A prototype S-band BPM system for the ILC energy spectrometer

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Abstract

This note describes the design of a cavity beam position monitor (BPM) for the ILC energy spectometer and installation of a prototype cavity in the End Station A (ESA) test facility at the Stanford Linear Accelerator Centre (SLAC). We provide a brief description of the BPM assembly, control and readout electronics and signal processing. We give some more insight into important design issues and choices that were made in order to optimise the BPM for spectrometry purposes.

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1 Introduction

This note reports on efforts to design and fabricate a high precision, high accuracy cavity Beam Position Monitor (BPM). The focus of the research and design work was to provide the energy spectrometer project with an instrument to measure the beam position with a high accuracy and additional requirements of high stability to extend the lifetime of the energy calibration and simplicity of the design for easy fabrication, operation and low cost.

We describe the system which was installed in the End Station A (ESA) at the Stanford Linear Accelerator Center (SLAC) in the framework of the T-474/491 test beam experiment. This experiment was designed to demonstrate the performance of the energy spectrometer required for the International Linear Collider (ILC) physics program. We give some details on features of the BPM system and discuss the problems we faced during our work. In order to complete our description we review both the position and reference cavities, mover system we used for the calibration, analogue down-mixing electronics and digitisers.

2 Position and reference cavities

2.1 General considerations

The choice of the cavity BPM structure is mainly a decision between a square and a cylindrical cavity. A better accuracy of machining can be achieved for a cylindrical cavity but it needs tuning to reduce the internal cross-coupling between x and y channels if a single cavity is used to read out both. In case a single rectangular cavity is used for both x and y the frequencies can be made different for the two polarisations of the position dependent dipole mode, which means that the polarisations are decoupled, but the signal processing usually becomes more complicated.

Our design of the position cavity evolved from the cylindrical ATF2 BPM to which we also contributed to, which in turn is a follow-up of the cavity built by the Budker Institute group (BINP, Novosibirsk) and used in all NanoBPM studies [1]. The BINP cavity has two waveguides - one for the x and one for the y direction [2]. The waveguides couple to the cavity via rectangular slots in the flat side of the cavity. This arrangement allows the unwanted monopole modes to be suppressed by a factor depending on the machining accuracy, typically 30–40 dB, and efficiently couple the dipole mode.

The ATF2 BPM operates at the same frequency (6.5 GHz) as the BINP cavity and includes some practical improvements such as orientation of the waveguides parallel to the beam axis for a more compact design suitable for mounting directly onto quadrupole magnets, two waveguides for each transverse direction to make the cavity symmetric and gain an additional 3 dB of the signal strength, and push-pull tuners for tuning the frequency and improving the x to y isolation. The ATF2 cavities were tested by the KEK group and showed very good results. In particular, an isolation between the x and

y ports exceeding 40 dB was measured after tuning. Some more details on that cavity can be found in [3].

The major changes for the spectrometer BPM were the dipole mode frequency and the decay time. The frequency was reduced down to 2.9 GHz for the following reasons:

Firstly, a lower frequency results in a better stability of the system. Even though the relative change of the frequency due to the temperature drifts is to the first order the same for any cavity made of the same material, the absolute change is different. So, for a 1 degree temperature change a 2.9 GHz cavity will drift by about 50 kHz and a 6.5 GHz cavity by 110 kHz. Assuming for simplicity a solid, 20 m long copper cable we would see the length changing by 340 μm per degree, which means about 1.8° phase change at 2.9 GHz and 4.1° at 6.5 GHz. This change does not contribute to the stability directly as we measure the phase relative to the reference cavity [4], but means that the cables must be of the same length and the accuracy required scales with the frequency.

Secondly, for machine protection reasons the aperture of the BPM for the spectrometer has to be about 30 mm, so that if for any reason the cavity mounted on a mover is driven by 5 mm in the direction opposite the direction of the bend in the spectrometer chicane and the total beam offset in the BPM is 10 mm, the beam would not hit the BPM. The beam pipe should also not be larger than required as because the dipole mode field grows almost linearly from the centre towards the edges of the beam pipe and the maximum field is usually close to that edge, so the gradient, and hence the offset sensitivity, is higher for a smaller beam pipe. Clearly, the diameter of the cavity has to be larger than 30 mm, but the rule of thumb is that the diameter of the cavity should be at least three times the aperture. In a cavity smaller than that the dipole mode field would leak into the beam pipe resulting in higher incline sensitivity.

