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Demonstration of a non-contact x-ray source using an inductively heated pyroelectric accelerator

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ABSTRACT

X-ray emission from pyroelectric sources can be produced through non-contact thermal cycling using induction heating. In this study, we demonstrated proof of concept device induction heating powered x-ray source. An induction heater operating at 62.5 kHz provided a total of 6.5 W of delivered peak thermal power with 140 V DC of driving voltage. The heat was applied to a ferrous substrate mechanically coupled to a cubic 1 cm^3 Lithium Niobate ($LiNbO_3$) pyroelectric crystal maintained in a 3–12 mTorr vacuum. The maximum temperature reached was 175 °C in 86 s. The cooling cycle began immediately after heating and was provided by passive radiative cooling. The total combined cycle time was 250 s. x-ray photons were produced and analyzed in both heating and cooling phases. Maximum photon energies of 59 keV and 55 keV were observed during heating and cooling, respectively. Non-contact devices such as this, may find applications in cancer therapy (brachytherapy), non-destructive testing, medical imaging, and physics education fields.

1. Introduction

The pyroelectric property of several classes of ferroelectric crystal produces a spontaneous depolarization upon bulk heating or cooling of pre-polarized crystals [1–5]. If a crystal is cut across its axis of polarization, the two formed faces of the crystal (denoted as Z+ and Z−) can have large differential potentials generated during either bulk heating or cooling [6,7]. At sufficient potential, either field-emission of electrons or ionization of gas molecules at the crystal surface combined with a long mean-free path for ions and electrons, leads to particle acceleration [1,8,9]. When the charged electrons or ions interact with surfaces, x-ray photons are generated through characteristic and bremsstrahlung emission processes [10].

Thus far, studies of pyroelectric x-ray production have relied on thermal differences created by a cryogen [11], peltier junction [5,8,12], or resistor [8,13] to cycle pyroelectric sources. A non-contact method for crystal cycling has not been extensively investigated to date. In our study, we use induction heating to thermally cycle a pyroelectric x-ray source. A non-contact power source provides the ability to place accelerators in distributed locations without electrical interconnection. New commercial products including non-contact mobile phone chargers and medium range, high-load power transfer systems are actively being developed by the company Witricity [14–18]. Investigations are currently underway to use these systems and other manefestations of this technology for implanted biomedical applications [19]. Pyroelectric x-ray emission sources have been investigated for imaging [20] and medical therapy applications [21,22]. The ability to hermetically seal and isolate an entire emission source, along with the thermal generator, adds greatly to the potential use in medical and distributed-source imaging, as well as therapy applications.

The power for thermal cycling is provided through radio frequency induction heating of a ferrous substrate that is in direct contact with the pyroelectric crystal. The cooling portion of the cycling process employs thermally radiative and conductive heat loss from the crystal. Induction heating of conductive material relies primarily upon joule heating due to induced eddy currents within the heated material. In ferromagnetic material, hysteresis loss heating also occurs due to the shifting of induced magnetic dipoles. This effect occurs negligibly in non- ferrous materials. This mechanism contributes to substrate heating up to the Curie temperature, above which, the spontaneous magnetization properties of the material are lost. As both the ferromagnetic Curie point of iron and the ferroelectric Curie point of $LiNbO_3$ are above

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the final heating temperatures used in this study, Curie point discontinuities can be ignored. The power delivered due to joule heating is defined as $I^2 R$. The substantial current flowing through a material of moderate resistance results in efficient heating. The high resistivity of water, pyroelectric crystals and glass (on the order of $10^{-14}\,\Omega^{-1}\,m^{-1}$) [23] lead to negligible induced eddy current flow in these materials, and consequently to negligible heating. Despite negligible induced current flow, the dielectric effect contributes to the heating of non-conductive materials. This effect requires higher operational frequencies to be effective [24,25]. Selective heating requires the addition of a ferroelectric substrate mounded on the pyroelectric crystal to permit efficient inductive heating.

In this study we evaluate the parameters associated with the development of a pyroelectric x-ray generator. We have constructed a model source and have evaluated operational properties.

2. Materials and methods

2.1. Pyroelectric x-ray source design

A first order approximation for maximum generated voltage is solved by treating the pyroelectric crystal itself and the gap between the crystal surface and the measurement electrode as a set of two capacitors [9] as shown as below

$$V = \frac{Q}{C_{sys}} = \frac{\gamma \Delta T}{\varepsilon_o((\varepsilon_{CR}/d_{cr}) + (1/d_{gap}))} \approx \frac{\gamma \Delta T}{\varepsilon_o \varepsilon_{cr}/d_{cr}} \quad (1)$$

The terms in the equation correspond to generated charge (Q) [Eqs. (1) and (2)] the permittivity of free space (ε_o), the crystal dielectric constant ($\varepsilon_{cr,}$), the crystal thickness (d_{cr}), and the acceleration gap distance (d_{gap}), respectively. As a first order of approximation (Eq. (1)), acceleration gap distance (distance between crystal face and electrode) can be assumed as infinite. The low thermal conductivities of lithium tantalite and lithium niobate limit the effective thickness at 1 cm, with increased potential not observed with thicker crystals [8].

