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Gravity modification experiment using a rotating superconducting disk and radio frequency fields

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Abstract

An experiment is described which attempts to replicate the results of Podkletnov et al. concerning an alleged detection of a gravity-like force above a spinning superconductor. The experiment is based on Podkletnov's published descriptions plus personal communications but found no evidence of a gravity-like force to the limits of the apparatus sensitivity. A full description of the apparatus and operation is given.

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1. Introduction

This report summarizes the results of experiments performed at Hathaway Consulting Services in an effort to confirm the reported results of Podkletnov [1,2].

In 1992 in an article in Physica C [1], Podkletnov and Nieminen claimed to demonstrate the existence of a gravity-like force from spinning bulk YBCO ceramic superconductors influenced by combined magnetic levitation forces and RF illumination. A small test mass suspended above the superconductor apparently showed a 0.05% weight loss under certain conditions. A relatively large size (145 mm diameter × 6 mm thick) sintered single-layer disk with specific grain size distribution of relatively small grains was required to be levitated by Meissner magnetic levitation up to 7 mm above a single "pancake" coil operated at frequencies of $50–10^6$ Hz. In addition, the disk was spun to high speeds using edge-oriented pseudo-rotating magnetic fields provided by a magnetic stator positioned around the periphery of the disk and operated at similar frequencies. The experiment was performed below 60 K in the vapours of liquid helium.

In 1997, Podkletnov published an updated version of the experiment on the Los Alamos Physics web site [2]. This was essentially the same experiment as reported in 1992 and achieved up to 1–2% weight loss in test objects but with the following experimental differences. A much larger superconducting disk in a ring configuration (27 cm outside diameter × 8 cm inside diameter × 1 cm thick) was used with a small–medium grain size distribution in a bi-layer structure. One layer was superconducting and the other was a normal

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conductor at the experimental operating temperatures. The disk was levitated above either three or six individual solenoidal coils and two toroidal coils threaded through the center hole of the disk and operated in a 2-phase mode to drive the disk in rotation. Determination of weight loss (or gain) was by test masses of dimensions similar to those of the superconducting disk itself.

It was decided to attempt a replication of the experiment by combining several attributes of the 1992 and 1997 published procedures. In consultation with Podkletnov [3], the final experimental configuration was settled upon (Figs. 1 and 2). Bilayer YBCO disks of 160 mm outside diameter × 40 mm inside diameter × 7–10 mm thick were fabricated in-house using one of several methods

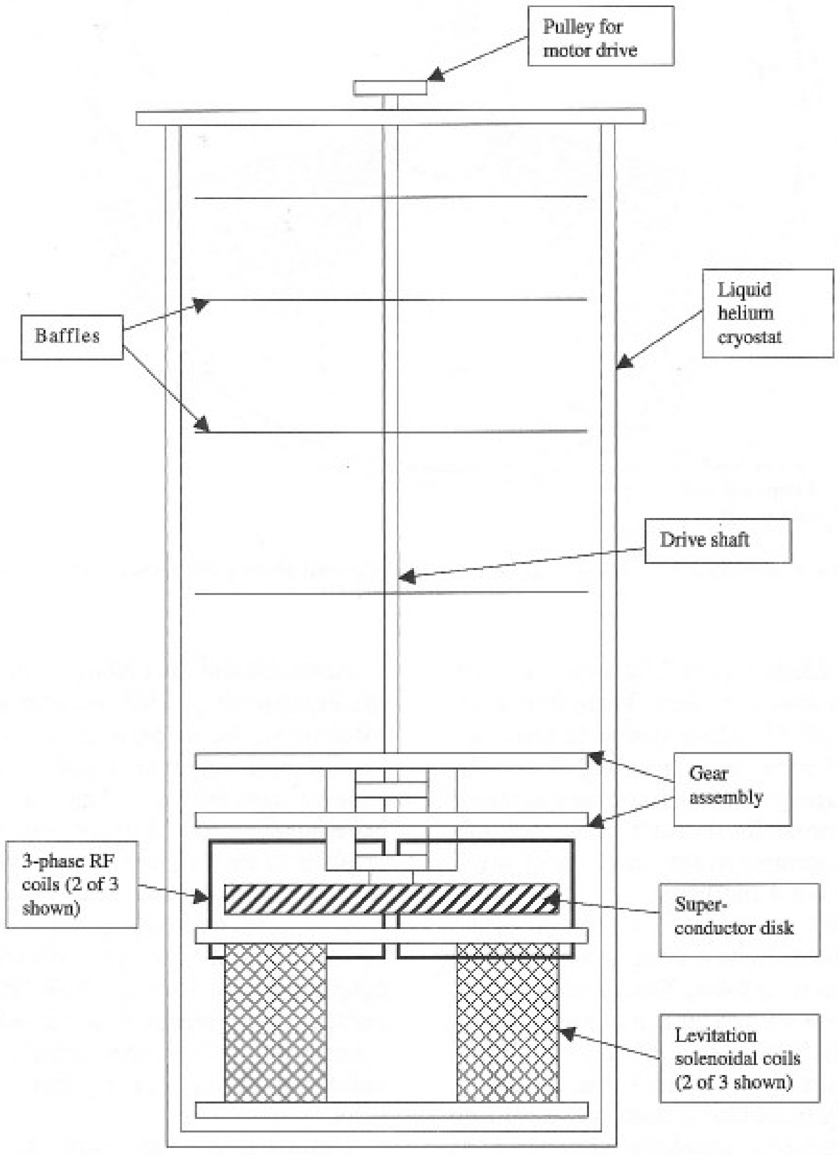

Fig. 1. Schematic view of main components.

