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Control server for the PS orbit acquisition system

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Abstract

CERN's Proton Synchrotron (CPS) has been fitted with a new Trajectory Measurement System (TMS). Analogue signals from forty Beam Position Monitors (BPM) are digitized at 125 MS/s, and then further treated in the digital domain to derive positions of all individual particle bunches on the fly. Large FPGAs are used to handle the digital processing. The system fits in fourteen plug-in modules distributed over three half-width cPCI crates that store data in circular buffers. They are connected to a Linux computer by means of a private Gigabit Ethernet segment. Dedicated server software, running under Linux, knits the system into a coherent whole [1].

The corresponding low-level software using FESA (BPMOPS class) was implemented while respecting the standard interface for beam position measurements.

The BPMOPS server publishes values on request after data extraction and conversion from the TMS server. This software is running on a VME Lynx-OS platform and through dedicated electronics it can therefore control the pickup sensitivities also making it a complete system. APIs for hardware experts are also available in order to either calibrate the system or to adjust the different TMS settings needed for each cycle.

Running this system in operational mode has already given very good results compared to the old CODD system and some of them will be presented in this document.

Geneva, Switzerland
October, 2009

1. Introduction

The purpose of this document is to describe the functionalities of the new PS orbit front-end server. This includes the type of data published, the timing events used to trigger the different software processes, an overview of the real-time mechanism, a presentation of the calibration strategy and the gain control, and finally a view on the JAVA expert application. As the system has started to be used in operational mode, a presentation of some first results will also be included.

2. Measurements acquired

2.1. Measurement definition

The acquisition system measures the trajectories of particle bunches in the PS. Each individual bunch, of which there may be up to 21, is measured. Measurements of 40 pickups are collected and combined on demand from the operational application programs to form several kinds of measurements:

[*Available from 2009*]

Bunch-By-Bunch Trajectory Measurement: Trajectory measurements of all bunches for all pickups over a specified number of turns (up to 200 000 measurements in total) starting from a specified delay in number of revolution periods. *Position [bunches][number of turns][H |V]*
Beam Orbit Measurement: The mean position of all bunches and for all pickups over a millisecond at 1ms interval. *Position [number in ms][40H | 40V]*
Beam Mean Radial Position (MRP): The mean of the beam orbit measurement over all pickups at 1ms interval. *Position [number in ms][H |V]*

[*Available from 2010*]

Bunch-By-Bunch Orbit Measurement: The mean position per bunch and for all pickups over a millisecond at 1ms interval. *Position [bunches][number in ms][40H | 40V]*
Bunch-By-Bunch Mean Radial Position: The mean of the bunch by bunch beam orbit measurement over all pickups at 1ms interval. *Position [bunches][number in ms][H |V]*

2.2. Calculation of the position

Raw sigma and delta data (turn by turn and 1ms averages) are provided by the TMS and converted into positions using the formula shown below (1). The FESA server calculates the MRPs by making an average of the orbit positions over all pickups.

$$Position = Offset + \frac{K * Delta}{Sigma} \tag{1}$$

Position: Position in 1/10mm units.
K: Scaling factor calculated during calibration, in 1/10mm units.
Delta and *Sigma*: Raw data acquired from the TMS in arbitrary units.
Offset: Mechanical offset (based on the last survey campaign cf. 9.) + electrical offset (alignment default of the electrodes inside the pickups measured by the surveyors cf. 9.) + error correction (calculated during calibration cf. 3.4), in 1/10mm units.

3. FESA control server

The BPMOPS real-time process, triggered by different timing events, manipulates data acquired from the TMS and publishes it to the different software clients. Settings, data and status are handled by the communication process (server process) which gives access to the internal FESA fields via a generic standard interface. The list of properties and fields has been specified while respecting the BI-SW software convention for position measurements [2] and extended in cooperation with operators, application program developers and hardware experts who are the main clients.

3.1. Real-time overview

The TMS system uses a fixed list of hardware timing events along the cycle. At the same time, the FESA server triggers three different RT actions consecutively. Before each cycle, the BPMOPS informs the TMS about the desired trajectories (Prepare). At the end of the flat top, it imports data from the TMS and it processes the data (Publish). On user request, it can also trigger an acquisition of the diagnostic signals (sigma, gate, baseline restore and local oscillator) with a resolution of 8ns during a time window of 32us which is explained in section 3.5 (Acquire).

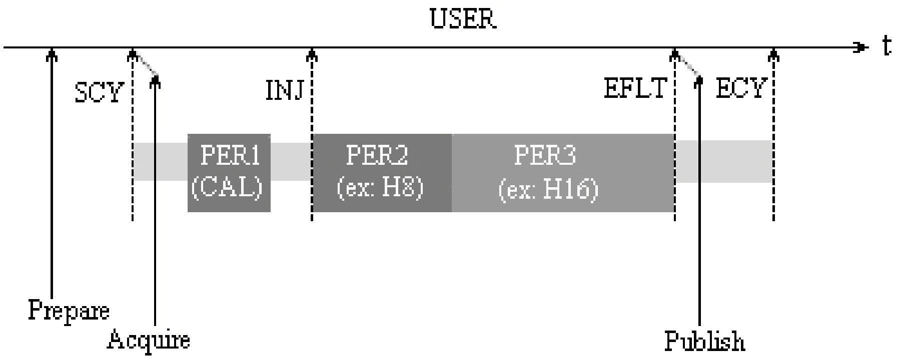


Figure 1 Hardware and real-time triggers

3.2. Instrument use

Three families of properties for interfacing with the BPMOPS server have been defined. This is needed to differentiate between 1) operators, 2) hardware experts and 3) software experts.

Operators should be able to acquire the orbit measurements requested in a specific way per cycle and to control the acquisition gating used in the low hardware level.

Setting (and LSA)*: Per cycle, the user can set the sensitivity, the delay in milliseconds and in turn number as a starting point for the acquisition of the trajectories.

Acquisition(s) (and LSA) & Sampler: Per cycle, acquisition of the MRP, the orbits and the trajectories in the H and V planes. These properties include information fields like measurement time stamps, cycle properties, number of measurements acquired etc. The number of points for the MRP and orbits should be equal to the number of milliseconds between the injection and the end of the flat top. The number of trajectories is linked to the number of bunches (harmonic number) and should not exceed 200000.

