Radiation damage studies of silicon photomultipliers

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Abstract

We report on the measurement of the radiation hardness of silicon photomultipliers (SiPMs) manufactured by Fondazione Bruno Kessler in Italy (1 and 6.2 mm²), Center of Perspective Technology and Apparatus in Russia (1 and 4.4 mm²), and Hamamatsu Corporation in Japan (1 mm²). The SiPMs were irradiated using a beam of 212 MeV protons at Massachusetts General Hospital, receiving fluences of up to 3 \times 10^{10} protons per cm² with the SiPMs at operating voltage. Leakage currents were read continuously during the irradiation. The delivery of the protons was paused periodically to record scope traces in response to calibrated light pulses to monitor the gains, photon detection efficiencies, and dark counts of the SiPMs. The leakage current and dark noise are found to increase with fluence. The leakage current is found to be proportional to the mean square deviation of the noise distribution, indicating the dark counts are due to increased random individual pixel activation, while SiPMs remain fully functional as photon detectors. The SiPMs are found to anneal at room temperature with a reduction in the leakage current by a factor of 2 in about 100 days.

1. Introduction

During the last several years, we have investigated the use of silicon photomultipliers (SiPMs) [1,2] to collect light from bundles of 1 mm fibers optically connected to the scintillators of the hadron calorimeter of the Compact Muon Solenoid (CMS) [3] at the Large Hadron Collider (LHC) [4]. The SiPMs developed for use at the LHC must be sufficiently radiation hard to withstand the expected fluence. Damage in silicon detectors depends on the flux, type and energy of the particles. The damage produced by protons depends on their energy-dependant non-ionizing energy losses (NIEL). For LHC detectors, particle fluxes have been calculated in 1 MeV neutron equivalent fluxes. The damage produced by the 212 MeV protons used for these measurements is about 0.8 of that produced by 1 MeV neutrons [5]. The fluence for one LHC lifetime in the proximity of the CMS hadron outer (HO) photodetectors is expected to be approximately equivalent to 10^{10} per cm² [6–10]. While many silicon devices have been proven to be robust under LHC fluences [11], no previous measurements are available for the latest generation of SiPMs with an active area (A) of several mm².

The SiPMs chosen for irradiation were A = 6.2 mm² round diodes from Fondazione Bruno Kessler (FBK, formerly ICT-irst) in Italy, and A = 4.4 mm² square diodes from the Center of Perspective Technology and Apparatus (CPTA) in Russia. We also irradiated A = 1.0 mm² square diodes from FBK, CPTA, and Hamamatsu Corporation (HC) in Japan. All of the SiPMs have a pixel size of 50 \mu m \times 50 \mu m [2]. In addition, we made measurements of a single pixel on an FBK 6.2 mm² SiPM.

2. Experimental setup

The radiation studies were carried out at the proton cyclotron [12] at the Massachusetts General Hospital Francis H. Burr Proton Therapy Center in Boston, MA, USA. The proton kinetic energy at the SiPMs was 212 MeV. The beam spot size was 4 cm diameter, allowing irradiation of three SiPMs simultaneously. The fluence delivered on target was measured directly during irradiation using a thin-foil transmission ion chamber whose response was calibrated to the fluence with a Faraday cup. The SiPMs were mounted in groups of four on printed circuit boards. The SiPM boards were mounted in a dark box together with a light-emitting
diode (LED) as indicated in Fig. 1. The three SiPMs to be irradiated were extended vertically above the circuit boards into the proton beam by their electrical leads. A fourth CPTA 4 mm2 SiPM was mounted on each circuit board out of the radiation area and monitored before, during, and after irradiation as a reference diode. The positioning of the SiPM within the beam profile was checked directly with a photographic film exposure as shown in Fig. 2.

Fig. 3 shows a block diagram of the readout. The nominal operating voltage ($V_b$) was set individually for each SiPM to be approximately 3 V above turn-on (zero current) for the CPTA and FBK devices using Keithley 6487 power supplies. The gain in this region of $V_b$ was measured to be linear, varying from about 20 fC/PE per V for CPTA 4.4 mm2 to 200 fC/PE per V for FBK 6.2 mm2. The resulting leakage current ($I_b$) per SiPM active area was in the range of 1–2 μA/mm2. The HC SiPMs have a steeper $I_b$ vs. $V_b$ curve and were set to be about 1 V above turn-on, resulting in a leakage current per area of about 0.1 μA/mm2.

The SiPMs were mounted on four different circuit boards and were irradiated as summarized in Table 1. Boards 1 and 2 were populated with like SiPMs (CPTA 4.4 mm2 reference, CPTA 1.0 mm2, HC 1.0 mm2, and FBK 1.0 mm2) and were exposed to fluences of $10^{10}$ protons per cm2 for board 1 and $3 \times 10^{10}$ protons per cm2 for board 2. Similarly boards 3 and 4 were populated with the same types of SiPMs (CPTA 4.4 mm2 reference, CPTA 4.4 mm2, FBK 6.2 mm2, and FBK single pixel) and irradiated to $10^{10}$ protons per cm2 for board 3 and $3 \times 10^{10}$ protons per cm2 for board 4. Boards 1 and 3 were irradiated in steps of 2.5 x $10^{9}$ protons per cm2 up to a total fluence of $10^{10}$ protons per cm2. The fluence for each step was delivered uniformly over a time of 5 min. Several minutes were taken between irradiation steps in order to record waveforms. Boards 2 and 4 were irradiated in steps of 2.5 x $10^{9}$ protons per cm2 up to a partial fluence of $10^{10}$ protons per cm2 and then further exposed with two more steps of $10^{10}$ protons per cm2, for a total fluence of $3 \times 10^{10}$ protons per cm2. The SiPMs were kept at nominal operating voltage during the irradiation to allow continuous monitoring of $I_b$.

