DESIGN, FABRICATION AND CHARACTERIZATION OF A MICRON-SCALE ELECTRON SOURCE BASED ON FIELD ENHANCED PYROELECTRIC CRYSTALS

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Abstract

As a part of the Micro Accelerator Platform (MAP) project, an electron source with a sub-micron size emitter is required. It is also desired that the source produces electrons with energies above the structure's minimum capture energy (about 25 keV) without the use of an external power supply. Field enhanced emission backed by field generation in pyroelectric crystals has been explored for this application. Here we present experimental progress towards characterization of electron, and x-ray emission. Purpose built diagnostics and specialized test assembly for optimized heat transmission are discussed.

INTRODUCTION

The Micro-Accelerator Platform (MAP) project has been under development for several years at UCLA and Manhattanville College. The MAP is a millimeter scale, dielectric based, laser-driven resonant structure aiming for gradients at GV/m level. Electrons injected in the structure can be accelerated to energies up to several MeVs and used for a range of applications, such as portable radiation sources.

In addition to a particle source, the MAP requires an injection method that accommodates the very small structure acceptance. To meet this challenge, we propose a novel micron-scale electron emitter, integrated with the accelerator structure. This unique source will deliver a beam, matched in size and current to the dimensions and capabilities of the MAP. The source consists of nanomachined emitting tips on a crystalline substrate; when the region is filled with laser energy, the tips undergo laser-enhanced field emission via multiple mechanisms. In this way, we produce sub-micron beams with controllable aspect ratios, which can then be captured by the accelerator structure. We also avoid the difficulties of applying external DC or AC voltages within a miniaturized portable device. The charge per microbunch remains low (~1 fC), ameliorating concerns about space charge and unreasonably high energy densities. Here, an optical period is ≈ 3 fs, implying a bunch length <1 fs, and bunch currents ~ 10 μA. Since each laser pulse will produce thousands of electron microbunches (over ps pulse lengths) and the laser's repetition rate is high (10-100 MHz), the total charge per second delivered by the device can be several orders of magnitude larger. Further, both source and accelerator can be powered by a single laser, simplifying the integrated device.

We are investigating pyroelectric crystals (PECs) as a potential source of sub-relativistic electrons for injection into the MAP structure. PECs are a subclass of ferroelectric materials known [4, 5, 6] for spontaneous electric dipole alignment (polarization) when out of temperature equilibrium. The uncompensated layer of surface charge can than produce large electric fields near the crystal surface. When forced out of temperature equilibrium, the bulk polarization generates electric fields in the order of 10^4–10^8 V/m, at the e.g. z-faces of the $LiNbO_3$ crystal surface. The sign of the field depends on crystals' orientation, and whether the crystal is being heated or cooled. Since there are virtually no charge transport channels in the crystal, the relaxation time for the return to equilibrium via bulk conduction is typically on the order of hours. Due to this quasi-constant surface field, pyroelectric electron emission (PEE) can occur via field emission or field ionization effects, both of which have been observed [6, 7]. Details of the surface interactions remain poorly understood and require further investigation.

Significant work has been done towards demonstrating that emission can be enhanced by adding needle-like cathodes or other sharp surface features, as has been well documented in conventional photoinjectors [8]. The combination of field generation by uncompensated charge in a PEC and field emission from a sharp tip represents an original approach to electron beam generation.

Past work has emphasized fabrication and qualitative results from these emitters. The work presented here focuses on quantifying repeatable measurements of output properties.

THEORY OF OPERATION

The accelerating field present between the crystal top surface and the adjacent grounded anode, located a distance d_g from the crystal is commonly estimated by [5]

$$E = \frac{\gamma \delta T}{\varepsilon_0} \frac{d_c}{d_c + d_g \varepsilon} \qquad (1)$$

where γ is the pyroelectric coefficient, $\delta T = T_1 - T_2$ the temperature departure from equilibrium, d_c the crystal thickness orthogonal to the emitting face, and ε the crystal's relative permittivity (Figure 1). It follows from (1) that temperature gradient is of greatest importance for the field generation, with weaker dependence on crystal thickness along the polarization axis. For typical material properties and geometries, fields of up to 140 kV are possible [4]. Tests with crystals from sub-mm to 1 cm thickness have shown stronger and more reliable field generation from thicker crystals, despite the longer time needed to generate the emission gradients. This anomaly could be due non-uniformities related mostly to manufacturing and supply, such as cuts not perfectly parallel to the z-axis, or fractured domains along the length of the crystals.

