Data/MC comparisons for forward calorimeter response to electrons

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1 Introduction

Forward calorimeter in ATLAS (FCal) is intended for determination of combined E_t^{miss} vector (together with other calorimeters) as well as for measurement of energy of forward (backward) going jets. They will appear in the production of Higgs bozon via vector bozon fusion mechanism. Energy resolution is not a crucial issue for the FCal, namely, $100\%/\sqrt{E}$+10% for jets is sufficient. Correct determination of **absolute energy scale** is more important. To do this one should know with reasonable precision intercalibration factors between FCal segments, electromagnetic (FCal1) and two hadronic (FCal2 and FCal3). These factors can be taken, e.g., as ratios of related **sampling fractions** (SF). The SF is defined as an energy of incoming particle deposited in an active medium (in our case: LAr) divided to a total energy deposition in a calorimeter (in our case: FCal segment). For **muons** this value, usually known as "dE/dx sampling fraction", is approximately equal to

$$SF \approx \frac{s(act)\rho(act)dE/dx(act)}{s(all)\rho(all)dE/dx(all)}, \quad (1)$$

where abbreviations *act* and *all* denote active medium and the whole calorimeter respectively. Deviations from these simple formula are due to possibility for muons to emit photons and to produce δ-electrons.

The situation with SF for **electrons** is even more complicated than for muons and analythical calculations are practically impossible. Electrons can intensively radiate photons which interact with matter via Compton and/or photoelectric effect depending on their energies. The cross sections of these processes are proportional to Z^n where n is large, namely $n \approx 5$ for the photoeffect [1]. So one would expect that the SF for electrons is smaller than for muons in the sampling calorimeters with ($Z_{abs} - Z_{act}$) ≥ 0 especially if this difference is large. It is the case for the FCal2 and the FCal3 with high-Z (mainly tungsten) absorber.

It is clear that the accurate knowledge of detector geometry is the key issue to calculate SF both for muons and electrons. Let's consider FCal geometry and its SF in detail.

2 FCal geometry and materials

Initial geometry and materials planned to be used in the FCal are described in detail in Ref.[2], part 9. However, some important items were changed. Final parameters for the FCal1 are described in Ref.[3]. Ref.[4], given as an Appendix 1 to this note, contains summary about all FCal segments. Being still preliminary, Ref.[5] represents the latest, updated information about hadronic part of the FCal.[1]. The most important information

[1]Note that the so-called "module 0" and the final FCal geometry and materials are essentially the same.

about FCal needed to calculate dE/dx sampling fraction, as well as dE/dx SF's themselves are shown in Table 1. One can use the following simple formulae for the SF.

$$SF = \frac{s(Ar)\rho(Ar)dE/dx(Ar)}{s(Ar)\rho(Ar)dE/dx(Ar) + s(matr)\rho(matr)dE/dx(matr) + s(rod)\rho(rod)dE/dx(rod)} \quad (2)$$

where s is a square occupied by LAr, absorber matrix and rod inside one *"unit cell"*. LAr density (MIP energy deposition) is taken to be 1.40 g/cm^3 (1.52 MeV/g/cm^2) respectively [1].

The following comments should be made:

- As pointed out in Ref.[5], the nominal slug density is 18.5 g/cm^3 while measurements give 18.3 g/cm^3;
- For the FCal2C (FCal2A) the averaged measured gap width is 0.378 mm (0.367 mm) while the nominal gap width is 0.375 mm; corresponding values for the FCal3C (FCal3A) are 0.509 mm (0.508 mm) although the nominal size is 0.500 mm;
- There are other (fortunately minor) differences between dimensions as can be seen comparing Ref.[3-6];
- dE/dx SF's shown in Table 1 are in 1-2% agreement with those given in Ref.[4].

Dimension	*FCal 1*	*FCal 2A*	*FCal 2C*	*FCal 3*
Matrix area, mm^2	13.56	16.39	16.30	18.41
Rod area, mm^2	8.71	9.53	9.53	11.88
LAr area, mm^2	2.09	3.05	3.14	4.79
Matrix density (w/o endplates), g/cm^3	8.70	15.21	15.21	15.24
Matrix density (with endplates), g/cm^3	8.70	14.56	14.56	14.59
Matrix minimal dE/dx (w/o endplates), MeV/g/cm^2	1.40	1.18	1.18	1.18
Matrix minimal dE/dx (with endplates), MeV/g/cm^2	1.40	1.21	1.21	1.21
Rod density, g/cm^3	8.96	19.15	19.15	19.15
Rod minimal dE/dx, MeV/g/cm^2	1.40	1.15	1.15	1.15
dE/dx SF (w/o endplates), %	1.60	1.27	1.31	1.69
dE/dx SF (with endplates), %	1.60	1.29	1.33	1.71

Table 1. Some FCal geometrical parameters and materials used as well as dE/dx SF's. The precision of the SF calculation is ~1%.

As for SF's for **electrons**, they cannot be directly measured in the test-beams, only ratios SF1/SF2 and SF1/SF3 can be extracted. Unfortunately, response to e^- of hadronic segments of the whole FCal was not studied experimentally. However, both EM and hadronic (FCal2) **modules 0** were exposed to electrons. Results of these studies can be found in Ref.[7]. "Intrinsic" ratio SF1/SF2=1.57 was derived from response linearity plots[2].

Concerning SF's for **muons**, they cannot be determined experimentally in the case of FCal, as the noise is too large to extract a signal.

[2]The measured ratio, being 2.10, was corrected for HV effect (factor 1.07) and for effect due to signal shaping (factor 1.25). Note that the last factor was calculated with a MC [8].

3 FCal in GEANT

FCal geometry was described in detail in GEANT. However, some simplifications were made. In particular, for reasons to save CPU, tubes are not coded neither in GEANT3, nor in GEANT4 [10]. Instead so-called "mixed absorber" which includes real absorber, tube material as well as some amount of passive LAr is used. Simulations show that such approximation should not result to "any loss in the physics outcome" [11].

For the same reasons, copper endplates in the FCal2 and FCal3 are not described. Fortunately this gives rise only to 2% change of the dE/dx SF2 and SF3 as seen from the last two rows of Table 1.

3.1 FCal in GEANT3/ATLSIM

Initially, TDR geometry [2] was put into GEANT3/ATLSIM-based simulation software [12]. It was later modified following real FCal specification, see Appendix 2.

Simulations of FCal response to electrons were performed by different people. Their results are summarized in Table 2. Note that different energy cutoff for low-energy electrons/photons and/or *stemax*, *stemin* and *epsil* settings were used. Also, the geometry model used in [11] and the "official" one were somewhat different, although rod and tube dimensions were similar.

