



AFRL-ML-WP-TP-2007-535

**SELF-PUMPED PHOTOREFRACTIVE REFLECTION
GRATINGS IN Fe:KNbO₃ (PREPRINT)**

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**Hardened Materials Branch
Survivability and Sensor Materials Division**

AUGUST 2006

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14. ABSTRACT <ul style="list-style-type: none"> • High gain confirmed in off-axis geometries for Fe:KNbO₃ • Mismatch between theory and experiment for mid-range crystal angles, especially for the a-c plane* • Large apparent variation in the effective trap density with crystal angle* • Modified theory gives a good fit to experimental data* • Mechanism for trap density anisotropy is uncertain, but may be due to stochastic layering of impurities during crystal growth*, or from the Franz0Keldysh Effect 					
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Self-Pumped Photorefractive Reflection Gratings in Fe:KNbO₃



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•23 – 25 August 2006

•Sand Key, Florida



Outline



- Potassium niobate as a photorefractive
- Theory
- Off-axis geometries
- Experiments
- Results
- A controversial suggestion.....
- Discussion
- Conclusion (confusion?)



Potassium niobate as a photorefractive



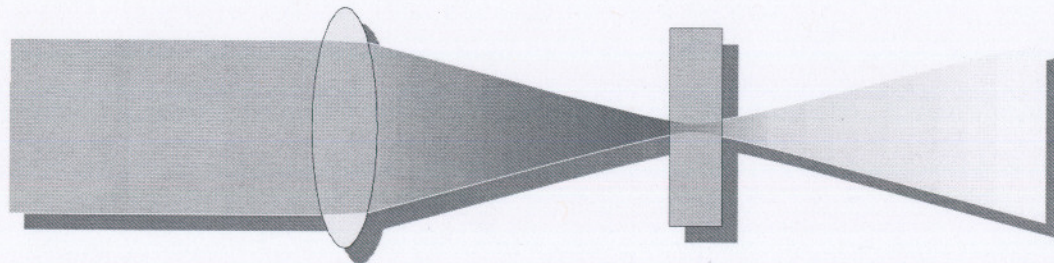
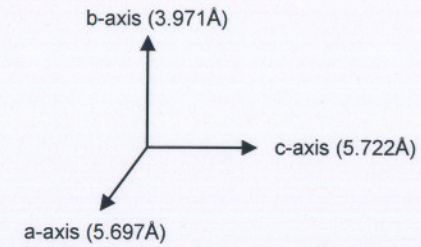
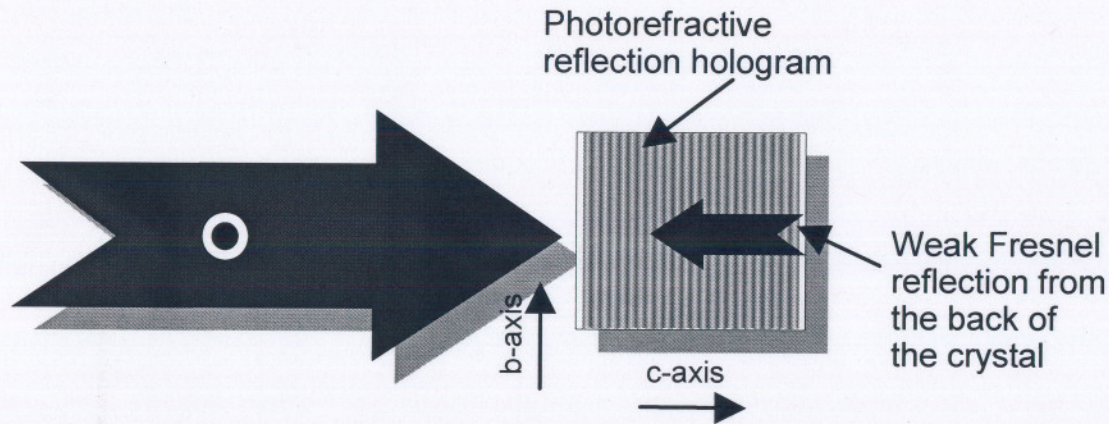
- High trap density
 - ↳ Allows efficient counter-propagating gratings to be written
 - ↳ Scope for further improvement of trap density!
- High sensitivity
 - ↳ Fast response times ($\sim 50\mu\text{sec}$)
- Broad spectral response
 - ↳ 400nm - $\sim 700\text{nm}$ (with Fe doping)
 - ↳ 400nm - $>700\text{nm}$? (with Ni doping)
- Difficult to grow reproducibly
 - ↳ Program under way to fix this (looks very promising!)
 - ↳ Series of 4 crystals now grown with almost identical performance



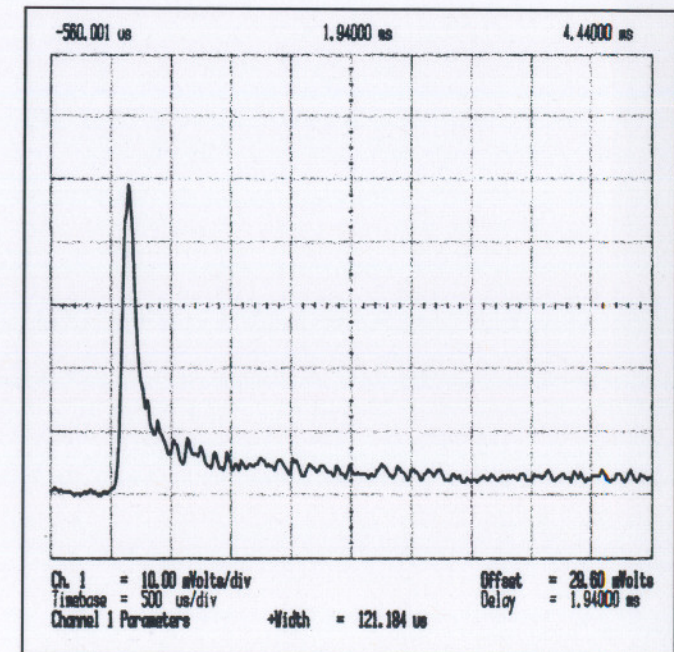
Geometry



- Self-pumped two beam coupling



Focal plane geometry





Standard theory



• Optical fields

$$E_s(z,t) = \frac{1}{2} A_s(z,t) \exp i(-kz - \omega t) + c.c$$

$$E_p(z,t) = \frac{1}{2} A_p(z,t) \exp i(+kz - \omega t) + c.c$$

$$I(z,t) = (I_s + I_p) \left(1 + \frac{A_s A_p^*}{I_s + I_p} \exp(2ikz) + c.c. \right)$$

$$\frac{dN_d^+}{dt} = s(I + I_{Dark})(N_d - N_d^+) - \gamma_r n N_d^+$$

$$\frac{dn}{dt} = \frac{dN_d^+}{dt} + \frac{1}{e} \frac{dJ}{dz}$$

$$J = e\mu n E_{sc} + \mu k_B T \frac{dn}{dz} + sI(N_d - N_d^+) e\delta$$

$$\epsilon_s \frac{dE_{sc}}{dz} = e(N_d^+ - N_a^- - n)$$

(Kiev group/Kukhtarev material equations)

• Intensity fringes





Standard theory



- Solving the Kiev group/Kukhtarev's equations for the space charge field gives:

$$\frac{a}{\tau_{di}} \frac{\partial E_{sc}}{\partial t} + bE_{sc} + cm = 0$$

- Where:

$$m = \frac{\sqrt{I_s I_p}}{I_s + I_p + I_{Erasure}} \exp(-i\varphi),$$

$$a = 1 + \frac{E_d}{E_m} - i \frac{E_0}{E_m},$$

$$b = 1 + \frac{E_d}{E_q} - i \left(\frac{E_0 + (N_a / N_d) E_{pv}}{E_q} \right),$$

$$c = E_0 + E_{pv} + iE_d$$

$$\tau_{di} = \epsilon_s \gamma_r N_a / e \mu s (I_p + I_s + I_{Erasure}) (N_d - N_a)$$

$$E_d = \frac{2\pi k_B T}{e\Lambda}$$

$$E_q = (1 - N_a / N_d) e N_a / 2k\epsilon_s$$

$$E_{pv} = \gamma_r N_a^- \delta / \mu$$

$$E_m = \gamma_r N_a / (\mu K)$$



Standard theory



- The space charge field modifies the refractive index through the linear Pockels effect
- Substituting the modulated index into the optical wave equation gives the coupled equations for the intensities and phase:

$$\frac{\partial I_p}{\partial z} = -\alpha I_p - \frac{2\pi n^3 r_{\text{eff}}}{\lambda} \sqrt{I_p I_s} \text{Im}(E_{sc} \exp(i\varphi))$$

$$\frac{\partial I_s}{\partial z} = +\alpha I_s - \frac{2\pi n^3 r_{\text{eff}}}{\lambda} \sqrt{I_p I_s} \text{Im}(E_{sc} \exp(i\varphi))$$

$$\frac{\partial \varphi}{\partial z} = \frac{\pi n^3 r_{\text{eff}} (I_p - I_s)}{\lambda \sqrt{I_p I_s}} \text{Re}(E_{sc} \exp(i\varphi))$$



Standard theory

- In steady state the space charge field and coupled equations reduce to:

$$E_{sc}(z) = \frac{-(E_0 + iE_d + E_{pv})m(z)}{1 + \frac{E_d}{E_q} - i\left(\frac{E_0}{E_q} + \frac{N_a E_{pv}}{N_d E_q}\right)}$$

$$\frac{dI_p}{dz} = -\alpha I_p - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}}$$

$$\frac{dI_s}{dz} = +\alpha I_s - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}}$$

Where

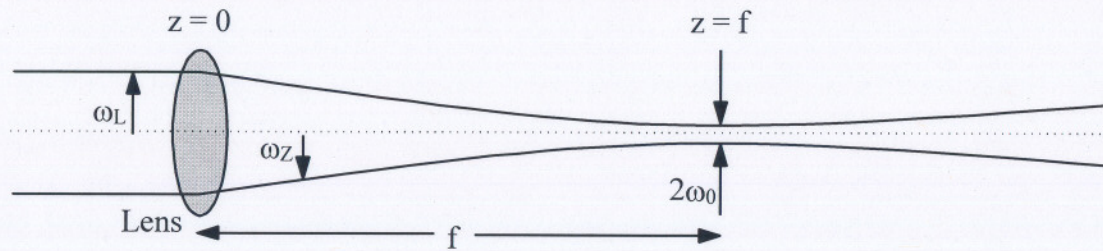
$$\Gamma = \frac{2\pi}{\lambda} n^3 r_{eff} \text{Im}(E_s)$$



Focusing



- Focusing



$$\frac{dI_p}{dx} = -\alpha I_p - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}} - \frac{2(z-f)I_p}{z_R^2 + (z-f)^2}$$
$$\frac{dI_s}{dx} = +\alpha I_s - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}} - \frac{2(z-f)I_s}{z_R^2 + (z-f)^2}$$



Extended theory

- Piezoelectric/photoelastic contributions^{1,2}

$$r_{ij}^{eff} = r_{ijk}^S \hat{n}_k + p_{ijkl}'^E \hat{n}_l A_{km}^{-1} B_m$$

$$A_{ik} = C_{ijkl}^E \hat{n}_j \hat{n}_l$$

$$B_i = e_{kij} \hat{n}_k \hat{n}_j$$

r_{ijk}^S is the clamped EO tensor

$p_{ijkl}'^E$ is the effective elasto-optic tensor

C_{ijkl}^E is the elastic stiffness tensor

e_{kij} is the piezoelectric tensor

- Scalar effective EO coefficient:

$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$

- 1) M. Zgonik, K. Nakagawa, P. Günter, "Electro-optic and dielectric properties of photorefractive BaTiO₃ and KNbO₃", J. Optical Society of America B, vol. 12, no. 8, pp 1416-1421, 1995.
- 2) M. Zgonik, R. Schlessler, I. Biaggio, E. Voit, J. Tscherry, P. Günter, "Materials constants of KNbO₃ relevant for electro- and acousto-optics", J. Applied Physics, vol. 74, no. 2, pp 1287-1297, 1993.



