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The Potential Role of Cryogenics in Insertion Magnets

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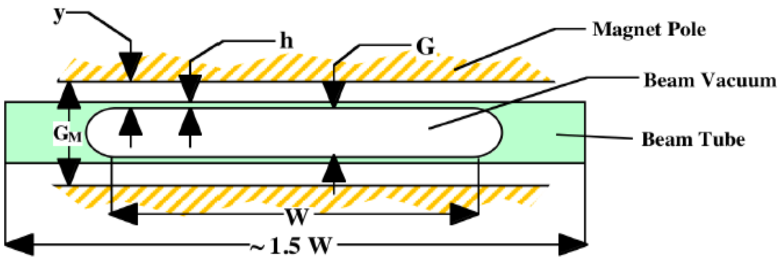
Types of Insertion Devices

- **Bending Magnets:** This type of magnet is part of the storage ring, so changes in this magnet affect the machine lattice. These magnets are like the 5.6 T superbend dipoles that were put three places in the ALS ring to produce keV range x-rays at the Lawrence Berkeley Laboratory.

- **Wiggler and Undulator Magnets**: These types of magnets have a field that goes from positive to negative as the beam moves down the magnet. There is no net bending, so the magnet has almost no affect on the performance of the storage ring.

Beam Tube and Beam Tube Heating

- A wide beam tube is shown below. The wall thickness is determined by the bending stress in the thin wall. The wall thickness t is determined by the yield stress of the wall material & the width W.



Wide Beam Tube Configuration

- There is RF beam heating caused by the bunches of particles going through the beam tube. See the equation below:

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

- The beam heating per unit length is a function of the beam current squared, the tube resistivity to the half power and the radius of the tube R = D/2.

S/C wiggler and undulator what are they?

For a simple planer undulator, the field on the beam axis B_y takes the following form;

$$B_y = B_0 \sin\left(\frac{2\pi z}{\lambda}\right)$$

where B_0 is the peak induction, and λ is the undulator period. The radiated photon energy e_n for n^{th} harmonic on z axis is given by;

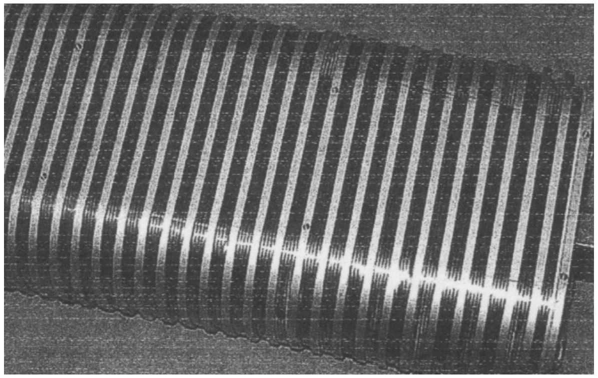
$$e_n(keV) = n\frac{9.498E^2(GeV)}{\lambda(mm)\left(1+K^2/2\right)}$$

where E is the electron beam energy and the deflection parameter K is defined by;

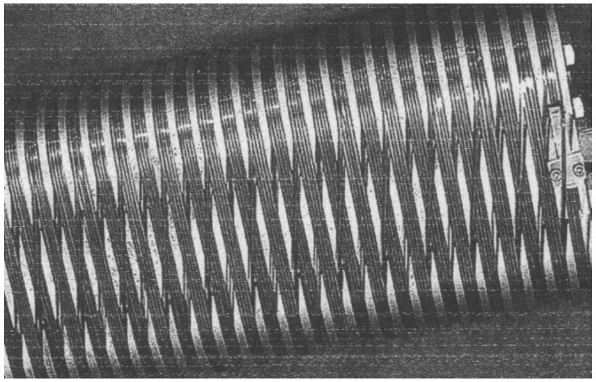
$$K = \frac{eB_o\lambda_o}{2\pi m_e c} = 93.4\ B_o\lambda_o$$

When k >> 1 the device is a wiggler. When $K \leq 1$, the device is an undulator that produces coherent light. When K = 1. For λ = 15 mm, B_0 is ~0.713 T.

