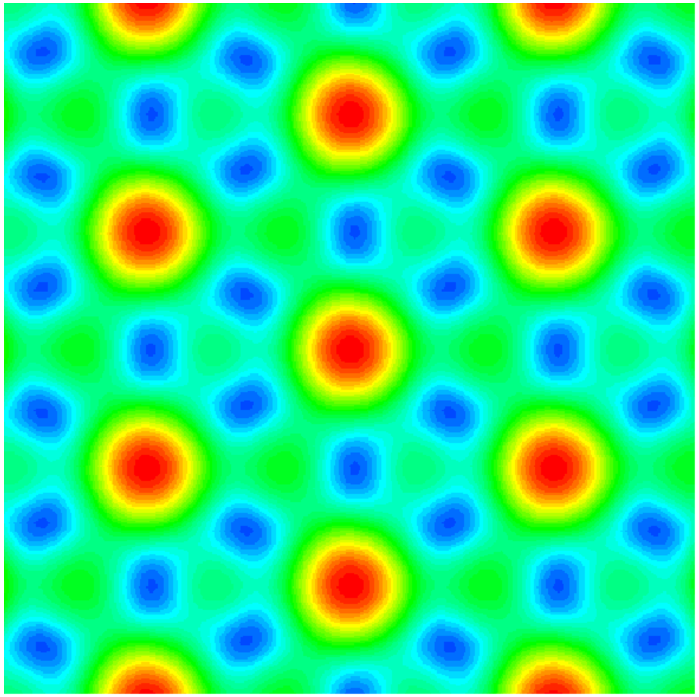
Near-field ultrasonic imaging of phononic crystals

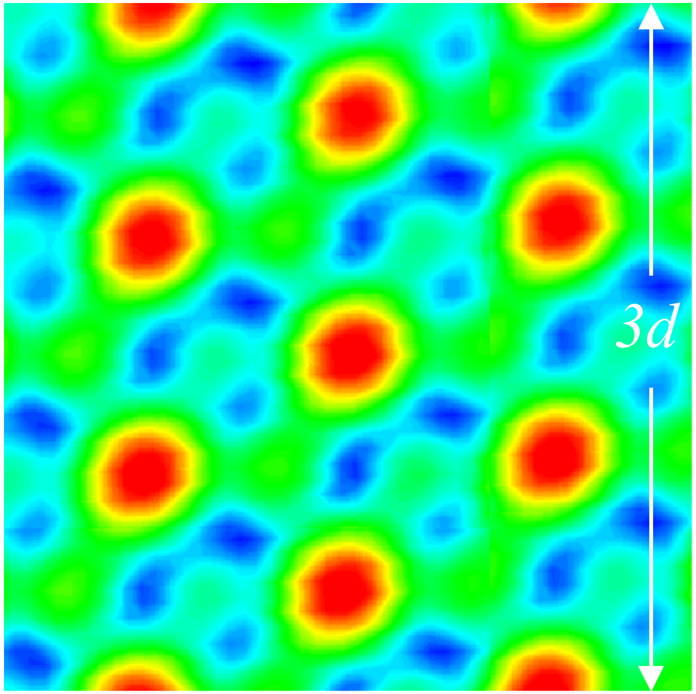
Use a small hydrophone to image the transmitted field just above the surface of the crystal (plane wave input)

Measure periodic near-field diffraction patterns (novel way of determining crystal structures?)

e.g. For a 7-layer fcc crystal (surface ⊥ [111]):



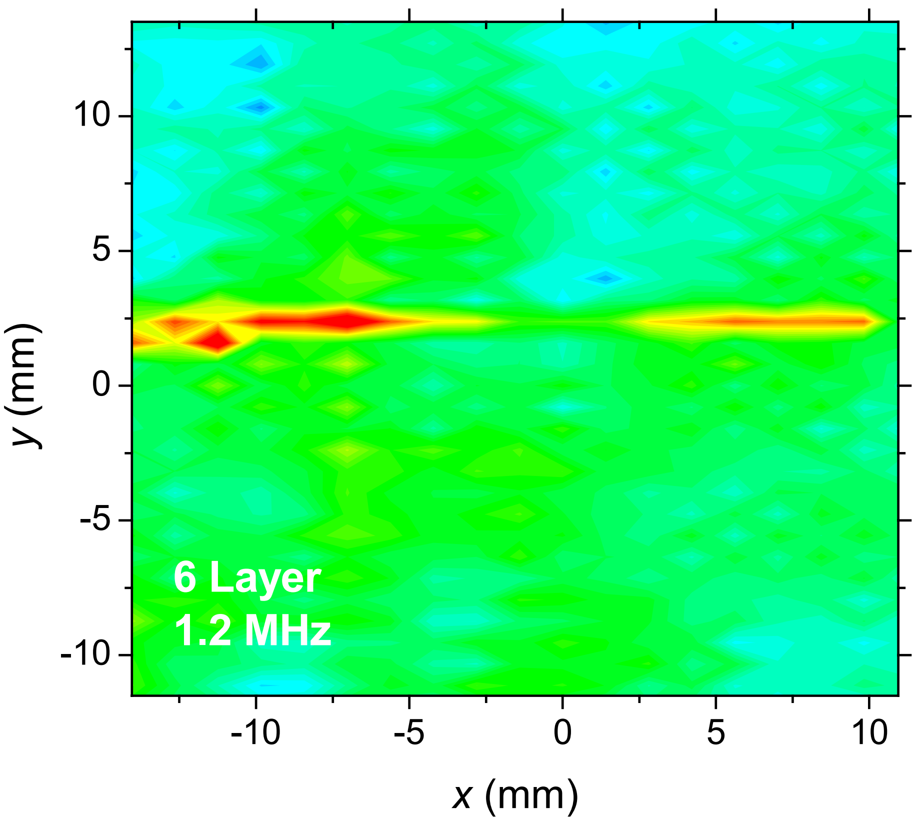
THEORY



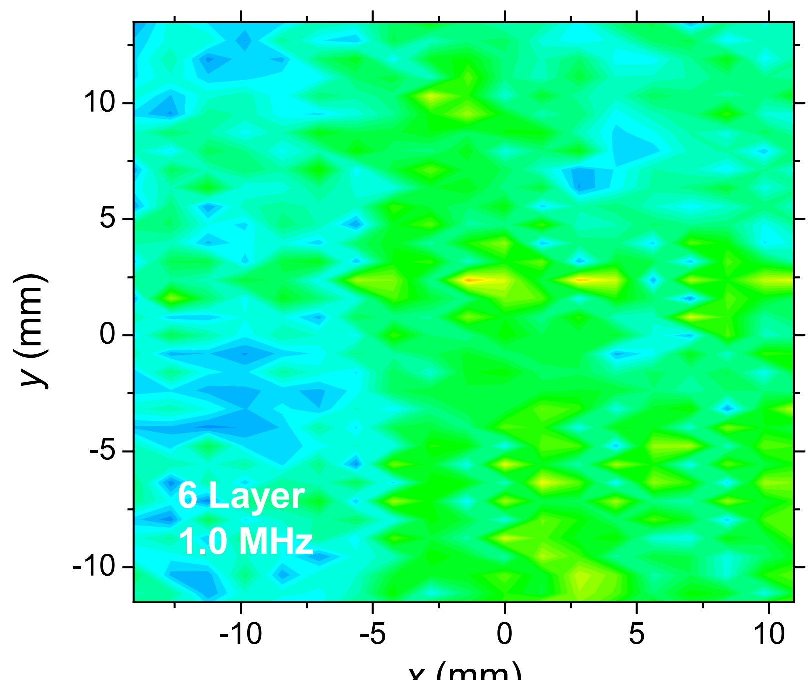
EXPERIMENT

Potential application: detecting and imaging subsurface defects.

