EFFECTS OF IRRADIATION ON HALL PROBE SENSITIVITY

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ABSTRACT

Four Hall probes from two different manufacturers were exposed to increasing amounts of radiation at the LLNL Advanced Test Accelerator and were compared periodically to an NMR Gaussmeter at magnetic field values of 2 to 8 kG. The radiation was primarily bremsstrahlung from a 45-MeV electron beam. The probes were mounted near a beam dump, along with LiF thermoluminescent detectors to keep track of the cumulative dose. The data show a threshold near 100 krad, beyond which point the probes tend to lose sensitivity and perform outside their nominal error limits.

Introduction

The interaction of an energetic electron beam with matter produces radiation that can degrade the performance of nearby electronic components. When device performance depends critically on accurately maintaining magnetic field levels, such as in the wiggler region of a free-electron laser, the magnetometer calibration must remain accurate to within fractions of one percent. The convenience of Hall probes makes them attractive for such measurements. However, existing information points to possible long-term radiation effects on solid-state electronics elements at dose levels as low as 1 krad for bremsstrahlung and 10^{12} N-cm^2 for neutron irradiation.[1] The experiment described in this note represents a low-budget effort to gather more empirical information on two specific types of transverse Hall probes that were exposed to radiation levels typically encountered near the beamline of the Advanced Test Accelerator at LLNL.

Apparatus and Procedure

Four Hall probes from two different manufacturers, together with a set of eight thermoluminescent diodes (TLDs), were mounted in the arrangement shown in Fig. 1. The probe array was pointed such that the narrow edges of the Hall chips were facing the radiation source, generally a beam dump or a high-radiation segment of beam pipe. To prevent interference with ongoing work at ATA, we frequently had to change the location of our probe array and follow the beam around as the machine was being adjusted. The radiation spectrum so produced was reasonably representative of arbitrary probe locations in the tunnel. We stopped the irradiations where necessary to maintain a constant beam energy of 45 MeV. The entire series of measurements stretched over almost one year; the chronology is given in Table 1. The dose variations given represent the approximate range of TLD readings. In view of the long time intervals, some annealing (spontaneous healing of radiation damage) most likely took place between or even during the exposures.

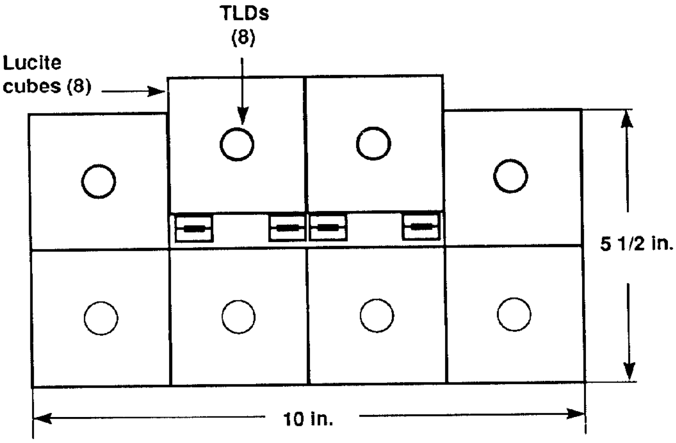

Fig.1. Mounting arrangement of the four Hall probes inside a TLD array

Table 1. Chronology of irradiation with 45 MeV bremsstrahlung

Date	Dose increment (krad)	Cumulative dose (krad)
3 December 87	0	0
23 March 88	78 ± (9)	78
21 April 88	41 ± (5)	119
1 June 88	37 ± (5)	156
8 September 88	47 ± (7)	203
13 January 89	81 ± (5)	284
3 March 89	30 ± (7)	314

After each irradiation session, we compared the Hall probes to readings from a Sentec Model 1001 NMR Gaussmeter over the range -8 to 8 kG. Changes in the resulting error curves proved to be difficult to interpret, so to track the radiation effects systematically we concentrated on the change in error readings at specific field values. A schematic of the calibration apparatus is shown in Fig. 2. The pole diameter of the laboratory electromagnet was 10.2 cm, with a 1.6 cm pole spacing and a measured field flatness of better than 50 ppm over a 3-cm-diam region centered on axis.