Reference	Cutoff, keV	*stemin*, μm	SF1	SF2	SF3	SF1/SF2	SF1/SF3
[11],[8]	10	50	0.0144	0.0096	0.0129	1.50	1.12
[3]	10	?	0.0144	-	-	-	-
[7]	100	?	0.0114	0.0070	0.0088	1.63	1.30
[13]	10	300	0.0127	0.0090	0.011	1.41	1.15

Table 2. FCal sampling fraction for **electrons** simulated with GEANT3/ATLSIM.

It is seen that SF's for **electrons** and their ratios can probably depend on GEANT3 parameters. However, this dependence for the **ratio** of FCal1 and FCal2 sampling fractions, the only measured quantity in the test-beam, is not strong, namely $\approx \pm 10\%$.

SF's for **muons** were also calculated and results can be found in Table 2'. Note that bremsstrahlung and δ-ray production were OFF. It is seen that numbers obtained from the simulation agree with the calculated "geometrical" dE/dx-weighted SF's within 5%.

SF1	SF2	SF3	SF1/SF2	SF1/SF3
0.0156	0.0127	0.0160	1.22	0.98

Table 2'. FCal sampling fraction for **muons** simulated with GEANT3/ATLSIM.

3.2 FCal and its SF in GEANT4

Historically, at first, standalone version of LArG4 [14] for simulation of ATLAS LAr calorimeters, including FCal, was developed. Later, it was integrated into the ATHENA [16] framework without any modifications related to FCal. Details about FCal parameters used are given in Appendix 3. It is seen that geometry is described reasonably well and differences w.r.t. GEANT3/ATLSIM geometry are minor.[3] New universal (and

[3]However, some bugs in the geometry description in GEANT4 were discovered. Some of them are already corrected.

independent on GEANT) ATLAS detector description called "GeoModel" is currently well advanced. It is not considered throughout this note.

Another important issue is GEANT4 version. A serious bug in the multiple scattering model for electrons which, in particular, results to significant underestimation of the calorimeter sampling fraction and, in some cases, to worse energy resolution than should be, was corrected in G4.8.0 [17]. Below the effect of this correction will be considered for the FCal1, FCal2 and FCal3. However, CPU time consumption per event at fixed value of the range cut is typically two times larger in the new GEANT4 version, see Table 2".

cut, μ	*300*	*100*	*30*	*3*	*1*	*0.5*
G4.7.0, FCal1	.14	.16	.17	.35	1.45	4.5
G4.8.0, FCal1	.30	.31	.38	.78	1.7	3.6
G4.7.0, FCal2	.08	.10	.12	.22	.70	1.7
G4.8.0, FCal2	.19	.21	.26	.51	1.0	1.9

Table 2". CPU time consumption per GeV per electron event (in NCU).[4]

3.2.1 FCal and its SF in G4.7.0

Results of simulations with G4.7.0 for the SF's obtained with 30μ range cut at arbitrary chosen energy point are presented in Table 3. Standalone and ATHENA-based results are compatible. Numbers are significantly smaller than those for dE/dx sampling fractions especially for the hadronic sections of FCal. There is clear disagreement between the data [7] and the G4 MC (1.57 vs 2.09) for the ratio SF1/SF2.

	SF1	SF2	SF3	SF1/SF2	SF1/SF3
G4 ATHENA	0.0131	0.0059	0.0085	2.22	1.54
G4 standalone	0.0134	0.0064	0.0085	2.09	1.58

Table 3. FCal sampling fraction simulated with GEANT4 at 30μ range cut.

However, let's remind that SF's for electrons can depend on the G4 range cut as was shown in Ref.[15] for the FCal1 (with GEANT version earlier than 4.8.0).

Detailed simulations were performed for 10 GeV, 100 GeV and 1000 GeV electrons with LArG4-standalone version with G4.7.0p01 and G4.8.0. Range cuts from 0.5μ to 700μ were tried with G4.7.0p01 and from 3μ to 300μ with G4.8.0. In addition, 20, 40 and 200 GeV points were considered with G4.8.0 for the FCal1 and the FCal2.

As FCal2 and FCal3 responses are expected to be significantly non-gaussian, SF's were calculated as the **mean values** of the energy deposition in LAr divided by the initial electron energy. Results for G4.7.0p01 were averaged over three energies considered.[5] They are shown in Table 4.

Above 3μm, all SF's are practically stable with the range cut. Hovewer, at 1μm and 0.5μm SF's increase especially for the FCal2 and for the FCal3 (having high-Z absorber). This results to range cut dependence of the "observables" SF1/SF3 and SF2/SF3. Rough agreement between the test-beam data and the MC for the ratio SF1/SF2 takes place only at very strong range cut, 0.5μm. There is strong discrepancy between average GEANT3 and GEANT4 predictions, both for the SF's themselves and for their ratios.

[4] NCU is an abbreviation of so-called "New CERN Unit". Roughly speaking, 1 NCU = 1 SpecInt2000 corresponds to one second on a typical 3(?) GHz PC processor.

[5] Let's remind that FCal response non-linearity for electrons is expected to be at the level of 1% [15].

Range cut, μ	SF1	SF2	SF3	SF1/SF2	SF1/SF3
0.5	1.50	0.87	1.13	1.72	1.33
1	1.45	0.75	1.00	1.93	1.45
3	1.32	0.62	0.82	2.13	1.61
5	1.24	0.60	0.80	2.07	1.55
10	1.27	0.60	0.80	2.12	1.59
30	1.34	0.64	0.85	2.09	1.58
50	1.33	0.63	0.83	2.11	1.60
100	1.30	0.62	0.82	2.10	1.59
300	1.26	0.61	0.81	2.07	1.56
700	1.24	0.59	0.79	2.10	1.57

Table 4. FCal sampling fractions vs G4.7.0p01 range cut. The incident electron angle was 3.0^0.

SF's for **muons** were calculated and results can be found in Table 4'. The second row corresponds to the case when bremsshtrahlung and delta-rays were switched off, as in GEANT3 (Table 2'). There is some discrepancy between calculated SF's and values presented in the second row. It is seen that numbers obtained from the simulation are smaller than those calculated from geometry especially for hadronic FCal segments.

It was checked that results for muons obtained with ATHENA, version 10.0.1, are compatible with those from the standalone version.

