Chapter 9

System Results and Conclusions

9.1 Calibration

The calibration factor is obtained per cavity and in the vertical plane y by measuring the position signal change as a function of the physical displacement of the cavity. Two factors are used to obtain each calibration : the movers' displacement versus voltage setting C_m [μm/V] and the cavity response versus voltage setting C_c [a.u./V]. Therefore the cavity calibration factor is $C_{bpm} = C_c/C_m$ [a.u./μm].

9.1.1 Movers' Calibrations C_m

Prior to installation, the movers' displacement versus voltage setting was measured per BPM block. An interferometer with better than 1 nm resolution was used to measure the BPM vertical position as in Fig. 9.1a. As the head is located on top of the BPM, positive displacement implies negative change in the intereferometer readout. Four cycles are shown in Fig. 9.1b, two descending and two rising, on the total dynamic range divided in 100 steps, 3 s settlign time between steps.

Block AB movers, Cedrat

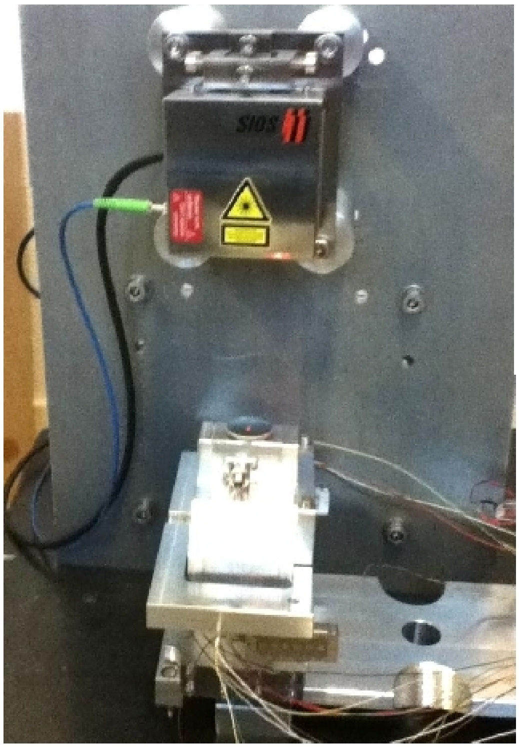
Linearity was tested in the four cycles with feedback. Fig. 9.2a shows the mover step and Fig. 9.2b shows the residuals from the linear fitting substraction on each cycle.

The calibration mean from these 4 cycles is $C_{mAB} = (-31.015 \pm 12)\mu$m/V. This value is valid for ranges were the residual is constant enough, therefore, it is recommended to use the movers with voltage settings in the middle of the total dynamic range and scans over less than 1 V. Inmproved calibration over full range can be obtained using a non-linear function.

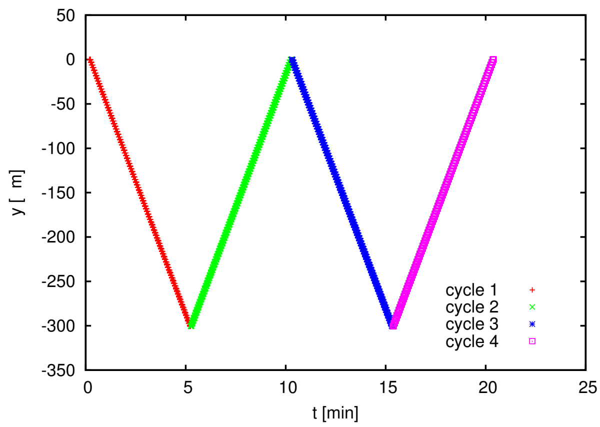
The step stability was tested by moving back and forth the voltage setting hundreds of times. Figure 9.3a shows that 10 nm steps are observable and Fig. 9.3b shows 1.1 nm of stability on each setting.

Coupling effect of horizontal displacement on the vertical plane was also tested. Fig (9.4) shows vertical position variation of 2.5 μm (1%) of total horizontal dynamic range.

Only the readbacks from strain gauges are available after installation. Results from readback linearity with respect to voltage setting on ranges below 1 V show that readbacks are limited by electrical noise of 0.8 mV. This noise is gaussian, and its effect can be minimized by



(a) Picture of SIOS interferometer used to test the movers. Precision is better than 1 nm.



(b) Four cycles are performed over the entire dynamic range of movers.

Figure 9.1 – Movers calibration test setup for the vertical plane.

