Results from a Future Linear Collider Energy Spectrometer Prototype

A. Lyapin[a], H.J. Schreiber[b], M. Viti[b], C. Adolphsen[c], R. Arnold[c], S. Boogert[d], G. Boorman[d], F. Gournaris[a], V. Duginov[e], C. Hast[c], M. Hildreth[g], C. Hlaing[h], F. Jackson[i], O. Khainovsky[h], Y. Kolomensky[h], S. Kostromin[e], B. Maiheu[a], D. McCormick[c], D. J. Miller[a], N. Morozov[e], T. Orimoto[h,j], M. Slater[f], Z. Szalata[c], M. Thomson[f], D. Ward[f], M. Wing[a], M. Woods[c]

[a]*University College London, London, UK*
[b]*Deutsches Electronen Synchrotron DESY Hamburg and Zeuthen, Germany*
[c]*SLAC National Accelerator Laboratory, Menlo Park, California, USA*
[d]*Royal Holloway, University of London, Egham, UK*
[e]*Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia*
[f]*University of Cambridge, Cambridge, UK*
[g]*University of Notre Dame, Notre Dame, Indiana, USA*
[h]*University of California and Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[i]*Daresbury Laboratory, Daresbury, UK*
[j]*California Institute of Technology, Pasadena, California, USA*

Abstract

The International Linear Collider and other proposed high energy e^+e^- machines aim to measure the Standard Model quantities and new, not yet discovered phenomena with unprecedented precision. One of the main requirements for achieving this goal is a measurement of the incident beam energy with an uncertainty of 10^{-4} or less. This article describes the performance of a protoype energy spectrometer commissioned in 2006-2007 in SLAC's End Station A beamline. The prototype was a 4-magnet chicane equipped with several beam position monitors restoring the beam orbit through the chicane. An energy resolution close to $5 \cdot 10^{-4}$ was estimated, which, however, needs to be improved for use in a linear collider. We also report on the operational experience with the prototype and devise ways of improving the performance of the chicane-based spectrometer.

Keywords: Energy measurement, Energy Spectrometer, Cavity Beam

[1]This work was supported by the Commission of the European Communities under the 6th Framework Programme "Structuring the European Research Arm," contract number RIDS-011899 and by the Science and Technology Facilities Council (STFC)

[2]This work was supported by the U.S. Department of Energy under contract DE-AC02-76SF00515

[3]This work was supported by the U.S. Department of Energy under contract DE-FG02-03ER41279

Position Monitor, BPM, End Station A, ESA, International Linear Collider, ILC

1. Introduction

The physics potential of the next TeV-energy Linear Collider depends greatly on precision energy measurements of the electron and positron beams at the interaction point (IP). Such measurements are mandatory in order to determine particle masses in high-rate processes. For example, measuring the top mass from a threshold scan to order of 100 MeV or measuring the Standard Model Higgs in direct reconstruction to about 50 MeV requires knowledge of the luminosity-weighted mean collison energy to a level of $1-2\cdot 10^{-4}$ to avoid center-of-mass energy ($\sqrt{s}$) uncertainties from dominating the experimental results. Incoming beam energy (E_b) measurements are a critical component to $\sqrt{s}$ determination as it sets the overall energy scale for the collision process.

The strategy proposed in the International Linear Collider (ILC) design [1] is to have redundant beam-based measurements capable to achieve a 10^{-4} relative precision on a single beam, which would be available in real time as a diagnostic tool to the operators. Also, physics reference channels such as $e^+e^- \rightarrow \mu^+\mu^-\gamma$ where the muons are resonant with the known Z-mass are expected to provide valuable cross-checks of the collison energy scale, but only long after the data have been recorded.

The primary method planned to perform E_b measurements at the ILC is a non-evasive beam position monitor (BPM) based energy spectrometer similar to a setup used for callibrating the energy scala for the W-mass measurement at LEP-II [2]. At the ILC, however, the parameters of the spectrometer are tighty constrained to provide limited emittance dilution at the highest ILC energy of 500 GeV.

Initially, a 3-magnet chicane located upstream of the interaction point just after the energy collimators of the beam delivery system (BDS) was proposed [3]. But the baseline ILC spectrometer design uses two dipole magnets to produce a beam displacement x, while two more magnets return the beam to the nominal beam orbit. For such a chicane, the beam energy is then given by

$$E_b = \frac{c \cdot e \cdot L}{x} \int_{magnet} Bdl \quad , \tag{1}$$

where L is the distance between the first two magnets and $\int Bdl$ the B-field integral in each magnet. The 4-magnet chicane avoids spurious beam displacement signals in the BPMs due to beam tilts, and thus systematic errors in E_b measurements. For this reason, a 4-magnet spectrometer, which maintains the beam axially with respect to the axis of the cavity BPMs, is preferable over a more conventional 3-magnet chicane. In both cases the B-field in the spectrometer chicane can be recorded and reversed for studying systematic effects without changing the beam direction downstream of the spectrometer.

When operating the spectrometer with a fixed dispersion of 5 mm at the center over the whole energy range, a BPM resolution better than 0.5 μm is needed. This resolution can be achieved with cavity BPMs [4]. Since the spectometer bending magnets need to operate at low fields when running the ILC at the Z-pole, the B-field measurement may not be accurate enough to provide the required level of precision. Significantly improved BPM resolution whould however allow to run the magnets at the same field for both the Z-pole and highest energy operation.

