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Pyroelectric crystal D-D and D-T neutron generators

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ABSTRACT: Pyroelectric neutron generators are a recent development utilizing the pyroelectric effect to produce an accelerating electric field and thus enabling creation of small electron and ion accelerators without external high voltage power supply. The principle of operation includes a pyroelectric crystal ($LiTaO_3$ for example) placed in vacuum and simple heating (or cooling) of the crystal to cause a change in polarization. The change in polarization creates free charges on the faces of the clyndrical z-cut crystal and due to its small capacitance this creates a high potential between one crystal face to the other which is placed at ground potential. To produce neutrons the crystal is placed in low pressure deuterium gas and when the crystal is heated or cooled it ionizes the gas and accelerates deuterium ions towards a deuterated or tritated target. A configuration with two crystals can double the acceleration potential and thus increase neutron production. When operating such a device x-rays with energy over 200 keV about 10^5 neutrons per heating cycle can be produced. Research is focused on improving the neutron yield, the emission reproducibility, and shortening the heating cycle. Neutron generators based on this technology can be made small portable and relatively cheap compared to sealed tube technology. Further development is needed in order to increase the neutron yield closer to the theoretical limit for a specific crystals size.

KEYWORDS: Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators); Ion sources (positive ions, negative ions, electron cyclotron resonance (ECR), electron beam (EBIS)); Accelerator Applications

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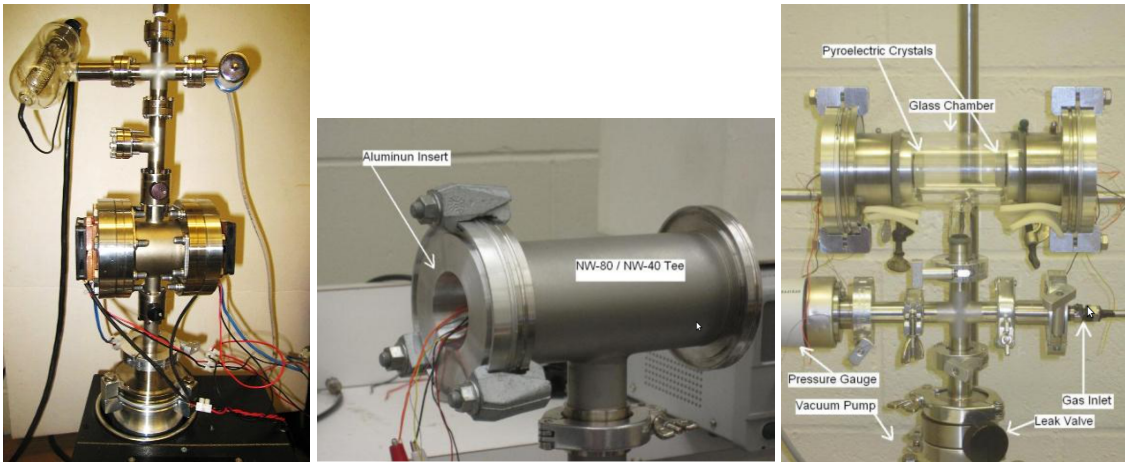
1 Introduction

Recent interest in pytroelectric acceleration lead to development of x-ray [1], ion [2] and neutron sources [3–5] based on this phenomena. All these applications use the pyroelectric effect to create an acceleration potential and thus eliminating the need for external high voltage power supply. A pyroelectric crystal is spontaneously polarized when it is in equilibrium conditions, heating or cooling of the crystal results in a change in the electric polarization which causes rearrangement of the charge on the crystal surfaces. Because of the high crystal resistivity and low capacitance when the crystal is placed in vacuum, and changes in polarization occur, it behaves like a charged capacitor [1]. Considering a simple arrangement of a z-cut cylindrical crystal and a metallic plate at a distance d to the crystal face, and assuming the charge generated by heating or cooling the crystal is q, the electric field between the crystal and plate E is given by $E = q/(d \cdot C)$ [6], where C is the capacitance of the crystal-plate system. The amount of charge q accumulated on the crystal face is proportional to the pyroelectric coefficient of the crystal and thus the crystal properties and the geometry of the system determine the accelerating potential between the crystal and plate. It is therefore desirable to select a crystal with high pyroelectric coefficient, high resistivity and low capacitance (low permittivity). With a temperature difference of about 120°C electron acceleration potentials of up to 300 keV were demonstrated with $LiTaO_3$ crystals [7].

Pairing two pyroelectric crystals such that one accelerates and the other attracts ions helped double the accelerating potential and thus increases the D-D fusion reaction cross section. Acceleration potential of about 200 keV were used for neutron production [3]. Gas ionization was achieved by ionization occurring near the crystal surface [8], a tip mounted to the crystal or by using nanorods [4]. The ion current is limited is by the crystal pyroelectric coefficient, the applied temperature difference and the efficiency of gas ionization and was reported to be a few tens of nanoampers [4]. For a system with two 1cm $\times$ 3cm diameter $LiTaO_3$ crystals with an average ion acceleration potential of $\sim$180 kV of D+ ion, the D-D fusion yield is expected to yield $\sim 10^7$ n/cycle [10]

To create a practical application research at RPI was focused on production of a portable pyroelectric neutron source with emphasis on improvements of the neutron production yield, reproducibility, and controlled emission length. Such sources can find uses in neutron detector calibration, research, and education.



