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An ultra-low magnetic field thermal demagnetizer for high-precision paleomagnetism

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Abstract

Thermal demagnetization furnaces are widely used paleomagnetic facilities for progressive removal of naturally acquired magnetic remanence or the imparting of well controlled laboratory magnetization. An ideal thermal demagnetizer should maintain “zero” magnetic field in the sample chamber during thermal treatments. However, magnetic field noises, including the residual magnetic fields of the construction material and the induced fields caused by the alternating current (AC) in the heating element are always present, which often greatly contaminate the paleomagnetic results at the elevated temperatures or for the magnetically weak samples. Here, we designed a new structure of heating wire named straight core solenoid to develop a new demagnetization furnace with ultra-low magnetic field noise. Simulation and practical measurement show that the heating current magnetic field can be greatly reduced by using the new technology. Thermal demagnetization experiments demonstrate that the new demagnetizer can yield low noise results even for weakly magnetic samples.

23

24 *Key words:*

25 Paleomagnetism, thermal demagnetization, furnace, AC magnetic field, residual magnetic field,
26 heating wire structure, straight core solenoid

27

28 **1. Introduction**

29 Paleomagnetism investigates the geomagnetic field through geologic time by the measurement
30 of natural remanent magnetizations (NRM) recorded by magnetic minerals in natural materials.
31 NRM of geological materials usually consists of multiple components. Therefore, to define the
32 stable characteristic remanent magnetization (ChRM) of geological interest, any secondary
33 remanent magnetization needs be removed using sequential demagnetization techniques (e.g., the
34 step-wise progressive thermal or alternating field demagnetization ([Irving et al., 1961](#); [Schmidt,](#)
35 [1993](#)). During thermal demagnetization, specimens are heated to a pre-selected temperature, held
36 for a period of time (e.g., 10-30 minutes), and then cooled down to the room temperature in “zero”
37 magnetic field environment ([Collinson, 1983](#)). This treatment will be conducted repeatedly with
38 progressive increased target temperature till the ChRM is isolated ([Thellier, 1966](#); [Collinson, 1975](#)).
39 Thermal demagnetization is one of the standard demagnetization methods, and thermal
40 demagnetization furnaces (or thermal demagnetizers) are standard facility in nearly all
41 paleomagnetic laboratories.

42 Although widely used, the experimental success rate of thermal demagnetization can be
43 relatively low for weakly magnetic samples such as sedimentary rocks. It is often found that
44 remanent direction of some specimens become seriously distorted at high temperatures, but the

45 ChRM can still be obtained by alternating field demagnetization using sister specimens. The failure
46 of thermal demagnetization could be attributed to irreversible thermal physio-chemical alterations
47 upon heating (e.g., Wasilewski 1969, Heller et al., 1970), partial thermoremanent magnetization
48 (pTRM) acquisition in the presence of a residual DC field upon cooling (Collinson, 1975), or
49 magnetic fields caused by the heating current (Heller et al., 1970). Although early studies did not
50 detect differences between inductive and noninductive heating wire (Irving et al., 1961), inductive
51 alternating fields (AF) can cause unwanted AF demagnetization at high temperature. Given that the
52 coercivity of magnetic minerals reduces quickly as the temperature approaches the unblocking
53 temperature or Curie temperature, this effect may be substantial. In the extreme, the NRM direction
54 could be biased by single axis AF demagnetization because of the stationary current field
55 (Stephenson, 1983) or through the acquisition of gyroremanence (Stephenson, 1980, Finn and Coe,
56 2016) at high temperature.

57 Reducing the residual fields present in thermal demagnetizers can significantly improve the
58 quality of paleomagnetic measurements, particularly for weakly magnetized specimens. Moreover,
59 for the study of meteorites in planetary science or magnetizations acquired near the onset of the
60 geodynamo, understanding the characteristic remanent magnetization acquired in low magnetic
61 fields, including extremely weak fields (nT range) is a topic of great interest (Weiss et al., 2010;
62 Tarduno et al., 2015; Wang et al., 2017). It is important that the technology around thermal
63 demagnetizers progress to keep pace with the changing demands of the scientific community.

