DESIGN AND EVALUATION OF A SHORT PERIOD Nb_3Sn SUPERCONDUCTING UNDULATOR PROTOTYPE*

S. Prestemon, D. R. Dietderich, S. A. Gourlay, P. Heimann, S. Marks, G. L. Sabbi, R. M. Scanlan, R. Schlueter, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA
B. Wang, B. Wahrer, Wang NMR, Livermore, CA, 94550, USA

Abstract

The design of a class of short period superconducting undulators is presented. We begin with a parameter-based analysis that provides insight into potential device performance as a function of the properties of superconducting materials. We present data on candidate low-temperature superconducting materials and the motivation to consider low-copper fraction, high Jc materials. Measured data on recent Nb_3Sn conductors is provided, together with wire and cable design issues that are tailored for undulator applications. Key design concerns are then addressed, in particular the quench protection system limitations and the system performance. Progress on the construction and testing of a prototype 30mm period device is described.

INTRODUCTION

The development of short-period superconducting undulators (SCU's) is critical to extend the capabilities of existing synchrotron rings and to leverage their future upgrades, and is a key component of a number of future synchrotron radiation sources, such as the proposed LUX at LBNL [1]. For a fixed period, increasing the field compared to conventional devices results in an extended photon energy range (on the higher end) and improved harmonic overlap.

Due to the important role of superconducting undulators in plans for existing and future light sources, an R&D effort has been initiated at LBNL to investigate the potential performance characteristics for a class of such devices, and to evaluate the performance of a Nb_3Sn-based design by constructing and testing a prototype.

We begin by presenting computed optimal designs and attainable fields as a function of conductor performance and coilpack parameters.

A review of the design of a Nb_3Sn 6-period prototype that is being constructed jointly by LBNL and Wang NMR and tested at LBNL is then provided. The motivation to use low Cu:SC ratio material is presented, together with a discussion of options for superconductors, in particular Nb_3Sn strands and cable designs. A winding method is described that is flexible with respect to period size and conductor geometry. The impact of choosing a low Cu:SC ratio conductor on the quench protection is discussed, along with a passive protection design.

This work was supported by the Director, Office of Science, of the US Department of Energy under Contract No. DE-AC03-76SF00098

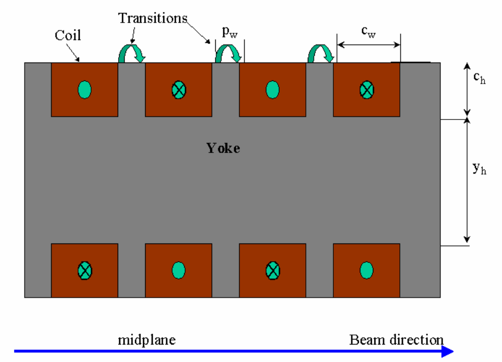

Figure 1 Superconducting undulator upper-halfplane.

Table 1 Parameters and variables used for undulator design optimization.

λ	Undulator period
h	Magnetic half gap (gap = $2h$)
p_w	Pole width (beam direction)
c_w	Coil width (beam direction)
c_h	Coil thickness
y_h	Yoke thickness
r_{pc}	$= p_w / c_w$
J_{av}	Engineering, or overall, current density
J_{sc}	Superconductor current density
J_{cu}	Copper current density (e.g. during a quench)
B_0	Peak field on the axis
$B_{\max}$	Peak field on the conductor
K	$= eB\dfrac{\lambda}{2\pi mc} = 0.934\lambda[cm]B[T]$

OPTIMAL DESIGNS

We consider planar undulators with soft iron poles and yoke, as shown in Figure 1. A list of parameters and variables is provided for reference in Table 1.

For design optimization, we consider a design variable set $\{h, \lambda\}$ and the design parameters $\{r_{pc}, c_h, y_h\}$. For a given average current density J_{av} the figure of merit $f_m = B_{\max} / B_0$ can be minimized with respect to the design parameters. An "optimal load line" $B_0(J_{av})$ for each design variable set, i.e. magnetic gap and period, can then be determined.

Peak performance for an actual device is derived from J_c data and the superconductor cross section, which is used to relate J_{av} to J_{sc}. The peak attainable field is defined by the intersection of the "optimal load lines" with the J_c curve, i.e. when $J_{sc} = J_c(B_{\max})$.

Data for "optimal load lines" has been calculated for design variables in the range $15 < \lambda[\text{mm}] < 30$ and $4 < gap[\text{mm}] < 16$, using a parametric 2D TOSCA script. As an example, performance curves obtained for a Nb_3Sn superconductor with $J_c(5\text{T}, 4.2\text{K}) = 8060$ A/mm^2 and with a $J_{av}/J_{sc} = 0.27$ (aggressive performance yet realistic, i.e. manufacturable – see parameters for the prototype in Table 2) are provided in Figure 2.

