THE ATLAS FORWARD REGION

John Rutherfoord, Leif Shaver, and Michael Shupe

Department of Physics, University of Arizona
Tucson, AZ 85721 USA

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The ATLAS forward region is subject to a bewildering number of competing pressures and concerns, making its optimization a frustrating exercise. We propose here an alternative to the current baseline which relaxes many of the constraints and allows for a cleaner layout. It also provides a design philosophy which will guide more refined optimization with flexibility to address unforeseen problems. In this approach the forward calorimeter is integrated into the endcap calorimeter. This improves the $E_T$ resolution, reduces backgrounds in the muon system, removes many conflicts between the calorimeter and muon coverage, decouples the detector from the accelerator, and allows more flexible installation and access.

Introduction

The forward region in a hadron collider detector is particularly challenging since particle densities and energies are highest, space is at a premium (a third of the $\eta$ coverage, $3 \leq |\eta| \leq 4.5$, is contained in 0.5% of the solid angle), and many subsystems are placed in conflict. High vacuum beam pipes, forward calorimetry, the muon system, shielding especially for the muon chambers, and beam line elements all have overlapping demands in this area.

Concerns raised by the present baseline design in the forward region include the following. 1) For particles in the transition region between the calorimeter endcap and the forward calorimeter (FCal) near $|\eta| = 3$, $p_T$ is not measured properly. 2) The performance of any FCal will be degraded by the material between it and the Interaction Point (IP). This material includes the beam pipe, flanges, vacuum pumps, valves, supports, cryostat walls, etc. 3) Backgrounds are likely to be a problem in the endcap muon chambers. Capture gammas originating from a very large neutron flux are difficult to reduce to acceptable levels. 4) The $\eta$ coverage of the calorimeters, of the muon chambers, and the need for neutron shielding are in conflict. If, after more realistic calculations, increased shielding is required, there is no room for it. 5) The FCal must hold within it the collimator for the Final Focus Quads (FFQ) of the accelerator. This degrades the performance of the FCal due to shower spreading from the collimator into the FCal and it creates an uncomfortable coupling between the accelerator and detector.
And 6) installation and access are difficult. The overall length of the detector and the shapes of the detector elements lined up along the beam line make movement of any one element difficult.

We present an alternate concept for the ATLAS forward region which is based on a simple strategy for dealing with the vexing problems inherent in the baseline design. The most prominent difference between the baseline and the alternate concept is the placement of the FCal. Rather than moving the FCal as far from the IP as possible, the FCal is integrated into the endcap calorimeter. So we call this the integrated solution to the problems of the ATLAS forward region.

The integrated solution has significant advantages compared to the baseline design. These include

- The performance of the FCal in the integrated solution is enhanced. The energy and angle resolution are better, yielding an improved $p_T$ resolution for particles and jets. This improved performance is important for a number of major physics signatures which could be seen at the LHC.

- The backgrounds in the muon system (neutrons, photons, etc.) can be reduced by at least an order of magnitude. Fluxes in the central tracker and EM calorimeters are the same as in the baseline. The activation of the FCal is the same as in the baseline but contained in a smaller volume, therefore easier to shield during accesses.

- Constraints on the muon system coverage are relaxed. The forward muon superlayers and the endcap toroid can extend to higher values of $|\eta|$. And there is more room for shielding, vacuum pumps, valves, flanges, etc.

- The detector is decoupled from the accelerator. The forward calorimeter does not contain within it the collimator for the final focus quads (FFQ's).

- Some installation and access issues are eased. There is no longer the need to open the FCal, exposing the highly activated FFQ collimator during access. The neutron shielding is a third the weight of the baseline if the present background rates in the muon planes are acceptable. The beampipe downstream of the endcap calorimeter need not have thin walls. Beampipe supports, flanges, and valves can be added as necessary without interference.

These features will make the ATLAS detector a superior instrument for probing new physics at the LHC.

The plan of this document is as follows. First we review a few physics processes particularly sensitive to the performance of the FCal. This is followed by a discussion of the problems encountered in the ATLAS forward region. The concept of the integrated solution is next described. In this discussion the strategy for attacking the forward problems will become manifest. Using conservative design parameters we have conducted some preliminary studies
comparing the magnitudes of the problems in the two concepts. Any design
has its own unique problems and we outline these as well. Included at this
point is a description of a liquid argon FCal integrated into the endcap. We
end with a short discussion of an intermediate solution. More work will be
required to work out the details of this concept. We are eager to contribute
to this effort and hope that others will as well.

