The potential role of cryogenics in insertion magnets

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Abstract. Most of the insertion magnets that are used for storage rings and free-electron lasers are room temperature permanent magnets.  Superconducting wiggler and undulator magnets have been built, but their performance has been limited by the engineering current density and stability of the coils. Superconducting undulators must have a small gap and cell length, which can be a hindrance even when the beam vacuum chamber is at room temperature. Beam heating is also an issue. To control, the heat leak at low temperature, the beam vacuum chamber should be cooled to a temperature between 20 and 40 K. Permanent magnets fabricated from Nd-Fe-B can be cooled to cryogenic temperatures with an increase in the magnetic field within the magnet gap. This permits the magnet gap to be reduced considerably when the vacuum chamber is at the same temperature as the permanent magnet. This paper discusses the cryogenic cooling of both superconducting and cryogenic permanent magnet wigglers and undulators.

1. Introduction
Insertion devices in storage rings create synchrotron light that can be used in various experiments outside the storage ring. Insertion devices fall into three categories, bending magnets that are part of the storage ring, wigglers, and undulators. A bending magnet that is an insertion device that affects the beam dynamics of the machine and as such they must operate in sync with the rest of bending magnets and quadrupoles in the machine. Wiggler and undulator magnets produce an alternating field and as such have little or no effect on the beam dynamics of the machine when their field is changed. An example of a bending magnet insertion device used for producing useful soft x-ray photon beams is the superbend magnet in the Advanced Light Source at the Lawrence Berkeley Laboratory [1].

Wiggler and undulator magnets are used to create brilliant photon beams within light source storage ring insertion devices and within free-electron lasers. The differences between a wiggler and an undulator are subtle. In general, an alternating field insertion device is wiggler when the bend in the half-cell (a section of the field at the same polarity) is greater than the synchrotron light generation angle $\gamma^{-1}$, where $\gamma$ is defined as the ratio of the accelerated electron mass to the rest mass of the electron. For electrons at 1.9 GeV, $\gamma = \approx 3725$. An alternating field insertion device is an undulator when the bend per half-cell is less than the synchrotron light generation angle. The light from a wiggler is incoherent, whereas the light beam from an undulator is coherent like that produced by a laser [2], [3], [4]. Coherence is determined by a factor $K$, which can be calculated using the following expression:

$$ K = \frac{eB_0\lambda_o}{2\pi m_ec} = 93.4 \hspace{1mm} B_0 \lambda_o $$

(1)

where $e$ is the charge of an electron ($1.6022 \times 10^{-19}$ C), $B_o$ is the peak induction in the solenoidal magnetic induction, $\lambda_o$ is the cell length (from the positive peak induction to the next positive peak induction), $m_e$
is the mass of an electron \( m_e = 9.1095 \times 10^{-32} \text{ kg} \), and \( c \) is the velocity of light \( c = 2.998 \times 10^8 \text{ m s}^{-1} \). The peak magnetic induction is given in T and the cell length is given in meters. When \( K \gg 1 \) the device is a wiggler because the light is incoherent. Coherence is sufficient when the product of \( B_o \lambda_o \) is \(< 0.01 \), because \( K < 1 \). Coherent light or x-ray beams are of great interest to material scientists.

In most of these devices permanent magnets made from oriented blocks from magnetized permanent magnet material such as Sm-Co and Nd-Fe-B. The permanent magnet material is arranged such that the magnetic field seen by the electron beam alternates. A single cell consists of two blocks of oriented permanent magnet material over a length of \( \lambda_o \). The arguments in favor of using permanent magnet material in an undulator are; the magnet is in air and there is no insulation required, there is an accessible way of installing the beam vacuum chamber into the magnet, and if beam chamber cooling is required, it can be water cooled within the insertion zone. For a device to be an undulator, the period \( \lambda \) must be short and the magnetic field must be low. High-field wigglers or undulators produce shorter wavelengths of light for a given electron-beam energy. One must have a short period length \( \lambda \) and a higher magnetic field \( B \) to produce shorter wave-length light in an undulator. This means that the gap between the magnet poles must be small \(< 10 \text{ mm} \). Hence any way of increasing the magnetic field while reducing the magnet gap is of interest to the light source and free-electron laser community [5]. Cryogenic magnets are potential solutions for achieving shorter wave-length of coherent light.