The hardware specialist needs to modify the TMS setting files that contain a description of a cycle. For example, the RF frequency at injection, the different harmonic periods along the cycle or even the number of bunches can be changed through the expert interface. Plotting of the raw hardware signals is important to diagnose and to evaluate settings but also to correlate it with the raw sigma signal (linked to the beam).

ExpertSetting: Setting of the arrays used for the calculation of the positions (offset, sensitivity…).
DiagnosticSetting: Acquisition trigger of the diagnostic plots.
ExpertSettingDiag: Settings for the diagnostic.
SptInterface: Interface to the TMS setting files.
ExpertAcquisitionDiag: Diagnostic plots.
Trig/ExpertCalibration: Triggering and acquisition of the calibration data.

Software flags dedicated for switching on and off special functions need to be set by the software specialist.

GuruSetting: Software settings to control the logging and to enable the gain control.
GuruAcquisition: Acquisition of all the data acquired by the real-time process.

** LHC Software Applications.*

3.3. Gain control

The system has several control modules, which interface with the control system in order to allow remote control of gains and the intensity of the calibration signal.

Each cycle, the gain is set according to the intensity setting selected by the operators. Sixteen predefined intensity settings cover an intensity range from 1E8 to 1E13 particles per bunch. However, only gains corresponding to bunch intensities from 1E9 to 5E12 are used.

Gain1	Gain2	Gain3	Gain4	Gain5	Gain6	Gain7	Gain8
1E8	2E8	5E8	1E9	2E9	5E9	1E10	2E10
Gain9	Gain10	Gain11	Gain12	Gain13	Gain14	Gain15	Gain16
5E10	1E11	2E11	5E11	1E12	2E12	5E12	1E13

Table 1 Intensity settings that can be set with the BPMOPS server (black colour: not currently used)

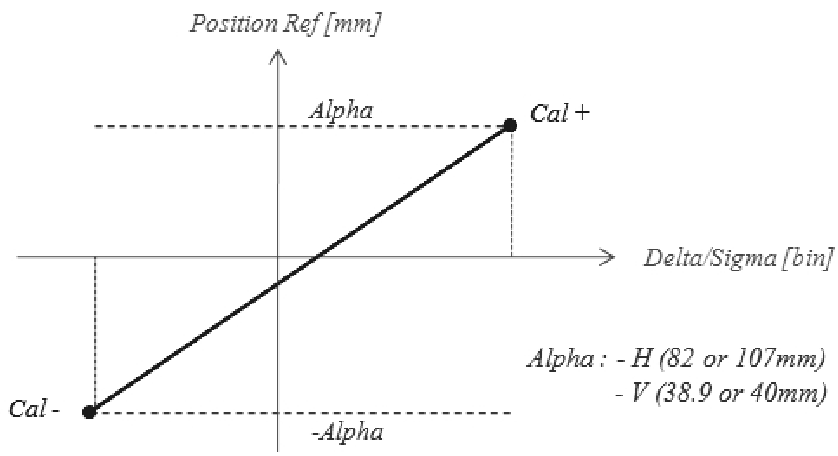
Each of the 40 pick-ups has its own gain tables for each of the three amplifier channels. Ten TRX transceiver modules are used. The intensity of the calibration signal is chosen by the hardware expert and, in this case, one DAC module is used.

There are six special-purpose pick-ups that are not part of the trajectory measurement system and their settings are controlled independently by dedicated RT programs. The four TRX transceiver modules driving these pick-ups are installed in the same front-end computer as those of the TMS.

3.4. Calibration

The calibration mode automatically calculates new scaling factors (K). Calibration generators simulate the injection of a single-bunch beam at a constant revolution frequency. The simulated beam circulates for about 100ms in the interval between the start of a cycle and real beam injection (PER1 in figure 1). The simulated reference positions are either of two diagonally opposite corners, with, in absolute values, 82.0 and 38.9mm for normal pickups and 107.1 and 40.0mm for enlarged pickups. The sign of coordinates depends on the test relay setting and the orientation of the electrodes in the accelerator. The pickups are wired such that the difference of the beam displacement signals has the right polarity.

Basic calibration proceeds in two stages. First, the gains of the amplifiers are adjusted for each pick-up. Then the server uses the normal acquisition chain to get 1000 measurements of the two simulated corner positions. From the sanitized and averaged data, it derives the slope and offset values to make the measurements match the simulated reference positions, according to (2) and (3).



Cal+: Simulates the maximum positive beam displacement.

Cal–: Simulates the maximum negative beam displacement.

The slope of the line which is determined by the Delta / Sigma is used to normalize the beam position measurements so that:

$$K = \frac{2 * Alpha}{\frac{Delta+}{Sigma+} - \frac{Delta-}{Sigma-}} \qquad (2)$$

$$AdditiveOffset = \frac{-K * (\frac{Delta+}{Sigma+} + \frac{Delta-}{Sigma-})}{2} \qquad (3)$$

Alpha is the pickup's sensitivity measured in the laboratory.

3.5. TMS settings

The TMS uses configuration tables to control the acceleration cycle sequences, machine filling patterns and fine timings for each possible beam type. The position measurement requires that several signals be aligned with the bunch. The tables contain many parameters that can be adjusted by the hardware expert. Some parameters, notably the alignment of the 'gate', 'BLR' and 'LO' signals, as well as the filling patterns, can be adjusted by the operators from the application program level via FESA.

