Top Quark Physics, Luminosity Spectrum and the Beam Energy Spectrometer at the International Linear Collider

1st Year Report

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June 9, 2006

Abstract

Measurements of the top quark production threshold will be one of the most important tasks for the International Linear Collider (ILC). An improved precision on measurements of the top quark mass, its width, and the strong coupling constant α_s , together with other electroweak parameters can provide tight constraints of the mass of the Higgs, and possible extensions of the Standard Model.

Important aspects of these measurements include precise predictions for the observable quantities at the top threshold and a precise understanding of the machine's luminosity spectrum. In this report I describe work on progress for a precision top threshold event generator, and the development of a beam energy spectrometer, a device that will enable us to better understand the luminosity spectrum of the ILC, and hence, together with the precision event generator, and more extensive studies of the luminosity spectrum, determine its effect on the top quark measurements at the ILC.

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1 Introduction : The ILC

In the next few years, particle physics will focus on the Large Hadron Collider (LHC) experiments at CERN, which are expected to shed light on many fundamental questions such as how do particles acquire mass; is there one or more Higgs-like particles; is there super symmetry; are there extra dimensions. Most of these questions should be settled by the LHC, but for particle physicists to understand precisely how the world works at its most fundamental level - the elementary particles and their interactions - another particle accelerator will be needed in order to make precise studies of the TeV scale: the International Linear Collider (ILC).

The ILC will be a 30 km long linear accelerator which will collide electrons and positrons at centre-of-mass energies of 0.5 - 1 TeV, thus having the same available energy scale as the LHC. The advantage of the ILC is that it is a lepton collider, naturally providing a cleaner environment for precision physics. This will enable physicists to precisely measure the Higgs boson, top quark parameters, decide between different flavours of supersymmetry, and make precision measurements of the exotic particles involved in such models.

A world-wide collaboration is working towards designing and prototyping ILC components, which together with physics studies provide a strong case towards starting construction of the accelerator early in the next decade. A proposed design of the accelerator (with two interaction regions) can be seen in figure 1.



Figure 1: The proposed design for the ILC (2005), taken from [1]

One of the first and most important goals for the ILC after its turn-on will be making detailed studies of the top quark production threshold. Being accessible at centre-of-mass energies of about 350 GeV, top quarks will be copiously produced in a clean lepton collider environment. Unprecedented precision measurements of the top quark mass, its width, the strong coupling constant α_s and the top-Yukawa coupling can be performed. For such a high level of precision to be achieved, new tools for describing the top quark threshold must be developed, together with new methods for understanding the luminosity spectrum of the accelerator, and performing bunch to bunch high precision measurements of the absolute energy of the beam.

In this report, I will outline the efforts of myself and the UCL ILC group towards these important goals.

2 Top Quark Physics at the ILC

2.1 Need for Precision Top Measurements

In e^+e^- collisions, top quarks are produced in pairs starting at about $\sqrt{s} = 2M_t \approx 350 \text{ GeV}$ centre-of-mass energy. This makes them accessible at the early stages of running of a 0.5 - 1 TeV linear collider, and so this is meant to be one of the first tasks for the ILC.

The top quark threshold at the ILC offers one of the most interesting ways to study Quantum Chromodynamics (QCD) systems. This is partly because of the large top quark mass which allows theoretical predictions to probe the QCD potential in the asymptotic regime, where the strong coupling constant α_s is small, and thus the system can be accurately described by perturbative QCD. In addition, the large top quark width Γ_t acts effectively as an infrared cut-off in the theory, which prevents hadronization effects to take place [2], and does not allow the usual resonance formation. This fact enhances the uniqueness of the top quark system since all the spin information is preserved in its decay products, allowing us to study top quark spin and polarization properties by studying the energyangular distributions of the decay products [3]. Also, top quarks decay mainly via the electroweak interaction through the channel $t\bar{t} \rightarrow b\bar{b}W^+W^-$, which can also be calculated reliably. All these properties make the top quark a unique QCD system since it behaves almost as a 'free' particle, and studying its properties at the ILC is an essential task for a complete understanding of QCD.



Figure 2: These plots indicate the impact of the top quark mass of the mass of the Higgs (left plot, from [7]), and distinguishing between different models of supersymmetry (right plot, from [6]).