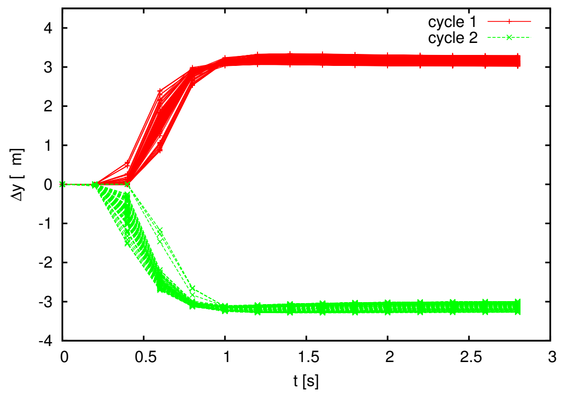
averaging over several readings. This noise does not affect stability because the readbacks and the feedback loop are independent.

Block C movers, PI

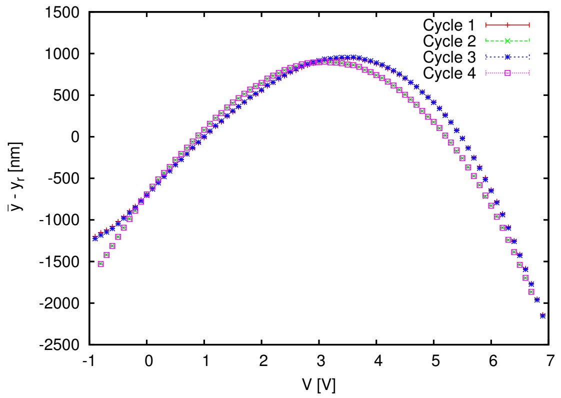
Linearity was tested in the four cycles with feedback. Figure 9.5a shows the settling time of the feedback and Fig. 9.5b shows the residuals from the linear fitting substraction on each cycle.

The calibration mean from these 4 cycles is $C_{mC} = (30.002 \pm 7)\mu$m/V. This value is valid for ranges were the residual is constant enough, therefore, it is recommended to use the movers with voltage settings in the middle of the total dynamic range and/or scan over less than 1 V.

The step stability was tested by moving back and forth the voltage setting hundreds of times.

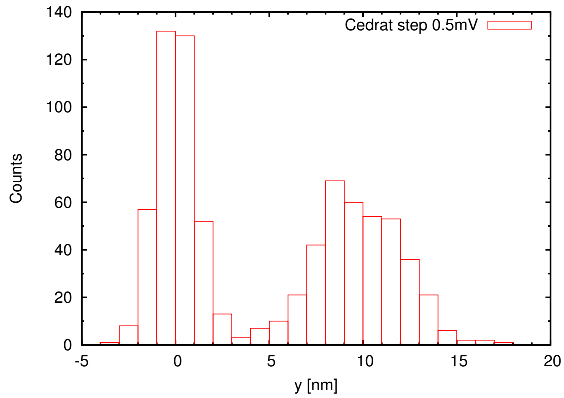


(a) Settling speed with feedback for Cedrat movers.

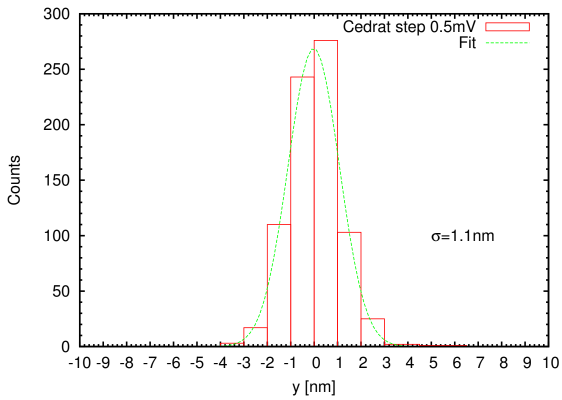


(b) Residual non-linearity (with fb), after substraction of linear fitting on cedrat movers.

Figure 9.2 – Block AB movers, linearity test over four cycles.



(a) Minimum voltage setting variation back and forth tested was 0.5 mV.



(b) Stability at fixed voltage setting.

Figure 9.3 – Block AB movers minimum step and stability.