Extended theory



- Dielectric “constant”:
 - Not a constant!
 - Varies with angle

$$\epsilon_r^{eff} = \epsilon_{ij}^S \hat{n}_i \hat{n}_j + \frac{e_{ijk} e_{mnl} \hat{n}_i \hat{n}_j \hat{n}_m \hat{n}_n A_{kl}^{-1}}{\epsilon_0}$$

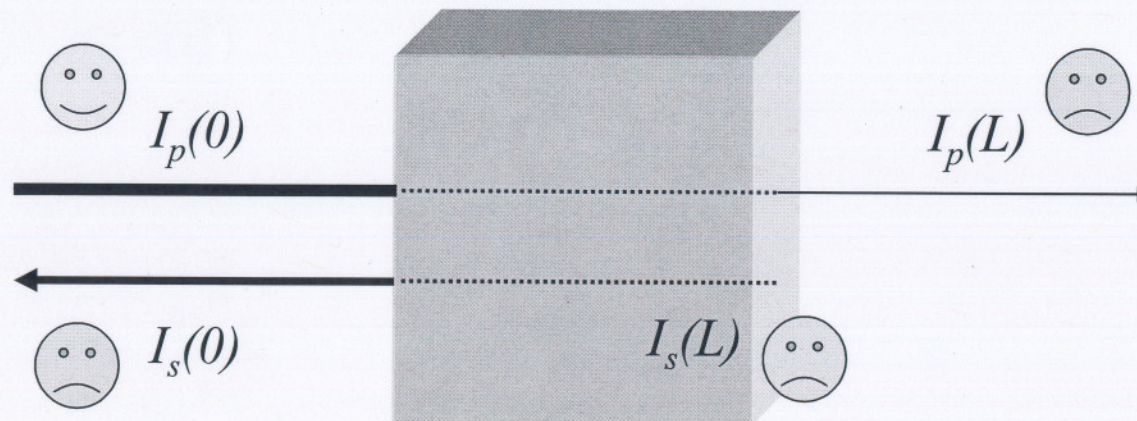
ϵ_{ij}^S is the clamped dielectric tensor

- Determines the saturation field
 - Affects the space-charge field and grating phase shift



Theory solutions

- No closed form solution to the coupled equations
- Numerical solutions only
- For self pumped two beam coupling the boundary conditions are known only for the pump input
- Iterative shoot and match methods are required

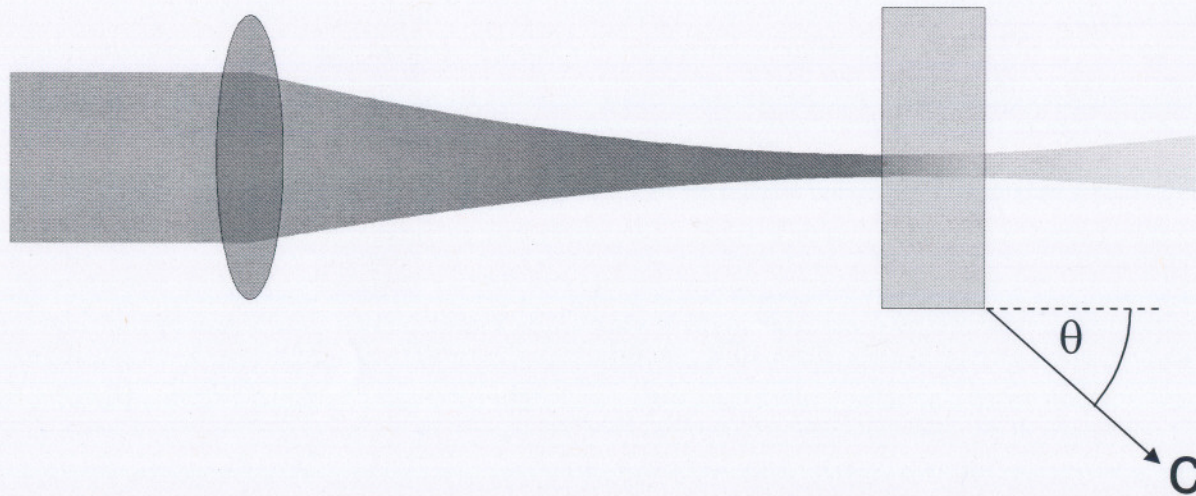




Off-axis concept



- Optical gain is potentially much higher away from the c-axis



- c-axis is best for Fe:LiNbO₃ owing to the huge PV effect
- The same is NOT true for Fe:KNbO₃

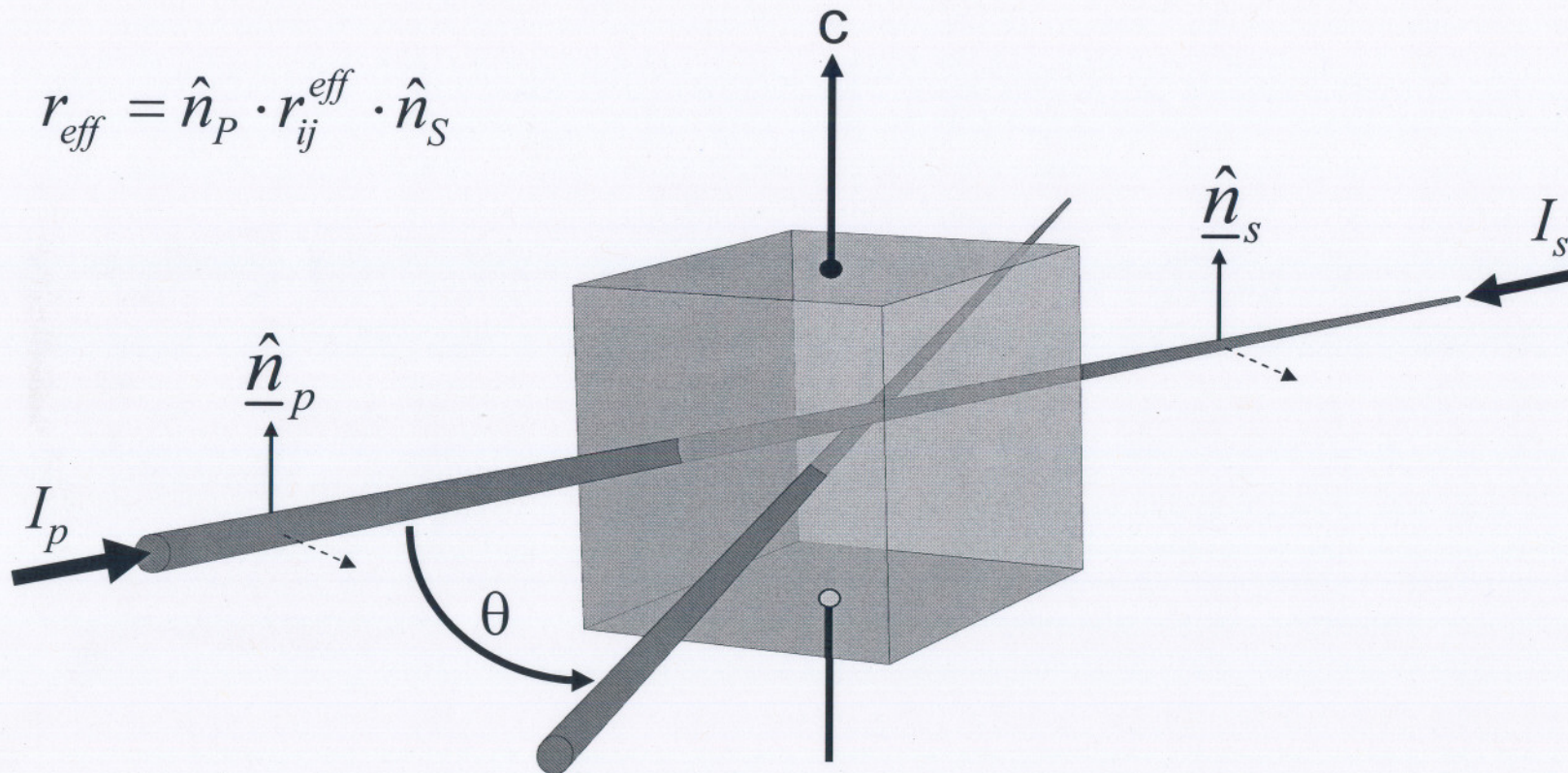


Off-axis effective electro-optic coefficient



- Beam axis rotation about the c-axis:

$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$



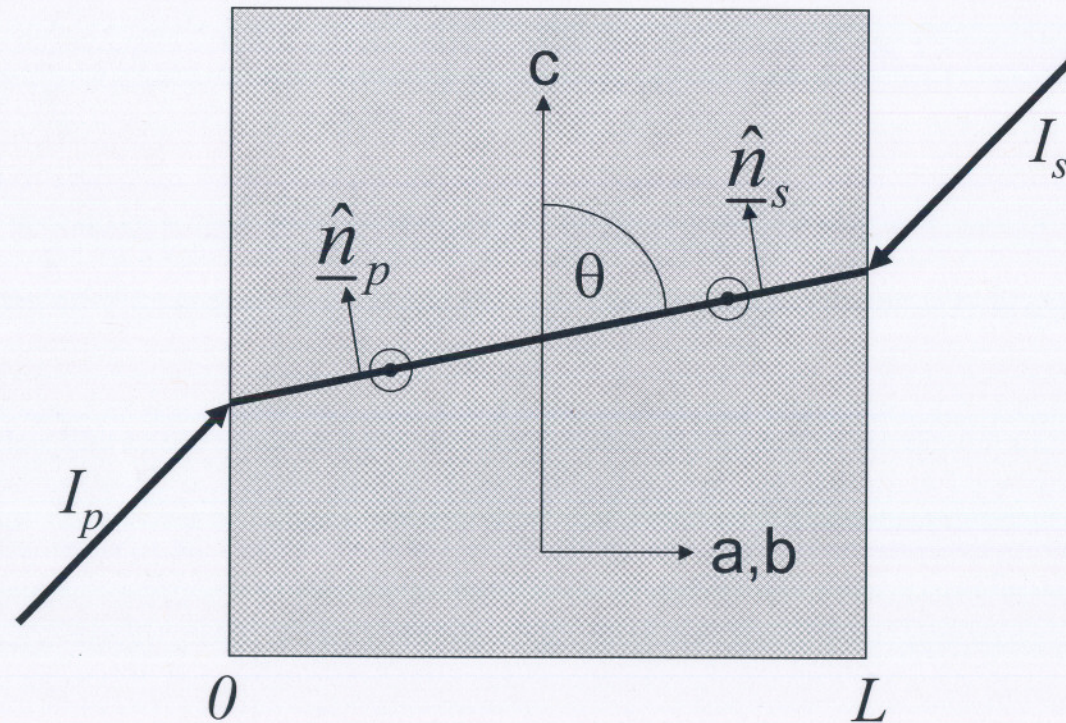
r_{eff} is zero for all parallel linear polarizations



Off-axis effective electro-optic coefficient



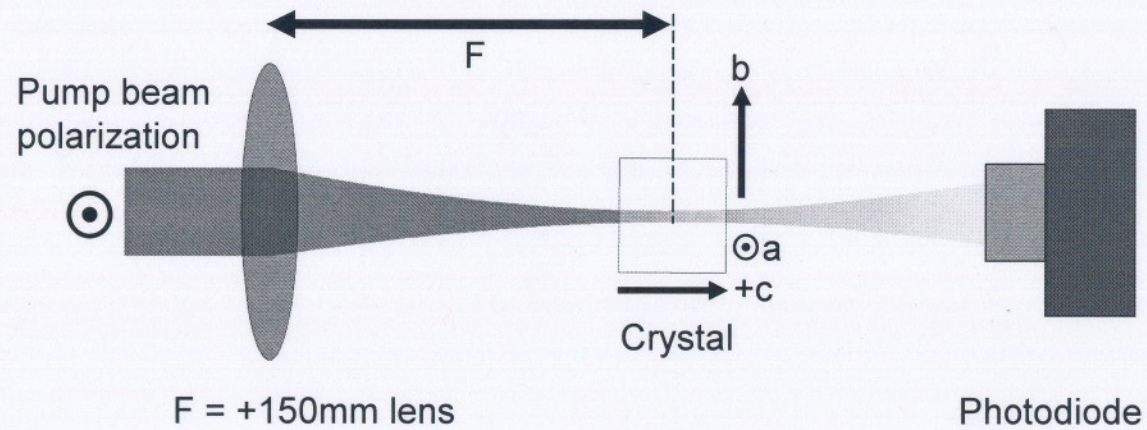
- Beam axis rotation in the a-c or b-c planes:



$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$



Determination of Γ and $I_{Erasure}$

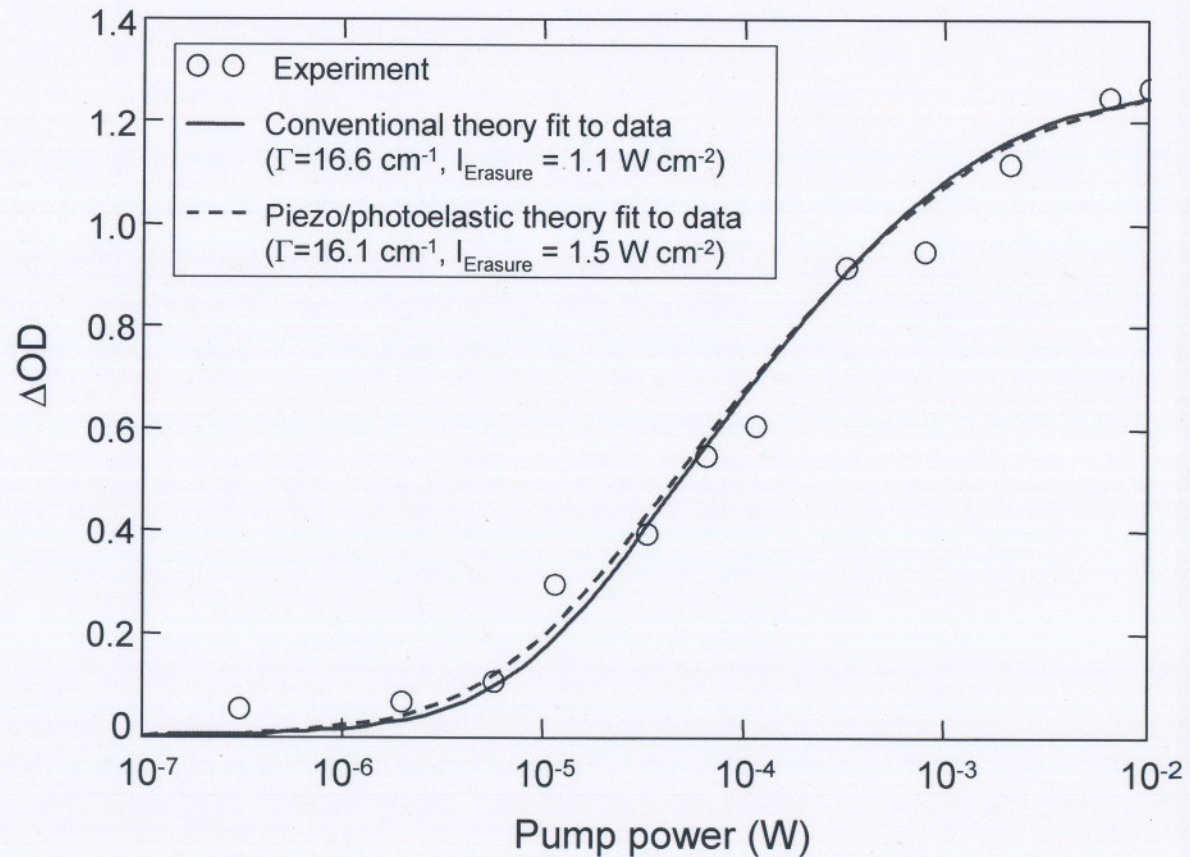




Determination of Γ and $I_{Erasure}$



$$\Delta OD = \log_{10} \left(\frac{T_{Linear}}{T_{SteadyState}} \right)$$



$$N_A \text{ (conventional)} = 2.1 \times 10^{16} \text{ cm}^{-3}$$

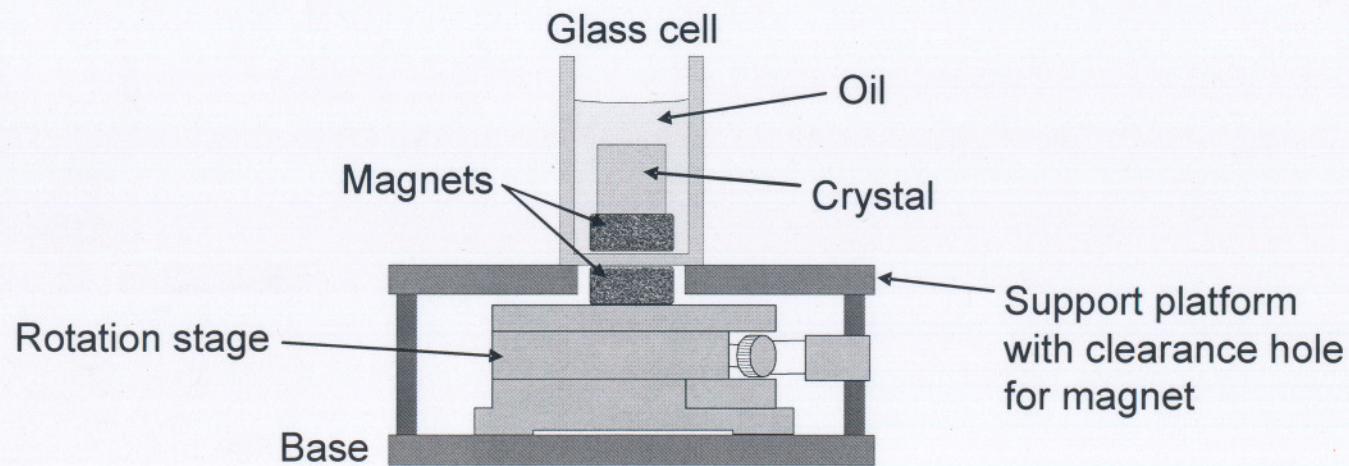
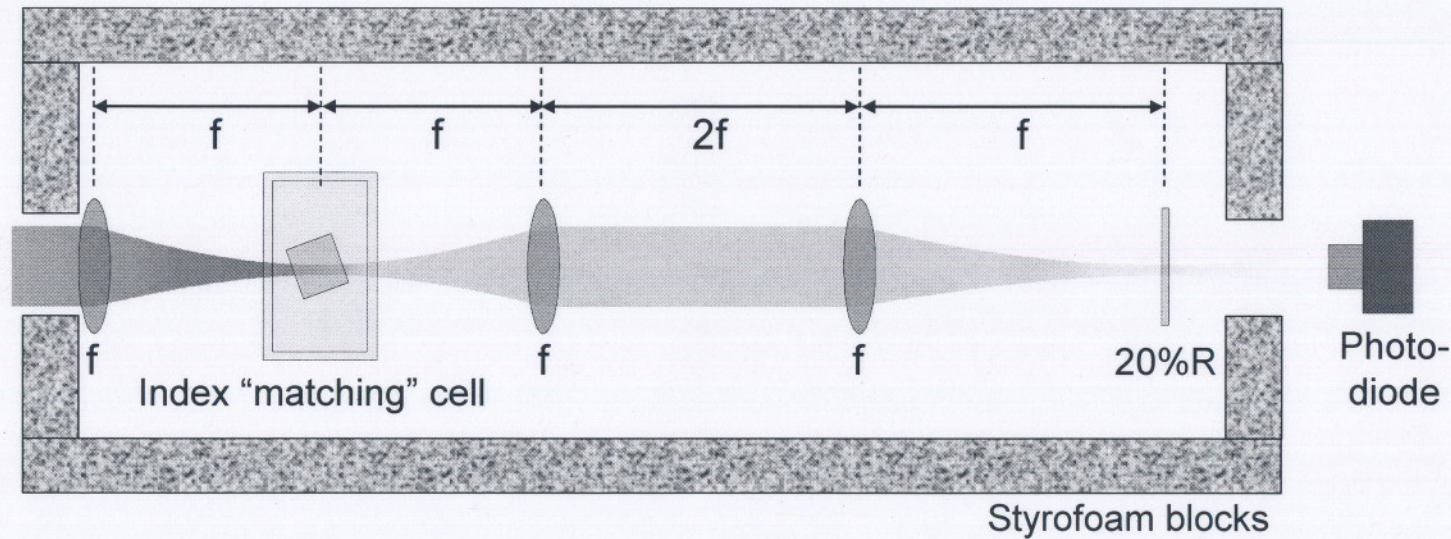
$$N_A \text{ (piezo)} = 5.0 \times 10^{16} \text{ cm}^{-3}$$



Measuring the off-axis gain in contra-directional Fe:KNbO₃

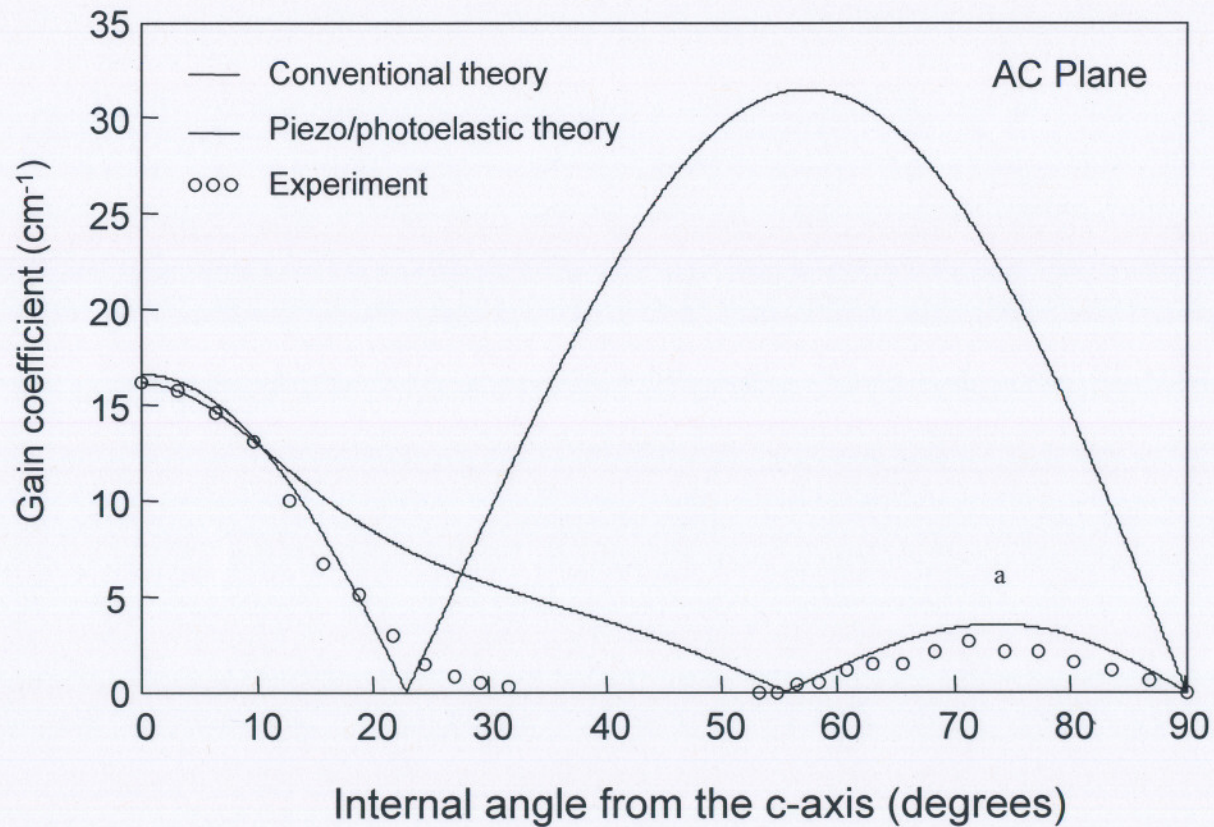


- Experiment:





Off-axis gain results

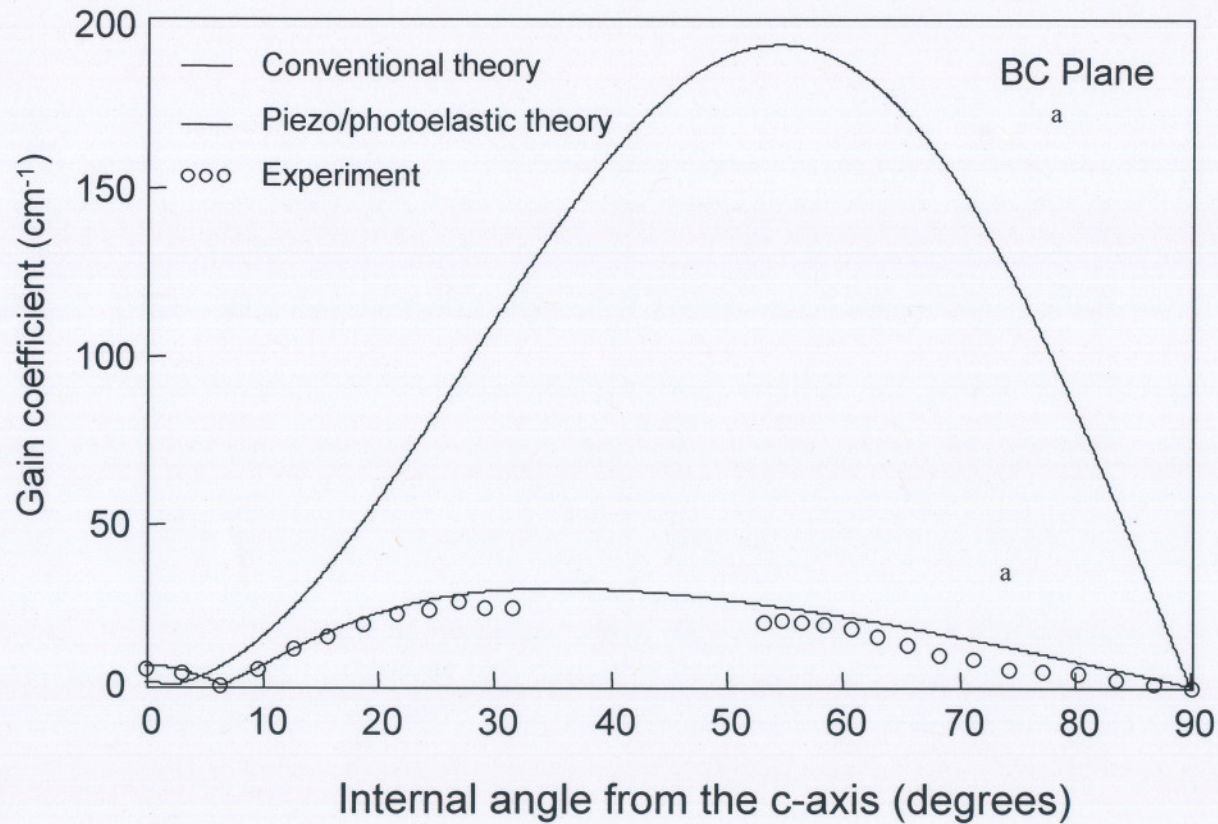


$$N_A (\text{conventional}) = 2.1 \times 10^{16} \text{ cm}^{-1}$$

$$N_A (\text{piezo}) = 5.0 \times 10^{16} \text{ cm}^{-1}$$



Off-axis gain results

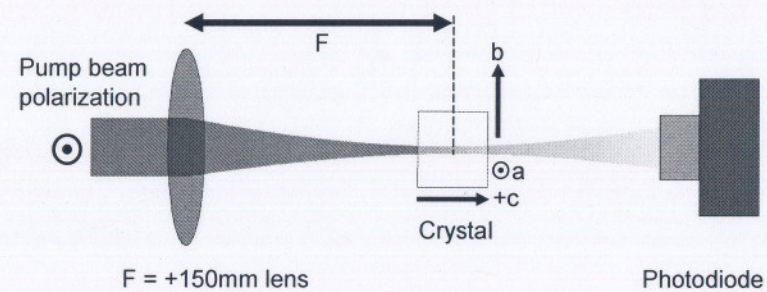
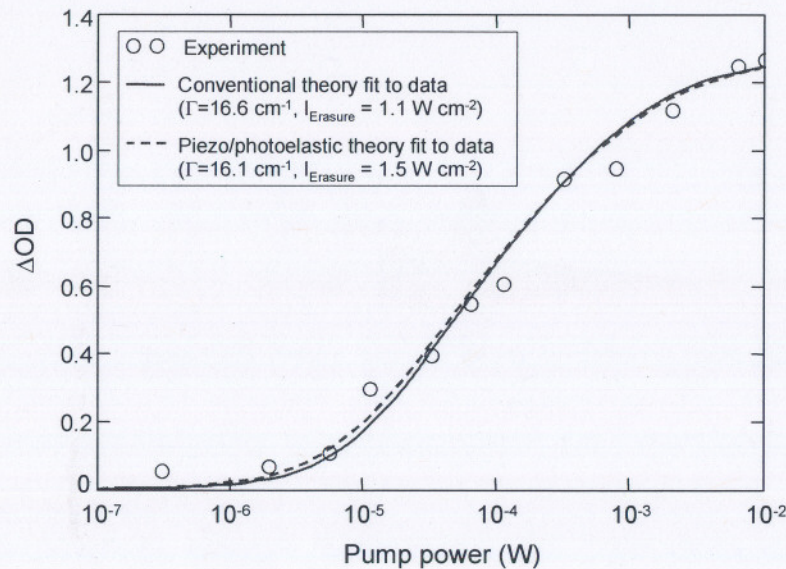


$$N_A (\text{conventional}) = 2.1 \times 10^{16} \text{ cm}^{-1}$$

$$N_A (\text{piezo}) = 5.0 \times 10^{16} \text{ cm}^{-1}$$



A controversial suggestion....

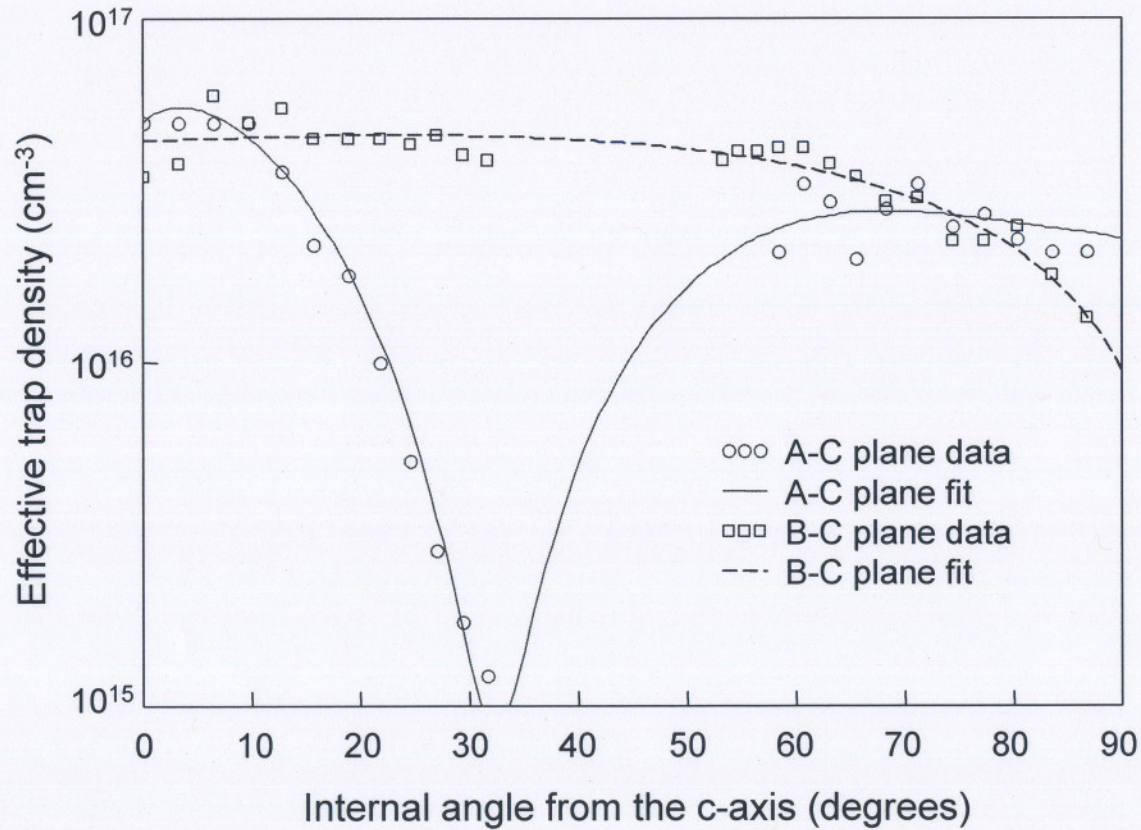


- Repeat previous measurements of Γ and I_{Erasure} for all crystal angles
- Calculate the effective trap density for each crystal angle

“Conventional” transmission/reflection grating method cannot be used reliably for trap density measurements owing to admittance angular restrictions at large crystal angles and competition from rear Fresnel reflection.



Effective trap density variations?

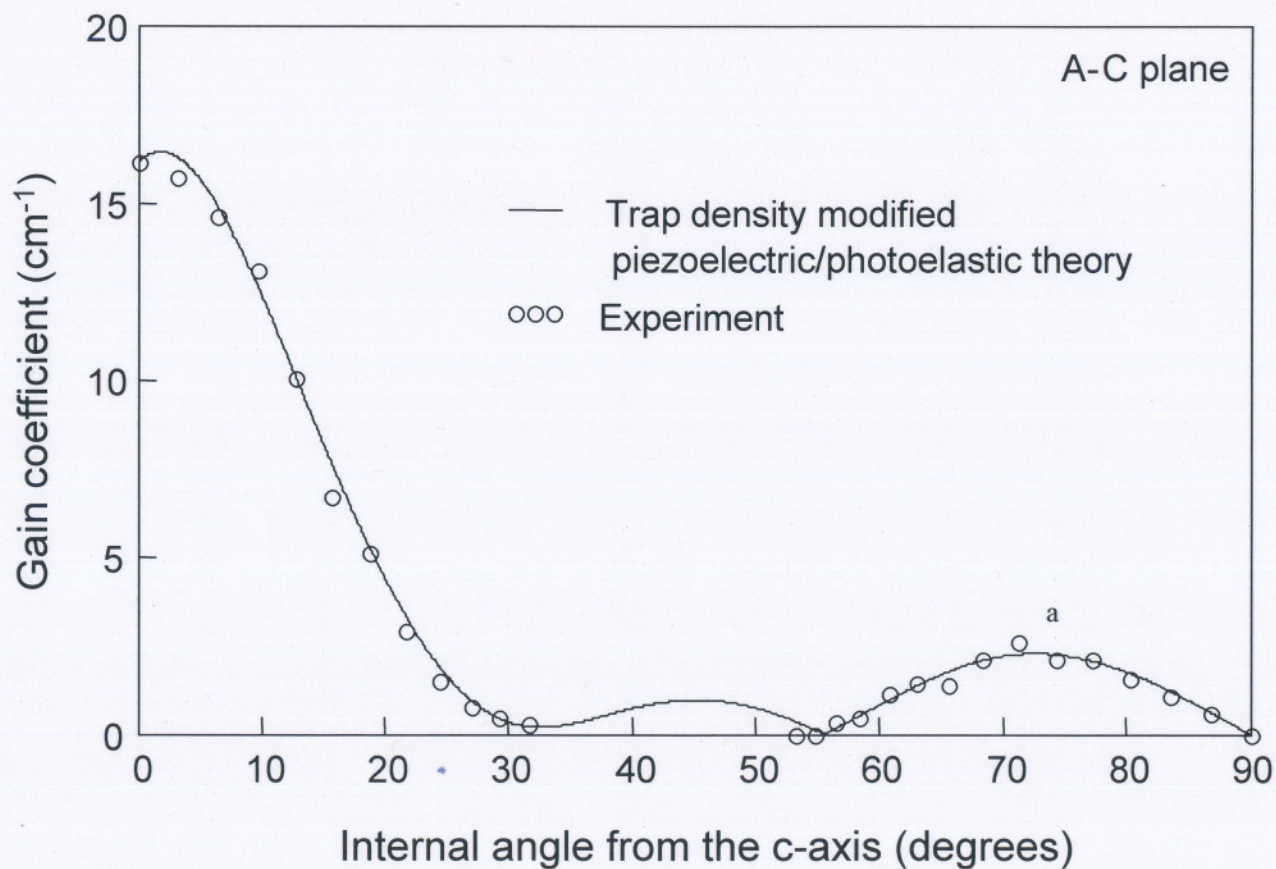


$$N_{A(AC)} = -9.09 \times 10^{12} \theta^6 + 3.03 \times 10^{15} \theta^5 - 3.85 \times 10^{17} \theta^4 + 2.26 \times 10^{19} \theta^3 - 5.67 \times 10^{20} \theta^2 + 3.21 \times 10^{21} \theta + 5 \times 10^{22}$$

$$N_{A(BC)} = -6 \times 10^{16} \theta^3 + 1 \times 10^{20} \theta + 4.42 \times 10^{22}$$