(a) **(b)** **(c)**

Figure 1. Several setups used for D-D neutron generation referred to as GEN II (a), GEN III (b), and GEN III+ (c). The main chamber holding the crystals is visible in the center, generation III+ used a glass chamber.

2 Pyroelectric neutron production

There were several generations of experimental setups developed at RPI in an attempt to achieve the three goals described above with most effort dedicated to improvements of the neutron yield. All systems utilized a double crystal configuration to increase the acceleration potential, several mTorr of flowing D_2 gas and a deuterated polyethylene target which coated one of the crystals (see figure 1). Gen-I system described in reference [3] utilized a large vacuum chamber where the crystals were attached to thermoelectric coolers (TECs) mounted on large copper heat sinks which did not allow for much control over the crystal heating or cooling rates. This system generated neutrons on cooling yielding about 6×10^4 n/cycle and acceleration potential of $\sim$200 keV. This system was later improved to include liquid cooling of the TEC which allowed the use of a computerized temperature control. Gen-II system was geared towards portability and described in detail in reference [9]. In this system the TEC was inside the vacuum chamber mounted to the chamber wall and was cooled using small fans mounted outside the vacuum chamber. This system used a computerized heating and cooling control and also produced neutrons during the cooling cycle yielding a maximum yield of $\sim10^5$ n/cycle. The system provided reproducible results giving $1.2\pm0.2\times10^4$ n/cycle averaged over five consecutive cycles. This system also demonstrated that the neutron production duration can be limited to $\sim$30 seconds.

The GEN-III system [10] was designed to improve performance of a sealed system by removing the TEC outside the vacuum system and providing the crystal heating and cooling through the specially made thin aluminium chamber walls. The TEC was vented using a small CPU fan. The Gen III+ system was designed with glass walls to study if the interaction of the electric field with the metallic wall of GEN III design is disruptive. In all these systems discharges were observed that resulted in complete loss of the charge on the crystal. To minimize discharge the face of the crystal and the copper disk holding the tip were kept smooth.

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3 Results

Reproducibility in the neutron yield is important when developing a practical neutron source, most of the research found in the literature [3–5, 12] report the highest neutron yield often obtained in a single experiment and could not be repeated and do not provide additional information on the reproducibility. The RPI GEN-II setup results presented in reference [9] and gave $1.2\pm0.2\times10^4$ D-D n/cycle in a reproducible way for at least 5 consecutive experiments. In an attempt to improve the gas ionization tungsten nanorods were used instead of the tip used in with previous work [10]. The problem with the tip is fast erosion; such that even if the system initially worked well after one or two emission cycles the tip deteriorated and the neutron yield was reduced [10, 12]. The work with tungsten nanorods in reference [10] indicated that the nanorods have the same problem; it is possible that carbon nanorods will be more robust and can provide a solution to this problem.

The more recent work in reference [11] addressed thermal issues as discussed above. It also improved the algorithms that control the two crystal hearting cycles trying to better match the heating and cooling rates in order maximize the acceleration potential. The concept of heating and cooling the crystals from outside the vacuum chamber worked well and reduced the number of components inside the vacuum such that a sealed system will have reduced vacuum contamination. However the best neutron production yield from this system was $4.6\pm0.5\times10^3$ n/cycle with reproducible values of $\sim2\times10^3$ n/cycle which is not an improvement of our previous results. Other issues that were considered include the tip length [13] and the type of ionization species produced [14]. It was found that an optimum tip length required to maximize the field near the tip can be approximated by a simple equation and for 70 nm tip diameter a 1 cm long tip is the optimum. A study of the ionization species produced near the tip was performed by using magnetic field and collimation to create a mass spectrometer that can analyze the ions produced by a pyroelectric crystal for different surrounding gases. For deuterium it was found [14] that most of the produced ions were D_2^+ and not the desirable D^+. This implies that the acceleration energy is divided by the two D ions and thus reduces the energy and cross section of the D-D reaction. However the tip used for these experiments could have been eroded which can results in a lower field around the tip and thus less efficient D^+ production.

4 Conclusions

Pyroelectric crystal accelerators were shown to be a viable way of producing D-D and D-T neutron. For the experimental geometries discussed in reference [10] the theoretical D-D yield assuming D_2 gas ionization efficiency of 100% is $\sim10^7$ n/cycle and could reach $\sim10^7$ n/s for the D-T reaction . The experimentally observed yields are on the order of 10^5 n/cycle and thus more research is needed in order to optimize the system and reach closer to the theoretical yield. It was demonstrated that the neutron emission during heating or cooling can be shortened to $\sim$30 seconds during a typical heating/cooling cycle of about 2–3 minutes. Pulsed operation at low repetition rate was also demonstrated by the LLNL group [15]. The current state of this technology allows production of a low cost sealed D-D or D-T neutron source with neutron yield which sufficient for testing of fast neutron detectors.

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