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Time Dependent Aspects of the Response of Some Avalanche Photodiodes to Fast Neutron Irradiation

J E Bateman and R Stephenson

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TIME DEPENDENT ASPECTS OF THE RESPONSE OF SOME AVALANCHE PHOTODIODES TO FAST NEUTRON IRRADIATION

J E Bateman and R Stephenson
Rutherford Appleton Laboratories, Chilton, Didcot, OX11 0QX, UK

Using the fast neutron flux available from the beam collector on the RAL spallation neutron source (ISIS) we have irradiated the two types of avalanche photodiodes (APD) {Hamamatsu S5345 (high capacitance) and the EG&G C30626E} up to a maximum fluence of 2×10^{13} neutrons per cm^2. We report the recovery behaviour of the device dark currents and noise characteristics following exposure to the neutron flux. Using the parameters derived from these observations we model the evolution of the dark current and noise through likely CMS activity schedules.

1. INTRODUCTION

A considerable program of work is in hand in a number of centres aimed at proving the viability of the APD as a scintillation light detector for the electromagnetic calorimeter (ECAL) on the CMS experiment at LHC. Some of this work has been summarised in reference [1]. One important requirement (among many others) is that the devices exhibit a useful electronic dynamic range of 10^5, which in turn demands a low electronic noise threshold. Measurements have shown [2] that with the best devices, RMS noise figures (referred to the input) of 50 electrons or less can be achieved at room temperature. APDs are, however, very sensitive to dark current-induced shot noise since the avalanche process amplifies any dark current present in the silicon of the conversion region just as if it were signal. The fast neutron flux generated by the ECAL is expected to be of the order of $2\times10^{12}/cm^2/$annum. Such levels of flux are known to cause increased dark current in silicon due to the creation of shallow traps which ionise readily at room temperature. Measurents made using a reactor facility at Saclay indicated a serious degradation of the noise performance of both types of APD in fluences comparable to one years running at LHC [1]. We repeated the measurements using the ISIS facility at RAL confirming the magnitude of the dark current and noise increases observed at Saclay and reported them in reference [3]. We have now followed the behaviour of the three devices irradiated for six weeks and have characterised long term and short term components in the radiation-induced dark current. The parameters from this analysis permit us to predict the noise response of the APDs to proposed schedules of CMS operation.

2. EXPERIMENTAL MEASUREMENTS

Measurements of the the dark current and noise of the three irradiated APDs were conducted using the equipment and protocols described in reference [3] over a period of 45 days following the final irradiations. Figures 1,2 and 3 show the dark current, RMS noise with $\tau=30$ns (amplifier CR-RC shaping time constant) and RMS noise with $\tau=500$ns for APDs H(Hamamatsu)048, H049 and E(EG&G)135. All were operated at a nominal gain of 50 at a temperature (uncontrolled) between 19C and 22C.

In all cases the dark current was found to fit well to a function of the form:

$$I_d = a + be^{-t/T}$$

where the recovery time constant T was found to be 13.3days for H048, 12.9days for H049 and 16.8 days for E135. The fraction of the dark current which anneals out is characterised by:

$$\alpha = b/(a+b)$$

For H048 we measure $\alpha=0.36$, for H049 we measure $\alpha=0.349$ and for E135 we measure $\alpha=0.468$. Clearly, the parameters of the two Hamamtsu APDs agree within the fitting tolerance. Since H049 was irradiated unbiassed, this is a useful confirmation of the conclusion reached in our previous report [3] that biassing the APD makes no significant difference to the radiation damage effects.

The situation with E135 is complicated by the fact that some strange behaviour was observed in the guard ring current under the neutron irradiation. After a total of 5×10^{12} n/cm^2 the very large (40μA) guard ring currents (observed under initial irradiation) disappeared and the guard ring was observed to draw only about 13% of the APD current. Since the noise and APD current levels were plausible we concluded that the device was probably operating normally and that the wild guard ring currents were possibly a reaction of the packaging to the irradiation. We therefore present the data of figure 3 as being probably representative of the behaviour of the EG&G devices.

Knowing the relations between the dark current and the electronic noise derived from our previous results [3], it is possible to see if the same relationship is valid during the recovery period. In figures 1-3 the following relations are plotted:

for H048/049 $$\sigma = \sqrt{(7129^2 + 15300 I_d)} \quad (\tau = 30\text{ns}) \qquad \{1a\}$$

$$\sigma = \sqrt{(13400^2 + 584000 I_d)} \quad (\tau = 500\text{ns}) \qquad \{1b\}$$

for E135 $$\sigma = \sqrt{(1578^2 + 47900 I_d)} \quad (\tau = 30\text{ns}) \qquad \{1c\}$$

$$\sigma = \sqrt{(1671^2 + 885000 I_d)} \quad (\tau = 500\text{ns}) \qquad \{1d\}$$

σ is expressed in electrons and I_d in nA. The first term under the square root represents the amplifier noise contribution.

Bye and large the above relations {1} predict the observed noise well. Only in the case of H048 is there an anomaly in which the noise dips below the predicted curve for about twenty days between day five and day twenty five. Thereafter the noise follows the predicted path. The discrepancy is about -15% maximum and temporary, so we feel justified in using the above relations for our predictions of irradiations distributed in time.

Our previous results [3] showed that the neutron-induced dark current fitted well to the form $I_d = cD^d$ where D is the cumulative neutron fluence in n/cm^2 and c and d are constants. In the case of the two types of APD we obtained the relations:

H048: $$I_d = 250 + 365 D^{0.765} \qquad \{2a\}$$

E135: $$I_d = 6 + 305 D^{0.705} \qquad \{2b\}$$

where I_d is expressed in nA and D in units of 10^{11} n/cm^2.

Since the recovery time constant (T) is comparable to the period over which the irradiation was applied to the APDs (although the heaviest irradiations were all performed in the last five days) it seemed a good idea to check these relations by fitting the incremental dark current increases, so correcting at least partially for any recovery during the exposure period. Figure 4 shows the data from H048 (the only data set complete enough) plotted in this way. The fitted curve should be the derivative of relation {2a} above.

Integrating the fit for M=50 gives:

$$I_d = 250 + 301.7D^{0.802} \qquad \{2c\}$$

The inevitably noisier differential data make it difficult to say that the differences between {2a} and {2c} are significant. (The same process applied to the M=1 data derived identical parameters from the integral and differential measurements.) We have used relation {2c} in the following calculations.

3. MODELLING THE RESPONSE OF THE APDs TO CMS OPERATION

In operation at full luminosity (10^{34} $cm^{-2}s^{-1}$) the ECAL is expected to experience a fast neutron flux of $2x10^{12}$ n/cm^2/annum. Assuming (for the purposes of our model) that this is delivered in nine months of running with a three month rest period we obtain a daily flux (g) of 0.074 units of 10^{11} n/cm^2. During the run periods the long term component of the dark current builds up continuously according to the relations {2} above but the short term component is continuously decaying and follows a more complicated curve, increasing until the decay rate just balances the generation rate giving a constant addition to the long term component. In a three month rest period this contribution completely disappears leaving only the long term value at the start of a new run period.

We can model the behaviour of the short term component as follows: let I be the short term dark current, then

$$dI/dt = -I/T + gdI/dD$$

(definitions as above). As figure 4 shows $dI/dD = aD^b$. We also assume that the neutron flux is constant, i.e. D=gt. Substituting in our differential equation we have:

$$dI/dt = -I/T + ag^{1+b}t^b$$

Rewriting this in the conventional form:

$$dI/dt + I/T = ag^{1+b}t^b$$

permits us to integrate to get:

$$I(t) = a(gT)^{1+b} F(t/T)$$

where

$$F(x) = e^{-x} \int x^b e^x \, dx \qquad (x=t/T)$$

The non-integer nature of b means that F(x) must be evaluated numerically. Figure 5 shows the resulting function with b=-0.198 (the value for H048). As expected an asymptotic dark current is attained. However the singular nature of x^b at the origin produces a very sharp rise of the short term component when the beam is switched on with a maximum at $x \approx 2.5$ (i.e.

about 1 month after switch-on).

We can now formulate the total dark current as a function of time during a run period as the sum of the long and short term contributions:

$$I_d = I_0 + (1-\alpha)cD^d + \alpha a(gt)^{1+b} F(t/T)$$

Substituting D=gt and converting the differential parameters a,b to their integral equivalents c,d we get:

$$I_d = I_0 + (1-\alpha)c(gt)^d + \alpha cd(gt)^d F(t/T) \qquad \{3\}$$

Figure 6 shows the predicted total dark current in the first nine month run period at full luminosity (with a fresh Hamamatsu APD). The time is expressed in terms of decay time constants (13.3 days). During a rest period the short term component dies away exponentially with the same time constant. Figure 7 shows the dark current curve to be expected in three years of high luminosity running (starting with a fresh APD). Using the relation {1a} we can convert this into a noise curve for H048 (figure 7). Figure 8 shows the same period of running for low luminosity (i.e. 1/10 high luminosity).

