Électrotechnique et électroénergétique

DIAMAGNETIC LEVITATION – HISTORICAL MILESTONES

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Nowadays scientists can easily levitate diamagnetic substances in the powerful field of a superconducting magnet. Pyrolytic graphite and strong NdFeB permanent magnets can be bought by every levitation enthusiast for building his own levitation device. But the way towards this was long. First of all diamagnetism had to be discovered and investigated in detail. Then the theoretical fundament for diamagnetic levitation had to be set. And of course suitable technologies had to be developed and tested for practical demonstrations of diamagnetic levitation. At all it took 161 years from discovery of diamagnetism to the first practical levitation demonstration. This paper gives an overview on this historical development and additionally emphasises the most important achievements from the very beginning up to now.

1. **INTRODUCTION**

The main macroscopic behaviour of diamagnetic materials is that they are repelled by magnetic fields. This property can be used for stable and free levitation of diamagnetics in inhomogene magnetic fields. In recent years scientists have extensively studied diamagnetic levitation for different applications: Weightless fluid dynamics [1], containerless crystal growth [2], high precision gyroscopes [3], high sensitive sensors [4], low friction bearings [5] etc.

Although diamagnetic levitation has become more and more public, the long history of diamagnetic levitation is not widely known. It started in 1778 with the discovery of diamagnetism and found its temporary climax in the development of a magnetic micro-manipulation chip in 2004.

This paper gives an overview on this historical development and emphasises the most important achievements from the very beginning up to now. The results of the bibliographical research, which spans more than 220 years, are chronologically ordered based upon the known reported documents.

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2. **THE DISCOVERY OF DIAMAGNETISM**

In the last third of the 18th century the Dutch philosopher and natural scientist Anton Brugmans – Fig. 1, investigated the phenomena of magnetism and in particular the action of a permanent magnet on a plurality of substances. For detecting the magnetism of several substances Brugmans used a sensitive determination method: The water- or mercury-test. Thereto the substances were brought onto the surface of water or mercury. In his experiments Brugmans chose water or mercury depending on form and consistence of the substance. Pulverised material was supported by a little sheet of paper. Supported by surface tension the specimen could align almost frictionless in the field of a bar magnet which was brought near to the specimen. Brugmans investigated many different substances: Different soils and stones, gemstones, ores, salts of the sulfuric acid, asbestos, different metals and many more. He mainly focused on providing evidence that the investigated substances contain iron or not, respectively whether they where attracted by a magnet or not. But in 1778, as Brugmans investigated bismuth, he made a new observation [6]:

> *…Only the dark and almost violet-coloured bismuth displayed a particular phenomenon in the study; for when I laid a piece of it upon a round sheet of paper floating atop water, it was repelled by both poles of the magnet.*

Fig. 1 – Anton Brugmans about 1761.

In this moment Brugmans had found a new form of magnetism which later was named “diamagnetism”. But due to the weak diamagnetic forces and the lack of stronger magnets Brugmans did not have the possibilities to further investigate the observed phenomenon. He had to leave this to the following generations of scientists.

3. **THE SYSTEMATIC INVESTIGATION OF DIAMAGNETISM**

Independent observations by Le Baillif, Saigey, Seebeck, Coulomb and Becquerel [7] in the first third of the 19th century also showed a repelling force exercised by a magnet on very certain substances (*e.g.* bismuth and antimony). But no further examinations followed these isolated observations.

This changed in the year 1845. On the 13th September of this year the famous British scientist Michael Faraday – Fig. 2 discovered the magneto-optical effect while experimenting in his laboratory at the Royal Institution in London [8]. There Faraday had found that the rotation of the plane of polarization of a light beam passing through a piece of heavy glass[1] could be influenced by a magnetic field. While examining other materials he found further transparent materials which also showed this effect. Faraday quickly named these materials "dimagnetics" in analogy with dielectrics.

Fig. 2 – Michael Faraday about 1845.

Fig. 3 – Faraday’s great electromagnet.

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[1] silico borate of lead

On November 4th Faraday experimented again with a piece of heavy glass which this time he had hung between the poles of a powerful electromagnet - Fig.3.

Faraday could observe that the heavy glass alligned itself equatorially between the magnet poles when the magnet was powered [9]. Not knowing the previous work considering this phenomenon Faraday had rediscovered what he later called diamagnetism. He systematically investigated this phenomenon and exposed the most different substances to the action of his magnet: A piece of apple, caffeine, dried blood, sulphates, minerals, acids, different metals among uranium, phosphorus, arsenic, different gases and so one. Faraday classified the investigated substances in dependency on their reaction to the magnetic field. Substances which were attracted towards the magnet poles he called “magnetic” and substances which were moved from stronger points of the field to weaker points “diamagnetic”. Furthermore he arranged the substances according to the strength of the attracting and repelling force.

