Development of Nano-Structured HTSC for Application in Medicine

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Microscopy is very important in scientific research, particularly in the development of new materials for several engineering applications including medicine. The recently developed high-\(T_c\) superconducting materials and their performance at higher magnetic fields and higher temperatures are crucial for real applications. The performance properties are mainly controlled by nanostructures within the materials. The experimental results clarified that the demand to operate at the economical liquid nitrogen temperature and in high magnetic fields \((> 15 \, \mathrm{T}, \, H//c\text{-axis})\) is only possible by controlling and tailoring the nanostructures during the growth process. The scanning tunneling microscope (STM), transmission electron microscope (TEM), and dynamic force microscopy (DFM) analysis enabled to optimize the material performance by a thorough analysis of the nanostructures. As a result, the newly developed LRE-123 bulk material were observed to have an extraordinary performance up to the liquid oxygen temperature. Further, calculated trapped field values using experimental \(J_c-B\) data and numerical simulation for NEG-123 with 30 mol% Gd-211 (70 nm particles) clarified that nanostructures are the key to improve the performance of the materials around liquid nitrogen temperature. The present results indicate that the melt-processed high-\(T_c\) superconductor material will enable to construct superconducting super-magnets for several industrial uses including medical applications.

Keywords: superconductors; drug delivery; nano-structures; melt textured material; super-magnets

