

# Supplementary Materials: In situ electric-field study of surface effects in domain engineered $\text{Pb}(\text{In}_{1/2}\text{Nb}_{1/2})\text{O}_3\text{-Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ relaxor crystals by grazing incidence diffraction

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## 1. Sample Details

- 2 The sample is a single crystal of an [011] grown [110] poled PIN-PMN-PT single crystal of
- 3 composition ~24%PIN, supplied by CTS Corporation, USA. Our sample details - see Table S1. The
- 4 sample was supplied by CTS Corporation, USA, and has nominal composition as indicated.

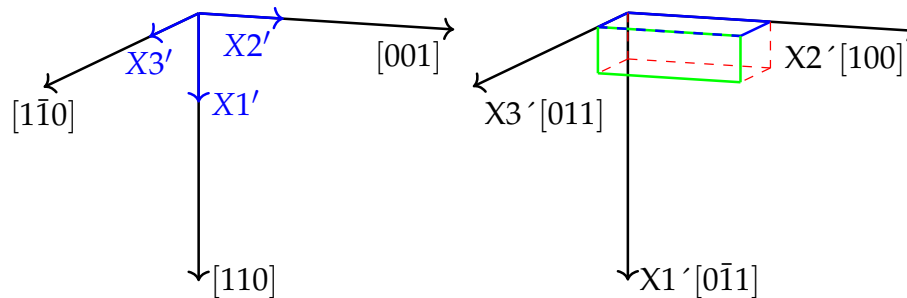
Sample #	Batch Number	Manufacturer	Measured $k_3^T$	Measured $d_{32}$ (pC/N)	Estimated composition PIN/PMN/PT
14	WO-00476	4145	4011	1614	0.24/0.44/0.32
2	418565-1	3721	3674	1320	0.24/0.45/0.31
34	418565-1	3278	3243	1144	0.24/0.46/0.30

**Table S1.** Composition and some properties of samples measured in this study.

The specular surface in the chosen coordinate system of the sample is  $[01\bar{1}]$  oriented, with the sample's long direction along the  $[100]$  and the field parallel to  $[011]$  axis. This coordinate system was not used whilst aligning and recording the diffraction contrast. The following rotational transformation,  $M$ , of axes from XMaS geometry to the aforementioned traditionally assigned coordinates was chosen:

$$M = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}$$

- 5 such that the relationship between sample geometry (s) and crystal geometry (c) is:
- 6 X1  $[01\bar{1}]_s$  is equivalent to  $[110]_c$
- 7 X2  $[100]_s$  is equivalent to  $[001]_c$
- 8 X3  $[011]_s$  is equivalent to  $[\bar{1}10]_c$
- 9 The coordinate systems are shown in figure S1.

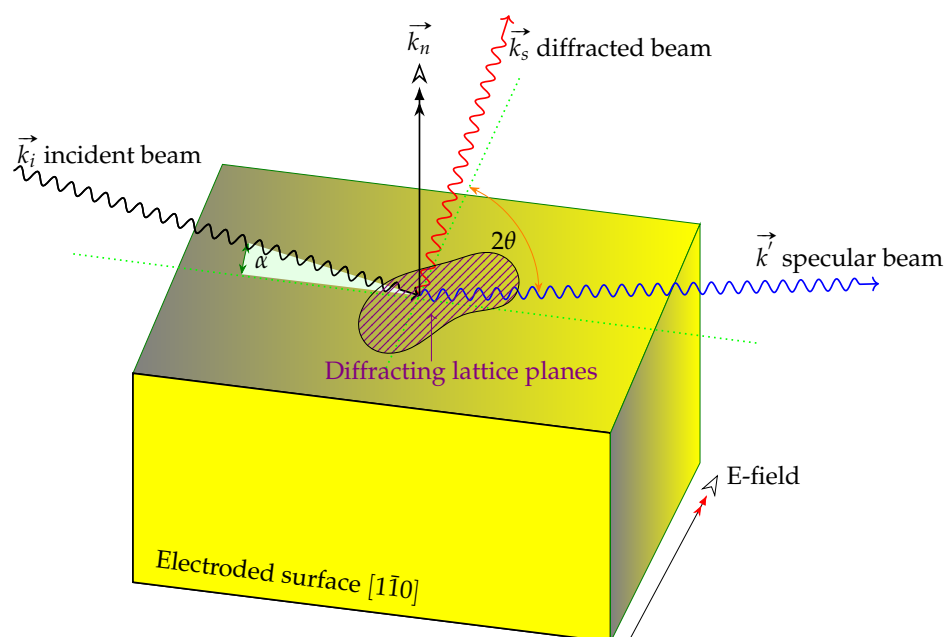


**Figure S1.** Two coordinate systems used in the study. Green is electroded face, and blue is specular face in right hand diagram.