Furthermore, the top quark mass in conjunction with other electroweak precision observables can also be used to constrain the Standard Model (SM) or possibly select between different extensions [6]. The plots on figure 2 indicate the impact of the uncertainty of the top quark mass and W mass on predictions of the mass of the Higgs, and on selecting between different models of supersymmetry. The current best measurement of the top quark mass comes from the Tevatron experiments: $M_t = 172.5 \pm 2.3$ GeV [4]. The ILC claims it can reduce this value by more than an order of magnitude to an uncertainty of 50 – 100 MeV [5]. If the ILC can reach this level of precision, then it could possibly differentiate between SM extensions. The aim of my thesis is to determine if the claimed ILC precision can be achieved.

2.2 Luminosity Spectrum and the Top Threshold

The beam energy of an accelerator usually has physics and machine related effects influencing its value. The way to describe it is to understand and measure precisely the luminosity spectrum of the machine.

At the ILC, there are three main energy loss mechanisms influencing the luminosity of the machine. These are:

- **Initial State Radiation** (ISR) is the physics process in which the electrons (positrons) in the accelerating beams emit a photon. The emitted photon carries some of the electron's momentum and thus the energy of the beam is reduced. ISR is calculable to high precision in QED.
- **Beam Spread** is the spread of energy introduced by the machine in each accelerated bunch of particles. Since the particles are accelerated in bunches, not all of them travel the same mean path in the accelerating cavities, so depending on the position of each particle in the bunch, slightly different accelerating gradients are experienced, thus introducing a spread in the energy of the bunch¹.
- **Beamstrahlung** is a new energy loss mechanism which will be first seen at the ILC, and is the result of the high energy and high luminosity of the machine. To achieve high luminosity, the beam size must be 'squeezed' as much as possible, and thus a strong electromagnetic field surrounds each bunch of particles. When the opposing bunches approach, each bunch experiences the opposing bunches' electromagnetic field, which exerts a transverse force on it causing some of the bunch's particles to radiate photons, and hence lose energy. This effect increases in occurance as a particle travels a larger path through the opposing bunch until it collides.



Figure 3: Left - The three components of the luminosity spectrum. Right - Effect of luminosity Spectrum on the top threshold total cross section.

On the left of figure 3, the three components of the luminosity spectrum can be seen plotted together. The x axis represents the scaled centre-of-mass energy $\frac{\sqrt{s}}{\sqrt{s_n}}$.

The observable top threshold total cross section at the ILC will have smearing effects from the luminosity spectrum, this is described by the luminosity folded total cross section given by the expression :

$$\frac{d\sigma_{obs}^{e^+e^-}}{d\Omega}(\sqrt{s}) = \int_0^1 dx_1 dx_2 D_{e^+e^-}(x_1, x_2, \sqrt{s}) \frac{d\sigma^{e^+e^-}}{d\Omega'}(x_1, x_2, \sqrt{s}) \tag{1}$$

¹Beam spread is not necessarily a loss mechanism, since because of it, some particles in a bunch might end up with higher than the nominal beam energy

where $D_{e^+e^-}$ is the energy spectrum, and $\frac{d\sigma^{e^+e^-}}{d\Omega'}$ is the bare cross section.

The plot on the right of figure 3, shows the effect of the luminosity spectrum when applied to the top threshold. It can be seen that the cross section loses its peak structure, and hence this introduces a complication on the top threshold measurement.

It is therefore clear that if we want to achieve a high precision measurement of the top quark properties, a precise understanding of the luminosity spectrum must exist. Also it is essential that the event generator used to model the top threshold provides a very precise theoretical prediction for the threshold observables, and can incoperate luminosity spectrum effects in its predictions.

In addition, the proposed ILC energy spectrometer will provide a bunch to bunch measurement of the beam energy, which will provide the absolute energy scale of the luminosity spectrum (i.e. the position of the peak on the left plot of figure 3).

2.3 Top Quark Threshold

The measurements of top quark properties at the ILC will be performed by a precise measurement of the line-shape of the total cross section $\sigma_{t\bar{t}}(e^+e^- \rightarrow Z^*, \gamma^* \rightarrow t\bar{t})$ for centre-of-mass energies around the top threshold $\sqrt{s} = 2M_t$.

