A new approach to magnetic field stabilization for electron microscopy

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Abstract

We investigate a new approach for improving the performance of magnetic lenses for electron microscopy and other applications where highly stable magnetic fields are required. The temporal stability of magnetic fields in magnetic lenses is limited by several sources of interference, including fluctuations of the current in their coils and the fact that a ferromagnetic yoke can act as an antenna, which couples external electromagnetic interference or magnetic fields generated by movable magnetic objects to the electron beam. Both the movement of magnetic domains (Barkhausen noise) and thermal current fluctuations (Johnson-Nyquist noise) inside the yoke can lead to statistical fluctuations of the magnetic flux that propagates through it. In addition, since the permeability of the yoke is temperature-dependent, fluctuations in temperature can result in variations in the magnetic field in the lens. We have proposed using superconducting loops around the ends of the pole piece to stabilize magnetic fields in the ferromagnetic yokes of magnetic lenses for electron microscopy [1].

Our proposal involves introducing a superconducting loop around a ferromagnetic yoke, in which the magnetic flux should remain constant to a much greater precision than the stability of the power supply allows. Fluctuations of the magnetic field in the yoke induce a current in the superconducting loop, which results in an oppositely directed magnetic flux in the yoke that compensates these fluctuations exactly. Because the superconductor has no resistance, the induced current can flow indefinitely and the magnetic field in the ferromagnetic yoke can be maintained indefinitely. In this way, the current induced in the superconducting loop compensates fluctuations in the magnetic field, while the required direct current (DC) value of the magnetic flux is provided by the coils. By positioning the superconducting loop outside the magnetic field of the lens, dissipation of the induced currents due to creep of Abrikosov vortices can be avoided.

Physical background

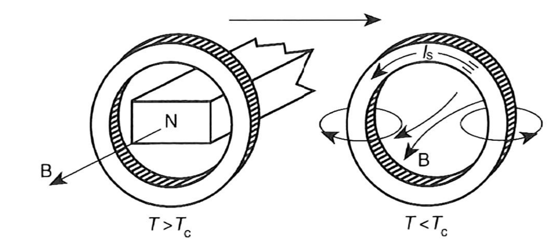

Figure 1. Excitation of persistent current I_s in a superconducting (SC) ring [2].

Magnetic flux Φ through a SC ring of area A and inductance L is constant:

$$\Phi = BA = LI_S = const$$

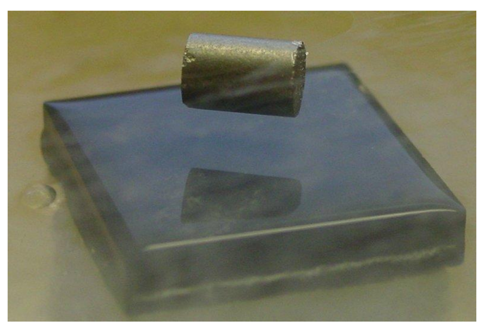

Figure 2. Levitation of $SmCo_5$ magnet above $YBa_2Cu_3O_7$ ceramic.

Figure 3. Levitation of 1 cm^2 substrate with 100 nm $YBa_2Cu_3O_7$ film under $SmCo_5$ permanent magnet.

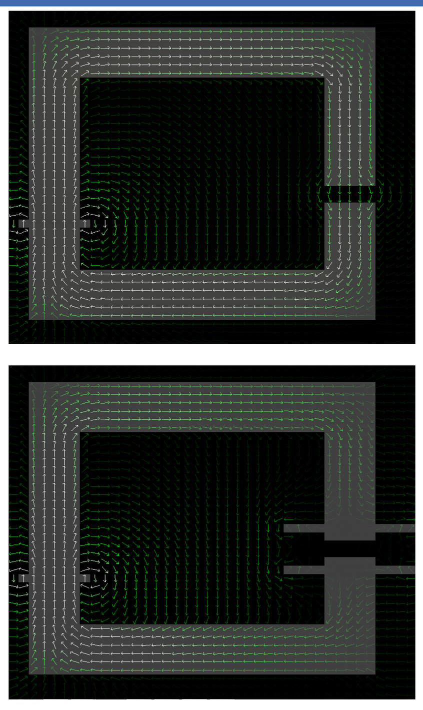

Figure Computer simulation of magnetic fields without SC stabilizer (top) and with SC stabilizer (bottom) .

