Performance of Small-Radius Thin-Wall Drift Tubes in an SSC Radiation Environment at the MIT Research Reactor

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Abstract—**Drift tubes of 1.9-mm radius and 25-μ wall thickness were exposed to neutrons and associated gamma radiation from uranium fission at the MIT Research Reactor. In 45 hours of irradiation, the drift tubes received a neutron fluence with energy greater than 0.5 MeV of 1.1×10^{13} cm^{-2} and accumulated a charge per wire length of 0.08 coul cm^{-1}, about that expected for three years of operation at the SSC for a lead scintillator calorimeter at a 1-m radius and for drift tubes at a distance of several tens of centimeters from the beam axis. Measurement of the pulse height, pulse shape, counting rates, and currents showed no degradation in drift tube performance. Fast (few nanosecond rise time), sharp (20-ns width) pulses were observed at counting rates of 5 MHz using CF_4 as the drift gas.**

We have developed small-radius (1.9 mm) thin-wall (25-μ) drift tubes for precision tracking in a magnetic field for the purpose of lepton identification in the final states of high-energy high-luminosity proton–proton collisions at the Superconducting Super Collider (SSC). We report here first results of the general performance characteristics of these drift tubes at high counting rates (5 MHz) after a neutron fluence (energy greater than 0.5 MeV) of 1.1×10^{13} cm^{-2} and an accumulated charge per wire length of 0.08 coul cm^{-1} obtained at the Massachusetts Institute of Technology Research Reactor (MITR-II).

The harsh radiation environment at the SSC will impose more stringent constraints on the radiation durability of particle detectors and associated electronics than any previous particle physics facility. At the SSC design luminosity of 10^{33} cm^{-2}s^{-1} one expects the rate of minimum ionizing particles from proton–proton collisions to be 7×10^8 s^{-1} pu pseudorapidity ($\eta = -\ln \tan \theta/2$, where θ is the angle with respect to the beam axis). For a tracking detector a distance r from the beam axis, this translates to an annual (live time of 10^7 s) dose of 40 Mrad cm$^2 r^{-2}$. This radiation dose from charged particles does not include the effect of trapping of low momentum particles in a magnetic field, which is detector dependent and can be a factor of two larger for a large solenoidal detector [1]. Furthermore, the annual fluence of neutrons in the central cavity of an SSC detector due to backscattering from a calorimeter is calculated [1] to be approximately 8×10^{12} $(1\ \mathrm{m}/R)^2$ cm^{-2} (for uranium scintillator), where R is the inner radius of the central cavity. This fluence varies as a function of the calorimeter material and is calculated, for example, to be about a factor of two smaller for the case of lead scintillator and a factor of three larger for uranium–argon [1].

The work we describe in this paper was motivated by the realization that the tracking detectors that will occupy the central cavity of an SSC detector may be prone to damage by the neutron flux. Silicon tracking detectors are well-known examples that are quite sensitive to MeV neutrons, characteristic of neutrons in the central cavity [2]. At the other extreme would be detectors not relying on innate crystalline perfection for their performance, such as gas-based tracking devices. However, the suitability of gas detectors at the large SSC rates has not been demonstrated.

A convenient neutron source for our group in Boston is the MITR-II, a 5-MW reactor with numerous external beam and internal irradiation facilities. This work was performed at the Fast Spectrum Facility, which is well-suited for SSC radiation simulations. It consists of a slab (2×2 m area and 0.5-m thickness) of uranium slightly enriched in ^{235}U (2%), which is irradiated by thermal neutrons from the reactor core. A boron thermal shield allows high-energy fission neutrons to uniformly irradiate the area where our detectors are placed. The prompt neutron energy spectrum from fission of ^{235}U is well-fit by the expression [3]

$$dN/dE = 0.453 \exp\left(-E/0.965\right) \sinh\left[(2.29\,E)^{1/2}\right]$$

where dN/dE is in units of neutrons/MeV normalized to unity with the energy E expressed in MeV. The peak of the spectrum is at 0.6 MeV and it falls off rapidly with energy. Each fission produces about 2.5 fast neutrons. About 8 gammas per fission are emitted (prompt and fission product) with the energy spectrum as tabulated in Table I.

