

A Superconducting Wiggler for the LCLS*

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Abstract

A strong wiggler is likely to be required for the LCLS to reduce bunching that would cause beam instabilities due to coherent synchrotron radiation in the second linac bunch compressor. This wiggler will be located in a 3 m straight section immediately upstream from the bunch compressor at SLAC linac sector 24-7, where the e-beam will have an energy of 4.5 GeV. The peak field of the wiggler will have to be at least 5T, so a superconducting device is required. In this technical note, we describe a general design approach, and a specific proposal for this wiggler.

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Executive Summary

At the present state of our calculations and modeling, beam instability due to bunching upstream from the second bunch compressor in the LCLS is unacceptable. A strong wiggler will be required to generate sufficient energy spread to mitigate the beam instability due to coherent synchrotron radiation in that bunch compressor.

After an extensive analysis of the various design options, we determined that a multipole superconducting wiggler would generate sufficient energy spread but with acceptable (<5%) emittance growth. A very favorable design is that of the Oxford/BNL wiggler, originally intended for use on BL-17 at NSLS. This 11 pole device (+ two end poles), if modified to run high current through all poles, would give sufficient field strength (5.5 T) and low dispersion, which causes low emittance growth.

There are two possible strategies presented. We could obtain the existing Oxford/BNL device, and modify it for our use. Or we could build a superconducting wiggler based on the Oxford/BNL design.

In the first option, the present current leads would have to be replaced, and the coils rewired so as to allow them all to run at high current. Presently only the center coils are wired this way. The direct cost of this is about \$635k and 18 man-months of labor. Some miscellaneous items, like design reviews and installation costs would be additional. The overall schedule time is estimated to be well under one year, with items line transfer lines and storage dewars (common to both approaches) dominating the schedule. Quench protection and mechanical support has to be upgraded from the BNL design in order to run at higher field, this entails new engineering and some uncertainty as to feasibility.

In the second option, we propose to design the device in-house and have its components built by vendors. We are unlikely to be able to obtain detailed Oxford designs, and Oxford will not build the device. This option will cost about \$1.1M and require about 37 man-months of in-house labor. The overall schedule time is estimated to be 3.5 years. To have this device ready by the time tests are begun on the LCLS bunch compressors (2006) would require starting the design process very soon.

There is a significant issue with regard to spares. A complete spare could be switched in about two weeks, a spare cold mass might require a month, and fixing a broken device could require several months. If it is decided to have a complete spare, then building two wigglers from scratch would require engineering only one project. Building one device from scratch and modifying the Oxford/BNL device would require engineering two projects.

Since a wiggler is most likely required, the question of acquiring the Oxford/BNL device should be addressed immediately. If it can be acquired, then work on it can proceed at a somewhat relaxed pace. If it is not acquired, then the schedule becomes quite demanding.

Introduction

The extremely short electron bunch length in the LCLS can give rise to a micro-bunching instability driven by coherent synchrotron radiation (CSR) during compression. [1] The instability can be suppressed by Landau damping from the finite incoherent energy spread in the electron beam. For the LCLS, a short but strong wiggler located just upstream of the second bunch compressor chicane (BC2) at 4.5 GeV can be used to increase the incoherent energy spread enough to significantly damp the instability, while not impacting the SASE x-ray FEL performance. Since the bunch is still relatively long prior to BC2 (200 μm rms), the effects of CSR in the wiggler are weak.

For the nominal LCLS, with 1.5 \AA radiation at 15 GeV electron energy, the FEL gain is not significantly changed by an incoherent energy spread $<1 \times 10^{-4}$ (or 1.5 MeV). Allowing for the factor of 10 bunch compression in BC2 at 4.5 GeV, the maximum tolerable energy spread prior to BC2 is then 150 keV (or 3×10^{-5}). This level is much larger than the incoherent energy spread generated by the RF photocathode gun, and is used as the target value for the damping-wiggler (with some small overhead up to 4×10^{-5}). The bend-plane emittance growth due to spontaneous radiation in the wiggler is controlled by choosing a sufficiently small beta function in the wiggler and by keeping the period short enough for a small dispersion function.

Fig. 1 shows the CSR micro-bunching gain versus current modulation wavelength over the entire LCLS with and without the damping wiggler. The wavelength is measured prior to BC2. The smooth curves are theoretical calculations and the points are from particle tracking. The agreement is reasonable and the wiggler suppresses the gain over much of the short wavelength end of the spectrum.

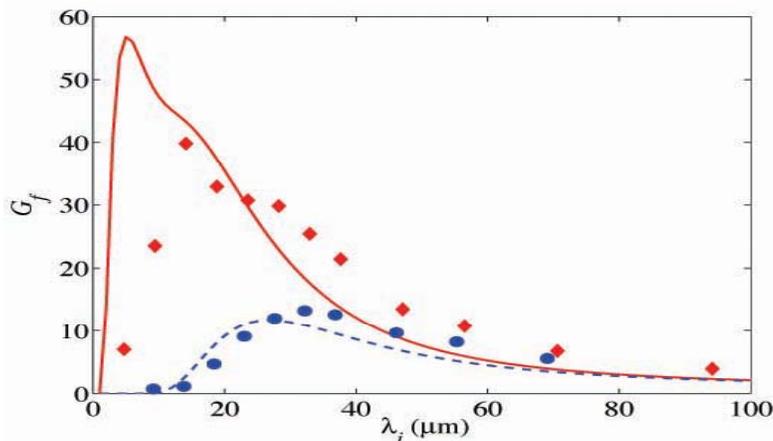


Figure 1: CSR microbunching gain for the entire LCLS versus current modulation wavelength after the first compressor chicane shown with (dash/blue) and without (solid/red) damping wiggler. The continuous curves are a theoretical calculation while the points represent particle tracking.

Theory

Each bend of the wiggler we propose contributes an energy spread, which we calculate from [2]

$$\sigma_E^2 = \frac{55}{24} \frac{r_e E_e^5 L}{\sqrt{3} (m c^2)^6 |\rho^3|}$$

Taking the derivative with respect to L, and substituting

$$\frac{1}{\rho \text{ (m)}} = \frac{B(s) \text{ (T)}}{3.33 E_e \text{ (GeV)}}$$

we have:

$$\sigma_E^2 = \int \frac{d\sigma_E^2}{dL} ds = 4.13227 \cdot 10^{-11} \left(\frac{m^2}{\text{GeV}^5} \right) E_e^2 \text{ (GeV)} \int \left| \frac{B(s) \text{ (T)}^3}{3.33^3} \right| ds$$

Taking the square root of this integral gives the energy spread.

It is also desired that the total emittance increase not be more than about 5%.; This value is calculated by generating a proposed magnet design, calculating the fields, and then using these fields in tracking codes like BETA, assuming a 72 m beta function in the wiggler.

In this device, most of the energy spread comes from the action of the central coils of the wiggler; the endcoils have the function of zeroing the dispersion caused by the central coils. Putting the formulas above together, we see that the energy spread will scale as:

$$\sigma_E \sim B^{3/2} L^{1/2} E_e$$

The wiggler for the LCLS must produce an energy spread in the 4.5 GeV e-beam at Sector 21 of 3-4e-5.

Design Constraints

There are several practical constraints on the magnet design besides the energy spread and emittance requirements. These include magnet gap, magnet length, critical fields and current density in the superconductor. The magnet gap must accommodate a 20 mm ID warm (~ 300K) beampipe (though this might be squeezed down to 16 mm if necessary), a layer of superinsulation, a cold shield tube (77K) and another layer of superinsulation. This will require a magnet gap of around 40 mm. The electron beam in this region is 100 μm horizontal and 80 μm vertical, but the beampipe ID is determined by our desire not to be the smallest aperture in the system.

