Laser Wire and Beam Position Monitor tests

Boogert, S T (RHUL) et al

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LASERWIRE AND BEAM POSITION MONITOR TESTS

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Abstract:
This subtask involved two main activities; Firstly the development and subsequent usage of high resolution beam position monitors (BPM) for the International Linear Collider (ILC) and Compact Linear Collider projects (CLIC); and secondly the development of a laser-wire (LW) transverse beam size measurement systems. This report describes the technical progress achieved at a large-scale test ILC compatible BPM system installed at the Accelerator Test Facility 2 (ATF2). The ATF2 is an energy-scaled demonstration system for the final focus systems required to deliver the particle beams to collision at the ILC and CLIC. The ATF2 cavity beam position monitor system is one of the largest of its kind and rivals systems used at free electron lasers. The ATF2 cavity beam position system has achieved a position resolution
of 250 nm (with signal attenuation) and 27 nm (without attenuation). The BPM system has been used routinely for lattice diagnostics, beam based alignment and wakefield measurements. Extensive experience has been gained in the operational usage of high resolution CBPMs in a realistic accelerator environment. Hardware development of cavity was conducted in the context of CLIC, where devices were designed, prototyped at the CTF3 facility at CERN. Similarly technical progress is reported for the laserwire system installed at ATF2, where micrometre beam sizes have been measured with uncertainties of less than 10%. The horizontal to vertical aspect ratio of low emittance electron beams is typically large and this causes a problem for laser focii. We developed a method to extract the electron beam size when the Rayleigh range of the laser focus is comparable to the horizontal beam size. This involved fitting using a full convolution of the laser photon and electron number densities. In parallel to the ATF2 LW, the PETRA3 laserwire has developed the use of fibre lasers for Compton scattering and the progress using fibre lasers is reported.
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<tr>
<td>Authored by</td>
<td>S. T. Boogert, F. Cullinan, A. Lyapin, L. Nevay, J. Snuverink</td>
<td>RHUL</td>
<td>15/02/13</td>
</tr>
<tr>
<td>Reviewed by</td>
<td>S. T. Boogert</td>
<td>RHUL</td>
<td>02/10/2013</td>
</tr>
<tr>
<td>Approved by WP Coordinator</td>
<td>E. Jensen</td>
<td>CERN</td>
<td>03/10/2013</td>
</tr>
<tr>
<td>Approved by Project Coordinator</td>
<td>Jean-Pierre Koutchouk</td>
<td></td>
<td>03/10/2013</td>
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1. EXECUTIVE SUMMARY

This deliverable report covers the developments of two prototype systems that are the most likely candidates for advanced beam diagnostics for future lepton linear colliders (LCs), such as the International linear collider (ILC) and Compact Linear Collider (CLIC). The most important beam instrumentation tools in any accelerator are the beam position monitoring system and emittance diagnostics. Most of the developments of these two diagnostics systems are performed at the Accelerator Test Facility 2 (ATF2), which is a prototype final focus system (FFS) for LCs.

**Cavity beam position monitor**: These are typically the largest beam instrumentation system (in terms of cost and number components) in an accelerator. BPMs monitor the beam position vertically and horizontally at important points in the accelerator lattice (magnet locations) and the measurements are used to safely transport the high-energy beam through the accelerator. Furthermore the position measurements are used to optimise the accelerator performance.

The CBPMs installed at the ATF2 were designed by KEK (the national high-energy accelerator laboratory of Japan), built by Pohang Accelerator Laboratory (South Korea) and maintained and operated by RHUL in collaboration with SLAC National Accelerator Laboratory (USA) and KEK. RHUL provided the main readout and control code and performed the operational support for the system.

Prototype cavity beam position systems (three devices) have proven position resolution at 10s of nanometres. The report outlines the progress at using approximately 40 devices at a test facility with similar features as an LC. The experimental methodology used and studies taken to verify the stable system performance are given. This section concludes with examples of how the devices have been used to measure and optimise the ATF2 accelerator.

**Laserwire scanner**: Laserwires are devices that measure the transverse beam size of accelerated beams. Multiple beam size measurements are typically used to reconstruct the phase-space (emittance) occupied by the charged particle beam. This section explains the basic operation principles of laserwire scanners (LWS) and describes the technical progress towards devices that can be used to measure the beam phase space of the beam.

For FC operation beams of one micrometre must be measured without disrupting the charged particle beam. Existent technology to measure beam sizes usually use a solid material (wire or screen), which intercepts the beam to generate some detectable radiation used to image the particle beam. The laserwire uses a focused beam of laser light that interacts with the charged particle beam. This method does not disrupt the normal operation of the accelerator but requires a complex high power laser system and optical focusing.

A laserwire project was initiated at ATF/ATF2 in 2005 and over the last eight years has progressed towards the final goal of micrometre scale beam size measurements. Royal Holloway and the University of Oxford constructed the entire laserwire system (apart from the laser which was loaned from KEK). During EuCARD the laserwire has achieved its technical goal measuring one micrometre vertical beam sizes, from 5 to 10 micrometres at the start of the project. This section outlines the laser measurements and data analysis improvements that yielded the required improvements.
2. INTRODUCTION

There are two competing and complimentary technologies to achieve high luminosity lepton collisions in the energy range above the approximately 200 GeV achieved at the Large Electron Positron Collider. The International Linear Collider (ILC) [1] is based on superconducting niobium elliptical cavities to accelerate electrons or positrons to 500 or 1000 GeV. The Compact Linear Collider (CLIC) [2] uses normal conducting copper cavities to reach energies in the TeV range. After acceleration a beam delivery system manipulates and focuses to the requisite beam sizes required to create the luminosity.

The two most important diagnostics systems for future Linear Colliders (LCs) are beam position monitors and emittance measurement, this report covers the development of these two diagnostics essential for LC operation. The majority of the experimental work was conducted at the Accelerator Test Facility 2, in KEK, Tsukuba, Japan. This is energy scaled demonstrator for the compact final focus systems (FFS) [3] required for both ILC and CLIC.

The beam position monitoring system measures the location of the beam, typically compared to magnetic guiding elements of the accelerator. A precise and robust BPM system is mandatory for almost all measurements of low emittance beams. The required position measurement resolution for LCs is below 50 nm and in some extreme cases down to 5 nm.

The emittance measurement scheme for LS uses multiple beam size measurement systems, typically more than four to measure the vertical and horizontal beam sizes at different phase advances [4]. The ILC requirement is for beam size measurements down to a micrometre with uncertainties of 10%. The requirement for CLIC is similar or lower.