## 11 2. Experimental details

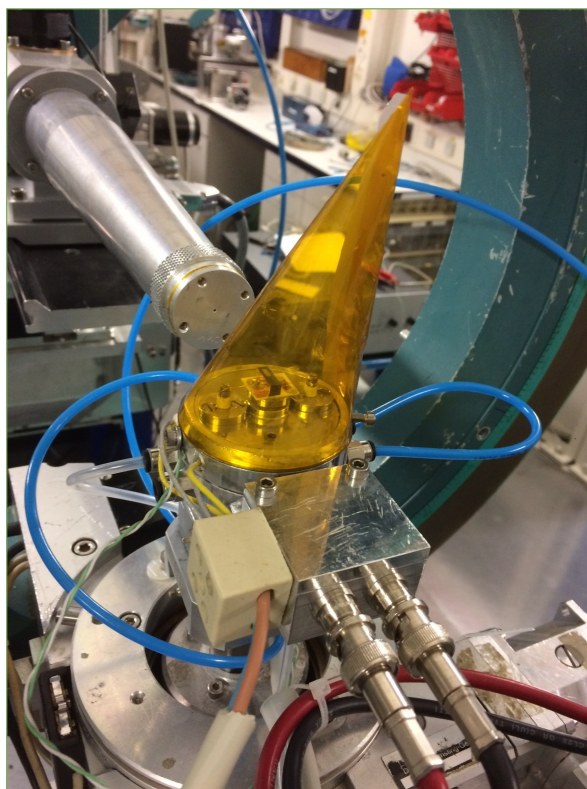
12 The XMaS facility is a synchrotron beamline funded by the UK EPSRC research council. It is  
 13 embedded in the heart of the European Photon and Neutron (EPN) Science Campus in Grenoble,  
 14 France and is managed by the Universities of Liverpool and Warwick. The beamline was originally  
 15 conceived in the mid-1990s primarily to perform high resolution diffraction and magnetic X-Ray  
 16 scattering [1], hence the acronym X-Ray Magnetic Scattering (XMaS). The scientific areas tackled on  
 17 the beamline cover a broader remit than is normally found on a single beamline, and a wide range of  
 18 materials are now studied, using a variety of X-Ray techniques. Experiments are routinely performed,  
 19 such as surface X-Ray diffraction [2], small/wide angle scattering (SAXS/ WAXS) measurements of  
 20 soft condensed matter systems and X-Ray absorption spectroscopy (XAS) within a wide range of  
 21 in-operando sample environments [3,4] and under a range of external stimuli (applied electric and  
 22 magnetic fields). Although the original design specification was for a diffraction beamline, both small  
 23 (SAXS) and wide angle X-ray scattering (WAXS) along with grazing incidence (GI) capabilities have  
 24 been added to the operational portfolio [5].

25 The set up at the XMaS beamline is horizontal geometry Mode 4C (fourC) with the angle of  
 26 incidence ( $\alpha$ ) varied between  $0.01^\circ$  to  $0.5^\circ$ , see figure S2. A six-circle 4S + 2D diffractometers (psic  
 27 geometry) experimental condition with  $N_{az}$  fixed,  $\alpha$  fixed,  $\mu = \nu/2$ ,  $N_{az} = 90$ ,  $\alpha$  (incidence  
 28 angle set) was chosen for the grazing incidence detection, with the diffractometer matrix set up  
 29 on primary reflection (222), with secondary reflection at (330). In Grazing Incidence geometry, our  
 30 diffractometer matrix had primary reflection at (223). Our lattice parameters were refined to  $4.04\text{\AA}$ ,  
 31 cubic symmetry. A single crystal cut monochromator at d-spacing  $3.1333\text{\AA}$  with  $E = 12.4\text{keV}$  yielded  
 32  $\lambda = 0.999871\text{\AA}$ .



**Figure S2.** Grazing Incidence X-Ray diffraction for PIN-PMN-PT, with grazing incidence angle denoted by  $\alpha$ , and diffraction conditions in horizontal geometry given by the usual  $2\theta$ .