Faraday's experimental results and theoretical treatments considering diamagnetism were published in the "Philosophical Transactions" of the Royal society and thus were available for a broad scientific community [10]. This fact should essentially influence the further historical development as the next chapter shows.

4. THE FEASIBILITY OF DIAMAGNETISM

The year 1847 was the birth of diamagnetic levitation. Just shortly after Faraday's observations the grand Irish-Scottish scientist and engineer William Thomson[2] – Fig. 4 showed theoretically the feasibility of diamagnetic levitation [11]. At this time Thomson was just 22 years old and lectured as a professor for natural philosophy at the University of Glasgow, Scotland. In May 1847 the Cambridge and Dublin Mathematical Journal had published his article titled "On the Forces experienced by Small Spheres under Magnetic Influence; and on some of the Phenomena presented by Diamagnetic Substances". Therein Thomson developed a formula for the calculation of the force on a specimen in a magnetic field which would be written nowadays as:

$$\boldsymbol{F} = \left(\frac{\mu_{\mathrm{r}} - 1}{2\mu_0} \right) V \nabla B^2 . \tag{1}$$

Thomson recognized from this formula that a stable equilibrium position could only exists at a point where B^2 diminishes in every direction from it (local minimum, $\nabla B^2 > 0$) and that additionally to this the term $(\mu_{\text{-}r} - 1)$ has to be negative.

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[2] Better known as Lord Kelvin.

Thomson had known from Faraday's previous work that there exists diamagnetic substances for which $(\mu_{r} - 1)$ would be negative. And he also knew from Faraday's observations that diamagnetic substances are repelled by the strong inhomogeneous magnetic field of an electromagnet which was in full accordance with his calculations.

Fig. 4 – Professor William Thomson (Lord Kelvin) about 1846.

Vorlage: Universitätsarchiv Tübingen

Fig. 5 – Professor Werner Braunbek about 1950.

Finally Thomson concluded that a diamagnetic specimen could be held in a stable equilibrium position in the field of a hollow cylindrical bar magnet if the magnet would only be strong enough. For a magnet with a radius r very great compared to its thickness and very small compared to its length Thomson theoretically found a stable equilibrium position just below the lower end of the magnet at $r/\sqrt{2}$. But he doubted whether it would be ever possible to levitate a diamagnet in a magnetic field:

> "*It will probably be impossible ever to observe this phenomenon, on account of the difficulty of getting a magnet strong enough, and a diamagnetic substance sufficiently light, as the forces manifested in all cases of diamagnetic induction hitherto examined are excessively feeble.*"

5. THE FIRST DEMONSTRATION OF DIAMAGNETIC LEVITATION

In 1939, 92 years after Thomson's prediction about the feasibility of diamagnetic levitation, the German physicist Werner Braunbek – Fig. 5, could demonstrate diamagnetic levitation of tiny pieces of graphite and bismuth in the inhomogeneous field of a strong electromagnet for the first time in history [12]. At this time Braunbek lectured as a professor for theoretical physics at the University of Tübingen, Germany. Before his practical demonstration of diamagnetic levitation Braunbek had investigated theoretically the possibility of free levitation of bodies in static electric or magnetic fields in a stable equilibrium position [13]. He wanted to figure out if it is possible to levitate a body freely against the gravitational field i.e. without contact to any solid, liquid or gaseous matter. Braunbek excluded the following levitation technologies from his definition of free levitation[3]:

- Levitation with the support of an automatic control → no stable equilibrium position!
- Levitation of bodies in alternating fields → no static field!
- Levitation of bodies in a surrounding medium which acts through its buoyancy or its electric or magnetic differentness → no free levitation!

