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RADIATION HARDNESS TESTS OF GaAs AMPLIFIERS FOR LIQUID ARGON CALORIMETRY

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1 Introduction

The high luminosity at LHC requires a high radiation resistance for the detectors, especially for those parts of calorimeters which cover the maximum of the electromagnetic shower. The total neutron flux expected after 10 years of LHC running is up to about 10^{15}n/cm^2 and the γ - dose about $(10 \div 20)$Mrad [1]. These radiation levels are estimated for the region of $\eta = 3$, but vary with different detector positions [2] and decrease by one or two orders of magnitude in the region of the end-cap hadronic calorimeter. The electronics which is installed inside the detector should withstand these radiation levels. The GaAs technology is one candidate for radiationhard electronics. In the context of the RD33 experiment, preamplifiers, summation and shaping electronics were designed in GaAs technology to be used for an electromagnetic liquid argon calorimeter [3]. The working point of the electronics is optimized for a temperature of −187°C. The GaAs technology is based on n-channel transistors. The preamplifier is a current sensitive amplifier which means that the feedback capacity was chosen to be low. The amplification factor is described by the transfer function which is the ratio between the output voltage at the terminating resistor and the input current. The linearity and the noise are the main characteristics which were measured at different dose levels and fluences in the present study. The radiation hardness tests of GaAs electronics were performed in the Joint Institute for Nuclear Research, Dubna.

2 Dubna Facilities for Radiation Hardness Tests

JINR has rather good facilities for radiation hardness tests. There are two reactors which are the sources of fast neutrons as well as γ's, and a powerful γ-source of ^{137}Cs.

The Frank Laboratory of Neutron Physics has two fast neutron, high flux, periodically pulsed reactors (IBR-30 and IBR-2). The reactors operate in the regime of periodic, short power pulsations with a high average power rating. The power pulses of IBR-30 and IBR-2 are generated by external modulation of the reactivity. A short - duration state of superprompt - criticality is achieved periodically, during which the power increases rapidly. At other times, in between the power pulses, the reactor is highly subcritical and its power is small.

2.1 Reactor IBR-2

Some general characteristics of the reactor IBR-2 are listed below [4]:

• average thermal capacity	2MW
• working frequency	5Hz
• peak power in pulse	1800MW
• critical mass	100kg PuO_2
• half-width of fast neutron pulse	230μsec
• neutron leakage from reactor into solid angle 4π (time-averaged)	$1.75 \cdot 10^{17}$n/sec
• flux density of neutrons ($E > 0.01$MeV) in central channel (time-averaged)	$3 \cdot 10^{14}$n/(cm^2 $\cdot$ sec)

The reactor is surrounded by two concentric shielding walls with about 3m space in between. This space can be used to place the equipment for irradiation. The experimental hall is directly outside of the concrete shield. It serves also as an area for assembly of reflectors, water moderator, etc.

There are a total of 14 horizontal channels for the extraction of neutron beams, some of which are accessible for radiation tests. The geometrical cross section is typically $10 \div 40$cm in vertical and horizontal direction. The neutron fluxes vary between a few 10^8n/cm^2/sec and a few 10^{12}n/cm^2/sec depending on the shielding and position. The shape of the fast neutron energy spectra is rather similar for the various channels. The ratio between the neutron flux and the γ-dose can be varied by several orders of magnitude due to shielding. The average dose rate of γ-rays without filters is in the range of 1Gy/min. A pneumatic system provides for the transport of the test objects to and from the irradiation zones during the irradiation [5].

The channel which was used for this study has the following characteristics: the geometrical acceptance is 20×40cm^2 with a fast neutron flux density of $\sim 10^{10}$n/cm^2/sec.

2.2 Reactor IBR-30

The reactor IBR-30 with an average power of 30 kW has the same operational principle as IBR-2. The half-width of the fast neutron pulse is about 4μsec and the fluence of fast neutrons is 10^{13}n/cm^2/sec. The active core is installed in a special hall of 10×10m^2 with a safety concrete shielding. One may install test samples near the the active core; a few beam channels may be equipped if necessary with electronics cables and cryogenics.

2.3 γ - Source

The γ-source used for the radiation hardness tests irradiates a cylindrical hole with the diameter of 15cm and height of 30cm. The hole has four special slits at symmetrical positions. Beyond each slit there is a movable platform equipped with a remotely controllable rotating mechanism and with tubes containing ^{137}Cs isotope sources. One can change the γ rates by selecting sources of different activity (20, 200 or 1800 Ci) in front of each slit. The γ energy is 661.7keV.

