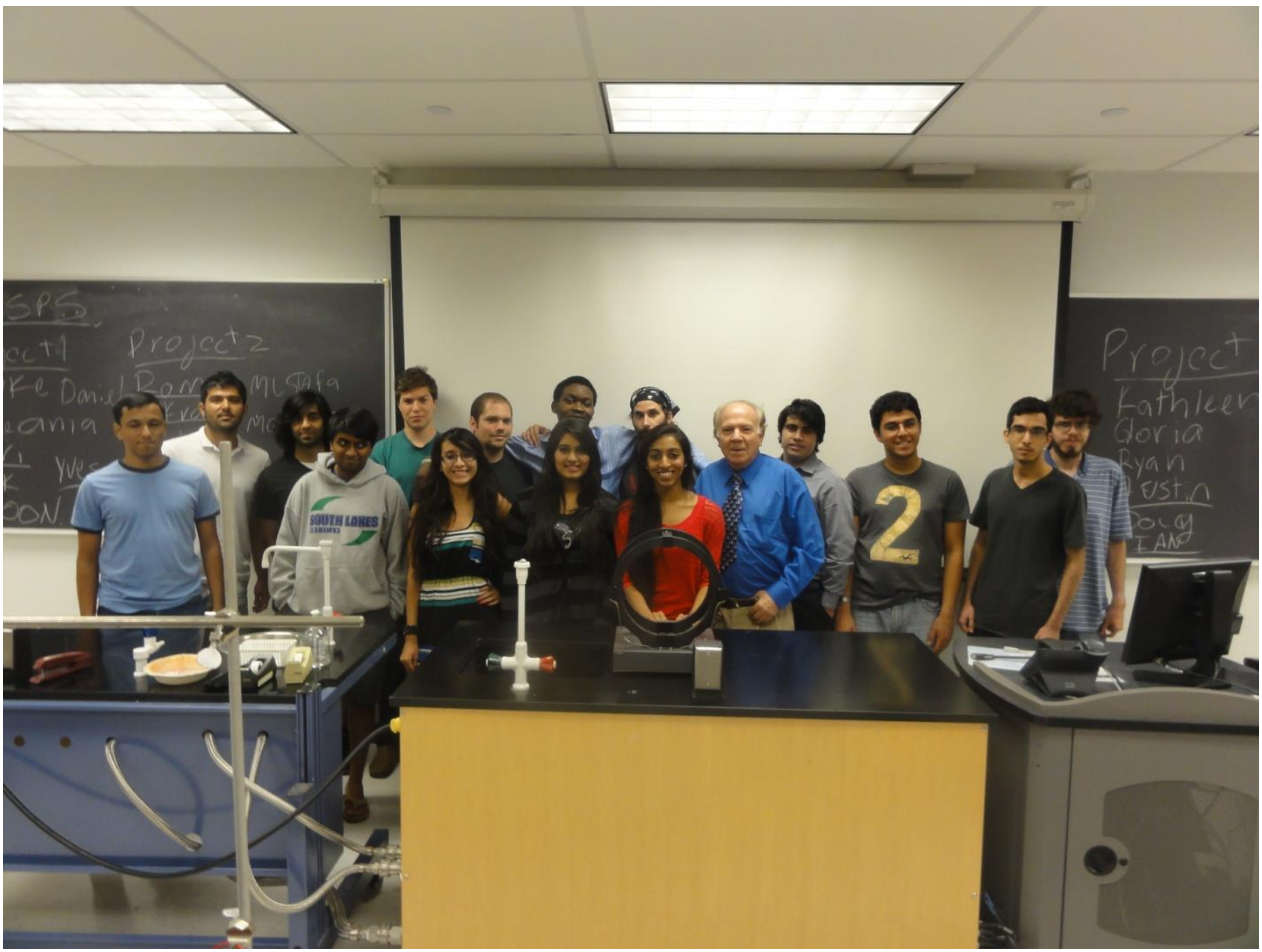
Undergraduate Research Grant for the SPS Chapter at the Northern Virginia Community College, Annandale, VA 22003.

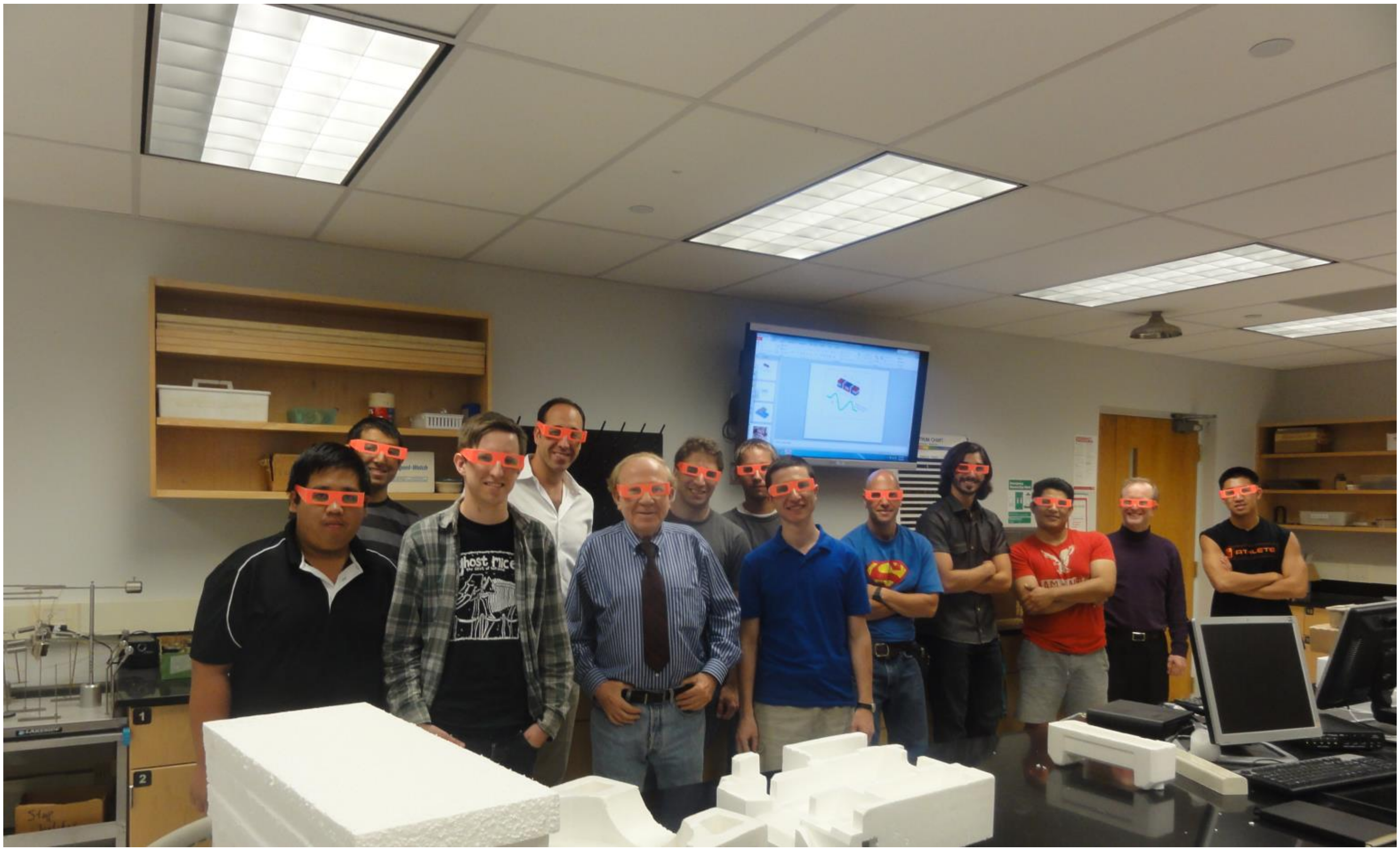
Final Report for the project "Experiments in Electrodynamic Levitation and Toroidal Dipole Moment"

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.