An absolute energy measurement requires that the beam orbit measurement is referenced to the orbit with no field applied. Unfortunately, the residual fields still have an impact on the beam orbit at a level that may affect the overall beam energy accuracy. There is an ongoing R&D program to determine how to perform accurate field mesurements for very low magnetic fields [5].

Some original energy resolution studies of the SLAC prototype 4-magnet chicane were published by M. Viti in his PhD thesis [6]. His analysis used calibrated beam position readings but revealed that due to small differences between the magnets in the chicane the beam inclination also needs to be considered. It was soon realised that the same analysis could be extended by using complex BPM readings that contain the information on both the beam offset and inclination. This approach eliminates the need for position calibration of the BPMs, while the whole system could be calibrated by means of an energy scan.

In this publication we present the analysis based on that idea, estimate the resolution of the spectrometer to compare it with the result of $8.5 \cdot 10^{-4}$

measured in [6]. We also consider the impact of different systematics on the energy measurement in order to improve the resolution to below the 10^{-4} level in future experiments.

2. Test Beam Setup and Spectrometer Hardware Configuration

A protype test setup for a 4-magnet chicane was commissioned in 2006 (the T-474 experiment) and extented in 2007 (the T-491 experiment) in the End Station A (ESA) beamline at the SLAC National Accelerator Laboratory [7].

In our experiments the electron beam generated by the main Linear Accelerator at SLAC was transported to the ESA experimental area through the 300 m long transfer line A including bending and focussing magnets, and diagnostic instruments such as stripline and RF cavity BPMs, charge sensitive toroids, a synchrotron light monitor, profile screens and diodes. The SLAC linac was providing single bunches at 10 Hz and a nominal energy of 28.5 GeV, a bunch charge of $1.6 \cdot 10^{10}$ electrons, a bunch length of 500 μm and an energy spread of 0.15%, i.e. with beam properties similar to the ILC expectations at the highest energy currently available for electrons.

These unique beam parameters allowed to test the capabilities of the proposed spectrometer under realistic beam conditions. Two feedback systems were in place for the ESA beam: one for its position and one for the energy. The position feedback stabilised the beam position and angle using cavity BPMs and corrector magnets upstream the ESA area. The energy feedback stabilised the energy feeding back on the phase of the klystrons of the linac and was also used for offsetting the energy from the nominal in $\pm$100 MeV range.

The setup, as schematically shown in Fig. 1, includes four bending magnets denoted as 3B1, 3B2, 3B3 and 3B4, forming a chicane in the horizontal plane and high-precison cavity BPMs upstream, downstream and in between the dipole magnets. Two of which (BPMs 4 and 7) in the middle of the chicane were instrumented with precision movers. Horizontal positions of three monitors (BPMs 5, 4 and 7) were monitored with a Zygo interferometer [zygo ref].

10D37 magnets from the old SPEAR injection beamline refurbished for the use in the chicane are 37" long, 10" wide on the pole faces and have a 3" gap. They were run in series from a single power supply to minimize relative drifts. We studied the magnets during a set of measurements in

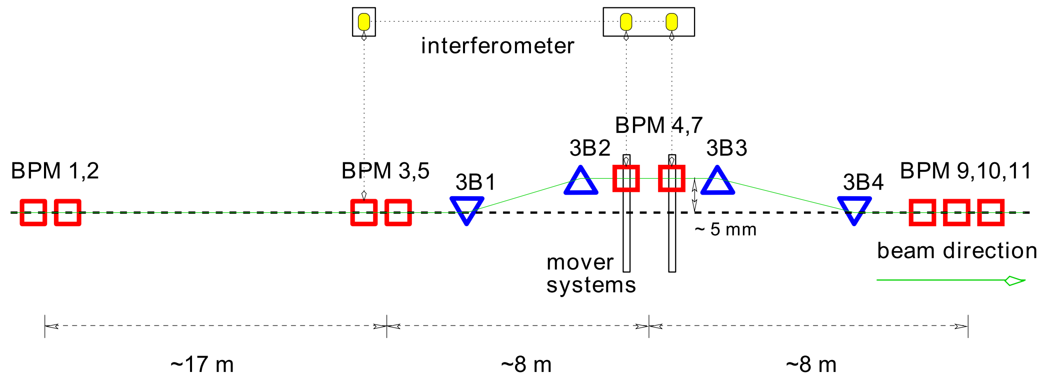

Figure 1: Schematic representation of the prototype spectrometer in ESA.

the SLAC's Magnet Measurement Laboratory. Magnetic field maps of the vertical field component B_y were taken using NMR and Hall probes, while each $\int Bdl$ was measured using a flip coil, which was calibrated against a moving wire system. Stability and reproducibility were at the focus of these measurements. Details of the field measurements can be found in [8, 6, 9].

In situ at ESA, two NMR probes wth different but overlapping working ranges and one Hall probe were installed in the first magnet 3B1, while one NMR probe was positioned in each other three magnets, so that field integral values could be monitored. In the test data runs, the nominal B-field was 0.117 Tesla·m which corresponds to a magnet operation with 150 A. The stray field outside the magnets in the middle of the chicane was monitored using two low-field fluxgate magnetometers. One was placed on the girder to obtain x- and y-field components and the other on the beam pipe measuring the y-component only. Properties of the probes and the fluxgate monitors are summarized in Tab. 1.