Using the parameters appropriate to the EG&G APD (E135) one can repeat the above analysis. Figure 9 shows F(x) as evaluated for E135. The lower value of d makes the initial rise in the short term component faster than for H048, leading to very rapid initial increases in the dark current and the noise during the first run period (figure 10). The effect on the noise is particularly dramatic because of the very low amplifier noise contributed by the low capacitance of E135. Figure 11 shows the behaviour of E135 during three successive runs at low luminosity.

It is probable that LHC will run a schedule with the first three years at low luminosity followed by seven years at high luminosity. Figure 12 shows the long term component of the dark current and noise plotted (for H048) during run periods over this schedule. The short term component adds a few tens of percent to the noise during a run but always dies away during the rest period. Due to its poor initial value the noise of H048 is predicted to double in the ten year period with only a small increase in the three years at low luminosity. On the other hand the excellent performance of E135 is rapidly degraded even at low luminosity and finally it achieves a noise level similar to that of H048 in the later years at full luminosity (figure 13). Figure 14 compares the noise performance of the two APDs in the ten-year schedule.

4. CONCLUSIONS

Since there is a great shortage of scintillator light from lead tungstate, it is clear that the performance required from a viable APD lies much closer to the specification of E135 than to that of H048. A low capacitance and initial leakage current will be essential to reach the desired threshold and dynamic range. If the radiation environment experienced in the ISIS test beam is a fair approximation to that in the ECAL then it is clear that the performance of any low noise silicon APD will be degraded severely within six months of operation even at low luminosity. Radiation-induced dark current is the achilles heel of the APD because the diode amplifies it and so generates serious shot noise. There is thus no option to increase the gain or increase the amplifier shaping time constants to combat amplifier noise. Running the APDs at low temperature would appear to be the only possible method of ameliorating the situation.

REFERENCES

1. Investigation of avalanche photodiodes for EM calorimeter at LHC, A Karar et al, Ecole Polytechnique, IN2P3-CNRS, X-LPNHE/95-10 (Presented at "The First Workshop on Electronics for LHC Experiments", Lisbon, 11-15 September 1995

2. Gain and noise measurements on two avalanche photodiodes proposed for the CMS ECAL, J E Bateman, S R Burge and R Stephenson, RAL-TR-95-001

3. The response of some avalanche photodiodes to fast neutron irradiation, J E Bateman and R Stephenson, RAL-TR-96-009

FIGURE CAPTIONS

1. The dark current and RMS electronic noise of the APD #H048 plotted as a function of time after the termination of a sequence of exposures to a total neutron fluence of $2x10^{13}$ n/cm^2.

2. The dark current and RMS electronic noise of the APD #H049 plotted as a function of time after the termination of a sequence of exposures to a total neutron fluence of $1.34x10^{12}$ n/cm^2.

3. The dark current and RMS electronic noise of the APD #E135 plotted as a function of time after the termination of a sequence of exposures to a total neutron fluence of $5x10^{12}$ n/cm^2.

4. The differential dark current increase measured as APD #H048 progressed through the irradiation schedule.

5. The numerical integral defining the transient component of the dark current in the case of APD #H048. ($x=t/T$)

6. The total radiation-induced dark current calculated for a single run period of 9 months at full luminosity starting with a fresh Hamamatsu APD. Time is in units of x (i.e. 13.3 days).

7. A simulated period of 3 years of LHC running at full luminosity starting with a fresh H048. Dark current and RMS electronic noise are plotted.

8. A simulated period of 3 years of LHC running at 10% of full luminosity starting with a fresh H048. Dark current and RMS electronic noise are plotted.

9. The numerical integral defining the transient component of the dark current in the case of APD #E135. (x=t/T)

10. A simulated period of 3 years of LHC running at full luminosity starting with a fresh E135. Dark current and RMS electronic noise are plotted.

11. A simulated period of 3 years of LHC running at 10% of full luminosity starting with a fresh E135. Dark current and RMS electronic noise are plotted.

12. A plot of the long term component of dark current and noise for H048 subjected to a proposed LHC schedule of 3 years at 10% and 7 years at 100% luminosity. A run period of 9 months and a maintenance period of 3 months is assumed. The gaps represent the rest periods.

13. A plot of the long term component of dark current and noise for E135 subjected to a proposed LHC schedule of 3 years at 10% and 7 years at 100% luminosity. A run period of 9 months and a maintenance period of 3 months is assumed. The gaps represent the rest periods.

14. A comparison of the noise performance of H048 and E135 during the proposed 10 year schedule.

FIGURE 1

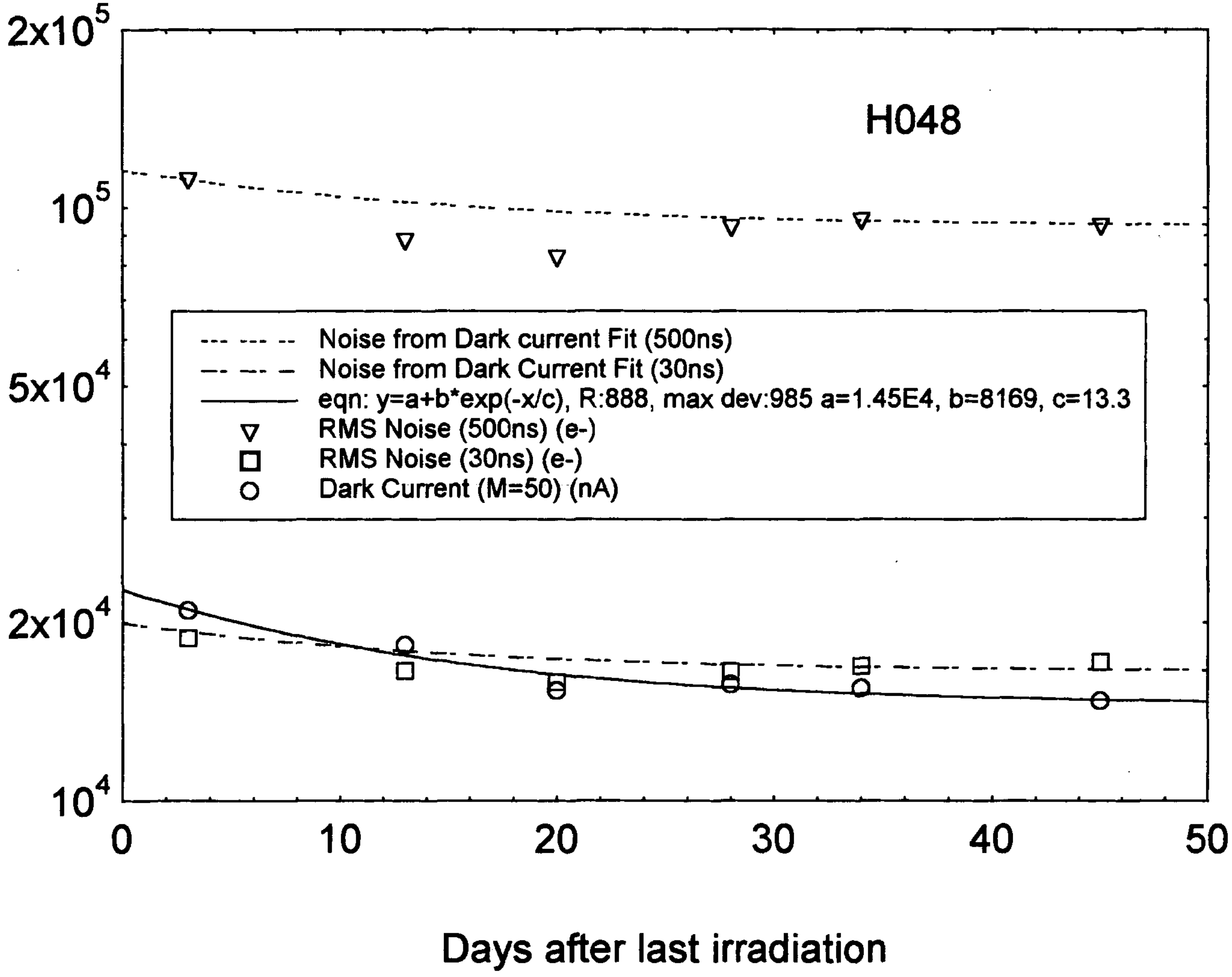
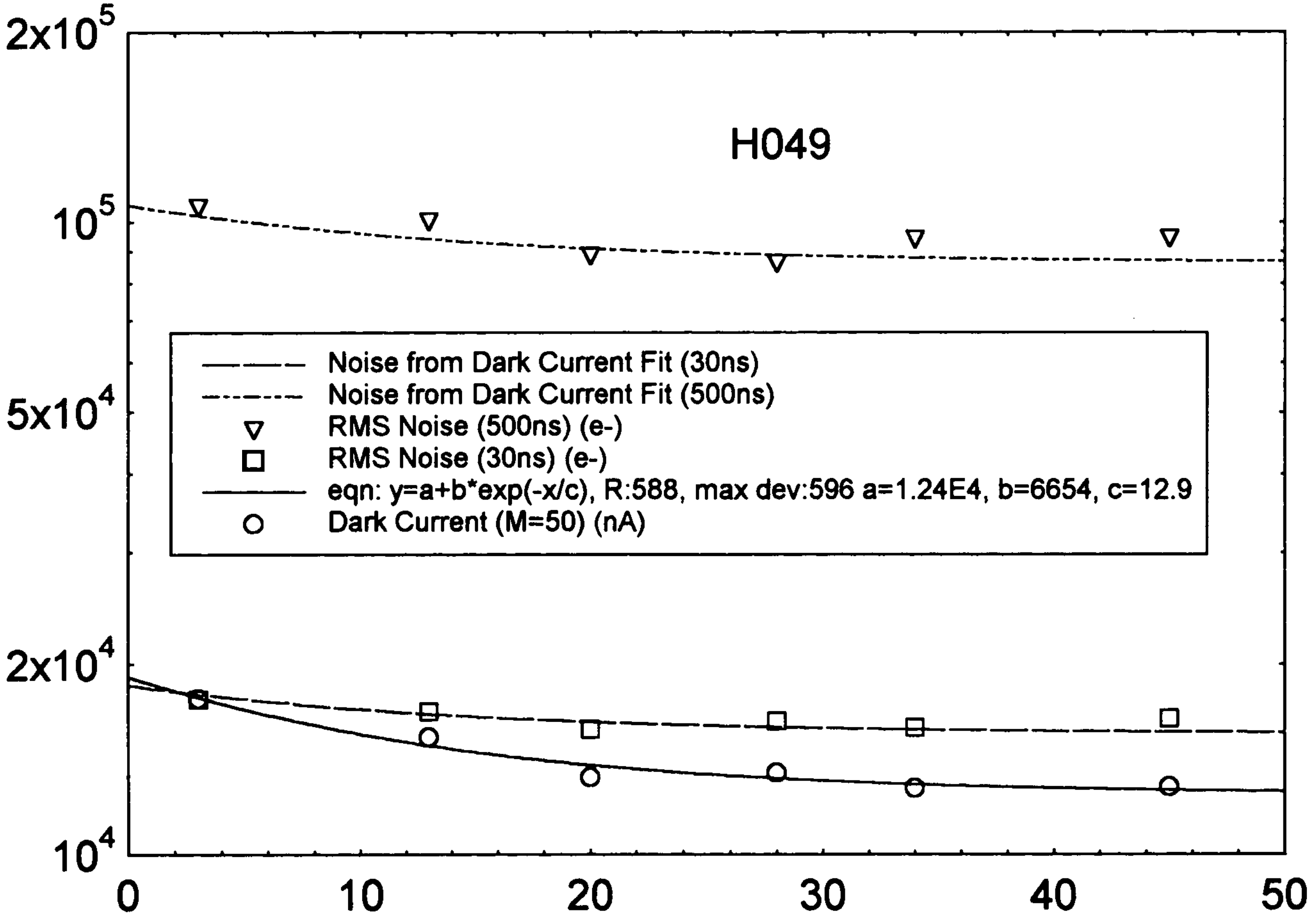