The optimization methodology outlined above is applicable to all types of superconductor. A thorough comparison of the theoretical performance of SCU's using different superconductors is beyond the scope of this paper, as it involves detailed comparison of stability and protection characteristics associated with the choice of the Cu:SC ratio, analysis of the attainable insulation thickness and packing factor in each case, and an understanding of the cryogenic operating conditions and cooling method.

UNDULATOR PROTOTYPE

A 6-period prototype Nb_3Sn undulator is currently being fabricated that will test key design issues that arise when operating in the type of regime discussed above (see table 2). Issues that are being addressed include selection of a suitable state-of-the-art conductor, determining a coil winding method that is applicable for a variety of undulator designs and conductor geometries, and quench protection for designs with extremely high Cu current densities (~ 6000 A/mm^2). Increasing the allowable copper current density will allow for the full benefits of advanced superconductors to be realized (see figure 3).

Superconductor selection

Superconductors for SCU's must support very high current densities in order for these devices to exceed the performance characteristics of pure permanent magnet and hybrid magnet devices. Due to the relatively low peak field on the conductor (typically ~4-6 T), extremely high superconductor current densities are possible. In the case of a quench the current is carried by the Cu stabilizer, and the protection system and conductor Cu fraction must be correctly matched.

The importance of increasing J_{cu} is shown in Figure 3. Traditional magnet designs keep J_{cu} to ~ 2000 A/mm^2 or less. Under such conditions the use of advanced superconductors, such as APC NbTi or Nb_3Sn, will result in a higher Cu fraction (which increases the conductor stability and facilitates protection), but will not translate into a significant increase in attainable axial field (see figure 3, line A).

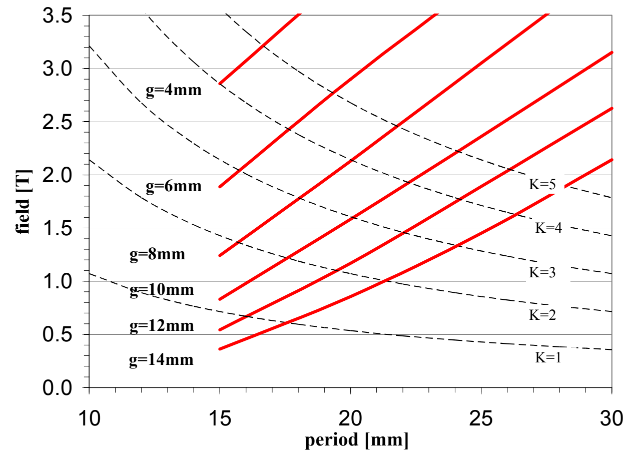

Figure 2. Performance curves for Nb_3Sn superconducting undulators (see text for assumptions)

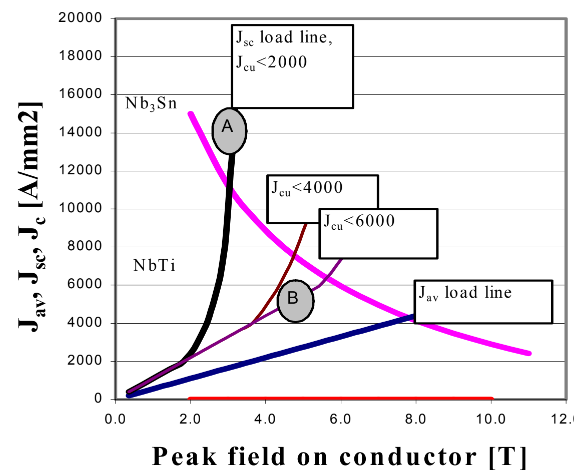

Figure 3 Effect of a copper current density limitation on the attainable performance of a device. The model corresponds to a linear B(J) load line and assumes Cu:SC=1 at low current. Once the J_{cu} limit is attained, the copper cross section is "increased " to keep J_{cu} constant.

High copper current density can be achieved by using a high J_c superconductor with a low Cu:SC ratio, traits found in recent Nb3Sn conductors. We have investigated both internal-Sn mono-element conductors [2] and Oxford jelly-roll strands [3]. J_c measurements were performed at LBNL. The internal-Sn strands were unstable below 10 T, perhaps due to flux jumps occurring under high transport current conditions. The jelly-roll strand (see cable parameters in table 2), was stable throughout the field range of interest (5-6 T), and yielded $J_c(5.9\text{T}, 4.2\text{K}) = 6115$ A/mm^2. A six-strand Rutherford cable was then fabricated at LBNL and is being used in the undulator prototype.