2. Beam heating at cryogenic temperatures
Since the magnet gap \( G_M \) is an issue with any undulator operating at low temperature, one must cool the beam chamber to temperatures \( T < 80 \text{ K} \), so that there is less distance between the magnet pole and the beam vacuum chamber \( y \). This means that the beam vacuum chamber beam heating becomes part of the magnet refrigeration load. There are heat loads on the vacuum chamber due to thermal conduction and radiation in the vacuum chamber from 300 K or 80 K, depending on whether the ends of the vacuum temperature are liquid nitrogen cooled. Figure 1 is a schematic of a beam chamber in a magnet.

![Figure 1](image)

**Figure 1.** A schematic of the undulator beam chamber. \( G_M \) is the magnet gap. \( G \) is the vacuum chamber gap. The beam gap \( G = G_M - 2y \). The MLI insulation space is \( y - h \), where \( h \) is the tube thickness.

Beam heating is due to currents induced on the beam tube inner surface due to the passage of electron beam bunches. The induced currents are within a skin depth of the inner surface of the bore tube. There are two skin depths to be considered the ordinary skin depth [6] and the anomalous skin depth [7]. The ordinary skin depth varies as the square root of the bore tube material resistivity \( \rho \) and the frequency of the beam \( \omega \). The anomalous skin depth, which isn’t a function of \( \rho \), kicks in when the ordinary skin depth is less than the mean free path for the electrons flowing in the metal lining of the beam tube. The anomalous heating skin depth represents the lower limit for the beam heating in the beam tube. For the range of RF frequencies of interest for beams in light sources, the ordinary skin depth applies at beam tube \( T > 70 \text{ K} \). For low temperatures \( T < 50 \text{ K} \), the anomalous skin depth effect may apply depending on the residual resistance ratio (RRR) of the material that lines the beam tube inner surface, assuming that this material is at least one skin depth thick. An example of material that might line a beam tube is annealed 1099-Al inside of a 6061-T4 beam tube. This layer of Al reduces the beam heating because it has a much lower \( \rho \) than the 6061-Al that makes up the rest of the beam tube.
The beam heating per unit length of a light source beam tube that is at a high enough temperature for the ordinary skin depth equation to apply can be calculated using the following expression [7]:

\[
P \frac{P}{L} = \Gamma \left( \frac{3}{4} \right) \frac{2^{3/2} c M \mu^{1/2} \rho^{1/2} c^{1/2} I^2}{8 \pi^2 R L^{3/2} m}
\]  

(2)

where \( C_M \) is the machine circumference; \( \mu \) is the permeability of the beam tube material; \( \rho \) is the electrical resistivity of the bore tube material, \( c \) is the velocity of light, \( I \) is the beam current in the storage ring; \( R \) is the radius of the beam tube \( (R = G/2) \); \( L_B \) is the beam bunch length and \( m \) is the number of beam bunches in the ring. \( \Gamma(3/4) \) is the gamma function of 3/4, which equals 1.2254.

The anomalous skin depth, which for high RRR beam tube material is in a layer at least one skin depth thick, yields lower beam heating than the equation above [7]. For estimating purposes one can use the equation above, but the actual beam heating can be worse if the material inside the beam tube is rough or cracked. It is best to test the proposed beam tube section in the beam to get a correct beam heating value [8]. Beam heating must be removed at a temperature greater than 20 K.

As one can see from equation 2, the beam heating is inversely proportional to the radius of the beam tube or the gap between flat sections of the beam tube. This radius (or gap) will be small in an undulator used to produce short wave length light. Making the beam tube gap smaller also increases the chance of beam scraping and potential radiation damage to the magnet whether it be a superconducting magnet or a cryogenic permanent magnet.

3. Cooling a superconducting undulator at 4.0 to 4.5 K

Superconducting coils in wigglers and undulators have the potential for increasing the amplitude of the periodic magnetic induction on axis, when the magnet gap is small [9]. For a given magnet gap, the larger the current density in the superconducting coils, the higher the amplitude of the periodic magnetic field on axis. Over a wide range of currents, the amplitude of the gap field is linear with coil current density for a given magnet gap and period. Over the same range of currents, the peak field in the superconducting coil goes up with the coil current density, but is independent of the magnet gap [10]. As the period of a wiggler or undulator goes up, the peak induction in the superconductor goes down.

The key issue with superconducting undulators is increasing the undulator coil current density. In Nb-Ti coils the conductor copper to superconductor ratio must be low (< 1). The superconductor \( J_C \) must be > 3000 A mm\(^{-2}\) for a coil current densities > 1200 A mm\(^{-2}\). Race track coils made from Nb-Ti with a low copper to superconductor ratio often train in a dipole that is potted [11].

