Towards a crystal undulator

S H Connell[1] J Härtwig[2], A Masvaure[1], D Mavunda[1, 3], T N Tran Thi[1]

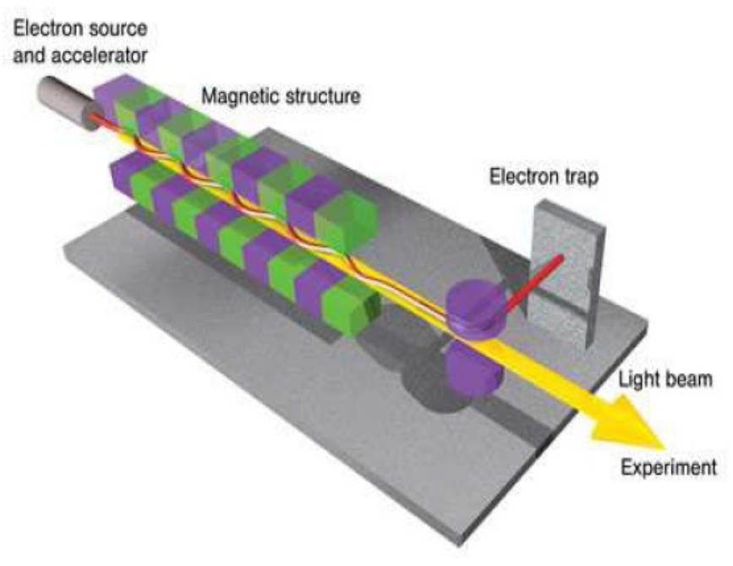
1. University of Johannesburg, Johannesburg, South Africa
2. ESRF, Grenoble, France
3. NECSA, South Africa

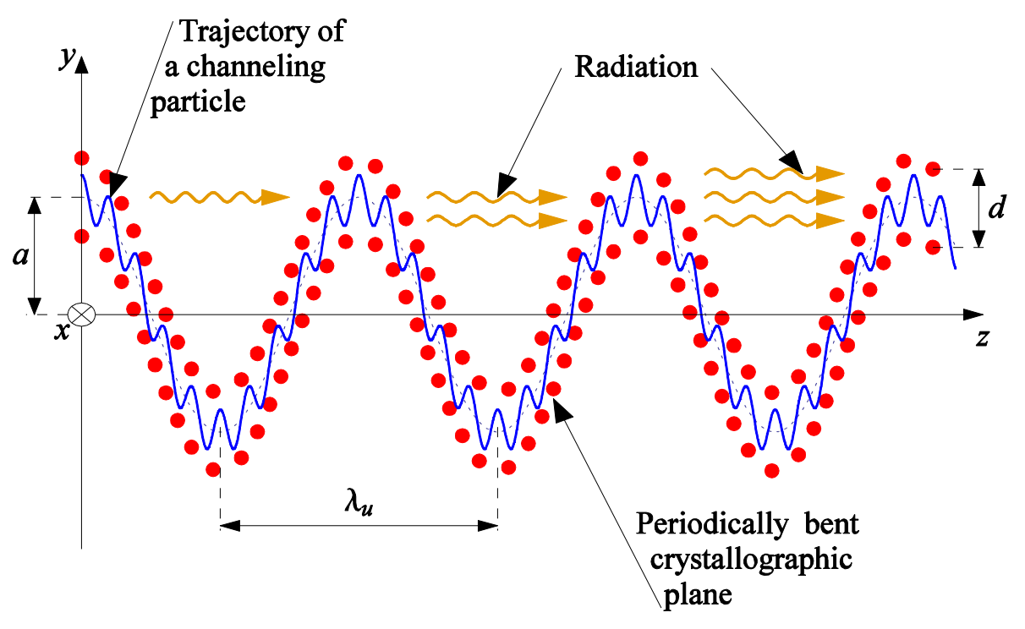
Introduction

A crystal undulator is similar to a normal undulator as typically found at a synchrotron to produce extremely brilliant X-ray beams. The difference is the magnetic lattice is realized by the periodic electrostatic potential of a crystal lattice seen from the reference frame of the GeV range electron or positron beam. The extremely relativistic incident particle beam would need to be captured in a high index crystallographic channel of a crystal superlattice. The particle beam will then "see" a many Tesla range periodically varying magnetic field with a few micron pitch. This method could theoretically lead to an MeV range gamma ray laser by the FEL principal.

IRSES-CUTE : The Consortium

Partner name	Partner short name	Country
Frankfurt Institute for Advanced Studies, Goethe University	**FIAS-GU**	Germany
Aarhus University	**UAAR**	Denmark
Institute for Nuclear Physics, Mainz University	**Uni-Mainz**	Germany
Sensors and Semiconductors Laboratory, University of Ferrara	**SSL-FU**	Italy
St. Petersburg Polytechnical University	**PTU**	Russia
University of Johannesburg	**UJ**	South Africa
Zagazig University	**ZU**	Egypt



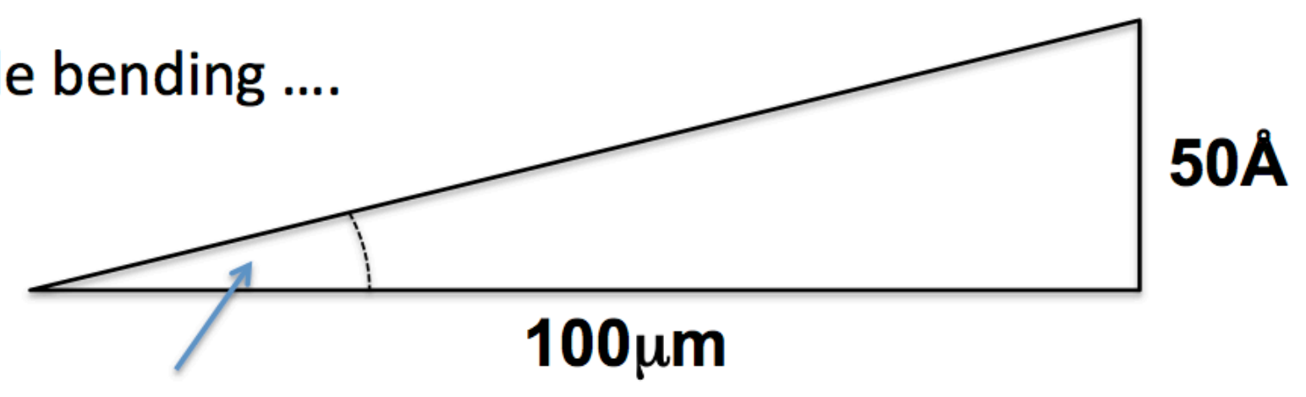


We have investigated a prototype diamond superlattice using x-ray diffraction topography. The undulator fabrication principle involved CVD growth of diamond on a diamond substrate while varying the concentration of boron in the gas phase during growth. This should lead to the periodic variation of the lattice dilatation by the varying concentration of the single substitutional boron impurity atom.

