THE ATLAS CALORIMETER PREAMPLIFIER: PERFORMANCE, RADIATION DAMAGE, ELECTROSTATIC DISCHARGE RESISTANCE, RELIABILITY AND MANUFACTURING ISSUES*

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Abstract

The requirements, design, measured specification of the ATLAS liquid argon (LAr) calorimeter preamplifiers are reviewed. The experience gained so far in production, the quality assurance and testing, as well as the reliability estimate according to MILSTRESS standard will be discussed.

1. INTRODUCTION

The preamplifiers are the first amplification stage in the LAr readout architecture, which set the noise performance of the calorimeter. They amplify the analog signal generated at the calorimeter electrodes.

Figure 1 shows a picture of the liquid argon Front-End Board (FEB). The preamplifiers are at the input of the board and are connected via a transmission line to the detector electrodes. The space allocated on the FEB for the preamplifiers have dictated the aspect ratio of the circuits and, up to certain extent, the technology adopted for the production.

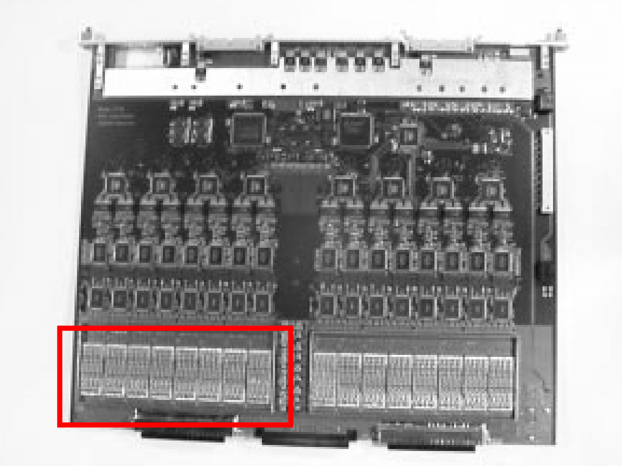

Figure 1. Photograph of a FEB board. The input signals come into the board from the two external connectors at the bottom. The preamplifiers are immediately above the input connectors. Eight hybrids are encircled in the picture.

Each FEB contains 128 channels of amplification, 64 channels on each side of the card grouped in two block of 32 channels each. The preamplifiers are moreover grouped in block of four channels and have been realised in a hybrid package the dimension of which are 53.3 mm in length and 23.0 mm in width. The preamplifier hybrids are independent units that plug into the FEB.

About 190,000 read-out channels or about ~47,500 hybrids are needed for the LAr calorimeter.

More than one type of preamplifier/hybrid is required to accommodate the different characteristics of the detector. The detector structure (impedance, capacitance, etc.), the estimated maximum energy deposited per readout cell as a function of rapidity, together with the need of a maximum output signal of about 3 to 4 Volt, determine that three types of preamplifiers must be used. These three type of preamplifiers share a same general circuit diagram which has been properly “optimised” for the different sections of the calorimeter.

2. PREAMPLIFIER DESIGN

2.1 Requirements and Specification

The preamplifier requirements and specification are described in detail in the ATLAS LAr Technical Design Report (TDR) [1].

The most important ones can be summarised as follow:

- Noise: as low as possible with respect to pile-up, Rnoise = 10 Ω, typical Equivalent Noise Current (ENI) values are in Table 1.
- Uniformity: TDR: < 5 % in amplitude for trigger sums (< 1 % meas.), TDR: < +/- 2 ns timing (< +/- 1 ns meas.).
- Power dissipation: TDR: < 100 mW/ch.
- Environment: must tolerate 20 Gy/year (2 krad/year) and 10^{12} n/cm^{2}year.
- Reliability: < 0.5 % missing channel per year.
- ESD discharge: must withstand 4 mJ multiple discharge without damage (i.e. 2 KV on 2 nF typical).
- Stability: must be stable even in case of presence of faults in the signal chain (short, open).
- Output impedance: must be able to drive a 50 Ω load (i.e. the shaper input impedance).
- Dynamic range: up to 10 mA, depending on rapidity range.

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Table 1: Typical noise values

Preamp type	ENI [nA]
50 Ω / 1mA	50 @ C_D = 330 pF, tp = 46 ns
25 Ω / 5mA	125 @ C_D = 1500 pF, tp = 53 ns
25 Ω / 10 mA	270 @ C_D = 2200 pF, tp = 40 ns

2.2 *Preamplifier circuit*

The LAr preamplifiers are coupled to the detector by a transmission line. As the signal duration is long compared to the shaping time, current preamplifiers are used which provide a voltage output directly proportional to the input current.