Some modifications of the top cover of the source were made to allow for the cryogenic transfer line. It was not reasonable to move the cryostat from and into the hole during the tests, and the position of the platforms was found corresponding to the minimal (background) γ-dose rate inside the irradiated zone. This was the set-up when all the sources were removed far from the slits.

3 Measurement setup

The electronics was irradiated step by step when operating in liquid argon, until the maximal dose value was achieved. After each step the main parameters (transfer function, linearity and noise) were measured. A pulse generator connected with attenuators was feeding signals to the GaAs preamplifiers which were placed on a motherboard inside the cryostat. The triangular shape of the pulse is provided by a 150pF capacitor connected with a 1kΩ resistor on the board. The input line is terminated by a resistor of 50Ω. The outputs of the preamplifiers and of the GaAs shapers were connected to a scope which was read out by a personal computer. For the noise measurement an additional shaper with variable shaping time was inserted between the GaAs electronics and the scope, the "La Taile shaper" [6].

The motherboard has four preamplifier chips with 8 preamplifiers in each chip and four summing/shaper chips with two summing/shapers in each chip. They are arranged in four identical units on the mother board. The board is split in two halfs with independent power supplies. One part (PART 1) was connected to the power supply during the whole period of irradiation whereas the other (PART 2) was switched off during irradiation. Each unit has one preamplifier chip and one summing/shaper chip. The first summing/shaper is connected with one preamplifier whereas the second summing/shaper is connected with three preamplifiers. Therefore there are two output channels $SU_{(1)}$ and $SU_{(3)}$. These four preamplifiers have one common input. Three of the other four preamplifiers have different detector capacitance in front ($19pF$, $134pF$ and $839pF$) and are connected to a second common input line. The outputs are called $PA_{(19)}$, $PA_{(134)}$ and $PA_{(839)}$, respectively. The capacitance of the preamplifiers connected to $SU_{(1)}$ and $SU_{(3)}$ is $19\ pF$.

The motherboard was placed into a cryostat and cooled by liquid nitrogen. Two thermal resistors ($PT100$) where used for remote control of the nitrogen level.

The noise was measured using the La Taile shaper for various shaping times having no input at the preamplifier. The noise in terms of input current is the r.m.s. voltages measured at the scope (terminated with 50Ω) divided by the transfer function. The transfer function was measured with the input signal height of 3V attenuated by 50db.

For the measurement of linearity the height of the output signal was measured for various attenuators setting between 45db and 2db but fixed pulse height of the pulse generator ($3V$). The peaking voltage and time were estimated by fitting the output signal with a Gaussian.

4 Irradiation by fast neutrons

The irradiation of the electronics by fast neutrons were carried out at the two Dubna reactors, IBR-2 and IBR-30, with a similar set-up of the equipment. The cryostat was surrounded by a 5mm thick layer of B_4C to absorb thermal neutrons which would produce an additional γ-dose through their capture in the nitrogen and the surrounding material. A 5cm thick lead wall in front

suppressed the direct γ-irradiation from the reactor. During the first run of neutron irradiation at IBR-2 the cryostat with its shielding was fixed on a special stable frame on a moveable platform. The cryostat was placed as close as possible to the inner shielding ring of the reactor. The counting room was about 15m from the outer shielding ring. The signal cables had a total length of 40m.

A set of activating foils (as energy threshold detectors) was temporary mounted inside the cryostat for the monitoring of the neutron flux. Also a wide nickel foil was fixed on the back side of the board for the whole irradiation period. The γ–dose was determined with pills of thermo - luminescent detectors. The pills were placed at different positions around the cryostat inside the boron shield.

4.1 Measurement of the neutron flux and corresponding γ - dose

The energy spectrum of the neutrons and the γ-dose were measured in dedicated monitoring runs at a decreased reactor power. The main irradiations were performed at the nominal operating conditions. As the flux is proportional to the reactor power, the final flux is given by the result of the monitoring run multiplied by the ratio of the reactor powers. The neutron energy spectrum as obtained with a set of activated foils is presented in Fig. 1. The average flux of neutrons with energies between 0.4 and 15MeV is $(9.3 \pm 0.9) \cdot 10^9 \mathrm{n/cm^2\,sec}$. Neutrons with energies between 0.1 and 0.4MeV contribute an additional 30 % to the average flux. The expected damage from low energetic neutrons is negligible compared to the high energy component. Therefore all total fluxes mentioned are with respect to the energy interval of $0.4 - 15$MeV. It takes about 35 hours of irradiation to collect the total neutron flux of $10^{15} n/cm^2$ at the IBR-2 reactor power of 2MW. The neutron energy spectrum at the IBR-30 reactor is similar to IBR-2. The density of the fast neutron flux in the cryostat was measured to be $(3.0 \pm 0.3) \cdot 10^9 \mathrm{n/cm^2}$ which is only a factor of three lower than at IBR-2.