33 Sample electrodes were evaporated gold, deposited onto the  $[1\bar{1}0]$  faces (perpendicular to the  
 34 sample surface normal), see figure S1 and figure 1a (main paper) for more details of sample orientation  
 35 and figure S2 for diffraction configuration. After the surfaces are ground and polished to  $\sim 1/4\mu\text{m}$ , the  
 36 sample is mounted using low melting temperature wax onto an insulating substrate. High voltage  
 37 wiring is affixed to the sample jig, and routed out of the diffractometer using high voltage S-BNC  
 38 cables, to a TREK 610E HV amplifier (TREK Inc. Lockport, New York 14094 USA). Details are provided  
 39 in reference [4], and shown in figure S3. The TREK was set at its 10kV output range and its monitor



**Figure S3.** Sample and fixture assembled and attached to the goniometer, set with a heating stage. Note Kapton tent providing both safety barrier to high voltages and also ability to present a dry nitrogen atmosphere around the sample.

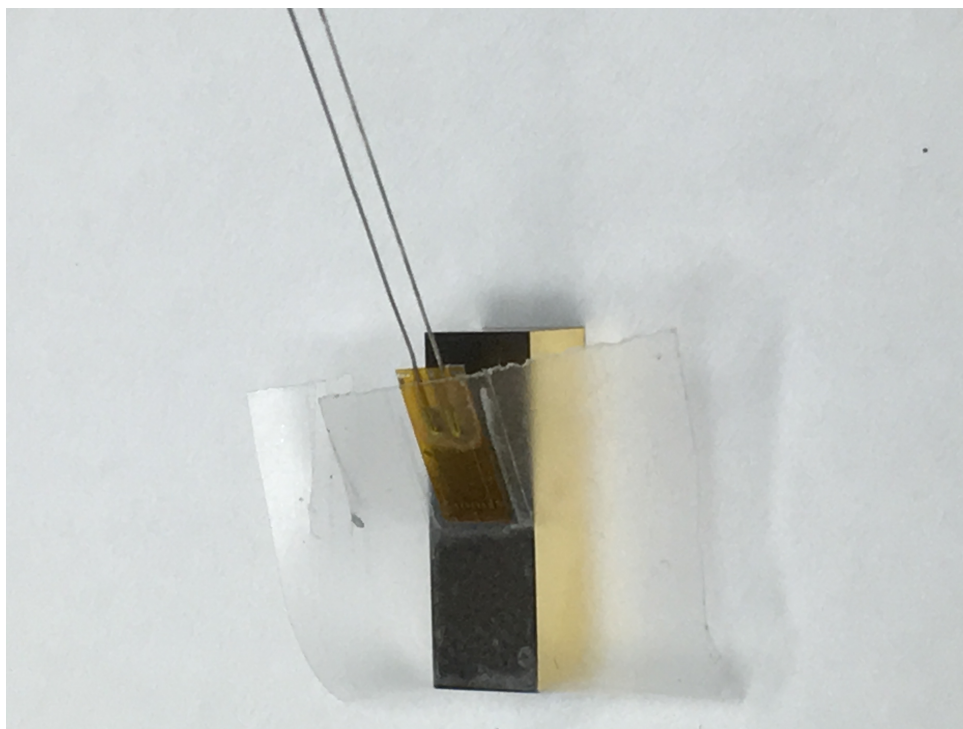
40 signal (1/1000 output voltage) was recorded. The high voltage amplifier safely connects to the high  
41 voltage coaxial cables and is interlocked with the beamline hutch.

42 The setup within the XMaS SPEC software UB Matrix (U-rotation matrix describing the orientation of  
43 the crystal in the laboratory frame, B - an orthogonalisation matrix, which defines a set of orthogonal  
44 axes based on the crystal axes, so the UB matrix defines how the crystal is oriented with respect to  
45 the laboratory coordinate system), assumed a pseudo cubic symmetry of the bulk single crystal, with  
46 a priori knowledge that these crystals take rhombohedral, orthorhombic and tetragonal symmetries  
47 under E-field and monoclinic variants at all other times.

48 The advantages of using a synchrotron over a laboratory-based X-Ray system is an increase of at least 3  
49 orders of magnitude signal to noise and hence reduction in counting times per reciprocal lattice image  
50 using the 2D Pilatus3 300K detector.

