

**Undergraduate Research Grant for the SPS Chapter at the Northern Virginia
Community College, Annandale, VA 22003.**

**Final Report for the project “Experiments in Electrodynamical Levitation and Toroidal
Dipole Moment”**

SPS Chapter at the Northern Virginia Community College in Annandale, VA was created in the Fall of 1990, 23 years ago. Its permanent advisor is Dr Walerian Majewski, who in 2001 was granted a title of an Outstanding SPS Chapter Advisor. Our chapter at least 6 times was named as an Outstanding SPS Chapter, and we have won 6 SPS Undergraduate Research Awards. In 2013 we won both SPS recognitions. Over years about 300 students were our members. Several of them are now PhD researchers in physics. Our current XXIIIrd President in 2013-2014 academic year is Ian Bean, our officers: Agustin Mierez, Brendon Knopes, and Douglas Zabransky.

Spring 2013 NVCC SPS Chapter



Fall 2013 NVCC SPS Chapter (diffracted)



Our grant was used to purchase Nd magnets, air-core inductors, motorized wheel, lab supplies, to cover the cost of printing posters and attending meetings.

Our research was presented at the following venues:

1. Three posters were presented by nine of our students at the Spring Meeting of the **American Physical Society**, March 2013, at the Baltimore Convention Center:

- Inductional Effects in a Halbach Magnet Motion Above Distributed Inductance
- Physical Models of a Toroidal Dipole
- Experiments on Inductive Magnetic Levitation with a Circular Halbach Array

2. On April 6, 2013, seven program participants attended a meeting of the **American Association of Physics Teachers**, Chesapeake Section (CSAAPT), at J. Sargeant Reynolds Community College in Richmond. They presented the above topics as oral presentations.

3. SPS Zone 4 (Mid-Atlantic) Meeting: Towson University, Towson, MD, April 26-27

Six SPS members traveled to Towson University and made three PowerPoint presentations plus displayed and discussed three posters related to those topics.

Spring 2013

- **Three posters presented at the Spring Meeting of the American Physical Society, March 2013, by NVCC SPS Chapter members:**



Austin Raymer, Chapter's Co-President, reports:

Our trip to Baltimore dramatically changed my ideas about physics. Before, I believed that physics was best done with nothing but a sheet of paper, a pencil, my professor's words, and a healthy imagination. What I saw, though, is that the field is more populated, more specialized, more dynamic, but, still, more collaborative than I had thought.

When our group first arrived at the conference, I was shocked to be around so many physicists. There were researchers gathered around every outlet in the convention center, grouped around the cell phone hot spots, and streaming in and out of the many lecture halls. Wherever there was space there were people, and all of them were talking physics. Every one of them was talking in their own excited but equally complex jargon. Somehow, though, there was networking going on. People were discussing experiments, exchanging business cards, and placing orders for equipment. We were just standing in line for registration, but scientific progress was happening all around us.

As time went on, though, people started to move on to the different sections. We got our first visitors then. The first of them were students. Some were curious about what their peers were working on, others; we found out, were just happy that there were projects they could understand. That was my first taste of sharing ideas with colleagues. Our conversations revolved around the basics of our project, what the theory really meant, what we were planning on doing with our research, and what articles we had read. A lot of the time they had things to teach us, new ways of looking at our experiment. Those were the best conversations that I had at the conference.

Around three PM our audience changed. Experts started visiting our posters. They immediately began testing us on how much we knew about our work. One professor who visited was familiar with our project and taught us quite a bit. However, some of our projects more interesting applications were new to him. It was a humbling, but encouraging, experience. After all, we were able to field questions from professional physicists.

As for the two Nobel Prize lectures we attended later, there isn't much I can say. The talks were over my head, but thorough. They discussed every aspect of their prize winning research so carefully that I left convinced that with enough hard work and just a little luck, any of us could end up on that stage too.

• **'Inductional Effects in a Halbach Magnet Motion above Distributed Inductance'**

Abstract: We experimented with attempts to levitate a linear (bar) Halbach array of five 1" Nd magnets above a linear inductive track. Next, in order to achieve a control over the relative velocity, we designed a different experiment. In it a large wheel with circumferentially positioned along its rim inducing coils rotates, while the magnet is suspended directly above the rim of the wheel on a force sensor. Faraday's Law with the Lenz's Rule is responsible for the lifting and drag forces on the magnet; the horizontal drag force is measured by another force sensor. Approximating the magnet's linear relative motion over inductors with a motion along a large circle, we may use formulas derived earlier in the literature for linear inductive levitation. We measured lift and drag forces as functions of relative velocity of the Halbach magnet and the inductive "track," in an approximate agreement with the existing theory. We then vary the inductance and shape of the inductive elements to find the most beneficial choice for the lift/drag ratio at the lowest relative speed.

Inductional Effects in a Halbach Magnet Motion with Respect To Distributed Inductance

Ian Bean, Daniel Morgan, Munira Sibai
Society of Physics Students, Northern Virginia Community College, Annandale, Virginia

Introduction

We experimented with attempts to levitate a linear (bar) Halbach array of five 1" Nd magnets moving on a linear inclined Al inductive track. Next, in order to achieve a control over the relative velocity, we designed a different experiment. In it a large wheel with circumferentially positioned along its rim inducing coils rotates, while the magnet is suspended directly above the rim of the wheel on a force sensor. Faraday's Law with the Lenz's Rule is responsible for the lifting and drag forces on the magnet; the horizontal drag force is measured by another force sensor. Approximating the magnet's linear relative motion over inductors with a motion along a large circle, we may use formulas derived earlier in the literature for the linear inductive levitation (Inductrac). We measured lift and drag forces as functions of relative velocity of the Halbach magnet and the inductive "track," in an approximate agreement with the existing theory.

Our Halbach

Basic Inductrac Equations

Induced voltage ϵ and current I in each coil of inductance L and resistance R from variable horizontal magnetic flux of amplitude Φ_0 in relative motion with velocity v :

$$\epsilon = L \frac{dI}{dt} + RI = \omega \Phi_0 \cos \omega t$$

$$F_{lift}/F_{drag} = \omega(L/R)$$

for large ω
 $\omega = (2\pi v)/\lambda$, λ is the space period of the magnet

Our experiments

- Constructed linear Halbach magnet and measured its magnetic field
- Conducted acceleration experiments with linear Halbach array on an incline
- Used aluminum track
- Used motion sensors to measure velocity and acceleration

Results from our first experiments

Magnetic field on weak side

Magnetic field on strong side

Results from our first experiments

Magnetic field on weak side

Magnetic field on strong side

Theory

Space period of Halbach $\lambda = 0.10m$

$$\frac{F_{lift}}{F_{drag}} = \frac{(2\pi v)^2 L}{\lambda R} = \left(\frac{2\pi v}{0.10m} \right) \left(\frac{5mH}{2.32\Omega} \right) = 0.135v \left(v \text{ in } \frac{m}{s} \right)$$

Results

Drag vs. Velocity

$y = -0.1273x^2 + 0.0386x + 0.0346$

Lift vs. Velocity

$y = 0.0028x^2 + 0.2358x - 0.1655$

Ratio of Lift/ Drag vs. Velocity

$y = 0.0158x^2 + 0.1006x - 0.0295$

Dependence of the average drag force on relative velocity between 87 and 210 rpm

Dependence of the average lift force on relative velocity between 87 and 210 rpm

Ratio of Drag/Lift vs. Velocity

$y = 0.5191x^2 - 4.0623x + 9.6442$

Acceleration of Halbach cart on inclined Al track vs. distance

Velocity vs. Angle, θ

Force vs. Time at 1.16 m/s

Apparent Weight vs Time at 1.16 m/s (weight=12.8 N)

Force vs Time at 3.64 m/s

Apparent Weight vs time at 3.64 m/s (weight=12.8 N)

Conclusion
 We experimented with a linear Halbach magnet, moving linearly or in a circle with respect to a distributed inductance. General character of repulsive/drag forces agrees with the theory. In the future experiments we need to have more tightly spaced inductors, to produce larger and less oscillating lift force, and use higher rotational velocities. An interesting option is to build a large circular Halbach with strong field on the rim, rotating on a horizontal axis above or below a linear inductive path. Or to build a large wheel with inductance distributed on the rim, rotating below a suspended linear Halbach as shown in Figure 18.