[check the probes location, discuss NMRs]

In order to measure the beam orbit, 8 cavity BPMs all operating in the S-band of the RF, were installed. Three of them were SLAC prototype ILC BPMs (3, 4, 5) using cylindrical cavities with x- and y-waveguides for the dipole mode coupling and monopole mode suppression. Each of the five SLAC linac type BPMs (1, 2, 9, 10, and 11) consists of three cavities: two rectangular ones for x and y separately to avoid x-y couplings, and one cylindical cavity to provide charge and phase information. BPM 7 was a dedicated ILC prototype designed and manufactured in the UK for the use

Table 1: Types of probes used for the magnetic chicane in ESA.

Name and Type of the device	Field component	Working range
NMR 3B1A		0.043 - 0.13 T
NMR 3B1B		0.09 - 0.26 T
NMR 3B2C		0.09 - 0.26 T
NMR 3B3D		0.09 - 0.26 T
NMR 3B4E		0.09 - 0.26 T
Hall probe	Y Component	
Fluxgate 1	Y/X Component	
Fluxgate 2	Y Component	

in the spectrometer. Unfortunately, this monitor could not be used in the analysis due to manufacturing problems [ukbpm]. Details on the performance of the BPM system and information on the A-line configuration can be found in [4].

BPMs 12 and 24 in the A-line are placed in high-dispersion points [check numbers] of the bending arc. In our experiment, they were instrumented with the same high-sensitive electronics as all other BPMs in the ESA beam-line, so that energy measurements in the A-line and in the chicane could be performed simultaniously and cross-checked against each other.

3. Performance of the Prototype Spectrometer

3.1. Reconstruction of the beam orbit in the middle of the chicane

As the chicane magnets bend the beam in the horizontal (x-) plane, we are mainly interested in the horizontal beam position and angle, and, unless specified otherwise, we talk about the x-coordinate throughout this section.

The offset of the beam trajectory in the middle of the chicane, see eq. (1), has to be measured with respect to the nominal orbit position reconstructed using BPMs outside of the chicane. In order to predict the readings of BPM 4 data from run 2747 were taken, with zero-current in the magnets and neither the beam nor the hardware were manipulated. Data from a run with magnets on could also be used for relative measurements and would result in some better prediction, but due to the residual disperion in the beamline beam positions before and in the middle of the chicane are correlated. For that reason, only data from a run with magnets off were used.

When the magnets are on, BPMs 9, 10 and 11 were excluded from the prediction matrix because the impact of the chicane on the beam orbit is not fully compensated due to of the differences between the magnets.

Due to alignment errors, there is also a correlation between the vertical beam position and angle before the chicane and the horizontal beam position and angle in the mid-chicane. Therefore, both x- and y-readings from the BPMs upstream of the chicane (x1, x2, x3, x5, y1, y2, y3 and y5) were used in the analysis.

In our system signals generated by the BPMs were digitized and stored in data files for each event, i.e. for each beam trigger. They are then digitally converted to the baseband to decode the envelope [4]. A complex digital local oscillator signal allows to decode both the amplitude and the phase of the signal's phasor along the waveform. Sampled at a point close to the peak and normalized by the phasor from the reference cavity, it gives the real, in-phase (I), value and the imaginary, quadrature (Q), value, which contain the information on the beam offset as well as the inclination.

In order to reconstruct the beam orbit in the mid-chicane, the I and Q values from BPM 4 are correlated to the I and Q values from the upstream BPMs we used the Singular Value Decomposition (SVD) method [10] from several thousands of readings. Inversion of the matrix of the measured I and Q values for the selected BPMs provides a vector of coefficients which relate the I's and Q's of each BPM to those of BPM 4 so that a prediction can be made:

$$I_{BPM4} = \alpha_0 + \sum_i \alpha_i^{(I)} \cdot I_i + \sum_i \alpha_i^{(Q)} \cdot Q_i \qquad (2)$$

$$Q_{BPM4} = \beta_0 + \sum_i \beta_i^{(I)} \cdot I_i + \sum_i \beta_i^{(Q)} \cdot Q_i, \qquad (3)$$

where α's and β's are the SVD coefficients.

The difference between the predicted and the measured values is called residual. In our case, the RMS residual is the precision of the orbit prediction and the resolution of BPM 4 added in quadrature. It sets the limit on the spectrometer resolution. The measured and predicted values for I and Q are plotted against each other in fig. 2. The points in these plots lie around the $x = y$ bysector lines shown in solid, which means the prediction works correctly. The histograms in the bottom part of fig. 2 show the residuals, for both the I and Q values.