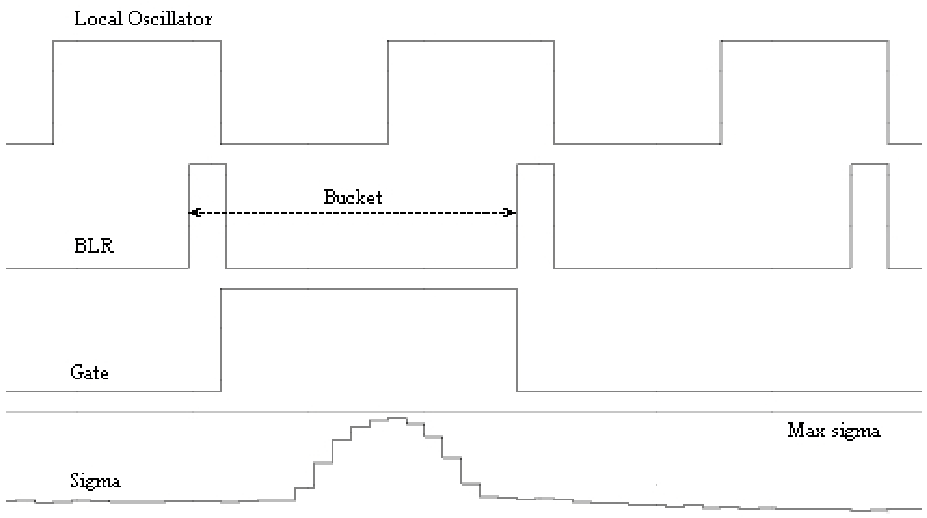


Figure 2 TMS settings

4. Experts graphical user interface (GUI)

The expert application has been written in Java. It can be found at this location and opened via a terminal server: http://bdidev1/bdisoft/operational/applauncher.php?launch=BPMOPS.
The application window is divided in two parts. The upper part is used to select the cycle for which settings and acquisitions will be done. The rest is to either visualize measurements and diagnostic or to control settings and calibration.

Figure 3 Expert GUI

4.1. Acquisition and settings

All measurements are accessible via different panels containing specific plots. Trajectories can be visualized with an image that shows the evolution along the cycle for all pickups (cf. figure 4). Associated are two other 2D plots that show positions turn by turn for all pickups or trajectories per pickup along the cycle. This is the same for the orbit measurements where the x-axis is in milliseconds (cf. figure 14). Into these panels, graphical JAVA components allow the user to select a bunch, to switch between pickups or to point to a specific turn (or millisecond for the orbit). The MRP panel contains two 2D plots for the H and V planes (cf. figure 15). Each of these measurement panels includes both information about the measurement and, if needed, extra data visualization components (ex: the polar plot).

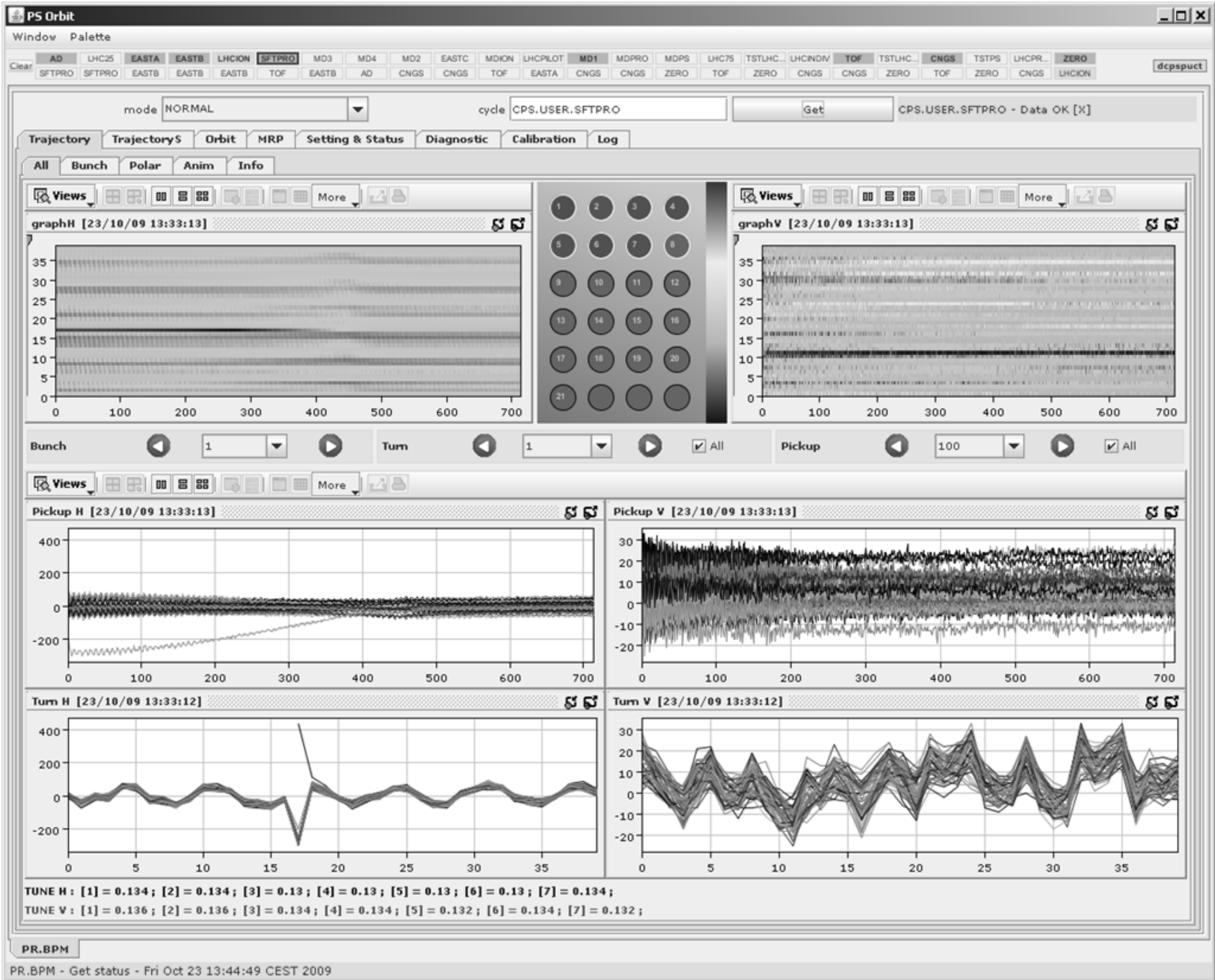


Figure 4 Trajectory panel (SFTPRO at injection)

Acquisition start for the trajectories as well as gain can be set using the setting panel (cf. figure 13). This panel also shows status information about BPMOPS.

4.2. Calibration

The calibration panel allows the user to trigger a calibration in automatic mode (for all gains) and to analyse the results per pickup and per gain. Results are saved in tables located at the bottom of the window in order to study the variation of the scaling factors as well as the additive offsets.