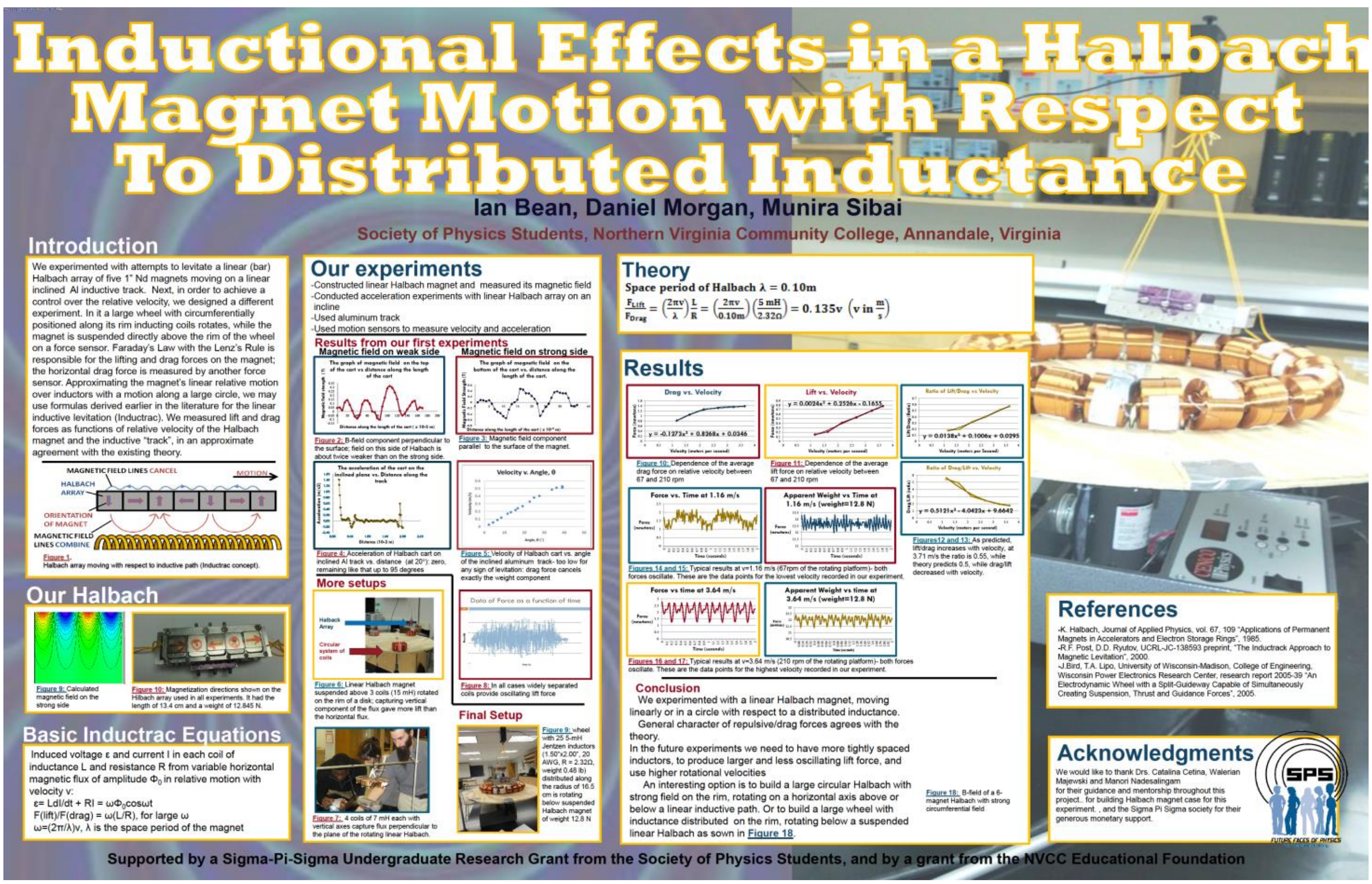
When our group first arrived at the conference, I was shocked to be around so many physicists. There were researchers gathered around every outlet in the convention center, grouped around the cell phone hot spots, and streaming in and out of the many lecture halls. Wherever there was space there were 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 inducting 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.



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:

$\varepsilon = L dI/dt + RI = \omega \Phi_0 \cos\omega t$

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

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

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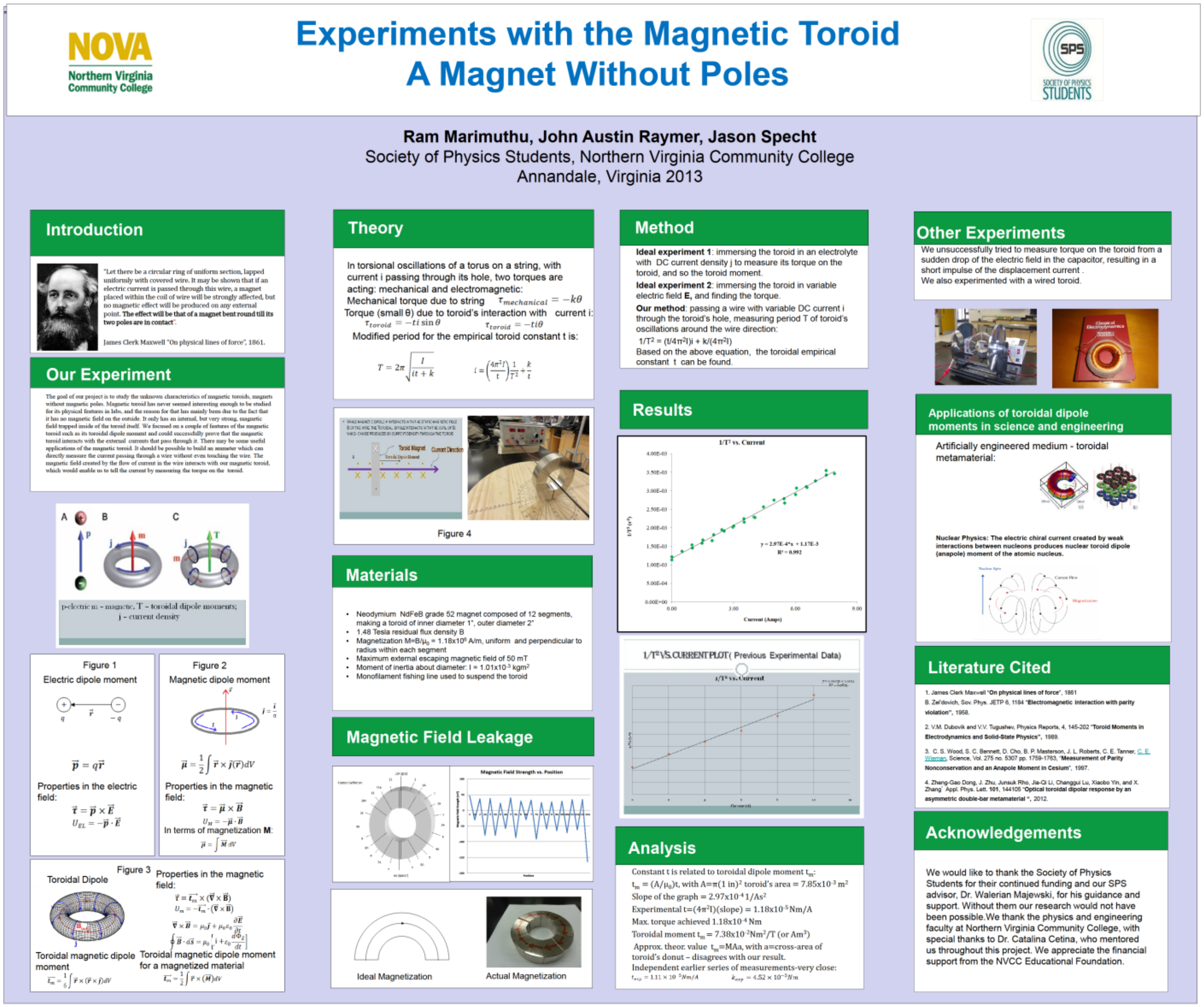
Munira Sibai, Ian Bean and Daniel Morgan display and explain their poster

