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Hardware Article

DONALD: *A 2.5 T wide sample space permanent magnet*

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ABSTRACT

The permanent magnet apparatus described herein is based upon the C-shaped permanent magnet. It is designed to maximise field strength while increasing the pole gap to 5 mm, providing a sample volume large enough for wide applicability. The production of this equipment aims to provide a homogeneous, high field (~2.5 T) magnetic sample environment with a volume large enough to accommodate solution crystallisation experiments in sample chambers such as NMR tubes and cuvettes whilst simultaneously allowing direct observation of the sample from a wide angle. Although the resulting rig is not lightweight at 26.5 kg it is eminently more portable than an equivalent electromagnet system (of the order of 625 kg), and provides a max field strength of 2.468 T with relatively low stray field.

Specifications table

Hardware name	Directionally Orientated NIB Array Large Diameter (DONALD)
Subject area	Engineering and Material Science
Hardware type	Mechanical engineering and materials science, High magnetic field laboratory magnet, Desk top permanent magnet, Crystal growth
Open Source License	Attribution-ShareAlike 4.0 International
Cost of Hardware	€ 750.00 (EUR)
Source File Repository	N/A

1. Hardware in context

The use of magnetic fields in standard laboratory experiments is relatively under explored despite a slew of interesting results [1–6]. This is, in part, due to an issue with reproducibility in these reported systems [7] typically associated with a lack of consistency in permanent magnet equipment e.g. the surface of a block magnet is not a neat single field strength over the entire area. In order to ensure reproducibility in experiments involving the application of magnetic fields, homogeneity of the field is essential. At higher fields, one must normally sacrifice the size of the sample space or resort to expensive electromagnets [8] or specialist facilities [9]. This can curb innovation as high (> 1 T) magnetic fields are inaccessible to most on a daily basis, even in a well-equipped research laboratory [10]. The inability to directly observe the sample in situ also forces a reliance on post analysis of the sample [11].

These specific equipment issues become barriers to any line of enquiry requiring higher fields over long time-scales, exemplified by magnetic field-mediated crystal growth. In the majority of cases, single crystals large enough to fully characterise, take time-scales

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on the order of days to grow. These systems can also require complex solvent/anti-solvent mixes which are not suitable to be used in a sealed sample tube or sample space requiring a vacuum [12], large volumes or a specific, non-ambient atmosphere of gasses [13] to be held under magnetic fields over a prolonged period of time.

An ideal sample environment would also allow for direct observation of the system during crystallisation, requiring an arrangement in which access to the sample space is maximised. Direct observation from as wide of an angle as possible of the system is necessary in order to maximise strategies for data collection and increase the generic applicability of the unit. Existing permanent magnets for sale above 2 T are mostly cylindrical with a small ~1 cm in diameter or C-shaped with a pole cavity of ~1 mm. While the unit discussed in this paper was produced with the field of crystal growth in mind, such a sample environment would also find general use in any field of research requiring a relatively high, sustained magnetic field, without having to resort to expensive solutions.

Currently available permanent magnets above 2 T are Halbach cylinders, arrays designed to maximise magnetic flux within a circular cavity whilst minimising that outside by selective arrangement of the poles of wedge-shaped magnets [14]. This is necessarily restrictive as the sample space is within a tube accessible only from either end and to maximise magnetic field strength using permanent magnets, this space is restricted to small cavities ~1 cm in diameter [15]. Sample access can be expanded by the introduction of equatorial radial tunnels or by a thin slit in the walls of the cylinder if full equatorial access is required. This reduces the field at the centre of the gap and also the radial homogeneity of the field [16]. In theory such designs can produce fields of any strength, however in practice the logarithmic relationship between the outer radius of the array and the resulting field strength mean that fields above 3–4 T become impractical [16,17]. For practical purposes a C-shaped arrangement is preferred, as this allows 360° access to the sample space. Current examples of such C-shaped magnets have been able to achieve high field strengths of 3.2 T between pole faces of 1 cm^2 but with only a small 1.5 mm separation [18].

The permanent magnet apparatus described herein is based upon the C-shaped permanent magnet produced by researchers at Karlsruhe Institute of Technology [18]. The design has been modified to maximise field strength while increasing the pole gap to 5 mm to provide a larger sample volume. The production of this equipment aims to provide a homogeneous, high field (~2.5 T) magnetic sample environment with a large volume and easy accessibility. Although the resulting rig is not lightweight at 26.5 kg it is eminently more portable than an equivalent electromagnet system (of the order of 625 kg), and provides a maximum field strength of 2.468 T with relatively low stray field.

2. Design files

Design file name	File type	Open source license	Location of the file
Design Schematic	Fig. 1	Attribution-ShareAlike 4.0 International	*available with the article*
3D schematic of single pole end	Fig. 2	Attribution-ShareAlike 4.0 International	*available with the article*
2D FEMM calculation	Fig. 9	Attribution-ShareAlike 4.0 International	*available with the article*