A Few Physics Considerations

High quality performance of the ATLAS forward calorimeter is important
for a number of physics topics accessible to the LHC. Here we discuss a few
which are particularly sensitive to resolution parameters.

Low mass SUSY

For a 300 GeV mass gluino missing $E_T$ is of order 100 GeV. While the $p_T$
resolution of the forward calorimeter is important for such signatures so are
the tails on the resolution function, both the high side and low side tails.
This sensitivity to the tails comes from a large, steeply falling background
from QCD multi-jet events where mismeasurement of the $p_T$ of one jet (in the
FCal), either high or low, leads to missing $E_T$. Simulation shows that tails on
the resolution function for some calorimeter technologies are unacceptable.

Tagging Jets

WW scattering processes can be tagged with forward jets analogous to tag-
ging two-photon events with forward electrons at an $e^+e^-$ collider. A trigger
for such events might require a tagging jet with $p_T > 40$ GeV, $E > 1$ TeV
(i.e. $|\eta| \sim 4$) and no jets with $|\eta| < 3$ and $p_T > 30$ GeV. Tails on the high
side of the $p_T$ resolution function will pour backgrounds into the sample from
the large, steeply falling QCD two-jet cross section.

Technicolor

A number of extensions to the Standard Model mix leptons and quarks. An
example is extended Technicolor. A signature is the scalar leptoquark which
might prefer to decay to $b\tau$. While the $\tau$ direction is known with precision,
the $p_T$ of the $\tau$ is uncertain because of missing neutrinos. Good missing $E_T$
resolution allows the event to be reconstructed (even with two $\tau$'s) and the
mass of the leptoquark to be determined. This process is relatively insensitive
to the tails on the resolution function but requires very good $p_T$ resolution.
QCD Tests

There are a number of tests of QCD where a wide coverage in $|\eta|$ with good quality calorimetry is important. Recent theoretical work by J. Bjorken and A. Mueller summarizes this area of interest. It is incumbent on the LHC experiments to provide for this physics as long as higher priority physics is not sacrificed in the process.

We are developing a work list of physics processes which can be used as benchmarks for the performance of the ATLAS forward calorimeter. Help and advice are very welcome.

Problems with the Baseline Forward Region

FCal Performance

The ATLAS detector design is a dynamic concept, changing as new insights and optimizations come to the fore. The baseline design as of the most recent ATLAS week is shown in Figure 1. This is a GEANT description for use in simulations. Figure 2 shows, on a distorted scale, the forward region.

There are several problems due to the baseline geometry which contribute to a degradation in physics performance in the ATLAS detector. Any transition leads to problems in reconstructing events. The $\eta=3$ transition, for instance, gives $p_T$ "crossover" which biases the global $E_T$ measurement and complicates the reconstruction of jets (such as tagging jets in WW fusion processes). This crossover arises from particles which graze the edges of the endcap calorimeter and start a shower. Some of the shower energy escapes the calorimeter and is deposited in the FCal. When the FCal is far from the endcap this energy can be deposited in $\eta - \phi$ bins far removed from those in which it would have been deposited if there were no transition. The lever arm is the magnification factor which determines the severity of the problem. With an FCal at 15 m, the lever arm is large and therefore the mismeasurement due to the crossover effect is large.

Particles from the IP directed toward the High Pressure Gas (HPG) FCal, shown in Figure 3, must pass through a surprising amount of material. Figure 4 contains "haystack" plots in units of radiation lengths and absorption lengths of the material encountered by a particle from the IP as a function of $|\eta|$. The plots include active as well as passive materials. For instance the calorimeters themselves are included so not all material is detrimental. The particles can shower in the dead material upstream of the FCal with a subsequent spreading and absorption of energy. These plots show the amount of material in the present design but this is only a part of the problem.
Figure 1: GEANT geometry description of the present ATLAS baseline configuration of the full detector.

Figure 2: The ATLAS baseline forward region with the scale in y expanded in order to see detail.

