# EXPERIMENTAL STUDY OF SYNERGISTIC EFFECTS OF NEUTRON AND GAMMA RAY IRRADIATION ON LINEAR REGULATOR

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**Abstract:** Synergistic effects of linear regulator in mixed neutron and gamma ray irradiation environment are studied. The electrical tests of the linear regulator were performed in three irradiation environments: neutron, gamma ray, combined irradiation of neutron and gamma ray. Comparison of the output voltage and the power current of the linear regulator in these three radiation environments is presented. The experiment results show that single neutron radiation induces no degradation and synergistic effects of neutron and gamma ray are related with the operational modes of the linear regulator. For off-load mode, the output voltage of the linear regulator exhibits identical TID degradation in the mixed neutron and gamma ray radiation environment with that in single gamma ray radiation environment. However, for on-load mode, the output voltage of the linear regulator increases slightly in combined neutron and gamma ray irradiation environment and decreases significantly in single gamma ray radiation environment. Bias configurations of the transistors inside the linear regulator vary at different operational modes and have considerable impact on the synergistic effects of neutron and gamma ray.

**Keywords**: linear regulator, neutron, gamma ray, synergistic effect

## I. Introduction

Linear regulators are widely used in space applications, and can offers excellent ac performance with very low ground current. High power-supply rejection ratio, low noise, fast start-up, and outstanding line and load transient response are provided while consuming a very low ground current. In electronic systems, a linear regulator provides a stable dc output voltage over a wide range of load currents and input voltage variations. Although the main disadvantage of a linear regulator is its low efficiency, it is widely used in various electronic systems in space applications. However, linear regulators have been found to be very sensitive to radiation effects, especially total ionizing dose (TID) effects and displacement damage. The radiation responses for a linear regulator may range from transient output perturbations to permanent circuit failure depending on its technology process and topology [1–4].

To study the radiation hardness for a linear regulator, the estimation of the sensitivity to radiation is a mandatory step to get an insight about the impact of radiation on its electrical parameters and functions. In radiation ground accelerated tests, TID effect is usually decoupled from displacement damage, assuming these two effects are independent. However, this assumption may neglect the interaction between different radiation effects and would lead to a misestimate of radiation tolerance. Many literatures have reported that some electronic devices exhibit synergistic effects under mixed

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neutron and gamma ray exposure [5-7].

In this paper, synergistic effects of neutron and gamma ray are studied on a linear regulator using fabricated by an advanced BiCMOS fabrication process. MOS transistors inside the linear regulator are very sensitive to gamma ray-induced TID effects [8, 9], while bipolar junction transistors are very sensitive to neutron-induced displacement damage [10]. In mixed neutron and gamma ray exposure, the degradations for both MOS and bipolar junction transistors will lead to synergistic effects on the output voltage and current of the linear regulator. Interestingly, the experimental measures also show that the synergistic effects strongly depend on its load conditions.

## II. Test description

Device under test is TPS79333DDCR manufactured by Texas Instruments. The input voltage is adjustable from 2.7 up to 6.5 V. In the experimental testing the input voltage of the linear regulator was fixed to be 6 V, and the output voltage was 3.3 V before radiation. The schematic of the testing system is shown in Fig. 1. The EN terminal is an output enable signal which is connected to the input voltage. The NR terminal is a noise reduction signal and is floating during the measurement. Two operational modes of the device are tested. In the off-load state, the output is floating. In the on-load state, the electrical impedance is a resistor of 100 Ω.

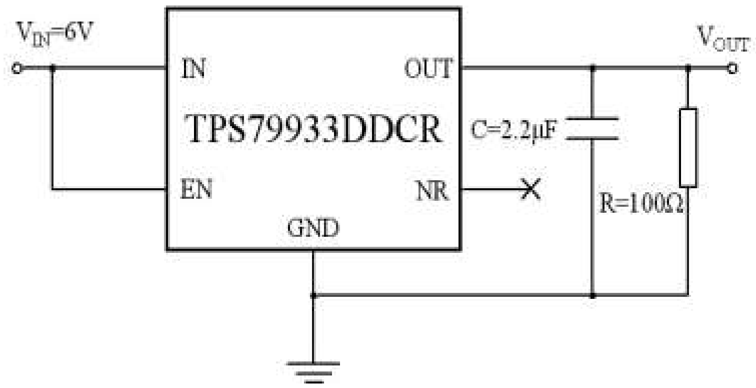


Fig. 1. Schematic of the test system.