The LED was pulsed with a 50 MHz Hewlett-Packard 8112A pulse generator and files of 5000 waveforms were recorded with a Lecroy LT594 digital scope to monitor the pulse shape, signal, and noise distributions. The signal and noise distributions allowed monitoring of the gain ($M$) and number of photoelectrons ($n_{PE}$). The mean signal ($S$) in response to the LED may be written as

$$S = Mn_{PE},$$

where the pedestal contribution due to electronic noise has been subtracted. The root mean square (RMS) deviation ($\sigma$) from the mean may be written as

$$\sigma = \sqrt{\frac{1}{S} \sum (S_i)^2},$$

where the electronic noise has been subtracted in quadrature and $F$ is defined to be the excess noise factor, a number which has been independently measured to be close to unity for the SiPMs [1]. The measured distribution of $S$ then allows determination of the product of gain times excess noise factor,

$$MF = \frac{\sigma^2}{S},$$

and the number of photoelectrons divided by the excess noise factor,

$$\frac{n_{PE}}{F} = \frac{S^2}{\sigma^2}.$$

3. Leakage currents during irradiation

Leakage currents were read continuously during the irradiation. Fig. 4 shows $I_b/A$ vs. time for the SiPMs on board 1. The plateaus correspond to partial fluences of $2.5 \times 10^9$, $5 \times 10^9$, $7.5 \times 10^9$, and $10^{10}$ protons per cm2, when the delivery of protons was paused in order to record SiPM waveforms. Fig. 5 shows $I_b/A$ vs. time for the SiPMs on board 2. The plateaus correspond to partial fluences of $2.5 \times 10^9$, $5 \times 10^9$, $7.5 \times 10^9$, $10^{10}$, $2 \times 10^{10}$, and $3 \times 10^{10}$ protons per cm2. A drop in leakage current due to room-temperature annealing is visible after each irradiation step.

Fig. 6 shows $I_b/A$ vs. time for the larger-area SiPMs on board 3. The peaks correspond to partial fluences of $2.5 \times 10^9$, $5 \times 10^9$, $7.5 \times 10^9$, $10^{10}$, $2 \times 10^{10}$, and $3 \times 10^{10}$ protons per cm2. A drop in leakage current due to room-temperature annealing is visible after each irradiation step.
7.5 × 10^9, and 10^{10} protons per cm^2. A drop in leakage current due to room-temperature annealing is visible after each step and is especially pronounced for the FBK 6.8 mm^2 SiPM. Fig. 7 shows I_b/A vs. time for the SiPMs on board 4. The peaks correspond to partial fluences of 2.5 × 10^9, 5 × 10^9, 7.5 × 10^9, 10^{10}, 2 × 10^{10}, and 3 × 10^{10} protons per cm^2. The leakage currents for the single pixel readouts show a similar time structure with fluence and were in the 50–200 nA range.

### 4. CPTA 4.4 mm^2 reference SiPMs

A CPTA 4.4 mm^2 SiPM was installed on each board and was not irradiated in order to serve as a reference signal to monitor the stability of the LED. The reference SiPMs were monitored before, during, and after the irradiation. Table 2 shows the currents, gain, number of photoelectrons and signal stability for the reference SiPMs. The data were taken at the same time that the indicated fluence was delivered to the other three SiPMs on each board. There was about an 8 h time difference between the first measurement on board 1 and the last measurement on board 4. The measurements on 15 April 2008 were taken 135 days later. The values of I_b/A were stable for all the reference SiPMs. The calculated values of MF from the mean and rms of the LED data were also stable at the few percent level. The values of n_{PE}/F were uniform to a few per cent, indicating that the light output of the LED was relatively stable over this period. A change of the signal response (S) divided by the initial value (S_0) was observed to drift by 5–7% over the measurement period.

### 5. CPTA 1.0 mm^2

 Measurements of I_b vs. V_b were taken before and after each partial fluence. Fig. 8 shows I_b as a function of V_b for CPTA 1.0 mm^2 on board 2 for fluences of zero, 5 × 10^9, 10^{10}, 2 × 10^{10}, and 3 × 10^{10} protons per cm^2. The shape of the I_b vs. V_b distributions indicate that the gain vs. voltage is relatively stable. A direct measurement of MF from the mean and width of the response to the LED as a function of voltage before and after irradiation shows that the gain in the region of nominal voltage varies by about 100 fC/PE per V for CPTA 1.0 mm^2 on board 1 and about 50 fC/PE per V for CPTA 1.0 mm^2 on board 2. At a nominal...
Fig. 4. Leakage currents per area measured during irradiation for SiPMs on board 1: CPTA 4.4 mm$^2$ reference diode (line), HC 1.0 mm$^2$ (circles), FBK 1.0 mm$^2$ (squares), and CPTA 1.0 mm$^2$ (triangles). The plateaus correspond to partial fluences of $2.5 \times 10^8$, $5 \times 10^8$, $7.5 \times 10^8$, and $10^{10}$ protons per cm$^2$. A drop in leakage current due to room-temperature annealing is visible after each step.