Thus a precise calculation of the total cross section near the threshold region as well as differential quantities (top polarization and Forward-Backward asymmetry (A_{FB})), is needed in order to enable us to make studies on the requirements and performance of the ILC for the top quark measurements.

A large effort from the theoretical physics community has been concentrated on precise calculations of the top quark threshold over the last 10-15 years [2, 3, 8, 9, 10, 11]. This has provided us with Next to Next to Leading Logarithm (NNLL) QCD calculations of the total top quark production cross section around threshold [10], as well as Next to Next to Leading Order (NNLO) differential quantities, polarization [9, 11], hadronization effects, and possible effects arising from more speculative theories (such as extra dimension models) [13, 14] at the ILC.

Top quarks produced near the threshold region will be non-relativistic with velocity $\nu \ll c$. This forces the physical scales that govern the threshold dynamics to be the top mass M_t , the relative momentum $M_t\nu$, and the kinetic energy scale $M_t\nu^2$, which are all widely separated from each other due to the low top velocity. This further causes ratios of these scales of the form $M_t/(M_t\nu)$ to occur in the standard calculations of multi-loop expansion in the strong coupling constant α_s , also known as Coulomb singularities, and so the threshold region cannot be calculated through these standard multi-loop methods [11].

This problem is solved by employing the use of Effective Field Theories (EFT) using the hierarchy $M_t \gg M_t \nu \gg M_t \nu^2 > \Gamma_t \gg \Lambda_{QCD}$ and by successively integrating out higher momentum terms [11]. In this framework of Non-Relativistic QCD (NRQCD), the employment of the Green function technique has been demonstrated to be the best method for solving exactly the Lippmann-Schwinger equation² in momentum space [9].

The top threshold event generator that is described in the next section relies heavily on the use of the actual Green functions, and hence I give a quick overview of this formalism.

The Lippmann-Schwinger equation using the notation from [9], reads :

$$[E - \frac{\boldsymbol{p}^2}{m_t} + i\Gamma_t]\mathcal{G}(\boldsymbol{p}, \boldsymbol{x}, E) = e^{i\boldsymbol{p}\cdot\boldsymbol{x}} + \int \frac{d^3k}{(2\pi)^3} V(\boldsymbol{p} - \boldsymbol{k})\mathcal{G}(\boldsymbol{k}, \boldsymbol{x}, E)$$
(2)

²The Lippmann-Schwinger equation is the momentum space analogue of the Schrödinger equation in position space, and is widelly used in Scattering theory.

where the G are Green functions, and V(p - k) is the QCD potential. Now the first two terms in a Taylor expansion with respect to **x**

$$\mathcal{G}(\boldsymbol{p}, \boldsymbol{x}, E) = G(\boldsymbol{p}, E) + \boldsymbol{x} \cdot i\boldsymbol{p}F(\boldsymbol{p}, E) + \dots$$
(3)

are solutions of the integral equation

$$G(p,E) = G_0(p,E) + G_0(p,E) \int \frac{d^3k}{(2\pi)^3} V(\boldsymbol{p} - \boldsymbol{k}) G(k,E)$$
(4)

$$F(p, E) = G_0(p, E) + G_0(p, E) \int \frac{d^3k}{(2\pi)^3} \frac{\mathbf{p} \cdot \mathbf{k}}{\mathbf{p}^2} V(\mathbf{p} - \mathbf{k}) F(k, E)$$
(5)

which are respectively the S and P-wave Green functions with

$$G_0(p, E) = \frac{1}{E - \frac{p^2}{m_t} + i\Gamma_t}$$
(6)

being the free space Green function propagator.

This can be also demonstrated by the relation of the Green functions to the vertex functions

$$\mathcal{K}_{S}(p,E) = 1 + \int \frac{d^{3}k}{(2\pi)^{3}} V(\boldsymbol{p}-\boldsymbol{k}) \frac{\mathcal{K}_{S}(k,E)}{E - \frac{\boldsymbol{k}^{2}}{m_{t}} + i\Gamma_{t}}$$
(7)

$$\mathcal{K}_{p}(p,E) = 1 + \int \frac{d^{3}k}{(2\pi)^{3}} \frac{\boldsymbol{p} \cdot \boldsymbol{k}}{\boldsymbol{p}^{2}} V(\boldsymbol{p} - \boldsymbol{k}) \frac{\mathcal{K}_{P}(k,E)}{E - \frac{\boldsymbol{k}^{2}}{m_{t}} + i\Gamma_{t}}$$
(8)

