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Direct Imaging of Ionizing Radiation via the Pockels' Effect in Electro-Optic Crystals

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Abstract

Progress towards a real-time, spatially-resolved solid-state radiation detector that utilizes the Pockels' effect in an electro-optic (EO) crystal is described. This new approach to radiation detection relies on optical detection of a localized index of refraction change generated by the interaction of ionizing radiation with the crystal. As an ionizing particle traverses the electro-optic crystal, a track of electron-hole (e-h) pairs is created. Application of an external electric field to the crystal facilitates migration of the charges, resulting in a locally varying electric field along the track. Due to the Pockels' effect, the crystal's refractive index changes in that region relative to the bulk material. We image this perturbation using a polarimetric method in which the crystal is probed with a laser and changes in the crystal's birefringence are manifested as amplitude modulations in the light. Proof-of-principle imaging results demonstrating the response of a $LiTaO_3$ electro-optic crystal to x-rays are presented.

Approach

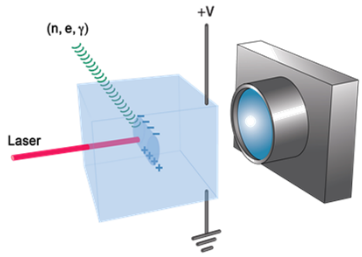
- Ionizing radiation enters the EO crystal, slows, and deposits its energy creating a track of e-h pairs
- An externally applied electric field promotes diffusion of the e-h pairs
- Resultant locally varying electric field along the track causes a change in the refractive index relative to the bulk material
- Laser-based optical methods image the radiation-induced change in refractive index

Benefits

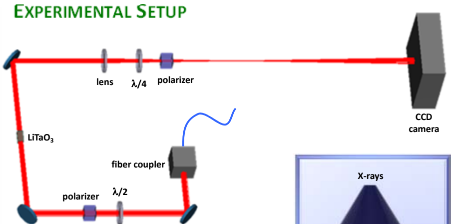
- Imaging tracks provides spatial and directional information of incident radiation particles in real time
- Observed signal does not rely on scintillation light created in the crystal or the ability to collect charge on electrodes
- Recombination of electrons and holes resets the detector

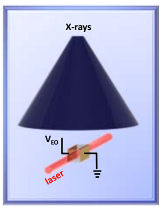
Challenges

- Fast recombination rate of e-h pairs
- Trade-off between imaged volume and track detection/resolution



Experimental Setup

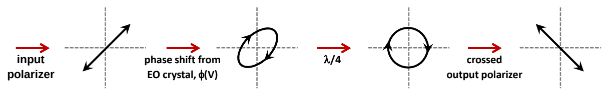




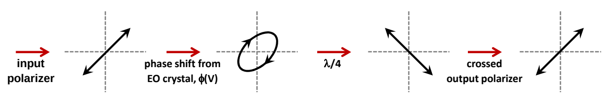
- X-ray source: 450 kV max
- Laser: cw, 845 nm, ~20 mW
- EO crystal: $LiTaO_3$, $5 \times 5 \times 20$ mm^3
- Applied voltages, V_{EO}: -3 — +3 kV

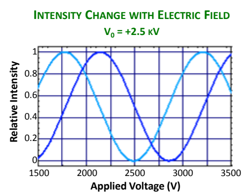
Detection Methods

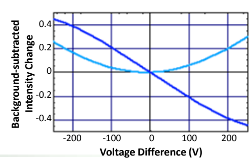
- Phase retardation of laser light in EO crystal determined by electric field
- Polarization evolution illustrates conversion of phase changes to intensity modulations:
  - **50% transmission: max slope**



  - **Nulled signal: min background**

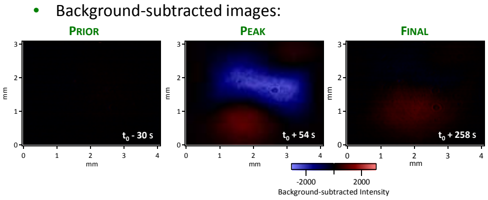




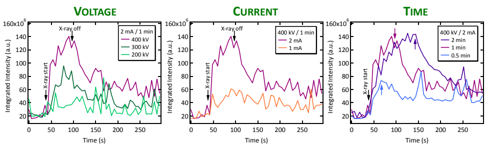


Response of $LiTaO_3$ to X-rays

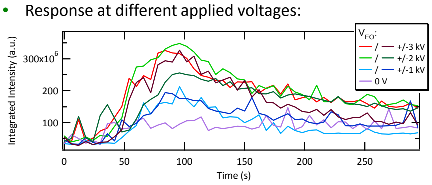
- Magnification : 1.6 ×
- X-rays: 400 kV / 2 mA / 1 min
- V_{EO}= -3.0 kV
- Max slope configuration
- Background-subtracted images:



- Variation of X-ray parameters:

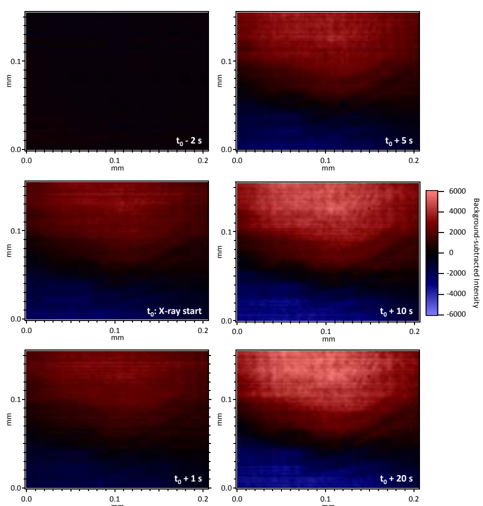


- Response at different applied voltages:



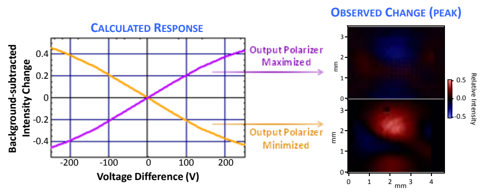
The Hunt for Individual Tracks

- Magnification: 30 ×
- Added shielding between source and region of EO crystal out of the image plane
- X-rays: 400 kV / 1 mA / 1 min
- V_{EO} = +2.5 kV
- Min background configuration

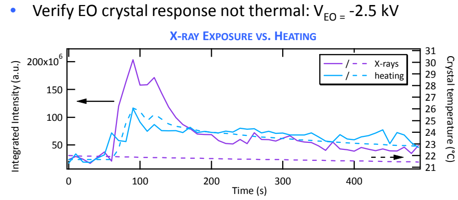


Additional Experiments Conducted

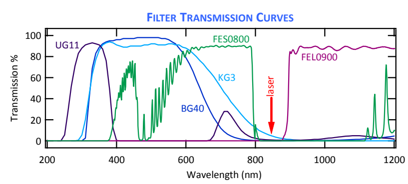
- Confirm direction of intensity change: no λ/4, V_{EO} = +2.5 kV



- Verify EO crystal response not thermal: V_{EO} = -2.5 kV



- Determine signal wavelength within ±50 nm of laser wavelength using color filters:



Conclusions

- Exposure of $LiTaO_3$ to X-rays induces a birefringence change that can be monitored optically
- Observed response is transitory; no annealing is required to reset the detector
- Individual radiation-induced tracks were not observed

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