The lever arm from the dead material to the FCal is also important. The showers spread more for longer distances.
Figure 3: HPG FCal at 15 m from IP. Also shown are the transverse sizes of showers and jets. The contours above the beam pipe show the 50%, 80%, and 90% containment radii for hadronic showers in the FCal. The contours near the bottom edge of the FCal show the same containment fractions in one transverse dimension. This can be used to estimate the fraction of an hadronic shower lost near a straight line boundary. Just above this and below the beam pipe is the 90% containment circle for electromagnetic showers. Ordinary jets, defined to lie within a cone radius of $\Delta R$ of 0.5, are indicated at two different values of $\eta$. In the forward region a jet cone size can be significantly smaller than an hadronic shower. The large circle defines the cone $|\eta| = 2.8$ at 15 meters. It is hoped to be a practical boundary of coverage for the muon system.

To assess the magnitude of the problem we have performed a GEANT simulation with gammas and charged pions from the IP uniformly distributed up to $|\eta| = 7$. For each generated particle the energy deposited in the sensitive volumes of the calorimeters is tallied, and the energy-weighted centroid estimated. From these the $p_T$ of the particle is reconstructed. In order to produce an easily interpreted display the reconstructed $p_T$ is divided by $\sin \theta$ where $\theta$ is the generated angle. Then each particle is accumulated in a 2-D histogram of $p_T/\sin \theta$ versus reconstructed $\eta$. For an ideal detector
the histogram would have entries only along a line $p_T / \sin \theta = p_{\text{generated}}$, i.e. a horizontal line. For a real detector there are fluctuations about this line due to 1) the calorimeter energy resolution, and 2) the calorimeter position resolution. Furthermore some energy is absorbed by dead material so the average $p_T$ response droops below the line. In the analysis of data this droop would be mapped and calibrated out. But another contribution to fluctuations comes from 3) fluctuations in the energy deposited in the dead material. Material far upstream of the calorimeter can cause 4) fluctuations in the direction of shower products leading to mismeasured angle and hence $p_T$. An example is the well-known “$p_T$ crossover effect”. Figure 5 is an example of such a 2-D histogram. The dramatic droop in response near $|\eta| = 5$ is due to the end of the FCal coverage. In the baseline design the entries beyond $|\eta| = 5$ and some of the fluctuation below $|\eta| = 5$ are due to the FFQ collimator. The smaller droop near $|\eta| = 3.5$ is due to the endcap cryostat walls. The integrated solution is more smooth in response and less spread vertically.

![Radiation Lengths](image1.png) ![Absorption Lengths](image2.png)

Figure 4: Haystack plots of the material in the ATLAS baseline design as a function of $|\eta|$. Along a given ray from the IP at fixed $\eta$ the material in units of radiation lengths and absorption lengths is accumulated in order. The shaded regions are active while the white regions are dead material which degrade performance.

For each bin in $|\eta|$ the mean and rms of the $p_T / \sin \theta$ distribution are calculated and summary plots produced such as the first plots in Figures 6 and 7. The second plot in Figures 6 and 7 shows the rms divided by the mean which is equivalent to $\delta p_T / p_T$, the fractional $p_T$ fluctuation. In this synthesis of the 2-D histograms important information is lost. Tails of the distributions can be of paramount importance for backgrounds to some important physics signatures. Here we've neglected tails because their effect depends on the physics. We will assume for now that we are pursuing a physics signature
Figure 5: Two-dimensional histograms of reconstructed $p_T$ normalized by the generated value of $\sin \theta$ for 200 GeV charged $\pi$'s in the ATLAS baseline and in the Integrated Solution calorimeter system versus the reconstructed $\eta$.

Figure 6: $p_T$ response and resolution for 50 GeV photons versus $\eta$ in the ATLAS baseline.

which is sensitive to the rms and not the tails.

In this simulation we have used the materials in the present version of the ATLAS baseline. These include the endcap calorimeter cryostat walls, the beampipe, flanges, valves, vacuum pumps, etc. We recognize that it is likely possible to optimize this region thereby reducing these materials. On the other hand the present design is still at an early stage and as more engineering details are added the materials budget may increase. For instance we have
been warned that the endcap cryostat wall thickness which we chose for the critical inner surfaces is too thin. For the GEM detector at the time of the Technical Design Report there were of order 10 radiation lengths of material between the IP and parts of the FCal and this FCal was only 4.4 m from the IP. This material would have been reduced as we further optimized this region but we do not know how much of a reduction would have been possible. So we take the present baseline as giving an order of magnitude estimate of the materials in front of the FCal.