![Figure 2. A Section of an LBL Nb₃Sn test coil for a small-gap FEL undulator [12].](image)

Several groups are looking at Nb₃Sn, which can have a current density of > 6000 A mm\(^{-2}\) at 5 T and 4.2 K in the non-copper sections of the conductor. One such effort is at the Lawrence Berkeley
Laboratory. Figure 2 shows a Lawrence Berkeley Laboratory test coil for an undulator for a free-electron laser. Nb$_3$Sn has had stability problems at high currents because the effective filament size is too large for intrinsic stability [13], and there isn’t enough copper in the conductor for dynamic stability [14]. Nb$_3$Sn dipoles are difficult to fabricate, because of the wind-and-react process and the brittleness of the conductor after reaction. Nb$_3$Sn dipole coils must be potted after reaction. Magnet training is much worse when the filament size is above the intrinsic and dynamic filament diameter. Magnet designs that must depend on helium in the superconductor for magnet stability present extra challenges in the cryogenic cooling system design. This will be explained later.

Cooling of an undulator magnet can be done using a large refrigerator at 4.5 K or two-stage coolers operating at around 4.3 K. If the undulator is part of a string of undulators or close to a central refrigerator, one can cool the magnet and cool-down the magnet using a forced two-phase flow circuit that is like that used or large detector magnets [15]. The problems with the central refrigeration are the magnet operating temperature is close to 4.5 K and there must be a source of gas at ~40 K for shield cooling, lead cooling and beam vacuum chamber cooling. The extra heat load from a vacuum chamber at 40 K is acceptable because the cooling at 4.5 K is not as limited as it would be using coolers.

For undulators that are isolated, coolers are a way of cooling and cooling down the magnet coils, the shield, the leads and the beam vacuum chamber [16]. The cold mass per unit length is ~200 kg m$^{-1}$ plus any support beam that is used to position and coils and prohibit the magnet from sagging. There are a couple of things to consider when selecting coolers for cooling an undulator and their position with respect to the undulator magnet coil. They are; the orientation of the cold head with respect to gravity, the magnetic field at the cooler [17], the magnetic field where the HTS leads are located [18], cooler maintenance schedule, and cooler vibration. Vibration is never mentioned in the literature, but when the ALS was being designed for the Berkeley site or a site at Stanford, measurements of ground motion vibrations was measured at both sites. Of the greatest concern were ground motion vibrations at frequencies below 20 Hz [19]. The author doesn’t know if this is still important factor.

In theory, one can use two-stage GM coolers or two-stage GM pulse tube coolers. GM coolers can produce cooling with the cold head at any orientation; a pulse tube cooler must be vertical with the cold end down. GM coolers are more sensitive to magnetic fields near the cold heads than pulse tube coolers. Because GM coolers have moving pistons, they produce over two orders of magnitude vibration than pulse tube coolers of the same capacity. GM coolers require more frequent maintenance than pulse tube coolers. The maintenance of a GM cooler often requires disassembly of the cold head, which is not required on a pulse tube coolers. Commercial GM coolers have a lower capital cost than commercial pulse tube coolers. Commercial GM coolers are also more efficient than the pulse tube alternative.

In a superconducting undulator, the coils don’t move while they are cold. The coils are attached together as shown in figure 2. Changes in the alternating magnetic field within the undulator are made by changing the magnet current. The support system is simple. An 800-mm long superconducting prototype undulator built at SINAP in Shanghai, used a self-centering tension-band support system for a cold mass of 160 kg [20]. A superconducting undulator support system should have a resonant frequency well above the vibration frequency of the coolers (0.8 to 1.0 Hz for commercial coolers). An alternative cold mass support system could be like the compression cold mass supports for Tevatron and LHC dipole magnets. The first type of support can put the magnet center in the correct position within 100 μm; the second type of support may require an adjustment of the two-coil package after cooling.

If the undulator coils are potted, one can cool the coils by conduction to a copper plate that is cooled with two-phase helium in tubes attached to the plate. The other place where the coil can be cooled is through a tube that runs down the center if the coils and through the iron. The two-phase helium is circulated by natural convection through thermal-siphon cooling loop like the one used on the Michigan State cyclotron gas-stopper magnet [21]. Two such circuits are shown in figures 3 and 4. With good cryogenic fabrication and assembly technique, the 4 K heat load should be < 3 W m$^{-1}$ of undulator length provided the shields and intercepts are at < 50 K. If liquid helium in the winding is required to stabilize the superconductor, there must be a helium vessel between the magnet pole and the beam vacuum chamber. For a given G this will add another 4 to 6 mm to the magnet gap $G_m$.  


