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SAND2011-3727C

National Nuclear Security Administration
Defense Nuclear Nonproliferation

Office of Nonproliferation and Verification Research & Development

SNM Movement Detection / Radiation Sensors and Advanced Materials Portfolio Review

RadSensing2011

Electro Optic Detector for Tracking Ionizing Radiation Events

Lorraine Sadler

Sandia National Laboratories

June 8, 2011

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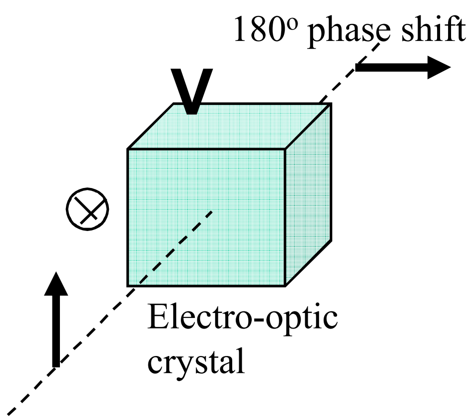
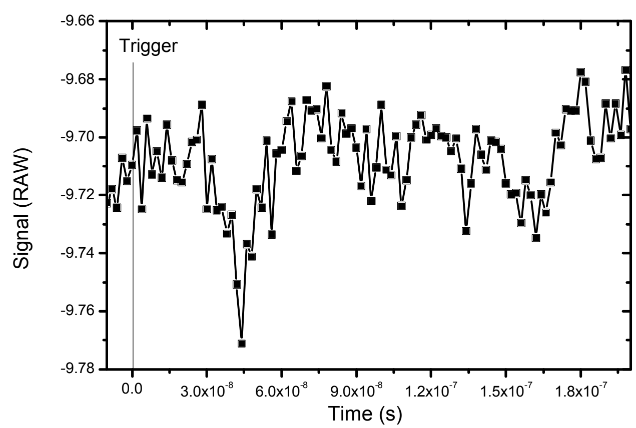
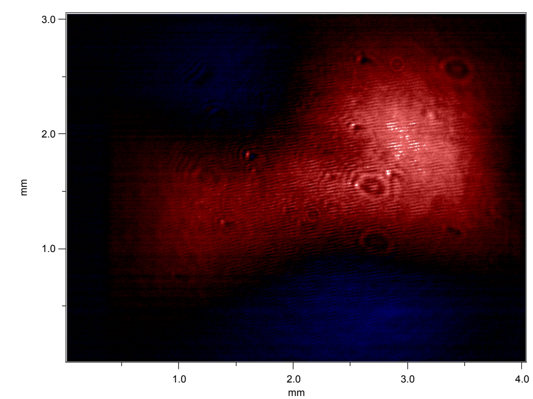
Outline

- Electro-optic detector motivation/background
- Timing information for the signal
- Imaging of X-rays in an electro-optic crystal
- Conclusion







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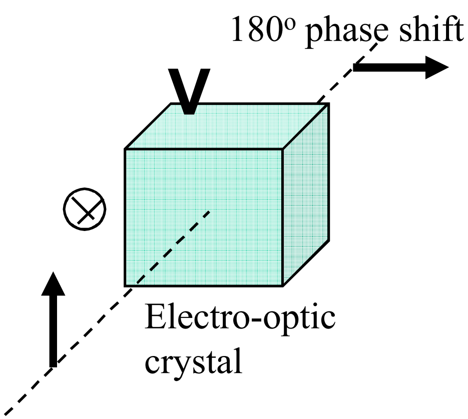