1. Introduction

Superconductivity, ever since its discovery in 1911, has demonstrated enormous potential in several industrial applications including MRI, especially in medical use. MRI applications have so far used low-\(T_c\) superconducting magnets constructed from materials such as NbTi and Nb₃Sn [1], which are two commercially available compounds. However, due to the low \(J_c\) at high magnetic fields, brittleness, an extremely low operating temperature at 4.2 K or even below and high operating cost are the limiting factors for the material to be commonly used in industry. In recent decades since the breaking discovery of superconductivity in the oxide material La-Ba-Cu-O by Bednorz and Muller [2], an outstanding progress has been achieved in the field. Thanks to the rapid development, the initial superconducting transition temperature of about 26 K raised above the boiling point of the cheaper liquid nitrogen (77.3 K) in YBaCuO [3], which was the most important step towards applications of high-\(T_c\) superconductors. Not only that the critical temperatures of the new superconductors are much higher than those of the conventional materials, it occurred that the brittle ceramic material is able to carry critical current densities at a level necessary for practical use, moreover in rather high magnetic fields. This placed cuprate composites into the focus of present material physics and technology. Liquid nitrogen cooling has promised construction of cryogenic systems being greatly simplified and capable of an economical operation. While the polycrystalline form of high-\(T_c\) materials could carry only low critical current densities, due to grain boundaries, weak links and crystal anisotropy [4], attempts to improve the critical current density have resulted in the identification of various pinning mechanisms at grain boundaries and lead to melt-texturing of LRE-123 composites [5-7]. The specialty of the melt textured LRE-123 material is that a superconducting pellet can be magnetized to a high external magnetic field, and then, a large part of the field is trapped in the pellet upon removing the external field and we get a superconducting permanent magnet or, shortly, a super-magnet [8]. Such a name is fully justified as high-\(T_c\) superconductors can trap magnetic fields by an order of magnitude higher than the best hard ferromagnets nowadays known [9]. The trapped field, \(B_t\), depends on the critical current density, \(J_c\), of the melt textured material and on the size of the single grain. Therefore, to achieve a large \(B_t\), one needs to enhance both \(J_c\) and the bulk material size. A further improvement of the critical current density and the fabrication of large homogeneous, good-quality single-grain superconducting disks capable of trapping high magnetic fields are fundamental issues for many industrial applications including the newly proposed high \(T_c\) superconducting magnets for drug delivery systems in medicine. LREBa₂Cu₃O₇, or short “LRE-123” (LRE: Nd, Sm, Eu, Gd, NEG, SEG, etc.,) is the material of choice for several industrial applications. Further improvements in critical current density, in particular in high magnetic field and at high temperature around liquid nitrogen temperature are crucial. This goal will be achieved by an improved fabrication technique through microstructural modification by controlling the processing and the initial composition [10-13]. The LRE-rich, LRE₁ₓBa₂₋ₓCu₃O₇, “LRE-123ss” clusters play an important role in enhancing flux pinning within a LRE-123 matrix [14-16]. Their role is similar to that of oxygen-deficient clusters: they are responsible for the formation of the secondary peak on the magnetization curve [17, 18]. As all light-rare-earth ions form solid solutions with barium, a strong pinning appears also in binary, ternary and quaternary LRE-123 compounds [19-23]. In
such mixed compounds, a new degree of freedom in pinning tailoring appears due to variation of the LRE elemental ratio. Different sizes of the LRE atoms introduce a strain disorder in the superconducting lattice, which contributes to flux pinning. In a narrow range of the Nd:Eu:Gd ratio values microstructure analysis revealed that the LRE-123ss clusters arrange into nanoscale planar structures, “lamellas”, filling the channels between twin plane boundaries. Due to their thickness and periodicity comparable to the coherence length $\xi$, these structures represent a very efficient pinning agent, especially at high magnetic fields, thus leading to a significant enhancement of the critical current density at higher magnetic fields and a high irreversibility field at liquid nitrogen temperature [24-26]. Besides, the melt-process technology enables introduction of non-superconducting secondary phase particles, RE$_2$BaCuO$_3$ “RE-211” that were found to enhance pinning at low magnetic fields. This increase is inversely proportional to a power of the size of such “large” particles (large with respect to the vortex core size, $2\xi$). Although the refinement of secondary phase particles up to the nanometer scale had been for a long time considered impossible, with the $\text{ZrO}_2$ ball milling of LRE-211 particles this goal was achieved. Such particles (sizes of 70–150 nm) not only survived the melt-texturing process but also further reduced their size up to 20–50 nm. Micro-chemical analysis identified these defects as Zr-rich ZrBaCuO and (NEG,Zr)BaCuO ones [27]. The effect of Zr in the diminution of the particle size stacks obviously in the chemical inertia of Zr in the superconductor matrix. Creating nanoscale particles based on some other inert elements, like MgO [28] or Y$_2$Ba$_2$CuZrO$_7$ [29] proved this hypothesis. The use of the initial powder composed of the nano-sized REBa$_2$CuZrO$_7$ particles and 35 mol% of sub-micron Gd-211 precipitates led to the super-current density of ~270 kA/cm$^2$ at 77 K. This improvement extended up to the liquid oxygen temperature. Further, record improvements in electromagnetic performance due to doping by nanoparticles from the same chemical group, namely Ti, Mo, and Nb are observed [27].

In this paper, emphasis is placed on the microstructure analysis of the nano structured LRE-123 and its importance for the development of the new class of superconducting super-magnetic for application in medicine.

### 2. Experimental Section

In the fabrication of nano structured LRE-123 superconductors the following technological issues are involved: (i) a proper setting of the matrix chemical ratio; (ii) doping by an appropriate, thoroughly ground secondary phase powder; (iii) formation of a point-like weak pinning disorder of LRE/Ba solid solution clusters via oxygen-controlled melt growth (OCMG); (iv) addition of small quantity of nano-meter sized TiO$_2$, MoO$_3$ and Nb$_2$O$_5$ particles etc., (v) optimum oxygenation with respect to the highest $T_c$. These five tools enabled to produce materials with the best critical current density and high irreversibility fields around liquid nitrogen temperature.

