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Energy Conversion Plasmas
Using Non-Centrosymmetric Crystals to Convert Thermal and Mechanical Energy into Plasma Generation

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Acknowledgements

Collaborators
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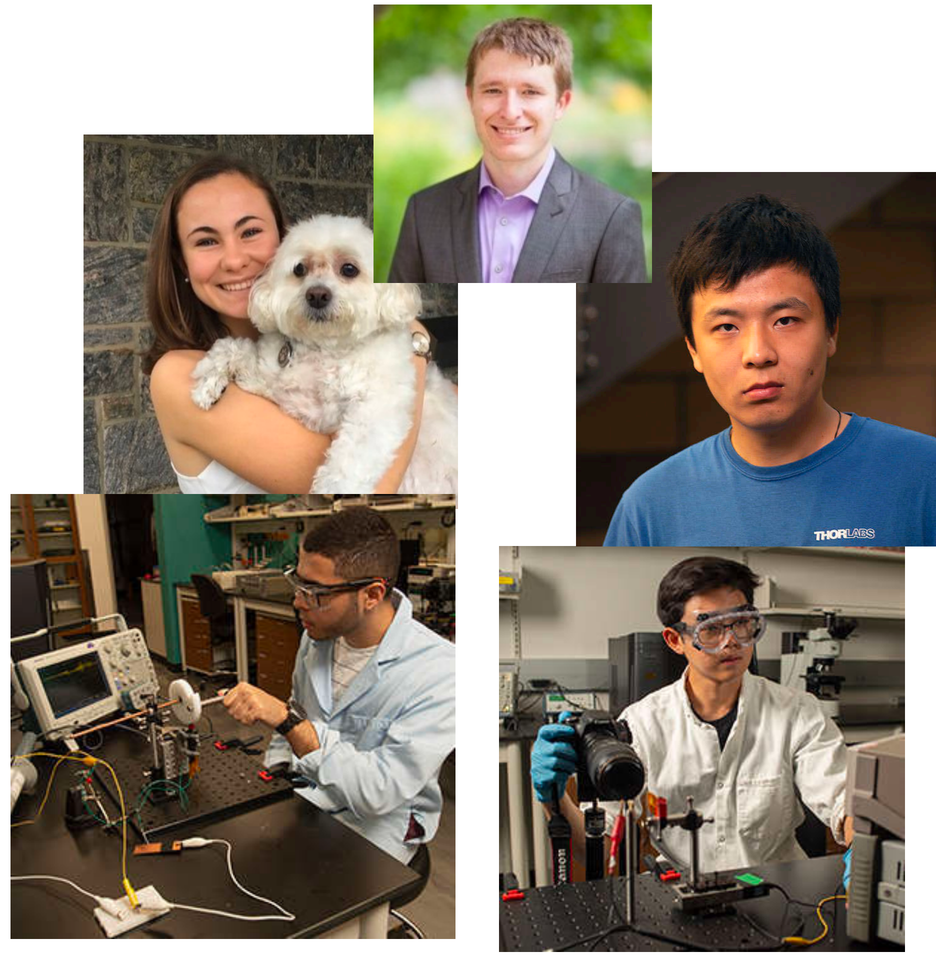
Korea University

Current & Former Students
Dr. Michael Johnson, Jinyu Yang (g), Olivia Jaenicki (ug), Federico Hita (ug), Se Hwan Jeon (ug)



NSF Grant
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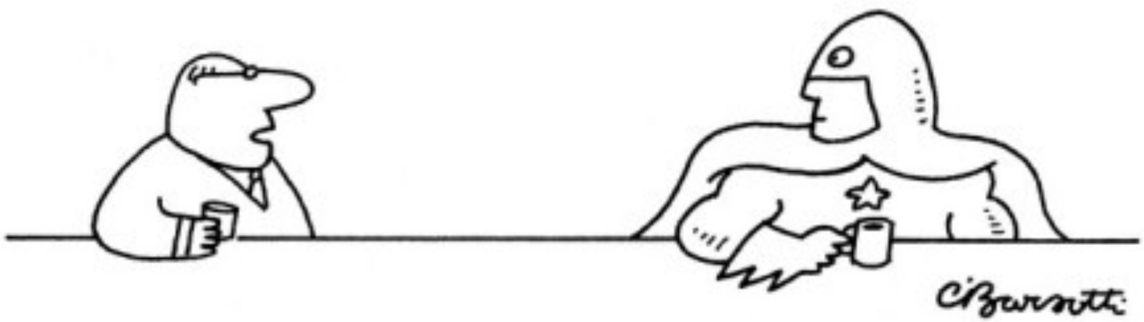
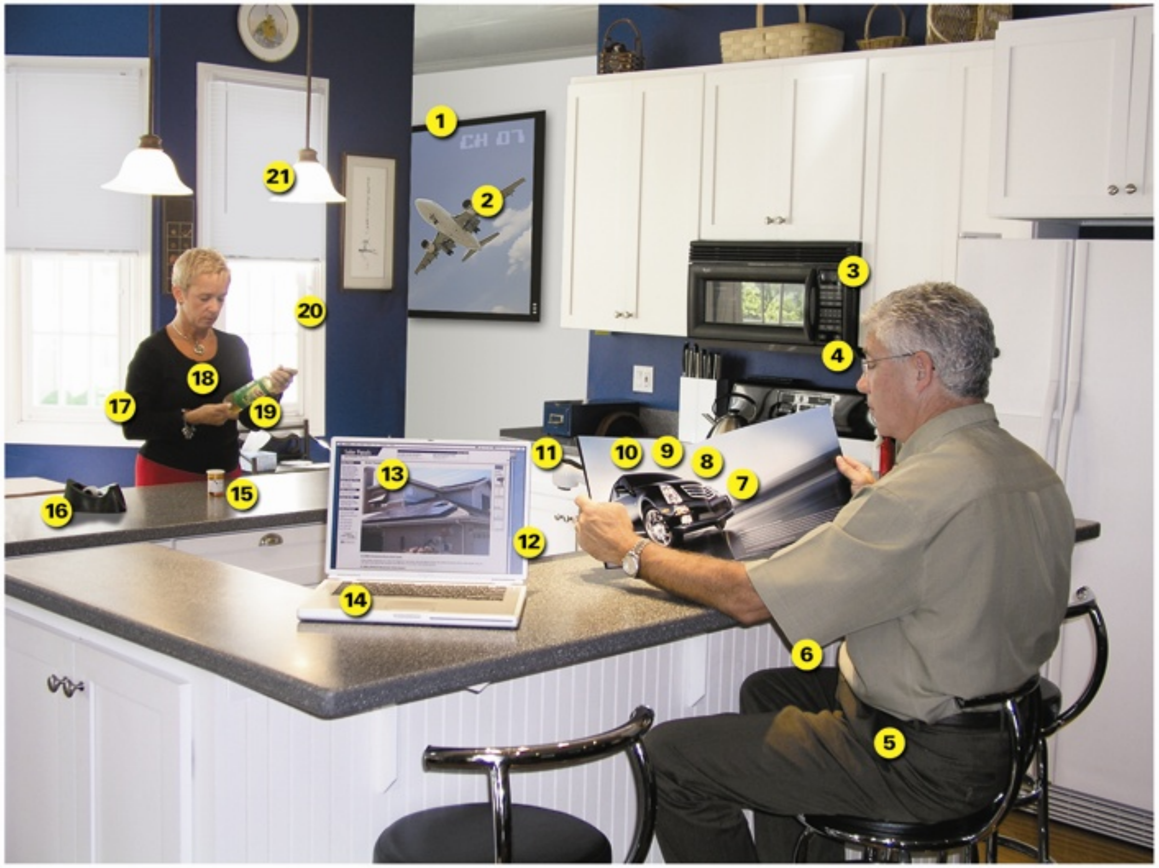


"Some of us are unsung heroes."

Plasmas are Essential To Society



01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

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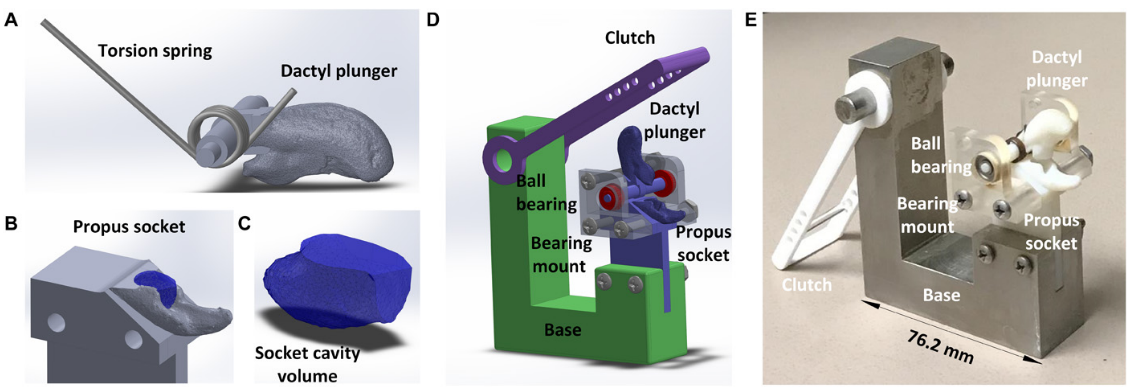
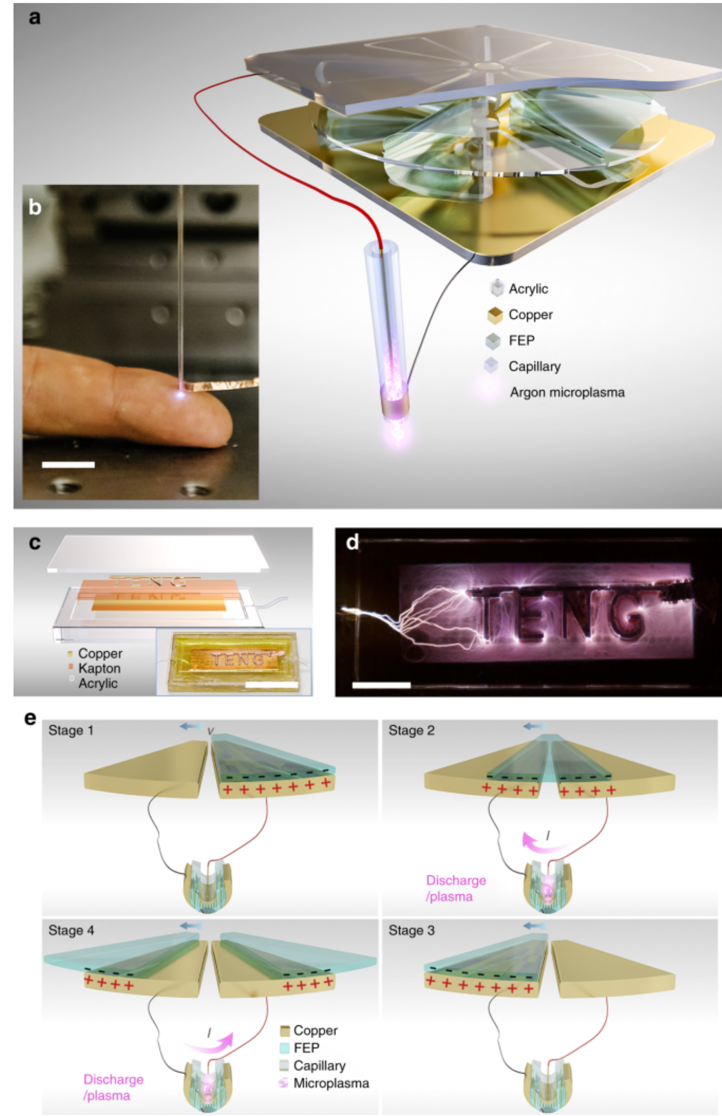
Do We Need a High-Voltage Power Supply?

https://www.sciencemag.org/news/2019/09/world-s-strongest-lightning-hits-not-summer-november-february

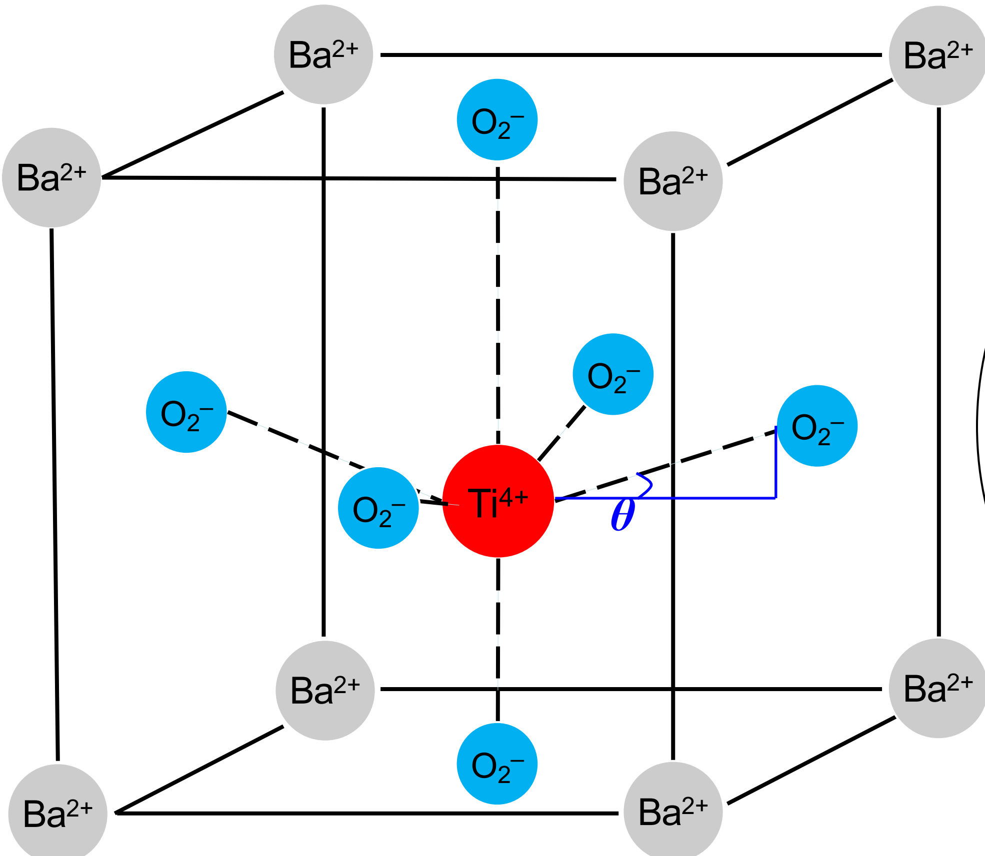


Tang & Staack, *Science Advances* (2019)

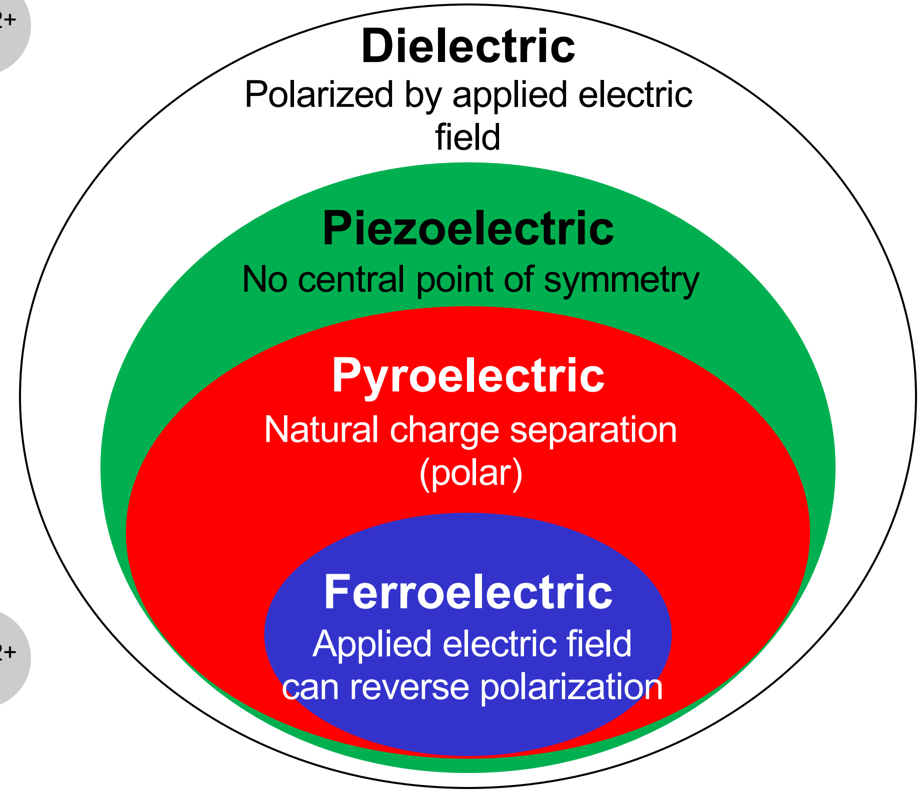


Cheng et al., *Nature Communications* (2018)

Non-Centrosymmetric Crystals as a Low-Voltage Discharge Source



crystal structure of barium titanate ($BaTiO_3$)



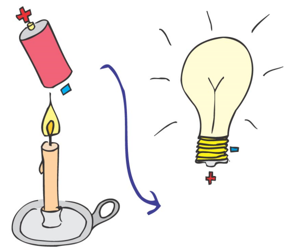
Piezoelectric – mechanical forcing
Pyroelectric – thermal forcing
Ferroelectric – electrical forcing