(a) Detecting a subsurface line defect in a 6-layer crystal:
The line defect shows up clearly above the gap...

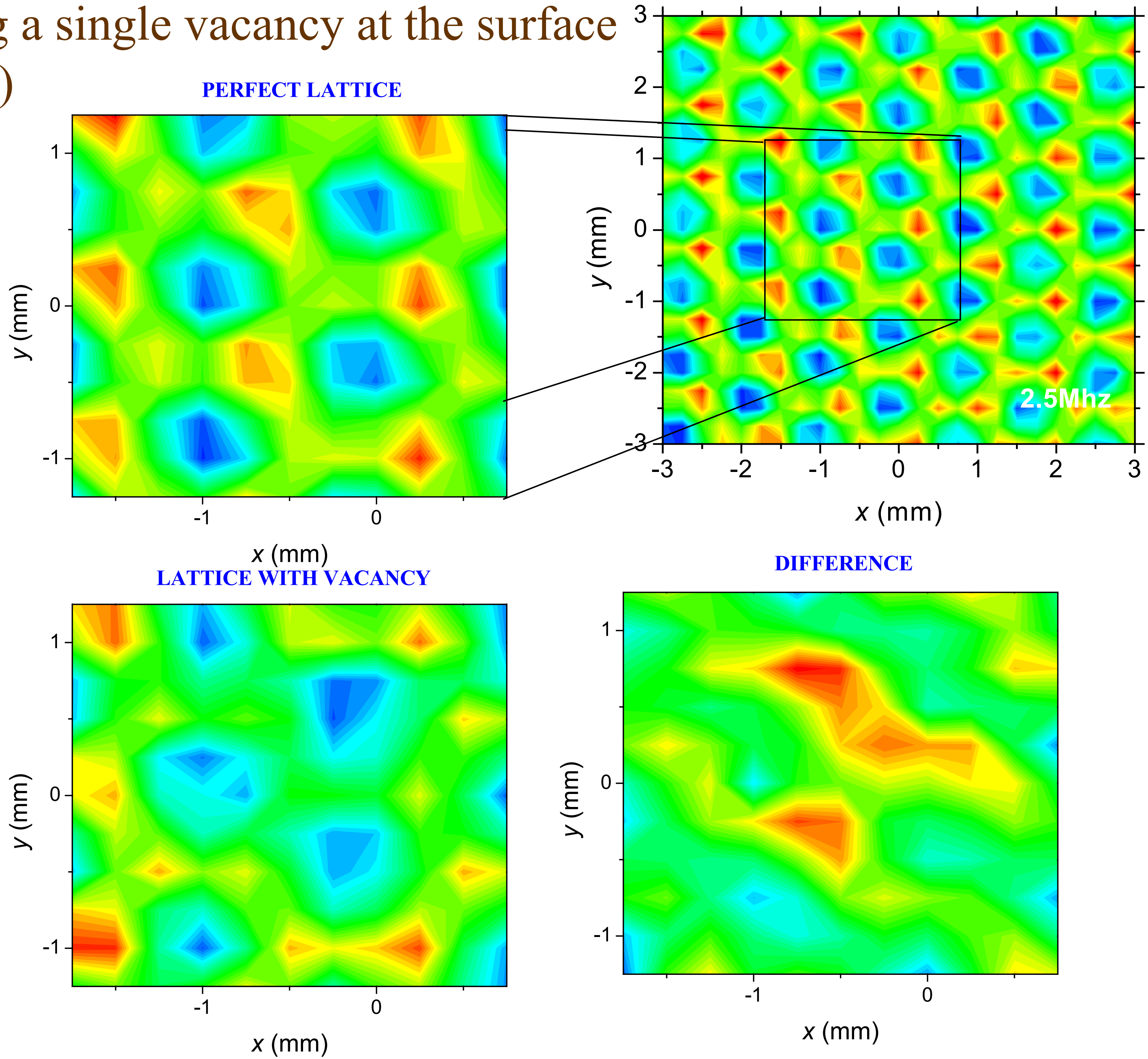


… but the defect barely shows up in the gap

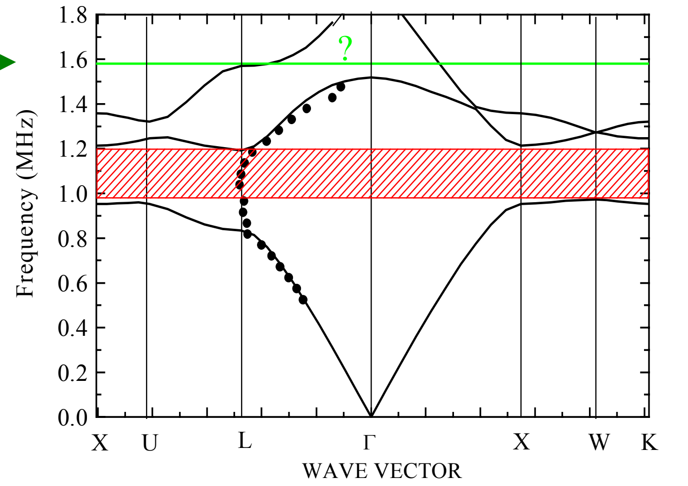


(b) Detecting a single vacancy at the surface (point defect)

