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Neutron irradiation of HF BJT and 0-T hybrids.

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Abstract

We have irradiated with fast neutrons at the SARA facility (Grenoble) a 25Ω/10mA and a 50Ω/1mA 0-T preamplifier, realized in thick-film hybrid technology as well as single bipolar devices biased at the conditions expected in the complete circuit. After 24 hours of irradiation test the maximum fluence was about $1 \cdot 10^{14} n/cm^2$ (1 MeV equivalent in Si). Variation of signal waveform in preamplifiers was measured as a function of fluence, but no noise degradation has been observed after irradiation. We have measured the dependence of the forward-gain of bipolar transistors with fluence and found that it is described quite well by Messenger-Spratt model and we have extracted the values of damage constants for each transistor.

1 Introduction

In the framework of the ATLAS Collaboration for LHC[1], we have realized 0-T preamplifiers using a hybrid technology. Although these preamplifiers will operate outside the cryostat, the radiation levels expected after 10 years of LHC operation with a luminosity of $10^{34} cm^2 s^{-1}$ reach, in the crack area (location of electronics) an integrated fluence $\approx 10^{13} neutrons/cm^2$ [1]. In the present paper we discuss the performance at room temperature of UHF and HF bipolar junction transistors (BJT) and hybrid circuits, before and after neutron irradiation, which was performed in Grenoble (SARA Facility) in July 1997, including the data taken on-line during this experiment. The main features of the SARA facility [2] can be summarized as follows:

- Neutrons are generated by a deuteron beam (E=20 MeV) striking a thick Be-target (Stripping reaction ${}^{9}Be(d,n)^{10}B$);
- The neutron spectrum is well characterized , an average energy $< E >$=6 MeV;
- The ratio of the real neutron fluence to the 1-MeV equivalent fluence is well known for Si and is equal to 1.5;
- The photon contamination is low: 3.6 kGy of γ's after $2 \cdot 10^{14} neutrons/cm^2$.

The neutron flux was monitored on-line by direct measurement of the deuteron charge collected on the Be-target, then, the final values of neutron fluences were deduced from ^{58}Co activities measured on irradiated Ni samples, put directly on the devices.

2 Experimental set-up.

We have irradiated two hybrids containing four channels each, and 8 bipolar transistors (two samples of each type) mounted on a single board. The arrangement of components and circuits is shown in fig.1. The hybrid 1 (25Ω/10mA) preamplifier was fabricated by Laben (Milano,Italy) and the hybrid 2 (50Ω1mA) was fabricated by NeOhm (Torino,Italy). Their electrical diagram is shown in fig.2. In channels 3 and 4 of hybrid 2 (we called them h2c3 and h2c4) we have substituted the fast pnp-type BF660 (f_T = 700 MHz) with slow 2N3906 (f_T = 250 MHz) transistors (marked as Q_4 in fig.2). The reason was to understand better the impact of choosing a fast or slow pnp transistor in the output stage on the preamplifier performance with irradiation.

Single bipolar transistors have been put in the setup to study the dependence of DC characteristics as a function of fluence. Two samples of NEC856 were biased exactly in the same way as the head transistors of PA's (I_c = 3 mA and V_{cb} = 1.5 V), while the other transistors had different values of currents and V_{cb} (see Table 1 and fig.1). The motherboard with devices and hybrids was put in front of the Be-target at a distance ≈10 cm. The estimated flux of neutrons at this position is about $10^9 n/cm^2/s$, which gives an integrated fluence after 24 hour run of about $10^{14} n/cm^2$. Signals from PA's and DC collector voltages from BJT's were delivered to Control Room via 6 m shielded coaxial cables.

In Table 1, the description and bias conditions of all 8 transistors are indicated. After integrating a step of flux, we stopped the beam to avoid e.m. pick-ups and started to make on-line measurements of signal waveforms and collector DC voltages of all BJT from which we extracted the value of forward gain. The measurements of signal waveforms have