51 The experimental methodology proceeded through triangular wave excitation of the sample to  $\pm$   
52 1500V applied to the 4mm wide sample creating a field of  $\pm 3.75\text{kV/cm}$ , whilst recording current,  
53 strain and X-Ray counts as described. In-plane strain is measured using a strain gauge affixed to the  
54 specular surface with strain direction along the long (001) sample direction. Attachment of the strain  
55 gauge (RS Pro 2.5mm gauges  $120\ \Omega$  632-146) to the single crystal was carried out using cyanoacrylate  
56 adhesive, leaving sufficient space for the X-Ray beam off this specular surface. Fixation of strain  
57 gauges must be carefully performed to make sure that good strain transfer exists from the cleaned  
58 sample surface and the strain gauge backing material, see figure S4. The strain is then measured using  
59 a Honeywell strain gauge amplifier in 3 wire setup to eliminate effects of temperature on resulting  
60 strain measured. Calibration is carried out using a 1% tolerance shunt resistor circuit.

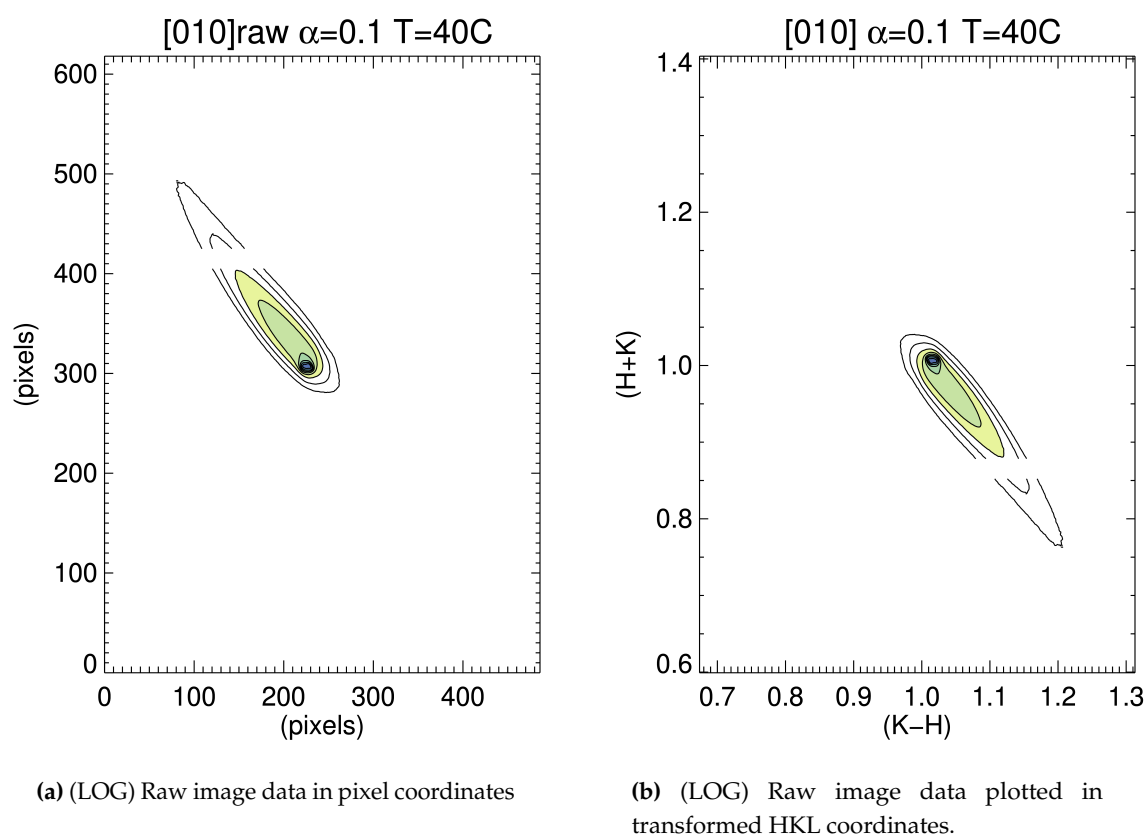
61 A large number of PILATUS3 X 300K reciprocal maps were recorded for each experimental parameter,  
62 and the centroid of the peak in each was automatically measured using code written in IDL with  
63 the pixel coordinate converted to (HKL) and plotted as HKL with field, strain with field (assuming