In figures 6 and 7 the first plot shows the response of the calorimeter system to the particle. The fluctuations include optimistic energy and position resolutions in the calorimeters. In the second plot the normalized rms fluctuations are shown after rebinning to improve statistics.

Backgrounds

The performance of the muon chambers in the endcap region is likely to be limited by singles rates due to gammas from neutron capture. While calculations to date indicate a concern, the highest rates do not appear to grossly exceed upper limits. However many important effects have not been included in the simulations yet. It is our understanding that the detector is presently treated as \( \phi \) symmetric, i.e. there are no non-uniformities in the detector in the \( \phi \) direction. Also the calorimeters are treated as uniform elements with no internal structure. And almost none of the material along the beam line such as flanges, valves, vacuum pumps, supports, cryostat walls, etc. is included in the simulations.
Figure 8: Neutron flux in the ATLAS baseline design.

Figure 9: Photon flux in the ATLAS baseline design.
In typical neutron shielding exercises cracks and holes become the dominate source of leakage neutrons after the first iteration on a neutron shielding design. In the ATLAS example secondary sources of hadronic spray from material near the beam line complicates the problem since the sources are distributed. More realistic neutron flux calculations are likely to show these effects. So there is concern that the background problem is actually worse than presently indicated. Figures 8 and 9 show our calculations of the neutron and photon fluxes respectively at $\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ using the same simplifications. Note that the scale is kHz/cm². These rates are roughly consistent with results quoted by A. Ferrari and I. Fisyak.

Conflicts in $\eta$ coverage

The muon coverage in $|\eta|$ ends at about 2.8 in the baseline design. The calorimetric coverage of the endcap calorimeter ends at about 3.0 and might possibly be extended to 3.2. The calorimetric coverage is not easily extended because the energy and density of particles is increasing rapidly in this region and the conventional liquid argon technique will fail when the ionization density reaches a critical value which is uncertain due to the uncertainty in the positive argon ion mobility. Reasonable estimates suggest that this limit is near $|\eta| = 3$ for $\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$. So the endcap calorimetric coverage and the muon coverage end at nearly the same value of $|\eta|$.

The third forward muon superlayer is mounted on the wall of the hall behind the HPG FCal. The physical (as opposed to fiducial) $|\eta|$ coverage of the HPG FCal almost overlaps the muon coverage since the HPG FCal must contain hadronic showers at the limits of its fiducial coverage. The platform and support stand for the HPG FCal do overlap the $|\eta|$ coverage of the third muon superlayer. Muons which must pass through this dead material will multiple scatter so that their momentum measurement will be spoiled a bit.

The real problem arises from the shielding which must be added in such a way that it does not intrude into the coverage of any of these systems. The conical shielding downstream of the endcap calorimeter must not protrude into the HPG FCal coverage nor into the muon coverage. This leaves a rather narrow $|\eta|$ range for this shielding. And it forces the inner radius of the endcap toroid outwards. Also shielding will be required around the HPG FCal since the FCal itself contains many channels through which backgrounds can leak out. This shielding will occlude the third forward muon superlayer.

Should it turn out that more shielding is needed than in the present baseline then there is no room for it. Space for additional shielding will likely come at the expense of $|\eta|$ coverage of the forward muon system.
Installation/Access

Installation and access are complex problems. Here we will only point out a few complications relevant to the forward region. The present mass of the shielding cone downstream of the endcap calorimeter is large because the cone angle is large. The support for this mass is a challenge and the insertion and removal of this mass adds to an already complicated situation.

The scheme to split the HPG FCal and lower it out of the beam leaving the FFQ collimator behind is rather cumbersome. And the FFQ collimator will need to be shielded from exposure due to activation before anyone can enter the hall.

The Integrated Solution

Description of the Integrated Solution

The forward calorimeter is integrated into the endcap calorimeter with its front face at a distance of 4.74 m from the IP. So shower maximum occurs at a distance from the IP of 1/3rd that in the baseline. This location can be seen in the GEANT geometry description of Figure 10 and in the distorted closeup of the forward region in Figure 11. Downstream of the integrated FCal is a scraper in the shadow of the FCal. Beyond this the beam pipe flares so that it and all the pumps, flanges, valves, etc. (not shown) are also in the shadow of the FCal. The beam pipe walls can be quite thick so that support is less of a problem. And flanges and valves can be located wherever convenient since their additional mass is of no consequence. Several endcap cryostat configurations are possible. Here we have tried a simple concept which is likely to require thinner walls. The inner region between the conical front of the cryostat and the front face of the FCal is filled with argon excluder in order to reduce the amount of dead material in front of the FCal. The total depth of the FCal is 10 \( \lambda \). The beam pipe diameter through the FCal is the canonical 120 mm.

