FURTHER EXPERIENCE WITH SLC PERMANENT MAGNETIC (PM) MULTIPOLES

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Abstract

PM multipoles have been used in the SLAC damping rings (DR) and their injection and extraction lines since 1985. Due to upgrades of the DR vacuum chambers for higher currents in 1993, there was an opportunity to check some of these magnets[1]. Nothing more was done until a program of real-time radiation measurements was begun in the electron ring to determine causes, levels and effects of integrated gamma and neutron doses on the strengths and harmonic contents for NLC purposes. We discuss results of the latest magnetic measurements, radiation measurement program, semiconductor dosimeters and a few unexpected but interesting conclusions.

INTRODUCTION

PM devices have many current and potential applications based on advantages in size, cost and simplicity e.g. they are self sustaining in the sense that they require no power, water cooling or control electronics for many applications. They do suffer from uncertainties related to environmental and damage effects. In the NLC, PM multipoles, solenoids, undulators and wigglers could have important uses if the limits of their stability to different kinds of high radiation environments could be established. We are revisiting this because future colliders imply beams with unprecedented energy densities, containment and damage problems. Further, the SLC DRs appear to be an ideal place to pursue such studies. As with most radiation measurements at such facilities, they are seldom real-time but only sweeps made after the beams go off for personnel entry and protection purposes. In contrast, we have been obtaining real-time measurements of the main radiation components around the ring i.e. the integrated dose of neutrons and gammas (n & γ).

Background

In 1985, it was difficult to justify using PM multipoles or any PM device in a storage ring. There were few radiation damage (RD) studies[2] and they weren't relevant. Further, there were few vendors and fewer reliable measurements of easy axis characteristics. However, because there was no alternative, 144 sextupoles were made and installed in the e$^{\pm}$ DRs for chromaticity correction as well as several quadrupoles for the injection and extraction lines[3]. In both cases, compactness was the essential ingredient. In 1993, 21 of the 144 sextupoles were replaced - mostly downstream of the injection kickers and in the electron ring either because their thermal stabilization temperatures of 80° C had been exceeded or because they showed serious mechanical deformation or high radiation levels (in some cases >1 R/hr on contact). These magnets were studied in various ways[1] and then stored. Several have been used for other purposes but not one PM magnet has ever caused loss of the beams or *had* to be replaced.

Current Situation

In 2002, one of the original sextupoles that had been in the ring for 17 years was removed, remeasured and replaced by one that had been stored in 1993 after it had also been remeasured. We then added two radiation detectors on the top and side of this magnet for remote monitoring. At the same time, we continued to monitor dose at other locations in the DR to understand the sources of damage. To our knowledge, no one has done real-time monitoring to ascertain the actual causes of beam loss and to correlate these with radiation damage to determine the actual or potential limits based on possible corrective measures. Likewise, no one has attempted to monitor all sources of radiation damage simultaneously i.e. n and γ in this case. Thus, the advantage of this work over others at this conference[4] is that it provides a more practical working test for NLC magnets in the SLC working environment so that it can be scaled to NLC and also provide guidance for the NLC design. In this respect, it is different but complementary and is, we believe, necessary because it uses real PM magnets with their range of load lines in a mixed, broad band radiation field that is impossible to simulate without artificial assumptions that make calculations practicable.

EXPECTED RADIATION DOSES

In electron and positron accelerators, damage depends on the materials, the location and the beam energy. At < 10 MeV or so, the damage comes predominantly from ionization and atomic excitation regardless of whether the beams are leptons or hadrons[4]. This is true when lepton energies $E^{\pm} < E_c$ – the critical energy for the material. In high energy lepton rings, radiative effects dominate. These come from synchrotron radiation, bremsstrahlung and bremsstrahlung produced photoneutrons via the (γ,n) giant resonances that typically occur above E_γ>10 MeV for any element. Analogously, hadronic resonances occur for E_γ>200 MeV. The main questions, of course, are what are the most damaging sources, where do they come from and how to eliminate them. Ref. [4] reviews the situation and shows that dose measurements alone do not determine RD. The difficulties of measuring neutrons makes it easy to ignore this source even though orders of magnitude more damaging per gray than electrons or photons.