Thirdly, the dimensions of a 2.9 GHz cavity are such that machining tolerances of 10–20 μm still provide a good accuracy of the frequency and coupling, while for a smaller cavity they may not be sufficient.

Finally, a 2.9 GHz signal for down-mixing, readily locked to the machine RF system, can easily be generated with a low multiplication number at both main ILC test facilities, ESA and ATF.

Any further reduction of the frequency down from 2.9 GHz would make the cavity too big and heavy, and make its installation and fabrication harder.

In some cases one has to consider the bunch length effects as they can reduce the signal level if the bunch length is comparable with the wavelength of the dipole mode. Luckily, the ILC bunches are short (300 μm) compared to the wavelength up to about 10 GHz, so there is no need to take into account the intra-bunch effects. This is also true for ESA (300–500 μm) and to some extent for ATF (8–10 mm).

The decay time was tuned to provide the best performance in both single-bunch and multibunch, 300 ns bunch spacing, modes. It mainly depends on our ability to separate the signals of sequential bunches. Decay times of 100–200 ns have been shown to produce good results in single-bunch mode while providing a good separation in multibunch mode. For a shorter decay time the separation would be better, but the part of the signal useful for the analysis would be too short and higher sampling rates would be necessary.

2.2 EM simulations

Unfortunately, even for a single cavity loaded with a waveguide and beam pipes the analytical solution is complicated and the result is often inaccurate, so electromagnetic (EM) field simulators are a common tool. We use GdfidL [5] to calculate shunt impedances, resonant frequencies, couplings, etc.

We chose the operating frequency to be 2877.4 MHz. A 2856 MHz signal, easy to produce at most linacs, can then be used as the Local Oscillator (LO) signal resulting in an Intermediate frequency (IF) of 21.4 MHz, which is low enough for digitisation but the period of oscillation is short enough in comparison to the decay rate. 21.4 MHz is a frequency frequently used as IF in some instrumentation (such as spectrum/network analysers).

We also optimised the normalised shunt impedance of the cavity as it is the measure of the coupling to the bunch field. Up to a certain limit, the longer the cavity, the higher is the shunt impedance, but at the same time the signals generated by the beam slope and bunch tilt contribute more into the dipole mode signal when the length is increased (fig. 1). It makes sense to keep the length of the cavity at least below 30 mm, we chose 20 mm, where the slope contribution is still small.

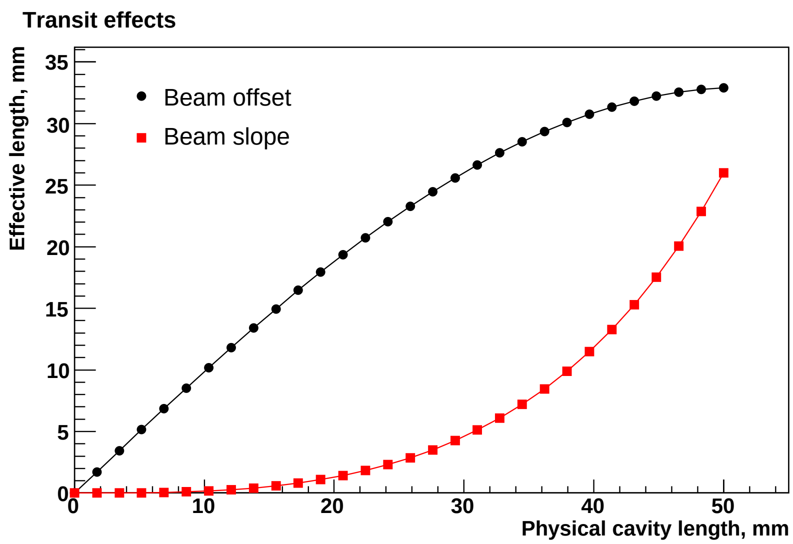

Figure 1: Effective cavity length for the position and incline contributions to the dipole mode vs. physical cavity length.