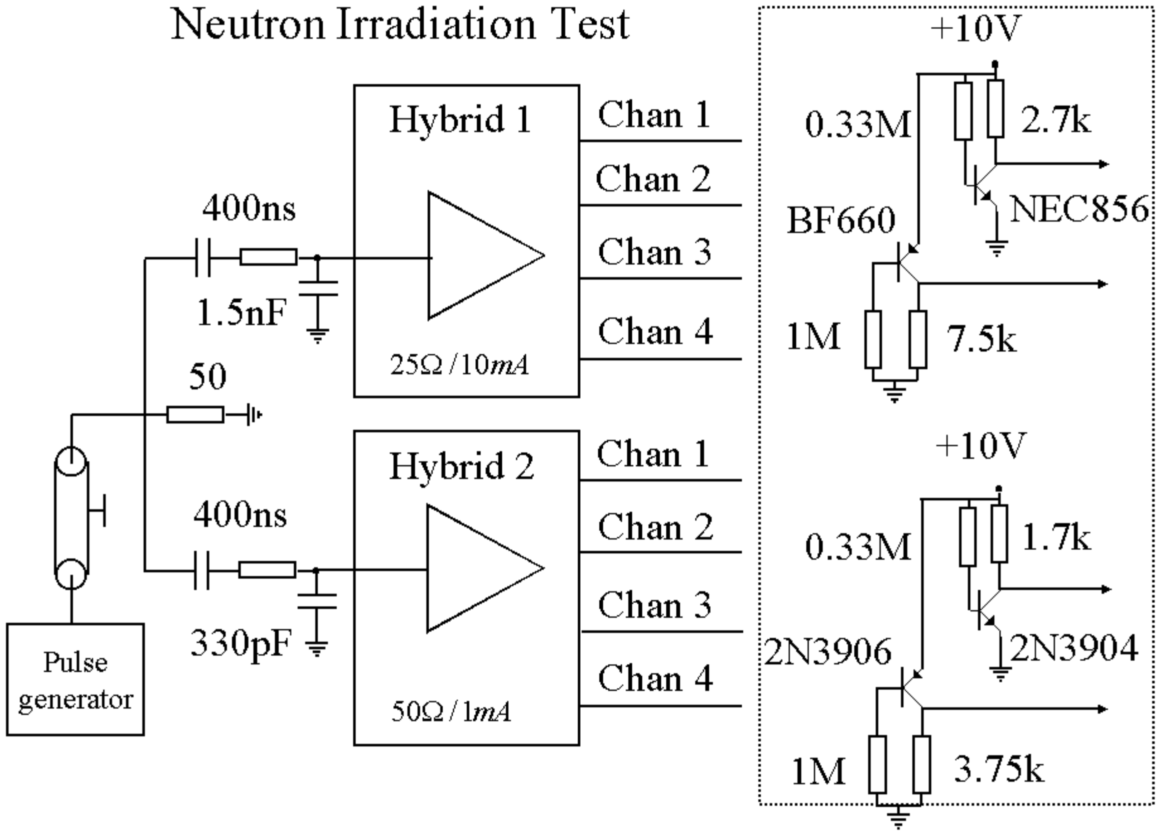
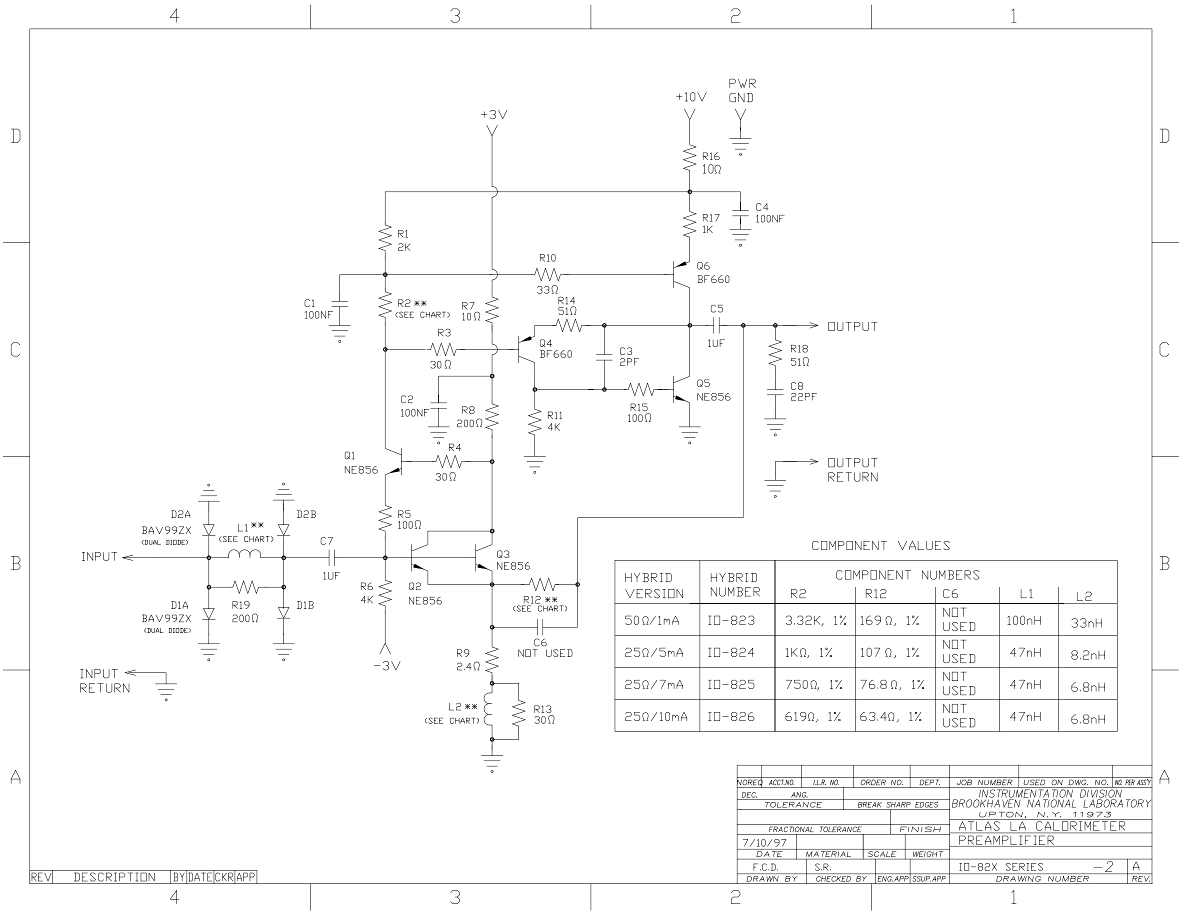