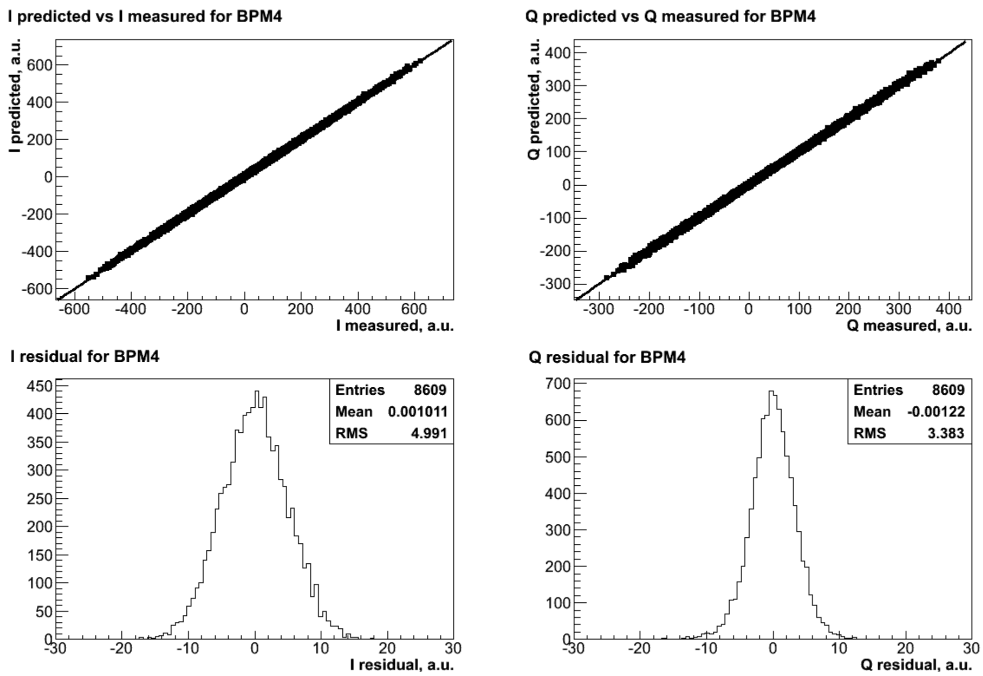

Figure 2: BPM 4 readings predicded from other BPMs in the beamline for run 2747: I predicted vs I measured (top left), Q predicted vs Q measured (top right), I prediction residual (bottom left), Q prediction residual (bottom right).

It is clear that the I and Q residuals for BPM 4 are small compared to the average I and Q values, but the results in fig. 2 are still hard to interpret quantitatively. In order to set a scale we used the mover scan data. During the mover scan BPM 4 was moved in 0.25 mm steps from -0.5 to +0.5 mm off the nominal position. Fig. 3 shows the scan data as well as the position residual, which was calculated for the data used in SVD computations above. A position residual of 2.73 μm was estimated, which is close to the estimate in [6], and the difference is down to the applied cuts. Taking into account a 5 mm average beam offset in the middle of the chicane for magnets on, this sets an energy resolution limit of $5.5{\cdot}10^{-4}$ for our spectrometer prototype.

Our earlier publications [4], however, revealed a 1 μm level of resolution of the BPM system. Due to the larger beam jitter during the energy measurements the gain of the BPM electronics had to be reduced for some BPMs, which, combined with a reduced bunch charge, decreased the sensitivity and therefore a worse resolution was obtained.

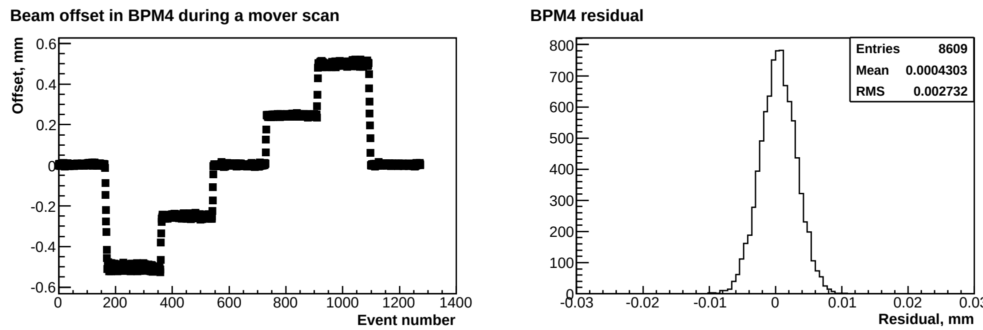

Figure 3: BPM 4 position for a horizontal mover scan (left), BPM 4 residual during a quiet period, run 2747 (right).

3.2. Dipole magnets

An essential prerequisite of the spectrometer is that the beam position downstream of the chicane is not energy dependant, and the upstream beam path is restored downstream. In other words, the chicane has to act on the beam in a symmetric manner. B-field measurements were performed in March 2007 to study the response of the chicane. Some results are shown in fig. 4. Here, the differences between the measured and nominal B-fields are plotted as a function of the nominal value, for negative and positive polarities.

In these measurements the field of the magnet 3B1 was monitored with a Hall probe, whereas for the other magnets NMR probes were used. As can be seen, 3B1, 3B2 and 3B3 follow the same trend, with a difference of a few tenths of a mT between 3B2 and 3B3, while 3B1 is off by about 1 mT. Magnet 3B4 shows field values much closer to the nominal ones, because only for this magnet a more accurate relation between the current and the field (as given in [6]) was determined and used for the field settings. The differences in fig. 4 can be attributed to the residual B-field, which was estimated to be $0.2 \div 0.4$ mT (see [6]), which is expected to depend on the history of the magnets and on the properties of the core material (as the design and composition of steel cores were not carefully accounted for). As a consequence, the path of the beam upstream was not fully restored downstream of the chicane, and

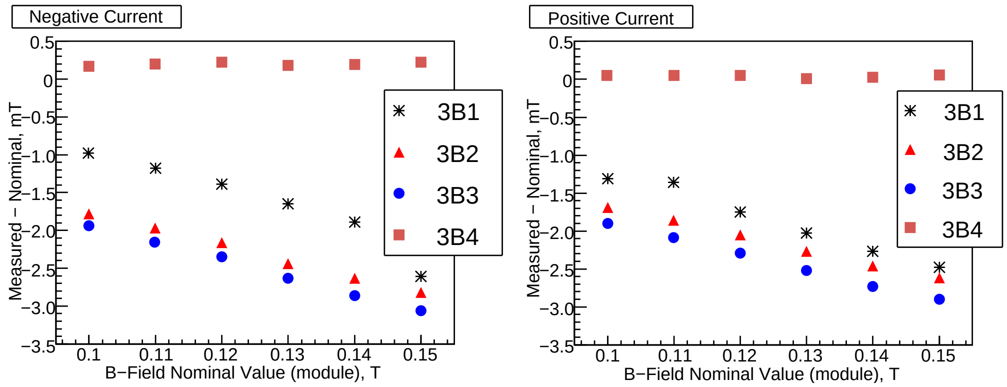

Figure 4: Differences between the measured and nominal B-fields as a function of the nominal value of the four magnets in ESA: Negative current (left); Positive current (right).

changes of the beam energy are converted into position variations in BPMs 9, 10 and 11.