On this basis Braunbek investigated a nonconducting, free moveable and stable body of arbitrary shape (system I) in a gravitational field ***G***, an electrical field ***E*** and a magnetic field ***B*** (system II). He could show with his calculations that free levitation is only possible if bodies with $\varepsilon < 1$ or $\mu < 1$ are present in system I and/or system II. Believing that no material exists with $\varepsilon < 1$ Braunbek formulated the following principle:

> *Static, stable, free levitation of a system I in the electrical, magnetical or gravitational field of another system II is impossible as long as not diamagnetic matter* is present in at least one of the both systems.*

For a practical realisation of diamagnetic levitation Braunbek used the strong inhomogeneous magnetic field of an electromagnet which had been constructed at the institute in Tübingen. The magnet consisted of two opposite cylindrical iron pole shoes. To achieve stable levitation the planar pole shoes had a special cross section – Fig. 6. A light concave curvature at the upper side of the shoes had been machined. The stable levitation point (E) lay in the middle between the planar pole shoes just above the cylindrical cross section. Fig. 6 shows also the course of the field lines between the pole shoes. The maximum flux density was 23 000 Oersted (2.3 Tesla) between the cylindrical pole shoes with 7 cm diameter and 5 mm gap distance. The radius of curvature of the concave curvature was 75 mm.

Braunbek let levitate tiny bismuth crystals and little pieces of glowed arc lamp coal. The largest piece of bismuth he could let levitate weighted 8 mg, had a length of 2 mm and a thickness of about 0.75 mm. The largest levitated piece of coal weighted 75 mg, had a length of 12 mm and a thickness of 2 mm.

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[3] The only levitation technology which Braunbek missed in his exclusion is a spin-stabilized rotating magnet which levitates above a repelling magnetic base. However this levitation device was invented only in later years by Roy M. Harrigan who filled the corresponding patent in 1979 (US patent 4,382,245).

*Or equivalent to this: Matter in superconducting state.

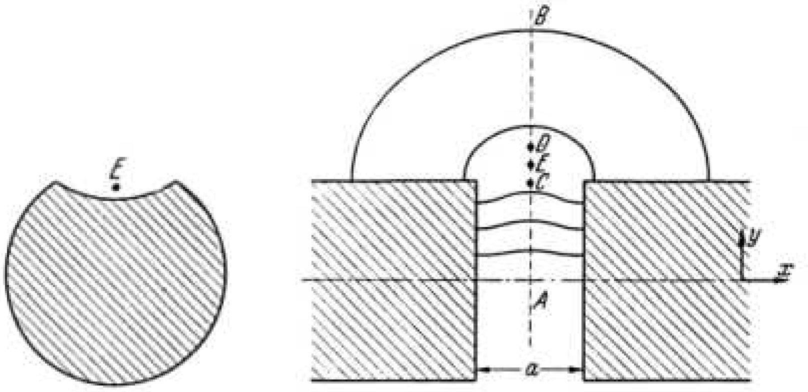

Fig. 6 – Cross section of the pole shoes and the course of the field lines between the pole shoes of Braunbek's electromagnet. The stable levitation point is labeled with E.

6. **LEVITATION WITH THE ASSISTANCE OF PERMANENT MAGNETS**

After the work of Braunbek the German *Steingroever* and the Dutch *Boerdijk* independently achieved diamagnetic levitation with the assistance of permanent magnets. Steingroever designed and built a diamagnetically stabilized bearing and Boerdijk repeated Braunbeks experiment with a permanent magnet instead of an electromagnet.

6.1. DIAMAGNETICALLY STABILIZED BEARING

In 1952 Dr. Erich Steingroever from the German magnet factory Bonn GmbH filed a patent [14] with the title “Magnetische Lagerung” (Magnetic Bearing). Steingroever claimed in this patent a measurement system as shown in Fig. 7. The system consists of a ferromagnetic bearing with the ring magnets 3 and 4, the shaft 1 and the disc 2. The ring magnets are magnetised axially in opposite directions as shown. Diamagnetic rings 5 made of e.g. graphite or bismuth are connected with both ends of the shaft.

The diamagnetic rings both dip into the strong inhomogenous field of a ring gap magnet system. The ring gap systems consist of a permanent magnet with the poles N and S, an iron pot-shaped return member and a pole plate.

The ferromagnetic bearing compensates the forces of gravity of the rotor. Additionally there is a centring force due to the different diameters of the ring magnets. The two ring gap magnet systems with the diamagnetic rings finally provide the necessary stability for free levitation.