3. Bill of materials

Designator	Component	Number	Cost per unit-currency	Total cost-currency	Source of materials	Material type
Magnet	$Nd_2Fe_{14}B$ block magnets	24	€ 20.67	€ 496 (Inc. VAT and shipping)	supermagnete.de (Q-40-40-20-N)	$Nd_2Fe_{14}B$
Pole Shoe	Pole Shoes	2	€ 17.5	€ 35	Shropshire Stainless & Aluminium – Bristol BS37 5QX	Mild Steel
Yoke	Yoke	1	–	€ 110	Shropshire Stainless & Aluminium – Bristol BS37 5QX	Mild Steel
Frame	Aluminium Magnet frame	2	–	€ 50	Shropshire Stainless & Aluminium – Bristol BS37 5QX	Aluminium 6082
Primary Shield	Aluminium shield large piece	1	–	€ 35	Shropshire Stainless & Aluminium – Bristol BS37 5QX	Aluminium 6082
Secondary Shield	Aluminium shield small piece	4	–	€ 17	Shropshire Stainless & Aluminium – Bristol BS37 5QX	Aluminium 6082
Screw	Brass screws	24	–	€ 5	Shropshire Stainless & Aluminium – Bristol BS37 5QX	Aluminium 6082

3.1. Component construction

The yoke was cut using a water jet from a single piece of mild steel of dimensions 330 mm × 151 mm × 77 mm before being milled to shape, threads were then machined into the sides in preparation for the aluminium magnet frames. Pole shoes were milled

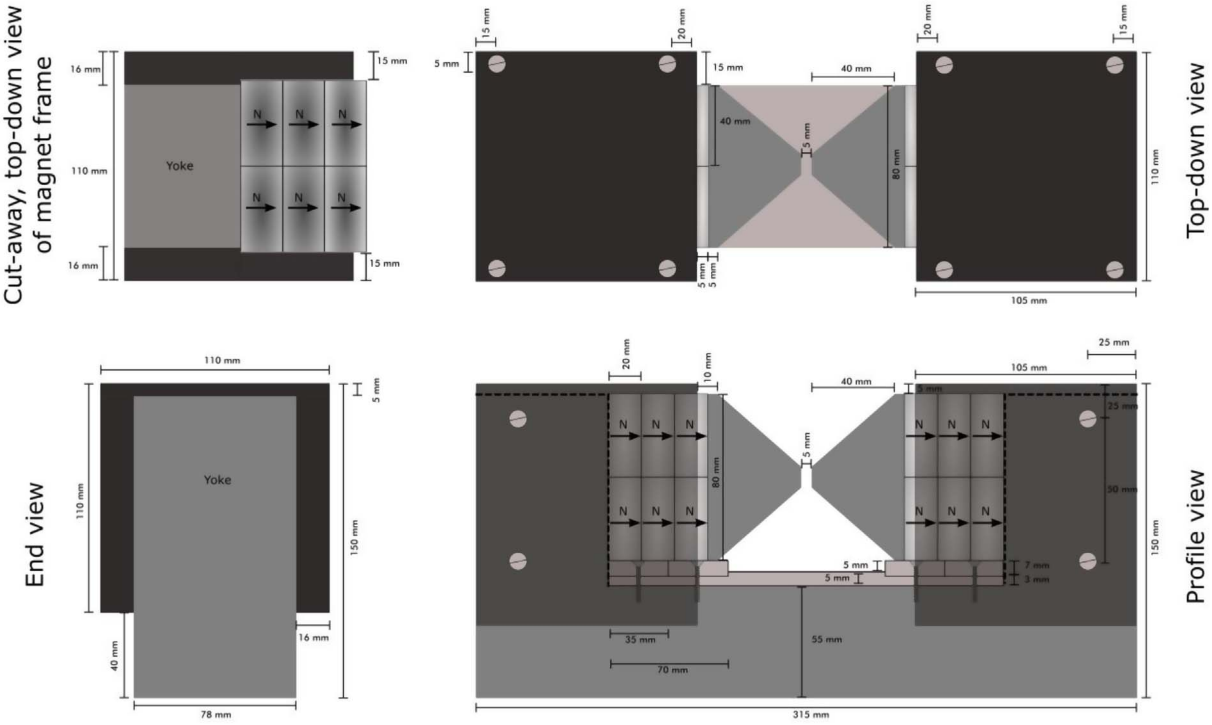

Fig. 1. Design schematic of the permanent magnet.

from single pieces of mild steel of size 80 mm × 80 mm × 50 mm. For stability, a thread was bored into the base and the whole piece clamped using a 10 mm steel screw. The screw was then cut and machined to form a smooth surface. All aluminium parts were milled from 6082 aluminium alloy sheets of thicknesses 16 mm, 7 mm and 5 mm. Aluminium magnet frames were assembled using brass screws after machining threaded holes into the sides of the thicker, 16 mm plate. The finished, fabricated components are described in more detail in the magnet rig assembly section.

4. Build instructions

4.1. Summary

The permanent magnet has been designed to provide a high magnetic field $> 2\,\mathrm{T}$ sample environment with sample space dimensions sufficient for solution crystallisation experiments while allowing in situ. interrogation of experimental progress. This is achieved without the need for investment in expensive electromagnet systems, which have high power consumption and require water cooling, using an array of permanent $Nd_2Fe_{14}B$ block magnets. A steel C-shaped yoke and pyramidal, steel pole shoes are used to guide the magnetic field, uninterrupted to each pole tip. Designs for the permanent magnet are shown in Figs. 1 and 2.