H048
2x10^5
10^5
5x10^4
2x10^4
10^4
0
10
20
30
40
50
Noise from Dark current Fit (500ns)
Noise from Dark Current Fit (30ns)
eqn: y=a+b*exp(-x/c), R:888, max dev:985 a=1.45E4, b=8169, c=13.3
RMS Noise (500ns) (e-)
RMS Noise (30ns) (e-)
Dark Current (M=50) (nA)
Days after last irradiation

FIGURE 2



Days after last irradiation

FIGURE 3

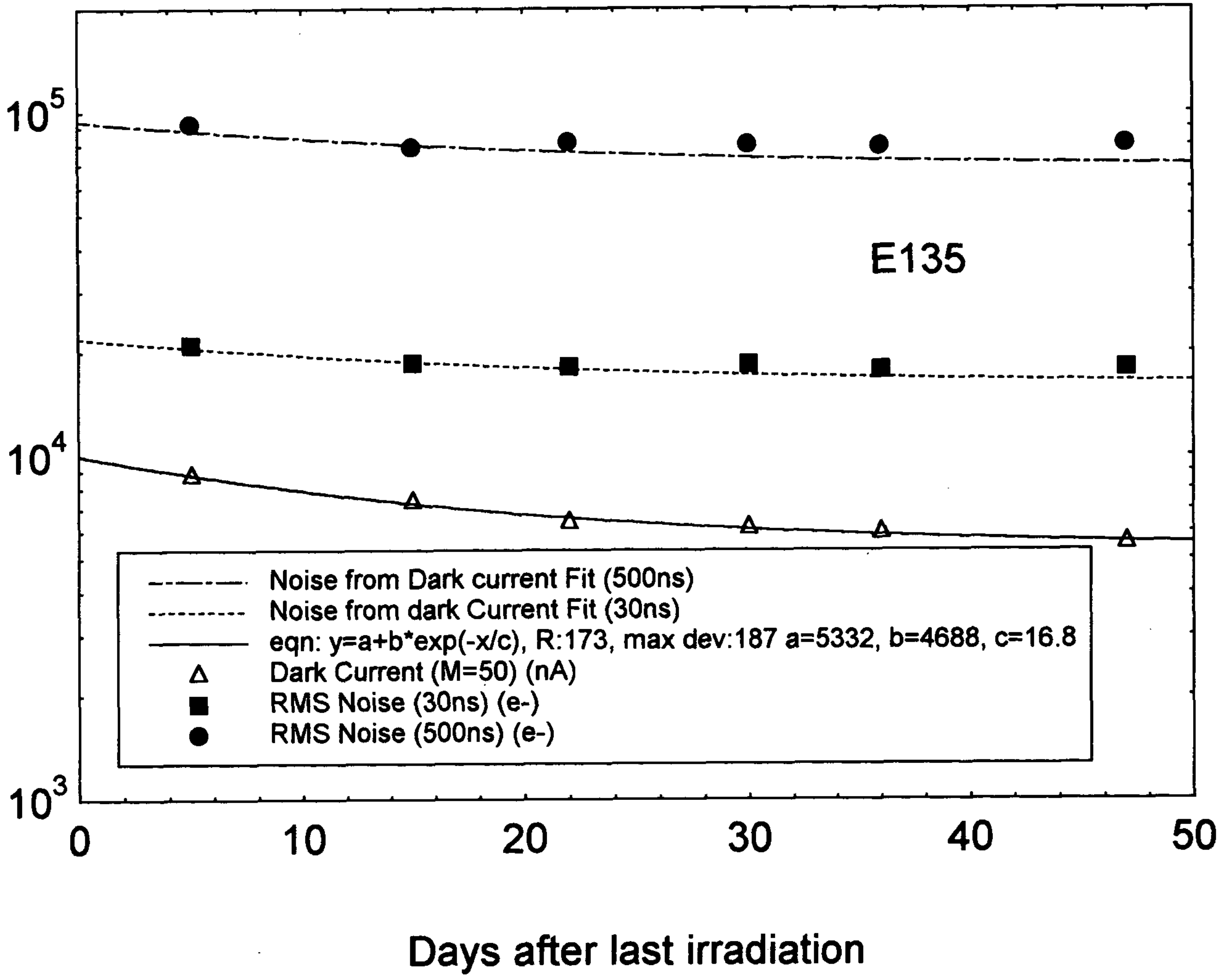

10^5
10^4
10^3
E135
Noise from Dark current Fit (500ns)
Noise from dark Current Fit (30ns)
eqn: y=a+b*exp(-x/c), R:173, max dev:187 a=5332, b=4688, c=16.8
Dark Current (M=50) (nA)
RMS Noise (30ns) (e-)
RMS Noise (500ns) (e-)
0
10
20
30
40
50
Days after last irradiation

