Ultrafast Fiske Effect and the Question of Chaotic Motion in Semiconductor Superlattices

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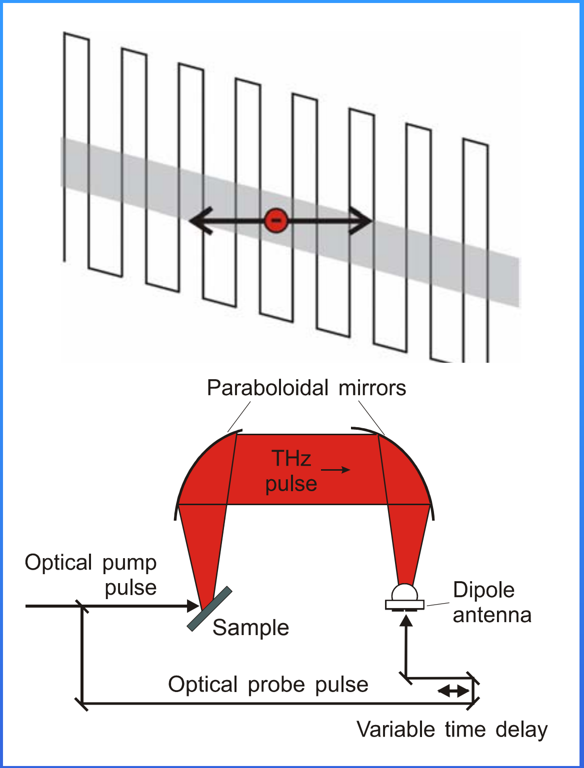
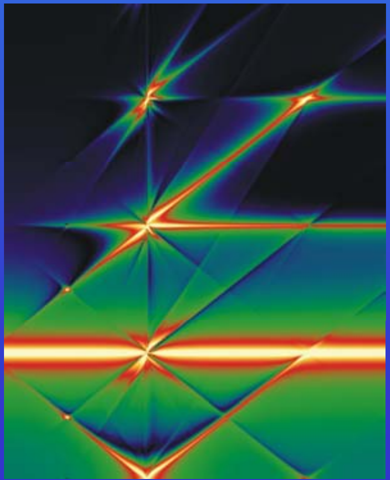
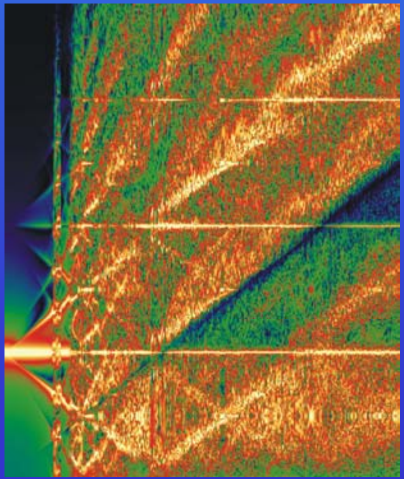
Outline

- Electrically biased superlattices: Bloch oscillations
- ... plus tilted magnetic field:
  - Ultrafast Fiske effect
  - Relationship to enhanced current associated with chaotic carrier motion (Fromhold et al., Nature 428, 726 (2004))







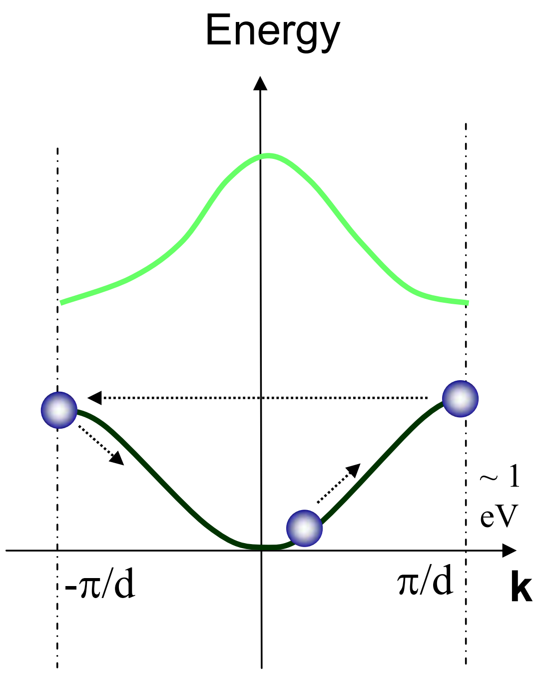
Bloch Oscillations, History

1928 **F. Bloch**: theory for the motion of electrons in the periodic potential of a crystal lattice.

1934 **C. Zener**: prediction of the periodic motion of electrons in a crystal under electrical bias (called Bloch oscillations).

1969 **G. H. Wannier**: theoretical prediction that under electrical DC bias, the continuous energy states split into a (Wannier-Stark) ladder of states. Bloch oscillations: quantum interference of states.

