EVALUATION OF IMMUTABILITY AGAINST RADIATION-INDUCED DEMAGNETIZATION FOR A HYBRID WIGGLER WITH NdFeB MAGNETS AT THE CANADIAN LIGHT SOURCE

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Abstract

The BioXAS beamline at the Canadian Light Source installed a hybrid wiggler in 2013. Quantitative studies building on the experience of other facilities suggest the wiggler's NdFeB magnets are at risk of demagnetization due to radiation induced by the synchrotron's 2.9 GeV electrons [1]. We use a phenomenological model to convert simulated peak demagnetizing fields into a radiation dose corresponding to a chosen %-demagnetization, and compare against an estimated dose per year due to injected beam. We find that injecting with the wiggler closed will cause 1% demagnetization in sections of its magnet blocks within 2 years of operation, assuming a worst case scenario. The wiggler has thus far been opened for injections, but this will cease to be an option when CLS moves to top-up operation. In a related test, qualitative measurements of radiation during injections with the wiggler closed were taken by covering its magnets in Polaroid film. We find that radiation drops significantly when the injection efficiency is well-tuned. Our results suggest the wiggler will not receive damaging levels of radiation at closed gap so long as the injection system remains optimized.

EXPERIMENT

Overview of Theory

The intrinsic coercivity of a magnetic material, H_{CJ}, plays an important role in the design of permanent magnet insertion devices (IDs). The opposing fields within an insertion device create demagnetizing fields, which may cause magnet blocks to lose field strength. One may calculate the demagnetizing fields of an array of magnets, with the intent of designing an ID such that the demagnetizing fields do not exceed the magnets' coercivity. However, as a material's coercivity decreases as temperature increases, there will always be some temperature at which the coercivity drops below the peak demagnetizing field. This so-called demagnetizing temperature is critical for in-vacuum IDs – where magnet blocks are heated for low pressure treatment – but is likewise an important measure of the ID's immutability to radiation damage.

Work at Cornell has developed a phenomenological relation between demagnetizing temperature [ºC] and radiation dose [kGy] causing demagnetization [1]. A separate study, performed at SPring-8, allows for Cornell's method to be extended to different electron energies [2].

In our study, the BioXAS wiggler's radiation immutability is estimated from calculated peak demagnetizing fields and the magnetic material's intrinsic coercivity. The immutability is then compared against an estimate of the expected radiation dose due to injected beam with the wiggler at minimum gap.

Relating Radiation Dose to Demagnetization

From the study at Cornell, we can relate sample demagnetization, dM/M, to accumulated dose D and demagnetizing temperature T_d. For our analysis, we gauge the material's radiation immutability by the dose that results in a given sample demagnetization (e.g. 1%):

$$D = -\frac{dM}{M} D^* 10^{\frac{T_d}{Ŧ}} \quad (1)$$

with experimentally determined constants D* = 2.5 ± 1.4 kGy and Ŧ = 41.4 ± 4.0 °C [1]. The uncertainty in D associated with the experimental uncertainties in D* and Ŧ can be determined via calculus. Taking error in quadrature, we arrive at:

$$\delta D = D\sqrt{\left(\frac{\delta D^*}{D^*}\right)^2 + \left(\frac{\delta Ŧ}{Ŧ^2}\, T_d \ln(10)\right)^2} \quad (2)$$

The accumulated dose corresponding to a certain sample demagnetization is thus exponentially dependent upon demagnetizing temperature (a material property). In Fig. 1 we show a logarithmic plot of the immutability to radiation-induced demagnetization. The relation holds for NdFeB magnets irradiated by 5 GeV electrons (the conditions of the Cornell experiment); unfortunately, the uncertainty scales with both dose and demagnetizing temperature, resulting in large error bars.

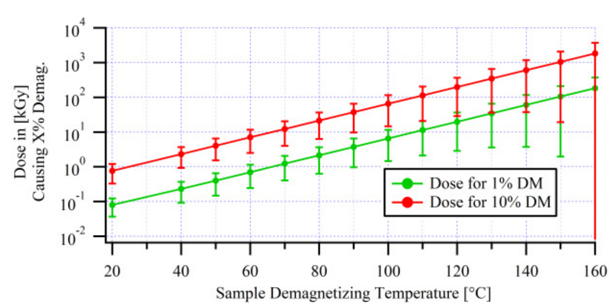

Figure 1: Immutability to radiation-induced demagnetization versus demagnetizing temperature for NdFeB magnets irradiated by 5 GeV electrons; relation developed from work at Cornell.