Brem/δ	SF1	SF2	SF3	SF1/SF2	SF1/SF3
ON	0.0150	0.0095	0.0125	1.58	1.20
OFF	0.0167	0.0119	0.0150	1.40	1.11

Table 4'. FCal sampling fraction for **muons** simulated with LArG4-standalone.

3.2.2 FCal and its SF in G4.8.0

Based on [17] one would expect that simulated with G4.8.0 values of SF's will be correct. The following procedure was used for their calculations. At first, we find a slope of the FCal response with energy at fixed range cut (assuming zero offset). Half-sum (half-difference) between **average** and **mean gaussian** response is considered as an energy deposition (its systematic error) respectively at given point. After this procedure, the obtained SF is averaged over range cuts considered. As a conservative estimate of the additional systematic error due to range cut dependence we take half-difference between minimal and maximal values of the SF's. Appendix 1 contains detailed summary about the simulated FCal1, FCal2 and FCal3 responses to electrons at different energies and range cuts. In this Chapter, one presents only the most important information.

FCal1 responses to electrons at different energies and $\theta = 2.98^0$ for 30μ range cuts are shown in Fig.1. Their shapes are symmetric and close to gaussians. It is not a case for the FCal2 (and FCal3), see Fig.2. Note that the widths of the related distributions for the FCal2 are much larger than for the FCal1 especially at very high energies. It is due to coarser granularity and denser absorber in the FCal2.

Deviation from the linearity of the FCal1 response to electrons is well below 0.5% (the response is linear within statistics) for 3 and 30μ range cuts while it is at the level of 1% for 300μ range cut, see Fig.3. So 30μ range cut looks like optimal.

The resulting sampling fractions are shown in Table 5. Note that for the SF1 the error is typically below 0.5% while for the SF2 and the SF3 it is around 1-2%. In addition, it should be noted that at 4.3^0 the values of SF2 are 5% higher than at 3.0^0 while there is no such effect for the SF1.[6]

Range cut, μ	SF1	SF2	SF3	SF1/SF2	SF1/SF3
0.5	1.51	0.93	-	1.62	-
1	1.54	0.93	-	1.66	-
3	1.565	0.955	1.25	1.64	1.25
30	1.595	0.95	1.23	1.68	1.30
100	1.56	0.93	-	1.68	-
300	1.53	0.91	1.21	1.69	1.26

Table 5. FCal sampling fractions vs G4.8.0 range cut. The incident electron angle was 3.0^0.

It is seen that in the region 0.5μ-3μ the range cut dependence is almost absent which is not the case in the GEANT4 version 7.0. In the 3μ-300μ interval SF1, SF2 and SF3 obtained with the version 8.0 are typically 20%, 50% and 50% higher respectively than those simulated with 7.0, see also Fig. 4 and Fig. 5. As a result, the measured quantity, SF1/SF2, becomes 25% smaller and now it is in 5% agreement with the test-beam data. A few % variation of the sampling fraction of any FCal with the range cut takes place in both versions of GEANT4.

3.3 FCal1 energy resolution for electrons in GEANT4

Based on [17] one would expect sizeable changes in the FCal1 energy resolution from G4.7.0 to G4.8.0. Energy dependence of the energy resolution is shown in Fig. 6. It is clearly seen that at 30μ range cut new G4 describes the test-beam data [11] reasonably well.[7] This is not a case for the old G4. Even at 3μ range cut there is no good agreement between the data and the MC.

4 Summary

Summarizing, new version of GEANT, G4.8.0, describes the test-beam data for the ratio of FCal1 and FCal2 electron sampling fractions as well as energy dependence of the FCal1 energy resolution for electrons, reasonably well. ATLAS default range cut, 30μ, looks like optimal in terms of "CPU-performance" ratio. As there are serious discrepancies between the test-beam results and those obtained with the older G4 versions both for electron sampling fractions of the FCals and for energy resolution of FCal1, it would be better to resimulate also pions with the new G4 version. One can propose to do it with the forthcoming official ATHENA release which will include G4.8.0 (or newer) version.

5 Acknowledgements

We would like to thank all related people from the ATLAS LAr community and from G4 team for fruitful discussions. Our special thanks to Prof. J. Rutherfoord for providing us with the summary table placed in Appendix 2.

[6]By mistake, results shown at the LAr meeting [18] were obtained at 4.3^0 instead of 3^0 for the FCal2.

[7]Some discrepancy at low energy points can be explained by inaccuracies of noise subtraction in the data. The noise contribution is taken as a gaussian σ of related pedestal distribution while also there is probably a non-negligible contribution from coherent noise.

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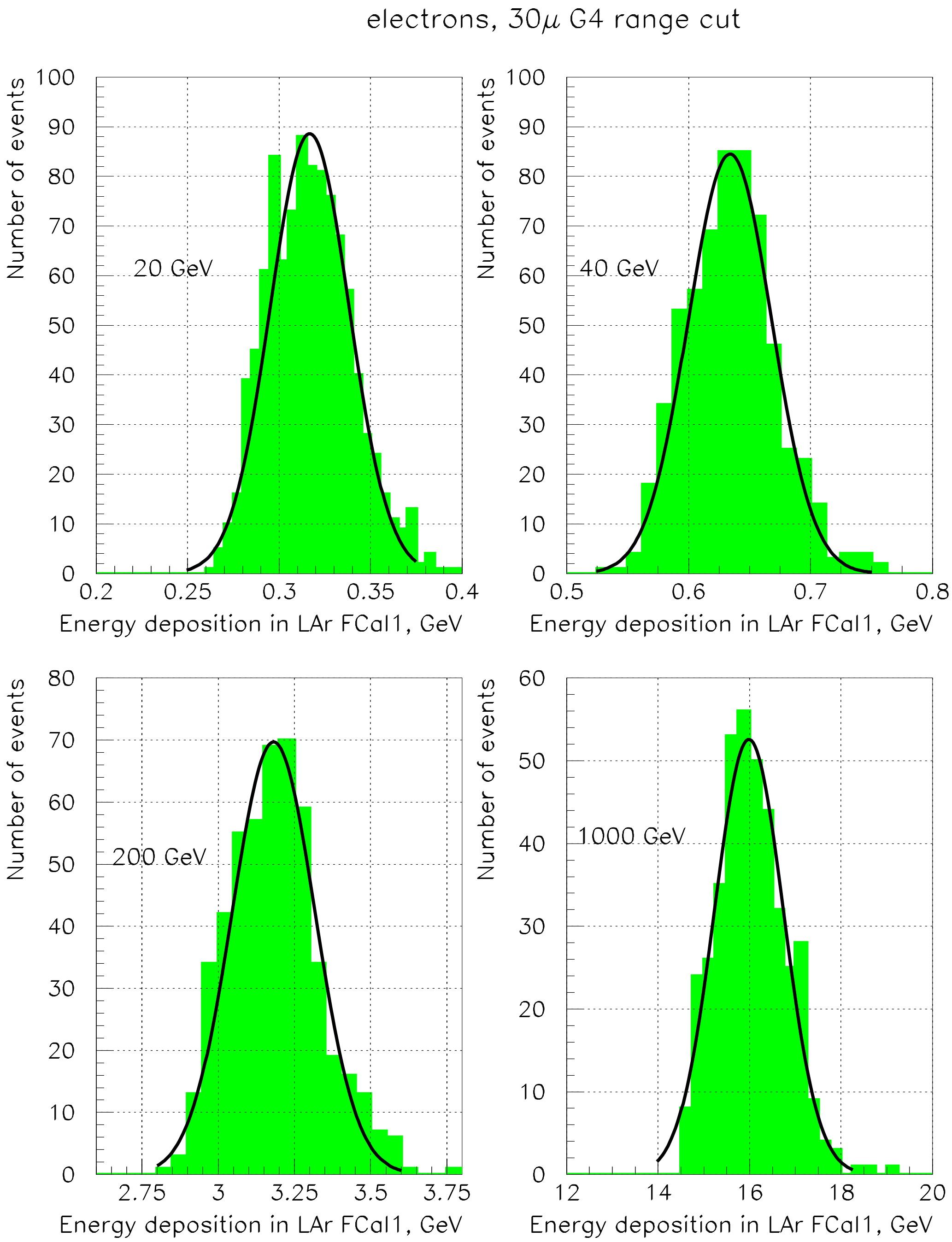

