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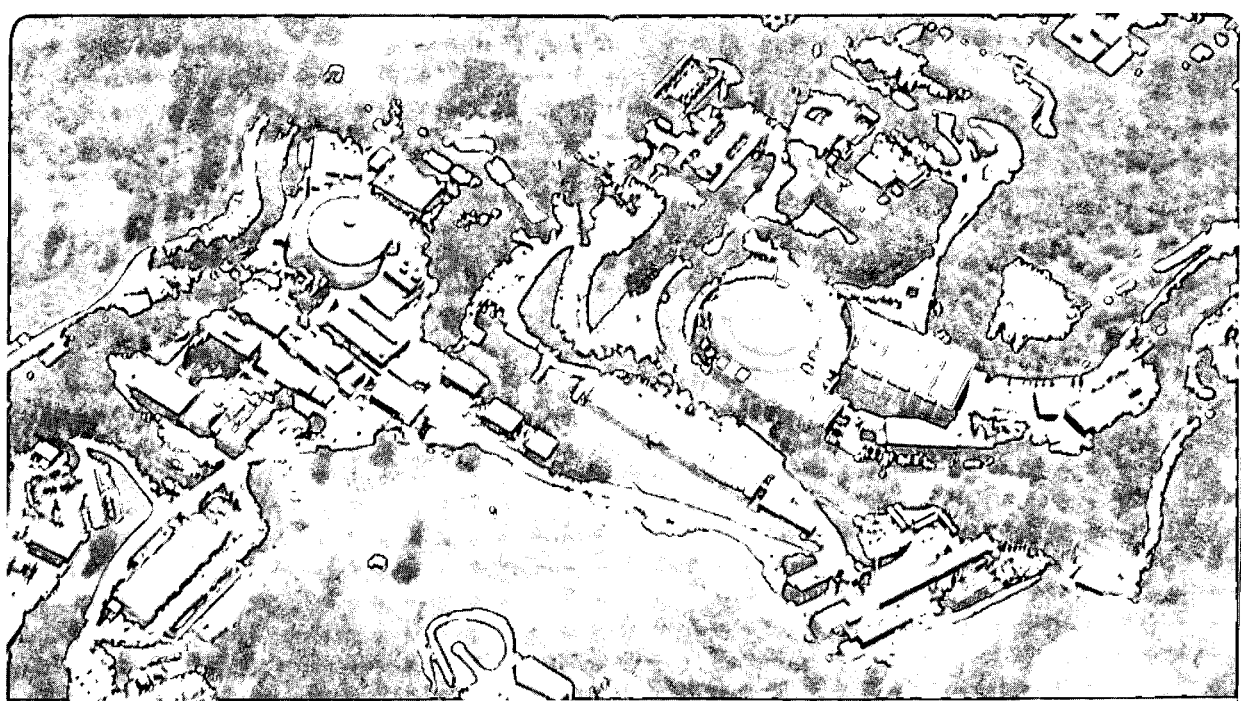
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IV International Conference on Calorimetry
in High Energy Physics

Beam and Radiation Tests of a Fast, Warm Liquid "Swimming Pool" Calorimeter*

WALIC Collaboration: (presented by J. Kadyk)

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Abstract:

A fast, warm liquid calorimeter module with lead absorber immersed in tetramethyl pentane (TMP) as the liquid medium (i.e. a "swimming pool" configuration) has been built and tested in a high energy beam at FNAL, and exposed to intense radiation from a strong Co^{60} source. A two-tower prototype, incorporating the concept of the electrostatic transformer for fast readout, exhibited very good uniformity and small cross-talk in the beam test. This same calorimeter was exposed to over 10 Mrad of radiation from the Co^{60} source, and the electron drift lifetime was measured as a function of accumulated dose. The lifetime improved significantly with small doses of radiation, up to a few hundred krad, then decreased gradually at higher doses, and extrapolated to a minimum useful lifetime of 0.1 μs at over 150 Mrad. This result was confirmed by measurements on a small single-electode test cell which was irradiated to more than 25 Mrad. In this case, the lifetime decreased from 10 μs to 0.1 μs when extrapolated to a dose of over 600 Mrad. This cell was also used to measure the effect of positive ion "space charge" buildup under intense radiation. The results suggest that such effects are small even at the highest intensity available, about 1.3 Mrad/day, for applied fields ≥25 kV/cm.

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I. Introduction

As part of an extensive R & D program on fast warm liquid calorimetry, the WALIC collaboration has built and tested a lead/TMP prototype of a 4π sampling hadron calorimeter designed for use at the SSC or LHC[1]. The results of a beam test and irradiation studies are presented here. These investigations are a culmination of our R&D program, because they bring together much of the information learned earlier[2-6] into a test of a realistic calorimeter prototype, with the following features:

- A "swimming pool" configuration, with lead absorber plates immersed in the liquid TMP, along with cables, insulators, structural materials, etc.
- Modular towers, for ease of construction
- Gap signals ganged in series as an electrostatic transformer[3] to optimize the impedance match from plates to preamplifiers and preserve the fast rise time.
- A ratio of lead to TMP thicknesses which achieves e/h compensation
- Electric fields up to 35 kV/cm for improved signal-to-noise ratio and reduced signal saturation[2,4,6]. Compensation requires about 20 kV/cm.
- Signal shaping time $\approx$0.1 μs. It is probable that this can be reduced to be competitive with the fastest detection techniques.

The calorimeter prototype is large enough to provide a meaningful proof-of-principle, as well as the first test of radiation hardness of a warm liquid calorimeter having a realistic ensemble of components.

Since much of the early work to develop warm liquid calorimetry was devoted to producing and maintaining liquids of high purity and long electron lifetimes, a major concern has been the anticipated decrease in lifetime from radiation damage. However, our results show that not only can large electric fields be used to keep electron transit times very short, but also that TMP is "self purifying" in the presence of radiation, maintaining an acceptable lifetime even at very large doses.

Finally, we have built and tested a special test cell to extend measurements to larger radiation doses and to explore the effects of positive ion space charge.

II. Description of Swimming Pool Modules

A. Two-Tower Prototype Calorimeter Module

The structure described here follows the conceptual design of a full SSC calorimeter[1]. A schematic drawing of the two-tower module is shown in Fig. 1. The design consists of absorber plates, which are also the electrodes, immersed in the TMP. Each tower has ten TMP gaps of 2 mm each, and nine lead absorbing layers each of area 11.5x11.5 cm^2 and of 1.0 cm thickness. An absorber layer consists of two 5 mm thick lead plates separated by a Kapton insulating sheet 125 μm thick. There are 5 mm gaps between the corresponding electrodes of neighboring towers. The front and rear boundaries of the 18 radiation-length thick towers are 5 mm steel end plates. The absorbers are supported between the end plates by 6 mm diameter aluminum tie rods (Fig. 2). The gap-defining ceramic insulators have long surface leakage paths to accommodate large electric fields (≈35 kV/cm). The central signal electrode also is split, with internal springs to close the gaps accurately without overstressing the insulators. The ratio of lead to TMP is optimized for e/h compensation.

For the beam tests, in which pulse height was measured as a function of electron beam energy, each tower was connected as two parallel five gap electrostatic transformers[3]. Alternate plates on each absorbing layer were connected to ground and high voltage through large resistors (≈1 MΩ). As seen by the transmission line connected to the center electrode and both end plates, the gap signals were added in series. Because calorimeter towers of this design have total capacitance 25 (=5x5) times lower than with the conventional parallel connection of gaps, large-capacitance towers can be connected to preamplifiers by transmission lines of manageable impedance (e.g. ≈50 Ω).

For the Co^{60} radiation tests described here,only the dc current was measured as a function of gap voltage, radiation intensity, and electron lifetime; signal pulses were not observed. The mechanical structure of the module was unchanged, but all the gap electrodes were connected in parallel, The radiation intensity[7] varied accurately as $1/r^2$, and was controlled by adjusting r, the distance from the source. The intensity could be varied over the range of 2 krad/day to 0.8 Mrad/day. The electron lifetime was monitored using a small photoelectric cell[8]. In this cell, electrons are produced at the photocathode by a light source pulsed at a slow rate, and these electrons travel to the anode through a 3 mm gap filled with TMP. Measurement of the charge transmitted across the gap yields the electron lifetime, since the transit time is easily calculated.