FCal Performance

The liquid argon FCal design with tube electrodes will meet the ATLAS performance requirements at a distance of 4.74 meters from the IP. The concept has been described in a separate document previously submitted to the ATLAS Calorimetry Panel along with test beam results. In a later section we will give some more details. Figure 12 is a view of the front face of the liquid argon FCal showing the segmentation and relevant sizes of showers and jets for reference. The open circles to the right of the beam line are jet
Figure 10: GEANT geometry description of the ATLAS integrated configuration of the full detector.

Figure 11: The ATLAS integrated forward region with the scale in y expanded in order to see detail.

cone sizes for $\Delta R = 0.5$. The multi-shaded contours at the top and bottom are hadronic shower profiles. The top one is for radial containment while the
bottom one is for lateral containment. The contours are for 50%, 80%, and 90% containment respectively. The black circle below the beamline is a 90% containment circle to set the scale for photon showers in the EM section. The whole device is quite small as can be seen from the scale and the GEANT person.

Note in particular, that in angle or $\eta$ space the sizes of hadronic showers are almost exactly the same in the HPG FCal (see Figure 3) and in the liquid argon FCal. Or put another way the transverse size of an hadronic shower in the HPG FCal is three times larger than in the liquid argon FCal. Two effects contribute to this difference. 1) In the HPG FCal a nuclear absorption length is approximately 20 cm while in the liquid argon FCal (Tungsten hadronic modules) it is about 10 cm. 2) The upstream material (some of it far upstream) initiates a large fraction of hadronic showers which spread before reaching the HPG FCal. There is much less upstream material in the integrated solution and what there is has a smaller lever arm. Photon showers are spread by upstream material by a surprising amount in the ATLAS baseline.

Several differences between the integrated solution and the baseline design lead to improved calorimetric performance in the $|\eta| \geq 3.0$ region. 1) The material in front of the integrated FCal is reduced. Figure 13 shows the corresponding haystack plots. Compare these with Figure 4 for the baseline design. The only differences occur in the $|\eta| \geq 3$ region. 2) The lever arm between this material and the integrated FCal is small. So showers initiated in the dead material upstream of the FCal do not spread very much before reaching the FCal. 3) The $p_T$ crossover problem is nearly eliminated because the lever arm from the $\eta = 3$ transition is small. The effects 1 to 3 show up in Figures 14 and 15 where the $p_T$ response and resolution are plotted for 50 GeV photons and 200 GeV pions. Compare these with Figures 6 and 7 for the baseline design.

The degree of pileup in the FCal depends on the signal collection time and on the hadronic shower size. Ordinarily one would tally the pileup in a jet cone but in the FCal the jet cone size must be convoluted with the transverse size of an hadronic shower because they are of comparable size. The time responses of the HPG FCal and the liquid argon FCal are roughly equivalent. Also the sizes of hadronic showers, measured in angle or $\eta$ space, are approximately the same. So pileup will be identical in these two options.

**Backgrounds**

The integrated solution offers a coherent attack on the background problem. There are several elements to this attack which are described here. They are based on the observation that the dominant source of particle energy
Figure 12: Front view of the EM section of the Integrated FCal showing the segmentation. Also shown are the transverse sizes of showers and jets as in Figure 3. The $\eta$ scale is the same as in Figure 3.

Figure 13: Haystack plots of the material in the ATLAS integrated design as a function of $|\eta|$. Along a given ray from the IP at fixed $\eta$ the material in units of radiation lengths and absorption lengths is accumulated. The shaded regions are active while the white regions are dead material which degrade performance.
Figure 14: $p_T$ response and resolution for 50 GeV photons versus $\eta$ in the ATLAS integrated solution.

Figure 15: $p_T$ response and resolution for 200 GeV pions versus $\eta$ in the ATLAS integrated solution.

is at the interaction point (IP). This situation is quite different from lower luminosity hadron colliders where particles from the collisions contributed to a negligible fraction of the backgrounds in the detectors. We will concentrate on the problem of backgrounds in the muon chambers since this is where the problem is the worst. We will comment later on backgrounds in the inner tracker.