- **'Physical Models of a Toroidal Dipole'**

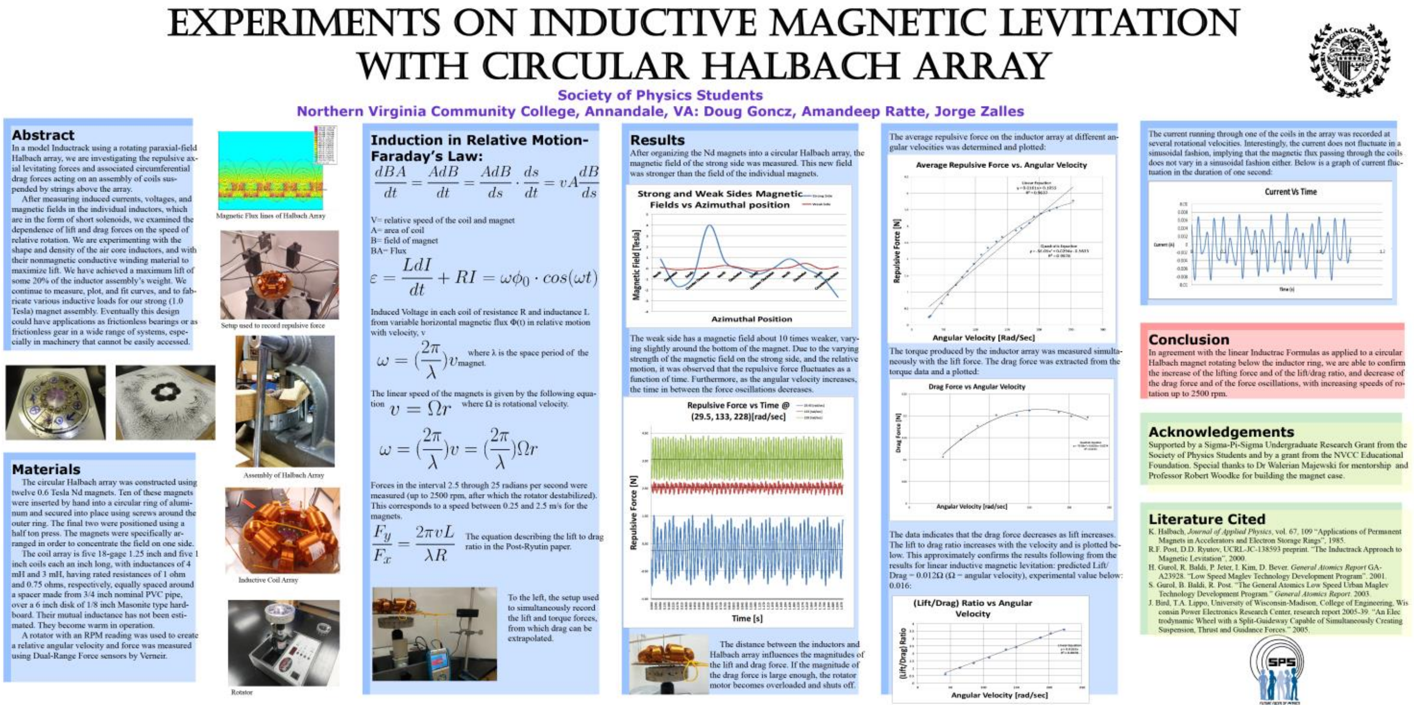
Abstract: We are investigating two models of the third (after well-known electric and magnetic dipoles) elementary dipole - the toroidal dipole. Its electric model is a toroidal coil connected to a DC or AC voltage, its magnetic version is a circumferentially magnetized ring of neodymium, at rest or 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



- **'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-gage 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 3/4 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 Verneir.

Magnetic Flux lines of Halbach Array

Setup used to record repulsive force

Assembly of Halbach Array

Inductive Coil Array

Rotator

Induction in Relative Motion-Faraday's Law:

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

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

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

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

$$\omega = (\frac{2\pi}{\lambda})v_{\text{magnet}}$$ where λ is the space period of the magnet.

The linear speed of the magnets is given by the following equation $v = \Omega r$ where Ω is rotational velocity.

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

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.

$$\frac{F_y}{F_x} = \frac{2\pi vL}{\lambda R}$$ The equation describing the lift to drag ratio in the Post-Ryutin paper.

To the left, the setup used to simultaneously record the lift and torque forces, from which drag can be extrapolated.

Results

After organizing the Nd magnets into 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 a 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 = 0.012Ω (Ω = 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 magnetic 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 Inductrac 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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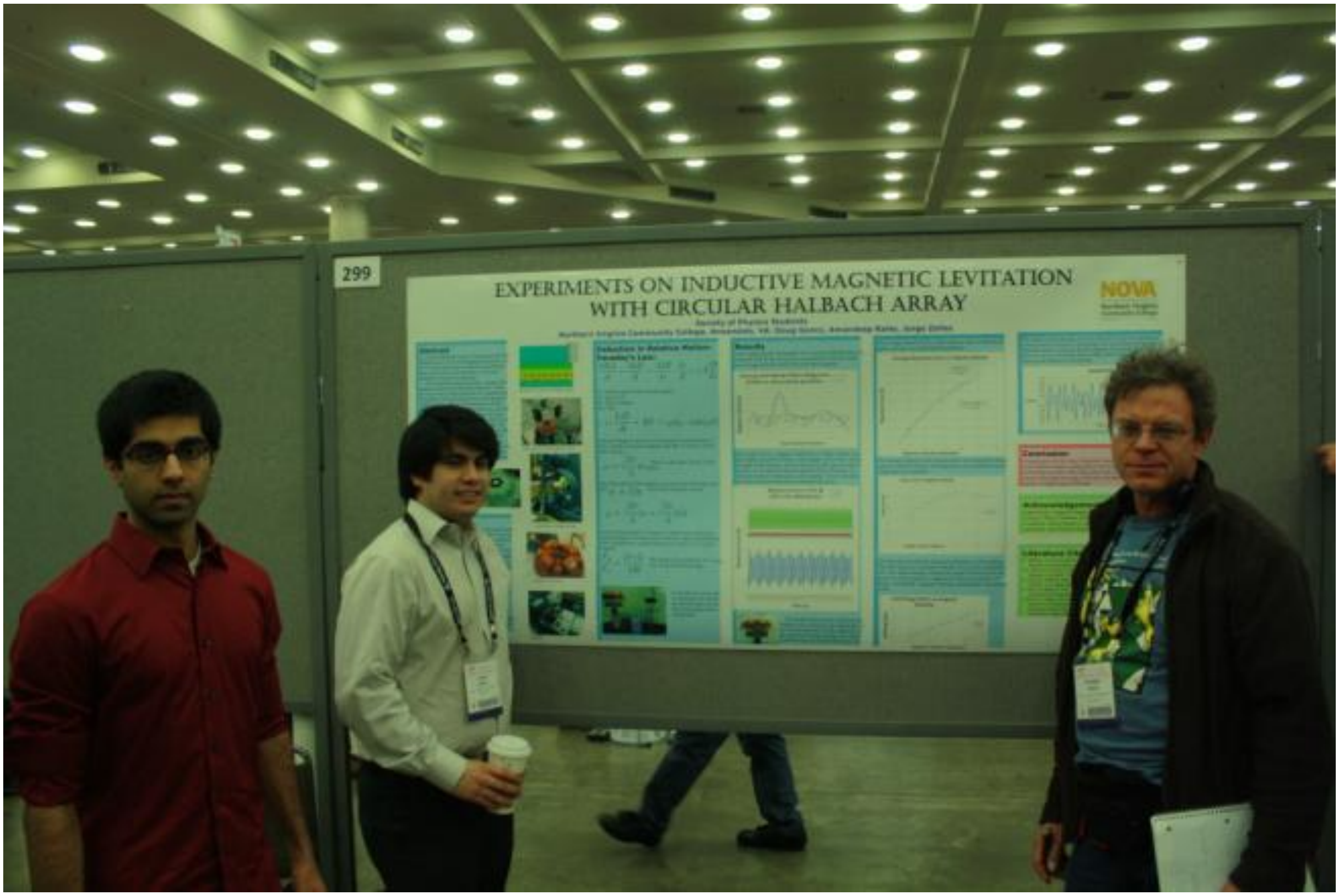
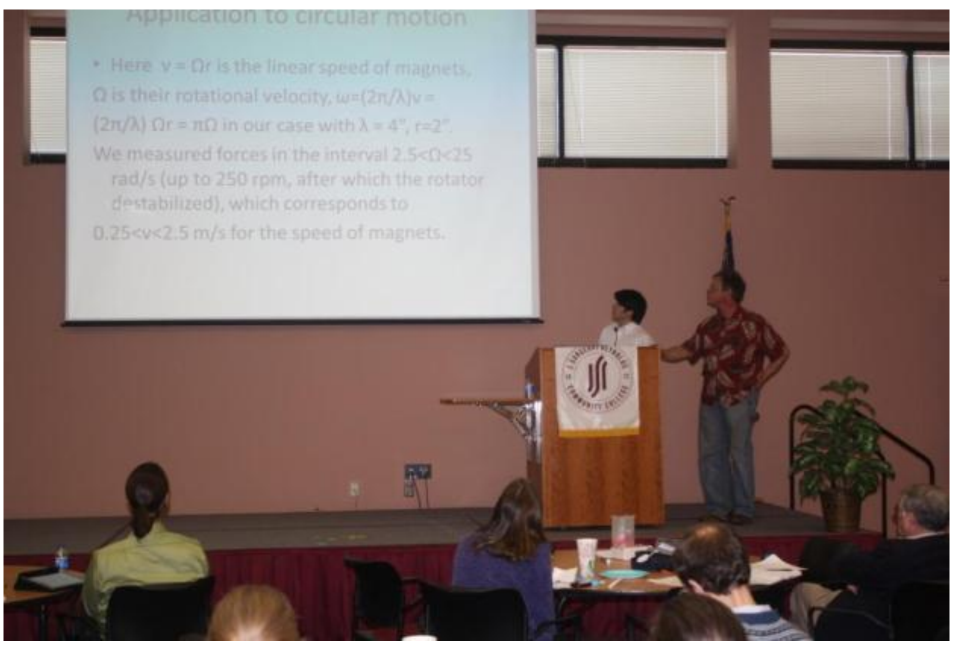


Amandeep Ratte, Ricardo Jorge Zalles and Doug Goncz are experts at levitating with circular Halbach magnets

- **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.”