The yoke and pole shoes were produced from mild steel instead of pure iron, trading a relatively small increase in field strength for a significant increase in corrosion resistance while reducing material and machining costs of elemental iron. To avoid inhomogeneity caused by air gaps and material interfaces within, where possible, steel components were crafted from a single piece. 6082 aluminium alloy was used for all non-magnetic structural pieces due to a low magnetic permeability of $1.26 \times 10^{-6}\,\mathrm{H\,m^{-1}}$ while remaining relatively inexpensive. Both the aluminium shield and frame require high mechanical strength whilst limiting the effects of stray field on its homogeneity within the yoke and pole shoes. An increased homogeneity within the magnet ultimately leads to increased field strength between the pole shoes. The use of truncated square-pyramidal pole shoes directs the field towards a single point, concentrating the magnetic field in 3 dimensions to maximise flux between the pole shoes.

4.2. Safety

Before working with magnets, any electronic devices (phones/laptops/watches), ferromagnetic or magnetic material should be removed from the vicinity, particularly loose items which could jump to contact. Wear eye-protection as colliding magnets may shatter. The construction of the magnet rig requires the handling and manipulation of $Nd_2Fe_{14}B$ block magnets. These individual, unmodified magnets already possess a strong magnetic field, 588 N of force and able to support (~ 0.66 T at the surface). The supplier suggesting a convenient hanger for a sledge hammer (up to 10 kg) as a possible use [20]. The manipulation of multiple block magnets must therefore be undertaken with great care due to the high risk of pinch hazards and flying metal shards as a result of shattering.

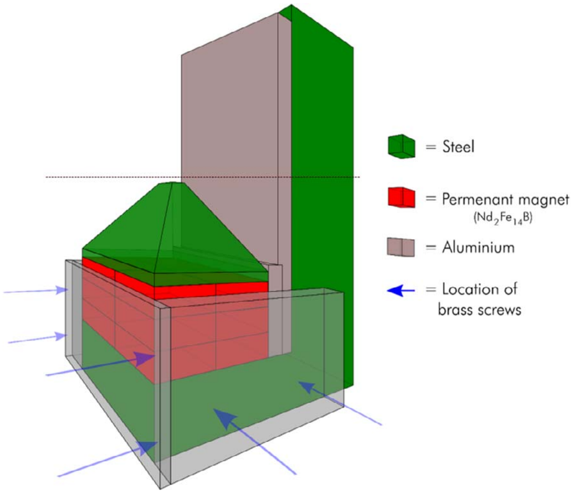

Fig. 2. 3D schematic of one half of the magnet showing rough location of brass screws and material types used for each component.

The strong attraction between block magnets can cause magnets to jump distances of up to 35 cm either shattering on impact or trapping items in between them. The block magnets should therefore be stored in the shipping packaging with accompanying shielding until required. During the build, individual magnets or magnet stacks must be stored at least 50 cm apart and with no ferromagnetic or magnetic material nearby. Magnets should be brought into contact in a controlled manner one at a time, approaching from a direction perpendicular to the magnet poles and making use of non-magnetic material (e.g. thick wooden blocks) as guides. More detail of basic magnet handling methods is given below.

The steel C-shaped yoke is heavy and should be handled with care to avoid pinch hazards.

4.3. Basic magnet handling techniques

4.3.1. Bringing two magnets into contact

When bringing two magnets into contact, secure the first magnet within a wooden template of thickness 20 mm, on a flat surface as shown in Fig. 3. A square cavity (approx. 40 mm × 40 mm) cut into the template restricts transverse movement of the magnet in place whilst the surface of the template provides a flat surface level with the top of the magnet. Place the thick edge of a wedge over the magnet and carefully bring a second magnet into contact with the wedge directly over the first magnet from above, being careful to make sure the poles are aligned (Fig. 3(b)). Whilst keeping the second magnet above the first slowly withdraw the wedge, thus bringing the magnets together. To produce three-magnet stacks, this process is repeated bringing the stack of two down onto the wedge. Be sure to store the prepared three-magnet stacks in a safe place.

4.3.2. Removing a magnet from a stack

If required, to separate magnets the wooden template must be held such that a single magnet protrudes above the wooden surface. The template should then be secured in place, for example by being placed flush to a wall. A second wooden panel is then placed flat on the template and used to push against the protruding magnet sliding it off the stack Fig. 3(c). The second panel must also be used

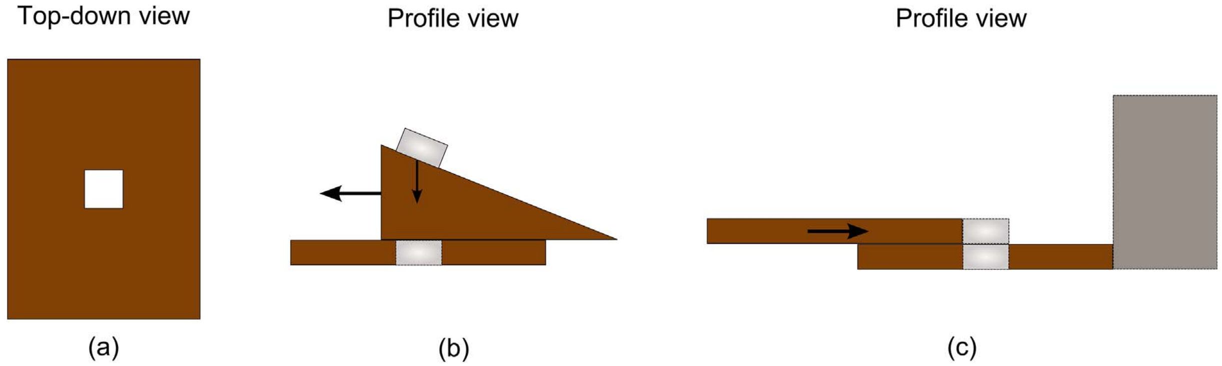

Fig. 3. Schematic showing the attachment and removal of a block magnet from a magnet stack. (a) the wooden base template with approx. 40 mm × 40 mm slot to hold a block magnet securely. (b) Attachment of two block magnets using a wooden wedge. (c) Separation of two block magnets with lower template held flush to a wall.

to prevent the magnet in the template from jumping out of the cavity.

