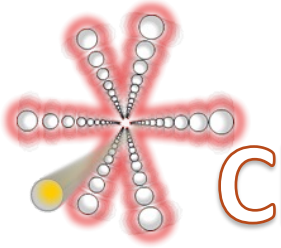


Channeling 23

John Adams Institute for Accelerator Science

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Stability of electrons and X-rays generated in a pyroelectric accelerator

Majid Ali

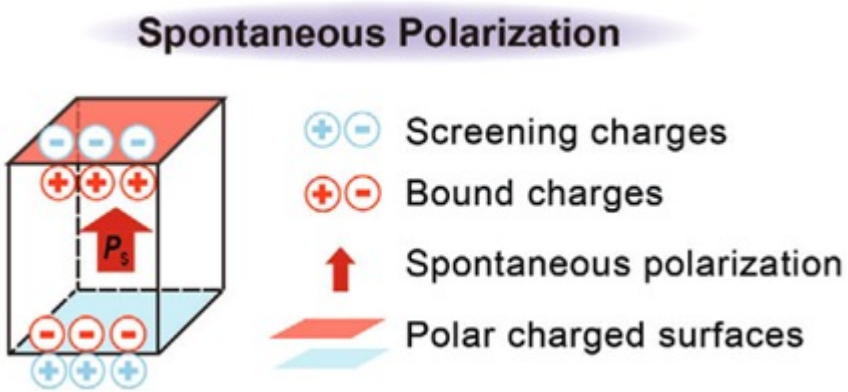
John Adams Institute at Royal Holloway, University of London, Egham, UK.

The 9th International Conference "Charged & Neutral Particles Channeling 23, 4-9 June 2023, Riccione, Italy

Outline

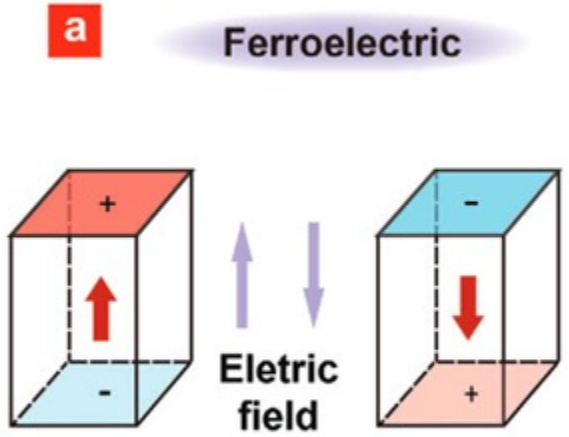
- ⟹ Pyroelectric effect
- ⟹ Particle generation and acceleration using pyroelectric effect
- ⟹ History and development of pyroelectric accelerator
- ⟹ Cool-X by Amptek
  Miniature X-Ray source based on Pyroelectric effect
- ⟹ Experimental layout
- ⟹ Experimental results and analysis
- ⟹ Conclusion and further development

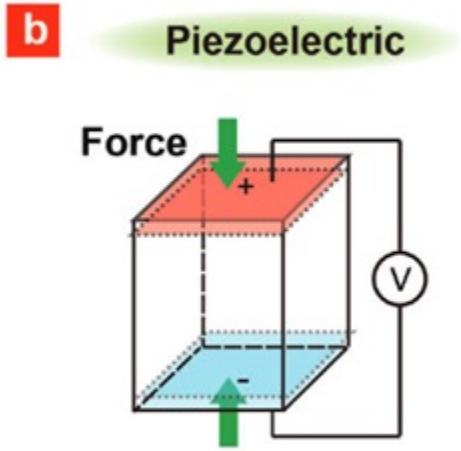
Pyroelectric effect?

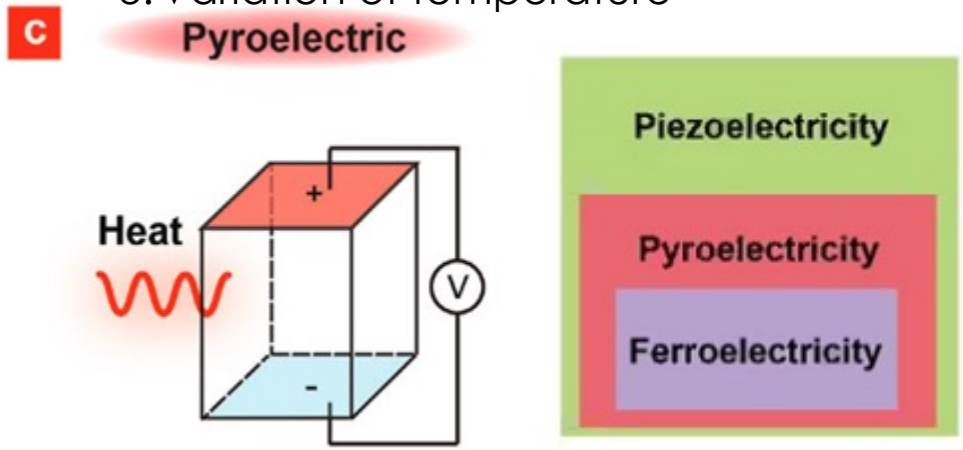


Main three ways to change the value or direction of spontaneous polarization.

1. Application of external electric field
2. Application of mechanical stress
3. Variation of temperature



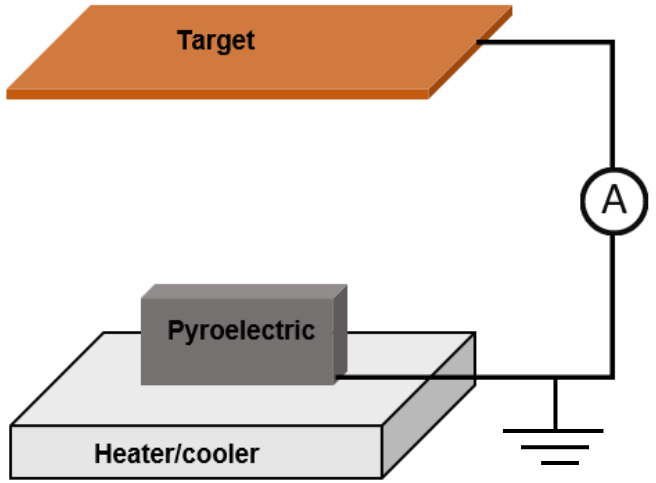


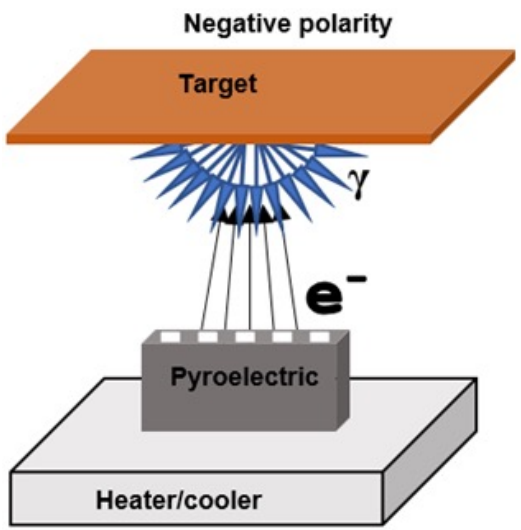


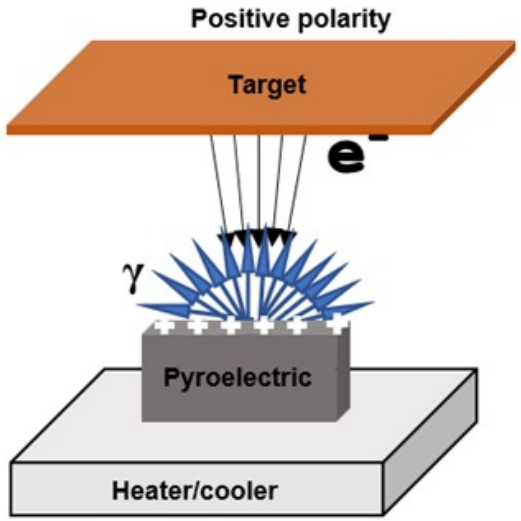
Wang, W., Li, J., Liu, H., Ge, S., Advancing Versatile Ferroelectric Materials Toward Biomedical Applications. *Adv. Sci.* 2021, 8, 2003074.

Particles acceleration using pyroelectric effect

Main Scheme of operation







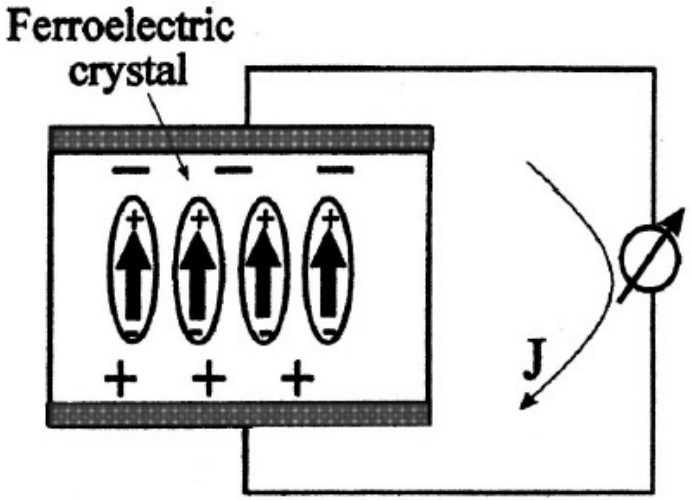
- **Pyroelectric materials used**
  Lithium Tantalate, Lithium niobate
- **Temperature variation**
  10-100 °c
- **Pressure Range**
  Up to 100 mTorr
- **X ray end point energy**
  Up to 200 keV
- **Electron current**
  Up to 10 nA
- **Positive ion generators**
  Nitrogen, oxygen, hydrogen, argon ions (max energy up to 150 keV)
- **Neutron generators**
  Fast neutrons energy up to 2.45 MeV