The samples of $(\text{Nd},\text{Eu},\text{Gd})\text{Ba}_2\text{Cu}_3\text{O}_y$ with various Nd:Eu:Gd ratios, presented in this work, were prepared by a standard melt-growth processing described in Ref. [30]. They were doped with 3 to 40 mol% of NEG-211 (Nd:Eu:Gd=1:1:1), 0.5 mol% of Pt was added for the secondary phase refinement and 10 wt% of $\text{Ag}_2\text{O}$ to improve the mechanical properties. The pellets were OCMG melt-textured under an oxygen partial pressure of 0.1% O$_2$ and a gas flow rate of 300 ml/min. These samples are compared to $(\text{Nd}_{0.33}\text{Eu}_{0.33}\text{Gd}_{0.33})\text{Ba}_2\text{Cu}_3\text{O}_y$ ones doped by 35 mol% Gd-211 + 1 mol% CeO$_2$, melt-processed in Ar-1% O$_2$ atmosphere [31, 32]. In this case, Gd-211 powder, ball-milled up to 70 nm size, was added before the melt growth process. Newly, nanoscale TiO$_2$, MoO$_3$ and Nb$_2$O$_5$ particles were added in amount of 0.1, 0.2, 0.3, and 0.35 mol% along with the Gd-211 secondary phase particles.

For magnetic measurements, small specimens with dimensions of about $a \times b \times c = 2 \times 2 \times 0.5$ mm$^3$ were cut from the as-grown pellets and annealed in flowing O$_2$ gas in the temperature range 300–600° C. The microstructure of these samples was studied with a transmission electron microscope (TEM), the atomic force microscopy (AFM), the dynamic force microscope (DFM) and the scanning tunneling microscope (STM). The chemical composition of the matrix was analyzed by energy dispersive X-ray spectroscopy (EDX). Magnetization hysteresis loops (M-H loops) were measured at 77 K using a vibrating sample magnetometer (VSM) with the maximum field of 14 T, parallel to the c-axis. The field sweep rate was 0.6 T/min. The magnetic $J_c$ values were estimated based on the extended Bean’s critical state model [33].

### 3. Results and discussion

#### 3.1 Nano-structured LRE-123 materials

Research in the area of high-$T_c$ superconductors, especially bulk superconductors, brought up a new class of superconducting super-magnets, which can trap magnetic fields as high as 17 T at 29 K (about 1.5 T at 77 K) [9, 34, 35]. Meanwhile, the development of nano-pinning media in these materials provides opportunities to improve the critical current densities around the economical liquid nitrogen temperature, which will be very important for several industrial applications including medical ones. Therefore, novel ideas are important for further proceeding towards nanocomposites containing melt processed material. Here, methods and techniques from nanotechnology are employed.
for the development of LRE-123 superconductors and the analysis is summarized. Furthermore, the application of nanostructured materials for application in drug delivery system is outlined.

3.2 Nano-stripes and nano-twins

The long-standing dream to utilize bulk high-\( T_c \) superconducting magnets at liquid nitrogen or liquid oxygen temperature (77.3 K or 90.2 K) has recently become much more feasible due to the progress in fabrication of high quality nano-structured NEG-123 materials. Although YBa\(_2\)Cu\(_3\)O\(_y\) “Y-123”, commonly used for levitation at 77 K, has a critical temperature of 91-93 K [36], which is lying only slightly below that of NEG-123, the pinning performance of Y-123 rapidly drops at high temperatures and is therefore insufficient for levitation at 90 K. In this aspect, the situation is even worse with BiSrCaCuO, TiBaCuO and other compounds exhibiting \( T_c \) above 100 K [37, 38]. These compounds cannot be used for levitation even with liquid nitrogen cooling, due to a low-lying irreversibility line. To date, only the LRE-123 composites exhibit a sufficiently good pinning performance up to 90 K which is possible by controlling the nanoparticles and nanostructures in these materials [39, 40]. The current bulk high-\( T_c \) materials are characterized by their very complicated microstructure on the nanoscale. In recent investigations, the presence of so-called nanostripes could be revealed by transmission electron microscopy (TEM), atomic force microscopy (AFM/DFM) and scanning tunneling microscopy (STM) measurements performed in ambient conditions [41-44]. The samples showing the most pronounced nanostripe structures are GdBa\(_2\)Cu\(_3\)O\(_x\) (GdBCO) and (Nd\(_{0.33}\)Eu\(_{0.38}\)Gd\(_{0.28}\))Ba\(_2\)Cu\(_3\)O\(_y\) (NEG). These nanostripes have typical dimensions of 10 – 60 nm width, and are extended over large areas of the sample [41-44]. This is illustrated in Figs. 1 – 2.