Conventional superconducting design would call for NbTi superconductor running at an operating point of about 4.5 K. This corresponds to a critical field of about 7 T, so that the design must not allow a field in the conductor any greater than this.

Typical NbTi superconducting wire with polymer film insulation can be wound with a packing factor of about 85%. However, the conductor is only about 25-33% NbTi, the remainder being copper. While it is possible to run as much as 2000 A/mm² in a short sample of such superconductors, we prefer to stay far below this limit, so that we stay well away from the critical fields of about 7 T.

If the end coils and main coils are driven by a common series power supply, there may have to be a separate dispersion correction supply for the end coils, because dispersion changes when the common current changes. Corrections can be made up by trim coils outside the wiggler, but the total magnitude of this correction will limit the range of currents allowable in the wiggler.

Magnetic Design

The authors originally began the design of a 2-pole superconducting wiggler for this purpose, but subsequently found at least three other superconducting wigglers already built in various places that might also serve. There is an 11-pole device built by Oxford for BNL, a 1-pole device at MAX-lab, and a 1-pole device at the National Institute of Radiological Sciences (NIRS) in Japan. We compared these four general designs, and decided that the Oxford/BNL design was the best, mostly because it had the lowest value of emittance growth.

The advantage of basing our design on an existing device is that it is a known quantity, having been engineered and tested already. A new device carries with it a full burden of engineering and the risk that it might not work up to specifications. There is the possibility of using an actual existing device, such as the Oxford/BNL wiggler, with some modifications. Even if we do not use the actual hardware of an existing device, we might use the design, and this would lower both cost and risk. The parameters all four devices are given in Table 1:

	NIRS	MAX-lab	Oxford/BNL	SLAC
Main poles	1	1	11	2
End half poles	2	2	2	2
Overall length with cryostat	1.2 m	0.93 m	>1.3 m	1 m
Gap between pole tips	66 mm	36 mm	40 mm	45 mm
Vertical beam aperture	20 mm	15 mm	19.5 mm	20 mm
Max main field	7 T	7.6 T	5.5 T	6.4 T
Calculated max energy spread	2.72e-5	2.74e-5	3.88e-5	4.1e-5
Calculated emittance growth at max energy spread	4.5%	2.7%	1.5%	10.7%
Calculated emittance growth at energy spread of 3.0e-5	6.4%	3.8%	0.6%	3.8%

Table1: Comparative performance parameters.

The Oxford/BNL device may be operated with fewer than 11 poles at main power, but these configurations do not give adequate energy spread. The full Oxford/BNL device with 5.5 T peak fields would give an adequate energy spread. The other two devices would not give adequate energy spread values used by themselves, but if two such devices were used, the energy spread adds in quadrature, so two would give about $3.8e-5$, an adequate value. Two NIRS devices would be a bit long, but could still be made to fit, and two MAX-lab devices would fit into the allowed space.

A RADIA model of the Oxford/BNL wiggler is shown in Figure 2:

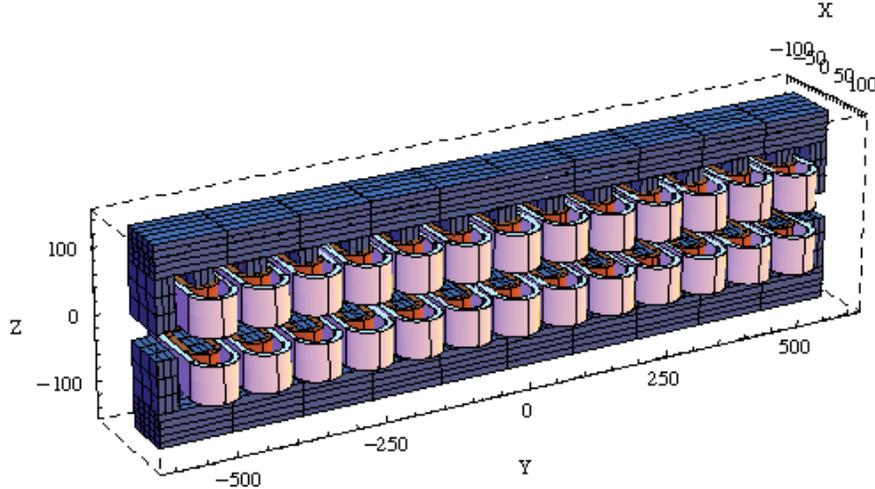


Figure 2: A Mathematica drawing of the Oxford/BNL device. Note the inner and outer coils. In the actual design, the flux return surrounds the coils; the flux return shown was used for the RADIA model. Dimensions are in mm.

The Oxford/BNL device has not been run at 5.5 T with all poles active. The device is specified to run at only 3.0 T with all coils energized, and 5.5 T when used only as a one-pole wavelength shifter. The limitation is apparently not critical field in the windings, but capacity of the current leads. The current leads for the central pole have greater capacity than those for the 11 pole configuration. The present current leads on the device would not allow 11 pole, 5.5 T operation, and it is a major operation to change the leads. If the Oxford/BNL device could be run at 5.5 T in 11 poles, it offers the best performance of all, with adequate energy spread and the lowest emittance growth. We will adopt this design as our proposed candidate for the LCLS.

The calculated magnetic field is plotted below:

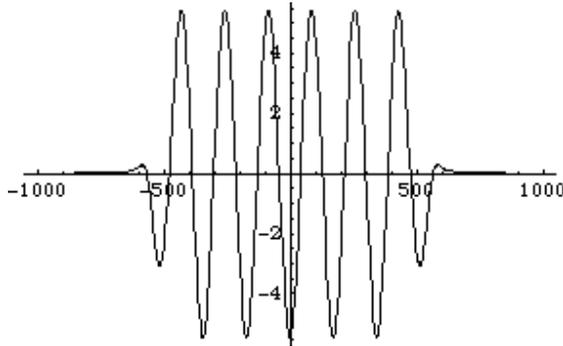


Figure 3: Magnetic field calculated with RADIA. The ordinate is in Tesla and the abscissa is in mm.

Some important parameters for the candidate design are given in Table 2:

Magnetic Gap	40 mm
Period	171.6 mm
Pole width	91.8 mm
Pole height	80 mm
Pole length (longitudinal)	31.8 mm
Coil height	57 mm
RADIA model flux return thickness	50 mm
Bulk current density of inner coils	267.2 A/mm ²
Bulk current density of outer coils	523.75 A/mm ²
Inner coil width (transverse)	60 mm
Inner coil ID and thickness	32.2 mm x 12 mm
Outer coil width	140 mm
Outer coil ID and thickness	56.4 mm x 10.08 mm

Table 2: Geometric parameters for Oxford/BNL design

The reason that the Oxford/BNL design has such low emittance growth is that it produces the least dispersion, because of the relatively large number of short poles. The dispersion curves for the four devices are shown below:

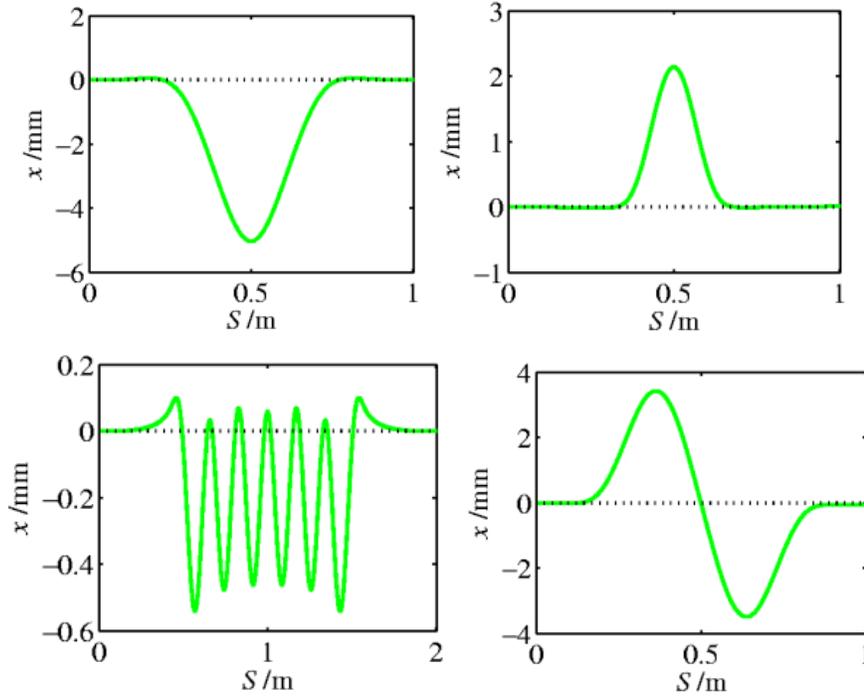


Figure 4: Dispersion for the four designs: Upper left – NIRS, upper right – MAXlab, lower left – Oxford/BNL, lower right – SSRL

Field Quality

In order to estimate the tolerances, assume the following parameters for a hard-edged dipole magnet system of the Oxford/BNL type, and assume the parameters given in Table 3.

Electron energy	4.54 GeV
$\langle B \rangle$	3.8 T
Bmax	5.4 T
η_x	0.5 mm
β_x	60 m
β_y	40 m
$\sigma_{E/E}$	0.8% RMS
ϵ_x - normalized	1 mm- mrad
ϵ_y - normalized	1 mm-mrad

Table 3: Parameters for purposes of magnetic tolerance calculations

The results of our estimates for the tolerances are given in Table 4:

Roll	<0.5 mrad
b1/b0 (quadrupole field)	0.04% at $x_0 = 12$ mm (scales as $[x/x_0]$)
b2/b0 (sextupole field)	< 3% at $x_0 = 12$ mm (scales as $[x/x_0]^2$)
b3/b0 (octupole field) rough estimate	<10% at $x_0=12$ mm (scales as $[x/x_0]^3$).
b4/b0 (decapole field) tol.	< 80% at $x_0 = 12$ mm (scales as $[x/x_0]^4$)
$\Delta B/B$ (steering error)	< 5E-6

Table 4: Magnetic tolerances calculated for the Oxford/BNL device installed in the LCLS.

In the calculation above, x_0 is the transverse position where the relative field drop-off is evaluated (e.g., harmonic probe radius). The quad-field error is correctable and so is the dipole field error but these numbers should be the design goals, unless they are too extreme. In that case we can refine the correction ideas. These are conservative numbers.

Synchrotron Radiation from the Superconducting Wiggler

The wiggler produces very high peak power, but low integrated power. For 120 Hz rep rate, and a 5T peak field the power averaged over one second of operation is:

$$\bar{P}_{\text{total}}(\text{W}) = 633 E^2 (\text{GeV}) B_0^2 (\text{T}) L (\text{m}) I (\text{A}) = 633 \cdot 4.54^2 \cdot 5^2 \cdot 1 \cdot 120 \cdot 10^{-9} \approx 0.04 \text{ W}$$

The power in a given 280 fsec pulse is:

$$P_{\text{peak}}(\text{W}) = \frac{\bar{P}_{\text{total}}(\text{W})}{120 \cdot 280 \cdot 10^{-15}} = 1.16 \text{ GW}$$

This radiation falls into a fan of width of about $K/\gamma = 10$ mrad (horizontal) \times $1/\gamma = 0.11$ mrad, (vertical) so if it hit a surface 1 meter away, it would be spread over 1.1 mm^2 . This load is much less than the spontaneous power from the LCLS, which is expected to strike a similar area on x-ray optics without serious damage. The critical energy of x-rays from this wiggler is 74 keV, and the absorption depth for x-rays of this energy in copper is about 1 mm.

Cryogenic Design

The cryogenic design includes the cryostat, helium storage, transfer lines, current leads, and quench protection system.

Cryogenic System

A superconducting wiggler requires a liquid helium cryogenic system in order to run at about 4.5 K. Reliability and maintainability are the key requirements of the system. The most conservative approach would be to immerse the magnet in a bath of liquid helium. Even if we were to go to a system of cooling the magnet with just small cryocoolers, bulk liquid helium would be required for the initial cooling of the magnet from room temperature to 4.2 K. Our baseline design is shown in Figure 5:

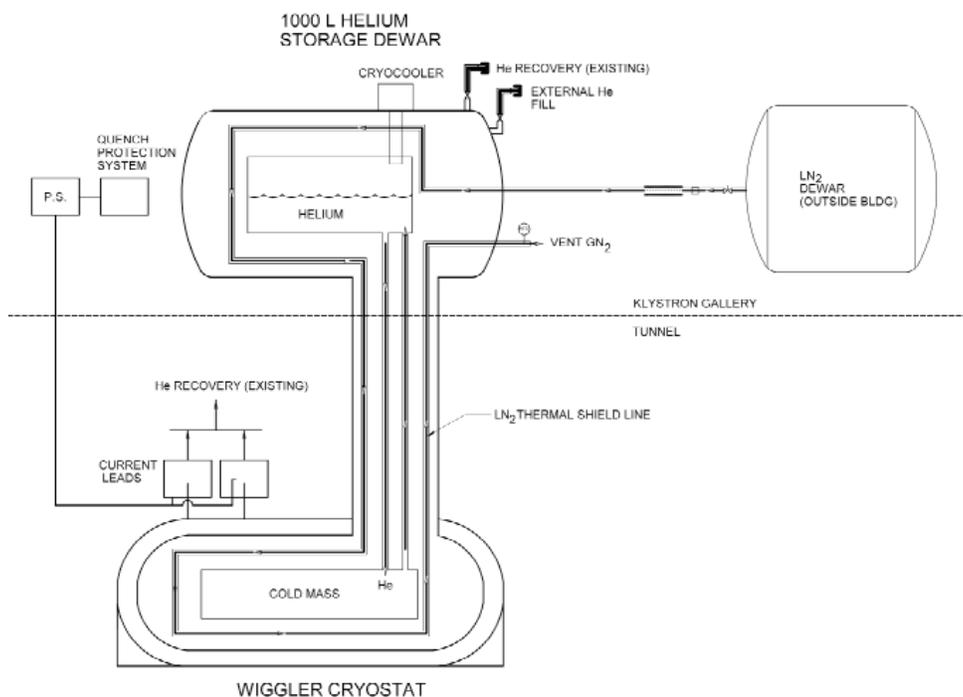


Figure 5: Schematic layout of the cryogenic system. The floor of the SLAC tunnel is about 10 m below the floor of the klystron gallery.

The magnet sits in a bath of saturated liquid helium at 4.2 K and 1 Bar. This helium is supplied by a 1000 liter helium dewar located in the klystron gallery immediately above the wiggler. The 1000 liter dewar is filled periodically by the SLAC Cryogenics group. A vacuum insulated transfer line connects the storage dewar and the magnet cryostat. In order to reduce the heat leak, and thus the liquid helium consumption rate, the storage dewar, transfer line and magnet cryostat will all contain a thermal radiation shield operating at roughly 77 K. This will be cooled by the flow from a LN₂ storage dewar located just outside the klystron gallery and filled by the SLAC liquid nitrogen vendor.

Refilling the liquid helium storage dewar requires manpower and we would like to lengthen the time between the refills. In order to reduce the liquid helium boiloff (and

thus lengthen the time between LHe fills) a commercially available 4.2 K, 1.5 W cryocooler (either a pulse tube or Gifford-McMahon type) will be installed in the storage dewar to reliquefy some of the boiloff. All the helium gas that is not reliquefied will be recovered for use in the large SLAC helium refrigerators. The nitrogen gas will not be recovered but will be vented to atmosphere.