Figure 1: *Scheme of a board with circuits and single devices, irradiated in July 1997 Run. The responses of each preamplifier and DC collector voltages of separate BJT's have been measured after each accelerator stop.*

been done with an automatic system, designed at ISN (Grenoble). It consisted of a digital scope and a pulser controlled by a Personal Computer via GPIB interface.

3 DC performance and β-measurements.

It has been well established that neutron irradiation, in general, causes changes in conductivity and in minority carrier lifetimes, due to the mechanism of creation of new vacancies, interstitial pairs or even defect clusters in the lattice of semiconductor under study. The specific phenomenon is that defects introduce trapping energy states, which correspond to actual physical recombination sites created within the lattice. These trapping sites remove the minority carriers in their transport through the base, thus reducing the minority carrier lifetime. This trapping reduction of the minority carrier life-time can be



COMPONENT VALUES

HYBRID VERSION	HYBRID NUMBER	COMPONENT NUMBERS				
		R2	R12	C6	L1	L2
50Ω/1mA	IO-823	3.32K, 1%	169 Ω, 1%	NOT USED	100nH	33nH
25Ω/5mA	IO-824	1KΩ, 1%	107 Ω, 1%	NOT USED	47nH	8.2nH
25Ω/7mA	IO-825	750Ω, 1%	76.8 Ω, 1%	NOT USED	47nH	6.8nH
25Ω/10mA	IO-826	619Ω, 1%	63.4Ω, 1%	NOT USED	47nH	6.8nH

Figure 2: *Schematic diagram of 0-T preamplifier. 4 channels are accommodated on a single hybrid. The table on the insert shows required values of components to adapt preamplifier to different dynamic ranges and detector capacitances.*

represented by a well-known relation [3,4]:

$$\frac{1}{\tau} = \frac{1}{\tau_i} + \frac{\Phi}{K_D}, \tag{1}$$

where τ_i is the unirradiated value of the minority carrier lifetime, Φ is the incident neutron fluence and K_D $(neutrons/cm^2 \cdot sec)$ is called the damage constant. To make a connection between the minority-carrier lifetime (τ_i) degradation and the common emitter (CE) current gain (β) degradation , we suppose that base transport is the dominant mechanism with respect to common emitter gain. The base transport factor α_T generally can be written as an expansion in even powers of $\frac{W}{L_n}$ [3]

$$\alpha_T = 1 - u_1 \cdot \left(\frac{W}{L_n}\right)^2 + u_2 \cdot \left(\frac{W}{L_n}\right)^4 - ... \approx 1 - u_1 \cdot \left(\frac{W}{L_n}\right)^2 \tag{2}$$

where W is the base width, $L_n = \sqrt{D_n \cdot \tau_i}$ is the diffusion length, D_n is the diffusion coefficient and $u_{1,2}$ are coefficients to be determined. Implying an emitter efficiency $\eta = 1$

Table 1: Description of type, transition frequency, DC current gain, bias conditions and measured value of damage constant. n stands for npn and p stands for pnp type transistor.

