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DESIGN OF A SUPERCONDUCTING WIGGLER SYSTEM

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Contents

1. Abstract
2. Introduction
3. Field Calculations and Superconducting Coils
4. Magnet Design
5. Cryogenics
6. Cost Estimates
7. References
1. Abstract

We present a wiggler system based on currently available superconducting technology. The system is designed to provide maximum central field of 4.4 tesla with a specified period length of 160 mm and a gap of 40 mm, while meeting the field quality requirements along all axes. Also included are preliminary cost estimates and a survey of world-wide R&D efforts on superconducting wiggler systems.

2. Introduction

A wiggler is a device that uses a spatially periodic magnetic field to cause a charged-particle beam to undergo transverse oscillations and, as a result, to radiate. Wigglers are used for two primary purposes: 1) as the primary element of a Free-Electron Laser (FEL) to produce intense laser light and 2) to extract intense, coherent, or partially coherent, light from synchrotrons. In either case, wigglers are unique in that they can produce coherent radiation that is selectable by design over a wide range of frequencies; LLNL has been involved in wiggler projects that have produced output from the microwave range (ELF experiments) to the x-ray (XCSF). One of the primary limitations in the choice of output frequency from wigglers is the accessible regime of periodicity and strength of the wiggler field. These two parameters are strongly linked, and the "difficulty" of a wiggler is a function of the ratio of wiggler field strength to period. Interest in very short-wavelength radiation, from the visible through hard x-ray, is quite high, particularly in the regimes where coherent sources do not presently exist. Such devices will require quite high wiggler-field-to-period ratios. Superconductors offer at least four avenues to access new regions of wiggler parameter space.

The first approach to employing superconductor technology in wigglers is simply to replace normal-conducting windings in iron-core-electromagnet wigglers with superconductors. Superconducting windings of the type needed

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for wigglers can be very compact, sustaining steady current densities of the order of 1000 A/mm^2 at fields up to 5 T and above. cursory analyses performed to date indicate that there may be an immediately obtainable increase of perhaps 25 to 50% in the magnetic field for a given wiggler wavelength. Somewhat shorter periods may be possible with the higher attainable current densities, but possibly even more important is that the use of superconducting windings in this application would allow steady-state operation. Really dramatic increases in field are moderated by saturation in the iron poles. Nevertheless, analyses and conceptual designs that would focus on the parameter space of interest for ECH heating of tokamaks should be performed.

A second approach could involve replacement of the iron. Previous work at LLNL and elsewhere has shown that use of holmium poles in conjunction with the superconducting windings will allow still further increases in field.[1] (Holmium only becomes ferromagnetic below 20 K, but has a saturation flux density of about 4 T.) Preliminary analyses indicate that a 5-T, 30 mm period superconducting wiggler system could be produced with a winding current density on the order of 1000 A/mm^2 . [2] This combination would allow the unique potential of superconductors to be more fully realized, allowing wiggler designs in the x-ray range. This concept is currently being evaluated by first performing detailed design analyses; if it appears that there is significant advantage in using superconductors with holmium poles, a one-period prototype wiggler will be developed for testing and demonstration.

Another type of superconducting wiggler that could be of interest is the iron-free, linear-electromagnet wiggler. This type of wiggler is not subject to the limitations imposed by ferromagnetic cores, but it is somewhat less efficient if normal-conducting windings are used. It is likely, however, that the use of superconducting windings will more than compensate for the loss of efficiency by eliminating the ferromagnetic poles, resulting in practical higher-field air-core devices. Analyses need to be performed to explore this concept using existing, well-developed expertise in the magnetic-fusion engineering area.

The fourth type of wiggler where superconductors could play a significant role is in helical wigglers, which produce circularly-polarized light, as opposed to the linear-polarized light produced by most wigglers. Helical wigglers seem well-suited to the use of superconductors with long, helically-wrapped windings. Practical limitations have prevented the production of iron-core helical wigglers; hence the fields produced in existing devices have been quite low. The application of superconducting technology could offer a factor of 10 increase in fields attainable in this type wiggler. This application could again be explored easily using the techniques and tools that have been developed in the superconducting magnet development group in the magnetic fusion area.