Energy Conversion Plasmas

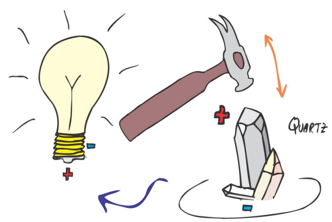
energy sources

heat

motion

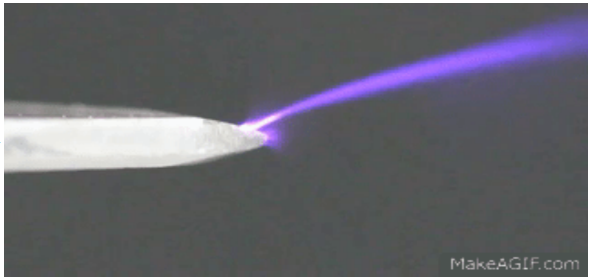


Pyroelectrics



Piezoelectrics

high surface potential



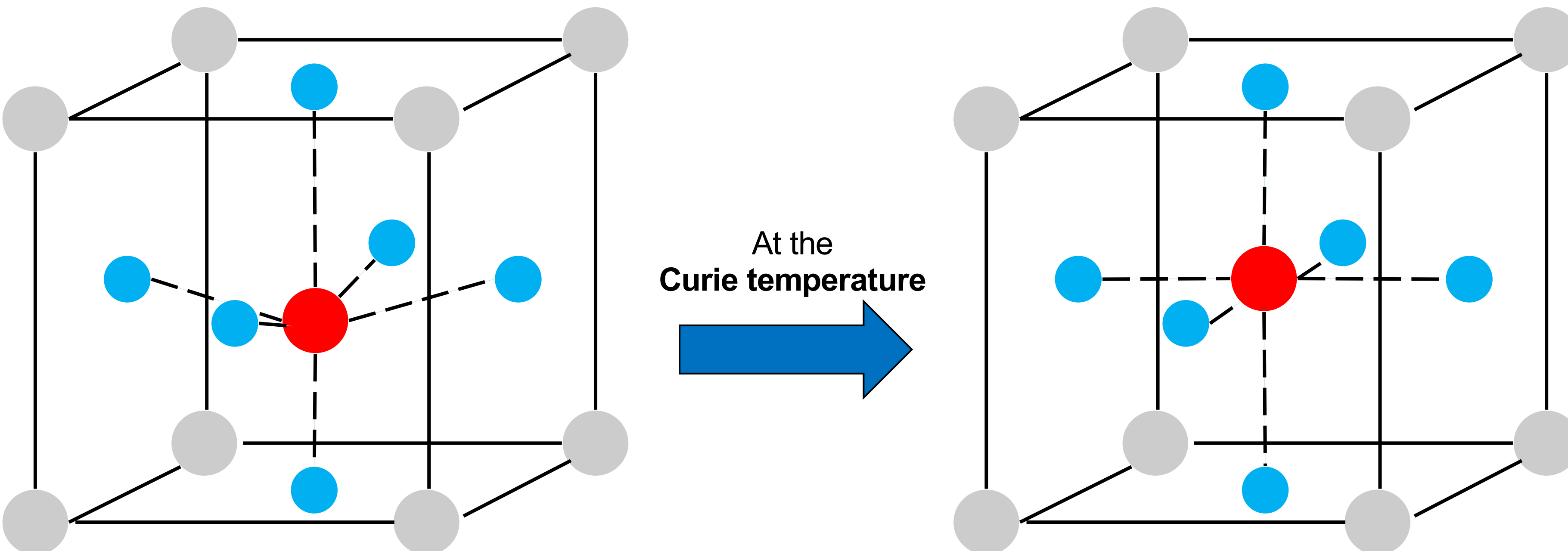
plasma

Energy conversion plasmas: Use pyroelectric/piezoelectric crystals to directly convert thermal/mechanical motion into a plasma source

Polarization Changes with Temperature

As **temperature** ⬆, **polarization** ⬇

As **temperature** ⬇, **polarization** ⬆



If you control the **temperature** of the pyroelectric, you can control the **polarization**

Surface Potential a Function of Temperature

Surface potential of the crystal depends on heating/cooling of crystal, the crystal orientation, and free charge at the crystal surface

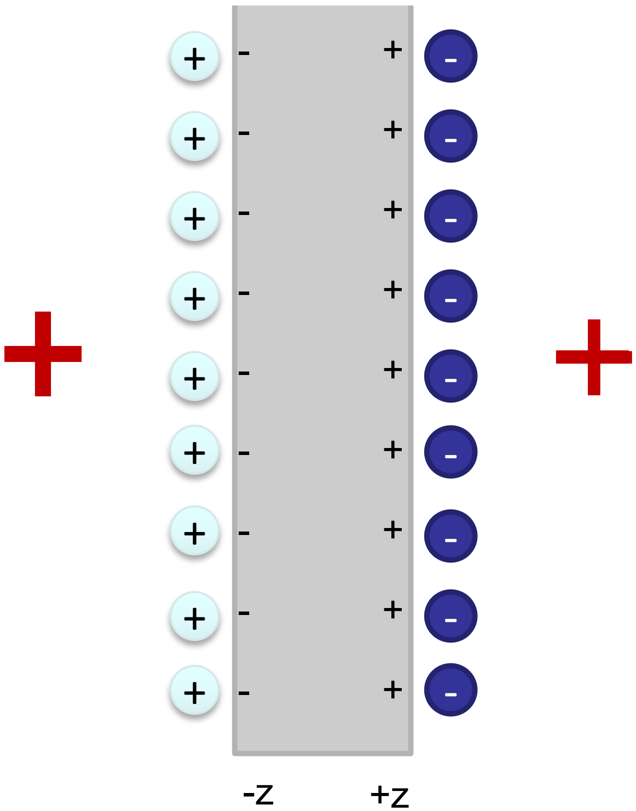
- heating leads to a net **positive** surface potential
- cooling leads to a net **negative** surface potential

pyroelectric equation

$$\Delta\Phi = \frac{\tau p \Delta T}{\varepsilon}$$

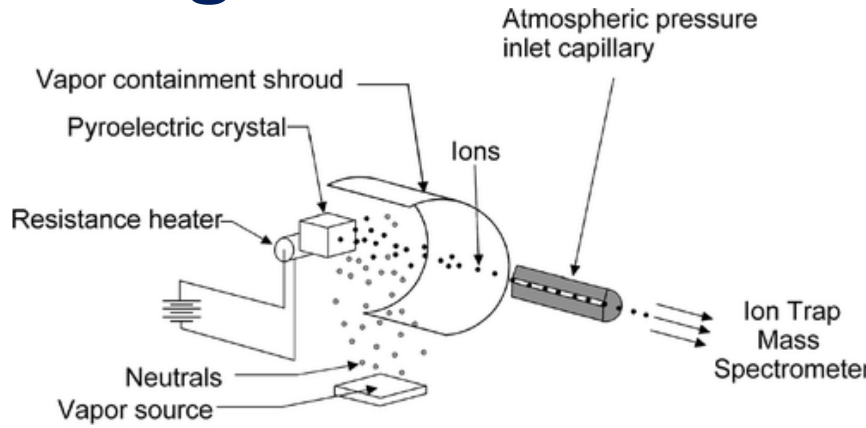
Φ = surface potential
τ = crystal thickness
p = pyroelectric constant
ε = crystal permittivity

during **heating**

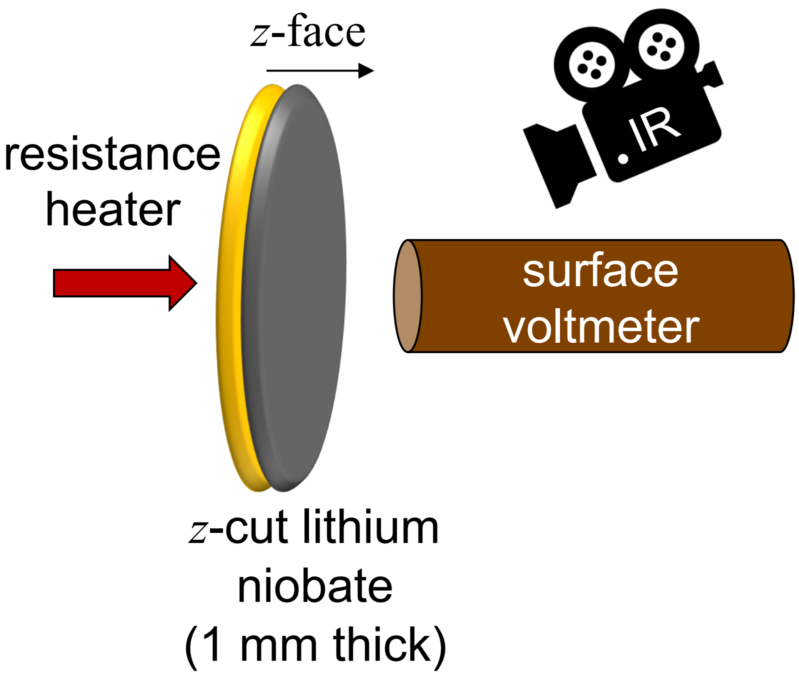


Pyroelectric-Driven Discharge

Generate a stable atmospheric-pressure discharge with a pyroelectric substrate:
Heating/cooling creates **surface potential** on crystal



Neidholdt & Beauchamp, *Analytical Chemistry* (2007)



<u>Measurements</u>

- surface potential of crystal (*voltmeter*)
- temperature of crystal (*IR camera*)
- current on sharp electrode (*picoammeter*)

Pyroelectric-Driven Discharge

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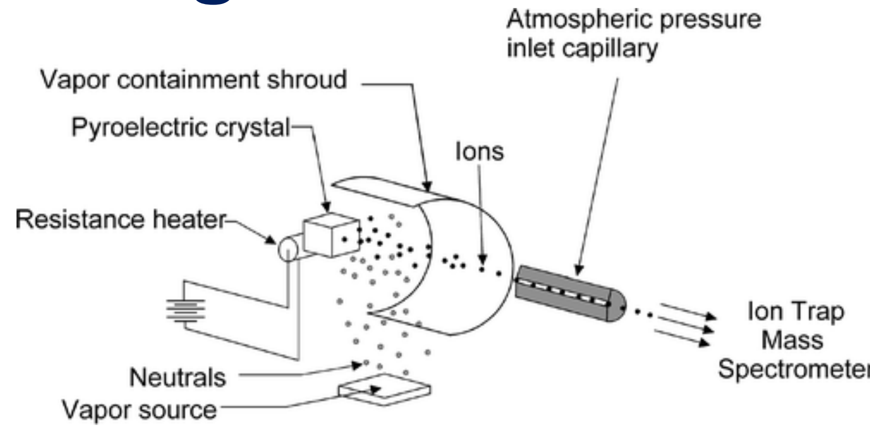

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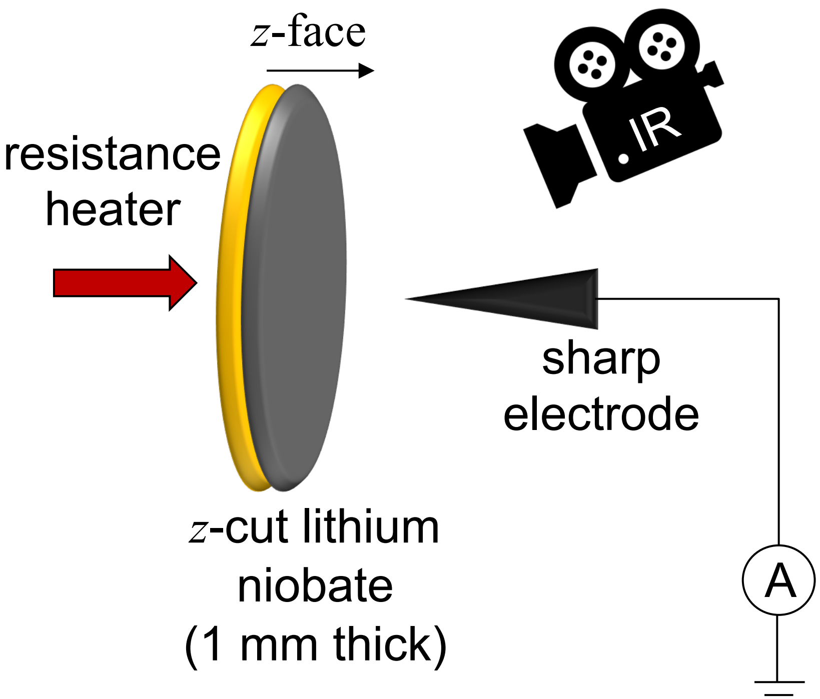

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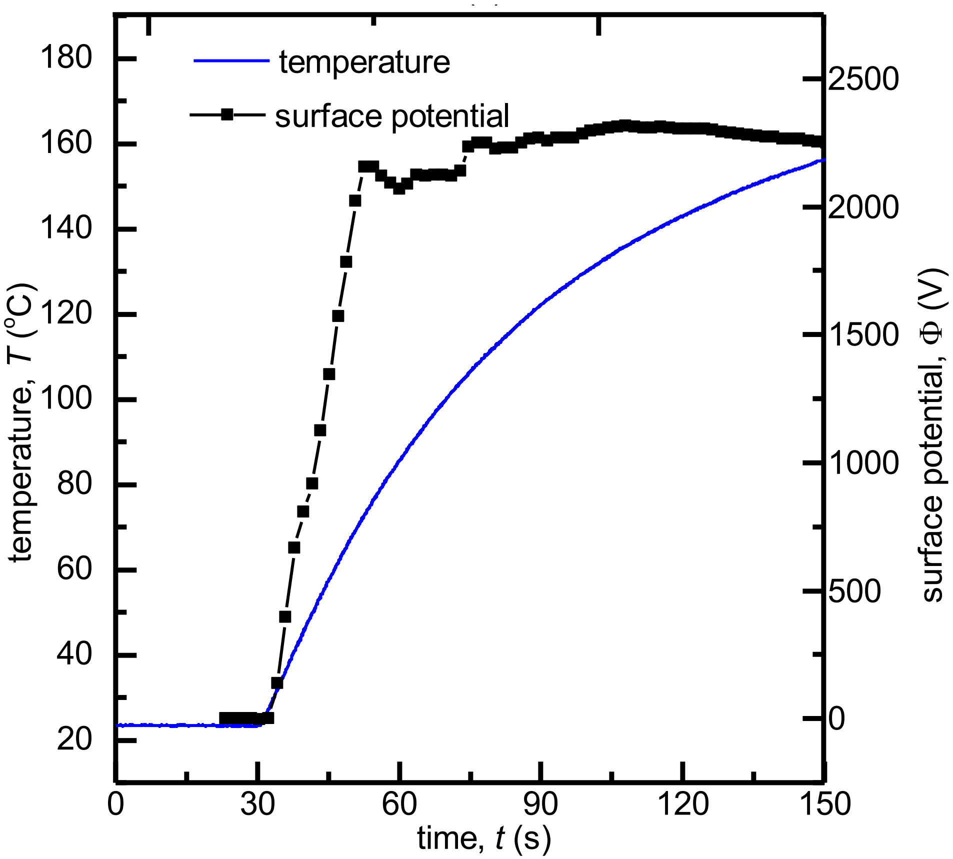
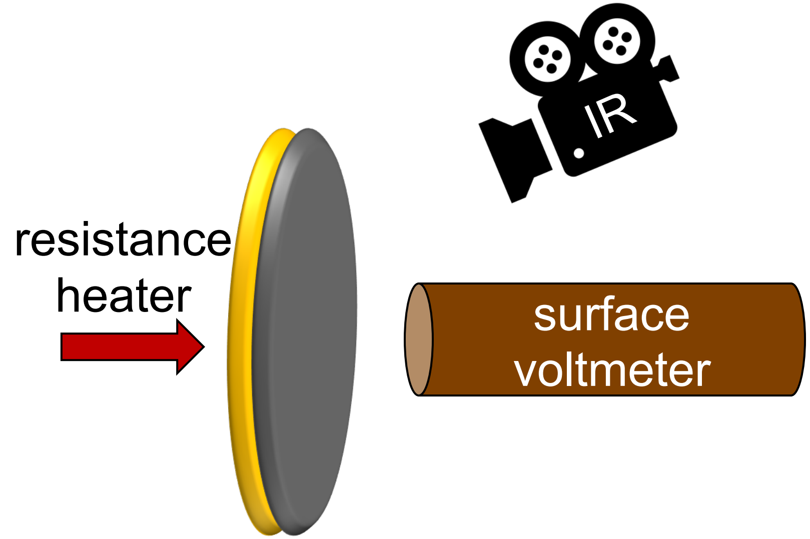
Temperature Change Generates Change in Surface Potential