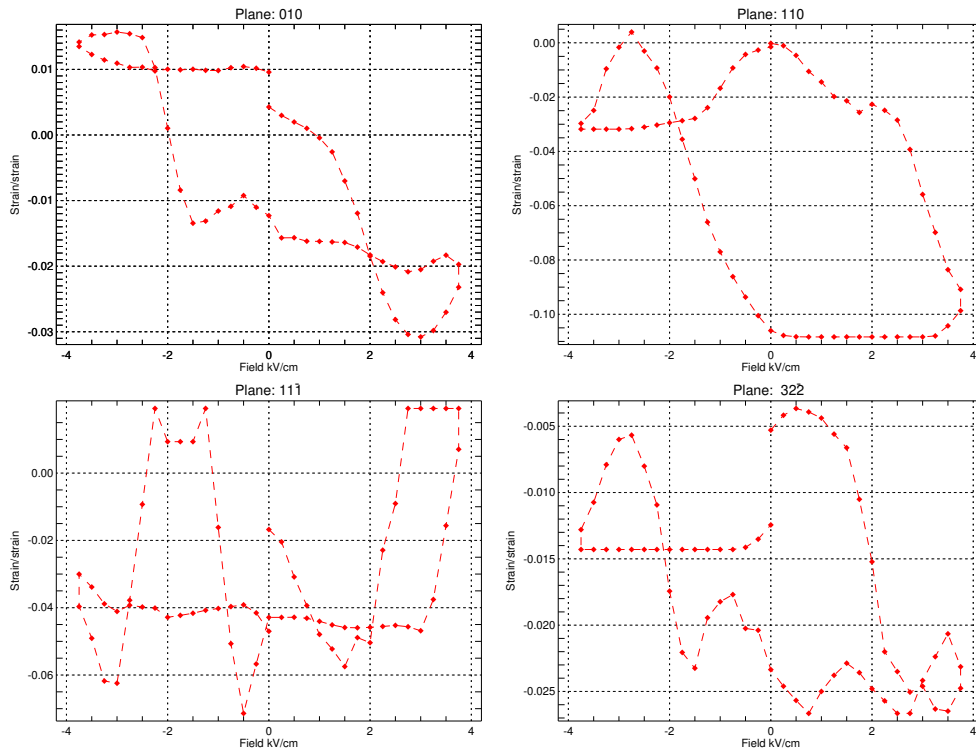
**Figure S4.** Attachment of the strain gauge (RS Pro 2.5mm gauges 120  $\Omega$  632-146) to the single crystal using cyanoacrylate adhesive, leaving sufficient space for the X-Ray beam off this specular surface.

64 pseudo cubic symmetry) and effective piezoelectric coefficients with depth through the specular  
65 surface. Procedure: (see also Figure 2 in main paper): From image analysis  $\rightarrow$  peak position locus  $\rightarrow$   
66 HKL conversion  $\rightarrow$  (see figure S5), lattice parameter based strain calculation  $\rightarrow$  strain through depth  
67 calculation (figure S10). During this process, data is interpolated only once within the HKL conversion  
68 process.

69 The HKL plot in figure S5 shows a) a 2D Pilatus image of the (010) reflection, in pixel coordinates  
70 alongside its b) HKL coordinate reference frame, demonstrating the conversion algorithms used in this  
71 study, and the approximate orientation of the camera with respect to the sample crystallography, with  
72 y-axis  $\sim [110]$  and x-axis  $\sim [1.10]$ . The detector was placed at a distance  $\sim 1\text{m}$  away from the sample,  
73 resulting in a very large field of view in HK space, necessitating the use of Region of Interest zooming  
74 algorithms to better define the changes in peak position of the reflection as a function of electric field.  
75 The variation in  $L$  is less than  $0.01\text{\AA}$ , for  $L = 0$  nominal across the whole scan. The errors introduced  
76 by the assumption that  $L$  is invariant and analysis of raw data using zooming interpolation are less  
77 than 2% in HKL, though future experimental statistics would be improved by moving the detector  
78 closer to the sample, and carrying out full 3D volume imaging, rather than this thin slice of 3D space.  
79 The data in figure S5 is at zero applied volts,  $\alpha = 0.1^\circ$  at  $40^\circ\text{C}$ . The spread of X-Ray intensity along  
80 approx. direction (110) is due to variations in the in-plane lattice parameter (010) arising, possibly  
81 from surface roughness [6], though primarily from the low angle of incidence of the interrogating  
82 X-Rays. The surface strains in the single crystal would yield a variation in interplanar spacing in both  
83 parallel and perpendicular directions with respect to the specular surface, through Poisson's ratio. The  
84 response from the (010) planes would suggest a significant variation in the [HH0] spacing compared  
85 to the orthogonal [0K0] direction would be observed, which is exactly what is observed in figure S5.  
86 The data presented in the figures S6- S9 examines the changes in position of centroid peak of all four  
87 reflections as a function of electric field (calculated as strain in these graphs), at a temperature of  $40^\circ\text{C}$   
88 at  $\alpha \sim 0.5\text{-}0.5^\circ$ , to demonstrate the data analysis approach: From image analysis  $\rightarrow$  peak position locus  
89  $\rightarrow$  HKL conversion  $\rightarrow$  (see figure S5a), lattice parameter based strain calculation  $\rightarrow$  strain through