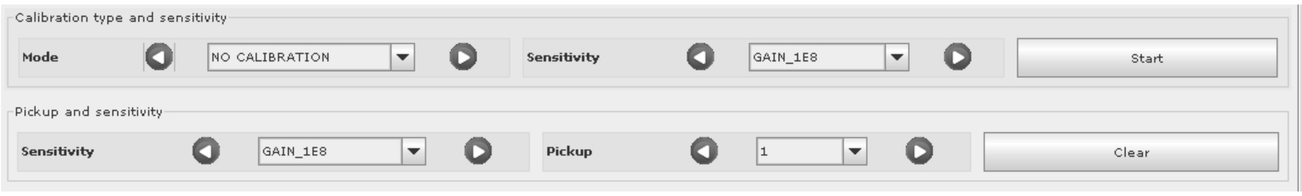


Figure 5 Calibration panel

4.3. Diagnostic and TMS settings

The panel “Diagnostic” allows visualization of the low level hardware signals. A 2D plot window shows 4 plot curves of sigma, BLR, gate and LO. Another panel with settings for the acquisition of these curves (ex: start time, pickup) is also available.

The panel for the TMS configuration allows the user to modify, for a selected cycle, the state and period table files. Different periods (state periods) are present in the cycle period. Gate, BLR, LO, harmonic number, filling pattern can be changed. Whenever the user selects a period, the application updates a plot panel (left side) with the hardware settings used. On the right side, the user can modify these settings and change the filling pattern as well.

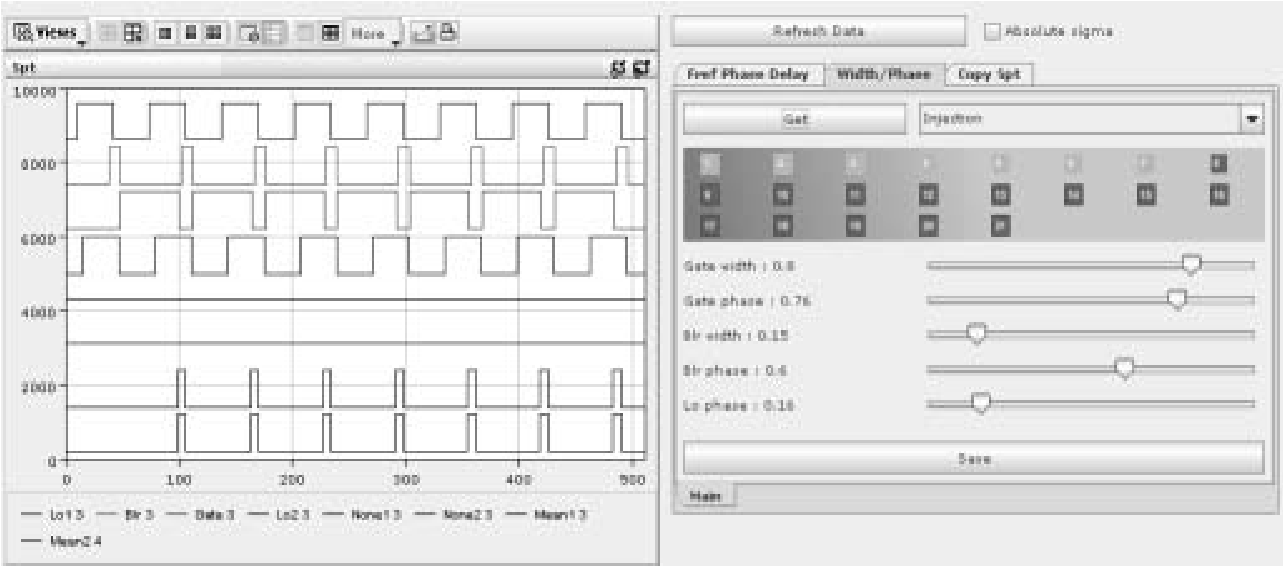


Figure 6 State and period table setting panel (PER2 at injection, SFTPRO)

5. Some first measured results

5.1. Comparison with the old CODD system

5.1.1. Measurement

Except for some particular situations, it is not possible to get independent sub-millimeter-precision data to validate the CODD or TMS trajectory measurements. Instead, in order to gain some insight in the quality of the results measured through the new system, we have made some *simultaneous* acquisitions of the *same* beams via both systems. It is not at all evident however, what proportion of any uncovered discrepancy should be attributed to either system. Even though the new TMS can measure all bunches, all the time, the results below concern measurements of two consecutive revolutions for a single bunch, a restriction imposed by the abilities of the CODD system.

One way to quantify the match between the measurements is to calculate the root-mean-square difference between CODD and TMS acquisitions:

$$\delta = \sqrt{\frac{1}{N}\sum_N \left(x_{CODD} - x_{TMS}\right)^2} \tag{4}$$

Here, N is the number of measurements in two revolutions (80). This quantity will show better (smaller) results for beams with small excursions, but when the beam moves a lot, such as immediately following injection, results will be poor.

Another measure of similarity is the correlation coefficient:

$$\rho = \frac{\sum_N \left(\overline{x_{CODD}} - x_{CODD}\right)\left(\overline{x_{TMS}} - x_{TMS}\right)}{\sqrt{\sum_N \left(\overline{x_{CODD}} - x_{CODD}\right)^2}\sqrt{\sum_N \left(\overline{x_{TMS}} - x_{TMS}\right)^2}} \tag{5}$$

With N as before and where $\overline{x}$ denotes the arithmetic mean of the variable considered. For data with large excursions, such as for injection trajectories, this measure will show better results (closer to unity) than for beams that have settled. Also, it is not affected by overall offset and scaling errors.

Most plots concern p^+ beams at injection. The first pick-up to see the beam is at index 17. A large positive displacement at that pick-up is typically seen on the first turn, followed by a somewhat smaller negative displacement on the succeeding turns. Ion beams are first seen by the pick-up with index 11.

For the measurement taken at C650, the beam follows virtually the same trajectory turn by turn. This provides an opportunity to estimate the measurement noise in each system. The RMS difference between the two successive turns measured by CODD is 0.3mm. For the TMS, this is 0.16mm, about twice as good.

