

# ULTRA-COMPACT PIEZOELECTRIC TRANSFORMER CHARGED PARTICLE ACCELERATION

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**Abstract:** The high voltage capability, compact size, and high output impedance of piezoelectric transformers makes them very attractive primary high voltage supplies for charged particle beam applications. This paper will present and contrast recent results utilizing piezoelectric transformers to accelerate electrons and ions, to produce x-rays and neutrons for imaging and active interrogation and to produce low energy ion beams for electric micro-propulsion of spacecraft. In both cases, the piezoelectric transformer acts as the primary power supply for beam acceleration, and in the micro-propulsion thruster the transformer additionally produces dense surface plasma for ion extraction.

**Keywords:** piezoelectric transformer, electron beam, ion beam, neutron source, micro-propulsion

## INTRODUCTION

In many areas of science and engineering, there is a steady push toward smaller, more compact, and more power efficient devices. And this drive to smaller devices still requires similar, if not additional device functionality. Recently, this drive has extended to charged particle sources, charged particle beams, and plasma sources. Applications for very compact charged particle beams and plasmas are varied, and include medical devices for blood coagulation [1], sources for chemical laboratories-on-a-chip [2], ion accelerators for space propulsion [3], and ion and electron accelerators for compact radiation sources [4]. A key component of any charged particle beam or plasma source is a very compact, efficient high voltage source. This paper concentrates on the application of piezoelectric transformers to compact plasma sources and charged particle accelerators. In particular, we discuss the use of piezoelectric transformers to generate plasma and accelerate ions to modest energies for micro-spacecraft propulsion. Also, we discuss the application of piezoelectric transformers to generate 10s to 100 kV and accelerate ion and electron beams for radiation generation, specifically to produce x-rays for diagnostics and imaging and neutrons for special nuclear material detection.

Piezoelectric transformers have a number of advantages in charged particle accelerators and plasma sources. As high voltage generators, they are light and small compared to magnetic transformers, very efficient, and simpler to insulate at high voltages. Very high voltage piezoelectric transformers are often also high impedance, matching them exceptionally well with the typical ion or electron beam load. As plasma sources they have a number of advantages as well. Plasma discharges can be formed directly on the

transformer surface, with the dielectric strength of the piezoelectric crystal or ceramic providing isolation and current limiting capability. A convenient plasma production regime, the micro-discharge, can be accessed on the surface of the device, enabling efficient dense plasma production with high electron temperatures and low ion temperatures. Plasma source impedances, particularly in these glow discharge regimes, are often very high as well making the naturally high output impedance of the piezoelectric transformer an advantage again.

This paper will present two piezoelectric transformer based devices: the ferroelectric plasma thruster (FEPT) and the piezoelectric transformer accelerator (PTA). The FEPT is a plasma source and low energy ion accelerator for propulsion on micro-spacecraft and fine attitude control on larger craft. The PTA is an integrated high voltage generator, ion source and accelerator for accelerating ion and electron beams. Descriptions of both devices will be presented, as well as recent results.

## DEVICE DESCRIPTIONS

### Ferroelectric Plasma Thruster

The FEPT consists of a small disc of LiNbO<sub>3</sub> held between two conductive electrodes, as shown in the diagram and photo in Figure 1. The LiNbO<sub>3</sub> is a single crystal rotated 45 degrees about the x-axis, 10 mm in diameter and 2 mm thick. One surface of the disc is electroded with a solid stainless steel electrode affixed to the disc with silver epoxy. The opposite electrode is also affixed with silver epoxy and has an aperture that is centered on the disc, with the polarization vector directed out through the aperture. The solid electrode is driven by a radio frequency power supply at frequencies ranging from 375 to 400 kHz at an amplitude of 200-300 volts. The apertured

electrode is ground, and is oversized to make an effective ground plane.