4.3.3. Removing a magnet from a ferromagnetic object

If an individual block magnet becomes attached to a ferromagnetic object (but not another magnet) the easiest method for removal is to slide the magnet to a corner and tilt it over the corner to minimise the contact area. Once removed, move the magnet quickly away from the object to avoid it jumping back into contact.

4.4. Equipment required

Workspace free of ferromagnetic and electronic items
C-clamps × 3
Bench mounted clamp
Wooden template
Wooden wedge
Flat wooden piece for magnet removal
Wooden blocks × 6 to shield C-clamp contacts
Wooden planks (guides × 2)
Wooden lid × 2 (one for forming dual stack, one for putting stack into holder)

4.5. Magnet rig assembly

Before beginning any assembly of the magnet, it is advisable to use a gaussmeter to identify and mark the poles of each magnet stack as inserting a stack in an incorrect orientation will greatly decrease the final field strength. Assembly of the magnet rig is broadly outlined pictorially in Fig. 4 with a detailed step by step guide provided below. The method for producing the dual magnet stacks used in this process is describe above.

4.5.1. Bringing two magnet stacks into contact

When strong magnets are brought together side by side, they will repel each other, attempting to flip and turn in order to come together end to end with poles aligned. For this reason, when bringing these stacked magnets together, they must be restricted in all dimensions other than that in which they are required to move. To bring two stacks into contact, wooden guides were used as shown in Fig. 5. Three people are recommended for this process. The two stacks are placed on a flat surface 40 cm apart and held between two wooden planks with a width of 6 cm to match the stack height, to prevent lateral motion. Wooden blocks are then placed on the outside edges of the magnets to prevent direct contact between the magnets and the C-clamp which will be used to force the stacks together. Finally a wooden lid is placed on top of the wooden planks to prevent any upward motion of the stacks. Keeping pressure on all sides of the housing as the clamp is wound together. Once the stacks are in contact, the wooden housing can be removed as the stacks will be held securely by the clamp.

4.5.2. Mounting the dual magnet stacks in the aluminium magnet holder

The aluminium frame was held securely in a bench mounted vice. The dual magnet stack (held securely between wooden blocks by a C-clamp) is then brought to the open end of the frame. The lower edge of the magnets should be level with the notch cut into the aluminium frame, which will support the base of the stacks. A third wooden block was placed on the top surface of the stack (shown as a dotted line in Fig. 6) to prevent vertical movement. A second C-clamp was then fitted perpendicular to the first making contact (shielded by wooden blocks) with the back plate of the aluminium frame and the wide face of the dual stack. This clamp was then used to slowly slide the magnet stack from between the restraining C-clamp into the aluminium holder.

Once the dual stack is within the arms of the of the frame, the restraining C-clamp can then be used to apply force to the arms of the frame as show in Fig. 4(b). Through continued application of even pressure the dual stack should be moved into position flush with the back plate of the magnet holder.

4.5.3. Mounting the dual magnet stacks onto the yoke base

The remaining two stacks to form the 2 × 2 array at a pole are attached directly to the yoke arm once the aluminium shields have been attached, shown in Fig. 4(c). As with joining individual block magnets together, a wooden wedge was used to lower each stack onto the surface of the yoke arm. Extra care must be taken as the magnets will be strongly attracted to all other parts of the yoke. It is recommended to use a barrier on the top of the stack to stop it jumping to the wrong yoke arm. Once attached, each stack can be moved into position by easily pushing it laterally and when adjacent, the stacks can be forced together using another C-clamp.

4.5.4. Mounting the magnet holder onto the yoke base

To complete the 2 × 2 array of magnets on each yoke arm, the loaded magnet frame was placed on the same surface as the yoke. Using a clamp, the loaded frame was pushed towards the two magnet stacks attached to the yoke. Once all four stacks were in contact, the aluminium frame was fixed in place using brass screws before the clamps were removed (Fig. 4(d)). This was repeated on both arms before the pole shoes were attached.

