Educational Applications of Pyroelectric Acceleration

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Abstract

In order to graduate the United States Military Academy (USMA) with an undergraduate degree in nuclear engineering or physics, each cadet must complete a capstone project. They also have the option of completing an independent study to graduate with honors or further their future educational opportunities. The Nuclear Science and Engineering Research Center (NSERC), a Defense Threat Reduction Agency (DTRA) office, sponsors these projects, providing resources and expertise in the fields on nuclear engineering and physics. One such resource is an experimental pyroelectric crystal accelerator to provide hands-on research and experimental experience for cadets. They can design their own experiments with the inexpensive tabletop accelerator that exists at USMA. The accelerator heats pyroelectric crystals, which creates a potential that ionizes and accelerates gas ions to energies upwards of ~150 keV. Currently, cadets working on the project are adding deuterium-deuterium (D-D) gas to create neutrons through fusion, creating a compact neutron source. This provides cadets with the opportunity to begin to live their learning and foster the development of critical thinking, as well as problem solving skills. This especially holds true because cadets can be innovative and determine their own experimental procedures and future research goals.

Introduction

The Department of Physics and Nuclear engineering at the United States Military Academy provides cadets majoring in either discipline the opportunity to participate in an advanced individual research project as part of the core curriculum or to satisfy the honors graduation requirement. Cadets majoring in nuclear engineering are also required to complete a two semester capstone design project as a graduation requirement. Department faculty provides support, guidance, and the materials and resources necessary for students to develop intellectually and to complete quality projects. The projects not only further DTRA objectives, but also introduce students to the broader world of academia, the scientific process, research methods, and further intellectual stimulation. The projects challenge reasoning skills, reinforce learning in the classroom, expose students to new learning methods, and provide the opportunity to present work at professional conferences and publish it in scholarly journals.

Pyroelectric Crystal Accelerator Project

The pyroelectric accelerator project represents one such academic opportunity for cadets at West Point by allowing cadets to challenge and expose themselves to research and experiments outside the scope of a traditional classroom. Cadets learn the basic physics behind pyroelectric crystal accelerators during the electricity and magnetism portion of the required introductory physics

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course generally taken during sophomore year. Cadets may validate this course through testing or by scoring a 4 or 5 on the calculus-based electricity and magnetism Advanced Placement exam during high school. With this basic background, cadets are able to understand the underlying principles of the project. The pyroelectric crystal accelerator project brings knowledge out of the classroom and into an environment where cadets can solve problems, conduct experiments, and begin to live their learning.

Experimental Apparatus

The accelerator apparatus at USMA uses two pyroelectric crystals (lithium tantalite, $LiTaO_3$), a heating/cooling system (thermoelectric heater/cooler (TEC)), a vacuum chamber, and a direct current power supply. Additionally, the experiment requires an x-ray detector in order to detect and analyze the Bremsstrahlung radiation produced when energetic electrons interact with objects inside the vacuum chamber as well as the chamber wall itself. It is possible to introduce deuterium gas into the chamber to perform D-D nuclear fusion experiments. D-D fusion has been achieved by several other institutions at the graduate level[1,2,3,4]. The focus at West Point is to have the cadets achieve fusion at the undergraduate level. For these experiments, a neutron detector is required to detect neutrons created in the D-D fusion reaction.

The Physics of Pyroelectric Crystal Accelerators

A pyroelectric crystal exhibits spontaneous polarization (P_s) under equilibrium conditions and this polarization changes with a temperature gradient across the crystal. Pyroelectric crystals are cut such that the two faces are normal to the dipole moments of the unit cells, effectively creating $-z$ and $+z$ faces. During thermal equilibrium, the $-z$ face has a negative spontaneous polarization, and the $+z$ face has a positive spontaneous polarization. The change in polarization due to a temperature gradient causes a charge to build on the crystal surface which gives rise to an electrostatic potential, creating an electric field capable of accelerating charged particles to energies on the order of hundreds of keV. The pyroelectric effect causes the polarization to change during heating or cooling of the crystal. When the crystal is heated, the spontaneous polarization decreases and charge migrates to the crystal faces to balance that change. Cooling the crystal causes the same charge migration, however, the spontaneous polarization increases.[5] The charge migration causes the polarization change to be masked, an effect which can be mitigated by performing the heating or cooling in a vacuum environment. Because a vacuum environment contains few residual particles to carry charge away from the crystal surface, a significant amount of negative charge will build on the +z face during heating and a negative charge will build on the same face during cooling. This causes an electrostatic potential to build, which creates an electric field that can ionize and accelerate residual gas ions and electrons. These ions and electrons, upon striking the surrounding environment, create Bremsstrahlung x-rays. Figure 1 shows an x-ray spectrum from the apparatus at West Point. The end-point energy shown in Figure 1 shows that charged particles accelerated up to ~150 keV was achieved.