Using the data from the upstream BPMs the nominal beam position in the downstream BPMs can be predicted. Consider only BPM 9 measurements after subtraction of the downstream BPM prediction for an energy scan we can clearly recognize a step-like behaviour in energy, fig. 5. This observation supports the assumption that the BPMs downstream of the chicane should not be used to predict the nominal beam orbit in BPM 4. At the same time we have to note that, although the net-integral field applied to the beam by the chicane is very small, and BPM 9, which has a higher resolution than BPM 4, is still able to resolve the energy changes during the scan.

3.3. Resolution of the energy BPMs

In order to estimate the resolution of the energy BPMs 12 and 24 we plotted their Q readings versus their I readings for an energy scan. Such a plot is shown in fig. 6 for BPM 12, left. When the energy changes, the readings should slide up and down the line fitting the measured points, while the noise can produce an offset from the line and move the IQ values along the line.

The scale for each energy BPM was also found from the energy scan data averaging the IQ amplitude for each step and comparing the change of the amplitude to the energy offset given by the linac feedback. The scales and

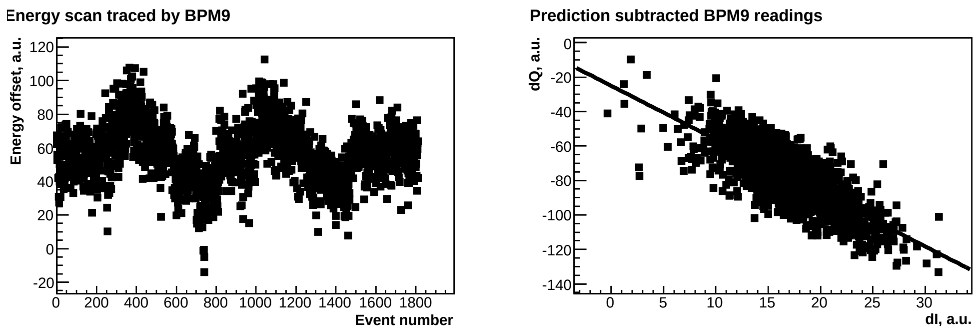

Figure 5: Energy measured by BPM 9 during the scan (left), IQ plot of the measured BPM 9 readings with the predicted readings subtraced (right). The fitted line shows the IQ rotation of the energy measurements.

IQ rotations allow for the energy offset to be calculated from the measured I and Q values for both BPMs 12 and 24.

Measuring the average residual between the fitted line and the measured points (fig. 6, right), we can estimate the resolution of the BPMs. As we know the scale, the resoltuion can be expressed in terms of the energy. In this way we found a 0.41 MeV resolution for BPM 12 and 2.26 MeV for BPM 24, or $1.4{\cdot}10^{-5}$, respectively, $7.9{\cdot}10^{-5}$ at the nominal 28.5 GeV beam energy. The difference can be explained by the fact that BPM 12 had an additional 20 dB amplifier installed in its electronics chain in order to compensate for cable losses, which reduced the effect of the noise and the granularity introduced by the digitizers.

These estimates only take into account the noise in the BPM itself. It does not take into account any other effects such as the beam jitter and the changes of the fields in the magnets which generate the high dispersion. In fig. 7 we compare the readings of BPMs 12 and 24 after the energy calibration. An RMS residual of 5.5 MeV ($1.9{\cdot}10^{-4}$) was found, which is about two times bigger than the noise measurements of 2.3 MeV from above if combined in quadrature. This indicates that the resolution of the energy measurements of BPMs 12 and 24 is not limited by the BPM noise alone, but still allows to measure small fluctuations of the energy and provides a reference energy value to better than $1.9{\cdot}10^{-4}$.

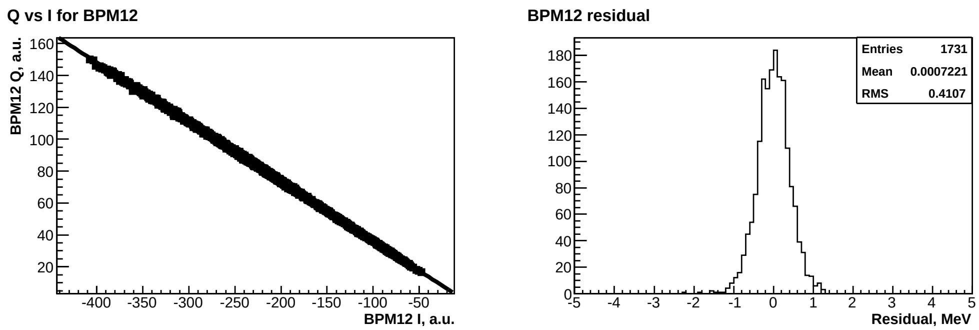

Figure 6: Resolution estimation for BPM 12: Q vs I for the energy scan (left), residual between the measured values and the IQ line in terms of energy, multiplied by the scale (right).