Electron emission from $LiNbO_3$

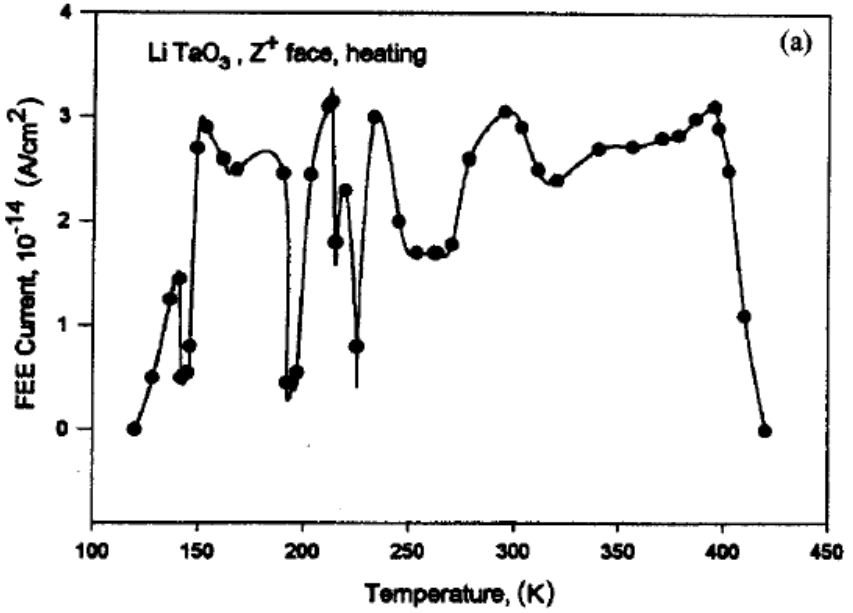
1974 - Stimulated electron emission by change in temperature of pyroelectric material

B. Rosenblum, P. Bräunlich, and J. P. Carrico, Thermally stimulated field emission from pyroelectric LiNbO3 Appl. Phys. Lett. 25, 17 (1974)

The scheme of measurement of ferroelectric electron emission.



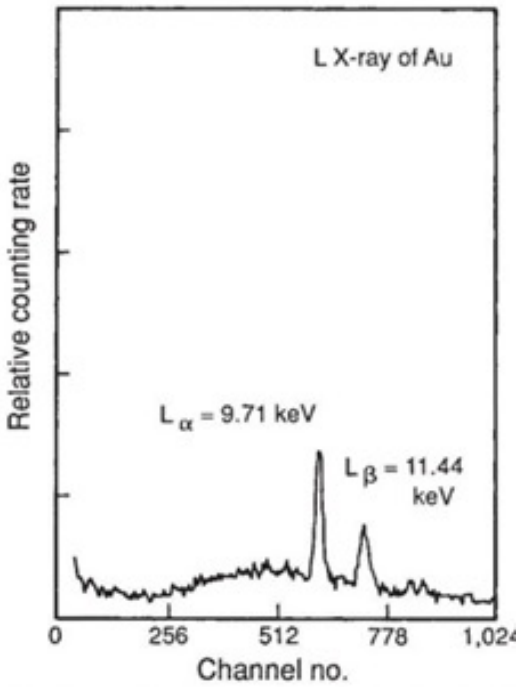
The curve of the current during heating of pyroelectric crystal



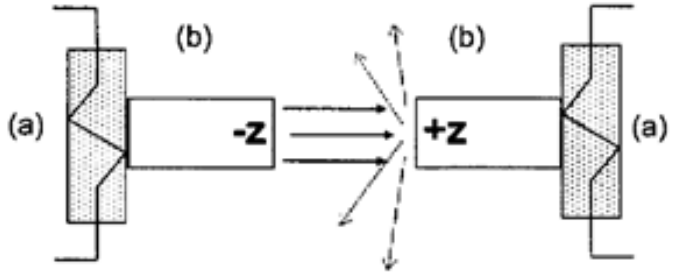
X-ray source based on pyroelectric effect

In 1992, Brownridge published the first report about X-ray generation stimulated by change in temperature of the pyroelectric material

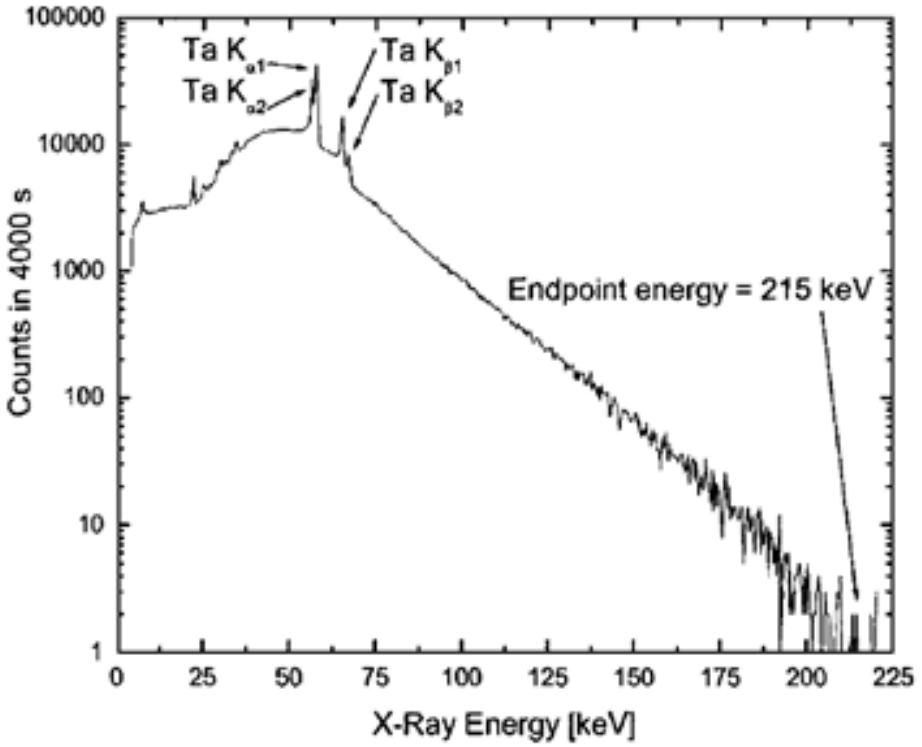
X-ray spectrum obtained using pyroelectric effect



Paired-crystal system



Development pyroelectric X-ray sources

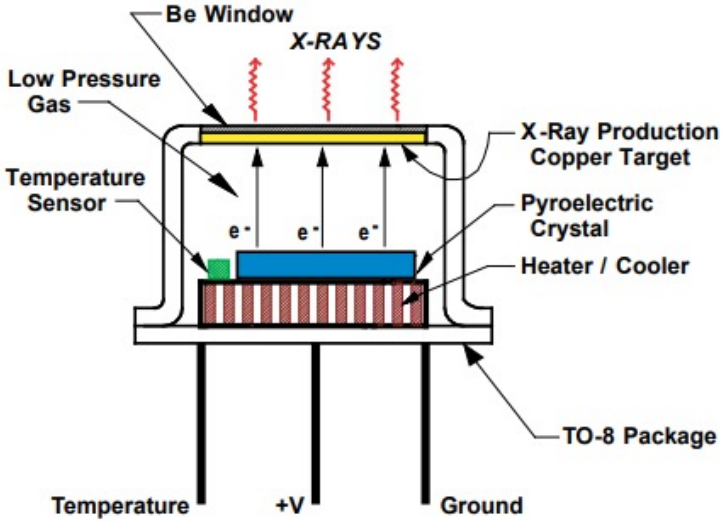


J. D. Brownridge, Pyroelectric X-ray generator, Nature ~London! **358**, 287 ~1992!.
Jeffrey A. Geuther *and* Yaron Danon , Journal of Applied Physics **97**, 074109 (2005); https://doi.org/10.1063/1.1884252

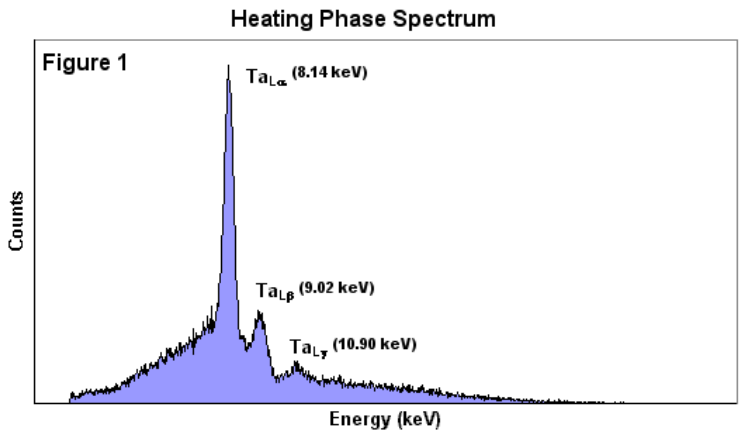
X-ray source based on pyroelectric effect,

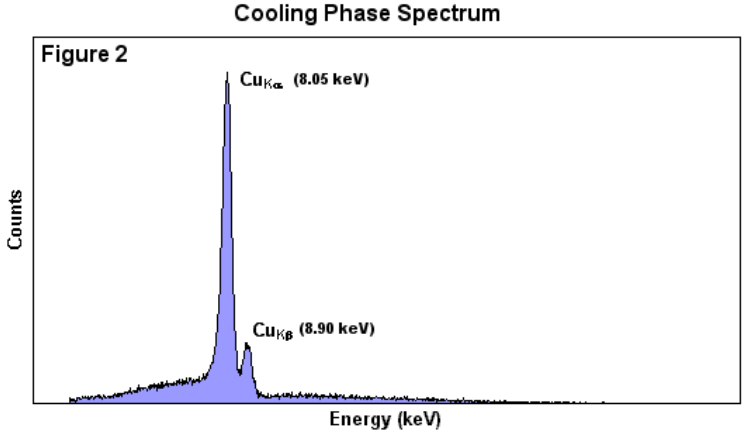
1/2

COOL-X shown with the Amptek XR-100CR X-Ray Detector



The x-ray spectrum obtained by COOL-X.





https://www.amptek.com/internal-products/obsolete-products/cool-x-pyroelectric-x-ray-generator