No	BJT	type	f_T,GHz	β_o	$I_c, mA(I_b, \mu A)$	V_{cb}, V	$K_D, n/cm^2 \cdot sec$
1	BF660	p	0.7	65	0.6(9.3)	5.5	$(2.82 \pm 0.1) \cdot 10^5$
2	NEC856	n	7	111	3.12(28)	1.57	$(1.34 \pm 0.36) \cdot 10^6$
3	BF660	p	0.7	65	0.8(9.3)	3.8	$(2.8 \pm 0.09) \cdot 10^5$
4	NEC856	n	7	111	3.11(28)	1.62	$(1.05 \pm 0.32) \cdot 10^6$
5	2N3906	p	0.25	243	2.26(9.3)	1.5	$(4.1 \pm 0.083) \cdot 10^5$
6	2N3904	n	0.3	149	4.2(28)	3	$(5.1 \pm 0.1) \cdot 10^5$
7	2N3906	p	0.25	190	1.78(9.3)	3.33	$(4.14 \pm 0.087) \cdot 10^5$
8	2N3904	n	0.3	167	4.67(28)	2.24	$(6.6 \pm 0.16) \cdot 10^5$

and a significant CE current gain $\beta > 3$ we can write the relation between α_T and β

$$\beta^{-1} \approx 1 - \alpha_T = u_1 \cdot \frac{W^2}{D_n \cdot \tau}. \tag{3}$$

In [3] it is shown by using continuity equations governing the excess minority carrier density and the corresponding current density that the coefficient u_1 is related to the gain-bandwidth product of the transistor f_T:

$$u_1 = \frac{D_n}{2\pi \cdot f_T \cdot W^2}. \tag{4}$$

If formula (3) is inserted into equation (1), the result is, using (4), the Messenger-Spratt CE gain degradation relation [5],[6]:

$$\frac{1}{\beta} = \frac{1}{\beta_i} + \frac{\Phi}{2\pi \cdot f_T \cdot K_D}. \tag{5}$$

This relationship was originally proven for homogeneous base transistors [5] and, later, it was shown in [6] that this relationship is true for any base doping profile, as long as the transistors retain a significant CE current gain $\beta > 3$. The results on relative gain performance as a function of neutron fluence, for different transistors, are presented in fig.3. The behaviour of β degradation is quite well described by the Messenger-Spratt relation and in Table 1 we have put the fitted values of K_D for all transistors. The difference between K_D for different transistors can be attributed to different emitter current density and/or to different resistivity of bulk semiconductor[3,4]. To estimate the variation of the damage constant K_D with the emitter current one can use an empirical relation between the constant K_D and the emitter current density, presented in [3]. In fig.4 we put experimental values of K_D for our transistor samples with indications of emitter currents on the theoretical curve, taken from [3].