The first line of defense against backgrounds in the muon system is a hermetic calorimeter, i.e. a calorimeter which fully contains hadronic showers, which
is deep enough that neutrons do not leak out the back. Both the integrated solution and the baseline have this feature. However the baseline coverage is up to $|\eta| \sim 3$ while the coverage in the integrated solution is out to $|\eta| \sim 5$. This difference is significant.

Particles from interactions at the IP can strike beam line material such as the vacuum pipe, flanges, valves, vacuum pumps, beam pipe supports, etc. and create secondary sources distributed along the beam line. Distributed sources are particularly hard to shield against. The integrated design dramatically reduces the effect of such sources. How this is done can be seen in Figure 11. The beam pipe in the inner tracker flares out just after the end of the Beryllium beam pipe and then flares back in again in order to pass through the FCal. This is so that secondary particles created in the beam pipe must be produced at large angles in order to get out of the tracker volume and therefore have lower energy. At the far end of the FCal there is a “scraper” whose aperture is larger than that through the FCal, i.e. the scraper lies in the “shadow” of the FCal. It’s purpose is to scrape away secondary spray created along the edges of the aperture through the FCal. After leaving this collimator the beam pipe flares again so that the walls of the beam pipe (and all flanges, valves, pumps, supports, etc.) lie in the shadow of the FCal. No material downstream of the integrated FCal can be hit by particles from the IP until the collimator for the Final Focus Quadrupole (FFQ) at $z = 16$ m. So there is one secondary source, the FFQ collimator. This collimator is enclosed in shielding with a re-entrant hole at the front end to optimally bury the energy from the IP.

The shadow cast by the aperture in the integrated FCal forms a narrow cone. Shielding can be located just outside of this cone (after leaving room for the beam pipe etc.). If the amount of shielding in the baseline is adequate then the weight of the shielding will be much smaller than in the baseline since the distance from the beam line is much smaller. And the muon chambers and endcap toroid can cover up to larger values of $|\eta|$. On the other hand if further refinements in the background estimates indicate that more shielding is needed then there is room for that shielding in the integrated geometry but not in the baseline. In the baseline design the physical edges of the muon superlayers extend to $|\eta| = 2.8$ while in the integrated solution shown here they extend to $|\eta| = 3.0$. The muon toroid also covers to larger $|\eta|$. So here we have chosen an intermediate amount of shielding between the two extremes.

One might argue that the FFQ collimator must be shielded anyway and that the high pressure gas (HPG) FCal performs that function so why replace it with inactive shielding. There are four responses to this question. 1) The HPG FCal has many channels through which backgrounds can escape into the muon volume. The HPG is made up of plates with wide gaps and
Figure 16: Neutron flux in the ATLAS integrated solution

Figure 17: Photon flux in the ATLAS integrated solution
tubes with large gaps through which neutrons can stream. Shielding will have to be added around the HPG FCal which will conflict with the muon coverage, i.e. the shielding will obscure the third muon super layer at large \( |\eta| \). 2) Hadrons from the IP strike the HPG FCal over its full front face so some hadrons are showering near its outer radius where the shielding protecting the muon system is necessarily thin. In the integrated design hadrons from the IP strike only a small circle of radius about 22 cm centered on the beamline at the FFQ collimator. The rest of the material surrounding this collimator serves entirely as shielding. 3) The shielding material can be chosen for maximal attenuation of backgrounds since this is its only function. 4) The shielding can be designed for easy installation and access since it is completely passive. For instance it can be made of blocks of convenient size which can be easily craned to an out-of-the-way corner of the hall.

Figures 16 and 17 show that the backgrounds in the muon chambers can be reduced about an order of magnitude in the integrated solution. And we haven’t had a chance yet to optimize the choice of absorber materials, a trial-and-error procedure. Note that the neutron flux and the photon flux in the inner tracker are the same as in the baseline.

Another source of backgrounds are beam-gas interactions. These are distributed along the beamline but likely concentrated in the warm sections of the beampipe where the vacuum is worse. A typical interaction will occur outside the central tracker volume. Those directed towards the IP will be shielded from the central tracker volume by the FCal in the integrated solution. While the singles rates and radiation damage caused by such events are negligible, there could be trigger problems depending on how the trigger is implemented.