Table 5 shows the heat leak estimates based on this design. These are conservative estimates and will be refined as a detailed design is developed.

Component	Estimated Heat Leak (W)	Equivalent Liquid Boil off at 4.2 K (liters/hour)
Magnet cryostat	0.5	0.75
Transfer Line ¹	1.65	2.48
Storage Dewar ²		0.2
Current Leads ³		1

Table 5: Heat leak estimates for the cryogenic system.

1. Assumes 0.165 W/m. This is a conservative number. In comparison, the measured heat leak of the Fermilab Tevatron transfer is 0.033 W/m. Our transfer line is taken to be 10 meters in length.
2. Assumes 0.5% boil off per day for a 1000 l dewar
3. Assumes American Magnetics Inc. vapor cooled leads operating at current 100 % of the time

Total liquid boil off is 4.43 l/h but the cryocooler capacity is 1.5 W or 2.25 l/h so the net boil off is 2.18 l/hr. Assuming a 1000 l storage dewar that we refill whenever it drops below 200 l, we have to refill the dewar every 367 hours or roughly every 14 days. This frequency of filling is well within the current capabilities of the SLAC Cryogenics group. Another option might be to use 2 cryocoolers which would further lengthen the time between fills. Its worth noting that there will always be some loss of liquid helium due to the flow through the current leads (roughly 1 liter/ hr). Since the storage dewar is outside the tunnel, the filling can be carried out without interrupting LCLS operation.

The cryogenic system design is conservative and similar to proven systems at Fermilab, DESY and the MRI industry. Commercial equipment, such as current leads and cryocoolers, are chosen as much as possible. The storage dewar, transfer line and magnet cryostat are custom devices but are well within the state of the art.

Current leads

The original design of the Oxford/BNL wiggler included High Temperature Superconductor (HTSC) leads. Such leads have a essential zero $I^2 R$ heating, up to ~70 K, and very low thermal conductance, and can be made to be have much lower heat leak than conventional vapor cooled leads. However, the leads are also fragile and on the Oxford/BNL wiggler were in fact broken twice: once during shipment and during a quench on the Oxford/BNL wiggler. Consequently Oxford/BNL elected to dispense with the HTSC leads and switch to vapor cooled leads. As we will have to at least replace the leads for high current ratings, we should at least revisit the issue of HTSC leads, particularly if Oxford/BNL has come to some understanding of what caused the failures

and what to do about it. Nevertheless, the device can be made to work at acceptable heat leaks with conventional leads.

According to American Magnetics Inc., a set of 325 A vapor cooled leads with Nb₃Sn "bus bars" will consume at least 1.04 l/hr/lead pair assuming the current is at 325 A which is equivalent to about 0.75 W dissipated into the liquid helium. These leads will have 'bus bars' of Nb₃Sn which go from the liquid helium to the bottom of the vapor cooled lead. The bus bars run superconducting and help efficiency by delaying the I²R heating to a higher temperature than is possible with NbTi wire. If there is no current flowing, then the vapor flow can be reduced to 0.62 l/hr/lead pair. The Oxford/BNL coils run up to approximately 295 A, which implies a boiloff of 1 l/hr for the leads. The leads will probably consume helium at this rate 24 hours a day unless special provision is made to change the flow rate when the magnets are not powered. So the consumption of helium by the leads will be around 170 liter/week, or 3 weeks per 500 liter dewar. This will probably be the bulk of the heat leak of the device, assuming the transfer lines can be well made.

Quench Protection

Based on the Oxford/BNL design for the poles we expect the total stored energy at maximum excitation is estimated to be about 512 kJ. The current is about 300 A so the inductance is about 5-10 [3,4,5] H. RADIA calculations of a model of the Oxford/BNL wiggler give a peak field in the coils is estimated of 6.27 T at a current of 295 A. From these numbers and from reasonable guesses as to the properties of the superconducting wire estimates of various quench parameters can be made. See Tables 6 and 7. These calculations are very preliminary but indicate that the parameters are within reasonable bounds. The current margin is a bit low and a more accurate calculation of the stored energy is needed.

The peak temperature to which a hot spot might get during a quench is a very important design parameter. Ideally the hot spot should not exceed a temperature which will damage the coil, even if quench protection fails. The peak temperature depends on how fast the energy is dumped (determined by the inductance and the circuit resistance which is growing as a function of time), how fast the coil is cooled which is governed by the thermal conductivity and heat transfer characteristics of the helium interface, and especially by how fast the normal zone grows which depends on the heating rate and the specific heat of the coil.

The peak voltage on the coil is also an important design parameter. It can be controlled by the choice of the external circuit resistance, assuming an external circuit is switched in when a quench is detected. More resistance slows down the ramp rate, which is good for quench development, but raises the voltage across the coil. We have estimated that with an external resistance of 3.3 Ohms the maximum coil voltage is limited to 1 kV. It would be better if the peak voltage was below about 300 V because the breakdown strength of helium vapor is particularly low. Electrical breakdown through the helium is believed to be capable of causing damage to the insulation.

With a thorough quench simulation we can determine if active quench protection is needed. The Oxford/BNL wiggler has only passive quench protection consisting of diode-resistor networks in the cryostat placed across the coils. It is likely that this will suffice for the LCLS design. If not a typical quench protection system would consist of a 300 A mechanical switch and dump resistors. Such systems are not expensive or difficult to design.

Quench detection is probably desirable even if passive protection is adequate. Otherwise it would not be possible to tell which coil quenched and quench training will be impossible to interpret. It would be difficult to tell whether the same coil is quenching over and over, which might indicate a problem with that coil, or if successive quenches are caused by different coils, which would be indicative of normal training. Input to the quench detection system might consist of 24 voltage taps, one across each coil and the one across each lead. The voltages would be measured in such a way as to eliminate the inductive voltage generated by ramping the current and only see the resistive portion caused by a normal zone. The electronics to read and interpret the voltages and turn off the power supply and optionally fire the quench protection switch are not an off-the-shelf item. They have been developed at many labs and designs may be largely copied. However the interface to the SLAC control system will be unique. The voltages are usually recorded in a buffer for subsequent interpretation. Lead voltages are especially important to measure in order to get the optimal cooling rate and to protect against runaway. A table of quench calculation inputs and results is presented in Appendix 1.

Magnet Discharge Safety

The BNL/Oxford magnet has a maximum stored energy of 170 kJ and is protected by subdivision using internal cold diodes. The cold diodes are used to shunt current around quenching coils protecting them from burnout or excessive thermal stress. If this magnet were used for LCLS, it must be operated with all poles powered to 5.5 T on axis increasing the total stored energy to ~510 kJ. It must be assumed that the cold diode protection is inadequate for this factor of three increase in total stored energy. Therefore, replacement of all the cold diodes and rewiring of all the coils will probably be necessary if this protection strategy is employed. Detailed calculations must be repeated to understand and guarantee the safety of the magnet with its higher total stored energy.

One can consider other protection schemes, however. The classic method of protection is to detect a quench by voltage imbalance and quickly switch an appropriately sized resistor in series with the magnet. If such a technique were used for the BNL/Oxford magnet with 1/2 MJ of stored energy, a 38 ohm resistor would be required to limit the maximum hot spot temperature in the superconducting wire to 300 K. This would impose an unacceptably high 11.2 kV across the magnet terminals and 5.6 kV to ground with a center point grounded dump resistor. If an ideal constant voltage discharge instead of an exponential discharge were used, this would only drop the terminal voltage by

exactly one third to 7470 V. A specially designed resistor using metals with a high temperature coefficient of resistivity or special varistors can be used to approximate this constant voltage discharge.