We simultaneously exposed two types of drift tubes at the MITR-II:

1) "PBAR" type, the same drift tube used in the PBAR

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TABLE I
ENERGY SPECTRUM OF GAMMAS FROM ^{235}U FISSION[1]

Energy Interval (MeV)	Photons/Fission
0.1 to 0.4	1.61
0.4 to 0.9	4.84
0.9 to 1.35	0.496
1.35 to 1.8	0.624
1.8 to 2.2	0.311
2.2 to 2.6	0.116
> 2.6	0.011

From [3].

balloon experiment [4] for which the first thin-wall drift tubes were developed (12.5-μ mylar + 12.5-μ polycarbonate + 1000 Å of aluminum) [5]. We monitored two tubes (PBAR-1 and PBAR-2 of an 8-tube PBAR prototype array for the test. The tube radius is 6.35 mm and the length is 20 cm. The anode wire is 20-μ gold-plated tungsten tensioned at 20 g. The wire alignment is held by a concentric precision arrangement of an outer brass plug, delrin inset, and stainless steel ferrule [4].

2) "SSC" type, a smaller-radius version developed by our group for potential use at the SSC. Two tubes (SSC-1 and SSC-2) were monitored during this experiment. The same wall material was used as for the PBAR tubes, but the tube radius is 1.9 mm and the length of the tubes is 30 cm. The SSC detector has 20-μ diameter gold-plated tungsten wires tensioned at 50 g. The endplug design is essentially a miniaturization of that used in PBAR. However, the challenge was to maintain the precision in the wire placement while still providing for adequate gas flow and a practical means for connection of high voltage in a small space. Special attention was taken to minimize the amount of material in the end plug design. This was accomplished with an aluminum endpiece, a delrin inset, and the same stainless steel ferrule used in PBAR. The aluminum inserts are glued to the insides of the tubes with conducting silver epoxy. The drift tubes are designed to achieve 100-μ spatial resolution, so we have machined the endpieces to hold a tolerance of 25 μ. We have checked the rough alignment of the wires in this design by recording the electron drift times in two staggered tubes for cosmic rays passing through the middle and near the two ends of the drift tubes using argon–ethane (50/50) as the drift gas. The tracking resolution of the SSC drift tubes will be addressed by our group in an upcoming beam test.

All the drift tubes were mounted parallel to one another and to the uranium slab with their axis in the horizontal plane. We note that the temperature in the Fast Spectrum Facility remains at room temperature during the exposure.

The gas used for these tests was CF_4, chosen for its high electron drift speed (about 100 μ/ns), which is highly desirable at SSC rates, although the final choice of gas for the SSC would include the addition of isobutane or dimethylether to improve tracking resolution. The gas flow was serial, first through the two SSC tubes and then through the PBAR tubes at a rather slow rate of approximately 15 cm^3/min. Two hoses 12 m in length with an inside diameter of 4 mm were used to deliver and receive the gas from the drift tube detectors. The input pressure to the delivery hose was 30 cm of water, the large value of which is due to the small gas passages used in the SSC endplug design. The output pressure of the receiving hose was regulated by a mineral oil bubbler set to 8 mm above atmospheric pressure.

High voltage was delivered to the tubes and signals received from the tubes by a single 7.6-m long coaxial cable for each of the four drift tubes that were monitored. A separate power supply was used for each drift tube. The tube voltages were maintained at 2200 V for SSC-1, SSC-2, and PBAR-1, and 2500 V for PBAR-2. A ^{55}Fe source (producing ^{55}Mn 5.9 keV K-shell X-rays) placed at the midpoint of the tube length yields a signal of 1.2 mV (after amplifier gain is divided out) out of the 7.6-m long coax trunk line into 50 Ω for 2200 V on an SSC tube, and the same for 2500 V on a PBAR tube. Sense wire gains were measured by pulse height analysis of the ^{55}Fe source before the exposure.