The activity of the wide nickel foil was used to measure the homogeneity of the neutron flux over the motherboard region. The flux was uniform within ±5%. The induced activity of the foil after the irradiation confirmed the value of the total neutron flux measured as described above.

The rate of γ-quanta was suppressed succesfully for the neutron irradiation at IBR-2 and IBR-30. The γ-dose rates were measured to be about $(4 \div 5)$krad per hour. Thus, during the 35 hours run at IBR-2 the total γ-dose did not exceed 170krad.

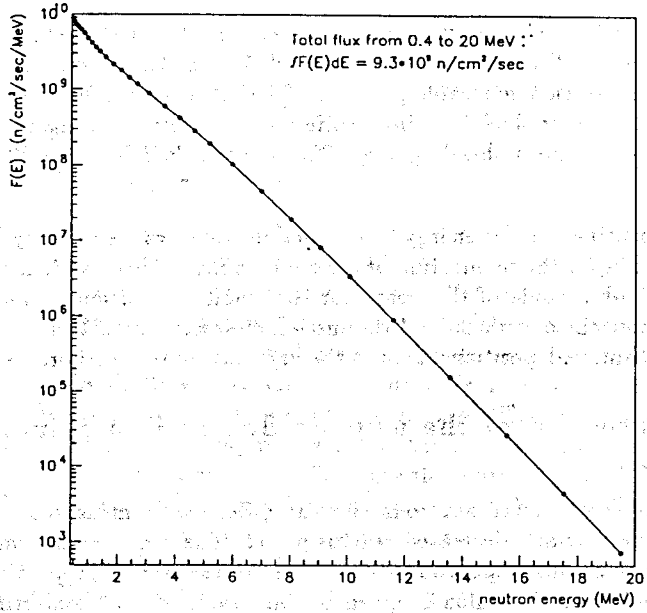

Figure 1: The measured neutron energy spectrum.

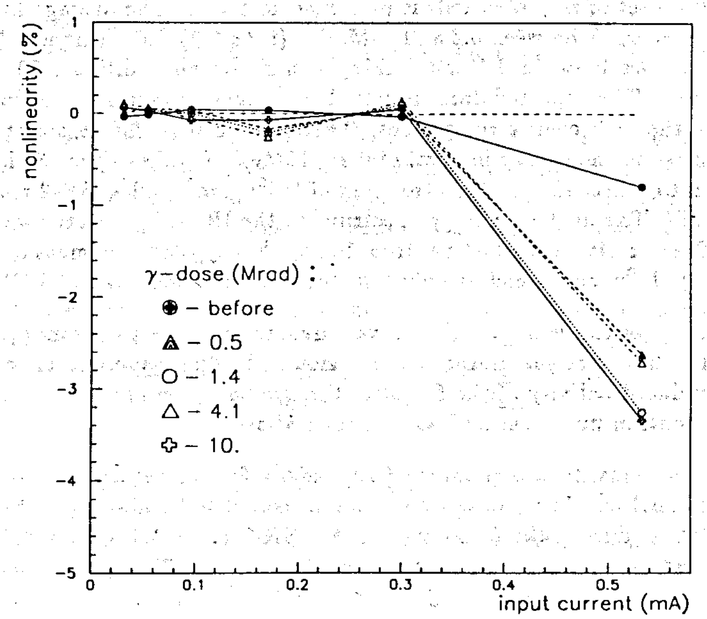

Figure 2: Linearity of the preamplifier with a detector capacitance of 134pF for different γ - dose levels.