which are solutions to the vertex function integral equation

$$\Gamma_{\mathcal{C}} = \mathcal{C} + \int \frac{d^4k}{(2\pi)^4} \left(-\frac{4}{3}4\pi\alpha_s\right) D_{\mu\nu}(p-k)\gamma^{\mu}S_F(k+\frac{q}{2})\Gamma_{\mathcal{C}}(k,q)S_F(k-\frac{q}{2})\gamma^{\nu}$$
(9)

and are related to the S and P-wave Green functions via

$$G(p, E) = G_0(p, E)\mathcal{K}_S(p, E), \qquad F(p, E) = G_0(p, E)\mathcal{K}_P(p, E)$$
(10)

with $C = \gamma_{\mu}$ or $\gamma_{\mu}\gamma_5$ for a vector current or axial-vector current driven e^+e^- annihilation.

By the use of the Green functions for describing the dynamics of the system, and the application of short distance coefficients for Higgs exchange and hard gluon contributions, one can match the EFT employed to full QCD and thus have reliable predictions of the total cross section and differential quantities. More details can be found in [9, 11].

In addition, things become even more complicated when gluon exchange between the decay daughters of one of the top quarks, and the other undecayed top quark is taken into account. Such contributions, called rescattering corrections, can be seen in the Feynman diagrams of figure 4 [12].



Figure 4: Lowest order rescattering diagrams, from [12]

The need for the high precision QCD calculations becomes obvious in the plot of figure 5, where the tree-level predictions for the total cross section of two general purpose event generators are compared to NNLO predictions as calculated by TTOPPIK [11].



Figure 5: Comparison of the predictions of the total cross section in the threshold region for Herwig, Pandora and the NNLO QCD calculation performed by TTOPPIK.

It is clear from the above plot that all useful information of the top threshold is lost in the predictions for the total cross section by conventional event generators. It is thus obvious that for precision studies of the top threshold at the ILC to be performed, there is a need for more advanced methods for event generation, a Monte Carlo event generator based on TTOPPIK.

2.4 Towards a $t\bar{t}$ Event Generator

Since a wealth of effects is going to be included in this generator, the theory input deserves a better description.

In the proposed generator, the top differential and total cross sections are going to be NNLO calculations based on the Green function technique described in the previous section. The inclusion of rescattering corrections is going to be based on NLO calculations [12] (NLO for rescattering corrections is enough for our purpose [11]), which act and modify the Green functions used in the NNLO calculation. Then, to get rid of theoretical uncertainties involved with the total cross section at NNLO, a renormalization group improved calculation at NNLL will be employed [10] to renormalize the total cross section, and free us from the NNLO calculation related uncertainties³.

The main problem with the TTOPPIK program that provides the NNLO quantities is that it is slow for large scale event generation, since it takes approximately 1.5 sec per calculation⁴. Thus the first and most major problem that needs to be tackled is to dramatically speed up the theory input of the generation process. This is tackled by implementing a fast 5-dimensional interpolation of the Green functions⁵.

Since the values of the Green functions are the building blocks of the calculation (and the major CPU consuming source in TTOPPIK - by solving the integral equation 2), if we manage to store a grid of Green function values, and then just perform interpolations on this grid, the process should be accelerated by a large amount. The fact that Green functions are complex quantities, and that the grid for the interpolation should have a range of the basic input parameters of the calculation (M_t , Γ_t , α_s , \sqrt{s}), make the interpolation non-trivial.

The first step in the interpolation process is to form the interpolation grid. This effectively means running TTOPPIK once for a range of values in the $(M_t, \Gamma_t, \alpha_s, \sqrt{s})$ parameter space, and storing the output of the calculation in a datafile so that it can be accessed by the interpolator.

³Unfortunately, in the framework employed for the NNLL calculations, it is not possible to extract differential quantities, and hence we cannot exclusively use it for the generator.

⁴On a 1.5GHz Dual CPU Pentium 4

⁵After attempts on dynamic parameterization of the Real and Imaginary parts of the Green functions failed.