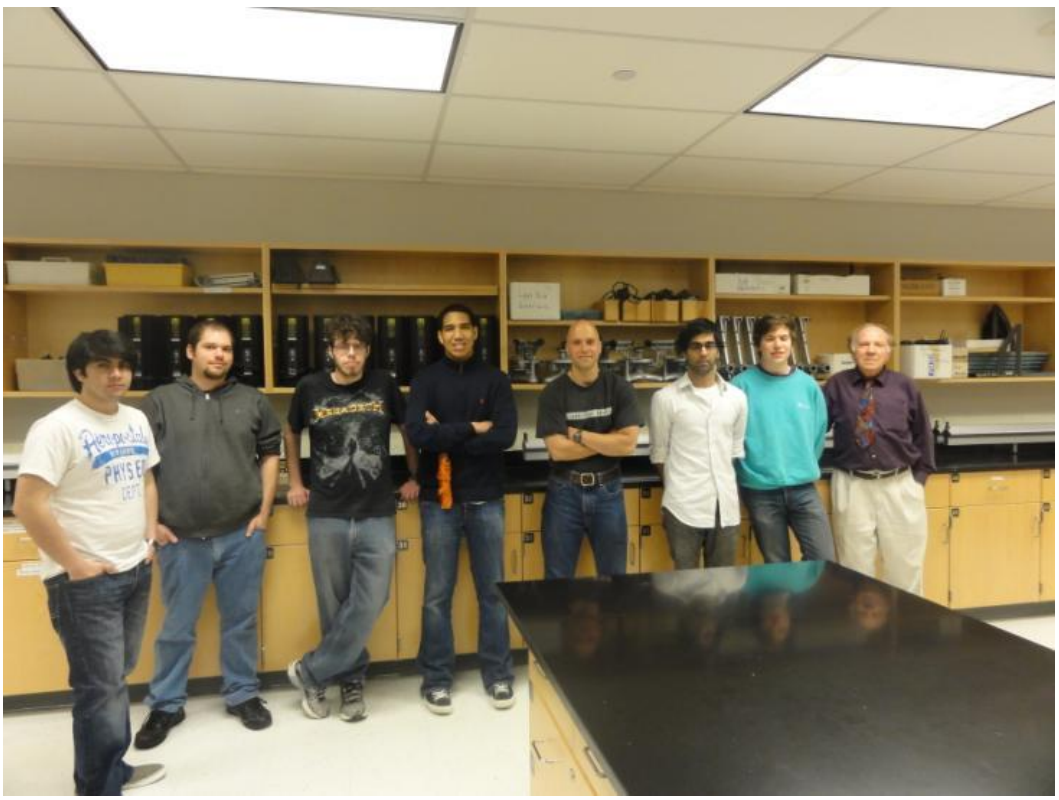
Our general impressions: “We were the only three relevant research groups of students presenting with real data and real analysis. I think it gave us a sense of the importance of the work we are doing and the importance of having a research program at NVCC…. The NVCC definitely had a very strong presence 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 out-weigh 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.

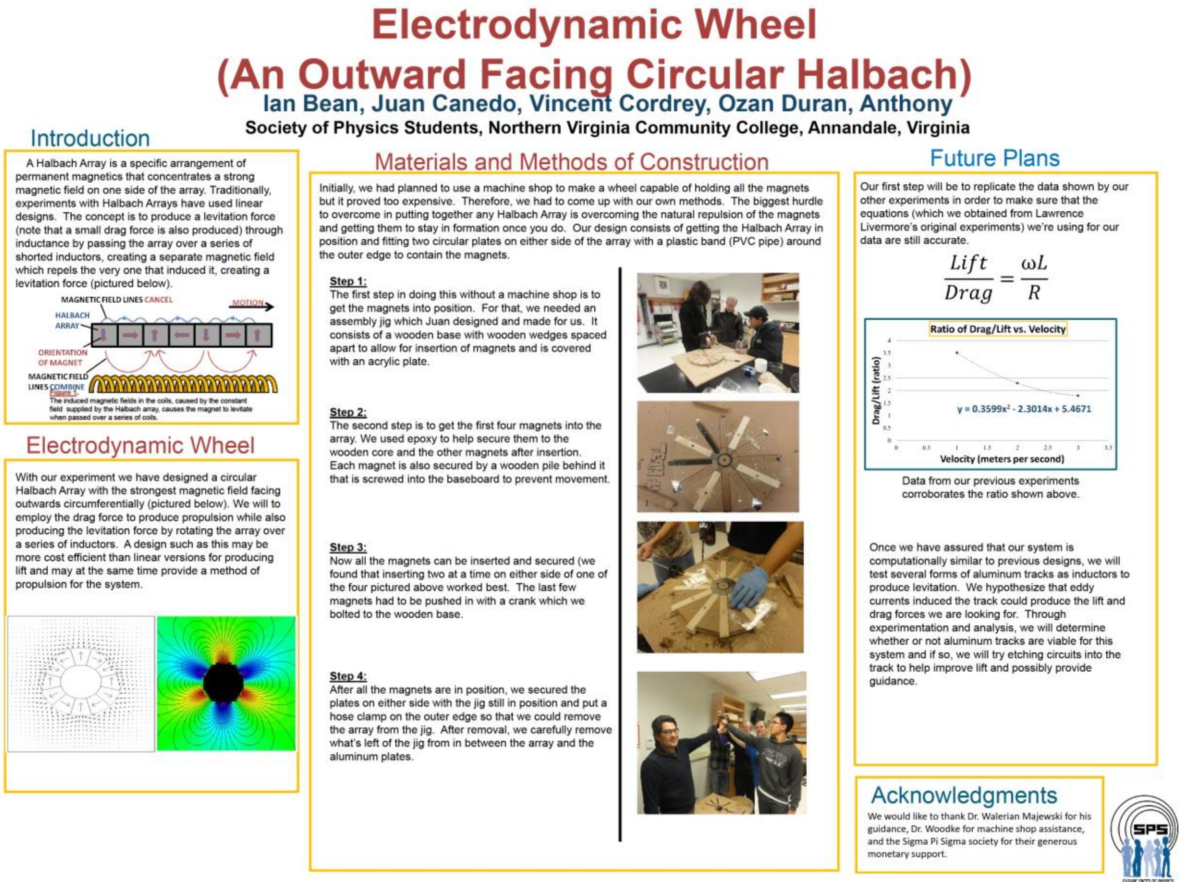


Here they are in our Physics Lab together with the Advisor Dr Walerian Majewski after the final review of the presentations

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

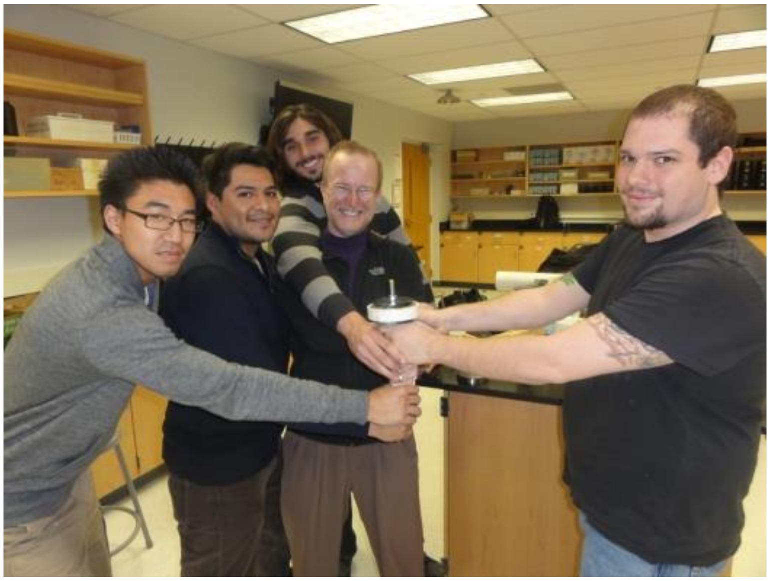


Team 1 has constructed a circular Halbach array of 12 large neodymium magnets, and the biggest hurdle to overcome in putting together any Halbach Array is overcoming the natural repulsion of the magnets and getting them to stay in formation once you do. Our design consisted of getting the Halbach Array 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