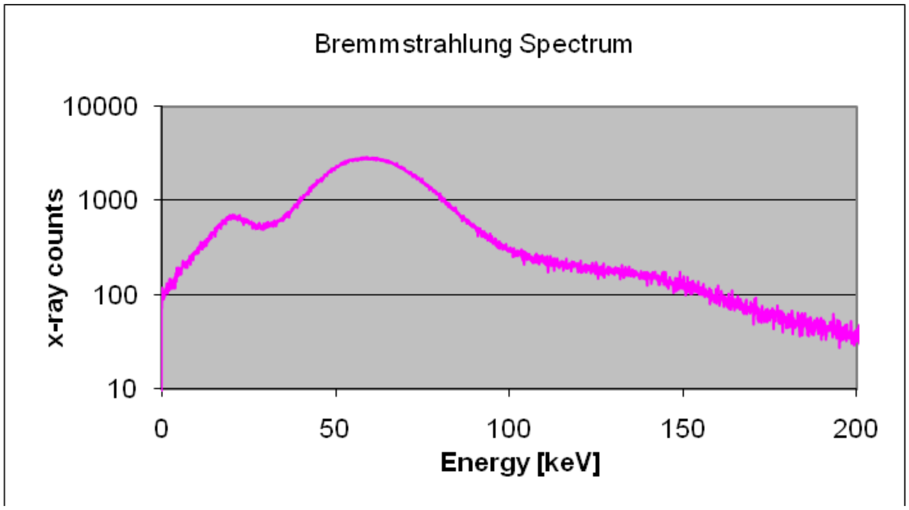

Figure 1. Bremmstrahlung x-ray spectrum from a NaI detector for a typical two crystal pyroelectric accelerator.

To achieve D-D fusion, deuterium gas is introduced into the vacuum chamber (1 – 20 mtorr). The pyroelectric accelerator ionizes this gas and accelerates these ions into a deuterated target at sufficient energies to achieve fusion.

Figure 2 shows the neutron branch cross sections as a function of energy.[6] Given the acceleration potentials achieved at USMA as shown in Figure 1 and the cross section data in Figure 2, cadets have already achieved the necessary environment to create D-D fusion.

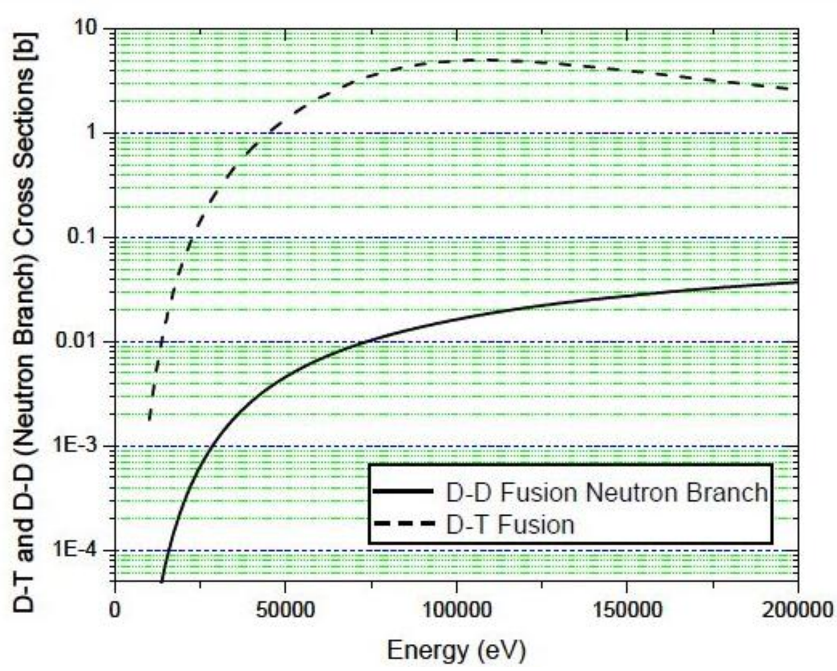

Figure 2. Neutron branch cross sections as a function of D+ energy.

Figure 2 shows that at ~150 keV, the fusion cross section is large enough to provide for an opportunity to achieve fusion. The neutron branch of D-D fusion reactions is given by[6]:

$$D + D \rightarrow He^3\ (0.82\ MeV) +\ n\ (2.45\ MeV)$$

showing that a mono-energetic source of 2.45 MeV neutrons is expected from the reaction. If the gas in the chamber were changed to tritium, an increase of neutrons by a factor of about 300 is expected due to the relatively larger cross section as shown in Figure 2. D-T fusion neutrons would have 14.1 MeV energy. Due to radiation protection safety, only D-D fusion is being done at USMA.