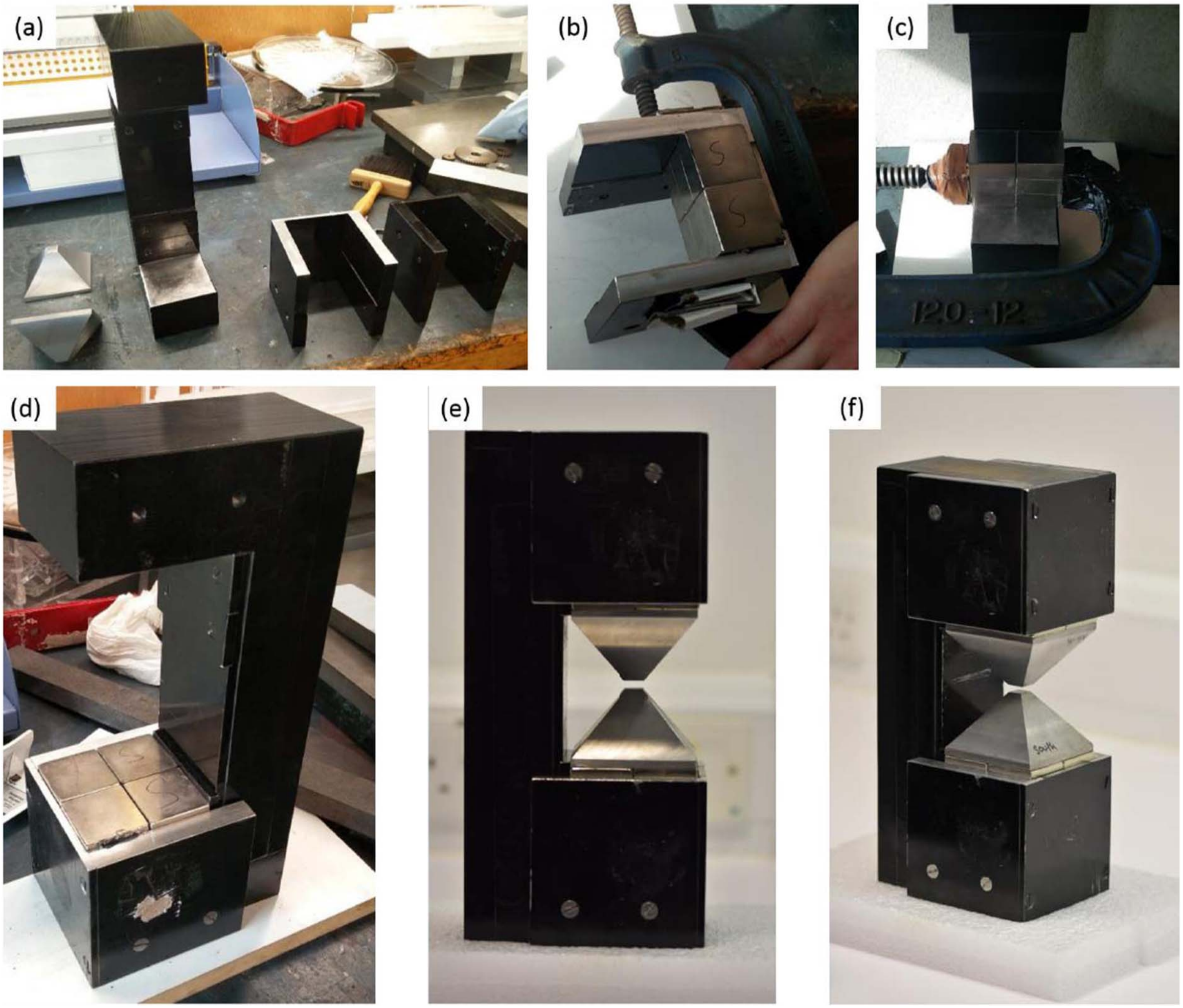

Fig. 4. Visual documentation of the build process. (a) Shows the fabricated magnet rig components. From left to right: Steel pole shoes x 2, Steel Yoke with Aluminium shielding fitted to upright section, Aluminium magnet frame x2. (b) Shows the insertion of two magnet stacks into a magnet frame with lowest magnet in the stack resting on the notch cut into the frame. The C-clamp provides extra support to the frame, resisting repulsion between the magnet stacks. Additional shielding from the magnetic field, provided by card or wooden blocks placed between the clamp and the frame, enabled easier removal of the clamps when required. (c) shows two magnet stacks held together by a shielded C-clamp and placed on the foot plate of the yoke piece. (d) the result of sliding the frame in (b) into place around the prepared yoke shown in (c), secured with brass screws. At this point clamps are no longer necessary for support the frame. (e) and (f) show the assembled magnet after stages (a–d) have been repeated for the second magnet frame and the pole shoes mounted.

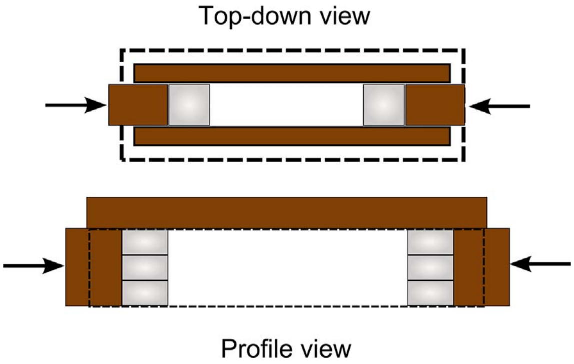

Fig. 5. Formation of dual magnet stacks using wooden guides and lid.