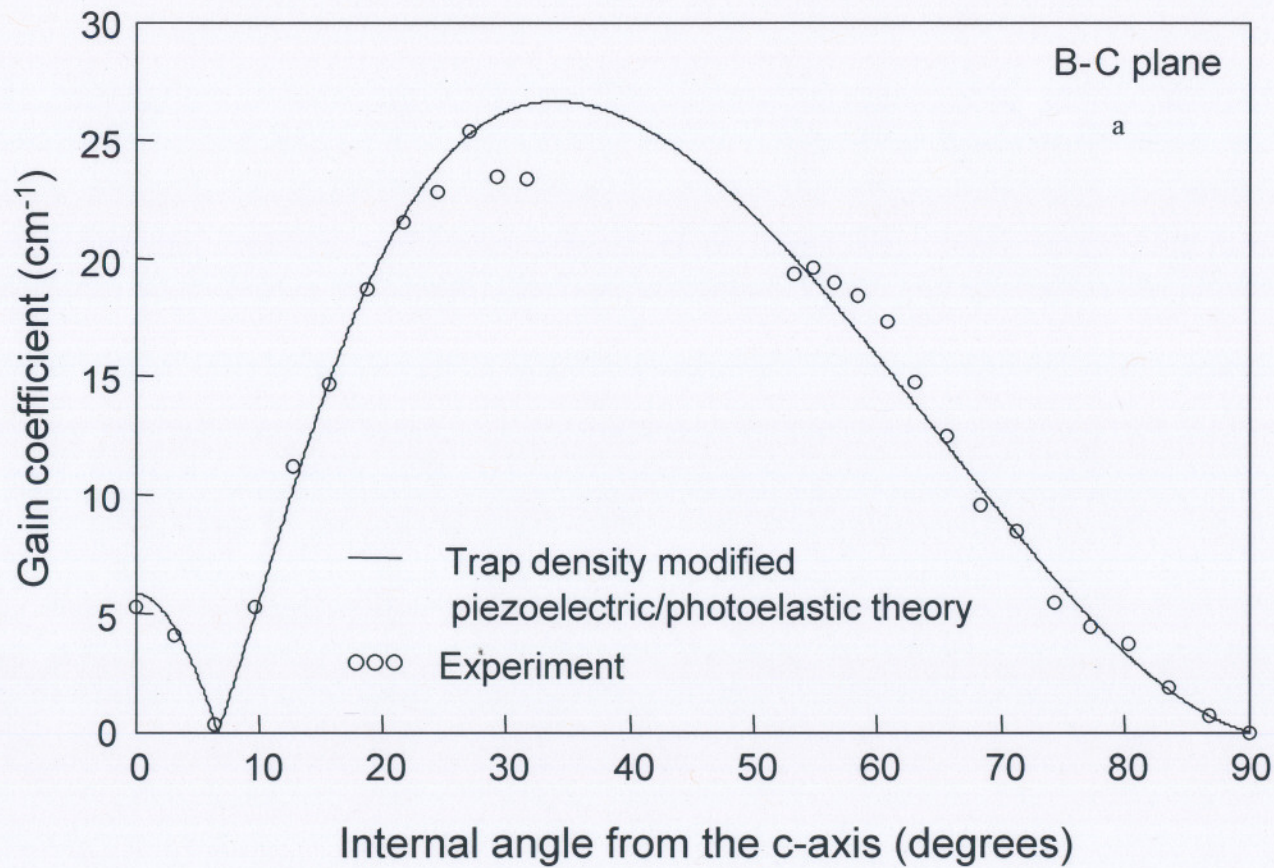


Theory modified for apparent trap density variations





Theory modified for apparent trap density variations

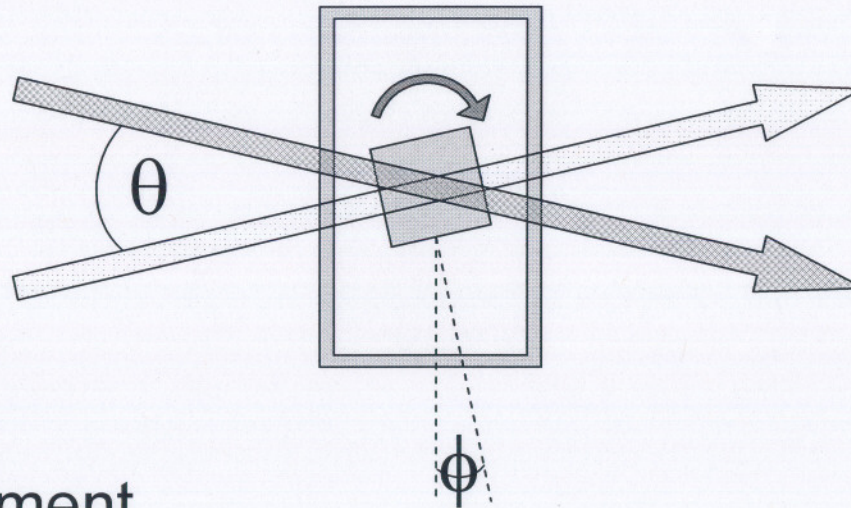




2nd attempt to verify trap density variations



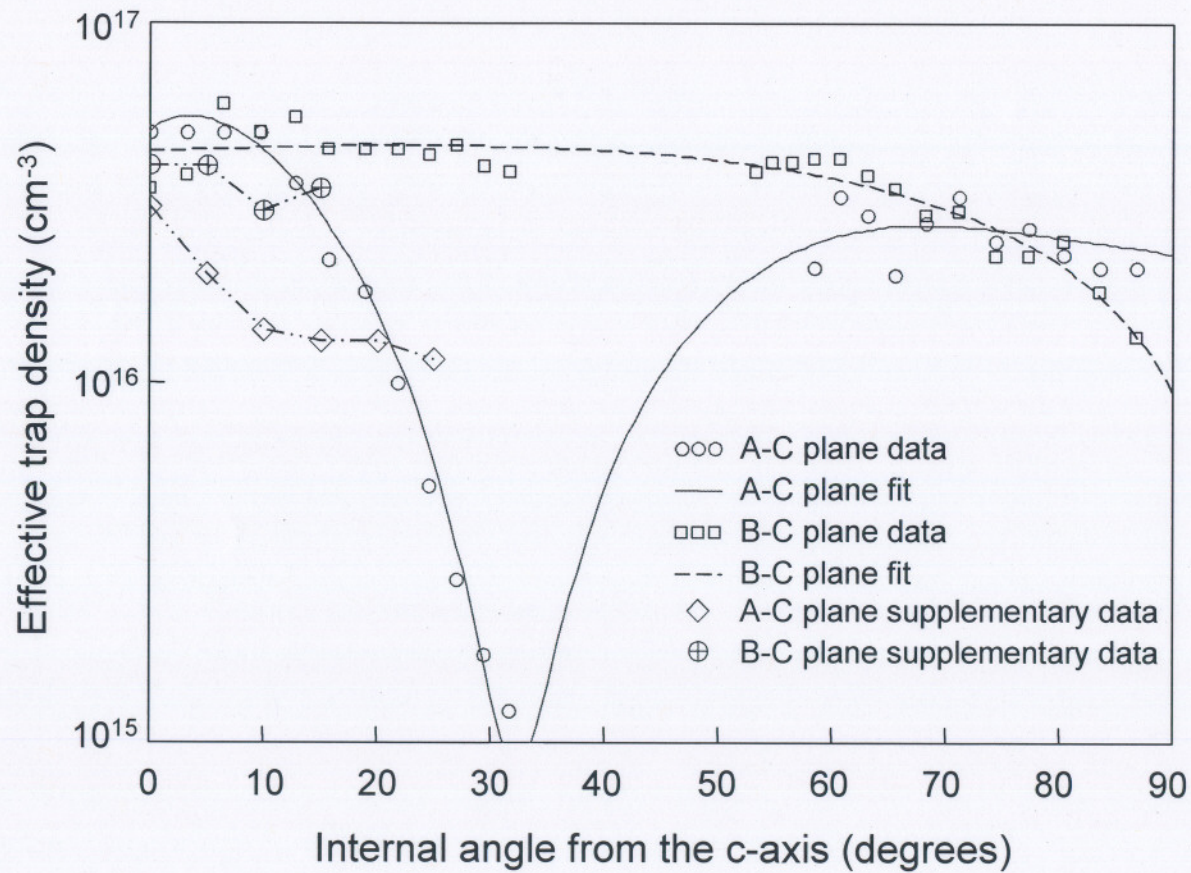
- Measure small signal gain as a function of grating spacing:



- Difficult experiment
 - Gain becomes very large – leads to competition from spurious beams
 - Difficult to maintain beam overlap at larger crystal angles
 - Pump and signal beam incidence angles become asymmetric, leading to a rotation of the grating k-vector. This requires a mechanical correction of the crystal angle at every measurement.



2nd attempt to verify trap density variations





Discussion



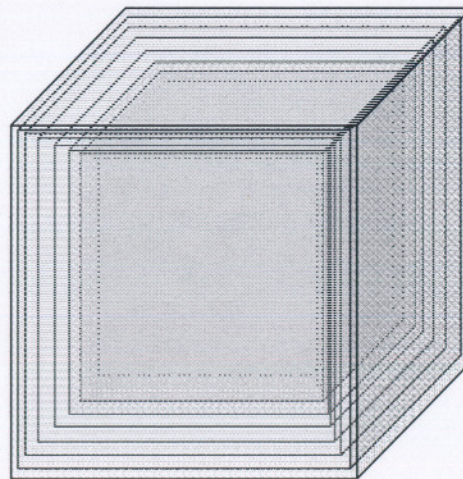
- An *effective* trap density is possible if the charges “remember” the original polarization state
- Delocalization of charges should randomize the charge state (can they “remember” the exciting polarization?)
- Rule out electron-hole competition (gain does not reverse with grating spacing)
- Trap density anisotropy has no physical meaning unless the grating spacing is greater than the mean trap separation..... But how can this occur?



