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MAGNETIC BREMSSTRAHLUNG RADIATION SOURCES USING THE MEISSNER EFFECT

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Abstract

Given the recent interest in high T_c superconductors, development of a radiation source that could exploit the novel properties of these materials has been suggested. One approach would be to use the Meissner magnetic field rejection phenomenon to create a high-field gradient region that could function as a source of magnetic bremsstrahlung. Physical structures containing superconducting components could serve as the basis for such magnetic bremsstrahlung devices as a Free-Electron Laser. A preliminary discussion of the merits and liabilities of the use of Meissner effect magnetic field manipulation in radiation source applications is presented. There are a number of reasons to believe that the Meissner effect will lead to an exciting new class of devices.

The discovery by Bednoriz and Müller [1] of a family of high T_c superconductors has engendered a great deal of speculation about applications that could exploit the novel properties of superconducting materials. The relatively high critical temperatures of the new materials make superconductivity much more practical; applications that were infeasible because of the prohibitive expense of superconductivity are now seemingly tractable. Recently, our group has been investigating the use of superconducting materials in the generation of electromagnetic radiation. Among the options we are considering is the use of the Meissner effect, *ie*, the diamagnetic property of superconducting material, to create a magnetic-field gradient region in which a moving charge is accelerated, resulting in the emission of bremsstrahlung radiation. Elementary geometries can be envisioned that would cause energetic electrons to follow curved trajectories leading to simple, compact synchrotron radiation sources. Further, periodic geometries can be constructed that will yield correspondingly periodic magnetic fields. Such fields are an integral component of most Free-Electron Lasers (FELs).

The fundamental idea for the Meissner-bremsstrahlung concept is depicted in Figure 1. A superconducting structure is inserted into an ambient magnetic field. The diamagnetic property of the superconductor causes perturbation of the magnetic field in the structure region. In this way the diamagnetisim of the superconductor is used to manipulate an ambient magnetic field to create a particular field profile in a manner analogous to well established techniques which use ferromagnetic materials. An energetic charge that initially travels along the ambient field lines will be transversely accelerated as it traverses the structure region. Electromagnetic radiation, commonly known as magnetic bremsstrahlung radiation, results from the transverse acceleration of the charge. Many radiation sources operate using this magnetic-bremsstrahlung principle, but by using the Meissner effect to generate the required magnetic field rather than permanent magnet or electromagnet field sources that are prevalent in existing devices, we gain three significant advantages.

- *Small Size*: Whereas conventional permanent-magnet structures are constrained in size by limitations on the sizes of the constituent magnets, the size of a superconducting structure is constrained only by limitations incurred in machining the superconducting material. Thus, use of the Meissner technique in creating small structures can easily be scaled well below the practical limits of either permanent magnets or electromagnets. This potential for creating small-field gradient regions is especially attractive for FEL applications, where the frequency of emission scales inversely with structure size.

- *High Field Intensity*: Since the new superconducting materials have exhibited relatively high critical field intensities [2], Meissner-bremsstrahlung sources using these materials can theoretically produce transverse fields comparable with those produced by permanent magnet or electromagnet structures for scale lengths in the centimeter range. For small-structure applications (*eg*, millimeter and submillimeter scale lengths), superconducting structures compare favorably with corresponding conventional sources.

- *External Field Source*: The ambient magnetic field source in the Meissner-bremsstrahlung concept is external to the structure. Physically separating the field source from the structure separates the engineering concerns of producing the ambient field from those of creating the structure. Hence, post-fabrication field tuning is possible, and the problem of permanent-magnet field variation is circumvented.

As with most engineering applications, exploiting the Meissner field- rejection phenomenon in a operational device also presents several potential problems:

- *Cryogenics:* Cooling the superconducting material to temperatures below its critical temperature is an inherent liability in a Meissner-bremsstrahlung device. For conventional superconducting materials, this is a prohibitively costly procedure. However, the required DC superconductivity has been demonstrated in the new high T_c ceramic materials at temperatures in excess of 120 K, with potential for significantly higher temperatures [5].