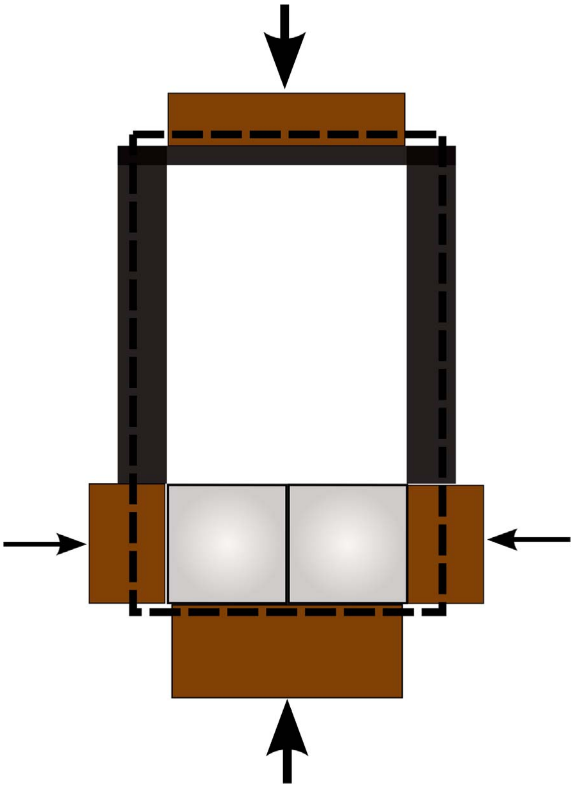

Fig. 6. Top view of mounting a dual magnet stack in aluminium magnet holder. Dotted line represents location of wooden top plate.

4.5.5. Mounting pole shoe

Pole shoes were placed on a platform raised to the same height as the surface of the 2 × 2 magnet array. Using wood to apply pressure to the pole tip in order to keep the shoe in position. The shoe was then moved laterally onto the array surface. A rubber mallet was used to adjust the fine position of the shoe once attached.

5. Operation instructions

The finished magnet should be sited on a stable surface, able to comfortably support a mass of 26.5 kg, 15 cm from any ferromagnetic materials or electronic devices. This choice of "safe zone" is based on stray magnetic field and is discussed in detail in Section 6. The rig may be sited horizontally or vertically depending on the desired application. Fig. 7 shows two examples of samples mounted within the pole gap. The sample can be interrogated, from the remaining angles, for example using a video camera, perpendicular to the field direction. Once assembled, guidelines for use are basic. Any sample holder that fits within a 5 mm cavity and is not ferromagnetic can be used with the magnet. Currently 5 mm cuvettes and NMR tubes are used when horizontal (Fig. 7) and glass slides when vertical, to hold liquid samples between poles. Due to the shape of the sample space, any interrogable equipment requiring close observation of the sample, for example cameras or optical fibres, can be used.

6. Validation and characterization

6.1. Field characterisation

To characterise the successful operation of the magnet rig, measurements of the field strength between the poles and mapping of the stray field were required. Detection of the stray field is necessary when used in a laboratory setting as applicability of a magnet reduces significantly if it cannot be used safely near other equipment. Magnetic interaction with any surrounding ferromagnetic metals or electronic devices is dangerous thus the stray field must be measured in order to assess a minimum safe distance for such equipment. To measure the stray field, a gaussmeter with transverse Hall probe was used to map the magnetic field strength parallel to the pole direction. Points were recorded at 5 mm increments across the plane to record the field contours which can be seen in Fig. 8.

The maximum field strength between the poles (2.468 T) is higher than expected from the field calculations in Fig. 9 which predicted a maximum field strength of 1.9484 T. This increased experimental value is expected since the calculations were performed using a 2D slice of the magnet rig, rather than a full 3D model. The stray field measurements correspond well with the calculations of