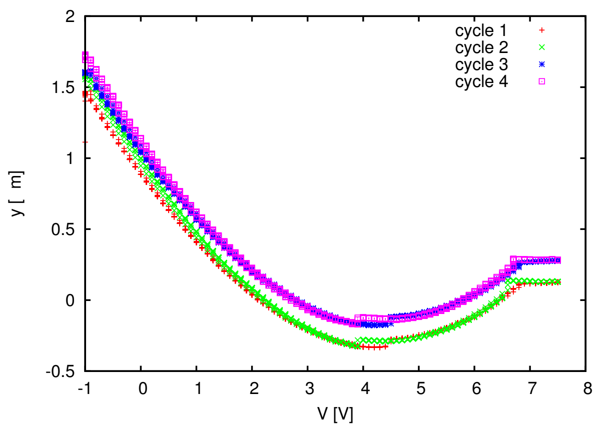
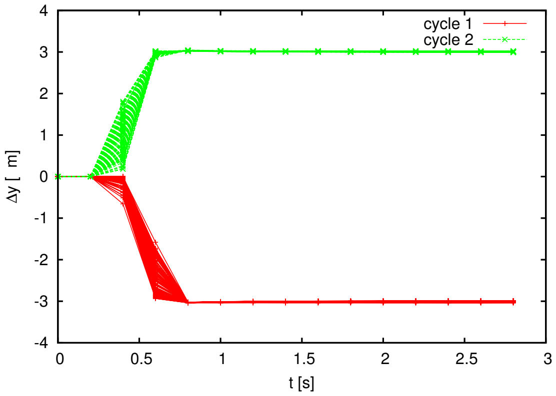


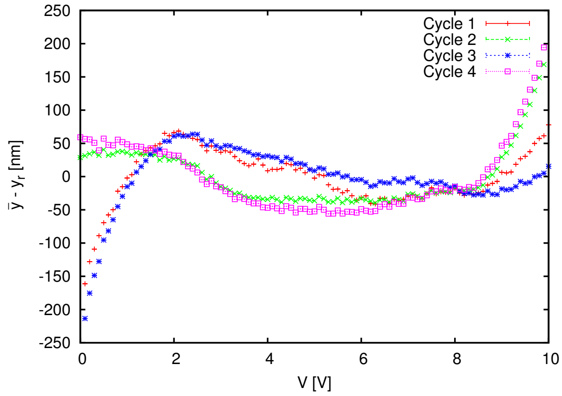
Figure 9.4 – Horizontal to vertical coupling of movers motion.

Fig. 9.6a shows that 20 nm steps can be resolved and Fig. 9.6b shows 1.13 nm of stability on each setting with feedback.

Coupling effect of horizontal displacement on the vertical plane was also tested. Fig (9.7)

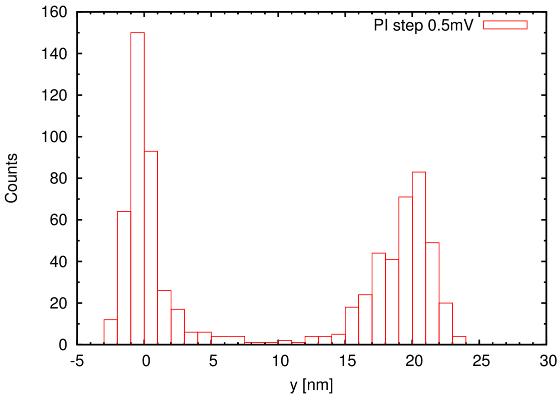


(a) Settling speed with feedback for PI movers.

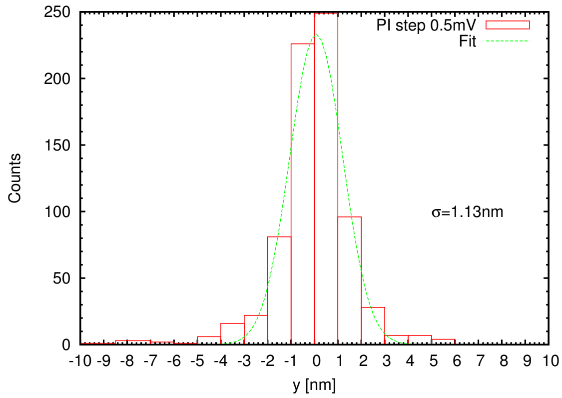


(b) Residual non-linearity (with fb), after substraction of linear fitting on PI movers.

Figure 9.5 – Block C movers, linearity test over four cycles.



(a) Minimum voltage setting variation back and forth tested was 0.5 mV.



(b) Settling speed with feedback for PI movers.

Figure 9.6 – Stability at fixed voltage setting.

shows vertical position variation of 3 μm (1%) of total horizontal dynamic range.

