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Estimate of Undulator Magnet Damage Due to Beam Finder Wire Measurements *

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Beam Finder Wire (BFW) devices will be installed at each break in the Undulator magnet line. These devices will scan small wires across the beam causing some electrons to lose energy through bremsstrahlung. The degraded electrons are subsequently detected downstream of a set of vertical dipole magnets after they pass through the vacuum chamber. This signal can then be used to accurately determine the beam position with respect to the BFW wire. The choice of the wire diameter, scan speed, and operating parameters, depends on the trade-off between the signal size and the radiation damage to the undulator magnets. In this note I estimate the rate of undulator magnet damage that results from scanning as a function of, wire size, scan speed, and average beam current. A separate analysis of the signal size was carried out by Wu [1].

The damage estimate is primarily based on two sources: the first, Fasso [2], is used to estimate the amount of radiation generated and then absorbed by the magnets; the second, Alderman *et. al.* [3], is used to estimate the amount of damage the magnet undergoes as a result of the absorbed radiation.

Fasso performed a detailed calculation of the radiation, including neutron fluence, that results from a the electron beam passing through a 100 micron diamond foil inserted just in front of the undulator line. Fasso discussed the signficance of various types of radiation and stated that photoneutrons probably play a major role. The estimate in this paper assumes the neutron fluence is the only significant cause of radiation-induced demagnetization.

The specific results I use from Fasso's paper are reproduced here in Figure 1, which shows the radial distribution of the integrated neutron fluence per day in the undulator magnets, and Figure 2, which shows the absorbed radiation dose all along the undulator line.

In the longitudinal dimension, Fasso's calculation, (see Figure 2), shows that the radiation dose is widely distributed all along the undulator line, but is highest around 70 m from the front of the undulator line where the foil is. At the 70 m point, for the purpose of calculating the demagnetization, I chose

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Table 1: Results from Alderman *et. al* showing demagnetization caused by fast neutron irradiation.

Total Fast-Neutron Fluence (n/cm^2)	Change in Intrinsic Remnant Induction	
	Irradiated Sample Magnets	Control Magnets
9.86×10^5	0.321%	0.228%
9.88×10^7	0.104%	0.042%
9.99×10^9	0.125%	0.062%
1.09×10^{12}	0.031%	0.083%
1.83×10^{12}	0.094%	0.146%
2.33×10^{13}	0.590%	0.000%
4.07×10^{13}	0.761%	0.021%
1.61×10^{14}	16.172%	0.042%

a conservative estimate for the effective neutron flux of 1.0×10^{13} n/cm^2/day. As can be seen in Figure 1, this choice is representative of the flux nearest the beam where it is the highest. A less conservative estimate, but perhaps more accurate, estimate of the effective flux, would be the average flux in the magnet block, which is roughly one half as much.

In Fasso's calculation the electron current was assumed to be 9.16×10^{11} electrons s^{-1}, which is equivalent to 7.91×10^{16} electrons in one day. So, in terms of effective neutron fluence, we have,

$$\text{nuetron fluence} = 10^{13}\ n\ cm^{-2} \text{ for } 7.91 \times 10^{16} \text{ electrons}$$

Alderman *et. al.* studied demagnetization damage caused by energetic neutrons. Table 1, which is taken from their paper, shows their results. I linearly scaled the measured damage from the highest irradiation point to get approximately

$$\begin{aligned} 1\% \text{ damage } &\approx 10^{13}\ n\ cm^{-2} \text{ or} \\ 0.01\% \text{ damage } &\approx 10^{11}\ n\ cm^{-2} \end{aligned}$$

Damage is expressed in percentage of magnetization loss.