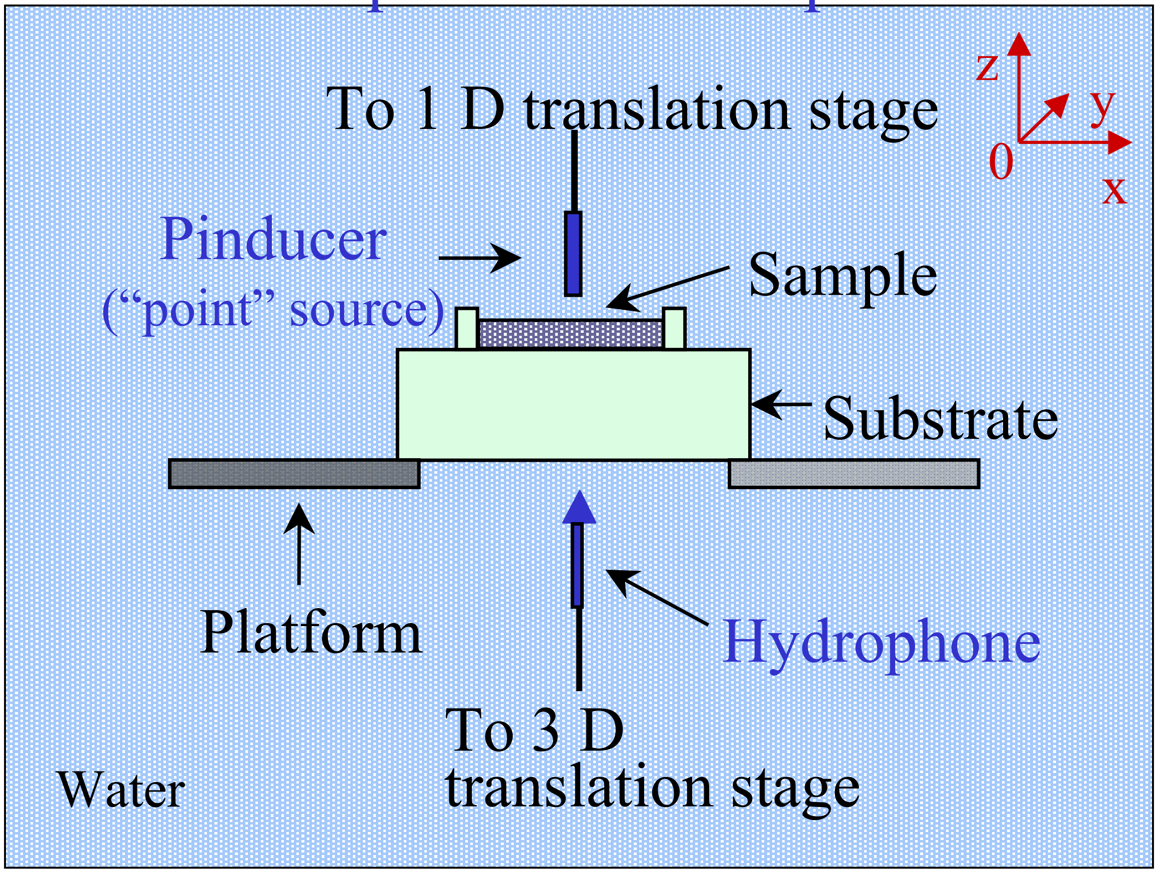
Field patterns at 2.5 MHz for a 7-layer sample



Focusing effects above the lowest band gap: (take advantage of crystalline anisotropy!)

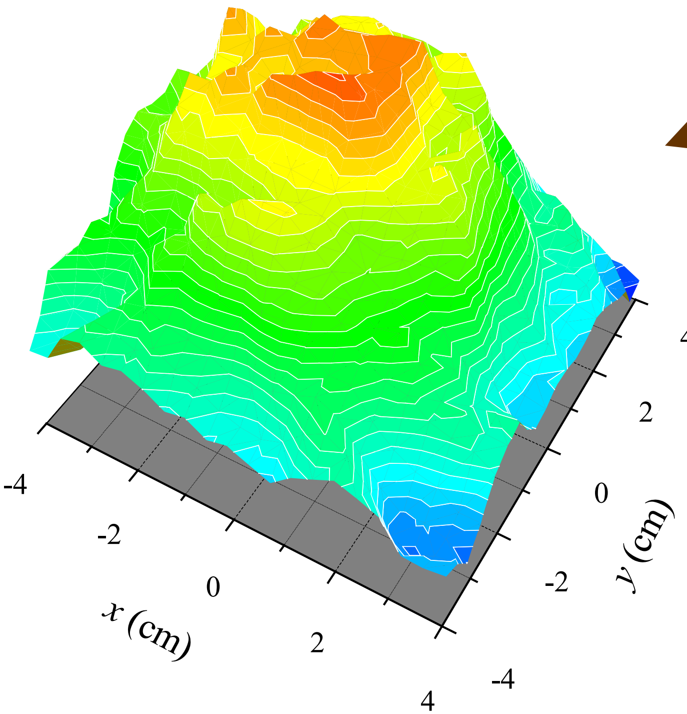


Experimental Setup



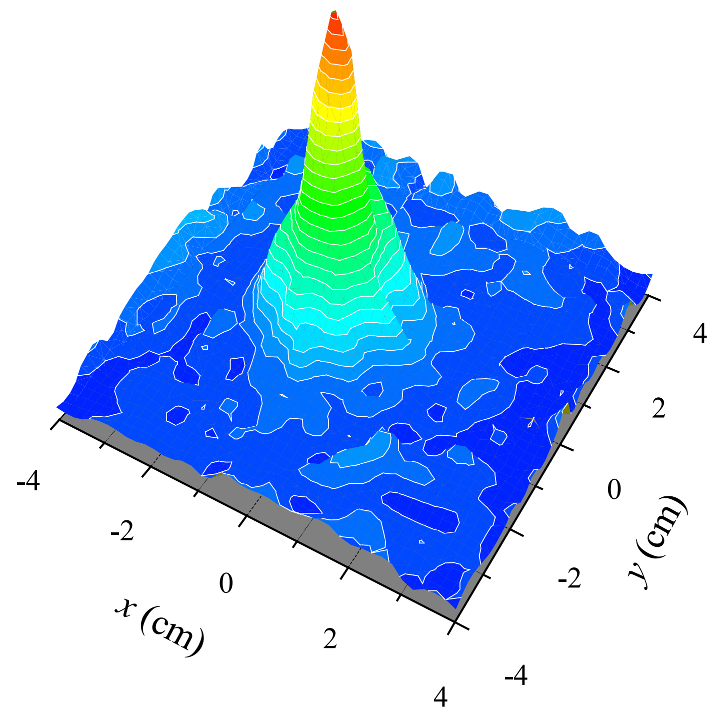
Focusing effects above the lowest band gap:

At 1.57 MHz



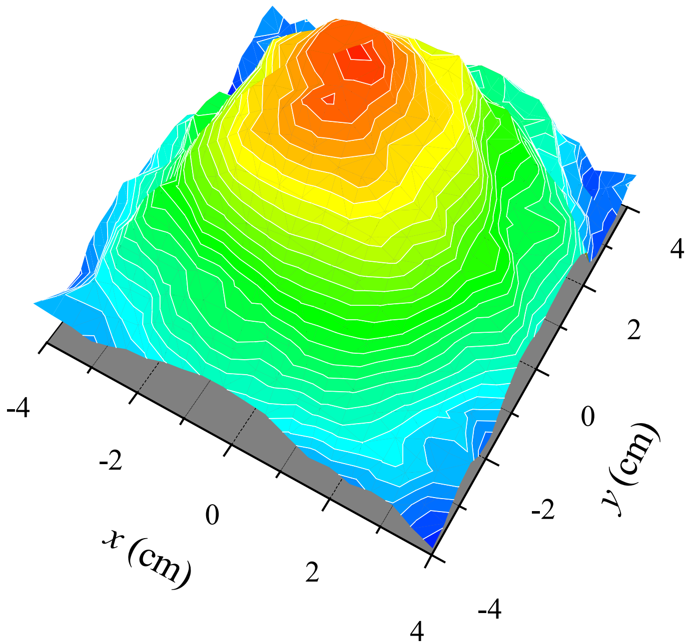
An initially diverging beam (from a point source) ...