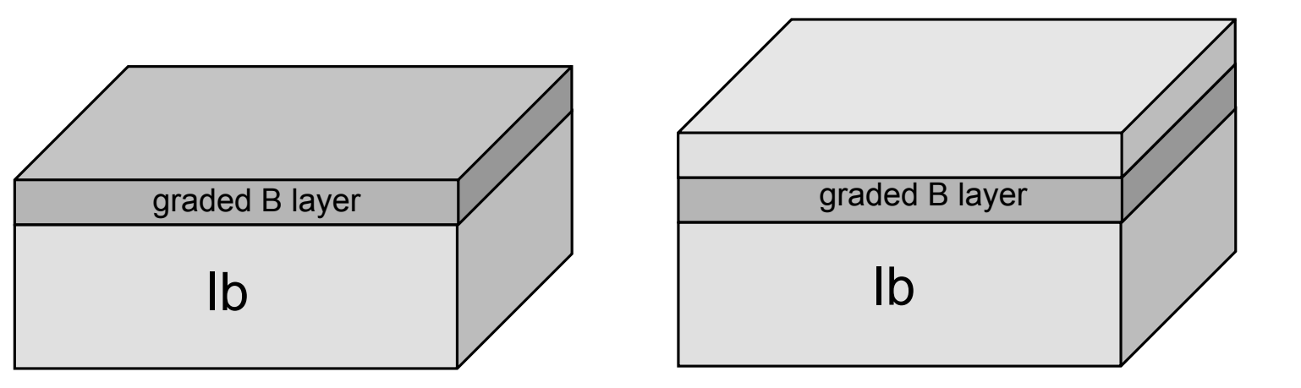
Doping with nitrogen, boron → expands the lattice. Boron is favoure. We expect one could obtain up to $C_B < 1.5$ at% maintaining excellent lattice quality. Using the "Lang" Dilatation Formula :

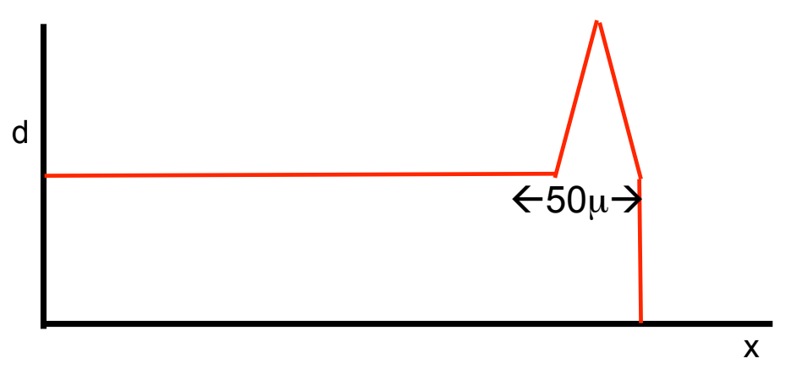
$$\frac{\Delta a}{a_0} = 0.144 \times C_B \quad \leftarrow C_B \text{ in at. fraction}$$

Achievable bending ....



2.86 mdeg / 50 µrad





The expected dilatation
$\delta d/d \sim 10^{-4}$
$\Delta\theta \sim 21'' >>$ Darwin width

→ Expect a multi-layer mirror behaviour

This is the start of the iterative process to produce the undulator.

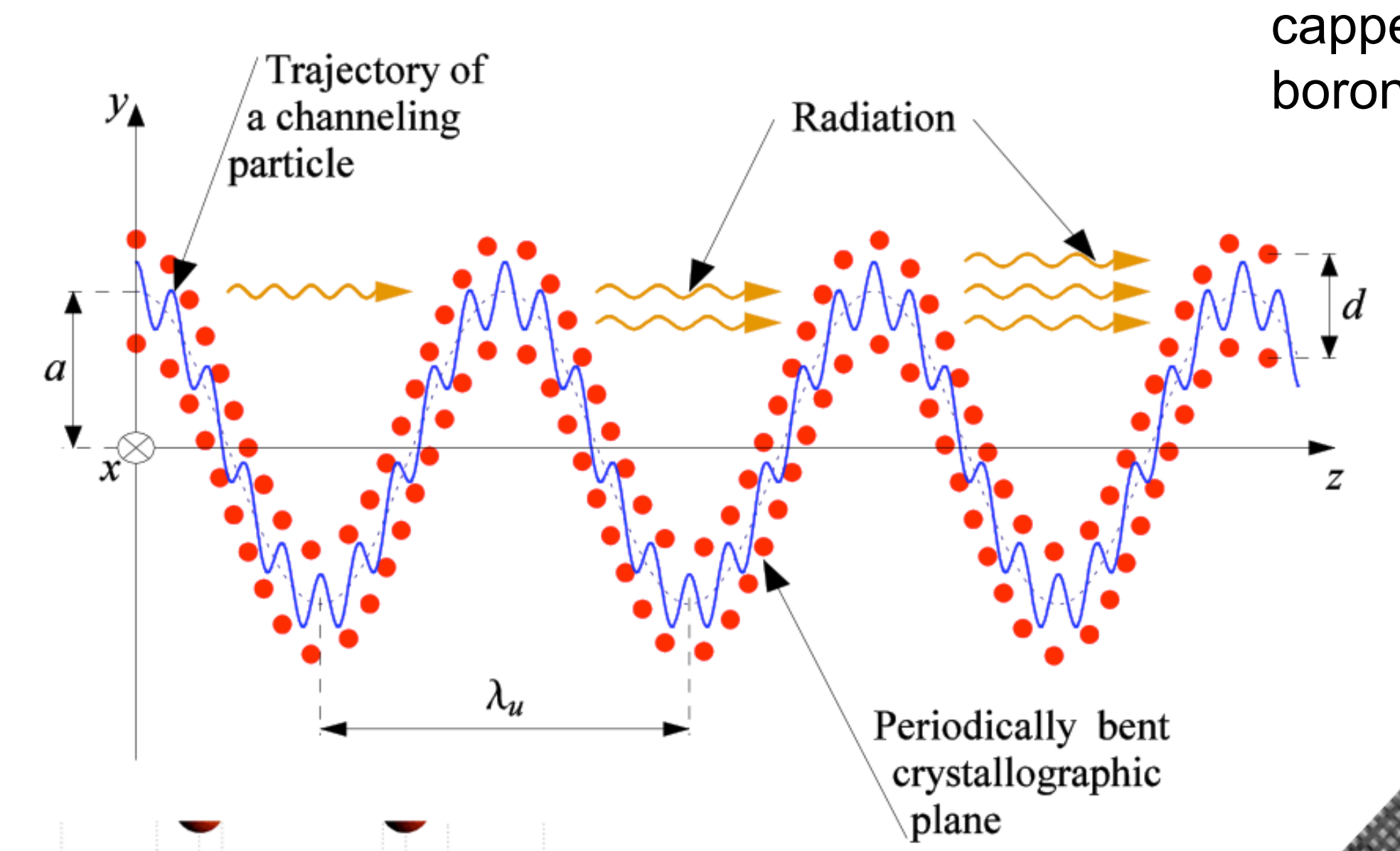
$$\frac{\Delta a}{a_0} = 0.144 \times C_B$$