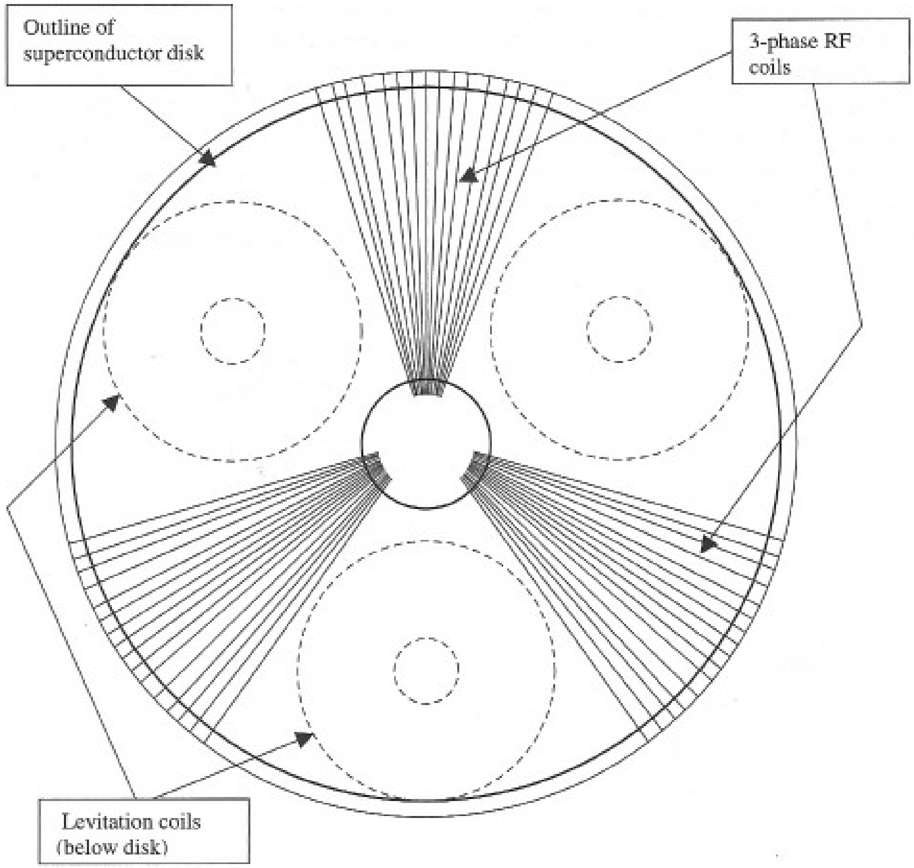

Fig. 2. Top view of superconductor disk threaded by 3 toroidal RF coils above 3 levitation coils (shown in dashed line).

proposed by Podkletnov [4,5]. The same or larger grain size distribution was used. Three individual levitation solenoids of similar design to that outlined in the 1997 paper were operated at 10^5 Hz. Three high-frequency coils in a 3-phase arrangement threaded toroidally through the center hole of the disk were operated at between 2 and 5 MHz. The disk was rotated mechanically by a bearing and gear assembly designed to operate at liquid helium temperatures from a drive motor external to the liquid helium cryostat. The experiment was performed between $\approx$5 and 20 K and the detection of the gravity-like force used a modified analytical balance of sensitivity exceeding that used by Podkletnov in [2]. In addition, attempts were made to measure the "reverse Josephson effect" so as to determine electrical properties of the disk.

After considerable effort, a full-scale version of the experiment as outlined above was performed three times. No evidence of a "gravity-like" force via test mass weight modification to the limit of the balance sensitivity was detected. One of the three experiments was preformed with a "dummy disk" in place of the bi-layer superconductor disk so as to help eliminate any unknown experimental errors or artifacts such as air currents generated by the apparatus or stray electromagnetic fields coupling to the balance. This "dummy disk" experiment was identical in all other ways to the experiments with superconductor disks and provided a solid base line to judge all subsequent results.

Unfortunately, the ability to actually float a disk using the 100 kHz magnetic induction field and thus allow unconstrained rotation of the disk using the 3-phase fields proved impossible at the power levels used. Successful levitation of a fine powder disk was achieved at frequencies of up to 5 kHz but Podkletnov specifically required [4,6] that the disk be of coarse-grained structure and the levitation frequency be at least an order of magnitude above that. Hence it was not possible to freely rotate the disk with the apparatus tested. Therefore, the external motor drive scheme was employed to rotate the disk. However, it is believed all other aspects of the experiment were followed in detail with respect to the required operating parameters of the experiment.

2. Summary of procedures and experiments

2.1. Superconducting disk preparation

Although he did not specify a bi-layer structure in the 1992 paper, Podkletnov [4] claimed that impurities in the 1992 raw materials used to fabricate his disks caused small islands of non-superconducting phases which allowed the anomalous weight modification phenomenon to be manifest. It was subsequently determined that bi-layer disks were essential to the success of the experiment [2]. Apparently the diffusion layer between the main layers ($\approx$0.5 mm thick) was responsible for the phenomenon. Better control of these non-superconducting phases could be had by producing a bi-layer structure.

The method specified by Podkletnov in [2] for production of bi-layer sintered disks was to heat the surface layer of $\approx$20–30% of the disk thickness by induction heating. This apparently melted that layer and changed its crystal structure to a non-superconducting phase that remained a normal conductor down to liquid helium temperatures. As the experiment was run in the vapours of liquid helium, a layer of normally-conducting material which became superconducting only below $\approx$5 K would be suitable. This method was tried several times on both large and small disks using a 5 kW, 450 kHz induction heater with specially-wound flat spiral load coils. Although heating to the required temperature did occur, it was confined to isolated areas on the disks resulting in uneven heating and the thermal shock caused disk fracture.