The ATF2 [5] is test accelerator that is designed according to the prescription given in [3]. The ATF2 uses the 1.3 GeV beam provided by the ATF damping ring, which is extracted and then focused by the ATF2. The goal of ATF2 is achieve a vertical beam size of 37 nm, effectively demonstrating the feasibility of the local chromaticity correction described in [3]. This beam size goal is becoming closer to being realised and the most recent measurements indicate a maximum focus size of 65 nm [16]. The ATF2 also acts as a test accelerator for the advanced diagnostics techniques require for LCs, so interference pattern and strong focus laser Compton beam size measurement systems, position feedback systems and advanced optical transition radiation beam size monitors. It is the perfect facility to test the diagnostics which need to be developed for FCs. This report describes the progress made during EuCARD on the ATF2 CBPM and pulsed laserwire systems. Development work on new cavity designs was done for CLIC and tested at CTF3, and a fibre laser was tested at the PETRA3 laserwire installation.

3. CAVITY BEAM POSITION MONITORS

The ATF2 and LCs have strong requirements on the beam position diagnostics to be used, typically sub-micrometer down to few nanometres resolutions are required. Until relatively recently position measurement devices of this resolution have only existed as experimental systems. Cavity Beam Position Monitors (CBPMs) have been successfully tested in numerous experiments, which have consisted of either closely spaced triplets [6, 7] or used with specialized optics configurations, like a ballistic beam in the case of [8, 9]. They have gained traction within the Free Electron Laser (FEL) light source community. Three full-scale production systems have been operating at LCLS [10], FERMI@ELETTRA [11] and SACLA
Among the various types of BPMs, such as the electrostatic BPM using four button- pickups or the strip-line type BPM, only the cavity CBPMs has a potential for achieving resolutions in the nanometre range and the center accuracy at the micrometre level. In order to achieve the ATF2 goal of a small beam size at the focus point the beam must be aligned to within 1 to 100 μm of the magnet centers, depending on the particular magnet. Studies of LC requirements yield a beam to magnet center accuracy 100 nm to 100 μm [5]. All beam based alignment techniques are dependent on the BPM resolution and stability, so a full test of CBPMs with resolutions required for ILC is highly valuable.

3.1. PRINCIPLE OF OPERATION

The allowed modes of a cavity are determined by the geometry of the cavity, with cylindrical and rectangular cavities typically used. The transverse magnetic (TM) cavity modes are excited by the passage of the particle bunch. The lowest frequency monopole mode field magnitude is typically only linearly dependent on the bunch charge $q$. The next highest frequency mode is dipole in shape and bi-linearly dependent on bunch charge and position $d$. The cavity is coupled to waveguide couplers that filter the dipole, position sensitive mode, which is subsequently coupled in to a coaxial cable. In general the voltage signal $V_{\text{dipole}}(t)$ as a function of time $t$ induced from a cavity is of the form

$$V_{\text{dipole}}(t) = q e^{-t/\tau_{\text{dipole}}} (A_{d}d + A_{d}\cdot d + A)$$

where $\tau_{\text{dipole}}$ is the dipole mode angular frequency, $d$ is the bunch displacement, $d$ is the bunch trajectory angle and $A$ is the bunch tilt, with corresponding constants of proportionality $A_{d}, A_{d}$ and $A$ that depend on the coupling of the bunch to cavity mode. From Equation 1 the position sensitive signal is 90 degrees out of phase compared with the signals excited due to trajectory angle and bunch tilt. The idea of exploiting CBPMs as bunch tilt and trajectory monitors has been envisioned but rarely exploited. This remains the case for CBPMs used at the ATF2 and considered for future LCs. To extract the beam position using Equation 1, an independent measurement of the beam charge and arrival phase is required. This is done using a reference cavity with a monopole mode with the same frequency as the position cavity; the output signal has the following form

$$V_{\text{monopole}}(t) = qA_{q}e^{-t/\tau_{\text{monopole}}}$$

where $\tau_{\text{monopole}}$ is the monopole mode angular frequency and $A_{q}$ is a constant of proportionality that depends on the cavity coupling to beam. Typically the monopole and dipole cavities are engineered to have identical as reasonably possible frequencies and decay times. In general there is an arbitrary phase shift between $V_{\text{dipole}}$ and $V_{\text{monopole}}$ due to different delays in electronics and cables. In general a single phase and proportionality constant is required to convert the ratio of the two voltages from Equations 1 and 2 to a beam position.

3.2. ATF2 BPM SYSTEM
The cavities used at ATF2 are based on previous developments with CBPM systems at the ATF [7]. The ATF2 has an extensive CBPM system with 35 C-band CBPMs and 4 S-band CBPMs. This report is based on and extends the experimental work reported in [14], which reviews in detail the CBPM system at ATF2. The C- and S-band cavity systems are similar enough to be discussed as one system, where differences exist they are highlighted in the relevant section. The BPMs are used for dispersion measurement, optics model verification, beam based alignment and beam feedback and steering applications. Figure 1 shows the layout of the ATF2 with the quadrupoles containing a CBPM marked.

![Figure 1: ATF2 lattice layout with BPMs highlighted.](image)

The ATF2 is instrumented with three types of CBPMs, referred to as C-band, located in most quadrupoles, S-band with large aperture in the final focusing section and finally interaction point (also C-band). Photographs of the C- and S-band cavities are shown in Figure 2. The cavities are cylindrical with monopole suppressing waveguides that extract the position sensitive dipole cavity mode. Some important parameters of the cavities are given in Table 1. All the CBPMs discussed have rotationally symmetric set of 4 ports, two for each dipole mode polarisation.

![Figure 2: Photographs of the C- (left) and S-band (right) CBPMs installed inside ATF2 quadrupoles.](image)
**Table 1:** Cavity parameters for C- and S-band devices. Frequencies and isolation measured in air, while $Q_L$ and $R/Q$ are values from electromagnetic simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C-band</th>
<th>S-band</th>
</tr>
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<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>6.423</td>
<td>2.888</td>
</tr>
<tr>
<td>Isolation (dB)</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>Shunt impedance-Q ratio</td>
<td>1.4</td>
<td>0.15</td>
</tr>
<tr>
<td>$R/Q$ at 1 mm ( )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity (V/mm/nC)</td>
<td>0.8</td>
<td>0.3</td>
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The ATF2 started with 33 C-band dipole cavities and 4 C-band reference cavities and 4 S-band dipole cavities and a single S-band reference. Over the course of ATF2 operation, three of the C-band reference cavities and two of the S-band BPMs in the final quadrupole doublet were removed and the focus point was instrumented with a special interaction point cavity with low-$Q$ and strong coupling to the beam [13].

The ATF2 CBPM system can be divided into the following sub-systems: cavity, rf signal processing electronics, digital signal processing, local oscillator (LO) and test tone signals, calibration procedure and software controls.

