Abstract—We have successfully developed a high gradient magnetic separation system for medical proteins using affinity magnetic nanobeads. Our system shows very high separation efficiency, and it can also be expected to realize lower cost due to larger production rate compared to the conventional system. The developed system consists of a 3-T superconducting magnet and a filter made of fine magnetic metal fibers. The superconducting magnet is wound with a NbTi twisted multifilamentary wire, and cooled by a 4-K Gifford-McMahon cryocooler. In order to achieve high recovery ratio of the magnetic nanobeads trapped on the filter located in a room temperature clear bore of cryostat, the AC degaussing system for the filter is fabricated using an inductance-capacitance resonance circuit composed of a series connection with the superconducting magnet and an additional capacitor. To perform the inductance-capacitance resonance more than a few cycles between superconducting magnet and capacitor, the superconducting magnet has a slit in the bobbin to prevent an eddy current coupled with an alternating magnetic field, and also has a control system for a high speed switching circuit. This magnet can successfully generate the magnetic field of 3.0 T in the clear bore of cryostat with a diameter of 30 mm in a relatively fast sweep time of 150 seconds due to the slit in the magnet bobbin. Using our degaussing system, a high recovery ratio of the nanobeads in pure water has performed about 94.1%.

Index Terms—Copper current leads, degaussing circuit, high gradient magnetic separation, superconducting magnet.

I. INTRODUCTION

SCREENING and purification technologies for medical proteins such as immunoglobulin using micro- or nano-size beads have been developed in recent decades. The target medical proteins can be captured and extracted by attaching affinity adsorbents on the beads, which are uniquely bound with them. In the screening technology with affinity beads, the decrease in their size as small as possible is very important to increase the surface areas for antigen-antibody reaction and suppress the time required for capturing. There are two types of affinity beads developed up to now, non-magnetic and magnetic beads. Although it is quite easy to manufacture non-magnetic nanobeads, it seems to take a long time to capture and extract them by means of affinity chromatography. On the other hand, it is very difficult to deal with magnetic nanobeads for screening and purification due to a weak magnetic force in the present system with a permanent magnet. Therefore, our group has developed a high gradient magnetic separation (HGMS) system with a superconducting (SC) magnet [1], [2].

In a usual HGMS system, magnetic particles can be trapped on thin magnetic wires located in a magnetic field due to a magnetic force proportional to the strength and gradient of the field around the wires [3]. Our HGMS system has also consisted of target substances (immunoglobulin), affinity magnetic nanobeads, magnetic filter, SC magnet, cryocooler, and degaussing circuit [1], [2]. Several number of immunoglobulin could be captured on each of a part of affinity magnetic beads in advance by mixing them in a chemical solution. When such a solution passes through the magnetic filter composed of fine stainless-steel wires located inside the energized SC magnet cooled by the cryocooler, almost of the affinity beads could be trapped on the filter. After the magnetization of the filter is eliminated by using the degaussing circuit, the trapped magnetic beads could be recovered by flushing the filter with an additional pure solution. The target immunoglobulin captured on the affinity beads could be eluted in a final chemical process. Our HGMS system has several advantages such as the short processing time due to the achievement of concentration in the absence of dilution, short mixing time using nano-size beads due to the increase in their total reacting surface area for the identical mass, trapping of magnetic nanobeads due to a high field around the filter generated by the SC magnet, and simple system using the cyogen-free conduction-cooled SC magnet operated without professional knowledge and skill of...
cryogenics.

In this study, a 3-T class SC magnet for HGMS system is designed, fabricated and tested. The SC magnet is cooled by a 4-K Gifford-McMahon (GM) cryocooler. A pair of copper current leads for the conduction cooling is also designed optimally. Furthermore, a prepared degaussing circuit is successfully operated to remove the magnetization of a filter located inside the SC magnet.

II. DESIGN AND FABRICATION OF SC MAGNETS

SC magnets for HGMS system are designed on the basis of an existing NbTi multifilamentary wire with the diameter of 0.642 mm, filament number of 636, copper ratio of 1.3, and twist pitch of 70 mm. This wire has the critical currents of 279 A, 217 A, and 146 A at 4.2 K in the magnetic fields of 6 T, 7 T, and 8 T, respectively. The specifications of SC magnets designed and fabricated using this wire are listed in Table I. It is supposed that the diameter of a room temperature clear bore is 30 mm and the field homogeneity inside a sphere of 30 mm in diameter is 5% for a central magnetic field of 3 T in the solenoid magnet. The inner diameter of SC winding is fixed at 60 mm to ensure a wall thickness of cryostat and a thickness of bobbin for winding support. If the packing factor of winding and the operating current are assumed to be 0.9 and 60 A, respectively, the outer diameter, length, and turn number of SC winding become 99.9 mm, 82.0 mm, and 4546, respectively.