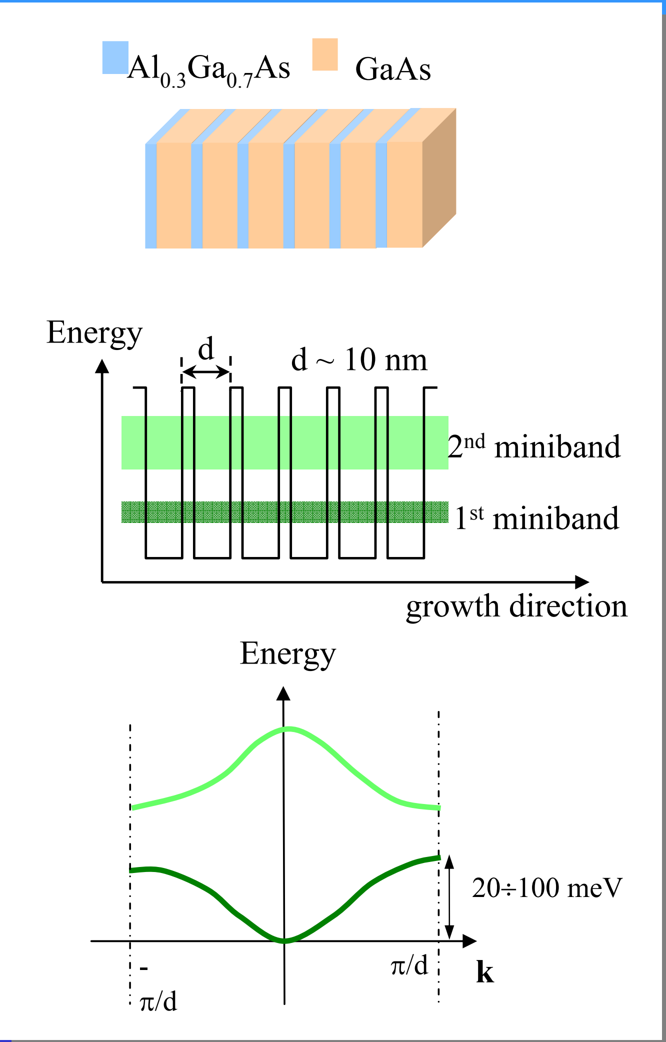
Around '90 : Observation of Wannier-Stark splitting and of Bloch oscillations in semiconductor superlattices by optical experiments.



Bloch frequency

$$\omega_B = \frac{eFd}{\hbar}$$

Semiconductor Superlattice



1970 **L. Esaki** and **R. Tsu:** suggest to use an artificial periodic structure - a semiconductor superlattice (SL) - for the observation of **Bloch oscillations** and as a potential source for **terahertz radiation**.

L. Esaki and R. Tsu, IBM J. RES. DEVELOP. **14**, 61 (1970)

Two proposals concerning THz lasers

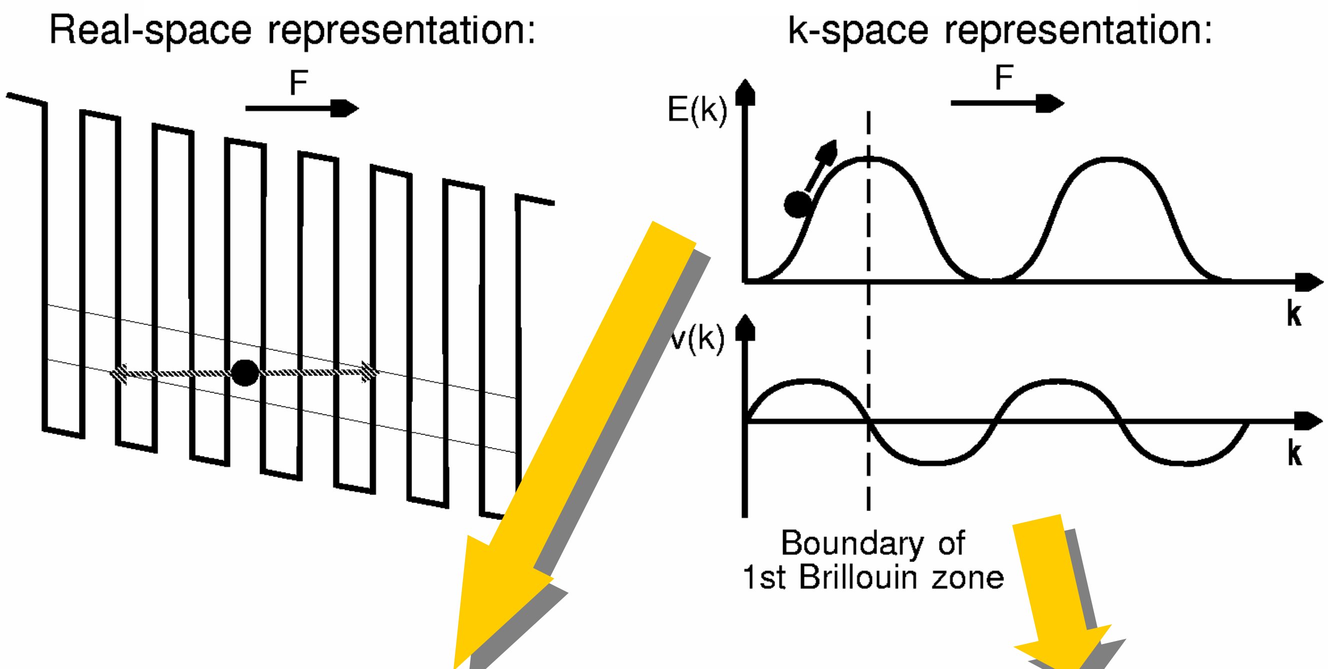
Employing population inversion between minibands