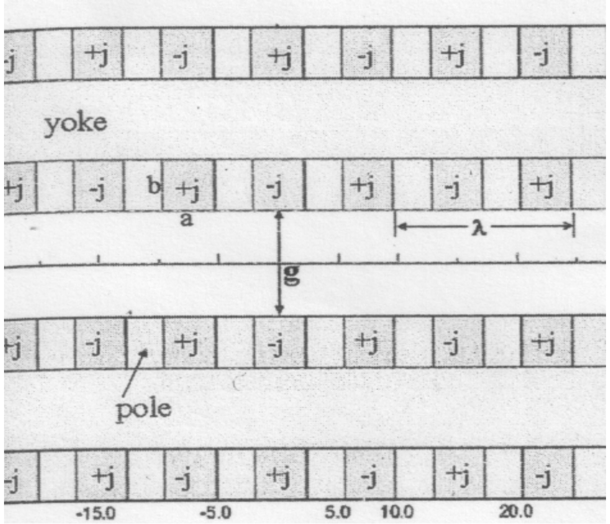
Planer S/C Undulator Coil wound with Nb-Ti



Gap side of the coils and iron pole pieces



Cross-over side of the coils and iron poles



Cross-section of the coils, iron poles, and the yoke

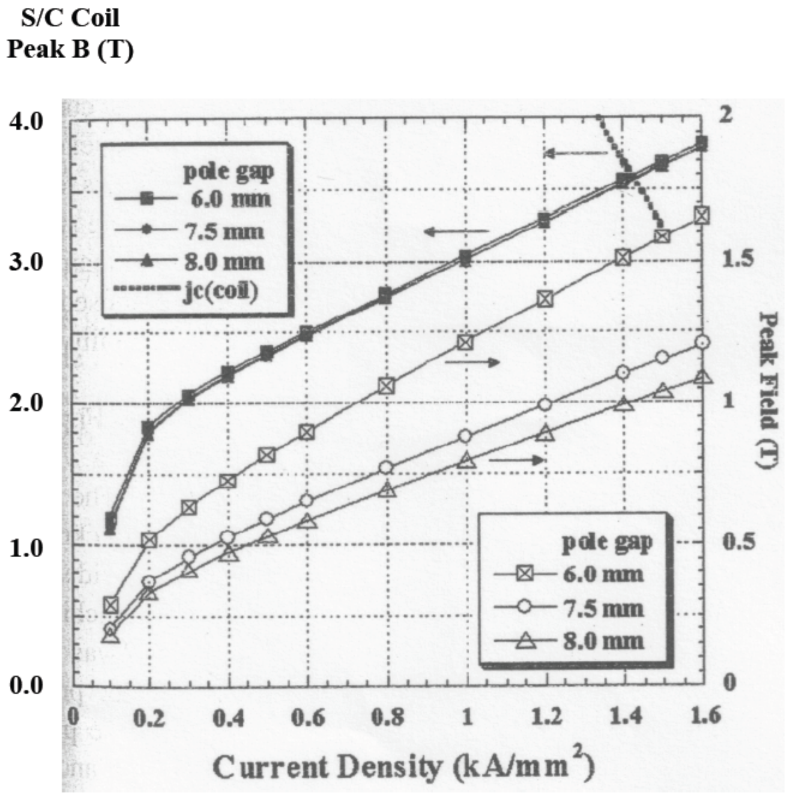
ANL S/C Undulator Parameters

λ= 15 mm
g = 8 mm
a = 4.32 mm
b = 3.89 mm

S. H. Kim, et al, *IEEE Transactions on Applied Superconductivity* 15, p. 1240 (2005)

Effect of gap on B_0 and peak B in the coil

- From the ANL studies of 2005, a decrease the gap between the poles results in a larger peak field on axis. The product of B and G_M is close to being a constant for given λ, it is more complicated than that.
- The coil peak field is not dependent on the magnet gap. It is only a function of the overall coil current density. The coil peak field is a function of the magnet geometry.
- In the ANL study, the measurements agreed with the calculations. At high current densities it took less energy to quench the coils.



S. H. Kim, et al, *IEEE Transactions on Applied Superconductivity* 15, p. 1240 (2005)

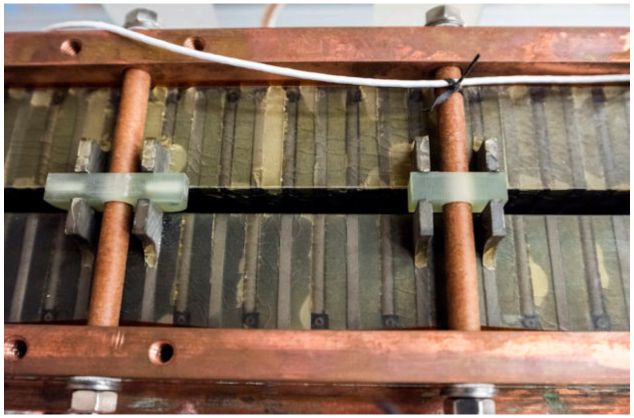
S/C Undulator Benefits and Problems

- If one wants to maximize the photon energy for a given electron beam energy one must shorten the period for an undulator.