FIGURE 4

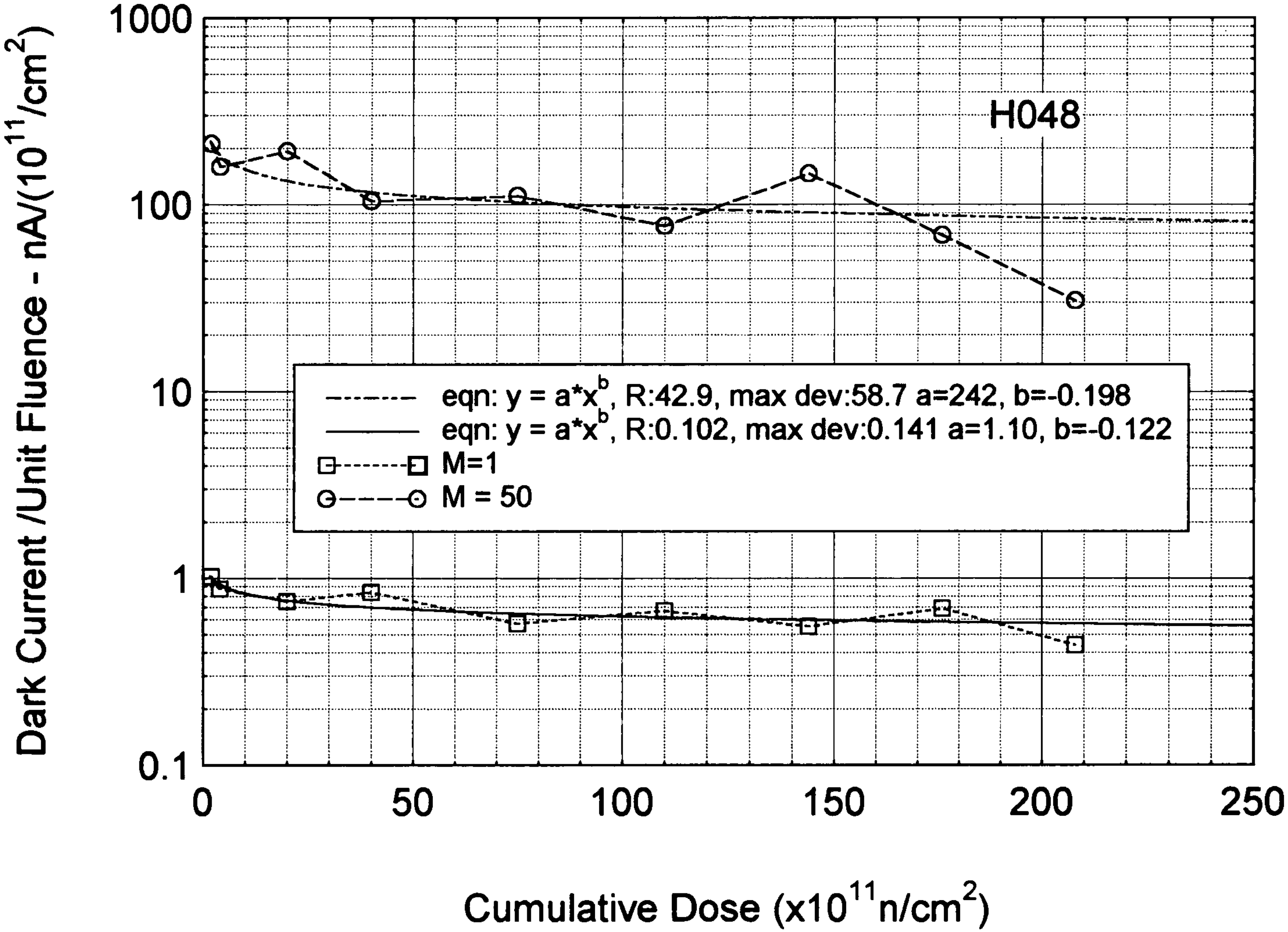

H048
eqn: $y = a*x^b$, R:42.9, max dev:58.7 a=242, b=-0.198
eqn: $y = a*x^b$, R:0.102, max dev:0.141 a=1.10, b=-0.122
M=1
M = 50
1000
100
10
1
0.1
0
50
100
150
200
250
Dark Current /Unit Fluence - nA/(10^{11}/cm^2)
Cumulative Dose (x10^{11}n/cm^2)