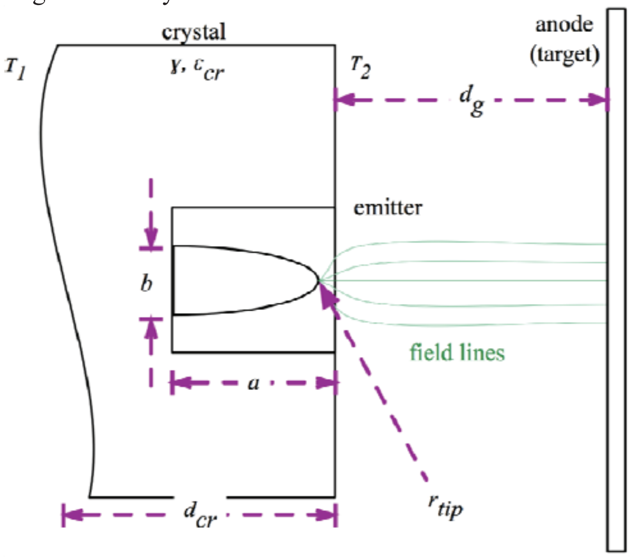

Figure 1: A cross-section of an emitter tip, showing an anode, and (conceptual) field lines.

The concept of field enhancing geometry is shown in Figure 1. The level of field enhancement for a long and narrow emitter is inversely proportional to the tip radius, and proportional to the length of the emitter. Brau provides a more detailed calculation for the field created by a needle-like emitter [9]:

$$E_{tip} = E_0 \frac{a^2}{b^2} \frac{\eta^3}{\arctan(\eta)-\eta} \quad (2)$$

where E_0 is the applied field, a is the emitter length, b is the diameter at the base of the emitter, and

$$\eta = \sqrt{1-\frac{a^2}{b^2}}, \quad (3)$$

is a convenient geometric parameter. The tip radius would be given by $r_{tip}=b^2/a$.

The level of field enhancement required is a function of the tip material and the applied field. For the cases of interest here, with fields in the 10-100 kV range over mm-cm gaps, the field enhancements are in the 100-1000 range, assuming metallic tips. We note that these required levels of field enhancement are rather modest, especially when compared with e.g. plasma TV and carbon nanotube levels.

EXPERIMENTAL SETUP

Experimental evidence has demonstrated the extreme sensitivity of PEE from Lithium Niobate crystals to the geometry and the detailing of the experimental setup [6]. The parameter space includes size and position of the crystal, ambient pressure, anode configuration, thermal contact, heat capacity of surrounding objects, and material composition of the holder.

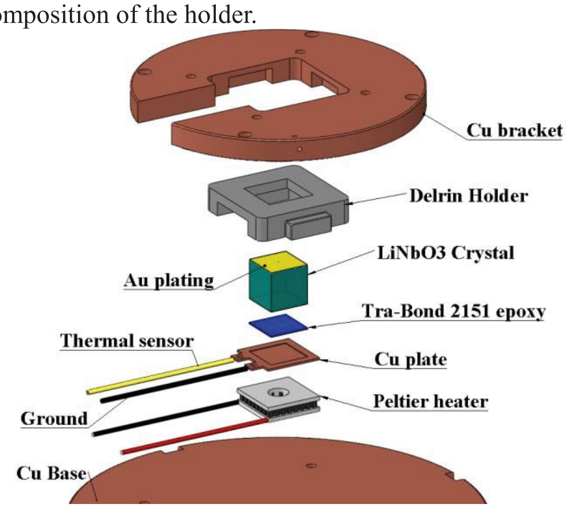

Figure 2: Holder assembly for optimized thermal transmission.

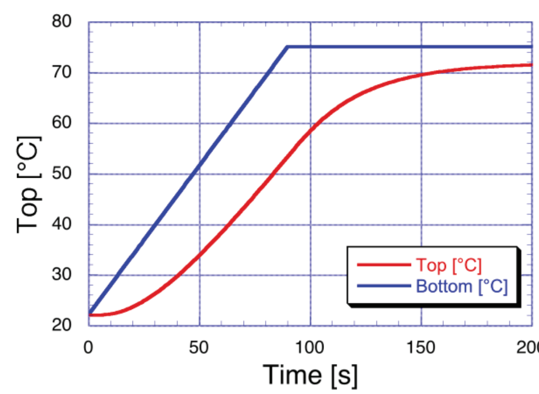

Figure 3: Simulation results (ANSYS). Lower curve (red) represents the temperature of the top surface.