If for some reason cold diodes were found to be unsatisfactory, other protection methods exist. These include safety leads, quench propagating electric heaters and "B dot" coils, closely coupled secondary windings and many others. Safety leads subdivide the coil but extract energy outside the magnet at room temperature. The penalty for using safety leads is increased heat load and mechanical complexity. Quench heaters are a classic method of protection, but require additional circuitry, increased heat load, and verification of their effectiveness. It is possible that the existing cold diodes could be sufficient for operation of the BNL/Oxford magnet at the 1/2 MJ level. They are probably not large enough to absorb the increased energy, but increased quench propagation velocities in the superconducting windings at the higher fields might be sufficient for protection. Only detailed calculations and/or testing could verify this.

If the BNL/Oxford magnet is not available to SLAC, but its overall magnet field design is used for a new coil, larger wire size and currents can be considered as a design option. With reasonable increases in wire size, voltages with a dump resistor are found to be still too high. Each coil of the BNL/Oxford design consists of an inner coil and outer coil with wire diameters of 1 mm and 0.7 mm respectively with an area ratio of two. With 1.75 mm and 1.25 mm wire diameters chosen for a new magnet, the area ratio would still be ~ two. The operating current would increase from 295 A to 940 A, and the inductance would fall from 11.7 H to 1.15 H. Using the same Cu/Sc ratio of 1:1 and peak hot spot temperature of 300 K requires a 4.9 ohm dump resistor and a peak terminal to terminal voltage of 4600 V. Cold diodes would still be the most likely candidate for magnet protection.

Mechanical Design

We assume that a workable design for the LCLS superconducting wiggler can be largely based on the Oxford/BNL wiggler. However, at this time the Oxford/BNL wiggler has not been delivered and the design documents and almost all drawings are proprietary. We expect that after acceptance of the wiggler by Oxford/BNL we will have access to the detailed design information, but for now many of the basic parameters must be inferred from information in published papers and conversation with Oxford/BNL personnel, or simply guessed at. The forces involved in running all poles at 5.5T are higher than any of the Oxford/BNL running modes; we must verify that these forces can be accommodated in that design, or if some improvements are required.

The planned location for the superconducting wiggler is shown schematically in the Figure 6. From magnetic edge to magnetic edge the distance is 3.15 m. The physical space available is less due to the fringe fields, coil ends, flanges, etc. The magnetic length of the Oxford/BNL wiggler is 2.23 m. Its physical length is not known but we believe that we can easily accommodate the warm to cold transitions and flanges in a space of about 0.5 m. Therefore a design with a physical length of 2.75 using the magnetic design

of the Oxford/BNL wiggler would appear to fit in the space indicated. There would be some space left over for the possibility of steering magnets or wire scanners. An additional 35 cm space can be provided by removing a pair of poles at the expense of about 10% decrease in energy spread.

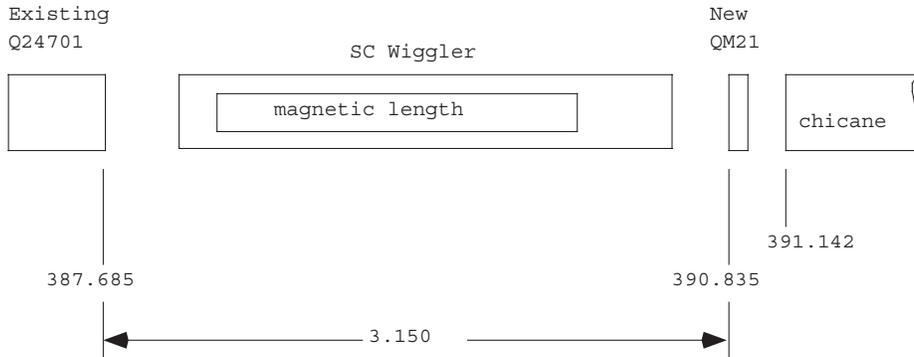


Figure 6: The physical constraints on the length of the undulator

The vertical or horizontal extents of the Oxford/BNL wiggler are not known. However one might guess that the width is safely within a ± 0.5 m of the beam line. The height could extend well above the beam line as the cryogenic utilities and current feedthroughs come from this side. Working out the details of the attachment of the cryogenic leads to the cryostat and the location of the valve box will be an important part of the design and may have to be modified from the Oxford/BNL design. For instance there may be an issue with having enough vertical room available to assemble a bayonet connection to the top of the cryostat.

The cold mass of the NLSL wiggler is about 500 kg. One can guess that the cryostat is of the order 500-1000 kg. The cryostat must be accurately placed relative to the beam especially in the vertical direction, so adjustable supports are required. Beam based alignment is not expected to be needed so adjustments need not be remotely controlled. There should be no external forces acting on the magnet from nearby iron or external magnetic fields. Gravitation forces should dominate with incidental loads from the cryogenic utilities, vacuum chambers, and current leads. There are many possibilities for the support structure and the design and implementation should be straightforward.

The outside of the cryostat remains near room temperature at all times, so thermal contraction of the cryostat or vacuum chamber relative to the supports is not an issue.

The Oxford/BNL wiggler has an elliptical warm bore of 59.5×19.5 mm. This will not accommodate a nominal 20 mm ID beam vacuum chamber, but will accommodate a squashed 16 mm inner vertical height chamber. If 20 mm vertical aperture is needed, there is a possibility of using the cryostat vacuum tube as the beam tube. This is often done in accelerator applications. There may be a need for some cooling to be added in this case.

Power Supply

The power supply for the wiggler is not likely to be very expensive or sophisticated. A modest voltage of 10 V is more than enough to supply 300 A without excessive lead drop. The ramp rate will be limited to 2 A/s with such a supply. It may take as much 5 minutes to ramp to full current, depending on lead resistance. Besides voltage and current the principle characteristics needed from the power supply are good stability, low ripple and freedom from trouble. Power supply glitches are particularly undesirable, because they can lead to quenching. In this application the stability requirement is weak because the magnet is supposed to produce no net deflection angle or offset. Ripple is largely filtered by the inductance of the magnet. It would be good to have a reasonably accurate current control so the magnet current stays where you put it. This can be accomplished with either Hall probe based current transducers or a dc current transformer at reasonable cost. The power supply should be self-protected with back-to-back diodes so that when the magnet is ramping down and a reverse voltage appears on the leads there is no damage to the supply

Testing and Installation

The wiggler system must work properly and reliably from the start. In order to ensure this, a significant amount of testing is required. In order to decouple the testing from other LCLS construction activities, the first set of tests will be done with the system in an experimental hall and not in its final linac position. These are the offline tests. Once the wiggler system is installed in its final location, a series of full system tests will be carried out to test operation and reliability.

It is expected the vendor will test the cold mass to verify the quench performance of the magnet.

The details of the testing will be developed during the design and construction of the system. However, typical tests include:

Offline Tests

- Leak testing of magnet cryostat, storage dewar and transfer line
- Hi Pot magnet, record all room temperature resistances
- Ramping of magnet to full design current
- Cycling of magnet from zero to full current and back
- Mapping of magnetic field distribution at full current
- Testing of the quench detection/protection system
- Quench magnet
- Testing of the magnet power supply
- Checkout of cryogenic instrumentation and control system
- Measurement of heat leak to the magnet cryostat, storage dewar and possibly the transfer line
- Testing of the cryocooler operation with the storage dewar

Online Tests

- Leak testing after installation
- Hi Pot of magnet after installation
- Checkout of quench detection system
- Checkout of instrumentation and controls
- Practice liquid helium fills from delivery trailer to storage dewar
- Extended time (weeks or more) operation of system at full current to verify proper operation and determine final liquid helium consumption rate.
- Quench magnet

The proposed schedule gives 6 weeks for installation of the system into its final location. This is fairly conservative. It does assume that any civil construction such as installation of a nitrogen storage tank outside the klystron gallery is already completed. Actually installing the wiggler in the beam line, aligning it, connecting the transfer line, current leads and instrumentation cables and leak checking is estimated to take 3 weeks. Frequent access to the tunnel during the on line tests will probably be required

Procurement Strategy and Spares

The superconducting wiggler is a custom magnet. Oxford Instruments has built a magnet very similar to what we need for Brookhaven National Laboratory (BNL), however, Oxford is no longer interested in building custom magnets. Other suppliers such as Danfysik or Accel might be interested in designing and building a magnet to our specification.