FIGURE 5

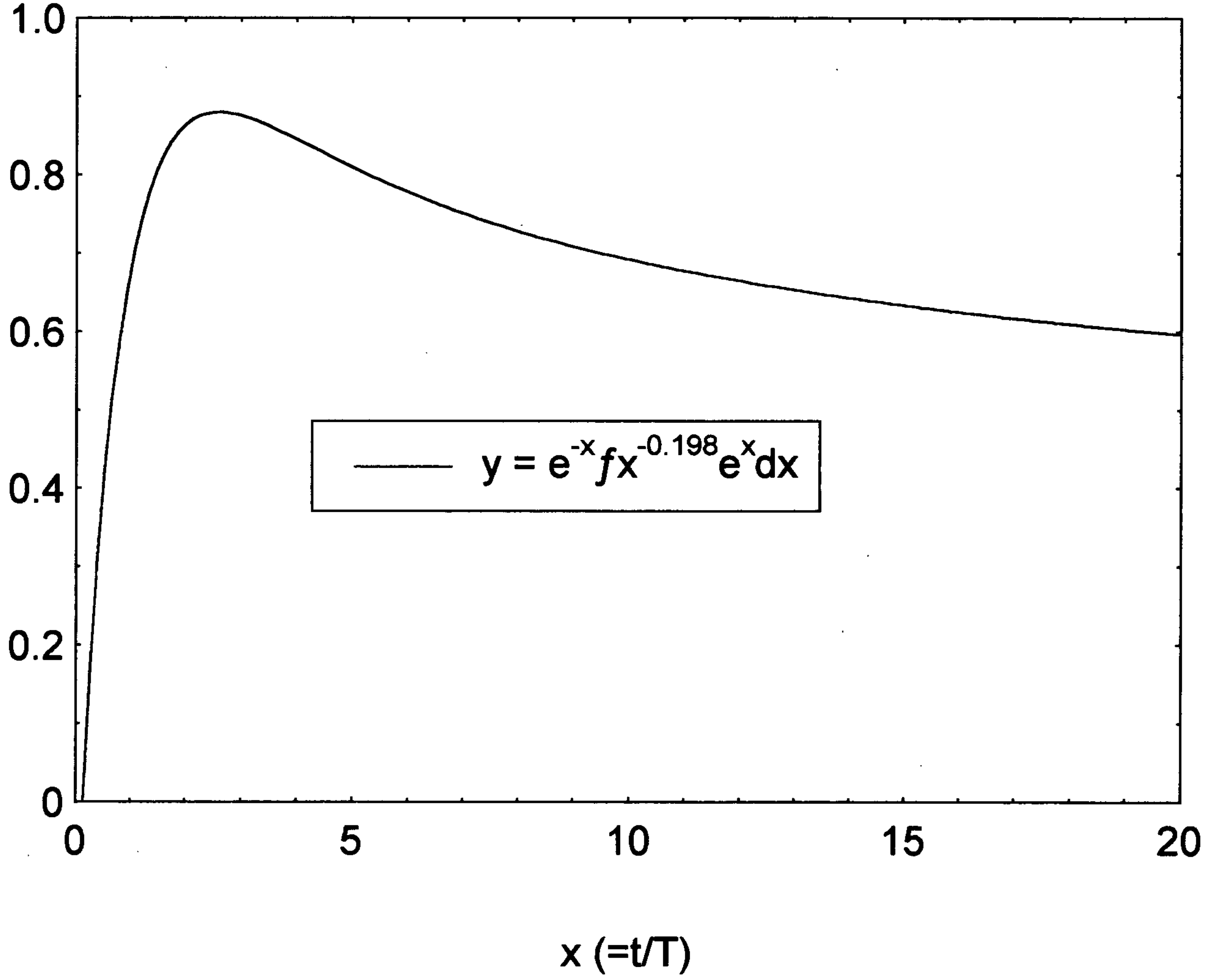


FIGURE 6

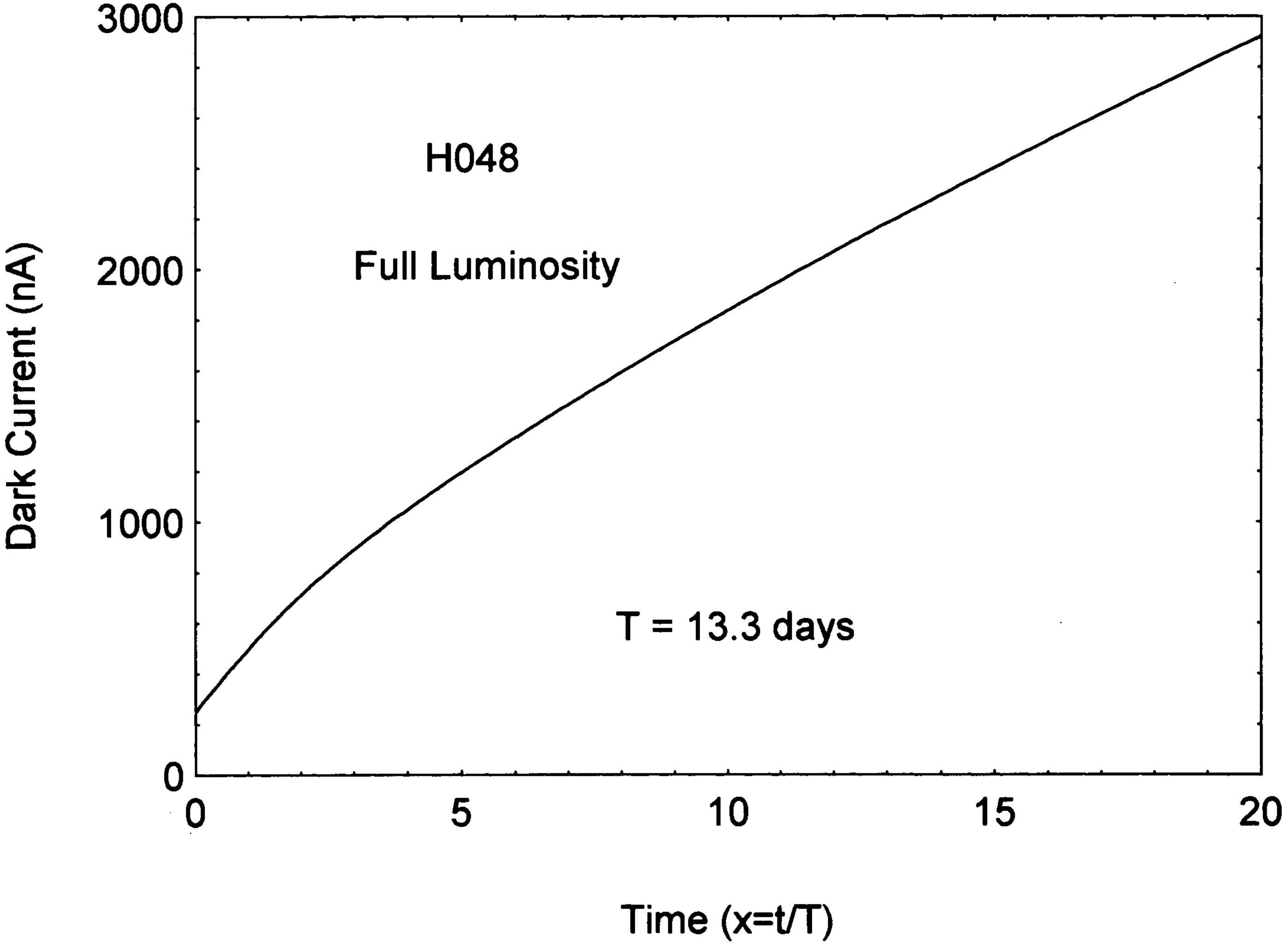

H048
Full Luminosity
T = 13.3 days
Dark Current (nA)
0
1000
2000
3000
0
5
10
15
20
Time (x=t/T)

FIGURE 7

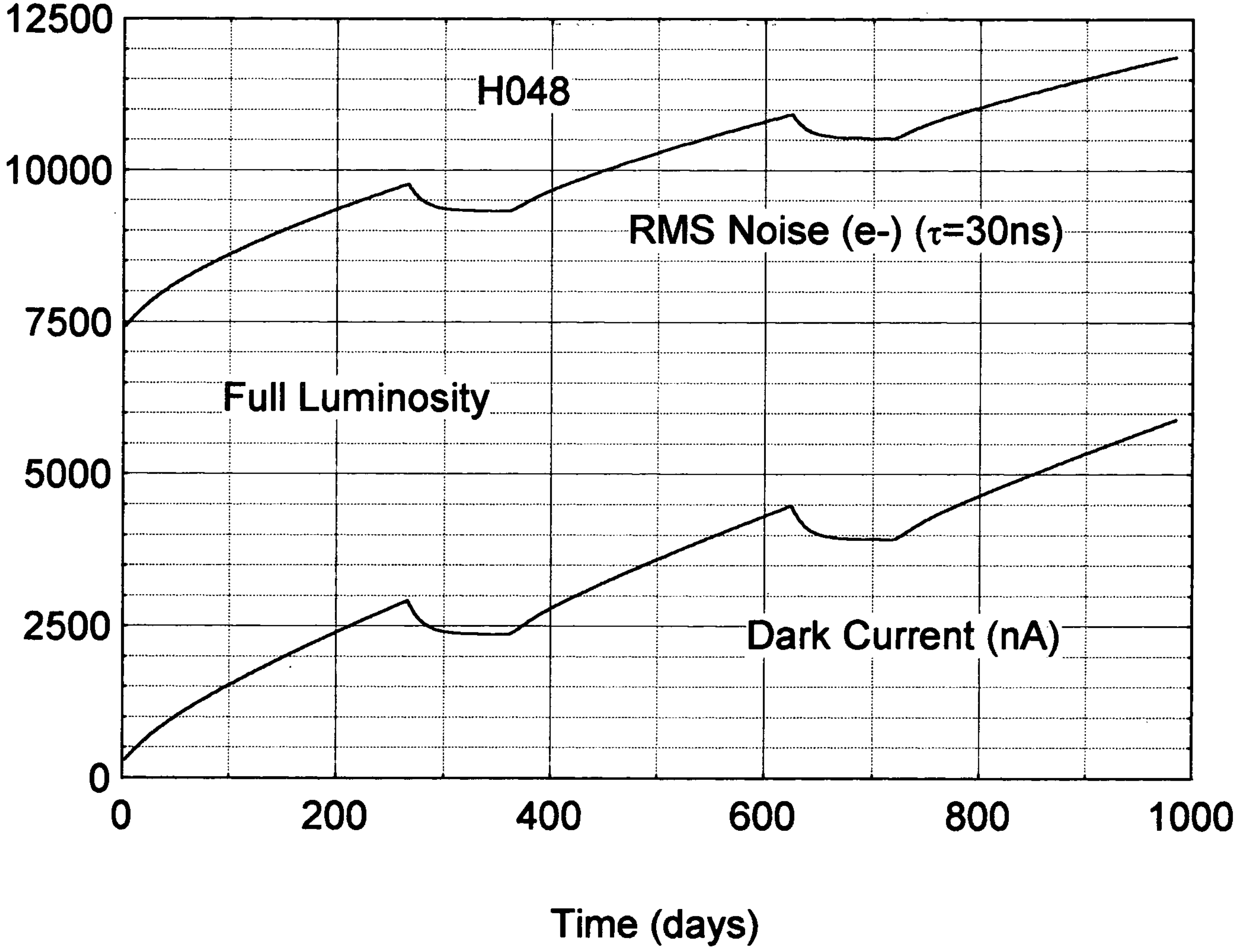

12500
10000
7500
5000
2500
0
0
200
400
600
800
1000
H048
RMS Noise (e-) (τ=30ns)
Full Luminosity
Dark Current (nA)
Time (days)