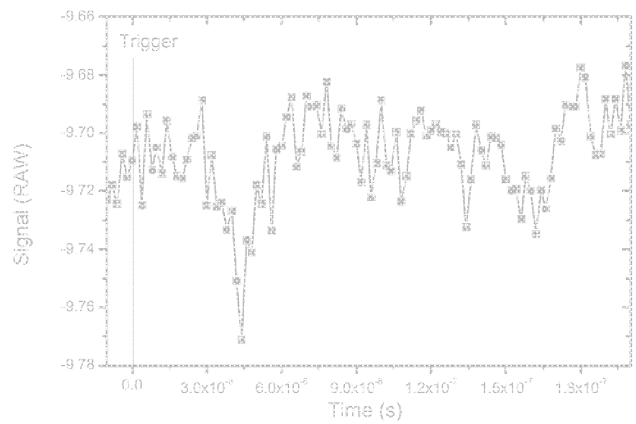

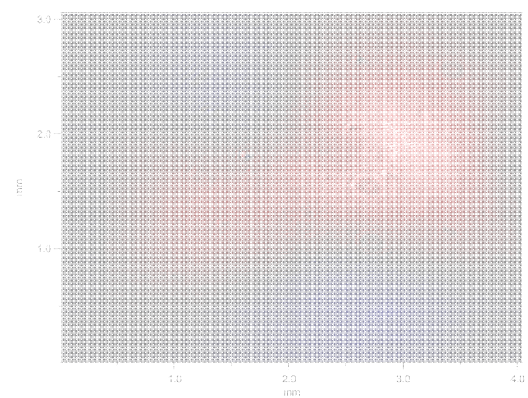

Background: Novel Radiation Detector Need

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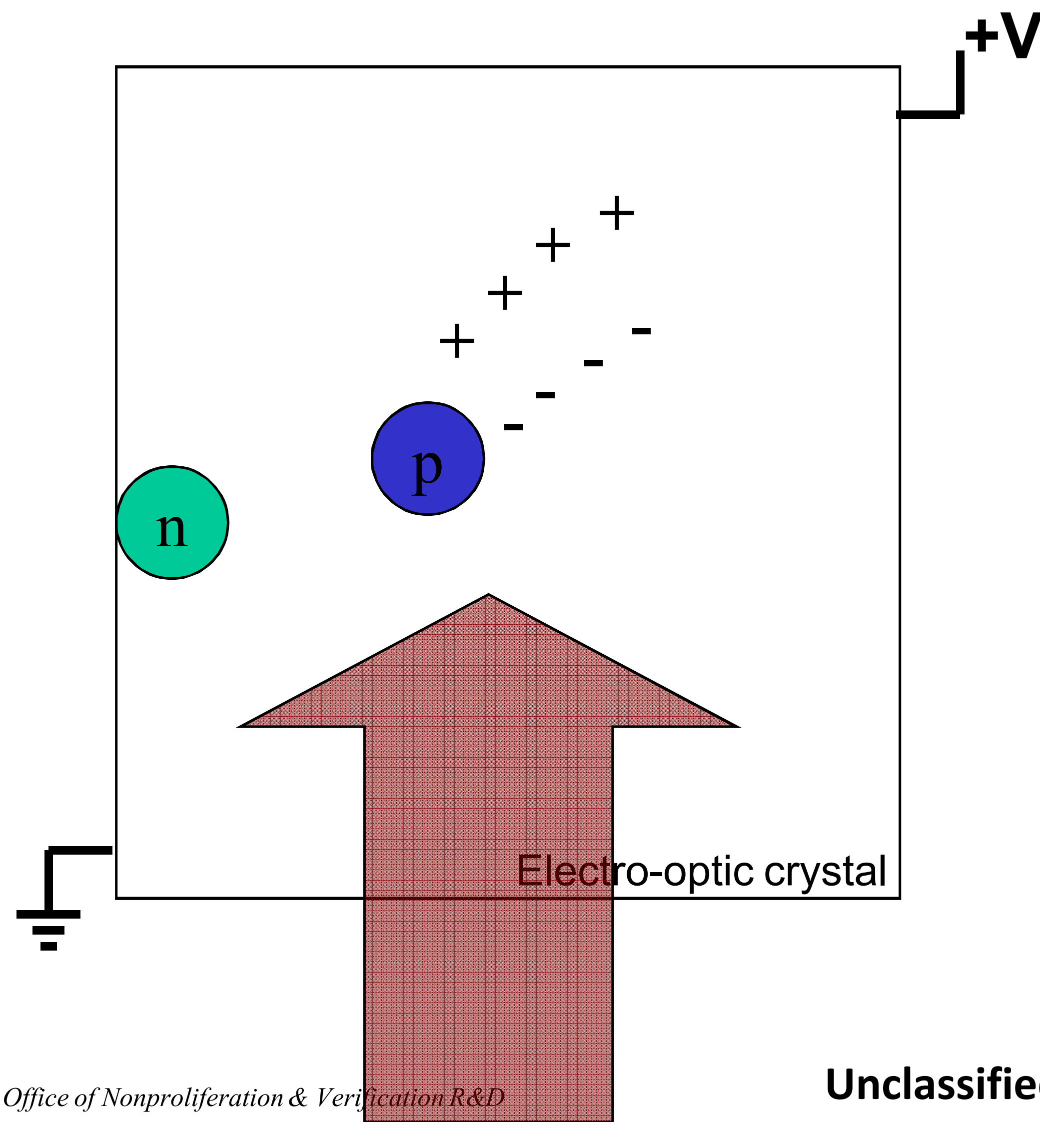
- **Standard radiation detectors have been identified as having shortfalls. Signal size (i.e. number of photons or electrons detected) is directly proportional to the energy and type of the incoming particle**
- **Readout mechanisms have limitations**
  - **Scintillating detectors use photomultiplier tubes (PMT) or photodiodes to detect light.**
    - **Best detection – 100 % detection of scintillation light however detector efficiency and solid angle reduce this signal further**
  - **Semiconductor charge collection -difficult geometries and contacts for charge collection and may require cryogenic temperatures**

Priority	Impact	Topic Area	Investment Option
High	High	Photon detection systems	Alternate radiation detection and readout concepts
			Spectroscopy algorithms for signal-starved spectra
		Neutron detection systems	Large-area, thermal neutron detection systems
			Algorithm development for exploitation of time-correlation observables
			Large-area, fission neutron detection systems
		Photon sources	Next-generation accelerator concepts
			Low-energy, monoenergetic, tunable sources
			Development of compact, mobile photon sources
		Neutron sources	Next-generation ion sources
			Robust, human-portable systems
			Directional beams of high-energy neutrons

Long term investment priorities for the SNM portfolio

From *Special Nuclear Materials Movement Detection Program Radiation Sensor and Sources Roadmap* NA22-OPD-01-2010

Electro-optic Detector



- Want to resolve *individual* ionizing radiation events
- Radiation (n,γ) interacts with the crystal creating electron-hole pairs
- Electrons drift due to an externally applied electric field
- Creates a locally varying electric field inside the crystal
- Due to the radiation interaction a locally varying index of refraction "track" can be probed with laser light
- Light can be analyzed through polarization spectroscopy imaging

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Electro-optic Crystals

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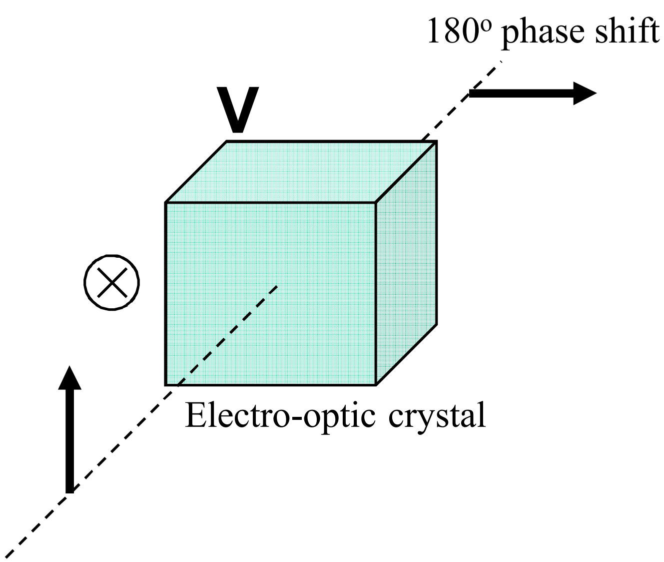

- Commercially available crystals include KDP, ADP, $LiNbO_3$, $LiTaO_3$
- Pockels effect- production of birefringence in a noncentrosymmetric crystal that is proportional to the applied electric field
- Applied electric field creates a change in index of refraction Δn.

$$\Delta n = -\frac{n_0^3}{2} r_{63} E_z$$

For KDP

n_0 =1.507

r_{63} = 11 x 10^{-12} m/V

E_z = V/d

Electro-optic Detector: New class of Radiation Detectors

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- Electro-optic detector is a new class of radiation detectors that does not rely on the collection of scintillation light or charge carriers
- Electro-optic detector relies on the local change in index of refraction of an electro-optic crystal to detect individual radiation particles in real time
- Allows for multiple detection photon interactions with the changed index tracks
- All work is being done at Sandia National Laboratories, Livermore, CA

Primary Technical Staff:

- Principle Investigator:
    - Lorraine Sadler, *Radiation and Nuclear Detection Systems*
- Experimental Work
    - Scott Bisson and Alex Hoops, *Remote Sensing and Energetic Materials*
    - Kevin Strecker, *Combustion Chemistry Department*

