Permanent Magnet Radiation Resistance in the SNS Linac

Robert Hardekopf
Los Alamos National Laboratory

1. Introduction

Los Alamos plans to use rare-earth permanent magnet material for focusing in the SNS drift-tube linac, which accelerates a high-intensity beam up to 86 MeV. The longevity of this material has been questioned based on degradation seen at Fermilab in permanent-magnet lattices. The Fermilab results, most recently published by J. Volk et al. [1], include both temperature and radiation effects. However, the Fermilab magnets use a strontium-ferrite material, which has different properties than the rare-earth material planned for SNS. A review of the literature [2] plus discussions with authors at Los Alamos and Fermilab [1-3] have confirmed that the rare-earth materials are far more resistant to radiation damage. Just how resistant, and whether we should expect any problems in the SNS application, are the subjects of this note.

2. Rare-Earth Magnet Material Irradiation Data

Data from Los Alamos showed SmCo (samarium-cobalt) rare-earth magnets to have much better radiation resistance than NdFeB (neodymium-iron-boron) [2]. The following figure shows a magnetization loss of less than 2% from neutron fluence of greater than 1E^15 n/cm^2 for the better SmCo material

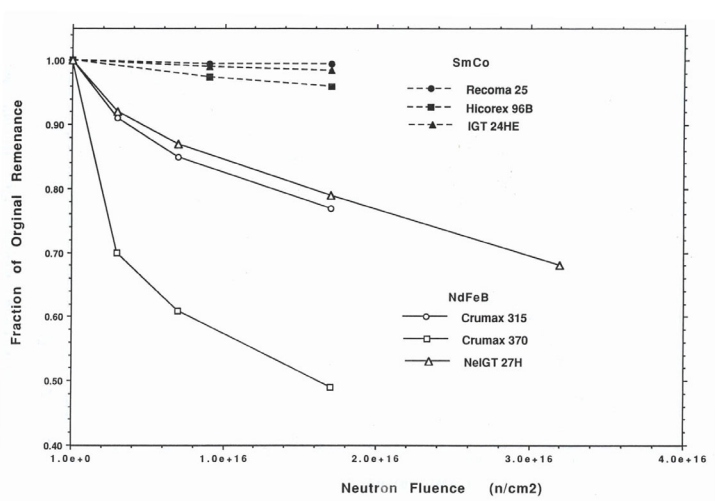

Figure 1. Irradiation results of SmCo (top) and NdFeB (bottom) rare-earth permanent magnet material.

More recent Los Alamos data from a 1997 LDRD (Laboratory-Directed R&D) experiment shows even higher radiation resistance for SmCo (2-17) material, which is being used in the SNS drift-tube linac. Several commercially available SmCo (2-17) materials withstood neutron fluence of over 1E^18 n/cm^2 with less than 0.5% change in magnetization, within the errors of the measurement, as shown below [3].

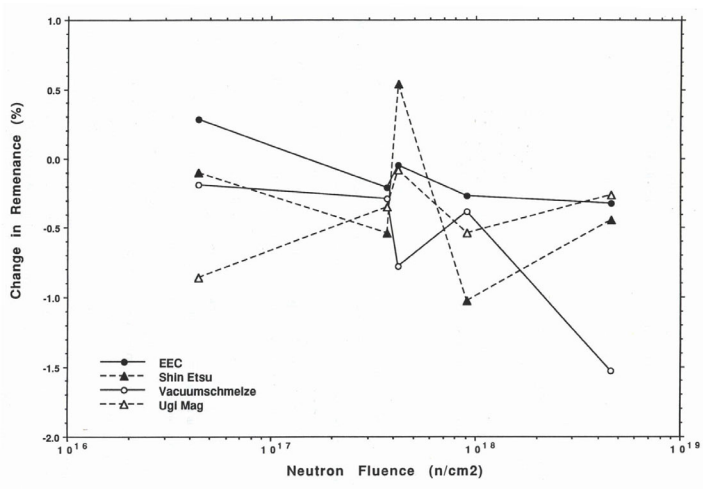

Figure 2. Irradiation results for SmCo (2-17) rare-earth magnet material taken in 1997. The vertical axis is from +1% to –2% change in remenance, and the horizontal axis is from 1E^16 to 1E^19 n/cm^2 fluence. The error bars on the individual measurements are about 0.4%.