Fig. 5. Leakage currents per area measured during irradiation for SiPMs on board 2: CPTA 4.4 mm$^2$ reference diode (line), HC 1.0 mm$^2$ (circles), FBK 1.0 mm$^2$ (squares), and CPTA 1.0 mm$^2$ (triangles). The plateaus correspond to partial fluences of $2.5 \times 10^8$, $5 \times 10^8$, $7.5 \times 10^8$, $10^{10}$, $2 \times 10^{10}$, and $3 \times 10^{10}$ protons per cm$^2$. A drop in leakage current due to room-temperature annealing is visible after each step.

Fig. 6. Leakage currents per area measured during irradiation for SiPMs on board 3: CPTA 4.4 mm$^2$ reference diode (line), CPTA 4.4 mm$^2$ (circles), and FBK 6.2 mm$^2$ (triangles). The plateaus correspond to partial fluences of $2.5 \times 10^8$, $5 \times 10^8$, $7.5 \times 10^8$, and $10^{10}$ protons per cm$^2$. A drop in leakage current due to room-temperature annealing is visible after each step.

Fig. 7. Leakage currents per area measured during irradiation for SiPMs on board 4: CPTA 4.4 mm$^2$ reference diode (line), CPTA 4.4 mm$^2$ (circles), and FBK 6.2 mm$^2$ (triangles). The plateaus correspond to partial fluences of $2.5 \times 10^8$, $5 \times 10^8$, $7.5 \times 10^8$, $10^{10}$, $2 \times 10^{10}$, and $3 \times 10^{10}$ protons per cm$^2$. A drop in leakage current due to room-temperature annealing is visible after each step.
operating voltage of $V_b = 34$ V, the leakage current increases from $1.9$ µA at zero fluence to $63.6$ µA at $3 \times 10^{10}$ cm$^{-2}$. Similar $I_L$ vs. $V_b$ curves were observed for the other CPTA 1.0 mm$^2$ on board 1, where the leakage current at nominal voltage (34 V) increased from $1.5$ µA at zero fluence to $51$ µA at $10^{10}$ cm$^{-2}$.

Table 3 shows the values of $I_L$, $MF$, and $n_{PE}/F$ as defined in Section 2, as well as the change in signal $S$ in response to the LED divided by that at zero fluence ($S_0$). The values of $n_{PE}$ are corrected for the measured deviation of the reference diode (see Table 2). The gain times excess noise factor is observed to decrease from 370 to 300 fC/PE for board 1 and from 230 to 180 fC/PE for board 2. At large bias currents, a drop in gain is expected due to a reduction in the bias voltage caused by a voltage drop across the 2 kΩ input resistor.

The pulse shape in response to the LED was monitored in 500 ns time bins. The pulse shape was observed to be stable at all fluences on both boards 1 and 2. Fig. 9 shows the average pulse shape on board 2 summed over 5000 events for (a) zero fluence, (b) $10^{10}$ cm$^{-2}$, and (c) $3 \times 10^{10}$ cm$^{-2}$. The pulse shape of the CPTA 1.0 mm$^2$ was observed to have a long time-constant component due to a large value of quantum efficiency.

The pedestal was summed over 200 ns (bins 1–100 of Fig. 9(a)–(c)) to get the noise distributions in fC shown in Fig. 9 for (d) zero fluence, (e) $10^{10}$ cm$^{-2}$, and (f) $3 \times 10^{10}$ cm$^{-2}$ for board 2. The rms noise increases from $192$ fC at zero fluence to $670$ fC at $10^{10}$ cm$^{-2}$ to $979$ fC at $3 \times 10^{10}$ cm$^{-2}$. The noise distribution for CPTA 1 mm$^2$ on board 1 was $277$ fC at zero fluence, increasing to $1205$ fC at $10^{10}$ cm$^{-2}$ for $V_b = 34$ V.

The pulse was summed over 200 ns (bins 151–250 of Fig. 9(a)–(c)) and the pedestal was subtracted to get the signal distributions in fC shown in Fig. 9 for (g) zero fluence, (h) $10^{10}$ cm$^{-2}$, and (i) $3 \times 10^{10}$ cm$^{-2}$ for board 2. To calibrate out any instability of the LED, the change in signal was monitored relative to the CPTA 4.4 mm$^2$ reference SiPM on the same board. The variation of the signals from the reference SiPM varied by 5% for board 1 and 7% for board 2. The signal on the CPTA 1 mm$^2$ SiPM on board 2, relative to zero fluence and corrected for the reference diode signal, was observed to drop by 10% at a fluence of $10^{10}$ cm$^{-2}$ and 25% at $3 \times 10^{10}$ cm$^{-2}$. Similarly, the signal for CPTA 1 mm$^2$ on board 1 was 12% lower at a fluence of $10^{10}$ cm$^{-2}$.

Fig. 10 shows the square of the rms noise as a function of $I_L/A$ for CPTA 1.0 mm$^2$ on board 2, for data taken immediately after the irradiation (2 December 2007). The approximate linear dependence indicates that the increase in noise is due to an increase in rate of dark counts, i.e. that the leakage current is proportional to the square of the number of activated pixels.