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- K. Halbach, Journal of Applied Physics, vol. 67, 109 'Applications of Permanent Magnets in Accelerators and Electron Storage Rings', 1985.
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- J.Bird, T.A. Lipo, University of Wisconsin-Madison, College of Engineering, Wisconsin Power Electronics Research Center, research report 2005-30 "An Electrodynmic Wheel with a Split-Guideway Capable of Simultaneously Creating Suspension, Thrust and Guidance Forces", 2005.

Acknowledgments

We would like to thank Drs. Catalina Cetina, Valerian Majewski and Marcel Nadezdingam for their guidance and mentorship throughout this project. For building Halbach magnet case for this experiment, and the Sigma Pi Sigma society for their generous monetary support.

Supported by a Sigma-Pi-Sigma Undergraduate Research Grant from the Society of Physics Students, and by a grant from the NVCC Educational Foundation

Basic Inductrac Equations

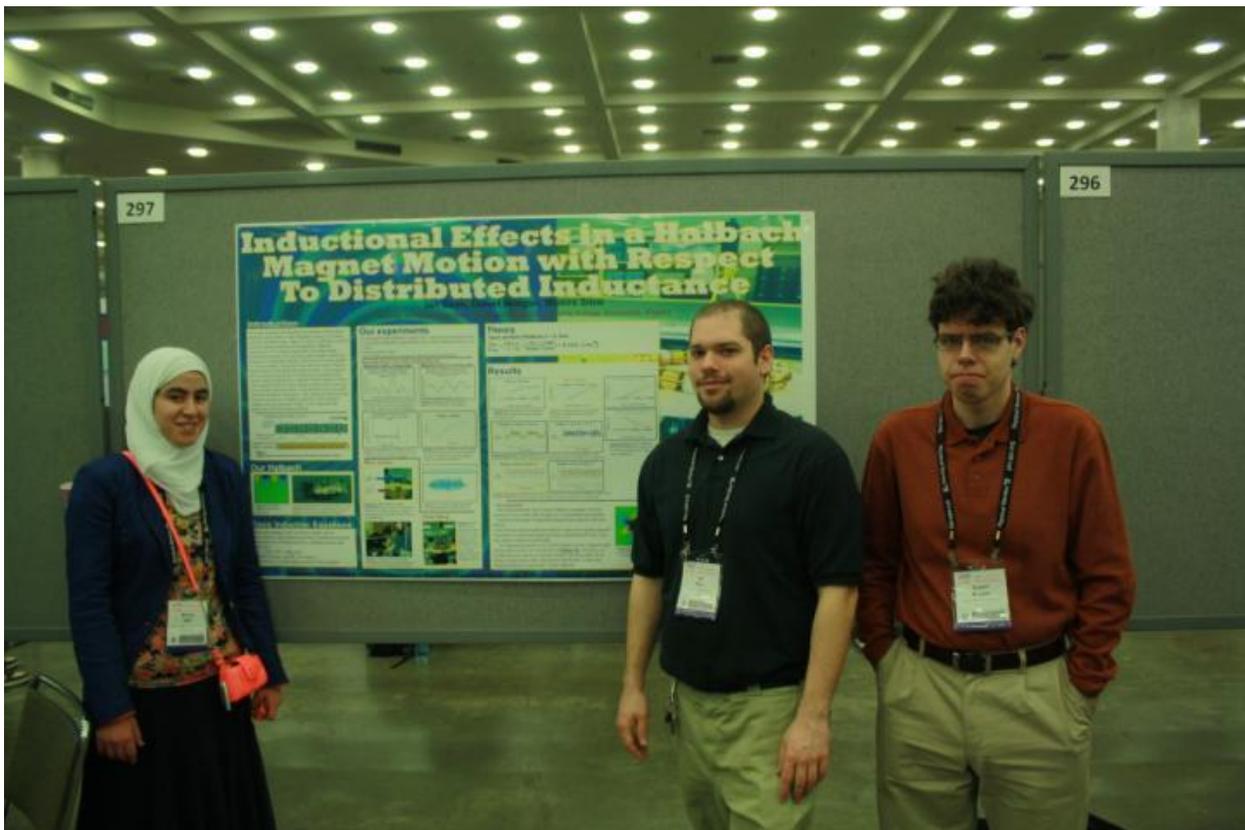
- Induced voltage \mathcal{E} and current I in each coil of inductance L and resistance R from variable horizontal magnetic flux of amplitude Φ_0 in relative motion with velocity v :

$$\mathcal{E} = L \frac{dI}{dt} + RI = \omega \Phi_0 \cos \omega t$$

- $F(\text{lift})/F(\text{drag}) = \omega(L/R)$, for large ω

$\omega = (2\pi/\lambda)v$, λ is the space period of the magnet

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Munira Sibai, Ian Bean and Daniel Morgan display and explain their poster

- 'Physical Models of a Toroidal Dipole'

Abstract: We are investigating two models of the third (after well-known electric and magnetic dipoles) elementary dipole - the toroidal dipole. Its electric model is a toroidal coil connected to a DC or AC voltage, its magnetic version is a circumferentially magnetized ring of neodymium, at rest or rotating. DC electric and magnetic toroids produce only inner magnetic field, and interact directly with a curl of the external magnetic field, that is - with a conductive current density or with a displacement current. Toroidal dipole moment was measured in interaction with the external current and compared with a calculated theoretical value. Rotating magnetic toroid or the AC electric toroid should each act as an electric dipole antenna and produce electric dipole radiation. We are attempting to detect and measure their near-zone electromagnetic fields, as well as an integrated value of the external magnetic vector potential A .



Jason Specht, Austin Raymer and Ram Marimuthu

Ram Marimuthu, John Austin Raymer, Jason Specht
Society of Physics Students, Northern Virginia Community College
Annandale, Virginia 2013

Introduction

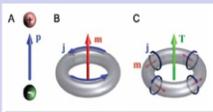


"Let there be a circular ring of uniform section, lagged uniformly with covered wire. It may be shown that if an electric current is passed through this wire, a magnet placed within the coil of wire will be strongly attracted, but no magnetic effect will be produced on any external point. The effect will be that of a magnet bent round till its two poles are in contact."

James Clerk Maxwell "On physical lines of force", 1861.

Our Experiment

The goal of our project is to study the unknown characteristics of magnetic toroids, magnet without magnetic poles. Magnetic toroid has never seemed interesting enough to be studied for its physical features in labs, and the reason for that has mainly been due to the fact that it has no magnetic field on the outside. It only has an internal, but very strong, magnetic field trapped inside of the toroid itself. It is found as a simple feature of the magnetic toroid such as its toroidal dipole moment and could successfully prove that the magnetic toroid interacts with the external currents that pass through it. There may be some useful applications of the magnetic toroid. It should be possible to build an antenna which can directly measure the current passing through a wire without even touching the wire. The magnetic field created by the flow of current in the wire interacts with our magnetic toroid, which would enable us to tell the current by measuring the torque on the toroid.



red line μ - magnetic, T - toroidal dipole moment, j - current density

Figure 1
Electric dipole moment



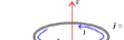
$$\vec{p} = q\vec{r}$$

Properties in the electric field:

$$\vec{E} = \vec{p} \times \vec{E}$$

$$U_{el} = -\vec{p} \cdot \vec{E}$$

Figure 2
Magnetic dipole moment



$$\vec{\mu} = \frac{1}{2} \int \vec{r} \times (\vec{J} dV)$$

Properties in the magnetic field:

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

$$U_m = -\vec{\mu} \cdot \vec{B}$$

In terms of magnetization \mathbf{M} :

$$\vec{\mu} = \int \mathbf{M} dV$$

Figure 3
Toroidal Dipole



Toroidal magnetic dipole moment

$$\vec{c}_m = \int \vec{r} \times (\vec{J} dV)$$

Properties in the magnetic field:

$$\vec{E} = \int \vec{c}_m \times (\vec{B} \times \vec{r})$$

$$U_m = \int \vec{c}_m \cdot (\vec{B} \times \vec{r})$$

$$\vec{B} \times \vec{r} = \mu_0 \vec{j} \times \mu_0 \vec{r} \frac{\partial E}{\partial t}$$

$$\vec{B} \times \vec{r} = \mu_0 \int \vec{c}_m \cdot \left[\vec{r} \times \left(\frac{\partial \vec{B}}{\partial t} \right) \right]$$