X-ray source based on pyroelectric effect,

PROS

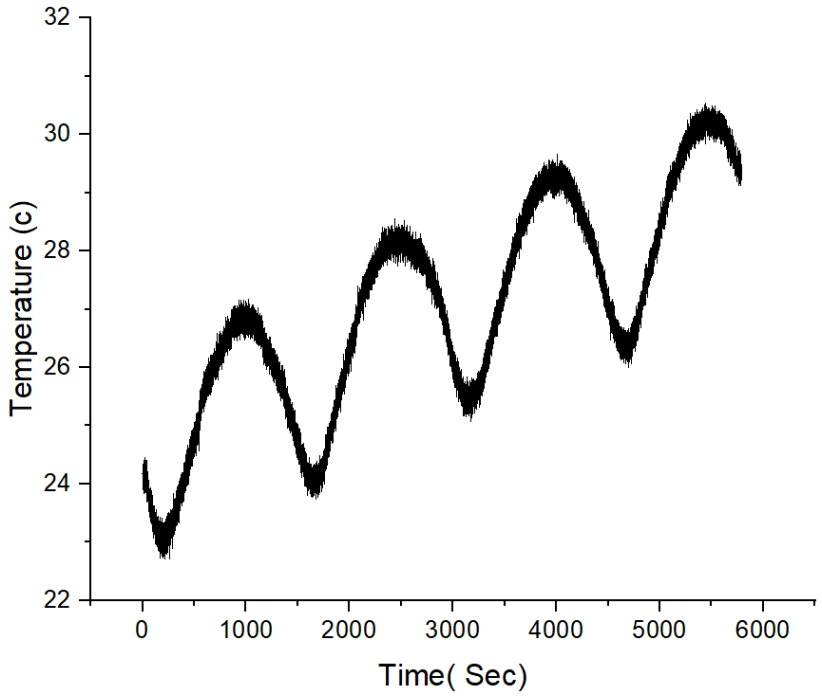
- ⇨ Compact pocket-style X-ray source
- ⇨ Low power: < 300 mW
- ⇨ No radioactive sources
- ⇨ Does not required external high voltage source: Runs on standard 9 V battery
- ⇨ Variable end point energy: up to 35 kV
- ⇨ Weight: 185 g

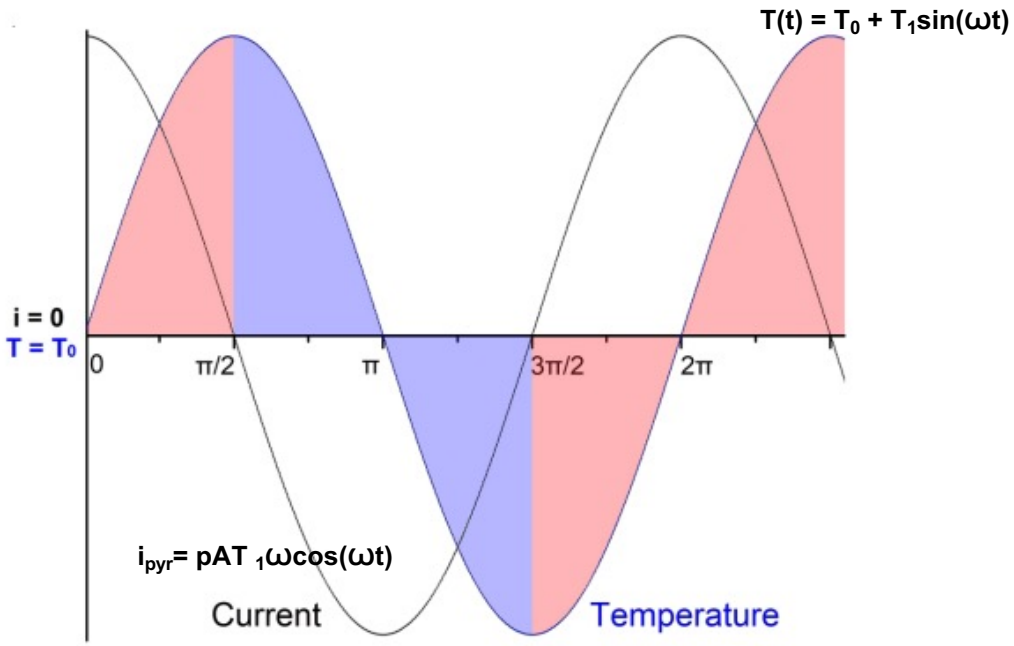
CONS

- ⇨ The x-ray flux varies vary from cycle to cycle.
- ⇨ Dead time: without x-ray generation, when thermal phase is change.
- ⇨ Interruptions of particle generation by electric breakdowns
- ⇨ Short lifetime: Approximately 200 hours.

Periodically varying temperature of LiTaO3

A periodically varying temperature of pyroelectric as a way of stabilizing particle yield





L. E. Garn and E. J. Sharp, J. Appl. Phys. 53, 8974 (1982)

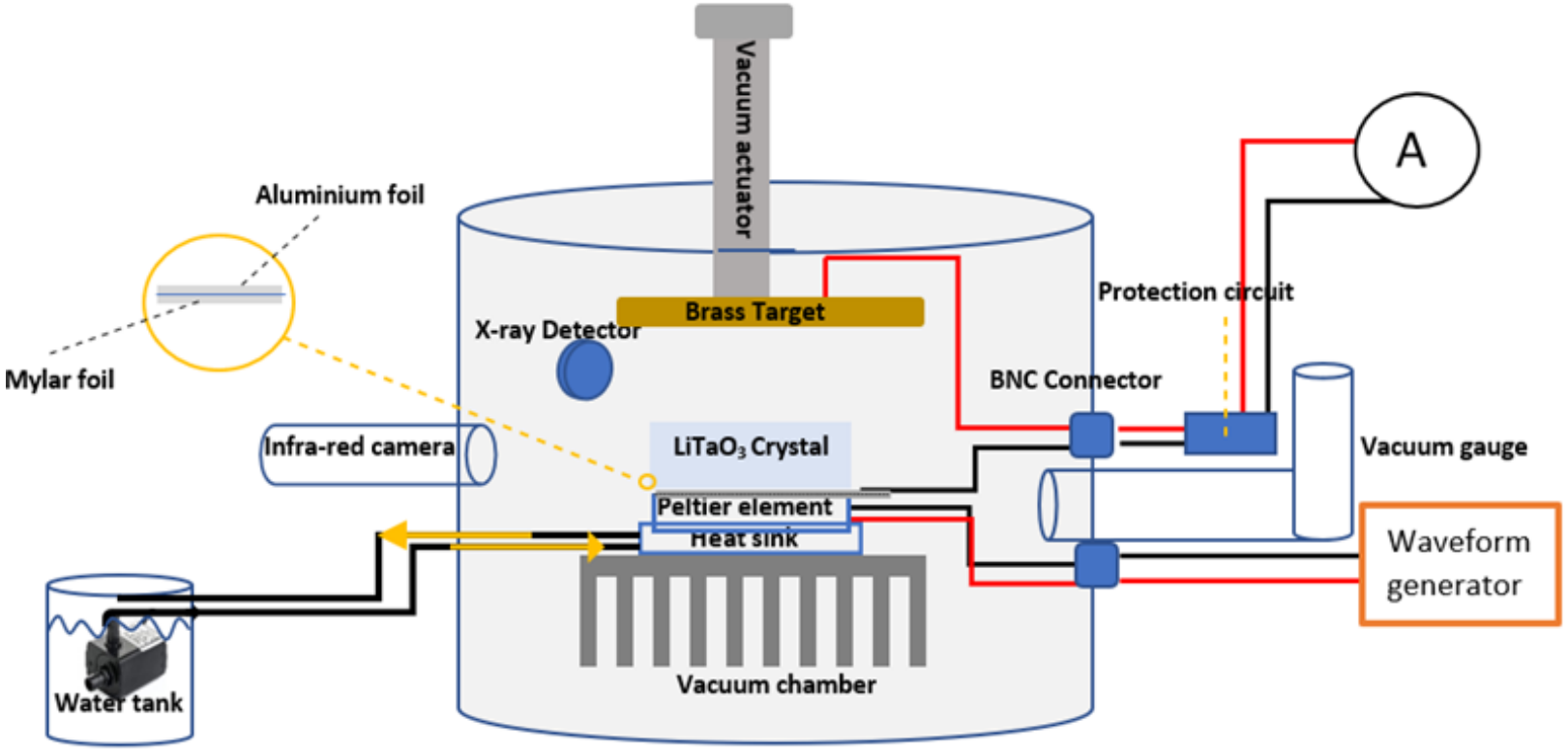
L. E. Garn and E. J. Sharp, J. Appl. Phys. 53, 8980 (1982)

Sinusoidal temperature variation enable us to produce stable, continues and reproduceable temperature variation cycle by cycle through operation. Which is the key to stable x ray generation.

Experimental layout

Scheme of experimental setup

1/2



Pyroelectric sample: Lithium tantalate ($LiTaO_3$)
Thickness: 10 mm
Area: 20×20 mm^2