One strategy we might pursue would be to acquire the BNL/Oxford magnet and modify it for our use, by changing the current leads to allow full current for 5.5 T fields in 11 coils, and an appropriate current in the two end coils. It could be modified by Oxford, though they are very likely to be reluctant. It could be modified at SLAC, using commercially available current leads. If the magnet could be obtained at nominal cost, this is likely to be the strategy that would be quickest to implement and cost least, though it is not at all trivial. The LCLS group will have to act promptly to arrange to acquire the magnet, if this option is to be pursued.

Our proposal is to develop a complete detailed design for the superconducting wiggler and its subsystems at SLAC and have the device built by outside vendors. There are a number of advantages to this method.

1. Doing the design ourselves allows us to develop a complete understanding of the equipment. This knowledge will be invaluable when it comes to installation and operation of the wiggler. Even if we went to a strategy that involved writing a specification for design and construction by the vendor we would have to carry out a fairly detailed design to ensure that we are getting exactly what we need. The superconducting wiggler is by no means a standard industrial component. Simply copying the existing Oxford/BNL

design with out fully understanding the engineering decisions behind it is risky

2. The wiggler system will have to interact with laboratory space limitations, utilities, cryogenics, safety and controls. Doing the design in house allows us to control these interfaces directly rather than try to communicate them to an outside vendor. Build to print provides a simpler interface solution.
3. Keeping the design in house allows us to control the design schedule and allocate resources directly to meet that schedule.

The design would be carried out by current SLAC staff mainly: W. Craddock (EFD), J. Weisend (EFD), R. Carr (SSRL), J. Welch (SSRL) and R. Rogers (EFD) Additional resources can be brought in as required. The design would stress the use of proven commercial components (e.g. current leads and cryocoolers) as much as possible

This approach means that the risk of creating a design that meets all the requirements is assumed by SLAC. We don't believe that this is a significant problem. While the superconducting wiggler is not a standard device, the design requirements are within the current state of the art. A good conservative design can be created that has a high probability of success. Given the cost and importance of the project it would be irresponsible to not have an external review of the design. A series of formal reviews are planned (see the attached project schedule). Possible members of the review committee include:

A.D. MacInturff - LBNL
S. W. Van Sciver – National High Magnetic Field Laboratory
T. Peterson - FNAL
G Ganetas - BNL
J. Zabasnik- LBNL
A. Devred -CEA Saclay
S. Wolff - DESY

All of these people have outstanding reputations in the field of superconducting magnets and cryogenics and would provide a reliable review of our design. Once the design is complete, there a number of laboratories and vendors that could build all or part of the system. These include: Accel, Danfysik, Fermilab, Brookhaven, the National High Magnetic Field Lab and others. It may well be that different vendors build different components. For example, the storage dewar may well be built by a different firm than the magnet itself. Off the shelf components, such as current leads and cryocoolers, will come from their suppliers.

An important issue is whether we need to include plans for a complete spare wiggler or to what extent spare parts are needed in order to not put the performance of the LCLS at an unacceptable risk. Generally superconducting magnets have proven to operate very reliably in accelerator facilities all over the world, despite the environmental hazards of

radiation, beam loss, high voltage, high power RF, dampness, etc. Most of the down time expected with a superconducting magnet system will be due to cryogenic or power supply problems, which do not require long down times to fix. For example an extended power outage will cause a loss of helium and may take a shift to recover from. However, there have been occasional failures of superconducting accelerator magnets, and magnets can be destroyed by accidents, so there is a chance that the wiggler could fail during service. The risk is not numerically known but it is in our opinion similar to the risk to a typical normal conducting large magnet such as the chicane magnets.

Some failure modes of the superconducting wiggler could take a significant amount of time to repair. The main difficulty is that the complexities are all buried inside the cryostat, so to get to work on any part requires opening the cryostat and afterwards sealing it back up. The cryostat can and should be made to accommodate such procedures, but it is nevertheless a slow and uncertain business and leaks are often a problem. The worst imaginable case is an open coil. The wiggler will be designed to be self protecting against excess temperature and voltage during a quench, so it is not clear how a coil could burn out even if the quench protection system failed, but it is instructive to consider this case. If a single coil is damaged beyond repair, it could be replaced with a spare coil in a relatively modest amount of time, perhaps two weeks given lots of overtime. The repair could probably be made in situ if needed. Most of this time would be to open and seal the cryostat. Another day or two would be needed to cool down, test and re-train the magnet. However, if there were no spare coil, making a coil from scratch could easily take several months. Thus one level of preparation would be to have spare coils and other critical parts, especially parts that are epoxied after assembly.

An intermediate level of preparation is to have a spare cold mass --- that is, a duplicate set of coils assembled into their yokes. The cold mass could be cold tested and trained and set aside as a spare. This option may have a time savings compared with the coil replacement, which will depend on the details of the design, but it is not likely to be more than a few days advantage. It has a definite advantage in that replacing the cold mass should fix a large percentage of the problems even if the nature of the actual problem is not really known.

The highest level of preparation is to have a drop-in spare, complete with a cryostat. This would minimize the downtime, though it is hard to imagine such a swap could be made in less than a week since the old magnet would have to be extracted and the new magnet brought in and connected and cooled down.

Cost Estimate Summary

A detailed cost estimate for a SLAC manufactured magnet based on the BNL/Oxford magnet field design is given in Appendix 2. When SLAC burden and contingency is added, the cost of this wiggler magnet system is expected to be \$1.1 million. This does not include engineering and design prior to the official start of this project, installation on the beam line, design and safety reviews, and electrical power installation. BNL paid Oxford \$1.3 million for the magnet. This price did not include the power supply, LHe

dewar, LN2 dewar, LHe transfer line, the cryocooler and other miscellaneous items. If these items were added in to Oxford's price using the same estimates for the SLAC produced magnet system, Oxford's equivalent price would have been \$1.6 million.

A second detailed cost estimate using the existing BNL/Oxford magnet is also given in Appendix. 3. This estimate assumes that the existing current leads must be removed and replaced with higher current leads. It also assumes that the existing quench protection system must be modified somewhat due to increased stored energy. It also assumes that cold mass supports and coil structure are sufficient for SLAC's requirement of all poles operating at 5.5 T instead of 3 T. Assuming that SLAC receives the BNL/Oxford magnet for free, an additional ~ \$660 K would be needed to integrate the magnet into a complete magnet/cryo system. Thus the savings would be approximately \$440 K. It is probably fair to assume that the total savings to SLAC would be even less if a second spare magnet is required. If a spare were to be required, much of the engineering and design for a new magnet would be required to build a "carbon copy" of the BNL/Oxford magnet, or Oxford would almost certainly require substantial compensation for their proprietary design information.

Schedule

The schedule will depend on whether we acquire the existing Oxford/BNL wiggler and modify it or whether we decide to build a new device. If we do the former, it will take about 18 months, including rework, and parts not included in the existing device, such as power supply, cryogenics and transfer lines, and controls. If we do the latter, there is some uncertainty as to the total time required. The original Oxford/BNL device was ordered in 1995 and is still not finally delivered, so a pessimistic estimate would be something like 7 years. On the other hand, a comparable wiggler built-to-print by MAXlab in Sweden was just completed in 2.5 years.