The internal Q-value has to be known as it characterises the losses in the walls of the cavity. It mainly depends on the material and the area of the cavity walls. The results of the simulation usually have a systematic error of 10–20% as they do not take into account the surface quality.

With GdfidL these values are found through frequency domain computations. We modelled the cavity accurately applying a dense computational mesh, usually 1 mm step in non-critical areas and 0.1–0.2 mm in the areas were more detailed modelling was required (such as slots, feedthroughs). GdfidL computes the eigenvalues of the cavity, corresponding to a set of resonant frequencies and fields of different modes. For example, the dipole mode filed plotted in 3D space is shown in fig. 2.

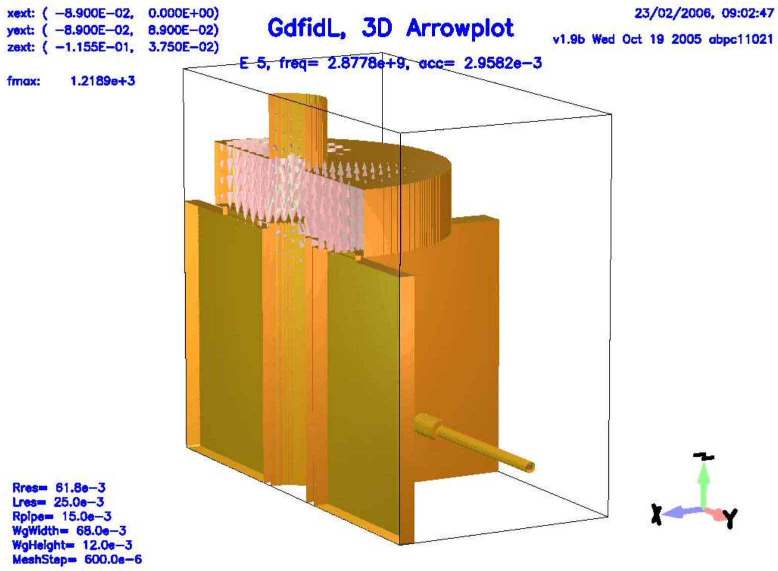

Figure 2: Dipole mode fields shown schematically as generated by GdfidL.

The drawback of the frequency domain calculation is that all the couplers which are matched are replaced with short circuits. In some cases that affects the resonant frequency significantly. A more accurate result for the resonant frequency can be obtained in time domain. It is possible to load the fields obtained through the eigenmode computation back into the solver and let them oscillate in time domain. The couplers are then represented by matched ports. For a more accurate simulation the adapter part of the waveguide can be included in the model, so that the effect of the reflections produced by it can also be taken into account.

The electromagnetic waves propagate into the ports resulting in a decay of the energy stored in the cavity. Calculating the decay constant we can obtain the external Q-value characterising the strength of the coupling to the external network.

These simulations were repeated in a few iterations to optimise the parameters, the final values are presented in table 1.

The corresponding dimensions of the cavity among with their tolerances are listed in table 2. To estimate the tolerances we simulated the cavity with the dimension increased by the size of one mesh step assuming that the change is small and the frequency dependence is linear.

Not all the dimensions affect the frequency evenly strongly and for those with a weaker effect the tolerances can be relaxed, while for the cavity and beam pipe diameters machining tolerances must be kept tight.

Parameter	First monopole mode TM_{010}	First dipole mode TM_{110}	Second monopole mode TM_{020}
f, MHz	1898	2878	4413
R/Q, Ohm	115	0.26/mm^2	36
Q_0	9500	11320	15140
Q_{ext}	-	2200	-

Table 1: Design parameters of the BPM.

Dimension	Value, mm	Sensitivity, kHz/μm	Tolerance assigned, μm
Diameter	123.61	-20.9	$\pm$10
Length	25	2.7	$\pm$50
Beam pipe diameter	30	-4.7	$\pm$10
Slot width	6	-1.0	$\pm$50
Slot length	30	-1.3	$\pm$50
Slot distance		0.9	$\pm$50

Table 2: Dimensions and tolerances of the BPM.