**3.2.1. ELECTRONICS AND SIGNAL PROCESSING**

The signals from the two output ports for a given direction are combined using a hybrid to increase signal amplitude. The electronics for the C- and S-band CBPMs consist of an amplification stage, single image rejection mixer down-converters and filtering with gains of 25 dB and 10 dB respectively. The other parameters of the rf electronics is given in Table 2.

**Table 2:** The rf signal processing electronics parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C-band</th>
<th>S-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>6.423</td>
<td>2.888</td>
</tr>
<tr>
<td>Noise floor (dBm)</td>
<td>-93</td>
<td>-80</td>
</tr>
<tr>
<td>1 dB compression point (dBm)</td>
<td>-20</td>
<td>10</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Noise figure (dB)</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>X-Y cross talk (dB)</td>
<td>-59</td>
<td>NA</td>
</tr>
</tbody>
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Most of the C-band CBPM output signals are attenuated by 20 dB, after the hybrid, to avoid saturation of the rf electronics and digitiser system and simplify the digital processing.
algorithm. The local oscillator (LO) signals for the C-band rf electronics are generated by dedicated phase locked electronics in the case of the C-band system and a low noise (but not phase locked) synthesiser for the S-band system. The intermediate frequency (IF) signals are digitised by 100 MHz Struck 8 channel, 14-bit waveform VME digitisers. The VME processor-controller publishes the waveform data through EPICS.

The digital signal processing is a digital down-conversion (DDC) algorithm used extensively for cavity BPM signals [7]. The IF signal from the electronics are digitized and then mixed digitally using a complex local oscillator of frequency $w_{DDC}$ to base-band and filtered using a Gaussian time domain filter, with a bandwidth of approximately 3 MHz to remove the $2w_{DDC}$ signal. The down-converted and filtered complex valued signal can be written as

$$y_{DDC}(t) = \sum_{j=0}^{n \text{ samples}} g(t) \exp(i w_{DDC} t) y_{dig}(t)$$

(3)

where $g(t)$ is the Gaussian filter and $y_{dig}(t)$ is the digitized waveform signal. For each cavity the DDC LO frequency must be chosen to leave a baseband signal. This is done by taking approximately 20 pulses of waveform data and down-converting the signal until there is no phase variation as a function of sample number, as clearly seen in Figure 3.

The amplitude $A$ and phase $\phi$ of the signal are measured at a single time $t_{\text{sample}}$ so

$$A = |y_{DDC}(t_{\text{sample}})|$$

$$\phi = \arg y_{DDC}(t_{\text{sample}})$$

(4)

The raw IF signal and processing steps are shown in Figure 3. The signal is first pedestal subtracted and the calibration tone removed. Then the signal is down-converted to baseband using Equation 3 and the signal amplitude and phase calculated using Equation 4. The amplitudes and phases are calculated in the same way for all the dipole and monopole cavities.
Figure 3: Example signals and signal processing for a single down-converted waveform. Top left is the raw signal, top right is the background subtracted signal, bottom left is the down-converted and filtered amplitude and bottom right is the down-converted and filtered phase.

From Equations 1 and 2, it is clear the bunch charge dependence must be removed and the phase of the dipole signal measured compared to a monopole signal. In-phase $I$ and quadrature $Q$ phase signals are calculated from the dipole and monopole amplitudes and phases as follows

$$I = \frac{A_d}{A_m} \cos(f_d - f_m)$$

$$Q = \frac{A_d}{A_m} \sin(f_d - f_m)$$

(5)

Usually the onset of saturation of the rf electronics is set to be at larger signal levels than the saturation of the digitiser system. Even if there is some form of signal saturation, it is still possible to recover beam position information by performing the analysis described but using signals recorded later in time, after the saturation has passed and the signal has decayed somewhat, although at reduced resolution.

3.2.2. CALIBRATION

There are two methods employed to calibrate the CBPM, firstly the quadruple holding the CBPM can be moved using the magnet mover system or the beam can be kicked using an orbit bump.

Starting from QM16FF, the magnets with the BPMs mounted on their poles are placed on movers. The movers, originally developed and used for the Final Focus Test Beam experiment are fully automated and capable of positioning magnets weighing up to 600 kg to a few microns over a range of several millimetres. There are CBPMs before QM16FF rigidly
fixed inside quadrupoles, the calibration of these devices require a beam bump that is created using upstream corrector magnets. This does have an ambiguity in that ab-initio calibration requires a reasonable understanding of the optics, although the calibration calculations are performed in the same way as for a quadrupole mover.

An example mover calibration is shown in Figure 4. The quadrupole containing the CBPM is typically moved over 500 micrometres in 5 to 10 steps and at each step 10 to 20 machine pulses are recorded, where typically only $I$ and $Q$ values are recorded.

![Figure 4: Example mover calibration of a single BPM.](image)

The in-phase and quadrature-phase signals can be related to displacement via

$$d = S (I \cos \varphi + Q \sin \varphi)$$

$$d = S \left( I \sin \varphi + Q \cos \varphi \right)$$

where $S$ is the scaling to position and $\varphi$ accounts for the relative phase between the dipole and monopole signals. Assuming the beam is purely moved in position then $\varphi$ is determined via a fit to $Q$ as a function of $I$ (shown in the top right of Figure 4). Then rotating to $I = I \cos \varphi + Q \sin \varphi$ and $Q = I \sin \varphi + Q \cos \varphi$, the position phase is clearly separated from the bunch trajectory and tilt (shown in the bottom two plots of Figure 4). Having obtained the correct rotation, the scale calibration can be identified as the gradient of a linear fit of $I$ to mover (or beam) position (shown in the bottom left plot of Figure 4). Provided there is no angular motion of the BPM the signal left in the quadrature phase should be small.

### 3.2.3. TEST TONE AND CALIBRATION STABILITY

With each machine pulse a continuous wave radio frequency tone is injected, after the beam induced signal into the electronics for both the dipole and monopole cavity electronics, which can be seen in the top left hand plot of Figure 3. The test tone data processed in the same way
as the CBPM data is used to monitor possible gain and phase variations in the processing electronics. Completely analogously to the CBPM signal, $I_{\text{test}}$ and $Q_{\text{test}}$ are calculated for each channel. The variations in the test tone amplitude and phase are cancelled in the calculation of $I_{\text{test}}$ and $Q_{\text{test}}$, see Equation 5. Furthermore, coherent changes in dipole and reference channel gain and phase are also removed, only leaving the differences between the two channels. Only incoherent changes between dipole and reference channels can affect the position measurement. Analysis of the test tone data covering 4 days, showed that the electronics drifts did not on average exceed ±0.99% in amplitude and ±0.57° in phase, shown for all CBPM channels in Figure 5.