**Figure S5.** A H-K reciprocal space contours Our data is taken using full 2D X-Ray images (Pilatus 300k camera) allowing us to very rapidly explore the nature of competing crystallographic transformations arising across quite a large reciprocal space, here centered on (010). The strip spanning the horizontal axis hides the data at those HKL values, and is associated with the internal detector arrays of the Pilatus camera, which does not impact this data analysis.



**Figure S6.** X-Ray derived Strain measured as a function of electric field for all grazing incidence reflections, at 40°C, for  $\alpha = 0.1^\circ$ , showing the complex ferroelectric switching strain field response with asymmetrical hysteresis within the surface of the single crystal sample.

90 depth calculation (see main paper). During this process, data is interpolated only once within the HKL  
 91 conversion process.

### 92 3. Grazing Incidence and penetration of X-Rays into solids

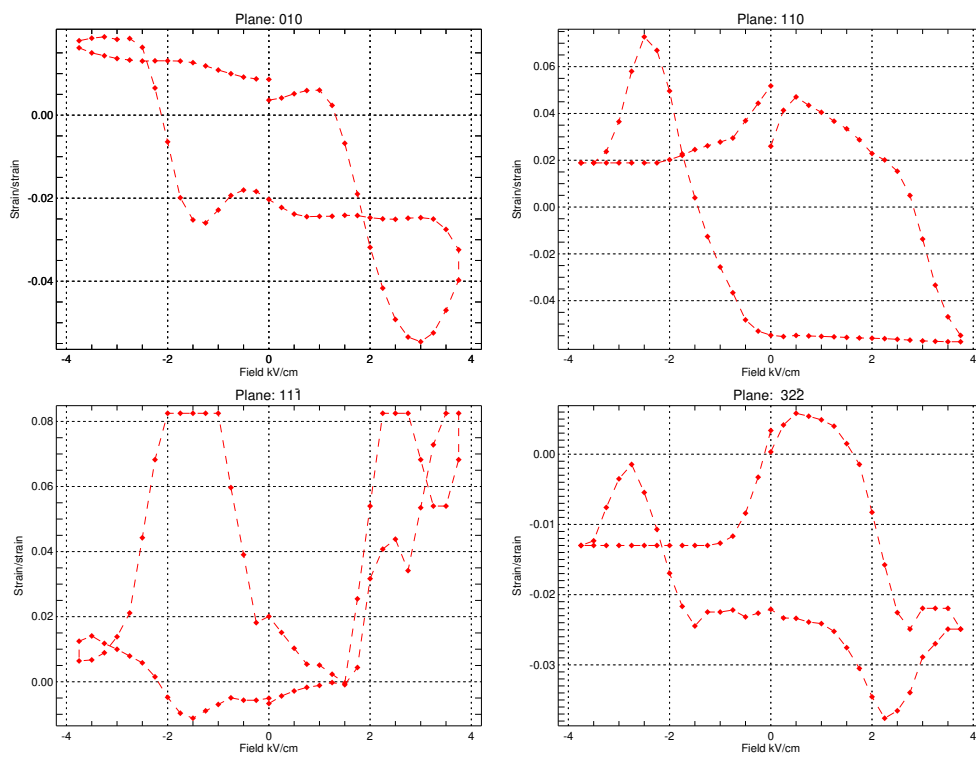
The degree of penetration of X-Rays into a solid depends on energy of the radiation, geometrical factors and sample parameters[6,7], and is in general a complex form of Snell's law based on the refractive index of a medium for X-Rays, according to equation 1:

$$n = 1 - \delta - i\beta \text{ with } \delta = \frac{2\pi\tau_0\rho}{|k|^2} \text{ and } \beta = \frac{\mu}{2|k|} \quad (1)$$