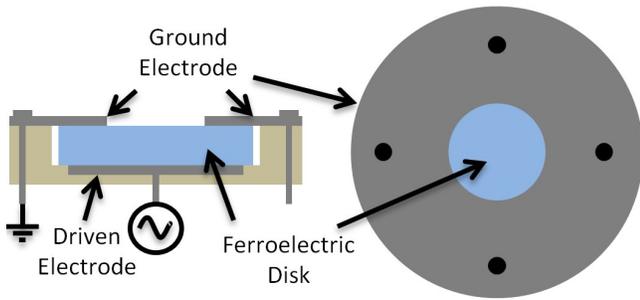


Figure 1. Diagram of the FEPT. The center aperture is about 7 mm in diameter.

The FEPT acts as a radial mode piezoelectric transformer to produce high electric fields on the surface of the device for plasma production and ion acceleration. The driving frequency is tuned to the radial vibration mode, creating voltages from the center of the aperture to the edges of several thousand volts. The high tangential electric field across the device induces surface discharges that ablate material from the crystal surface and fill the aperture with dense plasma. The aperture on the device surface allows some of the applied and induced electric field to leak through the aperture, producing a normal component of the electric field that decays quickly away from the crystal surface, as shown in electrostatic field plots in Figure 2. When the applied voltage is positive, ions in the surface plasma are accelerated away from the crystal surface by the normal electric fields. By the time the applied field reverses, the ions are in a region of much weaker electric field, so they continue away from the device producing thrust.

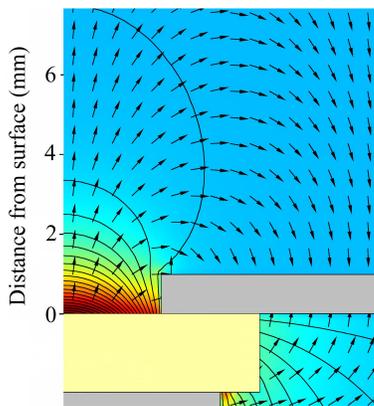


Figure 2. Plot of FEPT electric field (arrows) and potential (colors) calculated by Comsol finite element code.

### Piezoelectric Transformer Accelerator

The piezoelectric transformer accelerator (PTA) is built upon a high voltage Rosen-type piezoelectric transformer (PT). The PT is constructed from 135-degree rotated Y-cut LiNbO<sub>3</sub> single crystal, electroded with sputter deposited Al thin film electrodes. A photograph and diagram of the PT is shown in Figure 3. The PT was electroded both for unipolar and bipolar operation. For unipolar operation, the input electrodes were deposited over nearly half of the transformer length, producing high voltage at an output electrode at the transformer end. For bipolar operation, input electrodes were deposited on the center of the crystal, with high voltage developed at both ends of the transformer. The PT was operated at or near a resonant frequency of 43.5 kHz. The RF driving signal was provided by an Agilent 33220A waveform generator. The voltage was applied in bursts of approximately 1000 cycles with control over the applied frequency and voltage amplitude. The signal was amplified with an AR KAA1020 25 Watt RF amplifier. The amplifier had a 50Ω output impedance which was matched to the higher impedance of the crystal with an impedance matching transformer.

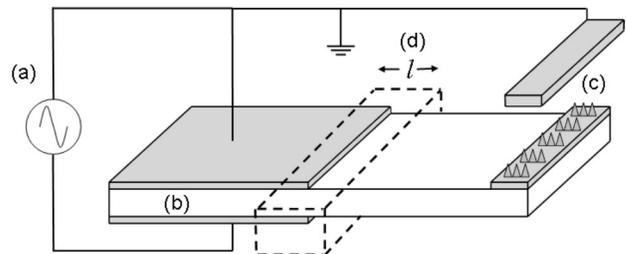


Figure 3. Schematic diagram of a unipolar output, high voltage piezoelectric transformer for the piezoelectric transformer accelerator. (a) RF source, (b) LiNbO<sub>3</sub>, (c) field emission diode, (d) parylene coating.

The PTA is intended to produce and accelerate electron beams to generate X-rays for imaging and surface analysis, and deuterium ion beams to produce neutrons in a deuterated target for active interrogation for nuclear safeguards. In both cases, electrons or ions will be produced by field emission at the output of the transformer. Electrons are produced by direct field emission from atomically sharp structures on the output. Ions are produced by field ion desorption from similar sharp structures. In both cases, the particles are accelerated into a target where the electrons are converted into x-rays by bremsstrahlung emission, and ions are converted into 2.45 MeV neutrons by

nuclear reactions with D loaded into the target. Particularly for neutron generation, ion energies must be 100 keV or greater for useful neutron yields to be generated. This puts a fairly stringent requirement on the PT, and introduces several complications into PT design.