USER-line	Intensity [ppb]	δ [mm]	ρ	Time
CNGS	3E12	2.8	0.97	Injection
TSTLHC75	3E12	2	0.99	Injection
SFTPRO	2E12	0.9	0.99	Injection
LHCION	1.2E10	1.3	0.997	Injection
EASTB	2.5E10	0.3	0.97	C650

Table 2 Summary of comparisons between measurements

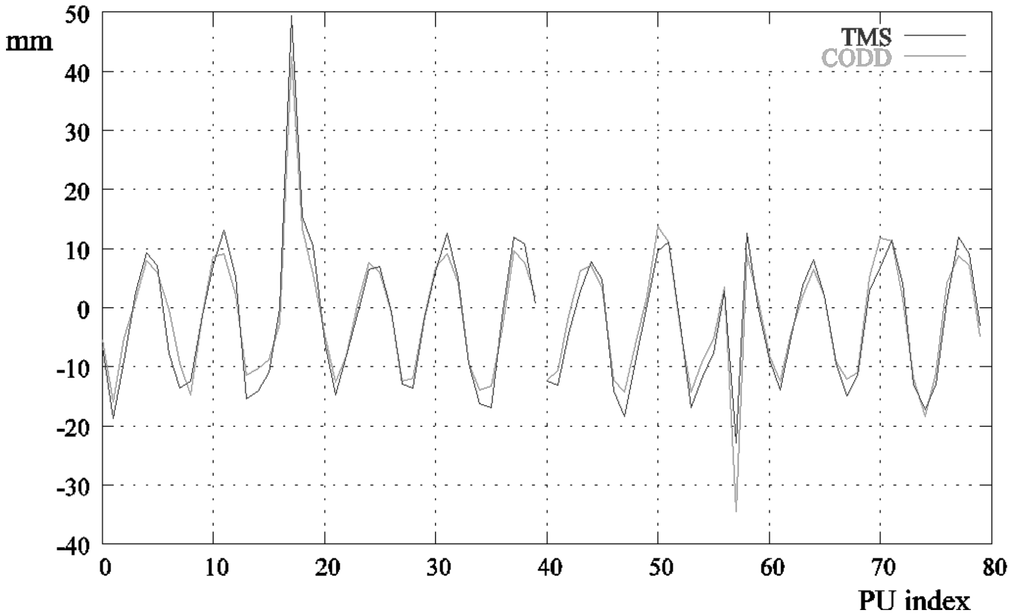


Figure 7 A two-turn trajectory of a CNGS beam at injection, as seen by TMS and CODD. Beam intensity is about 3e12ppb. The RMS difference δ=2.8mm and the cross correlation coefficient ρ=0.97

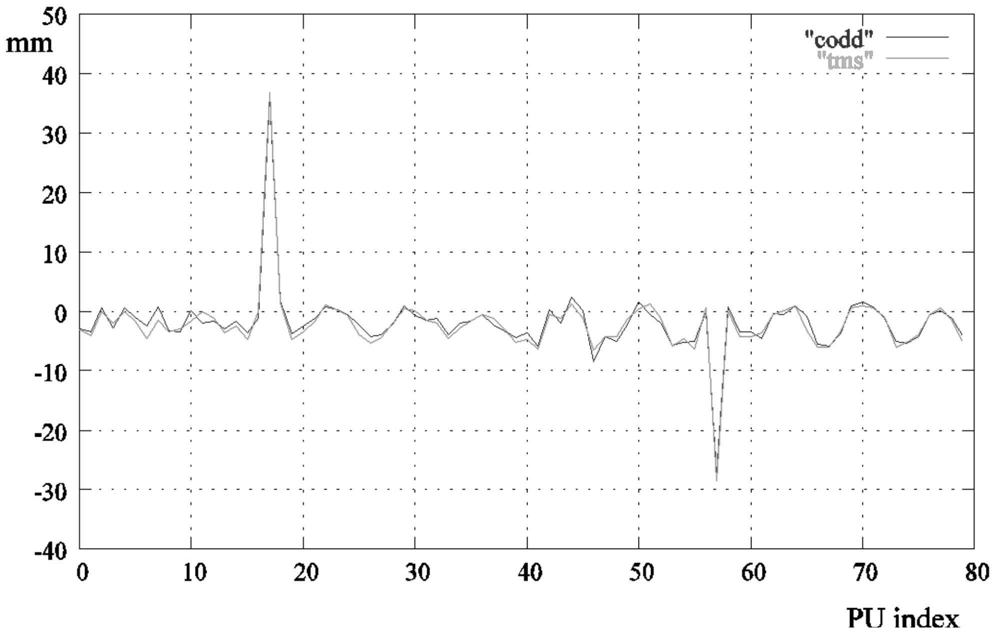


Figure 8 A two-turn trajectory of an STFPRO beam at injection. Intensity was about 2.3e10 ppb. The RMS difference δ=0.88mm and the cross correlation coefficient ρ=0.99

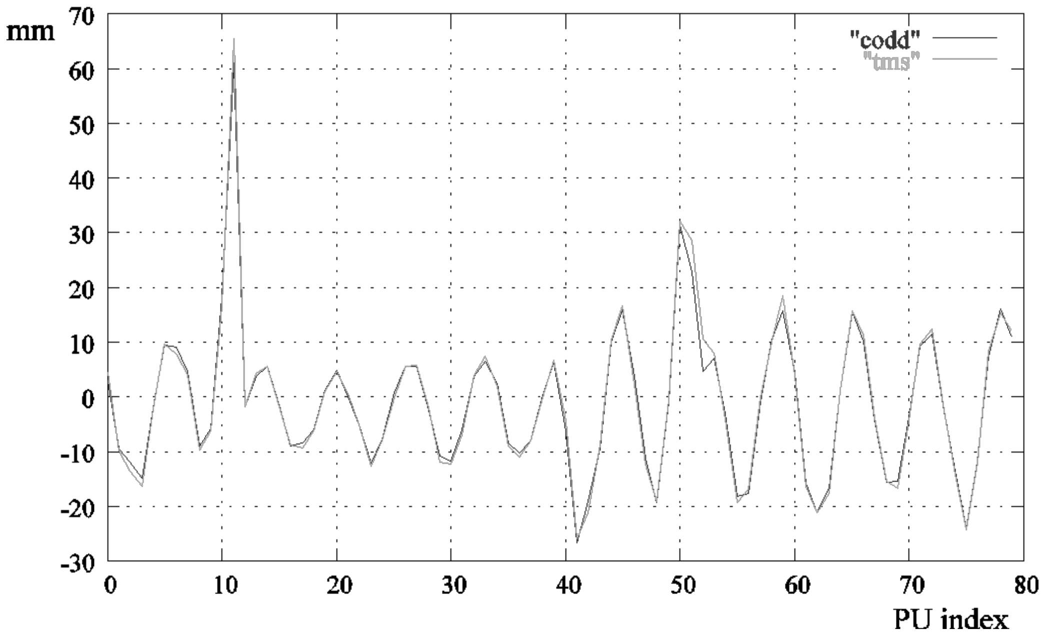


Figure 9 Injection trajectories of an LHCION beam at about 1.2e10 ppb. The RMS difference is δ=1.3mm and the cross correlation coefficient ρ=0.997