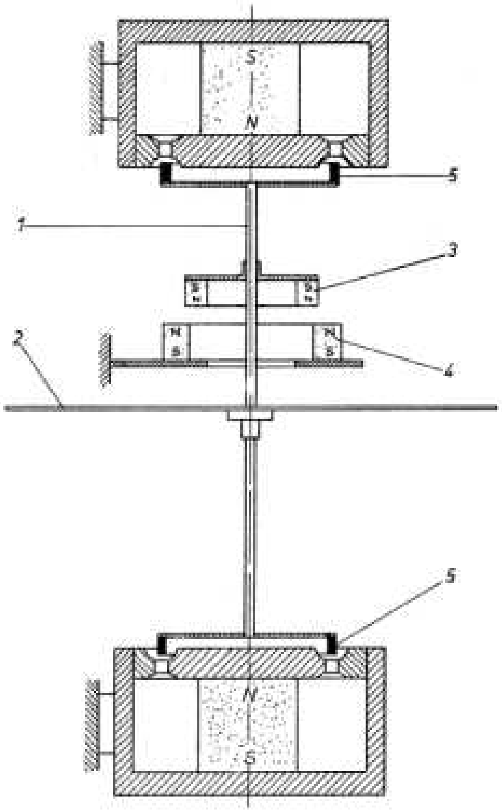

Fig. 7 – Diamagnetically stabilized bearing with permanent magnets from Dr. Steingroever (1952).

Steingroever claimed in his patent the use of this levitating rotor for the armature of a kilowatt-hour meter.

In 1968 the German journal "VDI Zeitschrift" published an article of Steingroever wherein he describes a further development of his measurement system [15]. A schematic drawing of this system and a photo of a practical implementation is shown in Fig. 8.

The advanced measurement system of Steingroever had no upper diamagnetic stabilization. For the ferromagnetic bearing he used no longer two ring magnets but a ring magnet 2 and two bar magnets 1 and 3. Steingroever explained: "The distance between the two bar magnets is adjustable. By adequate adjustment of this distance the lifting capacity of the ferromagnetic bearing does change minimally if the rotor is moved from the equilibrium position in the direction of the axis of the ring magnet 2. This dependency of the equilibrium position on the deflection is necessary if the diamagnetic bearing should stabilize the rotor."

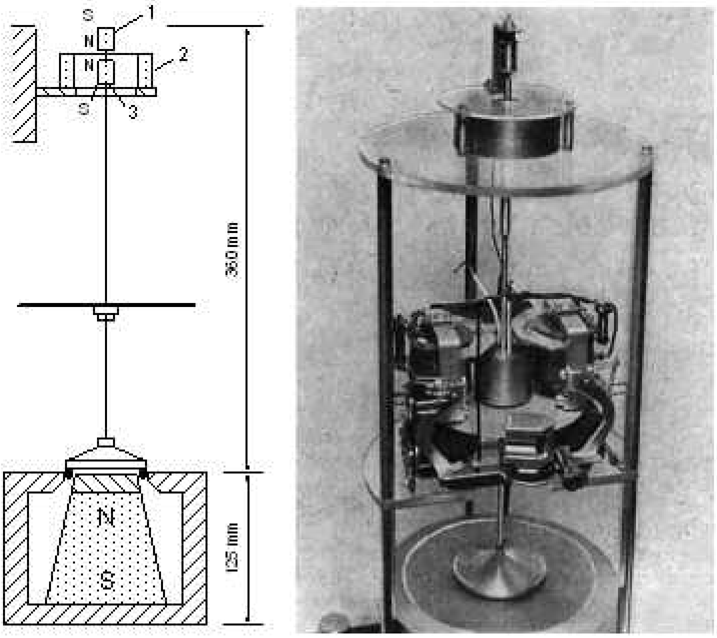

Fig. 8 – Schematic drawing and practical implementation of the diamagnetically stabilized bearing with permanent magnets from Dr. Steingroever (1968).

Steingroever also changed the shape of the permanent magnet in the ring gap magnet system from a cylinder to a frustum. Due to the smaller diameter of the upper end compared to the base he achieved a higher magnet field gradient in the ring gap. Thus the magnetic force on the diamagnetic ring and the grade of stabilization is higher.

Steingroever used the levitating rotor (aluminium disc) in a rotating induction measurement system – Fig. 8. The gravity force of the levitating rotor was 50 pond[4], which corresponds to 50 grams.

6.2. THE REPETITION OF BRAUNBEKS EXPERIMENT WITH A PERMANENT MAGNET

In 1956 the journal "Philips Research Report" printed a paper of the Dutch A.H. Boerdijk [16]. In his paper Boerdijk described the different technical possibilities to achieve levitation. He also mentioned diamagnetic levitation and repeated the experiment of Braunbek.

His experimental setup equalled Braunbek's setup but it was smaller and used a permanent magnet instead of an electromagnet – Fig. 9.