Another attempt at bi-layer fabrication involved a double chamber which exposed one side of an already superconducting single-layer disk to oxygen at a particular flow rate and temperature and the opposite side to nitrogen or other inert gas in an attempt to kill the superconductivity on one side. This, too, failed due to different diffusivity rates of the two gasses which prevented a non-superconducting layer from being formed. Yet another attempt involved the simple pressing of a non-superconducting phase YBCO layer and a superconducting phase YBCO layer of powders placed in the die and pressed into a suitable green body. Due to uneven shrinkage rates upon oxygen sintering, highly warped disks resulted.

The final and successful method settled upon was the cation substitution method. When a portion of the copper ions in YBCO is replaced by transition-metal ions, i.e. Zn^{2+}, Fe^{2+}, or Pr it gradually loses its superconductivity down to sub-liquid helium temperatures. $YBa_2Cu_{2.85}Zn_{0.15}O_x$, $YBa_2Cu_{2.6}Fe_{0.4}O_x$ or $YBa_2Cu_{2.3}Fe_{0.7}O_x$ (referred to hereafter as 'Z15', 'F40' and 'F70' respectively) were initially chosen as non-superconducting layer materials with critical temperatures of $\sim$40, $\sim$10 and $\sim$0 K respectively to gain experience in bi-layer fabrication [10]. Eventually, however, $PrBa_2Cu_3O_x$ ('Pr123') was selected as the most suitable non-superconducting layer material [11].

In order to produce a sintered bi-layer disk strong enough to withstand rotation at several thousand r.p.m., smaller grain sizes are generally recommended. Therefore, bi-layer disks with multiple-sized grains (Section 2.1.1) as well as the triple-sized large grains specified by Podkletnov [6] (Section 2.1.2) were fabricated. Podkletnov [6] specified large grains (and thus high porosity) primarily for increased thermoshock resistance.

In addition to the above, a bi-layer MTG disk was fabricated. Here, the superconducting layer was normal MTG and the non-superconducting layer incorporated another cation substituting for yttrium. The MTG processing incorporated low pressure oxygen solid state reaction techniques. Although the two layers bonded together quite well, the final bi-layer disk was warped and unsuitable for spinning.

2.1.1. Multiple-sized particle distribution

All YBCO powder used for the bi-layer disk fabrication was pure 123 phase as shown in the XRD plot of Fig. 3. Stoichiometric amounts of initial powders for the YBCO superconducting layer and the Z15, F40 and F70 non-superconducting layers were first calcined in air at 920 °C for 10 h (completely reacted), followed by ball milling in 2-propanol for 8 h. The YBCO powders were pressed and pre-sintered in air at 920 °C for 10 h while the Z15, F40 and F70 powders were pressed and pre-sintered in air at 930 °C for 10 h. Cakes were then crushed and sieved with particle sizes: 300–500 μm, 212–300 μm, 150–212 μm, 106–150 μm, 63–106 μm and <63 μm.

Pr123 powders were calcined in air at 920 °C for 10 h. Pr_6O_{11} was used as initial powder but was not fully reacted at this stage. Next the powders were ball-milled and re-calcined at 920 °C for 10 h (completely reacted), followed by ball-milling in 2-propanol for 8 h and then pressed and pre-sintered in air at 920 °C for 10 h. Cakes were then crushed and sieved with the same particle sizes as above. Multiple-sized YBCO and Z15, F40, F70 and Pr123 powders were used to prepare the bi-layer disks. Particle size distribution for powders was 30 wt.% of 212–300 μm, 20 wt.% of 150–212 μm, 15 wt.% of 106–150 μm, 15 wt.% of 63–106 μm, and 20 wt.% of <63 μm. Elvacite 2045 at 0.5 wt.% was added as binder.

The 160 mm die was loaded with non-superconducting powder to the top and the surface smoothed with a straight edge. The lower ram of the die was lowered just enough to allow space for the YBCO powder which was loaded and smoothed. The disk was then pressed at 120 MPa. Pressed disks were sintered in air at 930 °C using the following schedule:

$$\mathrm{RT} \xrightarrow{60\ ^\circ\mathrm{C/h}} 250\ ^\circ\mathrm{C} * 2\ \mathrm{h} \xrightarrow{60\ ^\circ\mathrm{C/h}} 600\ ^\circ\mathrm{C}$$

$$\xrightarrow{120^\circ\mathrm{C/h}} 930\ ^\circ\mathrm{C} * 5\text{–}10\ \mathrm{h} \xrightarrow{60\ ^\circ\mathrm{C/h}} 400\ ^\circ\mathrm{C} \xrightarrow{120\ ^\circ\mathrm{C/h}} \mathrm{RT}$$

After sintering, slight warping was observed. Shrinkage was around 1.5–3%. Sintered disks were oxygenated at 750 °C for 2 h and then cooled at 60 °C/h in an oxygen atmosphere. Weight gain (+0.06 wt.%) was detected. Density of sintered disks was 4.7–4.9 g/cm^3.

2.1.2. Triple particle size distribution

YBCO and Pr123 (see above) were chosen as the superconducting and non-superconducting materials respectively. Both of them were calcined at 920 °C for 10–20 h and pre-sintered at 930 °C for 10 h. After sieving, particle size distribution for both powders was 60 wt.% of 425–600 μm, 25 wt.% of 90–150 μm, and 15 wt.% of <25 μm. After pressing and binder burn-out, sintering in an O_2 atmosphere at 910 °C for 10 h was carried out as follows:

$$\mathrm{RT} \xrightarrow{8\ \mathrm{h}} 910\ ^\circ\mathrm{C} * 10\ \mathrm{h} \xrightarrow{2\ \mathrm{h}} 800\ ^\circ\mathrm{C} * 10\ \mathrm{h} \xrightarrow{2\ \mathrm{h}} 700\ ^\circ\mathrm{C}$$

$$* 10\ \mathrm{h} \xrightarrow{2\ \mathrm{h}} 600\ ^\circ\mathrm{C} * 10\ \mathrm{h} \xrightarrow{2\ \mathrm{h}} 500\ ^\circ\mathrm{C}$$

$$* 2\ \mathrm{h} \xrightarrow{2\ \mathrm{h}} 450\ ^\circ\mathrm{C} * 40\ \mathrm{h} \xrightarrow{4\ \mathrm{h}} 200\ ^\circ\mathrm{C} \xrightarrow{4\ \mathrm{h}} \mathrm{RT}$$