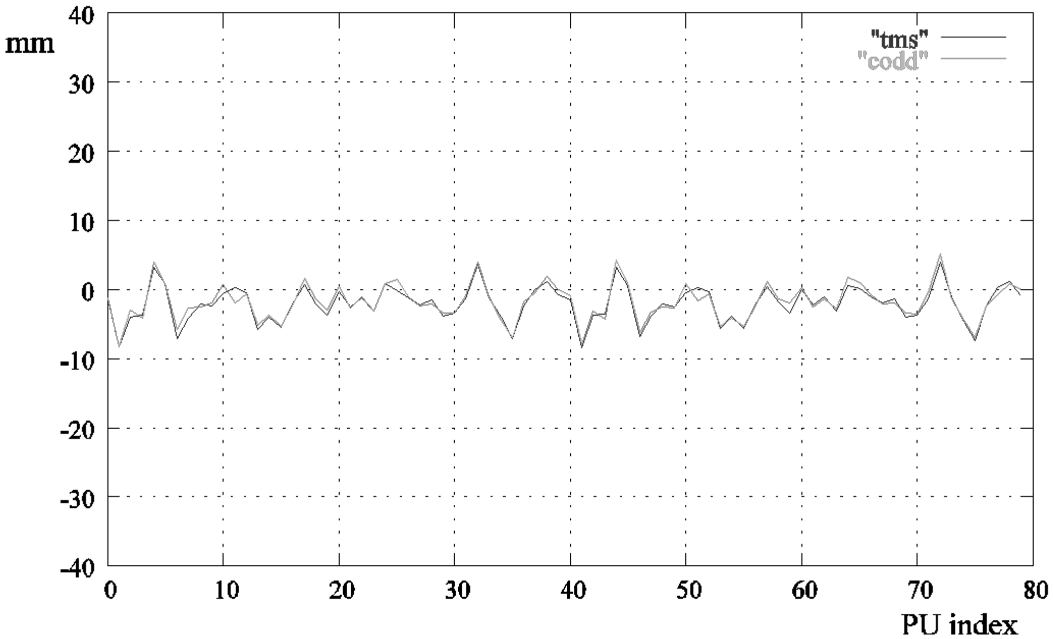


Figure 10 Two-turn trajectories of an EASTB beam at C650. Beam intensity was about 2.5e10 ppb. The RMS difference δ=0.7mm and the cross correlation coefficient ρ=0.9

5.1.2. Timing

Precision of the CODD timing has always been problematic as it was not possible to check it precisely. The acquisition trigger for the trajectories (resolution in turns) should be considered whenever comparing old and new trajectories. Small differences in nanosecond can thus make a big difference in position especially for the injection bump. This is still under investigation. Plus, comparison between the CODD, BPMOPS and the radial pickup MRPs has given more precise results. In fact, BPMOPS is synchronized with the radial pickup MRP even it has a different timing system. But, at the same time, the old MRP is delayed of ~7ms.

5.1.3. Performances

Different key points should be mentioned to give a clear idea why the new orbit system will improve beam operation:

Old CODD	BPMOPS
2 consecutive turns trajectories	Up to 5000 turns trajectories (one bunch)
2 MRP values based on trajectories	5000 MRP values based on trajectories
	Trajectories bunch by bunch
	Averaging of the sigma bunch by bunch (proportional to the bunch intensity)
MRP and Orbit at 200Hz (5ms)	MRP and Orbit at 1000Hz (1ms)
MRP and trajectory orbit not accessible at the same time	Parallel access to MRP and trajectory.

Table 3 Performances of the old and the new system

The BPMOPS server is based on the FESA software architecture. Accessing this server is now possible via standard generic tools. Furthermore, a list of common tools provided by BE-CO to monitor the server is also available.

BPMOPS combines functionalities that were executed before via many different servers located on different DSCs. As a matter of fact, it can acquire on request measurements per cycle, control the gain, make automatic calibration and interface the TMS settings and the low level signals.

5.2. New pickup configuration for the PS radial loop [3]*

The PS radial loop system is using three radial pickups out of the five available and the MRP shows a position jump of about -3.5 mm during the γ-jump at transition crossing.

Up to 1 mm maximum is linked to the fact that the orbit does not pass by the center of the quadrupoles used to run the γ-jump. Furthermore it has been noticed that the dispersion function seen by the current PUs combination is not a good sampling of the real optics operating during the γ-jump and the phase advances between those PUs are not optimum with respect to the orbit change. Other combinations were tried involving the most recently installed radial pickup in straight section 76. This choice was made according to the orbit change and its phase advance during the γ-jump measured using the new orbit measurement system, which allows taking trajectories turn by turn.

Finally, MRP measurements in 2009 demonstrate that the PUs combination 22-36-76-96 is the best solution, since comparisons on different users show that the beam is well centered all along the cycle and the MRP jump is at transition is reduced, making the operation easier.

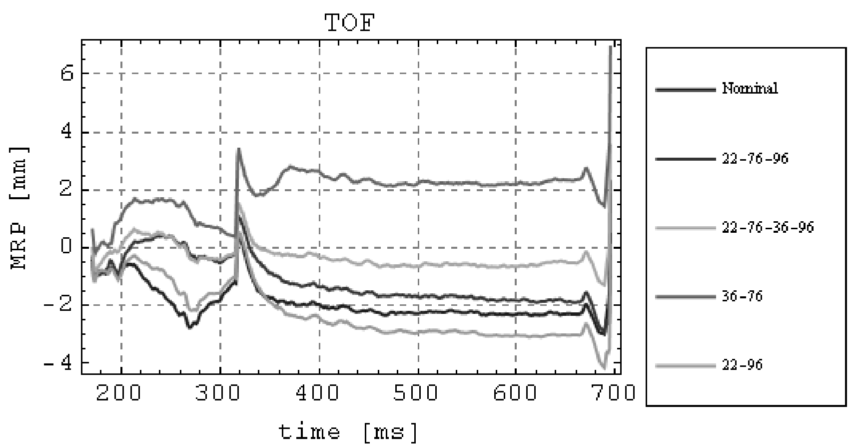


Figure 11: Comparison between MRPs (TOF)

** Thanks to Sandra Aumon & Simone Gilardoni.*

5.3. Multi-turns extraction [4]*

During 2008 commissioning of the multi-turn extraction (MTE) needed to analyse trajectories turn by turn during the extraction process. Triggering problems and limitation of the old CODD system limited this analysis. Using the new system allowed the MTE project team to acquire thousands of trajectories after the starting time of extraction. Analysis has given interesting results, confirming beam instabilities.

