Preliminary Results from Pyroelectric Crystal Accelerator

Tom Anderson[1], Ronald Edwards[1], Kevin Bright[1], Andrew Kovanen[1], Yaron Danon[3], Brian Moretti[1], Jeffrey Musk[2], Mike Shannon[2], Don Gillich[1]

[1]*Department of Physics and Nuclear Engineering, United States Military Academy, West Point, NY 10996*
[2]*Nuclear Science and Engineering Research Center, Defense Threat Reduction Agency, West Point, NY 10996*
[3]*Dept. of Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180*

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. Cadets in the Department of Physics and Nuclear Engineering at USMA are using pyroelectric crystals to ionize and accelerate residual gas trapped inside a vacuum system. A system using two lithium tantalate crystals with associated diagnostics was designed and is now operational. X-ray energies of approximately 150 keV have been achieved. Future work will focus on developing a portable neutron generator using the D-D nuclear fusion process.

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

Pyroelectric crystals have been used to achieve deuterium-deuterium (D-D) nuclear fusion by ionizing and accelerating deuterium gas particles into a deuterated target.[1,2] Cadets at the United States Military Academy are conducting pyroelectric crystal research to ionize and accelerate residual gas particles, generate Bremsstrahlung x-rays, and ultimately achieve D-D nuclear fusion. The maximum end-point energy of these x-rays gauges the acceleration potential of the system and an end-point acceleration potential energy of the two crystal system of approximately 150 keV has been achieved.

THE PHYSICS OF PYROELECTRIC ACCELERATION

The driving force behind the ionization and acceleration of the residual gas particles is the electrostatic force generated by the pyroelectric effect. These crystal unit cells have intrinsic dipole moments that exhibit spontaneous polarization during heating or cooling past their equilibrium temperature. Spontaneous polarization is the dipole moment per unit volume of material and is non-zero for a heated or cooled pyroelectric crystal.[3] Typically, pyroelectric crystals are cut to align the dipoles along the flat surfaces, thereby creating +z and –z faces. Spontaneous polarization of the crystal decreases or increases during heating and cooling and a charge is generated on the flat crystal surfaces to compensate for these polarization changes. For example, a +z face during cooling will result in a net change in the polarization and the face becomes less positive. As a result, an electric field is generated and attracts ions towards and electrons away from the flat crystal surface. During cooling, the electric field will attract electrons towards and accelerate positive ions away from the crystal face. The negative face of the crystal, typically grounded for the crystal with the field-enhancing tip, displays the same properties for charges of the opposite sign.[4]

The electric potential generated by a pyroelectric crystal can be calculated by:

$$V = \frac{Q}{C_{eq}} = \frac{\gamma \cdot \Delta T \cdot A}{C_{eq}} \qquad (1)$$

where γ, the pyroelectric coefficient, is normally given in terms of μC/m^2-K and ΔT is approximately 100 K for the experiments presented in this paper. C_{eq} represents the equivalent capacitance of the two-crystal system and A is the surface area of the crystal face. For $LiTaO_3$ crystals in the temperature range of interest, the value[5] for γ is 190 μC m^{-2} K^{-1}.

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Charged particles that are accelerated by the crystals interact with the chamber walls and other materials inside the chamber. The change in kinetic energy of these charged particles produces a Bremsstrahlung x-ray spectrum. The energy scale and maximum end-point energy of this spectrum is an indication of the acceleration potential of the system. In fusion experiments, it is assumed that deuterium ions are influenced by the same end-point energy of the acceleration potential between the two crystals.

EXPERIMENTAL SET-UP

The vacuum chamber was pumped down to an ambient pressure of 1 x 10^{-5} Torr to prevent electrostatic discharges from the crystals. Such discharges would necessitate a new thermal cycle to recharge the crystal faces. The vacuum was measured through pressure gauges. In fusion experiments, a gas leak valve will control the flow of D_2 gas into the vacuum chamber. In the experiments presented in this paper, the valve remained closed and only residual gas particles were ionized and accelerated to measure the Bremsstrahlung end-point energy and yield. Figure 1 shows a picture of the experimental setup.

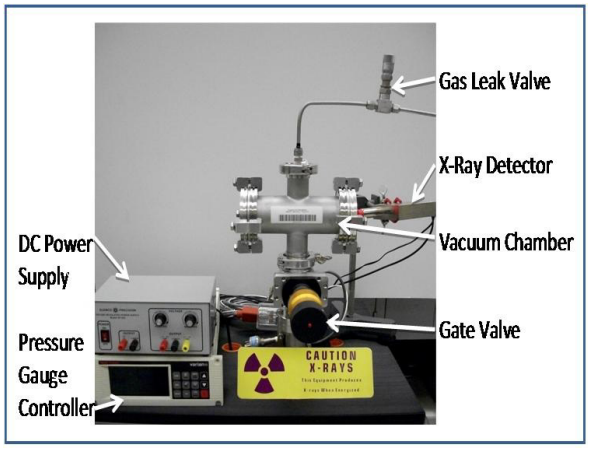

FIGURE 1. A picture of the experimental setup with associated diagnostics and power supply. The gas leak valve is not used until D_2 gas is added to the system. In the experiments presented here, Bremsstrahlung x-rays were generated by the ionization and acceleration of residual gas particles in the vacuum system.