B. 3-Inch Test Cell

For detailed investigation of radiation effects in the TMP itself, the two-tower module used in the tests described above is limiting in several ways: 1) its size prevents close access to the Co^{60} source for high intensities; 2) a large part of the TMP is shielded from radiation by the lead absorber plates; 3) some of the liquid volume is shielded by the collimator of the Co^{60} source; 4) absorption in the plates provides a very non-uniform radiation pattern; 5) it is difficult to be certain that the liquid mixing is good enough for measuring the average lifetime. For these reasons, a cell was built specifically for examining space charge effects, and extending the lifetime measurements to larger radiation intensity and total dose. A schematic drawing of this cell is shown in Fig. 3, and some of the differences from the two-tower module are as follows:

1) The dimensions are small enough to provide close access to the Co^{60} source.
2) The cell material was of low Z, so that except for the $1/r^2$ dependence, radiation levels were essentially uniform over the cell.
3) Since pulses cannot be measured in the very high radiation environment, the design was simplified for the measurement of dc current by using a single high voltage electrode.
4) The high voltage electrode, which operated at voltages as large as ≈6 kV, was carefully designed for a very uniform 1.6 mm gap on both sides and at its outer radius.
5) Kapton insulation and internal resistors were eliminated.
6) Using a heating tape for thermal pumping, the liquid was circulated continuously, once every several minutes, in a small, closed plumbing loop. The total liquid volume was ≈0.34 liters. This provided uniform exposure of all the liquid, and, because the photoelectric cell was included in the loop, the lifetime measurements were more reliable. The cell included a reservoir with a volume of TMP several times larger than that in the photoelectric cell and other external plumbing, simplifying the estimate of the average dose.
7) The loop also included a bellows to accommodate gas liberated by liquid decomposition. Analysis of the gas will provide information on the mechanisms of radiation damage to the TMP.

As with the two-tower module, the small test module was part of a closed system without any filters of or purification of the TMP, and was mounted on a movable service

cart to control the radiation intensity by varying the distance between the source and the module.

III. Beam Test of the Two-Tower Module

The two-tower module described in section II.B was exposed to a beam of electrons at 5, 25, and 100 GeV at Fermilab. This was in the same beam used for a study of e/h compensation with another TMP calorimeter[4,6]. The principal goals of the present beam test were to determine the viability of the swimming pool design and the electrostatic transformer signal configuration, by studying: a) the performance at high electric fields, b) signal response with the short shaping time of 0.1 μs, c) the crosstalk between towers, and d) the tower-to-tower uniformity of response. The absorber depth of the two-tower module was ≈18 radiation lengths in this design, not intended for complete containment of the showers at 25 and 100 GeV, but the module performed very well with respect to properties mentioned above. In Fig. 4 are shown the responses of each of the two adjacent towers when the 25 GeV beam was directed on that tower. The mean values of the pulse height distributions are as shown; the two towers give nearly equal responses, within 0.5%. In addition, the corresponding values are given for the adjacent tower, indicating that the crosstalk between the towers is ≈1%, which is acceptably small. This is significant since, in the electrostatic transformer design, the capacitance between adjacent towers is a larger fraction of the per channel tower capacitance than in a conventional parallel gap design. Although the electron lifetime measured just after filling was only 0.4 μs, the module gave very good signal response and operated reliably at 35kV/cm.

IV. Effects of Radiation

A. Radiation Damage Tests on the Two-Tower Module

The module described above was subsequently exposed to γ-rays from a Co^{60} source of 2000 Ci strength. The module was centered vertically with respect to the Co^{60} source, and the plates were oriented horizontally, as indicated in Fig. 5, so that the γ-rays were directed nearly parallel to the surface of the plates. At the smallest possible distance from the source, about 25 cm from the front face of the module, the exposure rate at the front surface was ≈0.8 Mrad/day, but the average dose corresponded to irradiation of only about 20% of the TMP, reduced by shielding from the lead plates. This corresponds to a maximum average dose of 0.16 Mrad/day in the TMP. The total dose to the TMP was ≈13 Mrad.

The electron lifetime was measured using the photoelectric cell[8] described in II.A, which was filled with the irradiated TMP during the lifetime measurements. Several measurements were made for each exposure: the TMP was mixed between measurements by rotating the entire assembly around a horizontal axis. The average spread of lifetime measurements made in this manner was less than 10%. Fig. 6 shows the electron lifetime as a function of the integrated dose, averaged over the TMP volume. During these irradiation tests, this module usually had a modest field, about 2.5kV/cm. For comparison, the results of independent measurements by two other groups[9,10] on small test cells are also shown. These differed from our tests because they did not generally have an electric field on the gap during the γ exposure, much smaller volumes were tested, and there were different materials in contact with the TMP (e.g. glass and stainless steel). Figure 6 shows that the lifetime behavior in our module was very different from that of two of the others: although our lifetime was initially small, about 0.4 μs, it increased with radiation to about 2 μs at a radiation dose of approximately 0.5 Mrad. At larger doses, it decreased, but at a smaller rate than for the other tests shown in Fig. 6. As Fig. 7 shows, two other liquids, tetramethyl silane (TMS) and tetramethyl germanium (TMG), have also been tested by others[10,11], and found to be far less radiation hard than TMP.

For two different periods of three weeks each, the two-tower module was left with no radiation or voltage. After the first period, preceded by a dose of 7 Mrad, the lifetime had decreased from to 1.6 μs to 0.60 μs. When voltage was applied to the plates for more than one day, there was no change in the lifetime, but when the radiation was also applied, the lifetime increased to 1.5 μs in about three hours. This test was repeated after

the module had received a considerably larger radiation dose, 13 Mrad, with a similar result: in this case, the lifetime increased from 0.3 μs to 1.1 μs after four hours. Another interesting result was obtained by reducing the radiation intensity. After each of the two tests discussed above, the dose rate was decreased from 160 krad/day to ≈40krad/day. and then to ≈10 krad/day. In the first test, the lifetime improved from 1.5 μs to 2.0 μs to 2.4 μs. These changes in intensity were repeated after the second test period described above, and the lifetime increased from 1.1μs to 1.5 μs to 2.0 μs.

At a total dose of 10 Mrad, the lifetime in our test reached a value more than an order of magnitude larger than for two of the results shown in Fig. 6. Also, the dependence of our lifetime on radiation dose has a significantly smaller slope than for any of the earlier results. Our result is similar to one of these previous measurements in lifetime, but not in slope. If we extrapolate to 0.1 μs, which we take to be the shortest useful lifetime for a fast calorimeter of this type, the corresponding dose is about 150 Mrad. It should be emphasized also that the TMP was contained in a closed system during these tests, without any filtering or other purification.

As can be seen in Fig. 6, the presence of electric field has a positive effect upon the lifetime in the presence of radiation. Without field, but with radiation exposure, our lifetime is much larger than all except one of the other results shown, and it increases by about 20% when electric field is applied. Therefore, the presence of the field does not by itself explain the difference between our lifetime results and the others shown. Moreover, in the presence of radiation, when the field has been off for some length of time and then turned on again, the lifetime increases in a few minutes to its value before the field was removed. In order to explore further some of these effects, and to investigate the effects of space charge at very high radiation rates, a smaller module, the 3" test cell, 7.6 cm in diameter by 7.6 cm long, was built and tested.

B. Measurements Using the 3" Test Cell

This module was built primarily to determine the effects of intense radiation flux on performance, such as would be experienced in a forward calorimeter at the SSC or LHC. It has been described in section II.B and a schematic drawing is shown in Fig. 3. It contains no lead plates and has aluminum electrodes, so that there was very little attenuation of the radiation by absorbing material. It is also smaller than the two-tower module and could be placed closer to the Co^{60} source. Intensities as high as 1.5 Mrad/day were obtained compared with only about 0.16 Mrad/day (average) for the two-tower module.

1. Lifetime Tests in the 3" Cell

This module has been used for electron lifetime measurements at γ-ray doses up to 25 Mrad. The results are summarized in Fig. 8. This module differs from the two-tower module in that ≈80% of the TMP is exposed to the γ-ray beam, and the photoelectric cell for testing lifetime has been built into the plumbing system. The TMP circulates continuously through the entire closed system, including the photoelectric cell, hence there is no need to "mix" the TMP prior to measurement. The measured lifetime behavior is similar qualitatively to that for the two-tower module: the lifetime increases with dose from an initially low value, to a maximum >10 μs at a dose of approximately 0.1 Mrad. Extrapolation of the high radiation measurements to a lifetime of 0.1 μs yields an estimated dose of more than 600 Mrad. As with the two-tower module, there appears to be an optimum dose rate to maximize the lifetime, at least in the region of large integrated doses (>10 Mrad). This is indicated in Fig. 8 by points plotted at ≈20 Mrad, taken with a dose rate of about 0.05 Mrad/day: the lifetime increased significantly when the test module was moved from a zone of very high intensity, ≈1- 2 Mrad/day, to a region where the intensity was 0.01 - 0.10 Mrad/day. Unlike the case of the two-tower module, the high voltage here has no effect on the lifetime because the gap represents a very small fraction of the total TMP volume.