The output voltage and the power supply current are tested in neutron radiation, gamma ray radiation and mixed neutron and gamma ray radiation environments. In each radiation environment, two samples are measured for each operational mode. The irradiation experiments were carried out at room temperature in Northwest Institute of Nuclear Technology, China. The information for all the radiation experiments is shown in table 1. The gamma ray exposure was performed using a Co-60 irradiator with a dose rate of 0.2 Gy(Si)/s. Neutron exposure and synergistic irradiation of neutron and gamma ray were performed using nuclear reactor in different states. The ratio of neutron flux and gamma dose rate (n/γ) is $7.7\times10^{11}$ n/(cm$^2$·Gy(Si)) in the neutron irradiation environment and $5.4\times10^{10}$ n/(cm$^2$·Gy(Si)) in the synergistic irradiation environment. The neutron energy ranges from $3.6\times10^{-3}$ eV up to 20 MeV and the neutron spectrum is shown in Fig. 2. The neutron fluence is given as 1 MeV equivalent fluence. In the higher n/γ irradiation the neutron radiation effect dominates, so the TID effect induced by parasitic gamma ray can be ignored.

Table 1. The radiation parameters in the experiments

| Radiation field | Neutron fluence rate ($n/cm^2/s$) | Gamma ray dose rate (Gy(Si)/s) | Total neutron fluence ($n/cm^2$) | Total gamma ray dose (Gy(Si)) |
|---|---|---|---|---|
| Gamma ray | 0 | 0.2 | 0 | $1.85\times10^3$ |
| Neutron | $2.7\times10^{10}$ | $3.5\times10^{-2}$ | $1.0\times10^{14}$ | $1.29\times10^2$ |
| Mixed neutron and gamma | $6.5\times10^9$ | 0.12 | $1.0\times10^{14}$ | $1.85\times10^3$ |

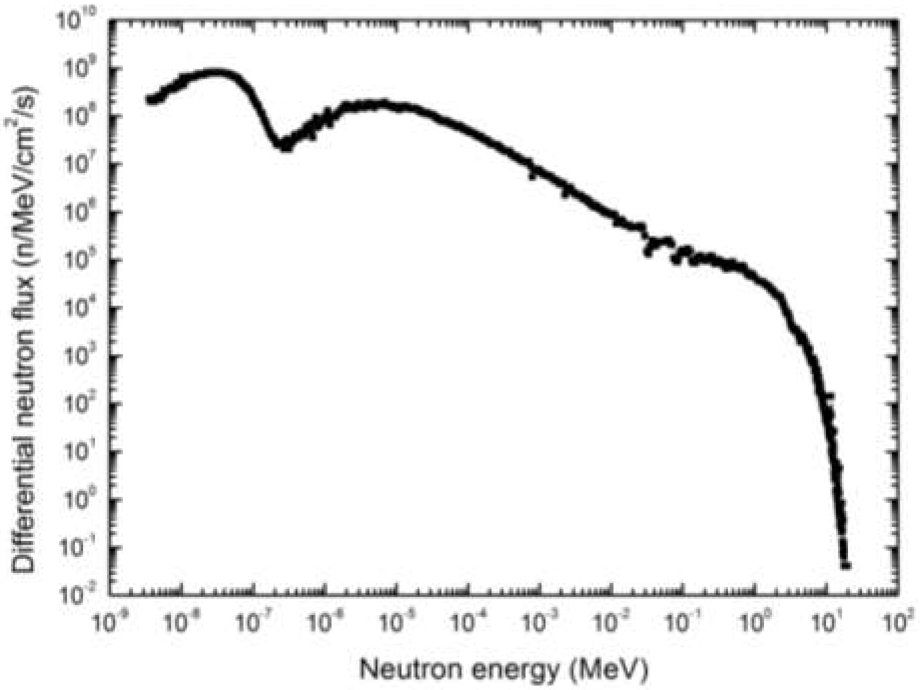


Fig. 2. Differential neutron flux at XAPR.