64 In this study, we will first describe the technology to reduce the residual magnetic field for a
65 newly designed thermal demagnetizer. The key point is to reduce the current magnetic field by
66 adopting a new structure of heating element. We then conduct some thermal demagnetization

experiments to test the performance of the new furnace.

2. Newly designed furnace for thermal demagnetization

The heating elements in thermal demagnetizers is typically constructed of non-inductive windings in order to minimize the AC demagnetization effect of the heating current (Chamalaun and Creer, 1964; Chamalaun and Porath, 1968). There are generally two types of non-inductive heater winding, one is a bifilar solenoid wrapped on a cylindrical form to heat specimens within (Figure 1a). This style of winding is widely used in small furnaces such as the Sogo Fine-TD furnace in Japan (Zheng et al., 2010a). It is also used in some Kapabridges and variable field translation balances (VFTBs) to heat specimens. In this configuration, the opposing currents of adjacent wires reduce the AC magnetic field. A disadvantage of this system, however, is that the specimen region has to be small in order to maintain an acceptable resistance and workable power consumption.

An alternative method is to use solenoids arranged in opposite direction (Figure 1b) or wound into a helix, as is used furnaces manufactured. It is usually assumed that the magnetic field generated by a uniform solenoid is only in the interior and both ends of the solenoid (Shaw, 2010), but this neglects the fact that in a real solenoid the wire loops (and current loops) are not perfectly circular, which results in non-zero external fields. Therefore, it is necessary to consider the magnetic field distribution outside a helical solenoid.

2.1. Simulated calculation of solenoid magnetic field

The magnetic field distribution outside a solenoid can be achieved using the Biot-Savart law. Assuming a current, I , flowing in a finite solenoid, the vectors of magnetic field at point P (Figure 2) produce by a differential current element $I d\vec{l}$ can be written as:

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{l} \times \vec{r}}{r^3}, \quad (1)$$

where r is distance from the point N on the filament to the field point P.

In cylindrical coordinates, dl and r can be expressed as:

$$d\vec{l} = \vec{i} dx + \vec{j} dy + \vec{k} dz = -\vec{i} R \sin \theta d\theta + \vec{j} R \cos \theta d\theta + \vec{k} a d\theta \quad (2)$$

$$\vec{r} = \vec{i} (x_0 - R \cos \theta) + \vec{j} (y_0 - R \sin \theta) + \vec{k} (z_0 - a\theta). \quad (3)$$

Therefore:

$$d\vec{l} \times \vec{r} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ -R \sin \theta d\theta & R \cos \theta d\theta & a d\theta \\ x_0 - R \cos \theta & y_0 - R \sin \theta & z_0 - a\theta \end{vmatrix}, \quad (4)$$

and we have

$$dB_x = \frac{\mu_0 I}{4\pi} \frac{[(z_0 - a\theta) R \cos \theta - (y_0 - R \sin \theta) a] d\theta}{[(x_0 - R \cos \theta)^2 + (y_0 - R \sin \theta)^2 + (z_0 - a\theta)^2]^{3/2}} \quad (5)$$

$$dB_y = \frac{\mu_0 I}{4\pi} \frac{[(z_0 - a\theta) R \sin \theta + (x_0 - R \cos \theta) a] d\theta}{[(x_0 - R \cos \theta)^2 + (y_0 - R \sin \theta)^2 + (z_0 - a\theta)^2]^{3/2}} \quad (6)$$

$$dB_z = -\frac{\mu_0 I}{4\pi} \frac{[(y_0 - R \sin \theta) R \sin \theta + (x_0 - R \cos \theta) R \cos \theta] d\theta}{[(x_0 - R \cos \theta)^2 + (y_0 - R \sin \theta)^2 + (z_0 - a\theta)^2]^{3/2}}. \quad (7)$$

As the radius of the solenoid tends to zero, the solenoid may be approximated as a straight wire. Then the field formula simplifies to the magnetic field generated by the straight wire when.