Experiments elsewhere have demonstrated a relation between radiation damage and electron energy [2], which might be explained by secondary effects such as neutron production from electrons interacting with nearby material (see [3], for example). A study at SPring-8 empirically determined this relation, and showed the following:

$$\Delta\Phi = -0.028 + 0.052e^{-0.366E} \quad (3)$$

where $\Delta\Phi$ is rate of magnetic field loss per 10^{13} electrons and E is beam energy in GeV. With Eq. (3), we may modify the 5 GeV-specific Eq. (1) to the CLS storage ring, which operates at 2.9 GeV. A given dose of 2.9 GeV electrons results in 0.51 as much demagnetization (i.e. roughly half) as the same dose of 5.0 GeV electrons. Hence, knowing demagnetizing temperature, a material's immutability to radiation-induced demagnetization from 2.9 GeV electrons is given by:

$$D_{2.9GeV} \cong 2D_{5.0GeV} = 2|\frac{dM}{M}|D^{*}\, 10^{\frac{T_d}{T}} \quad (4)$$

Calculation of Demagnetizing Fields

In the BioXAS hybrid wiggler, each iron pole is encased by two magnet blocks of different material grades. The magnet blocks are referred to as front or side blocks based on their position with respect to the pole. Material properties for each block type are listed in Table 1, and a single pole module is shown in Fig. 2. The pole is colored grey, front blocks red, and side blocks orange; additionally, narrow 2D planes in green indicate regions of interest, described below.

Table 1: BioXAS Wiggler Block Materials and Properties

Block	VACODYM Material	Room Temp. H_{CJ} (kOe)	Temp. Coeff. H_{CJ} (%°C^{-1})
Front	872 TP	28	-0.53
Side	776 TP	21	-0.61

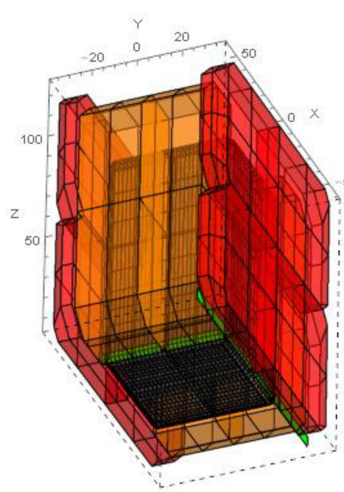

Figure 2: BioXAS wiggler module with materials color coded and green planes indicating regions of interest.

We model the wiggler using the magnetostatics code RADIA [3]. Only a few periods of the wiggler are modelled, so that magnet subdivisions can be increased without large demands on computer memory and computation time. The DMF are calculated across 2D planes spanning each magnet block face nearest the pole.

The DMF are strongest for small z, which is to say the vertical region nearest the air gap between the upper and lower magnet arrays. In Fig. 2, these regions are indicated by green planes for each magnet block type. We show the DMF across these regions for the front and side magnet blocks in Fig. 3 and Fig. 4, respectively. Demagnetizing fields peaks at -23.0 kOe for the front magnet blocks and -18.3 kOe for the side blocks.

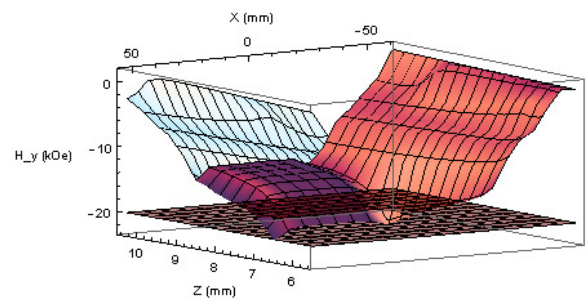

Figure 3: Demagnetizing field H_Y for wiggler front magnet blocks across region of interest, with red plane showing -20 kOe (arbitrary) threshold.

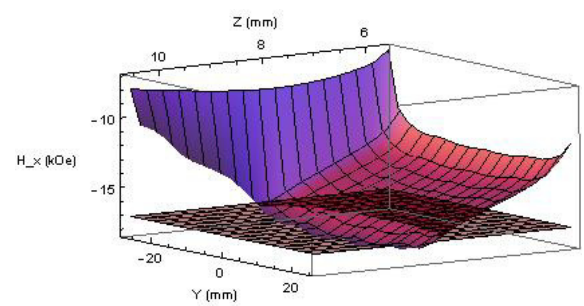

Figure 4: Demagnetizing field H_Y for wiggler side magnet blocks across region of interest, with red plane showing -18 kOe (arbitrary) threshold.