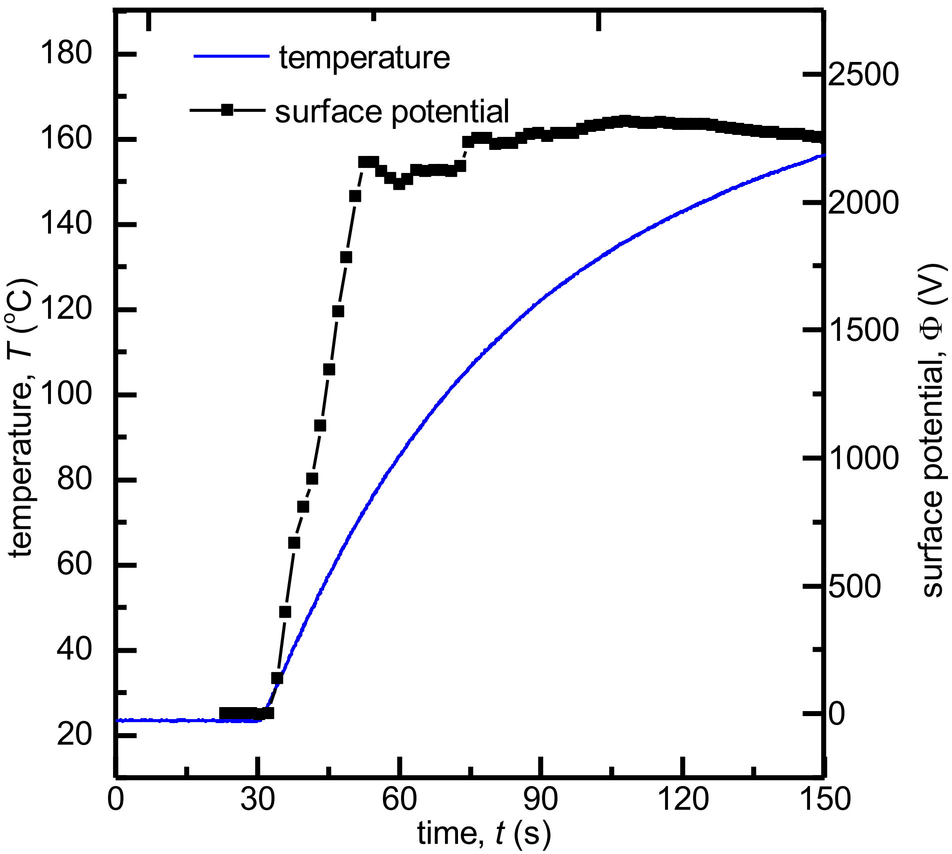


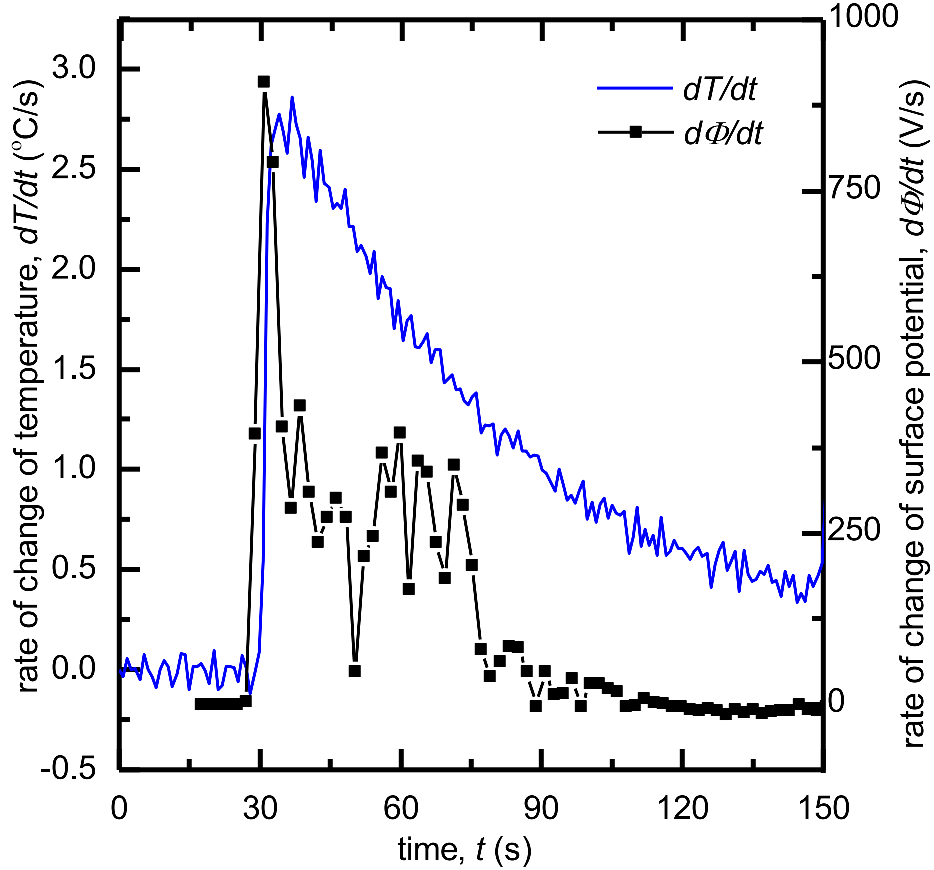


The surface potential of the crystal needs a **large change in temperature** to **overcome** accumulating free charge

Johnson, Linczer, & Go, *Plasma Sources Sci. Technol.*, **23**, 065018, 2014.

Temperature Change Generates Change in Surface Potential





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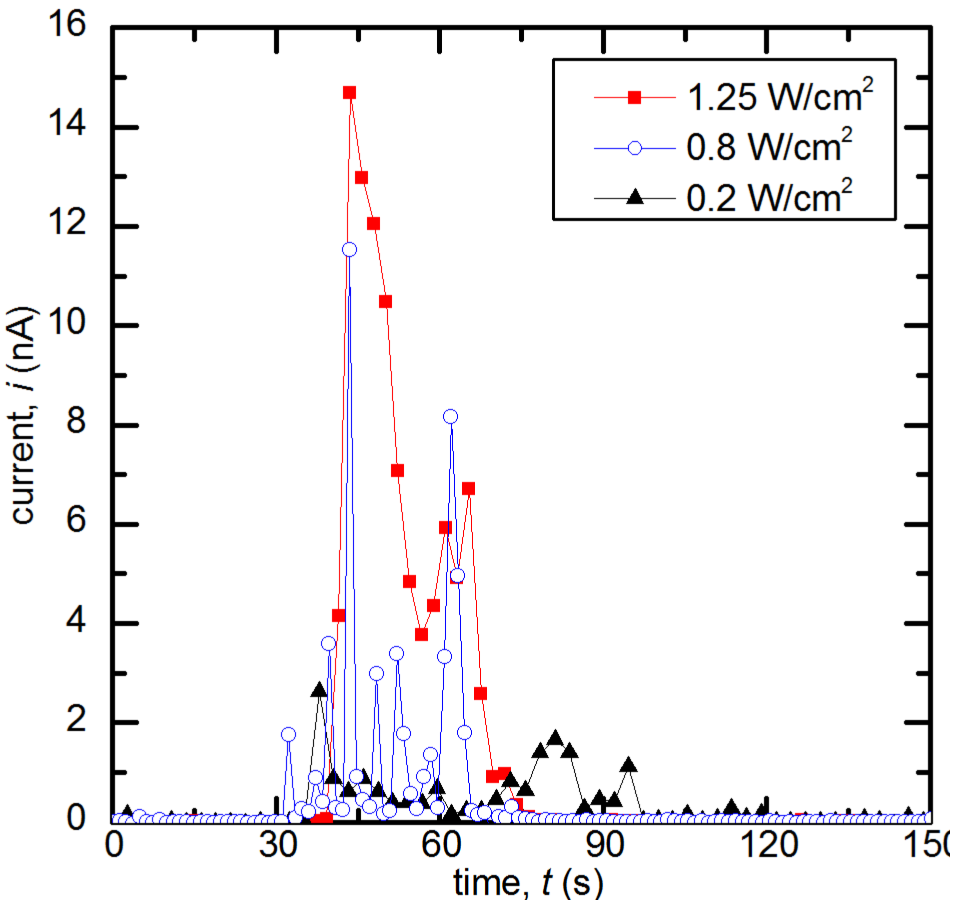
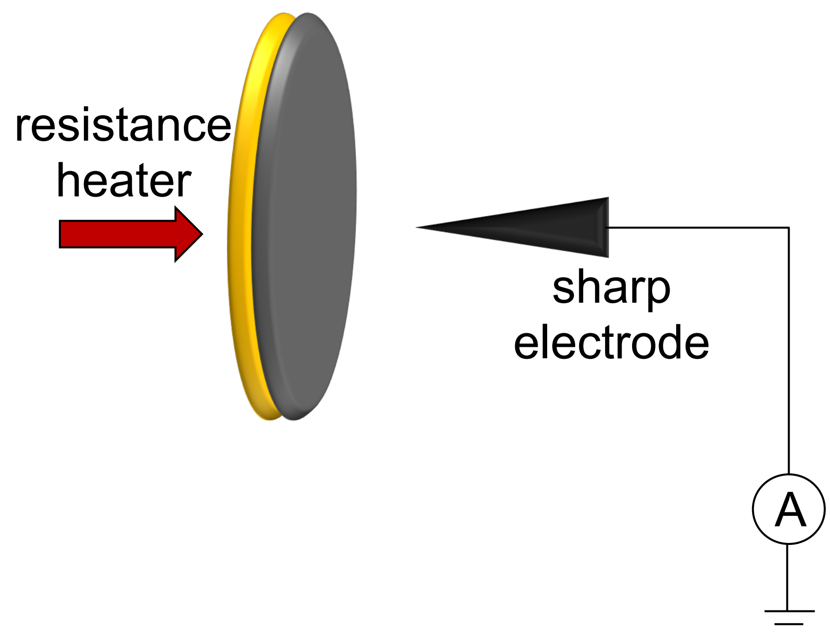
Johnson, Linczer, & Go, *Plasma Sources Sci. Technol.*, **23**, 065018, 2014.

Change in Surface Potential Generates Discharge

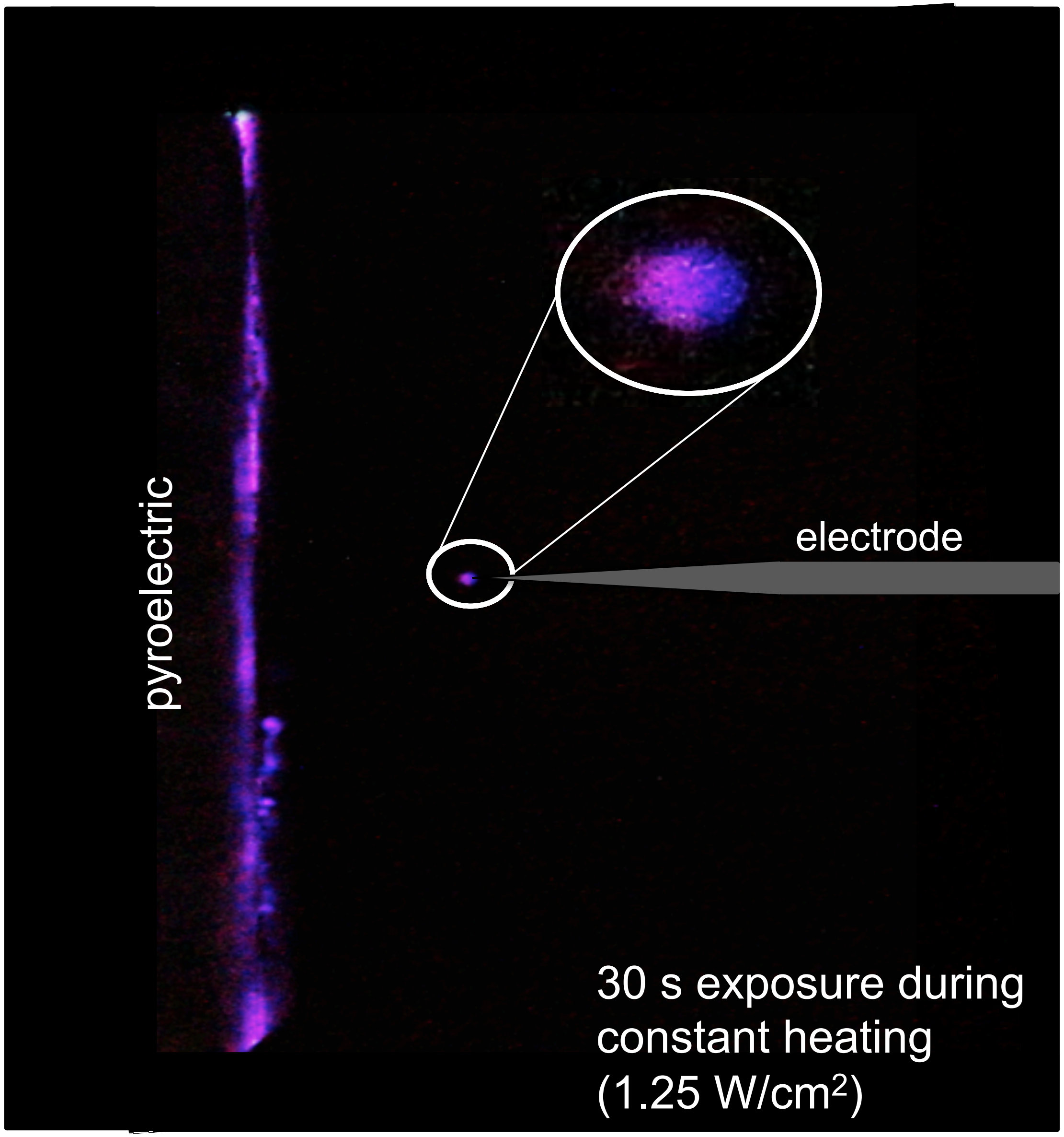




Free charge gathers on the surface of the pyroelectric and **extinguishes the discharge**, similar to a dielectric barrier discharge

Johnson, Linczer, & Go, *Plasma Sources Sci. Technol.*, **23**, 065018, 2014.

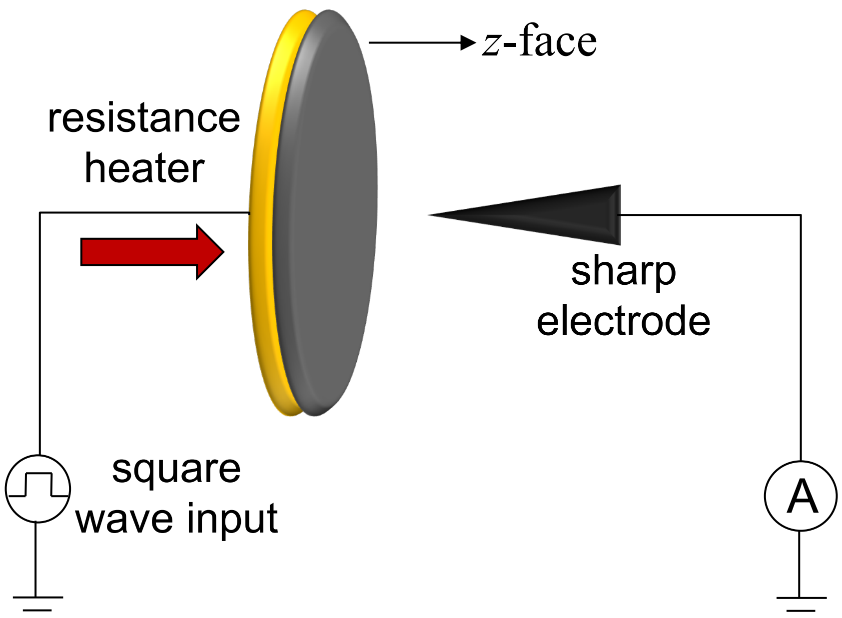
Heating Pyroelectric Generates a Glow



Johnson, Linczer, & Go, *Plasma Sources Sci. Technol.*, **23**, 065018, 2014.

Stable Discharge by Cycling Heat

Cycling heat will alternate surface potential (positive/negative), such that the effects of free charge are mitigated

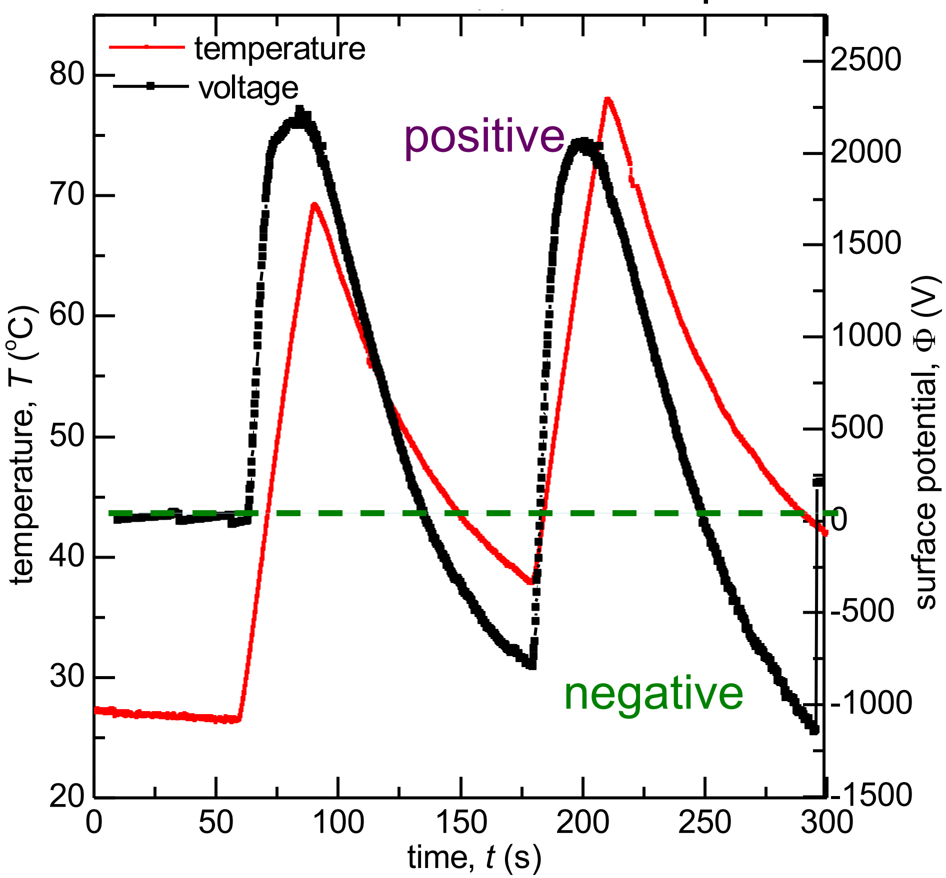


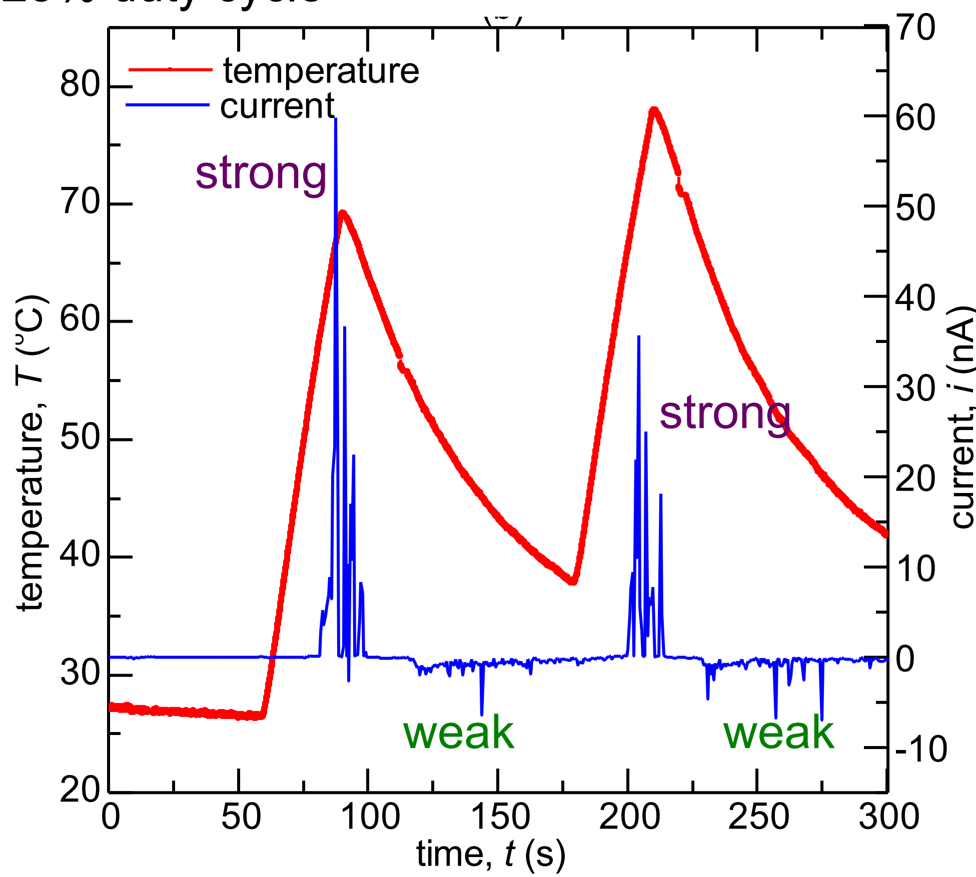
Pyroelectric-driven discharge will have characteristics of two standard atmospheric pressure discharges:

- DBD – alternating discharges extinguished by surface charging
- AC corona discharge – heating cycle (negative corona) and cooling cycle (positive corona)

Cycling Heat Enables Continuous Discharge

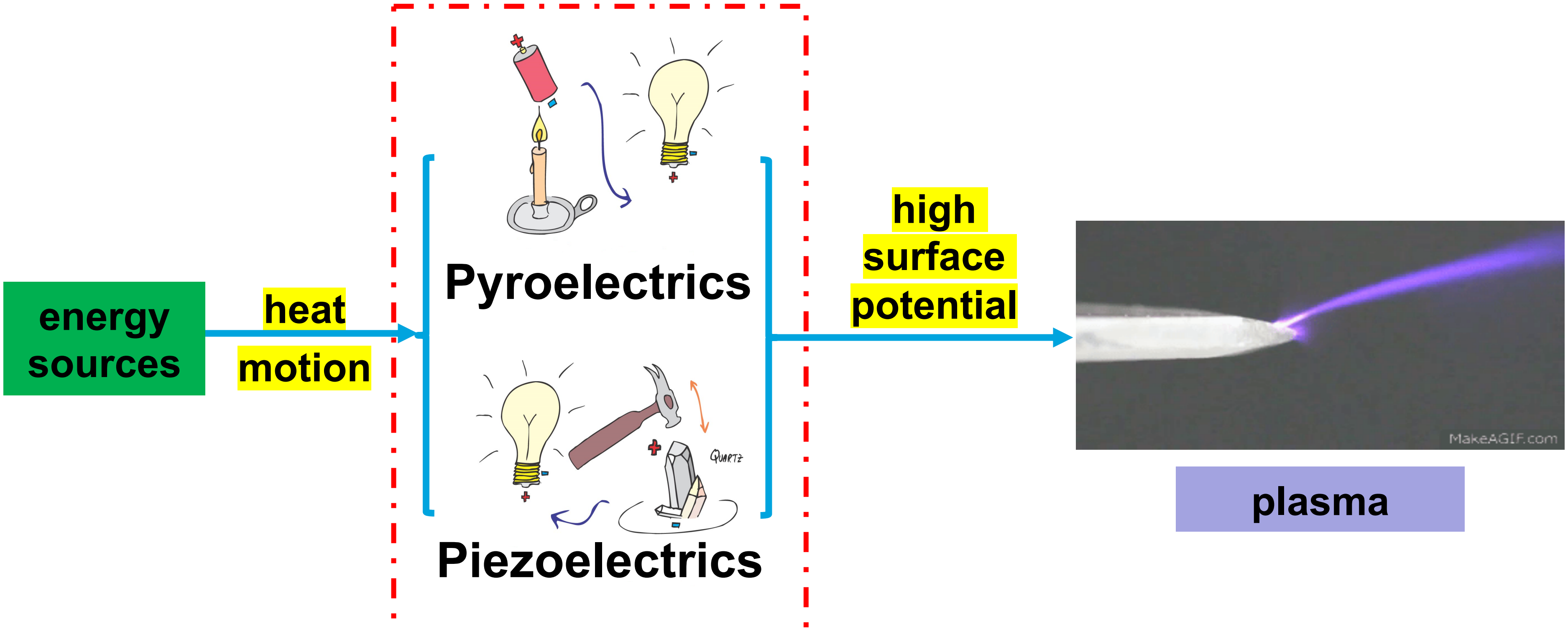
120 s period with 25% duty cycle





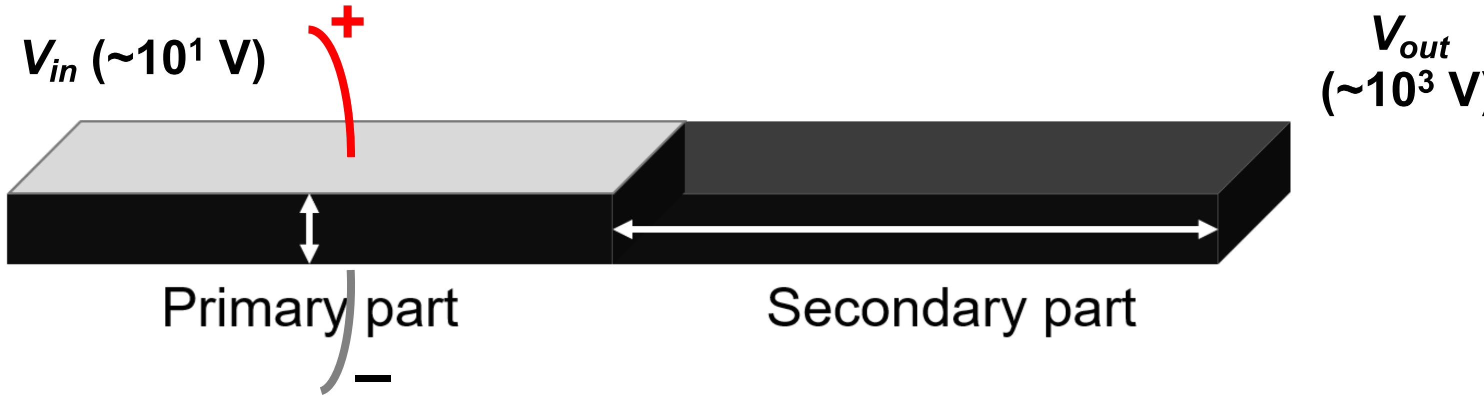
Cycling temperature generates alternating strong (heating) and weak (cooling) discharges, consistent with magnitude of induced surface potential.

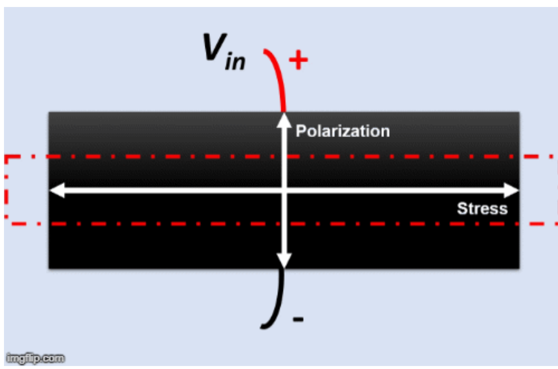
Energy Conversion Plasmas

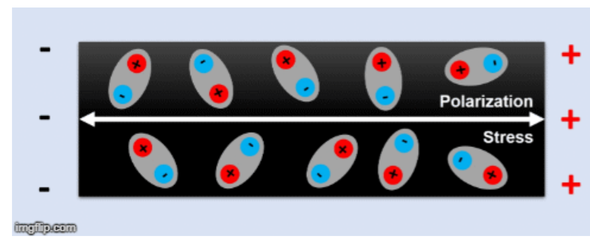


<u>Energy conversion plasmas</u>: Use pyroelectric/piezoelectric crystals to directly convert thermal/mechanical motion into a plasma source

Piezoelectric Transformers for Plasma Generation

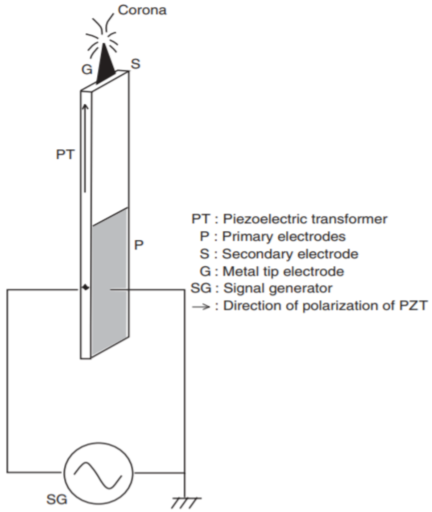




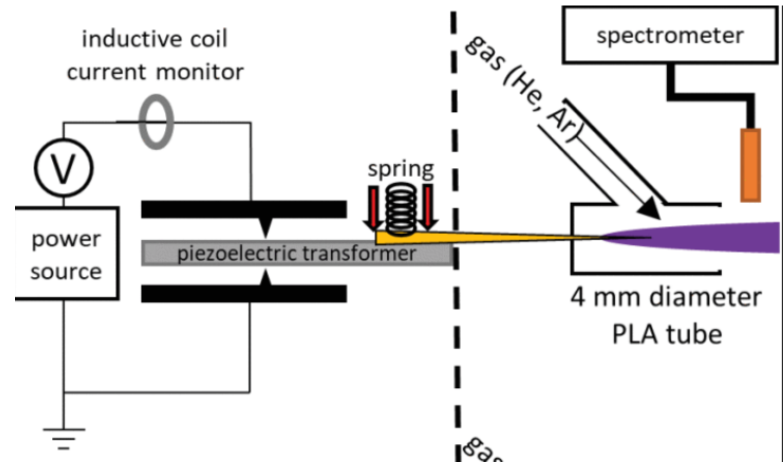


- PT amplifies the input voltage through an <u>electromechanical</u> coupling process.
- The voltage gain ~<u>10^2 – 10^3</u> when operating at its <u>2nd harmonic</u>.

PT-Driven Plasma Devices



Itoh et al., *Ozone Sci. Eng.* (2004)



Johnson et al., *IEEE Trans. Plasma Sci.* (2019)

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Piezoelectric direct discharge plasma

From Wikipedia, the free encyclopedia

Piezoelectric direct discharge (**PDD**) **plasma** is a type of cold non-equilibrium plasma, generated by a direct gas discharge of a high voltage piezoelectric transformer. It can be ignited in air or other gases in a wide range of pressures, including atmospheric. Due to the compactness and the efficiency of the piezoelectric transformer, this method of plasma generation is particularly compact, efficient and cheap. It enables a wide spectrum of industrial, medical and consumer applications.

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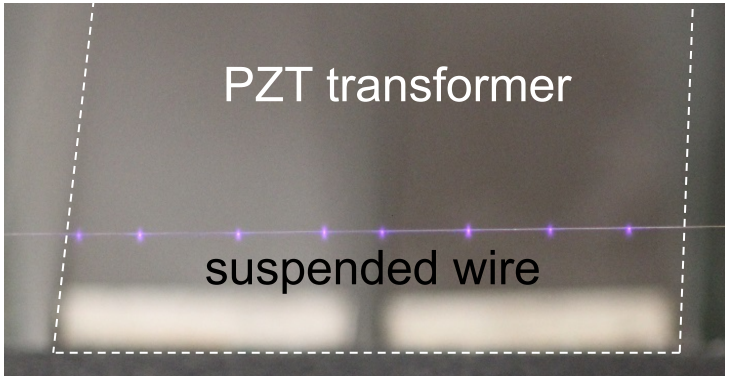
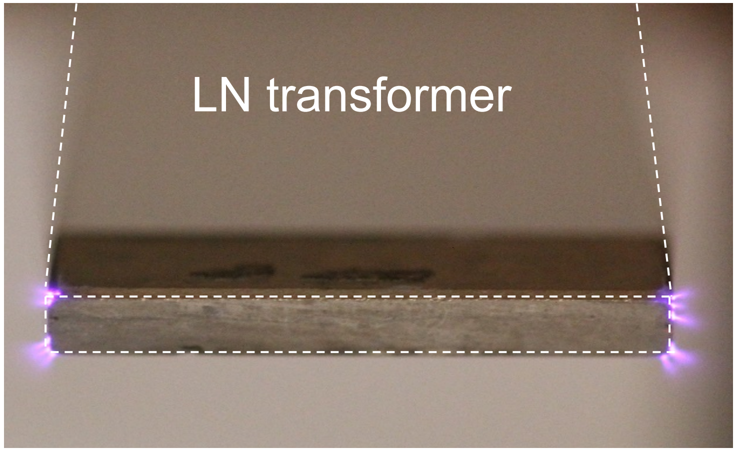
PT-Driven Plasmas Produce EHD Effect

counter electrode configuration

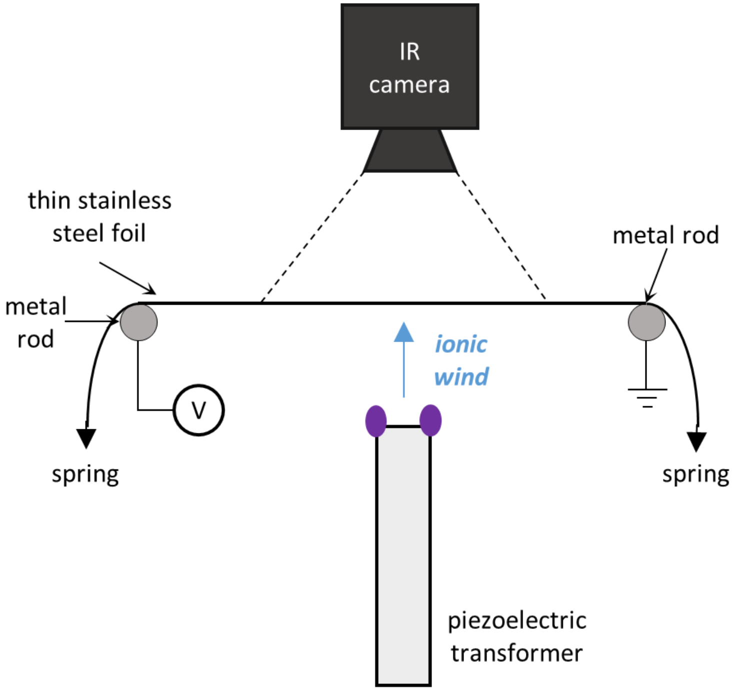


10 V amplitude sine wave

sharp electrode configuration



9 V amplitude sine wave



Johnson & Go, *J. Appl. Phys.*, **118**, 243304, 2015.
Johnson & Go, *Frontiers Mech. Eng.*, **2**, 7, 2016.

PT-Driven Plasmas Produce EHD Effect

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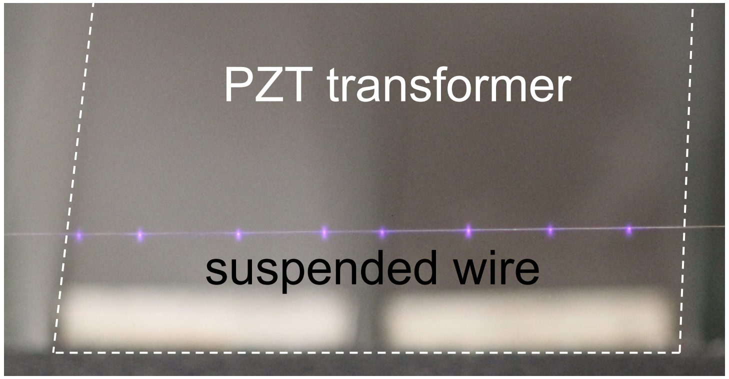

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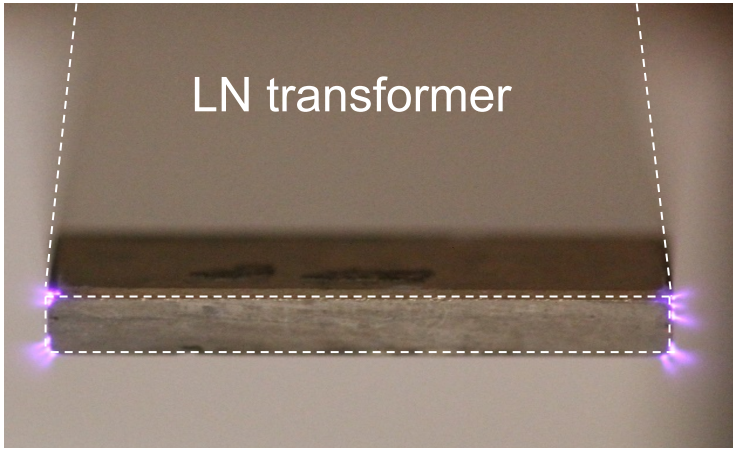