$$n\Delta a = 50\text{A} \qquad \Rightarrow \Delta a = 50\text{A}/\text{n}$$

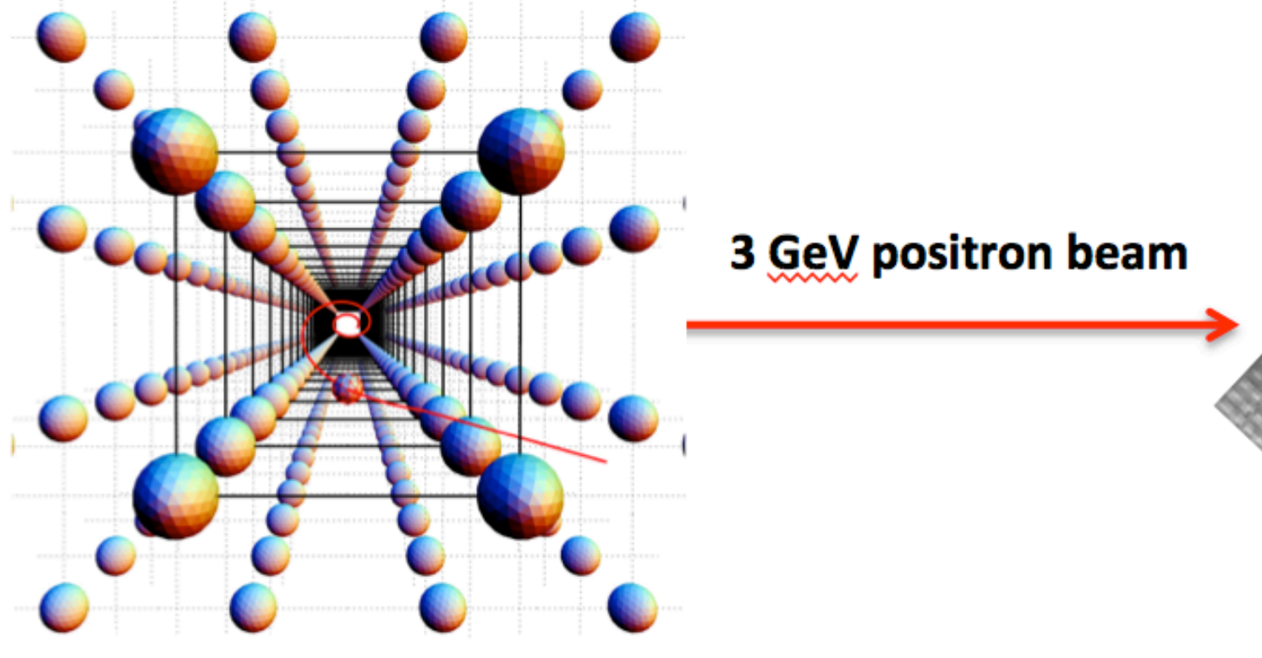
$$n = d/a_0, \quad d = 10^5\text{A} \Rightarrow n = 10^5\text{A}/a_0$$