Budget FY11: $775 K

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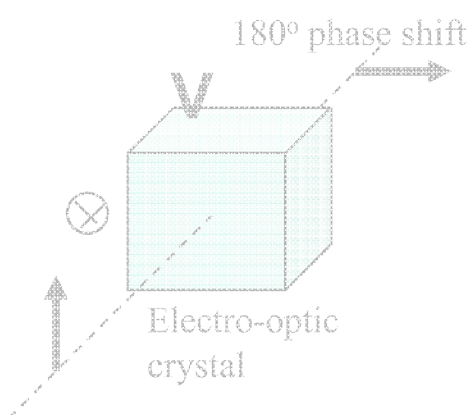
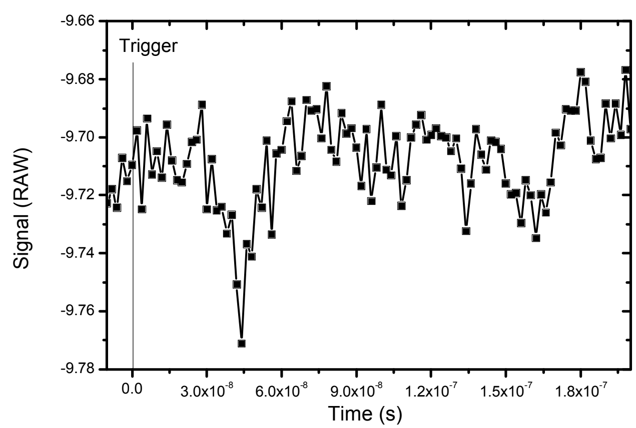
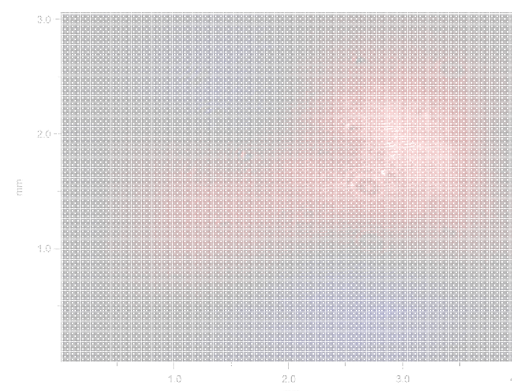
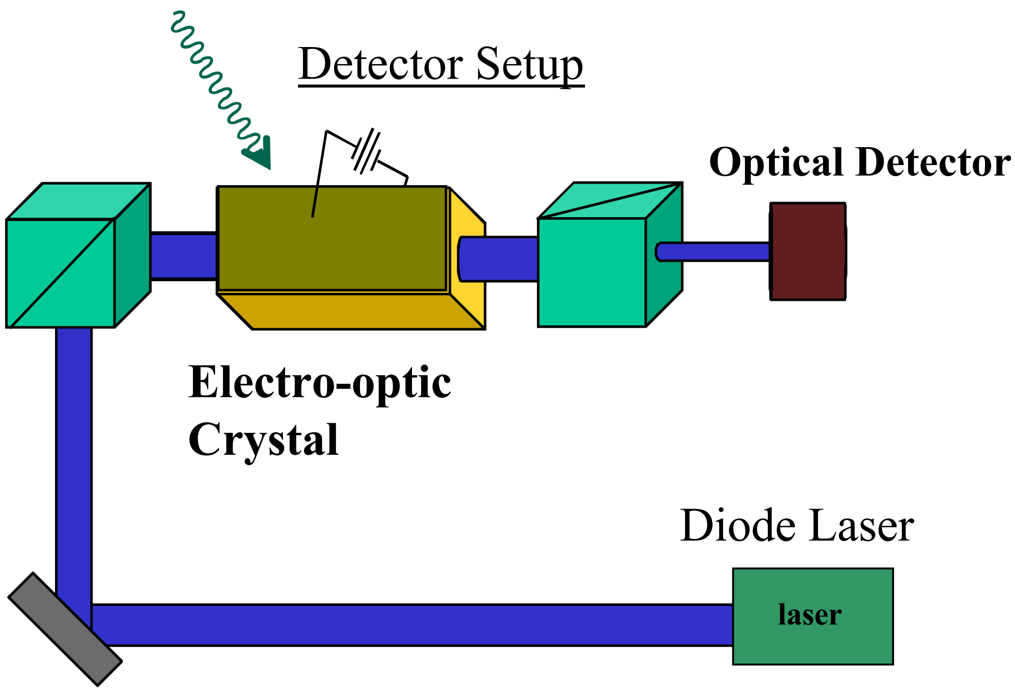




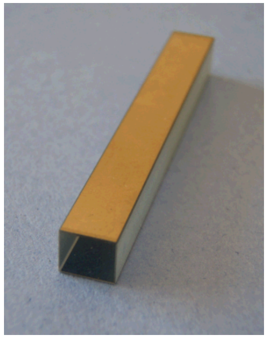


Experimental Setup-Signal Timing Experiments

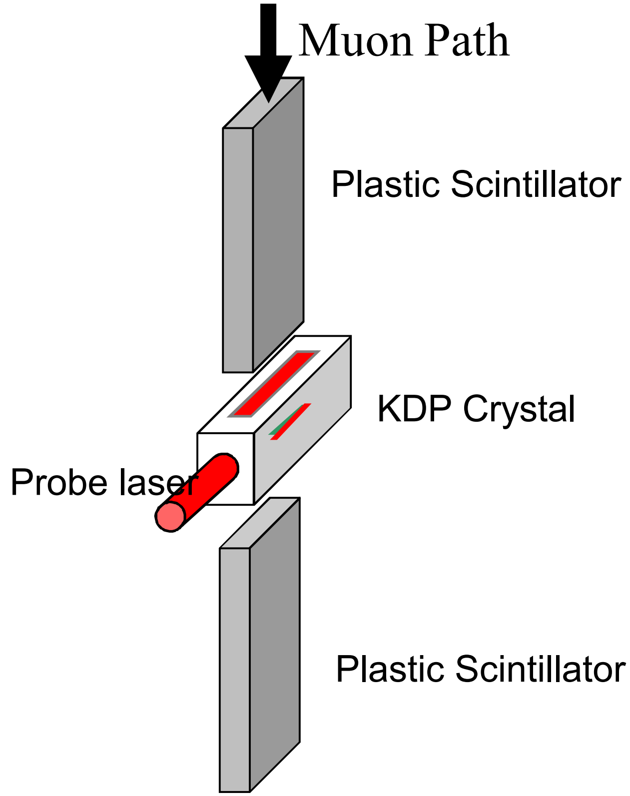
- Uses Polarization Spectroscopy:
    - Crossed polarizers extinguishes the laser beam.
    - Any change in the birefringence of the electro-optical crystal results in more light hitting the detector.