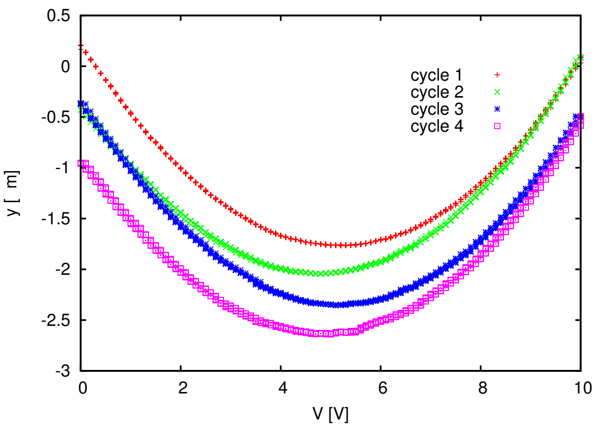


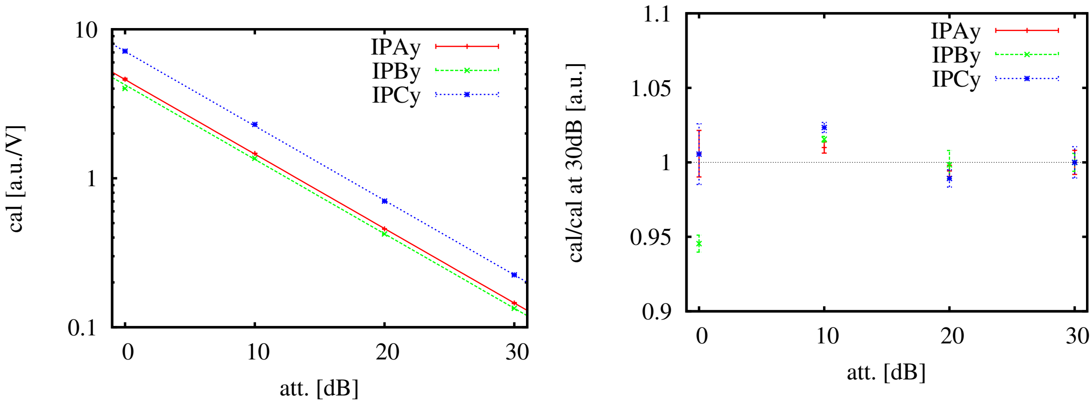
Figure 9.7 – Horizontal to vertical movers coupling.

Only the readbacks from strain gauges are available after installation. Results from readback linearity with respect to voltage setting on ranges below 1 V show that readbacks are limited by electrical noise of 5.3 mV. This noise is gaussian, and its effect can be minimized by averaging over several readings. This noise does not affect stability because the readbacks and the feedback loop are independent.

9.1.2 Cavity response calibration C_c

During beam time the cavity position is systematically changed and the amplitud of the cavity output signal is measured. Calibration is calculated from the movers voltage readbacks and choosing the signal peak from the acquired waveform, giving the factor $C_c = I'/V$ [a.u./V], and the IQ rotation angle ϕ.

Input signal can be attenuated from 0 dB to 70 dB in order to keep it inside of the electronics linear response and acquisition system limits. The system response with attenuation change can be seen in Fig. 9.8 where the variation of calibration is withing $\pm 5\%$ for charge between $(0.4 \sim 0.5) \times 10^{10}$ particles, except for IPBy at 0 dB. The reason for this is due to saturation of electronics shown in Section 9.2.



(a) Calibrations in the vertical plane for the three BPMs.

(b) Vertical calibrations scaled down and normalized to the measurement at 30 dB attenuation.

Figure 9.8 – Calibrations as a function of attenuation.

9.2 Dynamic Range

Dynamic range is defined in this section as the movers' voltage range in which the cavity response is linear within a tolerance, and where it therefore can be translated to position using the calibration factor, c_m, obtained in Sect. 9.1.1. The dynamic range is limited by the linear response of the cavity sensitivity, the processing electronics and the acquisition system.

9.2.1 Acquisition System

Every study case has been performed with signals inside the acquisition system dynamic range, described in 8.1.4. The initial FONT board has been recently replaced by a dedicated SIS digitizer with larger and configurable voltage range. This is no longer a limitation.