The point on a straight wire is $(0,0,a\theta)$, and filament became as $d\vec{l} = \vec{k} a d\theta$, and

$\vec{r} = \vec{i} x_0 + \vec{j} y_0 + \vec{k} (z_0 - a\theta)$, and therefore

$$dB_x = -\frac{\mu_0 I}{4\pi} \frac{y_0 a d\theta}{[x_0^2 + y_0^2 + (z_0 - a\theta)^2]^{3/2}} \quad (9)$$

$$dB_y = \frac{\mu_0 I}{4\pi} \frac{x_0 a d\theta}{[x_0^2 + y_0^2 + (z_0 - a\theta)^2]^{3/2}} \quad (10)$$

$$dB_z = 0 \quad (11)$$

It can be seen that when the solenoid diameter is small, the magnetic field generated by the solenoid is roughly the same as that of the straight wire. Therefore, to reduce the stray external fields of a solenoid, a straight wire can be inserted through its core and connected with solenoid at one

end, such that the current in the straight wire is flowing opposite to the current in the solenoid (Figure 1c). A new heating element is designed based on this configuration which we call it straight core solenoid, and will be used to manufacture our new thermal demagnetizer.

To simulate a heating element solenoid, we assume that the solenoid length is 1 m, the radius is 4 mm, and the pitch distance is also 4 mm. And the current is set to 1A. We simulate the fields along the direction of solenoid axis at a distance of 20 mm from central axis. The results are shown in Figure 3. Only absolute values of field are considered here. It is found that the perpendicular component (X) is higher than the radial component (Y) and parallel components (Z), and the X component can be reduced by two orders of magnitude if a straight wire with reverse current is passed through the center of the solenoid. The Y and Z components remain unchanged, since the magnetic field produced by the straight wire is only in the X direction. The fluctuations of field value were also observed at very close to the solenoid and the period is consistent with the pitch distance. The magnetic field distribution in other cases can be obtained by changing parameters of the solenoid, such as radius, pitch. It is useful to optimize the structure of heating wire before practical manufacture.

In fact, the whole heater group consists of a series of parallel or antiparallel heating element solenoid and its configuration determined the magnetic field inside the furnace. We calculate the magnetic field distribution in the furnace. The heater composed of 12 conventional solenoids or new heating elements with opposite current direction between adjacent is simulated (Figure 4). The parameters of each solenoid are the same as those used in Figure 3, and the current is still set to 1A. It can be seen that the magnetic field in the center of the furnace is extremely low for both configurations, but the low magnetic field area is considerably enlarged in the furnace with new heating elements. Different configurations which are consistent with some practical applications can also be simulated. The large magnetic field may be produced by parallel connection of heating wire groups (Figure 5). However, the magnetic field is still very low inside the furnace with same configuration using the new straight core solenoid.

2.2. Measurement of solenoid magnetic field

In order to verify the effectiveness and determine the magnetic field of the new heating

element, the respective magnetic fields produce by the conventional solenoid heating wire and the new heating element were measured with a triaxial fluxgate magnetometer (APS520). One solenoid heating element with length of one meter and diameter of 8 mm was placed inside a magnetically shielding cylinder with 1A DC current applied in the wire (Figure 6a). The fluxgate sensor was placed to the side of solenoid at vertical distance of about 20 mm and moved along the long axis direction. The magnetic field at different positions was observed with the current on then off. In the same way, we measured the magnetic field of our new straight core solenoid heating element, which is composed of the same solenoid with a straight wire passing through it (Figure 6b). The solenoid and the straight wire were isolated by a ceramic sheath. The results are shown in Figure 6c. The magnetic field of conventional solenoid is about 6000–7000 nT and field direction is almost perpendicular to the long axis of solenoid and is consistent with the simulation, which is almost equivalent to that of an axial line current. The stray magnetic field of the straight core solenoid is much lower than the standard solenoid, with a total field intensity of 26-535 nT.