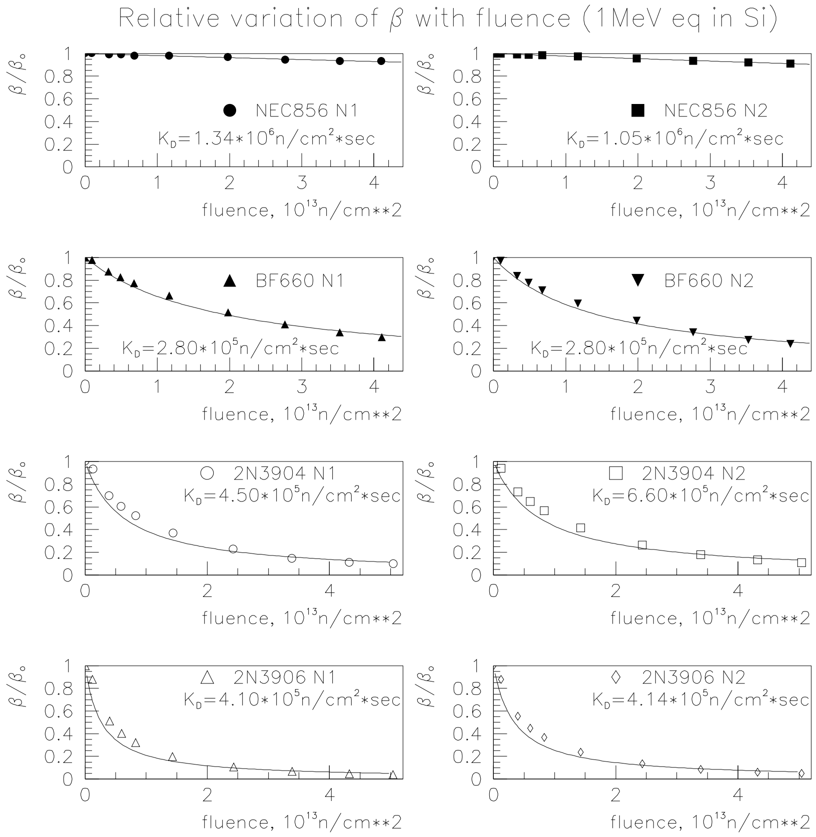


Figure 3: *The dependencies of relative forward gain* $\frac{\beta}{\beta_0}$ *on neutron fluence for 2 samples of NEC856, 2N3904, BF660 and 2N3906. The damage constant parameter* K_D *is extracted from fit using formula (5).*

4 Noise performance

Soon after the irradiation experiment in Grenoble, we have performed bench-tests of noise in our laboratory with a single transistor NEC856 and both hybrids. The set-up for the measurement of transistor noise spectral density is shown in fig.5. All the measurements have been done in two stages. First, the frequency response of the transistor and the amplifier A ($f_{-3dB} \approx 100$ MHz, gain 40) combined system has been measured. Then, the noise spectrum referred to the input has been determined as a ratio of the measured noise at the output of amplifier A to the frequency response. To reduce the noise contribution of HP4195A an attenuator 22pF:2040pF is inserted between the sweep generator S and the transistor under study. The absolute value of the measured noise was checked by varying the series resistance Z_s from 0 to 10Ω. The measured noise with inserted $Z_s = 10\Omega$ has been compared with the theoretical prediction by using the formula $U^2 = 4kT \cdot Real(Z_s)$. The results of measurements of noise spectra referred to the input of transistor NEC856, before and after irradiation, are shown in fig.6. No difference between both spectra has

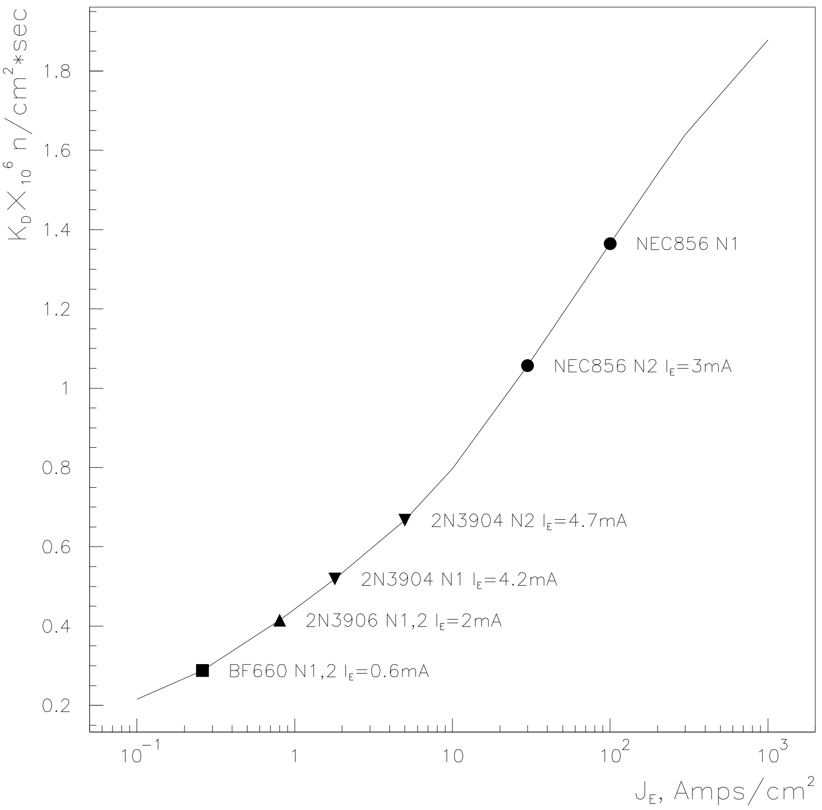


Figure 4: *The dependence of K_D versus emitter current density J_E, redrawn from [3], and experimental points for all samples under study.*

been observed.