Using thermally and electrically conductive epoxy, the 20 mm diameter, 10 mm thick crystals were glued to thermoelectric heater/coolers (TECs) which provided energy for the thermal cycles of the crystals. On the +z crystal face of one of the crystals, a copper disk collected the charge from the crystal surface and a 70 nm radius Tungsten tip was used to locally enhance the electric field and thereby, the ability to ionize residual gas particles. Both crystals had one of its faces grounded. The crystals are positioned on opposite ends of the cylindrical chamber such that the two electric fields generated by the crystals added by superposition to effectively double the potential between the crystals. A thermocouple was used to measure the TEC temperature and was assumed to be the same temperature at the grounded crystal surfaces. Figure 2 graphically depicts the experimental setup inside the vacuum chamber.

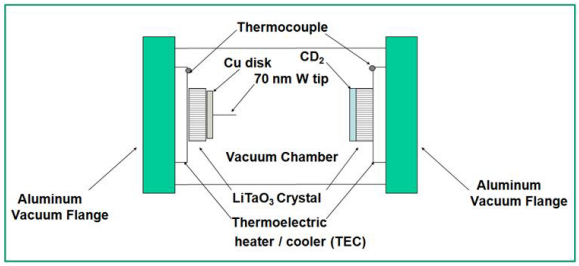

FIGURE 2. A diagram illustrating the experimental setup inside the vacuum chamber for the two-crystal pyroelectric accelerator at West Point.

The thermal cycle consisted of heating the crystal via the TEC for 5 minutes. The crystal was then set at a constant temperature for 5 minutes to allow for a more uniform heat distribution throughout the crystal. The TEC was then turned off and the crystal cooled down via conduction through the flange upon which it was mounted. The data was collected for 300 seconds.

EXPERIMENTAL RESULTS

Figure 3 shows the x-ray spectrum generated by a two-crystal pyroelectric system during the cooling phase of the thermal cycle as gathered by a sodium Iodide (NaI) detector. The Bremmstrahlung spectrum is an effect of the acceleration of positive residual gas ions away from the positive crystal face into the opposing target crystal and surrounding vacuum chamber walls. The maximum end-point energy of the x-rays is approximately 150 keV and it is assumed that residual gas ions experienced the same electric potential field. Previous results[1] have shown that this acceleration potential is adequate to achieve D-D nuclear fusion using a one crystal system. The Bremmstrahung spectrum appears cut off at lower energies. This is most likely due to absorption of lower energy x-rays in the aluminum flanges and the stainless steel chamber walls. To increase the probability of achieving fusion, USMA will replicate the two crystal system used at Rensselaer Polytechnic Institute.[2] Additional experimental work is planned to

achieve 200 keV ion energies at USMA. This work will include synchronizing the thermal cycles of the two crystals with a feedback control loop. The goal will be to match the electric potentials from both crystals such that superposition of the two potentials will result in an increased electric potential between the crystals.

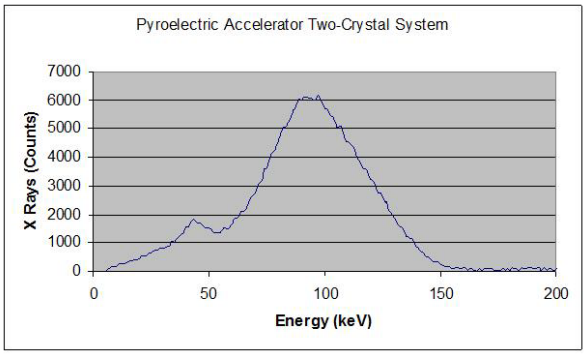

FIGURE 3**.** A graph of a Bremsstahlung x-ray spectrum generated by the field ionization and acceleration of residual gas particles from a two-crystal system inside a vacuum chamber over a 5 minute counting period. The end-point energy indicates an acceleration potential of approximately 150 keV. The lower energy x-rays may have been absorbed or scattered by the stainless steel vacuum chamber wall. A 5 minute background radiation spectrum was stripped out of these results.

FUTURE WORK

The ultimate goal of this project is to facilitate D-D fusion by leaking deuterium gas into the system and coating the negative crystal face (the target crystal) with deuterated polyethylene. Unlike fission, the probability of fusion is increased with high kinetic energy ions. To achieve higher energies, the acceleration potential must be optimized.

One method to optimize the acceleration potential is to precisely control the thermal cycle of the crystals through a proportional thermal controller.[4] This controller will utilize a LabVIEW program to read the temperature of the thermocouple, analyze the desired temperature at that time in the cycle, and adjust the TEC current accordingly. Once the acceleration potential is raised to 180- 200 keV, deuterium gas will be introduced into the system to achieve D-D nuclear fusion

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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