## III. Experimental results

As shown in Fig. 3, for on-load state with 100 Ω, the output voltage shows almost no degradation in single neutron radiation. The single gamma ray radiation first induces a slight increase from 3.3 V at $5.55\times10^2$ Gy(Si) to 3.4 V at $9.25\times10^2$ Gy(Si) and then a significant decrease to 0 V at $1.85\times10^3$ Gy(Si) for the output voltage. However, the output voltage under mixed neutron and gamma ray radiation kept constant up to $3\times10^{13}$ $n/cm^2$ and increased from 3.3 V at $3\times10^{13}$ $n/cm^2$ to 4.0 V at $1\times10^{14}$ $n/cm^2$. Single gamma ray radiation induces a significant decrease of output voltage, while single neutron radiation has almost no obvious impact on the output voltage. However, mixed neutron and gamma ray radiation cause a slight increase on the output voltage.

Similarly, as shown in Fig. 4, the power supply current shows no degradation in the single neutron radiation. In the single gamma ray radiation, the power supply current first increases slightly from $3.5\times10^{-2}$ A at $1.85\times10^2$ Gy(Si) to $4\times10^{-2}$ A at $9.25\times10^2$ Gy(Si) and then decreases greatly to $6\times10^{-3}$ A at $1.85\times10^3$ Gy(Si). In the mixed neutron and gamma ray radiation, the power supply current increases slightly from $3\times10^{-2}$ A to $4\times10^{-2}$ A. The synergistic effects for the power supply current are consistent with that for the output voltage. The linear regulator exhibits strong synergistic effects induced by mixed neutron and gamma ray for on-load operational mode, indicating the opposite trend due to the TID effects caused by single gamma ray.

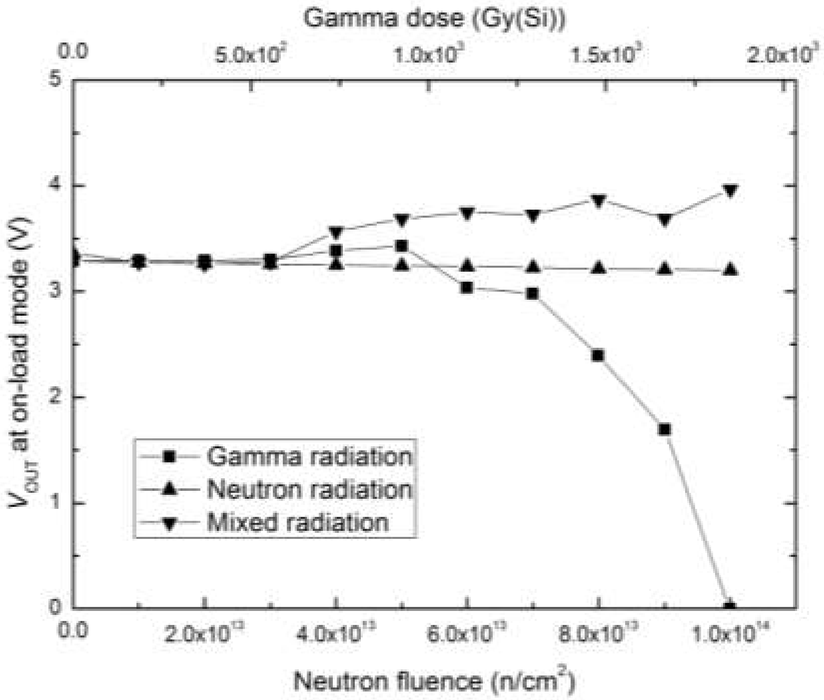


Fig. 3. Degradation of the output voltage in different radiation environments for on-load state.