Figs. 1 – 2. In some of the materials like SmBa\(_2\)Cu\(_3\)O\(_x\) (SmBCO) and (Sm,Eu,Gd)Ba\(_2\)Cu\(_3\)O\(_x\) (abbreviated: SEG), even a criss-cross pattern of these stripes could be observed, while other systems like NdBa\(_2\)Cu\(_3\)O\(_x\) (NdBCO) only exhibit the presence of nanoclusters. In recent measurements, it was found that the nanostripes are chains of nanoclusters, which correspond to islands of the LRE-rich phase formed in these materials. The nanostripes fill effectively the space between the twin boundary structure, which is always present in fully oxygenated bulk materials. In another recent publication, it was also shown that these nanostripes provide an additional source of flux pinning [39, 44]. These

![Fig. 1](image1.png)  
**Fig. 1.** Transmission electron microscopy (TEM), Dynamic force microscope (DFM) and Scanning tunneling microscope (STM) images of the (Nd\(_{0.33}\)Eu\(_{0.38}\)Gd\(_{0.28}\))Ba\(_2\)Cu\(_3\)O\(_y\) sample with 5 mol% NEG-211. Note the island structures appeared with in all techniques.

![Fig. 2](image2.png)  
**Fig. 2.** (left) Dynamic force microscope (DFM) images of the (Nd\(_{0.33}\)Eu\(_{0.38}\)Gd\(_{0.28}\))Ba\(_2\)Cu\(_3\)O\(_y\) sample with 5 mol% NEG-211. Note the nano-lamellar and modulation structure. (right) AFM-image in the tapping-mode on a (Nd,Eu,Gd)Ba\(_2\)Cu\(_3\)O\(_x\) sample; (b): STM-topography-image of the same sample. Below the images, selected height profiles are given.
investigations were performed using transport measurements. These electric transport/resistance measurements performed at temperatures close to the critical temperature have revealed a clear anisotropy between the directions parallel and perpendicular to the nanostripes. When extracting the information about the flux pinning properties from these I/V-measurements, one could see that the contribution of the so-called $\delta T_c$-pinning (i.e., flux pinning provided by a variation of the transition temperature, $T_c$) is increased when the current is directed parallel to the nanostripes [45].

Another recent publication [46] employing bulk superconducting NEG and GdBCO samples prior to the oxygenation step could show that the nanostripes are created during the material processing stage, while the twins are formed during the subsequent oxygenation process. The always present $(\text{LRE})_2\text{BaCuO}_5$ (abbreviated: LRE-211) particles do not alter the orientation of the nanostripes or the criss-cross patterns. This can be seen by the fact that the nanostripes are strongly deformed close to the twin boundaries [46], but the direction of the stripes is not influenced by embedded particles like 211 (see in Fig. 3), where the location of the twins is indicated in red. The nanostripes strongly interact with the twin structure and, in several measurements employing different techniques, we found that the nanostripes form an angle of about 31° in a distance to the twins. The sample LRE-based systems Nd-123, Sm-123, or mixed NEG-123 with large quantity of secondary phase around 40 mol% exhibit only moderate critical current densities, and eventually there is no nanostripes formation [47]. This was confirmed by several small samples by the STM and DFM analysis. Note that one can control the nanostripe strip size close to the coherence length, $\xi$, of the order of 3–5 nm in the $(a,b)$-plane of LRE-123 superconductors. Another important aspect for the microstructure of high-$T_c$ superconductors is the embedding of non-superconducting nanoparticles as flux pinning sites [47]. Several approaches to this topic can be found in the literature, but it is important to point out that only nanoparticles which do not alter the formation of the superconducting matrix are improving the flux pinning properties.

