Calibration of BPCE.41801
and SPS extraction bump
in LSS4

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Run no. | Date
12/08/02 | 16/09/02

Keywords: Extraction bump, Beam position monitors

Summary

The large aperture stripline coupler beam position monitor BPCE.41801 was calibrated
using the LHC beam in the SPS for different proton intensities corresponding to different
MOPOS gains. A polynomial correction of the data provided a correction on the absolute
position to the 0.5 mm level in the large range of interest. The powering of the newly
installed extraction bumper system was then checked against this monitor.

1 Introduction

The extraction from the SPS to the LHC in TI2 will be set up by means of a pilot
bunch. After the trajectory along the transfer line is adjusted, the position at
the extraction point needs to be controlled to within 200 μm when the nominal
beam leaves the SPS for reasons of equipment protection in both SPS and LHC.
Modified MOPOS acquisition software with the new BPCE.41801 should confirm
the position of the beam and lift the extraction inhibit only if the position is inside
the specified range.

At large amplitude, as is the case during the extraction, the coupler is no
longer linear and the direct reading given by the difference divided by sum sig-

nal needs to be corrected before being translated into a position. Laboratory
measurements, electrostatic calculations and beam measurements were under-
taken to find the correction algorithm and establish if the BPCE with its current
acquisition electrodes will suffice to operate safely within these requirements.

Once the BPCE.41801 coupler was calibrated and the absolute position of the
beam known, a comparison of the extraction bump powering against the coupler
readings was performed.
2 Coupler calibration

The coupler consists of a circular section cavity 221 mm in diameter with four electrodes 180 mm long by 20 mm wide. The linearization of the BPM reading has been done with three different methods: laboratory measurements, electrostatic calculations and beam measurements. All three methods produce a map of measured position $X_{\text{meas}}$ against set position $X_{\text{set}}$ of the beam inside the BPM [1, 2]. The correction needed to recover the real position from the measured value is then modeled as a polynomial function of the measured position. Finally, the correction is introduced in the acquisition algorithm and the final error evaluated.

2.1 Laboratory measurements

Before the installation of BPCE.41801 in the SPS, laboratory measurements were done using a small diameter antenna (3-6 mm) to simulate the beam (See Fig. 2.1). Under the condition that we do not approach the electrodes too close, the measurement of the capacitance between wire and electrodes is equivalent to a high frequency measurement with an adapted antenna which is not possible to implement since the required mobility mismatches the impedance. The antenna is displaced in the horizontal and vertical axis. The coupling capacity between electrodes is not considered. The measured data has to be corrected for a systematic offset of the antenna before the correction is applied.

![Figure 1: Schematic of the laboratory measurements and equivalent circuit.](image)

After fitting a fifth order polynomial to the difference between set and measured position, the final residual error is $\pm 0.2$ mm for amplitudes up to 70 mm in the horizontal axis as shown in Fig. 2.1.
2.2 Electromagnetic calculations

Electromagnetic calculations were performed using the Poisson-Superfish group of codes [3]. These codes solve the Laplace equations in a triangular mesh after the boundary conditions have been defined assuming an infinitely long structure. The beam is represented by a line charge density whose position is changed in both x and y planes. The “measured” position is calculated as the difference between the sum of the voltage induced in opposite electrodes. Fig. 2.2a shows the measured position given by the simulation before correction.

![Figure 2](image2.png)

Figure 2: Final error after correction using a fifth order polynomial fit on the measured data.

As expected, the linear approximation is valid up to one centimeter, beyond which correction is needed. This technique allows for a two-dimensional correction as both x and y are known at the same time. A first linearization is applied on the x and y axes as a seventh order odd polynomial. A second linearization is then done on the x=y axis using an even second order polynomial [1]. The positions after processing the data are given in Fig. 2.2b. Reasonable accuracy ($\delta \leq 1.0 \ mm$) is achieved up to a radius of 5 cm in any direction. For one-dimensional displacements however, as is the case during the extraction bump, the accuracy is much better, as shown in Fig. 2.2. The final error for the hori-
horizontal axis after correction is always less than 0.1 mm.