In most respects the measurements of lifetime vs. accumulated dose in this 3" module confirm those of the two-tower module: the lifetime increases from a low but still useful value, to a much larger one, and without purification or change of liquid, the extrapolation to the assumed minimum useful lifetime of 0.1 μs gives allowable doses in the range 10^2 - 10^3 Mrad. This level of radiation hardness is sufficient for operation in the most intense radiation zone of the SDC detector, e.g. the forward calorimeter.

2. Tests in the 3" Cell at High Radiation Intensity

Liquid ionization calorimeters exposed to radiation are affected by instantaneous as well as cumulative doses. The performance depends on electron lifetime, mobilities, recombination cross sections, operating voltage and gap width. Positive ions produced by ionizing radiation in TMP have mobilities ≈10^5 times less than electrons, so that at large radiation intensities, the high density of positive ions can cause a distortion of the applied electric field and a change in the rate of recombination with the drifting electrons. In our tests, the environment precluded the measurement of fast electron pulses, but some of

the expected performance can be inferred from the measurements of dc current as a function of voltage and dose rate. In order to investigate these "space charge" effects, the 3" module was placed at various distances from the Co^{60} source, corresponding to different intensities of radiation and therefore of ionization. The current through the module was then measured as a function of the applied voltage. Since the radiation intensity is expected to scale approximately as $1/r^2$, the data is plotted as Ir^2 vs. V in Fig. 9, where r is the source-module distance, I is the current, and V is the applied voltage. At small radiation levels and large electron lifetimes, the ratio of dc current to dose rate is seen to increase with electric field, as predicted by the Onsager effect[12]: Ir^2 α (ionization density) α $(1+E/E_0)$, where E is the electric field, and E_0=17.5 kV/cm. This limiting functional dependence defines radiation-independent performance.

At greater levels of radiation, the recombination of electrons with positive ions must reduce both the electron signals and the dc current. If the electron lifetime is not much larger than the electron transit time, the formation of negative ions also will remove a significant fraction of the electrons, and the dc current will be further reduced by negative-positive ion recombination. Hence, the dc current provides an indication, though indirect, of the effect of radiation on pulsed calorimeter performance. The major cumulative effect of radiation is to alter the composition and concentrations of impurities in the liquid, which in turn affect the recombination rates, and therefore the current and the lifetime. The details of recombination are affected by space charge distortion of the field. Under intense radiation, this also can affect the dc current. The techniques used here only allow average effects to be measured.

The plots of Ir^2 shown in Fig. 9 exhibit the types of behavior described above: at modest radiation levels there is a general increase in current with voltage, from the Onsager effect[12], and a suppression of current at low voltages which we interpret as the effect of recombination. We observe also that the current suppression diminishes as the voltage is increased, and at the highest dose rate possible, about 1.3 Mrad/day, there is less than a 10% decrease in the current at 26 kV/cm. Fortunately, the excellent electrical properties of TMP in this geometry permit operation with fields at least as high as 35 kV/cm, and the decrease in current is expected to be even smaller. Such high fields are also appropriate for e/h compensation in TMP calorimeters using lead absorbers[4,6]. However, since the test does not measure individual pulses, we cannot now be sure of the quality of the signal in fast calorimetry applications.

3. Evolved Gas

As a consequence of the intense irradiation of the 3" module, gas was evolved due to decomposition of the TMP. The gas was contained within the plumbing system, which included a bellows. The amount of gas was measured by recording the pressure before and after expansion of the gas into calibrated sample cylinders[13]. Assuming that the liquid is incompressible, this allows the amount of the gas to be calculated. The amount of dissolved gas has been estimated from the known gas pressure and the volume of the liquid[9]. It was found that after the ≈25 Mrad total radiation dose, there was a total of 0.011 moles of gas in the system (including the dissolved gas), which came from ≈400 cm^3 of TMP. This may be compared to the predicted yield[9], for our liquid volume: 0.025 moles of (H_2 + CH_4), a factor of 2.3 larger. It is possible that some of the evolved gas may have interacted with materials in the cell to remove them from the gaseous phase (e.g. adsorption), accounting for this difference. We think this is not bad agreement, considering the many uncertainties involved. The sample cylinders will be used later as input for a gas analysis, where we expect to be able to identify and quantify the gas constituents. Another similar test cell has been built, and will be used soon to repeat these measurements.

C. Other Possible Concerns

1. Fluctuations in Ion Current

There are ≈10^5 more positive ions than electrons in the TMP, the ratio of electron and ion mobilities. However, on average, as many positive ions as electrons are collected per second. Therefore, there is a similar contribution to the noise background from the electrons and ions, which is expected to be negligible.

2. Degradation of Electrode Surfaces

Polymerization or other mechanisms of deposition of material resulting from TMP radiolysis may cause the calorimeter to deteriorate. Since one possible mechanism for the improvement of the lifetime is the "pumping out" of electronegative impurities by the action of the electric field, there is reason to expect deposition on the electrodes. This can be investigated, in principle, by repeating the measurements shown in Fig. 9 as a function of radiation dose: if, after correcting for loss due to finite electron lifetime, there is a

decrease in the current collected at a given voltage and radiation intensity, then this would be evidence that electrode degradation has occurred. Such a test will be performed with a new test module, which has been filled with TMP, and will soon be irradiated. In order to confirm an observed degradation, the TMP could be exchanged for new, unirradiated TMP to observe whether the decrease in current persists.

D. Filtering TMP

A perceived problem has been the lifetime of TMP, and varying degrees of success in achieving large lifetimes have been reported, depending upon the sophistication of the filtration system. As indicated above, lifetimes in excess of 0.1 μs should be adequate for fast calorimeter performance. We have found a very simple way to produce >3 μs lifetimes using a commercially available Oxisorb/Hydrosorb filter[14] which operates at room temperature, is reasonably inexpensive, and is refillable. Due to the inadequacy of the rest of our purification system, that lifetime is a lower limit. A similar filter has been used successfully by the ICARUS collaboration for purification of liquid argon[15]. Thus, the early concern that this filter would dissociate the TMP molecule is not warranted.

V. Conclusions and Summary

A prototype warm liquid (TMP) calorimeter of the swimming pool design, consisting of two towers, each of 18 radiation lengths in depth, has been tested in a high energy beam at FNAL, and later exposed to radiation at a Co^{60} source. The performance in the beam was good, even though the initial electron lifetime was small, ≈0.4 μs. The uniformity of response between the two towers was within 0.5%, and the crosstalk was about 1%. During radiation tests, it was found that the lifetime actually improved with small doses, reaching a maximum of ≈2 μs at a dose of 100 - 500 krad. The lifetime measured at larger doses was at least an order of magnitude larger than two of the three previous measurements by other groups, which were made on smaller samples and in contact with different materials. The lifetime was found to depend also upon the intensity of radiation, and somewhat on the presence of an electric field. The rate of decrease of lifetime with γ-ray dose was smaller in our tests than in any previous tests, and when our data is extrapolated to 0.1 μs, the minimum usable lifetime, the corresponding dose is ≈150 Mrad. It is to be emphasized that this is without any purification or filtering.

In order to investigate the effect of recombination during very intense irradiation, a small module was tested very close to the Co^{60} source. At the highest radiation intensity,

≈1.3 Mrad/day, the decrease in current collected was only about 10% at 26 kV/cm. This intensity is more than predicted for the most strongly irradiated portion of the SDC forward calorimeter (at $\mathcal{L} = 10^{33}/cm^2$-sec). The electron lifetime vs. γ-ray dose was also monitored in this small module, and a behavior was observed similar to that for the larger prototype: the lifetime first increased from 0.4 μs to more than 10 μs, then decreased slowly with increasing dose, extrapolating in this case to >600 Mrad at 0.1 μs. The dependence of lifetime upon the dose rate was also observed to be similar to that of the two-tower module.

A relatively simple filtering scheme for TMP uses a commercially available, low cost Oxisorb/Hydrosorb filter[14] cannister, producing TMP with lifetimes of at least several microseconds, more than enough for operation of a fast calorimeter of the type discussed here. The filter operates at room temperature, and can be refilled.

In all tests of both the prototype and the small test module, the lifetimes were always large enough (>0.1 μs) so that finite lifetime would not limit fast calorimeter performance. Small doses of radiation improved the lifetime of our TMP samples, e.g. in our test cell , from 0.4 μs to >10 μs. Although measurements of current in high intensity radiation tests indicate that space charge should not be a limit on the performance, direct measurements of signals could not be made during these tests. Possibly there might be degradation of electrode surfaces by deposits, and tests for this have not yet been done.

Acknowledgements

We are grateful for several discussions with Dr. Jonathan Wise[13]. The method for measuring the amount of evolved gas was suggested by him, as were several other techniques of use to us. We also wish to acknowledge the help of Adrian Daw during the Fermilab beam tests.