Growth induced defect layers



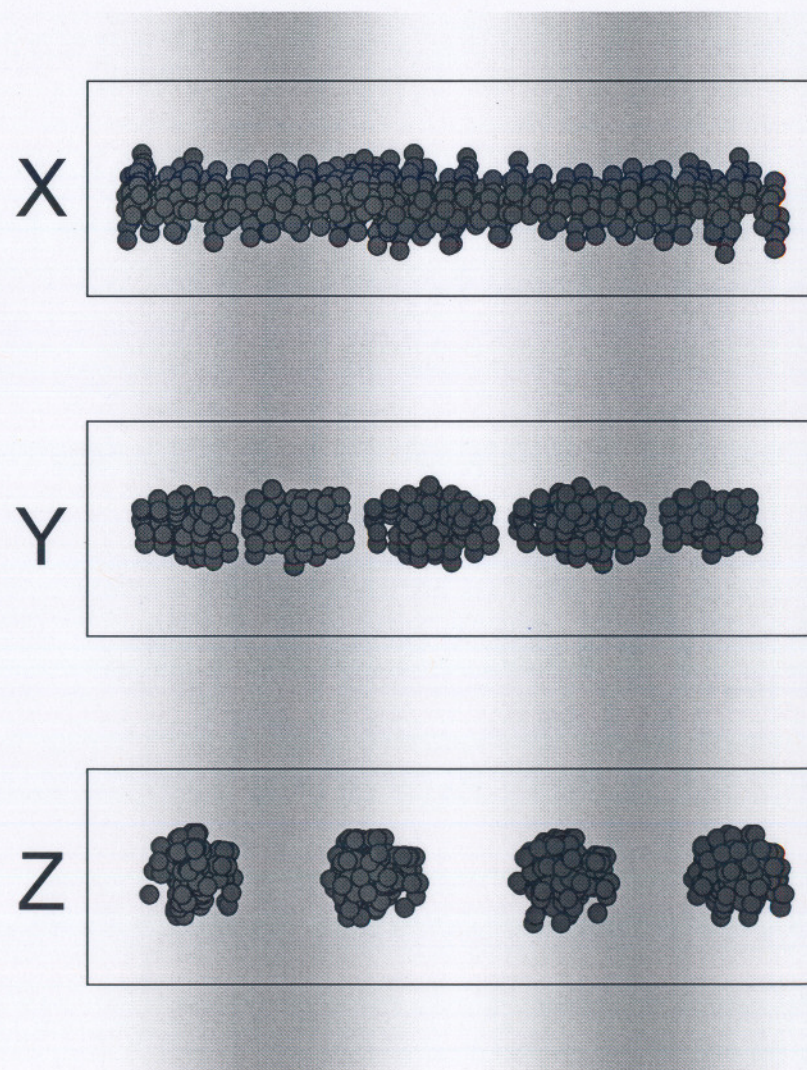
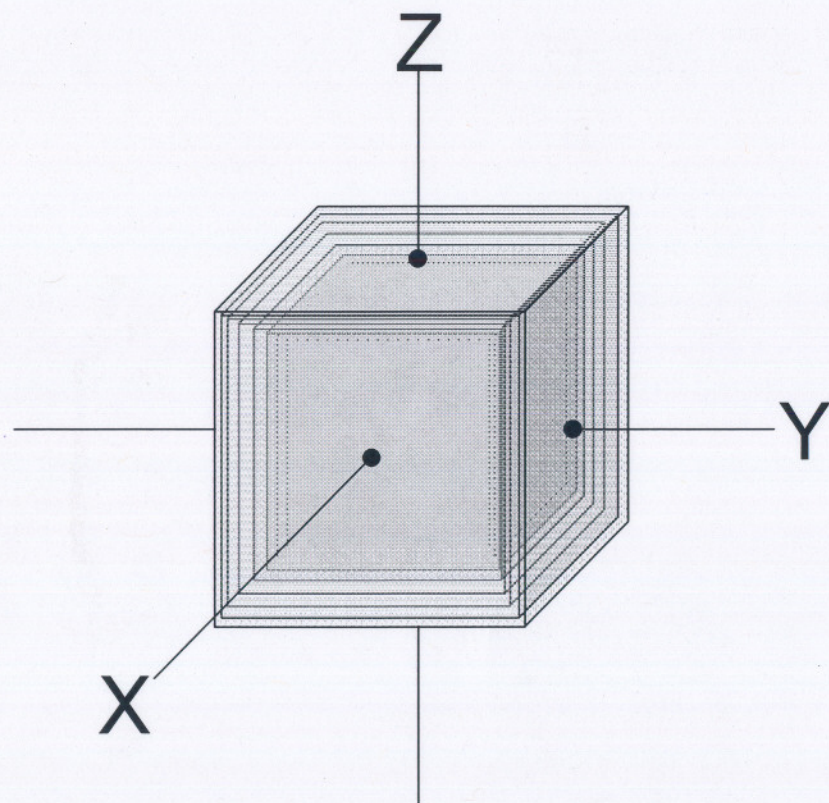
- Growth of potassium niobate does not occur smoothly
- Growth is stochastic, adding a plethora of microscopically thin layers
- Impurities (Fe) tend to segregate at the boundaries between these structures*
- It is therefore reasonable to assume the added impurities (Fe) form stratified concentrations of traps



* M. B. Mishra and S. G. Ingle, J. Appl. Phys. **45**, 5152 (1974).



Growth induced defect layers Transmission gratings

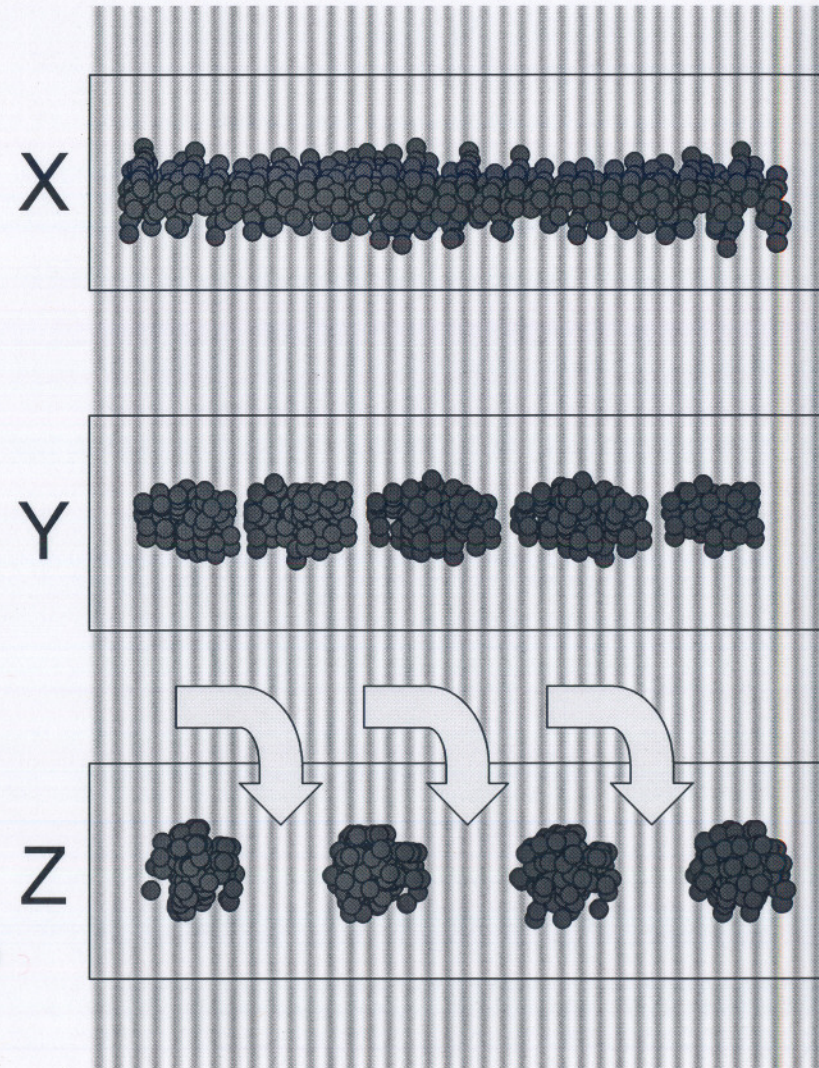
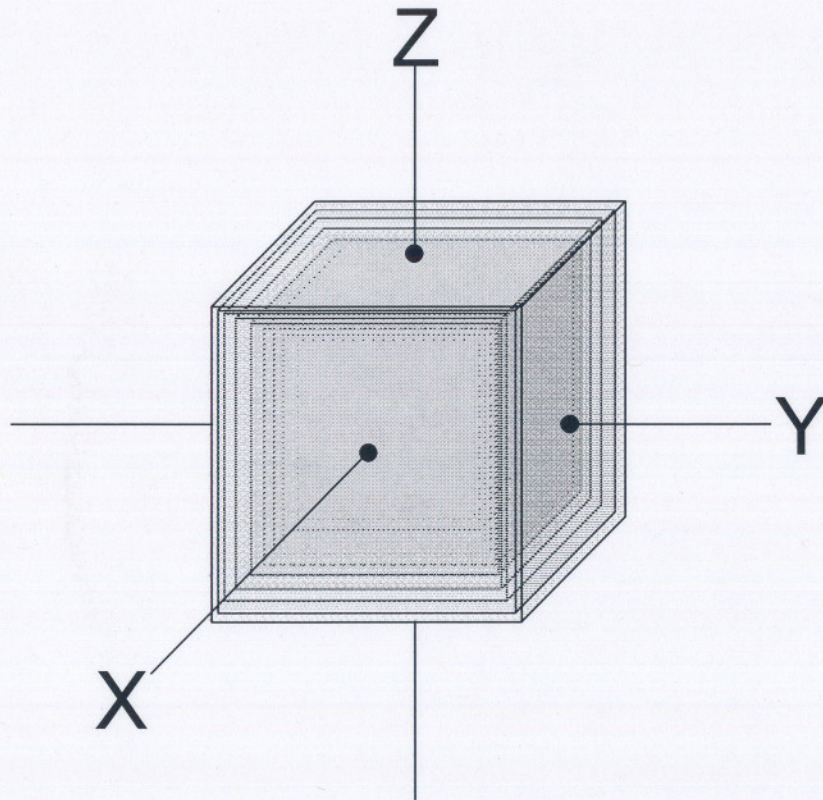


- Traps always coincide with fringes
- Average trap density remains approximately constant with direction
- Effect of defect "layers" not apparent



Growth induced defect layers

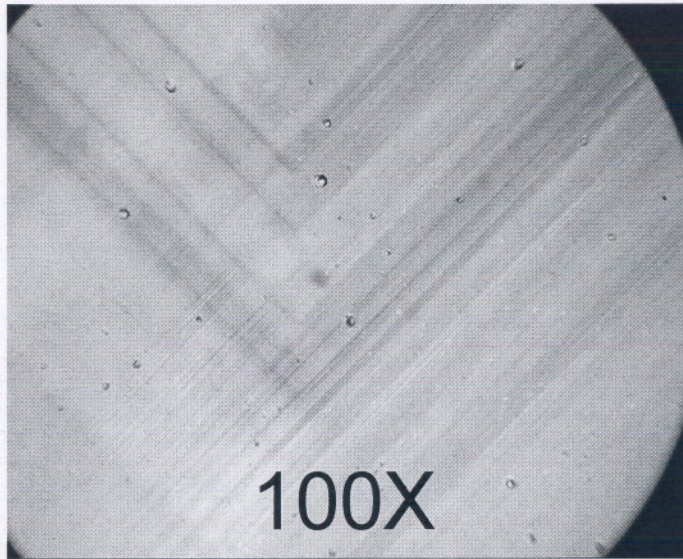
Reflection gratings



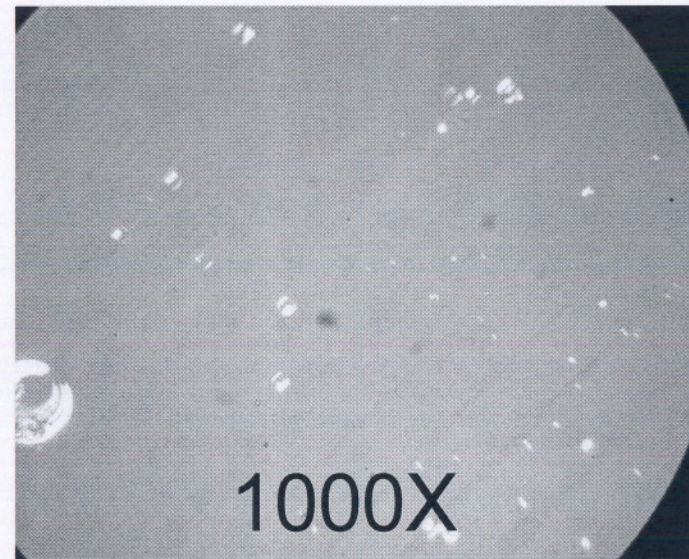
- Some fringes have a low trap density
- Local trap density becomes sensitive to direction
- Effect of defect “layers” becomes apparent