The main characteristic of the ATLAS preamplifier is the use of a local feedback in the input stage to attribute the functions of low noise and high dynamic range to two different transistors. This circuit configuration allows to improve the linearity and to reduce the noise while reducing the power dissipation by a factor of three (to about 50 mW) with respect of the first generation RD3 preamplifier [4]. The gain (i.e., the transresistance) and the input impedance can be chosen independently without changing the power supply voltages and power dissipation.

The principle of coupling a preamplifier to a high capacitance detector and a detailed description of the ATLAS implementation are described in ref. [2, 3]. The circuit schematic is shown in Figure 2.

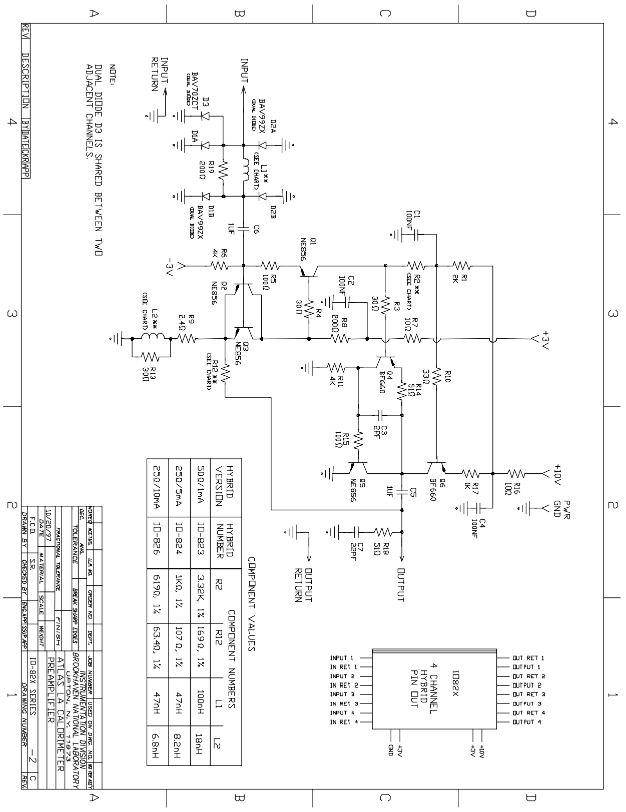

Figure 2. Preamplifier schematic.

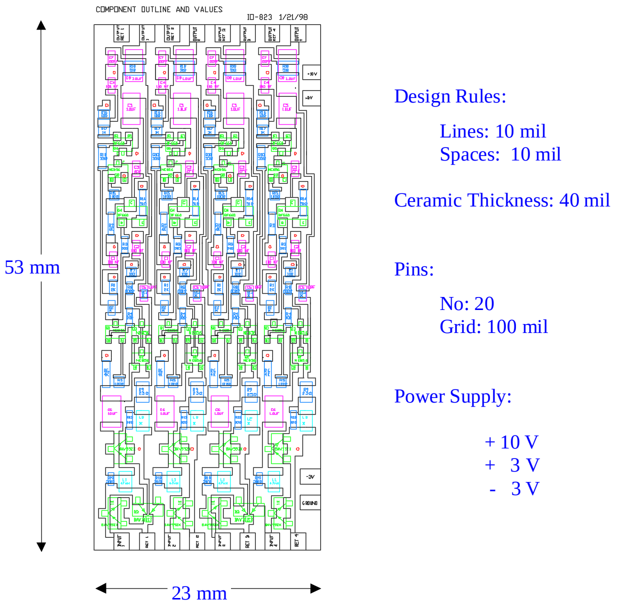

Figure 3. Hybrid Layout.

2.3 *Preamplifier Technology*

The preamplifiers have been manufactured by means of thick film hybrid technology. This technology is a well-known technology with predictable time schedule for production and high reliability, as proven in many high-energy physics experiments. Moreover each device can be chosen to optimise its function (e.g. low noise) and many different type of devices (NPN, PNP, decoupling capacitors, etc.) are available.

Use of a more advanced monolithic technology was rejected because of the higher development costs (a complementary bipolar process featuring low noise, radiation resistant transistors was necessary) and higher risks associated with the research and development, both in terms of performance and schedule.

The hybrid design has been carried out with very conservative design rules (10 mils line, 10 mils separation) to both expand the pool of manufacturers and to improve the production yield. The layout is shown in Fig. 2.