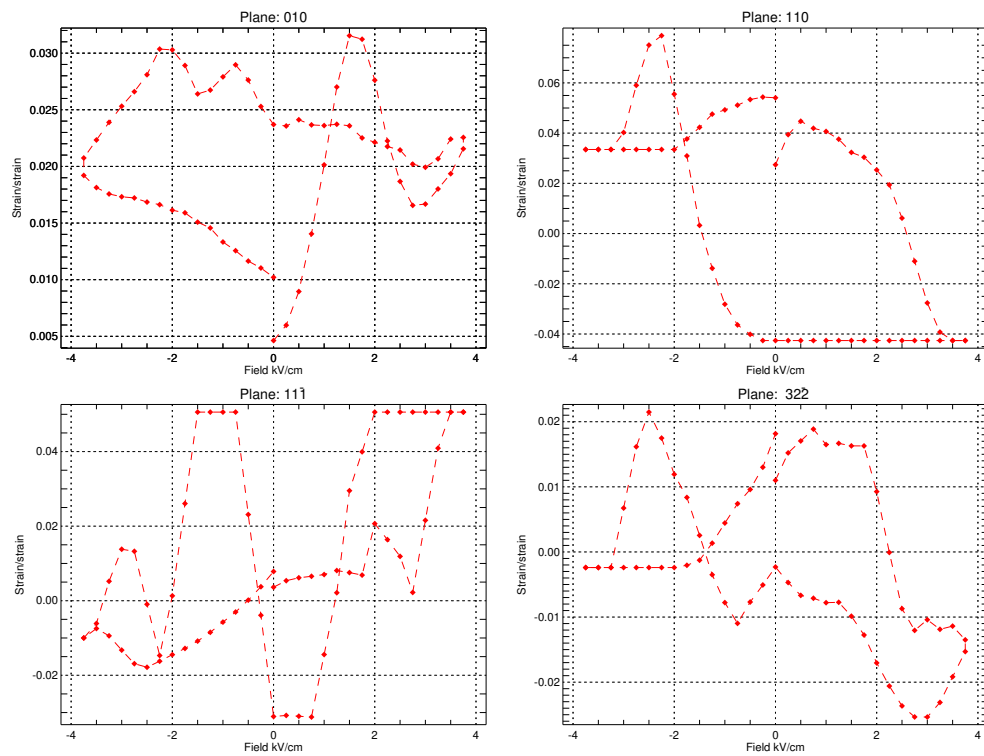
with  $\rho$  electronic density,  $\tau_0$  classical electron radius= $2.818 \times 10^{-5} \text{ \AA}$ ,  $\mu$  linear absorption coefficient and  $|k|$  length of incident wave vector ( $=2\pi/\lambda$ ), which may be used in the following equation governing penetration depth,  $\Lambda$ , of X-Rays:

$$\Lambda = \frac{1}{2k\Im(\alpha')} \quad (2)$$

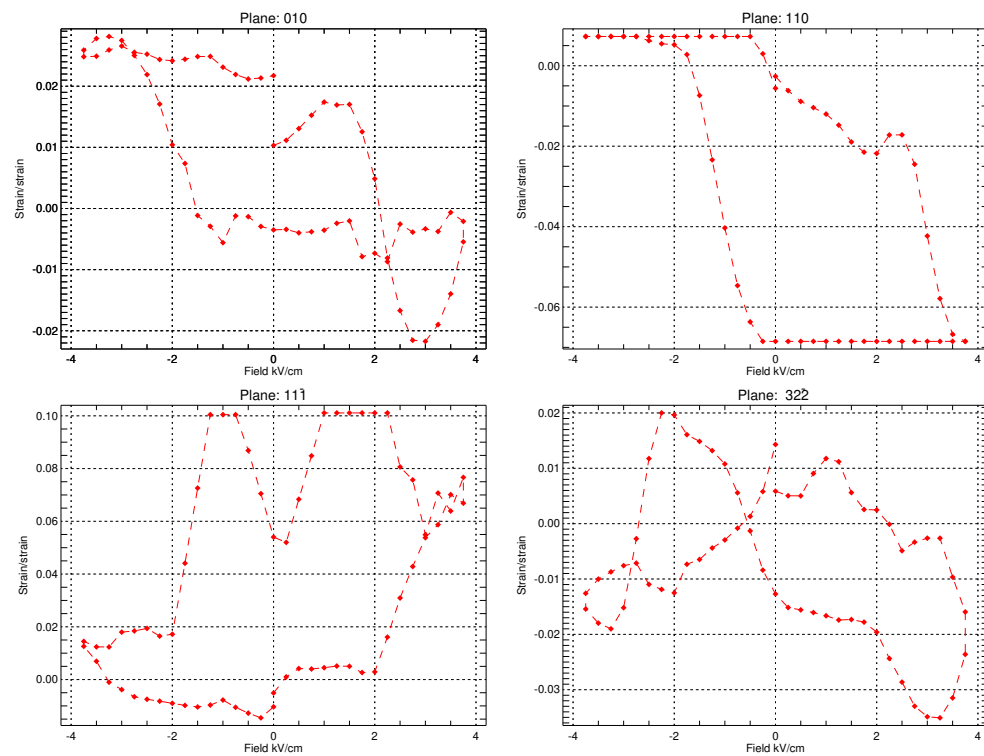
93 with  $\alpha$ =angle of incidence and  $\Im$  signifies its Imaginary component. The response, for  
 94 X-Ray Energy=12.4keV chosen in this experiment, is shown for average elemental composition  
 95  $\text{Pb}(\text{In}_{1/2}\text{Nb}_{1/2})\text{O}_3$ - $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ - $\text{PbTiO}_3$ , in figure S10.