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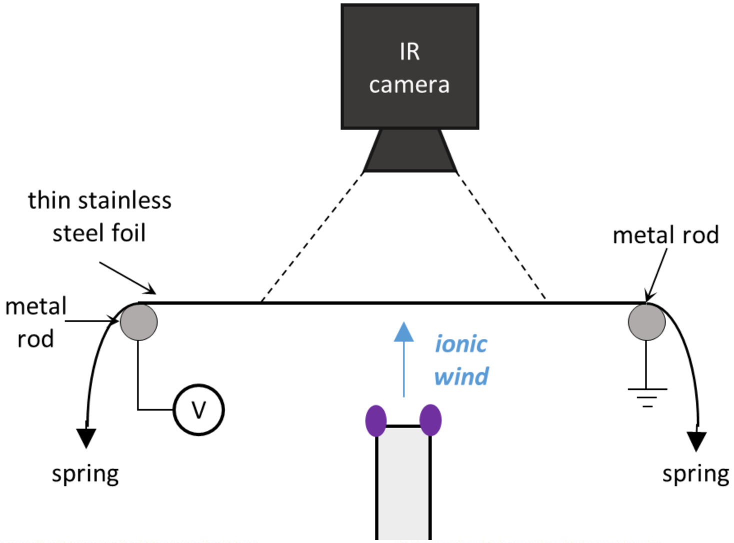
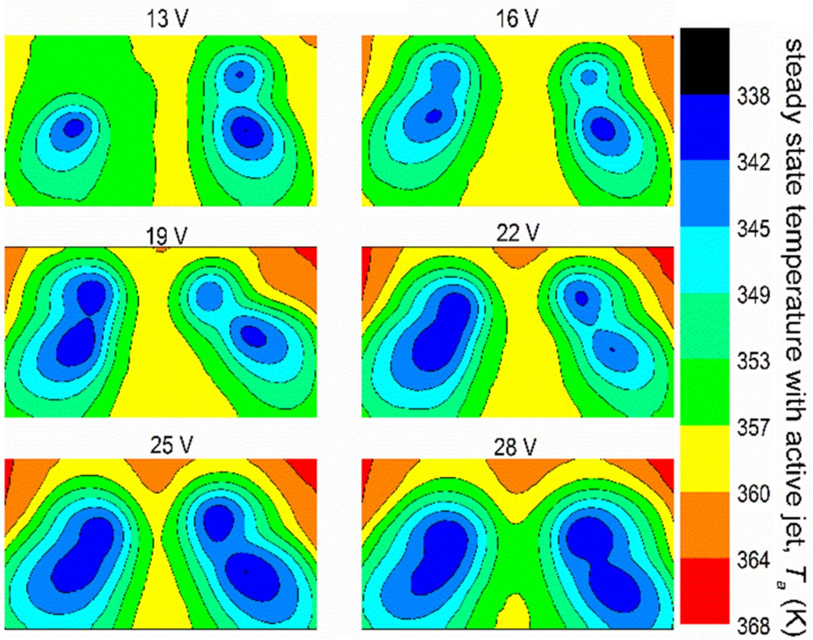
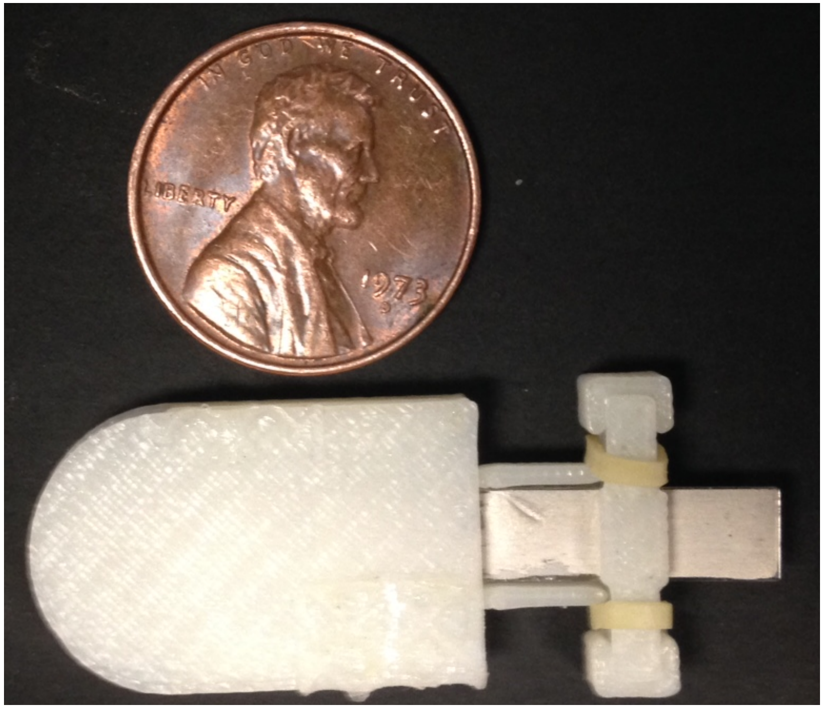




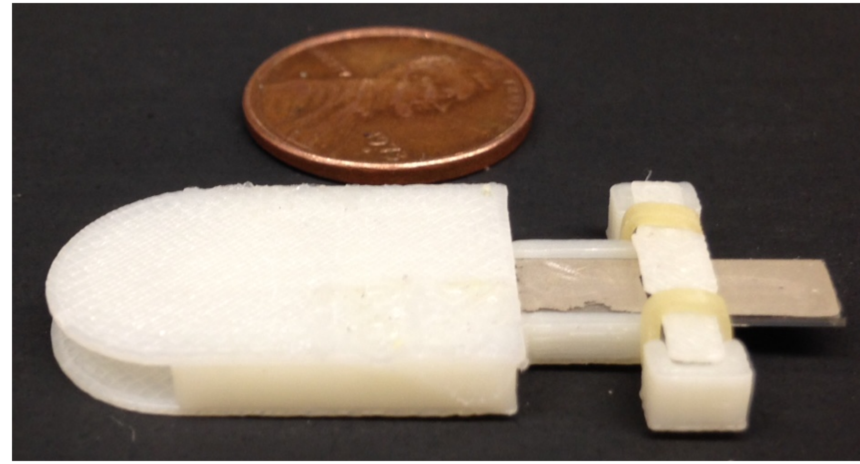
Johnson & Go, *J. Appl. Phys.*, **118**, 243304, 2015.
Johnson & Go, *Frontiers Mech. Eng.*, **2**, 7, 2016.

A Working Low-Voltage EHD Prototype



15 mm

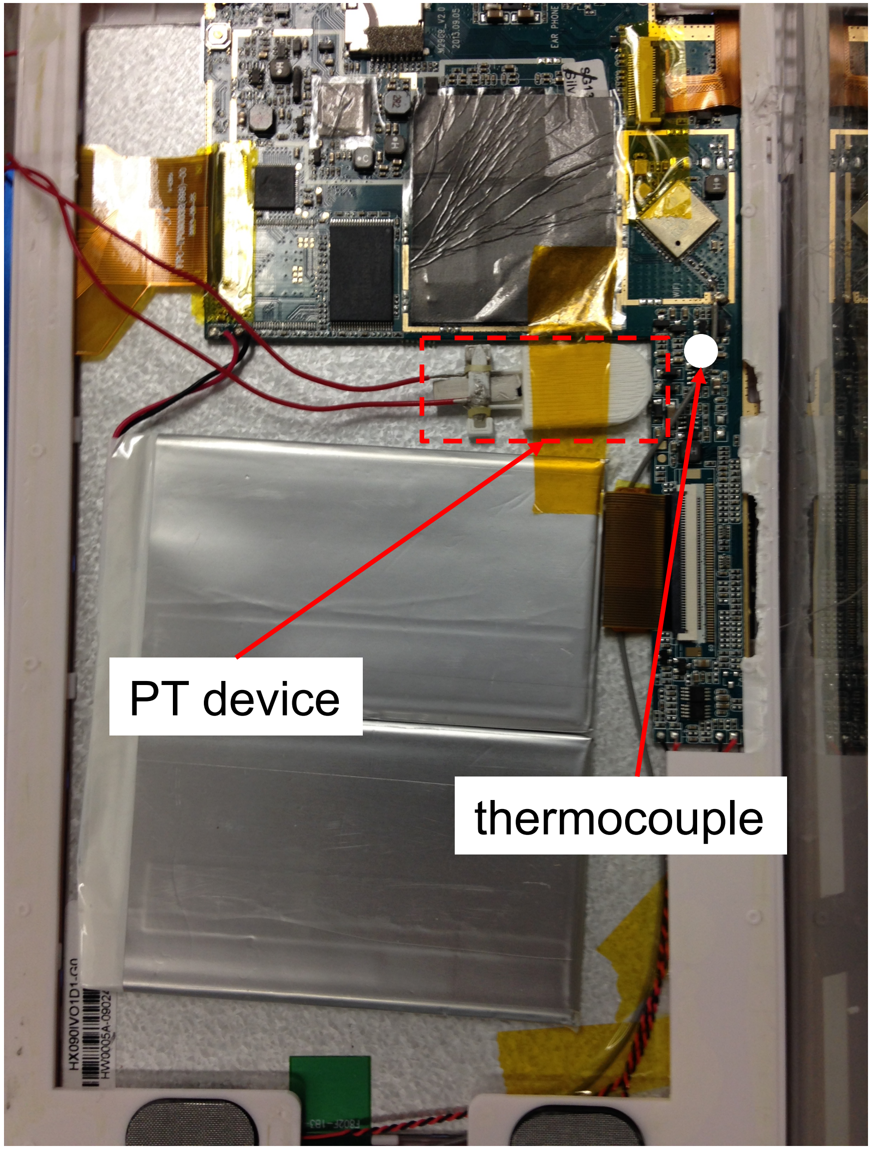
40 mm

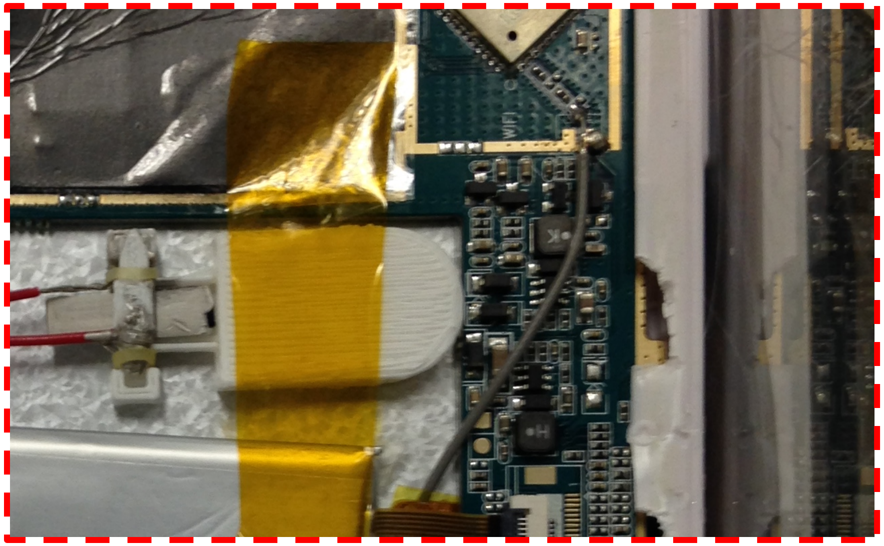


Operating parameters
12 – 18 V, 181 kHz

Ultra-thin prototype capable of fitting within portable electronic device

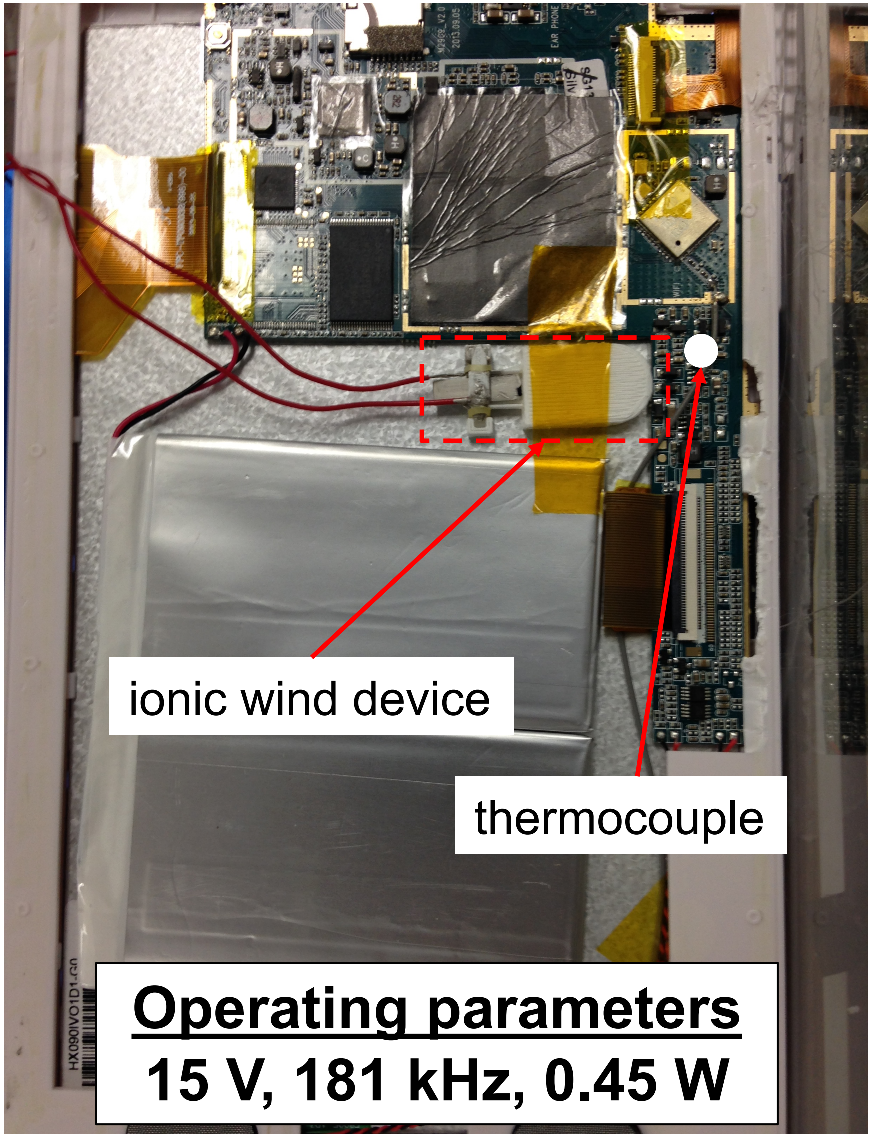
PT-Driven Device Integrated Within a Tablet





Haier 9” Tablet

PT-Driven Device Integrated Within a Tablet



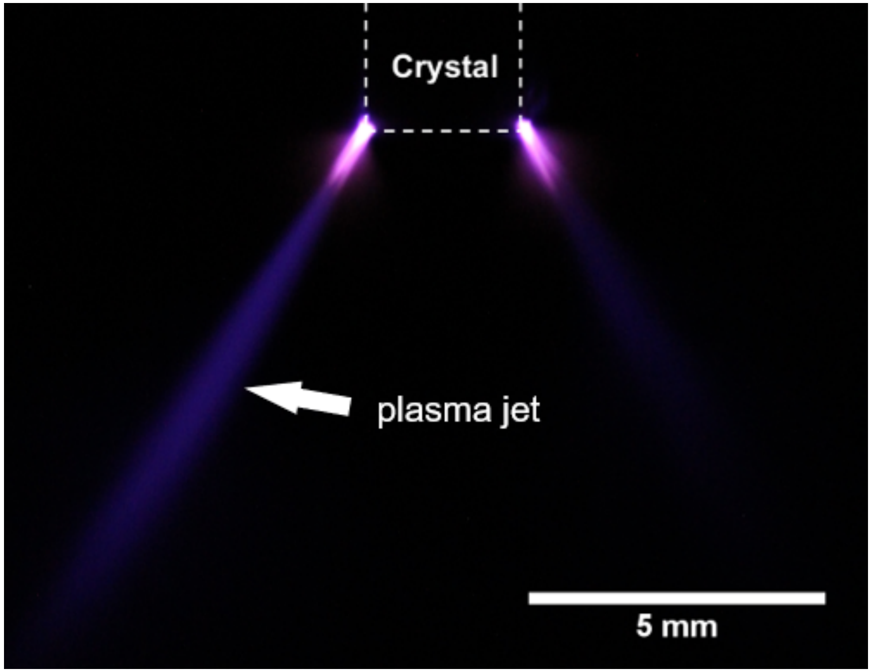
Operating parameters

15 V, 181 kHz, 0.45 W

temperature is in °F

Behavior of the PT-Driven Free Plasma Jet

- The plasma propagates into free space with a well-defined shape.
- The visible length is 15 - 20 mm.
- No low-ionization energy guiding flow.

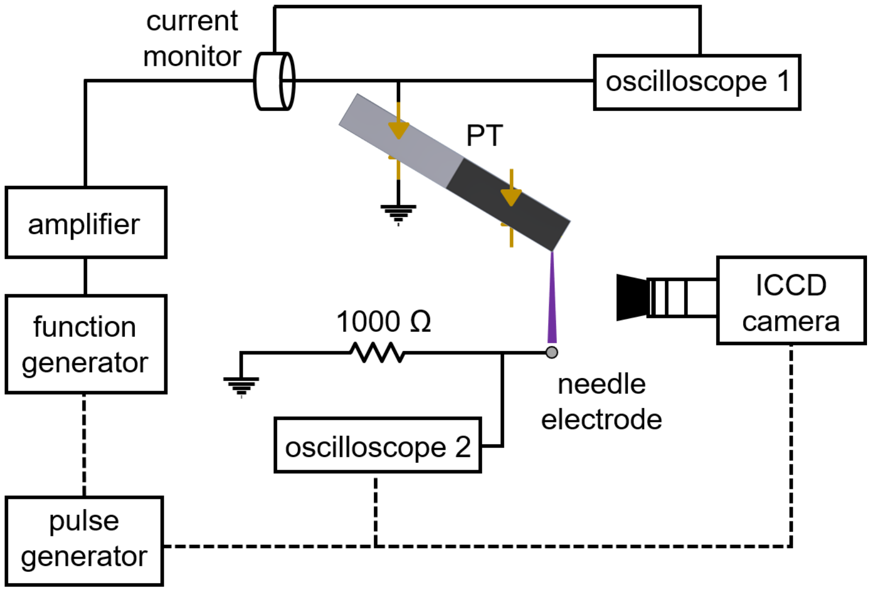


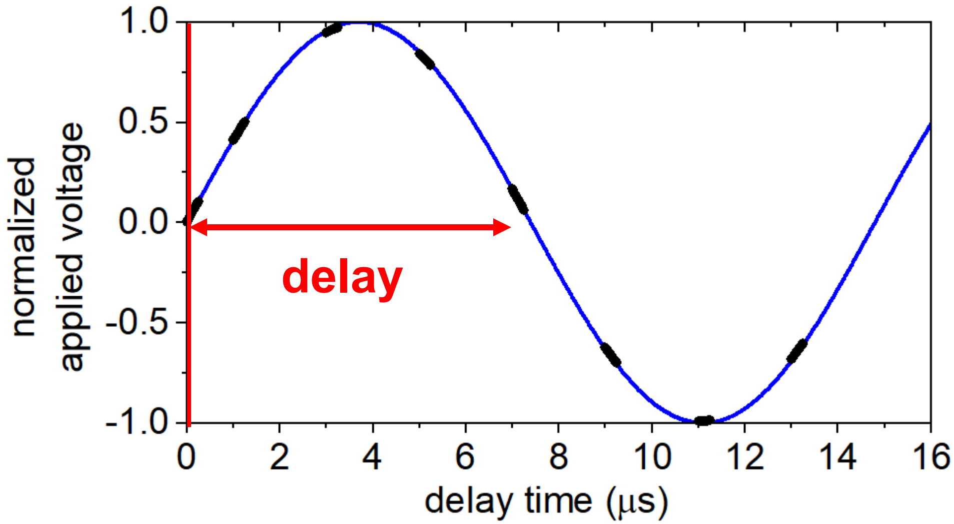
Time integrated image over 5000 input voltage cycles (0.5 s exposure time).