Any asymmetry of the coupling slots with respect to the cavity results in a coupling of the monopole modes and therefore must be kept to a minimum. In order to estimate the tolerances for machining the coupling slots we simulated the cavity with one slot offset by one mesh step with respect to the cavity's symmetry plane. We represent the results of this simulation in terms of the equivalent virtual beam offset. A slot offset of 100 μm would result in coupling a fraction of the monopole mode signal equivalent to 11 μm for the first and 230 μm for the second monopole. These numbers may seem big, but most of the monopole modes power is rejected in the front-end filters of the processing electronics. We specified tolerances of $\pm$20 μm to keep the monopole contribution well below a 1 μm level.

2.3 Reference cavity design

The reference cavity was designed to be compact and easy for fabrication. It has a re-entrant structure to reduce the size and only one coupler (fig. 3). The reference was designed to operate at the same frequency as the position cavity, which means that its first monopole mode is tuned to the same frequency as the dipole mode of the position cavity, so that any bunch length effects would be the same in both cavities. Note that because of the same frequency it must be kept away from the position cavity to avoid interference. The reference signal is processed in exactly the same way as the position signal and used for decoding the sign of the beam offset and charge normalisation.

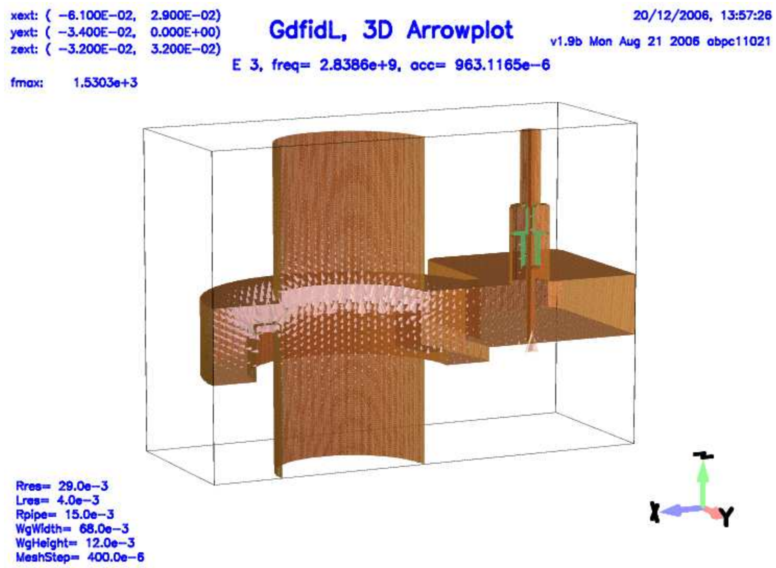

Figure 3: Inside structure of the reference cavity.

2.4 Model cavity

A model of the position cavity was fabricated in order to check the design. It was made of Aluminium and the parts were simply screwed together as the device did not have to be vacuum tight (see fig. 4). The model consisted of 4 parts: The main one included the cavity and the coupling slots. A part with a cruciform shape hosted the 4 coupling waveguides. The other 2 parts were the lid closing the cavity and the end plate sealing the waveguides.
One of the coupling slots was displaced by 200 μm in order to check the monopole mode coupling. Despite that large perturbation no coupling at the first monopole mode could be measured between any two couplers. Measurements with an external antenna confirmed that the coupling is extremely weak. Fig. 5 shows a frequency scan obtained this way; it is clear that both monopole modes are strongly suppressed, but this measurement is qualitative as the coupling depends on the antenna position, which was not fixed.

2.5 Vacuum prototypes

Vacuum prototypes of both the position and the reference cavities for the beam tests were developed in collaboration with Mullard Space Science Laboratory (MSSL). We chose the traditional technology for making warm type cavities, the parts of the cavity were made of oxygen free copper (OFC) and brazed together. This process also allows copper parts to be connected to stainless steel parts, which we used for attaching the beam pipes, tuning screws and feedthroughs.
The prototype of the position cavity (fig. 6) consisted of the same principal parts as the model cavity. For the prototype to sustain the vacuum in the accelerator beamline all