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Figure Captions

Fig. 1: A schematic drawing of the two-tower module connected in electrostatic transformer configuration[3]. Each absorber layer consists of two 5 mm thick lead plates separated by a 125 μm thick Kapton insulating sheet: the lead plates are alternately at ground and at high voltage. The signal is obtained from the center aluminum plate, which is at dc ground potential.

Fig. 2: A detailed view of the absorber plates and supporting ceramic insulators. There are long leakage paths and rounded edges to avoid electrical discharge.

Fig. 3: A sectional plan view of the 3" test cell near the Co^{60} source. Details of the internal design are shown.

Fig. 4: Pulse height distributions for each of towers of the two-tower module in the beam test at FNAL. The two distributions at the left are for the pulse height of tower A (top) and tower B (bottom), when the 25 GeV electron beam is directed on the center of the tower. The distributions on the right are for the tower adjacent to the beam-centered tower. The mean pulse height is the same within 0.5% for the two towers when exposed to electrons, and the crosstalk, which includes leakage and noise, is ≈1%.

Fig. 5: The two-tower module during Co^{60} tests in elevation view. The maximum dose rate averaged over the TMP volume was 0.16 Mrad/day.

Fig. 6: Electron lifetime vs. radiation dose for the two-tower module. a) Our result, shown along with three independent results[9,10]; b) results at large doses, showing details of lifetime behavior under various conditions. The lifetime improves as a result of irradiation up to a dose of about 0.5 Mrad. It then decreases more slowly than for two of the other tests, remaining in a useful range up to a dose of ≈150 Mrad, extrapolating from the results shown. The presence of voltage improves the lifetime only a little, ≈20%. There appears to be an optimum dose rate of ≤10 krad/day. After period of no radiation, the lifetime decreases somewhat, but is still adequate, and increases quickly when radiation is restored.

Fig. 7: Electron lifetime vs. radiation dose for TMS[10] and TMG[11], compared to TMP[10]. These tests show that TMP is more radiation hard than the other warm liquids.

Fig. 8: Electron lifetime vs. radiation dose for the 3" test cell. The lifetime is seen to increase with dose for small doses, as was observed for the two-tower module, reaching a maximum of >10 μs at ≈0.1 Mrad, and extrapolating to a maximum

useful dose, at a 0.1 μs lifetime, of >600 Mrad. Note the improvement in lifetime for low dose rate, at a total dose of 20 Mrad.

Fig. 9: Space charge tests for the 3" test cell. Curves showing the dependence of Ir^2 on electric field and radiation intensity, where I is the current, and r is the distance to the source, after a small dose (<0.13 Mrad, lifetime >10 μs). Since the intensity varies as $1/r^2$, these curves remove the direct effect of I on intensity, and exhibit the recombination and Onsager[12] effects. Our interpretation is that the increase of Ir^2 with voltage is due to the latter, and the spread of curves for different intensities at low fields is due to the former. At large fields, 35 kV/cm, there is only about a 10% difference between the curves, suggesting that the loss of signal may be no more than about 10%.

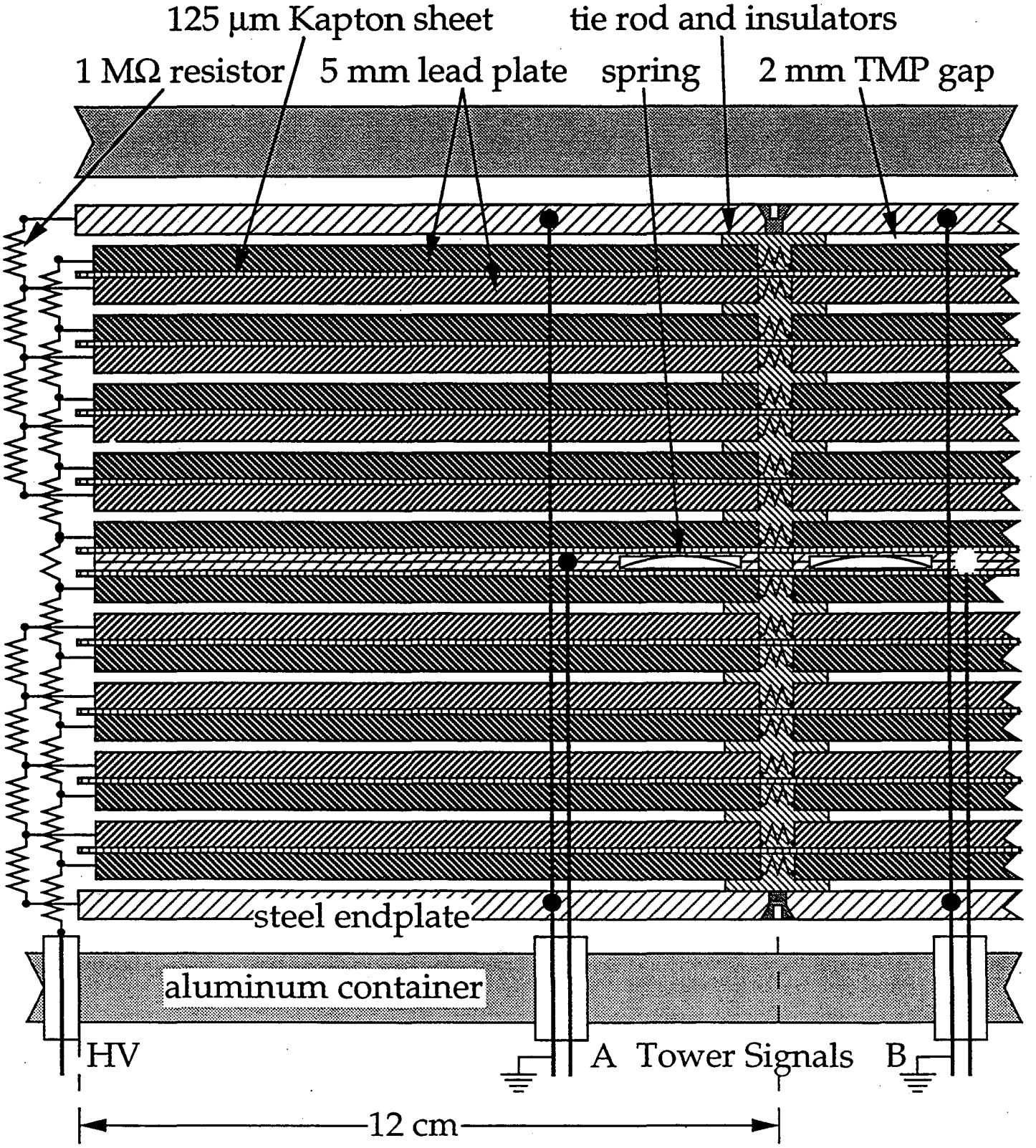

125 μm Kapton sheet
tie rod and insulators
1 MΩ resistor
5 mm lead plate
spring
2 mm TMP gap
steel endplate
aluminum container
HV
A Tower Signals B
12 cm