The beam chamber can be conduction cooled using two coolers like the Cryomech PT415 coolers or an equivalent cooler from Sumitomo, which can deliver from 40 to 70 W between 20 to 35 K [22]. The first-stages of the beam tube coolers should be connected to the shield, the cold mass support intercepts and the thermal intercepts for the HTS leads. The magnet leads may carry currents as high as 1 kA depending on the conductor used in the magnet. At 1 kA, the 50 K lead load is ~110 W, but the lead heat load to the cooler first-stages can be reduced by a factor of four by intercepting most of the copper lead heat into the liquid nitrogen intercept at ~80 K. The use of a liquid nitrogen intercept may permit one to reduce the number of coolers used or one can shut off one cooler, which can become a stand-by cooler. If more cooling is needed for the shield, leads and beam tube, one can use an additional large single-stage GM cooler [23] like a Cryomech AL-325 that can deliver 105 W at 20 K, 140 W at 30 K or 195 W at 40 K [24]. The potential problem with using this cooler is vibration. Vibration due to GM coolers is an unknown, even though LBL used a GM coolers to cool the Superbend magnet at the ALS. Vibration was not a problem in this application [25].

When the length of a single insertion device exceeds 5 or 6 meters, one should consider using a central helium refrigerator such as the 2016 version of 1400 refrigerator originally developed in the 1970’s. The capital cost of the refrigerator is less than 12 to 15 coolers and this machine will produce 80 to 100 W at 4.5 K (depending on the compressor used), liquefy 1.00 to 1.25 g s⁻¹ of helium at room temperature or any combination like 50 W of 4.5 K cooling plus 0.6 g s⁻¹ of liquefaction (gas flow to room temperature). The compressor can provide mass flows to the magnet up to 5 g s⁻¹ during a cool-down the magnet, the beam tube and the magnet shields. Using a conventional type of refrigerator can simplify the cryostat design and fabrication, and thus reduce the magnet capital cost. If HTS leads are used between 4.5 K and 80 K, one can cool the beam tube and the shield before the gas is used to cool a pair of 1000 A leads from 80 K to 300 K.

![Figure 3](image1.png) **Figure 3.** This is a thermal siphon cooling circuit off a liquid helium tank. Helium to the tank comes from a re-condenser or a refrigerator at 4 K [25].

![Figure 4](image2.png) **Figure 4.** This circuit cools-down and cools a 4.4 K magnet with a two-stage cooler. This circuit can contain very little helium [26].
## 4. Cooling a permanent magnet undulator to 80 K

It has long been known that the magnetic field generated by permanent magnet materials is a function of temperature. Cooling some classes of permanent magnet materials to cryogenic temperature will increase in remnant field [27]. Other materials such as SmCo$_5$ and Sm$_2$Co$_{17}$ can be baked to 120 C (for vacuum reasons) if the magnet is in the beam vacuum, but these materials lose their remnant field at low temperatures. Permanent magnets made of Nd$_2$Fe$_{14}$B and Pr$_2$Fe$_{14}$B will have higher remnant fields down to 140 K. [28]. Below 140 K, Nd$_2$Fe$_{14}$B undergoes spin reorientation causing the remnant induction to go down as it goes below 140 K (in a way like SmCo$_5$ or Sm$_2$Co$_{17}$). Pr$_2$Fe$_{14}$B will continue to improve below 100 K (see figure 5). If these materials have a coercivity > 2600 kA m$^{-1}$, the magnet can be baked to 120 C. Many of the Pr based permanent magnet materials have a coercivity that is < 2000 kA m$^{-1}$ at 300 K, which means they can’t be baked to 120 C.

If there is a separate beam vacuum chamber, the permanent magnet material in the undulator does not need to be baked. The presence of a beam chamber between the magnet poles increases that magnet gap $G_M \sim 1.5$ mm. If the beam vacuum is separated from the LN$_2$ cryostat vacuum, one can use standard types of superinsulation to reduce the 80 K heat load and one can cover all the surfaces with aluminized Mylar tape to reduce the emissivity of the surfaces within the cryostat. The required beam vacuum in the insertion device depends on whether the device is part of a storage ring or in a separate single-pass free electron laser [29]. The vacuum requirements for a storage ring <10$^{-8}$ Pa (~10$^{-11}$ torr). For single-pass FEL, the vacuum must be <10$^{-6}$ Pa (~10$^{-9}$ torr). A magnet that is the storage ring vacuum must be baked. The FEL vacuum is more forgiving, so one may get away without baking the magnet.

