Conclusion

As each chapter forms a well defined whole, the conclusions can be made for each of them independently. The observations and results are recapitulated with a strong emphasis on the original work performed.

Beam test of a prototype SCT module

The analysis of data gathered in a beam test of a prototype silicon-strip half-module equipped with analogue read-out chip SCTA128HC is presented in detail. The module was constructed in such a way to allow for a simultaneous measurements of 6 cm and 12 cm long detectors. While the detectors in ATLAS will operate at a constant tilt angle of 10°, in this beam test inclinations from 0° to 50° (in steps of 10°) were studied. The beam test set-up is described and the resolution of the beam telescope, at the point where the device under test was inserted into the beam, is found to be $2.5\,\mu$m. Extraction of clusters of hits from the raw data is performed and the efficiency versus noise occupancy for the detectors of both lengths is studied. The efficiency at an occupancy of $5 \cdot 10^{-4}$ is found to be 98.8% for the 6 cm detector and 97.2% for the 12 cm detector.

The resolution of the 12 cm detector at 10° was found to be $\sigma(dU) = 12.2\,\mu$m. There are 40% of single strip hits ($\sigma_1(dU) = 15.1\,\mu$m) and the remainder of them are two-strip hits for which the *eta* reconstruction method can be used ($\sigma_2(dU) = 10.3\,\mu$m). The average signal-to-noise ratio is 26 for the 6 cm detector and 20 for the 12 cm detector. Based on the difference between the detectors of different lengths, relative contributions to the noise from the electronics and the detector were estimated: the noise of the electronics is $\mathrm{ENC_{el}} = 730\mathrm{e}^-$ and the noise of a single, 6 cm strip is $\mathrm{ENC_{6\,cm}} = 390\mathrm{e}^-$. The net noise of the 12 cm detector is therefore $\mathrm{ENC_{12\,cm}} = 1510\mathrm{e}^-$.

The tested module fully conforms to the ATLAS specifications. Given the 10-year operational time in a high radiation environment with limited planned service access to the modules, the analogue read-out solution would provide a better control over detector noise and common-mode variations resulting in a more robust quality control that is essential for achievement of ATLAS's physics goals. The collaboration may, now that the feasibility of the analogue read-out has been proven, seriously reconsider its baseline solution for the SCT read-out electronics.

Electron reconstruction algorithm

The analysis of bremsstrahlung effects. Electron reconstruction in the ATLAS detector is compromised by the large amount of material in the tracking volume, which leads to frequent emissions of hard bremsstrahlung photons. As a consequence, the affected electrons curl away from their previous trajectory in a magnetic field and make the p_T measurement (based on measurement of a track's curvature) prone to errors. Especially at lower electron transverse energies (up to $p_T = 20\,\mathrm{GeV}$) an electron and the emitted photon can separate in their φ coordinate so much that the *electro-magnetic calorimeter* (ECAL) clustering algorithm, which operates with a fixed-size window, can not unambiguously make them fit into the same cluster. In this manner, the ECAL measurements of E_T and φ can also be affected.

It is demonstrated that by using position measurements close to the interaction point only (the first 5 space-points in the barrel and end-cap regions and the first 4 space points in the transition region), the mean value and `rms` of distribution of the measured p_T can be improved significantly. But even using the optimal track-length for each event, there are still 15%(barrel), 25%(transition) or 35%(end-cap) of events further than 10% away from the true value. As far as the ECAL is concerned, matching in η is shown to be unaffected by a bremsstrahlung while both E_T and φ residual distributions exhibit correlated tails that can be attributed to an electron or photon missing the EM cluster. The effect is well pronounced at $p_T = 5\,\mathrm{GeV}$ while at $p_T = 20\,\mathrm{GeV}$ the reconstructed EM cluster quantities are hardly changed even for electrons that lose more than 10% of their energy by the end of the pixel sub-detector.