![Figure 5: Two measurements of the processing electronics relative amplitude and phase separated by 4 days.](image)

To test the operating system stability, the calibration procedure was repeated as frequently as possible over a two-week period and the calibration constants recorded for all BPMs in both directions shown in Figure 6. The IQ rotation angle does not vary more than 1 degree, whilst the scale factor varied by about 5%, clearly inconsistent with the test tone measurements of Figure 5. This discrepancy can be explained by the beam motion whilst the calibration is being performed, by subtracting the beam jitter using the CBPMs upstream of the CBPM being calibrated the scale factors vary by less than 1%, in agreement with the rf electronics test tone measurement.
3.2.4. SYSTEM PERFORMANCE

The CBPM system performance is mainly determined via the single device resolution. This cannot be measured independently from CBPMs. The resolution of a BPM was investigated using a model independent analysis (MIA) as the beam motion is typically two or three orders of magnitude larger than the CBPM resolution. After the calibration procedure is performed for all the CBPM the $x$ and $y$ CBPM positions were recorded for approximately 250 machine pulses. The position data $d_{ik}$ for machine pulse $i$ and BPM $k$ is used to construct a linear system of equations of the form

$$d_{ik} = \sum_{j} d_{ij} v_{jk}, \quad (7)$$

where $v_{jk}$ is a set of correlation coefficients relating the positions in all the other CBPMs apart from the $k$th CBPM to the measured position in the $k$th BPM $d_{ik}$. The correlation coefficients are determined by inverting the data matrix $d_{ij}$ using singular value decomposition (SVD). Having determined the correlation coefficients it is straightforward to determine a predicted position in a given BPM given the set of spectator BPM measurements. The values used in the data matrix do not just have to be beam position but could alternatively be in-phase and quadrature-phase signal values and of course include both horizontal and vertical BPM information to remove the effects of device roll around the beam axis. This SVD method is applied for each BPM and the position residual can be calculated for each position measurement so

$$d_i = d_i - \sum_{j} d_{ij} v_{ij}, \quad (8)$$

The quoted CBPM resolutions are the root mean square (RMS) of this position residual. This measure is an over-estimate of the CBPM resolution but the error associated with the prediction from the spectator CBPMs is typically smaller than the single device resolution.

Figure 6: Histograms of the calibration constants for many BPMs over a two week period. Left: is the phase rotation $\phi$. Right: is the scale factor $S$. 
The resolution of each device is plotted in Figure 7, for two different beam orbit settings, one where the beam is well steered in the entire ATF2 and another where the beam has been steered to the centre of a triplet of CBPMs where the 20 dB attenuators have been removed. The same CBPM resolution data is plotted in Figure 8 as a histogram.

Figure 7: Horizontal and vertical resolution as function of BPM number along the ATF2. Left: with normal orbit, Right: with beam steered to centre of 3 CBPMs without attenuators (9,10,11)

Figure 8: Histogram of horizontal (top) and vertical (bottom) resolution of the C-band CBPMs.
With attenuators the average resolution is 250 nm in both the horizontal and vertical directions, without attenuators the beam recorded resolution is 30 nm, again consistent in both axes.

3.2.5. SYSTEMATIC EFFECTS

Although designed to operate at bunch populations of $10^{10}$ electrons per bunch, the wake-field effects described in Section 2.3 have pushed operation of the CBPM system with lower bunch charges. As the position is calculated as the ratio of two voltages ($V_{\text{dipole}}/V_{\text{monopole}}$), the statistical uncertainty scales as $\sim 1/q$, including an irreducible constant uncertainty in quadrature gives a charge dependence of the following form

$$s_d = A \frac{1}{q^2} + B^2,$$

where $A$ and $B$ are constants. Figure 9 shows the measured resolution, for a CBPM without attenuation, as function of bunch charge, which was varied by changing the photo-injector laser power. Even at bunch populations of $7.5 \times 10^8$ electrons per bunch, the resolution is below 100 nm. At higher charges it asymptotically tends to a value of approximately 27 nm.

![Figure 9: Resolution as a function of bunch charge, for a single CBPM without attenuation.](image)

The bunch length is of central importance to the wake-field studies presented in Section 2.3 as the peak wake potential depends on the bunch length. During wake-field measurement shifts the damping ring (DR) accelerating gap radio voltage was varied between 0.22 and 0.32 MV which corresponded to a bunch length change from 31 ps to 21 ps. The calibration procedure was repeated for a single CBPM at three different voltages and also the resolution was
measured, shown in Figure 10. There was no clear systematic effect of bunch length on the calibration constants, as expected and only a weak dependence of the resolution.

![Graphs showing calibration constants and BPM resolution as functions of damping ring rf voltage.](image)

**Figure 10:** Left: variation of calibration constants as function of damping ring rf voltage. Right: variation of a single BPM resolution as function of damping ring rf voltage.

Still to be investigated is the effect of saturation on the device resolution. It can be seen in Figure 7 that poor steering the beam-line leaves large offsets in some CBPMs and hence poor resolution. This is difficult to quantify as moving a CBPM also cause a downstream orbit change, which effects the resolution of spectator CBPMs.

### 3.2.6. SYSTEM USAGE AT ATF2

**Lattice diagnostics**

A Matlab GUI-based software package is used to measure the orbit response in the ATF extraction line (EXT) to the excitation of a selection of dipole correctors. This lattice diagnostics measurement is performed at the start of each machine-running period. The first-order optics of the EXT line is well understood, but this measurement allows us to quickly spot problems with the BPM readouts, such as sign flips in the BPM calibrations (rare). Given our understanding of the EXT line optics, automated model-based orbit correction is regularly used at the start of tuning. Figure 11 shows a typical Lattice Diagnostics measurement.
Dispersion correction

Changing the energy of the beam in the damping ring and observing the response on BPMs in the EXT and FF lines allow dispersion measurement in the EXT line. The energy change is accomplished by shifting the frequency of the DR RF. Typically the frequency is shifted by ±3 kHz (the nominal RF frequency is 714 MHz). The momentum compaction of the DR (≈ 0.002) leads to a relative beam energy change of ±0.2%.

The “leakage” dispersion in the nominally dispersion-free region downstream of the extraction dipoles is inferred by fitting a betatron oscillation to the observed BPM responses. This fit is then propagated backward to the DR and forward to the IP. Horizontal dispersion is corrected using a model-derived linear combination of the strengths of two inflector quadrupoles (QF1X and QF6X). Correction typically requires one or two iterations.

Figure 9 shows typical measured and fitted horizontal dispersion, before and after correction.