PT-generated discharge analogous to a corona streamer or a 'free' plasma jet.

Temporal Characterization

- Input voltage is 20 V_{rms} with frequency of 67.6 kHz.
- Camera exposure time is 250 ns.
- 1000 sequential images are taken at each phase delay.





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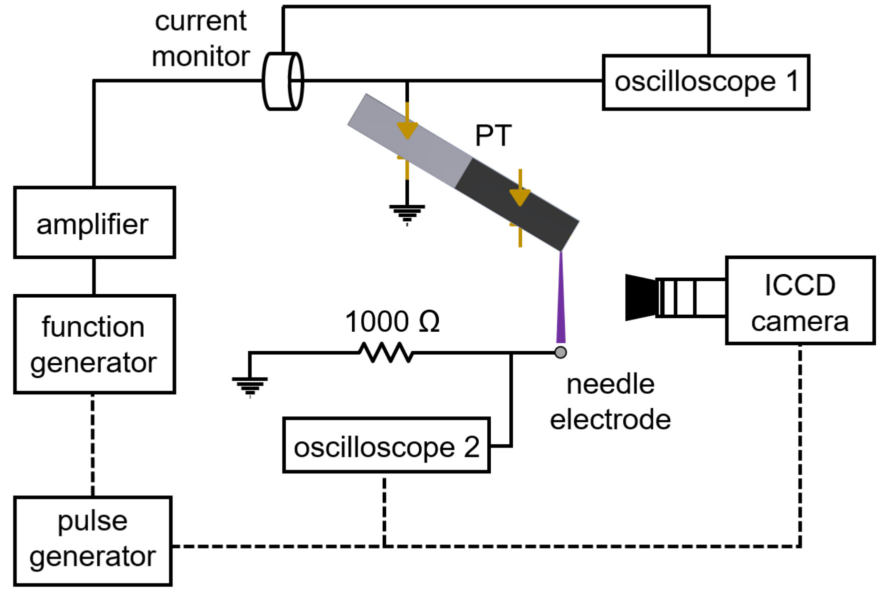
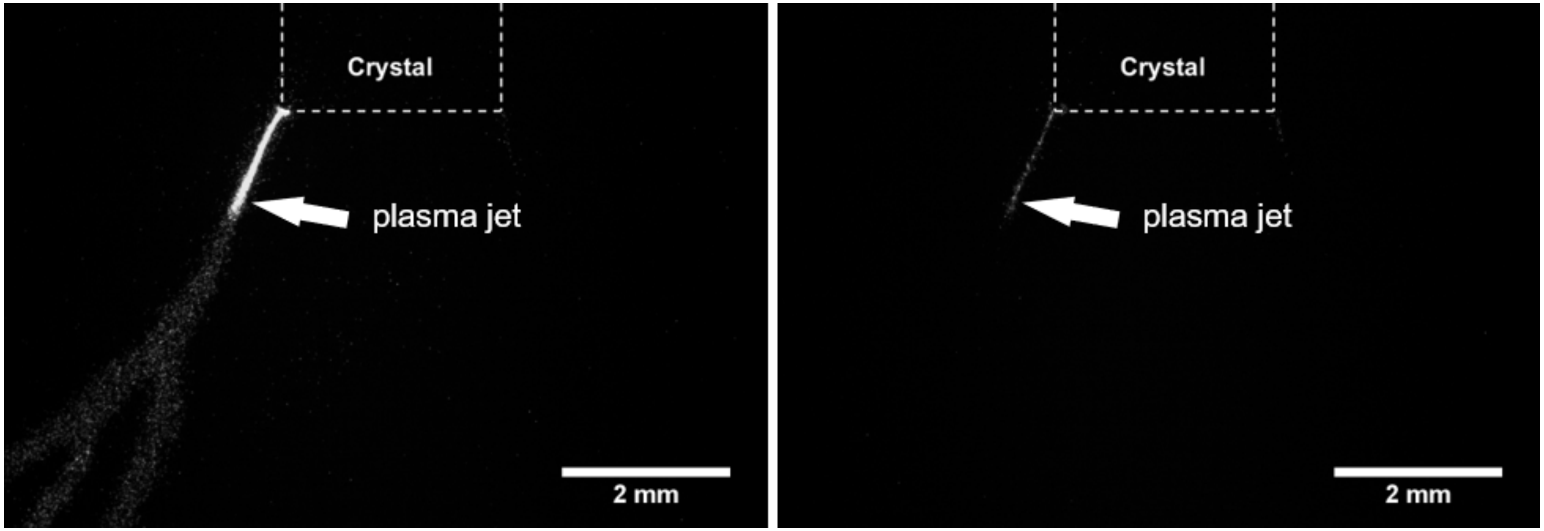
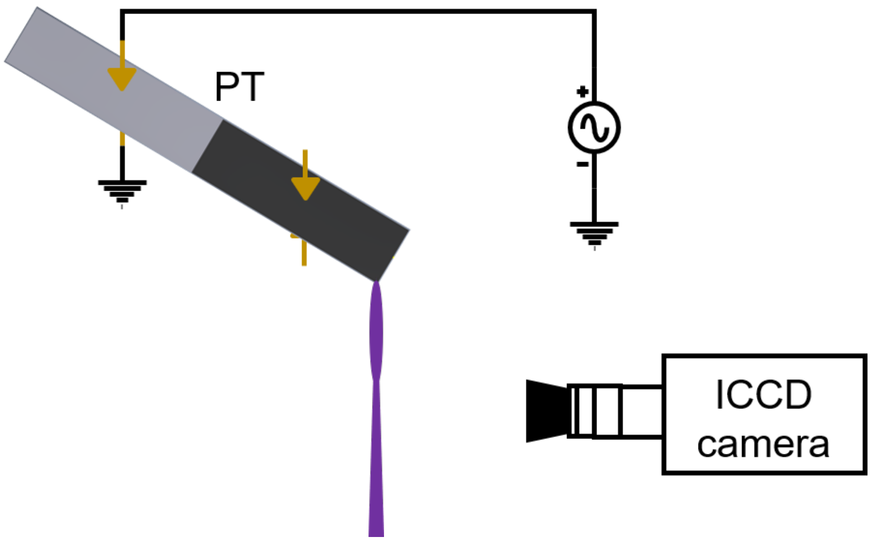


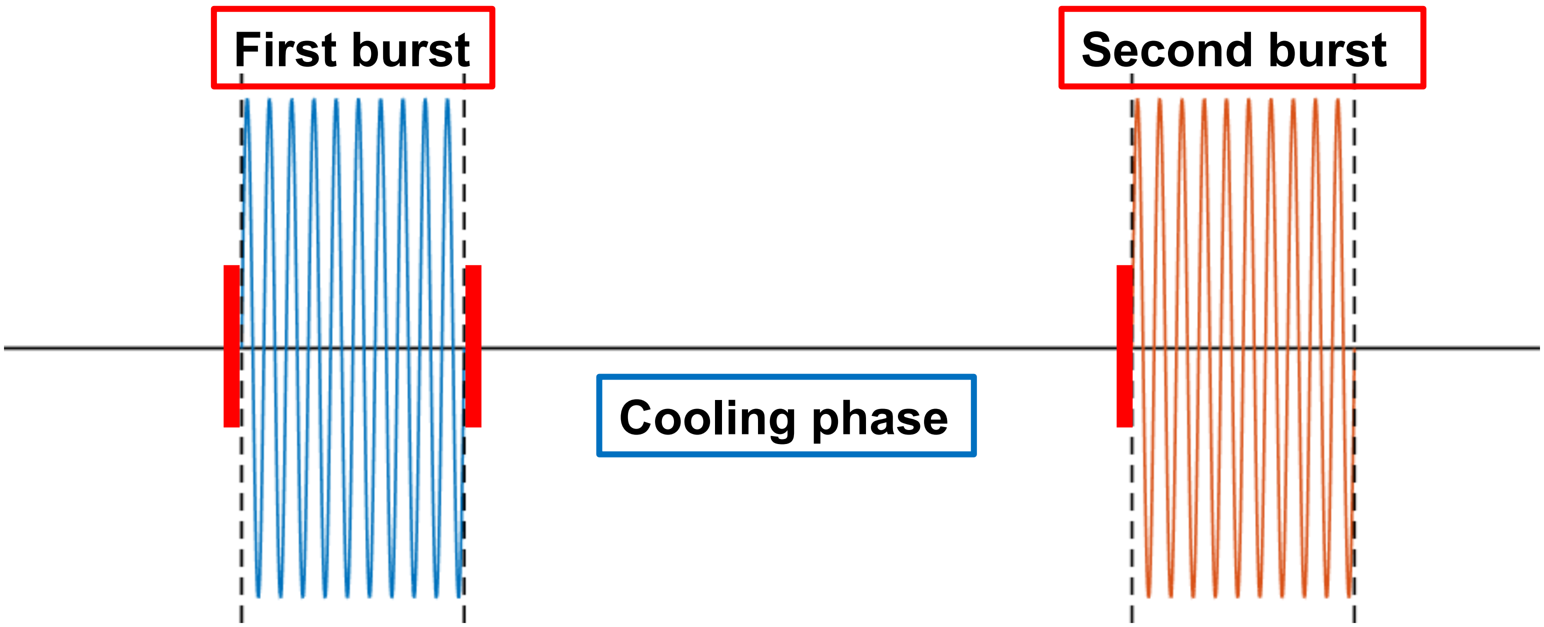


Stochastic behavior of the free plasma jet

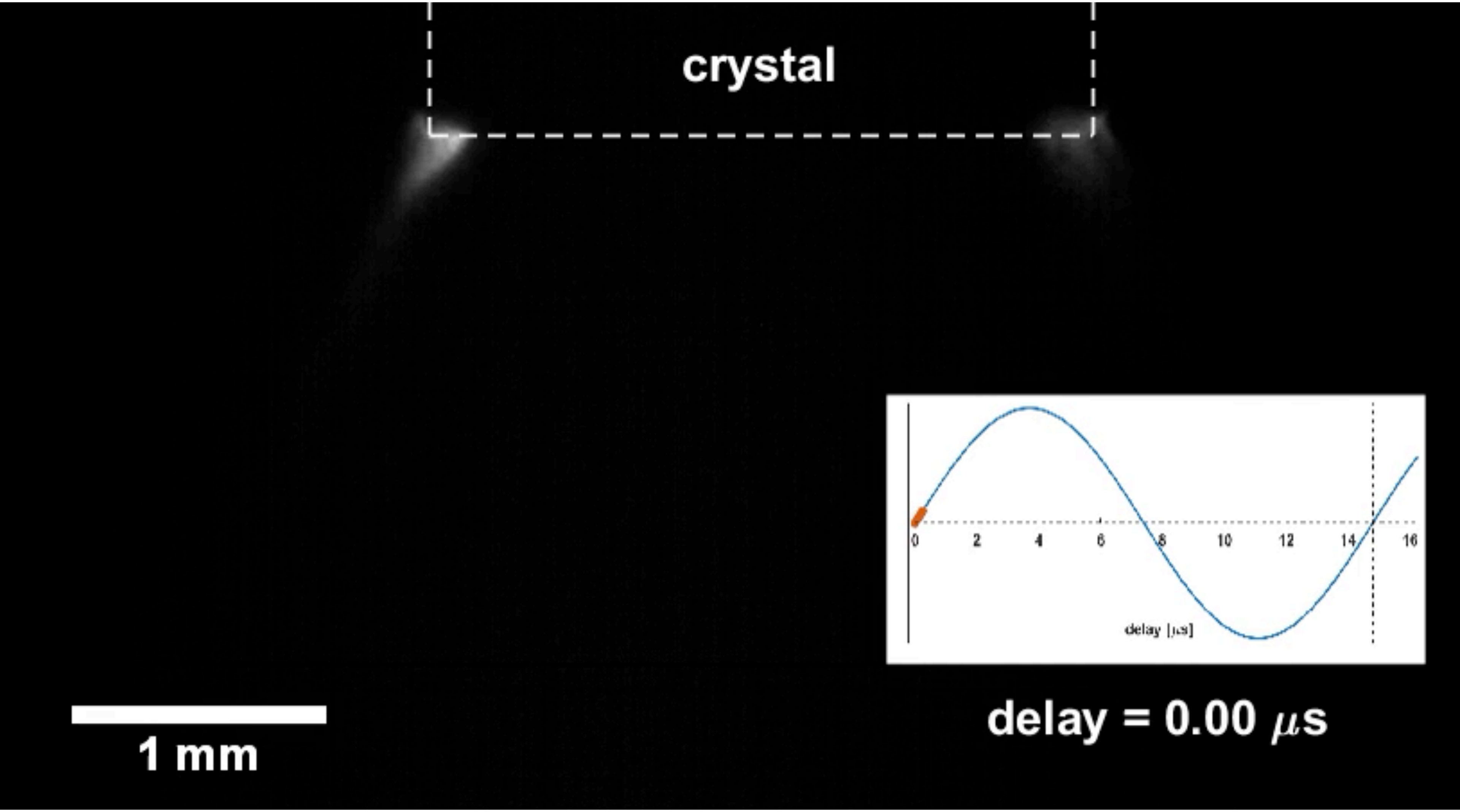
Burst Mode to Overcome Internal Heating

- PT is operated in a burst mode.
- Each burst has 1000 input voltage cycles, ~15 ms.
- There is ~85 ms cooling phase between two successive bursts.

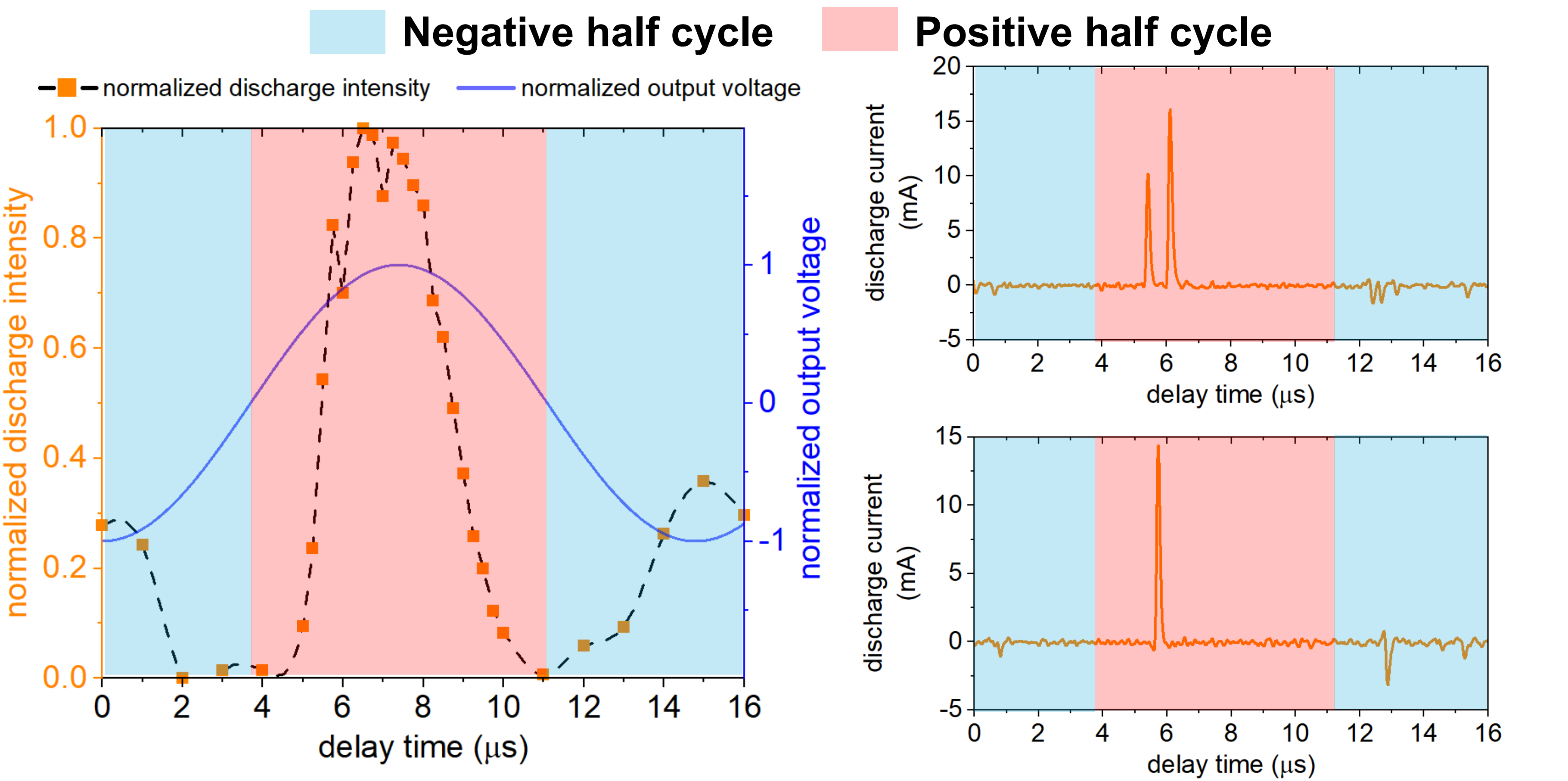




Temporal Evolution over One Cycle



Positive and Negative Half Cycle Behavior

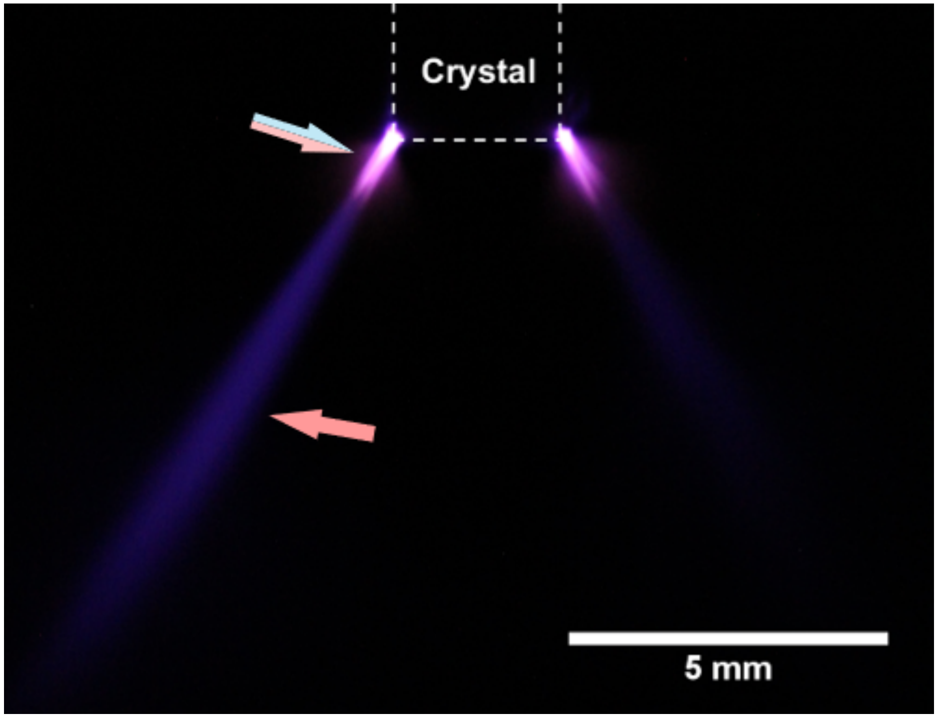


Both single and double strikes consistently observed

Yang, Im, & Go, *Plasma Sources Sci. Technol.*, **29**, 045016, 2020.