9.2.2 Processing electronics and cavity sensitivity

The processing and cavity response are combined in the calibration study showing linearity above ±5% in Sect. 9.1.2. However, Fig. 9.8b shows that IPBy calibration is just outside this range at 0 dB attenuation. In order to explain this behaviour the Q' signals from calibrations are shown in Fig. 9.9, where it is visible the difference between IPAy and IPCy with respect to IPBy. The decay of IPAy and IPCy Q' signals is consistent with system resolution studies shown in Sect. 9.3. However, IPBy Q' signal is close to $(0.2 \sim 0.3)$V in the attenuation range from 0 to 20 dB.

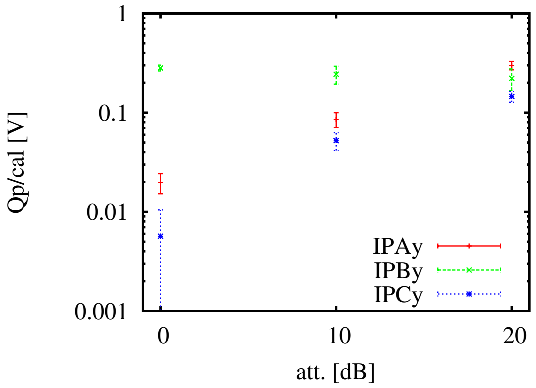


Figure 9.9 – Effect of attenuation in Q' signals from calibrations. Errors bars are RMS.

In the same way, the IPBy calibration vs charge is shown in Fig. 9.10, where the calibration values have been normalized to the minimum charge and attenuation is fixed at 10 dB. The calibration constant decays by more than 5% at charges above 0.4×10^{10} particles.

Using I' and Q' signals from the non saturated calibration at 0.36×10^{10} and 10 dB att. we obtain an IPBy dynamic range of 0.36 V, equivalent to 11 μm using c_{mAB}, where cavity calibration c_B varies less than ±5%. Similar dynamic ranges, in the order or 8 to 10 μm, have been found for IPAy and IPCy, however they lack the charge scan.

The IPBy Q' signal fills up almost all dynamic range at 10 dB attenuation and 0.4×10^{10} particles, and it is saturating the processing electronics at 0 dB.

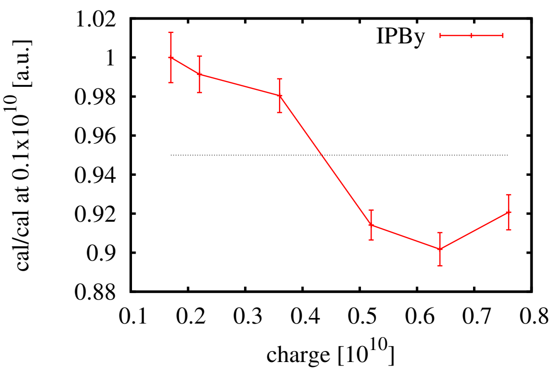


Figure 9.10 – IPBy Calibration vs charge normalized to the calibration at minimum charge.

To predict the measured dynamic range of IPBy it is necessary to put extra 6dB of attenuation in the processing electronics gain model (Sect. 8.1.2) . At the moment, it has been attributed to lower than expected sensitivity of the cavities in Section 9.3.2 and/or cable loss in the processing electronics interconnexion.

9.3 Resolution

Resolution is measured in nm using the calibration results from Sect. 9.1. It is limited by the cavity sensitivity, the electronics noise floor and the acquisition system resolution.

9.3.1 Acquisition System

The acquisition system resolution is specified in Sect. 8.1.4. Only the oscilloscopes had lower than required resolution, however, they have already been replaced by a dedicated SIS digitizer. This is no longer a limitation.

9.3.2 Noise floor and cavity sensitivity

The BPMs, processing electronics and conexions along the BPM signal path generate noise limiting the minimum detectable waveform. This minimum is estimated by scanning the measured jitter vs the attenuation value.

At large attenuations the noise floor is bigger than beam jitter at the BPM, while at low attenuations is the opposite. There is an inflection point where both are relevant. The cavity calibration are used to scale it in nm.

The jitter acquisition is the measurement of bunch position over several hundreds of pulses with a fixed BPM position. The readings from the 3 BPMs are shown in Fig. 9.11. Jitter for the three BPMs is in the order of $300 \sim 400$nm, consistent with true beam jitter because beam was not tuned after DR extraction kicker issue. At 40 dB the noise is larger than beam signal and by extrapolation the resolution limit per BPM is 13 nm for IPAy, 11 nm for IPBy, and 23 nm for IPCy at 0 dB.