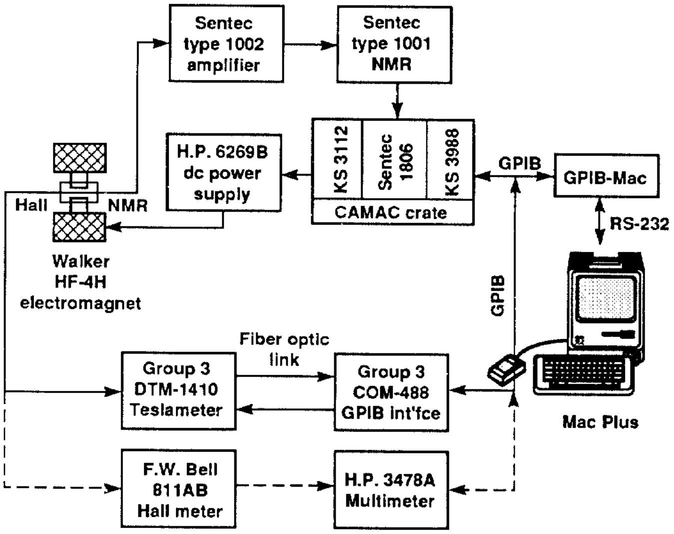

Fig.2. Electronics system for comparing the Hall probes to the NMR gaussmeter.

For the successive error calibrations, one probe at a time was mounted in a special Lucite holder directly opposite the NMR probe, with the active elements of the probes placed within less than 15 mm of each other and centered on the magnet axis. The Lucite holder was closely fitted to the pole pieces and to the Hall and NMR probe tips to minimize any position-related variations. The probe orientation with respect to the field also was kept the same from run to run. After a 1-hr warmup, the F.W. Bell probes were nulled in a zero-gauss chamber, and the calibration constant was set at the number stamped on each probe shell. The Group 3 probes were zeroed, their gain constant was set to one, and their offset was set to zero. Using LabView software in an Apple Macintosh computer, we first conditioned the electromagnet and then scanned through field values between -10 and 10 kG for the F.W. Bell probes, and between -6 and 6 kG for the Group 3 probes. Field reversal was achieved by reversing the electromagnet current. For each desired field value, we first allowed the power supply to settle for a few seconds and then took 10 field readings, alternating between the NMR and the Hall probes to minimize changes caused by power supply drift, nominally less than 300 ppm. The average for each set of readings was then computed and stored on disk. Because each NMR probe had only a limited range, these probes were changed as required during each run. The repeatability of our measurements was within 50 ppm.

The radiation spectrum is that of a 45-MeV, 1-2 kA electron beam striking a carbon beam dump or the stainless-steel beam pipe wall; we assume that it includes bremsstrahlung, neutrons, and scattered electrons. We infer the magnitude of the neutron component from earlier dosimetry measurements near two separate ATA beam dumps.[2] Using measured, normalized dose rates we find that a 50 krad bremsstrahlung exposure at ATA typically is accompanied by a neutron fluence of 0.2 to 5 x 10^{10}N-cm^{2}. However, because the absorbed dose is material dependent[3] the dose indicated by the TLD elements may differ from that actually absorbed by the InAs Hall chips by as much as a factor of 2 or 3. For simplicity, the data presented below have been indexed only to the TLD-indicated, cumulative dose.

Results

A typical calibration curve for an unirradiated Group 3 probe is shown in Fig. 3. The nominal accuracy of this probe is 100 ppm. Fig. 4 shows data for the same probe after irradiation with 314 krad. Both halves of the calibration curve now are tilted and offset from the zero error level. Figures 5 through 8 plot observed error levels vs cumulative radiation dose for all four Hall probes, each sampled at three distinct field values. Neither of the Group 3 probes shows any significant change until the 100-krad dose level is reached. Probe 43001 then begins to show an increasing error but settles near 1000 ppm. Probe 43002 behaves more erratically, with larger error excursions and stronger dependence on field value and polarity. The F.W. Bell probes largely stay within their 1000-ppm nominal error envelope, except for some steep excursions to 2000-ppm and beyond after the 100-krad irradiation level; these excursions appear to anneal out. For negative field values, probe 201675 begins to show some effect even with the first irradiation.

Based on Ref. 1, we believe that neutron damage is the mechanism responsible for the observed changes in error level. However, because the inferred, direct neutron dose was only about 5 x 10^{10}N·cm^{2}, which is two to three orders of magnitude below known damage thresholds, the observed effects are attributed to neutrons arising from gamma-n reactions nearer to the probes, possibly in the Lucite mounting blocks. We did not attempt a calculation of neutron yield from this source, however.