Positive and Negative Half Cycle Behavior

Negative half cycle Positive half cycle



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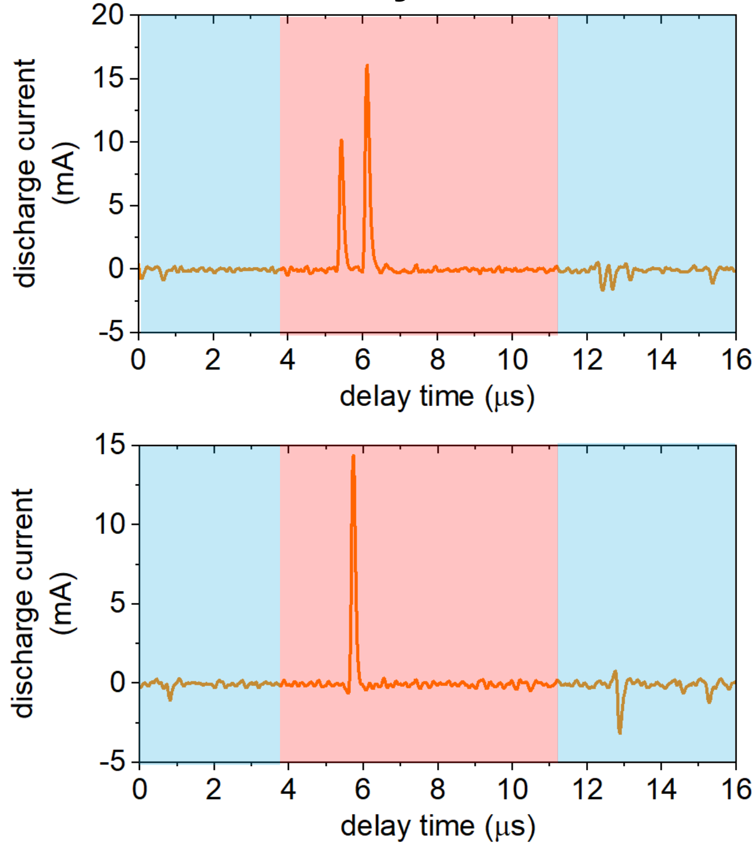
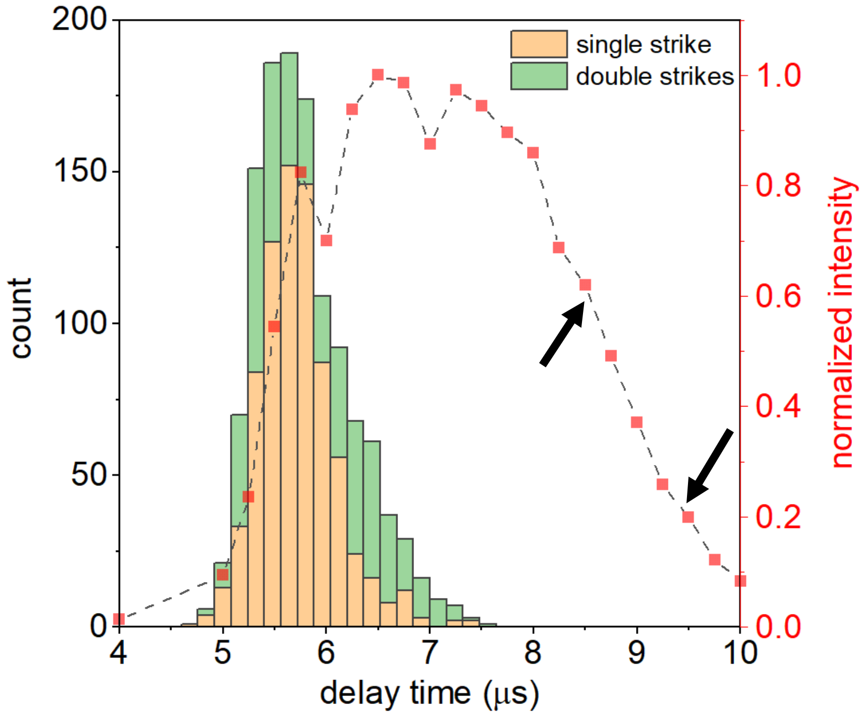


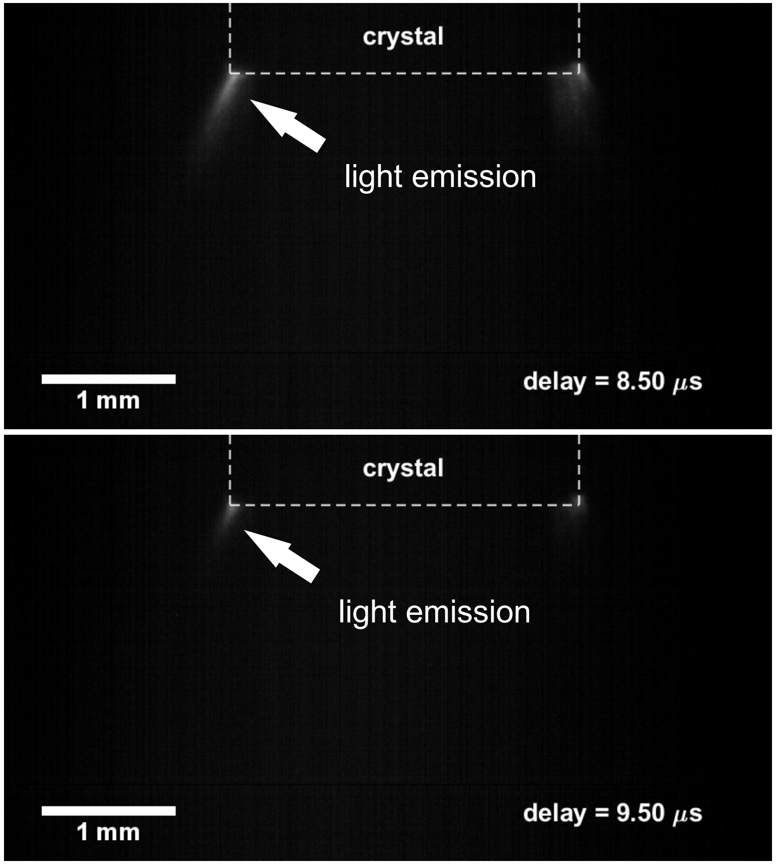
Positive streamers stretch are more intense and longer than negative streamers

Yang, Im, & Go, *Plasma Sources Sci. Technol.*, **29**, 045016, 2020.

Statistical Behavior

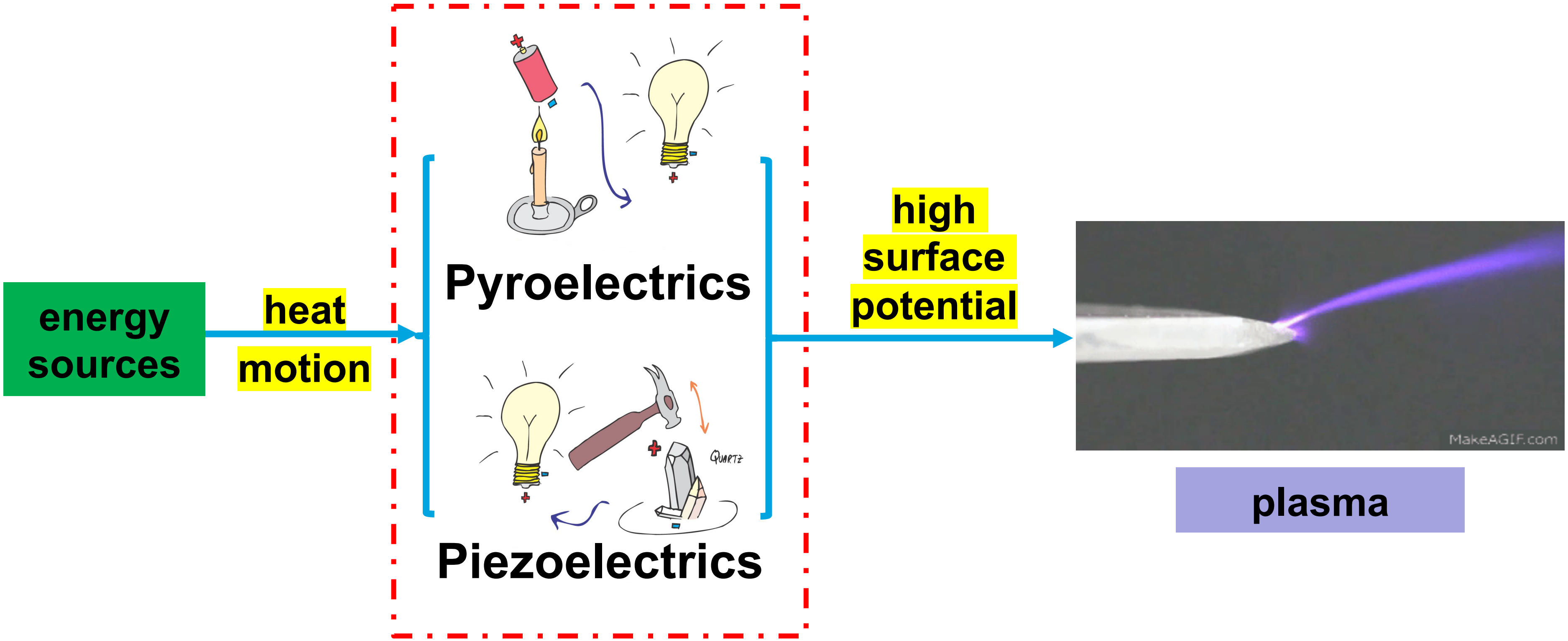
Positive strikes appear at the mean delay time of 5.79 ± 0.47 μs (68%).





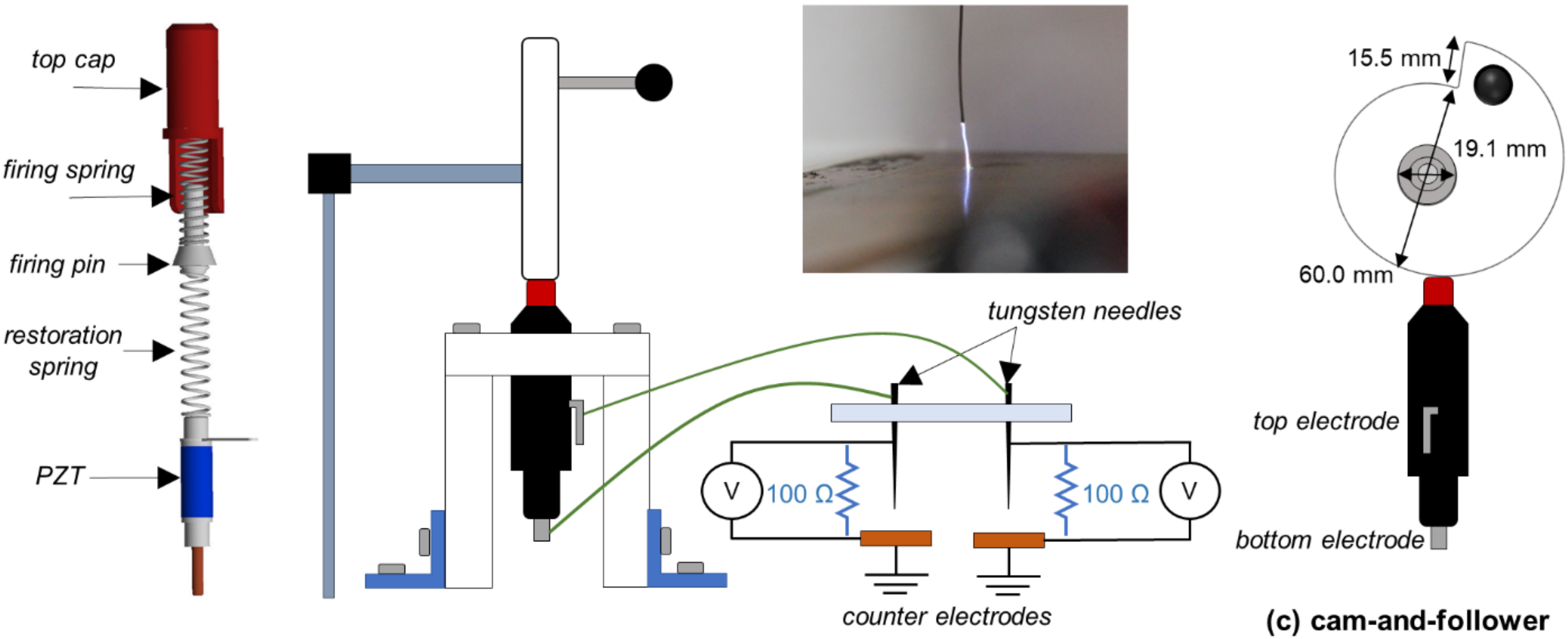
Phase difference between current spike and light emission indicates a strong afterglow

Energy Conversion Plasmas

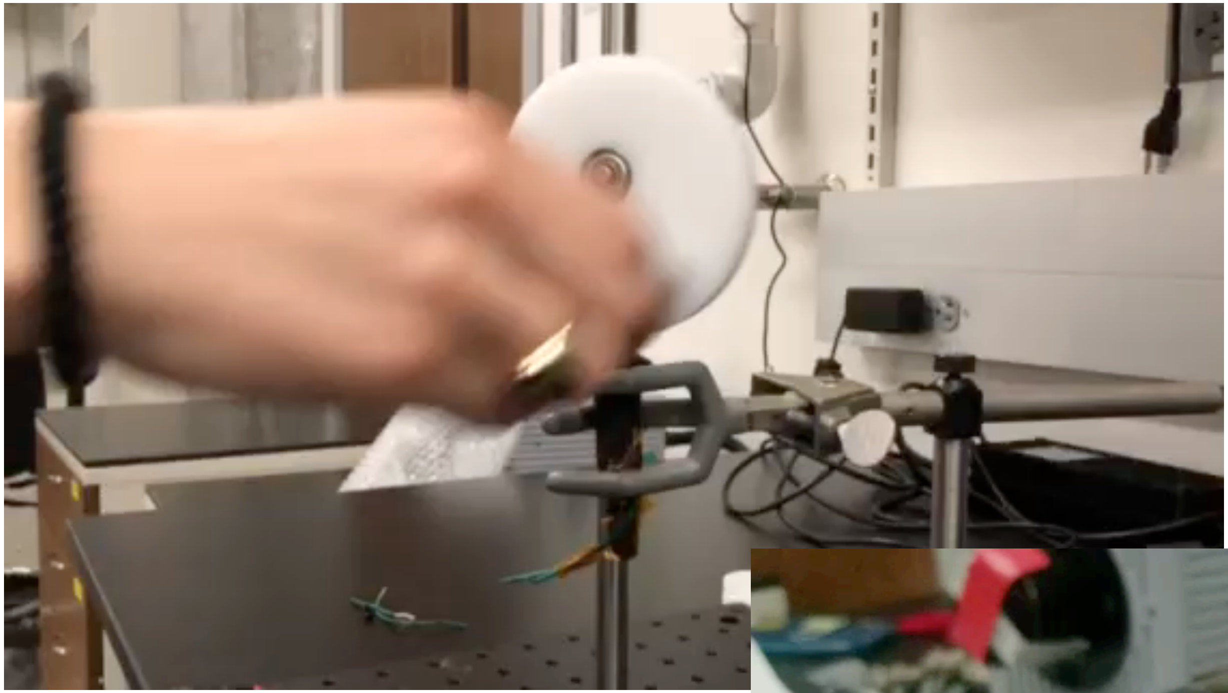


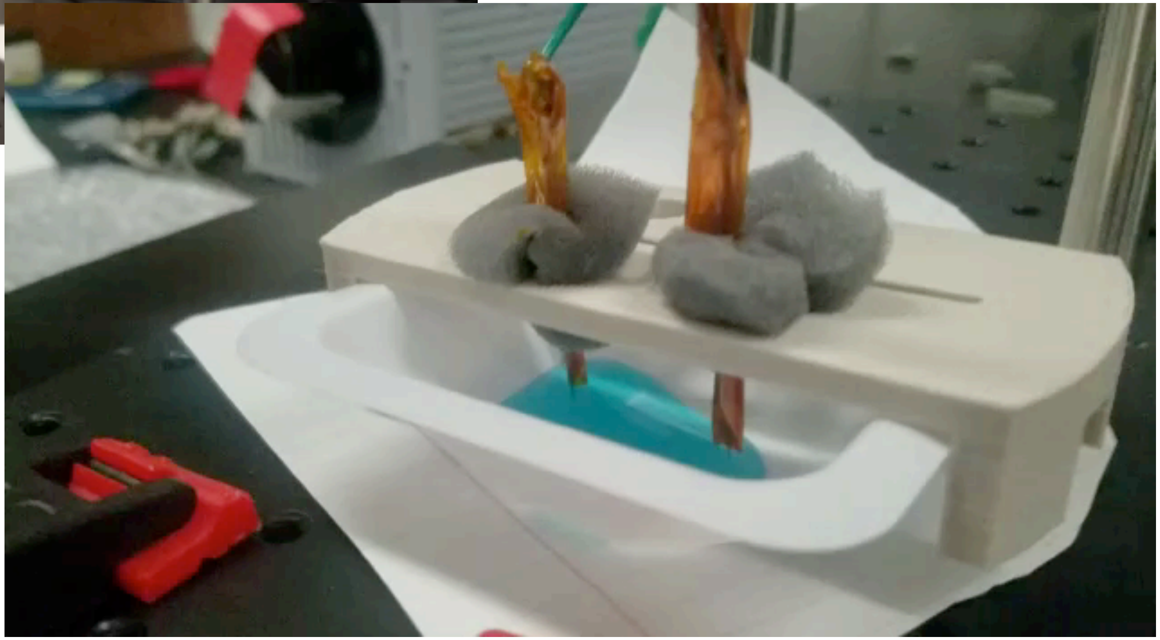
Energy conversion plasmas: Use pyroelectric/piezoelectric crystals to directly convert thermal/mechanical motion into a plasma source