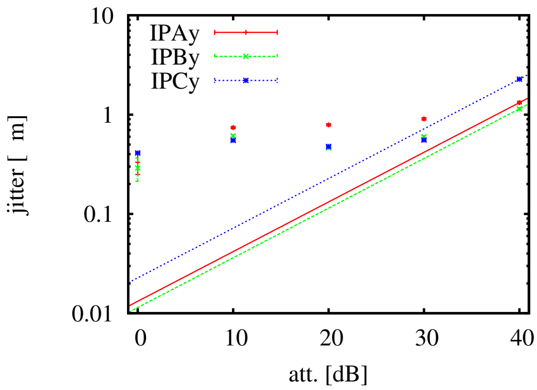


Figure 9.11 – Jitter measurement for the 3 BPMs.

It is also clear that IPC shows a worse resolution limit than IPA or IPB. Two possibilities arise: the electronics noise is larger for IPC or the sensitivity is lower.

Noise floor

Jitter measurement at 60 dB and 70 dB attenuation with 0.4×10^{10} particles shows that, after substraction of known gains from first, second down-mixing stages and hybrid, the noise floor value varies by only ± 1 dB among BPMs.

Although, it can not be considered a direct measurement of the processing noise floor as in [49] because additional losses are not included, it does indicate that the noise floor is similar for the three BPMs and it is not the explanation of the discrepancy seen in Fig. 9.11 between IPCy when compared to IPAy and IPBy.

A limit of 10 nm resolution per BPM is results from the processing electronics noise floor in the current state.

Cavity sensitivity

Cavity sensitivity and processing electronics gain change the calibration factors. Due to the 6dB mismatch between the dynamic range measured and predicted for IPBy, as shown in Sect. 9.2, and the lack of charge scans for IPAy and IPCy, it is not possible to conclude about the total gain without making assumptions.

However, the signal decay time from waveforms gives information about the cavity performance. The measurement of the decay time τ described in Sect. 8.1.1 shows a 6 ns decay for IPCy compared to 11 ns and and 12 ns for IPAy and IPCy. This difference indicates power losses which can be attributed partially tightened bolts during mechanical assembly of the BPM. In addition, 11 ns is short when compared with expected 17 ns from design. Althought, the cavity sensitivity is not affected by the power loss, it could increase the noise level making low voltage signals undetectable.

The electronics gain requires requires to be measured per component and losses need to be identify in order to conclude whether noise limit comes from processing electronics or the cavity power loss.

9.3.3 Resolution by trajectory reconstruction

The system resolution could be estimated by the reconstruction of beam trajectories. Two BPMs are used to measure the bunch position an to predict the measurement on the third BPM. The residuals from substraction of BPM prediction and measurement will depend on each BPM resolution.

Geometrical method

As longitudinal distances are know within a ± 0.1 mm over 250 mm, i.e. better than 1% precision, then, geometrical factors can be used to predict the beam trajectory [50], assuming that all three BPMs have the same resolution. The advantage of this method is that it is independent from beam optics as it does not fit parameter to do predictions. The following is an explanation of the method.

Being $f(y_A, y_B)$ the prediction at IPC from the measurements at IPA and IPB using the relative distances between the BPMs as in Fig. 9.12, its evaluation is substracted from the measurement in IPC as in Eq. (9.1). It would be possible to calculate the theoretical propagation of uncertainty of the residual, $\sqrt{\langle R_t \rangle}$, as in Eq. (9.2), from the individual resolution r_A, r_B, and r_c if they were known.

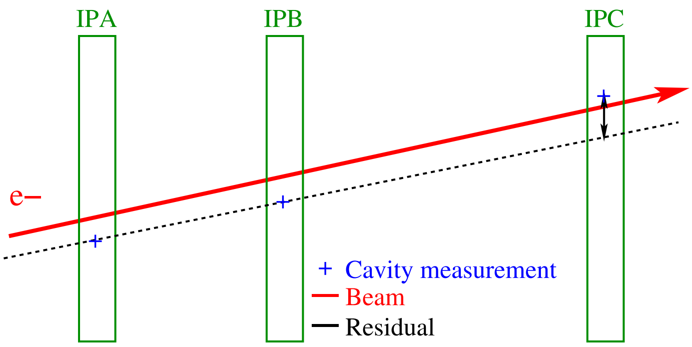


Figure 9.12 – Three BPM resolution. The position measurement at IPA and IPB are used to extrapolate to IPC. The residual from substraction of the measured and extrapolated position at IPC is used to estimate the system resolution.