R. Kazarinov and R. Suris, Sov. Phys. Semicond. 5, 707 (1971). → One form of Quantum Cascade Lasers

Dispersive gain due to carrier transport within a single miniband

S. Ktitorov, G. Simin, and V. Sindalovskii, Fiz. Tverd. Tela 13, 2230 (1971).

Semiclassical Picture of Bloch Oscillations



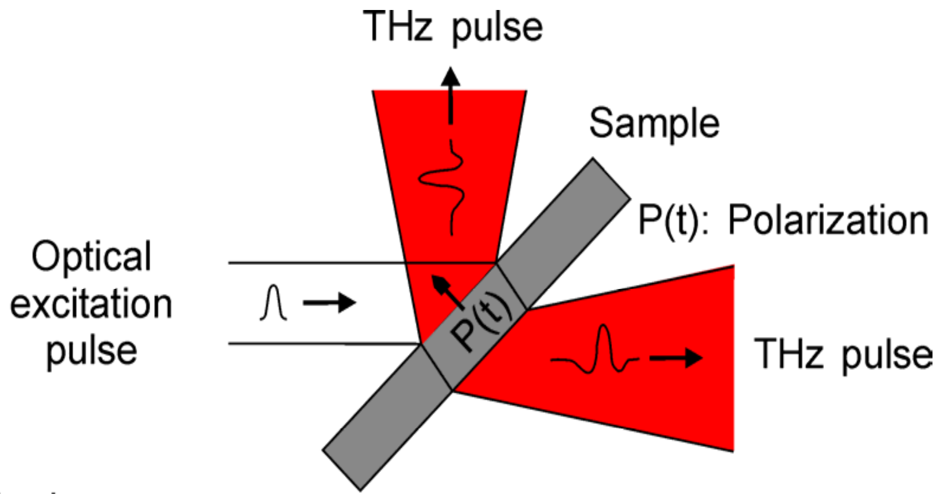
$$E(\vec{k}) = \frac{\Delta}{2}\left(1-\cos\left(k_x d\right)\right)$$

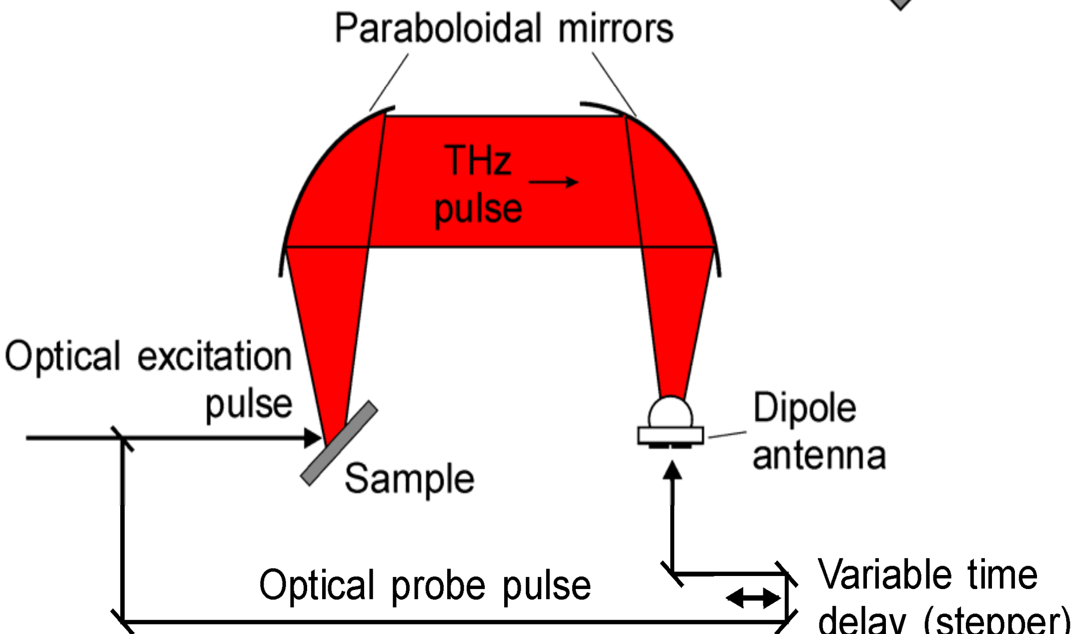
(tight binding)