** Thanks to Simone Gilardoni.*

5.4. Trajectory misbehaviour*

Analysis of trajectories at injection over many thousands of turns allowed detecting bad injection into the PS machine. Acquisition of the horizontal trajectories during a TOF user and averaged over all pickups (MRP trajectories shown in the expert GUI) gave a continuous slope of the mean position during the first four hundreds of turns (cf. figure 12). The problem is not yet understood and is being looked into.

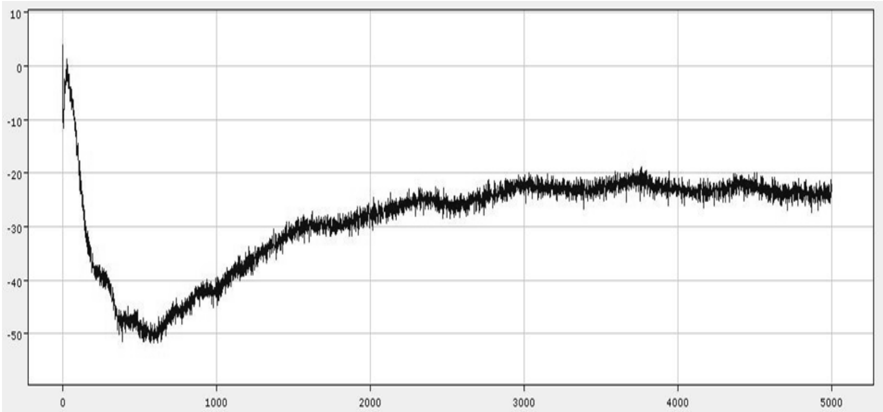


Figure 12 MRP trajectories at injection during TOF

** Thanks to Gabriel Metral.*

6. Conclusion

During 2009, the BPMOPS server was delivered and it is currently used in operational mode. Its functionalities were expanded since first specifications [5]. Concentration of the different module servers to a unique process has both consolidated implementation and allowed standardization at the software architecture level.

Many things still need to be done. Tests and analysis of the results as well as improvement of performance should be planned for the coming year. At the same time, a simple interface for the operators should be defined in order to change TMS settings per user. Gain control should be enabled so that the old CODD system can be suppressed. Analysis of the measurement during and after harmonic changes will also be achieved during 2010.

Performance of the new trajectory measurement system that delivers both individual bunch trajectories and averaged orbits over a large number of consecutive turns is very impressive compared to the old CODD. Using the new system should improve significantly the standard beam position analysis done by the PS operators.

7. References

[1] J.M. Belleman, S. Bart-Pedersen, G. Kasprowicz, U. Raich “Digital BPM Systems for Hadron Accelerators”, DIPAC’09, Bâle, June 2009.

[2] BI Front End Software Standard Interface for Beam Position Measurements [EDMS: 630857].

[3] S. Aumon, H. Damerau, S. Gilardoni “New pickup configuration for the PS radial loop”, MSWG Meeting, October 2009.

[4] A. Franchi, S. Gilardoni, M. Giovannozzi, “MTE Commissioning 2008”, APC March 2009.

[5] D. Korchagin, J. Belleman, S. Bart Pedersen, BI Front End Software Functional Specifications for the PS Orbit Measurement System [BPMOPS] [EDMS 855848].

8. Acknowledgments

The work described in this note is that of several people. The authors would like to thank L. Jensen and J-J. Gras, and to acknowledge the efforts of the CERN BI, CO, ABP and OP groups for the design, construction, installation and commissioning of the new PS orbit system.

9. Addendum

Different data tables are currently used by BPMOPS like the pickup information (cf. table 4) or the mechanical and electrical offsets (cf. tables 5-8).

Index	1	2	3	4	5	6	7	8	9	10
PU	100	3	5	7	10	13	15	17	20	23
Index	11	12	13	14	15	16	17	18	19	20
PU	25	27	30	33	35	37	40	43	45	47
Injection		ion					proton			
Index	21	22	23	24	25	26	27	28	29	30
PU	50	53	55	57	60	63	65	67	70	73
Index	31	32	33	34	35	36	37	38	39	40
PU	75	77	80	83	85	87	90	93	95	97

Table 4 Pickup information

1	9	3	9	-2	4	276	57	-3	17
6	-2	-3	12	20	3	-4	8	5	12
1	8	8	1	-4	3	1	5	-3	11
2	6	7	-2	19	3	0	8	3	7

Table 5 Horizontal mechanical offsets in 1/10mm

2	10	-3	-3	13	8	4	-1	-2	-3
-6	-4	6	10	4	-3	-2	7	-18	1
6	5	8	-1	6	-4	15	15	11	4
-2	11	3	-2	-5	-9	14	0	2	1

Table 6 Vertical mechanical offsets in 1/10mm

7	-4	7	-9	7	2	6	8	-4	-2
12	-9	-4	-2	1	4	-3	7	4	2
3	-3	0	0	5	11	1	-2	-7	8
2	3	4	-2	-3	0	1	-8	0	4

Table 7 Horizontal electrical offsets in 1/10mm

-2	1	-3	-11	-2	1	-5	-6	-6	-3
-4	-4	-5	-6	-2	-1	-9	-12	-2	-3
3	2	0	0	-4	-4	-2	-3	0	-2
-1	-5	1	-3	-4	2	-1	1	1	-2