The total charge generated by the pyroelectric crystal (Q) in one heating cycle of a given temperature range (ΔT) is estimated as the product of the surface area (A) of the crystal and the pyroelectric constant for the crystal (γ) is shown below

$$Q = A\gamma\Delta T \quad (2)$$

A pyroelectric accelerator was constructed within a modified 70 mm length borosilicate flat-bottomed test tube with 2.0 mm thickness and a 20 mm diameter (Fig. 1). The chamber was comprised of all glass, with either melted glass or semi-permanent Torrseal epoxy glass-metal interface seals (Varian, Inc., Palo Alto, California, USA) [26]. A K-type thermocouple was mounted onto the bottom of the tube and sealed with epoxy. A 1 cm^2 of 0.1 mm thick razor steel was bonded to the z-face of a 1 cm^3 cubic z-cut pre-polarized lithium tantalite crystal (Crystal Technologies, Palo Alto, California, USA) using 0.05 g of graphite-doped Torrseal. The addition of graphite permits electrical conductivity with a resistance of approximately 100 kΩ. Razor steel does not easily corrode during experimentation with prolonged contact to water, easy to source, is available in multiple thicknesses and heats well through induction. The crystal with the bonded metallic sheet was bonded to a K-type thermocouple using 0.05 g of graphite-doped Torrseal. A second glass tube, containing a copper electrode, was glass melt-bonded onto the side of the first tube at a height of 15 mm above the crystal. The electrode, comprised of oxygen-free copper with a 20° flat edge, was mounted with the angled edge facing the crystal. Hermetic glass sealing around the copper electrode support wire and thermocouple leads were accomplished through a metal-glass pinch Housekeeper seal [27,28]. The top of the borosilicate tube assembly was Torrseal bonded to a 2–3/4" conflat (CF) vacuum flange blank. This flange was used to interface the experimental accelerator into the backing vacuum system. The vacuum was provided by a diffusion pump (Type 0161, Varian, Inc.) with a fitted liquid nitrogen cold trap. The backing vacuum was provided by a 2-stage rotary vacuum pump (Model 2020, Alcatel Vacuum Technology, Annecy, France). The vacuum measurement was provided by a Baynard–Alpert gauge (Model 0571-K247, Varian, Inc.) and a thermocouple gauge (Model 500, Vacuum Industrial Products, Downers Grove, Illinois, USA). Simulation and experimental findings by Geuther, Danon et. al. determined that the charge distribution on the emitting surface of the crystal leads to self focusing of emitted ions and electrons and that this distance is approximately 7–10 mm for a 10 mm diameter cylindrical crystal [29]. Our group verified this conclusion using a luminous ZnS(Ag) phosphor sheet temporarily mounted to the electron target. We verified this same conclusion, although minor spatial distortion of the focused spot was due to the square emission geometry [8]. A 1 cm^3 cubic crystal and an 0.8 cm crystal to electrode spacing were used. We also determined that pyroelectric crystals composed of Z-polarized Lithium Tantalate ($LiTaO_3$) and Lithium Niobate ($LiNbO_3$) produced similar self-focusing results. Pilot study experimental findings within our group have also determined that dynamic pressures of 3–20 mTorr produce the highest x-ray emission rates for both types of crystals. These results were similar to those from other studies [10,21,30]. This pressure range was maintained during experimentation manually through the minor adjustment of a needle leak valve.

2.2. Induction heater design

To heat the metallic substrate of the pyroelectric crystal, a Royer-type induction heater was constructed. The design of this heater was largely based on a modified version of the "Roy" open source induction heater development project (Fig. 2) as sponsored by Fluxeon, Inc. (San Diego, California, USA). The magnitude of induced currents is highly dependent on induction heater and workpiece (heated material) geometry. As a first order approximation for small workpieces (Eq. (3)), penetration depth (δ) is calculated as a function of material resistivity (ρ), relative magnetic permeability (μ), magnetic permeability of free space (μ_o), and frequency (f) [31].

$$\delta = \sqrt{\frac{\rho}{\pi \mu \mu_o f}} \quad (3)$$

The main oscillator circuit of the induction heater consisted of a set of four insulated gate bipolar transistors (IGBTs) in a push–pull configuration. The running frequency of the oscillator was 62.5 KHz. A coupling transformer with a secondary load-coupling network provided current to a work coil built from a ferrite (Fig. 1a, c, and Fig. 2). A 0.5 mm thick, fibrous spacer was placed between both halves of the ferrite core to prevent magnetic core saturation. On the other side of the core, two 6-turn windings are on opposite sides of a 26 mm gap cut from the ferrite body. This gap serves as the location where the work piece is placed during heating. The high voltage (HV) DC power supply for this circuit supplied 140 V for operation. A shunting resistor and a relay control circuit provided TTL switched, rapid ramping of DC voltage between 0 V and 140 V within 0.25 s (within 10% margin of error for both values). A DC power supply of 140 V was chosen based upon the designed operating voltage for this circuit. By design, with the 15 V circuit logic-control supply still present, rapidly ramped HV supply voltage changes permit stable control of supplied radio frequency

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