Fig. 1 shows the photograph of an SC magnet fabricated by reference to the above-mentioned preliminary design. It can be seen that a slit in the vertical direction is cut into an aluminum-alloy bobbin in advance and thin glass-fiber-reinforced-plastic (GFRP) plate for electrical insulation is inserted there. Such a slit enables us to prevent forming a major loop for induction of an eddy current and realize a fast excitation of the SC magnet. The NbTi wire is wound on the bobbin of 60.0 mm in outer diameter and 82.2 mm in effective length. The outer diameter and turn number of fabricated winding finally become 98.5 mm and 4311, respectively. In this case, the SC magnet can produce the central field of 3.0 T by applying the current of 63.1 A theoretically, and its self-inductance is calculated as 0.789 H [4]. The SC magnet is located inside a cryostat with a room temperature clear bore of 30 mm in diameter.

III. DESIGN AND FABRICATION OF CURRENT LEADS

Fig. 2 shows the schematic illustration of a conduction cooling with a two-stage GM cryocooler for an SC magnet and current leads. A heat load in the second stage of the cryocooler can be reduced drastically by contacting it with the SC magnet and the cold end of high temperature superconductor (HTS) current leads thermally, and also the first stage with a thermal shield and the warm end of the HTS leads. However, a metal material such as copper has to be used for current leads from room temperature to the first stage, so that a heat input along these metal leads has to be cooled constantly by the cryocooler [5].

The one-dimensional thermal equilibrium equation for the metal current lead under an adiabatic condition is given by [5]

\[
\frac{d}{dx} \left( kA \frac{dT}{dx} \right) + \frac{\rho l^2}{A} = 0,
\]

where \( k \) is the thermal conductivity of the current lead, \( A \) the cross-sectional area, \( \rho \) the resistivity, and \( l \) the applied current. The boundary conditions are also fixed as

![Fig. 1. Photograph of fabricated SC magnet.](image)

![Fig. 2. Schematic illustration of conduction cooling with cryocooler for SC magnet and current leads.](image)
$T(0) = T_H$, $T(E) = T_L$,

where $\ell$ is the length of the current lead, $T_H$ the temperature at the warm end, and $T_L$ the temperature at the cold end. In the case where the thermal conductivity and resistivity have no dependence on temperature, the heat input $Q$ at the cold end becomes \cite{5}, \cite{6}

\[
Q = -kA \frac{dT}{dx} \bigg|_{x=t} = \frac{kA(T_H - T_L)}{\ell} + \rho I^2 \ell / 2A.
\]

It can be seen from (3) that the thermal conduction along the current lead in the first term on the right-hand side is proportional to the cross-sectional area $A$ and the inverse of length $\ell$, whereas the Joule heating in the last term has an opposite dependency. This means that there is a set of optimum values of the cross-sectional area and length of current lead for metal material and applied current.

Since the thermal conductivity and resistivity of a general metal depends on temperature, the numerical calculation is usually required to solve (1) and minimize the heat input $Q$. The heat input from 300 K to 55 K is estimated as about 2.7 W.

The self-inductance of the SC magnet is estimated as 0.787 H. This is acceptable for a 4-K GM cryocooler with a cooling power of about 6 W at a first-stage temperature of 55 K used in this study \cite{7}.

\section{Design and Fabrication of Degaussing Circuit}

In order to remove the magnetization of a magnetic filter located inside the SC magnet and recover affinity nanobeads trapped on the filter, an electric circuit as shown in Fig. 3 is considered in this study. In Fig. 3, the symbol $L$ denotes the self-inductance of the SC magnet, $E$ the voltage of a power source, $C$ the capacitance of an additional capacitor, $R$ the resistance of an additional resistor, and $R_0$ the resistance of a shunt resistor, which is much smaller than $R$, to observe a current $i$ flowing in the SC magnet. There are two switches, $S_1$ and $S_2$. If the switch $S_1$ is closed, the SC magnet can be energized to generate a magnetic field around the magnetic filter. After that, if the switch $S_2$ is closed and immediately the switch $S_1$ is opened, the magnet current $i$ is expected as

\[
i(t) = i_0 e^{-\alpha t} \left( \cos \beta t - \frac{\alpha}{\beta} \sin \beta t \right)
\]

for $R < (4L/C)^{1/2}$. The initial current flowing in the SC magnet just before opening the switch $S_1$ is represented by $i_0$. The parameters, $\alpha$ and $\beta$, are also given by $\alpha = R/(2L)$ and $\beta = [1/(LC) - \alpha^2]^{1/2}$, respectively. It can be found in (4) that the magnet current oscillates and decays with time. This means that the magnetic field generated by the SC magnet also oscillates and decays with time, so that the magnetization of the magnetic filter could be removed.

A prepared control box for degaussing has two relay switches, the capacitance $C$ of 47000 $\mu$F, the resistance $R$ of 0.11 $\Omega$, and the resistance $R_0$ of 0.75 m$\Omega$.