Table 2

| Board | Time       | $I_L/A$ (µA/mm$^2$) | MF (fC/PE) | $n_{PE}/F$ | S/S$_0$ |
|-------|------------|---------------------|------------|------------|---------|
| 1     | At zero    | 1.2                 | 51         | 146        | 1       |
| 1     | At 2.5 x 10$^9$ cm$^{-2}$ | 1.1 | 50 | 148 | 1.00 |
| 1     | At 5 x 10$^9$ cm$^{-2}$ | 1.1 | 48 | 150 | 0.97 |
| 1     | At 7.5 x 10$^9$ cm$^{-2}$ | 1.1 | 50 | 144 | 0.96 |
| 1     | At 10$^{10}$ cm$^{-2}$ | 1.1 | 50 | 146 | 0.95 |
| 1     | 15 April 2008 | 1.1 | 49 | 141 | 0.93 |
| 2     | At zero    | 1.6                 | 100        | 170        | 1       |
| 2     | At 5 x 10$^9$ cm$^{-2}$ | 1.6 | 100 | 170 | 0.98 |
| 2     | At 10$^{10}$ cm$^{-2}$ | 1.6 | 100 | 170 | 0.97 |
| 2     | At 3 x 10$^{10}$ cm$^{-2}$ | 1.8 | 100 | 160 | 0.93 |
| 2     | 15 April 2008 | 1.5 | 110 | 150 | 1.00 |
| 3     | Zero       | 2.3                 | 110        | 190        | 1       |
| 3     | At 2.5 x 10$^9$ cm$^{-2}$ | 2.1 | 100 | 200 | 0.94 |
| 3     | At 5 x 10$^9$ cm$^{-2}$ | 2.1 | 100 | 200 | 0.95 |
| 3     | At 7.5 x 10$^9$ cm$^{-2}$ | 2.2 | 100 | 190 | 0.95 |
| 3     | At 10$^{10}$ cm$^{-2}$ | 2.1 | 100 | 190 | 0.95 |
| 3     | 15 April 2008 | 2.0 | 100 | 200 | 0.99 |
| 4     | At zero    | 1.3                 | 120        | 140        | 1       |
| 4     | At 5 x 10$^9$ cm$^{-2}$ | 1.4 | 110 | 150 | 0.98 |
| 4     | At 10$^{10}$ cm$^{-2}$ | 1.4 | 110 | 150 | 0.98 |
| 4     | At 3 x 10$^{10}$ cm$^{-2}$ | 1.5 | 110 | 140 | 0.93 |
| 4     | 15 April 2008 | 1.4 | 20 | 140 | 0.99 |

The bias voltage was 34 V.

**Table 3**

| Board | Fluence (cm$^{-2}$) | $I_L/A$ (µA/mm$^2$) | MF (fC/PE) | $n_{PE}/F$ | S/S$_0$ |
|-------|---------------------|---------------------|------------|------------|---------|
| 1     | Zero                | 1.5                 | 370        | 46         | 1       |
| 1     | 2.5 x 10$^9$        | 16                  | 330        | 50         | 0.96    |
| 1     | 5 x 10$^9$          | 23                  | 340        | 48         | 0.96    |
| 1     | 7.5 x 10$^9$        | 39                  | 320        | 50         | 0.92    |
| 1     | 10$^{10}$           | 51                  | 300        | 51         | 0.88    |
| 1     | 15 April 2008       | 30.4                | 310        | 51         | 0.94    |

| 2     | Zero                | 1.9                 | 230        | 44         | 1       |
| 2     | 5 x 10$^9$          | 13.9                | 220        | 44         | 0.94    |
| 2     | 10$^{10}$           | 24.7                | 220        | 43         | 0.90    |
| 2     | 3 x 10$^{10}$       | 63.6                | 180        | 42         | 0.75    |
| 2     | 15 April 2008       | 35.8                | 200        | 41         | 0.78    |

The reference SiPMs were not irradiated. The data were taken at the time that the other SiPMs on the same board received the partial fluence indicated in column 2.
the time of irradiation corresponding to the same leakage current as interpolated from the measurements at fluences of $10^{10}$ and $2 \times 10^{10}$ cm$^{-2}$.

6. HC 1.0 mm$^2$

Fig. 11 shows $I_b$ as a function of $V_b$ for HC 1.0 mm$^2$ on board 2 for fluences of zero, $5 \times 10^9$, $10^{10}$, $2 \times 10^{10}$, and $3 \times 10^{10}$ protons per cm$^2$. The shape of the $I_b$ vs. $V_b$ indicates that the gain vs. voltage is stable, although the turn-on with voltage is much steeper for the HC 1.0 mm$^2$ than for the CPTA 1.0 mm$^2$. A direct measurement of $M_F$ as a function of voltage before and after irradiation shows that the gain in the region of nominal voltage varies by about $2 \times 10^3$ fC/PE per V for HC 1.0 mm$^2$ on both boards 1 and 2. At a nominal operating voltage of $V_b = 70.5$ V, the leakage current increases from 0.05 $\mu$A at zero fluence to 5.6 $\mu$A at $3 \times 10^{10}$ cm$^{-2}$. Similar $I_b$ vs. $V_b$ curves were observed for the other HC 1.0 mm$^2$ on board 1, where the leakage current at nominal voltage (70.5 V) increased from 0.1 $\mu$A at zero fluence to 2.5 $\mu$A at $10^{10}$ cm$^{-2}$.