Group velocity in real space

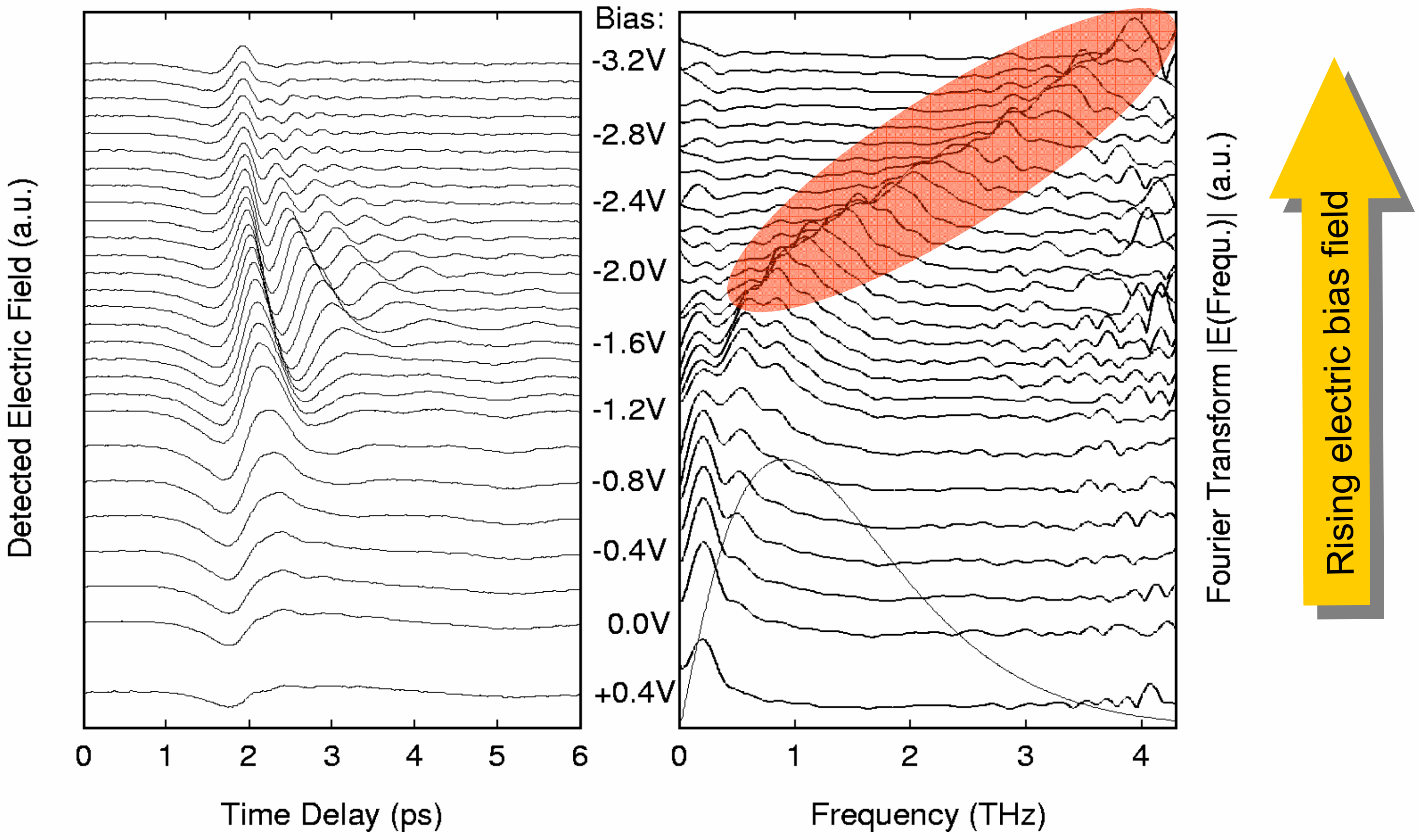
$$\vec{v} = \frac{1}{\hbar}\frac{\partial E}{\partial \vec{k}}$$

THz-Emission Spectroscopy





Bloch Oscillations Measured by THz-Emission Spectroscopy



Analogy

Josephson junction | Superlattice

AC current by DC voltage:

AC Josephson effect

$$\Phi(t) = \frac{2eU}{h} t$$

$$I(t) = I_c \sin(\Phi)$$

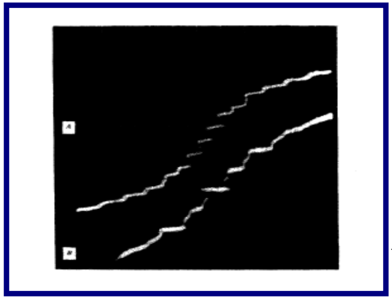
Bloch oscillations

$$k(t) = k(0) + \frac{e}{\hbar} E t$$

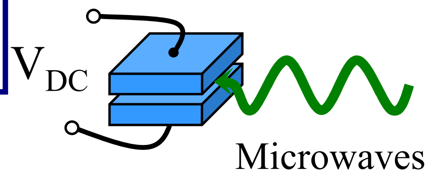
$$v(k) = \frac{\Delta d}{2\hbar} \sin(kd)$$