![Fig. 3: AFM tapping mode scans on a melt-textured Sn123 sample after oxygenation. The position of the twin boundaries is marked using dashed red lines. Figure (a) presents the undisturbed nanostripes in between the twins, whereas (b) and (c) give detail views of the curvy part of the nanostripes close to the twin boundaries.](image)

### 3.3 Nano-scale secondary phase particles

The morphology and dispersion of the nanometer-sized secondary phase particles in the NEG-123 matrix was studied on several samples by scanning electron microscopy [47, 48]. The data show an uniform dispersion of sub-micrometer sized particles (see Fig. 4). Further, recent experience says that such a particle size is too large for the observed significant effect on flux pinning at high temperatures. A better insight into the microstructure of this sample was obtained by TEM (Fig. 5, right). Three types of defects were recognized: large irregular inclusions of about 300 to 500 nm in size, round particles of 20–50 nm and bundles of particles with a size less than 10 nm, marked by white arrows. The chemical composition of the precipitates was studied by scanning TEM-EDX analysis. The analyzed spot of 2–3 nm in diameter enabled to unambiguously analyze even the smallest clusters. The quantitative analysis clarified that the
large particles were Gd-211/Gd-rich-NEG-211, in agreement with our earlier studies of the NEG-123 system [49, 50]. The last NEG-123 material features the highest flux pinning performance of all bulk RE-123 compounds developed up to now in Japan and to our knowledge, in the world. To control the pinning performance of the NEG material in a broad low-field range, various second phase precipitates have been tested in various contents. Gd-211 was found to produce always the highest flux pinning. Its optimum content was established to be around 35 mol%. In each further step, we have used the optimum composition obtained in the previous step. Thus, the Gd-211 content was also here just 35 mol%. Also the oxygen partial pressure has been chosen in accord with the best previous experience. The only variable in the experiment was the varying content of the nanometer-sized TiO$_2$, MoO$_3$, and Nb$_2$O$_5$ [31, 32, 51].

As a result, the critical current density was enhanced by factor 2, 3, and 4, respectively, in comparison to the best of our previous results [13, 14]. In all cases, the enhancement extended up to high temperatures. This record electromagnetic performance was always accompanied by an observation of clouds of exceptionally small precipitates (10 nm in size) within the NEG-123 matrix (Fig. 5, left). The large quantity of the smallest particles was characteristic for these new NEG-123 materials. The energy-dispersive x-ray (EDX) spectra of the nanoparticles in the Nb-doped sample are shown in Figure 6. The quantitative analysis clarified that the defects with size below 50 nm always contained a significant amount of Zr, in agreement with our earlier studies of the NEG-123 and SEG-123 systems [29, 49]. The smallest particles always contained a significant amount of Nb (see Fig.6: particle B1 and particle B2). The exact chemical composition of the former particles was determined as LREBa$_2$CuZrO$_y$ [50]. The appearance of such small defects correlates with the super-current enhancement in a wide temperature range, up to liquid oxygen temperature and the tendency in $J_c$-H$_a$ follows the theoretically predicted dependence for “large particles” [52, 53]. It seems that these defects help to shift the “large” defect size distribution average to a lower value, resulting in critical current density enhancement at low and intermediate magnetic fields, without contributing to the random point-like defect disorder. Although the size of the smallest particles came close to the vortex core size, $2\xi_a$ (in YBCO $2\xi_{ab}(77 K) \approx 4.5$ nm) and thus the limit of single-vortex interaction has been approached for these particles, no sign of a crossover to the secondary peak enhancement was observed. Note that a similar behavior was observed in the studies of Werner et al.
Fig. 6. The EDX-HADD-TEM pattern of 10 nm nanoparticles showing presence of Nb in the NEG-123 matrix (particles B1 and B2). On the other hand, the particle of 40 nm in size contains Zr, as in our earlier reports.