Table 8 Vertical electrical offsets in 1/10mm

Figure 13 Expert GUI - Setting panel

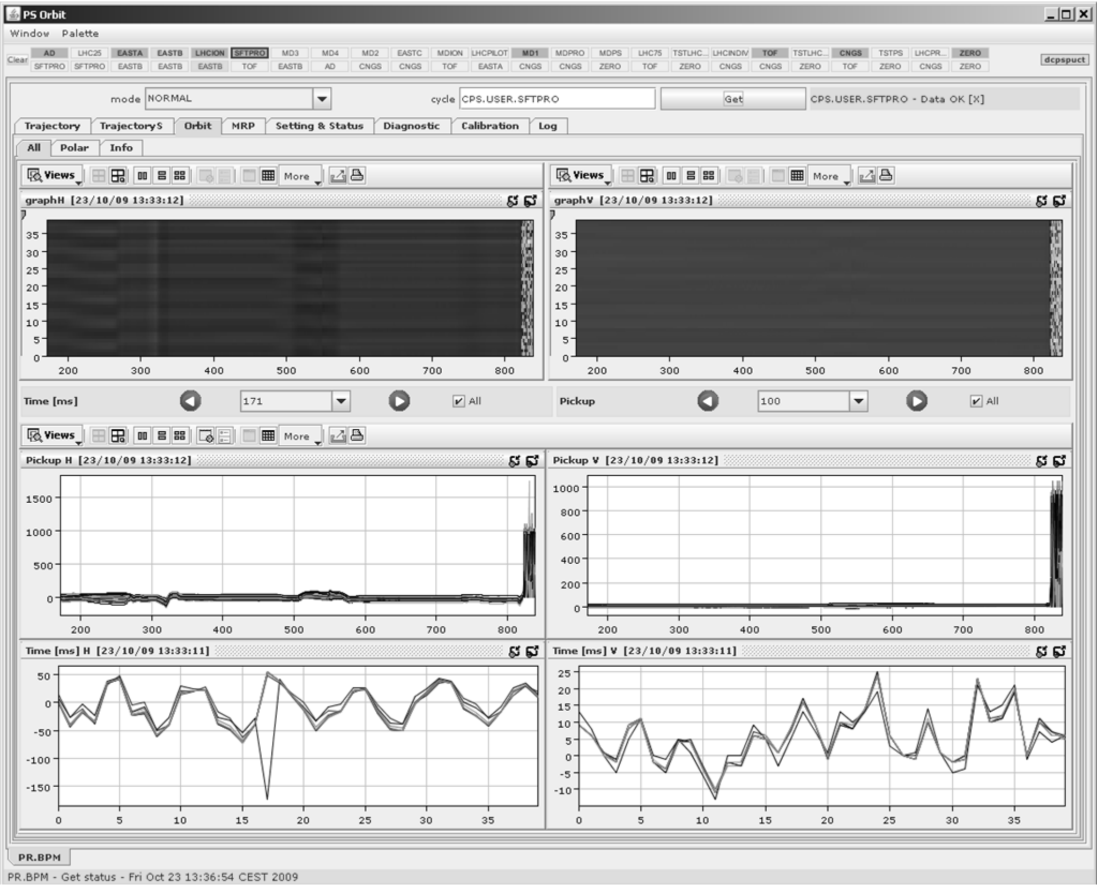


Figure 14 Expert GUI - Orbit panel (SFTPRO at injection)

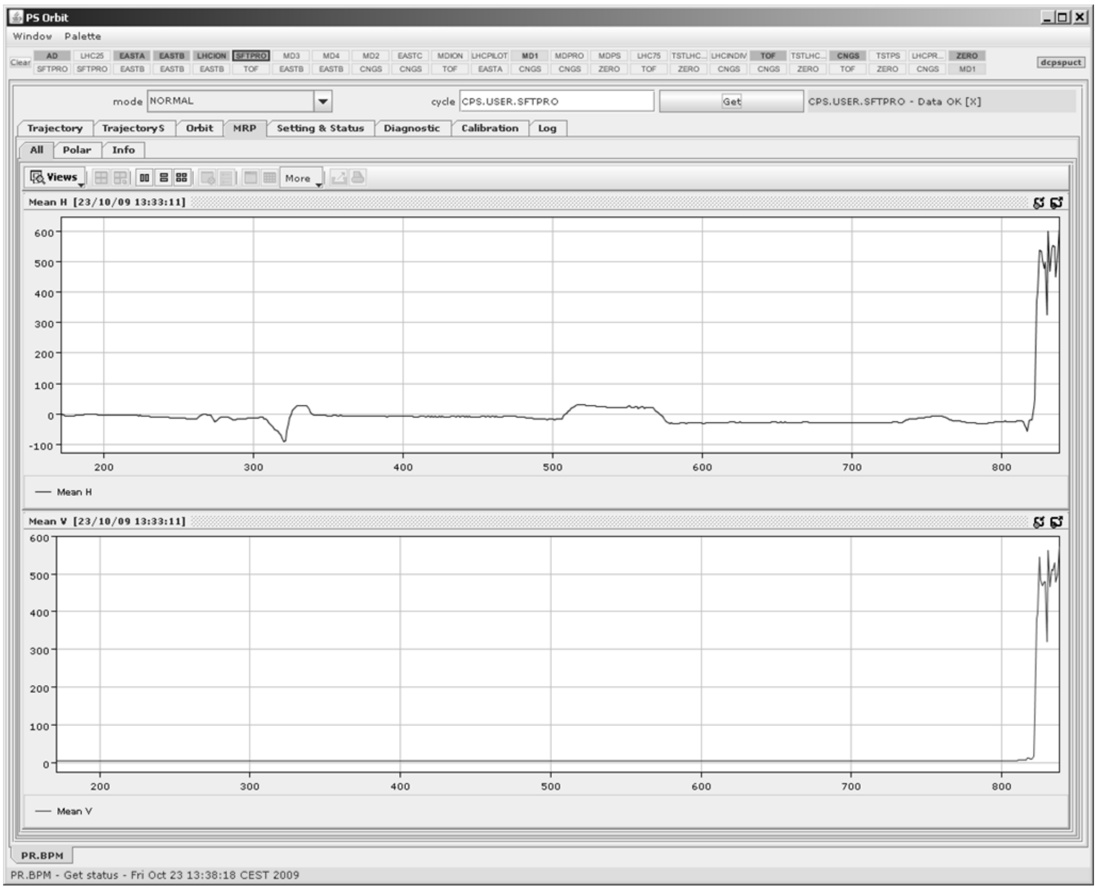


Figure 15 Expert GUI - MRP panel (SFTPRO at injection)