The following proposed schedule is based on the current understanding of the wiggler design, for a device we build from scratch. We would expect to have a conceptual design after about 3 months, a critical design review after 6 months, and a final design review at the end of the one year design period. The total time is estimated to be 3.5 years.

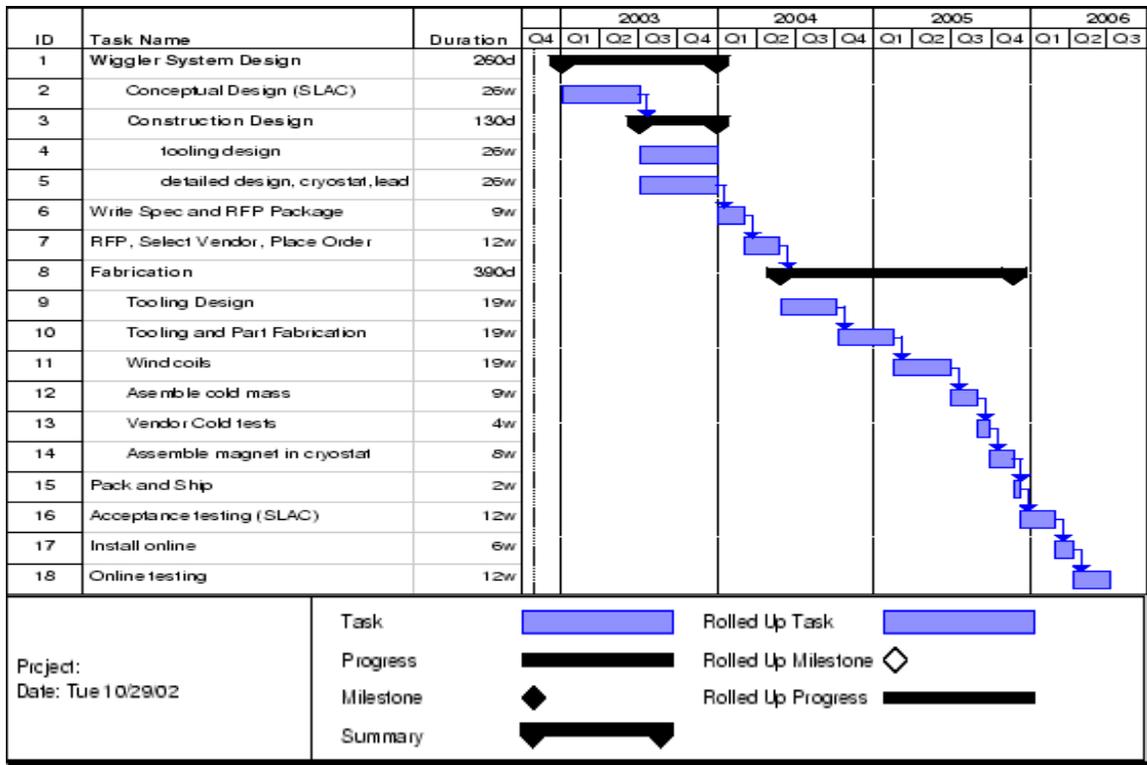


Figure 7: Design, Fabrication, and Testing Schedule

Acknowledgements

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Appendix 1: Quench Calculations

Input parameters for quench calculations	symbol	value	unit
wire bare diameter - inner coil	phi	0.967	mm
insulation thickness	t_insul	25	micron
Copper to SC ratio	CuSC	1	
thermal conductivity along wire	lambda_z	260	W/m/deg K
resistivity of Cu	rho	3.00E-10	Ohm - m
Critical current at 4.2 K, 5 T- Supercon 54s33	I_c_ref	675	A
Peak coil magnetic field at I_op	B_op	6.27	T
Bulk current density in coil block	J_block	285	A/mm ²
Bath temperature	T_b	4.5	deg K
Stored energy	E_stored	246682	J
Crit B at 0 deg	B_c0	14.5	T
Crit T at 0 B	T_c0	9.2	deg K
heat transfer coefficient	h_coef	1000	W/m ² /deg K
Specific heat Cu @ 5K	Cv_cu	2000	J/m ³ /deg K
Specific heat NbTi @ 5K, 6 T	Cv_nbti	9000	J/m ³ /deg K
Integral of J ² dt up t 100 K - typical	U_100	2.E+16	A ² s m ⁻⁴
resistivity at 100 K	p_100	4.E-09	Ohm m
reference temperature for quench heating	theta_0	100	deg K
coil length (half circumference)	l_coil_z	0.2	m
coil thickness (ave radial and azimuthal)	l_coil_r	0.075	m
Results of quench calculations	symbol	value	unit
Current in coil	I_op	295	A
wire area (bare)	A_w	0.73	mm ²
Fraction of bare wire area that is SC	eps	0.50	
Unit cell area	A_cell	1.03	mm ²
Jc(5T, 4.2K) wire dependent	Jc_ref	1838	A/mm ²
Operational current divided by bare wire area	J_op	401	A/mm ²
Operational current divided by unit cell area	J_op_bulk	285	A/mm ²
Operational current divided by SC area	J_op_sc	803	A/mm ²
Crit T at (B_op, J=0)	T_c	6.6	deg K
Crit B at (T_b, J=0)	Bc_T	10.2	T
T_tilda	T_t	0.3	deg K
B_tilda	B_t	1.3	T
Crit J at (B_op, T_b) - Morgan approx	Jc_bt	1214	A/mm ²
Crit I at (B_op, T_b)	Ic_bt	446	A

I _{quench} - linear approx for jc near op. pt.	I _q	339	A
Current margin	I _{margin}	15%	
B coil at I _{quench}	B _{q coil}	7.2	T
Current share temperature	T _{cs}	5.2	
Temp margin	T _{margin}	0.7	deg K
Wetted Perimeter	P _{wet}	0.0030	m
Heat generation per unit volume	G _{op}	2.4E+07	W/m ³
Heat gen. At critical current density	G _c	9.7E+07	W/m ³
Cooling rate at T _c	R _{cool}	2087	W
Stekly parameter, heat/cool	alpha _s	11	
Minimum propagating zone	l _{mpz}	15	mm
Average specific heat	C _{v ave}	5500	J/m ³ /deg K
resistivity @100 K averaged over bulk	p _{100 bulk}	5.E-09	Ohm m
v _{adiabatic} along wire	v _{adiab z}	14.1	m/s
Thermal conductivity perp to wire - kapton	lambda _r	0.22	W/m/deg K
v _{adiabatic} perp to wire	v _{adiab r}	0.4	m/s
ratio of v _{radial} / v _{along wire}	alpha	0.03	
Inductance of magnet	L _{tot}	5.7	H

Appendix 2: Cost Estimate based on Oxford/BNL design built from scratch

PURCHASED ITEM	COST BASIS	K \$	NOTES
Superconducting wire	70 K feet @ \$0.26/ft	18	Supercon 54S33, 2:1 Cu/SC, .04" dia, .042" formvar insulated
			~ 45 K feet required for winding, 25 K ft is practice and spare
Coil winding bobbins		10	
Coil outer structure		20	Not part of Oxford's magnet but included for a different concept
Internal LHe reservoir		1.5	
Electrical insulators & potting materials	estimate	2	G10, Kapton, epoxy, etc
Iron flux return (machined)		20	
Magnet thermal radiation shield		3.5	Includes copper sheets, standoffs and plumbing
High temp sc current leads	American Superconductor CS0500	3.999	500 Amp, ~ \$ 1 K more if lead is required to be sealed against
			He, ~ 2 sec burnout time, extra cost and heat load for > 2 s
Gifford McMahon 4 K Cryo Cooler	Sumitomo SRDK 415 DA	37.72	Air cooled 1.5 W @ 4.2 K + 45 W @ 50 K
Magnet Vacuum Shell		25	
Bellows, beam pipe, etc.	estimate	1.5	
Superinsulation + misc standoffs	estimate	1	
Sensors and feed throughs	Catalogs, (for all magnet systems)	12	Includes multipin magnet high voltage feed throughs
Temperature monitor	LakeShore Model 218E	2.484	Two 8 ch diode and RTD monitor/GPIB interface
PLC & PC hardware controls and inst.	estimate based on BaBar	11	Allen Bradley SLC 500 system + PC
PLC & PC software		3	LabView etc
Magnet low heat leak support system	worse case estimate	10	Inconel 718 tie rods with thermal intercepts + G10 + bellows
Custom integrated 1000 liter LHe dewar	Conservative estimate	100	Includes port for cryocooler, LN2 shield, 30 K shield,
			top feed through for LHe supply and bottom LHe withdrawl
			installed SC level probe and meter