Toroidal magnetic dipole moment for a magnetized material

$$\vec{c}_m = \int \vec{r} \times (\vec{J} dV)$$

Theory

In torsional oscillations of a torus on a string, with current I passing through its hole, two torques are acting: mechanical and electromagnetism:
Mechanical torque due to string $\tau_{mechanical} = -k\theta$
Torque (small θ) due to toroid's interaction with current I :
 $\tau_{toroid} = -II \sin \theta$ $\tau_{toroid} = -II\theta$
Modified period for the empirical toroid constant t is:

$$T = 2\pi \sqrt{\frac{I}{II + k}} \quad t = \left(\frac{4\pi^2 I}{I} \right) \frac{1}{II + k}$$

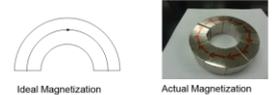
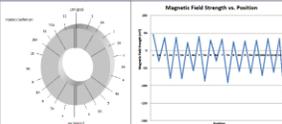


Figure 4

Materials

- Neodymium N48 grade 52 magnet composed of 12 segments, making a torus of inner diameter 1", outer diameter 2"
- 1.48 Tesla residual flux density B
- Magnetization $M=H_0 = 1.19 \times 10^6 \text{ A/m}$, uniform and perpendicular to radius within each segment
- Maximum external escaping magnetic field of 50 mT
- Moment of inertia about diameter $I = 1.21 \times 10^{-4} \text{ kgm}^2$
- Monofilament fishing line used to suspend the toroid

Magnetic Field Leakage



Method

Ideal experiment 1: immersing the toroid in an electrolyte with DC current density j to measure its torque on the toroid, and so the toroid moment.

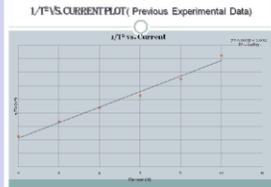
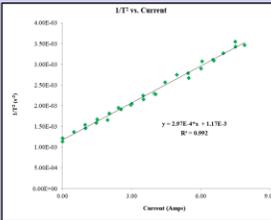
Ideal experiment 2: immersing the toroid in variable electric field E , and finding the torque.

Our method: passing a wire with variable DC current I through the toroid's hole, measuring period T of toroid's oscillations around the wire direction:

$$1/T^2 = (4\pi^2 II) + k/(4\pi^2 I)$$

Based on the above equation, the toroidal empirical constant t can be found.

Results



Analysis

Constant t is related to toroidal dipole moment c_m
 $c_m = (A/\mu_0)j$, with $A=(1 \text{ in})^2$ toroid's area = $7.85 \times 10^{-3} \text{ m}^2$
Slope of the graph = $2.97 \times 10^{-11} / \text{A}^2$
Experimental $t = (4\pi^2 I) (\text{slope}) = 1.18 \times 10^{-4} \text{ Nm/A}$
Max. torque achieved $1.18 \times 10^{-4} \text{ Nm}$
Toroidal moment $c_m = 7.38 \times 10^{-3} \text{ Nm}^2/\text{T}$ (or Am^3)
Approx. theor. value $c_m = MAa$, with $a = \text{cross-area of toroid's donut} = \text{disagrees with our result}$.
Independent earlier series of measurements-very close:
 $c_{m1} = 3.11 \times 10^{-3} \text{ Nm}^2/\text{A}$ $c_{m2} = 4.52 \times 10^{-3} \text{ Nm}^2/\text{A}$

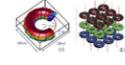
Other Experiments

We unsuccessfully tried to measure torque on the toroid from a sudden drop of the electric field in the capacitor, resulting in a short impulse of the displacement current.
We also experimented with a wired toroid.

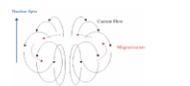


Applications of toroidal dipole moments in science and engineering

Artificially engineered medium - toroidal metamaterial:



Nuclear Physics: The electric chiral current created by weak interactions between nucleons produces nuclear toroidal dipole (tensor) moment of the atomic nucleus.



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Acknowledgements

We would like to thank the Society of Physics Students for their continued funding and our SPS advisor, Dr. Walerian Majewski, for his guidance and support. Without them our research would not have been possible. We thank the physics and engineering faculty at Northern Virginia Community College, with special thanks to Dr. Catalina Calina, who mentored us throughout this project. We appreciate the financial support from the NVCC Educational Foundation.

• 'Experiments on Inductive Magnetic Levitation with a Circular Halbach Array'

Abstract: Using a ring Halbach array, we are investigating a repulsive levitating force and a drag force acting on the magnet from a ring of inductors rotating below the magnet. After measuring induced currents, voltages and magnetic fields in the individual inductors (in the form of short solenoids), we investigated the dependence of lift/drag forces on the speed of relative rotation. The ratio of lift to drag increases with the angular velocity, as expected from a related theory of the induction effects in a linear motion. We are experimenting with the shape and density of inductors, and their material, in an attempt to maximize the lift at a minimal velocity of rotation. Eventually this design could have applications as frictionless bearings or as frictionless gear in a wide range of systems, especially in machinery that cannot be easily accessed.

EXPERIMENTS ON INDUCTIVE MAGNETIC LEVITATION WITH CIRCULAR HALBACH ARRAY



Society of Physics Students
Northern Virginia Community College, Annandale, VA: Doug Goncz, Amandeep Ratte, Jorge Zalles

Abstract

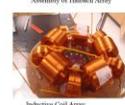
In a model Inductrack using a rotating paraxial-field Halbach array, we are investigating the repulsive axial levitating forces and associated circumferential drag forces acting on an assembly of coils suspended by strings above the array.

After measuring induced currents, voltages, and magnetic fields in the individual inductors, which are in the form of short solenoids, we examined the dependence of lift and drag forces on the speed of relative rotation. We are experimenting with the shape and density of the air core inductors, and with their nonmagnetic conductive winding material to maximize lift. We have achieved a maximum lift of some 20% of the inductor assembly's weight. We continue to measure, plot, and fit curves, and to fabricate various inductive loads for our strong (1.0 Tesla) magnet assembly. Eventually this design could have applications as frictionless bearings or as frictionless gear in a wide range of systems, especially in machinery that cannot be easily accessed.



Materials

The circular Halbach array was constructed using twelve 0.6 Tesla Nd magnets. Ten of these magnets were inserted by hand into a circular ring of aluminum and secured into place using screws around the outer ring. The final two were positioned using a half-ton press. The magnets were specifically arranged in order to concentrate the field on one side. The coil array is five 18-gauge 1.25 inch and five 1 inch coils each an inch long, with inductances of 4 mH and 3 mH, having rated resistances of 1 ohm and 0.75 ohms, respectively, equally spaced around a spacer made from 1/4 inch nominal PVC pipe, over a 6 inch disk of 1/8 inch Masonite type hardboard. Their mutual inductance has not been estimated. They become warm in operation. A rotator with an RPM reading was used to create a relative angular velocity and force was measured using Dual-Range Force sensors by Vernier.



Induction in Relative Motion-Faraday's Law:

$$\frac{dBA}{dt} = \frac{AdB}{dt} = \frac{AdB}{ds} \frac{ds}{dt} = vA \frac{dB}{ds}$$

v = relative speed of the coil and magnet
 A = area of coil
 B = field of magnet
 BA = Flux

$$\epsilon = \frac{LdI}{dt} + RI = \omega\phi_0 \cdot \cos(\omega t)$$

Induced Voltage in each coil of resistance R and inductance L from variable horizontal magnetic flux ϕ_0 in relative motion with velocity, v

$$\omega = \left(\frac{2\pi}{\lambda}\right)v_{\text{magnet}}$$

where λ is the space period of the magnets

$$v = \Omega r$$

$$\omega = \left(\frac{2\pi}{\lambda}\right)v = \left(\frac{2\pi}{\lambda}\right)\Omega r$$

Forces in the interval 2.5 through 25 radians per second were measured (up to 2500 rpm, after which the rotator destabilized). This corresponds to a speed between 0.25 and 2.5 m/s for the magnets.

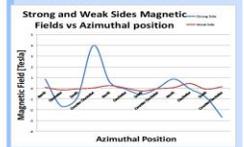
$$\frac{F_y}{F_x} = \frac{2\pi v L}{\lambda R}$$

The equation describing the lift to drag ratio in the Poise-Bryan paper.

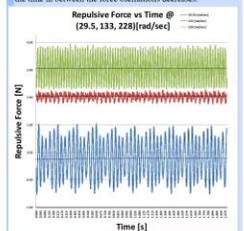


Results

After repositioning the Nd magnets to a circular Halbach array, the magnetic field of the strong side was measured. This new field was stronger than the field of the individual magnets.