- *Diamagnetism:* While very high critical fields, *ie*, H_{c1}, have been predicted for single-crystal materials, in particular, YBCO [2], this diamagnetic behavior has been difficult to verify in experiment [6]. In addition, bulk samples of the ceramic superconducting materials often do not exhibit complete Meissner-field rejection. This behavior is attributable to the polycrystalline nature of most existing bulk material. Fortunately, the polycrystalline properties can be mitigated for small applications. For the purposes of our ongoing analysis, perfect diamagnetism has been assumed, but the eventual success or failure of the Meissner- bremsstrahlung concept will largely be determined by the quality of the high-field diamagnetism that can be achieved.

- *Surface Properties:* While to first order the radiation fields from a relativistic charge do not interact with a superconducting structure, the Lorentz-contracted Coulomb fields of the charge will excite RF surface currents in the structure. Since the RF surface impedance of the high T_c materials can be significant [7], ohmic losses may well prove to be an important loss mechanism in a Meissner-bremsstrahlung device. It has also been observed that the high T_c materials are susceptable to radiation dammage [8], further compounding the problems associated with field-surface interaction. A detailed analysis of these effect are deferred to later publication.

- *External Field Source:* Finally, intrinsic to this concept is the incurred expense of an external source for the ambient magnetic field. Many applications, such as an FEL undulator, require an intense, uniform magnetic field, and the desired intensity and uniformity of a superconducting undulator field is ultimately limited by the quality of the external field source. Active sources such as solenoids have traditionally been used in similar roles, and it is expected that they would function adequately for this application.

Using the Meissner effect to create a magnetic bremsstrahlung source or, specifically, a synchrotron source or FEL undulator holds significant promise for the development of exciting new high-frequency devices. Assuming perfect diamagnetic flux expulsion, preliminary calculations we have made predicts generation of peak transverse fields on the order of 30 percent of the source field intensity. This leads to the speculation that compact Meissner-bremsstrahlung source structures that produce *kG* transverse fields could be constructed using this technique. This result is predicated on the availability of reliable diamagnetic behavior at these *kG* field intensities.

Given the current interest in applications of synchrotron radiation, the Meissner field distribution from a single superconducting right-circular cylinder holds the potential for creating an inexpensive, high- frequency, low-power synchrotron radiation source. Figure 2 depicts the Meissner effect magnetic field profile from a superconducting right-circular cylinder. One of the topics we are currently pursuing is the evaluation of this concept in a practical device.

Our preliminary analysis indicates that the use of a superconducting structure to create a short-wavelength FEL undulator is also a topic that appears very promising. One can easily envision superconducting geometries such as an alternating set of superconducting cylindrical rods or a superconducting helix which could be used to produce either a linear or helical undulator field. Given in Figure 3 is a set of cylinders arranged in an alternating geometry and the resulting magnetic field distribution. Analysis of this linear undulator field indicates that the resulting undulator parameter, a_ω [3], compares favorably with parameters for millimeter-scale electromagnet undulators of similar size [4,9]. However, significant high-harmonic content to the transverse field off the structure axis is observed, and of course, this would detract from the operational efficiency of the structure. Whether this high-harmonic content is intrinsic to the Meissner-field manipulation concept or a property of the particular geometry in question is not known at this time. The preliminary analysis indicates the Meissner-bremsstrahlung scheme could have a significant impact in the area of compact FEL undulators, and that a vigorous persuit of this line of research is warranted.

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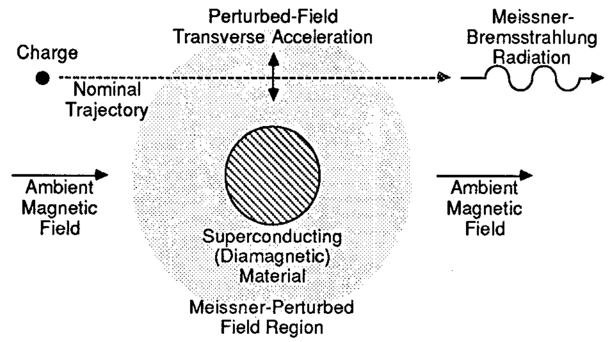

