"RADON-5E" Portable Pulsed Laser Simulator: Description, Qualification Technique and Results, Dosimetry Procedure

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Abstract

The original "RADON-5E" portable laser simulator for IC transient radiation effects investigation is developed and described. The parameters measurement procedure and qualification technique are worked out. The qualification tests results are presented. The dosimetry procedure is developed and "calibration curves" for several IC are measured in flash X-ray machine tests. Laser simulation errors were estimated in "RADON-5E" vs. flash X-ray machine comparative tests.

I. Introduction

Laser simulation tests are well known to be used for IC dose-rate investigation and IC's radiation hardness evaluation [1-12]. They have a lot of advantages as compared to the flash X-ray machine tests and practically have no alternative within IC design process [13, 14]. The simulation adequacy is based on the laser beam capability to ionize the IC semiconductor regions and on the ionization volume distribution or IC parameter deviations equivalencies under flash X-ray and laser radiation. The laser simulation adequacy analysis accounting the shadowing and high dose rate effects is be presented in [15]. The typical laser simulator parameters requirements are summarized in Table 1.

Table 1.
Laser simulators parameters typical requirements

Parameter	Value (range)
Wavelength, μm	1.06 to 1.08
Pulse energy, mJ, not less than	50
Pulse width, ns	7 to 15
Spot diameter, mm	3 to 15
Max. spot inhomogeneity[1], %	100

Required pulse parameters can be obtained using solid-state Q-switched laser source with the intensity of about 10 MW/cm^2, which is capable to produce the equivalent dose rate up to 10^{12} rad(Si)/s or more [14, 15]. Such a Nd-lasers are widely used for IC transient upsets and latch-up investigations. Unfortunately most of them are rather huge, involve the water cooling, generate the essential parasitic electro-magnetic interferences and, as a whole, are not specialized and adopted to the IC transient simulation tests.

There are also some difficulties in laser simulator qualification tests: the list of simulator radiation field parameters as well as their measuring technique are not specified in standards. It must be emphasized that it is not a pure laser beam, but somehow homogenized (diffused, partly non-coherent and non-polarized) optical radiation that is much more efficient to use in transient simulators in order to achieve the required homogeneity and to limit the shadowing and speckle effects. Therefore the traditionally specified laser beam parameters such as beam divergence and mode structure are no longer essential here. At the same time actual intensity distribution within the spot (illuminated region) becomes very important. So the conventional laser beam qualification parameters and their measurement procedure are to be justified.

The equivalent dose rate estimation within laser simulation tests procedure is also not specified in standards and therefore should be developed for both cases: if there is a possibility to provide comparative flash X-ray machine tests or not.

II. "RADON-5E" Description

The developed "RADON-5E" portable pulsed laser simulator is presented in Fig. 1.

The "RADON-5E" structural diagram is presented in Fig. 2. The $YAlO_3:Nd^{3+}$ laser head (1) with power supply (2) in a single unit operates in Q-switched mode provided by internal electro-optical modulator. It generates single laser pulses with 1.06 μm wavelength, 50 mJ to 60 mJ pulse energy and 7 ns to 12 ns pulse duration. The set of neutral filters (3) provides the intensity attenuation factor of up to 10^6. The plug-in homogenizer (mat plate) with tunable

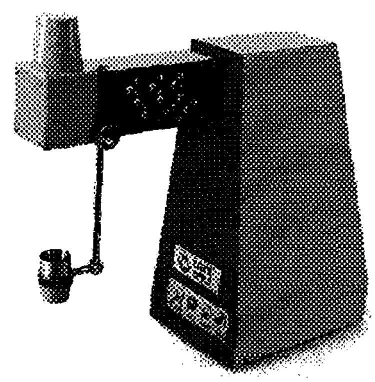

Figure 1.
"RADON-5E" pulsed laser simulator.

[1] Definition of inhomogeneity is given below in section III.