$$R_t = y_C - f(y_A, y_B) \tag{9.1}$$

$$\sqrt{\langle R_t^2 \rangle} = \sqrt{\left(\frac{\partial R_t}{\partial y_A}\right)^2 r_A^2 + \left(\frac{\partial R_t}{\partial y_B}\right)^2 r_B^2 + \left(\frac{\partial R_t}{\partial y_C}\right)^2 r_C^2} \tag{9.2}$$

Assuming that each BPMs position measurements is independent and gaussian distributed, the standard deviation of the residuals distribution σ_{Rm} from measurements should be equal to the theoretical value $\sqrt{\langle R_t^2 \rangle}$. Equation (9.4) becomes Eq. (9.5) by assuming that each BPM has the same resolution $r_A = r_B = r_C = r$. The factor in the square root in Eq. (9.5) does not longer contains any unknowns, as R_t is a linear extrapolation using distances, and it will be a constant, g, multiplying the standard deviation from measurements to estimate the BPM resolution r. This constant is known as the geometrical factor.

$$\frac{\sigma_{Rm}}{\sqrt{\langle R_t^2 \rangle}} = 1 \tag{9.3}$$

$$\frac{\sigma_{Rm}}{\sqrt{\left(\frac{\partial R_t}{\partial y_A}\right)^2 r_A^2 + \left(\frac{\partial R_t}{\partial y_B}\right)^2 r_B^2 + \left(\frac{\partial R_t}{\partial y_C}\right)^2 r_C^2}} = 1 \tag{9.4}$$

$$\frac{\sigma_{Rm}}{\sqrt{\left(\frac{\partial R_t}{\partial y_A}\right)^2 + \left(\frac{\partial R_t}{\partial y_B}\right)^2 + \left(\frac{\partial R_t}{\partial y_C}\right)^2}} = r \tag{9.5}$$

$$g\sigma_{Rm} = r \tag{9.6}$$

Following the same example with IPC, it is possible to plot the measured value versus the prediction to find the slope and correlation. Ideally, both, slope and correlation are one, however they are resolution limited.

Being C_m the measured value at IPC, C_p the predicted value at IPC from the measurement in other cavities, and $R = C_m - C_p$ the residual from substraction, it is possible to obtain the slope, m, as in Eq. (9.7). The factor $\langle C_m \cdot R \rangle$ indicates the over or under prediction of the measurement at IPC.

$$m = 1 - \frac{\langle C_m \cdot R \rangle}{\langle C_m^2 \rangle} \tag{9.7}$$

The correlation can be approximated as in Eq. (9.8). If the factor $\langle C_m \cdot R \rangle$ is small, then, the ratio $\langle R^2 \rangle / \langle C_m^2 \rangle$ shows how big is the residual with respect to the beam jitter.

$$cor^2(Cm, Cp) \approx 1 - \left(\frac{\langle R^2 \rangle}{\langle C_m^2 \rangle} - \frac{\langle C_m \cdot R \rangle^2}{\langle C_m^2 \rangle^2} \right) \tag{9.8}$$