This is the sintering schedule of Podkletnov [6]. After sintering, shrinkage was ~0.6%. A ~0.07% weight gain was measured after sintering in O_2. Density of the sintered bi-layer disks was 4.5–4.7 g/cm^3. In Fig. 4 a general view of the disk clearly shows the two layers. Fig. 5 shows a close-up of the disk edge whose overall thickness is 10.7 mm with a 3.5 mm thick upper layer of Pr123. The transition layer between the normal and superconducting layers is less than 0.5 mm. Average porosity is 10–15%. Shown in the scanning electron micrograph (Fig. 6) is the lower surface of the disk magnified ≈2000× and displaying some of the finer particles with sizes shown from several microns to ≈100 μm.

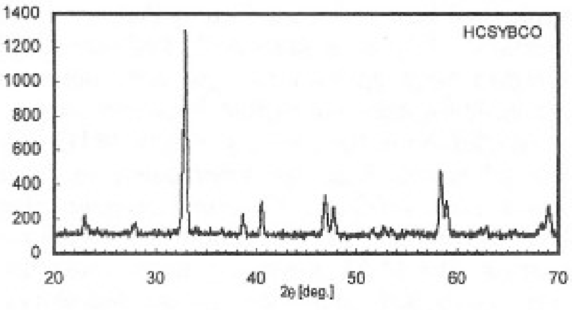

Fig. 3. Typical X-ray diffraction plot of YBCO powder.

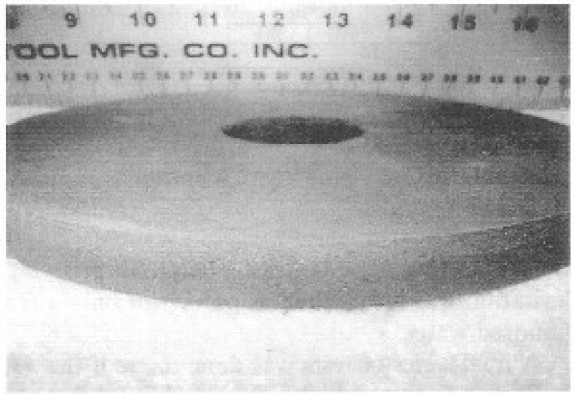

Fig. 4. General view of 160 mm diameter bi-layer disk with ruler in background.

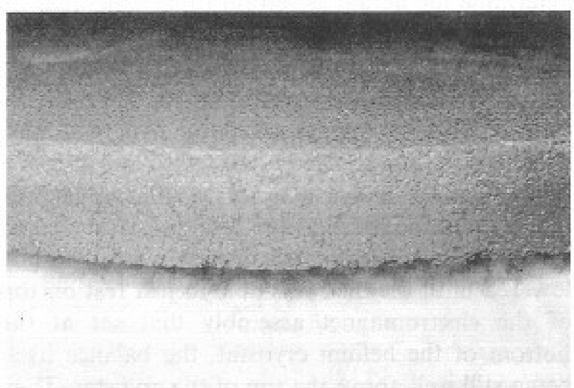

Fig. 5. Close-up of 160 mm diameter disk edge showing bi-layer structure.

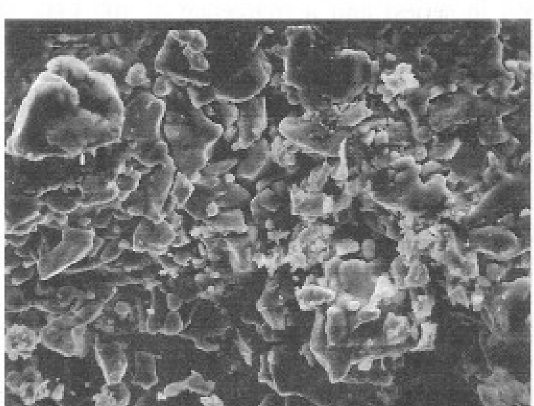

Fig. 6. SEM photograph of lower surface of bi-layer disk.

Resistivity measurements were performed using a 4-probe method with DC currents up to 0.5 A. Both top and bottom layers were measured at room temperature and while submerged in LN2. These results are depicted in Fig. 7. In the superconducting layer, the transition temperature was ≈85 K and low critical currents of ≈10^3 A/cm^2 were measured primarily due to the high porosity.

2.1.3. Disk balancing and strength determination

Since the disks were to be subject to high-speed rotation, they were statically and dynamically balanced in a custom-made dynamic disk balancer. Balance was obtained by judicious removal of material from the disk periphery in such a manner as to minimize radial and circumferential stress fractures.

In order to ensure that the disks would be able to withstand the hoop stresses applied during proposed high-speed rotation and that they would not fly apart causing damage to the toroidal coil assembly as well as the cryostat, they were tested prior to experimentation. The test apparatus consisted of a styrofoam enclosure into which the pre-cooled disk was placed. Liquid nitrogen was poured into the bottom of the enclosure. In some tests, multiple grain size single-layer disks withstood only ~1300 r.p.m. before shattering. This was an additional reason to limit the rotational speed to below 1000 r.p.m. in these experiments. Future experiments at higher speeds will require winding the periphery of the disk with carbon fibres or equivalent able to withstand extremely low temperatures without severe differential contraction.