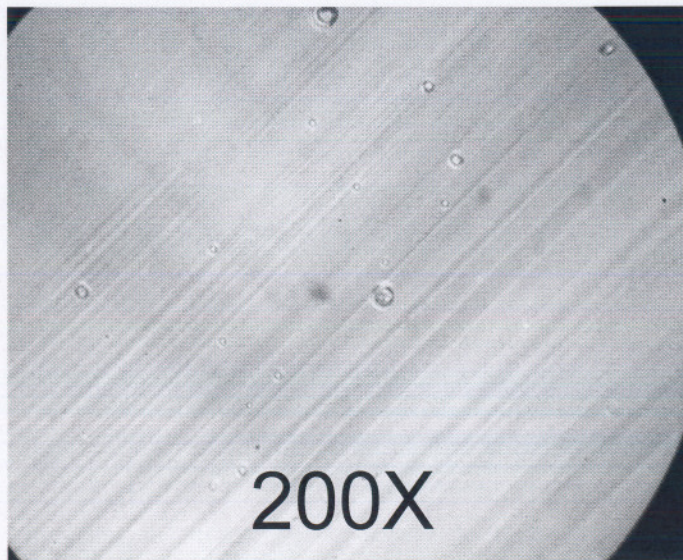
Defects in KNbO_3



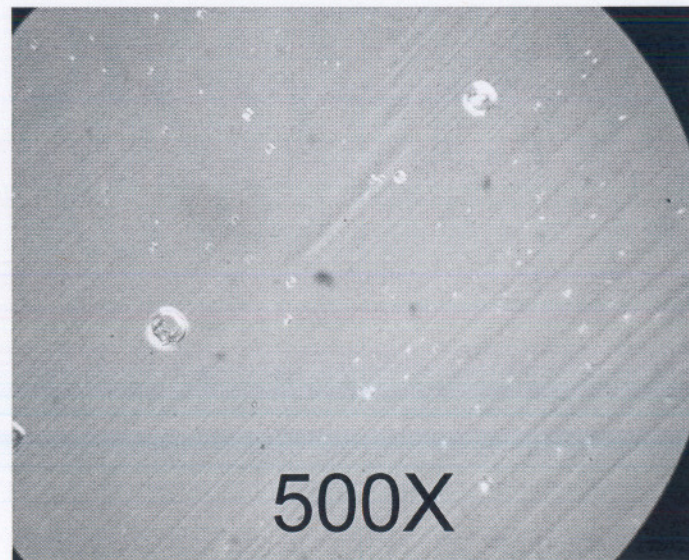
100X



1000X



200X



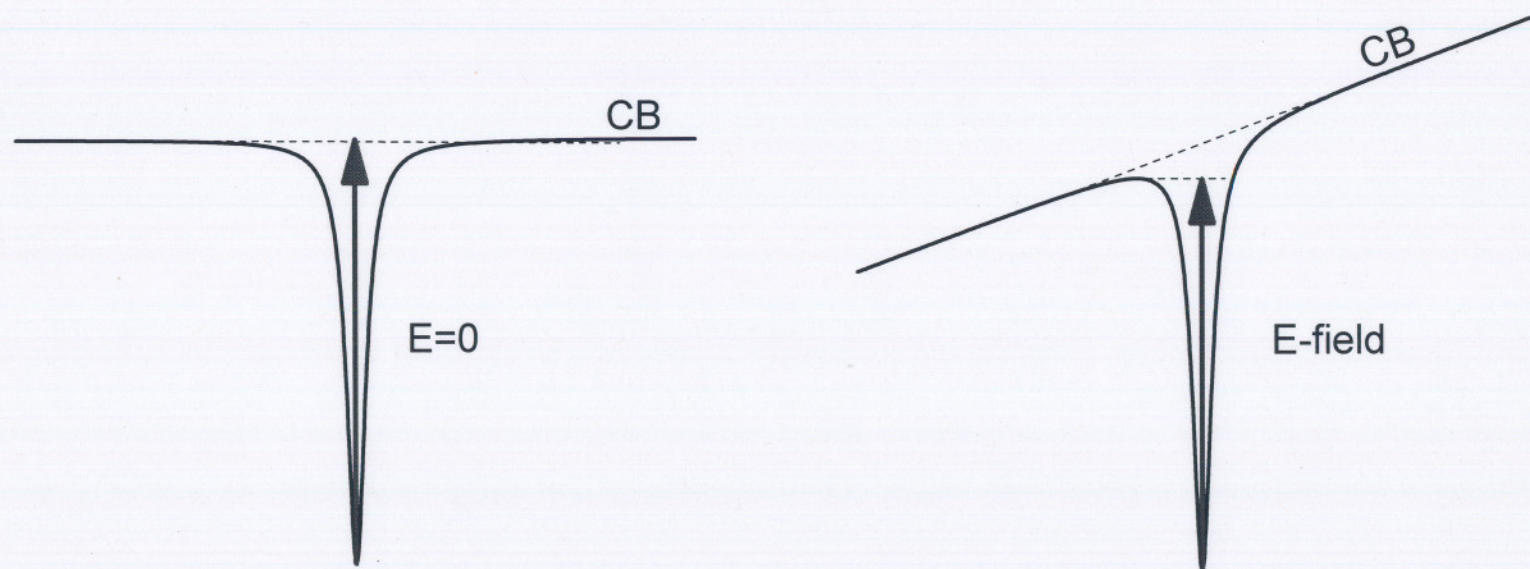
500X



Franz-Keldysh Effect.....?



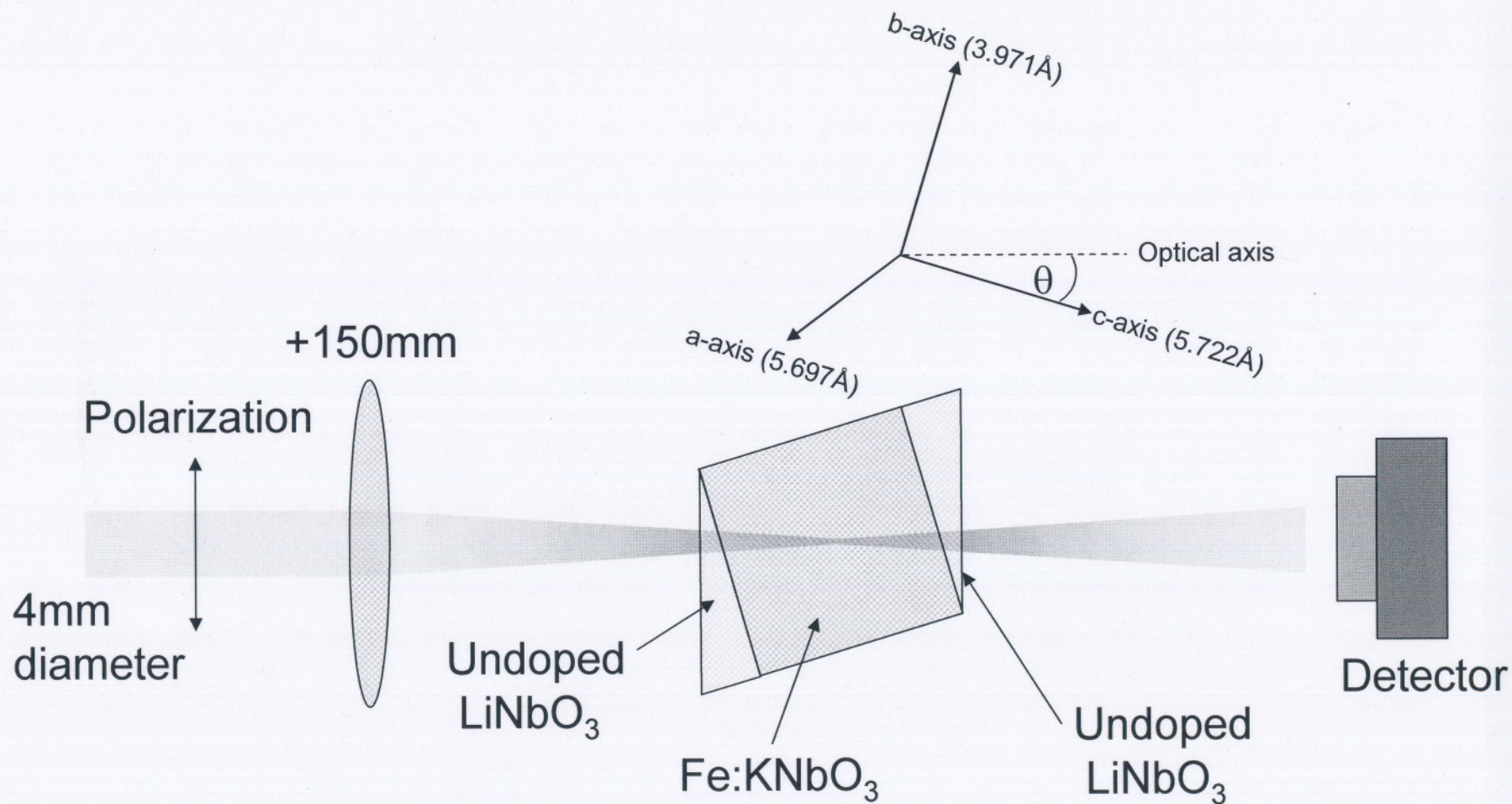
- Electric field induced absorption in bulk semiconductors
- Can **strain** have a similar effect? – growth and/or poling
- Strain induced trap depth – directional variation of the **effective** trap density



- Franz-Keldysh effect may also give a field dependent effective trap density
- Effective trap density, and hence saturation field, becomes nonlinear with grating spacing....