2.3 SPS beam measurements

For the SPS measurements, LHC type beam at 26 GeV was used on the MD cycle. The horizontal position at BPCE.41801 was scanned with a closed orbit bump. The readings of the BPCE.41801 were recorded together with the expected bump position.

In a first series of measurement, we applied a three corrector $\pi$-bump using magnets MDH.41607, MDHA.41804 and MDH.42007. At 26 GeV beam energy, the maximum bump height is limited to $X = \pm 30$ mm by the corrector strength. Measurements were taken for intensities ranging from $1.8 \cdot 10^{12}$ to $8.7 \cdot 10^{12}$ protons per batch corresponding to three different MOPOS gains 0, 10 and 20. After the data was taken, a calibration of these correctors was performed with LOCO [4] and showed that the correctors used for the $\pi$-bump are linear to within $\approx 1\%$ up to bumps of around $\pm 25$ mm.

In a later measurement, we used the same bump mentioned above up to $\pm 24$ mm, and then a three corrector 3$\pi$-bump using correctors MDH.41207, MDHA.41804 and MDH.42407 up to $\approx \pm 40$ mm. However, for the 3$\pi$-bump, there was a significant non-closure of the orbit which is also seen in MAD. It seems to be due to the machine sextupoles as the bump extends over the arcs and leads to systematic position shifts of $\approx 1$ mm for total amplitudes of $\pm 50$ mm. Simulations of the bump made with MAD showed that the $+50$ mm shift is actually $+51$ mm while the -$50$ mm is actually $-49$ mm. The shift due to the sextupoles is given by:

$$
\begin{align*}
\Delta X_{set} &= 1.82 \cdot 10^{-3} \cdot (X_{set} - 24)^2 & X_{set} > 0 \\
\Delta X_{set} &= 1.63 \cdot 10^{-3} \cdot (X_{set} + 24)^2 & X_{set} < 0
\end{align*}
$$

where $X_{set}$ is the position set by the bump and $\Delta X_{set}$ is the necessary correction.
to get the actual horizontal position in BPCE.4108.

Also, for the $3\pi$-bump, there is an additional position shift from the energy change induced by the correctors which are located in high dispersion areas. This new position shift is given by:

\[
\begin{align*}
\Delta X'_{\text{set}} &= -0.56 \cdot 0.8 \cdot (X_{\text{set}} - 24)/24 & X_{\text{set}} > 0 \\
\Delta X'_{\text{set}} &= -0.56 \cdot 0.8 \cdot (X_{\text{set}} + 24)/24 & X_{\text{set}} < 0
\end{align*}
\]  

(2)

Figure 5: Beam measurements on BPCE.41801 data taken on 12-08-2002 and 23-08-2002. Measurements were taken using gain 0,10 and 20. Comparison between different gains.

Fig. 2.3 shows the initial error for all four measurements after correcting $X_{\text{set}}$ using Eq. 1 and 2. Typical shot to shot fluctuations on the monitors of the SPS are $\approx 20$-50 $\mu$m due to noise and real beam changes. Both $\pi$-bump and $3\pi$-bump are shown. It can be seen that the agreement between measurements is very good even if the data is not exactly anti-symmetric as expected. A slight deviation that changes with intensity is noticeable for negative bumps. Further investigation of this phenomenon should be done in future machine studies.

The error calculation assumes the position set by the bump (after correction) as the actual position. Taking all data from the four different measurements, a fifth order polynomial was fitted as a function of the measured position as it was done for the lab and POISSON calibrations. The correction $\delta$ needed to retrieve the position inside the BPCE.41801 is given by:

\[
\delta = -1.527 \cdot 10^{-8} x^5 + 9.852 \cdot 10^{-8} x^4 - 1.099 \cdot 10^{-4} x^3 \\
\quad + 3.878 \cdot 10^{-4} x^2 + 2.332 \cdot 10^{-2} x - 3.645 \cdot 10^{-3}
\]  

(3)
The residual error after this correction is shown in Fig. 2.3. For a positive bump, the error is less than $\pm 500\mu m$ but outside the specification of $\pm 200\mu m$. We should point out however that accuracy is less important than reproducibility between measurements made at the same large position. In addition, the accuracy given by the bump correctors is $\approx 1\%$ which at 30 mm corresponds to 300 $\mu m$ well above the specifications. New machines studies are foreseen to study the reproducibility of orbit measurements on BPCE.41801 after implementing the correction given by Eq. 3.