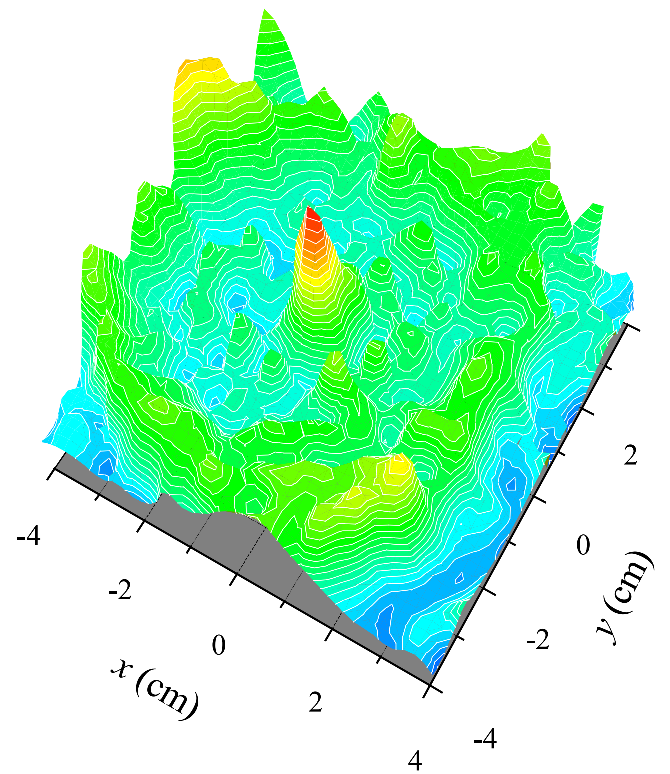
... is sharply focused by the crystal (12-layer fcc tungsten carbide balls in water)



But at 1.60 MHz (only 0.03 MHz higher!)

The initially diverging beam (from a point source) ...





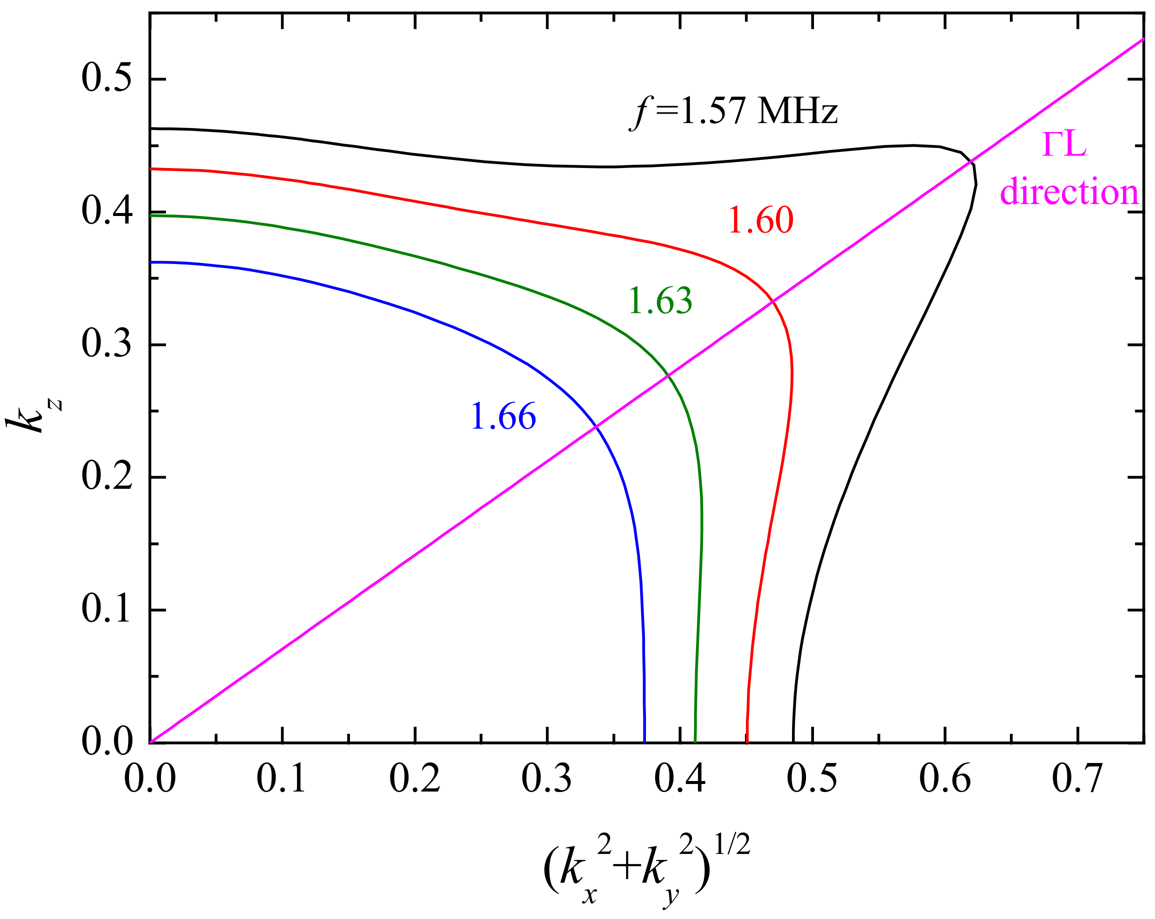
… is spread out (defocused) by the crystal.

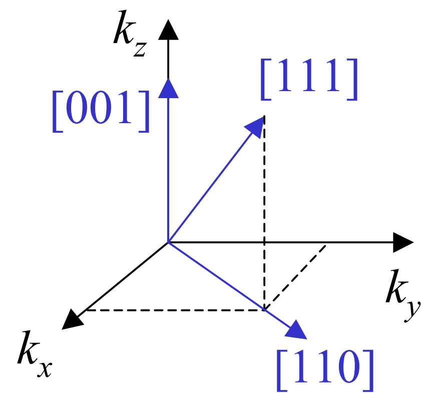
(12-layer fcc tungsten carbide balls in water)

The dispersion (or slowness) surface: a (3D) representation of the wave vector ($\propto 1/v_p$) anisotropy.

Calculate the dispersion surface from the bandstructure using the MST.