FIGURE 8

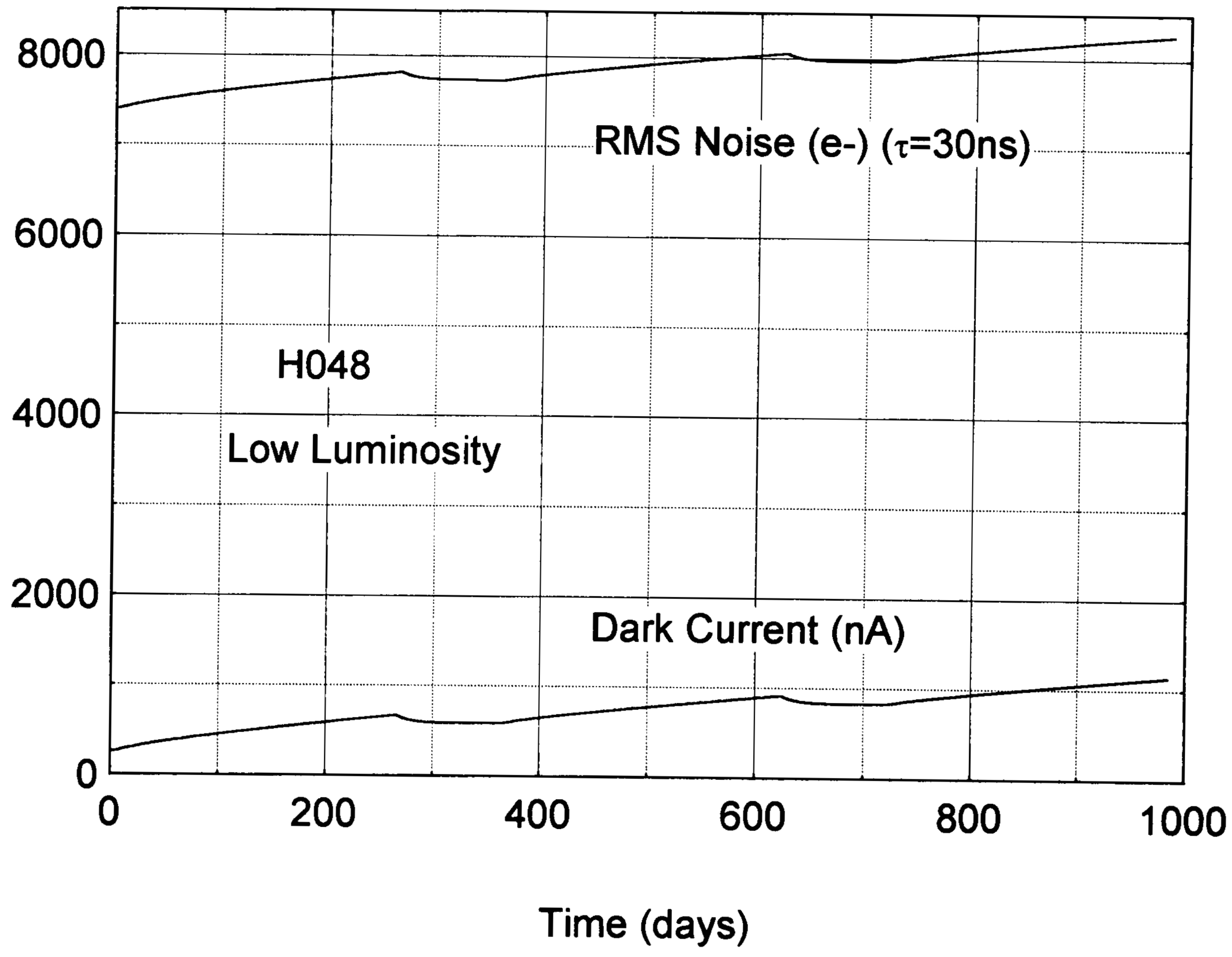

8000
6000
4000
2000
0
0
200
400
600
800
1000
RMS Noise (e-) (τ=30ns)
H048
Low Luminosity
Dark Current (nA)
Time (days)

FIGURE 9

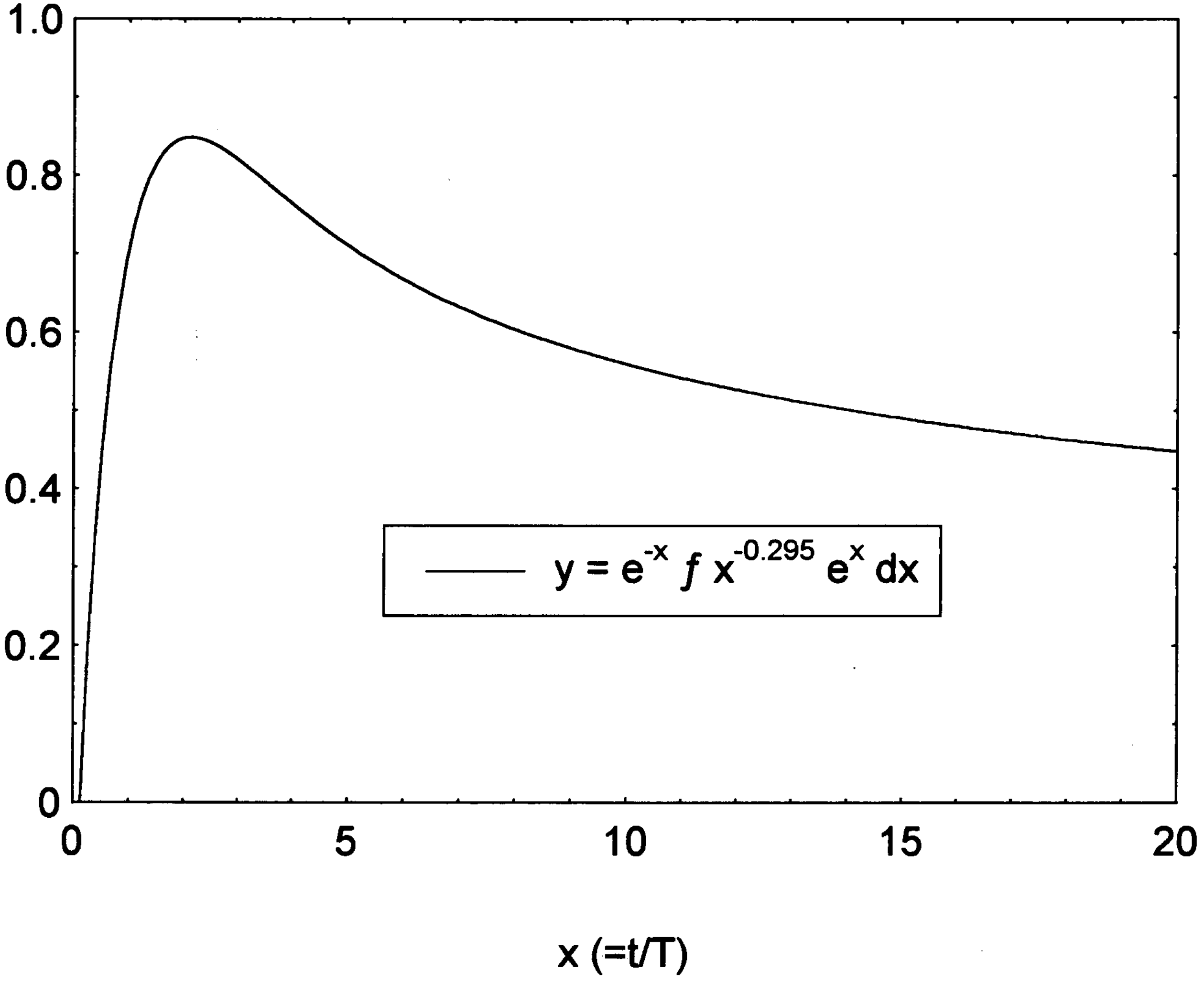
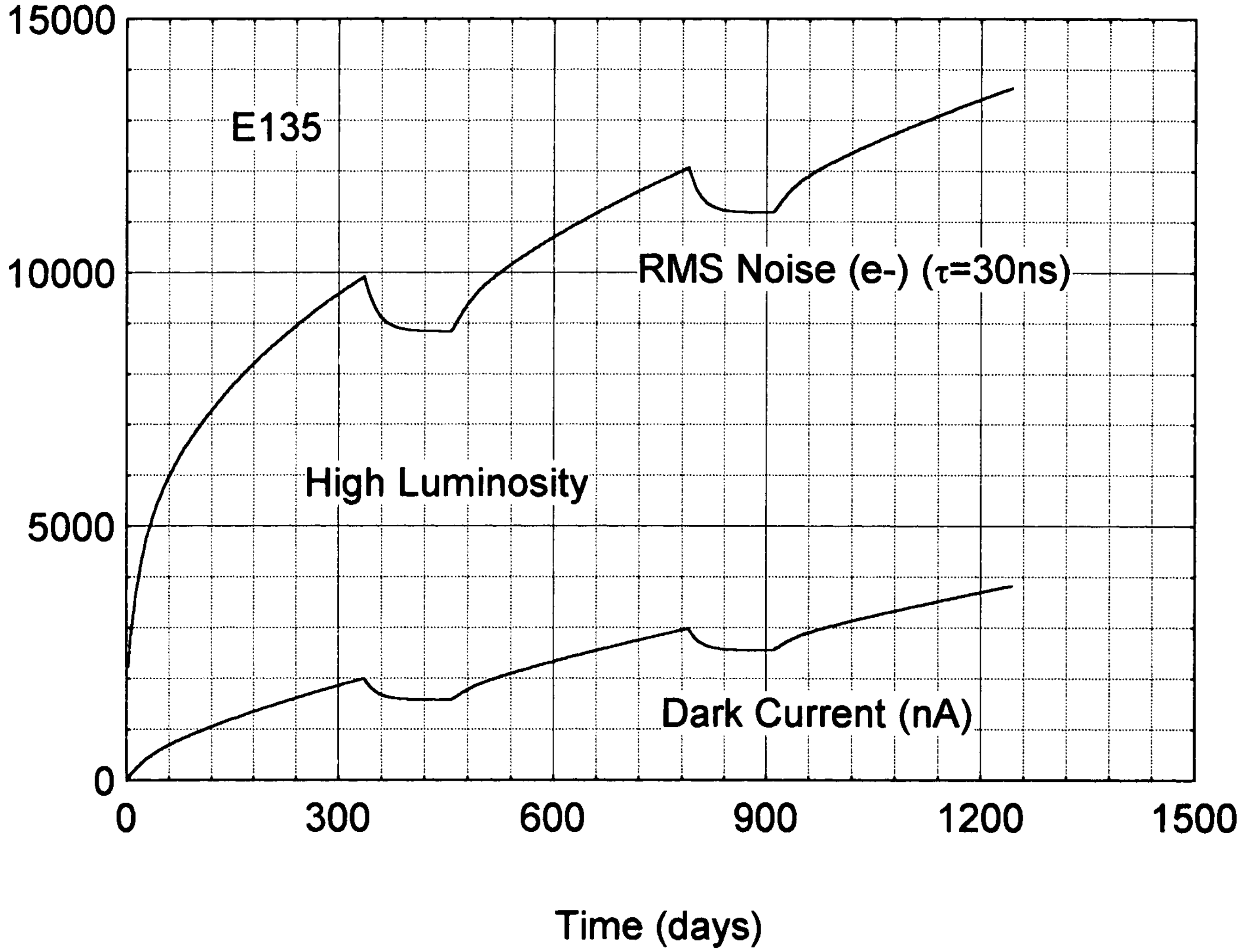


