, H.Schmickler "Practical Diagnostic Measurements" Beam-Measurement Joint-CERN Accelerator School, Montreux May 1998
[13] F.Zimmerman, "Measurement and Correction of Accelerator Optics", Beam-Measurement Joint-CERN Accelerator School, Montreux May 1998
[14] K.Scheidt, "Diagnostics : Mille-Tours BPM system", ESRF-Machine Workshop Sassenage, Jan-2000
[15] R.Nagaoka, "Beam Studies with 1000-Turns BPMs", ESRF-Machine Workshop Sassenage, Jan-2001
[16] L.Farvacque, ESRF-Machine tech.note 1-00/Theory, Jan.2000, "Processing of 1000-Turn BPM system"
[17] L.Farvacque, "Modélisation des erreurs de couplage et de focalisation", Journées Accélérateurs de la SFP Roscoff, March-2000
[18] D. Edwards and L. Teng, "Parameterization of Linear Coupled Motion in Periodic Systems", IEEE Transactions on Nuclear Science, NS-20, No. 3, June 1973.
[19] R.Nagaoka, "Work carried-out at the ESRF to Characterise and Correct the Coupling", EPAC-2000, Vienna, June-2000
[20] A.Ropert, "Measurements of the Lattice Characteristics with the 1000-Turn BPM system", ESRF-Machine tech.note 08-00/theory, May-2000.