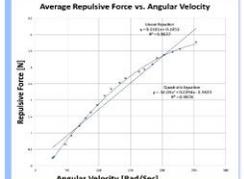


The weak side has a magnetic field about 10 times weaker, varying slightly around the bottom of the magnet. Due to the varying strength of the magnetic field on the strong side, and the relative motion, it was observed that the repulsive force fluctuates as a function of time. Furthermore, as the angular velocity increases, the time in between the force oscillations decreases.

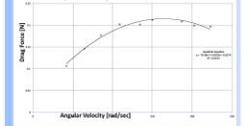


The distance between the inductors and Halbach array influences the magnitudes of the lift and drag force. If the magnitude of the drag force is large enough, the rotator motor becomes overloaded and shuts off.

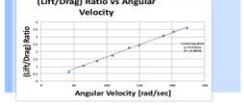
The average repulsive force on the inductor array at different angular velocities was determined and plotted.



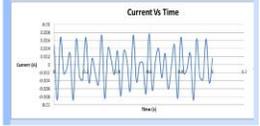
The torque produced by the inductor array was measured simultaneously with the lift force. The drag force was extracted from the torque data and is plotted.



The data indicates that the drag force decreases as lift increases. The lift to drag ratio increases with the velocity and is plotted below. This approximately confirms the results following from the results for linear inductive magnetic levitation: predicted Lift/ Drag = 0.0123 (1 - angular velocity), experimental value below: 0.016.



The current running through one of the coils in the array was recorded at several rotational velocities. Interestingly, the current does not fluctuate in a sinusoidal fashion, implying that the magnets flux passing through the coils does not vary in a sinusoidal fashion either. Below is a graph of current fluctuation in the duration of one second.



Conclusion

In agreement with the linear Inductrack Formulas as applied to a circular Halbach magnet rotating below the inductor ring, we are able to confirm the increase of the lifting force and of the lift/drag ratio, and decrease of the drag force and of the force oscillations, with increasing speeds of rotation up to 2500 rpm.

Acknowledgements

Supported by a Sigma-Pi-Sigma Undergraduate Research Grant from the Society of Physics Students and by a grant from the NVCC Educational Foundation. Special thanks to Dr. Walerian Majewski for mentorship and Professor Robert Woodke for building the magnet case.

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Amandeep Ratte, Ricardo Jorge Zalles and Doug Goncz are experts at levitating with circular Halbach magnets

- On April 6, 2013, seven NVCC SPS physics students attended a meeting of the American Association of Physics Teachers, Chesapeake Section (CSAAPT), at J. Sargeant Reynolds Community College in Richmond. We made three oral presentations of our projects.



Austin Raymer and Jason Specht described their calculations and “Experiments With Magnetic Toroid – a Magnet Without Poles.”



Jorge Zalles and Doug Goncz presented their paper “Experiments on Inductive Magnetic Levitation With Circular Halbach Array.”



Ian Bean and Daniel Morgan talked about “Inductional Effects in a Halbach Magnet Motion with Respect to Distributed Inductance.”

Our general impressions: “We were the only three relevant research groups of students presenting with real data and real analysis. I think it gave us a sense of the importance of the work we are doing and the importance of having a research program at NVCC.... The NVCC definitely had a very strong presence during the conference; our topics captivated the attention of the professors. It was interesting to be spoken to as a graduate student and be expected to think on that same level.... I now see the importance of everything we learn in the classroom as students but also that there is so much more beyond just the classroom. The Northern Virginia Community College definitely had a very strong presence during the conference; our topics captivated the attention of the professors mainly because of our work, but as well as we were the product of one of the strongest topics on the day "Undergraduate Research".

Austin Raymer, Chapter’s Co-President: “The CSAAPT conference was fantastic. Although my project didn’t receive any questions, the audience was engaging. Every time I looked out at the crowd of 40 professors I found the CSAAPT members staring intently at the equation or diagram that I was explaining. I came away feeling as though our talk could use some serious improvement, but that it had potential to be a pulling point in a conference. As an audience member I enjoyed the talks. For every professional field there seemed to be an undergraduate group doing equivalent work. Several professors were presenting on effectively teaching physics to students. These talks were encouraging. We knew that our teachers worked hard on our behalf, but it was awesome to see that they took part in conferences like these so that they could share their ideas and teach students the best they could. It was a great community to see and one that we all could see ourselves joining”.

Ian Bean, Chapter's Co-President: "One of the interesting talks was from Dr Shaheen Islam who went over the rewards and challenges of including undergraduate students in research. This stood out to me because the benefits and challenges closely resembled my experience thus far in SPS. Let it be said that the benefits far outweigh the challenges. There were many questions after our talk and quite a few listeners told Dan and I that we gave a good presentation. I even got a business card from a PhD who works to get more students involved in the S.T.E.M field who would like me to contact her about doing some work together. All said, it was a great experience and a great opportunity to get our personal work known as well as making a name for NVCC Annandale in the physics community. "

- **SPS Zone 4 Meeting: Towson University, Towson, MD, April 26-27**

Six SPS members traveled to Towson University and made three PowerPoint presentations plus displayed and discussed three posters related to those topics.



Here they are in our Physics Lab together with the Advisor Dr Walerian Majewski after the final review of the presentations

Dan Morton's impressions: We were well received at Towson, both our three talks and our three posters. All three teams sparked a strong interest from the people there about our topics, both during the talks and the poster session. Each of the teams was also able to answer any and all questions, and the talks went fairly smoothly. Most of the people in the audience were seniors about to graduate from Towson, with a few professors as well. Overall the experience was positive, and the presentations were exciting to the audience.

Spring SPS group has moved on to their transfer universities, and a different group of students, nominated by their physics instructors and enrolled at SPS, experimented on the following topics and prepared four research posters to be presented at conferences in the Spring 2014:

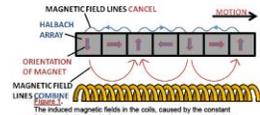
- Electrodynamic Wheel
- Levitation Effects in a Halbach Magnet Above Rotating Induction Wheel
- Measurements of the Lifetime of the Cosmic Ray Muons
- The Electromagnetic and Permanent-Magnet Toroids

Electrodynamic Wheel (An Outward Facing Circular Halbach)

Ian Bean, Juan Canedo, Vincent Cordrey, Ozan Duran, Anthony
Society of Physics Students, Northern Virginia Community College, Annandale, Virginia

Introduction

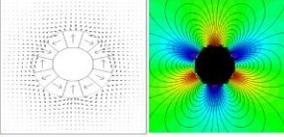
A Halbach Array is a specific arrangement of permanent magnetics that concentrates a strong magnetic field on one side of the array. Traditionally, experiments with Halbach Arrays have used linear designs. The concept is to produce a levitation force (note that a small drag force is also produced) through induction by passing the array over a series of shorted inductors, creating a separate magnetic field which repels the very one that induced it, creating a levitation force (pictured below).



MAGNETIC FIELD LINES CANCEL
HARBACH ARRAY
ORIENTATION OF MAGNET
MAGNETIC FIELD LINES CONCENTRATE
The induced magnetic fields in the coils, caused by the constant field supplied by the Halbach array, causes the magnet to levitate when passed over a series of coils.

Electrodynamic Wheel

With our experiment we have designed a circular Halbach Array with the strongest magnetic field facing outwards circumferentially (pictured below). We will to employ the drag force to produce propulsion while also producing the levitation force by rotating the array over a series of inductors. A design such as this may be more cost efficient than linear versions for producing lift and may at the same time provide a method of propulsion for the system.



Materials and Methods of Construction

Initially, we had planned to use a machine shop to make a wheel capable of holding all the magnets but it proved too expensive. Therefore, we had to come up with our own methods. The biggest hurdle to overcome in putting together any Halbach Array is overcoming the natural repulsion of the magnets and getting them to stay in formation once you do. Our design consists of getting the Halbach Array in position and fitting two circular plates on either side of the array with a plastic band (PVC pipe) around the outer edge to contain the magnets.

Step 1:
The first step in doing this without a machine shop is to get the magnets into position. For that, we needed an assembly jig which Juan designed and made for us. It consists of a wooden base with wooden wedges spaced apart to allow for insertion of magnets and is covered with an acrylic plate.