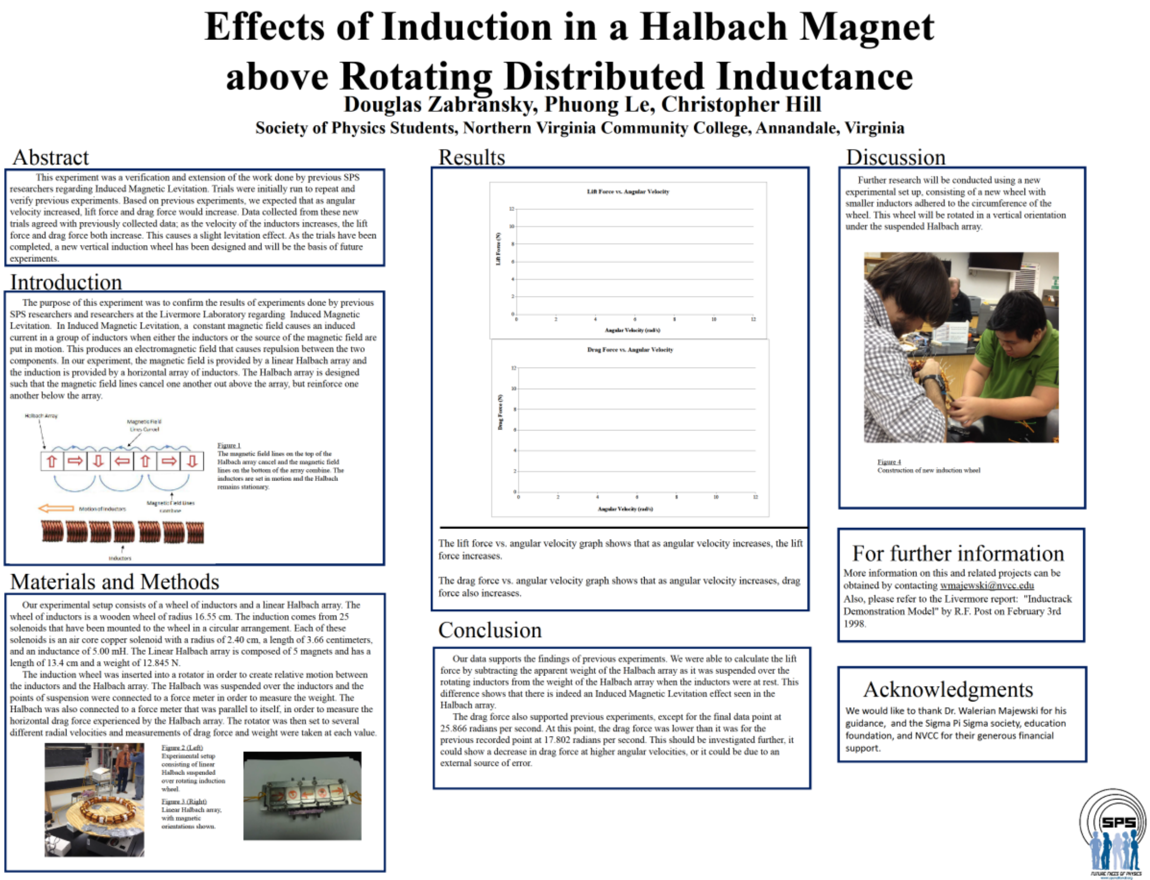
Each magnet was pushed toward the center along a separate channel

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

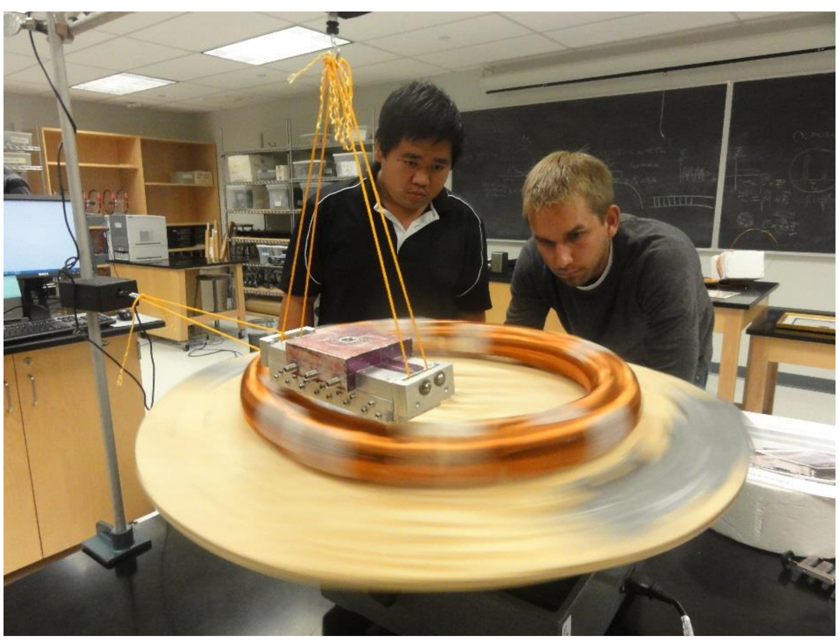


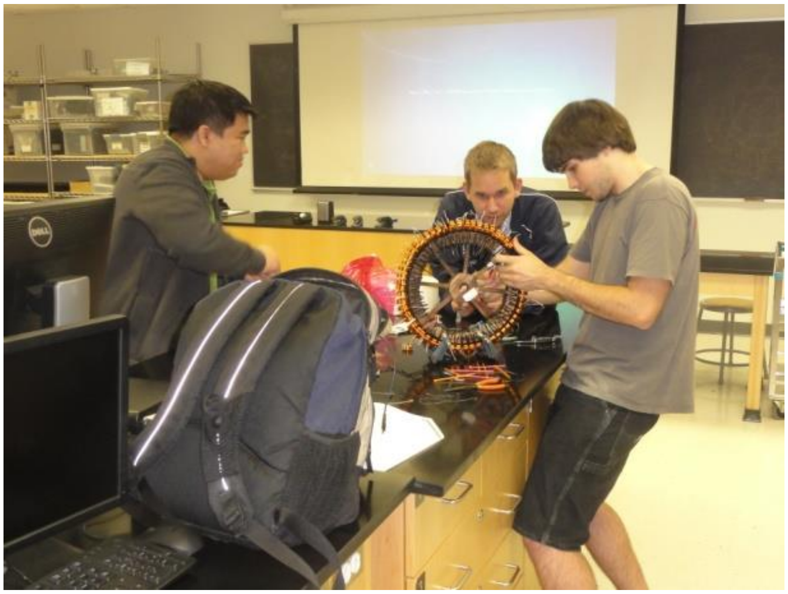
Eureka! Team 1 had every reason to celebrate a victory!

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.



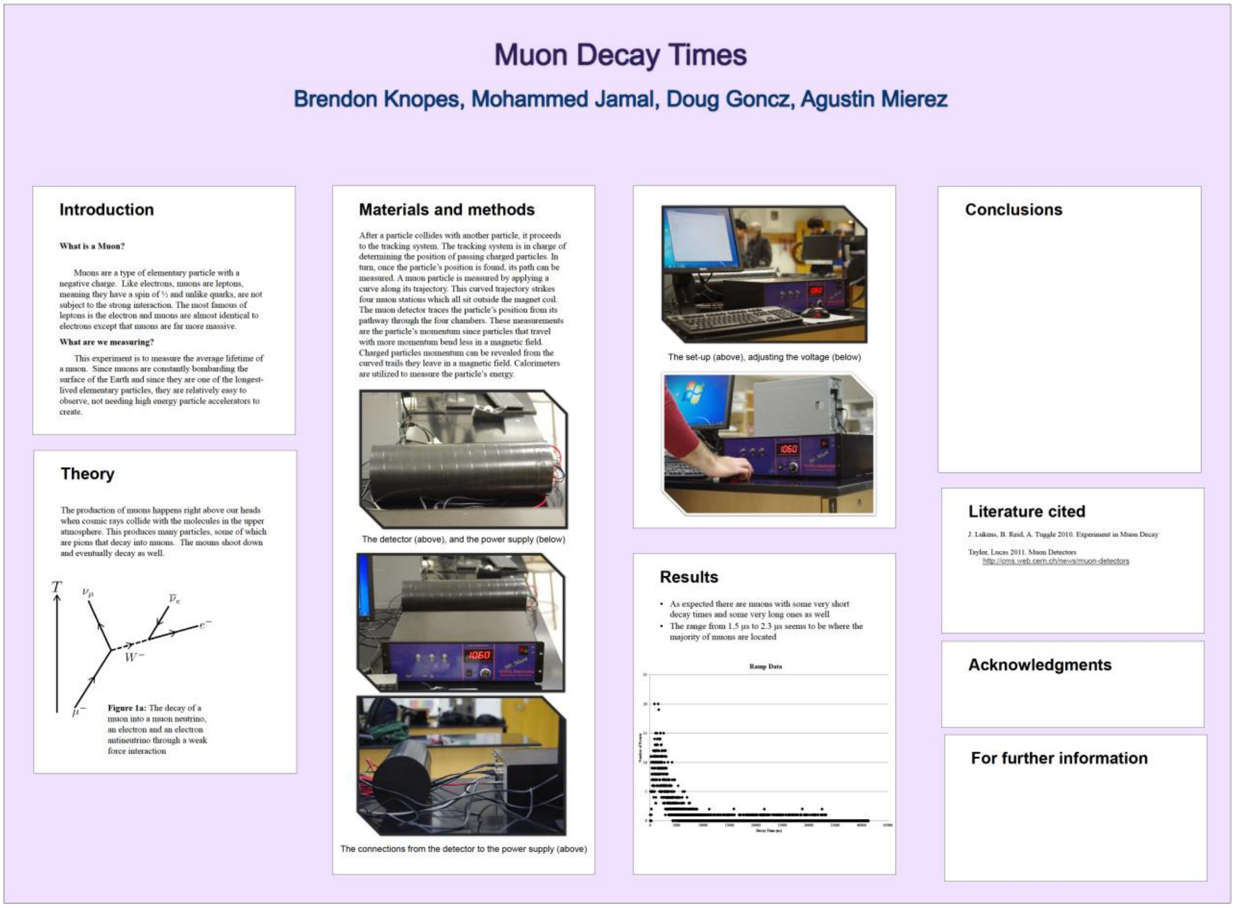
Team 2 experimented with horizontally rotating ring of inductors, and measuring lift and drag forces it exerted on a linear Halbach magnet suspended above it. Because of the small number of inductors the forces were highly oscillating.