Next, the question of second-order bremsstrahlung effects is addressed and it is shown that only about 50% of events with an appreciable energy loss can be handled by allowing for a single kink on the track (standard bremsstrahlung recuperation method). Then the coin is flipped and the fraction of events that can be handled by different pattern recognition methods is presented: 55% of events can be handled using the standard fitting procedure (less than 10% energy loss by the end of the SCT); 12% of events have a single measurable bremsstrahlung occurrence which can be reconstructed by allowing for a kink; 10% of the events have a hard bremsstrahlung before the end of the pixel detector and so the electron can only be reconstructed with a poorer p_T resolution; the rest (23%) undergo two or more hard bremsstrahlung-photon emissions and their recuperation is not covered properly by the existing algorithms.

The electron reconstruction algorithm was developed taking into account the results of the above analysis (christened `ieElRec`). Instead of trying to instantiate a full-length track in the track searching phase, the `iPatRec` pattern recognition package was modified to provide a list of secondary tracks (those that don't extrapolate to the vertex region). A special method for the extrapolation of those tracks through the TRT was also developed. By de-weighting silicon hits it tries to extend a track as far as possible into the TRT. Special attention was paid to obtain the best possible results with respect to electron identification, bremsstrahlung tagging and improvement of p_T resolution as well as perigee parameters of tracks reconstructed in the inner detector. The inputs for `ieElRec` are clusters reconstructed in the ECAL and tracks found by `iPatRec` (secondary tracks included). `ieElRec` then finds close matches of the tracks to ECAL clusters (if any) and proceeds with further scrutinization of the pair. If the matching track failed the TRT association, a matching secondary track is searched for and, if found, attached onto its tail. Surroundings of the ECAL cluster are scanned for any neighbouring energy depositions to determine track isolation and to recover some cases of hard bremsstrahlung. Detector hits, constituting the ID track (and its possible prolongation in a case of a hard bremsstrahlung in the mid-SCT, when two shorter tracks are reconstructed), are fitted using an increasing number of hits from the beginning of the track as well as from its end. By using pre-built look-up tables and heuristic rules, it then selects the fit that best realizes the ID/ECAL matching (the original fit from `iPatRec` is also considered). The selected rule characterizes the type of bremsstrahlung that occurred and can form a useful criterion in later analyses. Therefore: `ieElRec` doesn't attempt to build a long track (for purposes other than TRT association), but de-constructs the input track and takes the segment that best matches the ECAL cluster as a base for p_T and impact parameter measurement. Based on ID/ECAL matching, the *transition radiation* information and the properties of the EM cluster, the level of difference from a charged pion signal is estimated (*pion ambiguity*).

Single electrons in the transverse energy range from $p_T = 1.5$ to 60 GeV were analysed with respect to `ieElRec`'s performance and the quality of obtained track parameters. The reconstruction efficiency for good ID/ECAL matches ranges from 80% for low p_T to 86% for $p_T > 10$ GeV. The electron identification efficiency is about 12% higher over all energy range. At low p_T these events are tagged either as poor p_T measurements by the ECAL or as an unknown match type. As transverse energy increases, the fraction of events that are recognized to have undergone an early hard bremsstrahlung increases and above 10 GeV they represent all the events not classified as good matches. This fraction corresponds directly to the fractional probability of a hard early bremsstrahlung before the end of the pixel sub-detector. At lower energies precision of the ECAL is lower and splitting of an electron and its accompanying photon in the magnetic field can cause part of the original electron's energy to be irrecoverably lost, while at higher energies ECAL accounts correctly for all cases of hard bremsstrahlung.

The measurement of a track's p_T is improved by 1% at 1.5 GeV and this correction increases to 4% for $p_T > 20$ GeV. The correction is strongly η dependent, directly following the material distribution. The transverse impact parameter and the directional angle in the x-y plane are likewise improved by track truncation. On the other hand, the longitudinal impact parameter and the directional angle in the r-z plane are not degraded by this procedure.

The pion rejection based on the pion ambiguity and ID/ECAL match type as determined by `ieElRec` is studied. As a smaller fraction of pions than electrons pass the `ieElRec` cuts and provide a good ID/ECAL match, a rejection factor of 30 for $p_T \geq 10$ GeV was obtained (decreases with p_T, e.g., 15 for $p_T = 2$ GeV) before considering the pion ambiguity variable. Additional rejection, enforced by imposing a cut on pion ambiguity, can be obtained at a sacrifice of electron efficiency: for $p_T = 2$ GeV the rejection factor is 150 (2000) at a 90% (50%) electron efficiency.