Step 2:
The second step is to get the first four magnets into the array. We used epoxy to help secure them to the wooden core and the other magnets after insertion. Each magnet is also secured by a wooden pile behind it that is screwed into the baseboard to prevent movement.

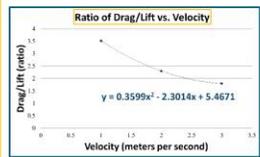
Step 3:
Now all the magnets can be inserted and secured (we found that inserting two at a time on either side of one of the four pictured above worked best. The last few magnets had to be pushed in with a crank which we bolted to the wooden base.

Step 4:
After all the magnets are in position, we secured the plates on either side with the jig still in position and put a hose clamp on the outer edge so that we could remove the array from the jig. After removal, we carefully remove what's left of the jig from in between the array and the aluminum plates.



Future Plans

Our first step will be to replicate the data shown by our other experiments in order to make sure that the equations (which we obtained from Lawrence Livermore's original experiments) we're using for our data are still accurate.

$$\frac{\text{Lift}}{\text{Drag}} = \frac{\omega L}{R}$$


Ratio of Drag/Lift vs. Velocity
Data from our previous experiments corroborates the ratio shown above.

Once we have assured that our system is computationally similar to previous designs, we will test several forms of aluminum tracks as inductors to produce levitation. We hypothesize that eddy currents induced the track could produce the lift and drag forces we are looking for. Through experimentation and analysis, we will determine whether or not aluminum tracks are viable for this system and if so, we will try etching circuits into the track to help improve lift and possibly provide guidance.

Acknowledgments

We would like to thank Dr. Walerian Majewski for his guidance, Dr. Woodie for machine shop assistance, and the Sigma Pi Sigma society for their generous monetary support.



Team 1 has constructed a circular Halbach array of 12 large neodymium magnets, and the biggest hurdle to overcome in putting together any Halbach Array is overcoming the natural repulsion of the magnets and getting them to stay in formation once you do. Our design consisted of getting the Halbach Array in position and fitting two circular plates (invisible here) on either side of the array with a plastic band (PVC pipe) around the

outer edge to contain the magnets. This system could have exploded any time into our very faces, so an extreme caution was necessary, and very slow progress from step to step.



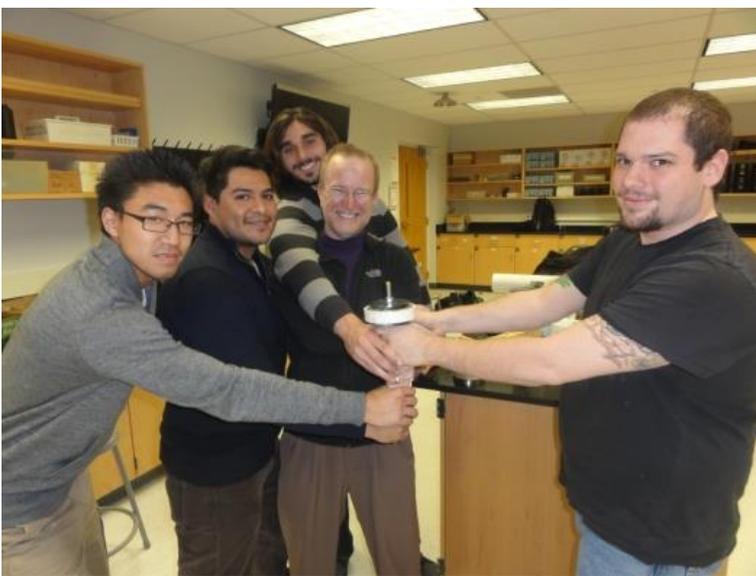
Ozan, Vincent and Jose are designing the contraption



Each magnet was pushed toward the center along a separate channel



All hands on deck! That is, 10 hands of Jose, Vincent, Ian, Ozan and Anthony.



Eureka! Team 1 had every reason to celebrate a victory!

Their Halbach magnet rotated above a conducting plate will serve as an Electromagnetic Wheel, and we will be measuring inductional levitation and propulsion forces exerted on it from the conductor as a function of the angular velocity.

Effects of Induction in a Halbach Magnet above Rotating Distributed Inductance

Douglas Zabransky, Phuong Le, Christopher Hill

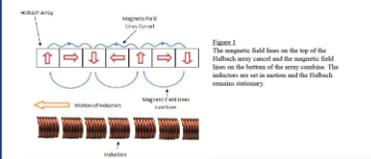
Society of Physics Students, Northern Virginia Community College, Annandale, Virginia

Abstract

This experiment was a verification and extension of the work done by previous SPS researchers regarding Induced Magnetic Levitation. Trials were initially run to repeat and verify previous experiments. Based on previous experiments, we expected that as angular velocity increased, lift force and drag force would increase. Data collected from these new trials agreed with previously collected data, as the velocity of the inductors increases, the lift force and drag force both increase. This causes a slight levitation effect. As the trials have been completed, a new vertical induction wheel has been designed and will be the basis of future experiments.

Introduction

The purpose of this experiment was to confirm the results of experiments done by previous SPS researchers and researchers at the Livermore Laboratory regarding Induced Magnetic Levitation. In Induced Magnetic Levitation, a constant magnetic field causes an induced current in a group of inductors when either the inductors or the source of the magnetic field are put in motion. This produces an electromagnetic field that causes repulsion between the two components. In our experiment, the magnetic field is provided by a linear Halbach array and the induction is provided by a horizontal array of inductors. The Halbach array is designed such that the magnetic field lines cancel one another out above the array, but reinforce one another below the array.



Materials and Methods

Our experimental setup consists of a wheel of inductors and a linear Halbach array. The wheel of inductors is a wooden wheel of radius 16.55 cm. The induction comes from 25 solenoids that have been mounted to the wheel in a circular arrangement. Each of these solenoids is an air core copper solenoid with a radius of 2.40 cm, a length of 3.66 centimeters, and an inductance of 5.00 mH. The Linear Halbach array is composed of 5 magnets and has a length of 13.4 cm and a weight of 12.845 N.

The induction wheel was inserted into a rotator in order to create relative motion between the inductors and the Halbach array. The Halbach was suspended over the inductors and the points of suspension were connected to a force meter in order to measure the weight. The Halbach was also connected to a force meter that was parallel to itself, in order to measure the horizontal drag force experienced by the Halbach array. The rotator was then set to several different radial velocities and measurements of drag force and weight were taken at each value.

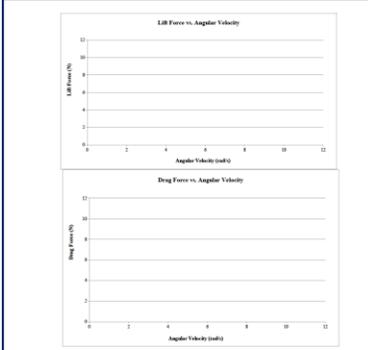


Figure 2: Linear Halbach array suspended over rotating induction wheel.



Figure 3: Linear Halbach array with magnetic orientation shown.

Results



The lift force vs. angular velocity graph shows that as angular velocity increases, the lift force increases.

The drag force vs. angular velocity graph shows that as angular velocity increases, drag force also increases.

Conclusion

Our data supports the findings of previous experiments. We were able to calculate the lift force by subtracting the apparent weight of the Halbach array as it was suspended over the rotating inductors from the weight of the Halbach array when the inductors were at rest. This difference shows that there is indeed an Induced Magnetic Levitation effect seen in the Halbach array.

The drag force also supported previous experiments, except for the final data point at 25.866 radians per second. At this point, the drag force was lower than it was for the previous recorded point at 17.802 radians per second. This should be investigated further, it could show a decrease in drag force at higher angular velocities, or it could be due to an external source of error.

Discussion

Further research will be conducted using a new experimental set up, consisting of a new wheel with smaller inductors adhered to the circumference of the wheel. This wheel will be rotated in a vertical orientation under the suspended Halbach array.



Figure 4: Construction of new induction wheel.