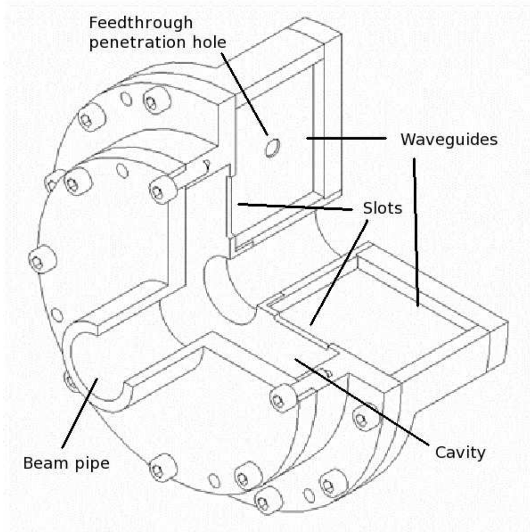

Figure 4: A 3D sketch of the model cavity.

the parts were brazed together at up to 870 °C. Special grooves for the brazing material and stop grooves preventing the material from leaking into the cavity were cut out in the joining surfaces.

All rotation symmetric surfaces were machined using a lathe. A wire cutting technique was used to produce the waveguide cruciform and achieve good surface roughness. Computer Numerically Controlled (CNC) machining was applied elsewhere.

Brazed parts become electrically the same whole, which is beneficial in the case of RF cavities, although any joints underfilled with brazing material may result in gaps and worsen the cavity's performance increasing the losses, and any joints overfilled may result in excessive material running out and into the cavity altering such parameters as frequency and Q-value, therefore the amount of brazing material has to be estimated and in many cases adjusted experimentally.

Unfortunately, in our case the engineering effort was too narrowly focused on avoiding the cavity to be filled with the brazing material, which resulted in critical joints being underfilled. As a result, some key parameters of the copper prototype were worse than measured with the model cavity, the quality factors and cross-coupling most severely affected by the gaps. The parameters are compared to the predictions and measurements with the model in table 3.

Together with the Special Techniques group at the UK Atomic Energy Agency (UKAEA) we carried out a few tests to optimise the brazing process. We found that the best results can be obtained if the copper parts are first plated with Nickel at the joints. A 7–10 μm layer was found to be sufficient to avoid the gaps while only a tiny amount of material was leaking into the cavity. The parts are then brazed together at about 1050 °C. The drawback of this method is that for the most cavity parts Ni-plating has to be done prior to some final machining stages, what complicates the fabrication. Also, higher brazing

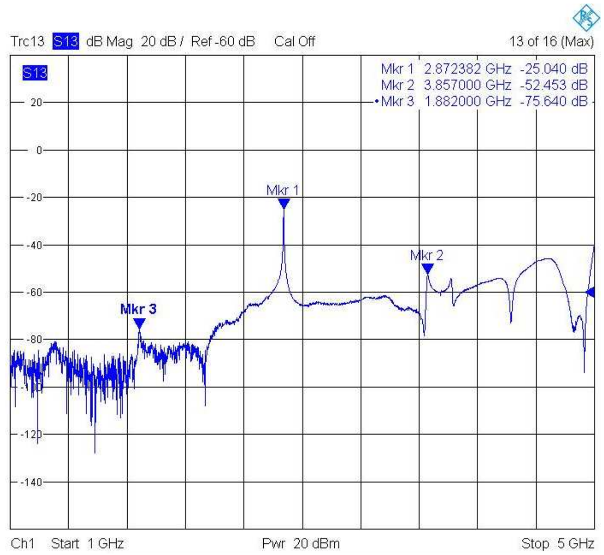

Figure 5: Frequency scan with an external antenna, marker 1 shows the dipole mode peak, marker 2 - second monopole, marker 3 - first monopole.