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DOSIMETERS

One needs only to look at a neutron damage vs neutron energy plot[5] to appreciate the difficulty of such measurements and why the convention of referencing damage to 1 MeV equivalent energy has gained general acceptance. Nonetheless, the same inspection shows why it is highly desirable to obtain spectral data to determine the source and its correction. This is difficult and seldom done. Even in the case of PM studies, it is rarely done except in the form of a post-mortem activation analysis[1]. Similarly, thermal neutron studies have not been done even though B, Co, Nd and Sm have isotopes with large capture cross sections. Various techniques have been used - especially on the assumption that photons are the primary damage source. From this line of reasoning, one eliminates the need for neutron or electron beam loss measurements since the photons are "collimated" around the beam direction. Optical absorption dosimeters are then a common choice based on color changes that do not distinguish between γs or neutrons. While these can cover ranges up to 30 kGy(Si), their neutron responses are typically 50 % of their photon response[6] so they are not interesting for our use. Semiconductor devices are enjoying increased use since they are compact and easily read out and because there is a correlation between RD in semiconductor devices and the displacement damage in bulk silicon. Thus, devices such as bipolar transistors and PIN diodes whose operation depends on volume mechanisms can be expected to provide measures of neutron flux while ones such as MOSFETs that are governed by surface effects should be more sensitive to ionizing radiation e.g. gain degradation in either case. One expects the MOSFET to be the more sensitive[5] and less temperature dependent.

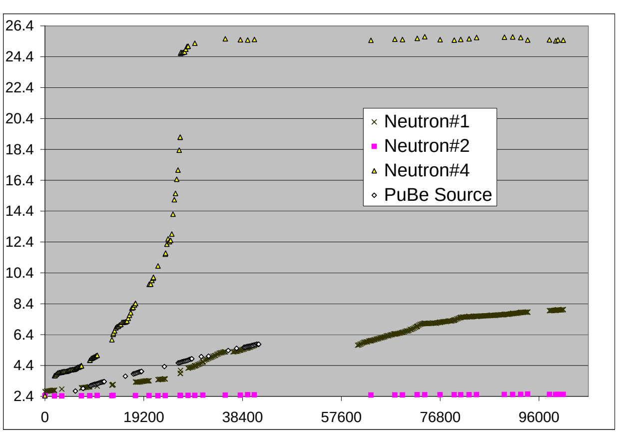

Figure 1: Some measurements of neutron dose in the SLC electron DR in terms of PIN voltage vs time in minutes.

One of many PIN diode[7] data samples at locations around the ring is shown in Fig. 1. Concurrent data for γ's was taken at these same locations with MOSFETs[7]. Fig. 2 shows the relative sensitivity of such detectors for the PuBe source of fast neutrons with $I_n/I_\gamma > 4$ located outside of the DR vault. Gaps in the data indicate beam turn-off or loss of readout hardware.

RADIATION MEASUREMENTS

The variations in Fig. 1 run from no observable damage at levels of 1 mGy up to saturation at $\sim$4 kGy or 25 Volts. The origin shows the values before beam turn-on with all detectors at 2.25 $\pm$ 0.02 V. The sensor varying linearly is the PuBe source. Detector N#4 was on top of a 1-in beam pipe downstream of the first dipole B560 after the extraction septum and in front of sextupole SF608. N#1 was at the exit crotch of the septum and N#2 was > 2 m above this area. There is a small rise during turn-on and tune-up with the abrupt rise to saturation on N#4 over $\sim$2 weeks indicating an average neutron dose rate of >10 Gy/hr.