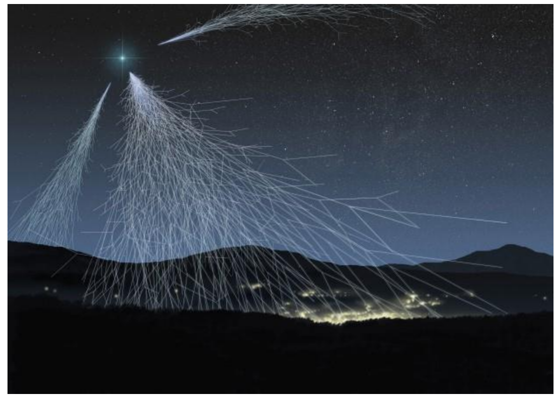


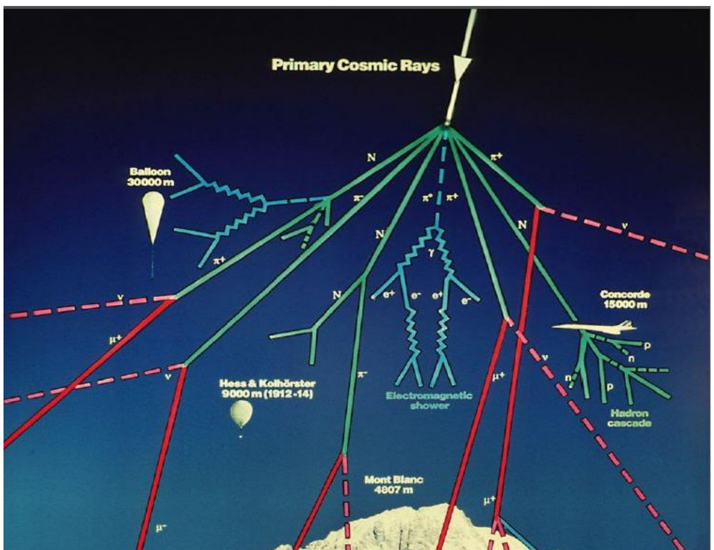
So Phuong, Chris and Dan have built a new induction wheel with 30 coils on its external rim, and will spin it in the vertical plane, again below a linear Halbach.

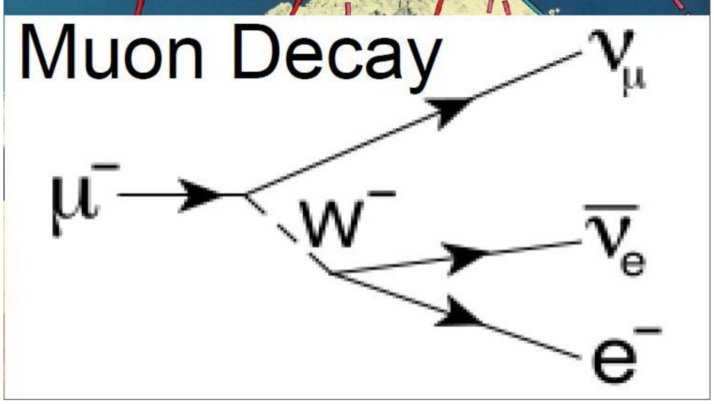
LIFE AS A MUON

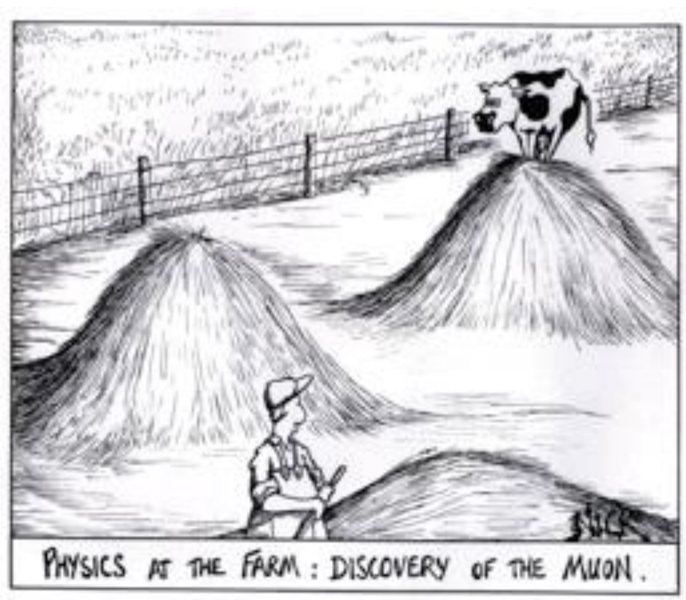


Team 3 started the measurements of the average lifetime of cosmic-ray muons, to compare it with the lifetime as predicted by the Standard Model of Particles. Muon is an unstable elementary particle, and its amazing decay involves creation of three more equally fundamental particles: electron, muonic 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”.