In fig.7 one can find the measured dependencies of Equivalent Noise Current (ENI) as a function of peaking time (5%-100%) of channel 1 of hybrid 1 (h1c1) and channel 1 of hybrid 2 (h2c1), before and after the irradiation test, as well as channels 2,3,4 of hybrid 2 only after irradiation. Preamplifiers, equipped with fast components did not show any degradation in noise till the fluence $1.3 \cdot 10^{14} n/cm^2$, but 2 channels , containing slow transistors in the output stage (h2c3 and h2c4), exhibited a certain degradation at short peaking time due to signal waveform distortion and input impedance mismatch.

5 Signal waveform measurements.

During the irradiation run, as said above, we have measured the signal waveforms for the 8 channels after each step in fluence. A rectangular pulse with 500 mV amplitude from a pulse generator (see fig.1) was injected in one of two calibration circuits via 6 m coaxial cable and then distributed to all channels of each hybrid simultaneously. At the output

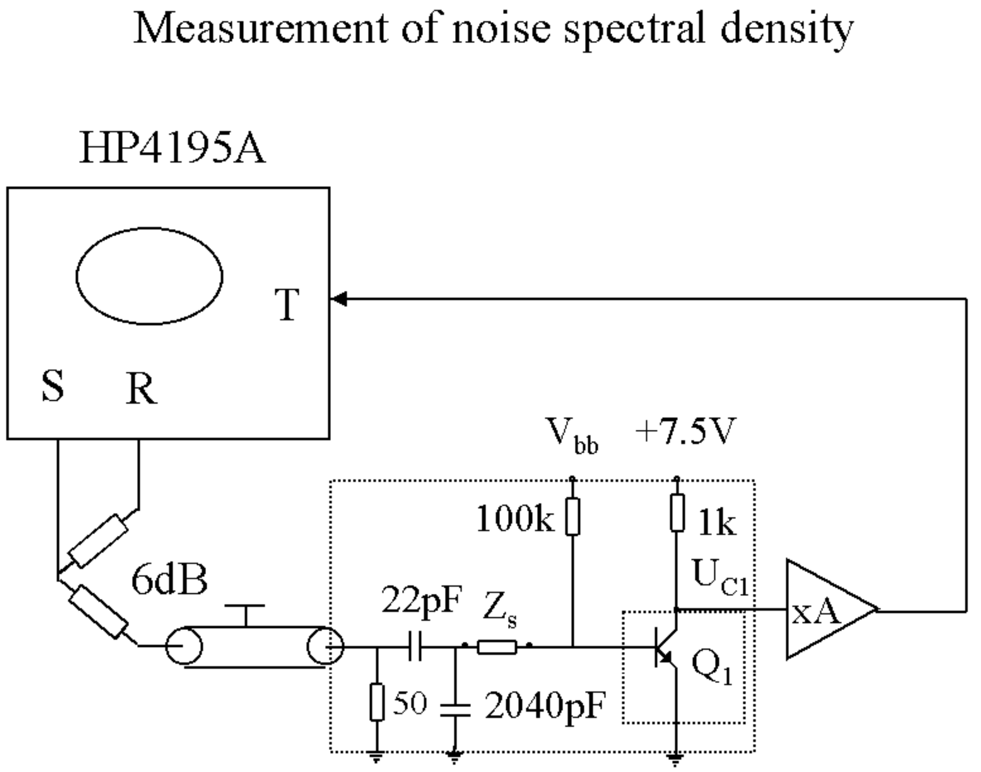


Figure 5: *The schematic diagram of the setup for measurement of noise spectral density of single transistors.*

of each calibration chain there was an exponential current pulse with 128 μA amplitude and decay time $\tau = 400$ ns. The response of each preamplifier was measured with a setup, designed in ISN (Grenoble). Signal waveforms are shown in fig.8, while the relative values of the gain degradation of preamps are presented in Table 2.

6 Conclusions

We have performed neutron irradiation of hybrid 0-T preamplifiers and single UHF BJ transistors at room temperature, keeping all the components biased. The main conclusions are the following:

- there is no noise degradation of NEC856 transistors till the fluence $5 \cdot 10^{13} n/cm^2$.
- degradation of forward-gain β follows the Messenger-Spratt relation and, at first order, is inversely proportional to f_T.