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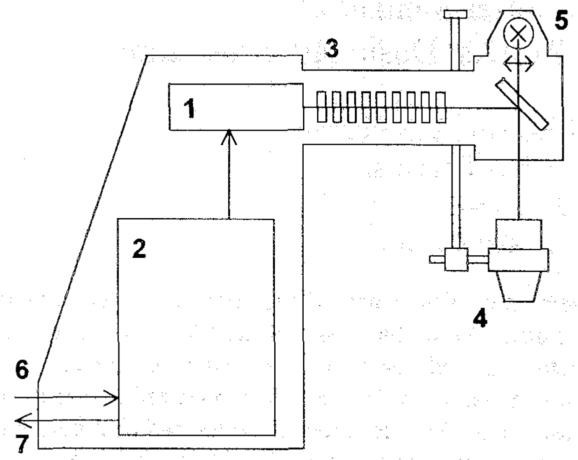


Figure 2.
"RADON-5E" structural diagram.

position (4) maintains the irradiation homogeneity within the spot in object plane. The collimated illuminator (5) is intended to point the position of laser beam on the device under test. The laser firing is obtained either from an external signal (6) or from the remote control. The synchro-output (7) to pre-trigger the external measurement units is also provided. The simulator produces laser pulses with repetition rate of 0...0.25 Hz without special cooling. The level of parasitic interferences is practically non-significant.

III. LASER PULSE PARAMETERS: MEASUREMENT TECHNIQUE AND RESULTS

The pulse energy, it's local inhomogeneity within the spot as well as the pulse duration, the pulse-form and their time stability are of primary importance for the simulation tests. Below the experimental technique and its application to the measurement of these parameters on typical sample of "RADON-5E" are discussed.

The total pulse energy with removed homogenizer was measured with a standard calorimeter, that gave (56±4) mJ as a result.

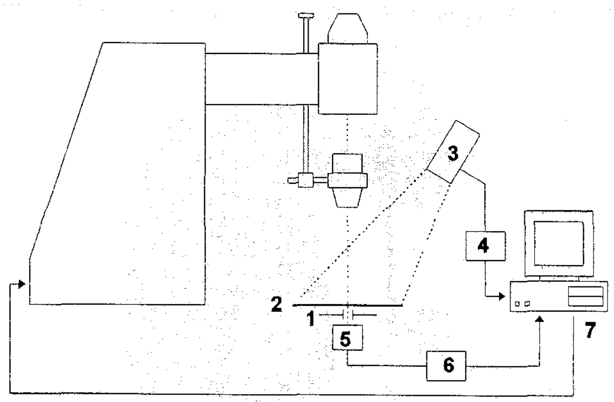


Figure 3.
Experimental set-up for measuring "RADON-5E" simulator parameters.

The experimental set-up for the local pulse energy distribution within the spot with simultaneous energy flux and pulse duration measurements is presented in Fig. 3.

The laser radiation passed through the homogenizer to the thin metallic diaphragm (1) covered by a special semi-transparent mat screen (2). This screen was mounted in the object plane of the 288×256 Charge Coupled Device (CCD) camera (3). The camera output signal through high speed 7-bit analog-to-digit converter (ADC) (4) was stored in a 4096 byte RAM. To measure the energy flux in the center of the spot the part of radiation having passed through the diaphragm was registered by integrating photodiode (5) and stored in RAM after the amplification and 10-bit ADC (6) processing. The whole information channel was previously calibrated with the industrial laser dosimeter. To perform pulse duration and shape measurements photodiode (5) was replaced by high-speed photosensor with 0.5 ns time resolution connected to fast storage oscilloscope (not shown). All units were monitored with a PC (7).

Fig. 4 presents the measured dependence of energy flux in the center of the spot vs. the distance z between the homogenizer and the surface of the device under test. The maximum value of energy flux in Fig. 4 corresponding to z=20 mm was measured to be (7.5±0.5) MW/cm^2.