\section{Test Results}

An HGMS system is constructed to demonstrate the trapping and recovering of magnetic nanobeads using the cryocooled SC magnet and a magnetic filter of stacked stainless-steel meshes \cite{7}, \cite{8}. Since the experimental results of the magnetic separation of nanobeads using the filter are reported elsewhere \cite{8}, this paper focuses only on the experimental results of excitation, discharge, and degaussing for the SC magnet in the forthcoming paragraphs. Two temperature sensors, $T_1$ and $T_2$, are attached on the magnet bobbin and the outside surface of winding, respectively. It takes about 8 hours to cool down the SC magnet from room temperature to cryogenic temperature, and the temperatures finally become stable at 4.2 K for $T_1$ and 5.0 K for $T_2$ \cite{7}.

Fig. 4 shows an example of the experimental results of the excitation and discharge of the SC magnet. It can be seen in Fig. 4(a) that it takes 150 s to energize the SC magnet up to 63.1 A, which corresponds to the central field of 3.0 T. The sweep rate of the current in the initial period is not constant because the power source is automatically controlled into a constant voltage mode due to its specifications. After the power source is automatically changed into a constant current mode, the sweep rate of current and the terminal voltage of SC magnet become almost constant. On the basis of these features, the self-inductance of the SC magnet is estimated as 0.787 H experimentally. On the other hand, the sweep rate of current and the terminal voltage of SC magnet are almost constant during the discharging process of 100 s as shown in Fig. 4(b). The identical value of the self-inductance is obtained in the latter case. A target value of 300 s to energize or discharge the SC magnet is satisfied for each case. The temperature rises during both the processes are also less than 0.5 K.

Fig. 5 shows an example of the experimental results of the current and temperatures in the SC magnet during the degaussing process. The current of 19.8 A is applied to the SC magnet at first, and corresponds to a central field of about 1 T. The switch $S_2$ in the control box for degaussing is closed and immediately the switch $S_1$ is opened at $t = 0$. Their time lag is set to 50 ms. It can be seen in Fig. 5(a) that the magnet current oscillates and decays with time as theoretically expected. It is also found in Fig. 5(b) that the maximum temperatures just after the operation exceed 9 K that is close to the critical temperature of NbTi superconductor, and then the temperatures gradually decrease with time due to the
continuous conduction cooling with the cryocooler. The decay
time constant of the current in Fig. 5(a) is estimated as 0.79 s,
which is equivalent to the resistance of 2.0 \( \Omega \) much larger than
the prepared resistor of 0.11 \( \Omega \). This might be because a part
of the winding becomes a resistive state during the degaussing
process. However, no quench phenomenon is observed at all,
and the SC magnet can be energized repeatedly after re-
cooling.

Through a series of the energizing, discharging, and
degaussing processes of the SC magnet as shown in Figs. 4
and 5, a high recovery ratio of the nanobeads in pure water
using the HGMS system has performed about 94.1\% [8].

In order to suppress the temperature rise of the SC magnet,
the decrease in the initial current is quite effective. Such a
treatment would not affect the performance of the degaussing
circuit to remove the magnetization of the filter if the pre-
applied field is large enough for magnetic saturation. Fig. 6
shows another experimental results of the current and
temperatures in the SC magnet during the degaussing process.
The initial current of 10.4 A corresponding to a central field of
about 0.5 T is applied to the SC magnet. It can be seen that the
maximum temperature rises are less than about 4 K for \( T_1 \) and
about 2 K for \( T_2 \). The decay time constant of current and the
equivalent resistance are estimated as 1.20 s and 1.3 \( \Omega \),
respectively. This might mean that a smaller part of the
winding still becomes the resistive state.

VI. CONCLUSION
The SC magnet and degaussing circuit for the HGMS
system to trap and recover affinity magnetic nanobeads were
fabricated and tested. The SC magnet wound with the NbTi
multifilamentary wire could be cooled down to the cryogenic
temperature by optimizing the cross-sectional area and length

![Fig. 4. Experimental results of applied currents and terminal voltages in SC magnet during (a) energizing process and (b) discharging process.](image)

![Fig. 5. Experimental results of (a) current and (b) temperatures in SC magnet during degaussing process. The current of 19.8 A is applied before turning on the degaussing system.](image)

![Fig. 6. Experimental results of (a) current and (b) temperatures in SC magnet during degaussing process. The current of 10.4 A is applied before turning on the degaussing system.](image)

of copper current leads from room temperature to the first
stage of cryocooler. The SC magnet was energized up to 3.0 T
with the slight temperature rise for 150 s, and also discharged
for 100 s. Furthermore, the AC degaussing circuit using the
inductance-capacitance resonance enabled us to remove the
magnetization of the filter for magnetic separation and recover
the magnetic nanobeads trapped on the filter.

REFERENCES
Ishiyama, “Design and test of filter of high gradient magnetic separation