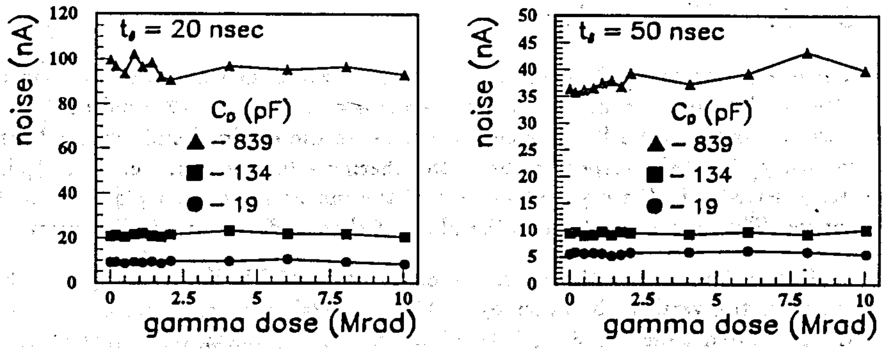

Figure 3: Noise of GaAs preamplifiers measured at the shaping time values of 20 and 50nsec with various detector capacitance and for different γ - dose levels.

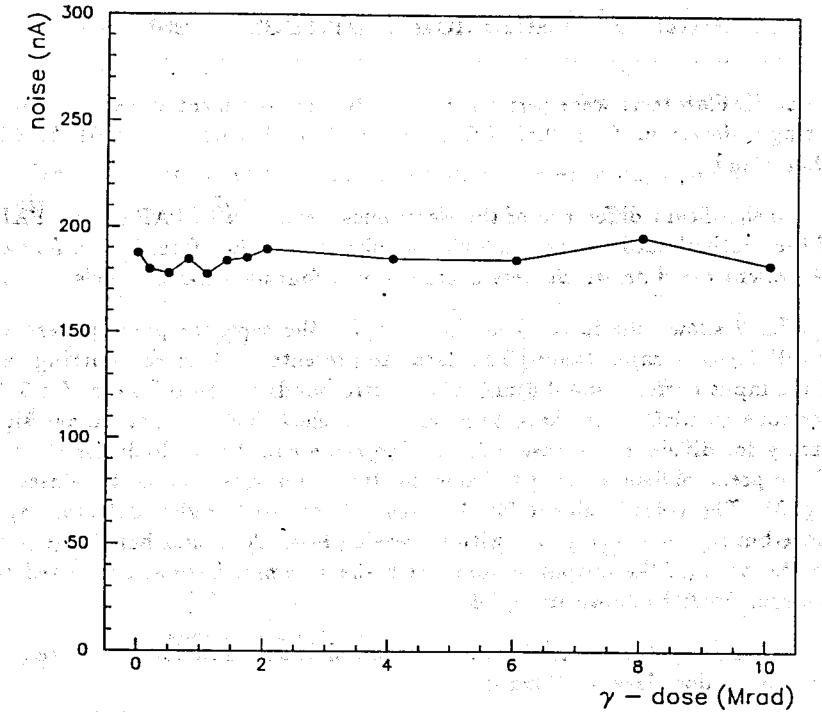

Figure 4: Noise of the output channel with summing/shaper and preamplifier for different γ - dose levels.

5 Irradiation by γ

The irradiation of the GaAs electronics with γ's was done using the ^{137}Cs source. The topology of the γ-doses in the cryostat was measured in a special run at two positions of the ^{137}Cs bars which correspond to the minimal and maximal total intensity. For this purpose a set of the thermo - luminescent detectors (pills) was inserted into the cryostat instead of the motherboard and placed into the source. The pills were glued to the plate at three different vertical positions.

It was found that the γ-dose is constant in the horizontal direction but varies in the vertical direction by $\sim$ 10%. The average maximal dose rate in the irradiated zone is (180 ± 26)krad/h whereas the background rate is about (402 ± 18)rad/h. The main irradiation was performed at a rate of 180krad/h, and the measurements were done at the minimal intensity of the source.

It took about 56 hours of irradiation to collect the total γ-dose of 10Mrad.

6 Results of Radiation Hardness Tests

γ **- radiation** tests were performed in twelve measurement steps with the following γ-doses: 0., 0.18, 0.49, 0.80, 1.10, 1.41, 1.73, 2.04, 4.06, 6.04, 8.05 and 10.05 Mrad.

No significant difference of the electronics behaviour of PART1 and PART2 of the motherboard (power on/off) was observed. Therefore, in the following we present the data which were averaged over four identical channels.

Fig. 2 shows the integral nonlinearity for the separate preamplifiers with 134pF detector capacitance. The data are presented within the working range of the input current $(0 \div 0.6)$mA which corresponds to the full range for 5 TeV electrons at LHC. The characteristics of the electronics do not change significantly for different γ - dose values. The same conclusion holds for the noise of the preamplifiers varying the shaping time from t_δ = 20nsec to 50nsec (see Fig. 3). The noise is higher for the preamplifiers with higher detector capacitance but it remains constant with increasing dose. A similar behaviour is seen for the noise of the output channel with the summing/shaper connected with one preamplifier (shown in Fig. 4).