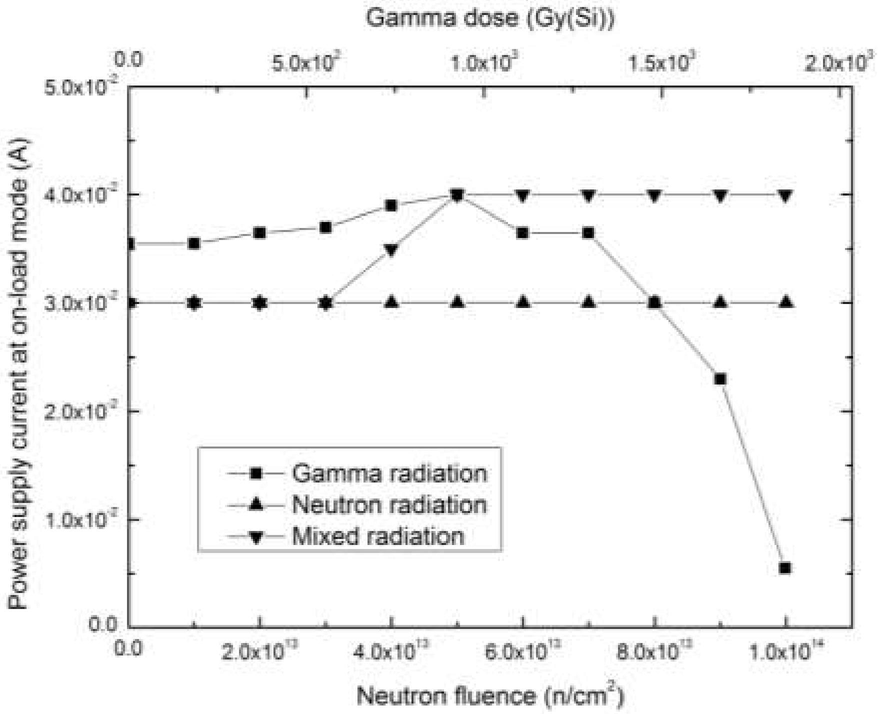


Fig. 4. Degradation of the power supply current in different radiation environments for on-load state.

For off-load state, the output voltage holds steady in single neutron radiation. However, the output voltage decreases from 3.2 V at $9.25\times10^2$ Gy(Si) to $8\times10^{-3}$ V at $1.11\times10^3$ Gy(Si) in single gamma ray radiation and mixed neutron and gamma ray radiation, as shown in Fig. 5. The power supply current increases from $1\times10^{-3}$ A to $5\times10^{-3}$ A during single gamma ray radiation. However, in neutron and mixed neutron and gamma ray radiation, the power supply current remains unchanged, as shown in Fig. 6. The radiation effects induced by mixed neutron and gamma ray are due to the TID effects induced by gamma ray component. Furthermore, the neutron radiation, to some extent, contributes to the restrain of the increase of the power supply current.

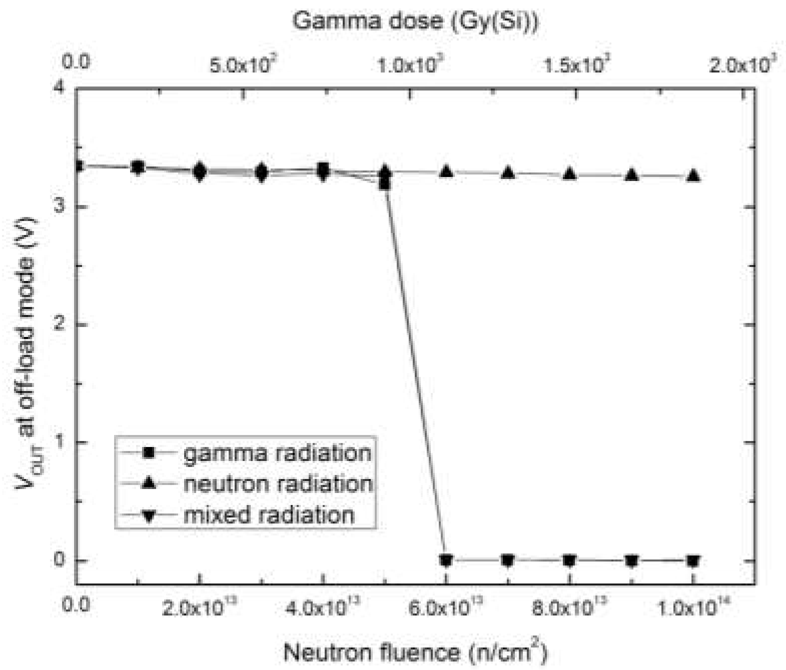


Fig. 5. Degradation of the output voltage in different radiation environments for off-load state.