Fasso's calculation is based on a uniform thickness foil, assumed to be large compared to the beam size. To estimate the radiation produced by a single wire in the beam I define $f(x, y)$ [electrons cm^{-2} $shot^{-1}$] as the electron fluence per shot incident on the wire. Scaling from the Fasso result, the neutron fluence on the magnets per shot is,

$$\text{neutron fluence } [n\ cm^{-2}\ shot^{-1}] = \frac{10^{13}\ n\ cm^{-2}}{7.91 \times 10^{16} \text{ electrons}} \times \frac{\delta[\mu m]}{100} \times \int_{\text{wire}} f(x, y) dx dy$$

where, for simplicity, the wire is assumed to be square with width δ. Assuming the wire is stretched in the $\pm y$ direction, taking the integral over the x coordinate gives approximately,

$$\int_{\text{wire}} f(x, y) dx dy \approx \delta \int f(x, y) dy$$

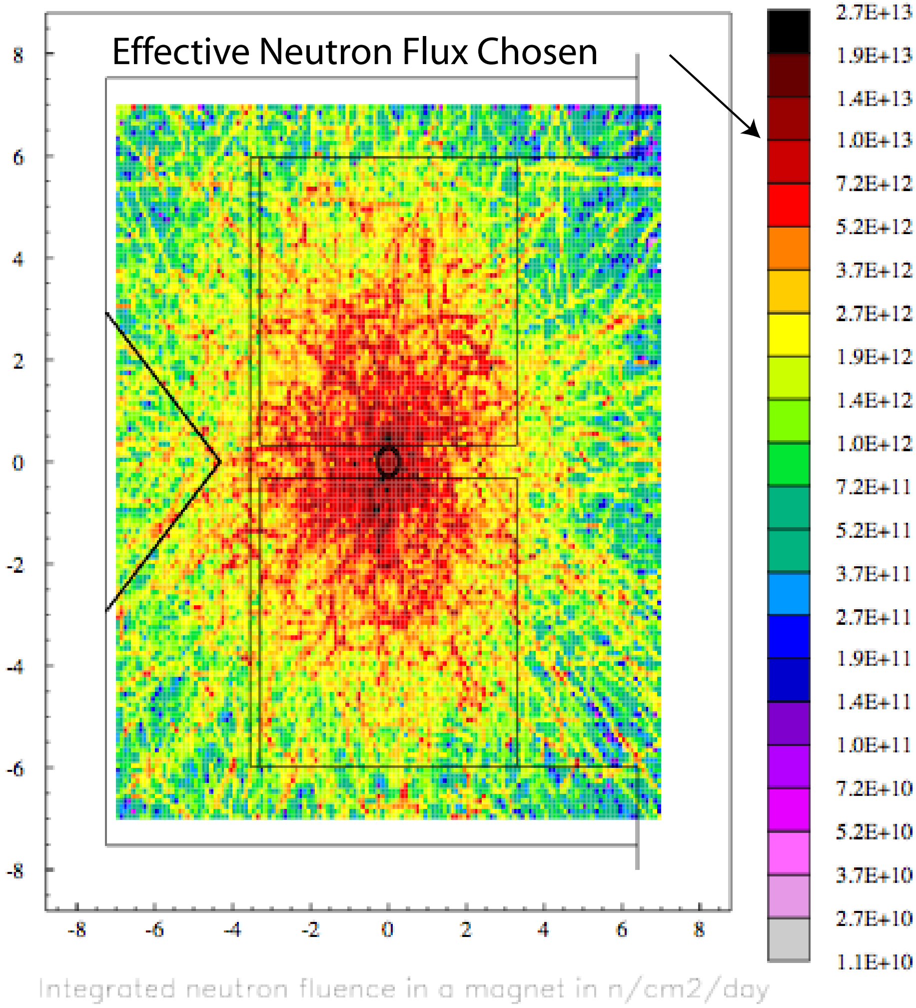

Figure 1: Neutron per day per cm^2 that are absorbed in the maximally exposed magnet for an constant incident beam of 9.16×10^{11} electrons per second on a 100 μm diamond foil.