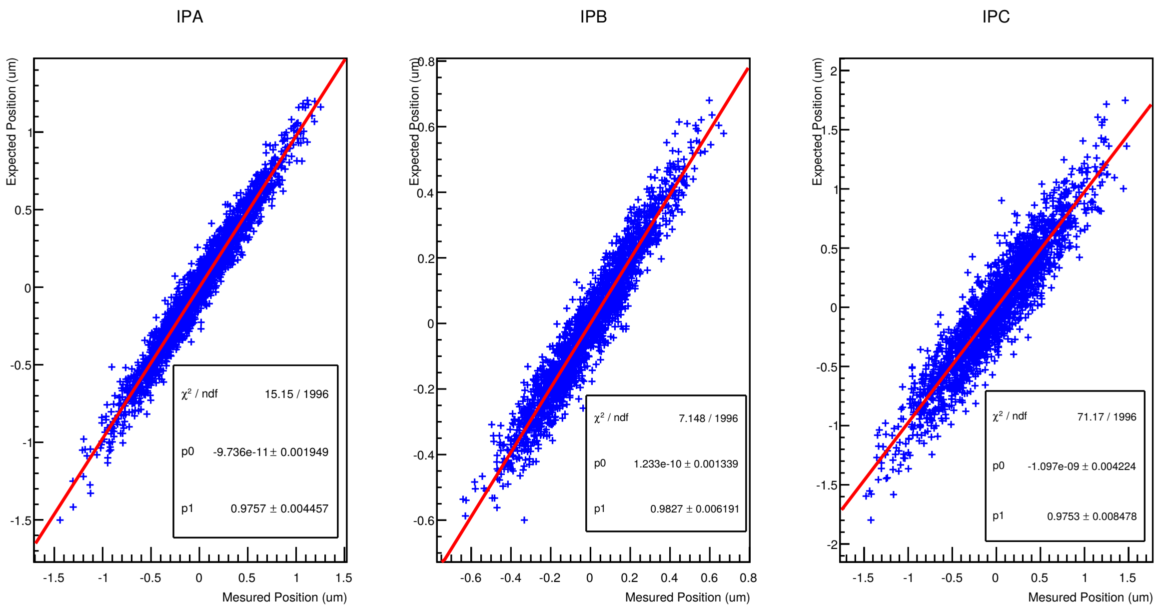


Figure 9.13 – Correlation of the three BPMs measurements and predictions.

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Figure 9.13 shows the correlation between the measured and predicted position at 4×10^{10} particles per bunch and 0 dB attenuation, where calibration has been modified by +3.7%, +10.9% and -2.8% for IPAy, IPBy and IPCy respectively in order to obtain unitary slopes within 2%.

The large correction made in the IPBy calibration could be explained by the results shown in Sect. 9.1.2, and the others lay within calibration precision limits.

The measured jitter and the residuals from substracting the predicted value are gaussian. The jitter values, slopes and correlations of predicted vs measured positions, and geometrical factors are shown in Table 9.1.

The resolution per BPM estimated with this method by calculating the residuals on each one of the three BPMs is (47.4 ± 0.7) nm.

Parameter	IPAy	IPBy	IPCy
Jitter [μm]	0.437	0.216	0.498
Slope	0.9757 ± 0.0044	0.9827 ± 0.0062	0.9753 ± 0.0085
Correlation	0.9798	0.9626	0.9322
Geometrical factor	0.5457	0.7988	0.2531

Table 9.1 – Results from trajectory reconstruction.

9.4 Feedback

For recent tests, a two bunch beam was used with a bunch spacing of 215.6 ns, and the signals from IPBy were input to the feedback system. Feedback has been tested by the FONT Group [51] obtaining a reduction of beam jitter down to 67 nm, compatible with the resolution shown in Section 9.3.

9.5 Status and Conclusions

Table (9.2) show summary of the current IP-BPMs results.

PARAMETER	REQUIREMENT	STATUS	Comments
Resolution	$\sim$nm@1×10^{10}	<50nm@$0.4 \sim 0.5 \times 10^{10}$	Calibration factors within 5% linearity BPM/Electronics noise : 10 nm per cavity IPC sensitivity and/or gain : +20nm X to Y coupling is still unexplored
Dynamic Range	$\sim 10\mu$m + extra	$9 \sim 11\mu$m@10 dB att.	Cavity response is linear within 5% Electronics starts to saturate at 0.4×10^{10} IPBy Q' signal saturates at 0 dB
Compatibility	IPBSM, EPICS	In progress	Calibration Software : Initial version released and in use. Requires comparison with offline results. Jitter analysis Software : Initial version released and in use. Requires comparison with offline analysis. IP-BSM, requires study of resolution vs low charge, $0.1 \sim 0.5 \times 10^{10}$
Feedback	Operative	Tested	Jitter reduction to 67 nm. Limited by BPM resolution.

Table 9.2 – IPBPMs status.

The efferts to improve over the results here listed are continuos. Precisely now, two improvements have been done on the system. First, the horizontal and vertical plane can be analized simultaneouly, and data can be checked for coupling from one plane to another. Second, filters are added to the system in order to reduce the effect of mismatch frequency from down-mixed signal.

At the moment, the first limitant to improve on resolution is noise limit. The target is to explore the origin of the noise and characterized the gain along the signals path. That will allow to conclude on the cavity sensitivity.

The IPBy Q' sigma is second limitant to avoid saturations and calibration errors. The reason is unknown for the moment, but it could be generated by a misalignment between cavities or a large static monopole signal. I think the monopole would affect also the horizontal plane, therefore the updates in electronics will help to diagnose the system.

In all cases the electronics needs to be updated because it saturates at half the bunch charge required. Extra dynamic range in electronics for residual Q' signals would solve the problem.

Under the current conditions the characterization of the resolution at low charges is possible, if data synchronized with the IP-BSM system, then it will provide useful information when tuning the optics, leading to finally include the IPBSM as a regular measurement instrument.