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**Figure 5.** The ratio of the undulator peak induction at a temperature T with undulator peak induction at 300 K.

**Figure 6.** A typical undulator magnet made by a commercial company.

The ratio of the peak inductions of an undulator magnet at a temperature T less than 300 K with the peak induction at T = 300 K. At temperatures > 240 K, the Pr$_2$Fe$_{14}$B undulator peak inductions decays faster than the Nb$_2$Fe$_{14}$B magnet peak induction. The reason that this is true is that the Pr-Fe-B material has a lower curie temperature than the Nd-Fe-B material (330 C versus 585 C) [23]. The remnant induction of the two materials is nearly equal a 140 K [24]. The ratios shown in figure 5 were made on undulators fabricated at synchrotron SOLEIL in France. Unfortunately, the magnets that the two materials were used in were not identical. Part of the improved peak field ratio at 140 K may be differences due to the magnet design and fabrication. Pr-Fe-B permanent magnet material is better than the Nd-Fe-B material at liquid nitrogen temperature despite the difference in curie temperature.

Having the permanent magnet material in the beam vacuum isn’t the only problem with cold undulators. Figure 6 shows a typical commercial undulator circa 1998. The field in a typical undulator is adjusted by changing the magnet gap size $G_M$. There are other adjustments that can be made to control the polarization and other factors in the light generated by the undulator. These adjustments must be
made with the magnet cold, which complicates the cryostat design and the cold mass support system for the cold magnet. The instrumentation that verifies that the desired changes have been made is also more complex when permanent magnet material is cold.

A nitrogen cooled permanent magnet can be cooled using parallel natural convection circuits like the circuit shown in figure 3, which is shown as a liquid helium circuit. The nitrogen is stored in a tank above the magnet section being cooled. For a thermal-siphon circuit to work properly the liquid nitrogen must leave the bottom of the tank and the two-phase gas and liquid mixture must enter the tank in the gas space so that phase separation can occur. The nitrogen tank can be filled from a central source of liquid nitrogen or the nitrogen can be re-liquefied using a cooler. There are commercial coolers that will produce up to 1 kW of cooling at 80 K. If the cryostat heat load is low enough, there are commercial pulse tube coolers that can produce adequate cooling at 80 K. A pulse tube cooler may be preferable for vibration reasons. Cooling of a long series of nitrogen-cooled undulators for an FEL may come from a central liquid nitrogen plant.

5. Concluding comments
Cryogenic insertion devices have been discussed for more than twenty years. The first cryogenic insertion devices were superconducting bending magnet that produced light of much shorter wave lengths than had been previously possible. Superconducting wigglers and undulators have been under development for fifteen years. Cooling permanent magnet wigglers or undulators has also been under discussion for over fifteen years. During this same period, there have been improvements with room temperature permanent magnet wigglers and undulators. As with all things the addition of cryogenics to the mix increases the cost and adds questions about reliability.

Superconducting undulators may come into their own, if the niobium-tin undulator at LBL works as well as the recent tests show. Magnet stability is a problem with the niobium-tin conductors. These magnets will become important if the coils can be cooled to 4.5 K by conduction to a liquid helium flow circuit. If helium is needed in the coils for stability, the superconducting undulator is less attractive because the gap will be larger and there will be a question of coil reliability. ReBCCO HTS tapes are being studied for undulators. These tapes are potentially capable of coil current densities of greater than 2500 A mm$^{-2}$. There are stability issues with these conductors and quench protection is a serious issue. HTS coils at the current densities needed will operate at temperatures close to 5 K.

Permanent magnet undulators operating at 80 K are seriously being considered. Those that are looking at the option want to operate the magnets is the same vacuum as the beam. This is a challenge in an electron storage ring environment. This author would argue that having a separate vacuum chamber would be desirable for both the beam and the refrigeration requirements for the nitrogen cooled permanent magnet. In the case of permanent magnets, cryogenics adds a lot of complications that are not there when the magnet operates at room temperature. As with the superconducting magnet option, the permanent magnet would be cooled by conduction from a cooling system that is either a thermal-siphon cooling circuit or a forced two-phase circuit directly from a large tank.

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