Proof of Concept

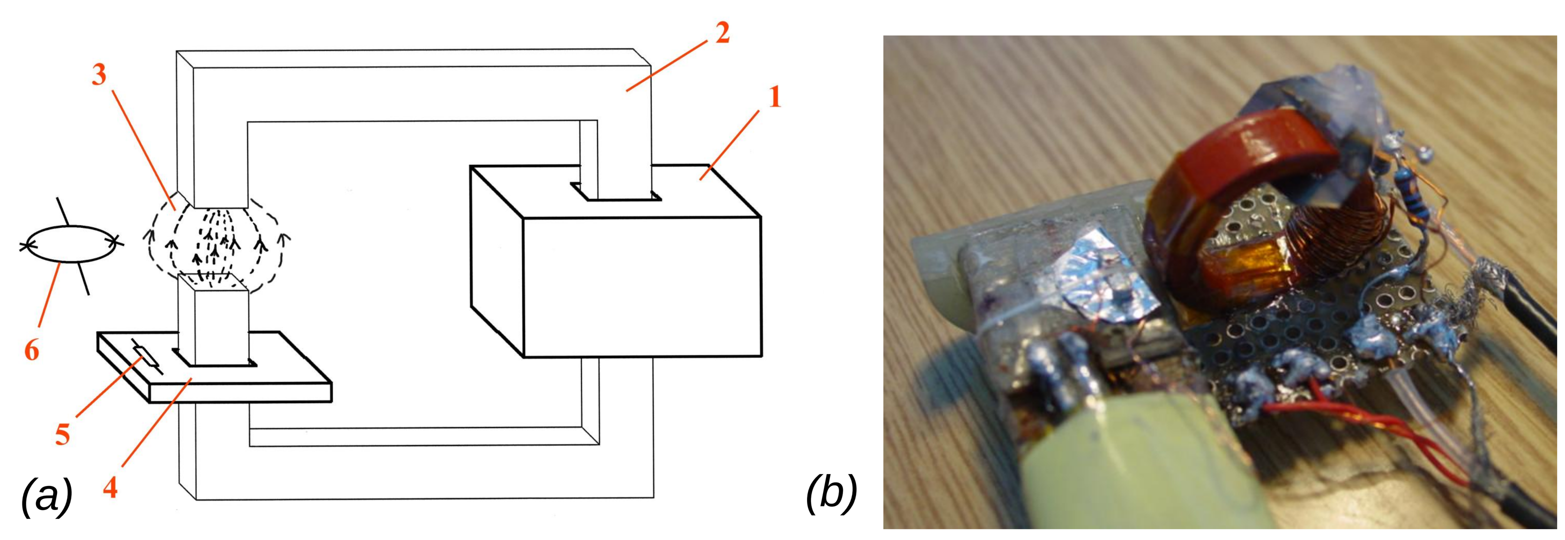

Figure 5. (a) Sketch of experimental setup with main field coil (1), soft magnetic yoke (2), stabilized magnetic field region (3), superconducting ring (4), local heating element to allow flux entrance into the superconducting ring for a change of flux (5) and SQUID detector (6) to monitor the flux in the stabilized region. (b) Photograph of experimental setup, which was placed in liquid nitrogen for the measurement.

