Roman Marcarelli, Class of 2019

Physics and Math

Investigation of Laser Wakefield Acceleration in Plasmas
Biographical Sketch

My name is Roman Marcarelli, and I’m a junior math and physics major in the college of Arts and Sciences. I was born in Boston, MA, but moved to Florida at age 7 in 2004. As a kid, I was always encouraged to go outside and explore my backyard, where I naturally found a love for wildlife and the outdoors. At one point, Steve Irwin was my idol, and following in his path, I often loved to catch and release animals such as insects, lizards, snakes, and turtles.

I believe that my initial interest in nature and the outdoors is what sparked my interest in science in elementary and middle school, since biological sciences are one of the first taught. However, the field of science I was primarily interested in changed when I was introduced to physics. Something about the fact that our universe can be described quite elegantly by mathematical laws always fascinated me, and this fascination has only grown as I’ve learned more about theoretical physics.

Now, I live with four other Cornell students in Ithaca, where I spend much of my time learning physics and presiding over the Society of Physics Students. In my free time, I enjoy walking along the various trails on Cornell’s campus and in Ithaca, and I also spend a lot of time with my roommates and other friends at Cornell.

Abstract
Laser Wakefield Acceleration and Direct Laser Acceleration are two mechanisms through which one can accelerate electrons within a plasma. With the right combination of the two and with a high enough energy, these processes can produce high-energy electron beams, which have applications in the area of high-energy particle physics. Such mechanisms are not only useful in creating electron beams, but may also be able to accelerate ions after being applied to a thin sheet of plasma. The goal of my project is to simulate such effects and search for potential applications.

Statement of Purpose
My summer project will be in the field of applicational plasma physics, in which I’ll primarily be investigating the properties of a phenomenon known as Laser-Wakefield Acceleration via computer simulations. Particularly, I will be modeling the combination of Laser-Wakefield Acceleration and Direct Laser Acceleration for the purpose of efficiently generating high-energy electron beams and even accelerating positive ions.

Plasma physics is a broad area of physics that encompasses the theory and applications of the fourth state of matter, plasma. Although matter in the plasma state may seem rare to most, as it hardly shows up in our daily lives, it is actually the most common state of matter in the universe. It is what gives us lightning and the spectacular Aurora Borealis, it forms a layer around the Earth known as the Van Allen radiation belt which protects us from harmful cosmic rays, it comprises every star in the universe, and it even permeates the space between galaxies [1]. Despite its prevalence, it hadn’t been described until the 1920s by Langmuir, and has since gained much popularity in the area of physics research [2].

Plasma is most commonly described as an ionized gas, in which some electrons in the gas are knocked free from the orbitals of the atoms in the gas, leaving electrons and ions to move independently from one another. However, there are specific conditions that must be met for an ionized gas to exhibit the properties of a plasma. In particular, there are three criteria for an ionized gas to be considered a plasma: First, the plasma must have a net charge of zero when in equilibrium, meaning that the negative charges from the electrons and the positive charges from the ions must cancel. Second, the plasma must have Debye shielding, in which any electromagnetic perturbation in the plasma is quickly shielded by the electrons in the plasma such that it only has an influence at distances much smaller than the size of the plasma. Finally, the oscillations of the particles within the plasma must have higher frequency than the frequency of collisions of the particles in the plasma [1]. Under these conditions, the plasma becomes an interesting topic of research, because, unlike the case of an ordinary gas in which the only
interactions are collisions, there are short-range non-local interactions between the particles in the plasma due to their electromagnetic influence on one another. Because of this property, plasmas have applications ranging from nuclear fusion and spacecraft propulsion to photolithography in nanofabrication [3], but there are still many applications waiting to be discovered. Of particular relevance to my summer project is a recently-discovered process known as Laser Wakefield Acceleration, which has known applications but may have many yet-to-be-found applications by virtue of its novelty.

Laser-Wakefield Acceleration is the process of accelerating the electrons within a plasma by applying a high-frequency laser pulse to the plasma. The phenomenon was first proposed to be a viable source of electron plasma acceleration in 1979 by T. Tajima and J. Dawson [4]. However, Plasma Wakefield Acceleration, in which an electron or proton bunch is propagated through a plasma to induce the acceleration, wasn’t observed experimentally until 1988 by Rosenweig [5], and the more effective Laser Wakefield Acceleration hadn’t been observed to produce GeV-energy electron beams until as recently as 2006 by Leemans et al [6]. Laser Wakefield Acceleration has potential applications in the realm of high energy physics, medicine, and industry, and is thus a topic that has gained more interest in recent years.

At the crux of Laser Wakefield Acceleration is a mechanism known as the ponderomotive force. When an electron moves in an oscillating electric and magnetic field with constant spatial variation, one would expect the electron to simultaneously oscillate about a fixed point, the time-average of its position. However, in the presence of spatial variation, the electron will tend to move in the direction of lower intensity, and the ponderomotive force is precisely what gives rise to this motion[7]. In a plasma, the electrons are much more susceptible to electromagnetic fields than the ions because they are much lighter, and will thus block the field through Debye shielding before the ions are significantly disturbed from their original positions. Since laser pulses have higher gradients in intensity as one approaches the center, it follows that applying a laser pulse to
a plasma ejects the electrons in the vicinity of the pulse by the ponderomotive force, leaving a positively-charged ion bubble in the wake of the pulse. This bubble is what subsequently leads to electron acceleration since electrons at the wake of the laser are strongly attracted to the positive ion bubble.

My research will involve investigating this effect, in combination with Direct Laser Acceleration (in which the longitudinal electric field of the laser pulse is directly responsible for electron acceleration), via simulations using the programming languages C and Mathematica. In particular, I will attempt to use my simulations work to determine how to most efficiently generate high-energy electron beams from this project. High energy electron beams are particularly important in the realm of high-energy particle physics, because they are currently used to collide electrons together to learn more about subatomic particles, but they are quite expensive and difficult to make. Another topic I will potentially investigate is applying a laser pulse to a thin sheet of plasma as a mechanism for accelerating ions. Such a thin sheet of plasma is created in a lab via nanofabrication processes by fabricating a thin sheet in solid form from some neutral material, then using the heat of the laser beam to vaporize and ionize the solid, turning it into a plasma. When the laser pulse is propagated through the sheet, the ejected electrons attract the ions in the sheet, causing it to be accelerated forward. This acceleration is usually small for a flat sheet, but if the sheet has a particular three-dimensional profile, the photon pressure from the laser beam imparts momentum onto the sheet, leading the sheet to collapse into a ball as it accelerates forward. Such a process would also be useful in high-energy particle physics, since it is often proton collisions that are studied.