✓ **Current measurement system**

0.01 pA – 20 mA

✓ **X-Ray detection system**

0.5- 150 keV

✓ **Vacuum system**

Variable pressure from 0.1 mTorr-atmospheric pressure

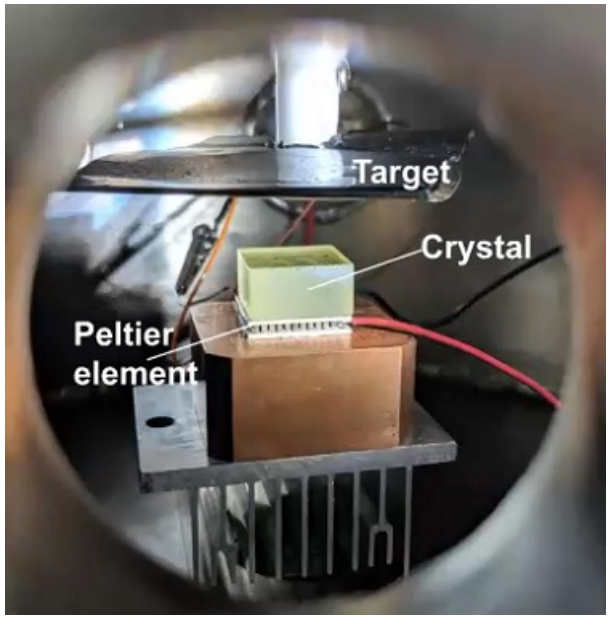
✓ **Changing temperature system**

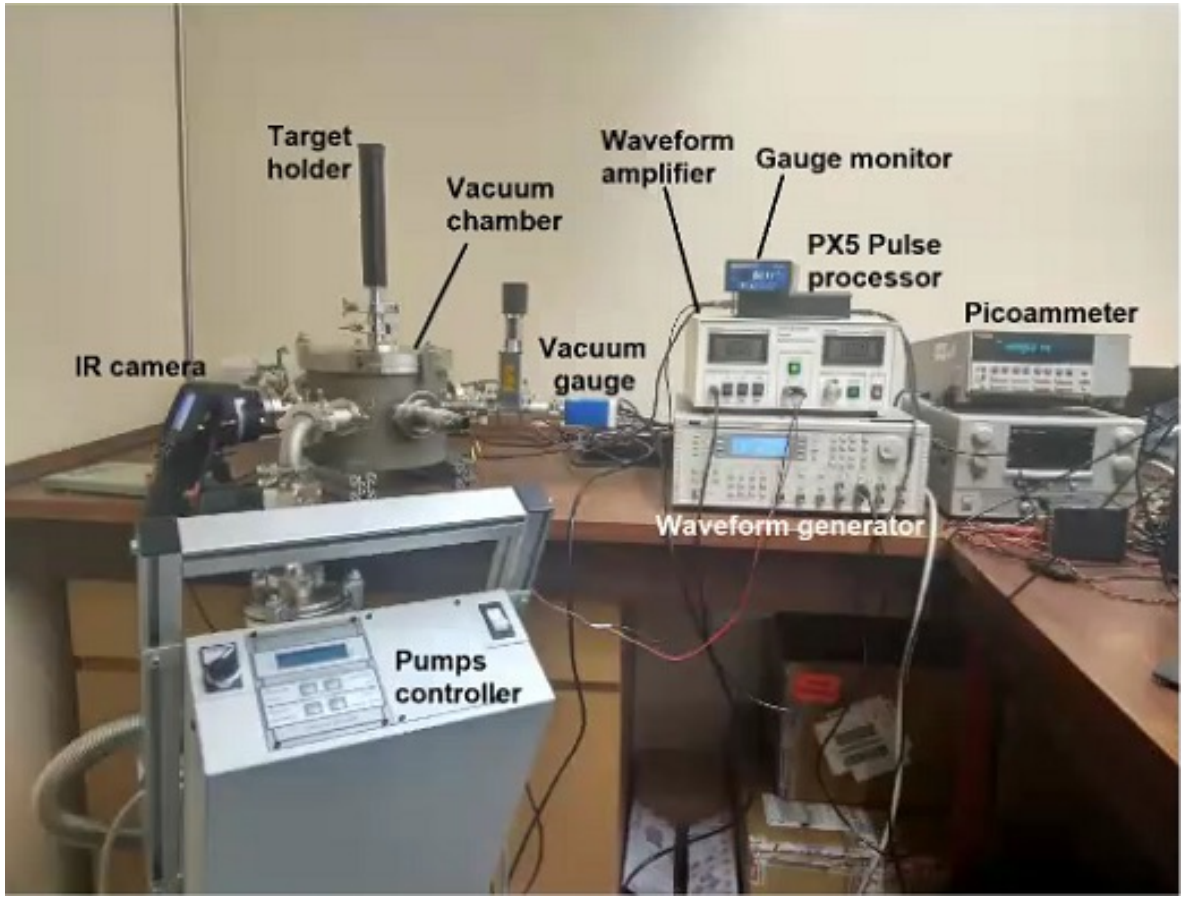
Roughly 5-70 °c (depend on the frequency of temperature variation)