3. PREAMPLIFIER CHARACTERISTICS

The hybrid preamplifier design has been tested and verified through the productions of 200 prototypes first and 1600 hybrids to equip LAr Mod0, subsequently. The information gathered during these preliminary phases would be used to optimise the final production.

Gain, peaking time, noise and input impedance were the main parameters of interest. Radiation tolerances to ionising radiation and to neutrons were also measured.

The results obtained are summarised in the following sections.

Finally stability analysis was performed. The preamplifiers were found stable for any value of cable length and detector capacitance foreseen for the LAr calorimeter [5].

3.1 Parameter Distribution

The preamplifier characteristics meet and exceed the specification. Figure 3 illustrates peaking time, amplitude and noise distribution for the preamplifier type Z_{in}/I_{max} = 50Ω / 1mA.

All the preamplifiers are within +/- 3σ from the average value. Similar results were obtained for the other preamplifier types.

The preamplifier input impedance for each hybrid type is summarised in Table 2.

Table 2: Input impedance

Preamp Type	Z_{in}	Tolerance
50 Ω / 1 mA	51.4 Ω	+/- 2.9 %
25 Ω / 5 mA	25.8 Ω	+/- 1.8 %
25 Ω / 10 mA	26.3 Ω	+/- 1.7 %

3.2 Preamplifier Radiation Tolerance

Expected gamma doses over the life of the preamplifiers is estimated to be approximately 2 x 10^4 rad silicon. It is expected that the total possible dose would be no more than five times this number or 10^5 rad. Two hybrid preamplifiers under power were exposed to a total of 10^5 rad. One was a 50 Ω impedance device and the other was a 25 Ω impedance device. Both hybrids were measured for gain, peaking time, ENI, and input impedance before irradiation and after total doses of 5 x 10^4 and 10^5 rad of ^{60}Co gamma radiation. Gain, peaking time, and ENI changed by less than the measuring error for both hybrids after 10^5 rad.

Average input impedance (of 4 channels) at selected doses for the two devices is shown in Table 3.

Table 3: Input impedance versus dose

unirradiated	5 x 10^4 rad ^{60}Co	10^5 rad ^{60}Co
51.3 Ω	50.1 Ω (2.3% change)	48.8 Ω (4.9% change)
25.4 Ω	25.3 Ω (0.4% change)	25.2 Ω (0.8% change)

Preamplifier hybrids were irradiated with fast neutrons at the SARA facility, Grenoble [6].

No noise degradation was measured till a fluence of 5 x 10^{13} n/cm^2. The neutrons induce a degradation of the forward-gain β of the NEC856 (NPN) transistors used in the circuit. The β degradation follows the Messenger-Sprat relation and, at first order, is inversely proportional to f_T.

The impact of the β degradation of transistors on the preamplifier gain is very small. The 25Ω preamplifiers exhibit about 3% of gain loss after 1.1 x 10^{14} n/cm^2, while the 50Ω preamplifier, has about 7% gain loss after the same fluence.

The measurement of input impedance of all irradiated preamplifiers indicated that there is no stability problem with irradiation. All of them have positive real part of input impedance in a frequency range 1-200 MHz.