Mechanical stress analysis shows that at the rotational speeds achieved prior to shattering, the tangential stress in the material was ≈0.5 MPa, and was concentrated around the inner circumference. The radial stress was ≈1/3 of that. This very low value of mechanical strength is indicative of large grain sizes used as well as the multitude of stress fracture concentration sites around the inner periphery of the disk especially at cryogenic temperatures.

2.2. Superconducting disk levitation tests

Considerable effort was made to try to get the disks (typically with weights of 600–800 g) to freely

	YBCO/Pr123*		YBCO/F70		YBCO/F40		YBCO/Z15	
	YBCO	Pr123	YBCO	F70	YBCO	F40	YBCO	Z15
room temp. (mΩ.cm)	3.0	48.6	1.3	12.0	1.3	3.2	1.3	2.0
LN2 (mΩ.cm)	0	5.3×10^{3}	0	7.8	0	2.8	0	0.2

- note YBCO/Pr123 is a triple-size disk

Fig. 7. Resistivity measurements of both layers of 4 bi-layer disks at room and liquid nitrogen temperatures.

levitate above an electromagnetic coil assembly at liquid nitrogen or liquid helium temperatures. Many different electromagnetic coil designs were tested (e.g. pancake and solenoidal coils of various geometries, winding methods and wire types). These were excited by DC or AC currents with frequencies of from 60 Hz to 100 kHz. Further tests were done with an array of high energy density NdFeB permanent magnets to confirm how well a disk would levitate using very strong magnetic fields.

DC current of 12 V at 100 A or 135 V at 48 A would not levitate any of the sintered disks at liquid nitrogen temperature. A small diameter melt-textured disk (10 cm diameter) could be levitated to a height of roughly 2–3 cm when using a single pancake coil and a DC current of 20–30 A. The 3-solenoid coil could not levitate any of the disks using DC current.

Many tests were done using AC currents at low and high frequencies. Three large diameter disk types were investigated: YBCO fine powder of single grain size, YBCO coarse powder of multiple grain size distribution, and melt-textured YBCO (MTG). The only successful levitation at liquid nitrogen temperatures occurred using a 60 Hz 3-solenoidal coil design with soft iron pole pieces. The MTG and fine powder disks performed better than the coarse powder disk, however the levitation height was only 0.5–1 mm. Also, excessive vibration due to the low frequency 60 cycle magnetic field made this method of levitation impractical. Further tests were done at 100 Hz to 2 kHz with peak coil currents of 20–50 A and 400 V but no levitation using any of the disks tested was successful.

Tests at liquid helium temperatures confirmed that the maximum frequency for successful levitation was ≈5 kHz above a pancake coil wound using litz wire in a universal winding configuration. Unfortunately also, the only disk type able to be levitated was fine powder YBCO. Surprisingly, levitation was up to 2 cm at powers of only a few hundred watts.

A final series of tests was done to see if the AC levitation force could be increased by doing the tests at liquid helium temperatures and powering the various coil designs with current supplied from a high power (up to 1 kW) 100 kHz oscillator. To determine the actual levitation force generated by the disks, a counter weight and balance beam set-up was used to make a quantitative measurement of the Meissner force induced within the disks. A large (160 mm) superconducting disk was suspended by a long thread connected to one arm of a beam balance, and a counter weight, which was made equal the mass of the disk, was fastened to the other arm. The balance assembly was carefully lowered until the disk was able to just rest on top of the electromagnet assembly that sat at the bottom of the helium cryostat, the balance itself being still well above the top of the cryostat. Then the disk (pre-cooled in liquid nitrogen) was slowly cooled to below 20 K with some tests done at 5 K. With a maximum power of 1000 W (e.g. 50 W reflected, 6.6 A peak coil current into 3-solenoidal coils in series) and a frequency of 100 kHz, the levitation force on the disk was determined to be no greater than 5 g. Also, a room temperature test was compared to the low temperature tests and it was found that a non-superconducting YBCO disk would produce only a marginal force (less than 1 g force). Furthermore, the rapid induction heating at room temperature cracked the non-superconducting disk into two pieces within 3 s.

As a result of these tests it was decided that either the coil designs were inefficient at producing large enough magnetic flux densities to levitate a large diameter superconducting disk, or very large, multi-kilowatt power levels were required to achieve true AC Meissner levitation. However, the fundamental limitation in these experiments was the very high AC voltage present across the coils due to their high impedance at these frequencies. In order not to damage nearby coils and power supplies, a maximum voltage of 8 kV across the coils was maintained. Furthermore, it was only the MTG disk types that actually levitated with considerable height (2–3 cm) above the permanent magnets. The fine and coarse powder sintered disks would only produce strong magnetic pinning forces and would not levitate as well above the permanent magnet assembly.

In order to obtain a stronger levitation at high AC frequencies, Podkletnov [4] suggested preparing MTG disks and crushing them. This crushed material would then be used as the superconducting layer of a bi-layer disk. To test this hypothesis, MTG particles prepared in-house were then pressed into a single layer disk. Unfortunately, the levitation height was insufficient for the experiment and this method was also abandoned. Furthermore, the mechanical strength of the resulting disk was not sufficient to withstand high rotational speeds.

Given that Podkletnov had noted [7] that a small effect (on the order of 10% of that seen in his 1992 experiments) would result even with insufficient Meissner levitation, it was decided to proceed with the experiments anyway as our analytical balance had ample sensitivity.