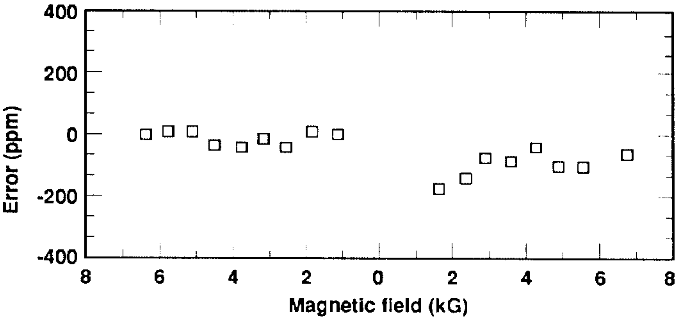

Fig.3. Calibration curve of an unirradiated, Group 3 Hall probe, using the NMR magnetometer as the standard.

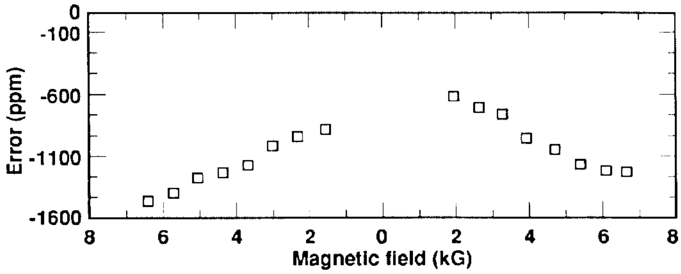

Fig.4. Calibration curve of a Group 3 Hall probe after irradiation to 314 krad.

The conductivity of semiconductors irradiated by neutrons will decrease because of induced carrier removal, i.e., trapping of carriers in radiation-induced trapping centers.[1] As a result of thermal motion, an annealing process may take place, where many of the displaced-atom trapping centers break up and disappear. This process has a time scale ranging from seconds to days and weeks. The observed, nonmonotonic behavior of the error curves is consistent with such annealing.

Conclusion

We incrementally exposed four Hall probes from two different manufacturers to approximately 300 krad of 45 MeV bremsstrahlung radiation at the LLNL Advanced Test Accelerator. Periodic comparison of the probes with an NMR Gaussmeter, at magnetic field values of 2-8 kG, indicates a damage threshold near 100 krad, beyond which point the probes tend to exceed their nominal error tolerance. We conjecture that the loss in sensitivity may be caused by crystal dislocations in the InAs Hall chip arising from neutrons generated in gamma-n reactions. We observe that the radiation effects are not monotonic with cumulative dose, and in some cases appear to go away at the higher doses; we attribute this to annealing of the probe material during or in between the successive irradiations.

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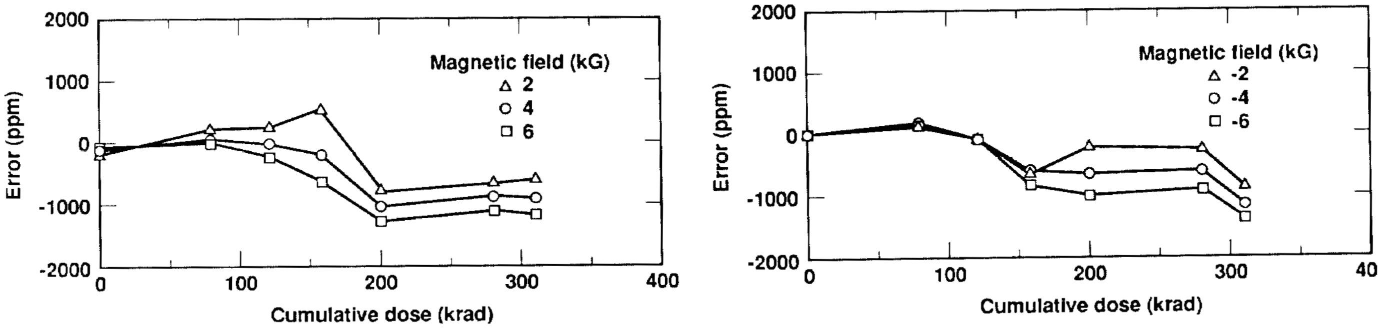

Fig.5. PPM error vs dose for Group 3 Hall probe #43001. The parameter in Figs. 5-8 is the magnetic field value (both polarities).

