A SHORT PERIOD UNDULATOR UTILIZING A NOVEL MATERIAL

F. O'Shea*, G. Marcus and J. Rosenzweig, University of California, Los Angeles, CA 90095, USA
F. Gruener and R. Weingartner, Ludwig-Maximilians University, 85748 Garching, Germany
A. Gaupp and J. Bahrdt, BESSY, 12489 Berlin, Germany

Abstract

The fundamentals of insertion device physics demand that to have access to ever higher photon energies either the beam energy must increase or the undulator period must decrease. Recent advances in accelerator technology have increased beam energies and at the same time insertion device technology has developed creative ways of producing light of the desired energy, characteristics and quality. This paper describes the simulation work for the design of a 9 mm period in-vacuum planar undulator using a new rare-earth magnetic material.

MIXED RARE-EARTH MAGNETS

The maximum achievable on-axis field in a permanent magnet based insertion device is set by the energy stored in the permanent magnets and the geometry. Smaller magnets store less energy simply because they have a smaller volume. In order to maintain the on-axis field strength with decreasing period, and therefore magnet size, the gap between the two halves of a planar undulator is decreased. The minimum gap size is governed by what the beam can tolerate in terms of wakefields and physical aperture and how much radiation the magnets themselves can absorb before irreversible damage is sustained.

Eventually, device design demands that the magnets store more energy. It has been known for some time that cooling $Nd_2Fe_{14}B$ leads to larger energy density through a larger number of aligned spins. However, below 140 K the easy axis of magnetization begins to move away from the c-axis of the crystal; by as much as 30° at 4.2 K [1]. Recently it has been demonstrated that Praseodymium based magnets with with small amounts of Neodymium maintain a single magnetization axis down to 10 K [2]. This is the material used in the magnet simulations.

The magnetization curve of the new material is modeled using the RADIA formula for an anisotropic nonlinear material [3]. The model parameters at 80 K and 300 K for an initial fit to data are given in Table 1. The effects an approximately 10 μm surface layer that does not act like the bulk material are small and are left out of simulation.

Table 1: Material Specifications

Temperature	80 K	300 K
ms1	0.966 T	0.705 T
ms2	0.403 T	0.349 T
ms3	0.155 T	0.266 T
ksi1	7.787	79.742
ksi2	0.641	3.369
ksi3	0.081	0.358
$\chi_\perp$	0.16	0.16
$\chi_\parallel$	0.05	0.05

UNDULATOR SIMULATION

The incredible investment, in both time and money, required to build a high brightness x-ray source limits the number of users who can have access to such sources. To allow proliferation of such sources they will have to become much smaller than the kilometer scale synchrotron rings and Free Electron Lasers currently in use or development. The Table Top Free Electron Laser (TT-FEL) project at Ludwig-Maximilans University aims to produce a "two room" X-ray Free Electron Laser capable of producing tens of GW of x-ray power with a 5 m saturation length using hundred kA electron beams [4].

The undulator under development is the first iteration of a magnet lattice intended for use in the TT-FEL. The electron source is a Laser Wakefield Acceleration structure which has demonstrated 1 GeV electron production [5, 6]. This beam energy requires sub-centimeter undulator periods to reach angstrom wavelengths. To investigate the options available a parameter search was performed using RADIA to model the undulator.

One of the goals of the prototype project is to create an incoherent light source for diffraction experiments. In order to maximize the photon count we searched for the largest undulator parameter, K, possible that produces few keV photons. Previous experiment had shown that the beam can tolerate an undulator gap of 1.2 mm. For these reasons a hybrid permanent magnet design was chosen to take advantage of the better performance at small gap to period ratios [7, 8].

Table 2: Element Dimensions

Element	Length	Width	Height
Magnet	2.25 mm	17 mm	16 mm
Pole	2.25 mm	15 mm	15 mm

Simulation has shown that a 9 mm period undulator is a good compromise between photon flux and magnet resilience to demagnetization. The dimensions of the elements of the undulator are displayed in Table 2. Thinner magnets would allow higher energy photons but are also more easily demagnetized, while longer magnets are more robust but make higher energies more difficult to at-

* foshea@physics.ucla.edu

tain. The offset (salience) between the vanadium permendur poles and the rare earth magnets was chosen to be zero for two reasons. First, simulation showed that offsetting the magnets produced larger higher harmonics (3rd harmonic and higher) which do not participate in incoherent light production [9]. Second, to partially mitigate the large wakefields created in a small gap undulator a copper/nickel sheet $\leq 60\ \mu$m thin is magnetically attached to the face of the undulator to reduce the resistive wall wakefield [10]; that fastening is more reliable if the salience is null.

