Radiation Limits for CBETA Halbach Magnets

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1. Introduction

The radiation damage calculation proceeds via several stages to get from energy lost by the beam to the field degradation from radiation damage:

- Beam energy lost → Specific radiation dose. This just divides the absorbed energy by the mass it was deposited in to convert from J to Gy=J/kg, or rad=0.01Gy.
- Specific radiation dose → Magnetisation loss. This depends on the permanent magnet material grade as well as the magnetisation geometry (the "H" field). Magnetisation loss rates have been studied in the literature and this note will follow the formula in [1].
- Magnetisation loss → Field change in beam aperture. For uniform magnetisation loss, this is simply proportional (1% less magnetisation = 1% less field). For nonuniform demagnetisation, nonlinear fields errors are also introduced.

As the magnetic material has mu_r ~= 1, in this note the H and M fields will be scaled by mu_0 to put them in units of Tesla, which allows easy comparison with B fields and the residual field Br.

2. Beam energy lost → Specific radiation dose

This calculation only requires the mass of the piece of magnet in question. A typical whole magnet (QF) has 5.14kg of NdFeB material, so 1kJ of energy absorbed by that magnet would be 1kJ/5.14kg = 195Gy = 19.5krad dose averaged over the material. The mass of single column of two blocks in a magnet is for example 321 grams in the case of the largest blocks of the BD magnet.

Note that beam energy lost does not necessarily equal energy absorbed by the magnets if absorption of electrons by the beam pipe is taken into account. Until simulations of this are available, the pessimistic approach is to assume that all energy lost by the beam is absorbed by the permanent magnets. In which case the 1kJ loss above would be 6.67uC of charge at 150MeV, or 1nA loss for 1 hour 51 minutes, in a single magnet. Larger total losses could be allowed if distributed between all ~200 magnets.

3. Specific radiation dose → Magnetisation loss

Temnykh's data in [1] agrees with the model that the dose for a 1% demagnetisation has the following formula (eqn. (12) in [1]):

Dose_1% = 10^m0 * 10^(T_demag/Tbar)

Here, **m0=-2.68** is a fit constant to the data.

T_demag is the "demagnetising temperature" of the material sample, basically the Curie temperature, which depends on how the material B-H curve changes and when the demagnetising part of the curve hits the "working point", which is determined by the local "H" field, which is determined by the material shape. So, both the material grade and geometry affect T_demag. Note that T_demag is in degC and assumes some "room" temperature: around 30C for the study in [1], which is also correct for CBETA.

Tbar=41.4K is another fit constant that shows the change in Curie temperature that causes a 10x decrease in radiation damage levels for neodymium material. This produces an exponential dependence of radiation damage rate with T_demag, so the exact material grade chosen and "H" field present is important.

For CBETA's material grade N35EH, the stated T_demag measured by the vendor is 200C. This is measured in a square sample, in which H=-0.67T. Simulations show that the largest negative H field in corners of the Halbach magnet is H=-1.3T. The change in the demagnetising H level per Kelvin is 11.9mT/K based on B-H curves measured at different temperatures. Extrapolating T_demag to the worst location in the Halbach magnet gives **T_demag** = 200C + (-1.3-(-0.67))/(11.9e-3) **= 147C**.

Plugging these values into Temnykh's formula gives Dose_1% = 74kGy (7.4Mrad). Or alternatively a 0.0134% magnetisation loss per 1kGy dose.

4. Magnetisation loss → Field change in beam aperture

A uniform irradiation at the 1kGy (100krad) level produces a 0.0134% field loss, which is "1.34 units" in magnet terminology where a unit is 10^{-4} of the main field level. This amount of field loss is basically negligible to the machine, perhaps detectible at the precision level, but can't endanger the running of the machine at all. Non-uniform irradiations of this amount to part of the magnet will still not produce multipoles above 1.34 units.

As an example of non-uniform irradiation, a BD magnet with one large near-midplane segment (out of 16) weakened by 1%, scores 0.258 on the CBETA figure of merit. In this figure of merit, 0.75 is marginally-acceptable as determined from tracking studies by William Lou. This would require 0.321kg * 74kGy = 23.7kJ of energy deposited in that particular segment of the magnet. The uniform example described earlier would require 5.14kg*1kGy = 5.14kJ of energy spread over the whole magnet.

5. Conclusion

Keeping lifetime radiation doses at the magnets below the 1kGy (100krad) level will ensure very safe operation with very small field errors generated. This equates to ~5kJ lost per magnet over its lifetime, or 10 rad/hr at the magnet with 10000 hr machine operational life.

6. References

[1]   *Measurement of NdFeB permanent magnets demagnetization induced by high energy electron radiation*, A.B. Temnykh, NIM A **587** (2008) 13–19.