Wakefield measurement
Achieving sub-100 nm vertical beam size at ATF2 required lowering the bunch charge from the nominal 1x10^{10} electrons by a factor of 10. Although this had a positive side effect of reducing the Compton signal background of several beam diagnostics, small beam sizes need to be demonstrated at the nominal bunch charge, close to the values required for future linear colliders to achieve their design luminosity. One of the main contributors to the beam size growth is thought to be the effect of wakefields. The extracted bunch length at ATF is relatively large: 7-9 mm, resulting in a wakefield kick of the particles in a bunch by the fields it produces. This has two consequences: the orbit of the bunch as a whole (i.e. centre of mass) alters according to its total charge and position with respect to the wakefield generating elements; and the particles along the length of the bunch arrive at the interaction point (IP), where the beam size is measured, with slightly different offsets, perceived as a beam size increase.

The initial design of the ATF2 beamline did not include a thorough study of the wakefield effects of all the elements. This is normally justified for a single-pass beamline such as ATF2, where collective beam effects do not accumulate. The ATF2 beamline included a number of high impedance elements, such as cavity beam position monitors (CBPMs), unshielded bellows, vacuum ports, step transitions, etc. A study began to identify the major wake kick contributors, understand the wakefield effect on the beam size, and measure the produced kicks.

![Figure 13: The orbit change with respect to the wakefield setup position for two reference cavities after pulse averaging and jitter subtraction of the CBPM readings in the vertical direction near quadrupole QD2BFF.](image)

### 3.3. CLIC MAIN BEAM BPM
A beam position monitor (BPM) for the main linac and beam delivery system of the compact linear collider (CLIC) is under development. A prototype cavity BPM has been designed and built. The microwave pick-up has been measured in the accelerator laboratory at Royal Holloway, University of London. Royal Holloway has also been involved design of the first iteration of the processing electronics and the beam tests on the probe beam-line at the 3rd CLIC Test Facility (CTF3). The ultimate goal of the project is to demonstrate a 50 nm spatial resolution with a 0.6 nC bunch charge and the ability to measure multiple beam positions within a single bunch train.

The resonant frequency and quality factors of the two pick-up cavities were measured from the transmission from a weakly coupled antenna probe to each of the output ports of the BPM pick-up, measured using a network analyser. This was done before and after brazing of the assembly. The results are summarised in Table 3. The reference cavity had to be modified because it had the wrong resonant frequency due to an error in the mechanical design, which is why some results are missing.

The dependence of the resonant frequency on temperature was measured over one weekend. The temperature was measured every minute using a temperature probe and the resonant frequency, every 10 minutes from the transmission between opposing ports.

**Table 3: Radiofrequency characteristics of the cavity beam position monitor pick-up**

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Parameter</th>
<th>Predicted</th>
<th>Measured</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Before brazing</td>
<td>After brazing</td>
</tr>
<tr>
<td></td>
<td>Reference cavity Q_L</td>
<td>150</td>
<td>74</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Reference cavity Q_0</td>
<td>383</td>
<td></td>
<td>357</td>
</tr>
<tr>
<td></td>
<td>Temperature stability/kHz °C⁻¹</td>
<td>-247</td>
<td></td>
<td>-308</td>
</tr>
<tr>
<td>Position</td>
<td>Position cavity frequency/GHz</td>
<td>14.990</td>
<td>14.993</td>
<td>15.012</td>
</tr>
<tr>
<td></td>
<td>Position cavity Q_L</td>
<td>274</td>
<td>224</td>
<td>198</td>
</tr>
<tr>
<td></td>
<td>Position cavity Q_0</td>
<td>450</td>
<td>306</td>
<td>292</td>
</tr>
<tr>
<td></td>
<td>Temperature stability/kHz °C⁻¹</td>
<td>-247</td>
<td>-243</td>
<td>-359</td>
</tr>
</tbody>
</table>

**Electronics**

A schematic of the first iteration of electronics is shown in Figure 14. They were constructed from connectorised components that were measured both individually and combined in a full processing channel. The results for the full channel measurements are summarised in Table 2.
Installation

The beam position monitor system was installed on the probe beamline of CTF3 in January 2013. The location, on a straight line downstream of the final spectrometer magnet and just before the beam dump, was chosen so that the small 8 mm beam pipe aperture of the BPM did not affect the main experimental program of CTF3. It also meant that the beam was diverted during other operation, which protected the receiver electronics from saturation due to high current beams and large offsets.

The electronics are installed close to the pick-up in order to minimise cable losses at the high frequency. The signals are then transported at the intermediate frequency to the 2 GS/s digitiser, which is outside the tunnel. The control for the variable attenuator is on a board that has its own housing and is protected from radiation in the tunnel by lead shielding. It is controlled over RS232 via a serial device server connected to the CERN technical network. The local oscillator (LO) generation is also separate. It consists of a voltage controlled oscillator and power amplifier with +27 dB gain and has eight outputs, three of which are used. The necessary DC power supplies are located outside of the tunnel, including the control voltage for the LO source.

Table 4: Summary of the measured parameters of the down converter electronics

<table>
<thead>
<tr>
<th>Channel</th>
<th>Gain/dB</th>
<th>Bandwidth/MHz</th>
<th>Worst isolation/dB</th>
<th>Flatness/±dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>5.0±0.1</td>
<td>216</td>
<td>-82.2±0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Y</td>
<td>5.19±0.05</td>
<td>204</td>
<td>-81.0±0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>REF</td>
<td>4.13±0.06</td>
<td>205</td>
<td>-87.0±0.5</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Figure 14: Schematic of the electronics used for the first beam tests

Figure 15: Picture of the cavity BPM pick-up installed on the CTF3 probe beamline. The beam direction is out of the picture and the reference cavity is downstream. The three cables come from the reference cavity and X and Y output ports of the position cavity and go directly to the down-converter.

Figure 15: Picture of the cavity BPM pick-up installed on the CTF3 probe beamline. The beam direction is out of the picture and the reference cavity is downstream. The three cables come from the reference cavity and X and Y output ports of the position cavity and go directly to the down-converter.
A prototype diode detection system was also installed on one of the reference cavity output ports. This consists of a Schottky diode rectifier and an amplifier and is designed to have a short signal rise time.

**Beam Tests**

The first tests of the beam position monitor on the electron beam were performed from February to May 2013. The beam charge was varied via the attenuation of the photoinjector laser so that the sensitivity of the reference cavity signal to charge could be measured. The beam position was then varied using dipole corrector magnets so that the sensitivity of the position cavity signal to beam offset could also be measured. Fits were made to the output signal peak amplitude and power. These can be seen in Figure 16 and the results are summarised in Table 3 and 4. In both cases, the predicted values were calculated from the laboratory measurements and simulations using ACE3P and GdfidL. The diode detection system successfully produced a signal with a rise time of 11-12 ns and so there will be a larger installation of three diodes, one to replace the prototype and two for the two position cavity channels.