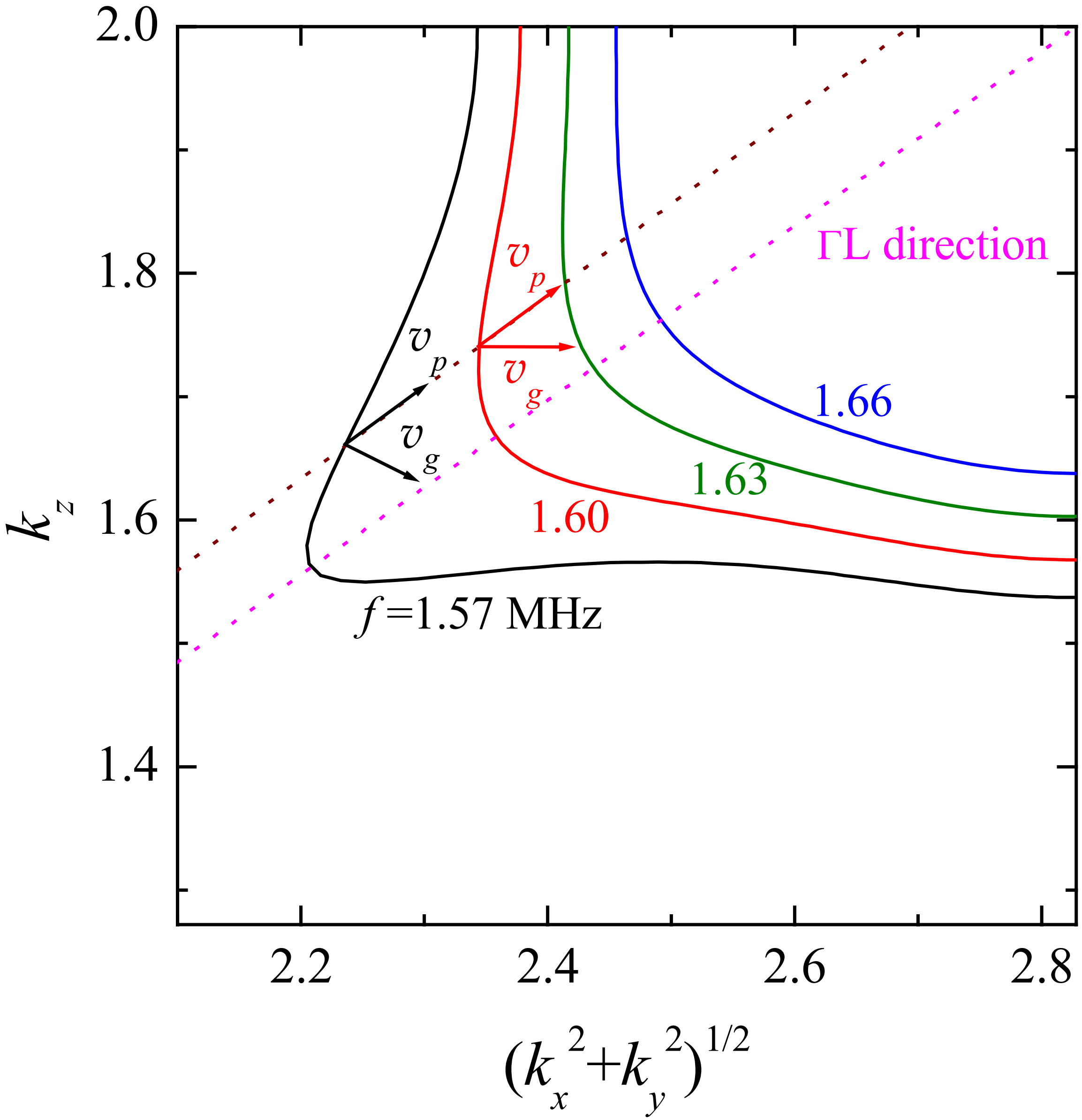
Cross sections of the dispersion surface in the first Brillouin zone:





Translate to the extended zone scheme to describe plane wave propagation

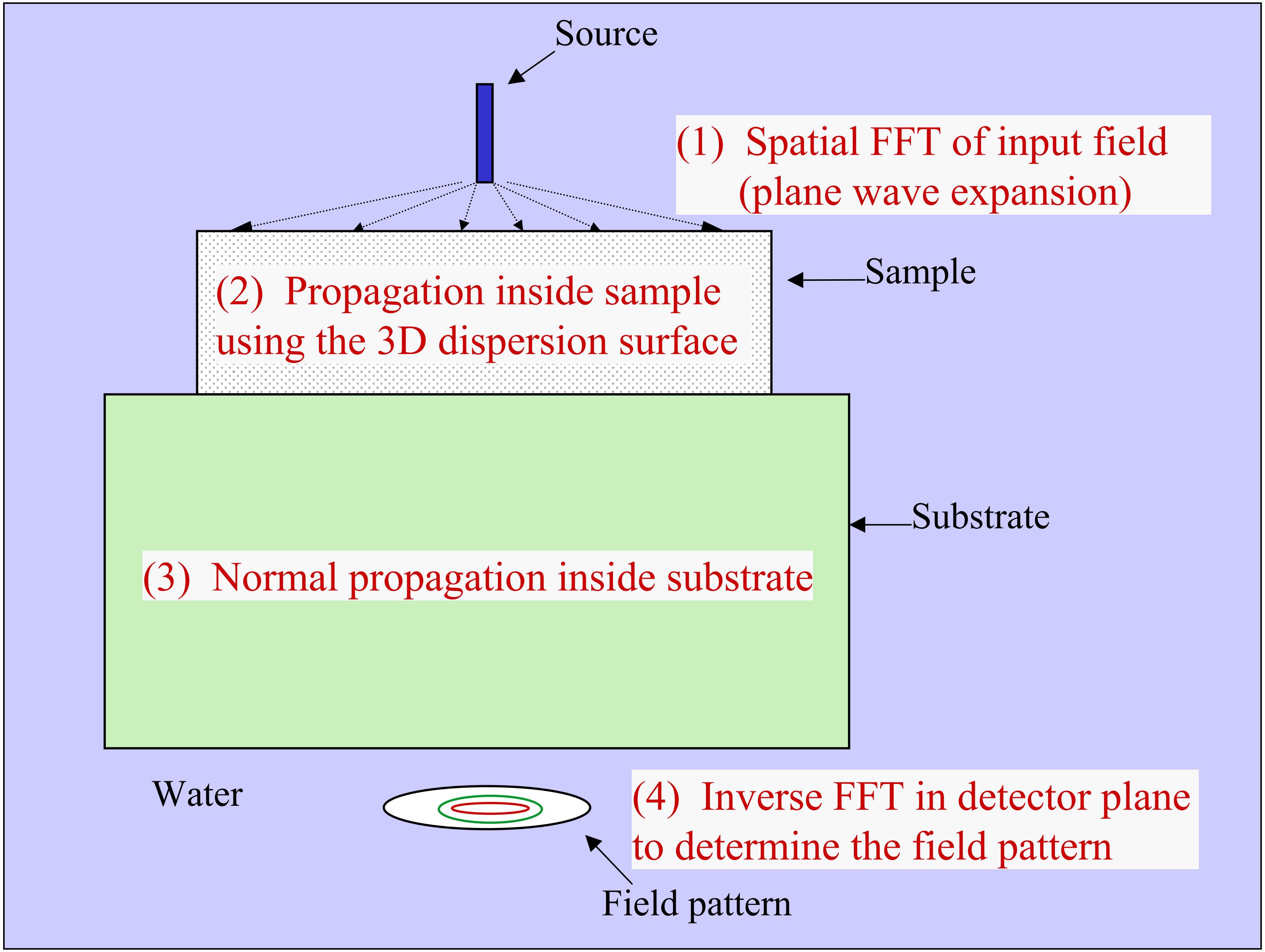
$$\vec{k} \rightarrow 2\vec{G}_{111} - \vec{k}$$