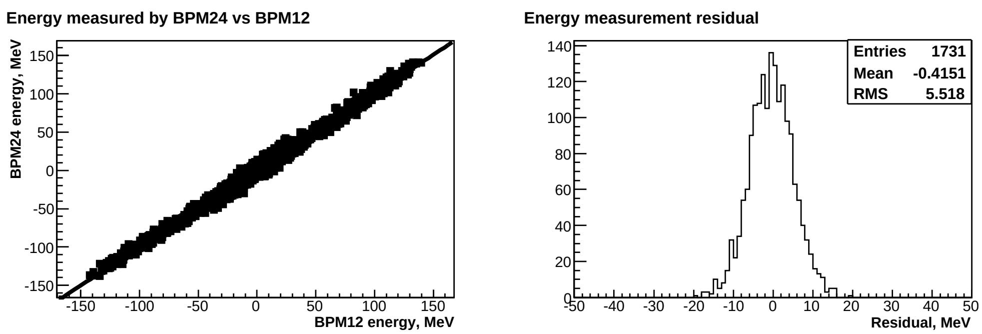

Figure 7: Comparison of BPMs 12 and 24: BPM 24 energy measurement vs BPM 12 (left), residual between BPM 12 and 24 measurements (right).

3.4. Energy resolution of the spectrometer

The readings predicted for BPM 4 by all other BPMs can be subtracted from the measured values and, when the magnets are on, provide energy measurements as the position and angle change in the mid-chicane (fig. 8). The energy, in turn, can be predicted from the energy BPMs 12 and 24. The residual, besides the resolutions of each BPM, depends on the fluctuations of the magnetic fields, mechanical vibrations, as well as drifts and other systematic effects and non-linearities.

We first compare the relative energy measured by BPM 4 with the measurements of BPM 12 (fig. 8, top). This results to a resolution of 27.3 MeV or $9.6{\cdot}10^{-4}$. As this is much higher than the precision of the orbit reconstruc-

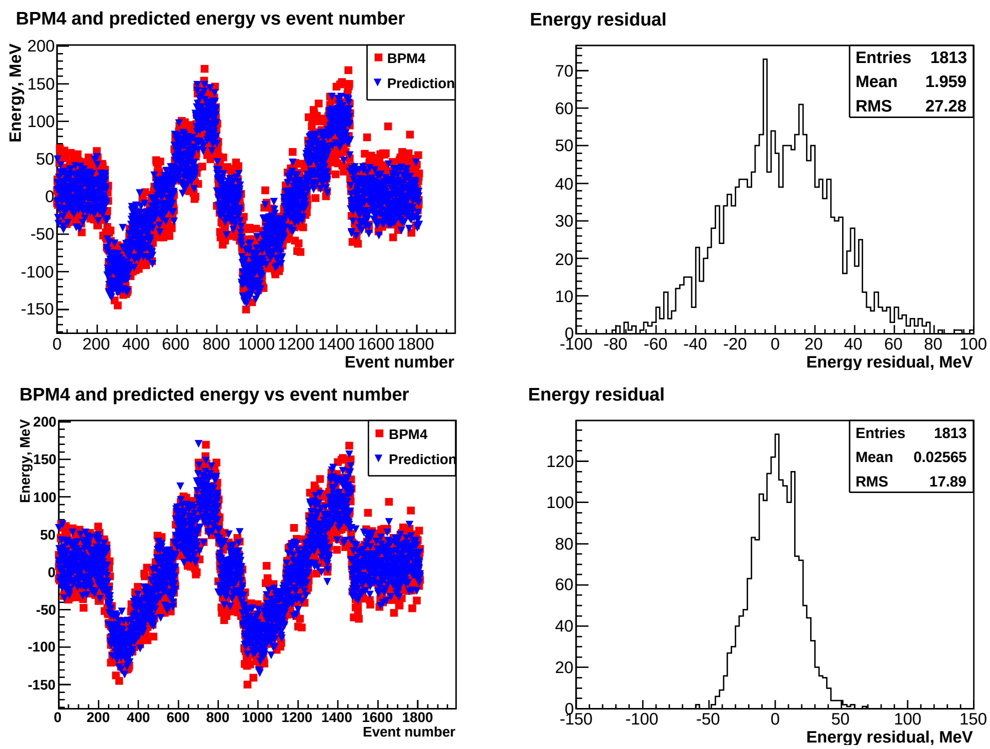

Figure 8: Energy resolution measurement: energy measured by BPM 12 and BPM 4 (top left), residual between BPM 12 and BPM 4 readings (top right), energy measurement predicted by BPMs 12, 24 and additional parameters and BPM 4 reading (bottom left), residual between the prediction and BPM 4 reading (bottom right).

tion, we decided to look for correlations using additional data and applying the SVD method by starting again from BPM 12 (but this time the scale is corrected by SVD to better match BPM 4 readings which results to a lower residual) and then adding more data in the matrix to better reconstruct the spectrometer measurements and understand the systematics. Table 2 summarises the results. together with the residuals calculated using the same coefficients for a quiet period when the magnets were on and nothing was changed in the system. Looking for consistent improvements of the residual, we can identify the main sources of systematic errors.