2.3. Reverse Josephson junction effect

A series of tests was performed in an effort to measure, qualitatively, the "reverse Josephson junction effect" (an AC current passed through an insulating junction between superconductors will generate a micro-volt DC signal). These tests were done to confirm the existence of Josephson junctions within the YBCO materials being fabricated in our laboratory as suggested by Podkletnov [2] as a possible requirement for the successful outcome of the experiment. These junctions would appear at the non-superconducting grain boundaries between superconducting grains.

Several rectangular superconducting samples ($\approx 30 \times 12 \times 10$ mm) of sintered and MTG YBCO material were used, including a dummy graphite sample. Four electrodes were placed on the surface of each sample using conductive paint. Two electrodes served as AC input terminals of RF current, varying from 0.05 to 10 MHz. The second set of electrodes was connected to a sensitive micro-voltmeter. According to Podkletnov [8], a DC voltage of several micro-volts should appear when an AC input current is passed through a "good" sample (i.e. that producing substantial "gravity-like" force in the experiment). The AC input frequency should correspond to the Josephson junction frequency (usually in the range of 1–10 MHz). All tests were done at liquid nitrogen temperature.

The test set-up comprised an RF generator, linear RF amplifier (3 W maximum output power) and a 50 Ω non-inductive load. The samples to be tested were placed in series circuit with the 50 Ω load, so RF current would pass through the test sample and terminate into the 50 Ω impedance. Two noticeable micro-volt signals were detected, one at $\approx$1.6 MHz and the second at $\approx$4 MHz. Unfortunately, when the graphite sample was exchanged in the test set-up for the superconducting sample, the 4 MHz signal was still detected, which indicated a resonance artifact in the experimental set-up. The 1.6 MHz signal was not seen in the "dummy" sample test, but it remains inconclusive if a real "effect" was detected due to the small DC amplitude observed. Further tests are needed to determine the proper test set-up required to detect the reverse Josephson junction effect in multi-grain bulk YBCO superconductors.

One additional test was done using a vector impedance meter in an effort to detect noticeable changes in the electrical impedance of a superconducting sample as the frequency was swept from 1 to 10 MHz. The electrical impedance of the sample was measured but the impedance was relatively constant as a function of frequency.

It is important to note that a 160 mm diameter YBCO/Pr123 triple grain size disk was sent (March 2001) to Dr. Podkletnov who declared its characteristics were acceptable and was able to confirm a small Josephson effect [9].

2.4. Analytical balance

The use of a commercial gravitometer placed above the experiment should be a very sensitive detector of changes in gravity in the volume of space above the spinning disk. Such a gravitometer consists of a tiny test mass affixed to the end of a hair-thin quartz rod in a cantilevered spring balance arrangement. The cross sectional area of the test mass is a few square mm. But the "gravity-like" force apparently created in the experiment was reported to be proportional to the cross-sectional area of the test mass relative to the area of the disk [4,7]. The more surface area of the test mass exposed to the "field" produced by the disk, the greater the force detected. This is why Podkletnov preferred to use a large-area test mass suspended from a balance. Indeed, in preliminary experiments using a gravitometer above the apparatus, no anomalous gravity-like behaviour was detected to a sensitivity of one part in 10^8 g.

In order to exceed the published weight detection specifications, a highly sensitive chemical analytical balance (Ainsworth type DL) was modified to accept the test mass ($\approx$50 g) suspended directly beneath one pan. This balance had original sensitivity specifications of 0.01 mg in 200 g but after modification had a repeatable sensitivity of 0.5 mg. A phenolic disk-shaped test mass, which had a circular diameter that equaled the diameter of the superconducting disk was chosen as this closely matched the force detection method utilized by Podkletnov [2]. The balance did not employ any electronic circuitry for detection purposes which eliminated any spurious electromagnetic fields from interfering with the test mass measurements. Tests confirmed the absence of electrophoretic or electrostatic forces in the range required to create measurable artifacts.

The test mass was suspended 35 cm below the balance beam and 1.2 m above the superconducting disk. Note that the superconducting disk was situated near the bottom of the liquid helium cryostat and there were 4 thermal baffles of 3 mm thick aluminum plate as well as three 9.5 mm thick structural aluminum plates between the test mass and the superconducting disk (see Fig. 1).

Every precaution was taken in the construction of the balance assembly so as to eliminate air currents and thermal effects (e.g. temperature gradients inside the balance enclosure). An acrylic cylinder housed the test mass which was suspended by a thread from one pan of the balance. This was made air tight and insulated with four alternating layers of metalized foil ("superinsulation") and foam sheeting. The entire balance enclosure (metal frame, glass windows and sliding door) was then covered in 3 cm thick dense insulating foam sheets to form an air-tight box. A CCD camera and light source (small flashlight of negligible heat output) were added to allow easy viewing of the needle marker on the graduated scale of the balance. A video tape recorder was used to record all balance measurements together with audio recording of the progress of the experiment.

The beam was exactly balanced using a counter weight and then the sensitivity of the balance was determined using precise milligram weights. It was determined the balance had a repeatable weight sensitivity of $\approx$0.5 mg for a needle marker movement of 1/2 a scale division, or a weight change of the test mass of 0.001%. Needle movements of less than 1/5 division were easily seen on the video record but were not as consistently repeatable. Podkletnov [1] reported a weight modification of 0.05%.

The balance was set up on a track such that it could be moved away from the cryostat during cool down and then slid into position above the cryostat during the experiment without loss of sensitivity.

2.5. Full set-up of the experiment

The 3-phase radio frequency system was designed to operate at a frequency of 2–5 MHz with a typical output power of 200 W per phase (forward power, SWR less than 1.5). Each toroidal coil of the 3-phase assembly was physically spaced 120° apart around (and through) the disk (see Fig. 2) and consisted of 13 turns of AWG 14 teflon insulated wire. Signal generation used to excite the 3-phase RF circuits was provided by phase locked-loop oscillators, each having a variable phase adjustment. Monitoring of the phase relationship of the three RF signals (nominally 120 electrical degree displacement) was done using a 4-channel oscilloscope. Once the custom-made impedance matching networks (one network per phase) and the phase of the RF signals were properly adjusted, the amplifier power could be easily applied to the 3-phase coil assembly.