To ensure that linear interpolation is possible, we must examine the variation of the Green functions when the $(M_t, \Gamma_t, \alpha_s)$ vary. The plots of figure 6 illustrate that the peak in the Green function distributions exhibits a linear translational behaviour for variations of the $(M_t, \Gamma_t, \alpha_s)$ when plotted against a range of \sqrt{s} values.



Figure 6: These plots illustrate that the variation in the peak position of the Green functions exhibits a linear translational behavior for variations in $(M_t, \Gamma_t, \alpha_s)$ (from left to right).

Now we have demonstrated that linear interpolation should be possible. The technique used can be illustrated graphically by considering the drawing of figure 7. This can be described as one side of the hypercube containing the $(M_t, \Gamma_t, \alpha_s, \sqrt{s})$ grid. According to which parameters need to be interpolated, this cube is rotated to that variables' parameter space, and linear interpolations between the different parameters are performed. Then, they are combined together by translations in the Green function values in order to output the desired result.



Figure 7: Drawing of one side of the interpolation hypercube. From [16].

The demonstration that the interpolator actually works comes from the plots of figure 8, where the black curves are the Green function phase distributions on the interpolation nodes, and the red curve is an interpolated distribution in between these nodes.



Figure 8: Solid and dashed black lines are Green function phase distributions on the interpolation nodes, and the solid red line is the interpolated quantity between these nodes, the plot on the right being zoomed at the peak.

To further demonstrate the precision on real and imaginary part interpolation of the Green functions, the plots of figure 9 are the difference plots (for 100 interpolations with

different parameters across the whole range of the $(M_t, \Gamma_t, \alpha_s, \sqrt{s})$ parameter space) between the real and imaginary values as calculated by the interpolator, and the actual Green function values as calculated by TTOPPIK. The precision demonstrated by these difference plots is considered to be satisfactory (both histograms have RMS in the 10^{-3} region).



Figure 9: Difference between interpolated and TTOPPIK Green functions, for 100 distributions for different points in the $(M_t, \Gamma_t, \alpha_s, \sqrt{s})$ parameter space.

With the interpolation method described, the CPU time improvement on the original TTOPPIK calculation is about ×5 faster, which is good but still not enough for a fast generator. Thus, a speed-up method is applied to the interpolator. Since in an event generator, you only set the $(M_t, \Gamma_t, \alpha_s)$ parameters once, and then generate a number of events based on these parameters, the interpolator has a method of saving the interpolated values (arrays) for these three parameters, and then performing interpolations only on \sqrt{s} , which accelerates this procedure by a factor of a million from the original TTOPPIK calculations, to < 1µsec per interpolation.

The next stage in this process has to do with the integration grid used in solving the Lippmann-Schwinger equation (eq.2). This is based on the Gauss-Legendre integration method, whereas an integral is approximated by the value of the integrand on a specific set of grid points, multiplied by weights. The mathematical expression for this is

$$\int_{-1}^{1} f(x) dx \approx \sum_{i=1}^{n} w_i f(x_i)$$
(11)

Currently, from the interpolator we have the values of f_i from the previous equation, but we know nothing about the weights w_i or the grid points x_i . The first approach to this problem was to include the grid points in the interpolator (for consistency), and try to interpolate (in a slightly more complicated nonlinear way) together with the Green functions. The interpolation of the grid points however proved more complicated than the Green functions, with a larger error associated with it. This can be seen in the difference plot of the momentum grid from the interpolator versus TTOPPIK in figure 10.

This is solved by calculating the integration grid and weights from scratch for the same parameters as used to drive the interpolator. These grid points and weights should correspond exactly to the ones used in TTOPPIK for sampling the f values, since the dependence on determining the grid points is an 'educated guess' function of M_t and $E = \sqrt{s} - 2M_t$. The integration grid (momentum grid) and corresponding weights as calculated and compared to TTOPPIK values, can be seen in figure 11, they agree exactly.

Now we have all the ingredients needed to perform fast calculations for the differential and total top production cross section using the framework of [9, 11]. To complete the input to the generator, all the short distance coefficients (Higgs exchange, hard gluon exchange etc), top pole mass evolution to the different schemes (1S, \overline{MS} scheme), and energy evolu-



Figure 10: Same as in the plots of figure 9, but for the integration (momentum) grid.