High voltage output necessary for the PTA introduces a number of complications to the design of a Rosen PT. The first such challenge is flashover of the crystal surface near the input electrode edges. Electric fields are highest at this point, and triple point effects result in flashover field strength of 180 kV/cm, which are easily exceeded. To eliminate this problem, 5-10  $\mu\text{m}$  of parylene was deposited over the transition region from input electrode to bare crystal. These depositions of parylene effectively eliminated flashover on the crystal surface. The second complication was exceeding the yield stress of the material before the desired high voltage output was reached. Stress and strain are highest for the unipolar Rosen transformer near the center of the crystal, and cracking of the crystal was observed in this location. Bipolar operation of the crystal has been adopted as a way of distributing the stress over a larger amount of the crystal, to achieve a higher voltage output for a given crystal before cracking occurs.

## RESEARCH RESULTS AND DISCUSSION

### Ferroelectric Plasma Thruster

Operation of the FEPT as an ion source and plasma thruster has been demonstrated and characterized. Ion current from the source was measured with a Faraday cup placed far enough from the source to avoid modifying the accelerating field. Figure 4 shows the applied voltage with measured current at the Faraday cup. Ion currents are measured during the positive half cycle, and electron current is measured during the negative half cycle. This is an important result, since the ability to accelerate both ion and electron beams enables the FEPT to neutralize itself, avoiding spacecraft charging without the need for the complication and mass of a separate ion beam neutralizer. The measured ion current varies cycle to cycle, but the average ion current for the current FEPT design is 4 mA. A quadrupole mass spectrometer provided insight into the composition of the ion beam. Lithium and niobium ions were observed, coming from the crystal itself, along with silver ions from silver paint applied to the crystal surface. By adding silver paint, composition of the ion beam could be adjusted to be predominantly silver. Since all materials observed were present on the device surface, it was found that the FEPT produces

surface plasma through ablation of surface materials, and that ion beams are extracted from this surface plasma.

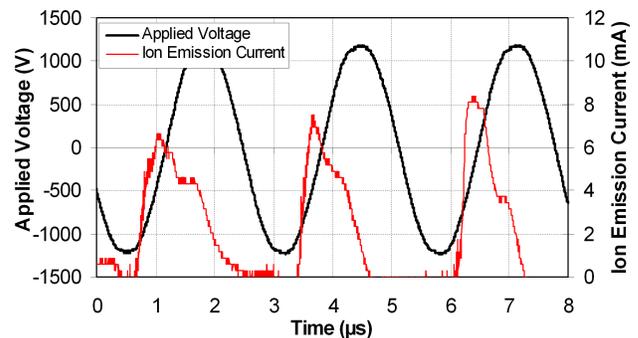


Figure 4. Applied voltage and current and measured ion current from the FEPT.

By using a retarding potential analyzer on the Faraday cup, ion beam energy distributions were obtained. The ion energy distribution peaks near 100 eV with an average ion energy of about 100 eV. Ion energies were clearly higher than can be expected from pure thermal expansion of the plasma, though they are lower than the applied voltage. One possible reason for reduced ion energy is shielding of the accelerating field by surface plasma.

Thrust and specific impulse produced by the FEPT were also measured. Thrust was measured with a calibrated, swinging gate style micro-thrust stand [3]. The tiny displacements of the vibrating arm were measured via optical interferometry. Specific impulse was measured by weighing the FEPT before and after operation and calculating the mass flow from the thruster. With a thrust measurement, the specific impulse could be calculated. The FEPT was found to produce between 68 and 87  $\mu\text{N}$  of thrust, at a specific impulse of 183 to 587 s. If all of the thrust were produced by an ion beam with 100 eV, the expected specific impulse is  $\sim 1300$  s. The smaller measured impulse indicates that a significant amount of the thrust is produced by hot neutrals flowing away from the source. With an input power of around 4-20 W, the thruster efficiency was found to be between 1 and 4.2 %, which is a respectable value for micro-propulsion thrusters.