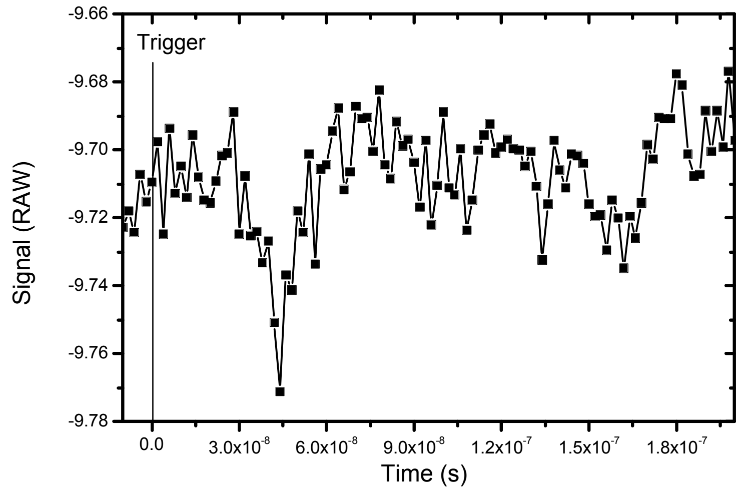


Typical crystal configuration



Experimental Parameters





- Requires high light levels on both upper and lower scintillator
- Creates 42 ns delay due to readout
- 0.2 mHz trigger rate

- 4 MeV/cm deposited within the crystal (KDP)
- 50,000 electron-hole pairs
- linear electron-hole pair density of 20 /μm.

KDP: Timing Signals vs. Crystal Voltages

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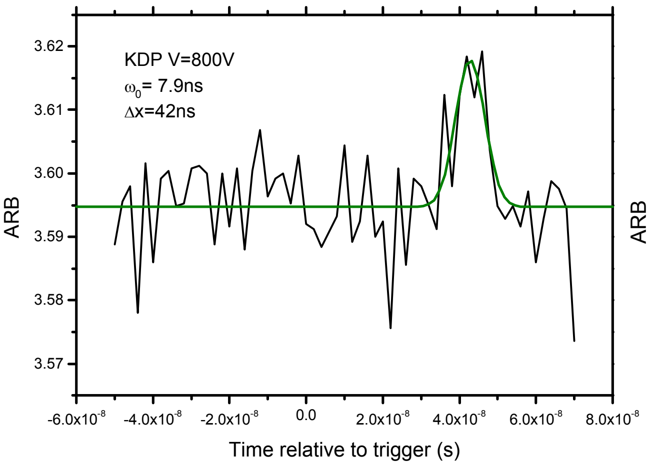

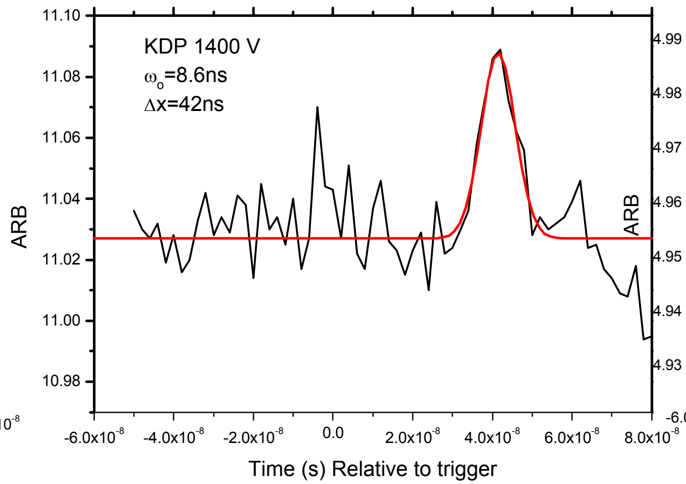

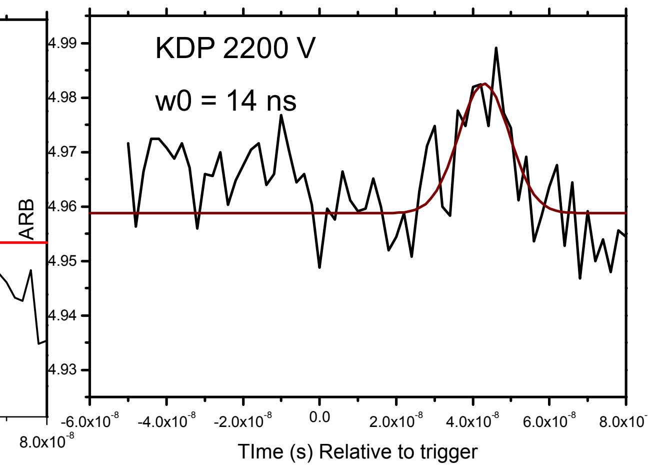

- Average of 130 triggers
- 0.5 % of the light on the tracks is rotated to pass through the cross polarizer
- 0.75 ns / 100 V change in the track duration
- Experimental verification- no signal seen:
  - $V_{crystal}$ = 0
  - Crystal is removed from setup
  - Laser was removed
  - Randomized trigger

- Significant reduction in noise due to polarization impurity
  - Replaced mirrors with metal coatings
  - True 45^o light reflections
- Limited by electronic noise