![Signal Amplitude and Peak Power](image)

**Figure 16:** Example fits to the signal amplitude and peak power from the position cavity against the relative beam position

**Table 5:** Summary of results for the reference cavity sensitivity measurements. The predicted single bunch value is 117 V nC⁻¹

<table>
<thead>
<tr>
<th>Beam pulse length/ns</th>
<th>Sensitivity/V nC⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long train</td>
</tr>
<tr>
<td>30</td>
<td>623±3</td>
</tr>
<tr>
<td>60</td>
<td>608±2</td>
</tr>
</tbody>
</table>

**Table 6:** Summary of the results of the position cavity sensitivity for the two types of fit. The measured charge during the measurement is 65.4±1.9 pC and the predicted value is 17.1 V nC⁻¹ mm⁻¹
3.4. CONCLUSIONS

The requirements for the two proposed LC designs both require CBPMs in large numbers. The resolution requirement for the ILC is typically hundreds of nanometres whilst the requirement for CLIC is more in the tens of nanometres. The CBPM system as developed for the ATF2 is quite suitable for the ILC, where the bunch spacing is sufficiently large that the signals from subsequent bunches do not interfere in the cavity. The situation is not so clear for CLIC, where it is impossible to separate the cavity signal from each bunch.

The ATF2 cavity CBPM system is one of the largest installed and operating, with 4 S-band and 33 C-band position sensitive cavities. The C-band cavity system operates well with a resolution of approximately 250 nm and 30 nm in CBPMs with and without attenuators respectively. Figure 7 shows the distribution of vertical and horizontal BPM resolutions for all the attenuated C-band BPMs (with resolutions below 1 mm). At the planned operating single bunch charge of $1 \times 10^{10}$ electrons per bunch the resolution should be stable at 30 nm without attenuators.

The lessons learned from the development and use of CBPMS at ATF2 and the application at an LC are the following:

1. Independent calibration of BPMs, so multiple BPMs can be calibrated simultaneously. Each CBPMs for example could be placed on its own mover system within each quadrupole.
2. Further specification of the diagnostics requirements are needed for ILC and CLIC as temporal and spatial resolution requirements are not sufficient.
3. CBPMs are not fixed resolution devices and the resolution depends on the beam offset and charge within the device. A CBPM with heterodyne electronics and waveform digitization can still be used to provide position measurement when there is a large beam offset, although at degraded resolution.
4. Identification of common elements to all CBPMs to try and keep as much of the rf electronics and signal processing common between different devices.
5. Mitigate the effect of the optics on diagnostics device calibrations, so CBPMs should be placed upstream of the quadrupole so the magnets strength does not affect the calibration constants.
6. Variable attenuation and phase control would be beneficial as all BPMs could be run with similar performance characteristics.
The development of a new CBPM has been performed which is compatible with the requirements for CLIC. The CBPM system required for CLIC, due to the low-Q nature of the devices, significantly more difficult to achieve the resolution of 50 nm. The first best tests are reported with beam measurements compatible with the simulation and rf bench measurements. These tests will continue beyond EuCARD to include multiple devices to measure the device resolution.
3.5. REFERENCES


4. LASERWIRE BEAM SIZE MONITORS

The emittance of future colliders such as the ILC and CLIC rely on non-invasive beam size measurement devices. The traditional methods of beam size measurement such as scanning metallic wires or optical transition radiation screens will not survive the damage inflicted by the high energy densities of the particle beam.

Laserwire scanners use a high-energy laser pulse that is collided transversely to the particle (typically electron, although positrons are just as possible) beams. Ideally both the laser and particle beams are Gaussians in their transverse coordinates. The laser photons are inverse Compton scattered to Gamma rays in the direction of the electron beam. The charge beam is deflected and the charge-less and hence deflected photons are detected in a suitable detector. Figure 17 shows a schematic layout of a LW system.

![Schematic diagram showing the principle of operation of a laserwire scanner.](image)

The LW work at RHUL has focused along two complimentary directions. Firstly to develop a system which can operate near the diffraction limit for a given laser wavelength. Laser systems commonly operate in the infrared (1064 nm for example) and the doubling of the frequency (to 532 nm) can be performed with an energy efficiency approaching 50%. Green laser light in the frequency range of 500 nm to 550 nm is relatively easy to measure using off the shelf optical devices and manipulate using relatively standard optics. The diffraction limit can be eased by tripling or quadrupling the laser frequency but at a significant operational cost.

4.1. ATF2 EXTRACTION LINE LASERWIRE

The extraction line laserwire system at the Accelerator Test Facility 2 (ATF2) at KEK, Japan, is a system developed to achieve a precise transverse beam profile measurement of an electron beam. The development of such a diagnostic capable of measuring micrometer-size beams will be crucial in future linear accelerators such as the ILC and CLIC where the small beam sizes and high charge densities are beyond the operating capabilities of current diagnostic techniques [18,19].

The laserwire at the ATF2 aims to demonstrate a \( 1 \, \text{mm} \) transverse beam profile measured using the Compton-scattered photons from a tightly focussed laser beam. The laser beam is...
scanned transversely modulating the flux of the Compton-scattered photons, which travel near parallel to the electron beam and are measured in a detector downstream after a bend in the beamline.

A laserwire installation at the ATF2 [20] was upgraded and commissioned in 2010 demonstrating initial transverse beam size measurements of 8.0±0.3 μm [21]. This system was moved to a different point in the ATF2 lattice where a micrometre scale beam could be generated. This paper presents the recent results of this laserwire system demonstrating high-resolution measurements of the electron beam, even with a large aspect ratio beam that is conventionally thought to limit the use of a laserwire.

### 4.1.1. EXPERIMENTAL SETUP

The laserwire was relocated in summer 2011 to the beginning of the ATF2 final focus section where strong, closely spaced matching quadrupoles allow a vertical electron beam size of ~1 μm to be achieved. The position of the laserwire interaction point in the ATF2 extraction line is shown in Figure 18.

![Figure 18: ATF2 extraction line lattice with laserwire and laserwire detector locations.](image)

The laser system consists of a Q-switched Nd:YAG amplifier seeded by a 357 MHz mode-locked oscillator that is locked by external frequency reference to the ATF2 master oscillator. The laser output is frequency-doubled delivering ~150 mJ pulses with a wavelength of 532 nm at the 1.3 Hz repetition rate of the ATF2 1.3 GeV electron bunches. The laser pulses are σt≈77 ps long and the electron bunches are σt≈30 ps long. The laser is located outside the accelerator enclosure and transported into it in free-space with mirrors before being focused by an aberration corrected fused silica lens to the laserwire interaction point. A telescope consisting of two lenses is used to manipulate the divergence of the laser beam to control the size of the laser beam on the laserwire lens system to provide the minimum focused laser beam spot size at the interaction point. Figure 19 shows the focusing lens mounted on interaction vacuum chamber.
Figure 19: Photograph of the laserwire chamber. A custom flange is used to connect the chamber to the two axis mover system. The lens (black at the centre) is connected directly to chamber and the laser focus moves with the chamber.