In summary, the GaAs electronics tested shows no deterioration of response up to a γ - dose level of 10Mrad.

The response of the GaAs electronics to the **neutron irradiation** was measured in a few exposures at the IBR-2 reactor up to a fluence of $1 \cdot 10^{15}$n/cm^2. Above 10^{15}n/cm^2 fatal changes of the signal shape for all channels were ob-

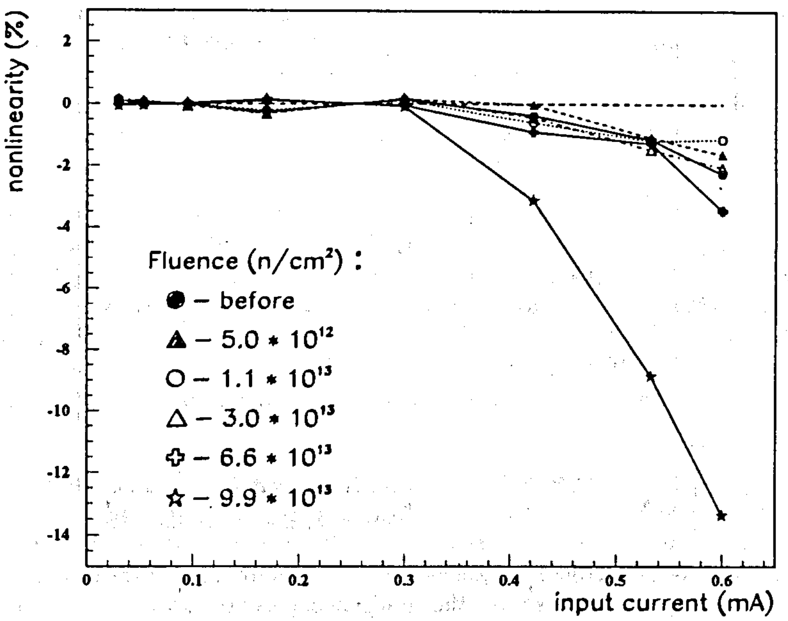

Figure 5: Linearity of the preamplifier with a detector capacitance of 134pF for different neutron fluence values.

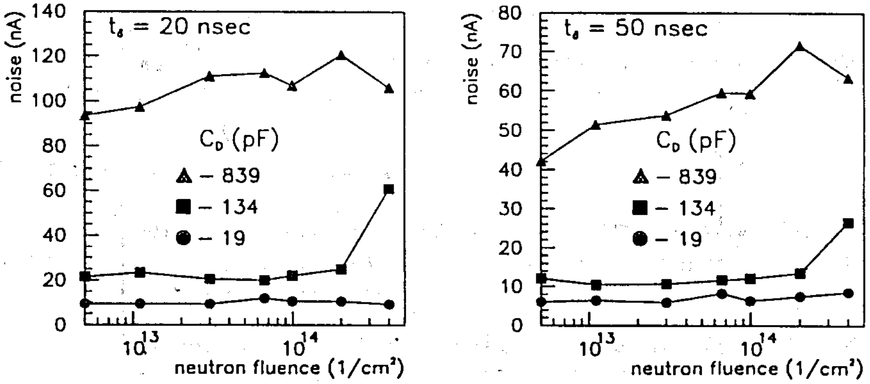

Figure 6: Noise of GaAs preamplifiers measured at the shaping time values of 20 and 50nsec with various detector capacitance and for different neutron fluence values.

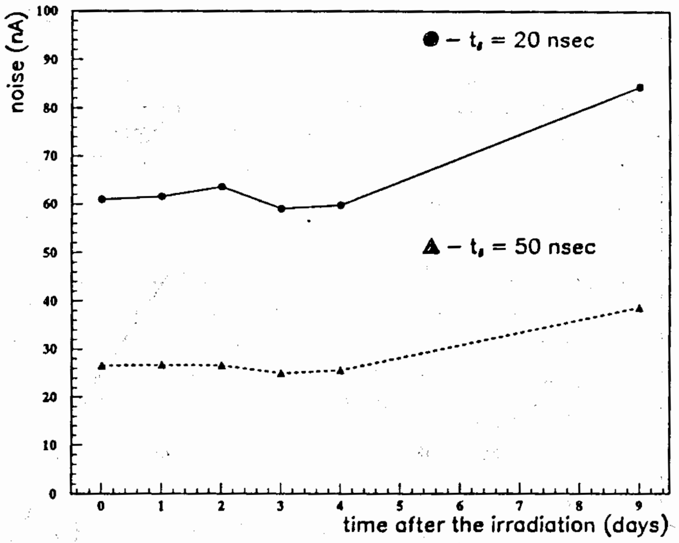

Figure 7: Noise of the preamplifier with a detector capacitance of 134pF measured during a few days after the irradiation (see text).