The performance of the drift tubes were monitored in a number of ways.

a) Currents from the high-voltage supplies (Bertan 375) for each drift tube were monitored throughout the run. Currents were measured both on the supply meters and the current monitor outputs. The accuracy of the current measurement from the monitor is 10 nA. Small currents can be measured from the meter to about 2 nA.

b) The counting rates of SSC-1, SSC-2, and PBAR-2 were monitored at a threshold corresponding to 0.3 mV (30 mV after 100 × amplification in two stages of a LeCroy 612A) at the line output into 50 Ω.

c) The coincidence rate (20-ns discriminator width, 30-mV threshold after 100 × amplification) of the SSC tubes, which were mounted horizontally adjacent to one another, transverse to a line to the uranium source, was monitored. Note that the maximum drift time in CF_4 gas is slightly less than 20 ns for the SSC tubes at 2200 V.

d) Pulse waveforms from SSC-1 and SSC-02 were recorded (after 10 × amplification) for coincidence triggers throughout the exposure with a LeCroy 9400 waveform digitizer (10-ns time samples) and minicomputer data acquisition system. This enabled us to monitor and record pulse quality and to determine pulse height spectra throughout the exposure.

e) Pulse height spectra were measured in the PBAR and SSC tubes with a ^{55}Fe source before the exposure, after 26 h of irradiation and again at the end of the exposure.

The data reported here were taken in three periods of peak reactor power of 4 MW: 1) a 15.7-h interval between at 03:50 and 19:33 on December 13, 1989, 2) a 10.25-h interval between 00:00 and 10:15 on December 14, 1989, and 3) a 19.33-h interval between 18:10 on December 20, 1989 and 13:35 on December 21, 1989.

We report first the details of our measurements during period 1) and then summarize the results from the total exposure of 45.3 h.

Fig. 1(a) shows the current in SSC-1 measured as the reactor was turned on for period 1) at power levels of 0.04, 0.25, 1, 2, 3, and 4 MW. The power is monitored in the reactor control room by measurement of the neutron flux

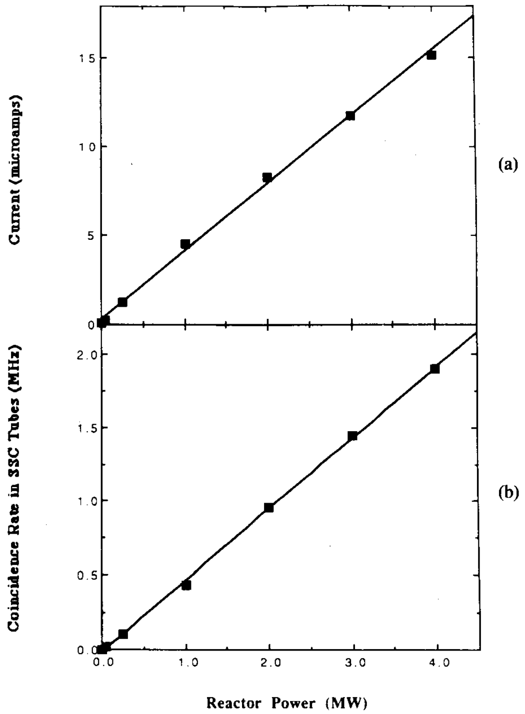

Fig. 1. (a) Current measured in SSC-1 and (b) coincident rate in SSC tubes as function of reactor power at beginning of experiment. Solid-lines are linear fit.

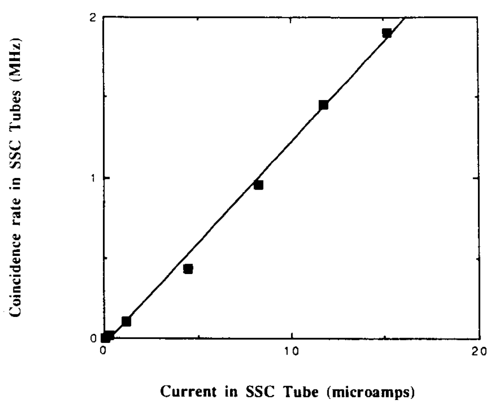

Fig. 2. Coincidence rate between SSC-1 and SSC-2 versus current in SSC-1 at beginning of experiment. Solid line is linear fit.