Semiconductor Suprelattices vs. SIS Junctions

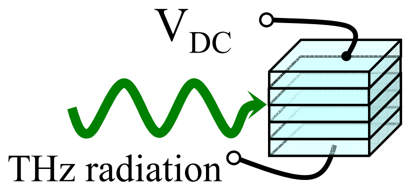
Shapiro effect

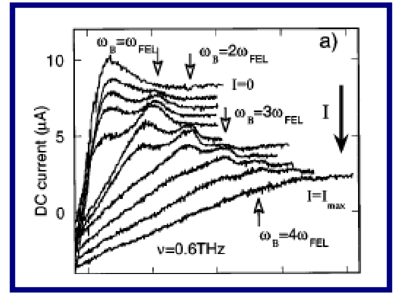


S. Shapiro, Phys. Rev. Lett. **11**, 80 (1963).



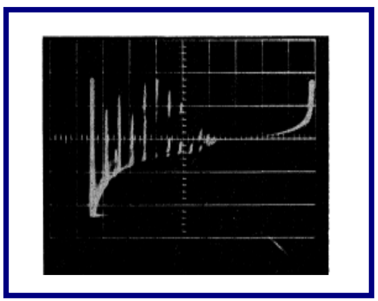
Superlattice analog for Shapiro effect



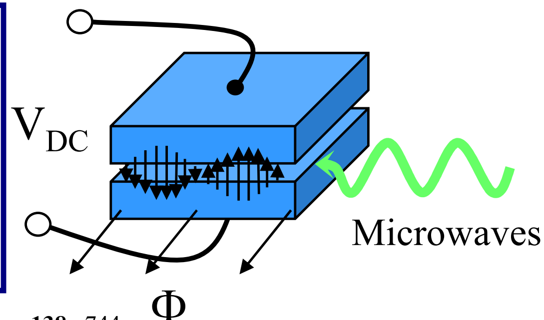


K. Unterrainer et al., Phys. Rev. Lett. **76**, 2973 (1996).

Fiske effect



D. D. Coon and M. D. Fiske, Phys. Rev. **138**, 744 (1965).



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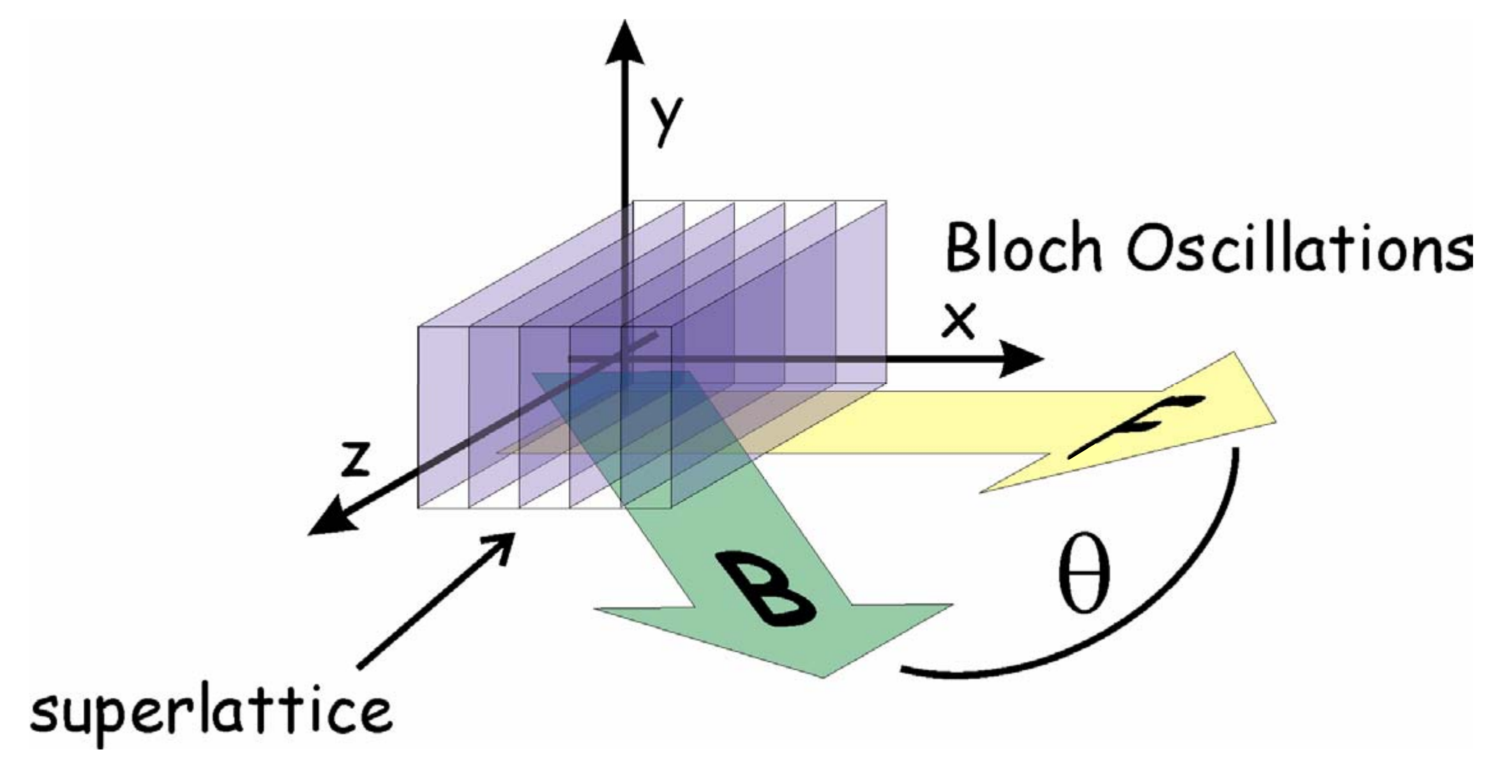
Ultrafast Fiske Effect

Tilted fields



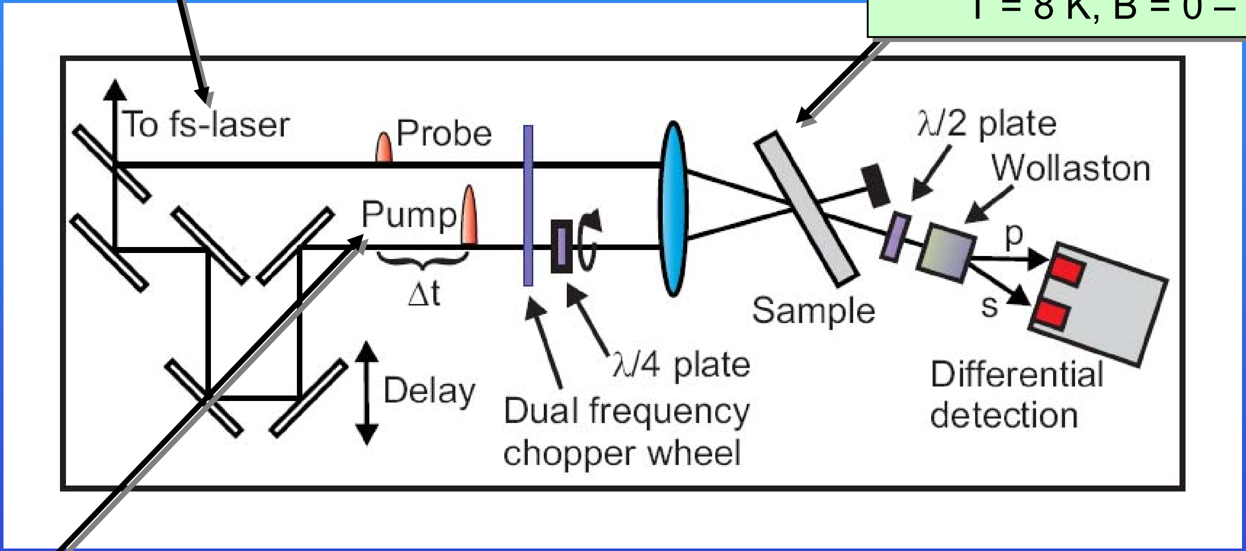
→ Ultrafast Fiske effect: Self-induced quasi-DC current by interaction of Bloch oscillations and in-plane cyclotron oscillations