The direction normal to the dispersion surface is the wave transport direction, since

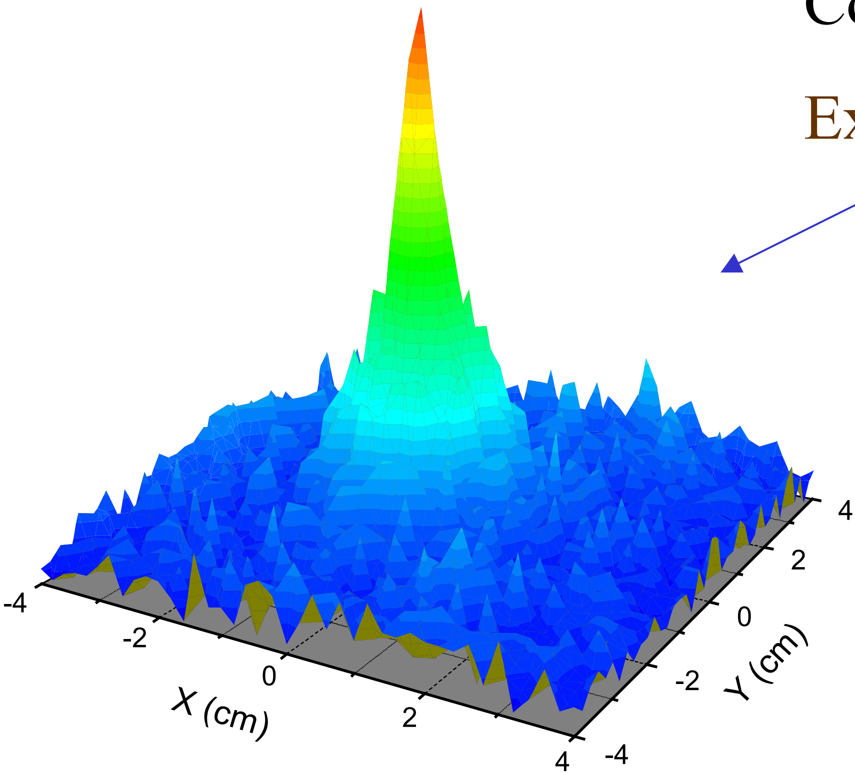
$$v_g = \nabla_k \, \omega(k)$$

Calculation of the field pattern:



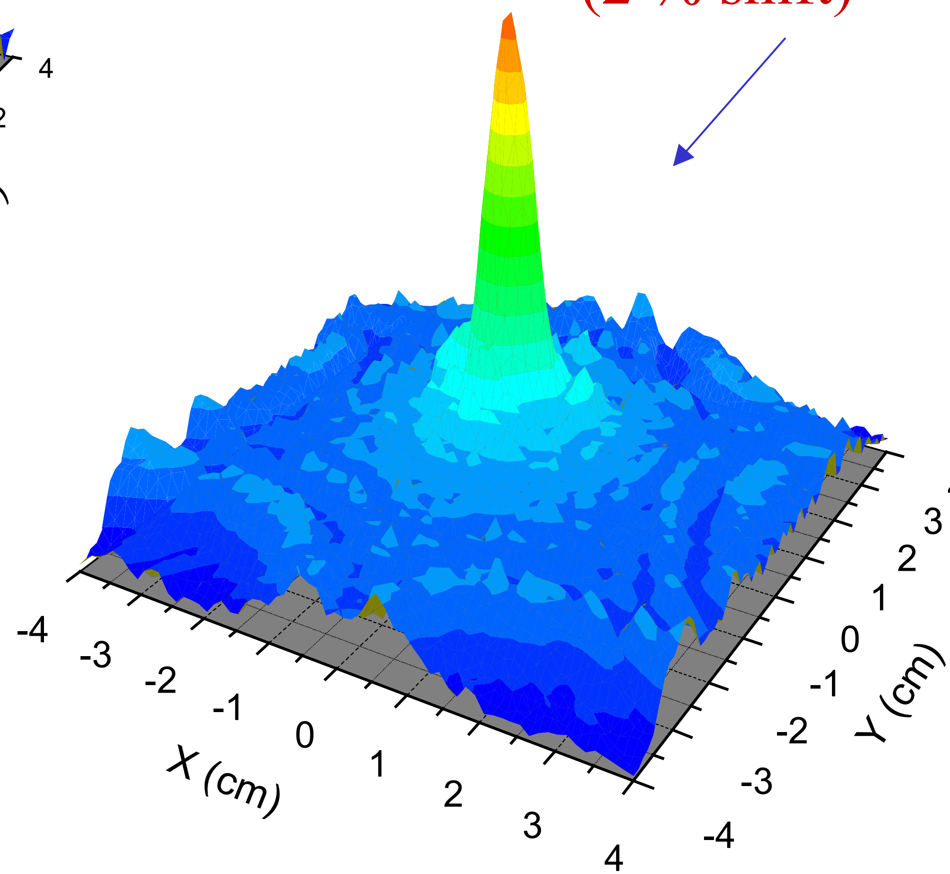
Compare:

Experiment at 1.57 MHz



&

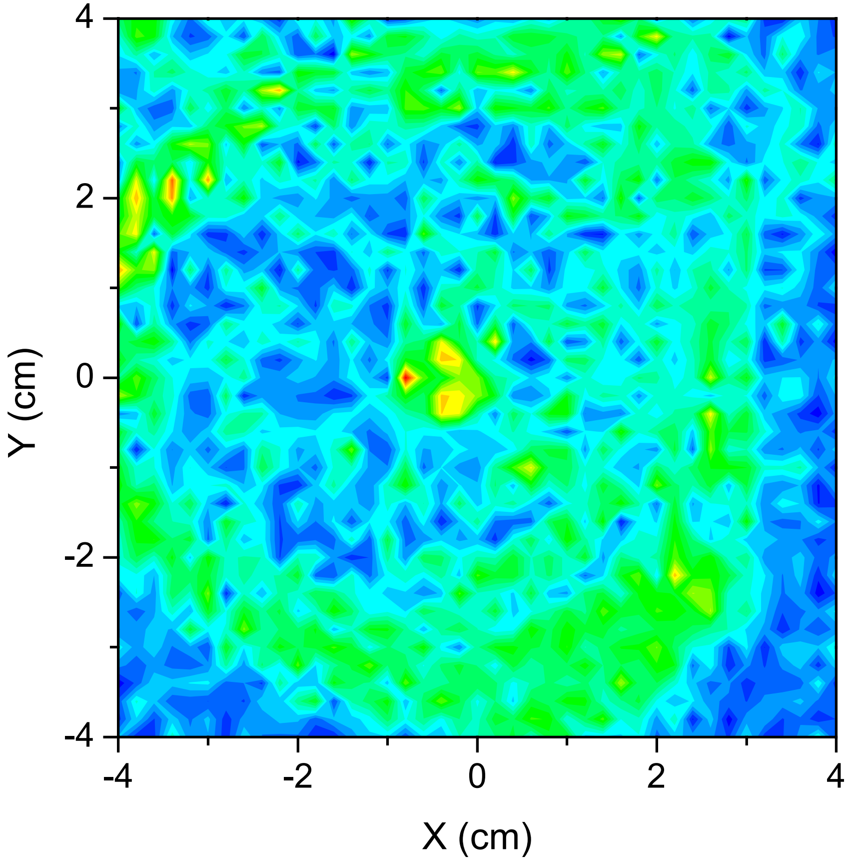
Theory at 1.60 MHz
(2 % shift)

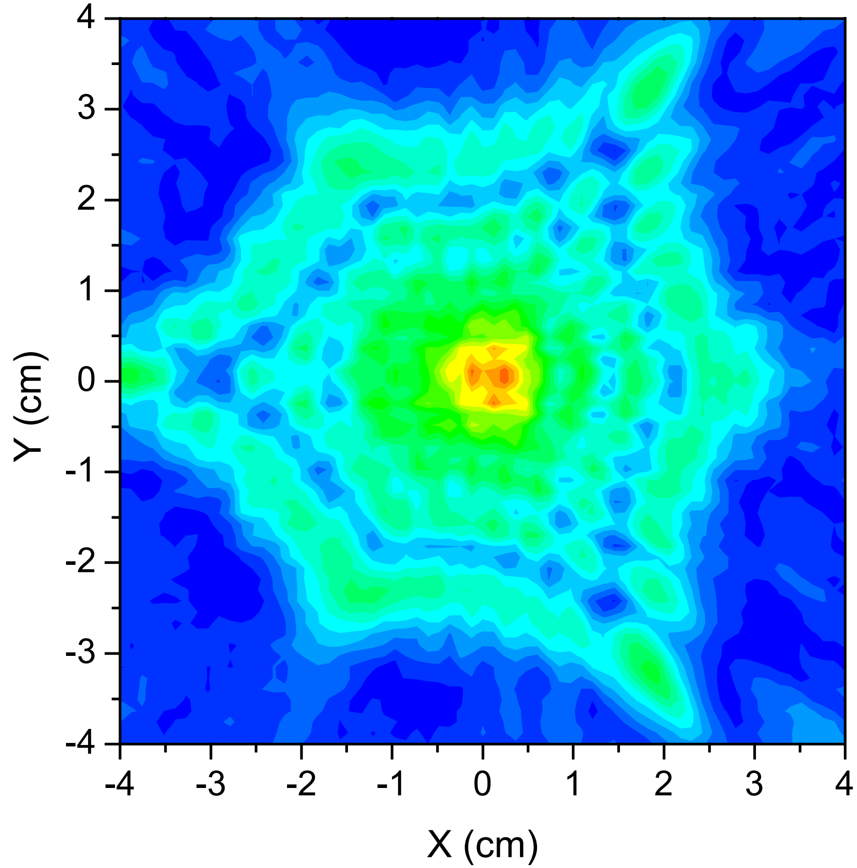


NB: The 2% shift in frequency corresponds to a difference between experiment and theoretical predictions for the the location of the pass band edge.

Compare:

Experiment at 1.60 MHz & Theory at 1.63 MHz (2% shift)





Comparison of phonon-focusing in natural crystals and phononic crystals

Natural Crystals

(*Imaging Phonons*, J. P. Wolfe)

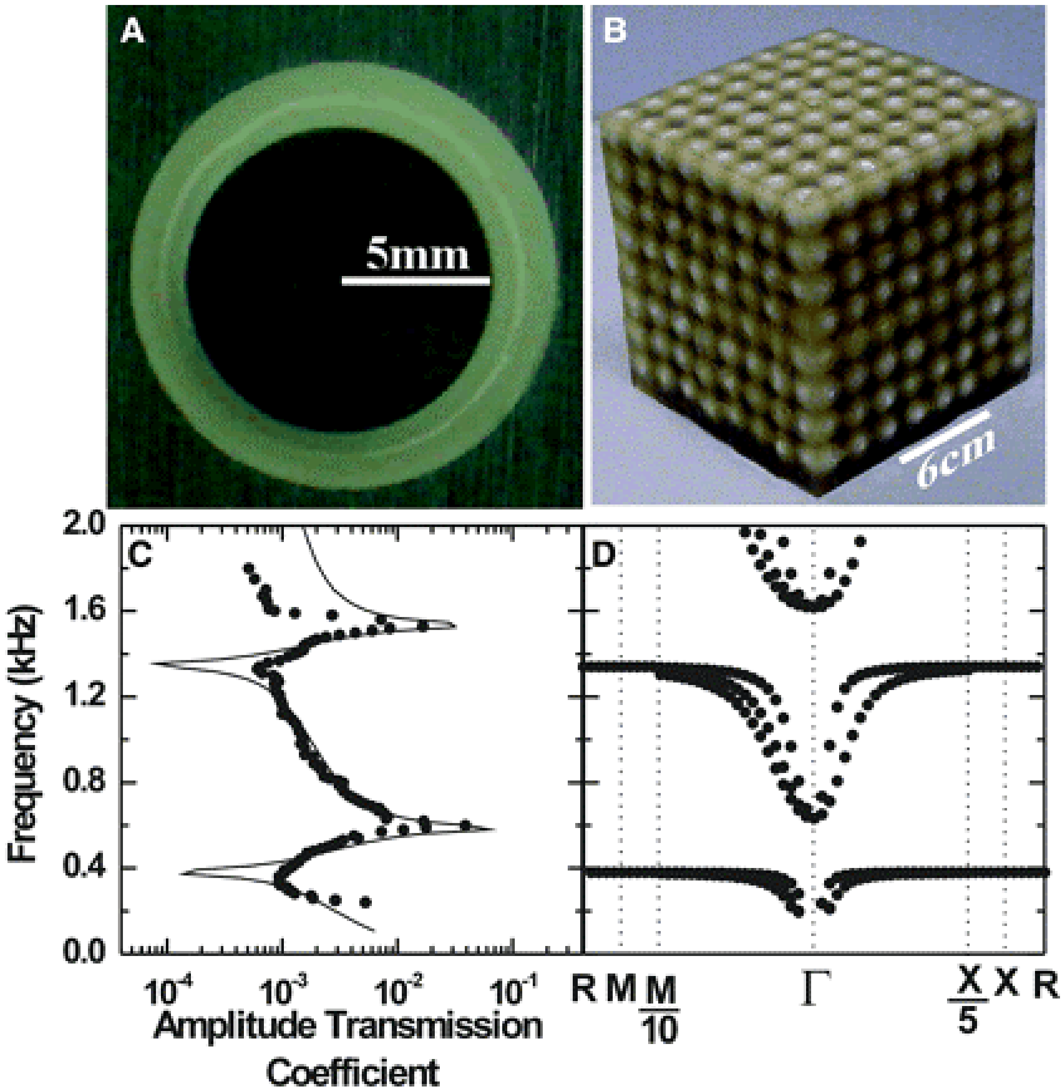
Usually measured with thermal phonons at low temperatures in the long wavelength limit ($\lambda >> a$), but can also be seen using ultrasound $\rightarrow$ elastic anisotropy is described by the 4th rank elasticity tensor. Dispersion surface is dependent on angle but does not change with the frequency. => Wave propagation is frequency-independent.