For further information

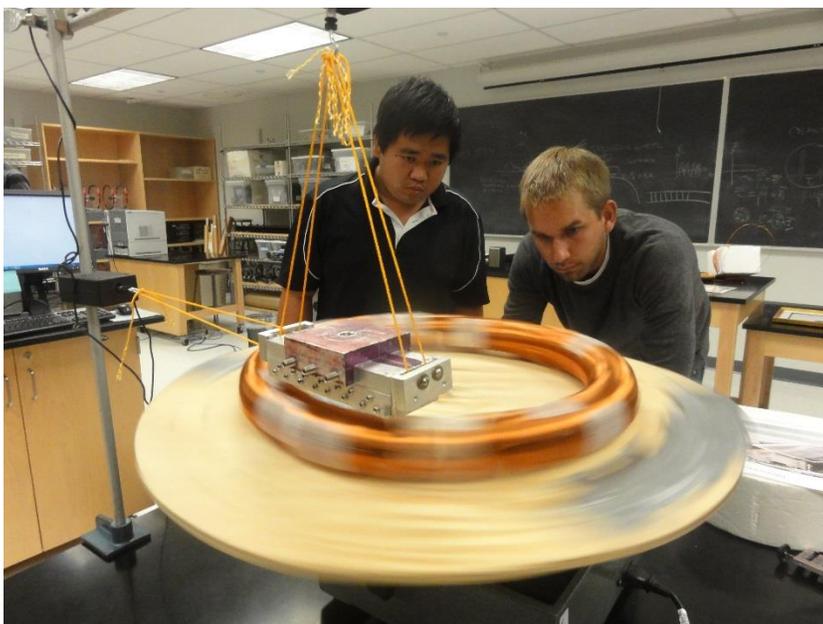
More information on this and related projects can be obtained by contacting w.majewski@nvcc.edu. Also, please refer to the Livermore report: "Inductrack Demonstration Model" by R.F. Post on February 3rd 1998.

Acknowledgments

We would like to thank Dr. Walerian Majewski for his guidance, and the Sigma Pi Sigma society, education foundation, and NVCC for their generous financial support.



Team 2 experimented with horizontally rotating ring of inductors, and measuring lift and drag forces it exerted on a linear Halbach magnet suspended above it. Because of the small number of inductors the forces were highly oscillating.





So Phuong, Chris and Dan have built a new induction wheel with 30 coils on its external rim, and will spin it in the vertical plane, again below a linear Halbach.

LIFE AS A MUON

Muon Decay Times

Brendon Knopes, Mohammed Jamal, Doug Goncz, Agustin Mierez

Introduction

What is a Muon?

Muons are a type of elementary particle with a negative charge. Like electrons, muons are leptons, meaning they have a spin of $\frac{1}{2}$ and unlike quarks, are not subject to the strong interaction. The most famous of leptons is the electron and muons are almost identical to electrons except that muons are far more massive.

What are we measuring?

This experiment is to measure the average lifetime of a muon. Since muons are constantly bombarding the surface of the Earth and since they are one of the longest-lived elementary particles, they are relatively easy to observe, not needing high energy particle accelerators to create.

Materials and methods

After a particle collides with another particle, it proceeds to the tracking system. The tracking system is in charge of determining the position of passing charged particles. In turn, once the particle's position is found, its path can be measured. A muon particle is measured by applying a curve along its trajectory. This curved trajectory strikes four muon stations which all sit outside the magnet coil. The muon detector traces the particle's position from its pathway through the four chambers. These measurements are the particle's momentum since particles that travel with more momentum bend less in a magnetic field. Charged particles momentum can be revealed from the curved trails they leave in a magnetic field. Calorimeters are utilized to measure the particle's energy.



The detector (above), and the power supply (below)



The connections from the detector to the power supply (above)



The set-up (above), adjusting the voltage (below)

Conclusions

Literature cited

J. Lukens, B. Reid, A. Tuggle 2010: Experiment in Muon Decay
 Taylor, Lucas 2011: Muon Detectors
<http://cms.usf.edu/cm/bruc/muon-detectors>

Theory

The production of muons happens right above our heads when cosmic rays collide with the molecules in the upper atmosphere. This produces many particles, some of which are pions that decay into muons. The muons shoot down and eventually decay as well.

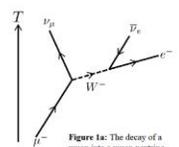
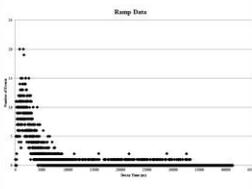


Figure 1a: The decay of a muon into a muon neutrino, an electron and an electron-antineutrino through a weak force interaction

Results

- As expected there are muons with some very short decay times and some very long ones as well
- The range from 1.5 μ s to 2.3 μ s seems to be where the majority of muons are located

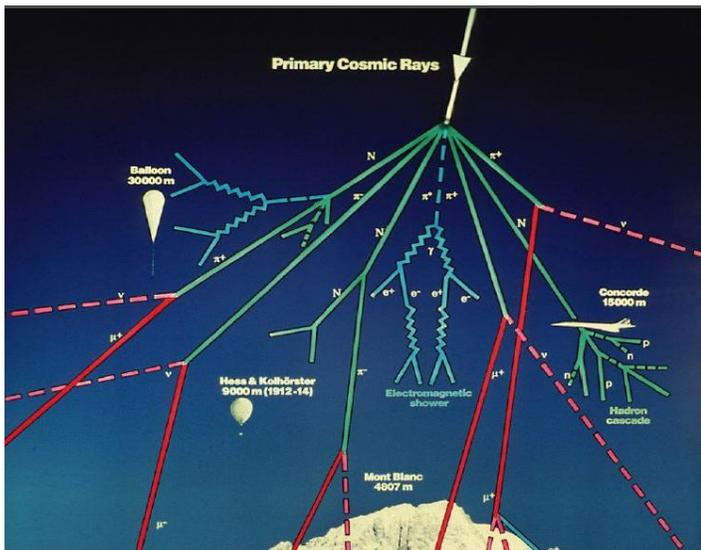
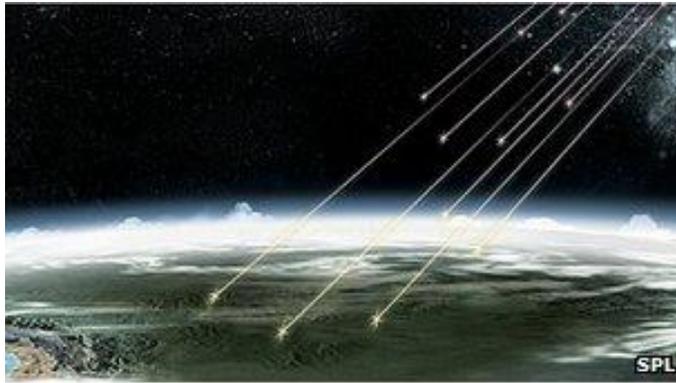


Ramp Data

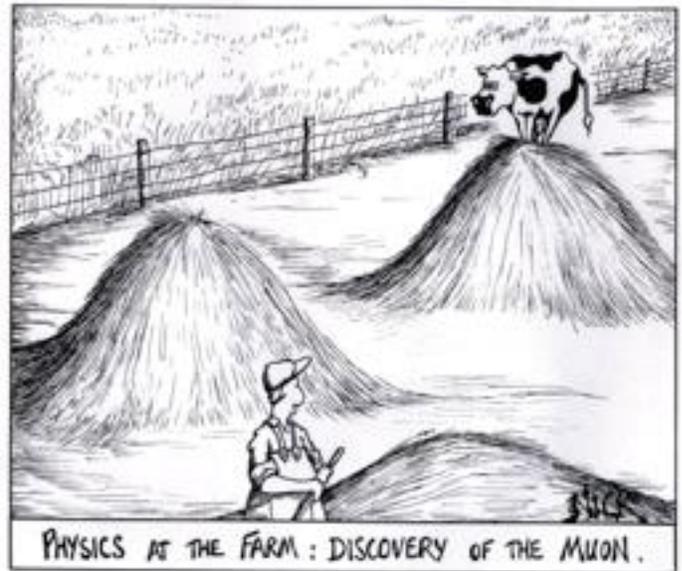
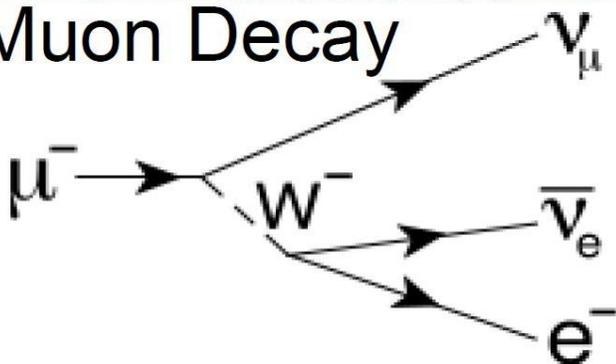
Acknowledgments

For further information

Team 3 started the measurements of the average lifetime of cosmic-ray muons, to compare it with the lifetime as predicted by the Standard Model of Particles. Muon is an unstable elementary particle, and its amazing decay involves creation of three more equally fundamental particles: electron, muonic neutrino and electronic antineutrino. In one single process we have here four of the total of 12 elementary particles described by the Standard Model of all visible matter in the Universe. Muons are coming from the upper atmosphere, where it is produced in collisions of high-energy protons with the nuclei, which thus serve as a “poor man’s accelerator”.