Experimental Setup

Time-resolved Transmittive Electro-Optic Sampling (TEOS)

Ti:Sapphire laser, 100 fs, 82 MHz, λ=800 nm (hν=1.55 eV)

GaAs/AlGaAs superlattice (Δ=18 meV) in He magnet cryostat
T = 8 K, B = 0 – 8 T



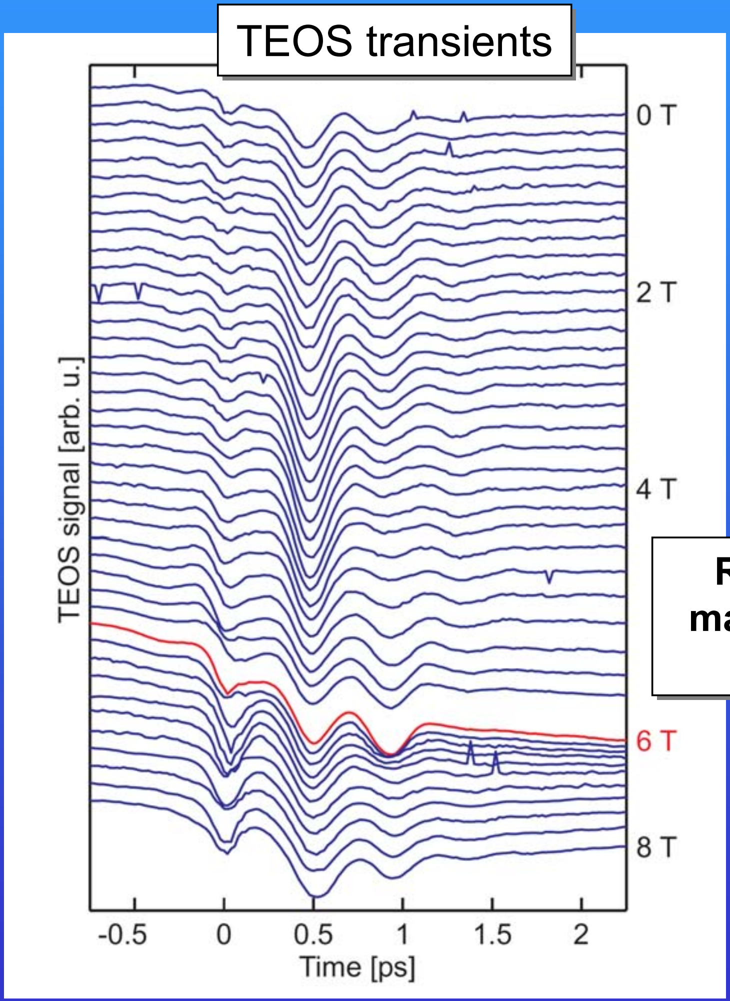
Volume excitation density:
~ $5 * 10^{15}$ per cm^3

TEOS measures internal electric field in the superlattice:

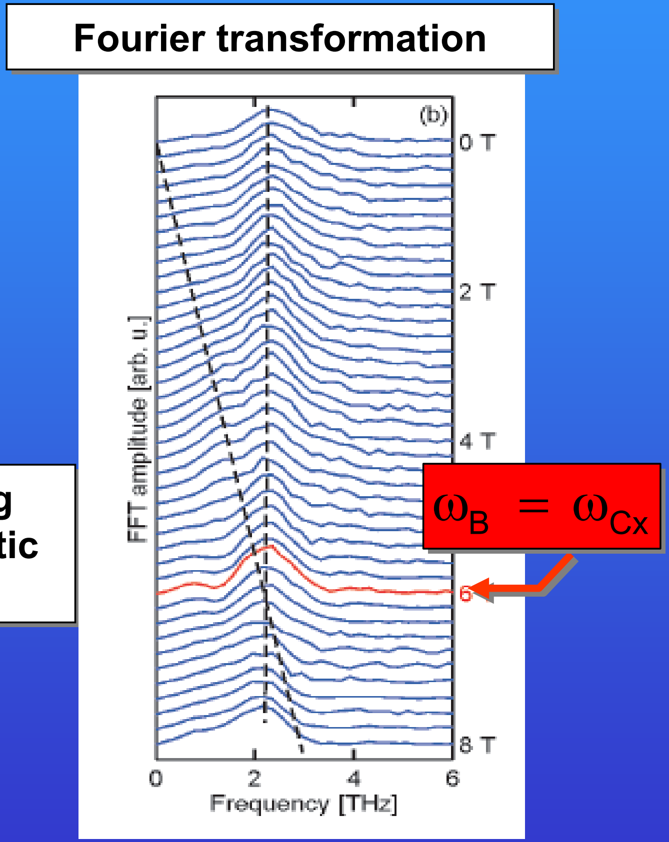
→ Internal field dynamics

Experimental Results

Fixed bias voltage ($\omega_B = 2\pi \cdot 2.2$ THz), variation of magnetic field B, $\theta = 30°$