The electrostatic potential (V) created by the pyroelectric effect may be calculated by dividing the charge (Q) on the crystal surface by the capacitance (C_{eq}) of a crystal system:

$$V = \frac{Q}{C_{eq}} \tag{1}$$

The capacitance (C) of one parallel-plate capacitor can be calculated by:

$$C = \frac{k\varepsilon_0 A}{d} \tag{2}$$

where d is the distance between the plates, A is the plate area, k is the dielectric constant, and ε_0 is the permittivity of free space.

The surface charge (Q) of the crystal face is equal to the spontaneous polarization (P_s). This polarization can be changed proportionally to the change in temperature (ΔT) times the pyroelectric coefficient of the crystal, γ, such that

$$Q = \Delta P_s * A = A\gamma\Delta T \tag{3}$$

The typical units for γ are $\mu C/(m^2 \cdot K)$ A is the area of the crystal face and ΔT is the change in temperature (100 K in experiments at USMA). The USMA accelerator utilizes two $LiTaO_3$ crystals that have a γ of 190 $\mu C/(m^2 \cdot K)$ for the temperature range of interest.[7] Substituting the above equation into equation 1, gives the following equation for the electrostatic potential of the system:

$$V = \frac{A\gamma\Delta T}{C_{eq}} \tag{4}$$

In a two crystal system, like the one shown in figure 3, the electrostatic potential across the gap is the potential acting on the gas particles in the chamber. It is given by:

$$V_{gap} = \frac{Q_{gap}}{C_{gap}} = \frac{-(Q_C C_{cr1} - Q_B C_{cr2})}{(C_{cr2} C_{cr1} + C_{cr2} C_{gap} - C_{cr1} C_{gap})} \tag{5}$$

where Q_b and Q_c the surface charges generated by the crystals and C_{cr1}, C_{cr2}, and C_{gap} represent capacitances on each crystal and the gap. Conservation of charge is used to derive this equation.[6]

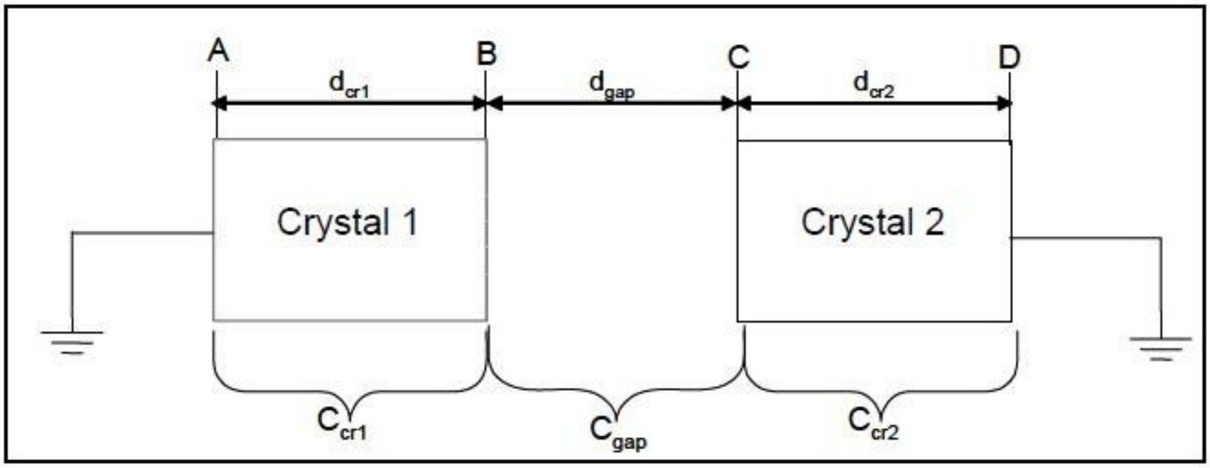

Figure 3. Two crystal system schematic.

Because the crystals used are identical with opposite polarity across the gap, C_{cr1} is equal to C_{cr2}, and Q_B is equal to negative Q_c. This yields the following general equation for the electrostatic potential for a two crystal system.

$$V_{gap} = \frac{2Q}{C_{eq}} \tag{6}$$

Future Cadet Research Projects

The main focus of the project rests in achieving D-D nuclear fusion; however, several potential student-designed projects can be created for independent study classes and capstone projects. These include, but are not limited to: testing a portable neutron generator, alternative crystal heating and cooling methods, and designing a management system to control the crystal thermal cycles.

Portable Neutron Source

Previous work shows that pyroelectric crystal accelerators can be used to achieve D-D nuclear fusion.[1,2,3,4] Cadets working on the project are attempting to achieve this for the first time at West Point, as well as improve the neutron yield once fusion is achieved. The two-crystal experimental setup is shown in Figure 4. A 70 nm radius tip enhances the electric field locally. This enhanced electric field increases the ionization of the deuterium gas leaked into the vacuum chamber and accelerates the gas ions to energies high enough for D-D fusion neutron production when the ions strike the deuterated target.