Figure 1: Simulated FCal1 response to electrons having impact angle 2.98^0 for 30μ range cuts (solid green histograms) with superimposed unrestricted gaussian fits (solid black lines).

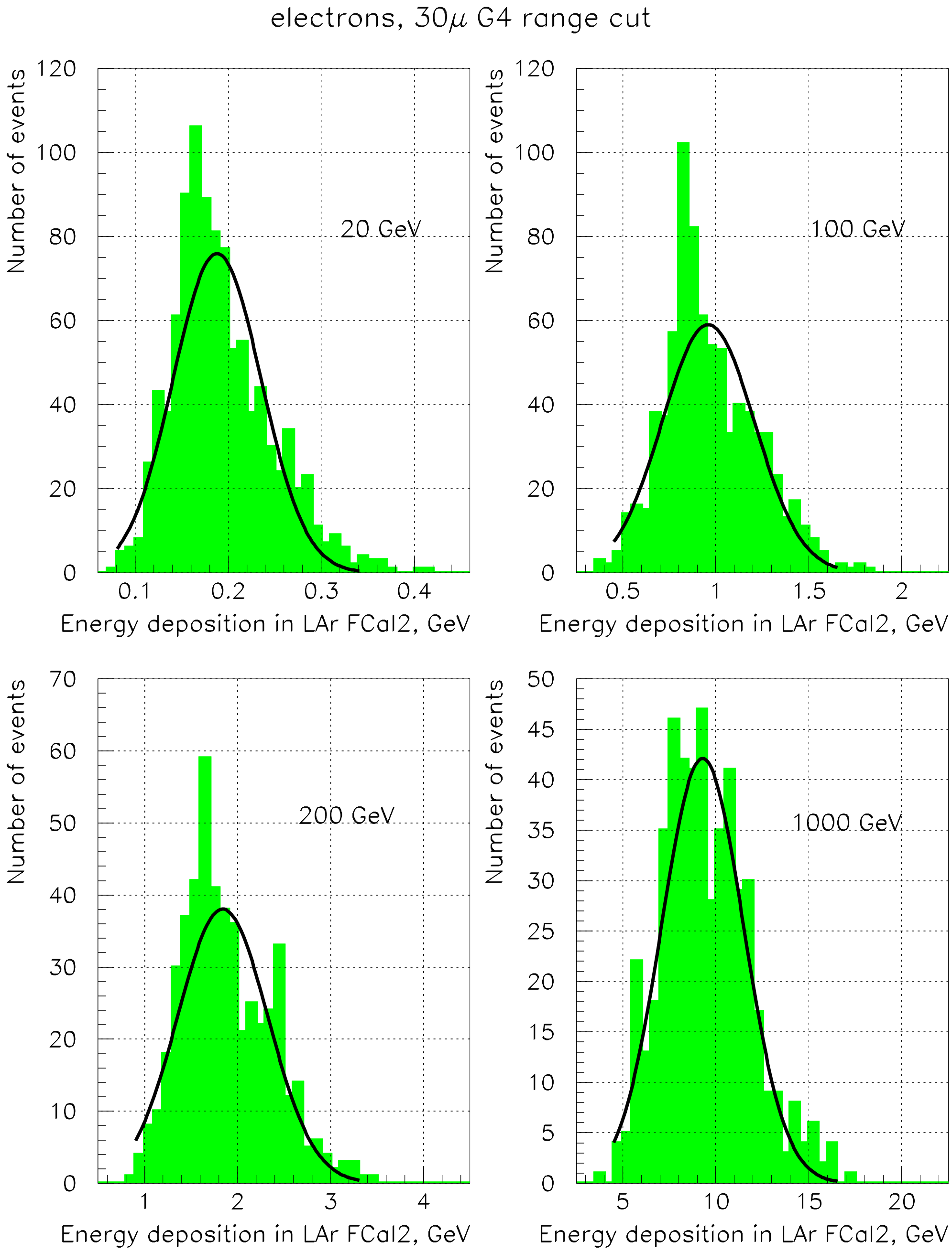

Figure 2: Simulated FCal2 response to electrons having impact angle 2.98^0 for 30μ range cuts (solid green histograms) with superimposed unrestricted gaussian fits (solid black lines).