Simulations and laboratory tests have shown that thermal contact between the crystal and the heater is of critical importance for reaching thermal gradients required for an emission. Transient thermal simulations performed in ANSYS have suggested that a 1 cm cube of Lithium Niobate would reach thermal equilibrium in about 3 minutes (Figure 3). After early tests produced thermal constants on the order of tens of minutes, the holder was redesigned to optimize thermal contact between heater and crystal, which reduced the heating times to match the simulation results. Our initial approach was a mechanical clamp, made of a dielectric (Delrin), to ensure good thermal contact between the bottom crystal face and the copper plate covering the Peltier heater. While effective, the mechanical clamping tended to produce pressure spots and scratches on the crystal surface. Such artifacts were evidenced in emission spots located near the edges of the holder. Our current design uses Tra-bond 2151 epoxy to secure the crystal to a copper plate, which is then mechanically clamped to the thermo-electric heater (Figure 2). This configuration has been very effective, further reducing heating times, and resulting in reliable emission with highly reproducible results even after hundreds of cycles.

RESULTS TO-DATE

Several variations of the test apparatus and emitter geometries have been required to produce consistent, stable electron output. To date, continuous, stable emission over several minutes has been measured repeatably. The average fluctuation level has been estimated at ±10%, although peak to peak fluctuations can be 100% over long time scales. The spot size with the scintillator (anode) within 2 mm or less appears to be resolution limited for the (few mm) thick targets used. With anode distances of several mm increasing spot sizes are observed indicating a divergent beam. Occasionally, larger "flashes" are observed. It is assumed that these are arcing events associated with imperfections on the crystal surface or metallic layer (e.g. scratches). SEM imaging of the emitter shows no damage even after hundreds of thermal cycles.

BEAM DIAGNOSTICS

To quantify the electron beam parameters, several techniques have been explored. A grounded, metalized scintillator (anode) and CCD camera (Figure 4) were used to image electron beam locations and intensity as a function of emission, tip geometry, anode distance, and heating/cooling pattern. Although in its present state this technique is not suitable for precise quantitative measurements, it has been appropriate for the determination of optimized mounting configurations, heating cycles, crystal response times, and beam spot size and location.

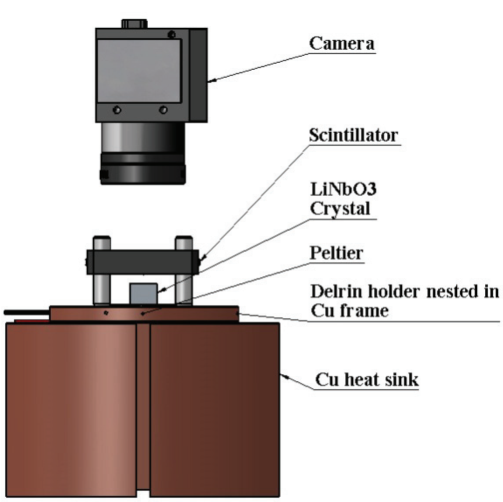

Figure 4: Experimental test stand.

In order to measure the energy of the electron beam a beam deflector has been designed and manufactured (Figure 5). It operates by accelerating electrons through a grounded anode into an area with a transverse electric field, and then imaged on a scintillator screen, with the degree of deflection used to measure the energy. Charge can also be measured using a Faraday cup. Both of these measurements are planned for the near future.

X-ray production through bremsstrahlung has been a complimentary goal of our program. It can also serve as an energy diagnostic for the electron beam. Production of x-rays has been confirmed through the use of a masked photodiode. Precise flux and spectral x-ray measurements are planned in the near future.

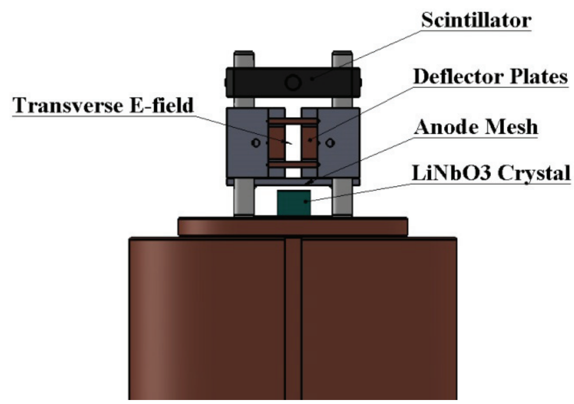

Figure 5: Deflector assembly.

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