Figure 11: Integration grid (left) and corresponding weights (right) as calculated by TTOPPIK (black) and the Gauss-Legendre implementation for the Generator (red).

tions were implemented in the generator version of the code, so that the only thing needed from TTOPPIK is one run to generate the interpolation grid.

The final check is to test predictions for the differential and total cross sections calculated by TTOPPIK to those from the interpolator. The plots of figure 12 illustrate the S-wave dif-ferential momentum distribution $\frac{d\sigma_S}{dp}$ for a specific point in parameter space (on the left) and the difference plot between the interpolated momentum distributions and the TTOP-PIK predictions, for 50 distributions (on the right).

The plots of figure 13 show the total cross section predictions for the interpolated distributions and TTOPPIK (left), and the corresponding difference plot (right). The 'dip' that appears at about 358 GeV seems to be a bug with the interpolator (yet to be discovered). Also, the fluctuation in the difference plot at 350 GeV (the peak of the distribution) is at a level of $2\%^{6,7}$. This could be less than the uncertainty introduced to the threshold cross section by the machine's luminosity spectrum, and hence not be an important effect. If however it is decided to improve on this, then it is straightforward to use the total cross section output from TTOPPIK, store it in the same datafile as the Green functions, and just perform (simpler) linear interpolations to it. This method has been demonstrated to work in [16].

⁶This happens because the total cross section is essentially an integration of the momentum distributions using the Gauss-Legendre tools, so any uncertainty related to the Green functions at a specific \sqrt{s} , is directly translated to σ_{tot} . ⁷The important thing is that there is no peak movement!



Figure 12: Left $-\frac{d\sigma_S}{dp}$ as calculated by the interpolated Green functions (red) and TTOPPIK (black). Right - The difference between these two distributions for 50 interpolations.



Figure 13: Left - Total cross section predictions from the interpolated distributions (red), and TTOPPIK (black). Right - The difference plot of the two distributions.

With these distributions produced in a fast (and precise) manner through the interpolator, together with predictions for the P-wave $\frac{d\sigma_P}{dp}$ differential cross section and $\frac{d\sigma_{S-P}}{d\cos\theta}$, the main obstacles preventing us from a top threshold NNLO event generator seem to be solved, since these are all the ingredients needed for event generation⁸.

So the next natural step in this project is to use these distributions in a Monte Carlo Integrator (Foam, miniFoam, Vegas) and try to generate some simple events. Then, the decay of the top quarks must be performed, by carefully considering the previously mentioned rescattering corrections. Finally, the decay daughters of the top will be feed to a standard multi-purpose event generator (Pandora, Pythia, Herwig) for decays and hadronization.

⁸Together with inclusion for top polarization, which has yet to be developed.

3 The Beam Energy Spectrometer

3.1 Energy Spectrometer Basics

The basic principle of an upstream beam energy spectrometry is measuring the amount of deflection of a charged particle beam when deflected by a pair of dipole bending magnets. By bending a particle beam through dipole bending magnets, with a well known field, and measuring very precisely with Beam Position Monitors (BPMs) the position of the beam before and after the bend, the energy of the beam can be determined. The beam energy is related to the deflection by

$$E_b = \frac{c \cdot e}{\Theta} \int B \cdot dl \tag{12}$$

where *c* is the speed of light, *e* is the charge of the particle, Θ is the bending angle, and the integral of $B \cdot dl$ is the integrated magnetic field of the bending magnet.

A drawing of this concept (with 4 bending magnets) can be seen in figure 14.



Figure 14: Layout of a 4-magnet design for a Beam Energy Spectrometer chicane. Red rectangles are BPM triplets, and purple triangles are bending magnets.

In the 4-magnet design of the energy spectrometer, the middle BPM unit (measuring the amount of deflection) can be moved for calibration purposes⁹ (and thus sits on a precision mover system - illustrated by green arrows in the drawing of figure 14). The later two bending magnets and the last BPM unit exist to ensure that the beam is bent back to its normal trajectory.

Now for a top quark measurement precision of $\frac{50MeV}{175GeV} \approx 3.10^{-4}$, a spectrometer with similar or better precision must be developed¹⁰.