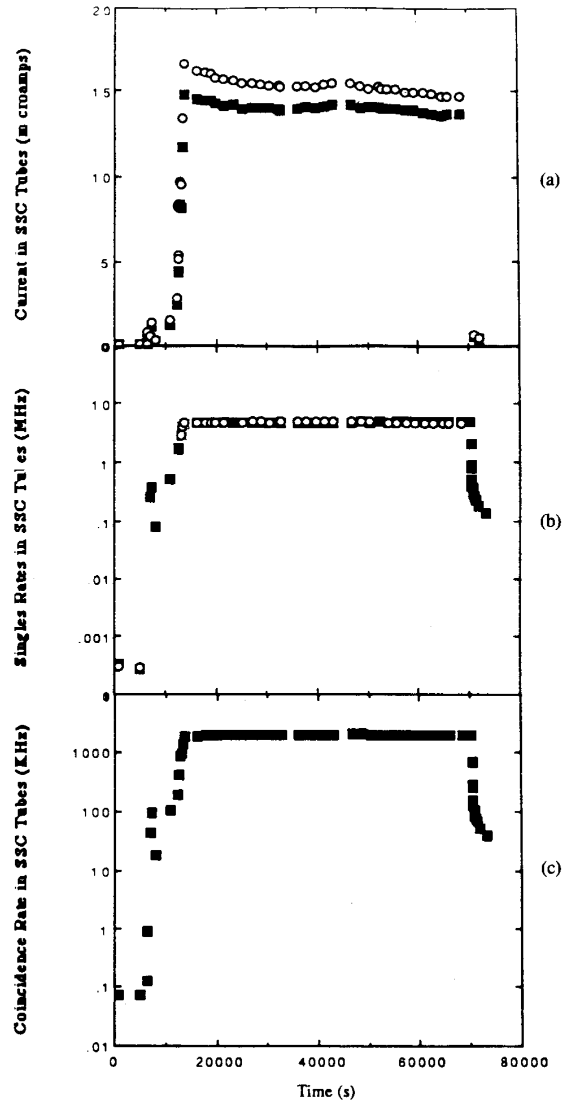

Fig. 3. (a) Current measured in SSC-1 (solid squares) and SSC-2 (open circles), (b) singles rates, and (c) SSC-1 and SSC-2 coincidence rate as function of time. Increases in currents and rates were observed as reactor was powered up. Small bump at about $t = 7000$ s represents abortive attempt to power up reactor. Reactor power was 4 MW for interval 13 800 s $< t <$ 70 380 s. At $t =$ 70 380 s reactor shutters were closed. Last two measurements shown were made 540 s and 1920 s after closing of shutters.

from the core. The current was observed to increase linearly with reactor power. The observed coincidence rate between SSC-1 and SSC-2 increases linearly with the reactor power as shown in Fig. 1(b), measured as the reactor was powered on for period 1). Fig. 2 shows the measured coincidence rate versus current as the reactor was powered on.

Fig. 3(a) shows the current in SSC-1 and SSC-2 as a function of time, $t = 0$ being defined as 00:00 on December 13. The little bump is due to an aborted attempt to start up the reactor during the time $t = 6300$ s to $t = 8100$ s. The sharp rise is due to the reactor being powered up during the period $t = 8220$ to $t =$ 13 800 s. The maximum current of about 15 μA corresponds exactly to the period of maximum reactor power. The neutron flux at our detector may fluctuate slightly during normal operation as fuel is consumed and rods are adjusted. The slightly higher (8%) current in SSC-2 is believed due to one or both of the following: a) the activation of an aluminum support stand, $^{27}Al(n,\alpha)^{24}Na$, which was in closer proximity to SSC-2 than SSC-1, and b) interactions in SSC-1 (SSC-1 was located between the uranium target and SSC-2). At $t =$ 70 380 s the reactor shutters were closed, cutting off the flux of thermal neutrons to the uranium slab. The currents corresponding to the largest times in Fig. 2 were taken 9 and 32 min after the closing of the shutters.

The singles rates in SSC-1 and SSC-2 as a function of time are also shown in Fig. 3(b). The rate was constant at 5 MHz maximum power and was identical to within 4% in the two SSC tubes. (The singles rate in the PBAR tube at 2500 V was observed to be about 2 MHz.) When the shutters were closed, the rate was observed to drop instantly to 2 MHz. It fell an additional factor of ten after 20 min.