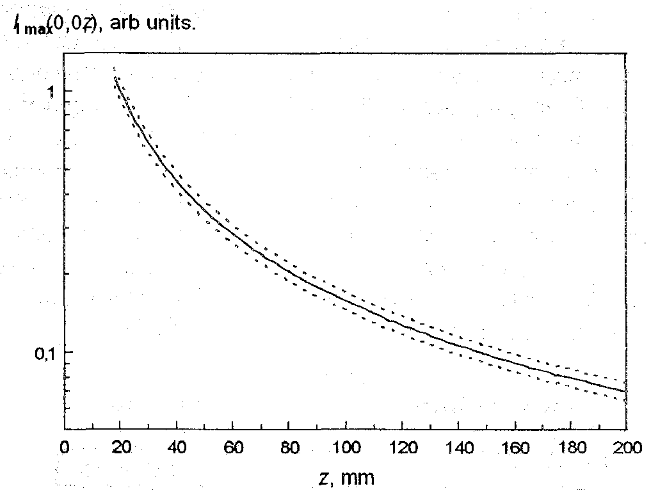
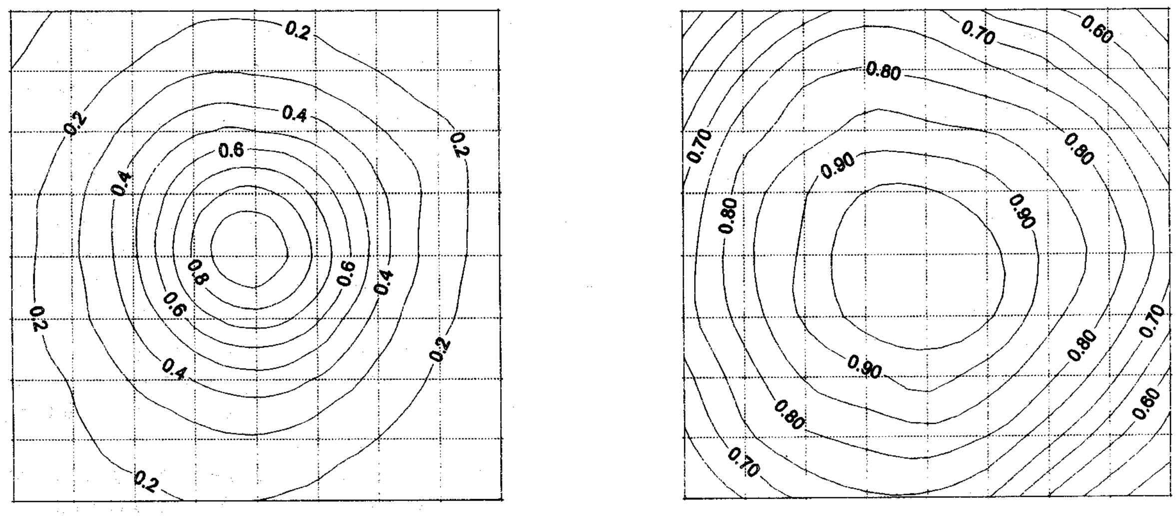


Figure 4.
Maximum energy flux vs. the distance from the homogenizer to object plane within 0.95 confidence range (dashed lines).

The example of spatial energy distribution within the spot is presented in Fig. 5. Using measured distributions at various homogenizer positions the dependencies of irradiation inhomogeneity on area size a and the distance z from the homogenizer to the device under test were calculated. Inhomogeneity η within the spot S was defined using the following equation:

$$\eta(S) = \left(\frac{I_{\max}(S)}{I_{\min}(S)} - 1 \right) \cdot 100\%, \qquad (1)$$

where $I_{\max}(S)$ and $I_{\min}(S)$ – measured maximum and minimum values of energy flux. The total error of η was not more than 24% with confidence value of 0.95.



(a) (b)

Figure 5.

The typical normalized spatial distribution of energy within the spot at z=20 mm (a) and 100 mm (b) (grid 2×2 mm).

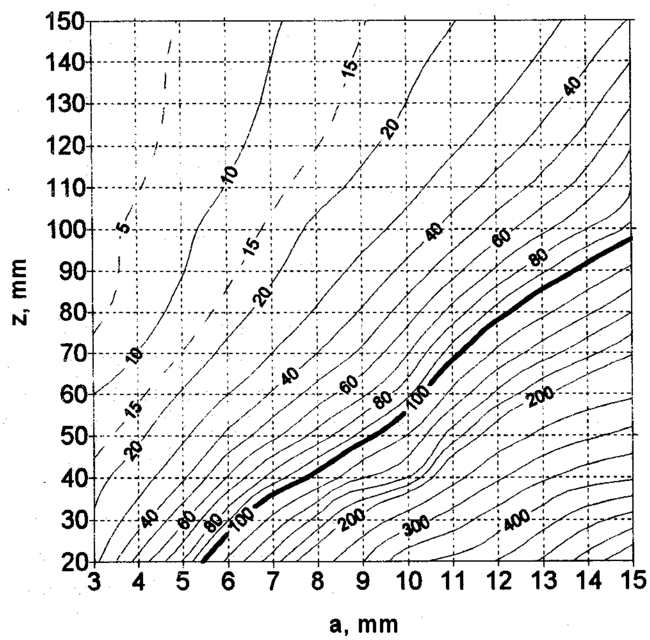


Figure 6.