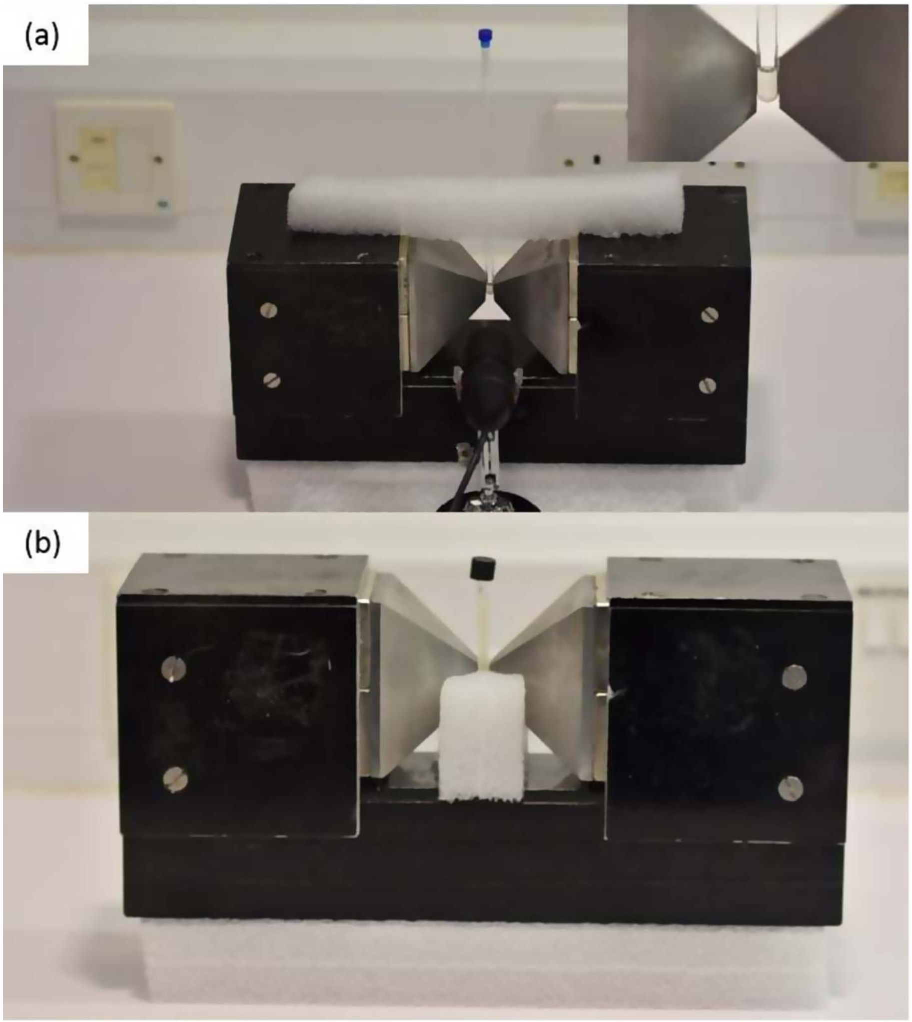

Fig. 7. Example experimental set ups using the magnet rig. (a) shows how a standard NMR tube can be used as a sample chamber, held in place between the poles using a foam support piece. In situ observations are possible using the video camera shown in the foreground of the image. Inset shows the region between the poles in greater detail. (b) gives an example of an alternative experimental set up using a 5 mm path length, screw top quartz cuvette. The rig is placed on a foam base to reduce vibrations and prevent damage to the work surface.

the stray field, dropping to 0.1 T within 5.5 cm from the pole centre and 0.01 T within 11.5 cm. For the calculated field these values are approximately 6 cm and 10.75 cm respectively. Beyond 12 cm the stray field is therefore negligible so maintaining a safe zone of 15 cm around the magnet rig which is free of ferromagnetic materials or electronic devices is recommended.

6.2. Crystallisation experiments within a magnetic field

The magnet, while compatible with a wide range of experimental techniques, was conceived as a sample environment for the investigation of molecular crystallisation under the influence of a magnetic field. The operation instructions given in Section 5 and the example mountings are thus designed with this application in mind. Molecular crystallisation from a saturated solution has been successfully observed in situ using a portable USB camera taking time lapse photos over periods of up to days. A video of a typical experiment can be viewed here: https://youtu.be/Yun54eb7-dE.

7. Hardware summary

The permanent magnet provides a homogeneous, high magnetic field environment suitable for direct observation of samples in 360°. Specifically, by adopting a C-shaped magnet arrangement, spatial restrictions intrinsic to a cylindrical Halbach array are avoided. The measured field strength has a peak of 2.468 T and has limited stray field that decays to background levels within 10 cm, which is in good agreement with 2D finite element method magnetic calculations. The use of permanent magnets limits the initial cost of the equipment to approximately € 750, relative to comparable electromagnetic systems of up to € 82,000 and eliminates

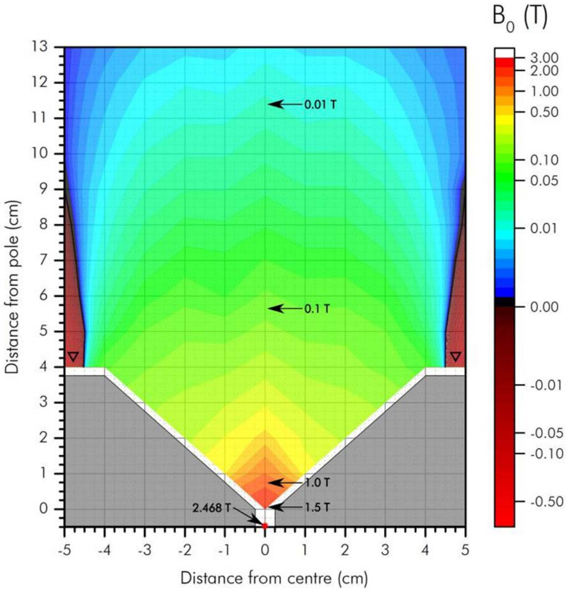

Fig. 8. 2D measurement of the stray magnetic field parallel to the pole direction. A peak field strength of 2.468 T is recorded between the pole shoes with the stray field dropping to < 0.1 T 5.5 cm from the pole and < 0.01 T 11.5 cm from the pole. Areas marked with a triangle show a region of field inversion. Measurements cannot be conducted using a Hall probe while in contact with a metal surface leading to the blank region immediately around the pole shoes.