Fig. 1

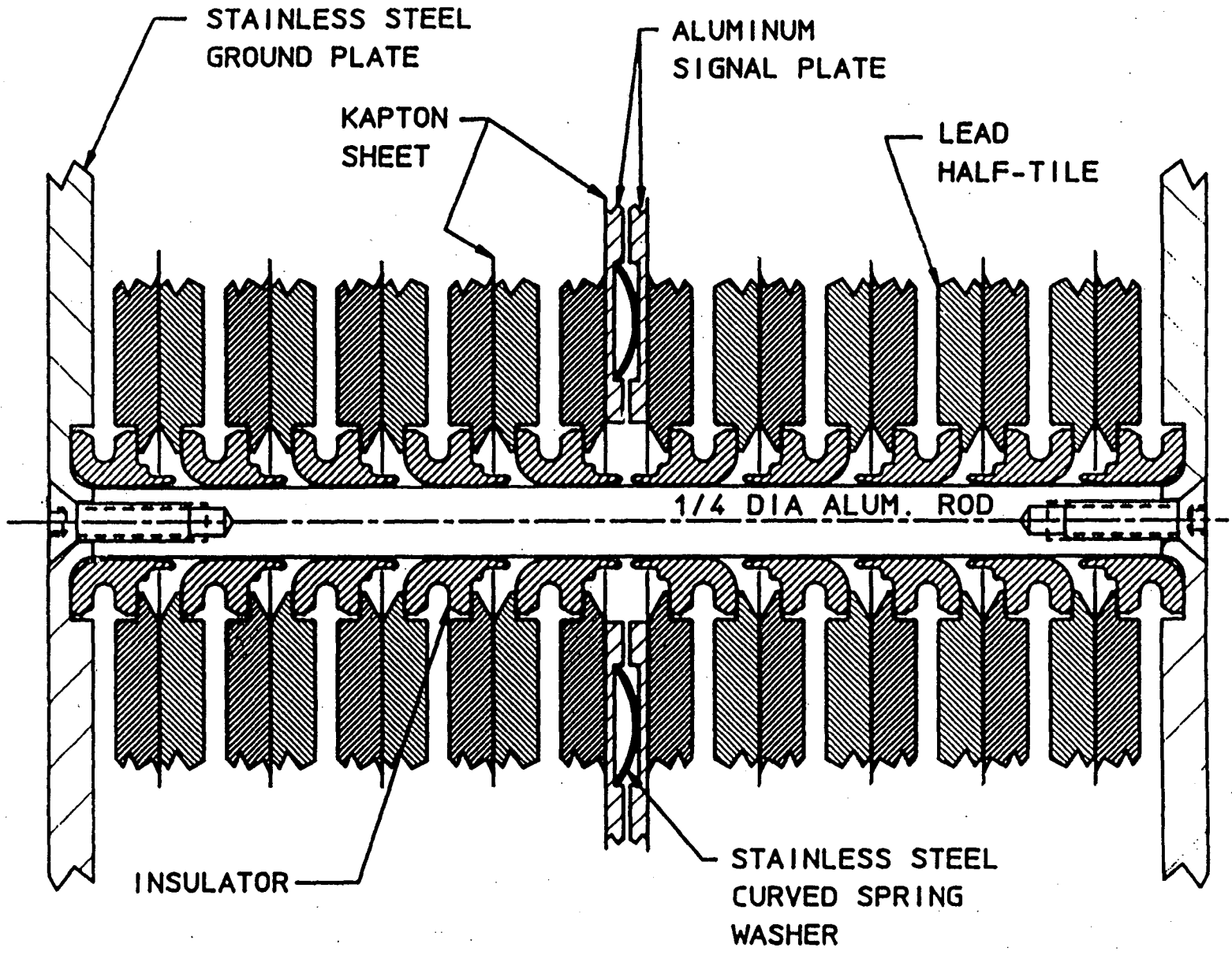

STAINLESS STEEL
GROUND PLATE
ALUMINUM
SIGNAL PLATE
KAPTON
SHEET
LEAD
HALF-TILE
1/4 DIA ALUM. ROD
INSULATOR
STAINLESS STEEL
CURVED SPRING
WASHER