The measured inhomogeneity (%) vs. device under test size a and distance z from the homogenizer to the object plane.

The result of calculations is presented in Fig. 6. This nomogram can be conveniently used to define the inhomogeneity of irradiation according to chip sizes and position of homogenizer or vice versa. For example taking from Table 1 the value of inhomogeneity ≤100% (thick line in Fig. 6) it is possible to obtain chip size limitations for various positions of homogenizer (see Table 2). This table also contains corresponding data on reachable energy flux calculated from Fig. 4.

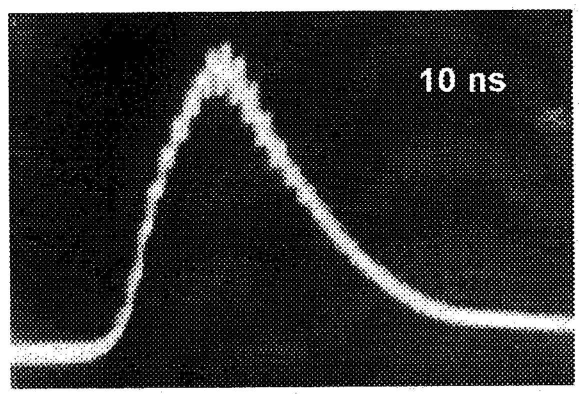


Figure 7.

"RADON-5E" pulse oscillogram.

Fig. 7. shows typical oscillogram of laser pulse. The measured pulse duration was (9.5±1.5) ns at the half-amplitude level.

The measured long-term instability of the pulse amplitude and duration within 4 hours of permanent operation was found to be not more than 10%.

Table 2

Maximum chip dimensions a and minimum energy flux I_l for inhomogeneity $\eta \leq 100$ % vs. distance from homogenizer z.

z, mm	20	40	60	80	100	120	140
max a, mm	3,5	5,2	7,5	9,5	11,2	13,2	15,0
$\min_S I_l$, MW/cm^2	3,75	1,46	0,75	0,46	0,31	0,22	0,17

IV. LASER RADIATION DOSIMETRY PROCEDURE AND COMPARATIVE TEST RESULTS

Laser simulation test dosimetry is aimed at the equivalent dose rate evaluation, which can be determined as the γ-radiation dose rate, causing the same IC response as compared to the corresponding laser pulse. Usually IC response is characterized by some essential electrical parameters (current or voltage) transient deviations and it is possible to choose one of them as the "calibration parameter" q_m. According to this "calibration" method the laser radiation equivalent dose rate P_e is equal to the γ–pulse dose rate $P\gamma$ if both of them cause the same calibration parameter q_m deviation:

$$P_e(q_m) = P\gamma(q_m).$$

The $q_m(P\gamma)$ or $P\gamma(q_m)$ functions are referred as "calibration dependencies" and are measured in flash X-ray machine tests. This curve, in fact, describes the device under test (IC) as a dosimeter.

IC calibration parameters are chosen according to the following criteria:

*their transient response must be determined by the dose rate (volume ionizing) effects;

*measurement simplicity in flash X-ray tests;

*low parasitic electromagnetic flashes sensitivity; the maximum sensitivity to $P\gamma$ and the maximum possible directly proportional region of the $q_m(P\gamma)$ dependence;

*q_m radiation transient deviation must represent the total IC dose rate response; q_m dependence must be rather smooth and monotonous.

As a rule it is the power supply transient current ΔI_{cc} that is chosen to be IC calibration parameter. The typical calibration curves, measured in the Flash X-ray machine tests in the range up to $1.6 \cdot 10^9$ rad(Si)/s are presented in Fig. 8. In this example latch-up (1) or current saturation due to parasitic effects (2) occur with the further dose rate increase and these calibration curves applicability is reduced.

