

Pyroelectric Crystal Accelerator In The Department Of Physics And Nuclear Engineering At West Point

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Abstract. The Nuclear Science and Engineering Research Center (NSERC), a Defense Threat Reduction Agency (DTRA) office located at the United States Military Academy (USMA), sponsors and manages cadet and faculty research in support of DTRA objectives. The NSERC has created an experimental pyroelectric crystal accelerator program to enhance undergraduate education at USMA in the Department of Physics and Nuclear Engineering. This program provides cadets with hands-on experience in designing their own experiments using an inexpensive tabletop accelerator. This device uses pyroelectric crystals to ionize and accelerate gas ions to energies of ~ 100 keV. Within the next year, cadets and faculty at USMA will use this device to create neutrons through the deuterium-deuterium (D-D) fusion process, effectively creating a compact, portable neutron generator. The double crystal pyroelectric accelerator will also be used by students to investigate neutron, x-ray, and ion spectroscopy.

Keywords: Pyroelectric Crystal Accelerator, Educational Accelerator, Nuclear Fusion, Neutrons

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INTRODUCTION

The Nuclear Science and Engineering Research Center (NSERC), a Defense Threat Reduction Agency (DTRA) office located at the United States Military Academy (USMA) at West Point, sponsors and manages cadet and faculty research in support of DTRA objectives. The NSERC mission is to increase USMA faculty and cadet research in support of DTRA objectives; enhance the professional development of USMA faculty; and contribute to the education of cadets, especially those majoring in nuclear engineering or physics.

The cadets at USMA represent the next generation of Army leaders and as such must be given the education and experience necessary for them to be successful junior officers. The NSERC-USMA link facilitates cadet work on projects to support DTRA scientific objectives, provides cadets with valuable educational opportunities, and directly addresses important scientific questions of the Department of Defense and other national agencies.

From the time the NSERC opened in 2007 to the present, the focus of cadet projects has primarily been

theoretical and computational in nature. In many of these DTRA-sponsored projects, cadets used the Monte Carlo N-Particle (MCNP) transport code, to answer scientific questions related to safeguarding America and its allies from weapons of mass destruction. To further expand the educational opportunities provided to cadets, the NSERC has now established a number of experimental projects. These projects both provide the cadets hands-on experimental experience, and assist DTRA in developing compact and portable systems for homeland security and defense applications.

NSERC RESEARCH STRATEGY

Cadets majoring in nuclear engineering at USMA are required to complete a two-semester capstone design project. The topic and scope of these projects are provided by the NSERC, which works with DTRA to identify research areas appropriate for undergraduates. The NSERC then sponsors and funds summer internships for cadets providing the cadets with a "head start" on their project and extending the two semester project to a full year design experience.

In addition, the NSERC funds faculty summer research in support of these projects.

Cadets and faculty conduct this NSERC-funded research at DTRA or other Department of Defense and Department of Energy locations during the summer and at USMA during the academic year. Project sponsors at DTRA (i.e. the “client”) are actively engaged in these projects via video teleconference, periodic travel to USMA to work with cadets, and by attending USMA Projects Day in April. The NSERC also arranges for cadets and faculty to travel to DTRA to present their findings to the clients and DTRA leadership. In addition, the NSERC often funds cadets to attend professional conferences, such as the Hardened Electronics and Radiation Technology (HEART) Conference and conferences run by the American Physical Society and the American Nuclear Society. Presenting at these conferences provides cadets both verbal professional experience and the opportunity to get results published.

PYROELECTRIC ACCELERATOR

The pyroelectric accelerator project is an ideal example of NSERC-sponsored research and provides a valuable experimental experience for faculty and undergraduates. The project is relatively inexpensive (crystals cost less than \$1000) and the vacuum system and radiation detection equipment were already on hand in the Department of Physics and Nuclear Engineering. In total, this project cost less than \$10,000 to begin.

In addition to its relatively low cost, another important advantage to a pyroelectric accelerator is that the basic physics of pyroelectric acceleration is taught during introductory- level electricity and magnetism (E&M) physics courses. At USMA, cadets are required to take two semesters of calculus-based physics, which includes E&M. As such, cadets already have the basic knowledge to understand the underlying principles of a pyroelectric accelerator. Detecting the x-rays and neutrons generated by a pyroelectric crystal accelerator also provides a significant educational opportunity for cadets.

Nominal Experimental Equipment

A pyroelectric accelerator experimental apparatus requires a pyroelectric crystal (lithium tantalate (LiTaO₃) is used here), a heating/cooling source (a thermoelectric heater/cooler), a direct current power supply, and a vacuum chamber. An x-ray detector is needed to detect the Bremsstrahlung radiation resulting from energetic electrons interacting with surrounding vacuum chamber materials. In addition,

deuterium gas, a deuterated target, and a neutron detector are needed to conduct D-D nuclear fusion experiments. For this project, we assume that the measured x-ray end-point energy equals the maximum acceleration field potential influencing the charged particles. At USMA, a two crystal system is used which pairs a +z face opposing a -z face to allow for double the acceleration potential between the two crystals (superposition).