[54] and Sauerzopf et al. [55, 56] done on various RE-123 and Y-124 single crystals irradiated by fast neutrons. Might be that the crossover between multiple- and single-vortex pinning is rather sharp and we are still not close enough to it. Or, the present defects are in some sense different from the typical point-like defects (oxygen vacancies and/or the LRE-123 matrix chemical fluctuation [17, 18, 22, 29]. These facts are strong indications that the enhanced pinning is due to a collaborative pinning by the operative pinning ensemble, the result being exceptionally sensitive to the smallest nanoparticles, in our work especially those containing Ti, Mo, and Nb, with about 10 nm in size. The pinning enhancement due to the new type of defects is so profound that it extends up to temperatures above 90 K. This implies that the limiting operating temperature for levitation experiments and other applications shifts from liquid nitrogen (77.3 K) to liquid oxygen (90.2 K) temperature [57-59].

3.4 Flux pinning and irreversibility field

The strong trapped magnetic fields (>3 T) were needed in all industrial applications, the above-described flux pinning enhancement in the LRE-123 system by nanometer-scale secondary phase, Zr, Mo, Ti, and Nb additives were effective in particular at low fields and high temperatures [31, 60]. The ternary composites can be, however, utilized for high field applications, too. Magnetic studies of the NEG-123 system with a varying LRE chemical ratio in the 123 matrix showed a narrow range, where the irreversibility line significantly shifts upwards. These data indicated that the

Fig. 7. Magnetic hysteresis loops for the composite (Nd_{0.83}Eu_{0.32}Gd_{0.28})Ba_{2}Cu_{3}O_{y} with 3 mol% NEG-211 (left), and 5 mol% NEG-211 (right). Both samples contained 0.5 mol% Pt and were measured at 77 K and H_{a}/c-axis.
optimum configuration of Nd:Eu:Gd in the NEG-123 system does not need to be necessarily 1:1:1 and that a variation in the chemical ratio can represent an additional tool in tailoring the pinning landscape in these complex composites. It was also found that each particular Nd:Eu:Gd chemical ratio requires a corresponding optimal concentration of the secondary phase particles [22, 24, 40]. A systematic study of this system finally led to the conclusion that the optimum ratio in the NEG-123 system lies around Nd:Eu:Gd = 33:38:28 and the corresponding optimum NEG-211 doping around 5 mol%, which provides irreversibility field above 14 T at 77 K, H//c-axis (see Fig. 7).

3.5 Nanostructures in large size LRE-123 materials.

For the application of magnetic drug delivery system, it is very important to produce single grains, with high performance and an uniform material. The high performance material needs the creation of nanostructures with a uniform distribution. However, up to date all the data presented in the literature reports on small samples (few mm size) cut from bulk melt processed material [39-47]. Recently, for the first time we investigated samples which were cut from large single grain bulk pellet with a diameter of 18 mm and a height of 10 mm. The original position of the small piece within the big pellet was varied in order to obtain a clear picture how the nanostructure pattern is developed when growing a bulk superconducting sample. In order to understand the formation of the nanostructure patterns depending on the position in the bulk materials, more than 12 small specimens were cut from the big sample, that is centre, middle and edge etc., and atomic force microscopy (AFM) and scanning tunnelling microscopy (STM) measurements were performed. More details for the sample positions in the bulk sample are reported elsewhere [61]. The AFM and STM topography scans indicated that the nanostructures are very pronounced in NEG high-\(T_c\) superconductors. The further observed important features are i) in the c-gs, only a small periodicity of 10—20 nm is observed, ii) in the a-gs, nanostructures are well developed, iii) close to the sample edge, the stripe pattern is lost and only aligned nanoclusters can be observed (see Fig. 8). These results clarified that the properties of the nanostructures are closely related to the grade of texture achieved during melt-processing. Further, these results indicated that careful processing is essential to produce controllable nanostructures.