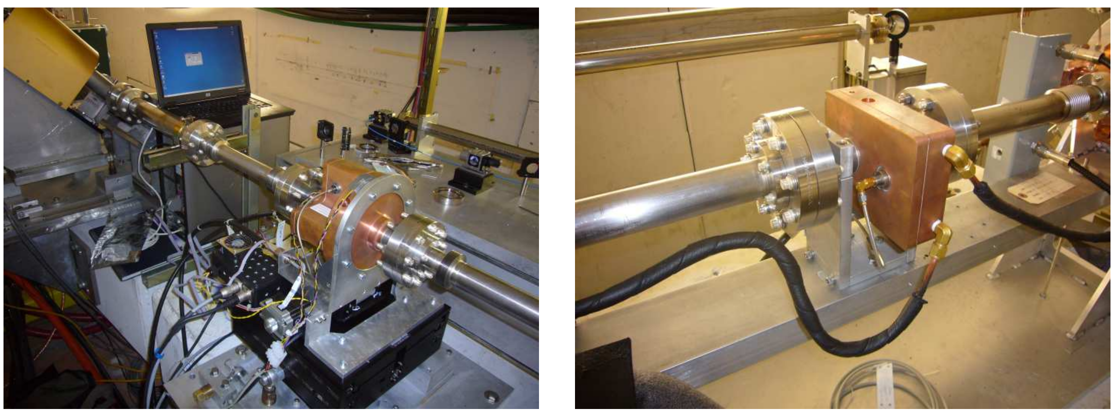

Figure 6: Vacuum prototypes of the position (left) and reference (right) cavities in the End Station A beamline.

temperature can potentially cause deformations of the copper parts, so additional tests may be required in order to check that.
We managed to design the reference cavity so that only CNC machining was required for its fabrication. The parts were still brazed together, but because there was only one critical joint, better coupling was achieved with this cavity. Due to poor fabrication, however, the resonant frequency was very low, almost 100 MHz lower then expected. Even with an additional tuning hole we only managed to increase the frequency by 56 MHz up to 2834 MHz, so that the cavity could be operated and its signal mixed to the negative sideband of the mixer.
Despite the poor fabrication and hence performance on the test bench it was decided to

Parameter	Expected value	Al model	Copper prototype
Frequency, MHz	2878	2871	2876
Q_0	up to 10000	2250	1000
Q_{ext}	Al-3500/Cu-2200	4000	3200
Q_L	1850	1450	700
x-y coupling, dB	20 (min)	15 (perturbed!)	10

Table 3: Comparison of the predicted and measured parameters of the cavity.

install the prototype in the End Station A beamline at SLAC. The cavity was mounted on a simple but robust setup consisting of an aluminium bracket attached to a horizontal stage mounted directly onto a vertical lifting stage. Once at SLAC, the whole setup was put on an adjustable platform to allow for the initial alignment (fig. 7). The travel range of both stages was limited to ± 5 mm. It was done for beam protection reasons – the cavity was installed in the centre of a magnetic chicane translating the beam by about 5 mm during the operation, the total offset of the beam in the cavity could not exceed 10 mm and the beam would have enough clearance in the 15 mm radius beam pipe.

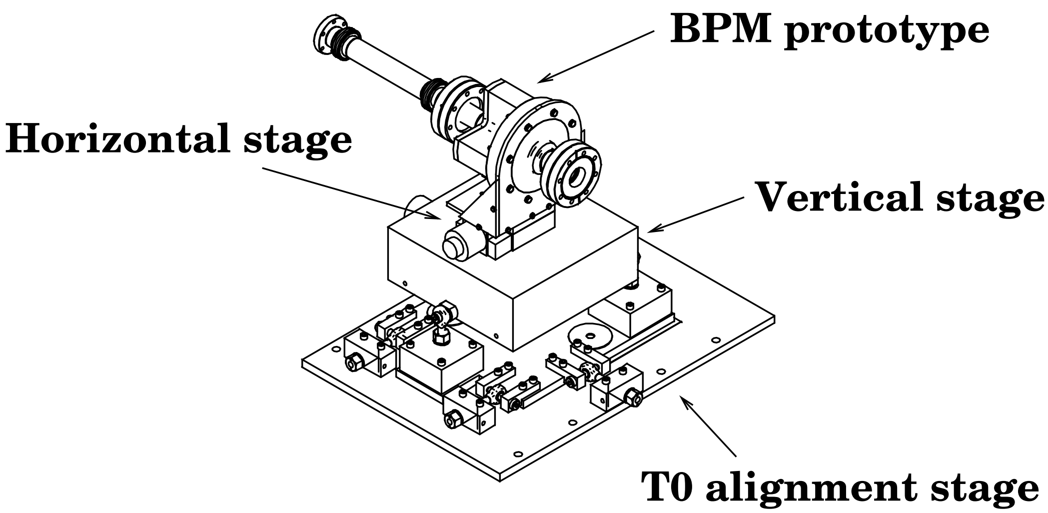

Figure 7: BPM prototype in assembly with the support stand, vertical and horizontal mover stages mounted on an adjustable supporting platform (T0 stage).