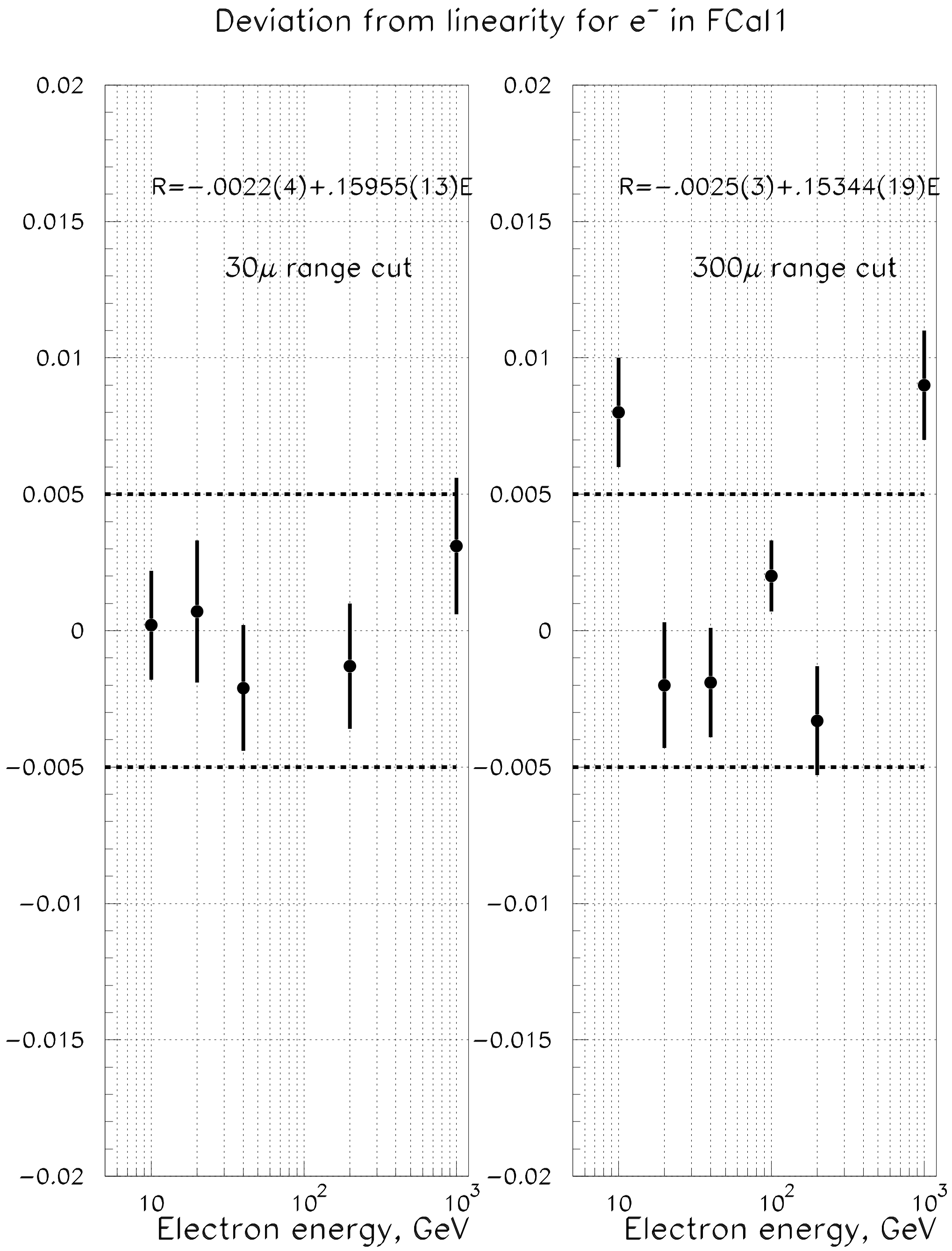

Figure 3: Deviation from the linearity of simulated FCal1 response to electrons having impact angle 2.98^0 for 30μ and 300μ range cuts (solid green histograms) with superimposed unrestricted gaussian fits (solid black lines).

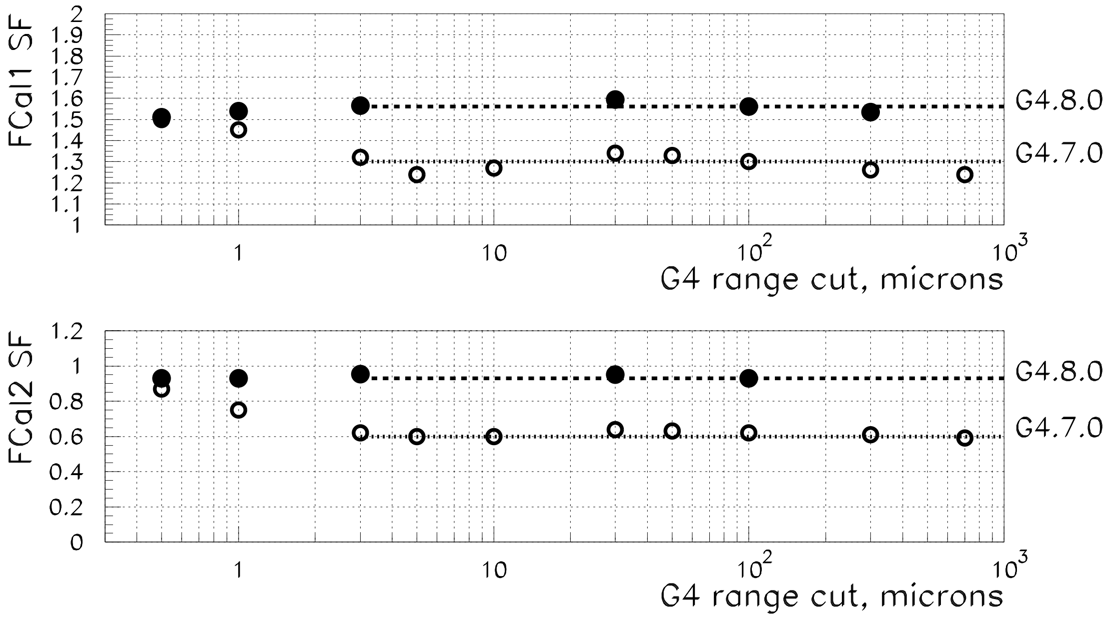

Figure 4: Simulated FCal1 and FCal2 sampling fractions as a function of range cut. The line shows SF2/SF1 ratio extracted from the TB 1998 data [7].