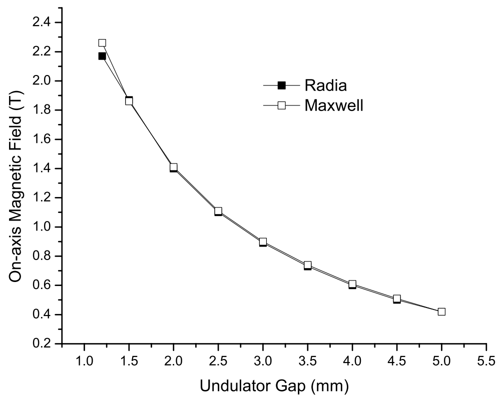

Figure 1: Calculated on-axis field for the 9mm period undulator. The divergence of the calculations at small gap is caused by the simplified geometry used in RADIA to expedite calculation.

To take advantage of the virtues of each of the software packages as well as confirm results two magnetic simulations were used. First, RADIA was used to perform the parameter search, calculate on-axis field and determine the magnetic forces between magnets. To compliment these simulations Ansoft Corporation's Maxwell 3D was used to calculate the fields inside the permanent magnets to locate sites of possible demagnetization and verify the RADIA calculation of on-axis fields [11]. Figure 1 shows that the agreement between the two programs is excellent except at small undulator gaps where the small differences in model geometry become important.

Demagnetization

There are two principle causes of the large magnetic fields within undulator magnets that cause demagnetization. The first is the thickness of the magnets. To keep the field as uniform as possible in the horizontal plane of electron motion, planar undulator magnets are typically a few times the period length wide. The height of the magnets is less important and is typically some fraction of a period length. Thin slabs of magnetic material demagnetize very easily because the field produced by two parallel plates of "magnetic charge" overlap and are potentially very strong in the region in between. Designing thin magnets is therefore a delicate balance between energy storage and coercivity.

Figure 2: One quarter period of both the chimera hybrid (a) and the conventional design (b). a) Half of the SmCo sheath has been removed for viewing. The black iron pole is in the back. The chamfer of the rare earth magnet has been filled with SmCo. b)Modifications made to the magnets in Table 2 to partially mitigate large flux concentrations in the rare earth magnets.

The second principle cause of demagnetization is the concentration of flux that occurs around sharp corners of equipotential objects which is a good approximation for high permittivity isotropic materials [12]. Because the transverse dimensions of the magnet must be larger than those of the poles to prevent cross-talk between poles a simple rectangular pole will naturally have its upper corners near a magnet. To reduce the flux through these corners they are chamfered 0.4 mm. Similarly, some of the flux from two adjacent poles will "round the corners" of the magnets nearest the beam instead of passing through the symmetry plane of beam motion. To reduce this effect the magnet edges nearest the beam are chamfered by 0.8 mm and the adjacent pole edges are chamfered by 0.3 mm. Both modifications are shown in Fig. 2 b.

Assembly Simulation

As the $(Nd_x, Pr_{1-x})_2Fe_{14}B$ material is cooled its coercivity grows from 1200 kA/m at 300 K to 5250 kA/m at 80 K while the energy density increases from 350 kJ/m^3 to 530 kJ/m^3 over the same temperature range [2].

Because of the relatively low coercivity at room temperature magnet handling during assembly is critical. Most important is to fix the pole pieces in place first. The asymmetric position of the poles directs a significant amount of flux away from the poles preventing two adjacent, oppositely polarized magnets from demagnetizing each other. It is also important to have each inserted magnet in between two poles, even at the ends to prevent asymmetry. RADIA simulation has shown that the forces on the magnets are $\sim$5 N, so assembly can be performed manually. Another possible route for reducing the potential for demagnetization is to assemble the undulator in a cold room or chamber.