The Physics Of Pyroelectric Acceleration

Each pyroelectric crystal unit cell has an intrinsic dipole moment with the bulk crystal material exhibiting spontaneous polarization when heated or cooled. Spontaneous polarization, P_s , is defined as the dipole moment per unit volume of the material and is non-zero for pyroelectric materials¹. Pyroelectric crystals are generally cut such that the dipole moments of the unit cells are arranged perpendicularly to the flat surfaces (named -z and +z faces).

During equilibrium conditions (constant temperature), free charged particles assemble at the faces of the crystal and screen the spontaneous polarization charge. When the crystal is heated (or cooled), however, the spontaneous polarization decreases (or increases) and charge moves to the crystal face to counteract the change. A thermal cycle is heating the crystal from equilibrium conditions (usually room temperature) to approximately 120 °C, holding the crystal at that temperature for a time to ensure thermal equilibrium across the crystal and then cooling the crystal back down to room temperature.

Experiments are usually done under vacuum at low ambient pressure (1 to 10 mTorr) to reduce the crystal discharge rate and to allow the electric potential to build by reducing the amount of free charge available at the crystal surface. The charge at the crystal surface creates an electrostatic potential which is used to ionize and accelerate residual gas particles. These accelerated ions (and electrons) interact with the surrounding environment (usually a vacuum chamber) to create Bremsstrahlung x-ray radiation.

The potential (V) generated by the pyroelectric effect can be calculated using the charge (Q) on the crystal surface divided by the equivalent capacitance (C_{eq}) of the system:

$$V = \frac{Q}{C_{eq}} \quad (1)$$

Typically a single crystal-target system is modeled as two parallel-plate capacitors added in parallel with one capacitor being the crystal itself and the other being the gap between the crystal and the target. The capacitance (C) of a parallel-plate capacitor is given by:

$$C = \frac{k\epsilon_0 A}{d} \quad (2)$$

where k is the dielectric constant, ϵ_0 is the permittivity of free space, A is the plate area, and d is the distance between the two plates. Adding the two capacitors in parallel yields:

$$V = \frac{Q}{C_{eq}} = \frac{Q}{C_{cr} + C_{gap}} \quad (3)$$

where C_{cr} is the capacitance of the crystal and C_{gap} is the capacitance of the gap between the crystal and target.

The amount of surface charge on each face of the crystal is equal to the change in spontaneous polarization, ΔP_s . This change can be calculated by multiplying the change in temperature by the pyroelectric coefficient, γ , such that:

$$\Delta P_s = Q = \gamma \Delta T \quad (4)$$

where γ is typically given in $\mu\text{C per m}^2\text{-K}$ and ΔT is in K. For the LiTaO_3 crystals used in this project in the temperature range of interest (293 to 313 K), the value² for γ is $190 \mu\text{C/m}^2\text{-K}$ and ΔT is approximately 100.

POTENTIAL CADET PROJECTS

There are several aspects of the cadet pyroelectric crystal project that directly relate to DTRA's mission of safeguarding America and its allies from weapons of mass destruction. These include development of a portable, battery operated neutron source, a portable mass spectrometer for aerosol chemical detection, and a compact x-ray generator. All three of these are outlined in this paper. In addition to these specific applications, cadets also gain experience designing their own experiments to investigate a wide variety of other physical phenomena using a pyroelectric crystal accelerator.

Portable Battery Operated Neutron Source

Pyroelectric crystal accelerators have been used to achieve D-D nuclear fusion.^{3,4} One of the products of D-D nuclear fusion is a highly penetrating 2.45 MeV neutron. The ultimate goal of this project is to develop an inexpensive, hand-carried neutron source for active interrogation of suspect packages at close range. Further work is required to develop pyroelectric acceleration technology to improve neutron yield per thermal cycle.

In the experimental setup presented here, a copper disk is used to collect the charge from the crystal

surface and transfer it to a sharp tip. This tip is used to locally enhance the electric field thereby increasing ionization of deuterium gas introduced into the vacuum chamber. This same electric field accelerates the deuterium ions to high enough energies (100 – 300 keV) to achieve D-D fusion and produce 2.45 MeV neutrons as the ions impact a deuterated target. Figure 1 is a graphical depiction of a two-crystal pyroelectric crystal fusion experimental setup.

Potential student projects relating to neutron generation include, to name a few: designing, constructing, and testing a portable prototype neutron generator; novel pyroelectric crystal heating and cooling schemes; designing a thermal management system to precisely control the thermal cycles of the crystals; and using more than 2 pyroelectric crystals to achieve pyroelectric crystal fusion.