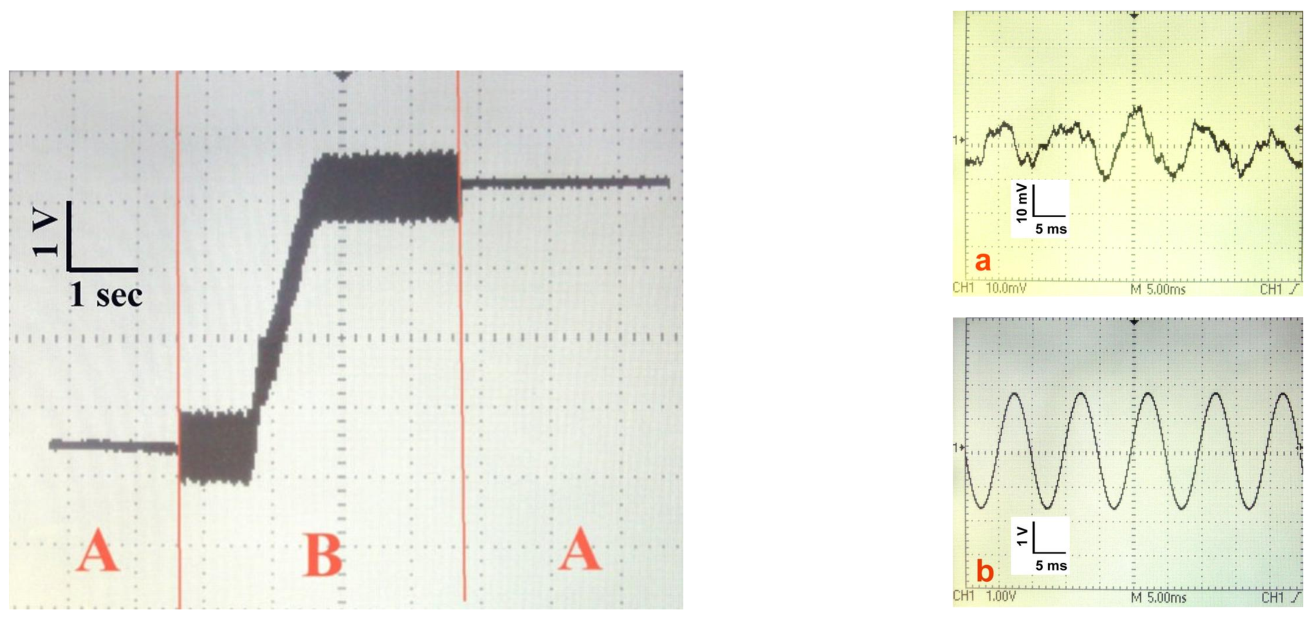

Figure 6. (Left) Oscillogram showing measured magnetic field in stabilized (A) and adjust (B) modes in the test setup. During timespan B, the additional interference, which was simulated by adding an AC field to the main (DC) field of the coil, appears. The measured DC field was then also changed to a different value during heating of the superconducting ring. (Right) Test signals with SC stabilizer ON (a) and with SC stabilizer OFF (b).

A "proof-of-principle" demonstration of the proposed approach was achieved by using the experimental setup shown in the form of a schematic diagram and a photograph in Figures 5a and 5b, respectively.
A high-T_c direct current superconducting quantum interferometer device (high-T_c DC SQUID) [3] operating at a temperature of 77 K was placed in the vicinity of a gap in a permalloy core VAC W867-01 and used for sensitive non-invasive characterisation of the magnetic field in the stabilized region.
Figure 6 demonstrates the operation of the superconducting magnetic field stabilizer. Magnetic field fluctuations were simulated by adding an alternating current (AC) field (~100 Hz) to the main DC field of the coil. The superconducting loop was made from an $YBa_2Cu_3O_7$ high-T_c thin film tape that was cooled to 77 K in stabilizing mode A. Even in the non-optimized demonstrator shown in Figure 5b, more than 99 % of the magnetic field fluctuations were removed by the stabilizer when compared to mode B, in which the superconducting loop was switched to its normal state by heating above the superconducting transition temperature. In mode B, adjustment to a new magnetic field value was possible, as shown in Figure 6 (Left). Figure 6 (Right) shows the magnetic field (a) in mode A and (b) in mode B measured with 5 ms time scale.