These data were taken with neutron irradiation, using a broad spectrum of neutrons produced at the LANSCE proton linac beam stop. It is believed that high-energy particle irradiation, e.g., neutrons or protons, causes a loss of magnetization through a mechanism where a single high-energy particle interaction can cause an entire magnetic domain, containing several million atoms, to reverse its direction of magnetization. Gamma and x-ray radiation is much less likely to cause loss of magnetization [2,3].

3. Beam Loss Specifications for the SNS Linac

The specification for beam loss in the SNS linac is <1 Watt/m on average, although local activation may be 10-100 times larger as shown, for example in the following figure. This was taken from the paper *Beam Loss and Activation at LANSCE and SNS* [4]. Although these data are from residual radiation levels of the coupled-cavity linac just downstream of a high-loss transition region, they illustrate that losses from mismatch can be far from uniform. On the other hand, with the careful matching designed for the SNS

linac, the primary loss mechanism is expected to be stripping of the H- beam from residual gas, which produces a uniform loss [4].

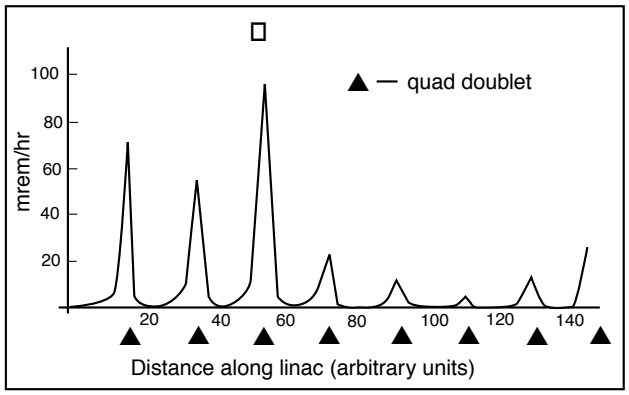

Figure 3. Relative losses along the LANSCE coupled-cavity linac, showing peaking of the losses near quadrupole magnets as result of a mismatched beam [4].

At ~100 MeV, a 1-Watt loss would correspond to a proton loss of 10 nA, or 6E^10 protons/sec. The following figure shows neutron production as a function of proton energy for copper or iron [4].

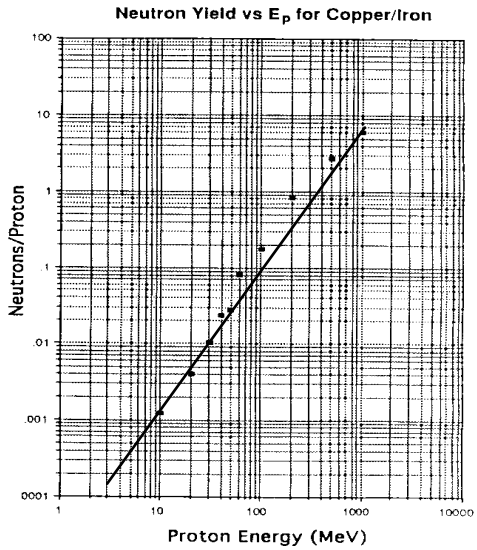

Figure 4. Neutrons per proton from spallation reactions on copper or iron as a function of energy.

At the maximum DTL energy of about 86 MeV; the number of neutrons per proton is about 0.1; therefore a 1-Watt loss would correspond to about 6E^9 neutrons/sec. A continuous loss for one year (~3E^7 sec) at this location would therefore yield about 2E^17 neutrons.

4. Localization of Beam Loss in the SNS Drift-Tube Linac

The following is a partial schematic of one of the drift tubes in tank 6 of the DTL, where the beam energy is increased to 86 MeV.