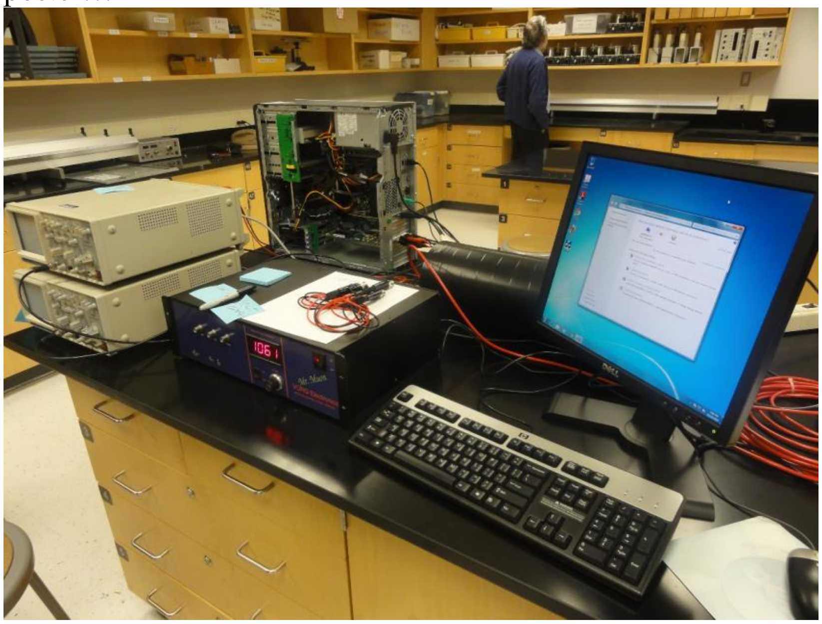




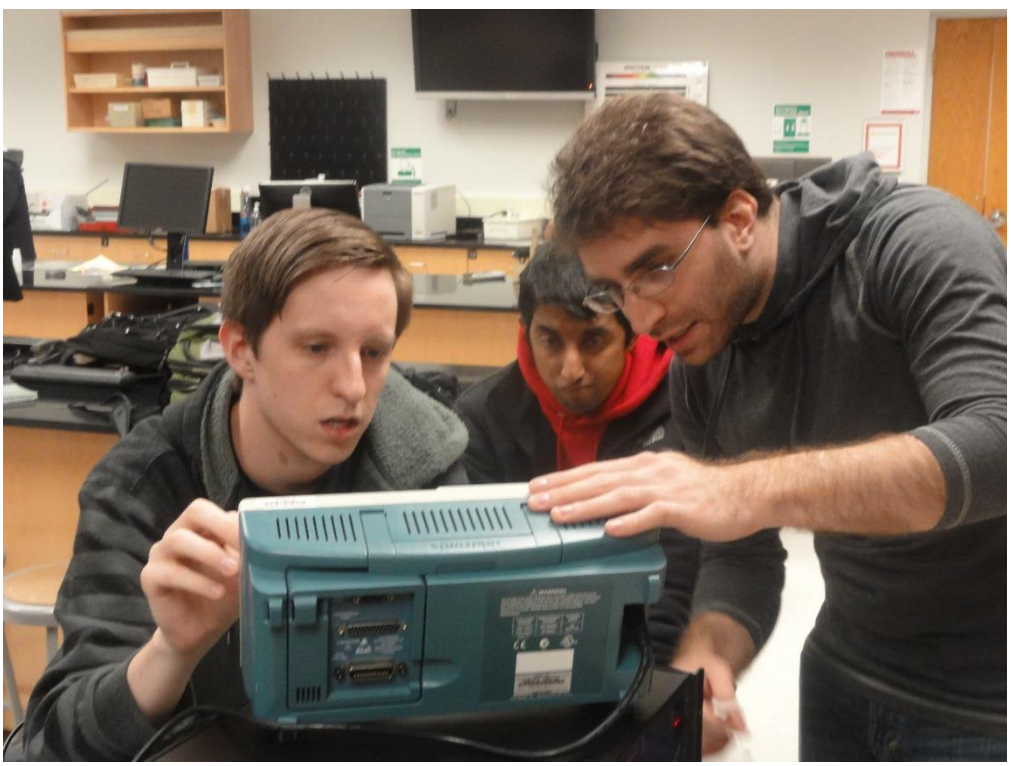




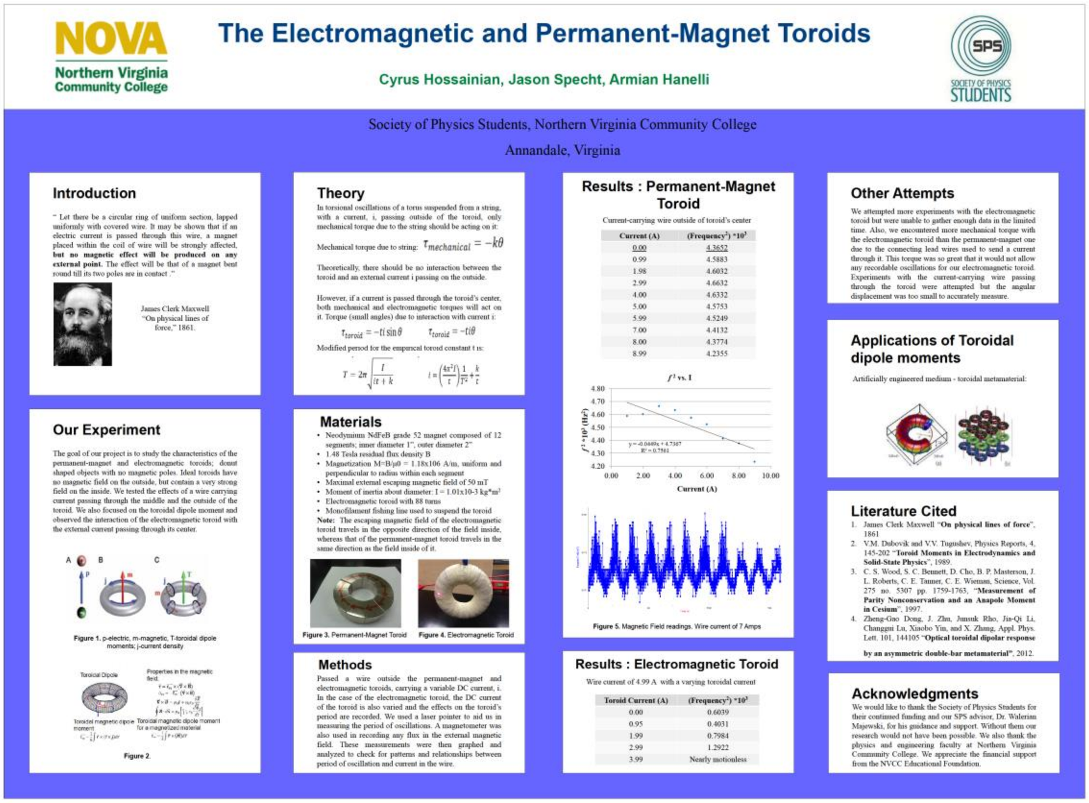
We recorded several thousand decays like: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ by registering in the scintillation detector an incoming muon and the outgoing electron, as well as a time delay between their corresponding voltage pulses. Both neutrinos escape invisible. Our detector was built 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 ± 0.00004 μs. 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