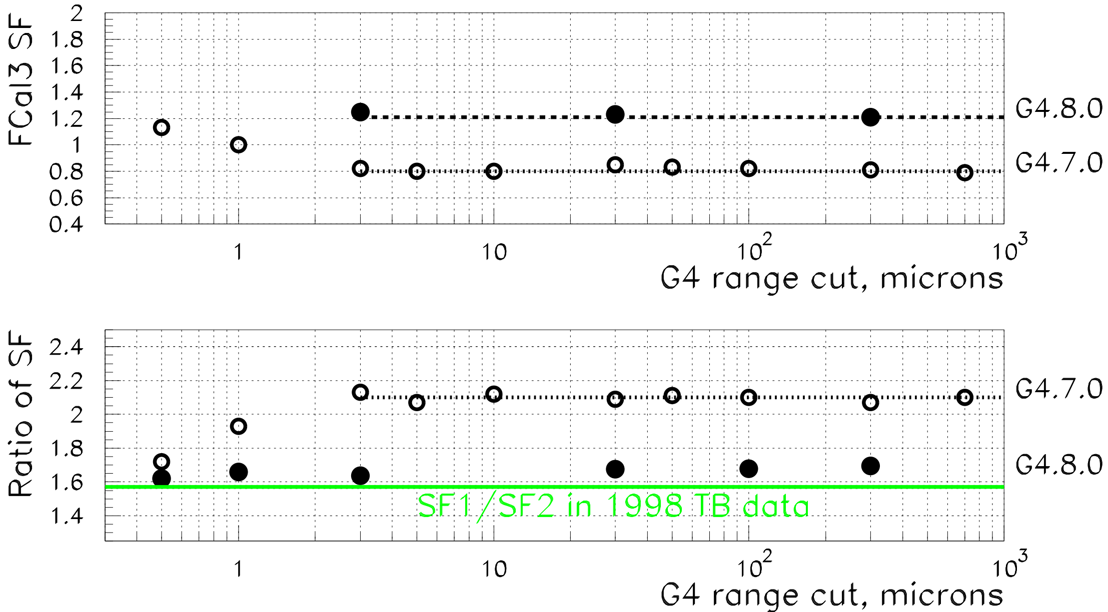

Figure 5: Simulated FCal3 sampling fraction and SF2/SF1 ratio as a function of range cut (top plot) and The line shows the SF2/SF1 ratio extracted from the TB 1998 data [7].

6 Appendix 1. Details about FCals responses to electrons

	3	*30*	*100*	*300*
		10 GeV		
3.0 m	.1550	.1579	-	.1518
r	.0137	.0141	-	.0137
r/m	.088	.089	-	.090
3.0 g	.1542(4)	.1571(3)	-	.1508(3)
σ	.1368(31)	.0130(23)	-	.0134(30)
σ/g	.0887(20)	.0827(15)	-	.0889(20)
		20 GeV		
3.0 m	.3104	.3170	.3128	.3043
r	.0209	.0228	.0225	.0218
r/m	.067	.072	.072	.072
3.0 g	.3098(10)	.3167(8)	.3110(7)	.3032(7)
σ	.0202(8)	.0216(5)	.0210(6)	.0207(6)
σ/g	.0652(26)	.0682(17)	.0675(20)	.0683(20)
		40 GeV		
3.0 m	.6229	.6347	-	.6102
r	.0359	.0367	-	.0365
r/m	.058	.058	-	.060
3.0 g	.6222(19)	.6339(15)	-	.6092(12)
σ	.0344(15)	.0341(10)	-	.0345(9)
σ/g	.0553(24)	.0538(16)	-	.0566(16)
		100 GeV		
3.0 m	1.564	-	-	1.531
r	.0783	-	-	.0761
r/m	.050	-	-	.050
3.0 g	1.564(3)	-	-	1.527(2)
σ	.0762(15)	-	-	.0761(16)
σ/g	.0487(10)	-	-	.0498(10)
		200 GeV		
3.0 m	3.130	3.187	-	3.064
r	.1404	.1481	-	.1424
r/m	.045	.046	-	.047
3.0 g	3.130(8)	3.182(7)	-	3.052(6)
σ	.0131(6)	.0136(5)	-	.0149(6)
σ/g	.0419(19)	.0427(17)	-	.0488(18)
		1000 GeV		
3.0 m	15.81	16.05	-	15.51
r	.741	.743	-	.726
r/m	.047	.046	-	.047
3.0 g	15.64(8)	15.99(4)	-	15.46(3)
σ	.863(66)	.756(36)	-	.762(29)
σ/g	.0552(42)	.0473(23)	-	.0493(19)

Table A1. Simulated with LArG4 FCal1 response to 10, 20, 40, 100, 200 and 1000 GeV