In recent years, there have been extensive research and development efforts made to produce practical superconducting wiggler magnet systems. Table 1 lists a survey of these systems in the world. However, it needs to be pointed out that although most systems worked up to their specifications, nearly all of them suffered from the effect of "training," whereby the magnet systems showed a progressive improvement in performance after repeated quenching. This can generally be ascribed to lack of "stability margin" or looseness in the windings.

Fortunately, significant technological progress recently has been made in manufacturing reliable high-performance NbTi superconductors for Superconducting Super-Collider (SSC) applications.[3] The specified minimum current density of the fine-filament composite strands generally exceeds 3000 A/mm^2 at 5 T, 4.2 K, nearly twice higher than before. It is strongly believed, with this additional "margin" and a sound winding scheme, a stable magnet can be made without degradation or "training."

3. Field Calculations and Superconducting Coils

For three-dimensional field calculation, the computer program "EFFI" was used for the five-coil segment of a wiggler magnet system, as shown in Figs. 1 and 2. Table 2 lists major parameters for magnet and conductor design. The major requirements of a wiggler magnet system can be summarized as follows:

- a. To provide appreciable central-field induction, approximately 5 tesla.
- b. To provide a gap of 40 mm with a period length of 160 mm.
- c. To provide the appropriate transverse field profile for beam focusing.

We achieve a and b primarily with superconducting windings with an average current density of 400 A/mm^2 and maximum field on the winding of 6.3 T; c was achieved with specially-shaped holmium poles. It should be noted that higher field (5 to 6 T) wigglers can be obtained with a "grading" scheme to achieve higher overall current density.

Figure 3 illustrates the wiggler field variation with axial (z) location, where a half period of 80 mm is shown. Wiggle-plane focusing is produced by hollow holmium poles (Fig. 1). We selected the specific pole shape also for convenience of modeling; it can certainly be further optimized. Focusing-field features in the horizontal, transverse direction in the wiggle plane are shown in Fig. 4, where a maximum variation of 11% is achieved at $x = \pm 30 \text{ mm}$. Also shown is the case where iron poles (with saturation field of 2 T) are used in place of holmium. Figure 5 illustrates on-axis transverse field profile for one-fourth period.

Table 1. Survey of Recent Superconducting Wiggler Systems

Institutions	B _m (T)	Gap (cm)	Period (cm)	No. of Period	Total Length (cm)	First Operation	Remarks	References
France - CEN Saclay Orsay (ACO)	5.0	3.0	26.0	5	123	1986		4
	0.46	2.2	4.0	23	--	1980		5
England - Daresbury (SRS)	5.0	3.0	50.0	3	150	1981		6
USSR - Novosibirsk (VEPP-2M) (VEPP-2E) (VEPP-3) Kurchatov	7.5	2.65	12.0	5	58	1984		7
	0.47	2.0	2.4	8	--	--	Helical undulator	8
	3.5	1.5	9.0	--	--	--		9
	4.0	2.2	--	--	35	--		8
Finland - Tampere Univ.	7.5	1.5	24.0	3	90	1988		10
JA - KEK	6.0	3.0	10.0	3	30	1983		11

Fig. 1 Model of 5-coil System
(x-z plane)

Fig. 2 Model of 5-coil System
(y - z plane)

Table 2. Superconductor Wiggler Design

Gap/period	40 mm/160 mm
Winding cross section	20 x 40 mm ²
J _{avg}	400 A/mm ²
Central field	4.4 T
Pole material	Holmium
B _{max} on conductor	6.3 T
Race track, straight section end-term radius	40 mm 20 mm
Number of turns	1250

Conductor Design

Cu/sc	1.8
Strand size	0.8 mm ϕ
J _c @ 6.3 T	> 800 A/mm ²
Estimated I _c @ 6.3 T	> 400 A
Operating current I ₀	260 A

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Figure 3
Wiggler Field Variation With Axial Location

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Figure 4
Transverse Focusing Field Variation

Fig. 5 On-Axis Transverse Field Profile

4. Magnet Design

The wiggler magnet design will use existing design and fabrication techniques that have been used to build similar superconducting magnets. The superconducting wire will be wound onto the holmium pole pieces using a "wet" winding method. The wire will be coated with a thermo-set epoxy as part of the winding process and oven-cured into a rigid pole/coil assembly after winding. Each coil will be tested at both room temperature and liquid helium temperature to verify that all coils meet the design requirements.