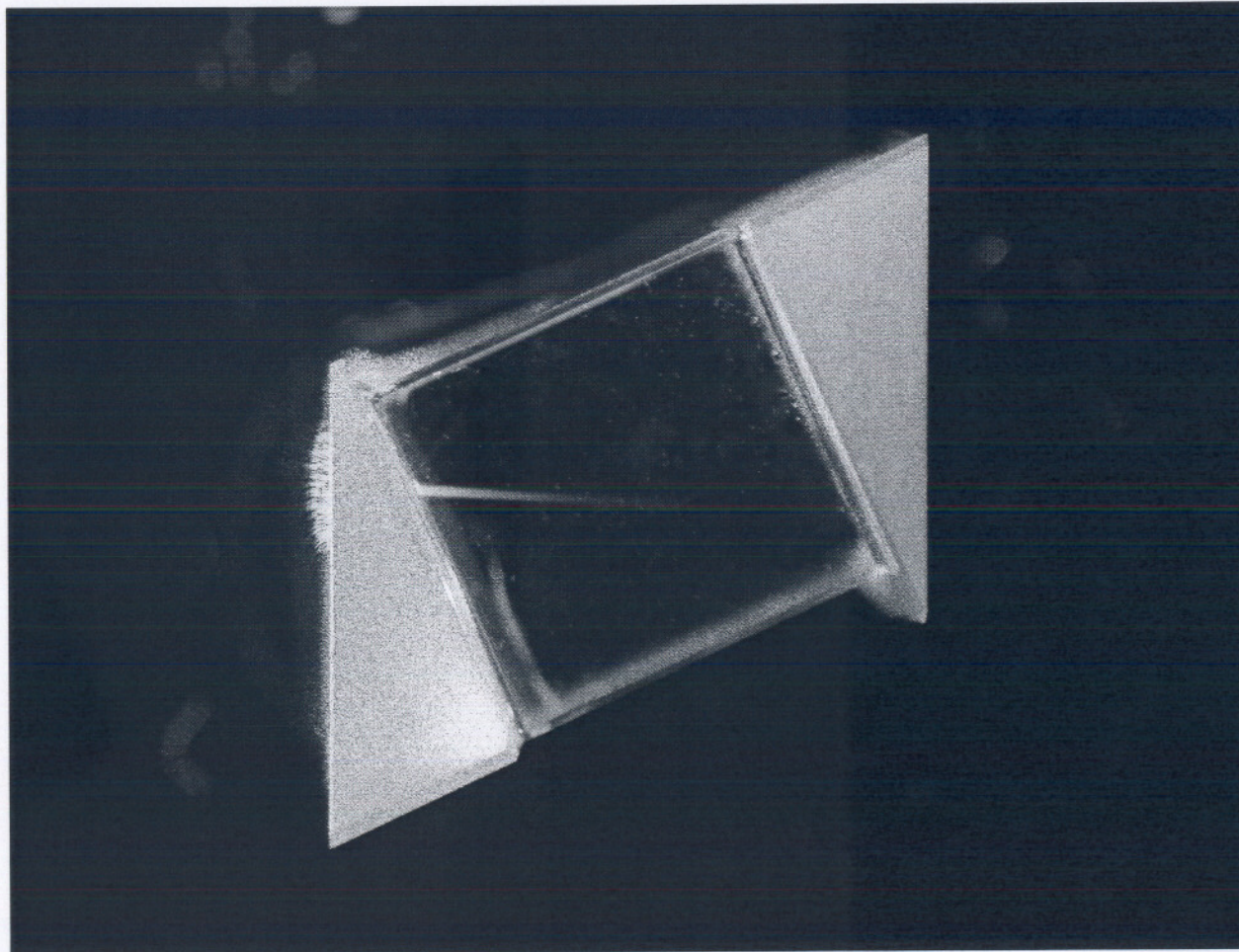


Real Off-Axis Testing



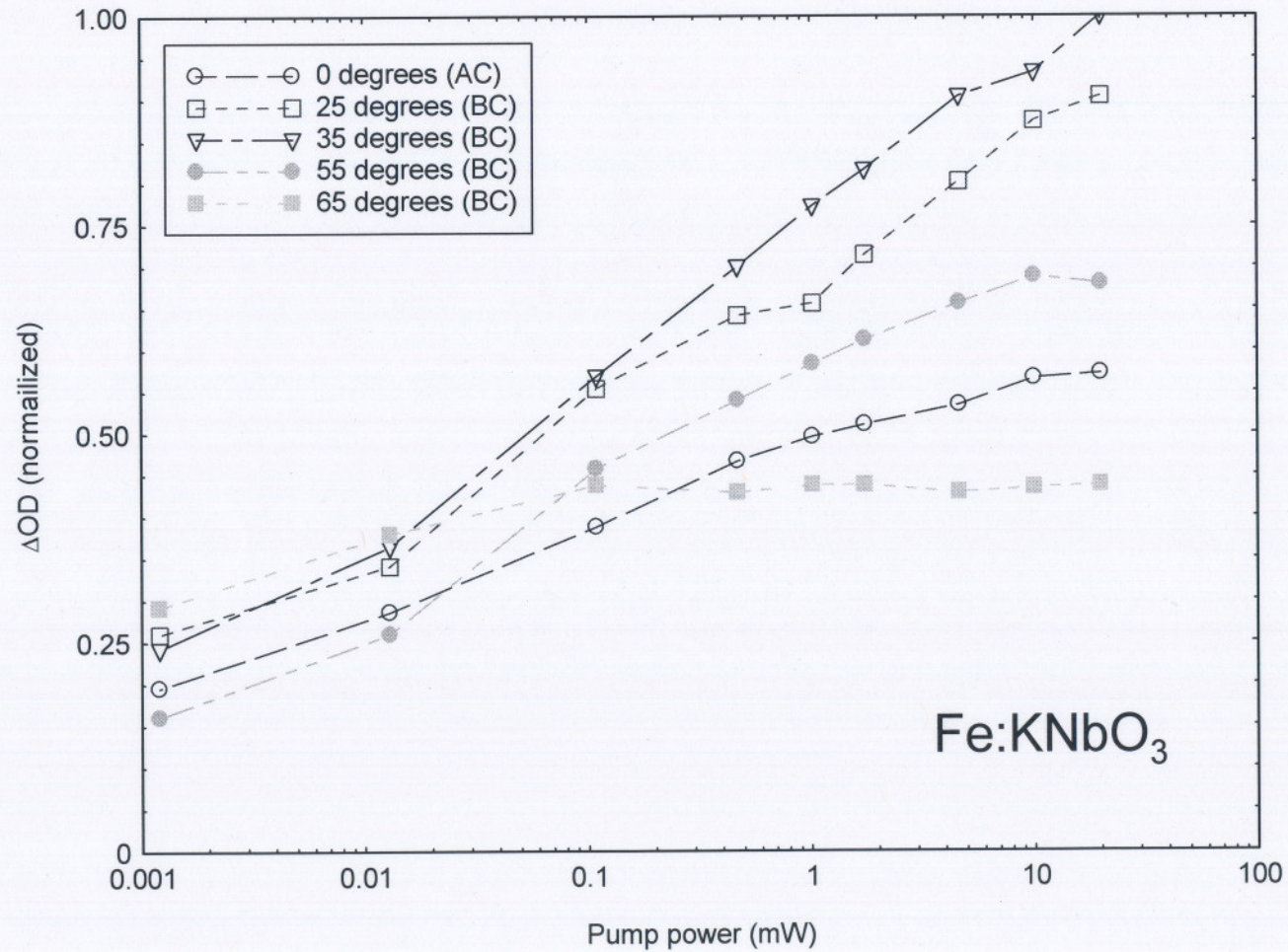


Real Off-Axis Testing - Results





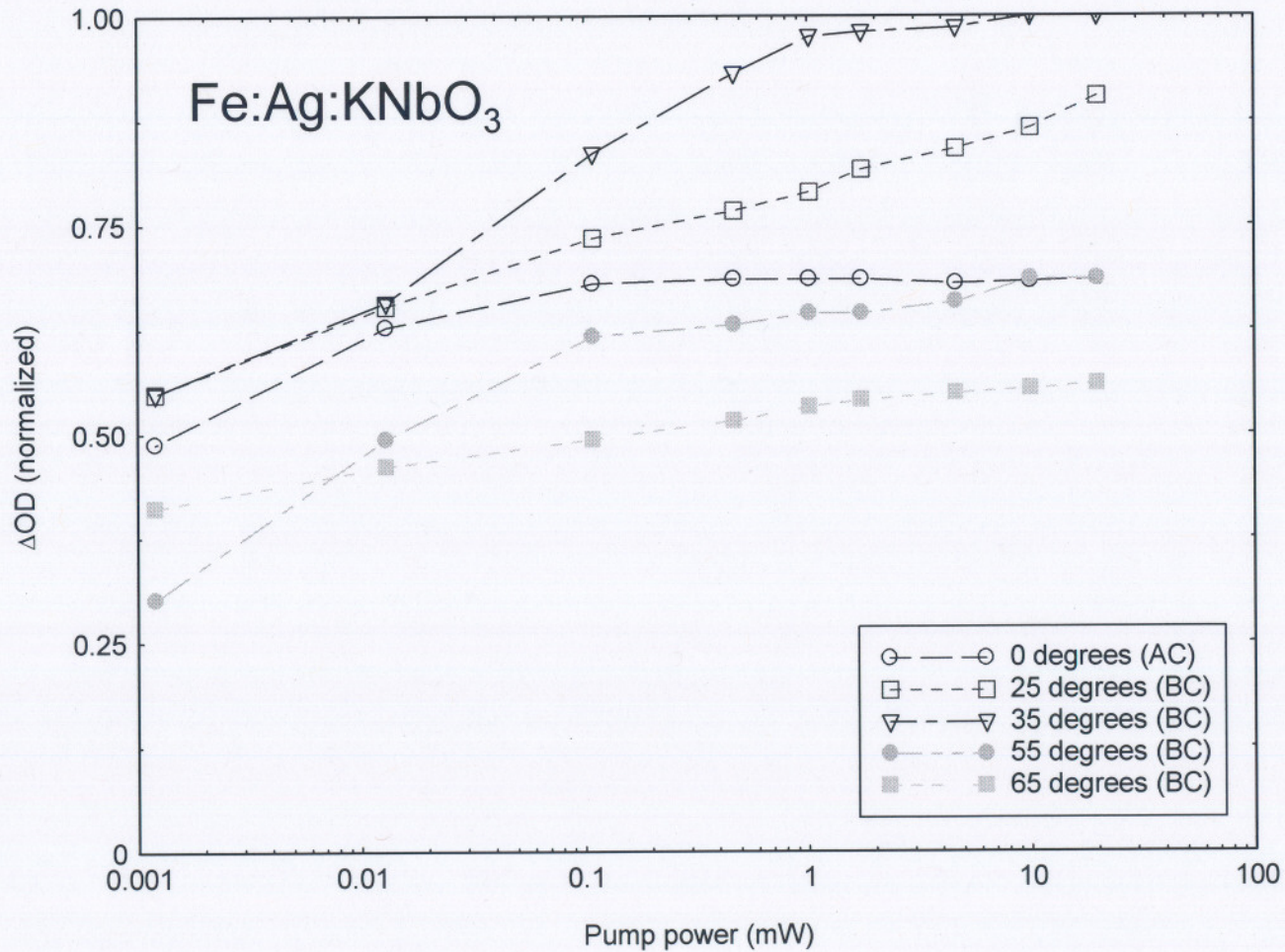
Real Off-Axis Testing - Results



- 80% increase in ΔOD



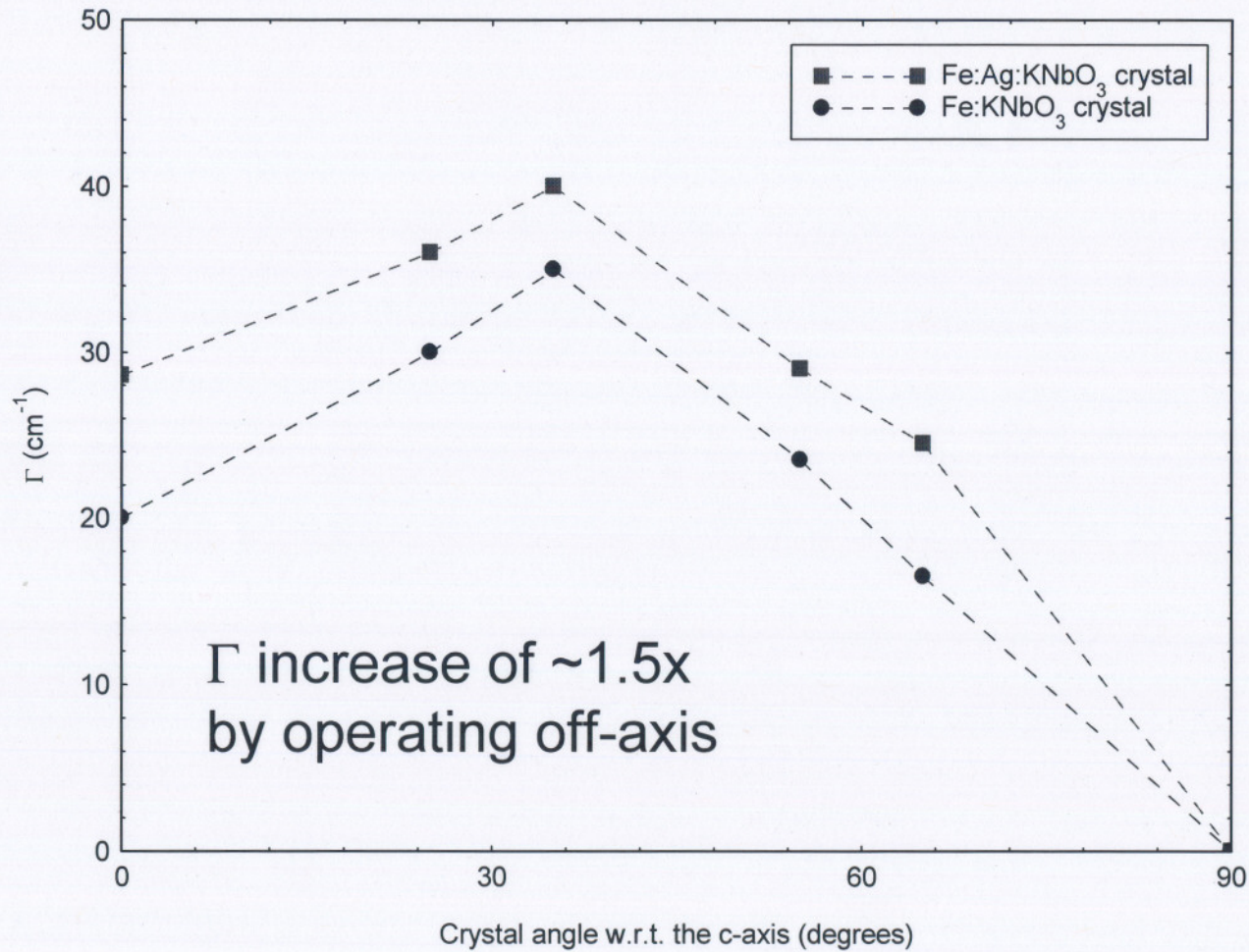
Real Off-Axis Testing - Results



- 55% increase in ΔOD



Real Off-Axis Testing - Results





Summary



- High gain confirmed in off-axis geometries for Fe:KNbO₃
- Mismatch between theory and experiment for mid-range crystal angles, especially for the a-c plane*
- Large apparent variation in the effective trap density with crystal angle*
- Modified theory gives a good fit to experimental data*
- Mechanism for trap density anisotropy is uncertain, but may be due to stochastic layering of impurities during crystal growth*, or from the Franz-Keldysh Effect

* G. Cook, J. L. Carns, M. A Saleh, D. R. Evans, accepted for Phys. Rev. B, 2006