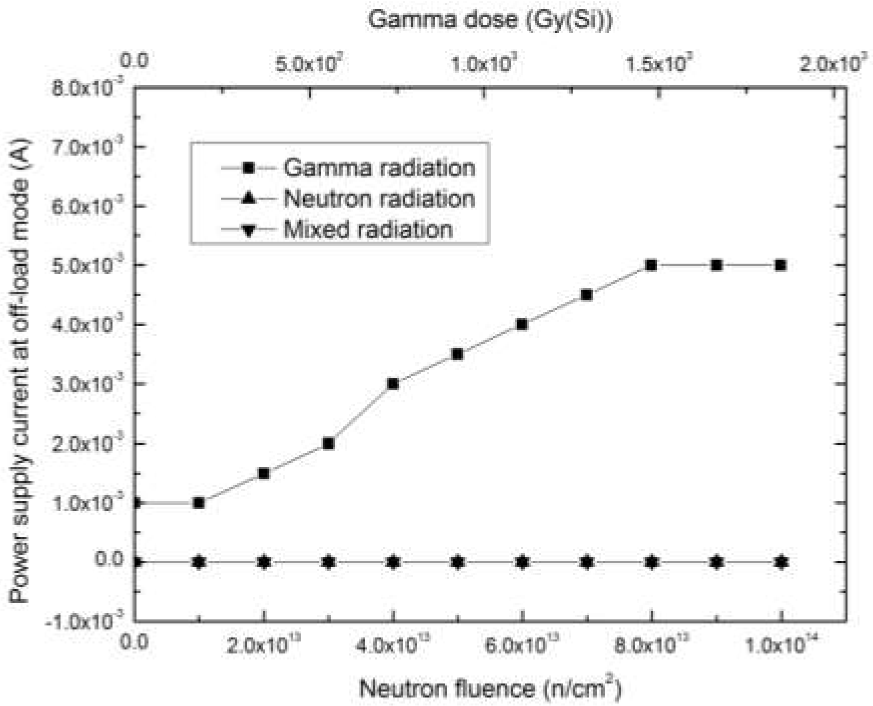


Fig. 6. Degradation of the power supply current in different radiation environments for off-load state.

## IV. Discussion

The linear regulator includes both MOS and bipolar transistors, which are sensitive to gamma ray and neutron respectively. The degradation between them has coupling effects in the circuit. Fig. 7 shows the linear regulator topology. It is composed of two MOS transistors, one operational amplifier, or gate, thermal shutdown, overshoot detect and some resistances.