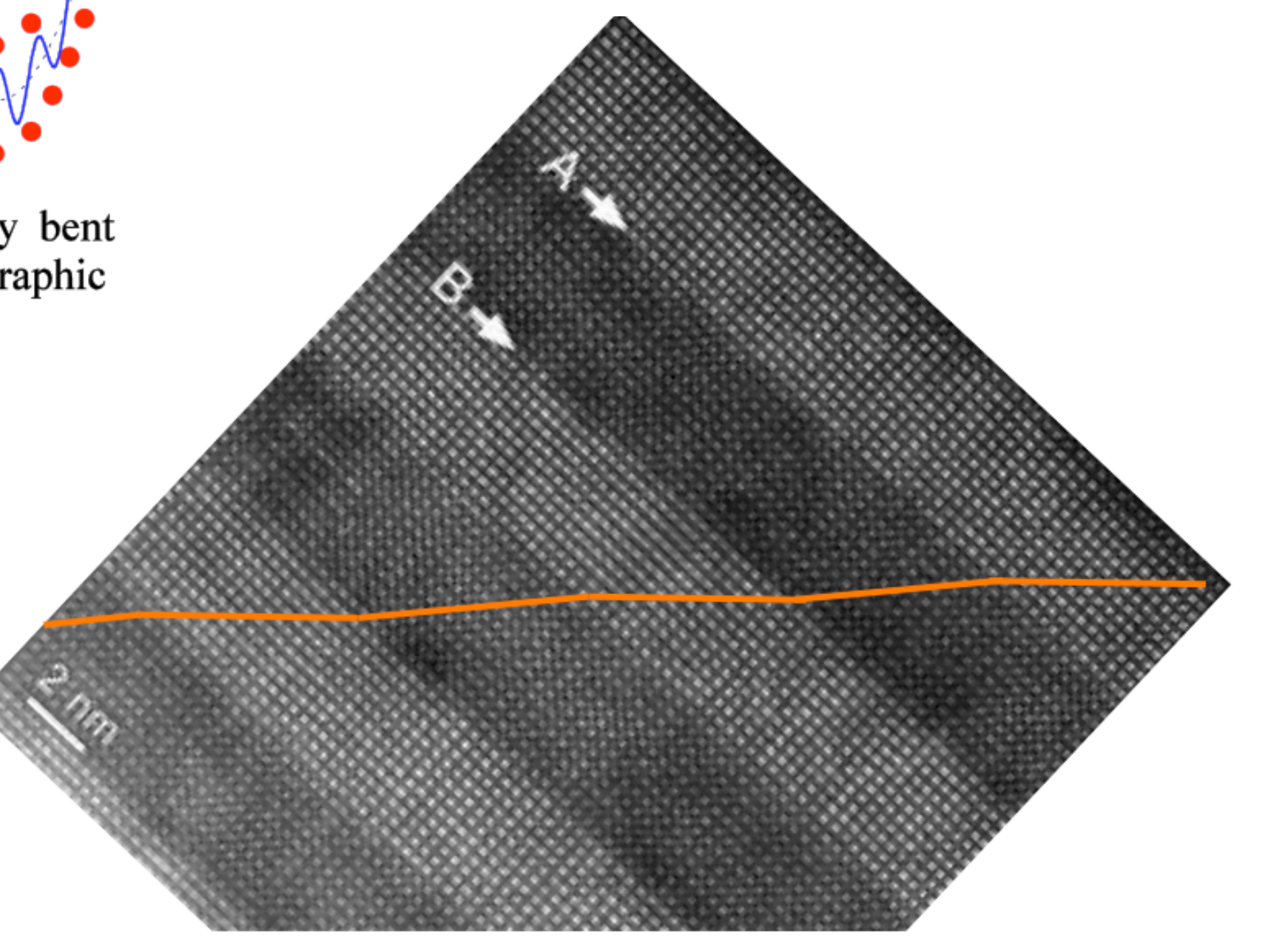
$$C_B = \frac{2}{\cos 45} \times \frac{\Delta a}{a_0}\frac{1}{0.144} = \frac{2}{0.7} \times 350\text{ppm} = 1000\text{ppm}$$

The first step to produce a diamond superlattice with a 100m period have been taken by Element 6. A single graded doped B layer was produced by varying the boron concentration was varied up to ~7x10^{20} at cm^{-3} (0.3% or 3000 ppm)as indicated, grown on a Ib substrate. The second sample is capped with an "intrinsic" layer, 5-53 ppb boron.



Schematic of a superlattice to indicate what dilated regions (boron doped) and intrinsic regions (impurity free) would look like and indicate their effect on an axial channeled direction.





- ***d=1…2 Å***
  the interplanar spacing
- ***a=(10…50)d***
  the amplitude of bending
- ***λ_u=(10^4…10^5) a***
  the period of bending