In our prototype thermal demagnetizer adjacent elements are arranged in opposite directions (Figure 7a). The magnetic field at different positions along the axis of the heating chamber were measured when a DC current of 1A is applied to the heating wire. The peak magnetic field in the sample region is about 130 nT (Figure 7b)

2.3 Degaussing the shield cylinder and the TD-PGL-100

In order to shield the influence of external magnetic field, the chamber of thermal demagnetization furnace is usually installed in a cylindrical magnetic shield cylinder. The residual fields in sample zone typically vary from several nT to 150 nT in different furnaces (Paterson et al., 2012), which is mainly determined by the remanent magnetization of magnetic materials within the furnace (Freake and Thorp, 1971, Thiel et al., 2007). A lower residual field can be archived by AF demagnetization of the shield cylinder. Early experiments found that the best shield demagnetization results were obtained by passing the AC current through conductors within the shield cylinders or

by passing the current longitudinally through the shielding material itself (Herrmannsfeldt and Salsburg, 1964). A circular magnetic field perpendicular to the central longitudinal axis will be produced in the cylindrical shield if a current conducting straight wire is passed through the longitudinal center axis of the shield cylinder, however, this requires a large current to reach peak demagnetization. In practice, we use a total of eight 4 mm² copper lines wound from inside to outside of the shield cylinder to form a large coil (Figure 8a), and connected to a transformer with a twisted-pair cable. The transformer has separated primary and secondary windings which can be pulled apart. Separating the windings will generate a nonlinear attenuation of the alternating current in the coil which performs AF demagnetization of the shield cylinder. The residual magnetic field in the sample region can be as low as 1 nT (Figure 8b), which makes it possible to further reduce spurious fields during thermal demagnetization.

A new furnace named TD-PGL-100 had been built based on above mentioned techniques. The furnace has a chamber of 120 cm length and 9 cm diameter, and the sample zone is designed as 60 cm in length, which allows up to 100 standard paleomagnetic specimens be treated together. Temperature gradient in the sample zone is within 10°C of target temperature below 600°C and 12°C at 700°C

3. Examples of thermal demagnetization experiment

In order to verify the effectiveness of the new furnace, thermal demagnetization experiments were carried out on 12 nature specimens and 8 synthetic specimens using TD-PGL-100. Nine sandstone specimens denoted as “B” were collected from Cenozoic strata in Yunnan, and three muddy limestone specimens denoted as “CM” were from Tibet. The main magnetic carrier mineral of sandstone specimen is hematite (Li et al., 2017). They have only a single univectorial component

decaying steadily toward high temperature. The muddy limestone specimens also contain hematite and have multi-component characteristics of different temperature ranges. Hematite specimens synthesized in the lab were chosen to avoid potential thermochemical changes during multiple heatings. The particles of hematite are cubic and with a broadly uniform size distribution with an average length and width of 570 nm and 545 nm, respectively.

We have also tried to evaluate the influence of the background magnetic field. After progressive thermal demagnetization of TRM was carried out to identify the unblocking temperature spectrum of the synthetic hematite specimens, the specimens were heated to 700°C for complete thermal demagnetization, then the progressive thermal demagnetization was repeated. Remanent directions and moments were measured with a cryogenic magnetometer system (2G Enterprises 755) installed in the magnetically shielded room with residual field < 300 nT at IGGCAS. Background noise is typically lower than $2 \times 10^{-12} \text{Am}^2$, and the background moment of the sample tray was kept less than $5 \times 10^{-11} \text{Am}^2$ during the measurements. All the experiments were completed in the paleomagnetic laboratory at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS).