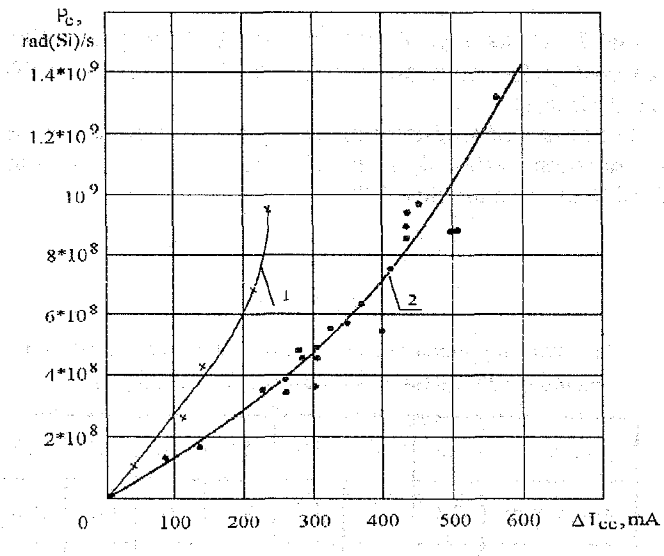


Figure 8.
Measured calibration curves for CMOS RAM 537RU6 (1) and ROM 1619RE2 (2).

In case of the laser simulation tests adequacy the equivalent dose rate values, determined with the various calibration parameters are to be the same (within the total measurement error). Therefore it is possible to use the equivalent dose rate vs. laser intensity dependence $P_e = P_e(I_l)$, which, as a rule, are directly proportional. This correspondence enables us to estimate P_e value even if there is no device under test or it is impossible to fulfill flash X-ray tests (for example within the IC design process). For example the $P_e = P_e(I_l)$ dependence can be analytically or numerically (with "LDR" software simulator [16]) calculated - this approach is presented in [14, 15].

The pulse average I_l measurements are based on the device under test replacement with the photosensor, which is preliminary calibrated in energy per square units. The irradiation area is determined by the specialized diaphragm, which cuts the necessary spot. The dosimeter operation in the linear region is provided by attenuator set. To choose the proper sensor for the laser dosimetry system it is necessary to meet the following criteria:

*sensor's spectral sensitive range must be in correspondence with the laser wavelength;

*sensor's sensitive surface diameter is to be not less than 8...10 mm;

*sensor's self-response time constant is to be much more than the laser pulse duration;

*sensor must have the low noise output, the sufficient sensitivity and wide dynamic range.

The FD-24K photosensor, which meet these requirements, has been used in the dosimetry system. The dosimetry calibration and linearity investigation were implemented with the standard laser dosimeter which supply the proper measurement accuracy. The "RADON-5E" maximum equivalent dose rate calculations give more than 10^{12} rad(Si)/s as a result [14].

We have to note, that to get an accurate dosimetry it is preferable to have flash X-ray test calibration results (even in one "point"). As an example in 564LN2V logical IC calibration flash X-ray tests it was found that the maximum laser intensity corresponds to 10^{11} rad(Si)/s at the distance 130 mm. Taking into account the chip size 3x3 mm^2 and the maximum non-homogeneity 100% the maximum reachable with "RADON-5E" equivalent dose rate $P_{emax}(z)$ dependence was calculated (Table 3). It is also possible to use the preliminary measured attenuation factors of the "RADON-

Table 3.

Maximum reachable with "RADON-5E" equivalent dose rates for logical IC 564LN2V (chip size 3×3 mm).

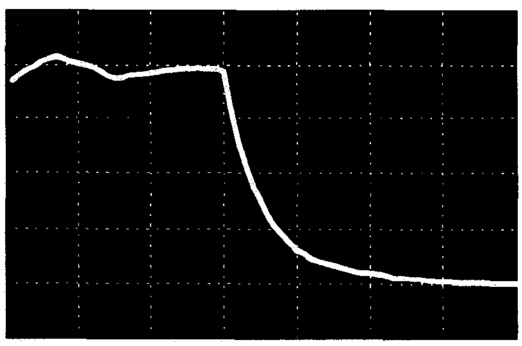
z, mm	20	40	60	80	100	120	140
P_{emax}, 10^{12} rad(Si)/s	6,40	2,87	1,68	1,06	0,73	0,51	0,38

Table 4.