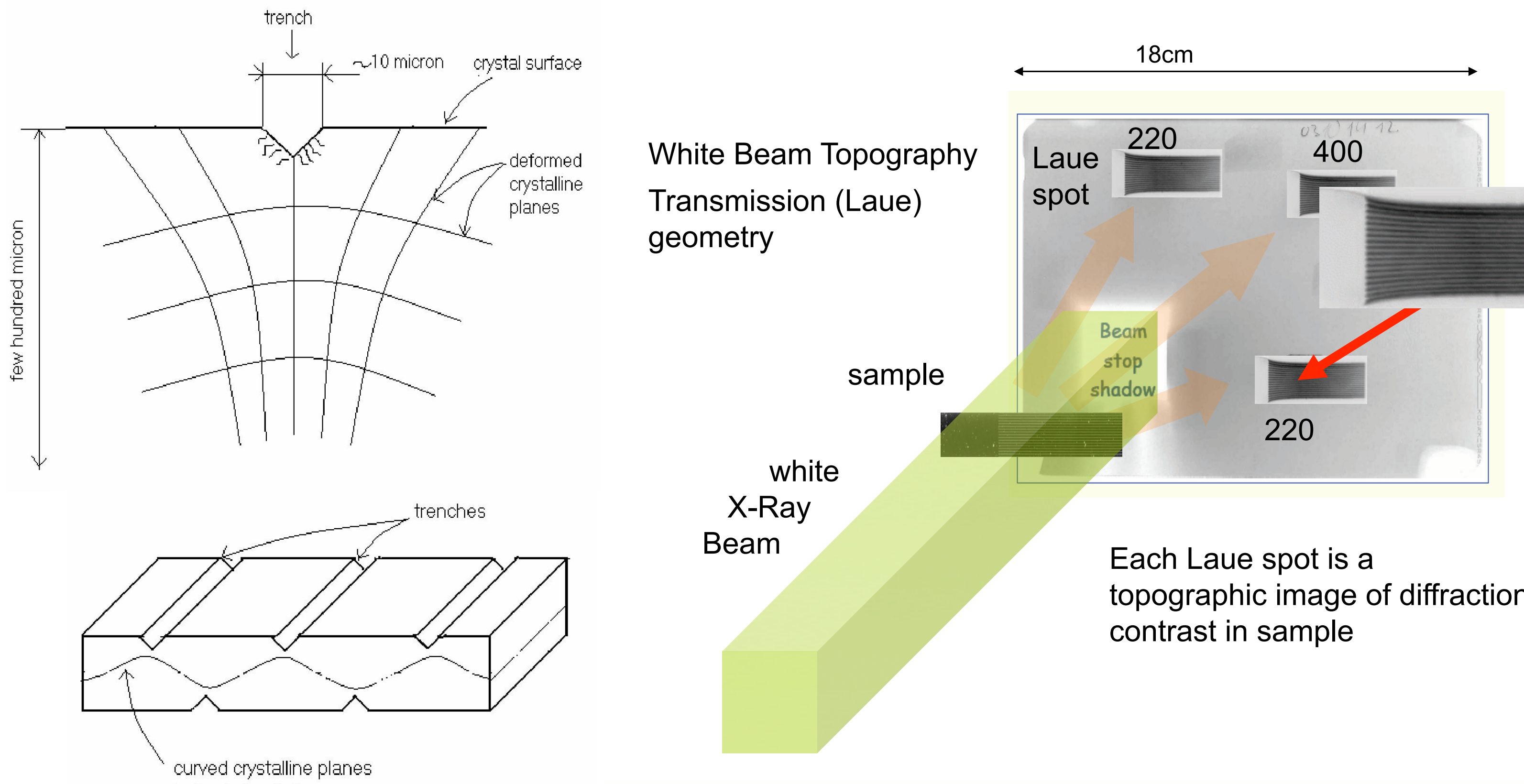
→ $d << a << \lambda$

KEY PHYSICAL PARAMETERS:
Undulator wavelength = λ_u (≈ 0.1 mm)
Undulator amplitude = a (≈ 50 Å)
Interplanar distance = d (≈ 1-2 Å)
Crystal thickness = t (≈ 1-4 mm)
Number of undulator oscillations = $N_u = t/\lambda_u$ (> 10)

Conclusions

1. The validation via x-ray diffraction topography proved non-trivial
   a. The pitch of the layer is much larger than the nano-scale, so the interference effects from Bragg scattering normal to the layer are not visible and able to be used in the characterization.
   b. The pitch of the layer is nonetheless rather small to use collimation in the entrance and exit channel to define the diffracting volume within the crystal
   c. Eventually, a large data set of both Bragg and Laue condition Rocking Curve Imaging measurements and Plane Wave Topography measurements could lead to a picture that was eventually promising.
2. Indeed, the lattice parameter evolves over the depth of the graded layer.
3. The graded B layer acts as a very effective multi-layer mirror.
4. It would be preferable to develop the graded layer on the best possible (lattice) quality substrates.

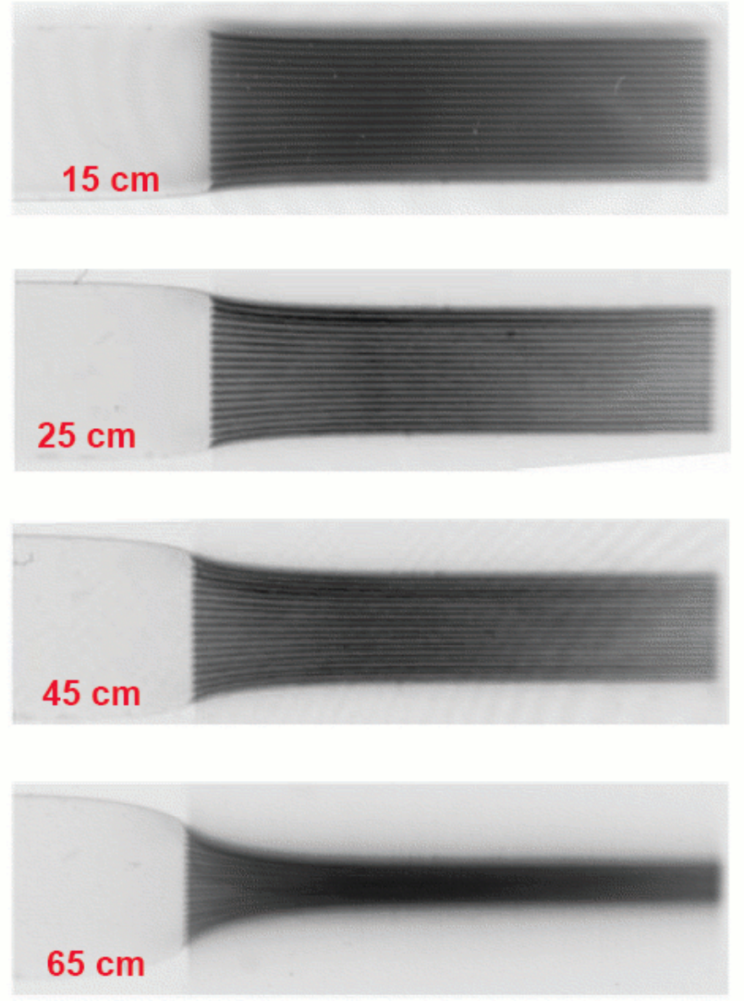
Before the superlatice … scoring



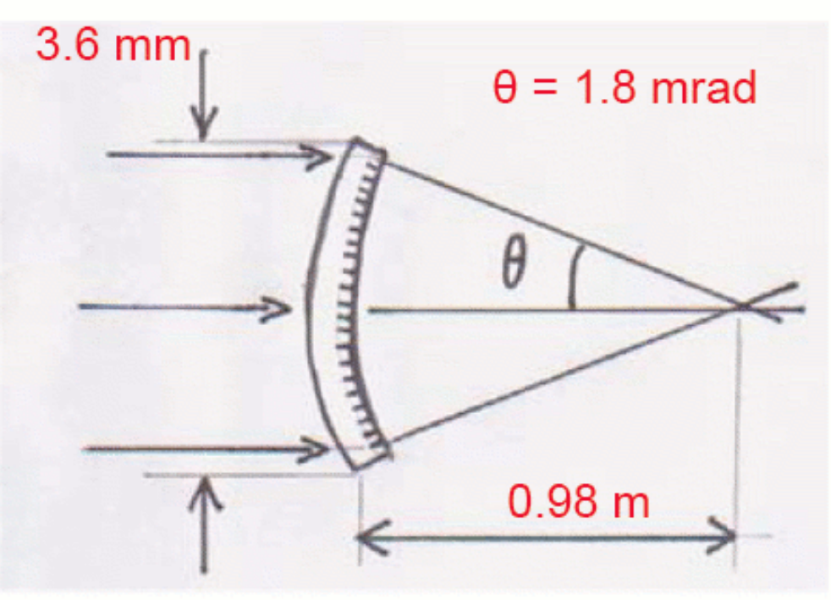
White Beam Topography
Transmission (Laue) geometry