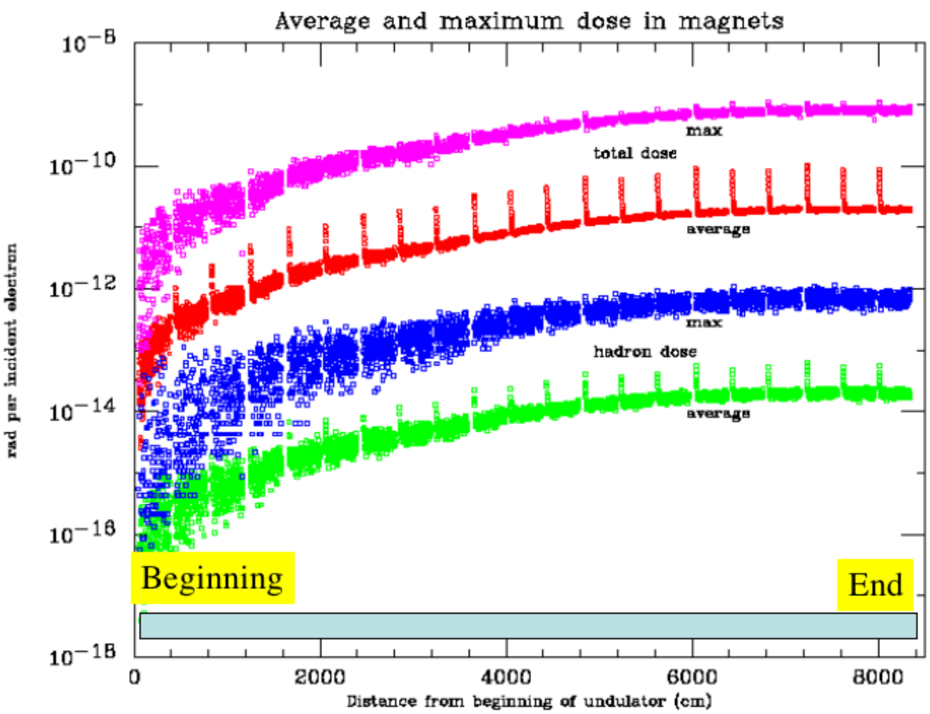

Figure 2: Hadron and total dose, both maximum and averaged over the magnet blocks, are plotted as a function of the distance along the undulator. The undulator is actually 131 m long but memory limitations curtailed the model. Nevertheless, the dose maximum is reached before the end of the undulator.

where x should be understood to be the position of the wire and it is assumed the wire size δ is much less than the beam size.

This expression for the neutron fluence per shot is the fluence produced by the wire at an arbitrary position with respect to the beam. The fluence per scan is the sum of the fluences from individual shots. That is,

$$\text{neutron fluence per scan} = \frac{10^{13}\ n\ cm^{-2}}{7.91 \times 10^{16}\ \text{electrons}} \times \frac{\delta[\mu m]}{100} \times \sum_{i=1}^{N} \delta \int f(x_i, y) dy$$

where x_i is the position of the wire at the ith scan point and N is the total number of scan points.

Assuming the scanned points are uniformly spaced with spacing Δx, then,

$$\sum_{i=1}^{N} \int f(x_i, y) dy = \frac{1}{\Delta x} \sum_{i=1}^{N} \int f(x_i, y) \Delta x dy \approx \frac{1}{\Delta x} \int \int f(x, y) dx dy = \frac{1}{\Delta x} \frac{Q}{e}$$

where Q is the charge per bunch and the e is the electron charge. In converting the sum to an integral I implicitly assumed that Δx is much smaller than the beam size.

Therefore the net neutron fluence per scan is

$$\text{neutron fluence per scan } [n\ cm^{-2}\ \text{scan}^{-1}] = \frac{10^{13}\ n\ cm^{-2}}{7.91 \times 10^{16}\ \text{electrons}} \times \frac{\delta[\mu m]}{100} \times \frac{\delta}{\Delta x} \times \frac{Q}{e}$$

Note that there is no dependence on the beamsize. For a fixed Δx (small compared with the beamsize), the damage should be independent of the beam size. A larger beam takes more steps to go through but has a lower density and the two effects cancel.