- As the undulator period is shortened, the peak field along the undulator axis must be increased. In a superconducting undulator one must decrease the gap of the superconducting magnet or one must increase the coil current to get a higher field.

- Decreasing the magnet gap means that the vacuum chamber must be smaller and it must be close to the beam resulting in more RF heating of the vacuum chamber by the beam. RF heating means that the vacuum chamber must be warmer than the coils. Decreasing the beam aperture means that the danger of beam scraping is increased.

The LBL Test Nb_3Sn Undulator with Potted Coils

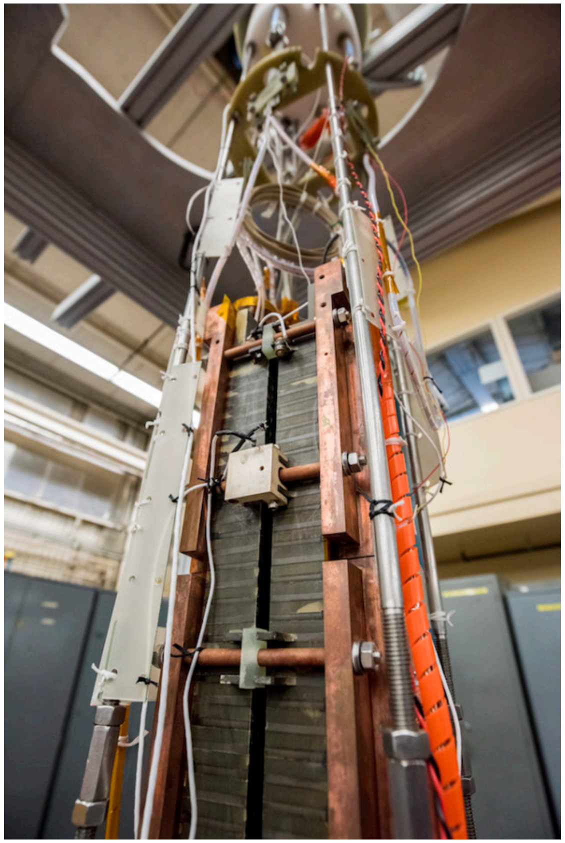


Coil Close-up

The magnet gap is 8 to 10 mm. The cell spacing is about twice the magnet gap. The coil shown was not designed for indirect cooling. LBL says that this is the best superconducting undulator they have built.

The coil is made with a finer filament Nb_3Sn, so the coil is more stable than the 2010 coil. This coil was tested in LHe. The cooling can be indirect, because the coil is potted after reaction.