3 Signal processing electronics and digitisers

We used simple one stage down-mixing electronics to process the BPM signals (see fig. 9). In our scheme signals from the two opposite couplers are supposed to be combined in a hybrid, although we did not use it in our initial tests taking the signal from one coupler only and terminating the other. The electronics were placed outside of the beam line tunnel protected by concrete walls. In that arrangement we had to use low-loss cables to minimise the attenuation of the signal. Upon reaching the electronics the signal first passes through a limiter thereby preventing all the components downstream from extreme signal levels. At the next step the signal can be attenuated and the attenuation controlled remotely via a control circuit. After that the signal is mixed with the Local Oscillator (LO) signal in the Image Reject Mixer (IRM), combined of two mixers and rejecting the image signal from the lower sideband. Finally, after some filtering to suppress the upconverted component and amplification the signal is digitised.

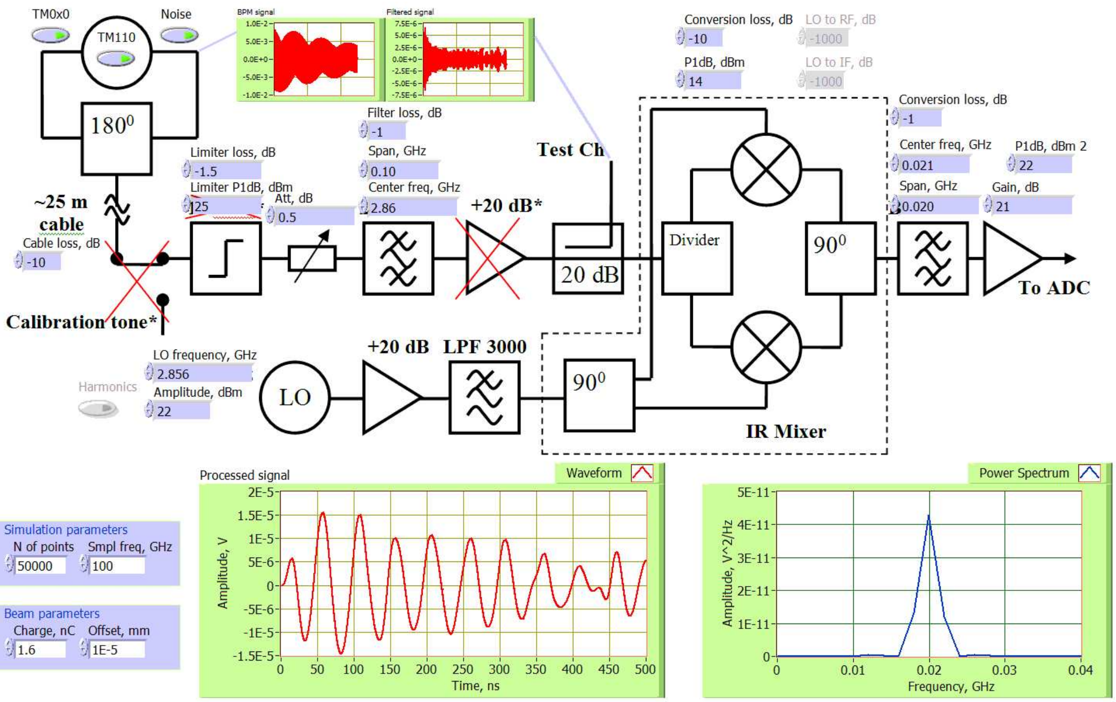

Figure 8: BPM processor schematic built into simulation program interface.

Downmixed signals are digitised at 100 MS/s (internal clock) or 119 MS/s (external clock synchronised to the accelerator RF) with help of Struck SIS3301 14-bit digitisers. They provide 75.3 dB signal-to-noise ratio, corresponding to a true resolution of 12.2 bit. Each SIS module has 8 inputs and so can serve up to 3 BPMs with 2 channels reserved for the reference and trigger signals. These digitisers have VME interface and a few of them can be installed in one VME crate.