The accelerator beam is exceptionally large in the FFQ’s so scraping along the beampipe is more likely. Secondaries and tertiaries from this scraping can enter the detector volume. Again the FCal in the integrated solution acts as another collimator to shield the central tracker from such sources.

Activation

The FCal will become activated by the same amount regardless of location. The same number of nuclei will be excited at 4.74 m as at 15 m. The density of activated nuclei will, of course, be different. This means that the exposure on contact will be different but the exposure at distances from the FCal will approach the same values.

The exposure due to activation is dominated by low energy (< 10 MeV) gammas. The hottest spots are concentrated near the beam pipe aperture. During access a simple, relatively small Pb plug will be placed in that area in
order to attenuate the activation gammas to acceptable levels. The fact that
the activation is more concentrated in the integrated FCal actually makes
the shielding job easier since a relatively small shielding plug is needed.

We are gearing up to make activation estimates. These follow directly from
the background studies on which we have already made good progress. We
expect to have results shortly.

Conflicts in $\eta$ coverage

In the integrated solution the conflicts in $\eta$ coverage are completely elimi-
nated. Now the forward muon system and the endcap toroid can completely
cover the required $|\eta|$ range without pressure from other systems. Further-
more no shielding or FCal supports occlude parts of the muon coverage.
This reduces multiple scattering of muons between superlayers. And there
is plenty of space for shielding if the background rates in the muon system
are not acceptable.

Installation/Access

If the backgrounds in the muon system are acceptable with the present thick-
ness of the shielding cone downstream of the endcap calorimeter then its mass
is reduced because the angle of the shielding cone is much smaller. We esti-
mate the mass of the shielding cone in the baseline to be 123 tonnes while
the same thickness cone in the integrated solution is 46 tonnes. On the other
hand if more shielding is needed then there is room for it.

Areas of Concern with the Integrated Solution

Any scheme has its own set of problems. Here we outline some concerns which
require further study. None appear to be major. 1) The clearance between
the beampipe and the warm wall of the new cryostat for the integrated FCal
and endcap calorimeter is tight. This requires more care when moving the
endcap calorimeter and leaves less room for superinsulation in the vacuum
space between the warm wall and cold wall. 2) The close clearance means
that the cryostat will cool the beam pipe a bit. This may have an adverse
affect on the pumping in that region. 3) Present forms of superinsulation are
not overly radiation resistant. We will want to experiment with new types
of superinsulation. 4) We do not yet have an installation scenario for the
shielding cone around the conical beam pipe. We hope to have one shortly.
5) We are working on schemes to install and remove the conical beam pipe
in the tight space downstream of the endcap calorimeter.
A Liquid Argon Integrated FCal

Figure 12 showed the front face of the liquid argon FCal with the readout segmentation. Figure 18 is a closeup of the region near the beampipe. In this figure the individual tube electrodes show up. Figure 19 is a perspective drawing of the three longitudinal sections of the FCal with the three concentric pipes through the center. The inner most pipe is the vacuum beam pipe, the next is the cryostat warm wall, while the outermost is the cryostat cold wall. In table I are the weights of each longitudinal segment and the total weight of the FCal. This contrasts with the estimated weight of the HPG FCal of 130 tonnes.

Table I

Weight of Liquid Argon FCal

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The important performance characteristics of a forward calorimeter are 1) very fast response in order to be less sensitive to pileup from events in neighboring bunch crossings, 2) resistance to radiation, 3) good energy resolution for both photons and hadrons, 4) good position resolution so that the angle of particles can be determined with precision, and 5) the resolution functions must have very small tails. This last requirement is often overlooked in technology comparisons but it can be of paramount importance. For instance consider an ordinary two jet event where one jet falls in the forward calorimeter. If the \( p_T \) of that jet is poorly measured then the event appears to have missing \( E_T \). While large mismeasurement is rare, so are real events with missing \( E_T \). So the problem reduces to one of detailed comparison. From such work we have found that large tails on an already marginal energy resolution function can significantly dilute the missing \( E_T \) capabilities of a detector if the tails are not well below \( 10^{-2} \) of the peak. Figure 20 shows the energy resolution function for the liquid argon forward calorimeter prototype over about three orders of magnitude. The function is very nearly Gaussian over this full range.

Also note that the liquid argon FCal technology has no projective cracks between modules because it is a monolith. An important feature of the accordion, for instance, is that it has no \( \phi \) cracks. This feature would be useful in the rest of the calorimetric coverage as well. Cracks provide regions
Figure 18: Close-up of the EM section of the Liquid Argon FCal in the beam pipe region.