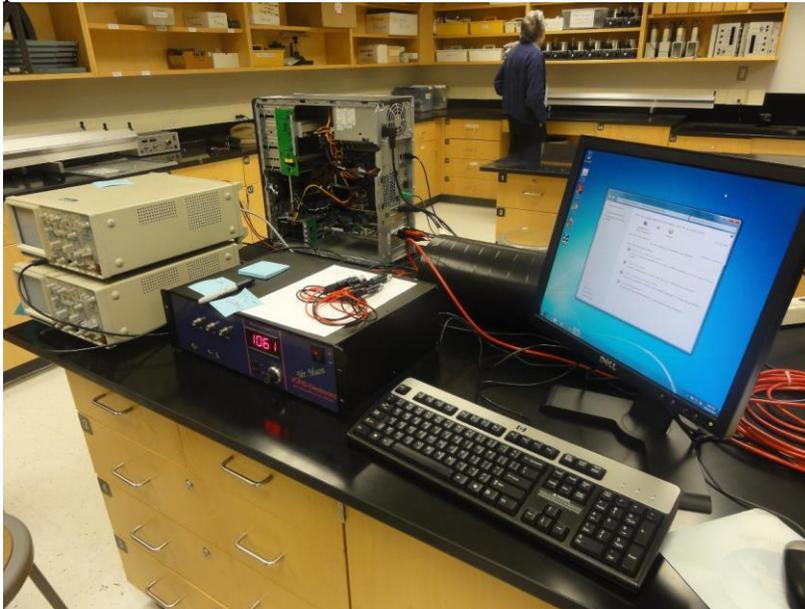


Muon Decay

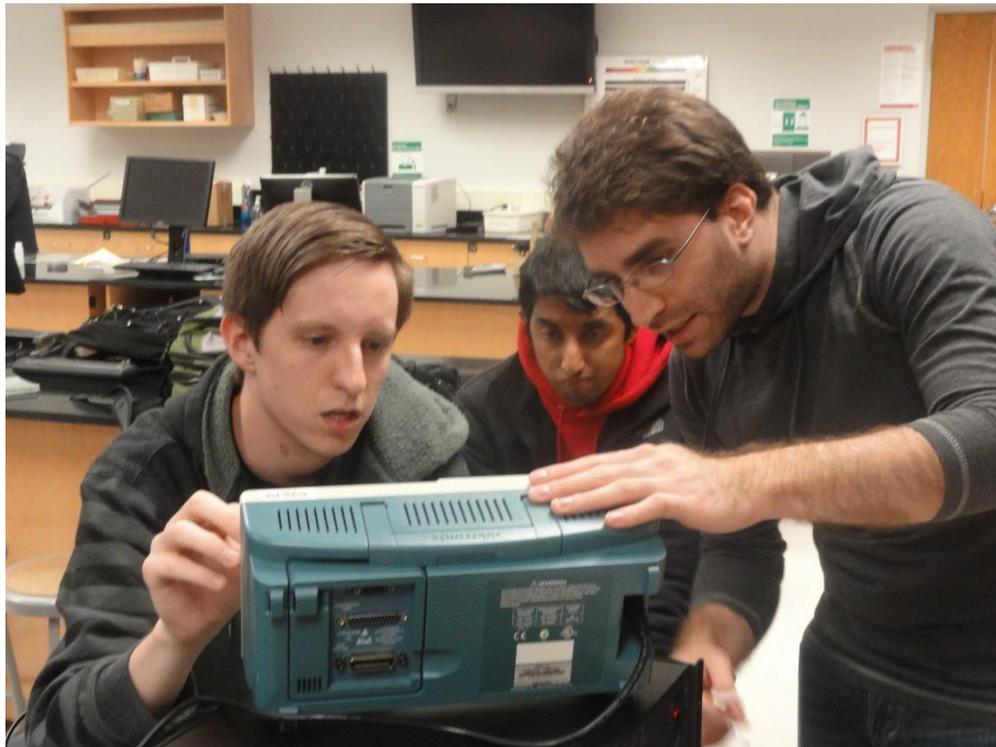


We recorded several thousand decays like: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ by registering in the scintillation detector an incoming muon and the outgoing electron, as well as a time delay between their

corresponding voltage pulses. Both neutrinos escape invisible. Our detector was built for us by the physicists from the Thomas Jefferson Electron Accelerator in Newport News, Virginia. We want to measure the muon lifetime and compare it with that calculated in the Standard Model to be $\tau = 192\pi^3 h^7 / G_F^2 m_\mu^5 c^4$ with the currently accepted value of $2.19703 \pm 0.00004 \mu\text{s}$. We will be also measuring muon flux and possibly its mass. At this point it is too early to formulate Conclusions on our poster...



Our set-up; black cylinder is our detector of muons and electrons moving at the speed of light



Counting muons by hand...almost

Introduction

"Let there be a circular ring of uniform section, lapped uniformly with covered wire. It may be shown that if an electric current is passed through this wire, a magnet placed within the coil of wire will be strongly affected, but no magnetic effect will be produced on any external point. The effect will be that of a magnet bent round till its two poles are in contact."



James Clerk Maxwell
"On physical lines of force", 1861.

Our Experiment

The goal of our project is to study the characteristics of the permanent-magnet and electromagnetic toroids. donut shaped objects with no magnetic poles. Ideal toroids have no magnetic field on the outside, but contain a very strong field on the inside. We tested the effects of a wire carrying current passing through the middle and the outside of the toroid. We also focused on the toroidal dipole moment and observed the interaction of the electromagnetic toroid with the external current passing through its center.

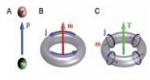


Figure 1. p-electric, m-magnetic, T-toroidal dipole moments, current density

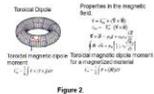


Figure 2

Theory

In toroidal oscillations of a bar suspended from a string, with a current i passing outside of the toroid, only mechanical torque due to the string should be acting on it.

$$\text{Mechanical torque due to string: } \tau_{\text{mechanical}} = -k\theta$$

Theoretically, there should be no interaction between the toroid and an external current (passing on the outside).

However, if a current is passed through the toroid's center, both mechanical and electromagnetic torques will act on it. Torque (small angles) due to interaction with current i :

$$\tau_{\text{toroid}} = -iI \sin \theta \quad \tau_{\text{toroid}} = -iI\theta$$

Modified period for the suspended toroid constant k is:

$$T = 2\pi \sqrt{\frac{I}{iI + k}} \quad i = \left(\frac{kI}{iI + k} \right)^{1/2}$$

Materials

- Neodymium N48 grade 52 magnet composed of 12 segments, inner diameter 1", outer diameter 2"
 - 1.48 Tesla residual flux density B_r
 - Magnetization M(B)_r = 1.18x10⁶ A/m, uniform and perpendicular to radius within each segment
 - Maximal external escaping magnetic field of 50 mT
 - Moment of inertia about diameter: I = 1.01x10⁻³ kg·m²
 - Electromagnetic toroid with 88 turns
 - Monofilament fishing line used to suspend the toroid
- Note: The escaping magnetic field of the electromagnetic toroid travels in the opposite direction of the field inside, whereas that of the permanent-magnet toroid travels in the same direction in the field inside of it.

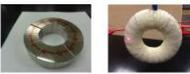


Figure 3. Permanent-Magnet Toroid Figure 4. Electromagnetic Toroid

Methods

Passed a wire outside the permanent-magnet and electromagnetic toroids, carrying a variable DC current, i . In the case of the electromagnetic toroid, the DC current of the toroid is also varied and the effects on the toroid's period are recorded. We used a laser pointer to aid us in measuring the period of oscillations. A magnetometer was also used in recording any flux in the external magnetic field. These measurements were then graphed and analyzed to check fit patterns and relationships between period of oscillation and current in the wire.