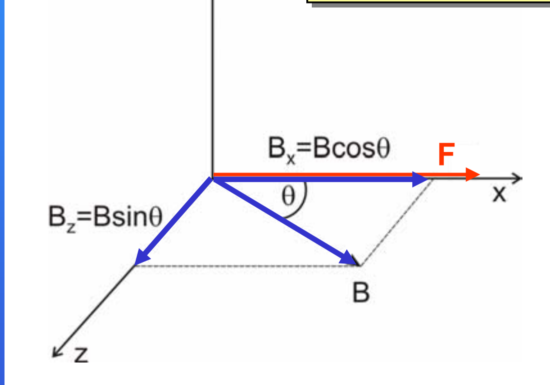


Rising magnetic field



Origin of Resonant DC Current

Model of Bloch-cyclotron coupling for tilted fields

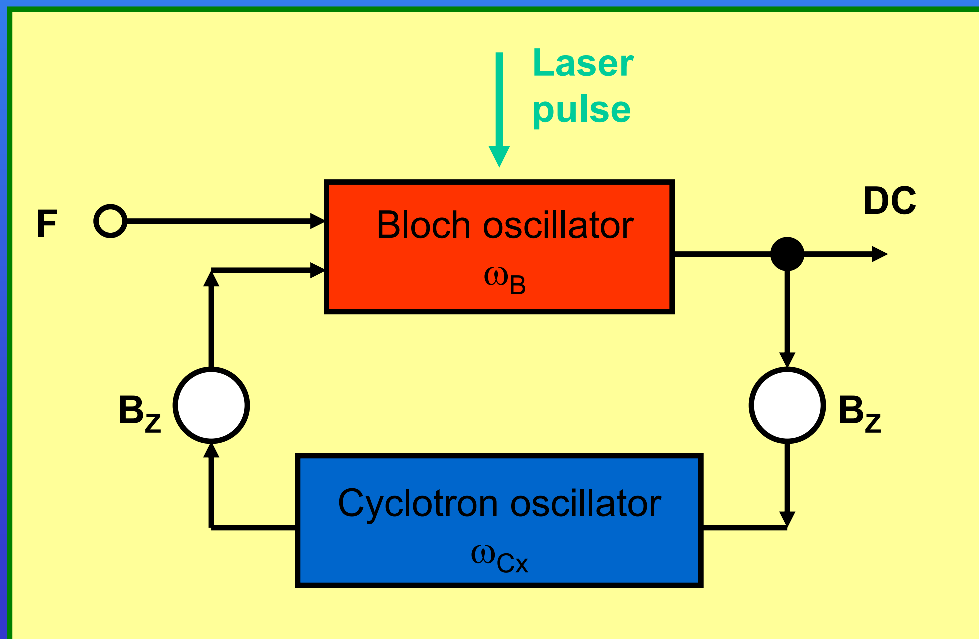


$$\underline{F}_L = e(\underline{v} \times \underline{B}) \;\Rightarrow\; \begin{aligned} F_{L,x} &= e v_y B_z \\ F_{L,y} &= -e v_x B_z \end{aligned}$$