The AC levitation system was powered by a solid state, high-power oscillator operating at 100 kHz with a typical output power of 1000 W (forward power, less than 50 W reflected, peak current 6.6 amps into the 3-coil load). A custom impedance matching network was designed to allow considerable circuit adjustment so the levitation coils could be properly matched to the 50 Ω output impedance of the power oscillator. The 3-solenoid coils were placed 120° apart on a platform directly underneath and in close proximity to the disk and each coil consisted of 253 turns of AWG 14 magnet wire. The three coils were connected in series. The outside diameter of each coil was approximately equal to the difference between the outer and inner radii of the superconducting disk.

In order to spin the disk, an external variable-speed DC motor drive mechanism was utilized because of the difficulties encountered in achieving sufficient AC Meissner levitation of the disk. The motor was situated on top of the liquid helium cryostat and connected by a belt drive to a central rotating shaft on special low-temperature bearings which ran down into the cryostat. A gear arrangement transmitted this shaft torque to the disk and allowed clockwise rotation (viewed from above). Typical maximum disk rotational speeds achieved were 400–800 r.p.m.

The cryostat was a custom-made 23 cm throat diameter × 91 cm deep stainless steel and aluminum dewar. To monitor the disk temperature inside the liquid helium cryostat, two thermocouples were placed just above and below the level of the disk. A liquid helium level indicator was used to check for the presence of liquid helium inside the cryostat. It should be mentioned that the experiment could be run satisfactorily using only the cold vapours from a liquid helium storage dewar given sufficient pre-cooling of the cryostat and the apparatus. Pre-cooling was done using liquid nitrogen. Then the liquid nitrogen was removed from the cryostat followed by further cooling using the vapours of liquid helium. Temperatures of 10–20 K at the disk and, when liquid helium was introduced into the cryostat, as low as ≈5 K, were attained.

A typical experimental run proceeded as follows. The helium cryostat was pre-cooled using liquid nitrogen before lowering the experimental assembly into the cryostat, then cooling continued with liquid nitrogen while monitoring the internal temperature. When the temperature reached ≈90 K, the 3-phase RF system is energized and 10–20 W forward per phase was applied to the 3-phase toroidal coils on the disk to "trap-in" magnetic flux. Once the system reached 77 K, the 3-phase RF power is switched off and the liquid nitrogen was removed from the cryostat. To ensure the disk was still superconducting, it was rotated slowly while applying 10 W per phase to the 3-phase coils and monitoring the small fluctuations on the SWR meter on each of the 3-phase matching networks. No fluctuation meant loss of superconductivity due to warming up above T_c after liquid nitrogen removal.

Next, transfer of helium vapours and/or liquid from the storage dewar into the cryostat was begun immediately while constantly monitoring the system and disk temperature. The balance was moved into position so that the test mass disk was exactly over the superconducting disk in the cryostat. Balance beam equilibrium was checked and the video tape recorder was started. When the required system temperature was reached, i.e. between 10 and 20 K, the disk drive motor was started.

With the system at, or below, 20 K, the motor speed was increased to as high a rotation speed as possible. Coincidentally, the AC levitation system was energized with 500 W forward power and the 3-phase system energized to around 100 W forward per phase. The power level of the 100 kHz levitation system was then increased to a maximum of 1000 W and the 3-phase system to a maximum of 200 W per phase at 4–5 MHz. Minor adjustments to the impedance matching networks of both the 100 kHz and 3-phase systems were required to ensure minimum reflected power (SWR readings were 1.5 or less).

The typical run time period during which disk rotation and maximum system power was applied averaged 60–90 s. Rapid boil off of helium vapours occurred, then all systems were turned off simultaneously to check for transient effects. The experimental apparatus was allowed to cool down again to the optimum operating temperature and then another system run commenced. Following each run period the internal cryostat temperature would rise to ≈40 K. As many as 8–10 runs per experiment were completed, then the experiment was stopped and the apparatus allowed to warm up, dismantled and then inspected.

Two examples (Figs. 8 and 9) depict balance readings over a typical 10 s period, once per second. Readings for Fig. 8 were taken with the dummy disk (see below) rotating in the vapours of liquid helium with full RF power applied. Fig. 9 shows one of the bi-layer disks subject to the same conditions. Each vertical unit represents a weight change of 0.1 mg, positive being a weight gain and negative a loss. The full vertical scale (−0.5 to +0.5 mg) represents twice the repeatability limit of the balance with the individual readings clustering around 0 mg, indicating negligible drift. Approximately 3 h elapsed between readings shown in the two figures.

Two superconducting disks and one "dummy" disk were tested as follows:

(A) YBCO/Pr123, bi-layer, triple grain size, 160 mm outside diameter;

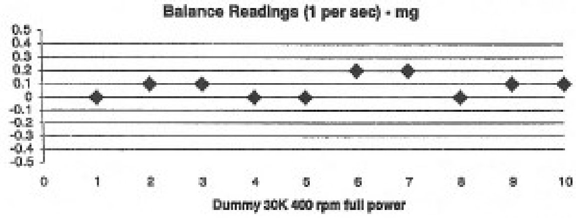

Fig. 8. Balance readings over 10 s for dummy disk (vertical scale: 0.1 mg/div).