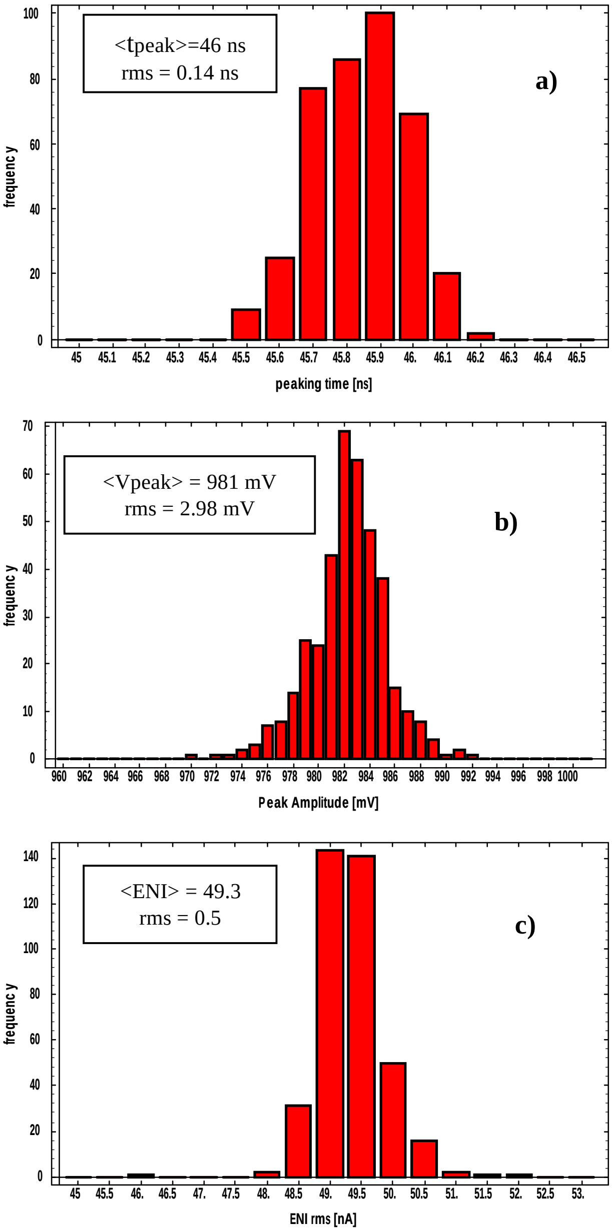

Figure 4. Parameter distributions for 50 Ω / 1 mA preamplifiers: a) peaking time, b) amplitude and c) ENI. The measurements conditions are C_D = 330 pF, td_line = 16 ns (RG174), tp_tr ~ 46ns (τ_{shaper} = 30 ns).

4. QUALITY ASSURANCE

4.1 *Burn-in study*

The first series of hybrid produced (200 units) after being tested for electrical functionality was subjected to 168 hours of an environmental stress screening (or burn-in) at ambient temperature to identify and eliminate deficiencies and early failures. Moreover few hybrids (eight units randomly chosen) were fully characterised in term of gain, peaking time and noise before and after burn-in to detect any possible variation of performances due to ageing effects.

At the conclusion of the burn-in only one channel failed to meet specification. The unit failed because a PNP transistor (Q4) in the white follower broke during burn-in. After replacing the transistor the channel was tested again and it met specification.

The hybrids that were fully characterised before burn-in did not show any performance variation due to the environmental stress.

The burn-in results brought to the conclusion that the environmental conditions adopted for the test were not sufficient to rule out all the early failure mechanisms. A more extensive burn-in study was adopted for the batch of hybrids produced for Mod0. The temperature was elevated to ~ 70 °C and the time were extended up to 432 hours. The combination of elevated temperature and extended time did not increase the number of failures. The only source of failures for thick-film hybrids was a “cold solder joint”.

Under the assumption that the same failure mechanism dominates in the ATLAS hybrids, was concluded that a burn-in of 168 hours at an elevated temperature of 70-80 °C, will be used to eliminate all causes of infant mortality. A higher burn-in temperature/shorter time is not achievable because some of the components used in the preamplifiers are not rated for temperatures higher than 100 °C, namely the inductors.

4.2 *Reliability Evaluation*

The reliability of the hybrids has been evaluated based on the internationally recognised method of calculating electronic equipment reliability given in “Military Handbook MIL-HDBK-217” (published by the US Department of Defense). This standard uses a series of models for various categories of electronic components to predict failure rates that are affected by environmental conditions, quality levels, stress conditions and various other parameters. These models are fully detailed in MIL-HDBK-217.

Most of the models in MIL-HDBK-217 use ten or more parameters for the calculation of the component failure rate. Commercially available programs, such as “Milstress” from ITEM software have been written to facilitate the calculation of failure rates. The calculation was performed using the Milstress software package.

The TDR specification for channel failure rate is “0.5 missing channel per year” or “868 missing channel per year”. If the worse case condition is taken, i.e. one channel missing means a full hybrid missing, the maximum tolerable failure rate per hybrid is “217 missing hybrid per year” or 0.57 frmh (where frmh stands for failure per million hours of operation) or $1.75\ 10^6$ hours “mean time between failure” (MTBF).