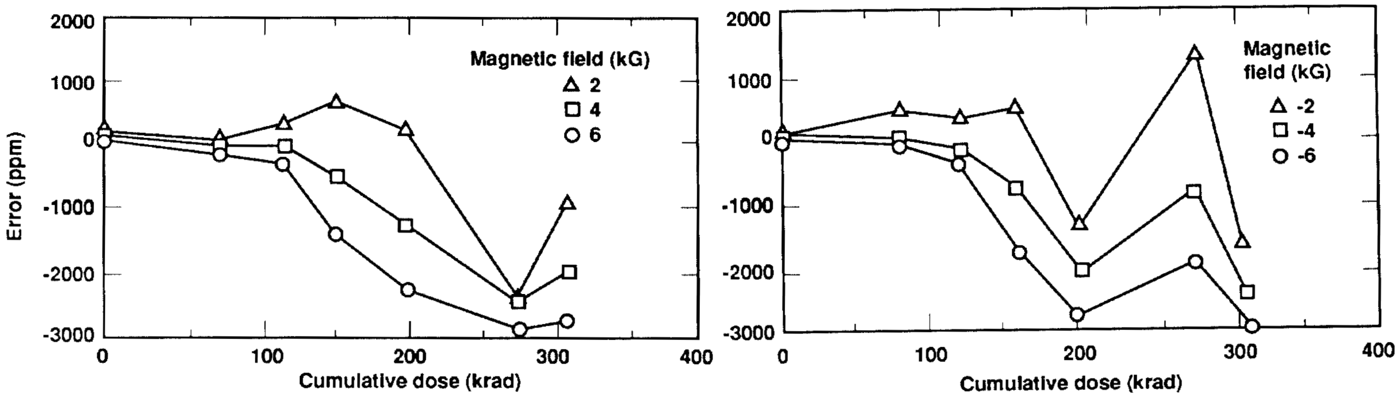

Fig.6. PPM error vs dose, Group 3 Hall probe #43002.

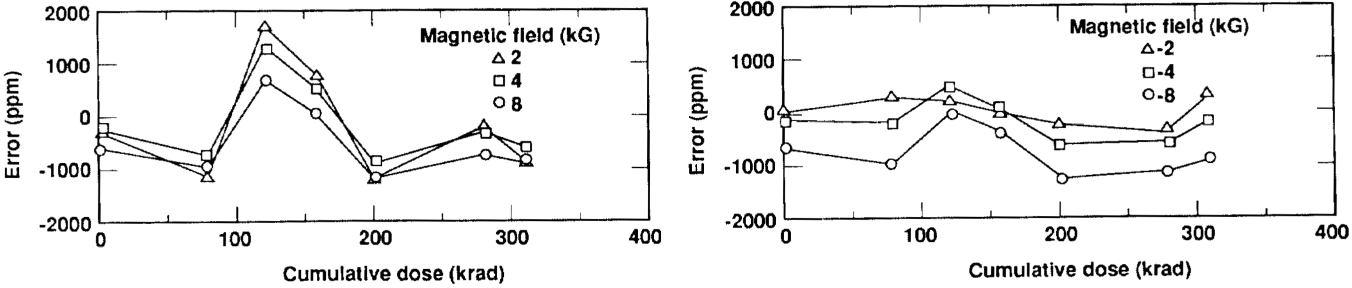

Fig.7. PPM error vs dose, F. W. Bell Hall probe #204690.

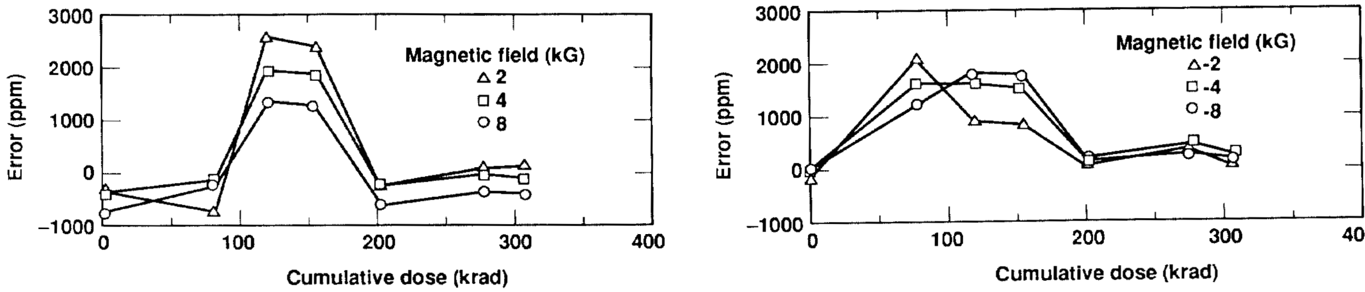

Fig.8. PPM error vs dose, F. W. Bell Hall probe #201675.

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