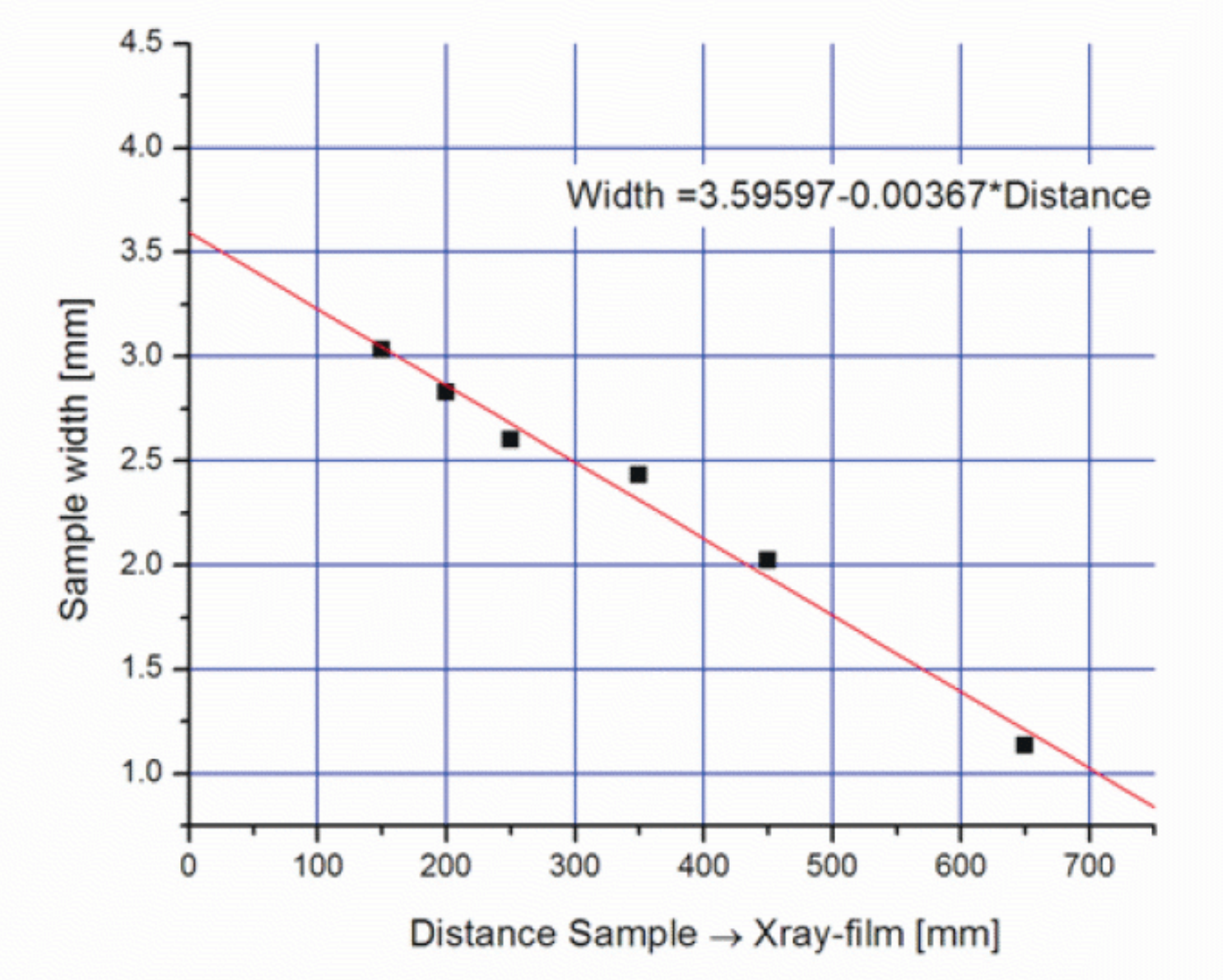
Each Laue spot is a topographic image of diffraction contrast in sample

ocussing in vertical plane



Bending across crystal corresponds to:
1 mrad/mm crystal!





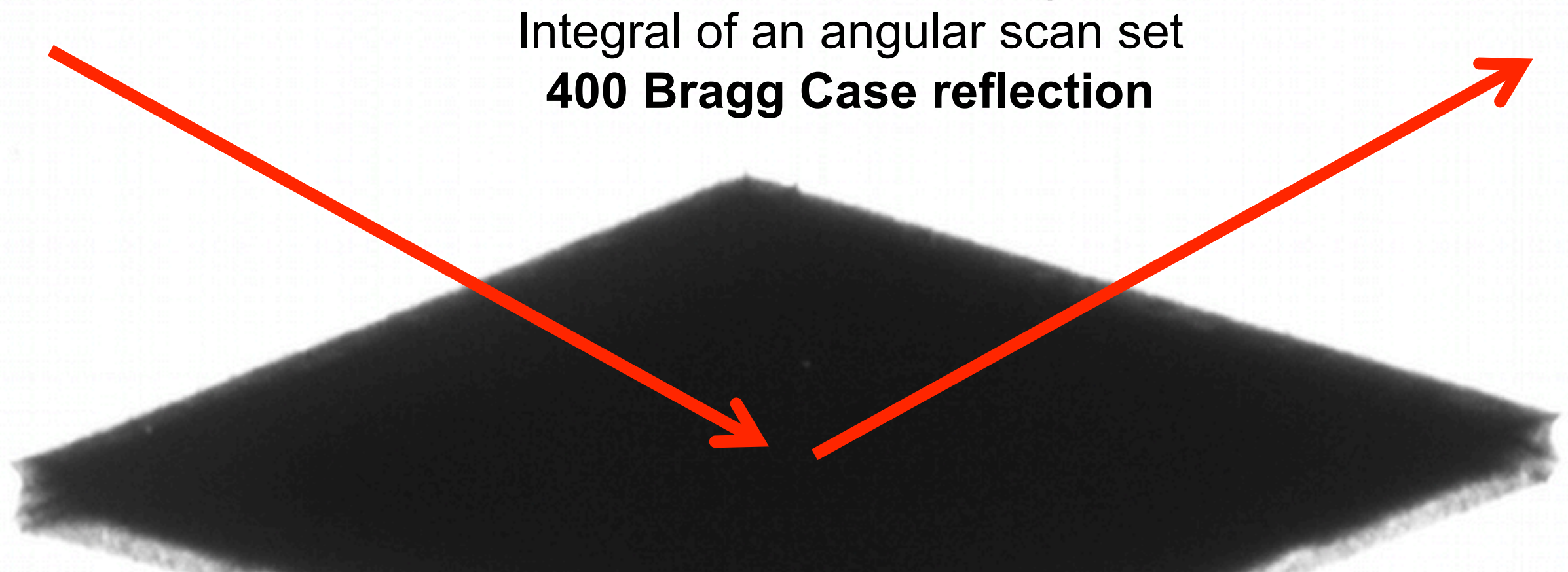
Problem :
Too much lattice damage and one achieves a distribution of undulator amplitudes within the crystal. → This is the motivation for a Diamond Superlattice