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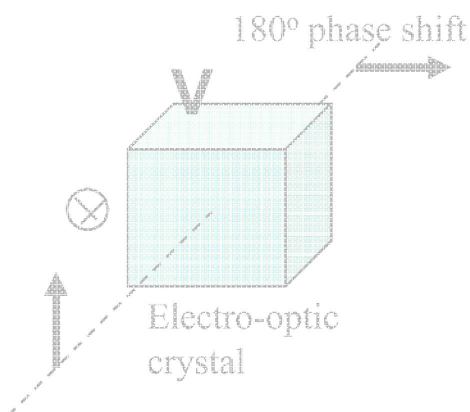
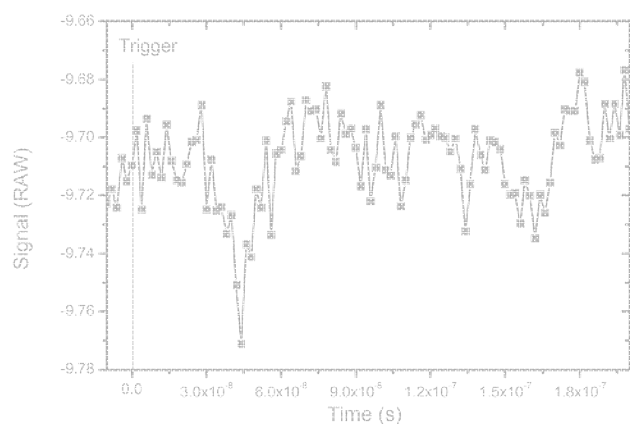
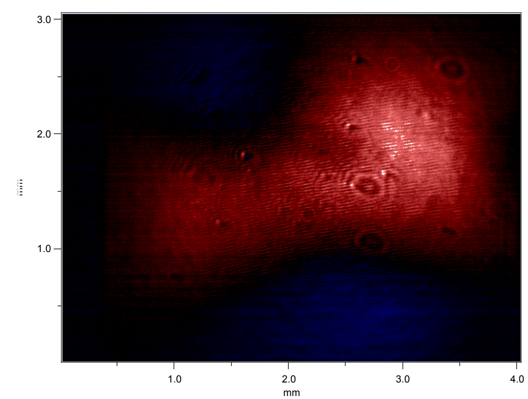
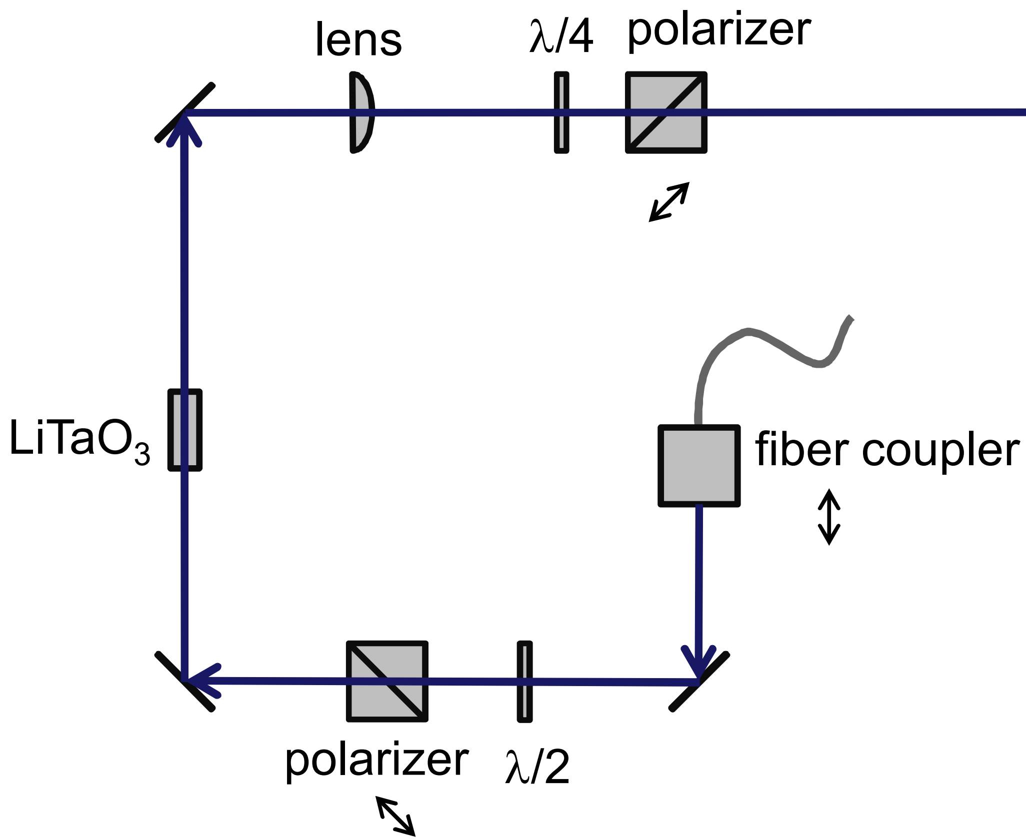






$LiTaO_3$ Imaging Experiment



- Input polarization set to 45°
- At each crystal voltage:
  - 2nd polarizer set to null signal
  - λ/4 set to give greatest intensity change with voltage

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Expected Intensity Response

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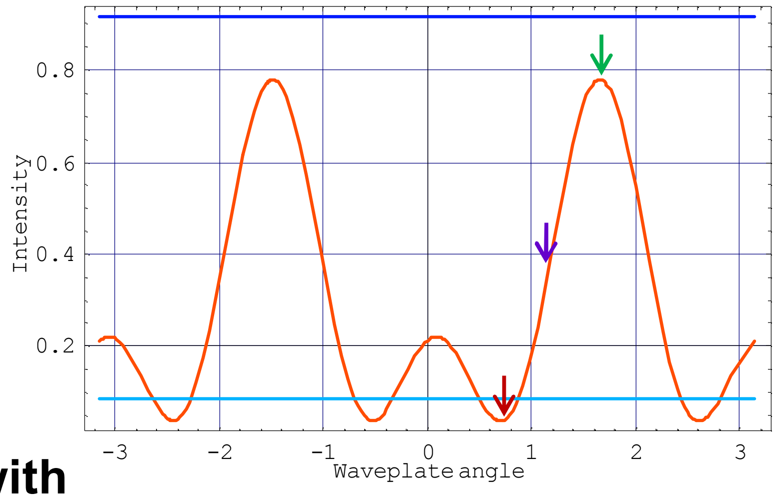
Intensity response with λ/4 rotation