A single support structure, which will extend the full length of the magnet, will be used to maintain an accurate, geometrical relationship between poles. The pole/coil assemblies will be installed onto this common support structure (Fig. 6). All coils will be connected in series with one set of vapor-cooled current leads exiting the cryostat. Non-magnetic stainless steel will be used to fabricate the support structure, helium shell, vacuum shell, and beam tube. All pressure vessel welds will be leak checked with a helium mass spectrometer. Superinsulation will be used to reduce thermal-radiation heat transfer between the room-temperature vacuum shell/beam tube and liquid-helium shell.

5. Cryogenics

Cryogenic requirements given here are based on the wiggler design listed in Table 2. It appears that the wiggler column could be housed in a 300- or 350-mm dia. tube. Two approaches could be used. First, the tube could serve as a dewar where a helium bath of liquid and vapor surrounds the beam column and magnets. Here a second outer tube would form a vacuum space. The second approach would be to cool the magnets by conduction from LHe tubing and have vacuum surround the beam column and magnets. In either case, heat load to the LHe coolant would be about the same. We are assuming the beam tube is at 300 K.

Case 1--Assuming a simple structure where no nitrogen shielding is used and no extensive effort is made to minimize losses via supports (i.e. vented supports are not used), losses similar to industrial vacuum-jacketed piping can be expected. These are estimated as:

a. Heat from the beam column	3 W/m of beam length
b. Heat from the external 30-cm container	3 W/m of beam length
Total	6 W/m

Case 2--By using special care to reduce support losses by intercepting heat with the vented helium, and adding LN₂ shielding to both the external vessel and beam tube, this heat load could be reduced by one-third, resulting in a 2 W/m load. This estimate is substantiated by industrial experience with LN₂-traced, vs. non-traced, VJ piping, where LN₂ tracing causes the heat load to be reduced by one-half. The reduction is not larger

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SUPERCONDUCTING WIGGLER MAGNET CROSS-SECTION

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Figure 6

because the heat load via conduction along the supports starts to predominate.

There appear to be no serious problem areas for cooling the magnets. Conventional technology, welding techniques, assembly techniques, etc., can be used at nominal cost, a conclusion that is similar to the one derived in our study last year for the LIL accelerator, where a beamline having superconducting magnets was proposed.[12]

Assuming a 10-m beamline and straight-forward structural design, 60 W refrigeration at 4.5 K will be required. A KPS 1430 helium refrigerator with screw compressor is rated at 114 W, and costs about \$252,000 for a complete system. A number of older refrigerators of similar design are around and might be obtained on inter-government transfer. Some cost savings are available by using less refrigeration; a KPS 1400 series refrigerator rated at 70 W is about \$230,000 (new cost). Further checking into the surplus market is needed to determine real savings associated with lower cryogenic loads.

6. Cost Estimates

The following estimates in Table 3 were based on a 10-m (60-period or 120-coil system) beamline. (Material costs for holmium of \$800/lb and for NbTi conductor of \$150/kg are assumed.)

Table 3. Cost Estimates of a 10-m Superconducting Wiggler System

Materials	Per Coil Pair (k\$)	125-Coil System (k\$)
Holmium poles	3.6	450
NbTi conductor	0.5	60
Engineering and design		150
Coil fabrication		150
Magnet fabrication		100
Component fabrication		100
Miscellaneous		50
Refrigerator		250
Subtotal		1300
Total with 15% contingency		1500 K\$

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