![Fig. 8](image)

**Fig. 8.** Typical images from the c-gs (a), the a-gs (b), and close to the sample edge.

3.6 Nanostructured LRE-123 materials for application in magnetic drug delivery system (MDDS).

Research in the areas of LRE-123 superconducting materials has witnessed tremendous improvement in processing and performance especially at higher temperatures around 77 K. As a result, the small melt processed samples themselves can trap large magnetic fields, which again motivated the scientists to develop the magnetic drug delivery system. Normally, when a drug is taken into the body to treat a medical condition, only a very small percentage of it actually reaches and treats the intended target site. This can be wasteful and some cases very powerful drugs will harm the human body. The speciality of the drug delivery system is that it can deliver drugs to affect only on the region requiring such drugs when needed. The research and development on the MDDS has began in the 1970s. However, at the time there were no strong magnets to produce the magnetic force which ultimately guides the magnetically seeded drug with the ferromagnetic fine particle to certain lesion. This is the ultimate therapy technology in these materials development of a novel magnetic drug delivery system. The drug delivery can be controlled by the superconducting magnetic force in the body, as a result, a high concentration of the drug is delivered to a targeted diseased part [62]. This will reduce the toxicity to the normal tissue, and hence MDDS will have a bright future in DDS. However, the strong superconducting magnets are needed in order to control the drugs located deep inside the body. The target will be to create a 5 T magnetic field at 0.5 T several centimeters inside the human body [60]. Prof. Nishijima (Osaka University) studied extensively on MDDS and suggested the following points to be considered for the MT-DDS system in practical use:
(i) a system to prevent dispersion of a drug by a magnetic force, (ii) a system to trap and accumulate a drug in some part of a blood vessel. (iii) a system to guide a drug in a desired direction to deliver it to an intended diseased part [62-67]. The first next generation prototype MDDS system was developed by the team of Institute of Advanced Biomedical Engineering & Science, Dept. of Neurosurgery, Tokyo Women Medical University and Hitachi under the NEDO support (see Fig. 9). The setup was subsequently moved to railway technical research institute (RTRI) for the future collaborative work and improvement in MDDS. The main parts of the MDDS are the small cryo-cooler, and a portable 5 T HTS bulk magnet.

3.7 Nanostructured NEG-123 material performance at 77 K.

One of the most advanced MDDS built to date is a system containing melt processed Gd-123 superconductors. The five melt processed superconductors are arranged vertically in the cryostat to constrict the portable HTS bulk magnet, which will produce 5T magnetic field at 38 K on the surface of the magnet. So far, a standard NEG-123 sample produced have a maximum size of 25 to 32 mm. Further, such a standard sample is capable to trap in remnant state at 77 K a maximum field of 1.2 T (see Fig. 10) [68]. However, nano-structured NEG-123 material will generate very high critical current density even at 77 K. We calculated TF values using experimental $J_c$-$B$ data and numerical simulation. NEG-123 with 30 mol% Gd-211 (70 nm particles) was selected for this purpose [69]. Based on these data, we calculated trapped field profiles for disks of 50 mm diameters and thicknesses of 10 mm and 20 mm, respectively [29]. The results are presented in Fig. 10. The trapped field reached more than 4 T in the remnant state at 77 K. A summary of the calculated TF values at 77 K and 90 K is presented in the right Fig. 11. It is clear that the NEG-123 samples can generate more than 5 T at 77 K with increasing the sample size to 60 mm diameter. The simulation results proved that the new material enables the construction of a superconducting magnet for drug delivery system operating at 77.3 K. Thus, these results represent a significant step forward in the technology of bulk high-$T_c$ superconductors towards novel engineering applications. The current task is development of nanostructured NEG-123 materials for medical applications.

![Fig. 9](image-url) Next generation of MDDS apparatus developed under the NEDO support at Tokyo Women Medical University (left); Navigation experiment at branching point of blood vessel using rat and permanent magnet (from Ref. 62).

![Fig. 10](image-url) Photographs for a standard melt processed NEG-123 samples and its performance at liquid nitrogen temperature.
The calculated trapped field distribution in the sample NEG-123 + 30 mol% Gd-211 (70 nm in size), melt processed in Ar-1% O2, at liquid nitrogen temperature. Diameter and thicknesses of the sample were assumed 50 mm and 10 & 20 mm, respectively. The high trapped field of 4.5 T was achieved in the remnant state at 77.3 K. The summary for the sample size vs trapped field at 77 K and 90 K in the remnant state is in the right figure.