✓ **Temperature monitoring**

Temperature monitoring of pyroelectric crystal inside vacuum chamber

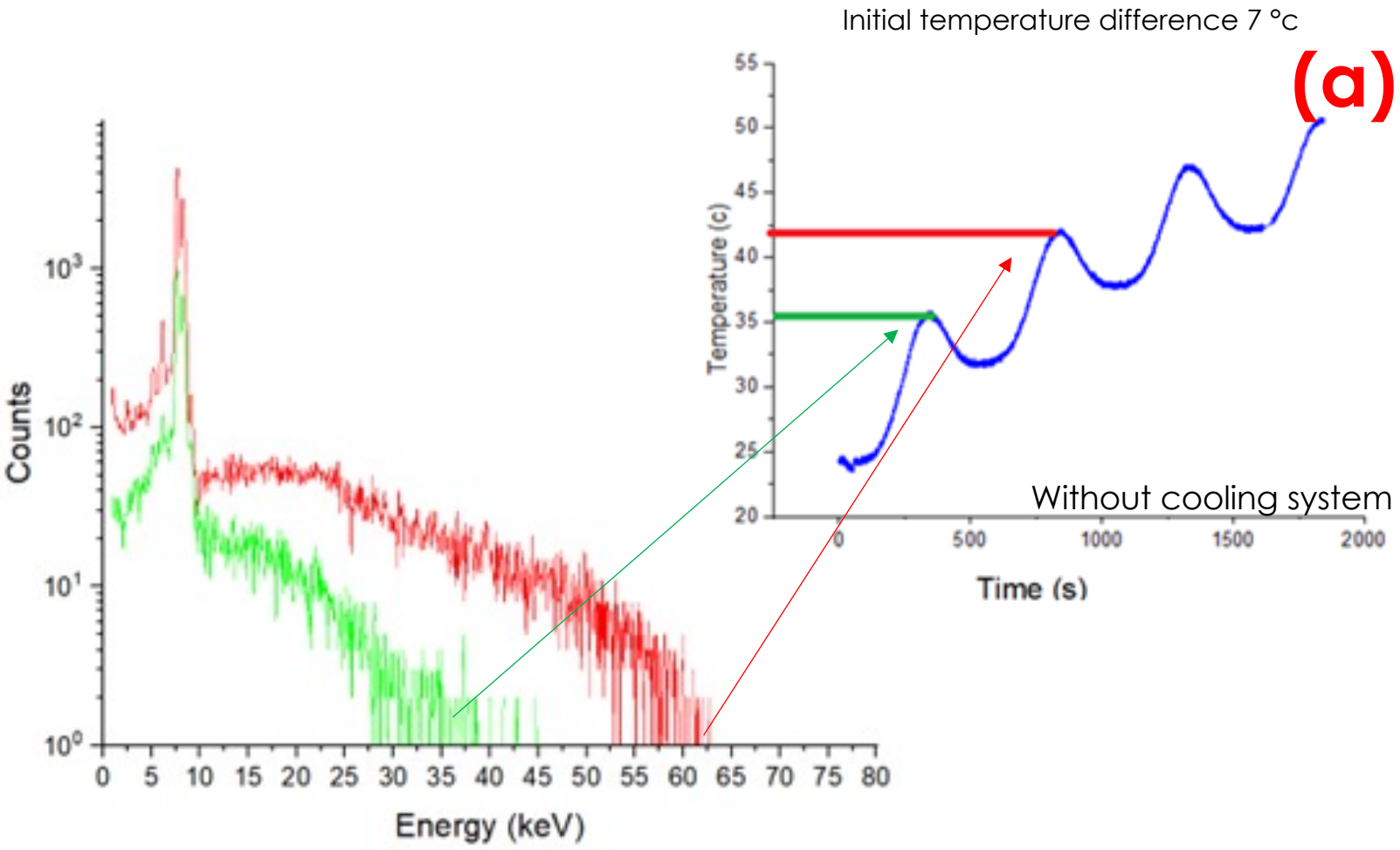
Experimental layout



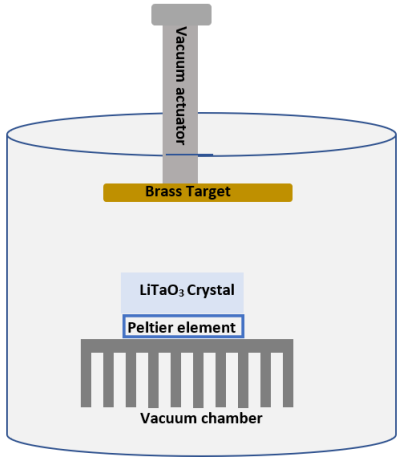


Impact of temperature oscillations shift on stability of particles generation

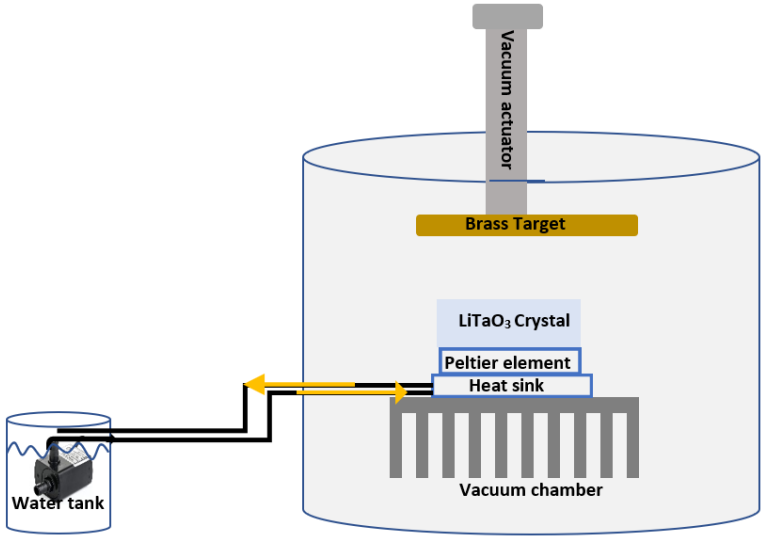
1/2

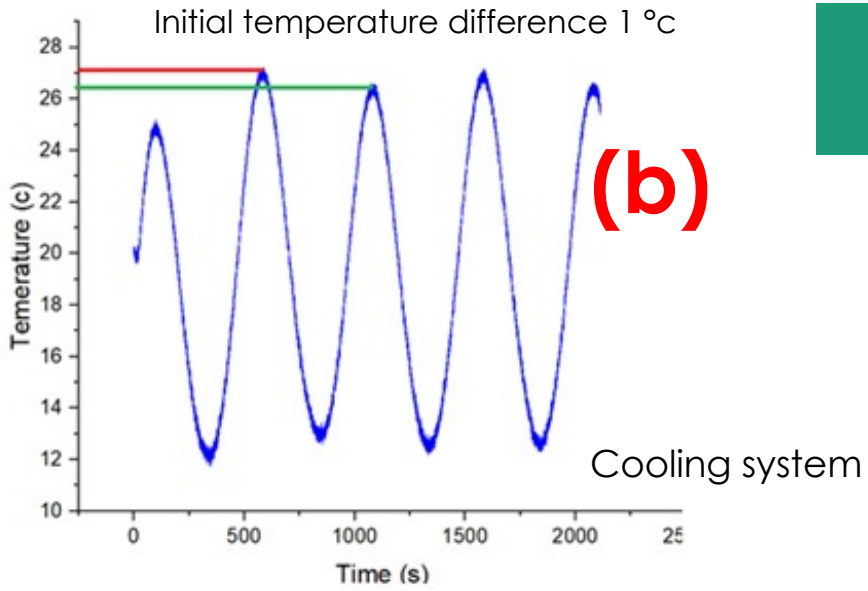


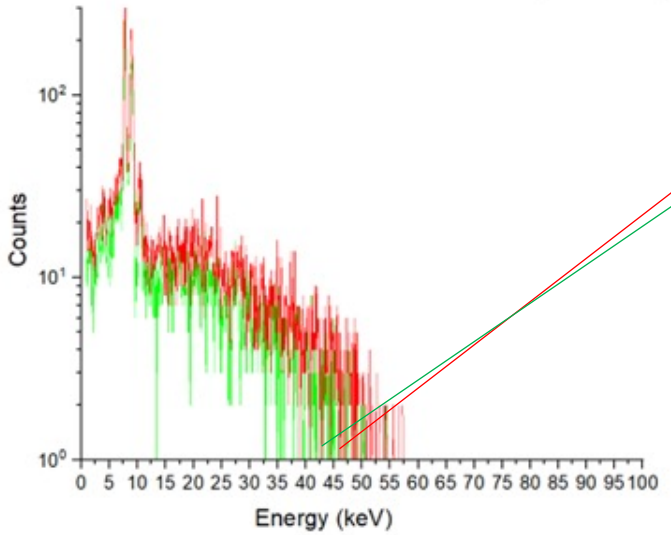
An example of the degradation of the X-ray spectrum recorded in one thermal cycle during periodic temperature variation with the frequency of 2mHz.

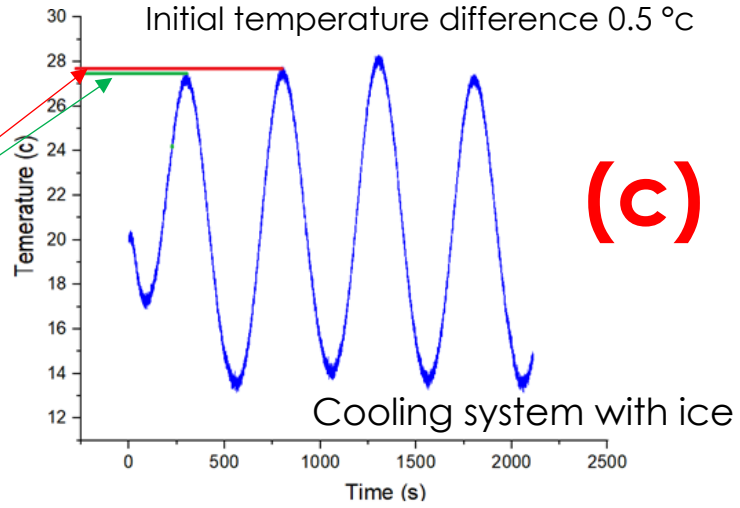


Impact of temperature oscillations shift on stability of particles generation





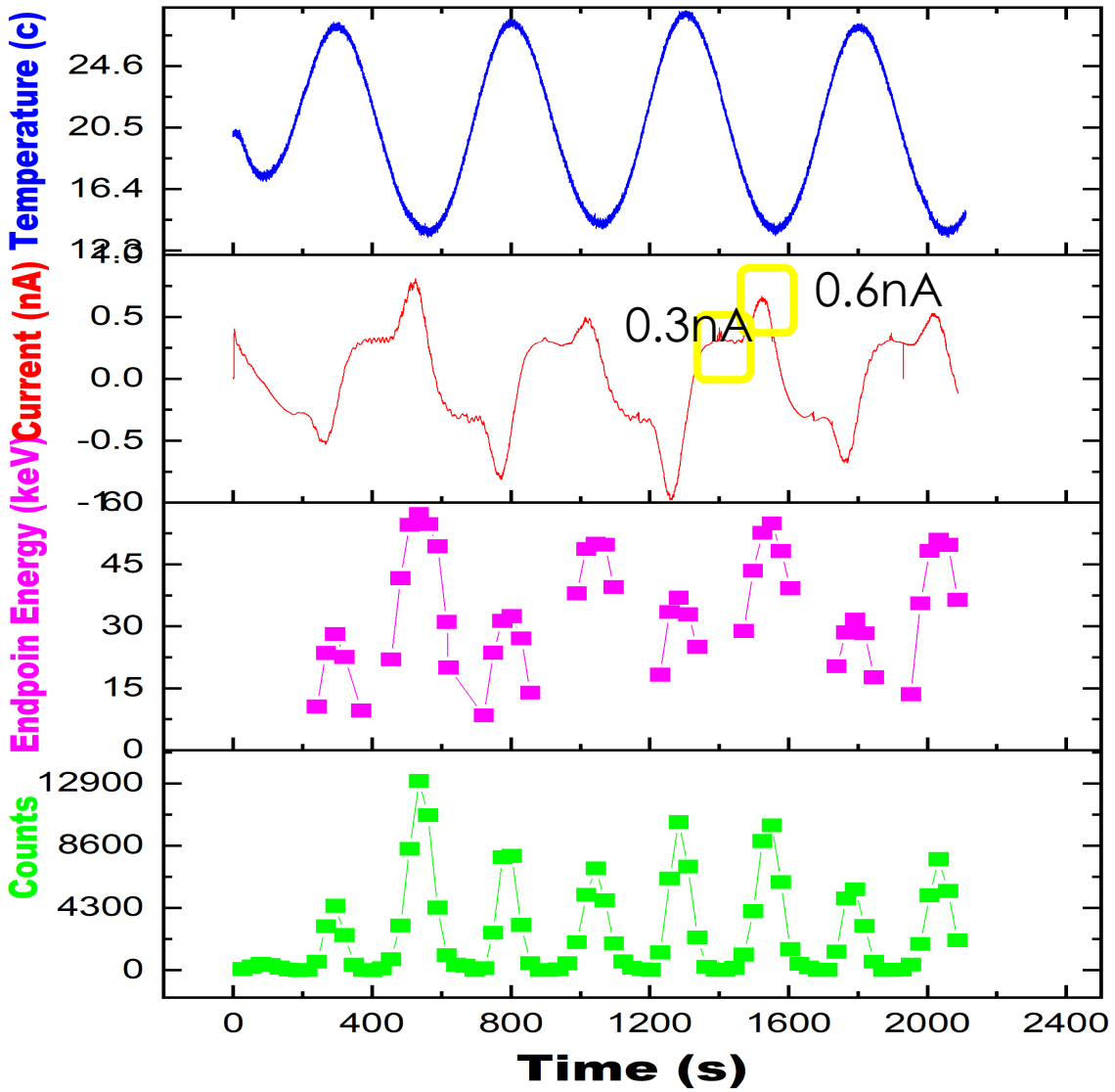


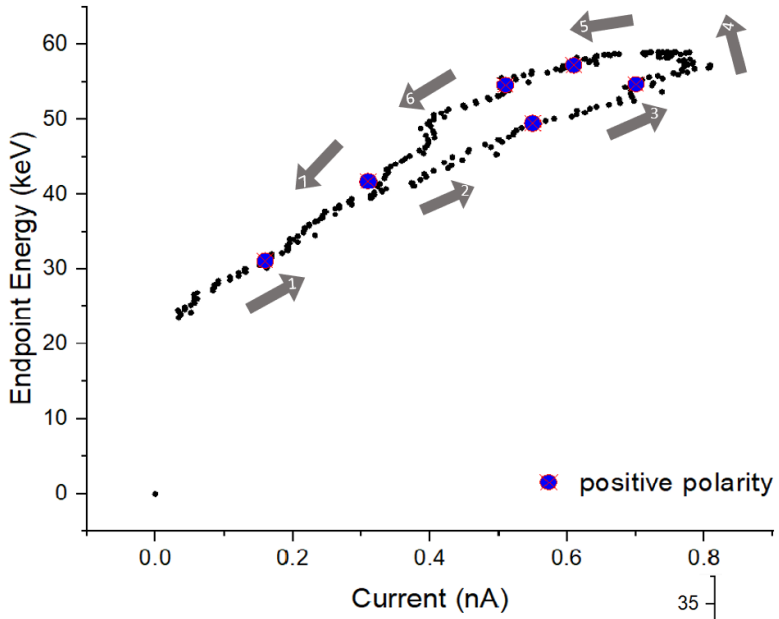


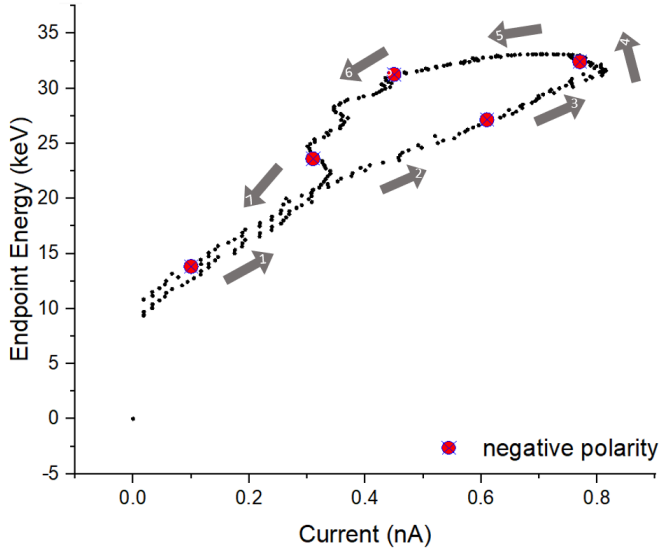
- ✓ A stable mode of periodic generation of an electric field of the approximately identical magnitude.
- ✓ Such conditions should provide the generation of electrons and X-rays in the same amount with almost the same periodicity.