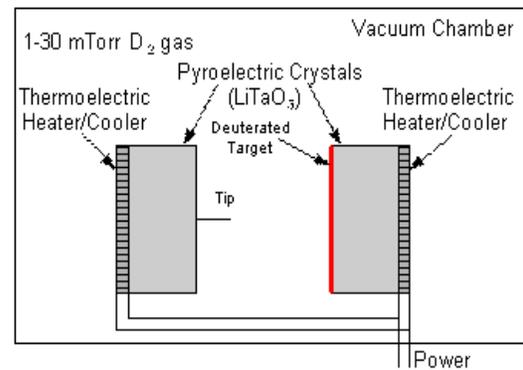


Figure 1. Experimental setup for a pyroelectric crystal accelerator neutron source.

Portable, Robust, Mass Spectrometer For Aerosol Chemical Detection

Previous work⁵ has shown that pyroelectric crystal ionization can accelerate gases through a magnetic field. As such, a novel mass spectroscopy system using pyroelectric crystals as the ion source can be created using a pyroelectric-generated electric field to ionize the gas, accelerate ions through a magnetic field, and measure their deflection. More experimental work needs to be done to determine if different gas species can be detected and resolved. Additionally, field-enhancing tips or an array of nanorods, nanotubes, or nanowires may improve ionization of the various gases. Figure 2 graphically depicts an experimental setup for these types of experiments.

Additional materials necessary to conduct these types of experiments include: an ion detector (previous work used a low-light camera and a ZnS screen which illuminated when charge particles impacted it), various gases and gas mixtures, and various field-enhancing tips. Potential student projects in this area include: designing, constructing, and testing a mass

spectrometer using pyroelectric crystals; conducting magnetic deflection simulations and experiments to determine an optimal magnetic field configuration; conducting experiments using various nanostructures to enhance the electric field; designing, constructing and testing an ion detection system; and using an air sampling system in conjunction with the mass spectrometer.

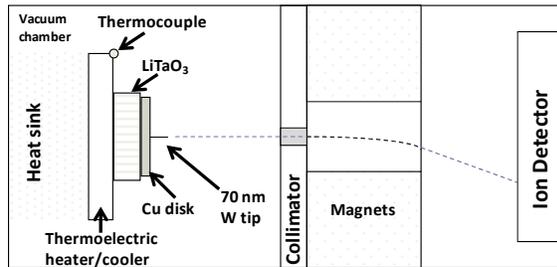


FIGURE 2. Experimental setup for a pyroelectric crystal accelerator Mass Spectrometer. The dotted line represents the path an ion would take through the magnetic field.

Compact X-Ray Generator

Building an inexpensive, hand-carried, energetic x-ray source for imaging of suspect packages is also a potential student project. Previous work^{2,5} has shown that a one-crystal system, using a 10-mm thick, 20-mm diameter cylindrical LiTaO₃ crystal, will yield ~100 keV x-rays and a two-crystal system will yield ~200 keV x-rays. The x-rays generated can be used to interrogate suspect materials to determine elemental composition. Ultimately, this new technology may provide a highly compact, battery operated, and inexpensive x-ray source. A pocket-sized x-ray generator using pyroelectric crystals is commercially available with the Amptek Cool-X⁶ which provides approximately 35 keV x-rays. The experimental project proposed here would use larger crystals to achieve higher energies and more penetrating x-rays. Figure 3 provides a sketch of the x-ray generator apparatus.

Potential student projects here include: designing, constructing and testing a portable, battery operated, and energetic x-ray source; conducting experiments using various target materials to determine which materials provide the highest x-ray yield; conducting experiments with an array of crystals (more than two) or larger crystals to achieve more energetic x-rays; designing and conducting x-ray fluorescence experiments for classroom use and for elemental analysis of unknown objects; and conducting imaging experiments to determine the feasibility of a portable x-ray machine that can be used for homeland security operations.

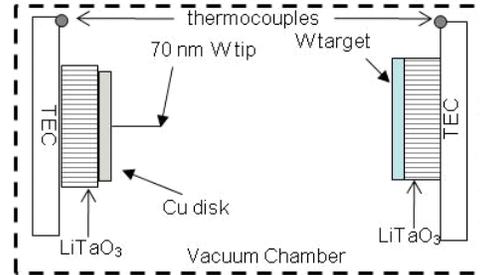


FIGURE 3. Experimental setup for a pyroelectric crystal accelerator x-ray generator. The tungsten (W) target is only an example, other types of target materials may be used to facilitate generation of x-rays.

CONCLUSION

The NSERC, through DTRA, is providing cadets at USMA with a hands-on educational experience using a pyroelectric crystal accelerator. The pyroelectric crystal accelerator at USMA has already been constructed and preliminary results are reported in Reference 7. The many student projects outlined in this paper are presented as examples of experiments that may be conducted once the experimental accelerator is fully constructed. This pyroelectric crystal accelerator is a relatively inexpensive and effective tool developed to give undergraduate students the opportunity to design and conduct their own experiments.

Disclaimer: The views expressed herein are those of the author and do not reflect the position of the United States Military Academy, the Department of the Army, the Defense Threat Reduction Agency, or the Department of Defense.

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