Reconstruction in jets was studied on a $B^0 \to J/\Psi \to ee$ sample, where different track multiplicities ($1 \leq N_T \leq 8$ charged tracks with $p_T > 1$ GeV) could be compared on a uniform data sample and also at transverse energies where the expected effects will be most pronounced (from 2 to 10 GeV). No change in the overall `ieElRec` efficiency can be observed. The most noticeable effect is that a fraction of events, tagged as 'poor ID measurement' increases linearly with track multiplicity and gets to 10% above the isolated electron level at N_T=8. This can be attributed to additional energy deposited into the EM cluster which tricks the algorithm into believing that a hard bremsstrahlung has occurred.

Pile-up effects are most pronounced in the ECAL where they manifest as noise as well as additional clusters due to minimum-bias events. Pattern recognition is burdened by the higher number of combinatorials but the charged track multiplicity (with $p_T > 1\,\mathrm{GeV}$) in a cone around the triggering EM cluster is 25 times lower than for the jet sample discussed above. The observed drop in reconstruction efficiency for good ID/ECAL match types was found to be 5% for $p_T \leq 5\,\mathrm{GeV}$, 2% for $p_T = 10\,\mathrm{GeV}$ and no change was observed for higher transverse energies. ECAL reconstruction efficiency, compared to the no pile-up sample with the same ECAL clustering cut $E_T > 1\,\mathrm{GeV}$, is increased, but this is a consequence of additional energy being deposited in the ECAL. `ieElRec` classifies these events into two categories: first, about 70% of these events are marked to have a poor p_T measurement, which is symptomatic of the addition of energy into an otherwise existing EM cluster. The rest of the events are tagged to be of unknown ID/ECAL match type which signifies that the track and ECAL cluster are not correlated.

It has been shown that use of an electron reconstruction algorithm that takes into account the fact that ATLAS's inner tracker *is* thick results in an approximate 5% increase in reconstruction efficiency and can be made almost insensitive to the effects of high-luminosity pile-up and the presence of jets. Also, all but the most catastrophic occurrences of an early bremsstrahlung can be tagged and at higher p_T's recuperated using the ECAL measurement. However, problems related to bremsstrahlung are here to stay and a further increase in the ID material,[1] especially in the pixel sub-detector, could result in the electron identification efficiency dropping below the limit needed for the attainment of the ATLAS physics goals. It should also be seriously noted, that it is the pixel sub-detector and the inner layers of the SCT that are crucial to a reliable electron reconstruction and identification. ATLAS should therefore make every effort to keep these layers operational during the whole data-taking period.

Applications of the electron reconstruction algorithm

To test the algorithm's performance on physical events of the type that will be observed (or searched for) and studied by the ATLAS collaboration, three physics channels were studied. The emphasis was put on quantities related to electron reconstruction. An important difference from the *Physics Performance TDR* productions was the inclusion of the realistic magnetic field.

The $\mathbf{B^0 \to J/\Psi \to} \boldsymbol{ee}$ process was as analysed in detail with respect to $J/\Psi \to ee$ reconstruction. The J/Ψ reconstruction efficiency was studied as a function of invariant mass cut and pion ambiguity. The efficiency varies from 40% to 78%; for a 10% cut on the reconstructed invariant mass the efficiency is 65%. Then the J/Ψ vertex reconstruction was addressed with respect to transverse (R_0) and longitudinal (Z_0) position. The overall R_0 resolution is $\sigma(R_0) = 110\,\mu\mathrm{m}$ with a variation by a factor of 2 over the η coverage and it degrades by the same factor over the available range of average transverse momentum of the final state electrons (getting worse with increasing momentum). The Z_0 resolution is strongly η dependent, deteriorating linearly from $250\,\mu\mathrm{m}$ at $|\eta| \sim 0.2$ to $3500\,\mu\mathrm{m}$ at $|\eta| \sim 2.3$.

[1] Recent changes in the ID layout will increase the amount of material in the beam-pipe, pixel detector services and supports by roughly 50% in the sensitive tracking volume. The exact values haven't yet been estimated.