Table 4 shows the values of $I_b$, $M_F$, and $n_{PE}/F$ and $S/S_0$. The values of $n_{PE}$ are again corrected for the measured deviation of the reference diode (see Table 2). The gain times excess noise factor is observed to decrease from 210 to 180 fC/PE for board 1 and from 250 to 210 fC/PE for board 2. The HC SiPM is especially vulnerable to a drop in gain due to increased bias current because of its sharp turn-on.

The pulse shape for 500 2 ns bins in response to the LED summed over 5000 events is shown in Fig. 12 for (a) zero fluence,
dark counts, i.e. that the leakage current is proportional to the square of the number of activated pixels. Detailed measurements were made after the irradiation as the SiPMs were allowed to anneal at room temperature. A substantial amount of annealing was observed. On 15 April 2008, 135 days after the irradiation, the dark current had dropped from 5.6 to 2.3 μA for HC 1 mm² on board 2 and from 2.5 to 1.1 μA on board 1. The rms of the HC noise distribution on 15 April 2008 was about 10% larger than that at the time of irradiation corresponding to the same leakage current as interpolated from the measurements at fluences of 10¹⁰ and 2 × 10¹⁰ cm⁻².

7. FBK 1.0 mm²

Fig. 8 shows I₀ as a function of V₀ for FBK 1.0 mm² on board 2 for fluences of zero, 5 × 10⁹, 10¹⁰, 2 × 10¹⁰, and 3 × 10¹⁰ protons per cm². The shape of the I₀ vs. V₀ distributions indicate that the gain vs. voltage is again relatively stable. A direct measurement of MF as a function of voltage before and after irradiation shows that the gain in the region of nominal voltage varies by about 170 fC/PE per V for FBK 1.0 mm² on board 1 and 110 fC/PE per V on board 2. At a nominal operating voltage of V₀ = 33.5 V, the leakage current increases from 1.6 μA at zero fluence to 20.8 μA at 3 × 10¹⁰ cm⁻². Similar I₀ vs. V₀ curves were observed for the other FBK 1.0 mm² on board 1, where the leakage current at nominal voltage (33.5 V) increased from 1.6 μA at zero fluence to 6.5 μA at 10¹⁰ cm⁻² (Fig. 14).

Table 5 shows that the values of I₀, MF, and nₑ/F and S₀/S₀. The values of nₑ/F are again corrected for the measured deviation of the reference diode (see Table 2). The gain times excess noise factor is observed to be stable in the range 430–450 fC/PE.

The pulse shape for 500 2 ns bins in response to the LED summed over 5000 events is shown in Fig. 15 for (a) zero fluence, (b) 10¹⁰ cm⁻², and (c) 3 × 10¹⁰ cm⁻² for board 2. The pulse shape was observed to be stable at all fluences on both boards 1 and 2.

The pedestal was summed over 200 ns bins 1–100 of Fig. 12(a)–(c)) to get the noise distributions in fc shown in Fig. 12 for (d) zero fluence, (e) 10¹⁰ cm⁻², and (f) 3 × 10¹⁰ cm⁻² for board 2. The rms noise increases from 131 fC at zero fluence to 305 fC at 10¹⁰ cm⁻² to 436 fC at 3 × 10¹⁰ cm⁻². The noise distribution for HC 1 mm² on board 1 was 126 fC at zero fluence, increasing to 330 fC at 10¹⁰ cm⁻² for V₀ = 70.5 V.

The signal was summed over 200 ns (bins 151–250 of Fig. 12(a)–(c)) and the noise was subtracted to get the signal distributions in fc shown in Fig. 12 for (g) zero fluence, (h) 10¹⁰ cm⁻², and (i) 3 × 10¹⁰ cm⁻² for board 2. The signal on HC 1 mm² on board 2, relative to zero fluence and corrected for the reference diode signal, was observed to drop by 6% at a fluence of 10¹⁰ cm⁻² and 15% at 3 × 10¹⁰ cm⁻². Similarly, the signal for HC 1 mm² on board 1 was 11% lower at a fluence of 10¹⁰ cm⁻².

Fig. 13 shows the square of the rms noise as a function of I₀/A for HC 1.0 mm² on board 2, for data taken immediately after the irradiation (2 December 07). The approximate linear dependence indicates that the increase in noise is due to an increase in rate of
Fig. 12. HC 1.0 mm² at $V_b = 70.5$ V on board 2: pulse shape (a) before irradiation, (b) after $10^{10}$ cm$^{-2}$, and (c) after $3 \times 10^{10}$ cm$^{-2}$; noise distribution (d) before irradiation, (e) after $10^{10}$ cm$^{-2}$, and (f) after $3 \times 10^{10}$ cm$^{-2}$; and signal distribution in response to LED (g) before irradiation, (h) after $10^{10}$ cm$^{-2}$, and (i) after $3 \times 10^{10}$ cm$^{-2}$.

Fig. 13. Pedestal rms noise squared vs. leakage current for HC 1.0 mm² on board 2, for data taken at the time of irradiation, 2 December 2007 (solid circles) and after room-temperature annealing on 15 April 2008 (open square).