3.8 MDDS experiments on Rat and Pig

The targeting of drugs to specific locations inside the human body can be studied first how the MDDS will work. Specially, i) magnetic field control, ii) ferromagnetic particle size and the control, iii) accumulation of drug near certain organs aiming at the enhancement of drug absorption and iv) drug navigation. Several scientists studied the issues specially experimental modals and simulation by the calculations [62-67]. Based on the results, the newly developed MDDS technology was applied to animals in order to solve the problems and to gain thorough understanding. Prof. Nishijima et al., conducted experiments to find the accumulation of the seed drug inside of living body. For this, they targeted an internal organ like the liver. A six weeks aged, 600 g weighing male Brown Norway rat was anesthetized [62]. Subsequently, the abdomen of the rat was opened under anesthetizing and the neodymium-iron-boron magnet with a surface magnetic flux density of 0.3 T was placed on the surface of the liver (see Fig. 9, right). 500 μl of magnetite suspension was injected into the portal vein for 1 minute and the accumulation of magnetite distributed in the blood vessel was studied using the biological microscope. It was found that the magnetite can be accumulated by a permanent magnet. Note that the permanent magnet (neodymium-iron-boron) does not generate enough magnetic force. On the other hand, the bulk melt processed Gd-123 materials were confirmed to produce an even higher magnetic force. The samples with 45 mm in diameter can produce around 5 T at 38 K. In this case, the HTS magnet was cooled by a cryocooler (see Fig.9, left). Note that the newly developed MDDS produced 0.2 T flux density and 8 T/m of magnetic field gradient at a 50 mm distance [63]. We hope that these present values will be tremendously improved when changing to nano-structured bulk melt processed magnets. Due to the large diameter of the HTS magnet, one cannot use it on a small animal like rat. Further, this experiment was applied to the larger animal, for example, a pig [62]. The weight of the selected pig was 36 kg. The suspension of the magnetite (average diameter of the particles 100 nm) was injected in to the abdominal aorta. Eventually, the bulk magnet was arranged so as to touch the surface of the liver. The distance between the magnet and the liver was estimated to be several millimetres. The results confirmed the MRI images and SQUID magnetometer that the accumulation of magnetite was very clear. However, the navigation experiments confirmed that Gd-123 bulk magnet makes an efficient magnetic navigation of the magnetic seeded drug possible. The present experimental results indicate that the first step in the design of MDDS is to choose a high performance nanostructured material [70], since the magnetic particles or seeds of various compositions with diameters around 100 to 2000 nm are readily available for this experiment. Targeted drug delivery is an important goal for a clinical applications. There is obviously a need for methods and compositions that seek to avoid systemic drug side effects. The newly proposed bulk melt processed MDDS could be applied in several clinical applications including skin cancer, bone tumours, and head cervical cancer, lung cancer, and liver cancer.

4. Summary

The efficiency of the newly developed high performance LRE-123 material and its nanostructures are characterized by scanning tunneling microscopy (STM), transmission electron microscopy (TEM), and dynamic force microscopy (DFM). The results indicate a dramatic change in the magnetic properties that occurs when the structural phenomena become comparable to the nanoparticle or nanostripe size. As a result, a record remnant critical current density of 925 kA/cm² at 65 K (pumping upon the liquid nitrogen bath) was reached, illustrating the effectiveness and the potential of these materials for applications in a broad temperature range. Further, one can use these materials to trap fields over 10 T at 77 K and H//c-axis. This unusual magnetic phenomenon, being always associated with the size and dispersion of...
nanoparticles or nanostripes is exploited herein to make superconducting super-magnets for several industrial applications including the MDDS. This advanced technology is expected to become a key technology in advanced clinical applications in the near future.

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