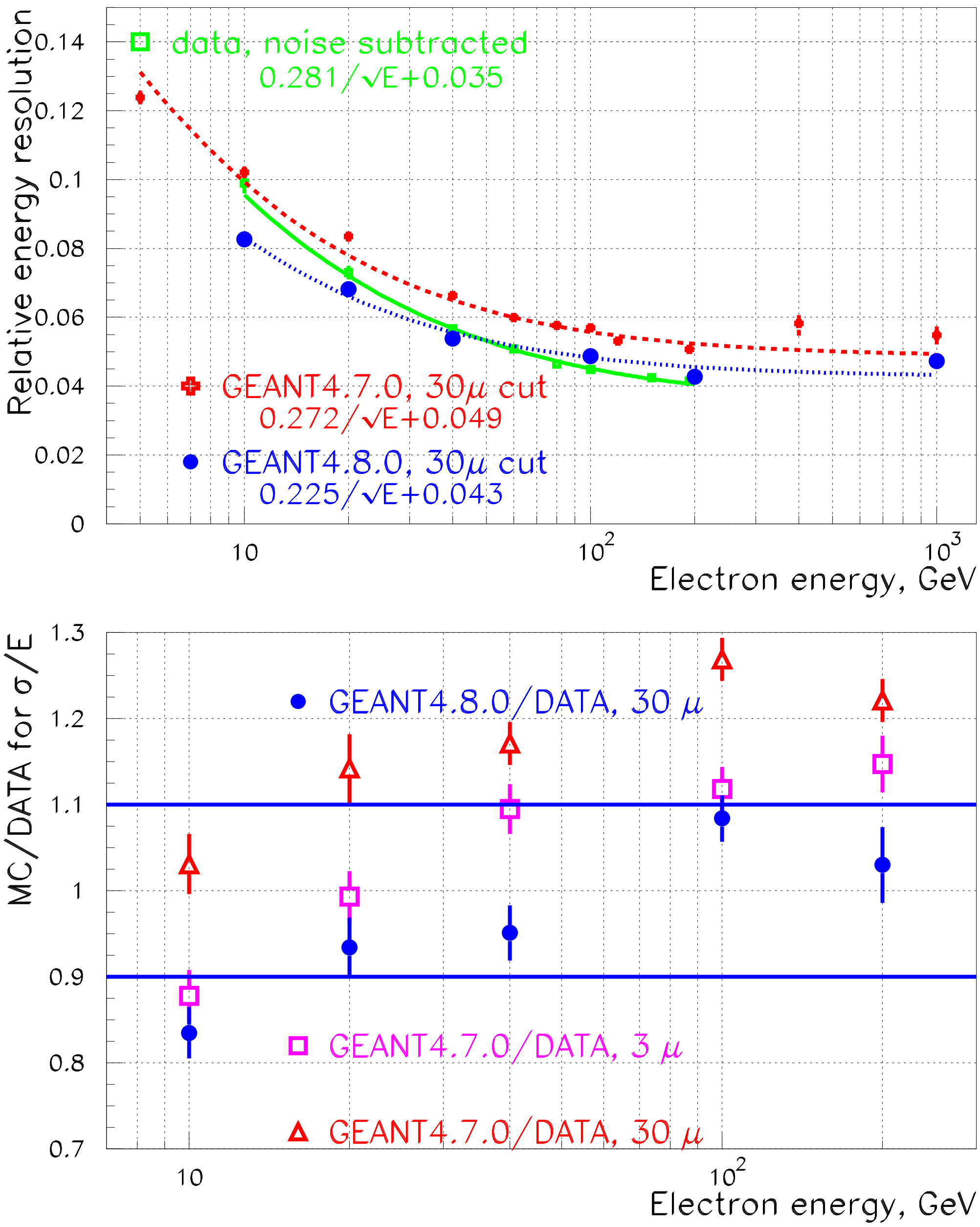

Figure 6: Energy dependence of the FCal1 energy resolution to electrons having impact angle 2.98^0

electrons at 2.98^0. Abbreviations "m", "r" and "g" stand for mean response, its r.m.s. and for an average value of gaussian respectively.

	3	*30*	*100*	*300*
		10 GeV		
3.0 m	.101	.098	-	.092
r	.0297	.0297	-	.0271
r/m	.29	.30	-	.29
3.0 g	.0996(16)	.0948(10)	-	.0902(10)
σ	.0280(14)	.0284(11)	-	.0264(11)
σ/g	.281(14)	.300(12)	-	.293(13)
		20 GeV		
3.0 m	.197	.193	.192	.186
r	.0522	.0526	.0552	.0504
r/m	.26	.27	.29	.27
3.0 g	.195(3)	.189(2)	.187(2)	.183(2)
σ	.0512(25)	.0479(20)	.0522(21)	.0495(15)
σ/g	.263(13)	.253(12)	.279(11)	.270(10)
		40 GeV		
3.0 m	-	.395	.373	.366
r	-	.109	.103	.0994
r/m	-	.28	.28	.27
3.0 g	-	.389(4)	.368(4)	.362(4)
σ	-	.0990(32)	.0955(37)	.0933(28)
σ/g	-	.0254(8)	.260(10)	.258(8)
		100 GeV		
3.0 m	.970	.969	.934	.919
r	.241	.247	.234	.239
r/m	.25	.26	-.25	.26
3.0 g	.950(15)	.960(10)	.930(9)	.892(9)
σ	.248(15)	.249(9)	.230(8)	.250(8)
σ/g	.261(16)	.259(10)	.247(9)	.280(9)
		200 GeV		
3.0 m	1.905	1.884	1.894	1.831
r	.462	.476	.480	.464
r/m	.24	.25	.25	.25
3.0 g	1.897(28)	1.841(25)	1.868(22)	1.806(19)
σ	.444(23)	.486(23)	.457(18)	.480(16)
σ/g	.234(13)	.264(12)	.244(10)	.266(10)
		1000 GeV		
3.0 m	9.74	9.48	9.32	9.03
r	2.26	2.34	2.20	2.13
r/m	.23	.25	.24	.24
3.0 g	9.51(14)	9.29(11)	9.25(9)	8.94(9)
σ	2.03(10)	2.20(10)	1.97(6)	2.21(10)
σ/g	.213(11)	.236(12)	.212(7)	.247(11)

Table A2. Simulated with LArG4 FCal2 response to 10, 20, 40, 100, 200 and 1000 GeV electrons at 2.98^0. Abbreviations "m", "r" and "g" stand for mean response, its r.m.s. and for an average value of gaussian respectively.

	3	*30*	*100*	*300*
		10 GeV		
3.0 m	.128	.131	-	.124
r	.0355	.0380	-	.0352
r/m	.28	.29	-	.28
3.0 g	.1197(20)	.1231(15)	-	.1200(14)
σ	.0303(20)	.0317(15)	-	.0318(12)
σ/g	.252(17)	.258(13)	-	.265(10)
		100 GeV		
3.0 m	1.269	1.252	-	1.204
r	.332	.313	-	.292
r/m	.26	.25	-	.24
3.0 g	1.265(24)	1.181(15)	-	1.192(11)
σ	.349(19)	.329(17)	-	.267(8)
σ/g	.276(15)	.279(14)	-	.224(6)
		1000 GeV		
3.0 m	12.52	12.33	12.35	–
r	3.04	2.83	2.80	–
r/m	.24	.23	.23	–
3.0 g	12.46(24)	11.93(17)	12.22(14)	-
σ	3.19(29)	2.94(10)	2.80(12)	-
σ/g	.256(23)	.246(9)	.229(10)	-

Table A3. Simulated with LArG4 FCal3 response to 10, 100 and 1000 GeV electrons at 2.98^0. Abbreviations "m", "r" and "g" stand for mean response, its r.m.s. and for an average value of gaussian respectively.

7 Appendix 2. J. Rutherfoord's FCal table

ATLAS FCal Module Parameters	EM	H1	H2
Module inner radius	72.0	79.0	86.0
Module outer radius	449.6	449.6	449.6
Module z front face	4668.5	5128.3	5602.8
Module z at middle	4890.6	5349.4	5823.9
Module depth	444.2	442.3	442.3
Rod OD	4.71	4.93	5.50
Tube ID	5.24	5.68	6.50
Gap in um	266.	375.	500.
Tube spacing	7.50	8.18	9.00
Tube C in pF	349.	263.	223.
Material			
Rod	Cu	W	W
Tube	Cu	Cu	Cu
Matrix	Cu	HM	HM
EndPlate	Cu	Cu	Cu
dE/dx Samp Frac (%)	1.61	1.32	1.68
dE/dx Samp Freq (1/cm)	0.60	0.35	0.34
Depth (X0)	27.58	91.20	89.46
Depth (Lambda)	2.66	3.68	3.61
Unit Cell volume ratios			
Lar gap	8.56	10.79	13.44
Interstitial spaces	3.56	4.96	4.45
Rod	35.80	32.95	33.87
Tube	9.01	8.04	7.56
Matrix	38.09	38.37	36.10
EndPlates	4.99	4.89	4.58
Unit cell density	7.87	14.52	14.20
Edge volume (in unit cells)	222.5	182.6	444.3
Number of electrodes	12336	10320	8128
Number of preamps	3084	1720	903
Number of electrodes/preamp	4	6	9
Mass of module (kg)	2145.	3920.	3821.
Q/E mip (ke-/GeV)	321.9	265.0	336.5