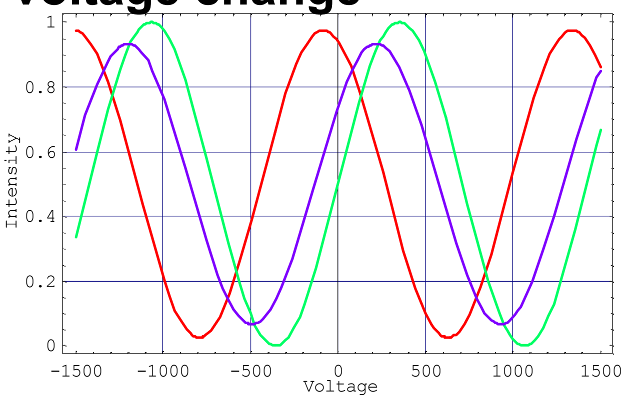


← Max intensity w/o λ/4

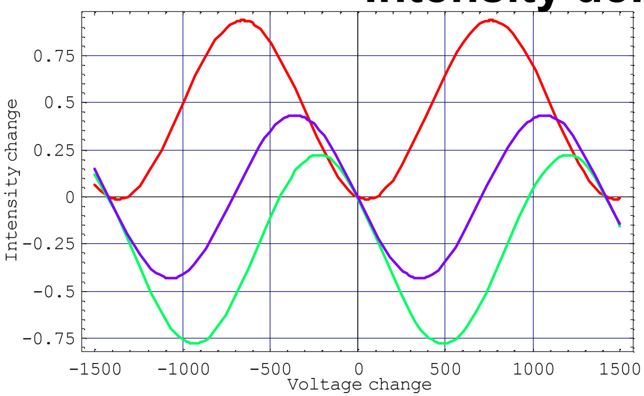
← Intensity w/λ/4

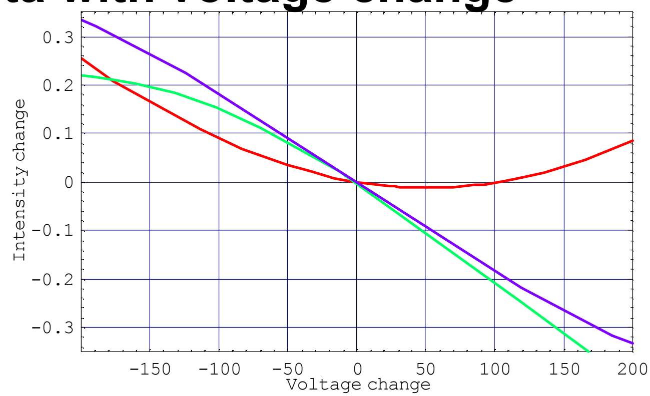
← Min intensity w/o λ/4

Intensity response with voltage change



Intensity delta with voltage change





Min intensity λ/4 — Max intensity λ/4 — Max slope λ/4

Exposure of $LiTaO_3$ to X-rays

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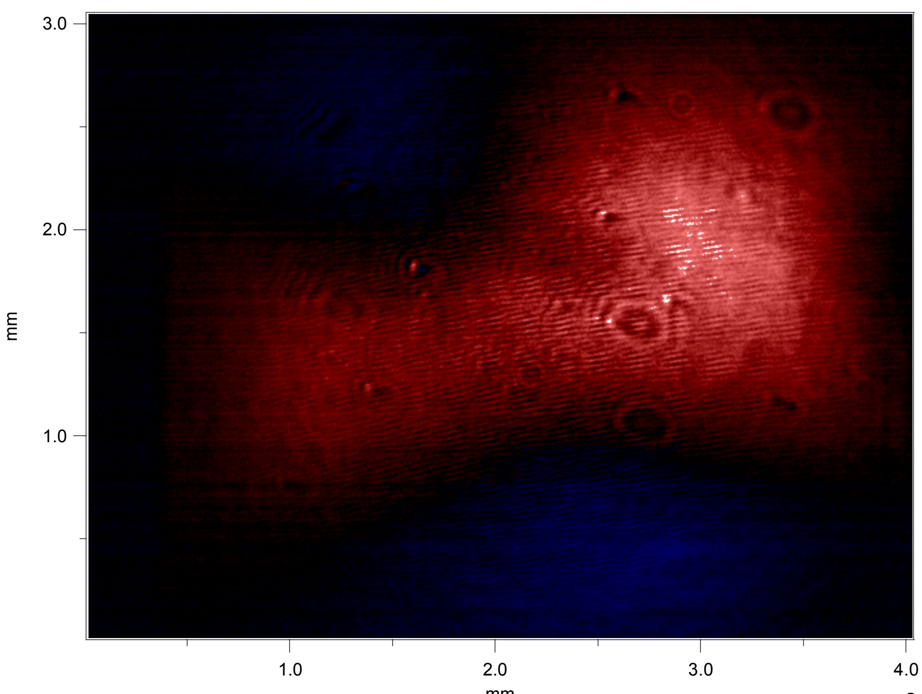
- X-ray source: 400 kV / 2 mA / 1 minute
- Applied E-field to crystal: $+4.0 \times 10^5$ V/m
- CCD camera:
  - **Exposure: 0.426 ms**
  - **Time between images: 6 seconds**
- X-rays on image 8, off after image 17



Applied voltage (V)	Max voltage-equivalent change (V)
+3000	-130
+2000	-110
+1000	-110
0	+20
-1000	-60
-3000	+70

Voltage Offset:

-150 V

-100 V

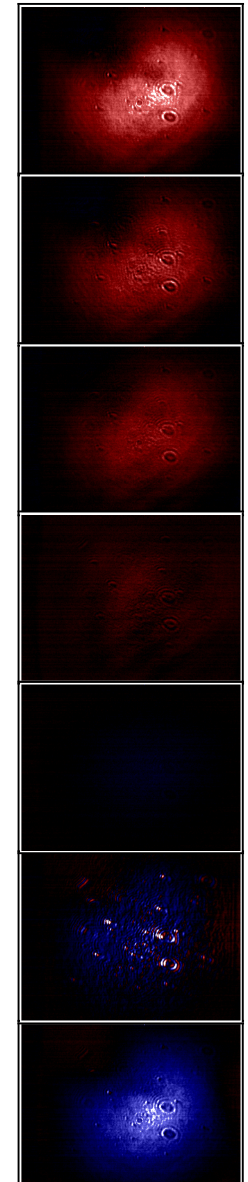
-50 V

0 V

+50 V

+100 V

+150 V



Unclassified

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$LiTaO_3$ Response at Varying Crystal Voltages