NOVA
Northern Virginia Community College
The Electromagnetic and Permanent-Magnet Toroids
Cyrus Hossainian, Jason Specht, Armian Hanelli
SPS
SOCIETY OF PHYSICS STUDENTS
Society of Physics Students, Northern Virginia Community College
Annandale, Virginia
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.
Theory
In torsional oscillations of a torus 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:
Mechanical torque due to string: $\tau_{mechanical} = -k\theta$
Theoretically, there should be no interaction between the toroid and an external current i 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:
$\tau_{toroid} = -\tau i \sin\theta$ $\tau_{toroid} = -\tau i\theta$
Modified period for the empirical toroid constant τ is:
$T = 2\pi\sqrt{\frac{I}{i\tau + k}}$ $i = \left(\frac{4\pi^2 I}{\tau}\right)\frac{1}{T^2} + \frac{k}{\tau}$
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.
A B C
p m j T
Figure 1. p-electric, m-magnetic, T-toroidal dipole moments; j-current density
Toroidal Dipole
Properties in the magnetic field:
Toroidal magnetic dipole moment
Toroidal magnetic dipole moment for a magnetized material
Figure 2.
Materials
• Neodymium NdFeB grade 52 magnet composed of 12 segments; inner diameter 1", outer diameter 2"
• 1.48 Tesla residual flux density B
• Magnetization M=B/μ0 = 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 as 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 for 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) | (Frequency²) *10³
0.00 | 4.3652
0.99 | 4.5883
1.98 | 4.6032
2.99 | 4.6632
4.00 | 4.6332
5.00 | 4.5753
5.99 | 4.5249
7.00 | 4.4132
8.00 | 4.3774
8.99 | 4.2355
f² vs. I
f² *10³ (Hz²)
4.80 4.70 4.60 4.50 4.40 4.30 4.20
y = -0.0469x + 4.7367
R² = 0.7561
0.00 2.00 4.00 6.00 8.00 10.00
Current (A)
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) | (Frequency²) *10³
0.00 | 0.6039
0.95 | 0.4031
1.99 | 0.7984
2.99 | 1.2922
3.99 | Nearly motionless
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 recordable 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:
Literature Cited
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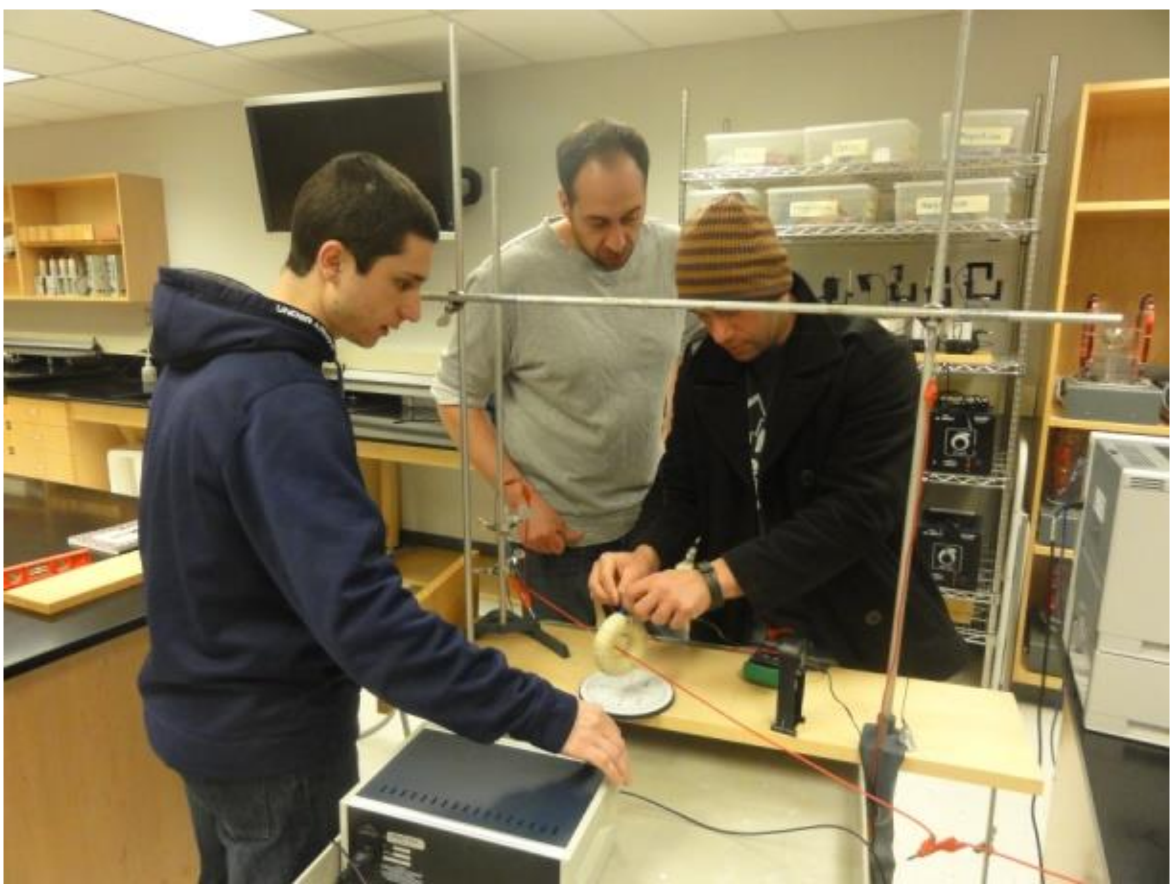
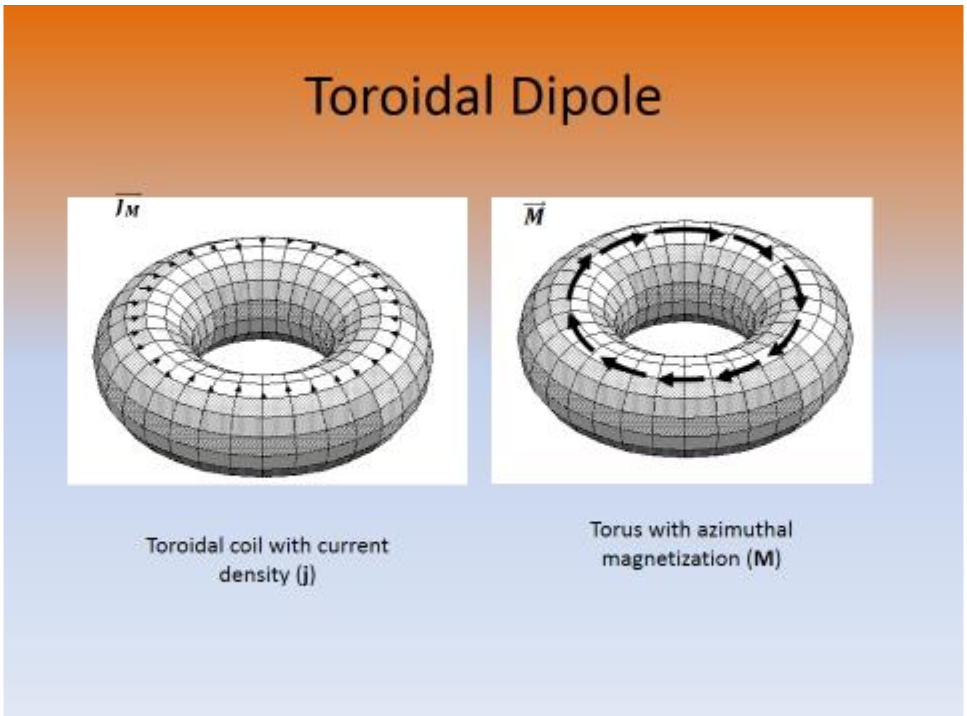
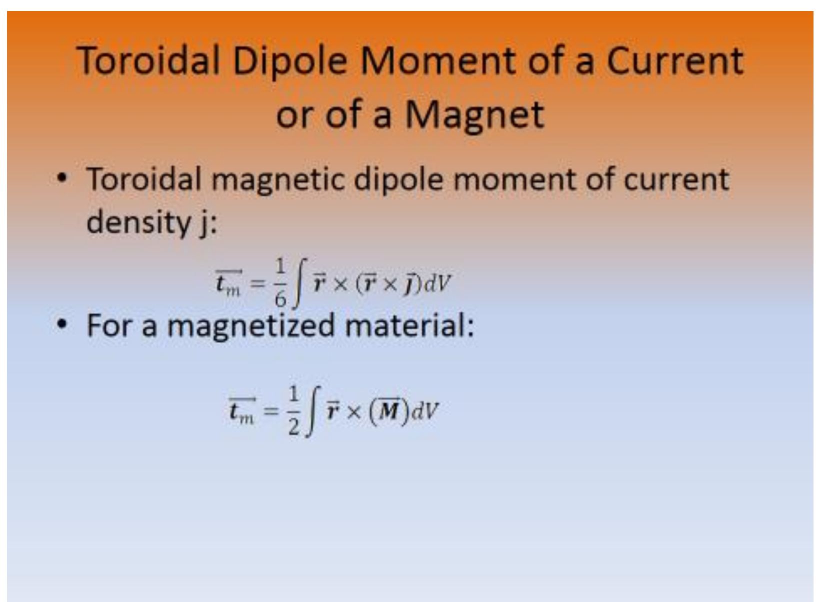
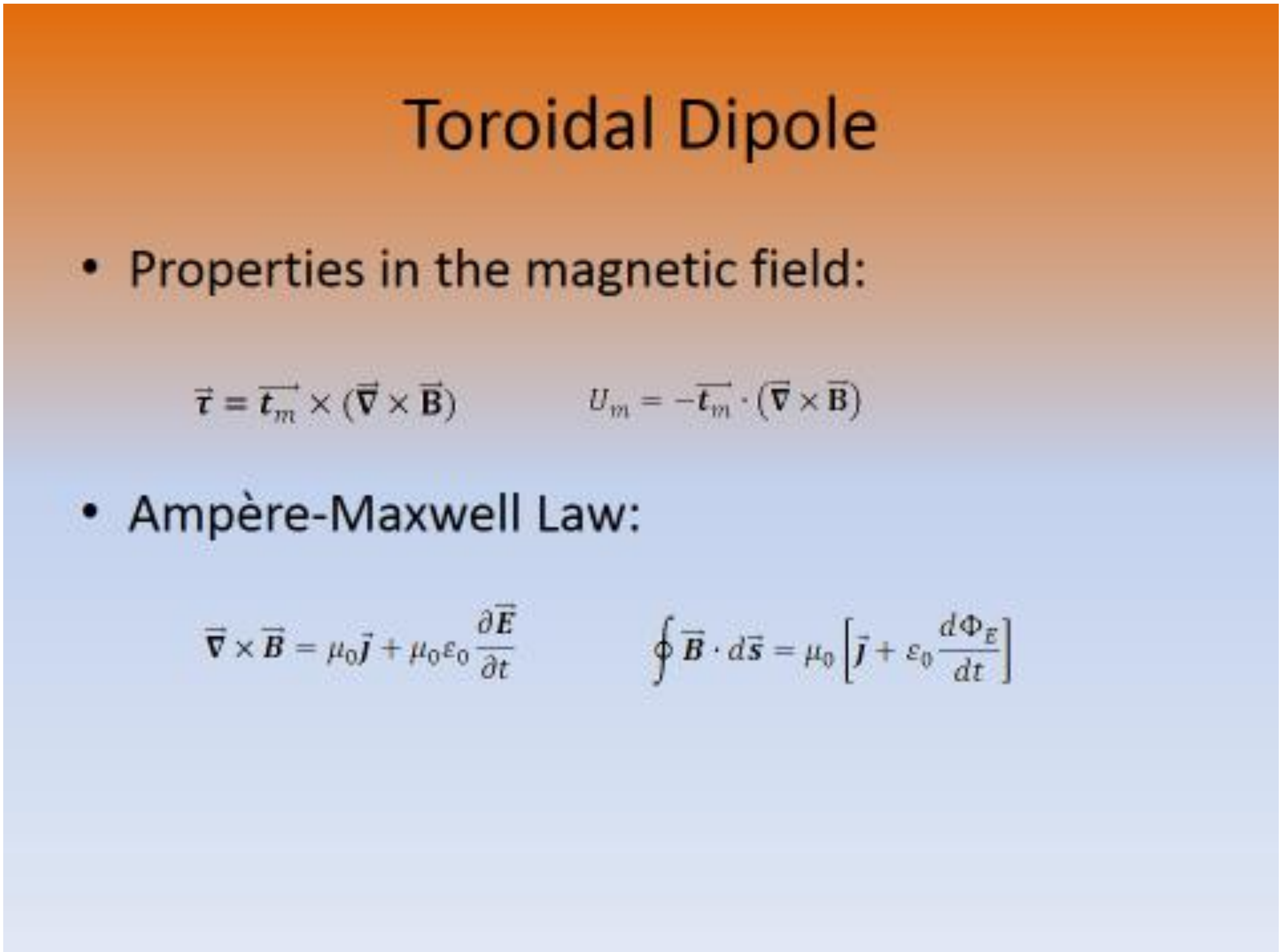


Team 4 has built an electric toroid and is comparing its properties with an equally exotic magnetic toroid. Toroidal currents represent the simplest of possible multipolar localized currents producing only localized, “contact”, finite-range magnetic field distributions, which as such are not included 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.







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.