Fig. 14. Leakage currents per mm² for FBK 1.0 mm² on board 2 as a function of bias voltage for varying proton fluence.
that the increase in noise is due to an increase in rate of dark counts, i.e. that the leakage current is proportional to the square of the number of activated pixels. On 15 April 2008, 135 days after the irradiation, the dark current had dropped from 5.6 to 2.3 μA for FBK 1.0 mm² on board 2 and from 2.5 to 1.1 μA on board 1 indicating a substantial amount of annealing at room temperature. The rms of the noise distribution on 15 April 2008 was about 2% larger than at the time of irradiation corresponding to the same leakage current as interpolated from the measurements at fluences of $10^{10}$ and $2 \times 10^{10}$ cm$^{-2}$.

### 8. CPTA 4.4 mm²

Fig. 18 shows $I_b$ as a function of $V_{b}$ for CPTA 4.4 mm² on board 4 for fluences of zero, $5 \times 10^8$, $10^{10}$, $2 \times 10^{10}$, and $3 \times 10^{10}$ protons per cm². The shape of the $I_b$ vs. $V_{b}$ indicate that the gain vs. voltage is stable. A direct measurement of $MF$ as a function of voltage before and after irradiation shows that the gain in the region of nominal voltage varies by about 19 fC/PE per V for CPTA 4.4 mm² on board 3 and 12 fC/PE per V for board 4. At a nominal operating voltage of $V_{b} = 37$ V, the leakage current increases from 2.6 μA/mm² at zero fluence to 5.7 μA/mm² at $3 \times 10^{10}$ cm$^{-2}$ for board 4. Similar $I_b$ vs. $V_{b}$ curves were observed for the other CPTA 4.4 mm² on board 3, where the leakage current at nominal voltage (37V) increased from 1.8 μA/mm² at zero fluence to 4.1 μA/mm² at $10^{10}$ cm$^{-2}$.

### Table 5

Measured properties of the FBK 1.0 mm² SiPMs at $V_{b} = 33.5$ V.

| Board | Fluence (cm$^{-2}$) | $I_b/A$ (μA/mm²) | $MF$ (fC/PE) | $n_{PE}/F$ | $S/S_0$ |
|-------|-------------------|------------------|--------------|-------------|----------|
| 1     | Zero              | 1.6              | 430          | 39          | 1        |
| 1     | $2.5 \times 10^9$ | 2.4              | 440          | 38          | 1.01     |
| 1     | $5 \times 10^9$   | 4.9              | 440          | 37          | 1.00     |
| 1     | $7.5 \times 10^9$ | 5.5              | 450          | 37          | 1.00     |
| 1     | $1 \times 10^{10}$| 6.5              | 450          | 37          | 1.00     |
| 1     | 15 April 2008     | 3.9              | 470          | 38          | 1.08     |
| 2     | Zero              | 1.6              | 460          | 35          | 1        |
| 2     | $5 \times 10^9$   | 5.4              | 460          | 35          | 0.98     |
| 2     | $1 \times 10^{10}$| 7.8              | 480          | 33          | 0.96     |
| 2     | 15 April 2008     | 10.7             | 450          | 33          | 0.92     |

The data of 15 April 2008 were taken after 135 days of room-temperature annealing.

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**Fig. 15.** FBK 1.0 mm² at $V_{b} = 33.5$ V on board 2: pulse shape (a) before irradiation, (b) after $10^{10}$ cm$^{-2}$, and (c) after $3 \times 10^{10}$ cm$^{-2}$; noise distribution (d) before irradiation, (e) after $10^{10}$ cm$^{-2}$, and (f) after $3 \times 10^{10}$ cm$^{-2}$; and signal distribution in response to LED (g) before irradiation, (h) after $10^{10}$ cm$^{-2}$, and (i) after $3 \times 10^{10}$ cm$^{-2}$.
Table 6 shows the values of $I_b$, $MF$, and $n_{PE}/F$ and $S/S_0$. The values of $n_{PE}$ are again corrected for the measured deviation of the reference diode (see Table 2). The gain times excess noise factor is observed to decrease from 66 to 61 fC/PE for board 1 and from 53 to 43 fC/PE for board 2.

The pulse shape for 500 2 ns bins in response to the LED summed over 5000 events is shown in Fig. 19 for (a) zero fluence, (b) $10^{10}$ cm$^{-2}$, and (c) $3 \times 10^{10}$ cm$^{-2}$ for board 4. The pulse shape was observed to be stable at all fluences on both boards 3 and 4.

The pedestal was summed over 200 ns (bins 1–100 of Fig. 19(a)–(c)) to get the noise distributions in fC shown in Fig. 19 for (d) zero fluence, (e) $10^{10}$ cm$^{-2}$, and (f) $3 \times 10^{10}$ cm$^{-2}$ for board 4. The rms noise increases from 179 fC at zero fluence to 189 fC at $10^{10}$ cm$^{-2}$ to 203 fC at $3 \times 10^{10}$ cm$^{-2}$.

The signal was summed over 200 ns (bins 151–250 of Fig. 19(a)–(c)) and the noise was subtracted to get the signal distributions in fC shown in Fig. 19 for (g) zero fluence, (h) $10^{10}$ cm$^{-2}$, and (i) $3 \times 10^{10}$ cm$^{-2}$ for board 4. The signal on CPTA 4.4 mm$^2$ on board 4, relative to zero fluence and corrected for the reference diode signal, was observed to drop by 20% at a fluence of $10^{10}$ cm$^{-2}$ and 49% at $3 \times 10^{10}$ cm$^{-2}$. Similarly, the signal for CPTA 4.4 mm$^2$ on board 3 was 24% lower at a fluence of $10^{10}$ cm$^{-2}$.
The drop in signal is due in part to a substantial drop in the number of photoelectrons (38% drop for board 4). This is due to the fact that the noise has increased to the point where a significant number of pixels are not available to respond to the LED light. This saturation is also seen in Fig. 7 where the slope of the leakage current vs. time shows a flattening during the last irradiation from $2 \times 10^{10}$ to $3 \times 10^{10}$ protons per cm$^2$.