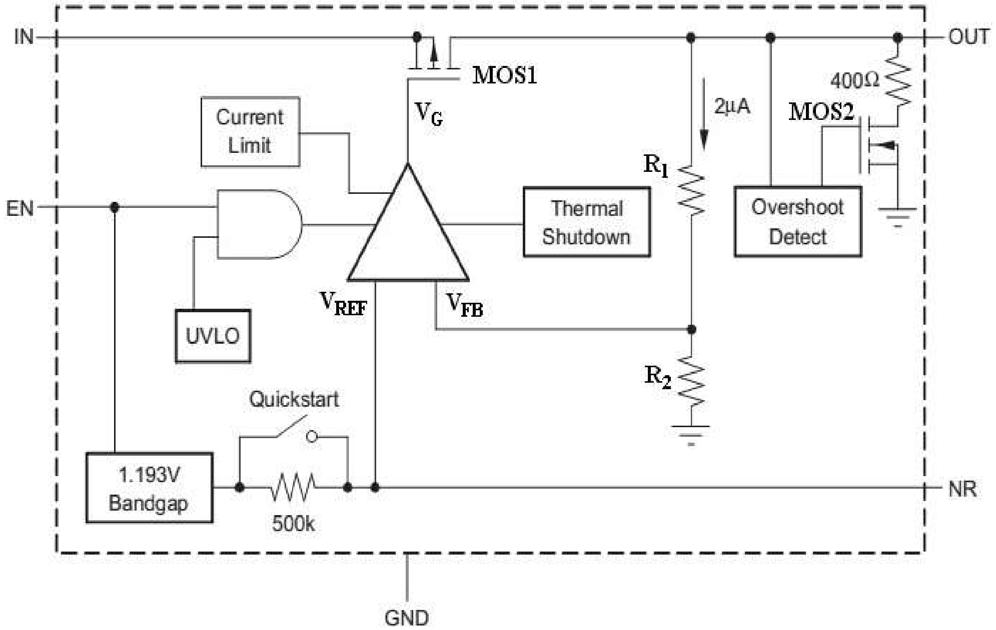


Fig. 7. Functional block diagram of the device.

The linear regulator utilizes a feedback circuit to regulate the output voltage. The operation mechanism is expressed as the following equations.

$$V_{\mathrm{G}} = A \cdot (V_{\mathrm{FB}} - V_{\mathrm{REF}}) \tag{1}$$

$$V_{\mathrm{FB}} = \frac{R_1}{R_1 + R_2} V_{\mathrm{OUT}} \tag{2}$$

Here $V_G$ is the gate-control voltage of MOS1, $A$ is the voltage gain of the operational amplifier, $V_{FB}$ is the voltage at the feedback point, $V_{REF}$ is the standard reference voltage of the linear regulator, $R_1$ and $R_2$ are the corresponding resistances in the linear regulator, and $V_{OUT}$ is the output voltage of the linear regulator.

Gamma ray-induced TID effects lead to negative shift of the threshold voltage for both MOS1 and MOS2. MOS1 is a p-channel MOS transistor, so the decrease of its transconductance due to the TID effects reduces the conductivity from input voltage terminal to output voltage terminal. On the contrary, MOS2 is an n-channel MOS transistor, so the increase of its transconductance due to the TID effects increases the conductivity from the output voltage terminal to the ground terminal. Therefore, the output voltage decreases due to the increasing TID. However, the variation of the power supply current of the linear regulator depends on the degradation of the two transistors. The degradation of MOS1 induces the decrease of the power supply current, while the degradation of MOS2 leads to the increase of the power supply current. For the off-load mode, the gate voltage of MOS1 is higher than that for the on-load mode and exhibits severer degradation.

Neutron-induced displacement damage mainly reduces the voltage gain of the operational amplifier, leading to the subsequent increase of the power supply current and the output voltage due to the decrease of gate voltage of MOS1. On the other hand, neutron radiation reduces the concentration of majority carriers, leading to the subsequent decrease of the power supply current and the output voltage. Under single neutron radiation, both the output voltage and the power supply current exhibit no significant variation due to these two competitive factors. However, under mixed neutron and gamma ray radiation, for the on-load mode, the decrease effect of voltage gain of the operational amplifier induced by neutron dominates and leads to the slight increase of the output voltage and the power supply current. For the off-load mode, the TID effects of MOS1 induced by gamma ray dominates due to its worst-case bias condition and leads to the synergistic effects of the linear regulator exhibit almost the same as TID effects. Therefore, synergistic effects strongly depend on the load conditions which have a great impact on the degradation degree due to different bias conditions.

## V. Conclusion

Radiation effects on the linear regulator exhibit a strong dependence with its operational modes. The synergistic effects of mixed neutron and gamma ray are observed for the on-load state. For off-load state, the radiation effects in mixed neutron and gamma ray are caused by the TID effects due to single gamma ray radiation. Gamma ray induces the shift of threshold voltage and degradation of series resistance in MOS transistors, while neutron induces the decrease of the current gain in bipolar transistors. The circuit with BiCMOS technology is very likely to exhibit synergistic effects of mixed neutron and gamma ray, due to coupling effects between the MOS and bipolar transistors. This innovative mechanism may cause a significant problem for the radiation hardness.

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