The thermal demagnetization experiments of natural specimens show that good demagnetization results can be obtained using the new furnace. The representative experimental results are shown in [Figure 9](#). The remanence directions of some specimens do not change much after demagnetization at high temperature, when the remanence intensity is less than 10% of the NRM intensity. The ChRM of high temperature can be successfully isolated for the specimens with multi-component characteristics. The magnetic moments of synthetic specimens during the repeated progressive thermal demagnetization are about 0.02-0.05% of the 30 μT TRM (*see detail in*

supporting information). It confirms that the influenced by undesirable magnetic fields from the furnace is very small.

4. Discussion

Although the heater configuration with conventional solenoids can also cancel out the magnetic field at the center, for effective cancellation of the fields generated in each solenoid, this design requires that opposing solenoids are perfectly antiparallel. Imperfect alignment results in the small, but potentially significant AC fields when large currents are applied during heating (Zheng et al., 2010a, b; Shaw, 2010). The new design with straight core solenoid can eliminate the dependence on symmetry of configuration, and can obtain a large space of low magnetic field.

For comparison, Zheng et al. (2010a, b) investigated similar 1A current field for the commercially available Sogo Fine-TD, Magnetic Measurements MMTD80 as ~240 and 840 nT, respectively. They also reported 0.5 A current field for the ASC TD48 and Natsuhara as being 3600 and 1600 nT, respectively (equivalent to 1 A fields of 7200 and 3200 nT, respectively). We use our new straight core solenoid heating element to build a new furnace named TD-PGL-100. Subsequently measurements in our later builds have peak current field of only ~95 nT/A. This new design, which holds up to 100 specimens, represents a 2-3 times reduction in AC fields compared to the eight specimen Sogo Fine-TD, and a 9 to 77 times reductions compared to other high capacity demagnetizers.

It should be noted that the current field is an alternating magnetic field. In thermal demagnetization, the current field is more like the effect of AF demagnetization, and the way to cut off the heating current (e.g., abrupt on-off, or gradual ramping etc.) may affect the demagnetization effect. However, the new design combined with the appropriate mode of AC supply has the potential

to further lower the impact. Although our improved heating element can greatly reduce the AC current field, it cannot completely eliminate it. If lower AC magnetic fields are required, the only alternative would be to heat the specimens outside of the primary electrical heating element region. This could be achieved by heating the sample region by hot gas flow heated outside the sample region. This style of furnace can reduce AC current field to practically zero (Heller et al., 1970). Such gas flow furnace systems, however, are limited to heating only a small number of specimens. Our new TD-PGL-100 thermal demagnetizer with lower AC current field and super low residual magnetic fields is a reasonable choice for most paleomagnetic laboratories.

5. Conclusions

Here we introduce a new heating element that is composed of a straight wire inserted into solenoid and connected in series at one end, a configuration we call a straight core solenoid. Such a configuration can drastically reduce the stray magnetic fields generated when a current is applied to the heating element. We also adopt a demagnetization procedure that can reduce the residual magnetic field in shield cylinder to less than 1 nT in sample zone. The TD-PGL-100 built with those technologies allows the successful recovery of weak magnetizations blocked at high temperatures and has applications in recovering sedimentary magnetizations, records of geomagnetic polarity reversals, signals of the earliest geodynamo, as well as extraterrestrial magnetizations. One of this new thermal demagnetizer has been running normally for three years in the IGCCAS laboratory, and results demonstrate its excellent performance especially for these weakly magnetic natural specimens (Jiang et al., 2017, Yan et al., 2018).

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List of abbreviations

NRM: The natural remanent magnetization

AC: the alternating current

ChRM: the stable characteristic remanent magnetization

pTRM: partial thermoremanent magnetization

AF: the alternating field

DRM: the detrital remanent magnetization

Authors' contributions

HQ: instrument development; experimental design; figures plotting; manuscript writing. XZ: instrument manufacture; key issues discussion; manuscript revising. SL: test of instrument. GP: key issues discussion; manuscript revising. ZJ: preparation of synthetic samples. SC: Experimental test and data analysis. JL: key issues discussion. QL: proposing idea; framework design; manuscript revising. RZ: supervision of work and manuscript evaluation. All authors read and approved the final manuscript.