Figure 1. The Meissner-Bremsstrahlung Radiation Source Functional Concept

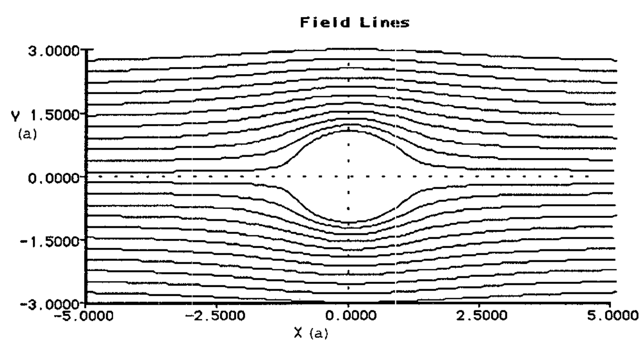

Figure 2. The Meissner-Perturbed Magnetic Field Profile of a Superconducting Right-Circular Cylinder

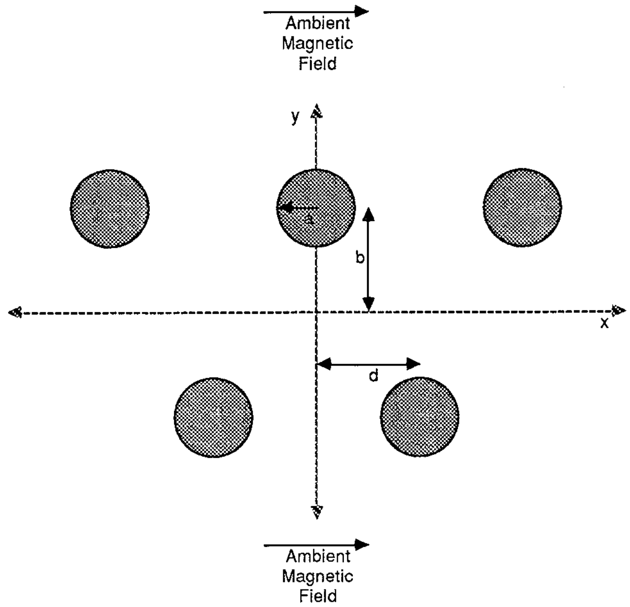

Figure 3a. The Meissner-Bremsstrahlung Linear Undulator Geometry

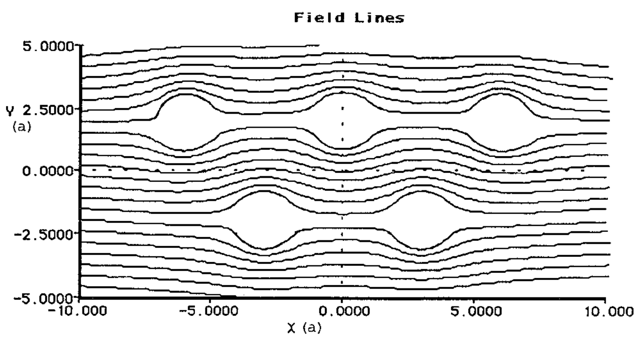

Figure 3b. The Linear Undulator Field Profile

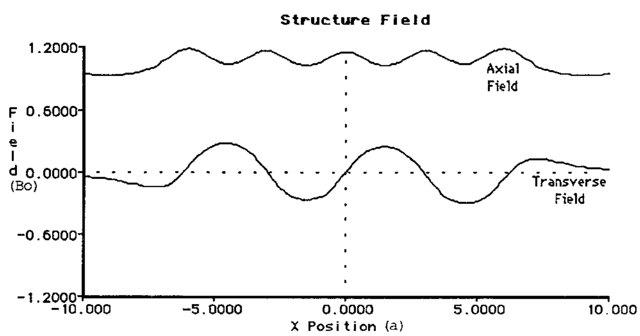

Figure 3c. On-Axis Axial and Transverse Fields of the Linear Undulator