Fig. 20 shows the square of the rms noise as a function of $I_b/A$ for CPTA 4.4 mm$^2$ on board 4, for data taken immediately after the irradiation (2 December 2007). On 15 April 2008, 135 days after the irradiation.

Table 6

| Board | Fluence (cm$^{-2}$) | $I_b/A$ (µA/mm$^2$) | MF (fC/PE) | $n_{PE}/F$ | $S/S_0$ |
|-------|---------------------|---------------------|-----------|-------------|---------|
| 3     | Zero                | 1.8                 | 66        | 180         | 1       |
| 3     | $2.5 \times 10^9$   | 2.6                 | 62        | 180         | 0.93    |
| 3     | $5 \times 10^9$     | 3.3                 | 62        | 170         | 0.87    |
| 3     | $7.5 \times 10^9$   | 3.8                 | 60        | 160         | 0.81    |
| 3     | $10^{10}$           | 4.1                 | 59        | 150         | 0.76    |
| 3     | 15 April 2008       | 3.0                 | 61        | 150         | 0.76    |
| 4     | Zero                | 2.6                 | 53        | 152         | 1       |
| 4     | $2.5 \times 10^9$   | 3.0                 | 52        | 145         | 0.93    |
| 4     | $5 \times 10^9$     | 3.4                 | 54        | 133         | 0.89    |
| 4     | $7.5 \times 10^9$   | 3.6                 | 51        | 134         | 0.84    |
| 4     | $10^{10}$           | 3.9                 | 52        | 123         | 0.80    |
| 4     | $3 \times 10^{10}$  | 5.7                 | 43        | 95          | 0.51    |
| 4     | 15 April 2008       | 3.9                 | 45        | 102         | 0.57    |

The bias voltage was 37 V.

Fig. 19. CPTA 4.4 mm$^2$ at $V_b = 37\,\text{V}$ on board 4: pulse shape (a) before irradiation, (b) after $10^{10}$ cm$^{-2}$, and (c) after $3 \times 10^{10}$ cm$^{-2}$; noise distribution (d) before irradiation, (e) after $10^{10}$ cm$^{-2}$, and (f) after $3 \times 10^{10}$ cm$^{-2}$; and signal distribution in response to LED (g) before irradiation, (h) after $10^{10}$ cm$^{-2}$, and (i) after $3 \times 10^{10}$ cm$^{-2}$.

Fig. 20. Pedestal rms noise squared vs. $I_b/A$ for CPTA 4.4 mm$^2$ on board 4, for data taken at the time of irradiation, 2 December 2007 (solid circles) and after room-temperature annealing on 15 April 2008 (open square).
the irradiation, the dark current had dropped from 5.7 to 3.9 μA/mm² for CPTA 4.4 mm² on board 4 and from 4.1 to 3.0 μA/mm² on board 3. The rms of the noise distribution on 15 April 2008 was about 7% smaller than at the time of irradiation corresponding to the same leakage current at a fluence of 10¹⁰ cm⁻².

9. FBK 6.2 mm²

Fig. 21 shows Iₛ as a function of Vₛ for FBK 6.2 mm² on board 4 for fluences of zero, 5 × 10⁹, 10¹⁰, 2 × 10¹⁰ and 3 × 10¹⁰ protons per cm². The shape of the Iₛ vs. Vₛ curves indicate that the gain vs. voltage is stable. A direct measurement of the leakage current at a fluence of 10¹⁰ cm⁻² for FBK 6.2 mm² on boards 3 and 4. At a nominal operating voltage of Vₛ = 34 V, the leakage current increases from 0.8 μA/mm² at zero fluence to 10 μA/mm² at 3 × 10¹⁰ cm⁻² for board 4. Similar Iₛ vs. Vₛ curves were observed for the other FBK 6.2 mm² on board 3, where the leakage current at nominal voltage (34 V) increased from 1.2 μA/mm² at zero fluence to 5.8 μA/mm² at 10¹⁰ cm⁻².

Table 7 shows the values of Iₛ, MF, and nₑ/F and S/βₑ. The values of nₑ are again corrected for the measured deviation of the reference diode (see Table 2). The gain times excess noise factor is observed to be stable at 200 fC/PE for board 1 and decrease from 340 to 310 fC/PE for board 4.

The pulse shape for 500 2 ns bins in response to the LED summed over 5000 events is shown in Fig. 22 for (a) zero fluence, (b) 10¹⁰ cm⁻², and (c) 3 × 10¹⁰ cm⁻² for board 4. The pulse shape was observed to be stable at all fluences on both boards 3 and 4.

The pedestal was summed over 200 ns bins 1–100 of Fig. 22(a)–(c)) to get the noise distributions in fC shown in Fig. 22 for (d) zero fluence, (e) 10¹⁰ cm⁻², and (f) 3 × 10¹⁰ cm⁻² for board 4. The rms noise increases from 616 fC at zero fluence to 1343 fC at 10¹⁰ cm⁻² to 1984 fC at 3 × 10¹⁰ cm⁻².