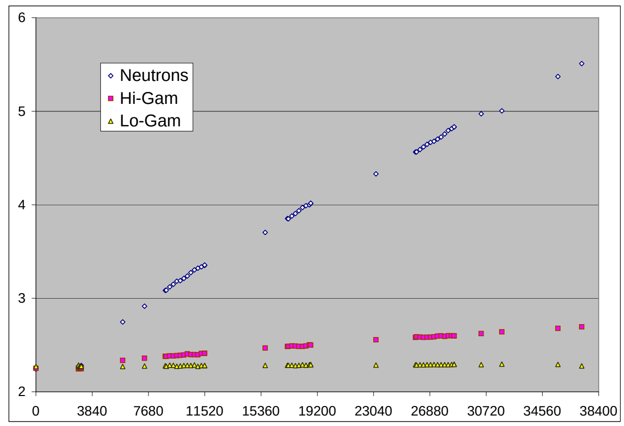

Figure 2: Simultaneous PIN & MOSFET measurements corresponding to the PuBe source data shown in Fig. 1.

High and low sensitivity γ sensors allow measurements up to $\sim$1 kGy and $\sim$30 kGy in Fig. 2. All sensors are nonlinear. The Hi Gam sensor is somewhat sensitive to neutrons and needs correction for optimal accuracy while the PIN sensor is more temperature sensitive. Both types need to have additional temperature readouts or corrections made. N#4 saturated well before Lo-Gam#4 and after Hi-Gam#4 indicating the sextupoles see significant, relative fast neutron flux.

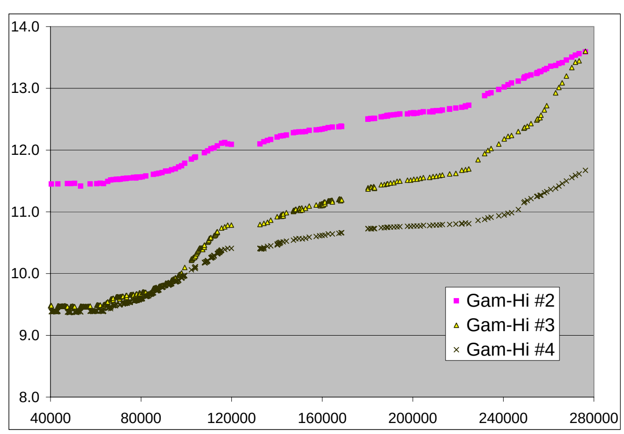

Figure 3: MOSFET data during the latest run cycle

Beam turn-on after unscheduled shutdowns often show significantly higher dose/damage rates in contrast to those that are well done as shown by the flat lines in Fig's. 3-4 where the first large gap defines the Christmas shutdown.

However, unscheduled outages that cause loss of beam and subsequent turn-on problems are not the worst cause of RD. From 1997-2001 there were 18 such failures per DR due to conventional magnet systems with a mean time to repair of $\sim$14 hours. These are hardly visible. Of more interest, are the two regions with steep slopes that lasted for 2 and 3 weeks. In the first, there were vacuum and septa problems, thunder related power outages and a push to obtain luminosity. The second was due to a water leak with one DR quad spraying another. Because this did *not* turn beams off it took nearly 3 weeks to diagnose and caused far worse RD. The only sensor changes between Fig's. 1,2 and 3,4 were #3 & #4 on the side and top of the newly replaced SD708. The Gam-Hi sensors at 5 cm and 2 m above the beam pipe track quite closely in Fig. 3.

MAGNETIC MEASUREMENTS

Following 2, 8[1] and 17 years of operation in the SLC DRs we have observed, within $\pm$0.25 %, a loss of sextupole strength of 0, 2.5 and 6.3 % respectively on single magnets selected at random. All harmonics through the first 16 were originally required to be $<$ 1 % and typically $<$ 0.5 %[3]. In those we remeasured, ignoring first order feeddown, we found no magnet with harmonics worse than $\sim$1.7 %[1].