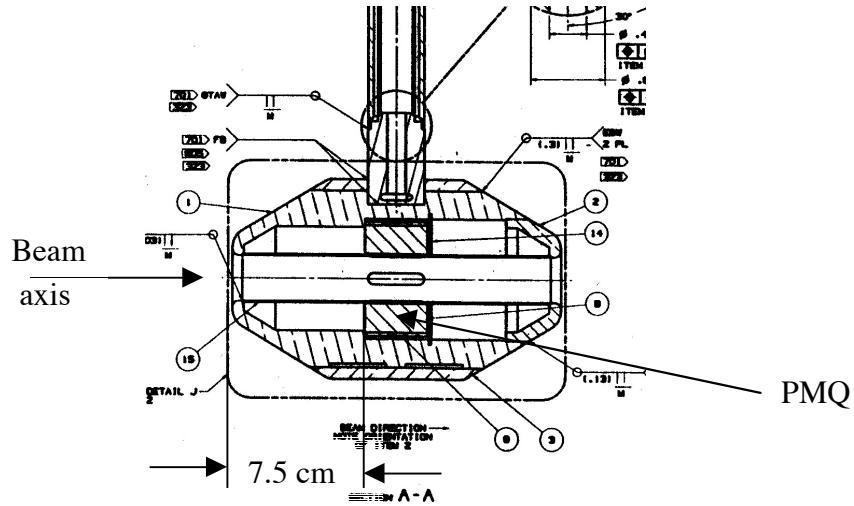

Figure 5. Schematic of a drift tube in DTL tank 6.

The loss budget of 1 Watt/m for the SNS linac is based on radiation levels measured after shutdown at a distance of about 30 cm (1 ft) from the beam line [4]. The activation produced at that location is the same whether the beam is lost at a single point, as might occur from a mis-steered or mis-focused beam, or continuously along the beam path, as would occur from gas stripping. This is because the radiation from a point source, which falls off as 1/r^2, and that from a line source, which falls off as 1/r, are the same at this distance (~1/π-m) from the axis [5]. However, a permanent magnet quadrupole is much closer to the beam. Therefore, for a conservative estimate we will assume that all losses within a 1-m length are concentrated at a single drift tube.

One could imagine an even worse condition where several meters of losses are concentrated at a single drift tube, but the installed radiation loss detectors and the machine protection system will be set to inhibit the beam for localized losses much in excess of 1 Watt/m [6]. From the figure below, at 86 MeV the radiation level just outside of the DTL tank would be about 10 Rad/hr. Since the loss monitors along the linac will be mounted near the tunnel walls, they will have to be set below this level for sustained operation. There will be two loss monitors per DTL tank, one near the middle and the other near the end of each tank. The loss monitors will produce a signal of ~70 nC/Rad, and with gating and averaging they should be able to measure down to ~1% of the prompt losses expected at 1 Watt/m [7]. Thus, losses in the DTL can be monitored to less than the 1 Watt/m level.

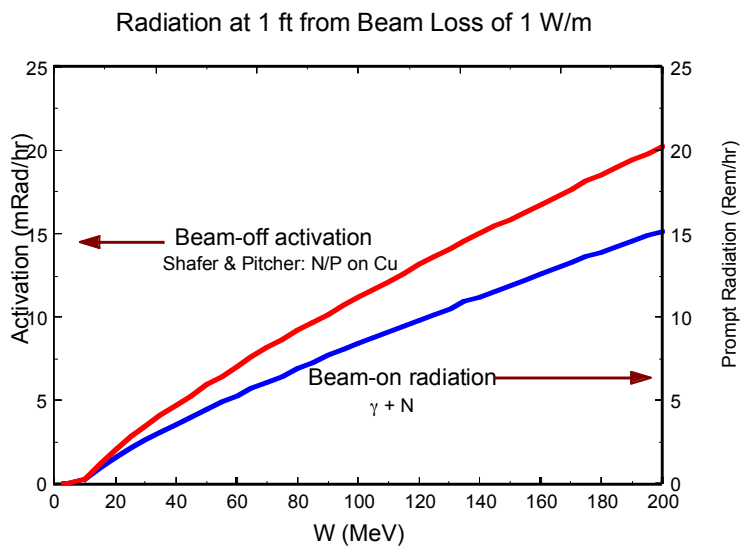

Figure 6. Radiation (right-hand scale) near the linac with maximum allowable beam loss of 1 W/m as a function of energy [5].