Fig. 2

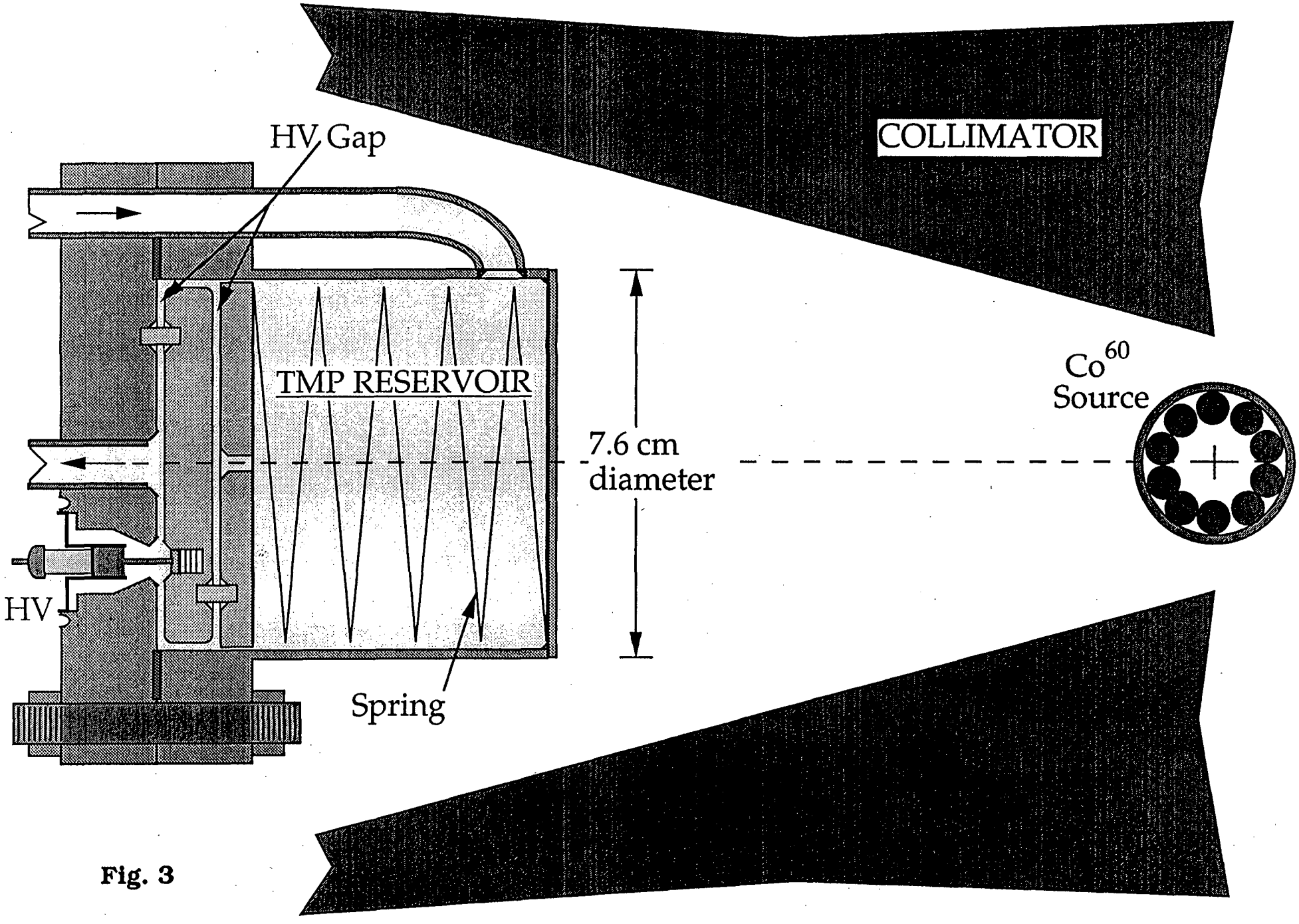

COLLIMATOR
HV Gap
TMP RESERVOIR
7.6 cm
diameter
Co 60
Source
HV
Spring

Fig. 3

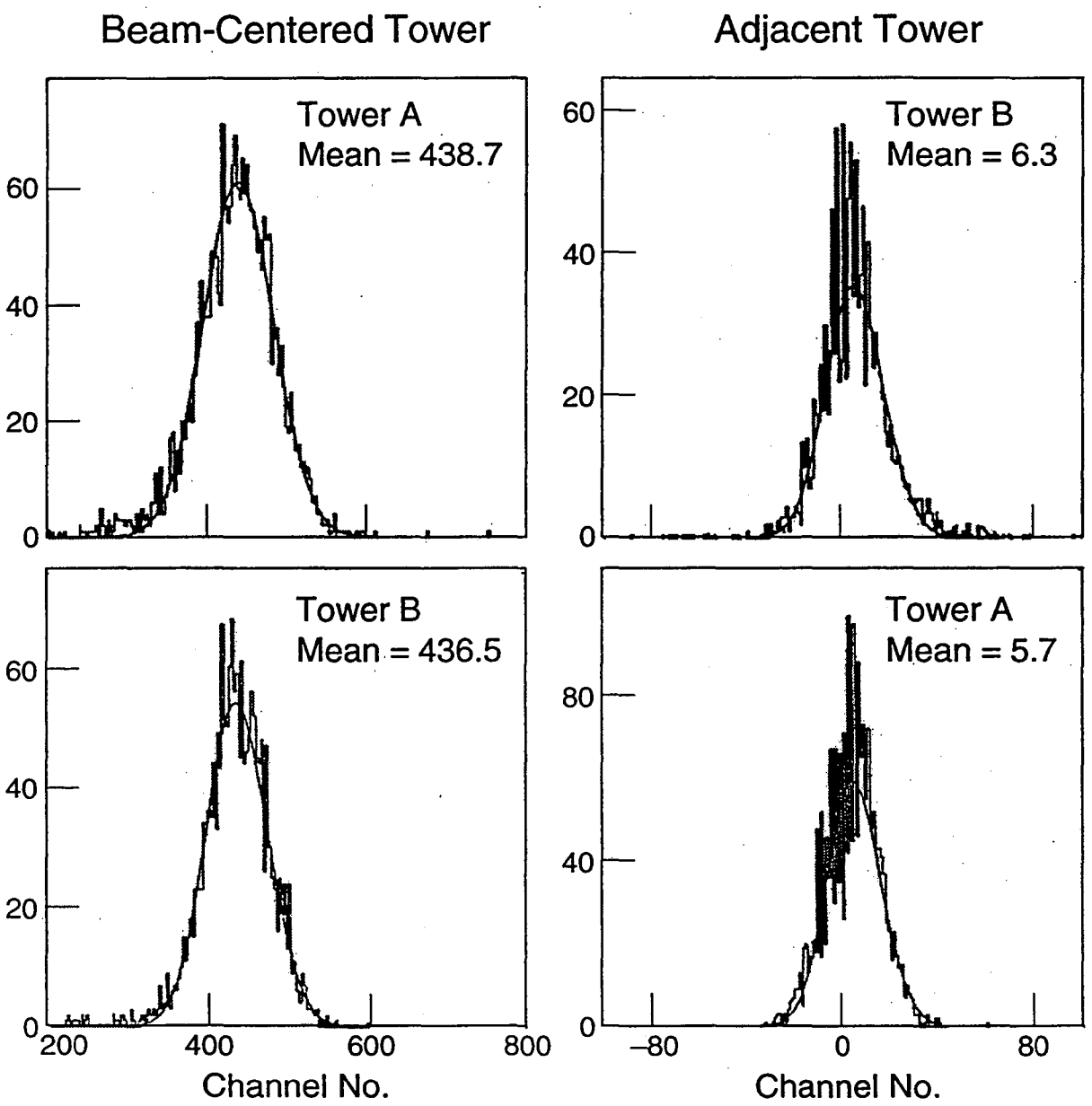

Beam-Centered Tower
Adjacent Tower
Tower A
Mean = 438.7
Tower B
Mean = 6.3
Tower B
Mean = 436.5
Tower A
Mean = 5.7
60
40
20
0
80
200
400
600
800
–80
0
80
Channel No.
Channel No.

Fig. 4

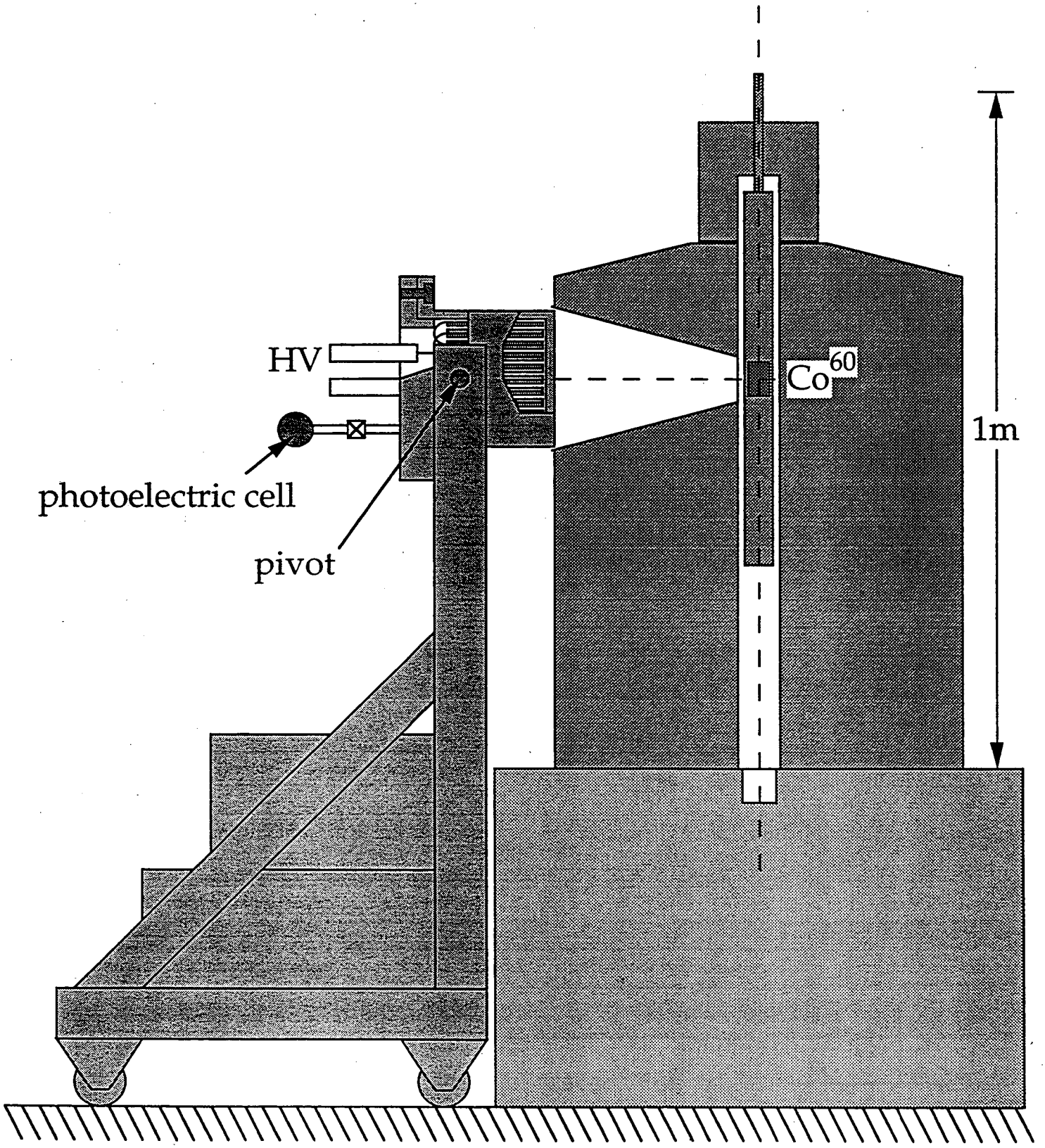


Fig. 5

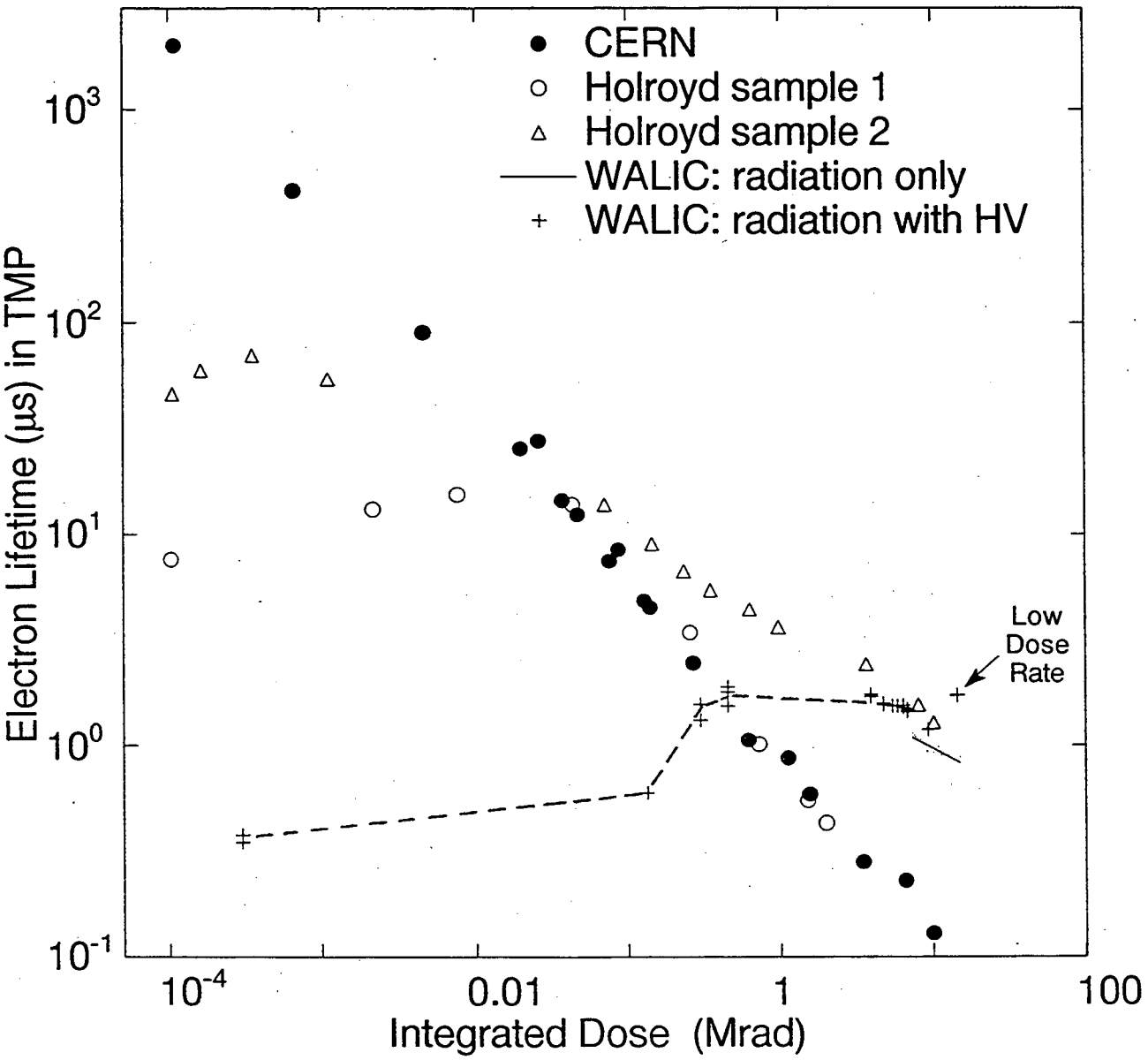

CERN
Holroyd sample 1
Holroyd sample 2
WALIC: radiation only
WALIC: radiation with HV
Low
Dose
Rate
Electron Lifetime (μs) in TMP
Integrated Dose (Mrad)
10^3
10^2
10^1
10^0
10^{-1}
10^{-4}
0.01
1
100