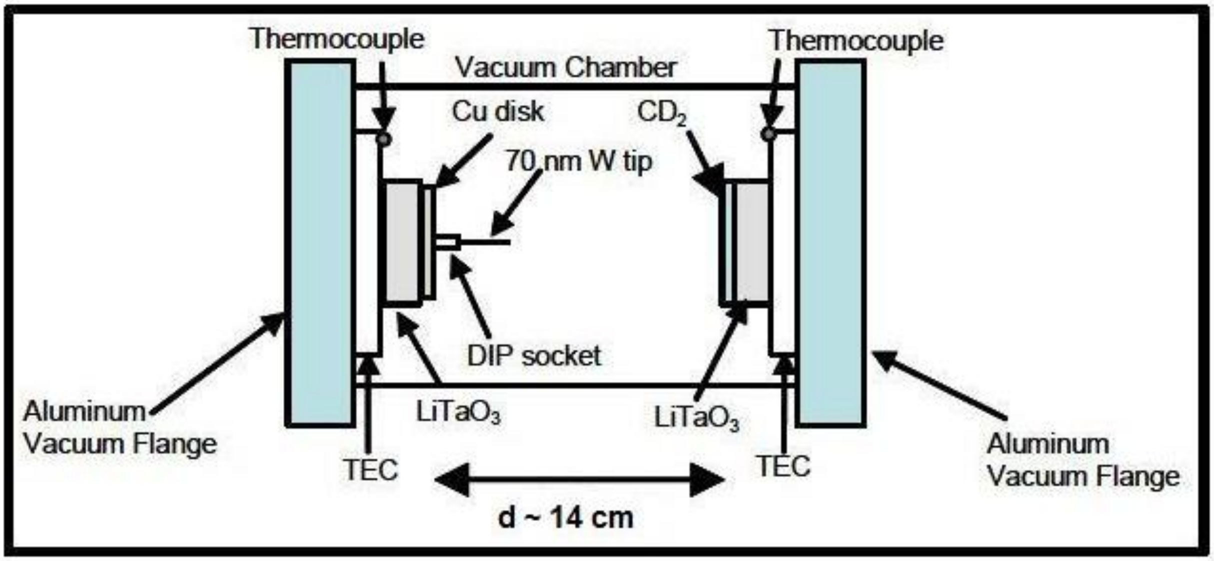

Figure 4. USMA pyroelectric crystal apparatus

Alternative Crystal Heating Methods

Currently, a thermoelectric heater/cooler (TEC) is being utilized to heat and cool the crystals. However, the exploration of other heating methods opens the door for multiple cadet projects in the future. Cadets have already developed and tested different heating methods in an attempt to improve the efficiency of the pyroelectric system. Experiments have been designed and conducted by cadets using a heating tape and a laser to potentially improve the heating portion of the thermal cycle. Experiments are still being conducted to improve the laser heating effectiveness and test its feasibility for future use in the pyroelectric fusion system. Both of these projects required the development and construction of alternative designs in addition to theoretical work on the heating properties of the crystal.

Thermal Cycle Control

The current thermal cycle includes a heating phase, a soak phase in which the crystal is kept at constant temperature, and a cooling phase during which the x-ray and neutron detectors acquire data. Because TECs heat the crystals from one side and that heat must propagate via conduction through the crystal, the soak phase is used to ensure the entire crystal is heated. Each phase is typically approximately 5 minutes, with the heating and cooling phase operating on a controlled ramp up/down. The computer sends a signal to the power supply based on temperature read off a thermocouple dictating how much power should be sent to the TEC to continue a controlled ramp. This feedback loop opens the opportunity for a cadet project creating a LabView or other program to precisely control the heating and cooling cycle. This precision control will allow cadets to better coordinate the electric fields of the two crystals in order to increase the energy of the deuterium gas ions and increase the probability of D-D fusion.

Assessment

Cadets are assessed on their experimental, research, and independent study effort through time invested, progress made, and the final product of the research. Typically, cadets must write a paper worthy of a peer-reviewed journal, construct and present a poster at a professional conference and give a presentation to the project sponsor at the end of the year. Additionally, cadets give a poster presentation at USMA's annual Project's Day held during the Spring semester each year.

Conclusion

The pyroelectric crystal accelerator at West Point provides the cadets in the Department of Physics and Nuclear Engineering a unique opportunity for outside the classroom, discovery learning. Cadets can apply classroom skills to real world applications while gaining valuable research, critical thinking, and problem solving skills. This project will help them to be more productive in future academic endeavors as well as in future career fields.

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