The Compton-scattered photons are detected approximately ten metres downstream immediately after a dipole magnet. The detector consists of a 4x4x0.6 cm lead plate followed by a similarly sized piece of silica Aerogel that acts as a Cherenkov radiator. A light tight pipe guides the Cherenkov light to a shielded photo-multiplier tube out of the horizontal accelerator plane. A data acquisition system based on EPICS is used to synchronously record data from the laserwire experiment as well as the extraction line cavity BPM system [22] and other ATF2 diagnostics.

The laser pulses and electron beam were synchronised for collisions using an optical transition radiation (OTR) screen mounted in the laserwire chamber [23]. The laser beam was directed below this and both the attenuated laser light and the OTR were detected in an avalanche photodiode negating any issues of detector synchronicity. The laser timing was adjusted until both were overlapped. The OTR screen was also used as an alignment tool by comparing the bremsstrahlung radiation as the screen was lowered into the electron beam to the referenced focus spot position of the laser relative to the screen. This method allowed immediately detectable collisions between the laser and the electron bunches, which were subsequently optimised to maximise the Compton signal. The geometry of the laserwire interaction point is shown in Figure 20. Figure 21 is a photograph of the LW chamber installed at the ATF2.
**Figure 20:** The geometry of the laserwire interaction point showing the directions of the electron beam, laser and OTR propagation.

**Figure 21:** Photograph of the laserwire system installed at ATF2, located between two (red) quadrupoles. The view is from the laser exit sides showing the post-collision laser diagnostics. The OTR screen manipulator can be seen at the top of the photo.

### 4.1.2. HIGH ASPECT RATIO ELECTRON BEAM

The electron beam at the laserwire location in the ATF2 lattice is approximately 100 μm × 1 μm in the horizontal and vertical planes respectively. The laser spot size \( s (x) \) about a focus at location \( x_0 \) of size \( o \) is described by...
\[ (x) = \sqrt{1 + \left(\frac{x - x_s}{x_R}\right)^2} \] \hfill (10)

where \( x_R \) is the Rayleigh range; the distance from the centre for the laser radius to increase by a factor of \( \sqrt{2} \). The Rayleigh range is dictated by the wavelength of the light and the spatial quality described by a linear scaling factor \( M^2 \).

\[ x_R = \frac{(2 s_o)^2}{M^2 l} \] \hfill (11)

In the case where the laser beam size is effectively constant across the electron beam, the laserwire scan is the convolution of the electron beam profile and the Gaussian transverse profile of the laser beam and can be easily deconvolved [24]. However, in the case of the ATF2 laserwire, where a visible wavelength is used to create a focussed laser spot size of \(~1 \; \text{mm}\), the laser divergence across the electron beam is unavoidable. Figure 22 shows a schematic of the electron beam and the laser diameter depicting that even when the focussed spot of the laser is not overlapping with the electron beam, the divergent laser beam continues to interact with the electron beam. To deconvolve the laserwire scans, the full overlap integral of the laser and electron beams must be used. This requires knowledge of the horizontal electron beam size to ascertain the vertical electron beam size from the laserwire scan.

![Figure 22: Schematic of laser propagation across a large aspect ratio electron beam.](image)

To accurately deconvolve the laserwire scans using the overlap integral, the laser propagation must be accurately known. The laser propagation was characterised using the \( M^2 \) model [25] that describes the laser beam size with reference to the propagation of a laser beam with a Gaussian transverse intensity profile. The transverse laser profile is sampled at various locations throughout the focus region using a laser beam profiler and fitted to Equation 10.

### 4.1.3. LASERWIRE RESULTS

The laser propagation was characterised using a larger scale focus created using an \( f = 1 \; \text{m} \) plano-convex lens. A scaled focus was used as the micrometre size laser focus is beyond the...
measurement resolution of CCD-based laser beam profilers as well as to avoid contaminating the measurement by the aberrations introduced by strong focusing lenses. Beam profiles of the laser were recorded at various locations throughout the focus and the diameters used to fit the data to the $M^2$ model, which was then scaled to the laserwire interaction focus using the measured input beam profile to the laserwire lens. The laser propagation for both axes of the laser beam is shown in Figure 23.

The laser propagation was found to be astigmatic and the axis of propagation rotated by $17.5 \pm 1.0^\circ$ to the lab frame. The individual propagation models of each axis were used to calculate the projected vertical laser propagation in the lab frame as that is relevant for deconvolving the laserwire scans. The projected size is described by

$$t = \sqrt{\left( \text{horizontal} \sin \theta \right)^2 + \left( \text{vertical} \cos \theta \right)^2}$$

When performing alignment of the laserwire to the electron beam with the OTR screen, a laser machined notch in the edge of the OTR screen was used as it allowed horizontal alignment as well as vertical alignment to be performed. The system was aligned to within 10 mm of the optimal vertical position using this method and after this initial alignment, Compton-scattered photons were detectable and the collisions were then optimised to provide the maximum signal.

To achieve an accurate measurement of the electron beam size, the laser focus must be centred on the electron beam, so the laserwire was first coarsely scanned vertically, then horizontally to centre the laser focus before finally performing a detailed vertical scan. The initial coarse vertical scan is shown in Figure 24 with a measured beam size of $2.71 \pm 0.18$ mm.
Figure 24: Initial vertical scan of the electron beam.

The initial vertical scan is fitted to a Gaussian function, which although not an accurate description, allows the centre and approximate size to be initially determined. To deconvolve the horizontal scan using the necessary overlap integral model, knowledge of the vertical beam size is needed. Similarly, to deconvolve the vertical scan, knowledge of the horizontal is needed. To overcome this circular problem, the two are fitted iteratively together until convergence is reached. The horizontal scan of the electron beam is shown in Figure 25.

Figure 25: Horizontal scan of the electron beam.

As the divergent laser beam continues to interact with the electron beam even when the laser focus is displaced from the electron beam, the vertical laserwire scans must cover a scan range significantly greater than the vertical size of the electron beam for an accurate measurement. However, the central part of the scan contains a very narrow peak. Therefore, a scan with nonlinear step sizes was crucial in performing accurate laserwire scans as well as minimising the required time per scan. In Figure 26, 61 laser positions were used and 20 machine samples were recorded at each location in the vertical scan.
4.2. PETRA3 LASERWIRE

The PETRA laserwire program started in 2003 and has been continuously upgraded and improved to its current state, which is described in detail in [26]. The system consists of a vertical optical breadboard that houses two independent laserwire scanners one for the vertical and another for the horizontal axes. Traditionally as with the ATF2 LW system, free space Q-switched injection seeded lasers have been used for LW scanners. The PETRA3 LW was chosen to test developments in fibre laser systems with 500 kHz repetition rate and fibre delivery of the laser light to the interaction point in the accelerator. Fibre lasers have lower pulse energy but high average power, then averaging or counting the Compton rate for many bunch collisions.