Fig. 6a

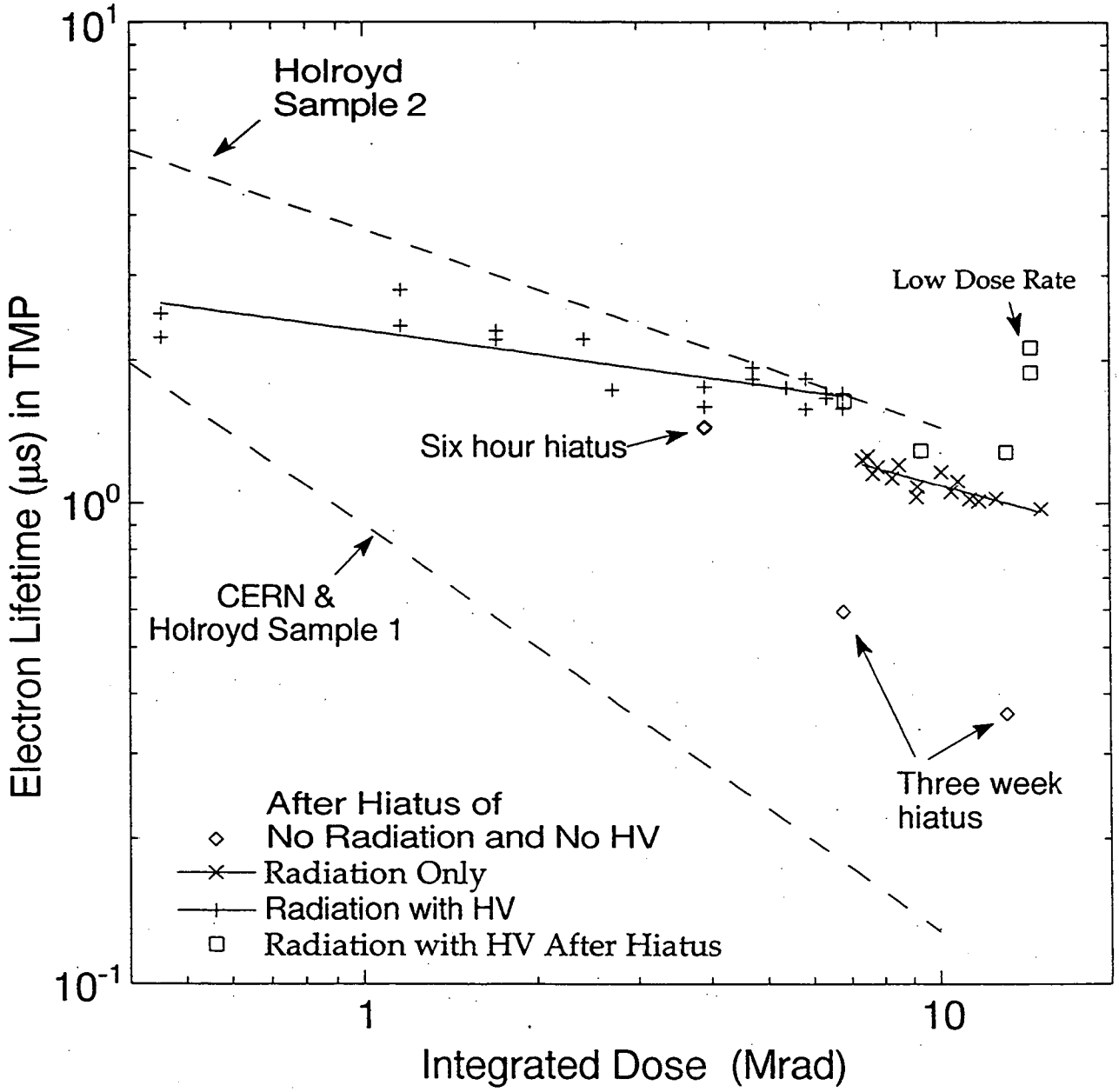

Holroyd
Sample 2
Low Dose Rate
Six hour hiatus
CERN &
Holroyd Sample 1
Three week
hiatus
After Hiatus of
No Radiation and No HV
Radiation Only
Radiation with HV
Radiation with HV After Hiatus
Electron Lifetime (μs) in TMP
Integrated Dose (Mrad)
10^1
10^0
10^{-1}
1
10

Fig. 6b

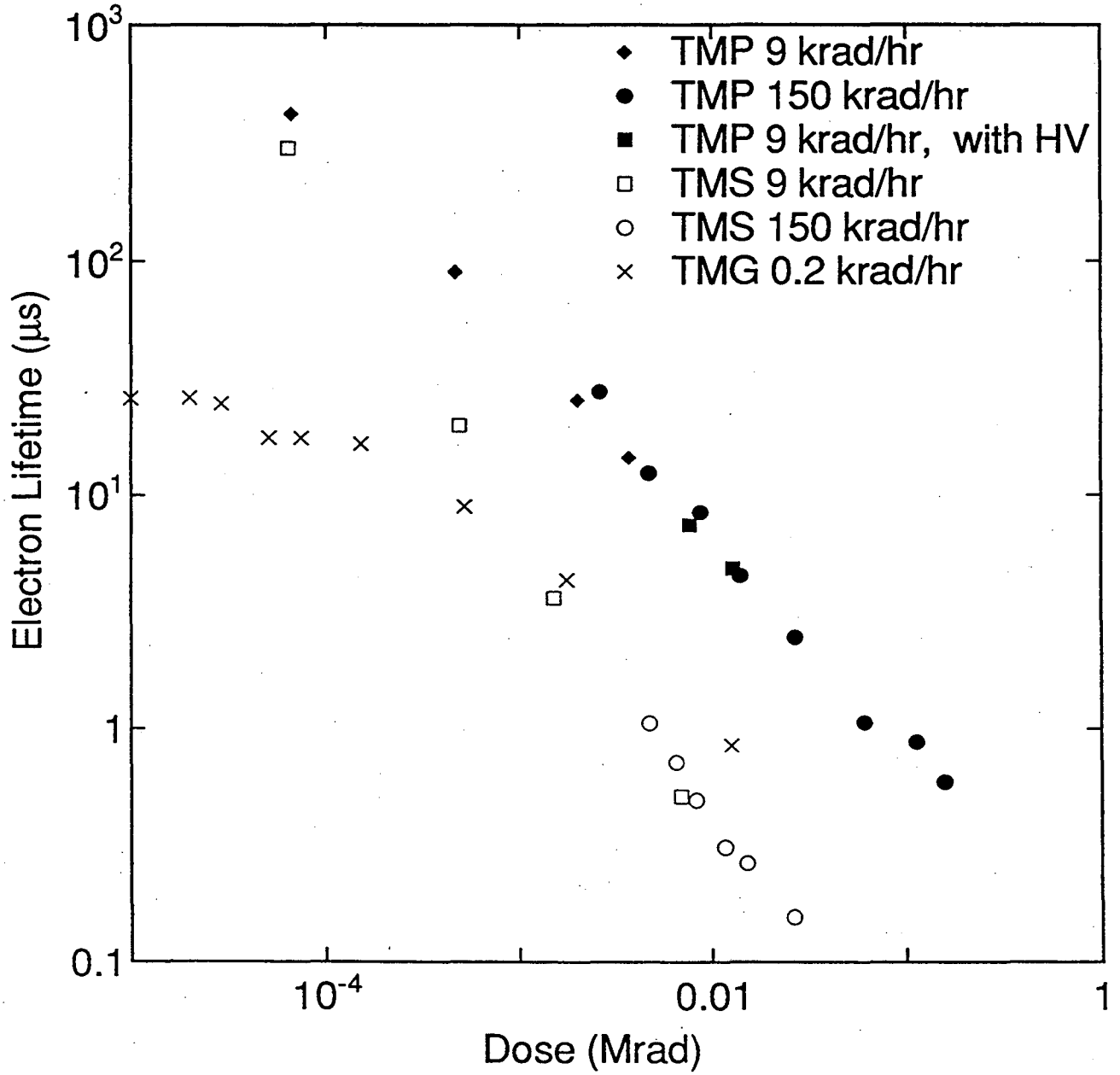

TMP 9 krad/hr
TMP 150 krad/hr
TMP 9 krad/hr, with HV
TMS 9 krad/hr
TMS 150 krad/hr
TMG 0.2 krad/hr
Electron Lifetime (µs)
10^3
10^2
10^1
1
0.1
10^-4
0.01
1
Dose (Mrad)