In order to check the electronics design, a simple simulation code was written in LabVIEW. The BPM signals including the first two monopole modes, dipole mode and noise are simulated from first principles and then propagated through the electronics. For the key components such as the mixer and amplifier we simulated the non-linear behaviour in order to see the harmonics generated and estimate the dynamic range of the electronics. This simulation software allowed us to optimise the filtering so that the transient

Figure 9: SIS3001 digitiser module (without the protective lid).

signal was minimised around the peak of the waveform, where we were sampling the data. With help of the code the dynamic range of the electronics was roughly estimated to 200 nm–1 mm.

4 Results from the test run

The BPM and electronics were tested at ESA during the run in July 2007. The main result was the sensitivity of the cavity as we knew that the fabrication was not a great success. Keeping the beam stable we moved the BPM in 1 mm steps and recorded the response with a high-speed oscilloscope (fig. 10). Averaging the output voltage over 50 bunches for each step we found a sensitivity of 0.5 V/mm/nC, which is very close to the 0.7 V/mm/nC predicted by simulations. The difference can be explained by the coupling reduced due to fabrication issues.

Although the sensitivity of the cavity was close to the one expected, we were unable to proceed with the full test due to enormous x–y coupling inside the cavity. About 2 μm resolution was measured in x while the beam was stable in y, but clearly this was limited by the jitter in y direction. The electronics tested in conjunction with the old SLAC cavities (which do not include the monopole mode rejective coupling) showed a resolution of about 200 nm and a maximum offset of about $\pm$1.2 mm as expected.

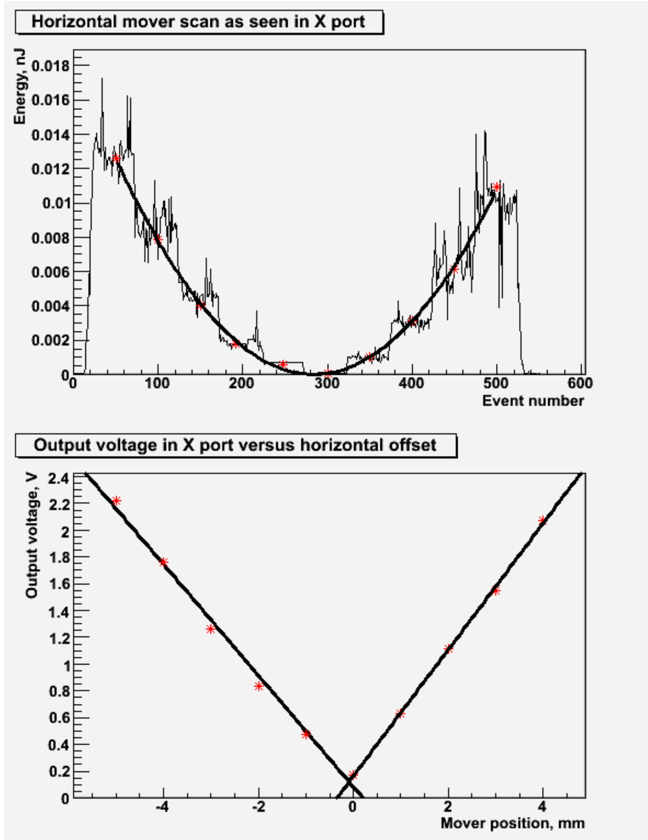

Figure 10: Results of the sensitivity measurement.

5 Conclusions

Despite the fabrication problems, the cavities showed the expected sensitivity during the beam tests. The electronics performed as expected and provided a dynamic range of 200 nm–1.2 mm even while tested with the older design cavities.
In order to fix the position cavity some refurbishment has to be done so that the axes of the dipole mode polarisations can be fixed to the geometrical x and y axes of the cavity with tuners. Beam tests could be done at KEK, where our reference cavity and electronics will be a part of the S-band BPM system.
Brazing tests were done to ensure a better fabrication and performance of the future prototypes and a better method of brazing the copper parts was found.

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