FIGURE 10



15000
10000
5000
0
0
300
600
900
1200
1500
E135
RMS Noise (e-) (τ=30ns)
High Luminosity
Dark Current (nA)
Time (days)

FIGURE 11

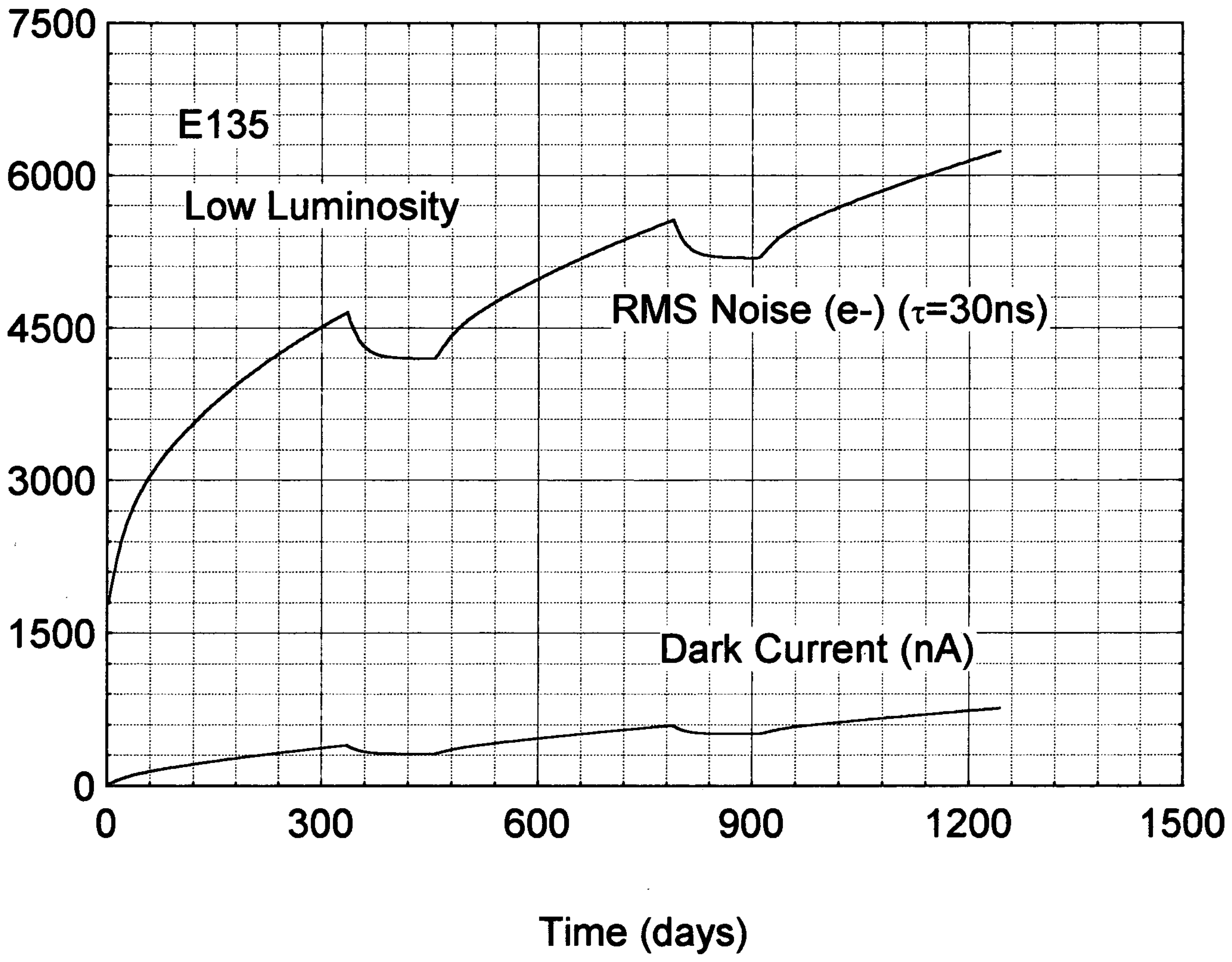

7500
6000
4500
3000
1500
0
E135
Low Luminosity
RMS Noise (e-) (τ=30ns)
Dark Current (nA)
0
300
600
900
1200
1500
Time (days)

FIGURE 12

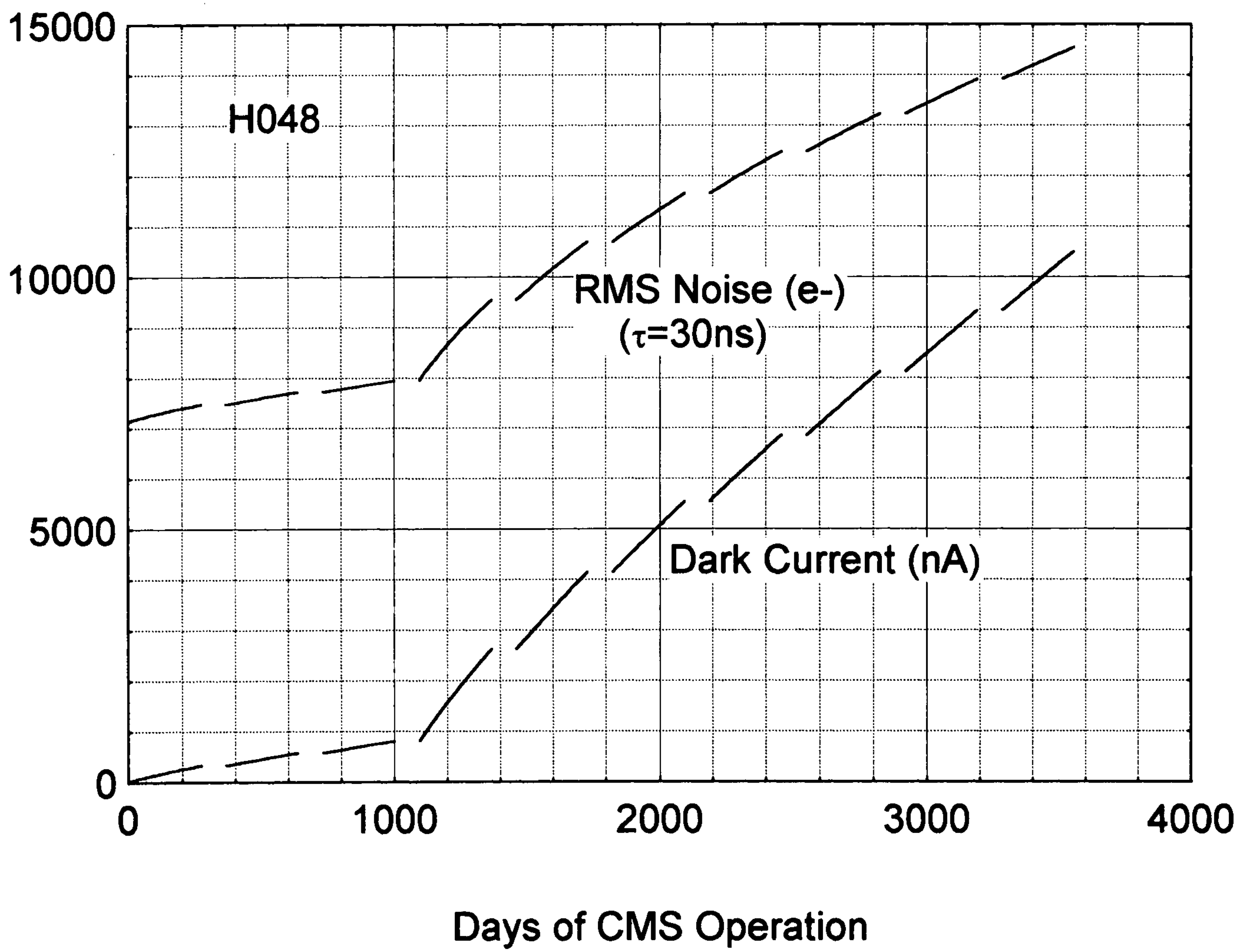

15000
10000
5000
0
H048
RMS Noise (e-)
(τ=30ns)
Dark Current (nA)
0
1000
2000
3000
4000
Days of CMS Operation