Fibre laser system

The laser system developed for PETRA3, consists of mode locked oscillator, two pre-amplifiers and two main amplifiers. A schematic of the laser is shown in Figure 27. The oscillator is a time bandwidth Nd:YVO4 solid state laser producing 850 nW of 1064 nm radiation, divided into 10 ps pulses with a repetition rate of 62.45 MHz, the 8th sub-harmonic of the PETRA3 bunch clock at 499.664 MHz. The oscillator is locked to an rf source, which can be phase shifted with respect to the master bunch rf to precisely time the laser pulses with respect to the electron bunches. The oscillator seed pulses are selected using an acousto-optic pulse picker, then stretched in a grating system ready for amplification. The two pre-amplifiers use a single mode Nd doped fibre pumped with 808 nm light from a solid-state laser. The power amplifiers are also divided into two stages, using large mode area Yb doped fibre, pumped with a continuous wave 25 W laser at 975 nm. The resulting amplified pulses are 200 ps in duration (due to the pulse stretching), at a repetition rate of 520 kHz. The average amplified power is 1.5 W, with individual pulse energy of 2.9 μJ, or 14 kW peak pulse power.
Example scan

The laser beam is scanned over the PETRA3 beam using a translation stage based scanning system, which moves the focusing optics. The time taken for a scan is typically tens of seconds, which is limited by the time taken to move the stages. The main difference in the analysis is that typically on one Compton photon is created per bunch collision and the signal from the Compton detector is thresholded and then counted. This results in a signal rate between zero and the laser repetition frequency. The Compton rate is then used opposed to the total energy of Compton photons as used previously in [26]. The program at PETRA3 is still ongoing, firstly to compare the results from the fibre-LW to existing transverse beam size diagnostics, but also to measure multiple bunches. This should be completed by April 2014 and a publication will be produced.
Figure 28: Screenshot of the PETRA3 laserwire control panel. Top left is the scan control panel. Bottom left is a timing schematic. Top right is the Compton rate as function of laser position. Bottom right is the extracted beam size and system status.

4.3. CONCLUSIONS

Micrometre size electron beam profiles with a resolution of less than 1 mm have been successfully demonstrated with a visible wavelength laser. The often-cited problem of laser divergence with a laserwire measuring a very large aspect ratio electron beam has been overcome to accurately measure both the horizontal and vertical dimensions.

Precise characterisation of the laser propagation is necessary to deconvolve the non-Gaussian laserwire scans accurately. Furthermore, it has been shown that a laserwire diagnostic with only one laser beam is capable of making a two dimensional profile of the electron beam.

A laserwire diagnostic based on a visible wavelength laser source allows the use of transmissive optics where shorter wavelength lasers would not. Although a shorter wavelength laser allows a smaller focussed spot size to be achieved and therefore a smaller minimum beam size measurement, the necessary use of reflective focussing optics to avoid the absorption of transmissive optics limits the scan range and prevents direct calibration as the focussed laser spot size cannot be measured without interrupting the incoming laser beam. This demonstration of micrometer-size laserwire scans using transmissive optics and a visible wavelength laser will be important in scaling from a single research diagnostic station to a robust multi-station emittance measurement system in a large-scale collider.

The general background level as well as the background encountered due to the horizontal defocussing of the electron beam as a consequence of the necessary strong vertical focussing presents a challenge to successfully operating this laserwire installation. With higher background levels, higher energy laser pulses are required to overcome this as well as a greater number of samples being required to overcome statistical variations. With lower background conditions, a more precise fit to the data could be achieved and future work is under way to develop suitable electron beam optics for this purpose.

The development and demonstration of the laserwire is a significant step forward to achieving a precise and reliable diagnostic for future linear colliders such as the ILC or CLIC. Further to this, there are several considerations for a laserwire system at both CLIC and the ILC for which design studies are underway:

- A more complete simulation of background sources, their transport and effect on detection of the laserwire signal. This is the case for both the low energy scenario at the ATF2 as well as for high energy at a future linear collider.
- With a fuller understanding of background sources and their level, it is possible that the required peak power in the laser pulses could be significantly reduced. If so, this could allow the use of lasers based on optical fibres as well as much more robust and safer transport in optical fibre.
• Reducing the wavelength further to the third harmonic in the soft ultraviolet part of the spectrum. At a wavelength of ~350 nm, the minimum spot size of the laserwire and hence the resolution would be increased as required by CLIC but would still allow the use of transmissive optics.

• A more compact installation using standardised components. To achieve the micrometre-sized focussed spot size, the vacuum window must not introduce optical aberrations. Therefore, it becomes an integrated part of the optical system with the lens placed a precise distance from the window and aligned to optical standards. Because of this constraint, the vacuum chamber with the lens attached must be moved to perform the laserwire scan. Furthermore, with the currently required megawatt to gigawatt peak power levels, damage from back reflections is likely within the lifetime of the diagnostic, in which case an arrangement with an easily replaceable vacuum window is key.

• Integration of an OTR-like screen within the laserwire vacuum chamber as an alignment aid. During the commissioning stages of both the laserwire stations and the accelerator, this will be very important in order to readily achieve collisions between the laser and electron beam.

The development work at PETRA3 has yielded the first laserwire scans using a fibre-based laser. The laser power is only sufficient to produce at most one Compton photon per collision, but these are averaged over many of the 520 kHz laser-electron bunch interactions. The system deployed at PETRA3 can uniquely hit individual bunches within a PETRA fill and measure the emittance of all the bunches within a couple of minutes. It is imagined that this fibre technology will be used for ILC/CLIC LW based emittance measurement stations.
4.4. REFERENCES


## ANNEX: GLOSSARY

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>ILC</td>
<td>International Linear Collider</td>
</tr>
<tr>
<td>CLIC</td>
<td>Compact Linear Collider</td>
</tr>
<tr>
<td>LC</td>
<td>Linear Collider</td>
</tr>
<tr>
<td>FF(S)</td>
<td>Final Focus (System)</td>
</tr>
<tr>
<td>BDS</td>
<td>Beam Delivery System</td>
</tr>
<tr>
<td>IP</td>
<td>Interaction Point</td>
</tr>
<tr>
<td>ATF2</td>
<td>Accelerator Test Facility 2</td>
</tr>
<tr>
<td>(C)BPM</td>
<td>(Cavity) Beam position monitor</td>
</tr>
<tr>
<td>DDC</td>
<td>Digital down conversion</td>
</tr>
<tr>
<td>LO</td>
<td>Local oscillator</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate frequency</td>
</tr>
<tr>
<td>LW(S)</td>
<td>Laserwire (scanner)</td>
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