Putting the neutron fluence result, the averaging effect of the scan, and the Alderman result together, the damage per scan is

$$\text{Damage/Scan} = \frac{0.01\%}{10^{11} n/cm^2} \times \frac{10^{13} n/cm^2}{7.91 \times 10^{16}\ \text{electrons}} \times \frac{\delta[\mu m]}{100} \times \frac{\delta}{\Delta x} \times \frac{Q}{e}$$

This can be written in a more convenient form for scaling as:

$$\text{Damage/Scan} \approx 0.01\% \times 10^{-7} \times \frac{\delta^2[\mu m]}{\Delta x[\mu m]} \times Q[nC]$$

Given the assumptions made above, the magnet damage per scan depends only on the size of the wire δ, how far the wire is moved between shots Δx, and the charge per shot Q.

Examples

Normally the entire Undulator beamline would be measured in one session using all of the BFWs. This involves 33×2 scans because there are 33 BFWs and the

Table 2: Various conditions that would cause 0.01% damage to the undulator, as a function of the BFW wire diameter, step size and charge per shot.

Total Number	Rate [day^{-1}]	Fault time [min]	Diameter [μm]	Scan step size [μm]	Charge [nC]
15000	1.5	7	10	20	1.0
3800	0.4	2	20	20	1.0
1700	0.2	1	30	20	1.0
950	0.1	0.5	40	20	1.0
600	0.06	0.3	50	20	1.0

scans are in both the x and y directions. Explicitly, the damage per undulator line measurement is,

$$\text{Damage per measurement} \approx \frac{1}{2} \times 33 \times 2 \times 0.01\% \times 10^{-7} \times \frac{\delta^2[\mu m]}{\Delta x[\mu m]} \times Q[nC]$$

The factor 1/2 takes into account the fact that BFWs at the end of the undulator should not do much damage while those at the beginning should maximize the damage.

Table 2 shows how many full undulator line measurements would result in 0.01% magnet damage for various carbon wire sizes. The column, 'Measurement rate' is just the maximum number of measurements divided by the number of days in 30 years (the planned facility lifetime), assuming 365 days per year.

The 'Fault time' is the amount of time that it would take for the damage to reach 0.01%, if one wire was inadvertently left near the middle of the beam while the beam was running at 120 Hz. It is scaled from the maximum number of scans, and is based on the simple assumption that during a normal scan the wire is in the core of the beam $2\sigma/\Delta x$ times. Clearly we must insure that the BFWs are not accidentally left in the beam. This is especially critical for the larger wires listed where the fault times are less than 1 minute.

In Table 2 the scan step size is set at 20 μm. This is sufficiently small that about three measurements will be made within $\pm\sigma$ of the beam center, where $\sigma \approx 35$ μm. The approximation that the wire size is small compared with the beam size is not accurate for the larger wire sized listed in the table. However, the error is not significant compared with the uncertainty in the damage response of the magnets to radiation.

Recommendation

If the wire size is 50 μm then we can expect to start to see appreciable magnet damage after 600 measurements, or about once every two weeks. Because the damage response of the magnets is uncertain, (perhaps by as much as a factor of ten) wires of 50 μm or larger are not recommended.

Wire sizes of 30 μm or less would allow for a measurement once a week or more often and have a reasonable margin to account for the uncertainty in damage response. These are preferred.

References

[1] J. Wu, P. Emma, and R.C. Field *Preliminary Study on Electron Signal Detection for the Beam Binder Wire of the LCLS Undulator*, LCLS-TN-06-07

[2] A. Fasso, *Dose Absorbed in LCLS Undulator Magnets, I. Effect of a 100 μm Diamond Profile Monitor*, RP-05-05, May 2005.

[3] J. Alderman, *et. al.*, *Radiation Induced Demagnetization of Nd-Fe-B Permanent Magnets*, Advance Photon Source Report LS-290 (2001)