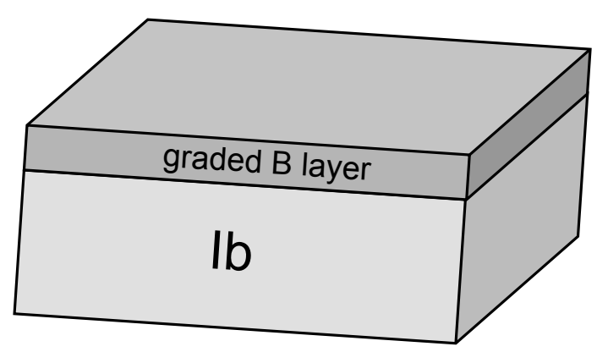
X-ray evaluation of the Graded doped B-layer

The graded boron doped layer was studied with X-ray diffraction techniques at the ESRF in Grenoble, beamline BM05.

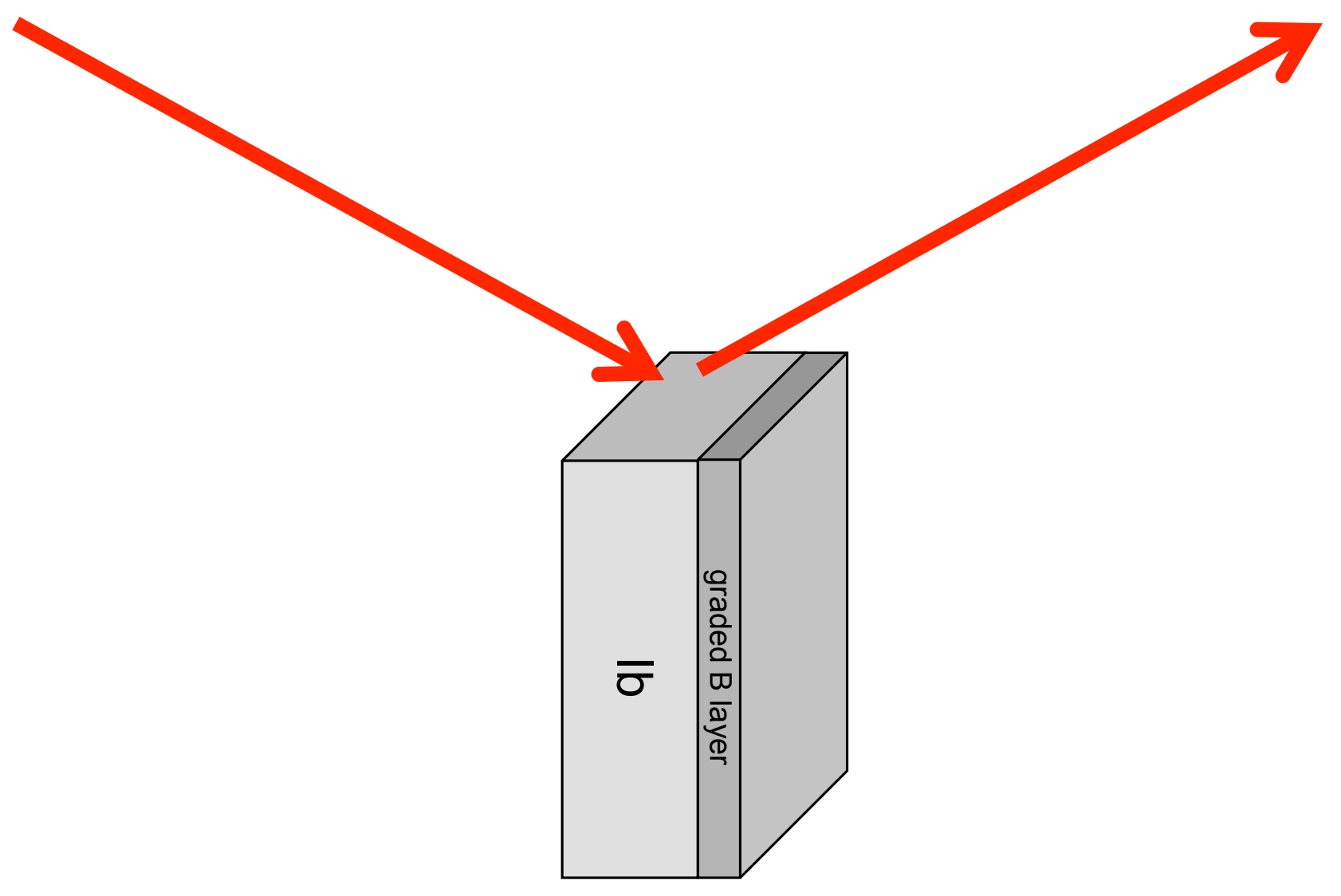
Graded B-layer acts as a multi-layer broad band pass mirror