8 Appendix 3. Piece of code for FCal description in the GEANT3/ATLSIM framework

```
Segm       = 1          ! 1-st Segment (EM)
Lsegm      = 44.37      !   length of the segment
Rout       = 45.0       !   Segment outer radius
Rinn       = 7.18       !   Segment inner radius
RodR       = 0.2375     !   rod radius for segment
HoleR      = 0.2625     !   hole radius for segment
Tdist      = 0.75       !   Tube-to-tube distance
```

```
*
 Fill  FWSi                      ! idem
       Segm       = 2            ! 2-nd Segment (HAD1)
       Lsegm      = 44.37        !   length of the segment
       Rout       = 45.0         !   Segment outer radius
       Rinn       = 7.88         !   Segment inner radius
       RodR       = 0.25375      !   rod radius for segment
       HoleR      = 0.29125      !   hole radius for segment
       Tdist      = 0.8179       !   Tube-to-tube distance
*

       Segm       = 3            ! 3-rd Segment (HAD2)
       Lsegm      = 44.37        !   length of the segment
       Rout       = 45.0         !   Segment outer radius
       Rinn       = 8.57         !   Segment inner radius
       RodR       = 0.275        !   rod radius for segment
       HoleR      = 0.325        !   hole radius for segment
       Tdist      = 0.9          !   Tube-to-tube distance

Material FC1,2,3 is mixture of:
---------------
   If (isegm = 1) then                     ! 1-st, e.m. segment
     Component  Cu       A=63.55 Z=29 W=0.988
     Component  LAr      A=39.95 Z=18 W=0.012
     Mixture    Matr1    Dens=8.393
   ElseIf (isegm = 2) then                 ! HAD A
     Component  W        A=183.9 Z=74 W=0.886
     Component  Ni       A=58.69 Z=28 W=0.018
     Component  Fe       A=55.85 Z=26 W=0.009
     Component  Cu       A=63.55 Z=29 W=0.077
     Component  LAr      A=39.95 Z=18 W=0.010
     Mixture    Matr1  Dens=15.37
   ElseIf (isegm = 3) then                 ! HAD B
     Component  W        A=183.9 Z=74 W=0.888
     Component  Ni       A=58.69 Z=28 W=0.018
     Component  Fe       A=55.85 Z=26 W=0.009
     Component  Cu       A=63.55 Z=29 W=0.075
     Component  LAr      A=39.95 Z=18 W=0.010
     Mixture    Matr1  Dens=15.45
   EndIf

Cu rod: pure Cu, density 8.96

W rod:
     Component  W        A=183.9 Z=74 W=0.9998  ! pure tungsten
     Component  Ni       A=58.69 Z=28 W=0.0001
     Component  Fe       A=55.85 Z=26 W=0.0001
       density 19.2 g/cm**3
}
```

9 Appendix 4. Extractions from the code for FCal description in GEANT4

```
 //---------------------
 // FCal1 overall volume
 //---------------------
 // --- material
 G4Material * thisAbsorber = FCalMaterials->Material("FCal1Absorber");
// FCal1 bulk absorber: Cu with a little bit of inactive argon
 density   = 8.701*g/cm3;
 name      = "FCal1Absorber";
 nElements = 2;
 m_Materials[name] = new G4Material(name,density,nElements);
 m_Materials[name]->AddMaterial(m_Materials["Copper"],massFrac=0.994);
 m_Materials[name]->AddMaterial(m_Materials["LiquidArgon"],massFrac=0.006);

 //--------------
 // Cable troughs
 //--------------
 // --- material
 G4Material * thisTrough = FCalMaterials->Material("FCalCableHarness");

 //-----------
 // Electrodes
 //-----------
 // --- material
 G4Material * thisElectrode = FCalMaterials->Material("LiquidArgon");
density = 1.396*g/cm3;
 a       = 39.948*g/mole;
 name    = "LiquidArgon";
 z       = 18.;

 //
 //---------------------
 // FCal2 overall volume
 //---------------------
 G4Material * mixFCal2 = new G4Material( "FCal2MixAbsorber",
                                         density,
                                         2 );
 mixFCal2->AddMaterial( thisCu, massFracCu );
 mixFCal2->AddMaterial( thisW,  massFracW  );
 // FCal2 effective absorber: slugs, Cu tubes and inactive argon
 density   = 15.366*g/cm3;
 name      = "FCal2Absorber";
 nElements = 3;
 m_Materials[name] = new G4Material(name,density,nElements);
 m_Materials[name]->AddMaterial(m_Materials["FCal2Slugs"],massFrac=0.913);
 m_Materials[name]->AddMaterial(m_Materials["Copper"],massFrac=0.077);
 m_Materials[name]->AddMaterial(m_Materials["LiquidArgon"],massFrac=0.01);
```

```
  //-----------
  // Electrodes
  //-----------
  // --- material
  G4Material * thisGap = FCalMaterials->Material("LiquidArgon");
  G4Material * thisRod = FCalMaterials->Material("Tungsten");
density = 19.3*g/cm3;
  a       = 183.85*g/mole;
  name    = "Tungsten";
  z       = 74.;


  // define the new mixture
  G4Material * mixFCal3 = new G4Material( "FCal3MixAbsorber",
                                          density,
                                          2 );
  mixFCal3->AddMaterial( thisCu, massFracCu );
  mixFCal3->AddMaterial( thisW,  massFracW  );
  // FCal3 effective absorber: slugs, Cu tubes and inactive argon
  density   = 15.366*g/cm3;   // to be fixed!
  name      = "FCal3Absorber";
  nElements = 3;
  m_Materials[name] = new G4Material(name,density,nElements);
  m_Materials[name]->AddMaterial(m_Materials["FCal2Slugs"],massFrac=0.913);
  m_Materials[name]->AddMaterial(m_Materials["Copper"],massFrac=0.077);
  m_Materials[name]->AddMaterial(m_Materials["LiquidArgon"],massFrac=0.01);
```