Chimera Hybrid Design

Samarium Cobalt magnets do not not suffer from the wander in the easy axis of magnetization that $Nd_2Fe_{14}B$ magnets do at cryogenic temperatures [2]. By surrounding the $(Nd_x, Pr_{1-x})_2Fe_{14}B$ magnets with a sheath of Samarium Cobalt the edges of the poles can be moved out into the much more resilient (at room temperature) material. Simulation has shown that this configuration significantly increases the stability of the $(Nd_x, Pr_{1-x})_2Fe_{14}B$ magnets. The design is illustrated in Fig. 2 a.

SPARX SIMULATION

To demonstrate the potential of the Chimera Hybrid magnets, Free Electron Laser simulations were run using the SPARX electron beam. The undulator is comprised of ten 1 meter long sections of 9 mm periods with quadrupoles in between. The beam was first run through ELEGANT to calculate the beam dynamics without lasing [13]. The beam is then run through GENESIS to calculate the x-ray beam power produced [14]. Figure 3 shows the beam current profile and the x-ray power of a small slice of the beam.

The result is 10^8 W of 6.5 Angstroms radiation produced in a little more than 11 meters using SASE start-up. During this distance the beam expands horizontally by a factor of 2. The proposed SPARX 2.8 cm undulator requires 25 m to reach the same power.

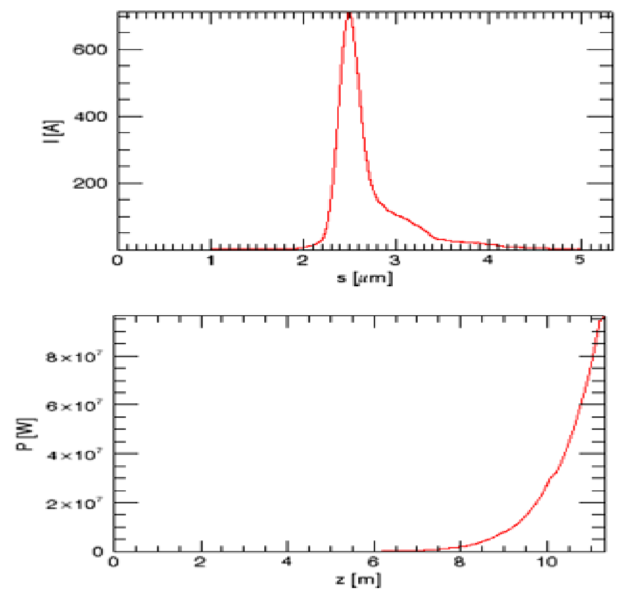

Figure 3: (Top) SPARX beam profile. The beam energy is 2 GeV. (Bottom) Laser gain of a single beam slice as a function of distance along the undulator lattice.

REFERENCES

[1] D. Givord, S.H. Li and R. Perrier de la Bathie, Solid State Commun. 51 (1984) 857-860.

[2] K. Uestuener, et al, "Sintered (Pr,Nd)-Fe-B permanent magnets with $(BH)_{max}$ of 520 kJ/m^3 at 85 K for cryogenic applications", 20^{th} REPM, Crete, Greece, September 2008.

[3] `http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/Radia`

[4] F. Gruner et al, Appl Phys B, 86 (2007) 431-435.

[5] J. Osterhoff et al, New Jour Phys, 9 (2007) 415-426.

[6] S. Karsch et al, Phys Rev Lett, 101 (2008) 085002.

[7] J. Clarke, "The Science and Technology of Undulators and Wigglers", Oxford (2004).

[8] H. Onuki and P. Elleaume, "Undulators, Wigglers and their Applications", CRC (2002).

[9] F. Sircilli, A. C. J. Paes, V. A. Serrao and Y. C. De Polli, IEEE Trans Magn, 37 (2001) 3810-3813.

[10] T. Hara et al, J. Synchrotron Rad, 5 (1998) 403-405.

[11] `http://www.ansoft.com/products/em/maxwell`

[12] J. D. Jackson, "Classical Electrodynamics", John Wiley & Sons (1999).

[13] `http://www.aps.anl.gov/Accelerator_Systems_Division/Operations_Analysis/software.shtml`

[14] `http://pbpl.physics.ucla.edu/~reiche/`