Fig. 7

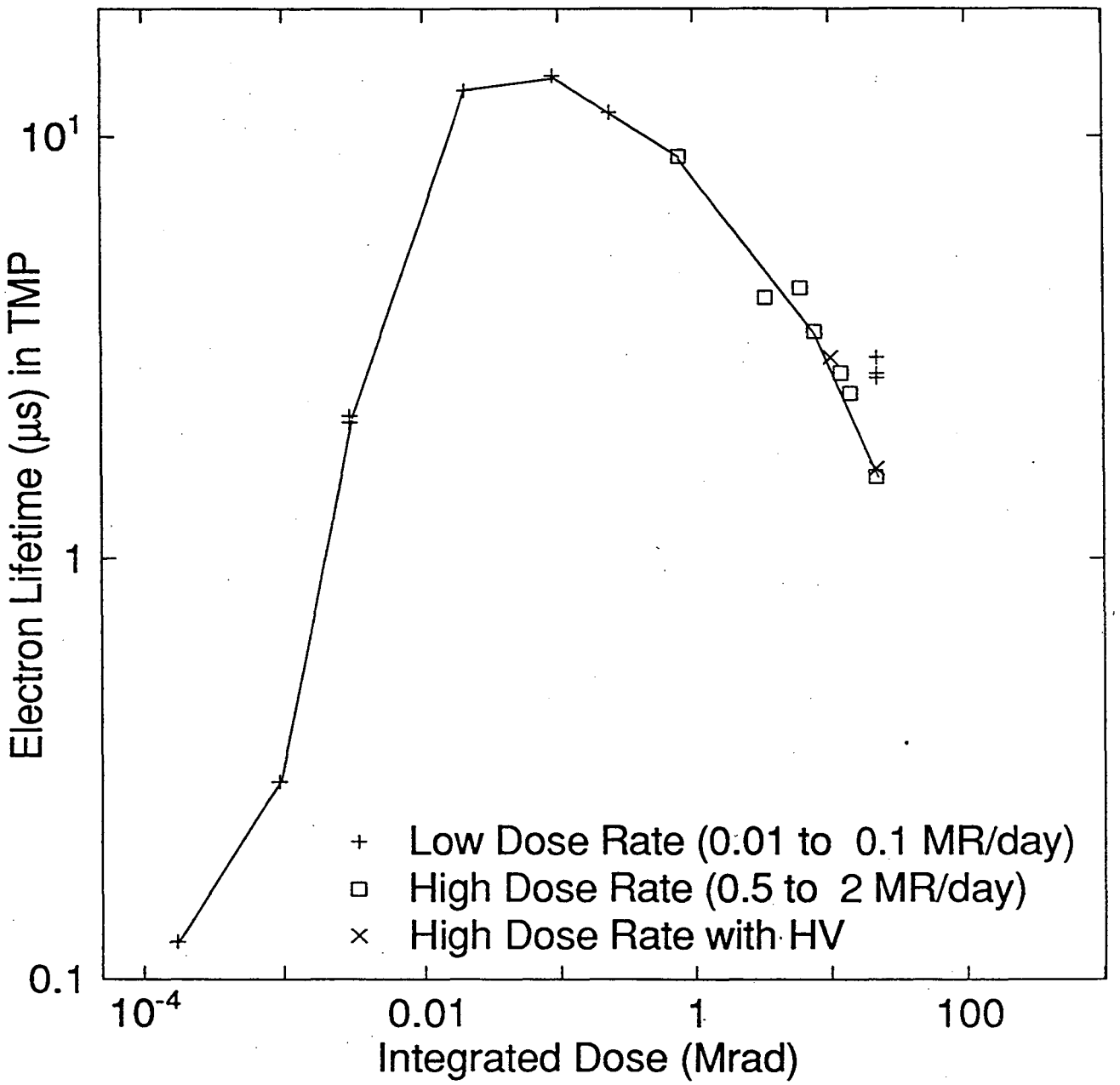

Electron Lifetime (μs) in TMP
10^1
1
0.1
10^-4
0.01
1
100
Integrated Dose (Mrad)
Low Dose Rate (0.01 to 0.1 MR/day)
High Dose Rate (0.5 to 2 MR/day)
High Dose Rate with HV

Fig. 8

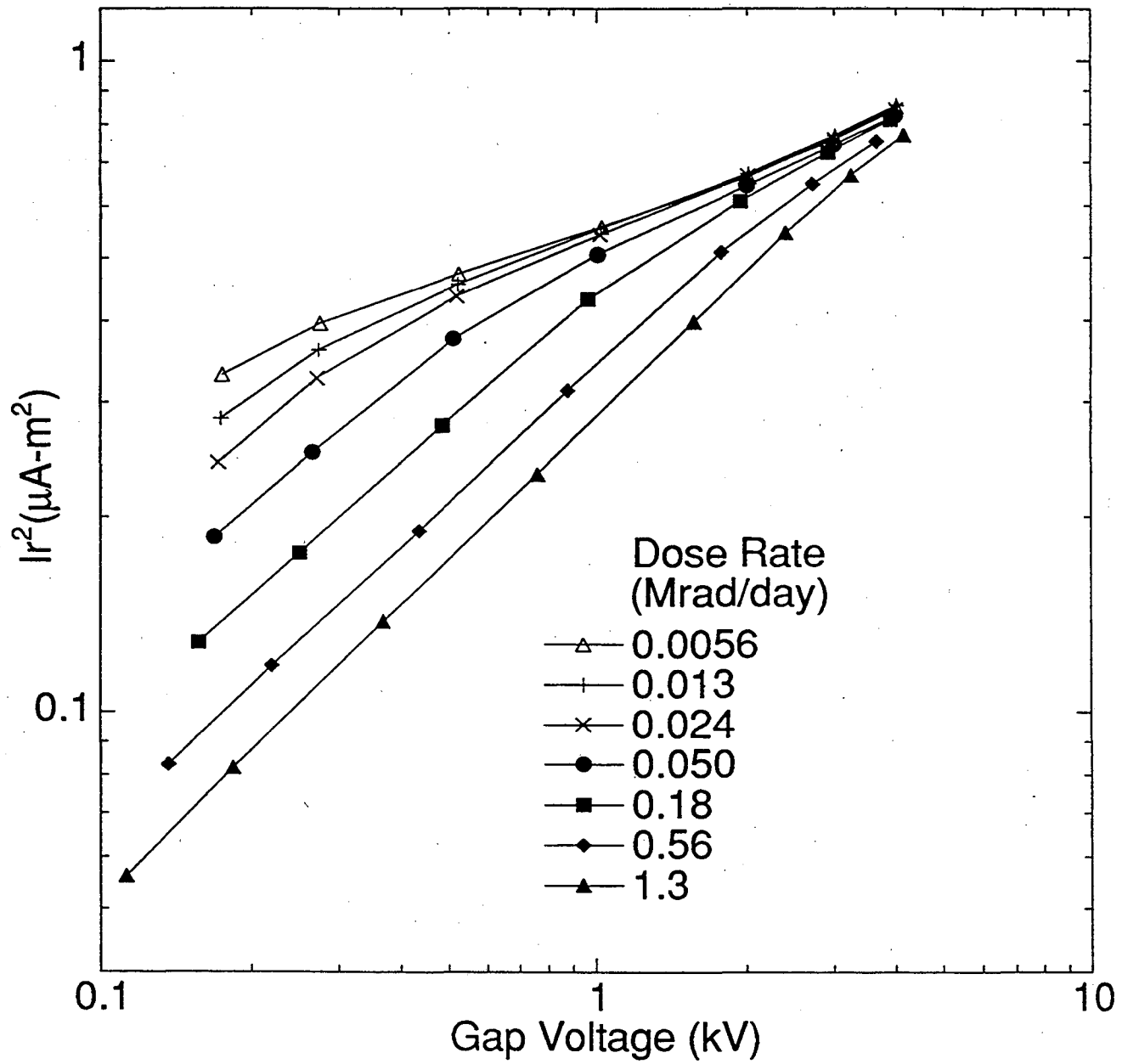

1
0.1
$Ir^2(\mu A\text{-}m^2)$
0.1
1
10
Gap Voltage (kV)
Dose Rate
(Mrad/day)
0.0056
0.013
0.024
0.050
0.18
0.56
1.3

Fig. 9

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