Coil winding method

The coilpack design keeps all turn-to-turn, layer-to-layer, and coil-to-coil transitions on the far side, away from the beamline (see figure 4). The reaction and potting fixtures are designed to force the coilpack flat on the straight sections. Only the potting fixture plate on the beam side needs to be removed during operation. In the flat coil section on the beam side the net Lorentz force is directed toward the yoke, i.e. away from the beam.

The coil-to-coil transitions incorporate "buttons" (see figure 4) so as to minimize hard-way bends in the conductor in the case of a cable or tape. The winding approach is applicable for any period size.

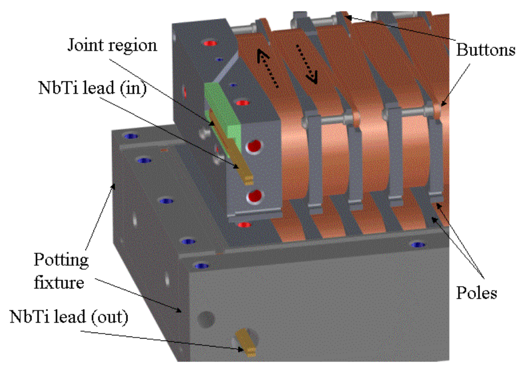

Figure 4 Model of the LBL 6-period Nb_3Sn prototype.

Quench protection

The jelly-roll strand is 52% Cu, resulting in $J_{cu} \simeq 5650\ \text{A/mm}^2$ during a quench at peak field. A simple thermal model [4] equating Joule heating and the heat capacity of the Cu yields

$$\int_{4.2}^{T_m} \gamma C_p(T)/\rho(T)\,dT = \int_0^{\infty} J^2(t)dt = J_0^2 t_d$$

where t_d is a characteristic heating time. For $T_m = 300\text{K}$ we obtain $t_d \sim 40\text{ms}$. A passive protection system incorporating diodes eliminates the uncertainty of triggering an active system with such a short time constant. Diodes in a parallel circuit across the upper and lower undulator sections will begin to conduct as soon as they see a voltage larger than ~5V. Most of the supply current will be diverted through them, and the coil current will decay rapidly. Since the inductance $L = 2E/I^2$ is low (see table 2), little voltage is needed to energize the coils and a single diode can be used for each undulator half.

Calculations show that a single coil can absorb half of the stored energy of the system (mutual inductance between the upper and lower halves will trigger a quench in the opposing coil) without exceeding ~350 K. By incorporating diodes, however, the design insures that most of the energy is diverted elsewhere.

Voltage taps are being installed at each period to provide experimental verification of the quench behavior. The protection system design is scalable to full length devices.

Table 2 Nb_3Sn prototype undulator design parameters and anticipated performance.

Coil Geometry	
λ [mm]	30
p_w [mm]	4.8
c_w [mm]	10.2
c_h [mm]	5.4
y_h [mm]	28
Average turn length [mm]	21.9
Turns/layer	5
Number of layers	5
Conductor	
Strand diameter [mm]	0.48
Number of strands in cable	6
Cable width (bare) [mm]	1.75
Cable height (bare) [mm]	0.90
Insulation thickness [mm]	0.065
Cu:SC	1.08:1
RRR	21
Cabling packing factor	0.72
Overall SC fraction	0.24
$J_c(5.9\text{T}, 4.2\text{K})$ [A/mm^2]	6115
Anticipated performance (h=5 mm)	
B_0 [T]	3.2
B_{max} [T]	5.9
I_{max} [A]	3200
E (stored energy/period) [J]	2000

CONCLUSION

Superconducting undulators have the potential to significantly enhance the operation of existing and future light sources. In order to make full use of the most advanced superconductors, the protection system must be capable of handling values of J_{cu} well beyond those typically used in superconducting magnet design. A prototype Nb3Sn undulator design is currently being fabricated to verify the passive protection method presented in this paper.

REFERENCES

[1] J. N. Corlett et al, "Initial feasibility study of a dedicated synchrotron radiation light source for ultrafast X-ray science", LBNL-48171, Oct., 2001.

[2] B. A. Zeitlin et al, "Progress on a high current density low-cost Nb_3Sn conductor scalable to modern NbTi production", Advances in Cryogenic Engineering (Materials), vol. 48B, pp978-985, 2002

[3] J. A. Parrell et al, "High Field Nb_3Sn Conductor Development at Oxford Superconducting Technology", to be published.

[4] Martin N. Wilson, "Superconducting Magnets", Clarendon Press, Oxford, 1989, p. 201