Prospective applications for electron microscopes

The superconducting magnetic field stabilizer can be applied to several types of scanning electron microscope or transmission electron microscope (TEM) lens.
Prospective setups for different TEM objective lenses ar

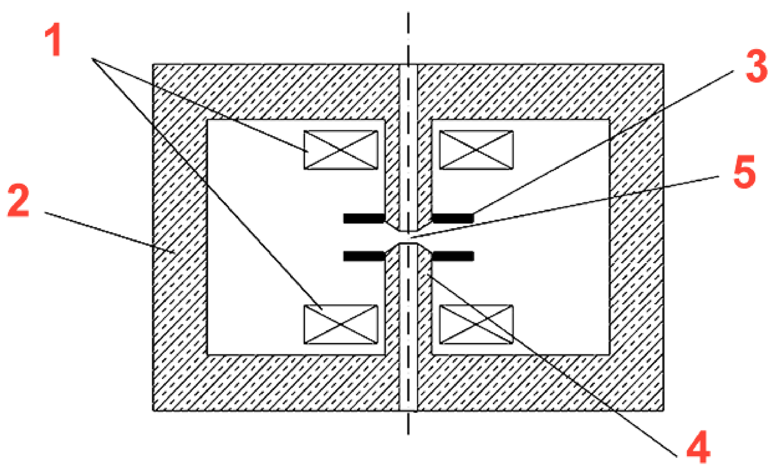

Figure 7. Sketch of prospective setup for a TEM objective lens. Coils (1) provide magnetic flux through the yoke (2). Two stabilizing SC rings (3) are placed near the pole piece ends (4) to stabilize magnetic field in the sample area (5) [1].

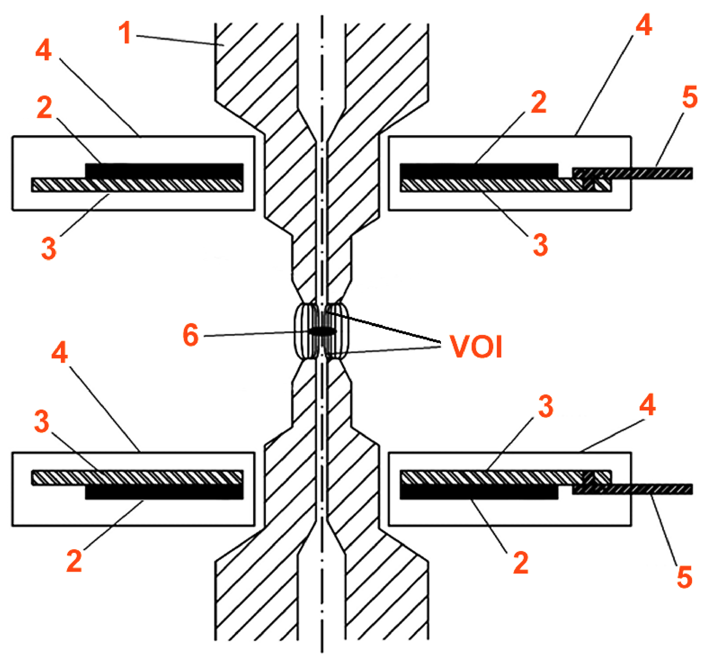

Figure 8. Sketch of prospective setup for a TEM objective lens. The coils (not shown) providing the main magnetic flux through the yoke (1). The poles are surrounded by SC rings (2), which are placed on heat conducting substrates (3) inside thermal insulations (4) and cooled through cold leads (5). Magnetic field is stabilized in volume of interest (VOI) near the sample (6) [1].