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[4] 1 kilopond = $g_N \cdot 1$ kg

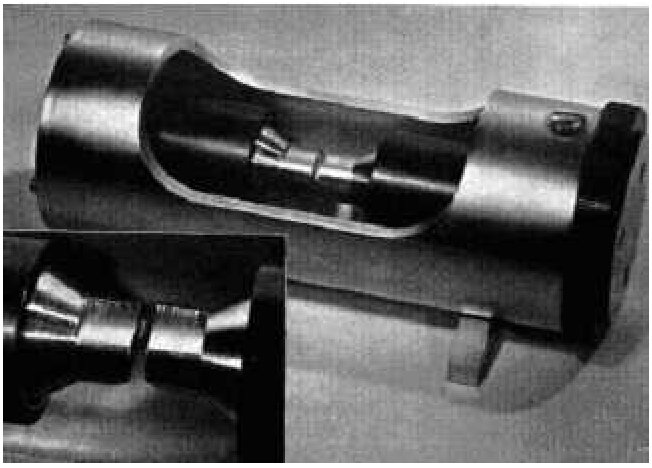

Fig. 9 – Permanent magnet with adjustable air gap and specially shaped pole faces, levitating a small piece of graphite just above the gap (by A. H. Boerdijk, 1956).

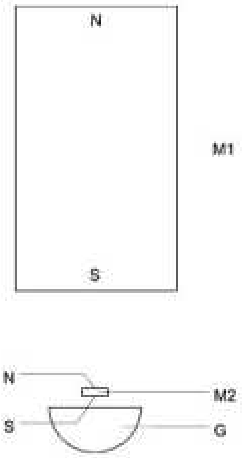

Fig. 10 – Diamagnetic levitation of a permanent magnet (by A. H. Boerdijk, 1956).

7. **DIAMAGNETIC LEVITATION OF A PERMANENT MAGNET**

Boerdijk not only repeated Braunbek's experiment but was also the first one who demonstrated levitation of a permanent magnet [17]. Fig. 10 shows his experiment from 1956. A small permanent magnet M2 experiences an upward repulsion force due to the diamagnetic body G. As the diamagnetic force is too small to lift the magnet M2 the gravitational force of M2 is mostly compensated by the attraction force of permanent magnet M1. By adjusting the distance between the two magnets properly the magnet M2 levitates just above the diamagnetic body. Boerdijk used very pure graphite for the diamagnetic body. The lifter magnet M1 was made of Ticonal[5] (30 cm long, 3 cm in diameter) and the small magnet M2 was a ferroxdure[6] disc (0.3 mm thick, 1 mm in diameter).

8. **THE USE OF ANISOTROPIC GRAPHITE FOR DIAMAGNETIC LEVITATION**

Dr. Erich Steingroever (see subchapter 6.1) was also the first who proposed in literature the use of anisotropic graphite for diamagnetic levitation to achieve

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[5] Trade name of a magnetic alloy made of cobalt, nickel, aluminium and titanium.

[6] A sintered oxide consisting mainly of the oxide $BaFe_{12}O_{19}$; used for the production of permanent magnets [18].

higher load capacities [19]. He knew that certain types of graphite have an anisotropic susceptibilty and described in a patent application from 1964 the use of anisotropic graphite for his diamagnetically stabilized bearing with permanent magnets.

Steingroever mentioned two types of graphite: A graphite mono-crystal, which occurs naturally (Ceylon graphite) and pyrolytic graphite, which is synthezised from purified hydrocarbon gases. In both types of graphite the susceptibilty perpendicular to the graphite crystal layers is much higher than parallel and also higher than in isotropic graphite. Due to the higher susceptibility the load capacity of the levitating diamagnetic object increases.

In 1965 Robert D. Waldron from the AiResearch Manufacturing Company in Phoenix, Arizona, also experimented with pyrolytic graphite for diamagnetic bearings [20]. Waldron built two vertical thrust bearings to study dynamic effects on a floating ring made of pyrolytic graphite.

Figure 11 shows his experimental bearing No. 1. The operational mass of the floating ring was 3.843 g including an acrylic ring. The graphite mass was 0.933 g, the outer diameter 3.99 cm, the inner diameter 3.35 cm and the height 0.114 cm. The ring levitated in a ring gap between the poles of an electromagnet.

To measure the deceleration rate of the rotor, Waldron placed his bearing into a vacuum bell jar. Previously he had accelerated the rotor up to 98.5 rot/min by a tangential capellary air bleed. The pressure within the bell jar was below $2.8 \cdot 10^{-5}$ Torr.