The signal was summed over 200 ns bins 151–250 of Fig. 22(a)–(c)) and the noise was subtracted to get the signal distributions in fC shown in Fig. 22 for (g) zero fluence, (h) 10¹⁰ cm⁻², and (i) 3 × 10¹⁰ cm⁻² for board 4. The signal on FBK 6.2 mm² on board 4, relative to zero fluence and corrected for the reference diode signal, was observed to drop by 4% at a fluence of 10¹⁰ cm⁻² and 16% at 3 × 10¹⁰ cm⁻². Similarly, the signal for FBK 6.2 mm² on board 3 was 2% lower at a fluence of 10¹⁰ cm⁻².

Fig. 23 shows the square of the rms noise as a function of Iₛ/A for FBK 6.2 mm² on board 4, for data taken immediately after the irradiation (2 December 2007). On 15 April 2008, 135 days after the irradiation, the dark current had dropped from 10 to 4.9 μA/mm² for FBK 6.2 mm² on board 4 and from 5.8 to 2.8 μA/mm² on board 3. The rms of the noise distribution on 15 April 2008 was nearly identical to the noise at the time of irradiation corresponding to the same leakage current as interpolated from the measurements at fluences of 10¹⁰ and 2 × 10¹⁰ cm⁻².

10. FBK single pixel

Two of the FBK 6.8 mm² SiPMs were wired electrically to read out a single 50 μm pixel. One of these SiPMs (on board 3) developed wire bonding problems prior to the irradiation and is not discussed further. The other single pixel readout (on board 4) was operated at high gain corresponding to Vₛ = 37 V to allow detection of single PEs. This SiPM was irradiated to a fluence of 3 × 10¹⁰ cm⁻². A total of 10k 1 μs waveforms were recorded for each partial fluence with no LED, and the pulse height was integrated over 200 ns. The resulting noise distributions are shown in Fig. 24. Note the data are plotted on a log scale. The location of the single PE peak is seen at approximately 800 fC above the zero PE peak. The leakage current prior to irradiation was 22 nA. At a fluence of 3 × 10¹⁰ cm⁻², the leakage current had increased to 150 nA, corresponding to the same order of magnitude value of Iₛ/A as measured in the FBK 1.0 and 6.2 mm² SiPM when extrapolated to Vₛ = 37 V. The single pixel becomes slightly noisier with increasing fluence as evidenced by the single PE tail, however, the location of the single PE peak remains stable indicating the gain does not change.

11. Summary

We have exposed SiPMs manufactured by Fondazione Bruno Kessler (1 and 6.2 mm²), Center of Perspective Technology and
Apparatus (1 and 4 mm$^2$), and Hamamatsu Corporation (1 mm$^2$) using a beam of 212 MeV protons at Massachusetts General Hospital in Boston, MA. The SiPMs received fluences of up to $3 \times 10^{10}$ protons per cm$^2$ at operating voltage. Leakage currents were read continuously during the irradiation, providing a good monitor of the condition of the SiPMs. The leakage current is found to increase in proportion to the mean square deviation of the noise distribution, indicating the dark counts are due to increased random individual pixel activation. At large values of bias currents, the gains are observed to drop due to a lowering of $V_b$ due to the voltage drop across the 2 kΩ input resistor. There is no evidence for any increase in the excess noise factor with irradiation. Signals in response to calibrated LED pulses (Fig. 25) drop by 25% for CPTA 1 mm$^2$, 15% for HC 1 mm$^2$, 4% for FBK 1 mm$^2$, 49% for CPTA 4.4 mm$^2$, and 16% for FBK 6.2 mm$^2$ SiPMs after exposure to $3 \times 10^{10}$ protons per cm$^2$. For the FBK and HC SiPMs, the reduction in signal is largely attributed to the reduced gain under large bias currents. The larger drop for the CPTA SiPMs, especially the 4 mm$^2$ CPTA (Fig. 25), can be explained by the large dead time caused by the very large quenching resistor, resulting in a $\mu$s dead time for each pixel. In spite of the drop in signals, all of the SiPMs remained fully functional as photon counters, albeit with increased noise due to increases in dark counts. The SiPMs are found to anneal at room temperature with a reduction in the leakage current by a factor of 2 in about 100 days.

**Fig. 22.** FBK 6.2 mm$^2$ at $V_b = 34$ V on board 4: pulse shape (a) before irradiation, (b) after $10^{10}$ cm$^{-2}$, and (c) after $3 \times 10^{10}$ cm$^{-2}$; noise distribution (d) before irradiation, (e) after $10^{10}$ cm$^{-2}$, and (f) after $3 \times 10^{10}$ cm$^{-2}$; and signal distribution in response to LED (g) before irradiation, (h) after $10^{10}$ cm$^{-2}$, and (i) after $3 \times 10^{10}$ cm$^{-2}$.

**Fig. 23.** Pedestal rms noise squared vs. $I_b/A$ for FBK 6.2 mm$^2$ on board 4, for data taken at the time of irradiation, 2 December 2007 (solid circles) and after room-temperature annealing on 15 April 2008 (open square).
Acknowledgment

We acknowledge support of the U.S. National Science Foundation.

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