FIGURE 13

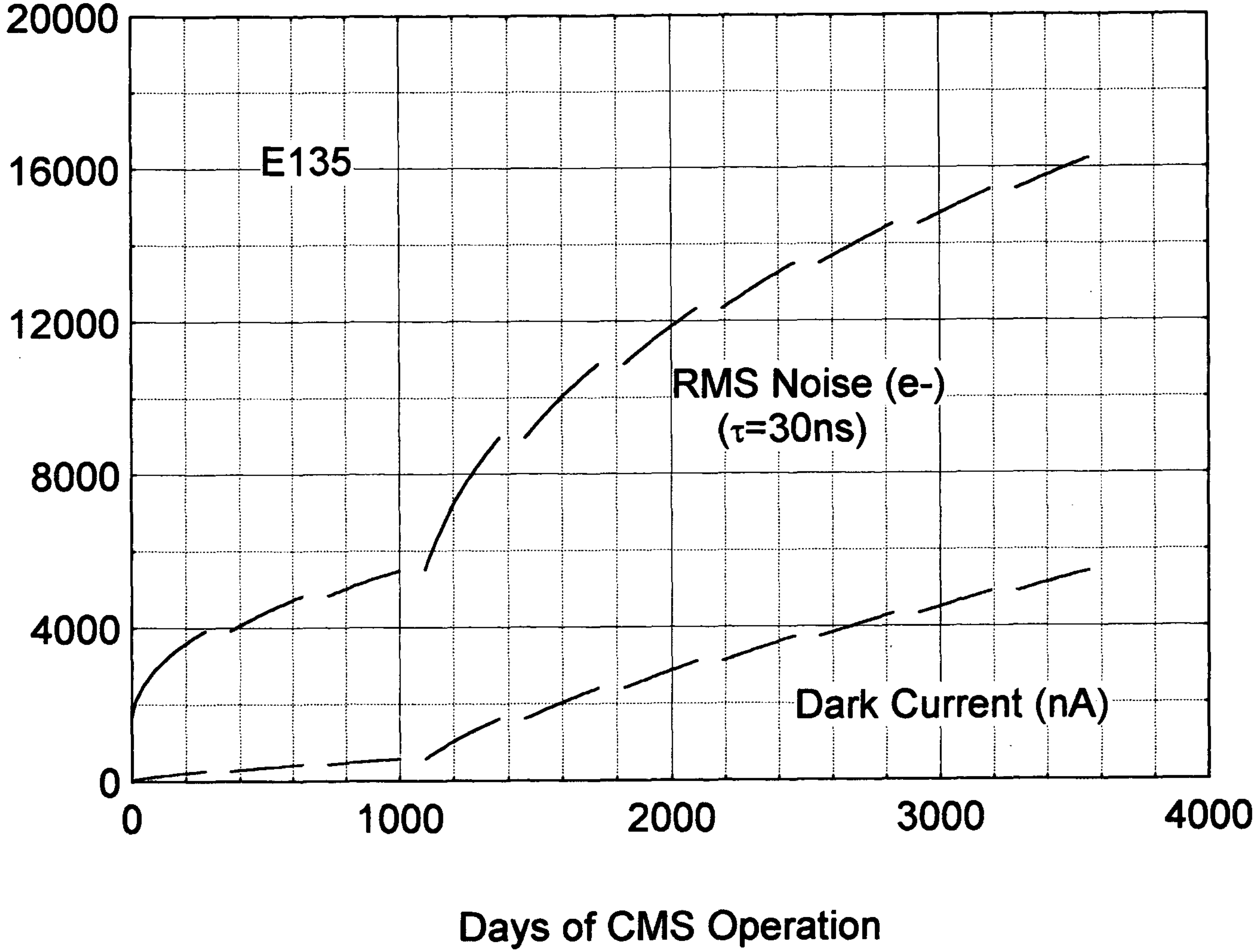
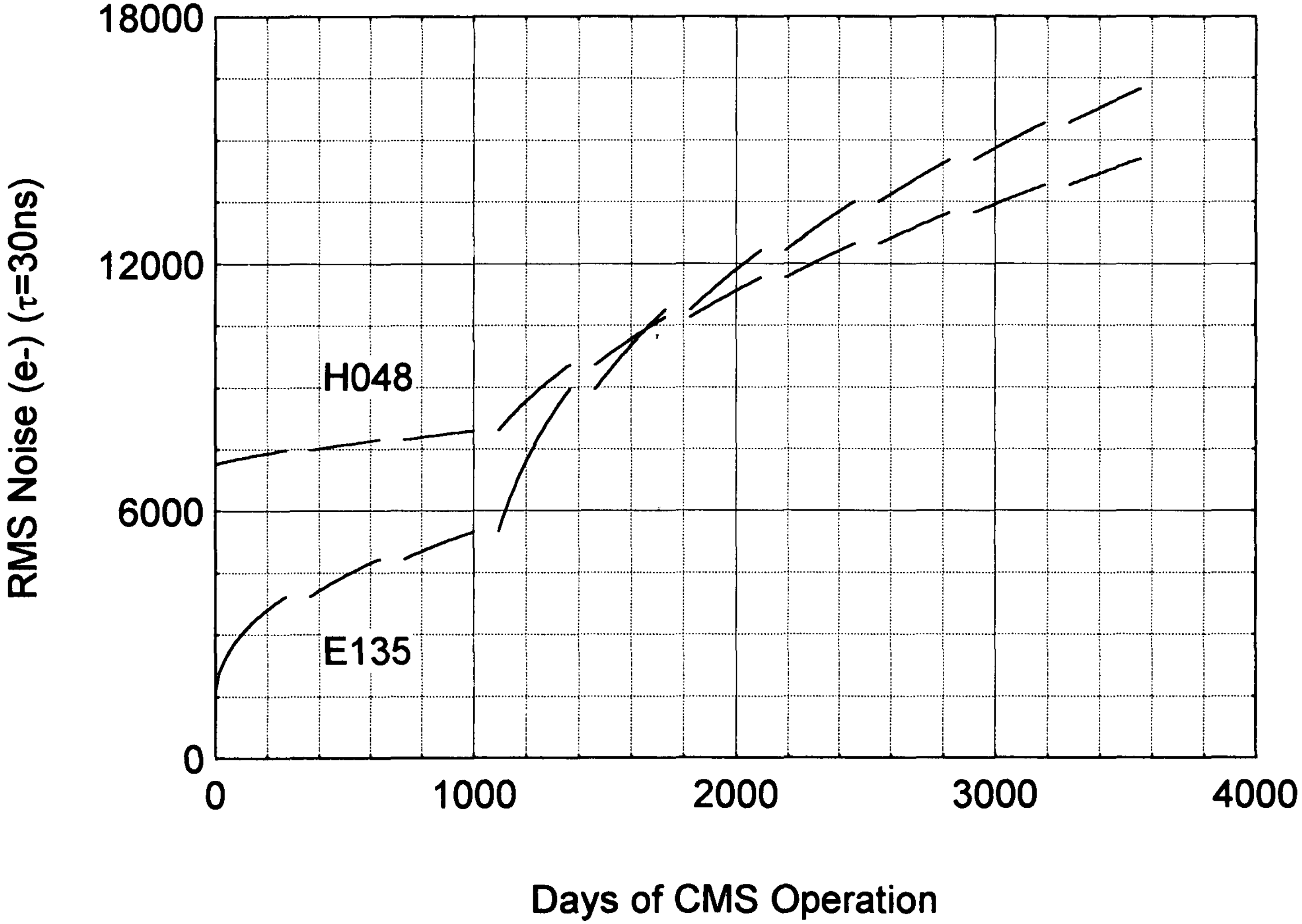

20000
16000
12000
8000
4000
0
0
1000
2000
3000
4000
E135
RMS Noise (e-)
(τ=30ns)
Dark Current (nA)
Days of CMS Operation

FIGURE 14


RMS Noise (e-) (τ=30ns)
18000
12000
6000
0
0
1000
2000
3000
4000
H048
E135
Days of CMS Operation