The average value is $\sigma(Z_0) = 1200\,\mu$m. J/Ψ momentum reconstruction was also studied. The transverse (P_T) and longitudinal (P_L) momentum resolutions are both improved by application of an invariant mass cut on the reconstructed $m_{J/\Psi}$. For a 10% cut, Gaussian widths of the normalised residual distributions are about 3%. The $m_{J/\Psi}$ reconstruction greatly benefits from the improved electron treatment. Even by using all ID/ECAL match types, an improvement of 20% is achieved on FWHM of the $m_{J/\Psi}$ distribution as well as a reduction of the tails by a factor of two. By further requiring a good ID/ECAL match, the resolution is improved by additional 10%.

The $\mathbf{Z \to ee}$ process is of prime importance for calibration of the ECAL. The role of ID electron track reconstruction is to provide the z vertex coordinate and directional angles as well as to tag events that have undergone a hard FSR or an early hard bremsstrahlung photon emission. The reconstruction efficiency as a function of invariant mass cut and ID/ECAL matching was studied and found to vary from 51%, with a 5% invariant mass cut and the requirement of a good ID/ECAL match, to 95% when no cuts were applied. The resolution of the z vertex position is $\sigma(z) \sim 55\,\mu$m in the barrel ($|\eta| < 1$) and then rises linearly to $115\,\mu$m towards the end of the η coverage.

The reconstruction of m_{Z^0} was studied with respect to its $|\eta|$ dependence. In the central barrel region the experimental resolution and the natural width are approximately the same while in the transition region the experimental resolution is worse by 60%. The tail content outside 2σ is well behaved over all the η coverage and only a minor asymmetry can be observed on the low-energy side of the residual distribution.

$\mathbf{H \to ZZ^{(\star)} \to 4e}$ was studied as an example of how `ieElRec` can be used in a real physics analysis. The process was considered for $m_{\rm H}$=(130, 150, 180, 200 GeV), the main differences being in distributions of invariant mass of the off-shell Z^0. This has a direct consequence in the electron transverse momentum distribution with a lower mean value for lower $m_{\rm H}$, in which case the ID track reconstruction has more clients for improvement of transverse momentum measurement. For $m_{\rm H} = 130$ GeV there are 39% of events with $m_{Z^\star}$ calculated using at least one ID measurement and the average correction is 1.3% of the invariant mass. For on-shell Z^0's the event fraction drops to 10% and the correction to 0.75%.

The reconstruction efficiency was again studied in a view of a cut on the reconstructed $m_{\rm H}$ and ID/ECAL matching. By using a 10% cut on the invariant mass and selecting good matches as well as those for which the ID p_T measurement shows on an early bremsstrahlung or FSR (the track directional parameters are not spoiled) a 10% improvement of reconstruction efficiency is obtained compared to the *Physics Performance TDR* ($\sim$ 81%). In a view of the reducible $t\bar{t}$ and $Z^0 b\bar{b}$ background rejection, impact parameter and z-vertex reconstruction was addressed. In the same spirit the Z^0–$Z^{0(\star)}$ opening angle was analysed.

The impact of usage of the ID p_T measurement and m_{Z^0} constraint on the mean value and resolution of the $m_{\rm H}$ measurement was studied. The ID p_T measurement improves the resolution by 4% for $m_{\rm H} = 130$ and to a smaller extent ($\sim$ 2%) also for $m_{\rm H} = 150$ and 200 GeV. The mean value is improved for $\sim$ 400 MeV. The m_{Z^0} constraint improves the resolution for $\sim$ 5% at $m_{\rm H} = 150$ and 200 GeV while at $m_{\rm H} = 180$ GeV the correction is 15%. The mean value improvement is $\sim$ 750 MeV.

It has been demonstrated that the electron reconstruction algorithm can be used in the physical analysis. In particular, the processes crucial for EM calorimeter calibration

($B^0 \rightarrow J/\Psi \rightarrow ee$ and $Z \rightarrow ee$), have been addressed and the usefulness of the algorithm for improving the track parameters of the low and intermediate p_T electrons as well as for the detection of a hard FSR or an early bremsstrahlung photon emission, has been established. Furthermore, in order to study a realistic physics process, the $H \rightarrow ZZ^{(\star)} \rightarrow 4e$ decay channel has been used and a 10% increase of the H reconstruction efficiency has been observed.