Results : Permanent-Magnet Toroid

Current-carrying wire outside of toroid's center:

Current (A)	(Frequency) ² * 10 ⁶
0.00	4.5532
0.99	4.5883
1.98	4.6032
2.99	4.6332
4.00	4.6332
5.00	4.5753
5.99	4.5249
7.00	4.4132
8.00	4.3774
8.99	4.2355

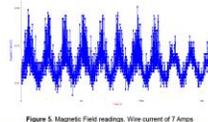
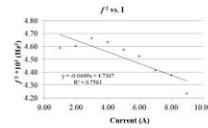


Figure 5. Magnetic Field readings. Wire current of 7 Amps

Results : Electromagnetic Toroid

Wire current of 4.99 A, with a varying toroidal current

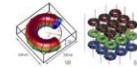
Toroid Current (A)	(Frequency) ² * 10 ⁶
0.00	0.6039
0.95	0.4031
1.99	0.7984
2.99	1.2022
3.99	Newly introduced

Other Attempts

We attempted more experiments with the electromagnetic toroid but were unable to gather enough data in the limited time. Also, we encountered more mechanical torque with the electromagnetic toroid than the permanent-magnet one due to the connecting lead wires used to send a current through it. This torque was so great that it would not allow any measurable oscillations for our electromagnetic toroid. Experiments with the current-carrying wire passing through the toroid were attempted but the angular displacement was too small to accurately measure.

Applications of Toroidal dipole moments

Artificially engineered medium - toroidal metamaterial

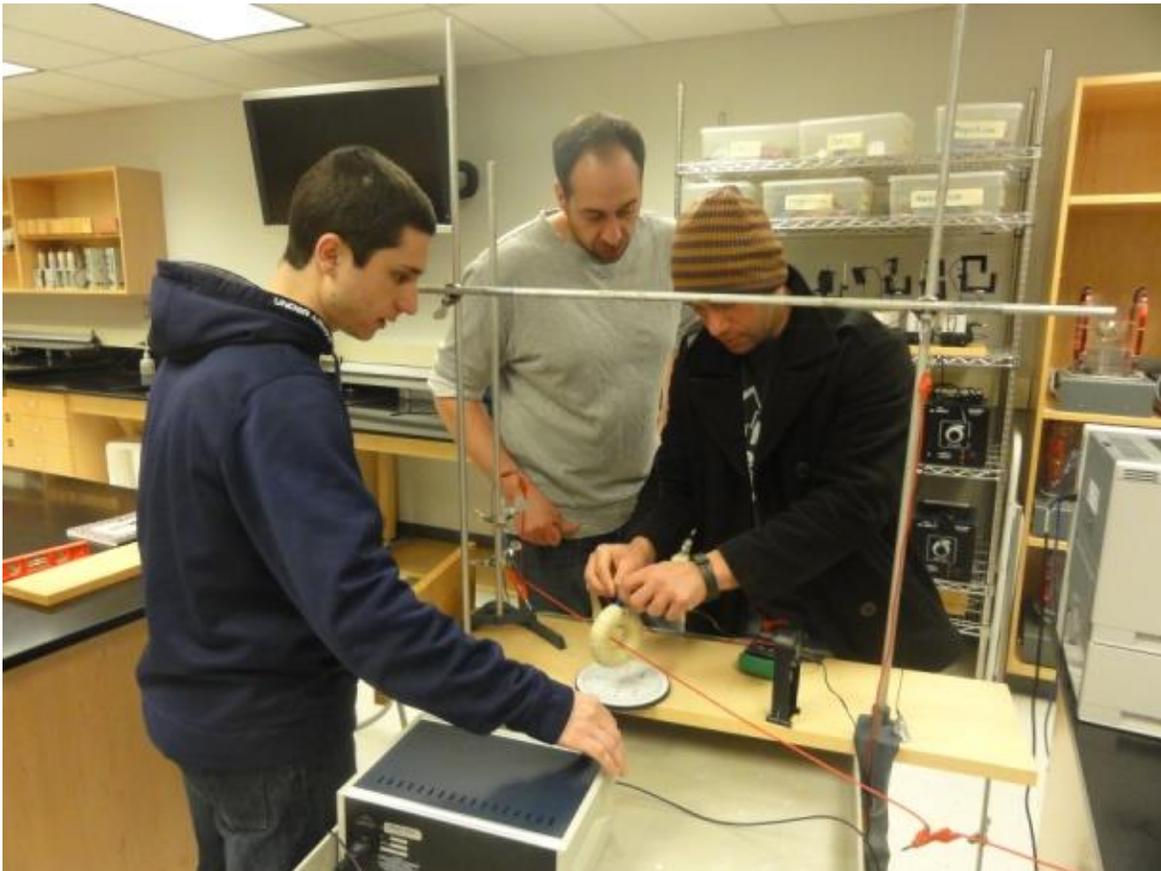


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3. C. S. Wood, S. C. Bennett, D. Chu, B. P. Masterson, J. L. Roberts, C. E. Tanner, C. E. Wieman, Science, Vol. 275 no. 5307 pp. 1770-1763, "Measurement of Parity Nonconservation and an Anapole Moment in Cesium", 1997.
4. Zhong-Guo Deng, J. Zhu, Junshu Bao, Jie-Qi Li, Changjun Lu, Xianbo Yin, and X. Zhang, Appl. Phys. Lett. 101, 144105 "Optical toroidal dipolar response by an asymmetric double-bar metamaterial", 2012.

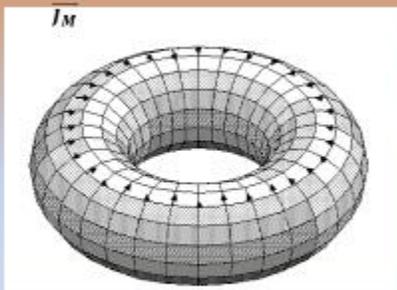
Acknowledgments

We would like to thank the Society of Physics Students for their continued funding and our SPS advisor, Dr. Waldemar Mazurkiewicz, for his guidance and support. Without their research would not have been possible. We also thank the physics and engineering faculty at Northern Virginia Community College. We appreciate the financial support from the NVCC Educational Foundation.

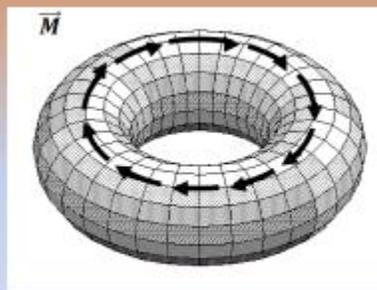


Team 4 has built an electric toroid and is comparing its properties with an equally exotic magnetic toroid. Toroidal currents represent the simplest of possible multipolar localized currents producing only localized, “contact”, finite-range magnetic field distributions, which as such are not included in the usual multipole expansions describing the field outside of the sources. We are measuring the toroidal dipole moments of our wire or magnet toroids from their interaction with the straight wire carrying an external current through the toroidal hole, to compare them with our calculated values. Toroidal dipole moments interact with the external current in the same way, in which magnetic dipole moments interact with external magnetic field – they feel a torque. We plan to rotate our toroids around their symmetry axis, hoping to observe theoretically predicted fascinating effect of the magnetic field (which is normally locked inside a toroid at rest) escaping outside of the rotating toroid. Toroids are important in creating new electromagnetic metamaterials.

Toroidal Dipole



Toroidal coil with current density (\vec{j})



Torus with azimuthal magnetization (\vec{M})

Toroidal Dipole Moment of a Current or of a Magnet

- Toroidal magnetic dipole moment of current density \vec{j} :

$$\vec{t}_m = \frac{1}{6} \int \vec{r} \times (\vec{r} \times \vec{j}) dV$$

- For a magnetized material:

$$\vec{t}_m = \frac{1}{2} \int \vec{r} \times (\vec{M}) dV$$

Toroidal Dipole

- Properties in the magnetic field:

$$\vec{\tau} = \vec{t}_m \times (\vec{\nabla} \times \vec{B}) \quad U_m = -\vec{t}_m \cdot (\vec{\nabla} \times \vec{B})$$

- Ampère-Maxwell Law:

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} \quad \oint \vec{B} \cdot d\vec{s} = \mu_0 \left[\vec{J} + \epsilon_0 \frac{d\Phi_E}{dt} \right]$$

Summa summarum:

Year 2013 was very successful for our SPS Chapter - supported by the SPS Undergraduate Research Grant, we experimented, learned a lot, traveled to conferences, and were recognized as an Outstanding SPS Chapter for the sixth time.