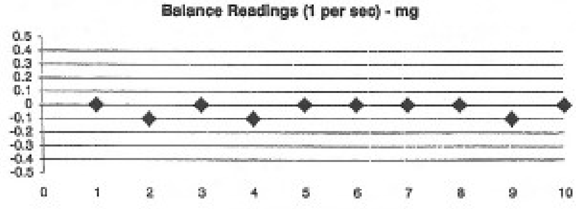

Fig. 9. Balance readings over 10 s for bi-layer disk A (vertical scale: 0.1 mg/div).

(B) YBCO/Pr123, bi-layer, triple grain size, 160 mm outside diameter (same batch as (A));

(C) acrylic disc similar in size to (A) and (B), but with a 1 mm thick copper disk fastened to the upper surface of the acrylic disk.

Note that the non-superconducting layer of the bi-layer disk was placed facing down. The copper disk used as part of the dummy was necessary to achieve a good RF load for the 3-phase system for the base-line tests.

3. Experimental observations

Three different experiments were completed. The first experiment used disk (A), the second was made using the dummy disk (C) and the third was performed using disk (B). Observations of the balance pointer were visually noted and captured on videotape as a backup. An example of the observed differences between the dummy disk and a bi-layer disk during various parts of the experiment is given in Fig. 10. Each solid dot represents the average of a set of 10 individual readings, such as shown in Figs. 8 and 9. Error bars are also shown and indicate that the precision of individual readings is greater than the overall balance repeatability.

The first two dots represent the dummy disk at ≈80 and 20 K with no rotation or RF power applied. The third dot shows the results at 30 K under full power and rotating at ≈400 r.p.m. Several hours later, a bi-layer disk was ready to test and it is shown as dots 4, 5 and 6, under conditions identical to the dummy disk. As all

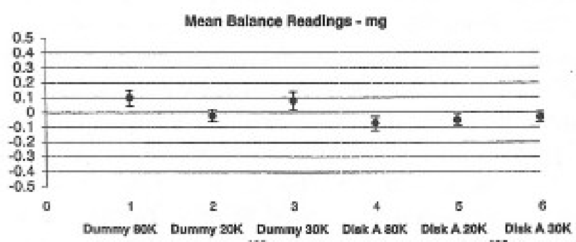

Fig. 10. Average of 10 balance readings for different configurations (vertical scale: 0.1 mg/div).

Data Set Description	Mean of 10 observations	Std Dev
Dummy 80K no power	0.1	0.082
Dummy 20K no power	-0.02	0.063
Dummy 30K 400 rpm full power	0.08	0.079
Disk A 80K no power	-0.07	0.067
Disk A 20K no power	-0.06	0.071
Disk A 30K 400 rpm full power	-0.03	0.048

Fig. 11. Mean and std. deviation for different configurations.

error bars fall well within the balance repeatability limits, we can draw conclusions with considerable confidence. A summary table of the averages and standard deviations for these six data sets is provided in Fig. 11.

The main experimental observations are as follows:

(1) No weight modification of the test mass was observed during the two separate experiments using bi-layer disks (A) and (B) to the 0.001% balance repeatability level regardless of RF frequency, levitation and RF power levels, sample temperature or rotational speed.

(2) No weight modification was detected during the "dummy" disk (C) experiment.

(3) A dragging force was present which slowed or sometimes even stopped the rotation of the disk whenever the 3-phase power level exceeded ≈100 W per phase and the drive motor was not at full output. At around 200 W per phase or greater, the disk would stop rotating and the motor drive would stall completely.

The maximum attainable disk rotational speed normally did not exceed ≈550 r.p.m. and the average was observed to be 400 r.p.m. This was limited by mechanical vibrations of the apparatus due to bearing and gear chatter at liquid helium temperatures. The 3-phase system became difficult to tune below a frequency of 4 MHz (could not get each phase to tune properly at 3.6 MHz while maintaining 120 electrical degree separation, for example) so most of the experiments were done at 4 and 5 MHz. During some experimental runs the 3-phase RF system had the phase relationship reversed to change the direction of the RF fields from A, B, C to B, A, C. The motor drive was always turning the disk in a clockwise direction (looking down from the top of the apparatus) and was never reversed during any of the runs.

4. Discussion and conclusions

The main conclusions of the experiments are as follows:

(1) No weight modification or gravity-like force has been detected to the 0.001% level. The experiments were run using sintered YBCO bi-layer disks with triple grain size and the maximum disk rotation was no greater than 550 r.p.m. Therefore, improvements to the experimental apparatus should be made so higher rotation speeds (1000–2000 r.p.m.) and both clockwise and counterclockwise directions can be tested (although as presented in [4] the gravity-like force was evident regardless of rotation direction).

(2) The method of detection of "Josephson junctions" internal to the superconducting disks needs to be clarified because the initial tests performed did not conclusively detect their existence.

(3) The ability to achieve true AC Meissner levitation at 100 kHz was not successful because of the large size and weight of the disks used in the experiments. Apparently, the magnetic field intensity of the solenoid assembly proved to be too weak. Therefore, either greater power levels are required (greater than 1 kW), or the coil design needs to be optimized.

Several questions and recommendations result from this investigation. What is the importance of attaining complete AC Meissner levitation of the disk? Should more flux be trapped during cooldown before rotation commences? Is the magnitude of trapped magnetic flux internal to the disk proportional to the intensity of the "gravity-like" force generated? Although the 3-phase RF field direction was reversed during certain test runs of the experiment, the rotational direction of the superconducting disk was not reversed. Therefore, a test should be done to investigate the importance of the RF field direction with respect to the disk rotation direction. Higher levitation powers at lower frequencies should also be examined.

These initial tests have, thus far, proved inconclusive as to the actual existence of the

Podkletnov "effect" which may still be indeed present at greater energy levels and higher disk rotation speeds than used herein. However, given that the sensitivity of the weight detection described herein was 50 times better than that that available to Podkletnov [1,2], one would have expected to see a definite weight change.

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