D-D Nuclear Fusion Using Different Size Pyroelectric Crystals

A. M. Kovanen, D. J. Gillich, T. Z. Fullem, and Y. Danon

Abstract—Theory predicts electrons play a detrimental role in creating the conditions for D-D fusion in pyroelectric crystal accelerators. Three different pyroelectric crystal sizes were paired in six different configurations to determine if experimental results agree with theory. An experimental configuration using a 30 mm diameter tip crystal opposite a 20 mm diameter target crystal yielded better neutron results than a 20 mm diameter tip crystal versus a 30 mm diameter target crystal as predicted by theory. Two 20 mm diameter by 20 mm thick lithium tantalate crystals yielded $-1 \times 10^4$ neutrons per thermal cycle.

I. INTRODUCTION

Pyroelectric crystals exhibit a nonzero spontaneous polarization due to the dipole moments of the crystal unit cells [1] and can be cut such that the dipole moments are perpendicular to the flat surfaces, known as the $+z$ and $-z$ faces. As a pyroelectric crystal experiences a temperature change, the dipole moments either become more or less aligned with the $z$ faces resulting in the spontaneous polarization either increasing or decreasing. This change in polarization causes charge to build on the $z$ faces. The amount of charge induced on a $z$ face, $\varphi$, is given by [2]:

$$\varphi = \gamma A_{cr} \Delta T$$  \hspace{1cm} (1)

where $\gamma$ is the pyroelectric coefficient of the crystal, $A_{cr}$ is the surface area of one of the crystal’s $z$ faces, and $\Delta T$ is the change in temperature. Since little if any charge migrates through the crystal, pyroelectric crystals can be modeled as parallel plate capacitors with a capacitance, $C_{cr}$, given by:

$$C_{cr} = \varepsilon_{cr} \varepsilon_0 A_{cr}/t_{cr}$$  \hspace{1cm} (2)

where $\varepsilon_{cr}$ is the relative permittivity of the crystal, $\varepsilon_0$ is the permittivity of free space, and $t_{cr}$ is the thickness of the crystal. For a two-crystal configuration in which opposite polarity $z$ faces oppose each other, the accelerating potential, $V$, is given by:

$$V = 2\varphi/C_{cr}$$  \hspace{1cm} (3)

For the two-crystal system shown in Fig. 1 using cylindrical lithium tantalate (LiTaO$_3$) crystals ($\gamma = 190 \mu C/m^2/K$, $\varepsilon_{cr} = 46$) [3] with a diameter of 30 mm and thickness of 10 mm, theory predicts the charge induced on each crystal face after undergoing a 100 K temperature change is 13.4 $\mu$C with an accelerating potential of 933 kV between the crystals. However, 200 kV accelerating potentials for such a system are more typical, likely due to the effects of charge migration and parasitic capacitance [4]. The theoretical limit of neutron production for the system described above with a 200 kV accelerating potential is about $2 \times 10^7$ neutrons per cooling cycle [5].

II. EXPERIMENTAL METHODS

LiTaO$_3$ crystals of three different sizes were used in this research. Table I lists the pertinent information of each crystal as well as the acceleration potential and induced charge on the $z$ face relative to a 20 mm diameter, 10 mm thick crystal.

<table>
<thead>
<tr>
<th>Name</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Relative Charge</th>
<th>Relative Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short (S)</td>
<td>20</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Wide (W)</td>
<td>30</td>
<td>10</td>
<td>2.25</td>
<td>1</td>
</tr>
<tr>
<td>Long (L)</td>
<td>20</td>
<td>20</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

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The $-z$ face of a LiTaO$_3$ crystal was mounted with conductive epoxy to a piece of copper tape that covered one side of a thermoelectric cooler (TEC). A section of copper tape extended off the TEC in order to ground the $-z$ face to the vacuum chamber. Attached to the $+z$ face with conductive epoxy (except for one trial during which JB Weld epoxy was used) was a copper disc with a thickness of approximately 0.5 mm and a diameter approximately 4 mm less than the diameter of the crystal upon which it was mounted (e.g. 26 mm diameter copper disc on a 30 mm diameter crystal). In all configurations except one, a dual inline package (DIP) socket was soldered to the center of the copper disc to facilitate the easy changing of tips. All tips used were 70 nm radius tungsten tips except for a single experiment that used a 100 nm radius tungsten tip. After removing the excess copper tape around the base of the crystal on the TEC surface, a bead of insulating lacquer was applied to the base of the crystal and part of the copper tape to prevent discharges coming from the $+z$ face of the crystal.

The tip assembly was secured to a 4.5 in Conflat (CF) aluminum blank-off with conductive epoxy. The target assembly was the same as the tip assembly (not considering crystal size) except the $+z$ face of the target crystal was mounted to the heater while the $-z$ face was covered in deuterated polyethylene. When using two 10 mm thick crystals, the crystals were approximately 7 cm apart once the blank-offs were secured to the vacuum chamber.

Temperature measurement was accomplished with a type T thermocouple mounted to both TECs with JB Weld. The JB Weld surrounding the thermocouple was coated with insulating lacquer. The deuterium gas pressure during experiments ranged from 3 mtorr to 35 mtorr. Typically, the crystals were heated from 30 °C to 130 °C over 5 minutes, remained at 130 °C for 5 minutes, and then cooled to approximately 40 °C over 6 minutes although different temperature profiles were also used. Temperature feedback and control was provided by two independent thermoelectric module controllers. In addition to the computer fans mounted on the air side of the aluminum blank-offs, two 10 inch household fans blew air onto the aluminum flanges for additional cooling.