The biggest step in residual reduction is observed when the data from BPMs 9, 10 and 11 was included in the computation. As we know, BPMs 9, 10 and 11 are sensitive to the energy, but also to the net-magnetic field of the chicane. Since our system did not provide bunch-to-bunch B-field measurements. only interpolated field data could be used. If such data were involved in the analysis we did not recognize a consistent improvement. It is therefore very likely that field changes are encoded in the downstream BPM data, which might be the reason for residual improvements if these data are accounted for in the analysis.

Some further improvement is also noted when the charge Q is included in the analysis, even though all the BPM data were normalised by the charge. This is best explained by the fact that BPMs 12 and 24, although very sensitive to energy changes, were not centered to their operating ranges, and could be running close to saturation.

Ultimately, in order to achieve an energy resolution approaching 10^{-5}, one has to monitor the relative motion of the BPMs in the beamline. An interferometer, once well tuned, seems to be a reliable, fast and precision tool. But since the mechanical vibrations observed were in the region of a few hundred nanometers, the Zygo interferometer in our setup only provided a moderate improvement to the energy measurement.

The final result of these investigations is shown in the bottom part of fig. 8. With additional data included, the prediction tracks the spectrometer measurement a bit better than given in the plot above. The resolution was measures to 17.9 MeV (or $6.3 \cdot 10^{-4}$) for an energy scan and 16.7 MeV (or $5.9 \cdot 10^{-4}$) for a quiet period. These numbers are very close to the estimate for the precision of the orbit reconstruction of $5.5 \cdot 10^{-4}$, which means that the weighting of different systematics has been performed correctly.

3.5. X to Y coupling

Even though the spectrometer chicane operates in the horizontal plane, the energy scan is also traced in the vertical plane. Firstly, because of the alignment errors the beam receives a small bend in the vertical direction. Secondly, there is an internal cross-talk between the x and y couplers of the BPM, a virtual offset in y is created by an offset in x.

In order to estimate the total cross-coupling between the x and y planes of the spectrometer we, again, considered the energy scan data (run 2743), but this time predicting the vertical beam position in BPM 4 using SVD coefficients obtained from data in run 2747. Clearly, the energy scan is traced in the measured y-offset (fig. 9, left). We had to take into account that the sensitivity of the x and y channels of BPM 4 was different, so we used mover scan data for both to get the position scale, which we then used

Table 2: Energy residuals calculated for BPM 4 including additional parameters.

Data included	Residual, MeV		$\Delta E_b/E_b$ contribution, x10^{-4}	
	energy scan	quiet period	energy scan	quiet period
BPM 12	26.83	24.63	–	–
BPMs 12, 24	26.41	24.76	1.7	+0.9
BPMs 12, 24 and B-field	25.94	25.88	1.7	+2.6
BPMs 12, 24, charge and B-field	23.48	22.52	3.9	4.5
BPMs 12, 24, 9, 10, 11, B-field and charge	18.15	17.47	5.2	5.0
BPMs 12, 24, 9, 10, 11, B, q and interferometer	17.89	16.71	1.1	1.8
BPMs 12, 24, 9, 10, 11, B, q, interferometer and fluxgate	17.89	16.71	–	–

to normalise the raw energy. For that reason the energy is in units of mm in fig. 9, although one should keep in mind that an energy change causes both the offset and the incline to change in the middle of the chicane.

The plot in fig. 9, right, shows the correlation between the energy measured in both planes. From the incline of the line fitting the data in this plot we calculated a rotation of almost 25°, or an x-y isolation of about 7.6 dB. The rotation is too large to be attributed entirely to the alignement, at the same time the x-y isolation is too poor to be caused by the BPM (usually providing about 20 dB isolation without tuning), which indicates that both effects take place. It is therefore important to minimize the x-y cross-talk in the BPMs and eliminate fake offsets, and carefully align the elements of the spectrometer to avoid negative effects on the beam and the energy measurement.

3.6. Estimate of the absolute beam energy

So far we have been talking about the relative energy measurement, i.e. a measurement of the energy offset from some nominal value, which we assumed to be 28.5 GeV, the beam energy we requested for our ESA runs. Below we

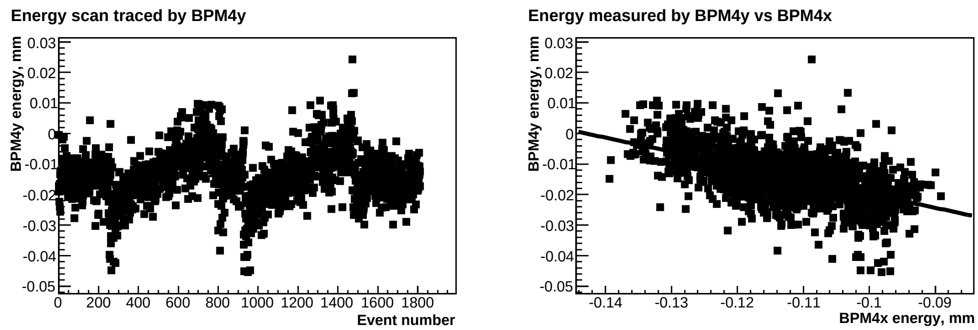

Figure 9: Effect of the chicane on the vertical beam trajectory: energy scan traced by BPM 4 in y (left), energy data measured by BPM 4 in y vs x (right), position calibration was used in order to exclude the difference in sensitivities, hence, the energy is calibrated in units of the offset (mm).

estimate the beam energy using the values we obtained in the previous steps of the analysis, such as the energy and position scales.