LHe fill station	estimate	10	Transfer line and valves from refill dewar to integrated dewar
LN2 cryo system hardware	estimate	5	LN2 dewar assumed to be free surplus or rented
LN2 controls		4	Includes valves, level sensors, etc.
Integrated LHe transfer line		6	Shop fabricated, field welded
LHe and cold helium gas valves		6	
Helium recovery line	Uses existing LINAC recovery line	1	
Local vacuum pumping system	Leybold PT50 turbo pump unit	24.2	Two units, one at magnet and one at dewar
Vacuum instrumentation	Leybold	6.6	Two systems: CM31 controller with 3 sensors and cables
Vacuum fittings and piping	estimate	3	
Power supply	Estimate from Danfysik	17	Estimate based on 350 amp, 15 V unipolar, 100 ppm
			includes internal crowbar switch and dump resistor
Power cables, misc	estimate	1.5	From power supply at ground level to beam line
Quench detection hardware	estimate from M. Berndt (SLAC)	4	
MATERIALS		\$371,003	
SLAC BURDEN 6.75%		\$25,043	
CONTINGENCY 15%		\$59,407	Includes contingency on burden
TOTAL MATERIALS		\$455,453	
LABOR	Man months		
Magnetic field and force calculations	2		
Coil stability, safety calculations	1		
Coil stress analysis	1		
Design drafting coil, cryostat, supports	2.5		
Design, drafting transfer line	1		
Design, drafting overall layout	0.5		

Winding setup design	2		
Winding setup and practice winding	1		
Coil winding (in house)	2		Could also be wound by an outside vendor
Coil assembly and potting in containment	2		
Coil/Structure assembly and potting in Fe	1		
Surveying coil into vacuum shell	0.1		
Single coil testing	1.5		
Thermal shield construction&assembly	1		
Cryostat/Magnet/Support Assembly	1.5		
LHe transfer line assembly and install.	1.5		
LHe transfer station	0.5		
LN2 transfer lines	0.5		
Quench protection circuit	1.5		Design and in house fabrication
Instrumentation & Controls setup	2.5		
Controls programming	1.5		
Initial 4.5 K power test of cold mass	4		
Initial cooldown	1		
Low current checkout	1		
Full field commissioning	1.5		
Field measurements	1		
LABOR	36.6	\$366,000	\$ 10 K per month
SLAC BURDEN 35%		\$128,100	
CONTINGENCY 30%		\$148,230	Includes contingency on burden
TOTAL LABOR		\$642,330	

TOTAL COST		\$1,097,783	
NOT INCLUDED			
Installation in beam line			
Beam line mounts			
Design reviews			
Safety reviews			
Electrical power installation			
Interface controls with MCC			

Appendix 3: Cost Estimate based on rework of Oxford/BNL device

PURCHASED ITEM	COST BASIS	K \$	NOTES
Electrical insulators & potting materials	estimate	0.5	G10, Kapton (reworking internal splices)
Magnet thermal radiation shield		0.4	Reworking internal plumbing, etc.
High temp sc current leads	American Superconductor CS0500	3.999	500 Amp, ~ \$ 1 K more if lead is required to be sealed against He, ~ 2 sec burnout time, extra cost and heat load for > 2 s
Gifford McMahon 4 K Cryo Cooler	Sumitomo SRDK 415 DA	37.72	Air cooled 1.5 W @ 4.2 K + 45 W @ 50 K
Magnet Vacuum Shell	guess	2	Rework.
Bellows, beam pipe, etc.	estimate	1.5	
Sensors and feed throughs	Catalogs, (for all magnet systems)	5	For dewars and transfer lines
Temperature monitor	LakeShore Model 218E	1.242	One 8 ch diode and RTD monitor/GPIB interface
PLC & PC hardware controls and inst.	estimate based on BaBar	11	Allen Bradley SLC 500 system + PC
PLC & PC software		3	LabView etc
Custom integrated 1000 liter LHe dewar	Conservative estimate	100	Includes port for cryocooler, LN2 shield, 30 K shield, top feed through for LHe supply and bottom LHe withdrawl installed SC level probe and meter
LHe fill station	estimate	10	Transfer line and valves from refill dewar to integrated dewar
LN2 cryo system hardware	estimate	5	LN2 dewar assumed to be free surplus or rented
LN2 controls		4	Includes valves, level sensors, etc.
Integrated LHe transfer line		6	Shop fabricated, field welded
LHe and cold helium gas valves		3	
Helium recovery line	Uses existing LINAC recovery line	1	
Local vacuum pumping system	Leybold PT50 turbo pump unit	24.2	Two units, one at magnet and one at dewar
Vacuum instrumentation	Leybold	6.6	Two systems: CM31 controller with 3 sensors and cables

Vacuum fittings and piping	estimate	3	
Power supply	Estimate from Danfysik	17	Estimate based on 350 amp, 15 V unipolar, 100 ppm
			includes internal crowbar switch and dump resistor
Power cables, misc	estimate	1.5	From power supply at ground level to beam line
Quench detection hardware	estimate from M. Berndt (SLAC)	1.5	Assumes reworking of cold diodes
Travel to BNL for information		1.5	
Oxford support for modification and test		25	
MATERIALS		\$275,661	
SLAC BURDEN 6.75%		\$18,607	
CONTINGENCY 15%		\$44,140	Includes contingency on burden
TOTAL MATERIALS		\$338,408	
LABOR	Man months		
Transfer of info from Oxford and BNL	1		
Magnetic field and force calculations	0		Assumes these are available from Oxford for safety review
Coil stability, safety calculations	0		Assumes these are available from Oxford for safety review
Coil stress analysis	0		Assumes these are available from Oxford for safety review
Design drafting coil, cryostat, supports	1		Assumes small rework of internal components
Design, drafting transfer line	1		
Design, drafting overall layout	0.5		
Surveying coil into vacuum shell	0.1		
Thermal shield construction&assembly	1		Must remove and reinstall for new current leads
Cryostat/Magnet/Support Assembly	1		Must remove and reinstall for new current leads
LHe transfer line assembly and install.	1.5		

LHe transfer station	0.5		
LN2 transfer lines	0.5		
Quench protection circuit	1.5		Analysis of reworked cold diode scheme or new ext. dump res.
Instrumentation & Controls setup	2.5		
Controls programming	1.5		
Initial 4.5 K power test of cold mass	1.5		Reduction of 2.5 months since magnet already tested
Initial cooldown	1		
Low current checkout	1		
Full field commissioning	0.5		
Field measurements	1		
LABOR	18.6	\$186,000	\$ 10 K per month
SLAC BURDEN 35%		\$65,100	
CONTINGENCY 30%		\$75,330	Includes contingency on burden
TOTAL LABOR		\$326,430	
TOTAL COST		\$664,838	
NOT INCLUDED			
Installation in beam line			
Beam line mounts			
Design reviews			
Safety reviews			
Electrical power installation			
Interface controls with MCC			