Plane wave monochromatic dispersive case
Integral of an angular scan set
400 Bragg Case reflection

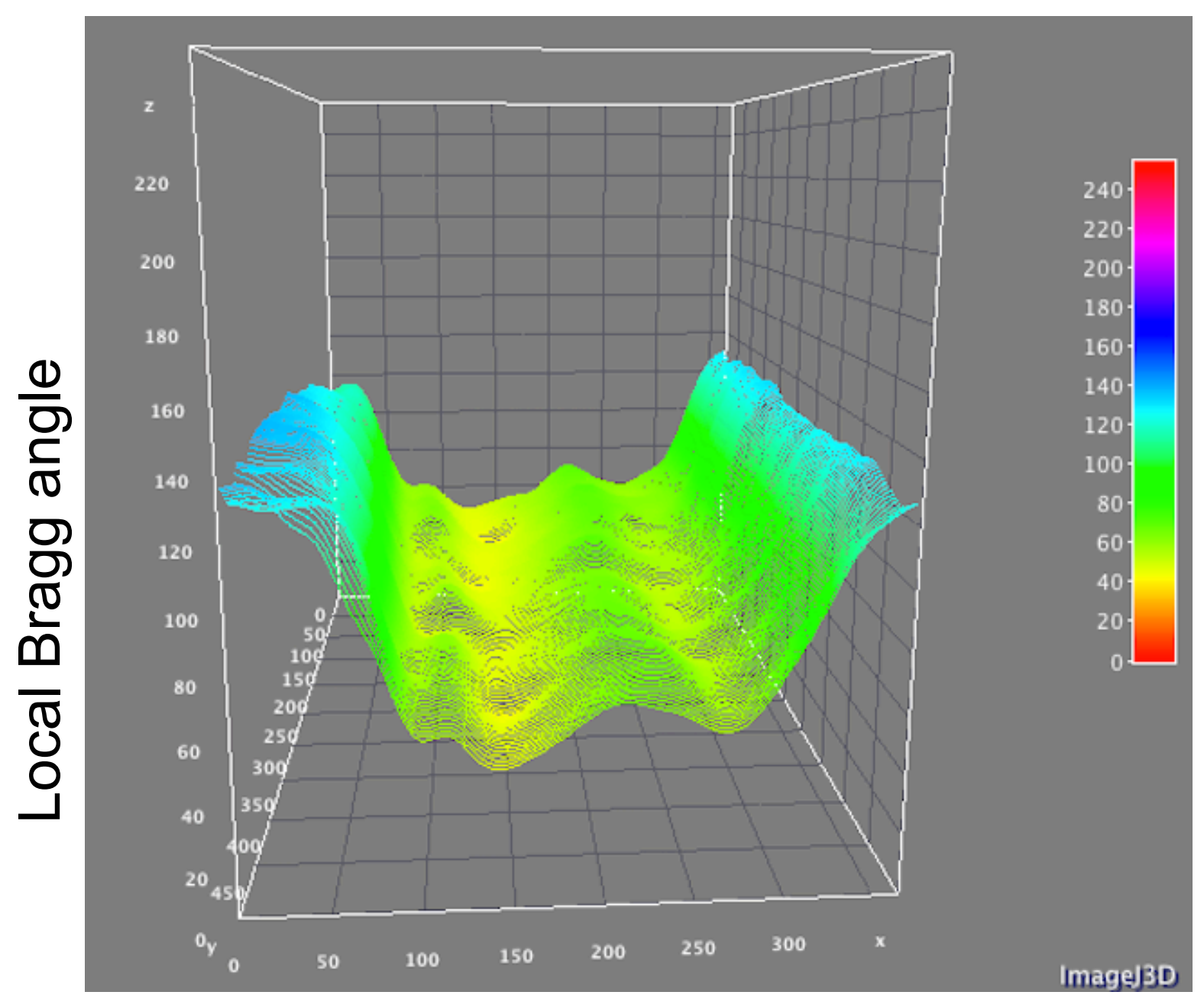




The diffraction vector is is parallel to the maximal change of the lattice constant in the graded doped layer. The geometry chosen presents a perspective view of the diamond crystal. The penetration depth of the x-ray beam is a complex mix of effects related to the angular and energy dispersion of the beam, the quality of the crystal, and the angle at which the rocking curve is taken. In this case, the image presented is the integral of several rocking curves. The reflectivity of the graded doped layer appears significant over the whole crystal surface. The continuous variation of the lattice constant over a relatively shallow depth in such a way that the acceptance of the crystal in the graded doped layer is much wider than the reflectivity curve of the interrogating beam. This is not true for the bulk of the diamond, as we can see in the perspective view, where the edge is not screened by the surface layer, one still has the usual view of the defects within this (lattice) quality quality CVD diamond.



Plane wave monochromatic dispersive case
Selected one fixed sample angle
400 Bragg Case reflection



Distance across edge

This geometry optimises the view of the sample edge. It was taken with a shield over the diamond main surface to reduce the Laue case component of the diffraction and emphasise the more surface sensitive Bragg case diffraction. A component of the strain due to the dilatation should still be visible, and this seems to be the case.

References

[1] M. Tabrizi, A. V. Korol, A. V. Solov'yov, and W. Greiner, "**Feasibility of an Electron-Based Crystalline Undulator**" PRL **98,** 164801 (2007)
[2] A. V. Korol, A. V. Solov'yov, and W. Greiner, "**Coherent radiation of an ultrarelativistic charged particle channelled in a periodically bent crystal",** J. Phys. G**24**, L45 (1998);
[3] A. V. Korol, A. V. Solov'yov, and W. Greiner, **"Channeling of Charged Particles Through Periodically Bent Crystals: on the Possibility of a Gamma Laser"**, Int. J. Mod. Phys. E **8**, 49 (1999)
[4] P. Balling, J. Esberg, K. Kirsebom, D.Q.S. Le, U.I. Uggerhøj, S.H. Connell, J. Härtwig, F. Masiello, A. Rommeveaux "**Bending diamonds by femtosecond laser ablation**", Nucl Instr and Meths in Phys Res B 267 (2009) 2952–2957

SAIP Conference – Johannesburg - July 2014