The coincidence rate of the SSC tubes as a function of time is shown in Fig. 3(c). Before the reactor was started, this rate was measured to be 72 Hz due to a small radioactive background in the Fast Spectrum Facility. A maximum power, the coincidence rate is observed to be 2 MHz or about 40% of the singles rate. Using Poisson statistics, we calculated the rate of accidental pulse overlap of 20-ns width pulses at 5 MHz rates to be 36%. The accidentals rate was measured to be 42% when SSC-2 was delayed by 55 ns. We attribute the coincidences to energetic Compton electrons produced outside the tubes (because the singles rates in SSC-1 and SSC-2 are nearly identical). The energy of the emitted gammas (Table I) is peaked at around 600 keV; thus Compton electrons produced by such gammas can easily penetrate two tubes (300 keV corresponds to practical electron ranges of 80 mg cm^{-2}, the tube wall thickness is about 3 mg cm^{-2}, and the CF_4 gas is about 1.3 mg cm^{-2} in an SSC tube). Neutron-induced proton recoils are unlikely to account for more than a few percent of the observed coincidences because it takes more than 2 MeV for a proton to make it through 2.5 walls plus the CF_4 in order to cause a coincidence. When the shutters are closed, the flux of neutrons to our detectors is cut off immediately, but a component of the gamma radiation is still present (see Fig. 2). From the measured coincidence rate (84 kHz) and currents (0.58 μA in SSC-1 and 0.68 μA in SSC-2) 9 min after the shutters were closed, we can determine that essentially all of the current with the reactor on was gamma induced.

Pulse height spectra were taken with an ^{55}Fe source on December 9 before installation at the reactor in all the drift tubes at several voltages. The signals from the drift tubes were input to a charge sensitive preamplifier (C = 10 pF) and a fast shaping amplifier (Ortec 575) and then to a pulse height analyzer (Ortec 7100). At 2000 V, with the fast amplifier gain set at 300, the location of the X-ray peak was at 6.68 V in SSC-1. We had access to the drift tubes on the morning of December 19 after 26-h of irradiation at 4 MW, at which time were measured the ^{55}Fe peak and found it to be at 6.58 V. On December 27, after 45 h of exposure at peak power, we had another access to the tubes during which the pulse height spectrum was again remeasured to be at 6.62 V. Thus, the ^{55}Fe peak was observed to be unchanged within measurement error (1%). The width was also observed to be unchanged (21% standard deviation). The PBAR tubes were measured in a similar fashion at 2500 V and the X-ray peaks were found to be unchanged within 1%.

The pulse waveforms from SSC-1 and SSC-2 were carefully monitored and recorded throughout the experiment. Fig. 4(a) shows ten sequential pulses in SSC-1 and SSC-2 generated by the Compton electron coincidences near the beginning of the run with the reactor at full power. The pulse height of a minimum ionizing particle is expected to be a few mV after ten fold amplification of the drift tube signal. The pulses typically have fast (few nanoseconds) rise times and widths of about 20 ns. Fig. 4(a) also gives us some measure of how difficult (or easy) it will be to do tracking in a background at 5 MHz singles rates (comparable to SSC rates). Note that there is little difficulty in identifying the pulse pairs, which generated the coincidence, that occurred near $t = 0$.

The quality of the waveforms was consistent throughout the run. In Fig. 4(b) we show 10 sequential pulses near the end of period 1) with reactor at full power. For comparison, in Fig. 4(c) we show 10 sequential pulses taken after the reactor shutters were closed and the coincidence rate has dropped to 57 kHz and the singles rates to 200 kHz.

By integrating the waveforms from 40 ns before the coincidence trigger to 40 ns after the trigger time, we can obtain pulse height spectra to continuously monitor the gain of the tubes during exposure. Spectra at the beginning and the end of period 1) during full-power operation are shown in Fig. 5(a) and 5(b). No obvious changes are to be noted.