Phononic Crystals

Observed using ultrasound at room temperature in the strong scattering regime ($\lambda \sim$ a). Dispersion surface has both frequency and angular dependence. => Field patterns have strong frequency dependence (2% change of the frequency $\rightarrow$ patterns are completely different).

Novel sound insulators using phononic crystals [Liu *et al.*, *Science* **289** 1734 (2000)]

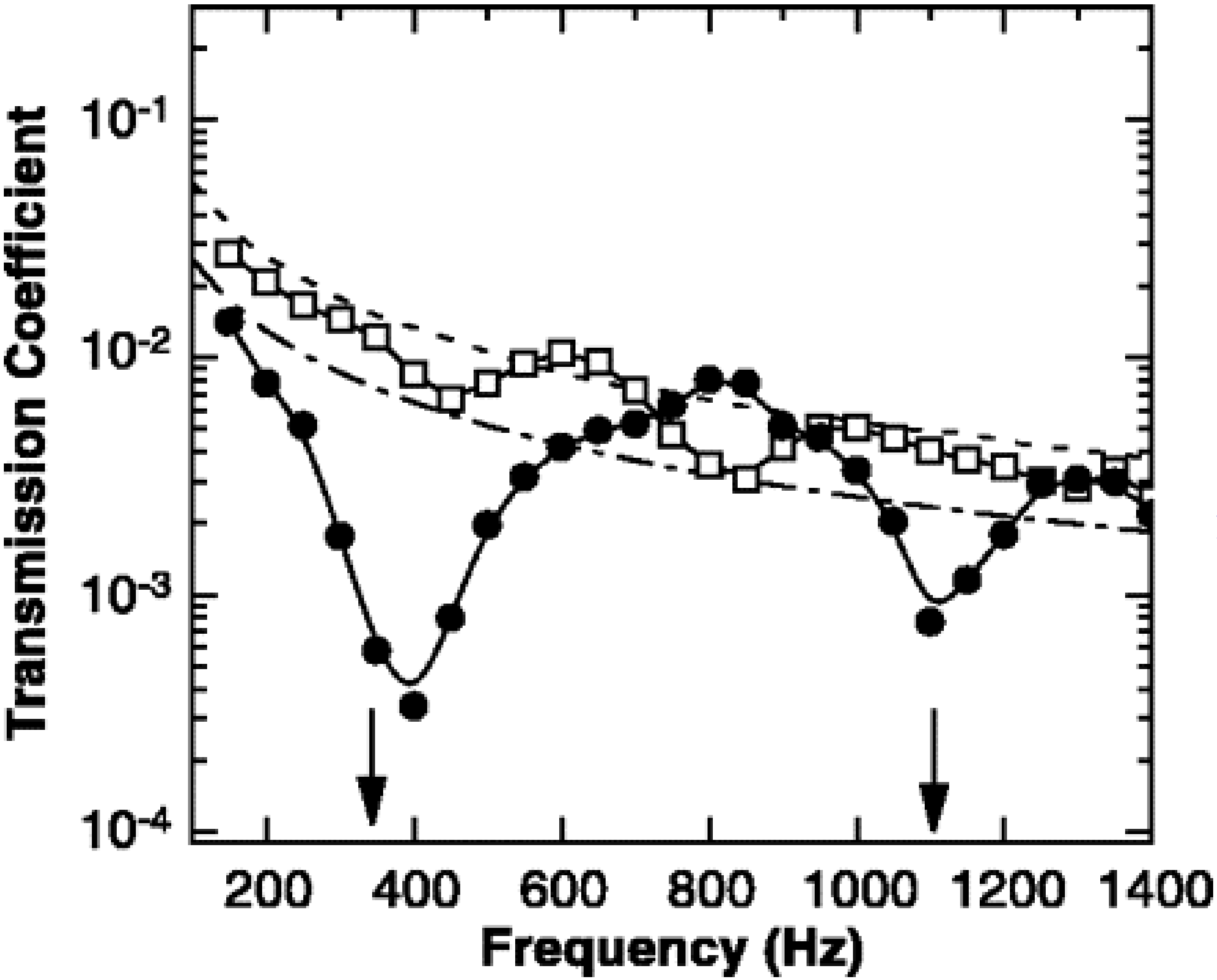
"Magic spheres" (strong local resonances) $\Rightarrow$ band gaps for $\lambda \sim 100 \times$ lattice constant!



Gap at 400 Hz:
sphere radius = 5 mm

λ_{air} = 800 mm at 400 Hz

Strong suppression of the transmission for random systems too!



Randomly packed coated spheres in epoxy

lead spheres (heavy) coated with silicone rubber (soft)

$L = 2.1$ cm

$\phi = 0.48$

Conclusions: Phononic Crystals

We have used pulsed ultrasonic techniques & Multiple Scattering Theory to study how wave pulses travel through 3D phononic crystals.
(Theory predicts a complete phononic band gap for fcc crystals of tungsten carbide beads immersed in water.)

Complete picture of wave propagation by measuring:

- Attenuation -- amplitude transmission coefficient
- Phase velocity -- band structure.
- Group velocity -- dynamics of the wave fields

Tunneling of ultrasonic waves in the band gap.

- Group velocity $\propto$ sample thickness.
- Tunneling time $\sim 1 / \Delta\omega_{gap}$ (in the middle of the gap)

Good overall agreement between theory and experiment.

Focusing effects above the lowest band gap.

- a result of crystalline anisotropy

Possible applications

sound insulators, lenses...