Calculation of Demagnetizing Temperature and Immutability against Demagnetization

Given peak DMF, room temperature H_{CJ} and its temperature coefficient $TC(H_{CJ})$, it is straightforward to calculate demagnetizing temperature, T_d. We first determine the magnet's intrinsic coercivity at operating temperature:

$$OpTempH_{CJ} = \frac{RoomTempH_{CJ}}{1+|TC(H_{CJ})|\times\frac{(T_{Op}-T_{Room})}{100}} \quad (5)$$

For example, from Table 1 the front magnets have a room temperature intrinsic coercivity of 28 kOe. Operating temperature in the CLS storage ring is 27 °C, which

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reduces H_{CJ} to 27 kOe. The demagnetizing temperature is then defined by the rise in temperature that results in the intrinsic coercivity falling enough to equal the peak DMF:

$$T_d = T_{Op} + \left|TC(H_{CJ})\right|^{-1} * 100\,\frac{OpTempH_{CJ} - PkDMF}{OpTempH_{CJ}} \qquad (6)$$

Again using the front magnet as an example, there is a 14.8% difference between the operating temperature H_{CJ} and peak DMF. This translates to a temperature rise of 27.9 ºC and hence the demagnetizing temperature is 54.9 ºC. We find T_d for the side blocks to be 41.8 ºC.

With these values, and recalling Eq. (4), we determine the radiation doses that would cause 1% and 10% demagnetization in the most sensitive areas of the wiggler's magnet blocks. Results are listed in Table 2.

Table 2: Radiation Immutability of BioXAS Wiggler Magnet Blocks considering 2.9 GeV Electrons

Block	Demag. Temp (ºC)	Dose for 1% Demag. (kGy)	Dose for 10% Demag. (kGy)
Front	54.9	1.06 ± 0.67	10.6 ± 6.7
Side	41.8	0.51 ± 0.31	5.1 ± 3.1

Estimation of Wiggler Radiation Dose

To compare against calculated radiation immutability, we estimate the BioXAS wiggler's radiation dose. To do so, we assume the following:

- Injected beam is the only significant source of radiation (i.e. omitting gas scattering, Touschek scattering, and stored beam termination);
- 20% of the injected beam is lost to the ID;
- All energy is deposited in the first ~40 cm of the ID (as done in [4]);
- Demagnetizing radiation occurs within a ± 10 cm vertical window about the beam axis, as supported by data in [5].

During normal operations, the CLS performs two refills per day, injecting from ~150 mA to 250 mA. Roughly 200 mA of electrons are injected each day. For a 170 m circumference ring, this translates to 113 nC of injected charge, or 328 J of injected energy.

With the wiggler at its minimum gap of 1.1 cm, there is an 8.9 cm vertical section of each magnet array within the ± 10 cm window of demagnetizing radiation. We additionally assume that the wiggler's full 11.9 cm transverse horizontal section is affected, and find the total volume of affected wiggler material (including upper and lower arrays) is 8400 cm^3.

The magnet array is composed of NdFeB magnets and cobalt-steel poles, which have densities of 7.7 and 8.12 g cm^{-3}, respectively. We approximate the overall density by taking their average, that is, 7.9 g cm^{-3}, and find the mass of the volume of concern is 66 kg. Given that 20% of the 328 J of injected energy is deposited into this volume, the accumulated dose for one day of normal operations is 0.99 Gy. Thus, for an operational year of 240 days, the accumulated dose is 0.24 kGy per year.

Qualitative Measurements of Radiation Dose

The above estimation admittedly uses a number of assumptions, notably that injection efficiency is at most 80% and that the majority of injected beam loss is lost to the ID. The second assumption may be an overstatement, as the CLS storage ring's limiting vertical aperture is not in the BioXAS straight section, and radiation monitors traditionally show the majority of radiation occurring elsewhere.

In fall 2015, the wiggler's radiation dose was measured qualitatively by covering its magnets in Polaroid film and filling the storage ring with the wiggler at minimum gap. Measurements were taken before and after tuning the injection system, with efficiency improving roughly from 70% to 80%. We observe a marked reduction in the level of exposure on the Polaroid films exposed after tuning injection. While qualitative, these measurements support the theory that an improvement in injection efficiency directly reduces the wiggler's accumulated dose due to injections at closed gap.

CONCLUDING OBSERVATIONS

Based on the relations developed in [1] and [2], the BioXAS wiggler at CLS can sustain 5.1 ± 3.1 kGy before sections of its magnet blocks incur 10% demagnetization. By our own estimates, the wiggler is expected to receive 0.24 kGy of radiation per year due to injected beam when the efficiency is at best 80% and the wiggler is closed for injection. In the worst case, 10% demagnetization will occur within 8 years of operation. In normal operations we open the wiggler for injection, which vastly reduces the risk of radiation-induced demagnetization. The wiggler will only have to remain closed for injections once CLS moves to top-up operation.

Our results show it is important to maintain optimized injection at CLS. With a well-tuned injector, the BioXAS wiggler will not receive damaging levels of radiation.

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