We emphasize that no rate problems were observed due to ion clearing. It has been stated that rates should be kept below 10^4 $mm^{-1}s^{-1}$ (corresponding to 3 MHz for our 30-cm long tubes) to avoid such problems [6]. To illustrate this we show in Fig. 5(c) the pulse height spectra taken after the reactor shutters were closed, with the coincidence rate at 57 kHz and the singles rates at 200 kHz. The low energy side is cleaner than with reactor on (Fig. 5(a)–(b)), but there is no serious gain degradation during the run due to ion clearing problems. We measured the pulse heights of chance coincidences and found them to be consistent with the low pulse height component observed in Fig. 5(a)–(b). The larger PBAR drift tubes did show a serious efficiency problem at high rates, likely due to ion clearing problems.

The neutron fluence for this run was determined by placing a nickel foil in the irradiation area adjacent to our drift tubes for period 1) and period 2). The nickel is activated by the reaction ^{58}Ni(n,p)^{58}Co. These foils were removed during the access on December 19, and gammas from ^{58}Co decay of energy 0.8 MeV (71.3 day lifetime) were counted in a calibrated detector by standard technique. The neutron flux for energies greater than 0.5 MeV was determined to be 7×10^7 $cm^{-2}s^{-1}$ with an estimated error of about 10%. The neutron flux with $E > 30$ eV was determined to be 3.3×10^8 $cm^{-2}s^{-1}$ from knowledge of the energy dependence of the spectrum at MITR-II from previous measurements.

The total amount of charge collected per wire is determined by measurement of the currents. For SSC-1, this measured to be 0.08 coul cm^{-1}. This direct measurement is in excellent agreement with the charge per wire length expected from minimum ionizing particles at the measured singles rate of 5 MHz and sense wire gain of 4.8×10^5 (limited streamer mode), taking the electron yield in CF_4 to be 100 electrons/cm. The SSC tubes when operated with argon–ethane (50/50) have a similar gain at 1750 V.

Fig. 5(d) shows the pulse height spectrum for coincidence triggers obtained from the integrated wave forms for SSC-1

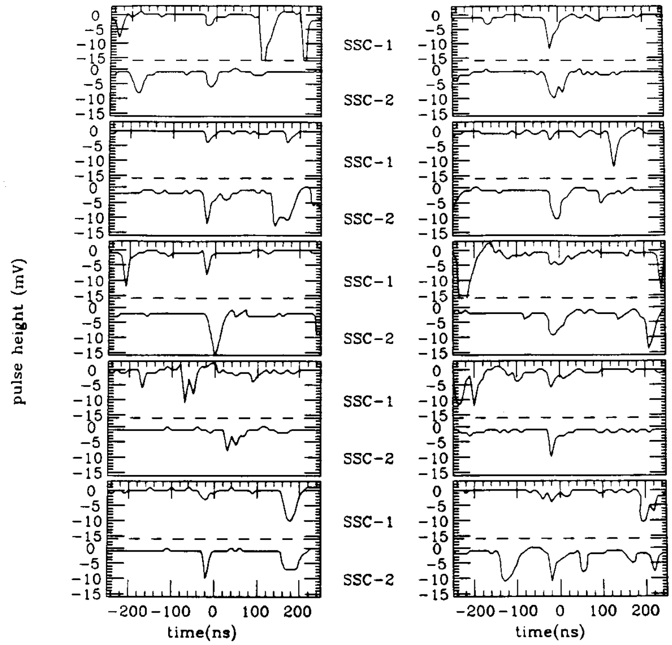

Fig. 4(a). Ten sequential waveforms for both SSC-1 (first trace) and SSC-2 (second trace) for coincidence triggers recorded during beginning of run with reactor at 4 MW. Coincidence rate was 2 MHz and singles rates were 5 MHz. Amplification factor is ten. Threshold for coincidence circuit corresponds to 3 mV on these traces, and trigger is at $t = 0$.