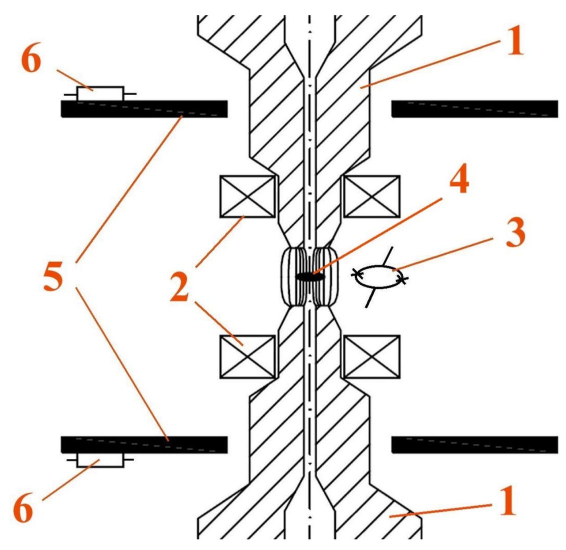

Figure 9. Sketch of prospective setup for a TEM objective lens. Apart from the coils (not shown) providing the main magnetic flux through the yoke (1), two additional coils (2) can be used together with a SQUID detector (3) in feedback mode for fine adjustment of the magnetic lens field near the sample (4). Two stabilizing SC rings (5) with local resistive heaters (6) are placed near the pole piece ends [1].

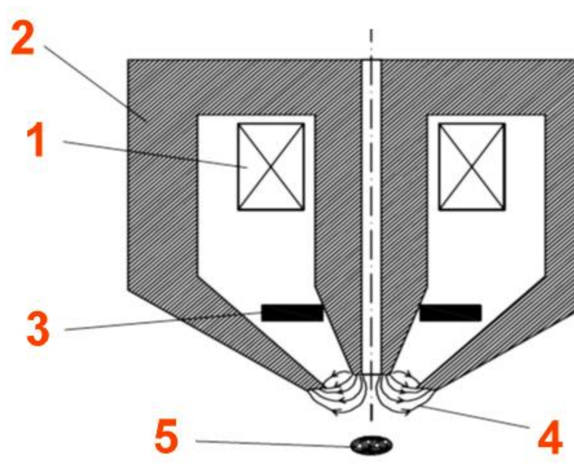

Figure 10. Sketch of prospective setup for an SEM conical objective lens. Coil (1) provides magnetic flux through a yoke (2). A stabilizing SC ring (3) is placed near the pole piece end to stabilize the magnetic field in the area of the strong magnetic field gradient (4), which focuses the electron beam onto the sample (5) [1].

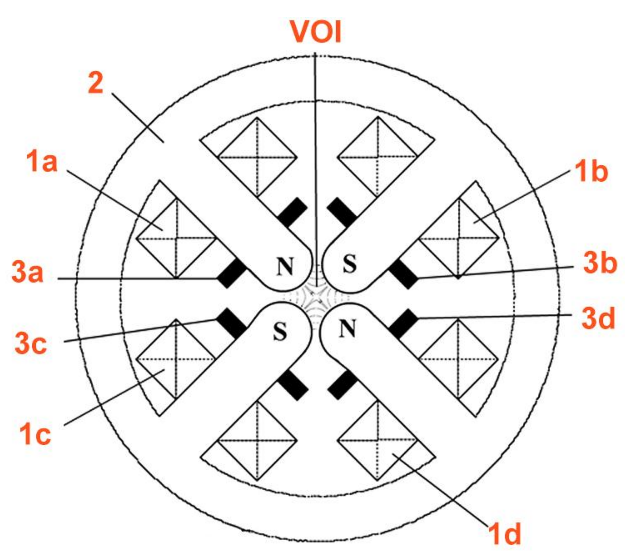

Figure 11. Sketch of prospective setup for a quadrupole lens. Coils (1a-d) provide magnetic flux through the yoke (2). Stabilizing SC rings (3a-d) are placed near the pole piece ends (S, N) to stabilize the magnetic fields and their gradients in the volume of interest (VOI) [1].

References

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2) W. Buckel and R. Kleiner, "Supraleitung", ISBN 978-3-527-41139-9 (2013) .
3) M.I.Faley, U.Poppe, R.E.Dunin-Borkowski et al., "High-T_c DC SQUIDs for magnetoencephalography", *IEEE Trans. Appl. Supercond.* **23** 1600705 (2013).

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