![Figure 6: Residual error after correction for BPCE.41801 using Eq. 3. The same correction is applied to all gains. The error specification $\delta = \pm 200\mu m$ is indicated by horizontal red lines.](image)

2.4 Methods comparison

Fig. 2.4 shows the agreement between the three different techniques used for the linearization of the BPM measure. We observe that agreement between the data taken during the MD and the results of the POISSON solver is very good, especially for positive displacements as it is the case during extraction. The measurements done in the laboratory are also shown but show a marked disagreement with the measured data that may be due to systematic error in the laboratory set-up, the finite size of the antenna, or because the dipolar nature of the antenna does not correspond to the proton beam.
3 Extraction bump calibration

The final experiment involved powering up the newly installed extraction bump magnet in LSS4 and comparing the theoretical position for a given magnet current with that given by the BPCE.41801 after correction. An schematic view of LSS4 is shown in figure 3.

Figure 8: Schematic view of LSS4 with the four newly installed bumpers (blue) and the beam position monitor (red).

We first, measure the closed orbit with bumpers off for reference. Then the bump amplitude was increased in steps of 25%. At each step, the bump closure was corrected using MPLH419 and MPSH421, we measured remaining RMS non-closure, and then, the displacement at BPCE418. Both measurements were taken
with respect to the reference. We used the LHC cycle with 12 bunches and $3 \cdot 10^{10}$ protons per bunch. The nominal bumper settings for the extraction bump during fast extraction in SPS LSS4, are (mrad):

\[
\begin{align*}
MPSH41402 & : -0.00032 \\
MPLH41672 & : 0.57855 \\
MPLH41994 & : 0.40171 \\
MPSH42198 & : 0.14502 \\
\end{align*}
\]

The results of the test are given in table 1. The position at BPCE.41801 was corrected according to Eq. (3).

<table>
<thead>
<tr>
<th>Bump [%]</th>
<th>Delta wrt nominal [mrad]</th>
<th>Orbit [mm]</th>
<th>Bump position [mm]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>414</td>
<td>416</td>
<td>419</td>
</tr>
<tr>
<td>25</td>
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<tr>
<td>100</td>
<td>0.000</td>
<td>0.000</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Table 1: Results of the test for the LSS4 bumper magnets. The difference in the angular kicks given by each bumper, the residual RMS orbit, the nominal and measured position at BPCE.41801. Values are averaged over five measurements.

As can be seen from these results, to close the bump we needed a systematic correction of about 0.015 mrad to MPLH419, and -0.015 mrad to MPSH421.

A similar series of measurements was taken without correcting the bump closure. The comparison between set bump values and the measured position in BPCE.41801 in both cases is shown in Fig. 3. The slope of the data for which the closure is corrected is 1.0006 indicating a small offset between BPCE measurement and set bump amplitude that is position dependent. There is an additional fixed offset of 1.07 mm between set and measured values. The variation between measurements was small for different cycles proving a good beam stability and BPCE reproducibility. It should be possible to use BPCE41801 to calibrate extraction bump (and interlock for out of tolerance position).

4 Conclusions

These studies have shown that the large aperture BPCE can be linearised to give good results for beam positions up to the half aperture. For future installations, in particular for the LHC, it is interesting to note that the direct Poisson calculations can be used to give a very good approximation for a stripline coupler linearity function. This is something which in practice is very difficult if not impossible to measure in the laboratory.
The current MOPOS orbit acquisition system has been shown to give an accuracy and reproducibility which is sufficient for the beam extraction interlock. A dedicated low-level software application dealing with the extraction interlock will be installed for 2003, which will allow further tests on the reliability, reproducibility and sensitivity of the system.

Finally the calibrated BPCE readings were used successfully to validate the extraction bump. An excellent agreement was found between the set bump amplitude and the corrected BPCE readings provided the non-closure of the bump was compensated.

References

[1] Borer, J ; Bovet, C ; Cocq, D ; Algorithmes de linearisation des pick-ups