Working on the Test Undulator



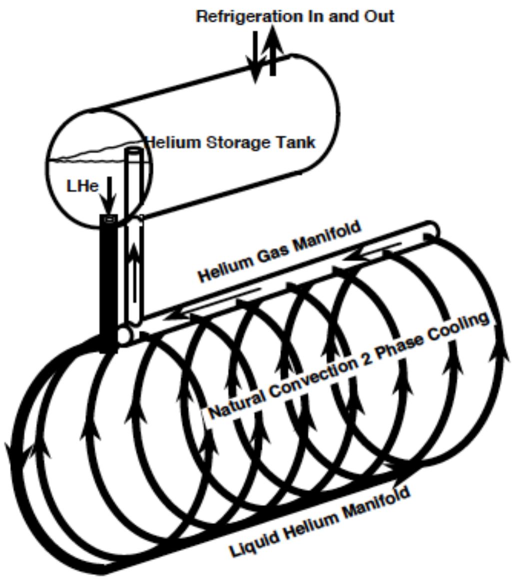
Lowering Undulator into Cryostat

Photos from LBNL June 2017

Colling and Coiling-down a Superconducting Undulator

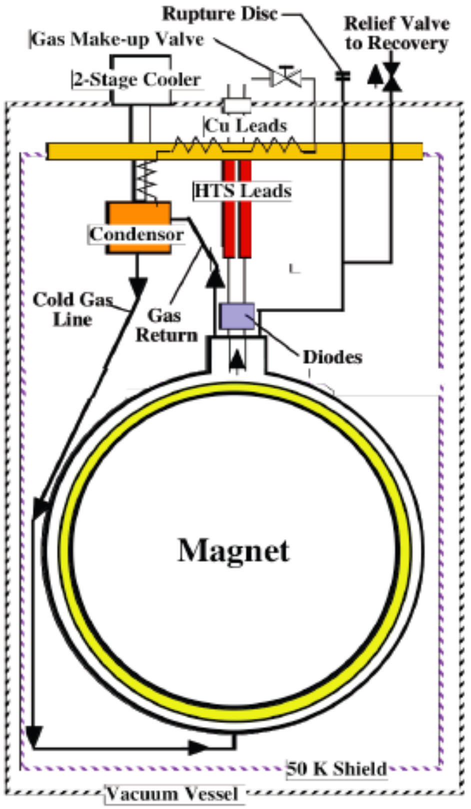
- **Cooling with 2-stage Coolers:** If the undulator is short (say <3-m) and there is no central refrigerator nearby, one can use small 1.5 W coolers to cool and cool-down the undulator. The number of coolers needed depend on both the 1st stage heat load and the 2nd stage heat load. The beam tube cooling can be provided by two stage coolers providing 20 to 35 W of cooling at 20 to 35 K. The first stage cooling can augment the shield cooling. A thermal siphon cooling loop can be used to distribute liquid helium cooling along the undulator.
- **Cooling with a large Refrigerator:** If the undualtor or a group of undulators is > 6-m long one should use a central refrigerator such a Linde 1400 machine, which produces 80 to 100 W at 4.5 K. This machine can provide cold gas to cool the beam tube, shield and the leads. If one uses this type of machine two-phase helium forced cooling can be used to cool and cool-down the undulator coils. The cryostat design is simplified.

Free-convection Cooling Loops for Cooling and Cooling-down a Magnet



Large Detector Magnet Cooling Loop

- The cooling loop on the left is a typical free-convection cooling system for cooling detector magnets. There is a separate cool-down circuit.
- The circuit on the right uses the same circuit to cool and cool-down a magnet using two-stage 4 K coolers to do the cooling. A large magnet at MUS uses this cooling method.