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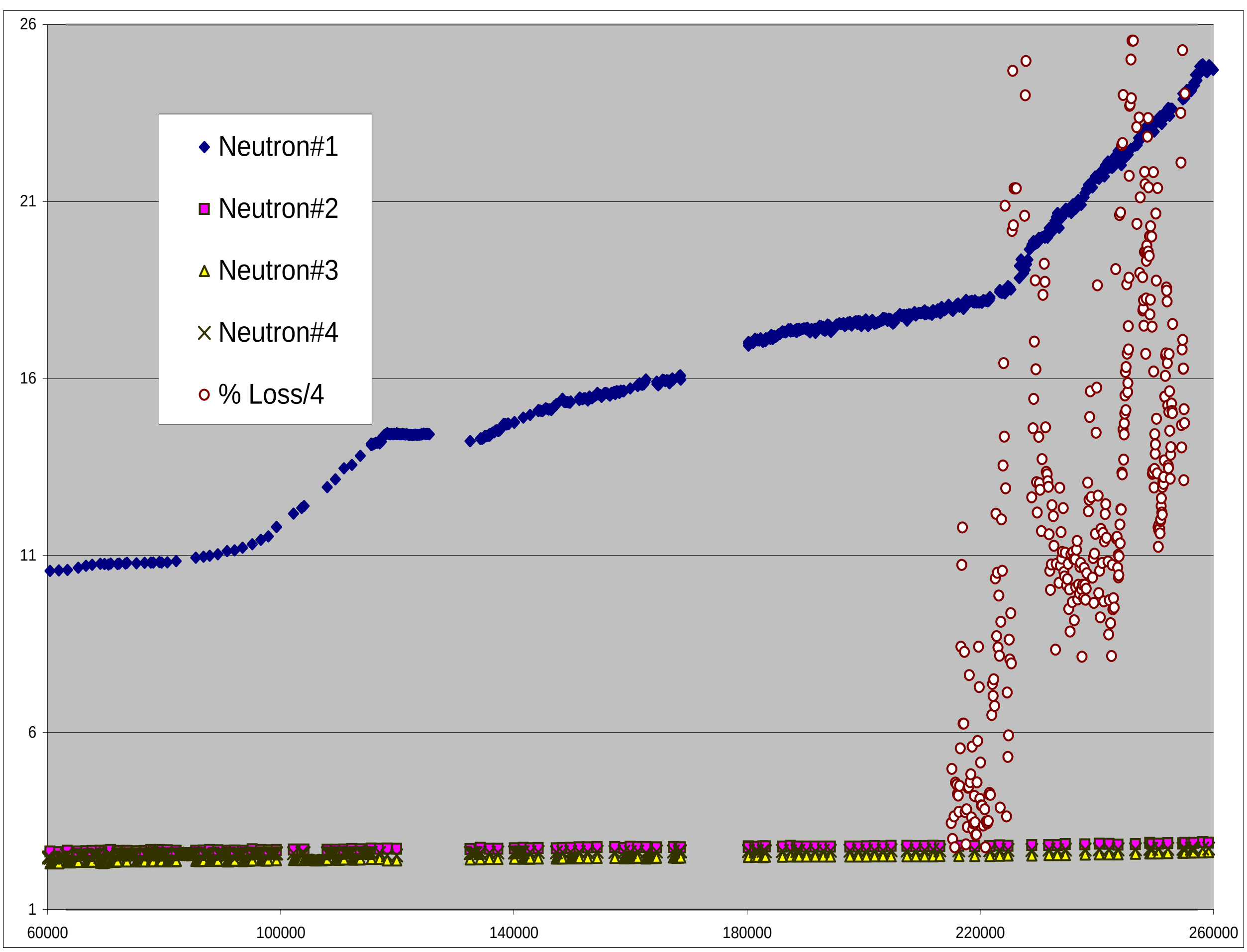

Figure 4: PIN data for Fig. 3 with correlated beam current loss (injected - extracted). Best efficiency was 90 %.