**Figure S7.** X-Ray derived Strain measured as a function of electric field for all grazing incidence reflections, at 40°C, for  $\alpha = 0.2^\circ$ , showing the complex ferroelectric switching strain field response with asymmetrical hysteresis within the surface of the single crystal sample.

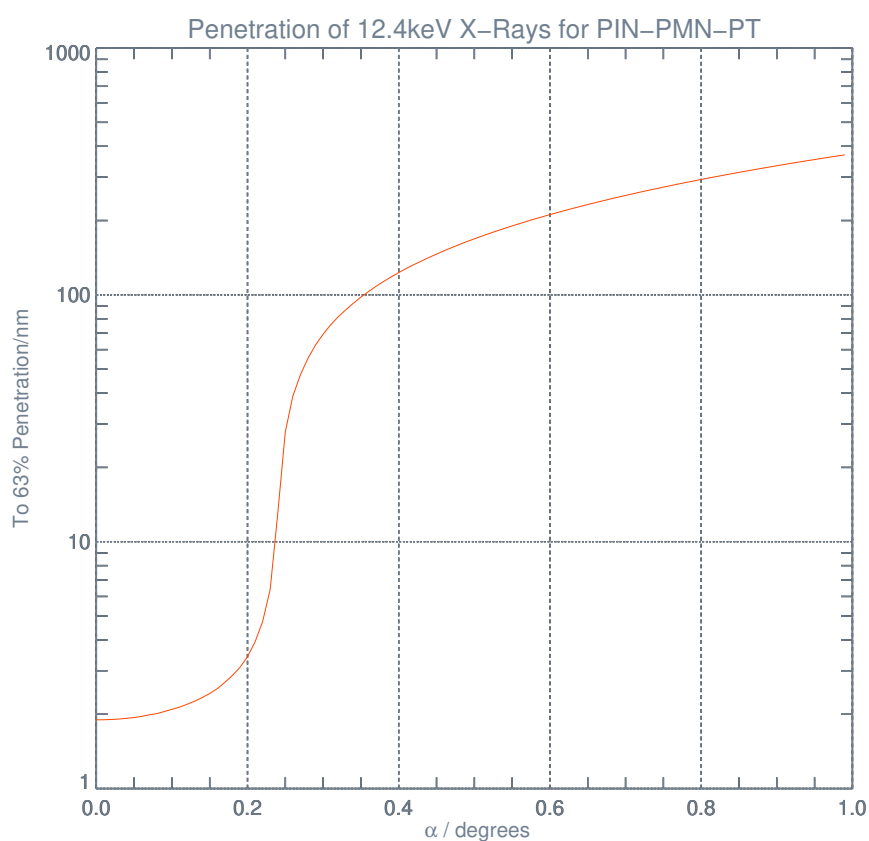


**Figure S8.** X-Ray derived Strain measured as a function of electric field for all grazing incidence reflections, at 40°C, for  $\alpha = 0.3^\circ$ , showing the complex ferroelectric switching strain field response with asymmetrical hysteresis within the surface of the single crystal sample.



**Figure S9.** X-Ray derived Strain measured as a function of electric field for all grazing incidence reflections, at 40°C, for  $\alpha = 0.5^\circ$ , showing the complex ferroelectric switching strain field response with asymmetrical hysteresis within the surface of the single crystal sample.





**Figure S10.** Calculation of the penetration depth of X-Rays at  $E=12.4\text{keV}$ , into PIN-PMN-PT average elemental composition as a function of grazing incidence angle,  $\alpha$ . The graph shows as a LOG plot, the corresponding penetration depth of X-Rays, such that  $\sim 63\%$  of emitted X-Rays originate from that sample depth defined by the penetration angle in degrees on the x-axis.

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