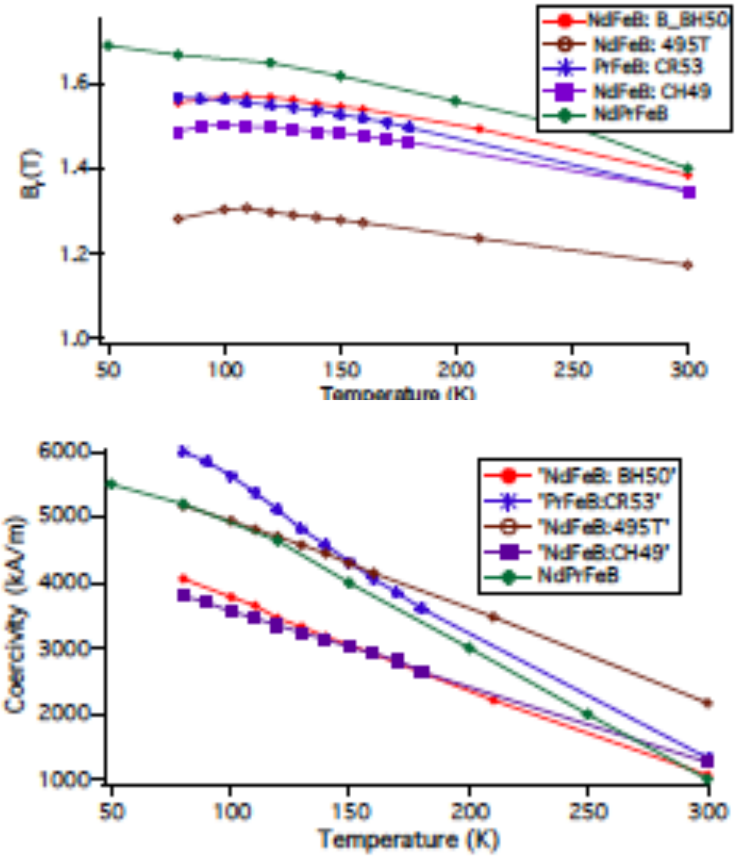
Cooling Loop to Cool and Cool-down

Cryogenic Permanent Undulator Magnet

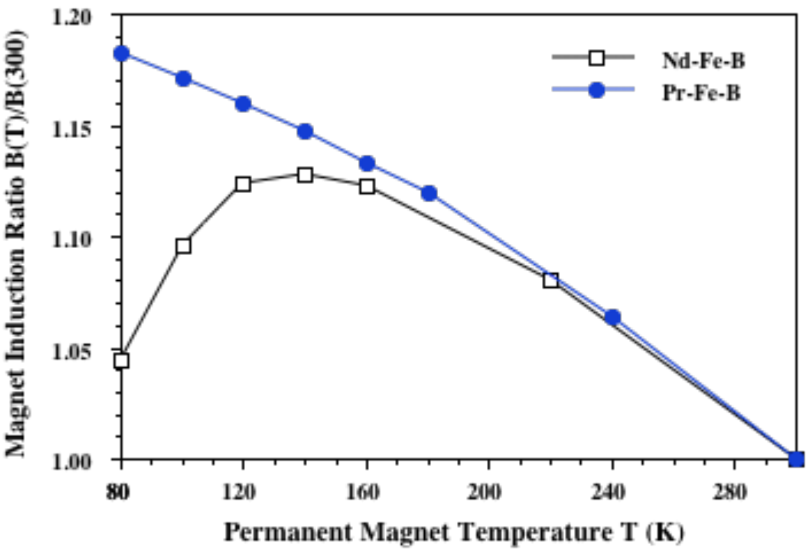
Typical Permanent Magnet Undulator

- Permanent magnet undulators oar made from oriented magnet materials. Samarium-cobalt is a common material used. This material has a strong remnant field and high coercivity. Other materials used are neodymium-iron-boron and praseodymium-iron-boron. $SmCo_5$ and Sm_2Co_{17} are not usable at cryogenic temperatures.
- The field change of an undulator with permanent magnets is done by changing the magnet gap. Since the cell period is fixed the only way to change K is to change the field.
- $Nd_2Fe_{14}B$ has an increasing remnant field from 300 K to 140 K. $Pr_2Fe_{14}B$ has an increasing remnant field down to 77 K. The coercivity of $Pr_2Fe_{14}B$ is low enough to prevent magnet baking up to 120 C. One may or not be able to bake a magnet a magnet so it can share the beam vacuum

The effect of the Permanent Magnet Material



M. E. Couprie, et al, Proceedings SPIE, p 951204 (2015)



C. Benabderrahmane, et al, IOP Journal of Physics, Series 425 p 032017 (2013)

- The top left figure shows the remnant field as a function of temperature. The bottom left figure shows the coercivity as a function of temperature. The right figure shows the gap field ratio at a temperature T divided by the gap field at 300 K

How does the permanent magnet material affect cooling?

- There is a desire to have the vacuum for the cryogenic permanent magnet undulator the same vacuum as the beam vacuum. This means the magnet must be baked to 120 C and the usual insulation systems can't be used. The heat leaks will be higher and the beam vacuum poorer. From a cryogenics standpoint one should use a separate beam vacuum from the cryostat vacuum.

- The fact that field change must be done by changing the magnet gap means the cold mass support system will be more complicated with increased heat load.

- The permanent magnet blocks, the support structure and the beam tube can be in a tank of liquid nitrogen with a nitrogen condenser. Forced flow or natural convection cooling can also be done. The beam heating is taken up by the magnet liquid nitrogen cooling system. One can use liquid nitrogen from a tank or one can re-condense the nitrogen that is used to cool the magnet.

Concluding Comments

- Superconducting undulators have the promise of higher fields and short cell length. This means that shorter wave length x-days can be created. Superconducting undualtors can be cooled using either coolers or a Claude cycle refrigerator depending on the length of the undulator. The beam tube must be cooled at a higher temperature than the coils. There will be a vacuum space between the beam tube and the coils. The coils must be powered so there is lead cooling that must be dealt with.

- Cooling a permanent magnet magnet unduator can increase the magnetic field by fifteen percent if the right magnetic material is used. From a cryogenic standpoint, it is not desirable to have the beam vacuum the same as the cryostat vacuum. Because changing the magnet gap changes the field, the cold mass support is more complicated. Cooling the magnet with liquid nitrogen is straight forward as long as the beam chamber is separate from the cryostat vacuum.