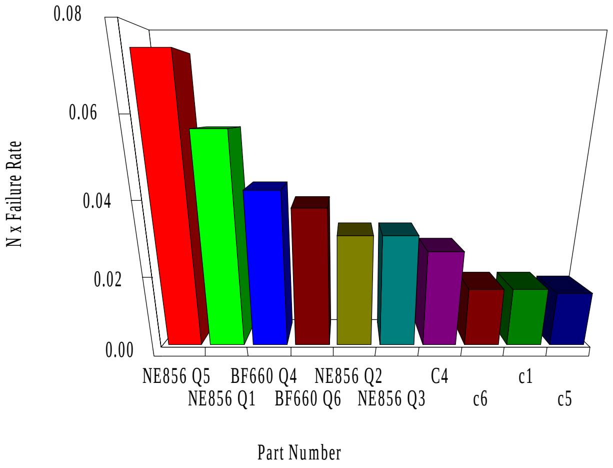

Figure 5. Significant component failure rates

The technology/component/design adopted for the hybrids has to be evaluated against this benchmark.

The reliability prediction presented in this section is for guidance, the purpose of this calculation is to establish, by means of a consistent and uniform method, the reliability of what has to be considered a “mature design”. The calculation is based on the two methods known as “Part Count” and “Part Stress Analysis” and the following assumptions have been made:

- Most of the details used in the project are known, in term of material and components.
- In a hybrid package, resistors and inductors are considered to contribute insignificantly to the overall hybrid failure rate and for this reason are assumed to have a failure rate of zero.
- The hybrid temperature has been assumed to be know and equal to 35 degree centigrade.
- The power dissipation of each hybrid component has been estimated from an actual hybrid sample and from design analysis. It has been compared with the maximum power from the component data sheet to obtain the “stress factor” for each individual hybrid component. The stress factor has been always rounded up to the second figure.
- The hybrid quality has been chosen equal to “class B microelectronic” as defined in Mil883-C screening procedure method 5004.9.

- The quality of the individual component used for the manufacturing has been set to “industrial grade, RE”.
- The environment has been set to “ground benign”

Based on this information a failure rate of 0.48 frmh has been calculated. This result shows that the solution adopted has a predicted reliability similar to the one requested by ATLAS TDR.

Figure 4 shows the significant component failure rates of a hybrid. The transistor Q5 (the NPN NE856) used in the white follower is the single largest contributor to the hybrid failure rate.

The failure rate is also temperature dependent as shown in Table 4.

Table 4: Failure as a function of temperature

Temperature (°C)	frmh
20	0.44
30	0.48
40	0.59
50	0.70
60	0.76
70	0.93

4.3 Highly Accelerated Life Tests

As an aid in testing the reliability and design limits of the preamplifier a Highly Accelerated Life Test (HALT) of a selected group of preamplifiers was performed at a Qualmark Corporation facility in Marlborough, Massachusetts. The purpose of this testing process was to induce failure in the tested product(s) in a non-destructive way so as to expose weaknesses in design or manufacture. This information then can be used to improve the devices and to select the manufacturing processes used in producing the devices.

Twelve preamplifiers, six 50Ω / 1mA and six 25Ω / 5mA, were mounted on a board with power and signal input/output lines so that the response could be monitored during the test. The board with the mounted preamplifiers was inserted in a computer controlled environmental chamber and tightened to a “platform” which can be vibrated by simultaneous triaxial shakers in a frequency range of 0 to 2 kHz.

The testing process was divided into 3 stages. The initial stage consisted of varying the temperature of the preamplifiers, first gradually and then in rapid temperature cycling (between - 100 °C and 100 °C). The second stage involved accelerating the preamplifiers at a fixed temperature (30 °C) starting at 5 Grms (Gravities root mean square) and increasing the acceleration in steps of 5 Grms up to a maximum of 50 Grms. In the final stage, both acceleration and rapid thermal cycling were combined.

The only preamplifier failure during the test was observed after many thermal cycles and at a vibration ~ 50 Grms, where all four channels of one hybrid became intermittent. The failure was caused by the failure of the + 3 Volt power pin. The edge pin solder joint broke due to the “fatigue” accumulated in the test.

At the conclusion of the test the pin was replaced and the hybrid was found working in specification.

A visual inspection identified that some of the hybrid power pins (the four pins on the longest side of the hybrid) were not centred into the pad and they were soldered to an angle in respect to the ceramic substrate.

The pins were the last components to be assembled were hand-soldered in place. The input/output pins on the contrary were assembled through “dipping and flowing” in one step operation. The pin assembly is the less automated part of the manufacturing process. A more stringent inspection will be required for the final production.

5. CONCLUSIONS

The design and technology used for the construction of the LAr calorimeter preamplifier have been extensively tested on 1,800 hybrids. These devices have met all physics requirements. No changes in design are expected. The hybrid quality has been successfully inspected. The final hybrid production is in progress.

6. ACKNOWLEDGMENTS

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