Stable electron and x-ray generation

1/2

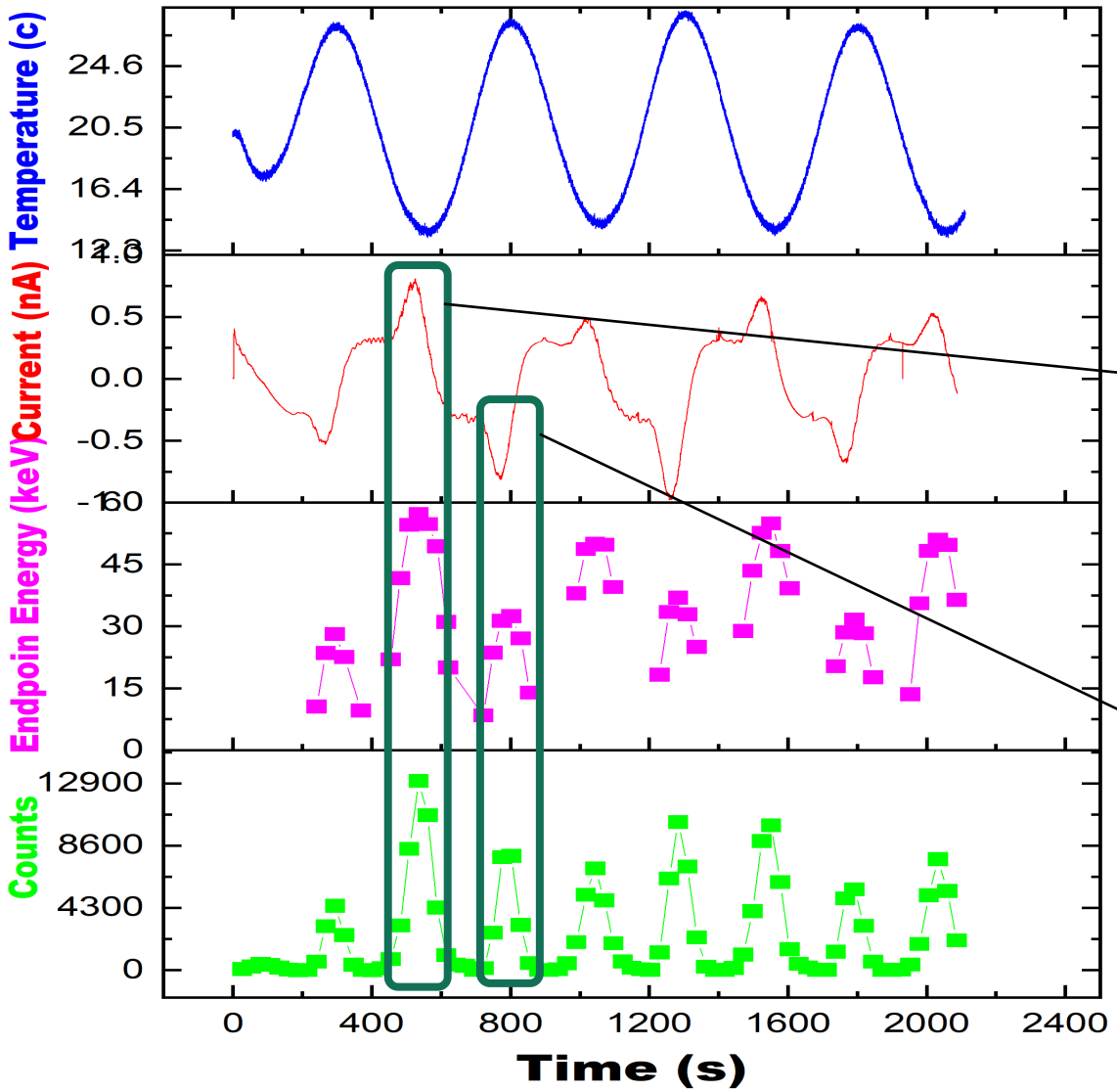






Stable electron and x-ray generation

2/2



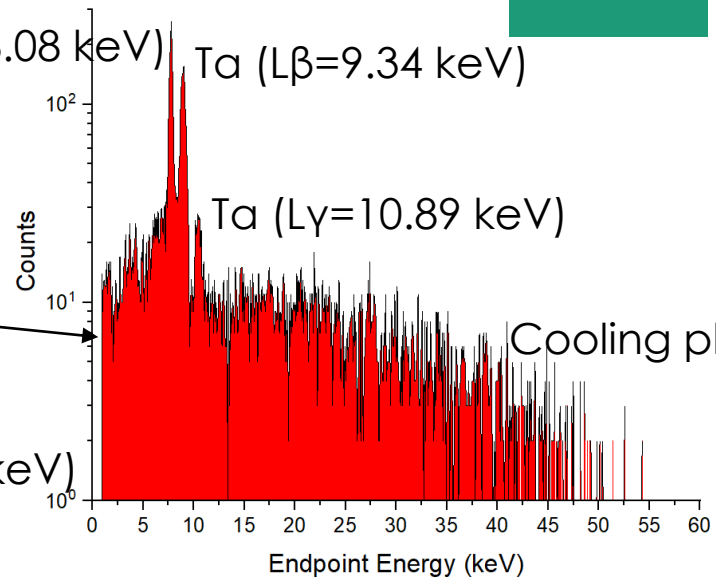
positive Polarity

Ta (Lα=8.08 keV)

Ta (Lβ=9.34 keV)

Ta (Lγ=10.89 keV)

Cooling phase



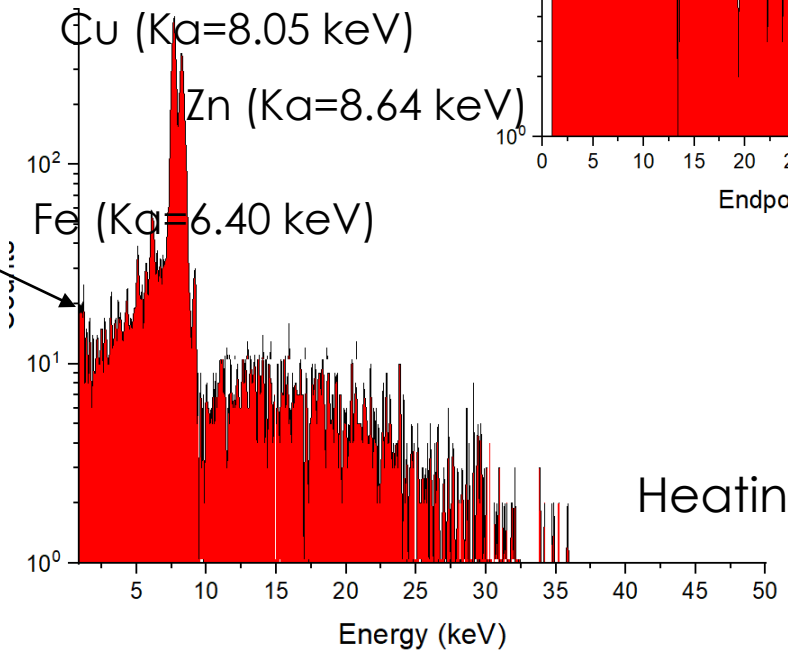
Negative Polarity

Cu (Kα=8.05 keV)

Zn (Kα=8.64 keV)

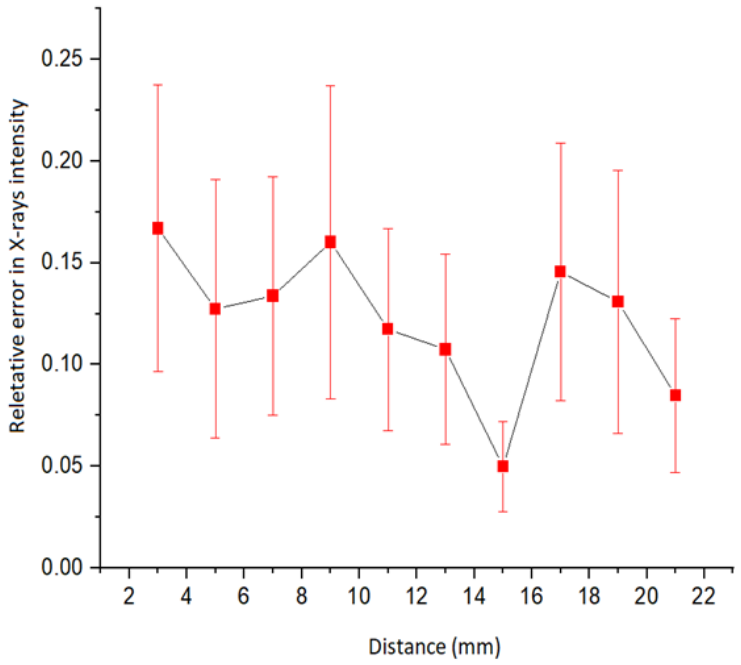
Fe (Kα=6.40 keV)