Detection equipment consisted of a cadmium telluride (CdTe) $\gamma$ ray/x-ray detector and an NE-213 liquid scintillator proton-recoil detector. The x-ray detector was used to measure the energies and production rate of Bremsstrahlung x-rays. The maximum x-ray energy served as an indicator of D$^+$ energy. The proton-recoil detector along with pulse fall time analysis software was used to detect neutrons.

**III. RESULTS**

Fig. 2 shows the total neutrons emitted for each experimental configuration while Fig. 3 displays the x-ray spectrum for each configuration. Table II presents the salient data from Fig. 2 and Fig. 3 in tabular form. The optimum deuterium gas pressure for the two highest neutron-producing configurations was between 30 and 35 mtorr. The best neutron-producing trials for the other configurations occurred with deuterium gas pressures between 10 and 20 mtorr.

![Fig. 2. Total neutrons emitted over 5 minutes after subtracting background and accounting for an absolute detection efficiency of (4.2 ± 0.3) %. Each data point represents the weighted average of three trials weighted by the statistical error with the uncertainties representing the weighted standard deviation of the counts and background counting statistics [8].](image)

The long target-wide tip configuration produced more neutrons (about 3.3 times more) than the wide target-long tip configuration, lending support to the idea that electrons negatively affect the mechanisms of neutron production. If the long target-wide tip configuration only produced 2.25 times as many neutrons as the wide target-long tip configuration, then the difference could be attributed to the 2.25 times greater induced charge on the tip crystal due to it having a $z$ face surface area 2.25 times that of the target crystal. However, the multiple being over 2.25 supports the idea that electrons being accelerated away from the target crystal toward the tip crystal have a detrimental effect on neutron production. Although the exact mechanism of how electrons degrade neutron production is unknown, electrons neutralizing positive charge on the tip...
crystal as well as providing a path to ground the tip crystal likely play a role in reduced neutron production.

The configurations using a long crystal for both the target and the tip produced significantly more neutrons than all other configurations. Although the increased x-ray endpoint energies of the dual long crystal configurations appears to be the obvious explanation for their higher neutron production, it should be noted that the dual long crystal configuration with the 100 nm radius tip produced 175% more neutrons than the standard dual long crystal configuration despite having a 35% lower x-ray endpoint energy. The standard dual wide crystal configuration, which theory predicts should have produced 2.25 times more neutrons than the dual long crystal configurations, only produced one half to one fifth the neutrons as the dual long crystal configurations despite having a similar x-ray endpoint energy.

**Table II. X-Ray and Neutron Data [8]**

<table>
<thead>
<tr>
<th>Configuration (Target-Tip)</th>
<th>X-Ray Endpoint Energy (keV)</th>
<th>Total Neutrons Emitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-Long</td>
<td>318 ± 30</td>
<td>5700 ± 600</td>
</tr>
<tr>
<td>Long-Long, no DIP socket</td>
<td>295 ± 28</td>
<td>7500 ± 2000</td>
</tr>
<tr>
<td>Long-Long, 100 nm radius tip</td>
<td>236 ± 22</td>
<td>9800 ± 1300</td>
</tr>
<tr>
<td>Wide-Wide</td>
<td>264 ± 25</td>
<td>2200 ± 200</td>
</tr>
<tr>
<td>Wide-Wide, JB Weld at copper disc/crystal interface</td>
<td>155 ± 15</td>
<td>990 ± 130</td>
</tr>
<tr>
<td>Long-Wide</td>
<td>161 ± 10</td>
<td>2100 ± 200</td>
</tr>
<tr>
<td>Wide-Long</td>
<td>92 ± 7</td>
<td>610 ± 200</td>
</tr>
<tr>
<td>Short-Long</td>
<td>139 ± 13</td>
<td>1300 ± 200</td>
</tr>
<tr>
<td>Wide-Short</td>
<td>150 ± 14</td>
<td>1500 ± 200</td>
</tr>
</tbody>
</table>

Fig. 3. X-ray spectrum for each experimental configuration. The lines overlaying the last four spectra are used to extrapolate their endpoint energies [8].

Inspection of x-ray multichannel scaler (MCS) plots reveals a possible reason why the configurations using wide crystals produced fewer neutrons than the dual long crystal configurations. It can be seen in Fig. 4 that the dual long crystal configurations produced x-rays over a longer period of time as compared to the dual wide crystal configuration. X-ray count rates suddenly dropping or ceasing altogether as shown in Fig. 4 (d) are believed to be caused by electrical arcing between the tip crystal and the vacuum chamber. If true, these so-called discharges would remove most if not all charge from the $z$ face of a crystal and end neutron production. The closest grounding point for a long crystal was the vacuum chamber wall, 21 mm from the edge of the $z$ face. The closest grounding point for a wide crystal was either the wall of the vacuum chamber or the CF blank-off onto which the crystal assembly was mounted, both 16 mm away. The wide crystal being 5 mm closer to a grounding point than the long crystal coupled with the greater number of discharges experienced by the dual wide crystal configuration provides compelling evidence electrons have a negative effect on neutron production.

**IV. Conclusions**

Experimental evidence supports the theory electrons are detrimental to neutron production in a pyroelectric crystal D-D fusion device. A long target-wide tip configuration produced 3.3 times as many neutrons as a wide target-long tip configuration – greater than the 2.25 multiple expected if electrons did not affect neutron production. The dual wide crystal configuration, which had a grounding point 5 mm closer than the dual long crystal configurations, discharged more than the dual long crystal configurations, an observation not expected if electrons did not affect the system. The dual long crystal configurations produced up to $10^4$ neutrons per thermal cycle. The management of electrons should be considered in order to increase neutron production from future pyroelectric crystal D-D fusion devices.
DISCLAIMER

The views expressed herein are those of the authors and do not reflect the position of the United States Military Academy, the Department of the Army, or the Department of Defense.

REFERENCES