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275

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284 **Competing interests**

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Figure 1. Configuration of non-inductive heating wires. (a) Bifilar solenoid wrapped for a small oven, (b) solenoid-like helical heating wires arranged in a larger oven, (c) the new straight core solenoid heating wires using in the TD-PGL-100. Arrows indicate the current flow direction.

Figure 2. Schematic diagram for calculating magnetic field outside of solenoid (R is the radius of solenoid and $2\pi a$ is the pitch distance).

Figure 3. Magnetic field simulations of single long solenoid. The black line represents the result of conventional solenoid and the red dash line represents the result of a solenoid with a reverse straight wire at solenoid axis.

Figure 4. Simulated magnetic field distribution in middle cross section of the furnace with composed of 12 conventional solenoids (a,b,c) and new heating elements (d,e). (f) The position of the solenoids and the corresponding current direction in adjacent. Letter X, Y, Z in the middle of the graph represents the direction of the magnetic field.

Figure 5. Simulated magnetic field distribution in the furnace with composed of 12 conventional solenoids (a,b,c) and new heating elements (d,e). (f) The position of the solenoids and the

corresponding current direction in adjacent. Letter X, Y, Z in the middle of the graph represents the direction of the magnetic field.

Figure 6. Magnetic field measurement of conventional solenoid and new heating wire. The length of solenoid is 1 meter, the radius is 4 mm and with pitch distance of 4 mm. The DC current of 1 A applied in the wire during measurement. The black line represents the result of conventional solenoid and the red dash line represents the result of a straight core solenoid.

Figure 7. (a) photo of furnace chamber. (b) current field (red triangles) with 1A applied to the heating wire along longitude axis in the newly designed furnace

Figure 8. (a) toroidal degaussing coil embody the shield cylinder. (b) Residual fields (black circles) along longitude axis in the newly designed furnace

Figure 9. Thermal decay curves and corresponding orthogonal plots of progressive thermal demagnetization of natural specimens. Solid (open) circles indicate projection on the horizontal (vertical) plane.

Figures

Figure 1

Configuration of non-inductive heating wires. (a) Bifilar solenoid wrapped for a small oven, (b) solenoid-like helical heating wires arranged in a larger oven, (c) the new straight core solenoid heating wires using in the TD-PGL-100. Arrows indicate the current flow direction.

Figure 2

Schematic diagram for calculating magnetic field outside of solenoid (R is the radius of solenoid and $2\pi a$ is the pitch distance).

Figure 3

Magnetic field simulations of single long solenoid. The black line represents the result of conventional solenoid and the red dash line represents the result of a solenoid with a reverse straight wire at solenoid axis.

Figure 4

Simulated magnetic field distribution in middle cross section of the furnace with composed of 12 conventional solenoids (a,b,c) and new heating elements (d,e). (f) The position of the solenoids and the corresponding current direction in adjacent. Letter X, Y, Z in the middle of the graph represents the direction of the magnetic field.

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Simulated magnetic field distribution in the furnace with composed of 12 conventional solenoids (a,b,c) and new heating elements (d,e). (f) The position of the solenoids and the corresponding current direction in adjacent. Letter X, Y, Z in the middle of the graph represents the direction of the magnetic field.

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Magnetic field measurement of conventional solenoid and new heating wire. The length of solenoid is 1 meter, the radius is 4 mm and with pitch distance of 4 mm. The DC current of 1 A applied in the wire during measurement. The black line represents the result of conventional solenoid and the red dash line represents the result of a straight core solenoid.

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(a) photo of furnace chamber. (b) current field (red triangles) with 1A applied to the heating wire along longitude axis in the newly designed furnace

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Figure 9

Thermal decay curves and corresponding orthogonal plots of progressive thermal demagnetization of natural specimens. Solid (open) circles indicate projection on the horizontal (vertical) plane.

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