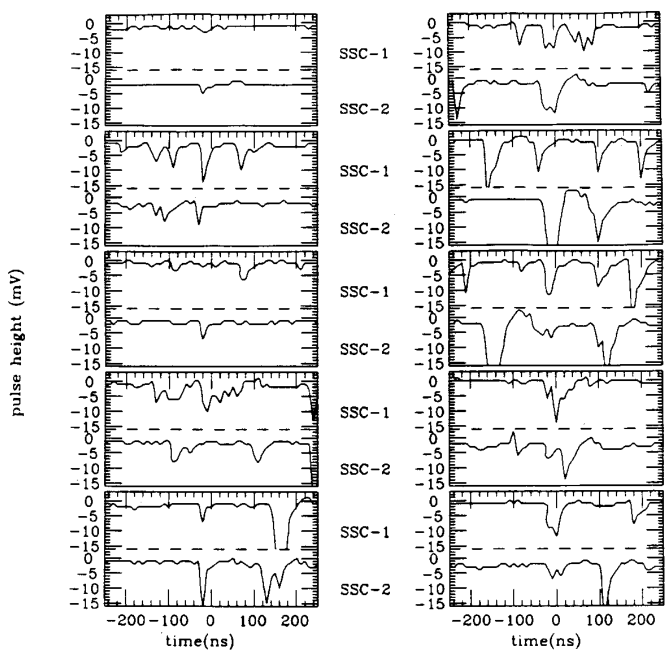

Fig. 4(b). Ten sequential waveforms for both SSC-1 (first trace) and SSC-2 (second trace) for coincidence triggers recorded at end of 15 h with reactor at 4 MW. Coincidence rate was 2 MHz and singles rates were 5 MHz. Amplification factor is ten. Threshold for coincidence circuit corresponds to 3 mV on these traces, and trigger is at $t = 0$.

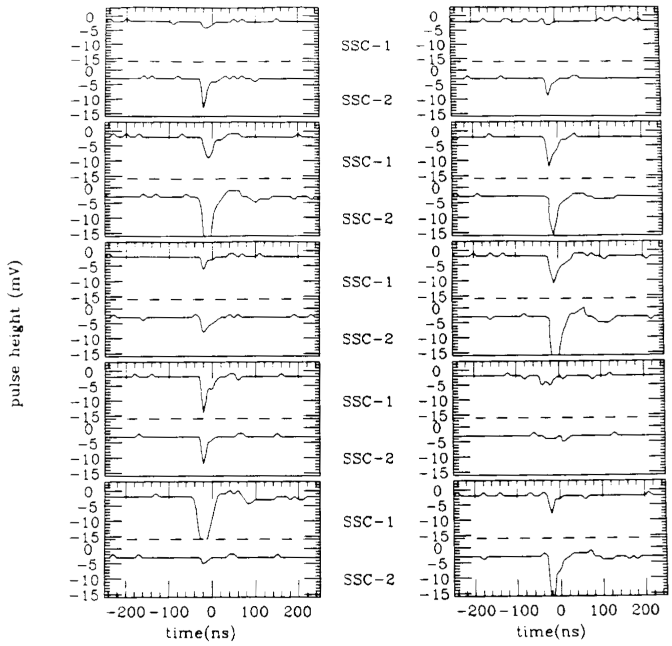

Fig. 4(c). Ten sequential waveforms for both SSC-1 (top trace) and SSC-2 (bottom trace) for SSC tube coincidences recorded after 15.7 h of exposure with shutters closed. Coincidence rate was 57 kHz and singles rates were 200 kHz. Amplification factor is ten. Threshold for coincidence circuit corresponds to 3 mV on these traces, and trigger is at $t = 0$.