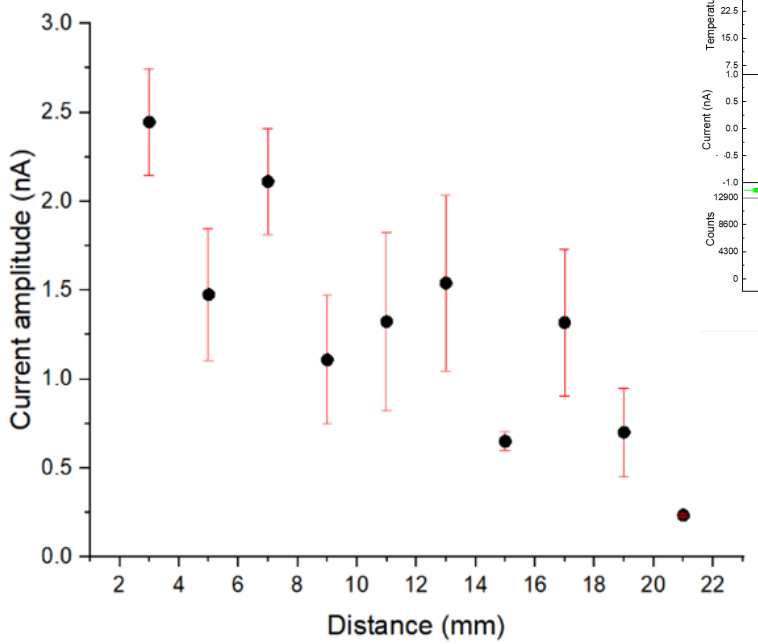
Heating phase

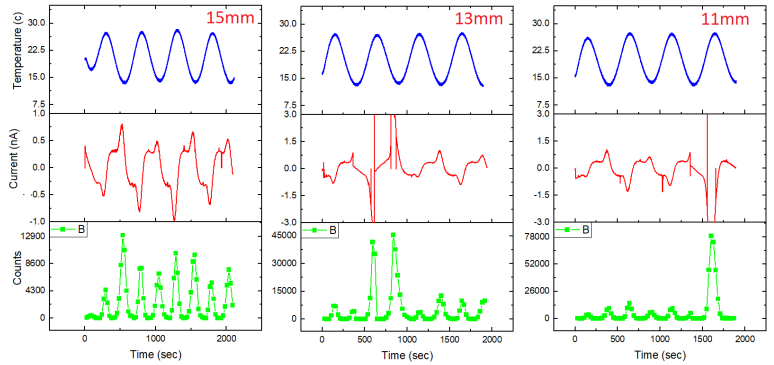


Impact of distance on Particles generation

Frequency: 2 mHz, **Pressure regime**: 1-2mTorr, **Amplitude:** 150mVrms



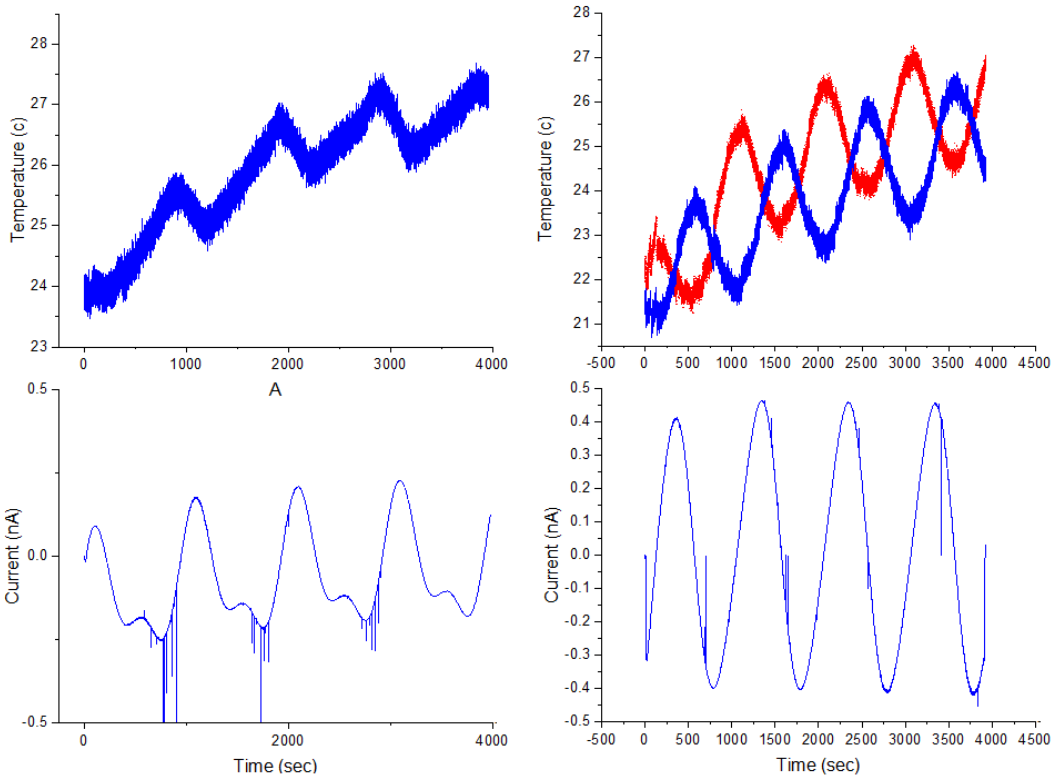


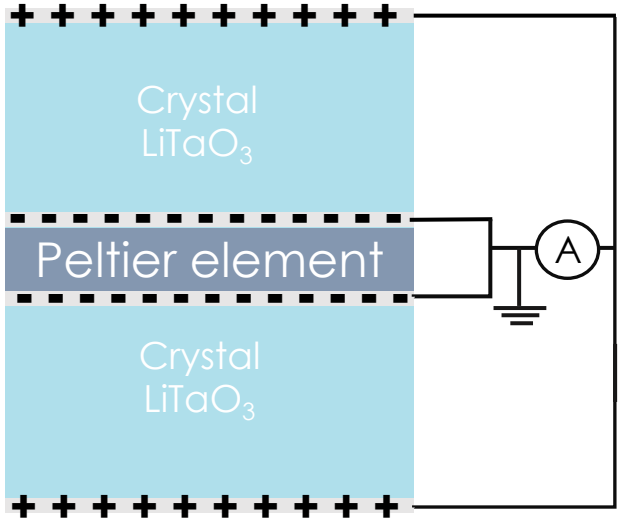


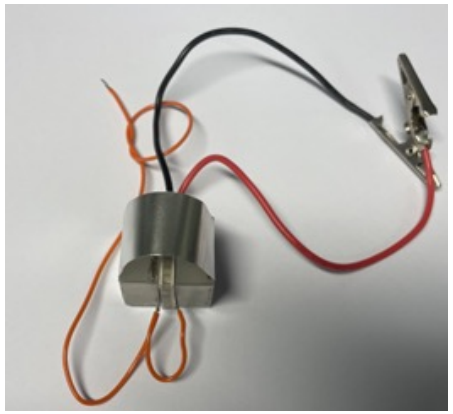
The electric field should allow charge particle to acquire enough energy to reach the target or crystal to initiate a discharge. If the distance is too short, the electron reaches the anode without colliding with molecule and if the distance is too long the electron gives its energy in a series of non-ionizing collisions

Paired-Crystal Setup

A paired crystal system was explored in which two 10 mm crystals were arranged in series to double the potential difference across the crystal was observed.

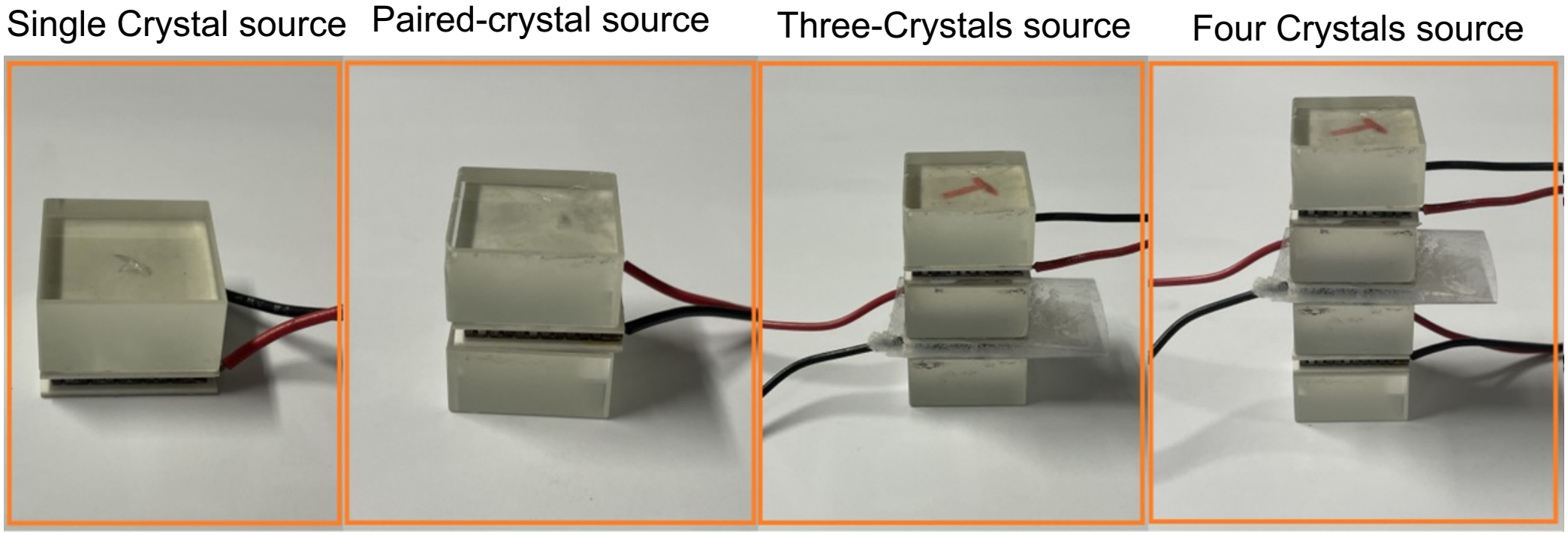






Multiple-Crystal Setup

Expected potential difference across the crystal will be double, triple and four time in 2, 3 and 4 crystals system respectively.



Conclusions and further work

- ✓ Periodically varying the temperature of LiTaO3 crystal with proper residual heat extraction enabled us to generate a stable particles generation and quasi-continuous X-ray beam.
- ✓ A clear correlation was observed between the temperature variation shift and the change in the generated particles from full thermal cycle to cycle.
- ✓ The impact of distance on stable particles generation was investigated.
- ✓ A proposed paired-crystal pyroelectric source can be used to approximately double the endpoint x-ray energy versus a single-crystal source.
- ✓ Unknow materials analysis, Use different materials as target.