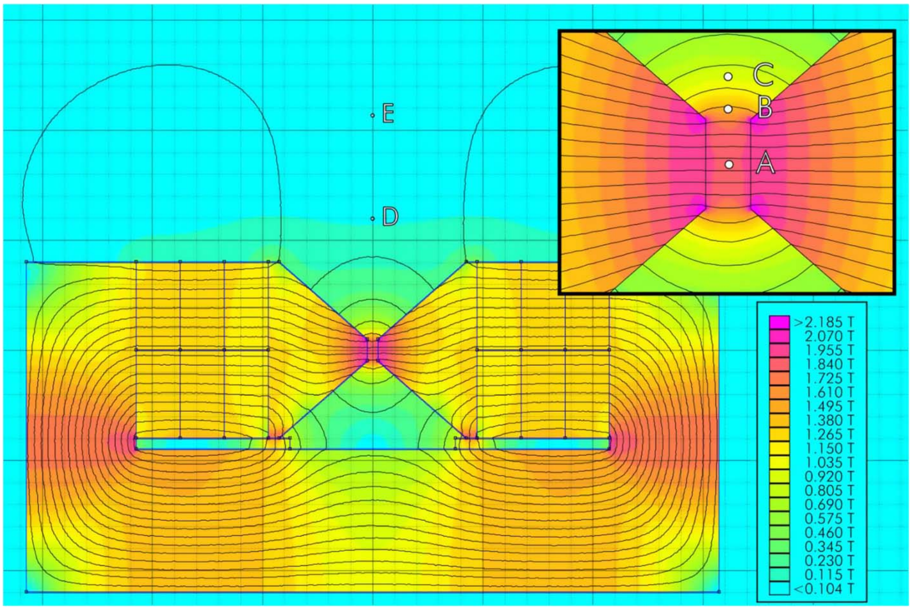

Fig. 9. Profile view 2D Magnetic field calculation produced using FEMM software [19]. Points marked A, B, C, D, E correspond to calculated field strengths of 1.9484 T, 1.5 T, 1 T, 0.1 T and 0.01 T respectively. Grid square correspond to 1 cm. The 2D nature of the software does not take into account the flux focussing from the 3rd dimension of the pole-shoe, lowering the calculated field.

running costs such as cooling systems and high current power supplies. The magnet also makes high field sample environments more accessible to the non-specialist user on a limited budget.

7.1. Capabilities/limitations

- Permanent magnet sample environment – no field variation possible without reassembly.
- Peak field strength 2.468 T at 5 mm.
- Sample environment volume restricted to 5 mm in a single dimension.
- Compatible with in situ sample interrogation via video camera, laser, X-ray beam, neutron beam

- Viewing angles of 360°
- No associated running costs
- Total Mass 26.5 kg
- Footprint including safe zone 63 cm × 41 cm

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ohx.2018.01.002.

References

[1] E. Beaugnon, et al., Material processing in high static magnetic field. A review of an experimental study on levitation, phase separation, convection and texturation, J. Phys. I France 3 (1993) 399–421.
[2] A. Nakamura, et al., Improvement in quality of protein crystals grown in a high magnetic field gradient, Cryst. Growth Des. 12 (2012) 1141–1150.
[3] N. Micali, H. Engelkamp, P.G. van Rhee, P.C.M. Christianen, L. Monsù Scolaro, J.C. Maan, Selection of supramolecular chirality by application of rotational and magnetic forces, Nat. Chem. 4 (2012) 201–207.
[4] M.I. Boamfa, S.V. Lazarenko, E.C.M. Vermolen, A. Kirilyuk, T. Rasing, Magnetic field alignment of liquid crystals for fast display applications, Adv. Mater. 17 (2005) 610–614.
[5] J. Potticary, et al., An unforeseen polymorph of coronene by the application of magnetic fields during crystal growth, Nat. Commun. 7 (2016).
[6] Y.H. Luo, J.W. Wang, C. Chen, Y.J. Li, B.W. Sun, Reversibly stretching the co-crystals by the application of magnetic field, Cryst. Growth Des. 17 (2017).
[7] R. Cai, H. Yang, J. He, W. Zhu, The effects of magnetic fields on water molecular hydrogen bonds, J. Mol. Struct. 938 (2009) 15–19.
[8] N.I. Wakayama, Effects of a strong magnetic field on protein crystal growth, Cryst. Growth Des. Des. 3 (2003) 17–24.
[9] J. Gielen, Supramolecular aggregates in high magnetic fields, Radboud Repository (2013).
[10] C. Sudha, R. Sivanarendiran, K. Srinivasan, Influence of magnetic field on the nucleation rate control of mono paracetamol, Cryst. Res. Technol. 50 (2015) 230–235.
[11] S. Honjo, M. Yokota, N. Doki, K. Shimizu, Magnetic field influence on the crystal structure of 2,2′:6′,2″-terpyridine, Kagaku Kogaku Ronbunshu 34 (2008) 383–387.
[12] G. Coquerel, Crystallization of molecular systems from solution: phase diagrams, supersaturation and other basic concepts, Chem. Soc. Rev. 43 (2014) 2286–2300.
[13] M.A. Perrin, M. Neumann, H. Elmaleh, L. Zaske, Crystal structure determination of the elusive paracetamol Form III, Chem. Commun. (2009) 3181–3183.
[14] K. Halbach, Design of permanent multipole magnets with oriented rare earth cobalt materials, Nucl. Instrum. Methods 169 (1980) 1–10.
[15] K. Halbach, Strong rare earth cobalt quadrupoles, IEEE Trans. Nucl. Sci. 26 (3) (1979) 3882–3884.
[16] H.A. Leupold, A.S. Tilak, E. Potenziani, Adjustable multi-tesla permanent magnet field sources, IEEE Trans. Magn. 29 (6 pt 1) (1993) 2902–2904.
[17] H. Raich, P. Blümler, Design and construction of a dipolar Halbach array with a homogeneous field from identical bar magnets: NMR mandhalas, Concepts Magn. Reson. Part B Magn. Reson. Eng. 23 (1) (2004) 16–25.
[18] Magnet Applications – High Energy Magnet – Supermagnete. (Online). Available: https://www.supermagnete.de/eng/Magnet-applications/High-energy-magnet?category=blocks_big (accessed 03 Oct 2017).
[19] Finite Element Method Magnetics: HomePage. (Online). Available: http://www.femm.info/wiki/HomePage (accessed 19 Oct 2017).
[20] Power Magnet Giant Magnet 60 kg Adhesive Force – Supermagnete. (Online). Available: https://www.supermagnete.de/eng/block-magnets-neodymium/block-magnet-40mm-x-40mm-x-20mm-neodymium-n42-nickel-plated_Q-40-40-20-N (accessed 18 Oct 2017).