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Realization of superconducting bulk magnets with higher magnetic field gradient to provide a quasi-zero gravity space on earth

学位論文要約

Bulk superconductors such as (RE)BaCuO (RE: rare earth elements or Y) can be utilized as a so-called trapped field magnet (TFM) that can "trap" the magnetic fields over several Tesla by exploiting the flux pinning effect of Type-II superconductors. The trapped field can be sustained inside the bulk with its induced supercurrent quasi-permanently once it is magnetized and kept at a constant temperature; hence, can replace conventional magnets as a compact and strong magnet for potential applications. It is noteworthy that there is a limit in the trapped field enhancement according to the tripartite relation between Electromagnetic field, Temperature, and Mechanical stress as the brittle ceramic nature. For more practical design, it is also desirable for the magnetic source to provide such a strong magnetic field even in an open space outside the vacuum chamber other than to be lightweight and mobile as a desktop-type apparatus. In this sense, the author newly developed two hybrid-type TFMs called as a hybrid TFM lens (HTFML) which can generate a concentrated field higher than the trapped field, and a high gradient-type TFM (HG-TFM) which can provide a higher magnetic force with its refined field gradient product, $B_z \cdot dB_z/dz$.

Firstly, a concept of the HTFML, which consists of two bulk components: an inner magnetic lens and an outer bulk cylinder, was discussed based on numerical simulation. A suggested magnetizing sequence requires that, during its magnetizing process, the outer TFM cylinder is in the normal state ($T >$ superconducting transition temperature, T_c) and the inner magnetic lens is in the superconducting state ($T < T_c$) when the external magnetizing field is applied, followed by cooling to an appropriate operating temperature, then removing the external field. This can exploit the "vortex pinning effect" of the outer bulk cylinder by field-cooled magnetization (FCM) and the "diamagnetic shielding effect" of the inner bulk magnetic lens by zero field-cooled magnetization (ZFCM), to generate a concentrated magnetic field higher than the trapped field from the outer TFM. Since 2019 to 2021, this concept has been explored, experimentally, for two potential cases: 1) exploiting the difference in T_c of two different bulk materials ("case-1"), *e.g.*, MgB_2 (T_c = 39 K) and GdBaCuO (T_c = 92 K) or 2) using the same material for the whole HTFML, *e.g.*, two GdBaCuO bulks, but utilizing the same cryostat with different cooling loops or coolants that keep the outer bulk cylinder at a temperature above T_c to achieve the same desired effect. As a result, the HTFML could reliably generate a concentrated magnetic field B_c = 3.55 T with an external magnetizing field B_{app} = 2 T in the "case-1", and a higher B_c = 9.8 T with higher B_{app} = 7 T in the "case-2," respectively. These HTFML devices deserve to be unique that suggests a new pathway to enhance the trapped field from the viewpoint of the magnetizing method in contrast to conventional approaches that depend on the superconducting properties of the bulk itself. Additionally, these new compact magnets can provide such large magnetic fields even in an open space inside/outside the vacuum chamber. Through detailed numerical assumptions, the HTFML device was considered for the magnetic levitation and separation inside a quasi-zero gravity space in the device that can provide an ultra-high magnetic field gradient product, $B_z \cdot dB_z/dz$, up to -3000 T^2/m with its large, concentrated field of 10 T. This is two times higher than that of existing superconducting magnets or large-scale hybrid magnets, and can fulfill the requirement of the magnetic levitation of water drop as high as 1400 T^2/m.

To realize a quasi-zero gravity space in an efficient way, a new High Gradient Trapped Field Magnet (HG-TFM) is proposed. In the modelling, slit ring bulks (slit-TFMs) are tightly stacked with TFM cylinders (full-TFMs), which is useful to improve the magnetic field gradient with its inverse field through the slits. A maximum $B_z \cdot dB_z/dz$ = 6040 T^2/m was obtained even by using the simpler conventional FCM with B_{app} = 10 T of the HG-TFM with 60 mm in outer diameter and 10 mm in inner diameter. This value may be the highest value ever reported compared to any other magnetic sources including the original HTFML. The $B_z \cdot dB_z/dz$ value decreased with enlarging the inner bore of the HG-TFM and with decreasing B_{app} during FCM. It was confirmed that the HG-TFM would work more effectively only for a higher B_{app} than 5 T and for narrower bores smaller than I.D. = 20 mm. These results showed, to improve the magnetic force efficiently, it would be more desirable to control the magnetic field gradient (dB_z/dz) profile by focusing on the gradient itself rather than improving the magnetic field (B_z). The HG-TFM has some advantages on the versatility, *e.g.*, a wider open space and its simple operation at one constant temperature other than its superior $B_z \cdot dB_z/dz$.

Relating to the applicational target of bulk magnet devices, it is generally known that the potential applicational area of bulk superconductors can be divided into three regions: Magnet application, Magnetic levitation application and Conductor application. These areas can be noted as the so-called existing targets, where the bulk materials can be a candidate to replace or co-exist with a conventional magnet. The apparatus can use the bulk magnets with several Tesla in an efficient way using a cryocooler or any coolants such as liquid nitrogen at 77 K. On the other hand, the author denotes another new potential target as high field application, which can be realized by only using a large magnetic field over 5 T. In recent years, some related studies exploiting magnetic microgravity condition have been reported in life/medical sciences such as biological characterization and protein crystallization, in which a conventional Nd-Fe based permanent magnet or large-scale superconducting magnets are utilized. It is expected that superconducting technologies, relating to bulk magnets, create a state-of-the-art innovation that can contribute significantly to the Sustainable Development Goals (SDGs) even in different regions including the medical science, space biology, environment and renewable energy. Now, since the prototype of proposed bulk magnet systems can be installed even in a laboratory scale and can provide the quasi-zero gravity space in an open space inside/outside the vacuum chamber, further applicational studies of the magnetic levitation process would be explored in a more practical setup towards new industrial application such as protein crystallization and cell culture.