Acknowledgements

I want to express my gratitude to my supervisor Dr Pavel Karataev for his supervision, comprehensive support Without his help, this research would not have been possible.
I express special gratitude to Dr Andrei Oleinik (Belgorod Nation Research University) for his comprehensive help and useful discussions in doing this work.
Finally, I would like to acknowledge the Science and Technology Facilities Council for providing me with the funds via John Adams Institute for Accelerator Science at Royal Holloway, University of London

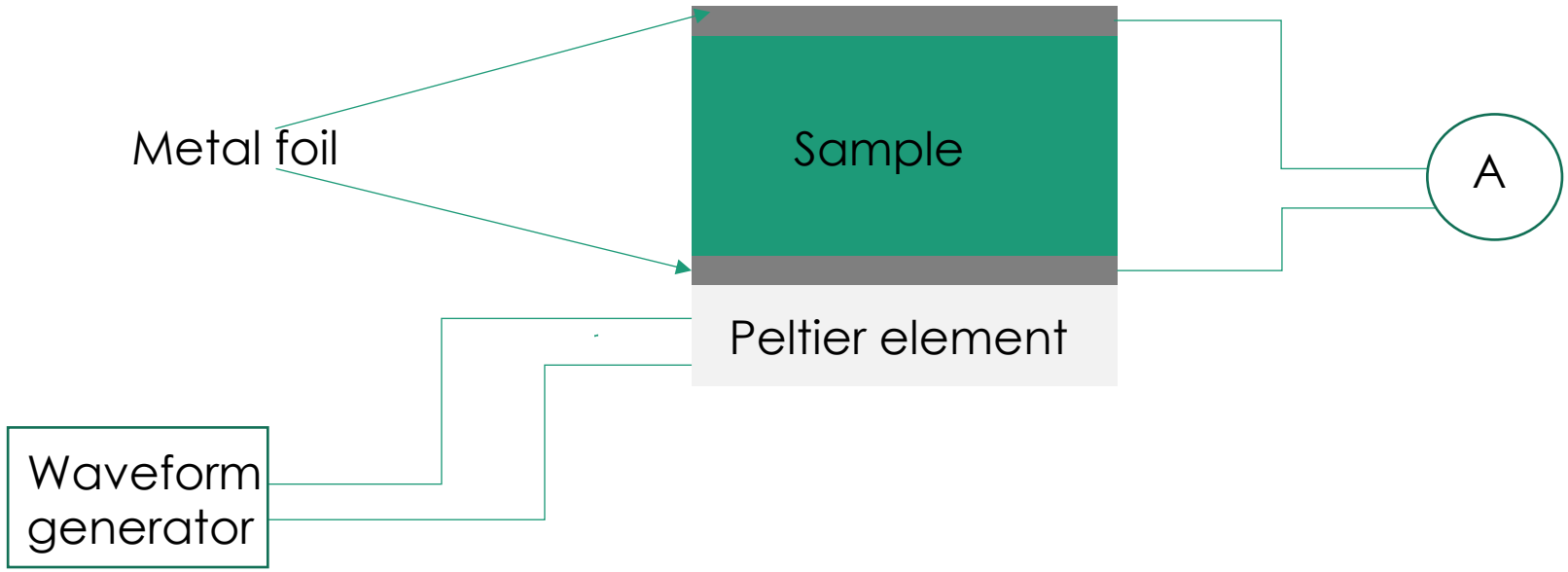
Thank you for your attention!

The features of samples of LiNbO3 and LiTaO3

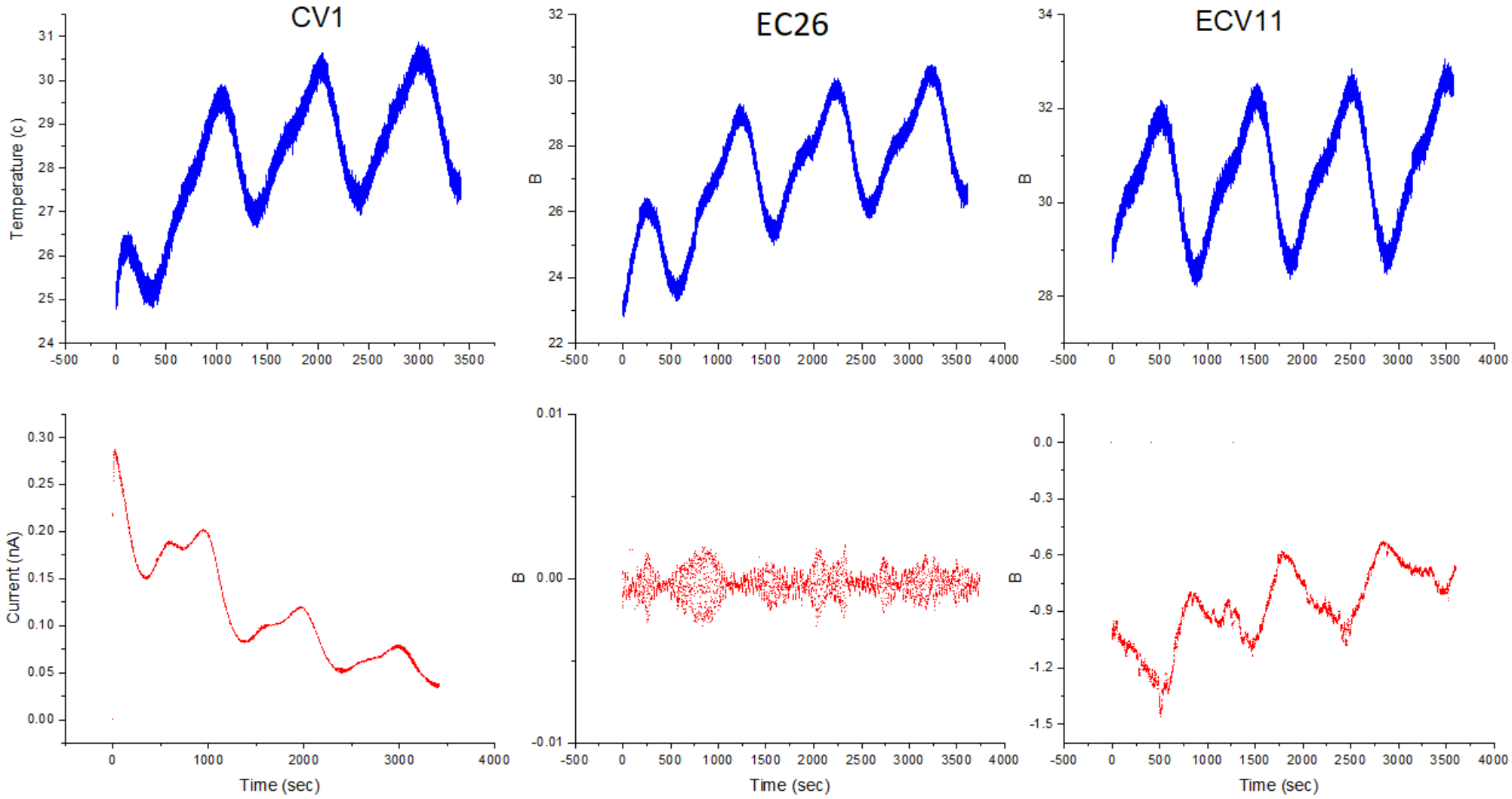
	$LiNbO_3$	$LiTaO_3$
Crystal symmetry and class	trigonal, R3c	trigonal, R3c
Density	4.648 g/cm^3	7,46 g/cm^3
Curie temperature	1145 °C	660 °C
Thermal conductivity	4 W/m °C	4.6 W/m °C
Specific Heat	0.633 J/g °C	0.251 J/g °C
Resistivity	2×10^{10} Ω cm	4.5×10^{10} Ω cm
Dielectric constant along Z-axis	32	45
Pyroelectric coefficient	0.7 C/°C/m^2	2.3 C/°C/m^2

- **X-ray generators**
  (Endpoint energy up to 200 keV, peak intensity is 10^9 counts/sr)
- **Electron generators**
  (Endpoint peak energy up to 180 keV, stream current up to 10 nA)
- **Positive ion generators**
  (Nitrogen, oxygen, hydrogen, argon ions, endpoint energy up to 150 keV)
- **Neutron generators**
  (Fast neutrons 2,45 MeV, peak flux up to 1000 n/s in 4pi)
- **Beam deflectors**
  (Deflection of non-relativistic continuous beam in scanning mode)

Main Scheme of operation

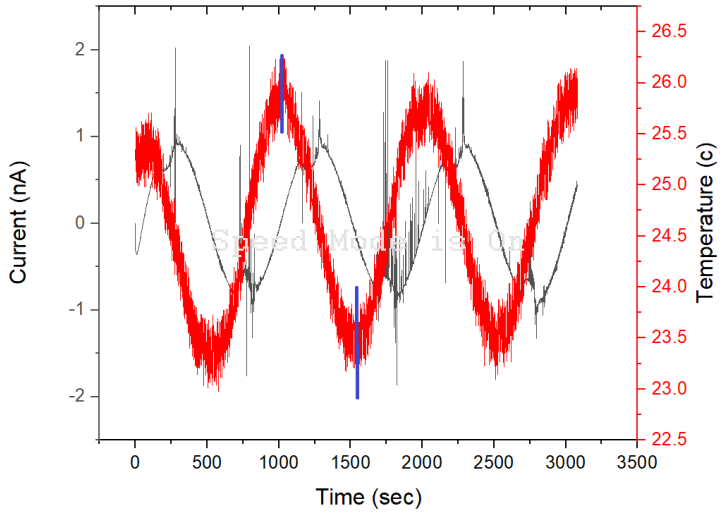


Pyroelectric property of new samples



Comparison of pyroelectric coefficient of lithium tantalate and new sample

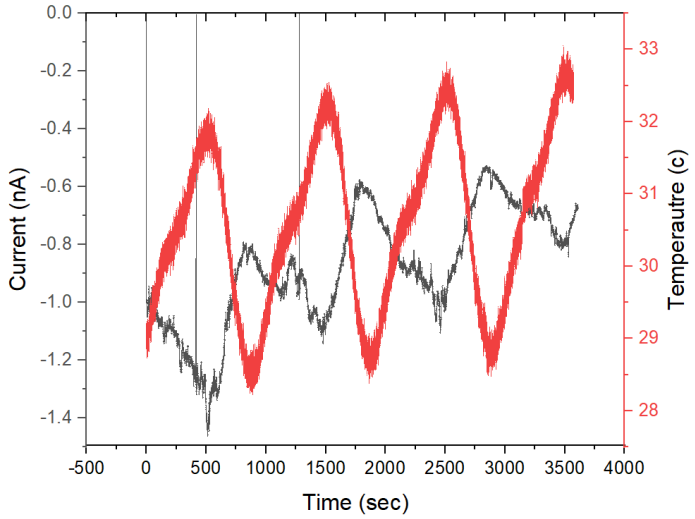
Lithium tantalate ($LiTaO_3$)



$$p = \frac{Q}{A\Delta T}$$

$$p = \frac{555.007}{4X2.6} = 53.36\ \text{nC/cm2} \times ^{\circ}\text{C}$$

New sample



649/3.14*3.56=55.38