When the magnets are turned on, BPM 4 is moved by a few mm in order to return the beam offset into its dynamic range. This move is observed by the precision Zygo interferometer. From prediction subtracted BPM 4 readings we found IQ rotations and scales for the position and energy changes.

According to the interferometer, BPM 4 was moved by 4.035 mm between runs 2743 (magnets on) and run 2747 (magnets off). Using the IQ rotation and scale we obtained from the mover scan we can predict the changes of the I and Q values of BPM 4 an offset of 4.035 mm would create, even though in reality large offsets saturate the electronics. Our calculations resulted in $I = 7078.6359$ and $Q = 3702.9554$, which we added to the prediction subtracted I and Q values obtained from the energy scan (fig. 10, right). In this process we rotate the IQ plane for the energy scan data, so we have to find the new value of the IQ rotation for the energy line, but the energy scale still applies. Using this scale and the new IQ rotation for the energy, we can now calculate the absolute energy (fig. 10, left). This calculation resulted in a measured nominal energy of 26.37 GeV.

Our estimate is over 2 GeV, or more than 7%, off the nominal value. The linac was likely to run at a lower energy at the time of the experiment as some of the klystrons were offline, but 26.37 GeV seems to be too low an energy. At the same time, looking back at our analysis, fig. 10 right, we motice that the absolute measurement is very sensitive to the BPM resolution: a

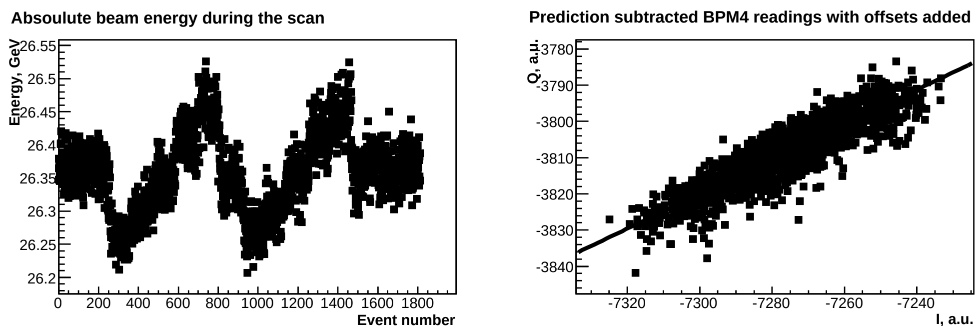

Figure 10: Reconstruction the absolute beam energy: a scan around the nominal energy(left), IQ plot for BPM 4 offset in both I and Q to take into account the BPM was moved horizontally by 4.035 mm (right).

small change of the energy line rotation applied to large I and Q values can significantly change the result. The same argument applies to the position IQ rotation and scales – small errors are exaggerated when combined and multiplied by large numbers.

Clearly, any improvement of the BPM resolution would have a positive impact on the absolute energy measurement, but simplifying the procedure itself, which means fitting the beam offset into the dynamic range of the BPMs, may be even more efficient as it eliminates the need for position calibration and excludes the associated systematics.

[Can we get the energy from somewhere else for comparison???]

4. Suggestions for the future experiments

improve BPM resolution

provide B-field measurements at the beam repetition frequency

make sure the beam is centered

3-magnet chicane (dublet-magnet-triplet-spectrometerMagnet-triplet-magnet-doublet) – but think about the residual dispersion, offset BPMs with magnets off to use the full range

Zygo for the triplets

5. Summary

References

[1] J. Brau, (ed.), et al., International Linear Collider reference design report. 1: Executive summary. 2: Physics at the ILC. 3: Accelerator. 4: DetectorsILC-REPORT-2007-001.

[2] R. Assmann, et al., Calibration of centre-of-mass energies at LEP2 for a precise measurement of the W boson mass, Eur. Phys. J. C39 (2005) 253–292. arXiv:hep-ex/0410026.

[3] V. N. Duginov, et al., The beam energy spectrometer at the International Linear Collider, DESY LC Notes, LC-DET-2004-031.

[4] M. Slater, et al., Cavity BPM system tests for the ILC energy spectrometer, Nucl. Instrum. Meth. A592 (2008) 201–217. doi:10.1016/j.nima.2008.04.033.

[5] N. Morozov, Progress report on developments of the magnetic field measurements techniques (21-23 May and 21-23 November 2005). URL http://zms.desy.de/aktuelles/veranstaltungen_in_zeuthen/konferenzen/2005/index_ger.html

[6] M. Viti, Precise and Fast Beam Energy Measurement at the International Linear Collider, Ph.D. thesis, dESY-THESIS-2010-007 (2010).

[7] M. Hildreth, et al., Linear Collider - BPM-based energy spectrometer (2004). URL http://www-project.slac.stanford.edu/ilc/testfac/ESA/projects/T-474.html

[8] H. Schreiber, et al., Magnetic Measurements and Simulations of a 4 Magnet Dipole Chicane for the International Linear ColliderParticle Accelerator Conference PAC07 25-29 Jun 2007, Albuquerque, New Mexico.

[9] S. Kostromin, M. Viti, Magnetic Measurements for Magnets 10D37, iLC-SLACESA TN-2008-1 (2008). URL http://www-project.slac.stanford.edu/ilc/testfac/ESA/TechNotes/TN-2008-1.pdf

[10] W. H. Press, et al., Numerical Receipes in C, Cambridge University Press, 1992.