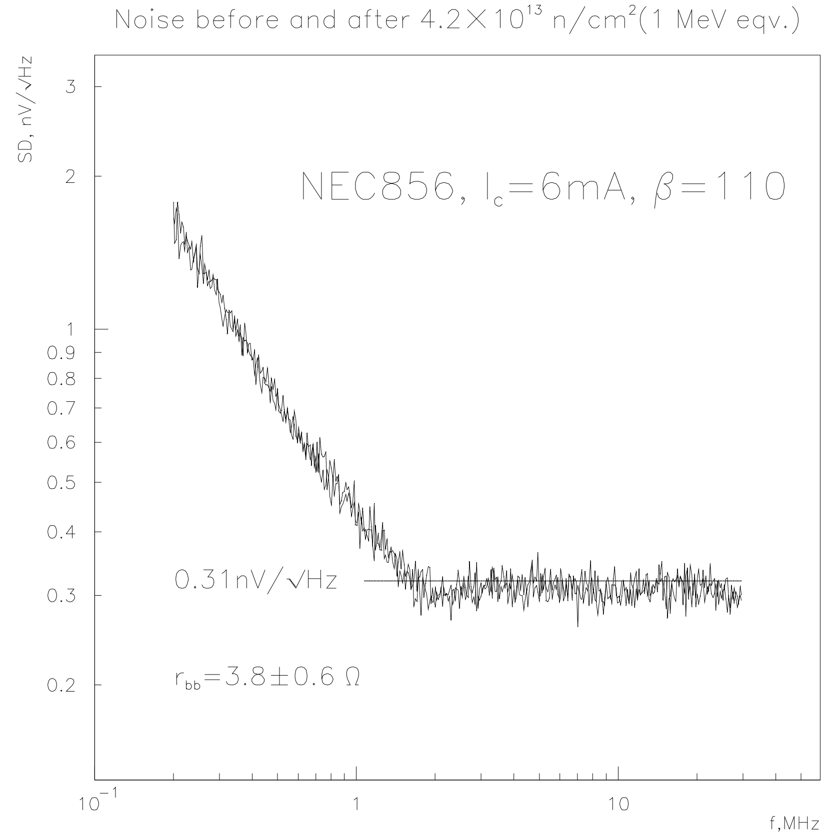


Figure 6: *The noise spectrum density of NEC856 BJ transistor referred to input of transistor before and after irradiation. The transistor was marked R24. By fitting the flat part of spectra one gets the value of the base spread resistance* $r_{bb'} = 3.8\Omega \pm 0.6\Omega$*, which is not changed after irradiation.*

- the impact of the β degradation of transistors on the preamplifier gain is very small. The 25Ω hybrid preamplifier, equipped with fast transistors (NEC856 and BF660), exhibits about 3% of gain loss (and, as a consequence, 3% change of input impedance) after $1.1 \cdot 10^{14} n/cm^2$, while the 50Ω preamplifier, equipped with the same fast transistors, has about 7% of gain loss after the same fluence.
- preamplifiers, equipped with slow pnp transistors at the output stage, exhibited after the same fluence 30% loss of gain and input impedance.
- 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.