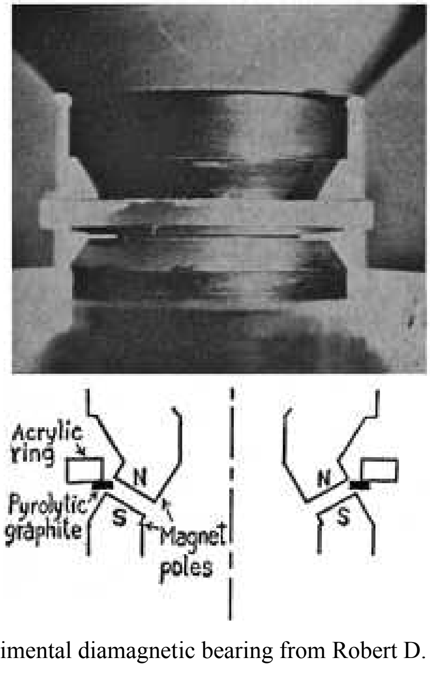

Fig. 11 – Experimental diamagnetic bearing from Robert D. Waldron (1965).

The first run had a duration of 7.25 h, which shows the extremely low frictional losses. Waldron calculated with the measured decelaration rate a power dissipation in the nanowatt range.

9. **THE LEVITATION OF DIAMAGNETS IN HIGH MAGNETIC FIELDS**

In 1991 E. Beaugnon and R. Tournier from the Centre National de la Recherche Scientifique (CNRS) in Grenoble demonstrated the levitation of various diamagnetic substances in a high static inhomogenous magnetic field of a 27 Tesla Hybrid Magnet [21]. They were also the first who made water levitate in this way.

The specimen were inserted in a handling tube into the 5 cm room temperature bore of the magnet – Fig. 12. In this way water, ethanol, acetone, bismuth, antimony, graphite, wood and plastic could be levitated. For the levitation of water a B_z between 26.5 T and 27 T was needed. Beaugnon and Tournier proposed to use high field magnet levitation for contactless material elaboration and microgravity experiments.

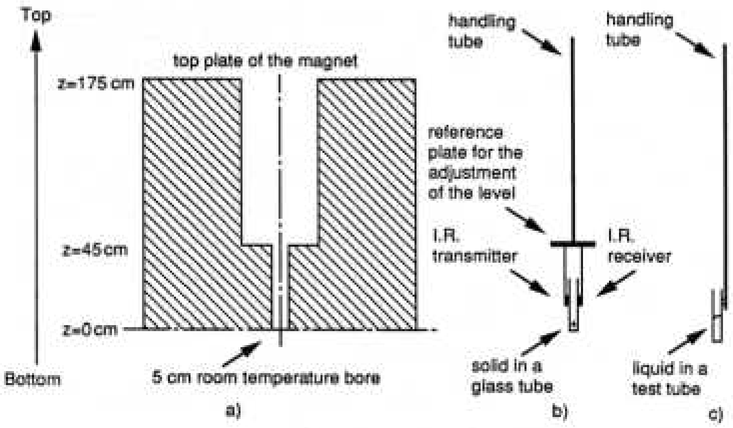

Fig. 12 – Schematic drawing of the 27 T hybrid magnet, apparatus for levitation of solids and apparatus for levitation of liquids (Beaugnon *et al.*, 1991).

10. **LEVITATING PERMANENT MAGNET ARRAY**

The availability of very strong neodymium iron boron (NdFeB) permanent magnets since the 1990’s has made possible new developments on the field of diamagnetic levitation.

In 1992 for the first time Ronald E. Pelrine from SRI International let levitate an array of NdFeB-magnets above a slightly concave basis of pyrolytic graphite without the support of a lifter magnet [22] – Fig. 13.

The array consisted of four tiny magnets (0.5 mm × 0.5 mm × 0.25 mm, $L \times W \times H$) of grade 35 megagauss-oersted. The magnets were arranged with alternating magnetization in a square configuration. This kind of array produces a high magnetic strength and a high field gradient. The lifting force produced by the interaction between the magnet array and the pyrolytic graphite is sufficient for levitation of the array above the surface. Due to the bowl shaped pyrolytic graphite the magnet array is kept in the center of the pyrolytic graphite and a stable equilibrium is reached. But the achievable gap between the array and the pyrolytic graphite is very small. Pelrine reported a gap between only about 25 μm to 50 μm.