5. Lifetime Neutron Fluence in the DTL Magnets

Assuming that the neutrons are produced isotropically at the nose of a drift tube, the neutrons passing through a 1-cm^2 area of permanent magnet material (located 7.5 cm from the front face of the highest-energy drift tube) would be 2E^17/4π(7.5)^2 = 3E^14 neutrons/cm^2 per year. This would give a total fluence of about 1E^16 neutrons/cm^2 in 40 years of continuous operation. With these assumptions, the worst-case neutron irradiation of the DTL permanent-magnet material should produce no noticeable effect.

6. Proton Irradiation of the DTL Magnets

However, at the highest DTL energy, the protons could penetrate the thin copper walls of the drift tube. The following graph shows that the range of 86-MeV protons in copper is about 10 mm, while the nose of the drift tube, shown in Fig. 5, is about 6-mm (0.25-inch) thick.

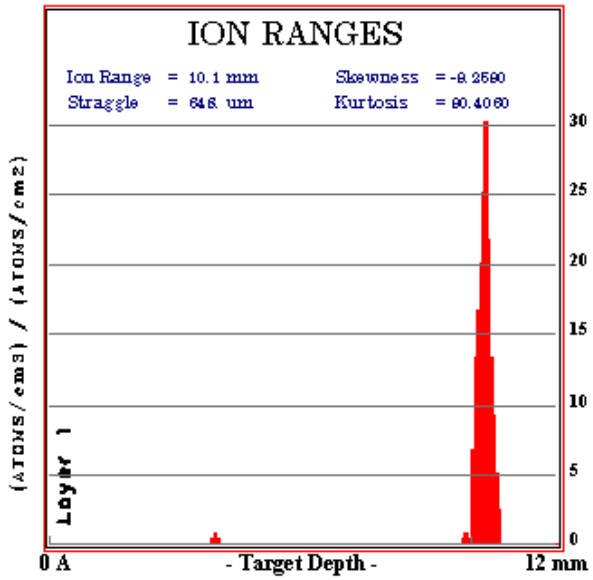

Figure 7. Range of 86-MeV protons in copper [5].

Therefore 86-MeV protons that hit the nose of a drift tube could penetrate the copper and impinge on the magnet, presenting an additional damage mechanism from direct proton irradiation of the material. A metal shield about 4-mm thick placed inside the drift tube in front of the magnet would be feasible [8], and this may be desirable in DTL tanks 4 through 6. In DTL tank 3 and before, the energy of the particles (<50 MeV) is low enough that the copper nose would not be penetrated.

6. Conclusion

This analysis shows that using reasonable assumptions about beam loss in the SNS Drift-Tube Linac, neutron irradiation of the SmCo(2-17) permanent magnet quadrupoles in the drift tubes should not cause significant loss of magnetization over the 40-year lifetime of the SNS. However, penetration of protons into the drift-tube bodies is possible for the three higher-energy DTL tanks, and stopping these protons in the magnet material should be avoided. A few-mm-thick copper or stainless-steel shield on the upstream face of the magnets may be advisable for this purpose.

8. References

[1] J. Volk, B. Brown, G. Foster, W. Fowler, H. Glass, G. Jackson, *Time Evolution of Fields of Strontium Ferrite Permanent Magnets,* PAC2001 (to be published).

[2] See, for example, R. H. Kraus, *Permanent-Magnet Material Applications in Particle Accelerators,* International Workshop on RE Magnets & Their Applications, 637; and R. H Kraus, in *Permanent Magnets and Their Applications,* S. G. Sankar, Ed., World Scientific Publishing.

[3] D. Barlow, R. Kraus, M. Borden, *Radiation Hardness Measurements of New Permanent Magnet Materials for High-Intensity Linac Applications,* Los Alamos National laboratory report LA-UR-97-3370.

[4] R. Hardekopf, *Beam Loss and Activation at LANSCE and SNS,* Proc. of the 7th ICFA Workshop on High-Intensity High Brightness Hadron Beams, Lake Geneva, WI, Sept. 1999, 62.

[5] R. Shafer, private communication.

[6] J. Stovall, private communication

[7] R. Witkover, private communication

[8] R. Martineau, private communication.