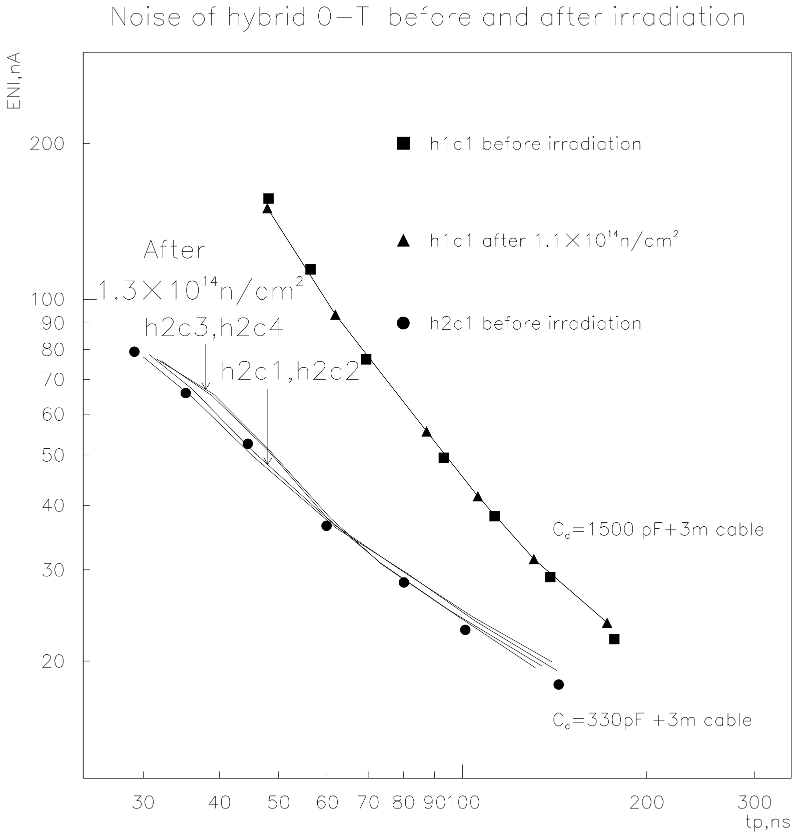


Figure 7: *The dependencies of ENI versus peaking time (5%-100%) of hybrids before and after neutron irradiation test. The channel 1 of hybrid 1 (h1c1) was measured at* $C_d = 1500$ *pF and 3m of warm cable, while the channels 1÷4 of hybrid 2 were measured at* $C_d = 330$ *pF.*

Table 2: Drop of gain of 0-T preamplifiers after $1.1 \cdot 10^{14} n/cm^2$ (hybrid 1) and $1.3 \cdot 10^{14} n/cm^2$ (hybrid 2). The output stage of h2c3 and h2c4 preamps was implemented with slow pnp 2N3906 transistors ($f_T = 250$ Mhz).

Channel	hybrid 1	hybrid 2
chan1	2%	7%
chan2	3%	5%
chan3	2%	28%
chan4	3.5%	26%

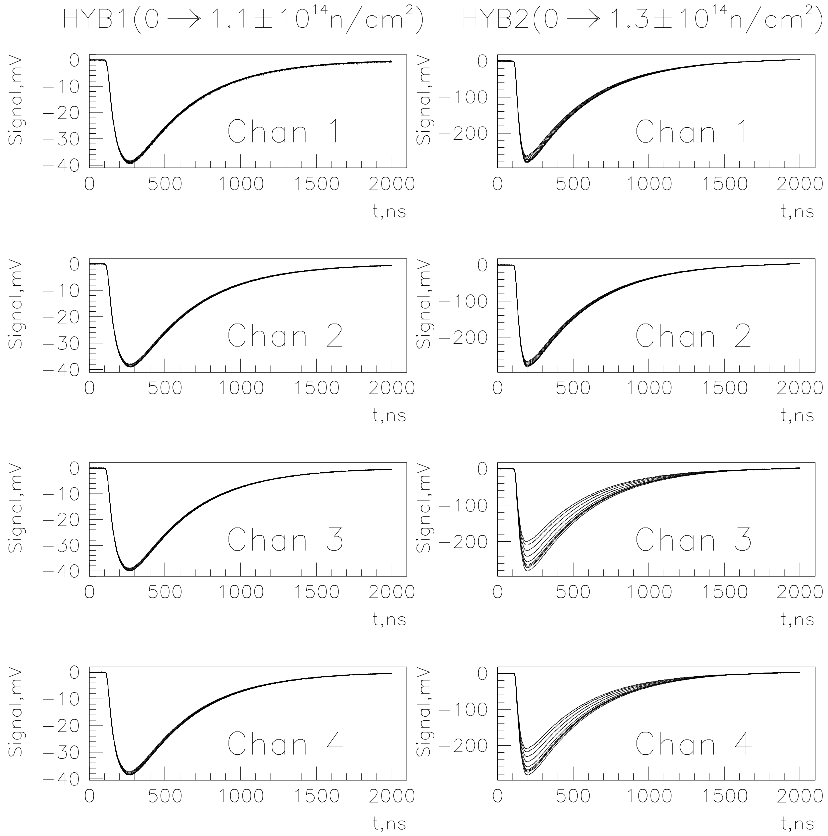


Figure 8: *The signal waveforms of 8 channels from hybrid 1 and hybrid 2, as measured on-line during irradiation test. Only the final values of the fluences are indicated in the figure for both hybrids.*

References

[1] ATLAS Technical Proposal CERN/LHCC/94-43, LHCC/P2 (15 December 1994)

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