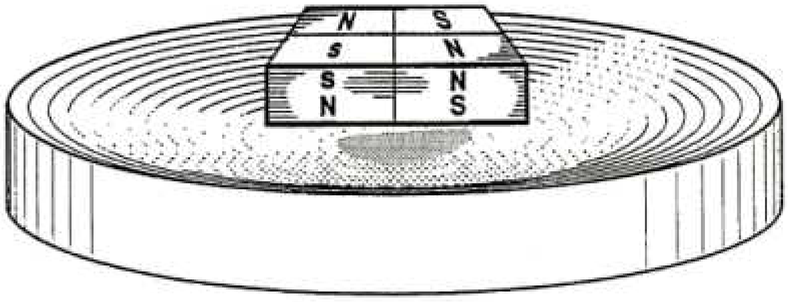

Fig. 13 – Levitation of a permanent magnet array above pyrolytic graphite (Pelrine, 1992).

11. LEVITATION OF A LIVING FROG

In the years 1997 to 2001 the physicist Andrey Geim[7] and his co-authors published several scientific papers in different reputable journals and in the internet. Therein they examined extensively the levitation of diamagnetics in a high static inhomogeneous magnetic field of a bitter magnet respectively of a superconducting magnet [23-28]. At first not knowing about similar previous research of other scientists [11, 19] in the field of diamagnetic levitation Geim and his co-authors had rediscovered diamagnetic levitation in 1997.

In their first experiments they levitated the most different things among hazelnuts, pieces of cheese and pizza, water droplets and living creatures including a mouse and frogs. Especially the pictures of a "flying frog" – Fig. 14 attracted the

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[7] Formerly at the University of Nijmegen, The Netherlands.

attention of media and broad public. A leader of a religious sect in England even offered £1 million for constructing a levitating machine made him levitating in front of his congregation. Figure 15 presents how even the human fingers can be used as diamagnetic stabilizers with a very strong superconducting magnet.

In the year 2000 Andrey Geim and Sir Michael Berry won the Ig Nobel prize, a price for scientific work that "first makes people laugh, then makes them think."

But of course the scientists work was not only about fun. At first Geim and M.V. Berry examined extensively the equilibrium conditions necessary for levitation of diamagnetics in the magnetic field of a solenoid. Stable levitation zones were calculated in detail for different solenoid geometries and different values of the magnetic field. Afterwards an experimental validation followed in the magnetic field of a powerful bitter magnet.

The experimental results had a very good agreement with the predicted stability zones.

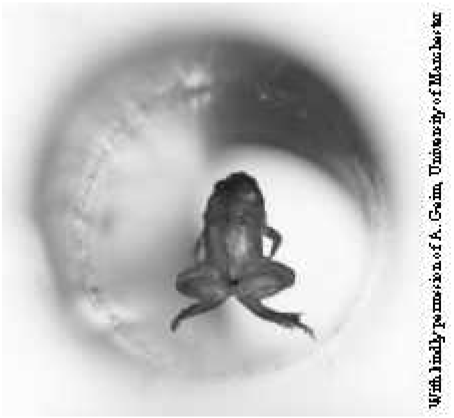

Fig. 14 – A living frog flying inside a Ø32 mm vertical bore of a Bitter solenoid in a magnetic field of about 16 T at the Nijmegen High Field Magnet Laboratory.

Fig. 15 – Levitation of a magnet 2.5 m below an unseen 11 T superconducting solenoid stabilized by the diamagnetism of fingers ($\chi \approx -10^{-5}$).

Geim proposed the application of diamagnetic levitation for studying weightless fluid dynamics, containerless crystal growth, high precision gyroscopes and influence of microgravity on the development process of animals and plants. Geim, Simon, Helfinger extended the stability calculations towards diamagnetically stabilised permanent magnet levitation [27, 28]. They calculated and demonstrated different magnet levitation arrangements among three new geometries – Fig. 16. Other scientists were inspired by these calculations and later extented them onto other arrangements [30, 31].

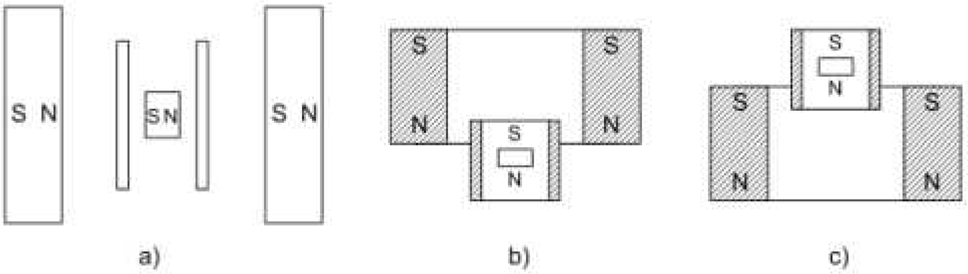

Fig. 16 – Three new diamagnetic levitation arrangements with permanent magnets proposed and demonstrated by Geim , Simon and Heflinger.