Figure 19: Isometric view of the integrated FCal
Figure 20: Response of Liquid Argon FCal to 100 GeV electrons. The inset shows the electronics noise on a linear scale. The horizontal scale is in units of 10,000 electrons of collected charge.

where energy is lost or poorly measured and often do not show up in test beam measurements since the beam is directed into the center of the module.

The Intermediate Solution

An alternative reworking of the ATLAS forward region is a less dramatic change from the present baseline. Because of the positive ion buildup problem in conventional liquid argon calorimeters the accordion endcap cannot be extended much beyond $|\eta| = 3$. However one could extend the endcap calorimeter coverage to higher values of $|\eta|$ with narrower sensitive gaps such as in the Arizona FCal design. Here we sketch a modification of the endcap calorimeter which includes a near FCal which covers an $|\eta|$ range up to 3.6. Values of $|\eta|$ beyond 3.6 are covered by an HPG FCal at 15 m from the IP as in the baseline but smaller in transverse dimensions. Figure 21 shows this
configuration while Figure 22 shows the forward region on a distorted scale. Although the drawing doesn’t show it, the part of the HPG FCal at $|\eta| \lesssim 3.4$ is meant to be passive shielding.

![Diagram](image)

Figure 21: GEANT geometry description of the intermediate configuration of the full detector.

In this intermediate design the cryostat walls of the endcap calorimeter are moved to larger values of $|\eta|$. This can be seen in the haystack plots in Figure 23. The transition is also moved to larger $|\eta|$ and so the degradation in performance due to these effects is translated to larger $|\eta|$ as can be seen clearly in Figures 24 and 25. So the intermediate design does not provide any better performance than the baseline and significantly poorer performance than the integrated solution.

This intermediate solution provides no more concerted attack on the background problem than the ATLAS baseline so we do not expect much improvement in the fluxes in the muon chambers except that allowed by the fact that there is more room for shielding. The neutron and photon fluxes in Figures 26 and 27 are quite close in magnitude to those in the baseline in Figures 8 and 9.

The intermediate solution does relieve some of the pressure for competition for space in the forward region. There is more space for either shielding, muon coverage, or the HPG FCal or some combination of all of these. In this version of the intermediate solution the transition comes at $|\eta| = 3.6$. But this is an arbitrary choice. A complicated optimization procedure should
Figure 22: The intermediate solution forward region with the scale in y expanded in order to see detail.

Figure 23: Haystack plots of the material in the intermediate solution as a function of $|\eta|$.

be employed to chose the best value for the transition. We guess that the optimal value for the transition is at the endpoint, i.e. at $|\eta| = 5.0$. 
Figure 24: $p_T$ response and resolution for 50 GeV photons versus $\eta$ in the intermediate solution.

Figure 25: $p_T$ response and resolution for 200 GeV pions versus $\eta$ in the intermediate solution.

Concluding Remarks

In this document we have outlined an approach to the design of the ATLAS forward region quite different from the present which has many advantages. 1) The calorimeter performance for $|\eta| \geq 3$ is improved due simply to the fact that there is less material far upstream of the FCal. In our simulations we do not yet include the fact that the integrated FCal is a better calorimeter than the HPG FCal. 2) The $|\eta| = 3$ transition is almost non-existent in the integrated solution. The lever arm is too short to produce an appreciable
Figure 26: Neutron flux in the intermediate solution.

Figure 27: Photon flux in the intermediate solution.
degradation in performance. 3) The backgrounds in the muon system can be reduced to manifestly manageable levels since there is more room for shielding. 4) Competition for space in the forward region is reduced since the overlap between different subsystems is largely eliminated. The forward muon superlayers and the endcap toroid can cover a larger $\eta$ range. 5) Certain installation and access issues are relaxed. For instance the FCal is no longer wrapped around the FFQ collimator. And the beam pipe downstream of the endcap calorimeter can be designed for easy assembly and disassembly with as many flanges and valves as necessary. If the present shielding cone thickness is adequate for backgrounds in the muon system then its weight is greatly reduced in the integrated solution since the cone is so much smaller in diameter and therefore more easily installed and removed.

There are many avenues to explore in depth and some effort required to get used to a new scheme. But it appears the improvements will be well worth the effort.