For such a level of precision, many parameters of the energy spectrometer must be carefully studied. These parameters include the stability and measurement precision of the integral bending magnetic field by the dipole magnets, and the precision and stability of the cavity BPMs that will provide the beam position measurements. Furthermore, a precise study of possible systematic effects influencing the energy measurement must be performed, with effects including stray magnetic fields, temperature variations and ground motion [18] at the spectrometer location. All these systematic effects must be well understood and monitored for the energy spectrometer to reach the required level of precision.

For these reasons, an extensive experimental programme is taking place at SLAC's End Station A, for studying the requirements and performance of all the systems that will eventually constitute the ILC Beam Energy Spectrometer.

⁹Calibrations of the system will be performed by changing the bending field in the dipole magnet, and moving the middle BPM unit to monitor this change.

¹⁰A more precise estimate for the performance of the energy spectrometer is expected after the completion of the top threshold studies described in the previous section

3.2 Tests at SLAC's End Station A

The SLAC main linac has the capability of delivering 28.5 GeV electron beam, with ILC parameters¹¹, to End Station A, and so it is an ideal place for making ILC Beam Delivery components studies.

The existing and planned tests at ESA include studies of different BPM systems for developing a spectrometer specific BPM design, studies on precision and stability (systematics and long-term) of the precision of the BPM systems, together with planned studies on magnet design and measurements, that will eventually lead to an ILC Spectrometer mock-up, so that studies on the performance of such a system can be performed.



Figure 15: The experimental layout at SLAC's ESA. The incoming electron beam comes from the left, and the two triplets of rf cavity BPMs can be seen on the right, two more BPM doublets exist upstream of this diagram. From [19].

The experimental layout at ESA can be seen in figure 15, the current tests of two experimental runs (January and April 2006) concentrated on commissioning and understanding the performance of the four BPM systems already installed at ESA. These are two BPM doublets¹² upstream of figure 15, for defining the beam orbit entering the End Station, a BPM triplet at the middle of drawing 15, which is a new cylindrical BPM design (Adolphsen linac-style cavities), and downstream of that a triplet of old SLAC BPMs (SLAC rectangular cavities).

3.3 Extraction and Analysis of Signal from BPM cavities

When a charged bunch of particles traverses through a cavity, it excites electromagnetic waves inside the cavity, and in particular the transverse magnetic monopole (TM_{010}, TM_{020}) and dipole (TM_{110}) eigenmodes of the cavity [17]. The amount of electromagnetic power stored in the dipole mode (the monopole mode is only dependent on bunch charge) of the cavity is linearly dependent on the beam position inside the cavity.

Hence, by careful extraction and analysis of the rf power created by the dipole mode, information on the position the beam transversed inside the BPM can be obtained.

The signal excited by the beam is extracted from the BPM via a coupled waveguide (carefully designed as to suppress monopole modes), and then passed through process-

¹¹Same Bunch charge (2.10¹⁰), bunch length ($300\mu m$), and energy spread (0.1 - 0.2%) as the ILC, and similar repetition range: 10Hz (1 bunch) at ESA and 5Hz (2800 bunches) at the ILC.

¹²BPM systems are used in doublets and triplets since two or more measurements are needed in order to define a line, and hence the beam trajectory.

ing electronics so as to be filtered and down-converted (the SLAC BPMs have a resonance frequency of 2.86 GHz) to a frequency where it can be digitized (70 MHz in our case).



Figure 16: A digitized waveform as extracted from the SLAC BPMs.

The digitized waveform (figure 16) must then be analyzed in order to extract beam position and tilt information from it. The waveforms have a decaying sine wave shape, thus the first step in the analysis chain is to extract the amplitude, phase and decay constant of the waveform.

There are two methods for doing this, either by fitting a decaying sine wave to the waveform and directly extracting the information, or by a process known as Digital Down Conversion (DDC), by which the waveform is down-converted to the base band, and then the amplitude and phase information are extracted.

For the ESA analysis, because of sensitivities in the fitting algorithm¹³, the DDC algorithm is used. In DDC, the raw waveform is multiplied with a local oscillator (LO) of the same frequency, which yields a zero intermediate frequency (IF). By passing the IF through a finite impulse response (FIR) low pass filter, the waveform is demodulated and one can extract the amplitude and phase components directly, or by a simple extrapolation [20].

The BPMs then need to be calibrated so that the values obtained from the DDC can be translated to actual beam position readings. This is done by using either a corrector magnet scan or moving the BPM with a precision mover by a known amount.