The work of Geim and his colleagues initialized a revival in diamagnetic levitation research. Today the papers of Geim et al are among the most frequently quoted sources in scientific papers and patents considering diamagnetic levitation.

12. **ON-CHIP MANIPULATION OF LEVITATED FEMTO-DROPLETS**

In 2004 Igor Lyuksyutov and his colleagues from the Texas A&M University presented a new device for the high precision manipulation of tiny floating diamagnetic droplets and particles [32]: The **M**agnetic **M**icro-manipulation **C**hip (MMC). The MMC consists of two separated NdFeB-permanent magnets (10 mm × 10 mm × 100 μ – 2000 μ, $L \times W \times H$). The gap between the magnets is about $0.25H$–$0.4H$ and the magnets are magnetized oppositely with magnetisation direction normal to the gap. This magnet arrangement – Fig. 17, produces a high magnetic field gradient with an energy minimum along a line between the magnets wherein the diamagnetic specimen can float. The flux density on the magnet surface in direction to the gap is about 0.5 T, the parameter[8] ∇B^2 is about $5 \cdot 10^3$ T^2/m. The magnetic force generated by the magnetic field is strong enough for the diamagnetic levitation of droplets and particles of pico to femtoliter volume which are injected into the MMC with an atomizer.

The position of a floating droplet can be controlled by current pulses through electrodes which are fabricated on the steel substrate. Lyuksyutov and his coworkers achieved a positioning accuracy of 300 nm or better by using small current pulses. The potential energy of floating droplets could be controlled with 0.2 zJ accuracy (zepto Joule, 10^{-21} J). The force accuracy laid in the femtonewton range (10^{-15} N).

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[8] For the levitation of water at least a ∇B^2 of $1.4 \cdot 10^3$ T^2/m is necessary.

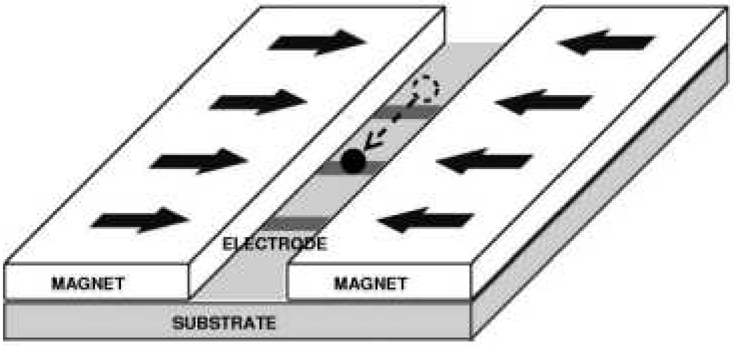

Fig. 17 – On-Chip manipulation of a diamagnetically levitated femto-droplet
(by Lyuksyutov *et al*., 2004).

With the MMC droplets and particles can be handled with a volume up to a billion smaller than in conventional microfluidic devices. The area of application for the MMC is wide. For example it can be used for the research in biochemistry und colloidal sciences. The floating femto-droplets can be loaded with cells, bacterias, viruses or chemicals. Then, in the MMC itself, they can be brought into reaction or be analyzed in further steps. According to Lyuksyutov further areas of applications could be the nanotechnology, microfluidics, atmospheric chemistry, aerosol science and crystal growth.

13. **CONCLUSIONS**

The magnetic micro-manipulation chip is the temporary last great achievement in the long history of diamagnetic levitation. But the scientific interest in the topic of diamagnetic levitation seems to subside again. Whereas in 2002 one could count about 20 patents and scientific publications considering diamagnetic levitation, the number of publications dropped significantly to only about 5 publications in 2006. The main obstacle for a technological breakthrough of diamagnetic levitation is the low diamagnetic force. Finding a much more stronger diamagnetic material than pyrolytic graphite would help to further develop this fascinating technology towards a broader spectrum of application. Physically nothing speaks against the existence of such a material. However, to the knowledge of the author, no specific research has be done yet considering this topic. That could be a new task for material scientists and chemists.

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IMAGE CREDITS

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