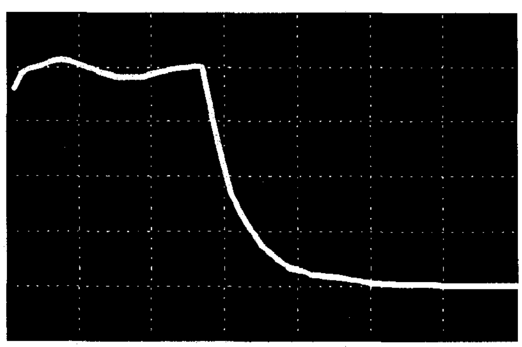
Flash X-ray machine vs. "RADON-5E" laser simulator comparative results with the calibration procedure baised on power supply transient current measurements.

IC	Sample #	Failure threshold relative error $\delta=(P_{\text{ýàð}}-P_{\text{yàð}})/P_{\text{yàð}} \cdot 100$ %				Failure time relative error, %
		Based on U_{oh}	Based on U_{ol}	Based on logic upsets	Based on latchup	
CMOS RAM 1617RU6	1	<21	+33	<30		–40
	2	<90	–38	<90		–20
	3	<80	+50	<100		–40
CMOS RAM 537RU6	1	–19	+85		<100	
	2	–17	+35		<90	
CMOS ROM 1619RE2	1	–32	+16			
	2	–28	–4			
	3	–14	–3			
CMOS ASIC 1810GF84	1	+100	+59			
	2	+7	+62			
CMOS RAM 537RU18	1	–37		–15		
	2	+3			<65	
	3	–34				
Bipolar ROM 556RT7	1		+37			
	2		+62			
Oper.ampl. 140UD8A	1	+53 (based on U_{bias})				+25
	2	+100 (based on U_{bias})				+39

5E" build-in attenuators for this "point" equivalent dose rate extrapolation in the upper or lower range. Thus determined "RADON-5E" maximum equivalent dose rate level is found to be about $5 \cdot 10^{12}$ rad(Si)/s.



(a)



(b)

Figure 9.

140UD8A operational amplifier output current transient response curves in flash X-ray machine (a) and laser (b) tests under dose rate $2 \cdot 10^{10}$ rad(Si)/s (hor: 10 mcs/div; vert: 0.2 V/div), $R_{load}=50\ \Omega$.

A lot of comparative laser vs. flash X-ray machine tests were performed for various IC with the aim to check "RADON-5E" performance. The same test samples, test procedure and instrumentation were used to maintain the comparability of test results. As an example 140UD8A operational amplifier output current transient response curves in flash X-ray machine (a) and laser (b) tests are presented in Fig.9. One can see the identical nature of both curves and a little difference in failure time is due to flash X-ray machine as compared to "RADON-5E" pulsewidth differences.

Comparative test results are summarized in Table 4. The calibration procedure was performed on the basis of power supply transient current measurements. Then transient output voltage U_{oh} or U_{ol} response, logic upset and latchup thresholds, operational amplifier bias voltage as well as failure time were comparatively measured in laser and flash X-ray environment. One can see that in all cases the total laser simulation error was not exceed 100%, which is in good agreement with previously reported estimations [6].

V. Conclusions

The "RADON-5E" original portable pulsed laser simulator description is presented. As compared to the other simulators it is rather small, have a minimum level of parasitic interferences and use the natural cooling and, as a whole, is specialized for IC dose rate effects investigation and IC radiation hardness evaluation.

The laser simulator qualification technique is worked out. The basic laser simulators parameters, such as pulse energy, the spatial energy distribution within the spot and pulse duration, are measured and analyzed for typical "RADON-5E" sample.

The laser simulation tests dosimetry procedure is developed with "calibration curve" determination in flash X-ray tests as the basic dosimetry method. The calibration curves were measured in comparative tests for several CMOS IC. The laser intensity measurement procedure is developed in order to use the results in the equivalent dose rate calculations. It is found that the "RADON-5E" parameters implement the equivalent dose rate up to 10^{12} rad(Si)/s and more.

Laser simulation error values were estimated in "RADON-5E" vs. flash X-ray machine comparative tests The worst case error was found to be not more than 100%. The developed laser simulator together with dosimetry system and appropriate hardware and software are a good tool for IC radiation effect investigation and hardness prediction.

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