The beam can be steered through the BPMs by using corrector magnets upstream of figure 15. By translating the beam to a known amount with the corrector magnets, and taking data for each position, the calibration of the BPMs can be performed. In addition, at the ESA setup, the middle BPM of the first triplet sits on a precision mover. So the same result as with the corrector magnets can be obtained, but by moving the BPM rather that the beam. The mover technique is better because the precision of the mover is much better than steering the beam, but unfortunately only one BPM is mounted on a mover system at ESA. However, this allows us to make studies of comparison between the two techniques.

The next step in the analysis chain is to obtain the IQ-Phase for every pulse. The amplitude and phase of the BPM can be plotted in a complex plane, and for a fixed position of the beam through the BPMs, this should result in a cluster of points in the IQ plane (see figure 17)¹⁴. If we plot on the IQ plane data from corrector or mover scans, the separation of the clusters is proportional to the actual movement of the beam through the BPMs, and thus a calibration of the scale difference between IQ plane and Position-Tilt plane can be obtained. In addition, by fitting a straight line through the clusters of points in an IQ plot resulting

¹³The fitting algorithm greatly depends on getting the initial phase of the waveform correct, and for some technical reasons (including high frequency of digitized waveform, and undersampling of digitization), this method proves unsuitable for our case.

¹⁴The actual spread in the cluster of points in IQ plane has information on the resolution of the BPM, or the position jitter of the beam.



Figure 17: Calibration using IQ plane rotation to Position-Tile plane, for a 3-position corrector scan. Taken from [20].

from a corrector scan, the phase Θ can be obtained, which is the angle between the IQ basis and the Position-Tilt basis. The IQ plane calibration is illustrated in figure 17, and an IQ calibration using the mover system is illustrated in figure 18.



Figure 18: Mover calibration of BPM (different colors illustrate different BPM position on the mover). Left : IQ plot of different mover positions. Middle : Position vs. recorded pulse for the different mover configurations (determines scale). Right : Phase determination.

Now that the BPMs are calibrated so that actual beam position readings can be performed, the resolution and stability of the BPMs must be studied. To obtain BPM resolutions, firstly the residual between different BPMs must be defined. The residual is the difference between the predicted position of the beam in one BPM, as calculated by the measured positions of the beam in two other BPMs, and the measured position in the BPM in question. Then the resolution is defined as being proportional to the distribution of residuals over many pulses. A schematic diagram of the definition of the residual can be seen in figure 19.



Figure 19: Definition of the residual. Taken from [20].

Finally, residual distributions giving BPM resolutions can be seen in figure 20. The distributions are fitted with Gaussians, and the width of the Gaussian is proportional to the BPM resolution.



Figure 20: Residual distributions giving the BPM resolutions.

Currently, work is in progress in optimizing the DDC algorithm so that it can be tuned to each specific BPM's parameters, processing the data with the optimized algorithms, and studying resolution and stability of the BPMs. Also, studies of stability of the BPMs against systematic effects (such as temperature variations, different bunch charge and bunch lengths etc) are being planned for the near future.

4 The Future

The future plans for this work include :

- Completion of the top threshold MC Event Generator. This could include a production version that can be distributed for detector studies etc, with an implementation for luminosity spectrum effects, and a version more specific to top quark threshold studies.
- Simulation of the luminosity spectrum, and studies on the extraction of the different components from Bhabha accolinearity [15] and possibly other methods.
- Luminosity spectrum studies together with top quark studies should enable me to provide (benchmark) the precision needed by the energy spectrometer for the bunch by bunch measurements in order not to compromise the precision of the top threshold studies.
- Continued participation in the running and analysis of Energy Spectrometer test beam experiments at SLAC, and possibly some hardware responsibilities there.
- Possible participation in test bench studies of BPM designs developed by the UCL group.
- Also possibly (time permitting) studies of detector effects in the top quark measurements at the ILC.
- Any other interesting thing that might come up ...

This project should by its completion provide a detailed study of many aspects of the top quark measurement at the ILC, together with developing a high precision top quark Event Generator software, a better understanding of the Luminosity Spectrum (which is also essential in many other physics studies), and contributions to test beam experiments for the ILC Energy Spectrometer, a device very complementary to the top quark studies.

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