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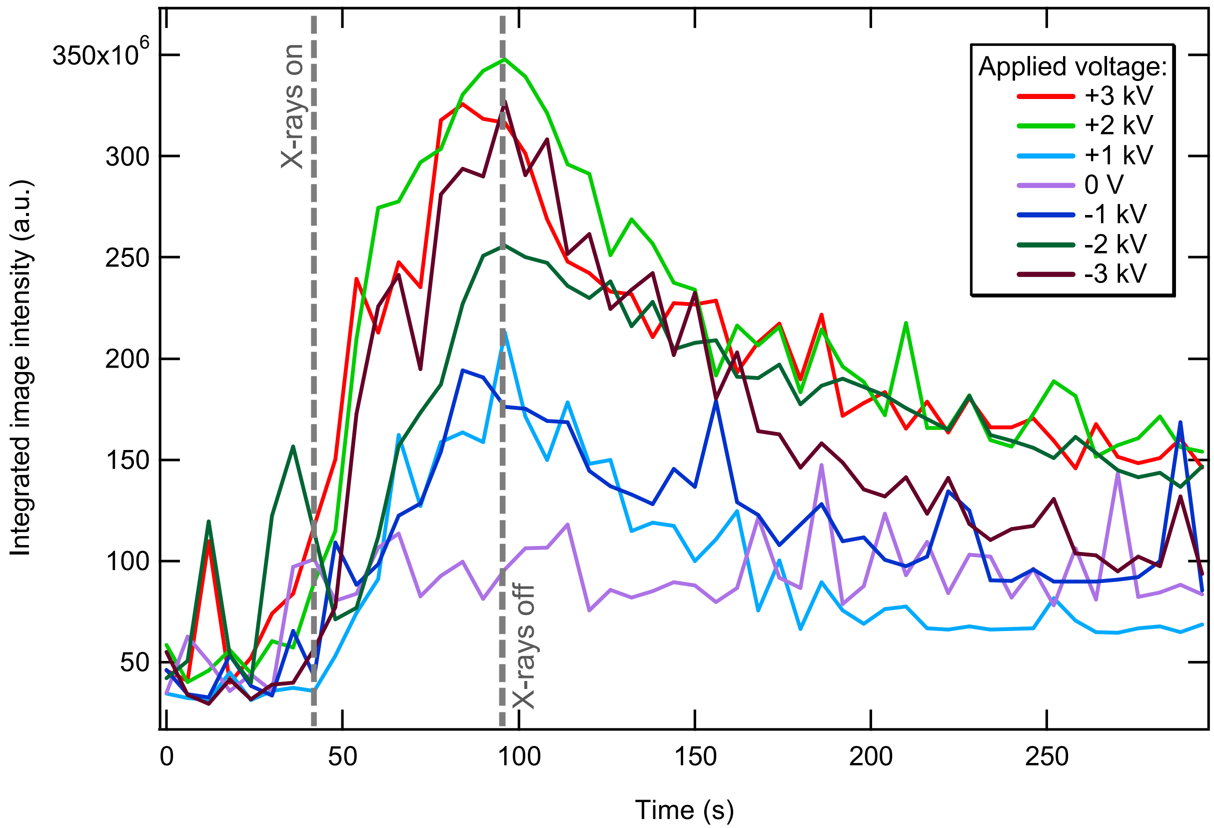
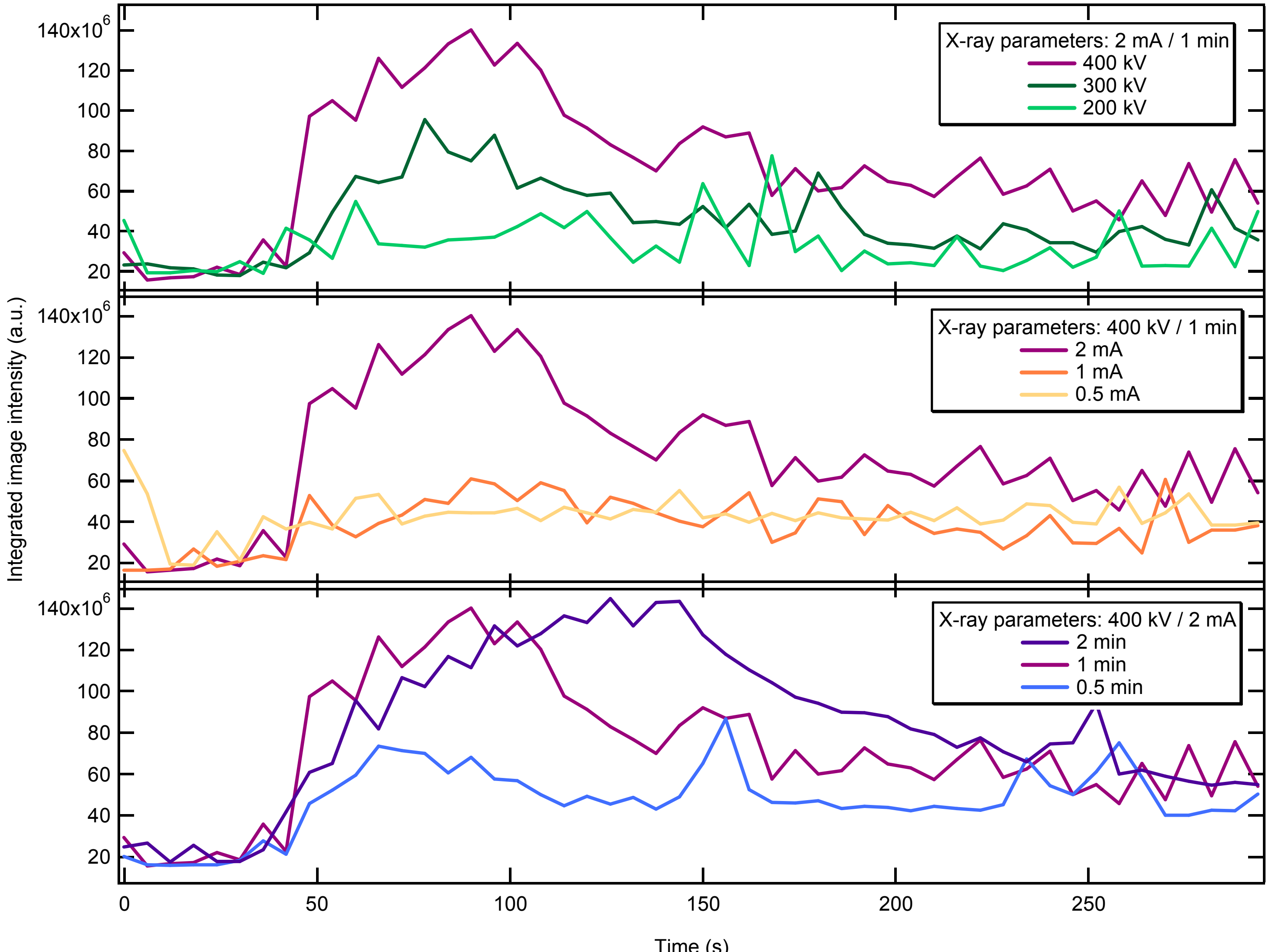
- X-ray source: 400 kV / 2 mA / 1 minute
- X-rays on at image 8, off after image 17



$LiTaO_3$ Response with Varying X-ray Parameters

- Applied E-field to crystal: $+4.0 \times 10^5$ V/m



Vary:

X-ray voltage

X-ray current

Time on

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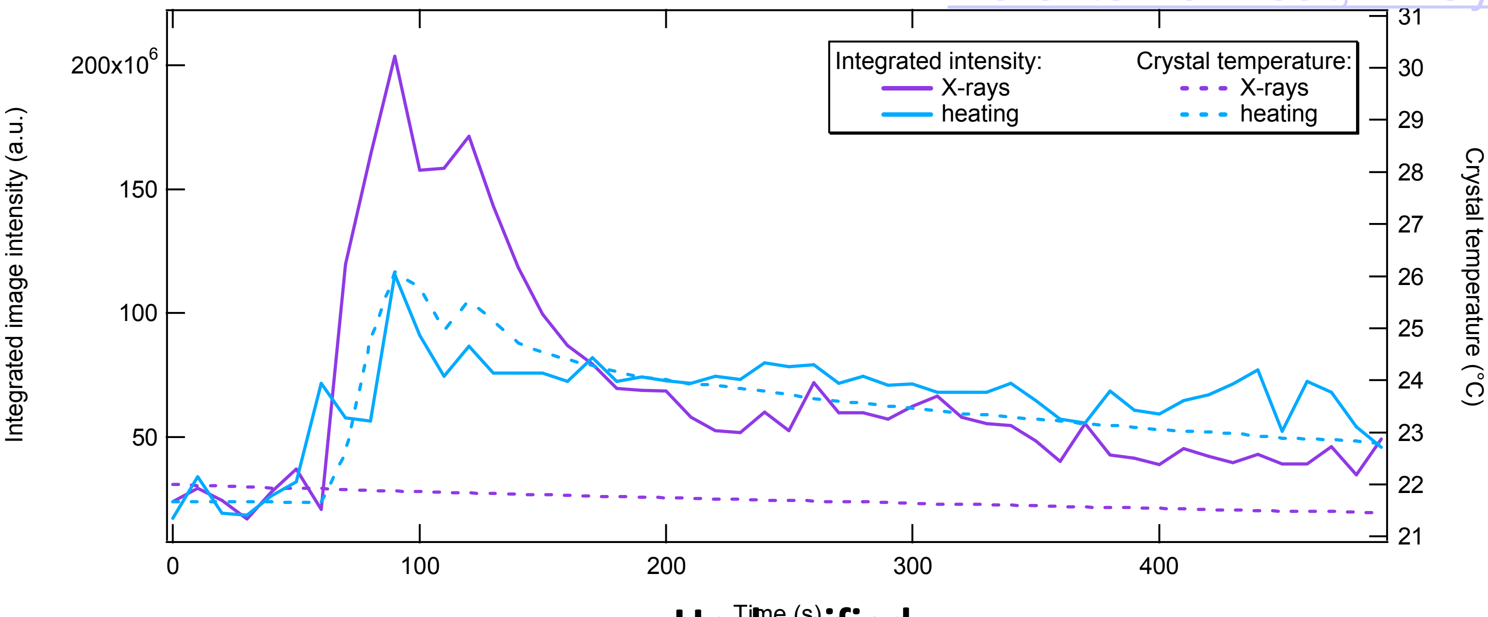
Temperature Response of $LiTaO_3$

- Applied E-field to crystal: -4.0×10^5 V/m
- X-ray source: 400 kV / 2 mA / 1 minute

- CCD camera:
  - Exposure: 0.682 ms
  - Time between images: 10 seconds
- X-rays on at image 8, off after image 13
- Background-subtracted images:
  - Heating crystal, no X-rays
  - No external heat, X-ray exposure



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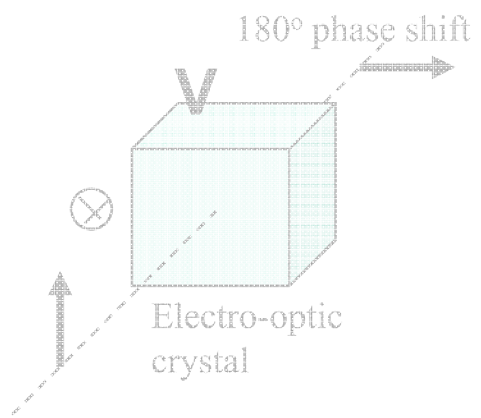

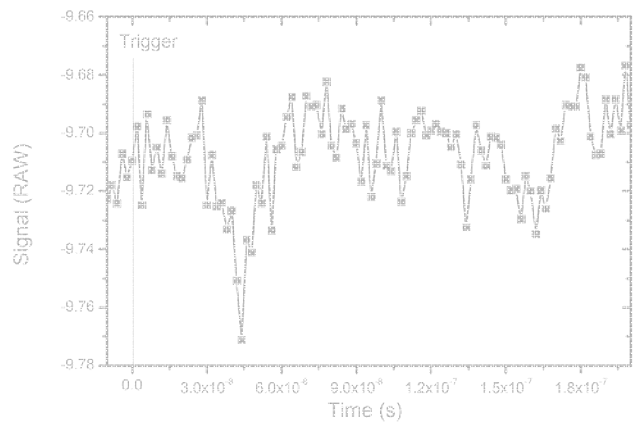

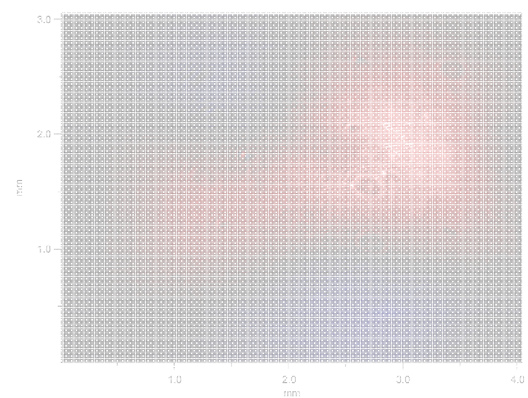

Technical Challenges

- Determining the physical size of the track in the crystal
- Understanding the response time in $LiTaO_3$ crystal
- Increasing the interaction rate of particles in the imaging region
- Distinguishing charged particle interactions within the crystal from background interactions in the CCD camera
- Increasing the interaction region that can be imaged at the appropriate resolution

Summary

- Electro-optic detector is a new class of radiation detector that does not rely on the collection of scintillation light or charge carriers
- Electro-optic detector relies on the local change in index of refraction of an electro-optic crystal to detect individual radiation particles in real time
- Accomplishments
  - **Experimentally measured a 7.9 ns lifetime of a change in refractive index due to an cosmic ray (muon) in KDP.**
  - **Imaged the internal fields in a $LiTaO_3$ crystal**
  - **Imaged the change in the index of refraction (bulk effect) in $LiTaO_3$ due to 450 keV X-ray source**
- Further Work
  - **Understand the parameters of the radiation induced tracks**