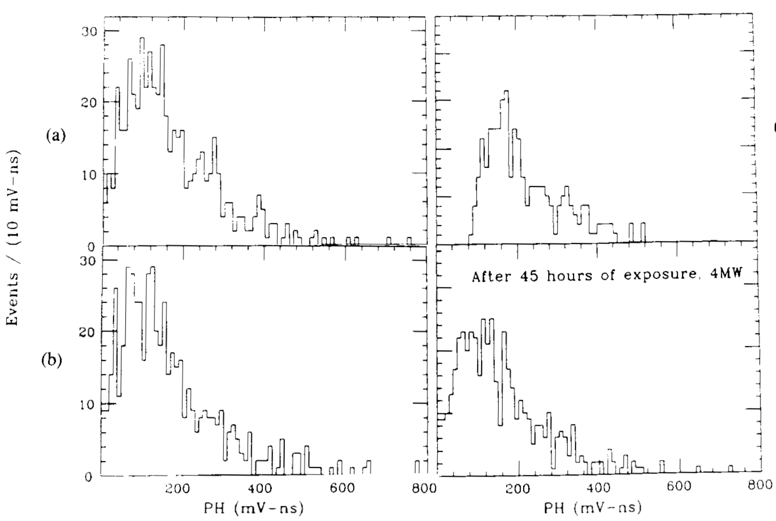

Fig. 5. Pulse height spectra for SSC-1 obtained by integration of recorded waveforms ±40 ns about trigger time for events recorded a) in first half-hour of run with coincidence rate at 2 MHz and singles rates at 5 MHz, b) after 15 h of exposure, (c) after reactor shutters were closed with coincidence rate at 57 kHz and singles rates at 200 kHz, and d) after neutron fluence of 1.1×10^{13} cm^{-2}s^{-1} and a charge per wire length of 0.08 coul cm^{-1} with coincidence rate at 2 MHz and singles rates at 5 MHz.

TABLE II

		SSC	This Experiment
MeV neutron flux	(U-scint., R = 1 m)	8×10^5 cm^{-2}s^{-1}	7×10^7 cm^{-2}s^{-1}
	(Pb-scint., R = 1 m)	4×10^5 cm^{-2}s^{-1}	
MeV neutron fluence	(U-scint., R = 1 m, 1 yr)	8×10^{12} cm^{-2}	1.1×10^{13} cm^{-2}
	(Pb-scint., R = 1 m, 1 yr)	4×10^{12} cm^{-2}	
Rate in 1.9-mm	($\Delta\eta$ = 1.5, R = 1 m)	0.6 MHz	5 MHz
radius tube	($\Delta\eta$ = 3, R = 0.5 m)	2.5 MHz	
	($\Delta\eta$ = 3, R = 0.25 m)	5.1 MHz	
Charge/wire length	($\Delta\eta$ = 1.5, R = 1 m, 1 yr)	0.002 coul cm^{-1}	0.08 coul cm^{-1}
	($\Delta\eta$ = 3, R = 0.5 m, 1 yr)	0.008 coul cm^{-1}	
	($\Delta\eta$ = 3, R = 0.25 m, 1 yr)	0.03 coul cm^{-1}	

Comparison of rates of neutrons, charged particle counting rates, and collected charge per wire length between that expected at the SSC (for various detector configurations) and this experiment. The SSC neutron fluxes are from [1]. The drift tube lengths for ($\Delta\eta$ = 1.5, R = 1 m), ($\Delta\eta$ = 3, R = 0.5 m), and ($\Delta\eta$ = 3, R = 0.25 m) are 2.12 m, 2.12 m, and 1.06 m, respectively. In the calculation of coul cm^{-1} at the SSC it is assumed that the charge collected is due to minimum ionizing particles only and no magnetic trapping with 100 primary electrons/cm produced and a wire gain of 10^4. The SSC neutron fluence and estimated charge/wire length correspond to one year.

at the end of period 3), with reactor at full power, compared to that obtained at the beginning of period 1). No significant change is noted. The neutron fluence for the total exposure was 1.1×10^{13} cm^{-2} and a total charge per wire length of 0.08 coul cm^{-1} was collected. Table II gives a summary of this exposure together with that expected at the SSC. Note that the neutron flux of this experiment is 100 times that expected at the SSC. Single-tube counting rates are comparable between this experiment and longer tubes at radial distances of several tens of centimeters at the SSC. At the SSC, we would expect to operate the drift tubes at the much lower gain of approximately 10^4. Bench tests have determined that minimum ionizing particles are clearly observable at this gain (1800 V for CF_4 and 1300 V for argon ethane), although better electronics are required. A large charge per wire length has been collected here in a short time due to the large particle flux and large sense wire gain used in these measurements. We note that the exposure reported here was only 45-h duration and that strong rate dependences have been observed in radiation damage effects [1].

It is our conclusion, based on these observations, that drift tubes of the type used here are good candidates for operation in the SSC radiation environment. Future tests are planned to extend the radiation exposure limits at the MITR-II and to determine tracking resolution at high rates with multiple drift tube arrays at the reactor.

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