### Piezoelectric Transformer Accelerator

Both high voltage operation and charged particle acceleration have been demonstrated by the PTA. In order to reliably measure the output voltage of the PTA, an exceeding high impedance diagnostic was needed with impedances very hard to achieve in an electrical probe. Hence, to measure high voltage

output without fear of loading down the transformer, a bremsstrahlung x-ray diagnostic was developed, as shown in Figure 5. For this diagnostic, atomically sharp Pt-Ir field emission structures were affixed to the PT output electrode. These structures emitted electrons via field emission, which were then accelerated across the gap into a Ti target to produce bremsstrahlung x-rays. X-rays and their energies were measured with an Amptek Si-PiN diode detector. The endpoint of the bremsstrahlung spectrum indicates the highest energy an electron received, and hence the peak output voltage of the device. The x-ray spectrum also demonstrated the ability of the PTA to produce and accelerate charged particle beams, as well as the suitability of the PTA as a compact x-ray source for imaging and surface analysis.

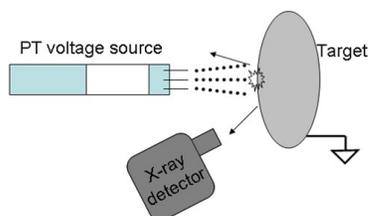


Figure 5. Bremsstrahlung x-ray measurement and high voltage diagnostic schematic.

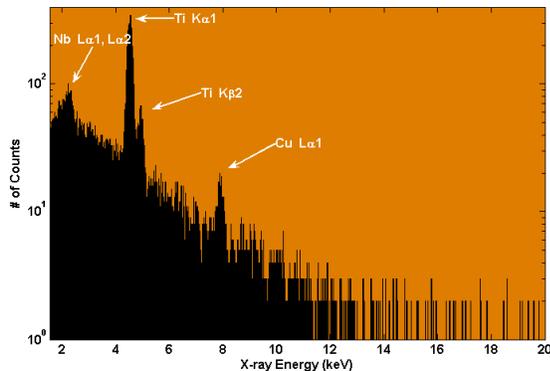


Figure 6. X-ray output from the PTA with field emission electron source and Ti target.

Both unipolar and bipolar output transformers were used to produce x-rays for output voltage measurement. Figure 6 shows a typical x-ray spectrum for a unipolar output high voltage generator. The endpoint of the spectrum indicates the peak voltage produced by the transformer, while the peaks in the spectrum are x-ray fluorescence from the Ti target as well as the niobium in the lithium niobate crystals. Using 70 mm long lithium niobate crystals, the maximum x-ray energy observed before the crystal fractured was about 14 keV, indicating an output voltage of 14 kV. With the bipolar output

transformer, the maximum x-ray energy was about 25 keV, demonstrating the enhanced output voltage available to the bipolar transformers.

## SUMMARY AND CONCLUSION

The FEPT and PTA have been demonstrated to be unique high voltage plasma, ion and electron beam sources for space propulsion, x-ray imaging, and nuclear safeguards. The FEPT has been shown to produce 68-87 uN of thrust at 183-587 s specific impulse. The thruster is 1-4% efficient, highly compact, potentially self-neutralizing, simple, and very low power. This makes the FEPT an interesting option for micro-propulsion applications, particularly when simplicity is key. The PTA has been used to accelerate field emission electron beams to energies of 25 keV. These electrons have been converted to bremsstrahlung x-rays in a Ti target.

Additional study of the FEPT and PTA will further expand our knowledge of these novel sources. FEPT studies are currently focusing on the surface discharge. It is hoped that by controlling the micro-discharges on the FEPT surface, the ion beam energy and thruster efficiency can be effectively controlled to provide additional functionality, higher specific impulse, and better thrust to power ratios. PTA studies aim to extend operation to ion beam production and acceleration, with the ultimate goal of producing neutrons via deuterium-deuterium nuclear reactions.

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