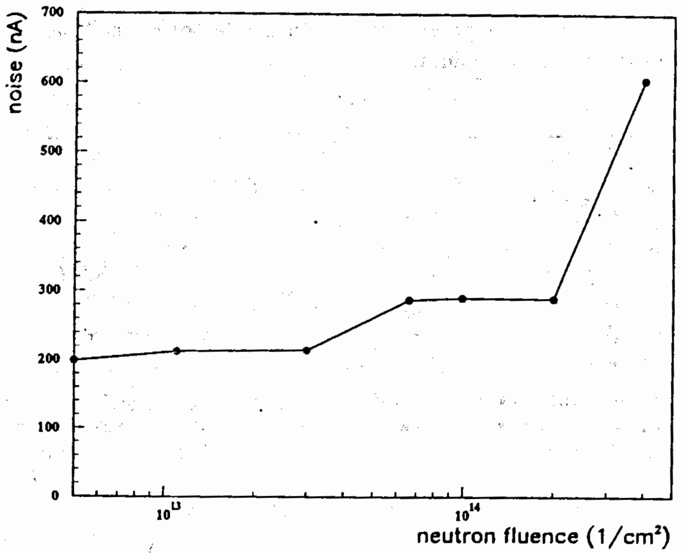

Figure 8: Noise of the output channel with summing/shaper and preamplifier for different neutron fluence values.

served. As for the integrated circuits, the input and output signals of the shaper were the expected agreement, but the functioning of the preamplifiers was obviously destroyed by the large neutron dose. A detailed study of the motherboard showed that all the components were working properly except the preamplifiers. At room temperature we observed no difference in the characteristics of the electronics in comparison with those before the irradiation.

To study the behaviour of the electronics with neutron fluence more carefully, a total of eight runs of detailed measurements were undertaken at IBR-30 reactor. The first one was done before the irradiation when the cryostat was installed at the position in the hall. Then the electronics was measured at the following values of the neutron fluence: $5.0 \cdot 10^{12}$, $1.1 \cdot 10^{13}$, $3.0 \cdot 10^{13}$, $6.6 \cdot 10^{13}$, $9.9 \cdot 10^{13}$, $2.0 \cdot 10^{14}$ and $4.0 \cdot 10^{14}$n/cm^2. After that we stopped the irradiation and continued with the measurements in order to estimate the relaxation effects if present.

Fig. 5 shows the nonlinearity of the preamplifier with 134pF detector capacitance at the input. It is seen that after a neutron fluence of the order of 10^{14}n/cm^2 the working range of the preamplifier became shorter and is quite nonlinear at $4 \cdot 10^{14}$n/cm^2. The noise measurements for the preamplifiers with different detector capacitance and shaping time values are presented in Fig. 6. For the preamplifier with $C_D = 134$pF the noise increased significantly when the fluence increased from $2 \cdot 10^{14}$n/cm^2 to $4.0 \cdot 10^{14}$n/cm^2. At this moment the irradiation was stopped but the motherboard was kept in cold inside the cryostat during four days. A series of standard measurements were performed, and the last one was done after five days when the electronics was at room temperature. The data presented in Fig. 7 indicate no relaxation effects.

As presented in Fig. 8, the noise of the summing/shaper connected with preamplifier increases after $2 \cdot 10^{14}$n/cm^2.

7 Conclusions

The GaAs electronics (preamplifiers and summing/shapers) designed for the TGT liquid argon calorimeter was tested with ^{137}Cs γ - source and fast neutron beams at the Dubna pulsed reactors.

We have observed no degradation of the electronics till the total γ - dose of 10Mrad.

The neutron fluence of the level of $2 \cdot 10^{14}$n/cm^2 is critical for the GaAs electronics tested.

In the region of the end-cap hadronic calorimeter of the ATLAS detector the radiation levels are about ten times smaller than those achieved during the tests we have performed. Thus, the designed electronics would be appropriate for the hadronic calorimetry of ATLAS.

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