Hand-Generated, Mechanically-Driven Plasma Device

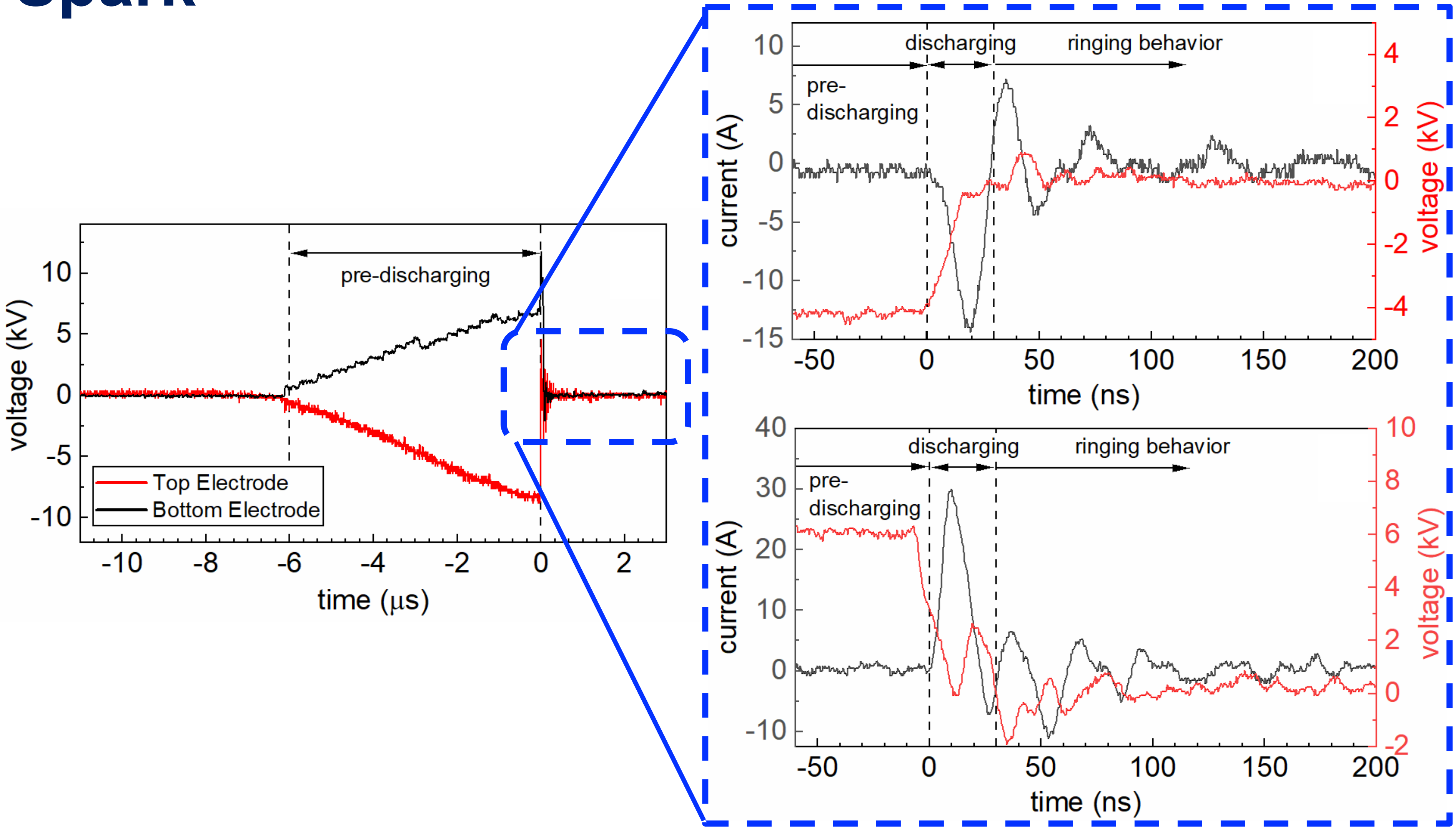


Mechanical-to-Plasma Energy Conversion



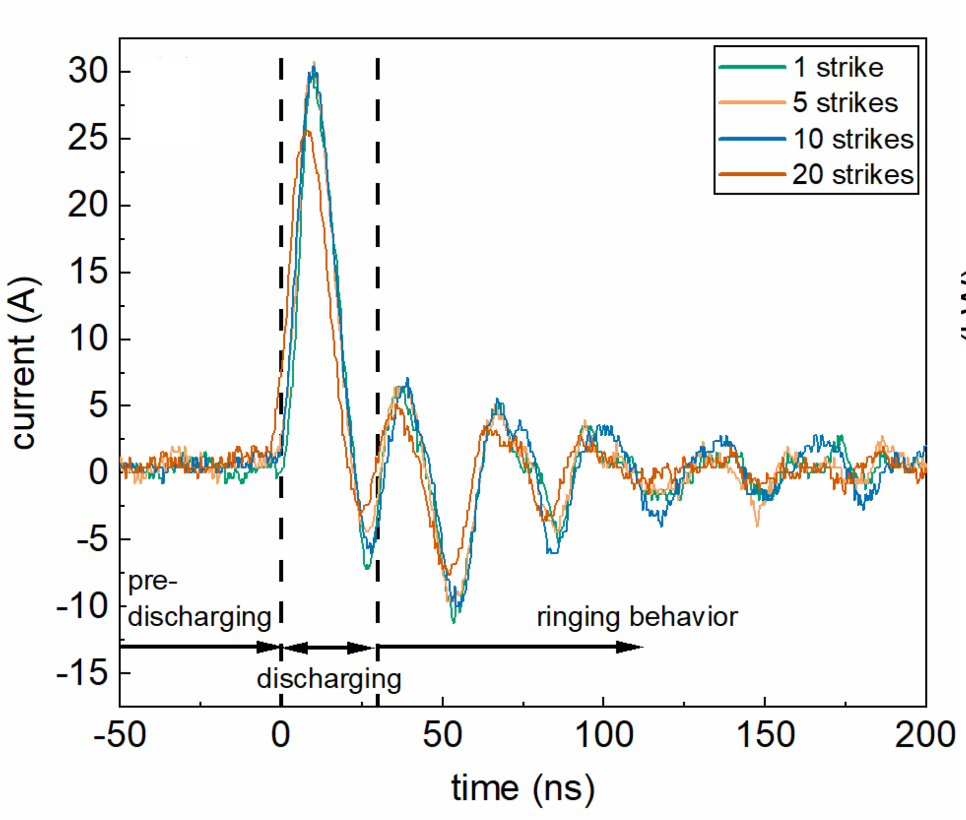


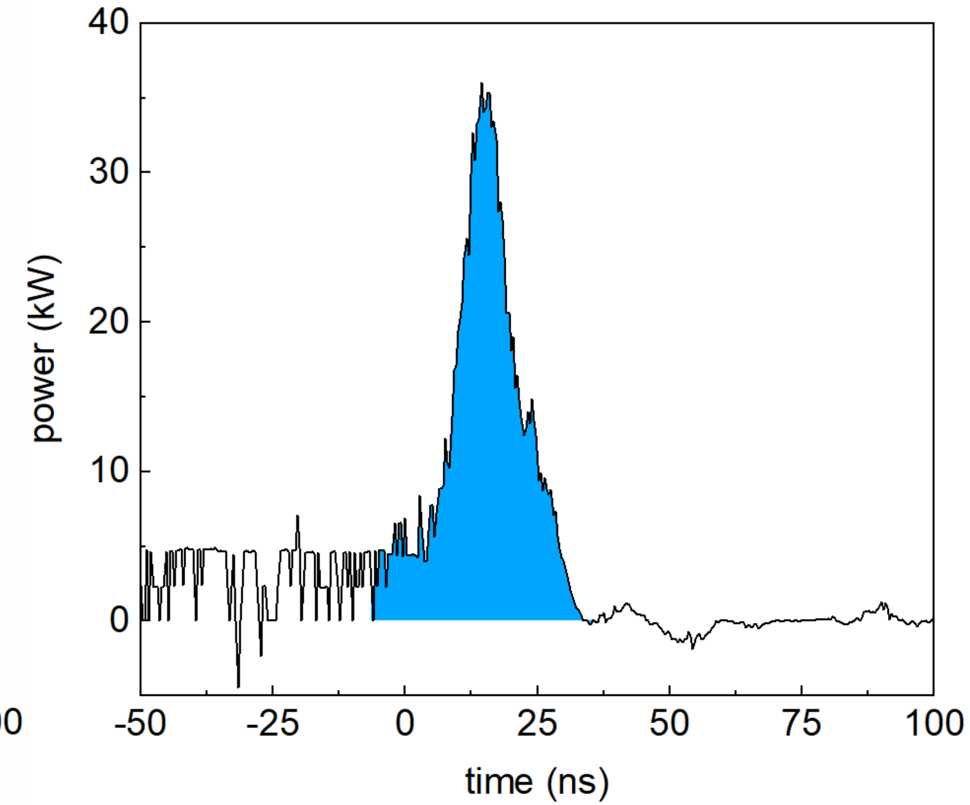
Plasma Has Characteristics of a Transient Spark



Jaenicke, Hita Martinez, Yang, Im, & Go, *Appl. Phys. Lett.*, **117**, 093901, 2020.

Plasma Generation Is Repeatable But Inefficient



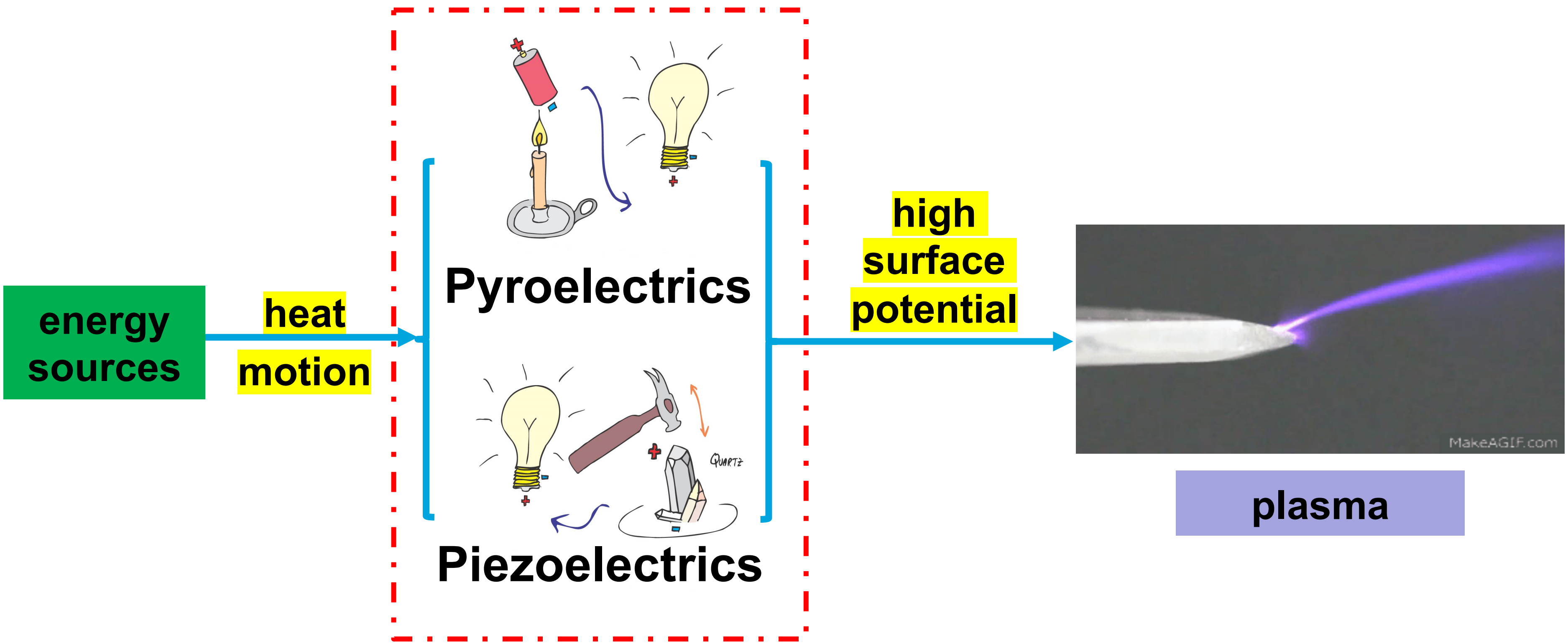


$$E_p = \frac{1}{2}kx^2.$$

$$\eta = \left(E_{d,top} + E_{d,bottom}\right)/E_p$$

η = 1.54 ± 0.12%

Energy Conversion Plasmas



Energy conversion plasmas: Use pyroelectric/piezoelectric crystals to directly convert thermal/mechanical motion into a plasma source

73rd Annual Gaseous Electronics Virtual Conference

Monday–Friday, October 5–9, 2020; Time Zone: Central Daylight Time, USA.

Session YF2: Atmospheric Pressure Plasma Characterization

1:00 PM–3:00 PM, Friday, October 9, 2020

Chair: Pedro Viegas, Dutch Institute for Fundamental Energy Research

Abstract: YF2.00007 : Spatially-resolved Optical Emission Spectroscopy Measurements of Free Plasma Jets Formed off the Surface of a Piezoelectric Transformer*

2:30 PM–2:45 PM Live

Preview Abstract

← *Abstract* →

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Session RW2: Poster Session IV (4:30pm - 6:30pm)

4:30 PM, Wednesday, October 7, 2020

APS -73rd Annual Gaseous Electronics Virtual Conference - Event - Hand-generated piezoelectric mechanical-to-electrical energy conversion plasma

Abstract: RW[illegible]ectric mechanical-to-electrical energy conversion plasma*

Preview Abstract

← *Abstract* →

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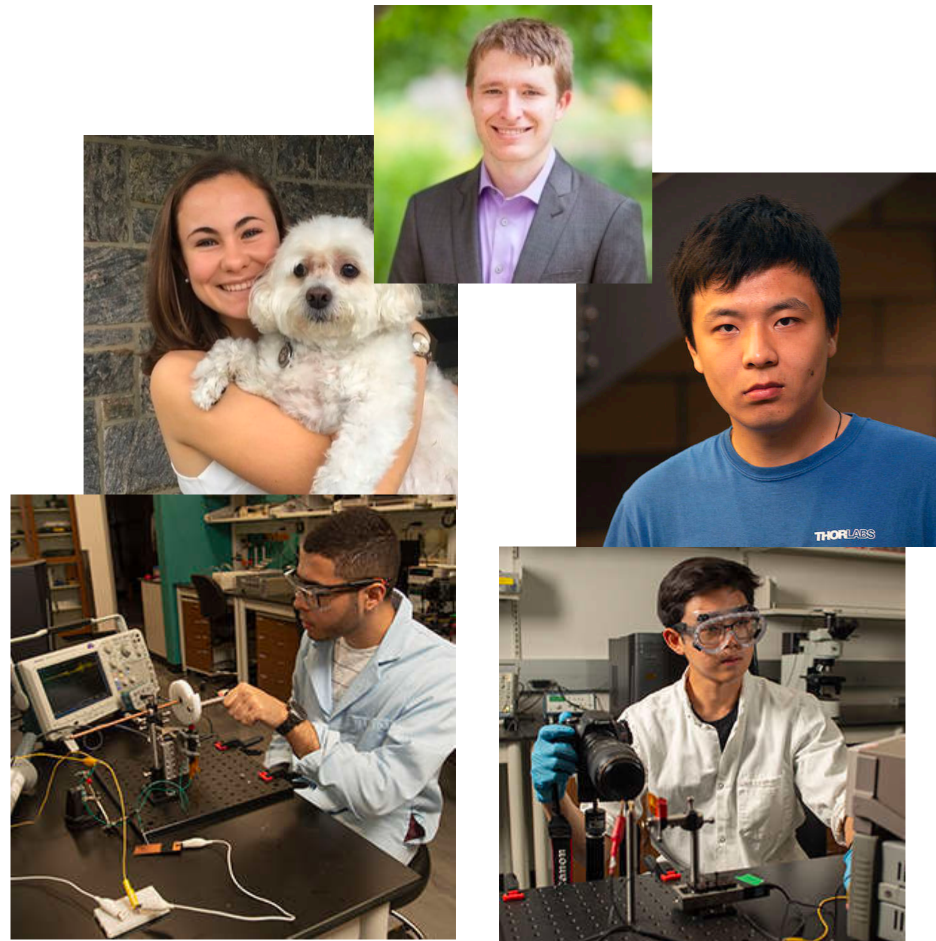

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