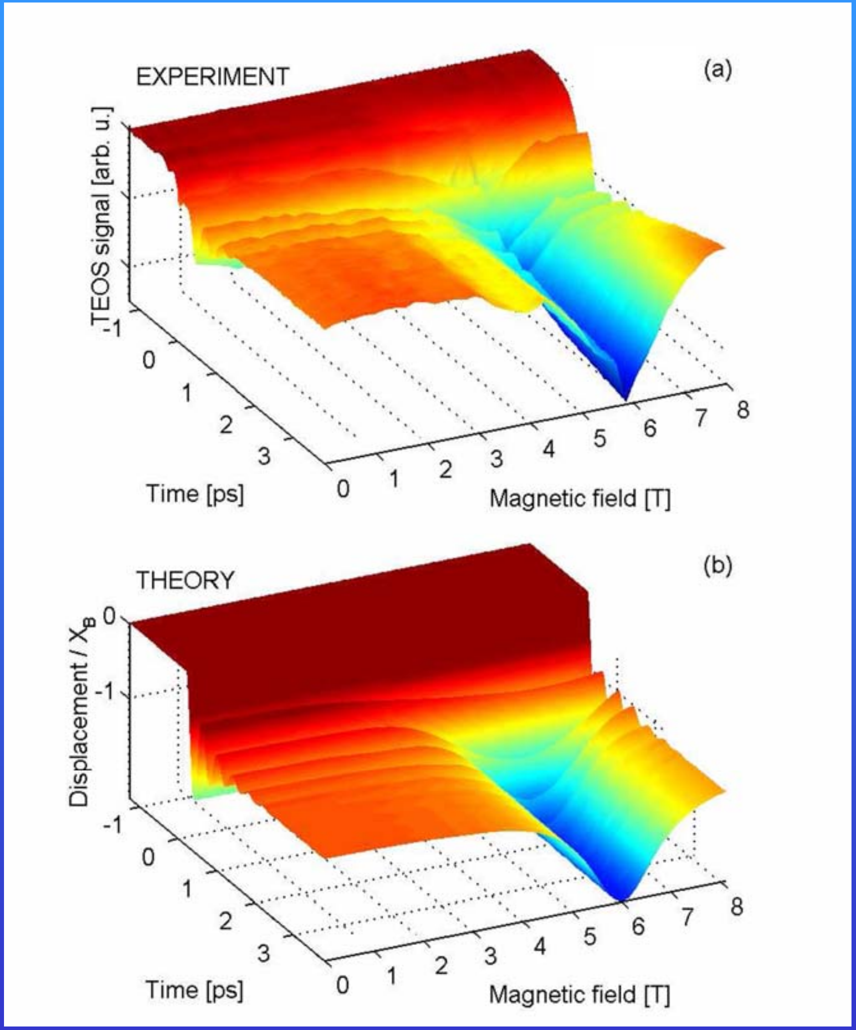
$\Rightarrow$

- B_z couples v_x and v_y,
- Coupling strength parameter $\kappa=(eB/m_{||})\sin\theta$

Phase-locked-loop picture



Comparison – Experiment and Theory



Numerical solution of the equation of motion yields the electron displacement X(t).

Measured depolarization field

$$F_X^{dep}(t) = -\frac{e}{\varepsilon_0 \varepsilon_\infty} N \cdot X(t)$$

Good agreement between experiment and theory

τ_C = 1.04 ps (Cyclotron dephasing)
τ_v= 0.70 ps (Momentum relaxation)
$\tau_\varepsilon \rightarrow \infty$ (Energy relaxation)

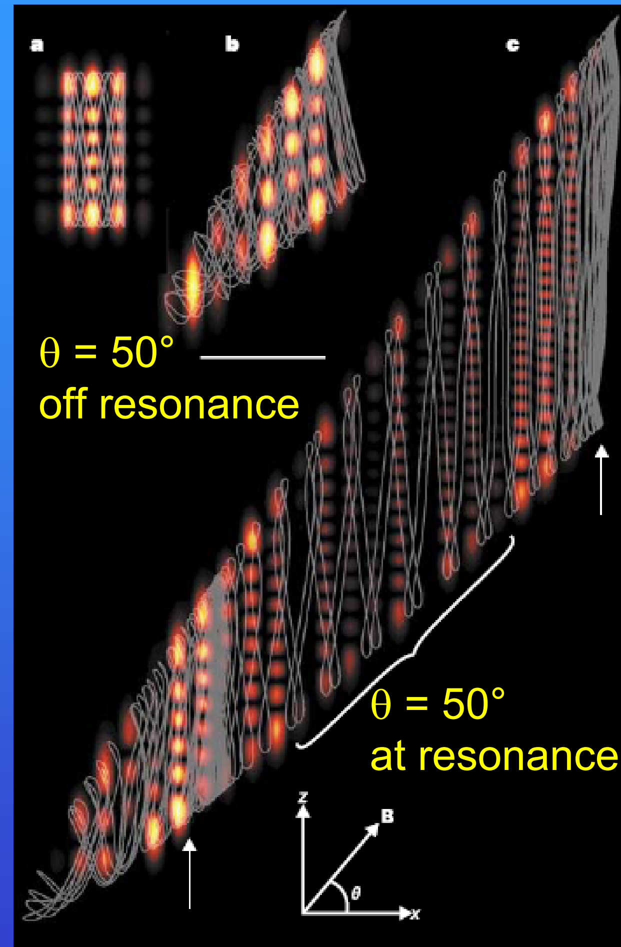
Related work: Nature 428, 726 (2004)

Chaotic electron diffusion through stochastic webs enhances current flow in superlattices

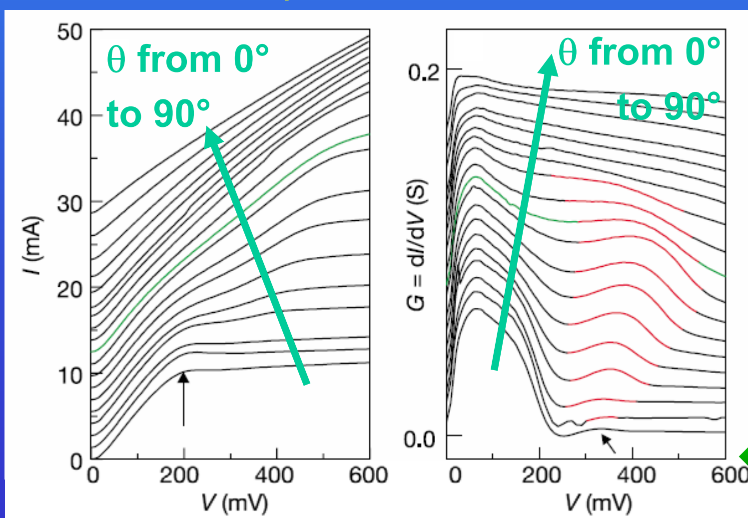
T. M. Fromhold, A. Patanè, S. Bujkiewicz, P. B. Wilkinson, D. Fowler, D. Sherwood, S. P. Stapleton, A. A. Krokhin*, L. Eaves, M. Henini, N. S. Sankeshwar* & F. W. Sheard

School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK

Electron trajectories / wave functions



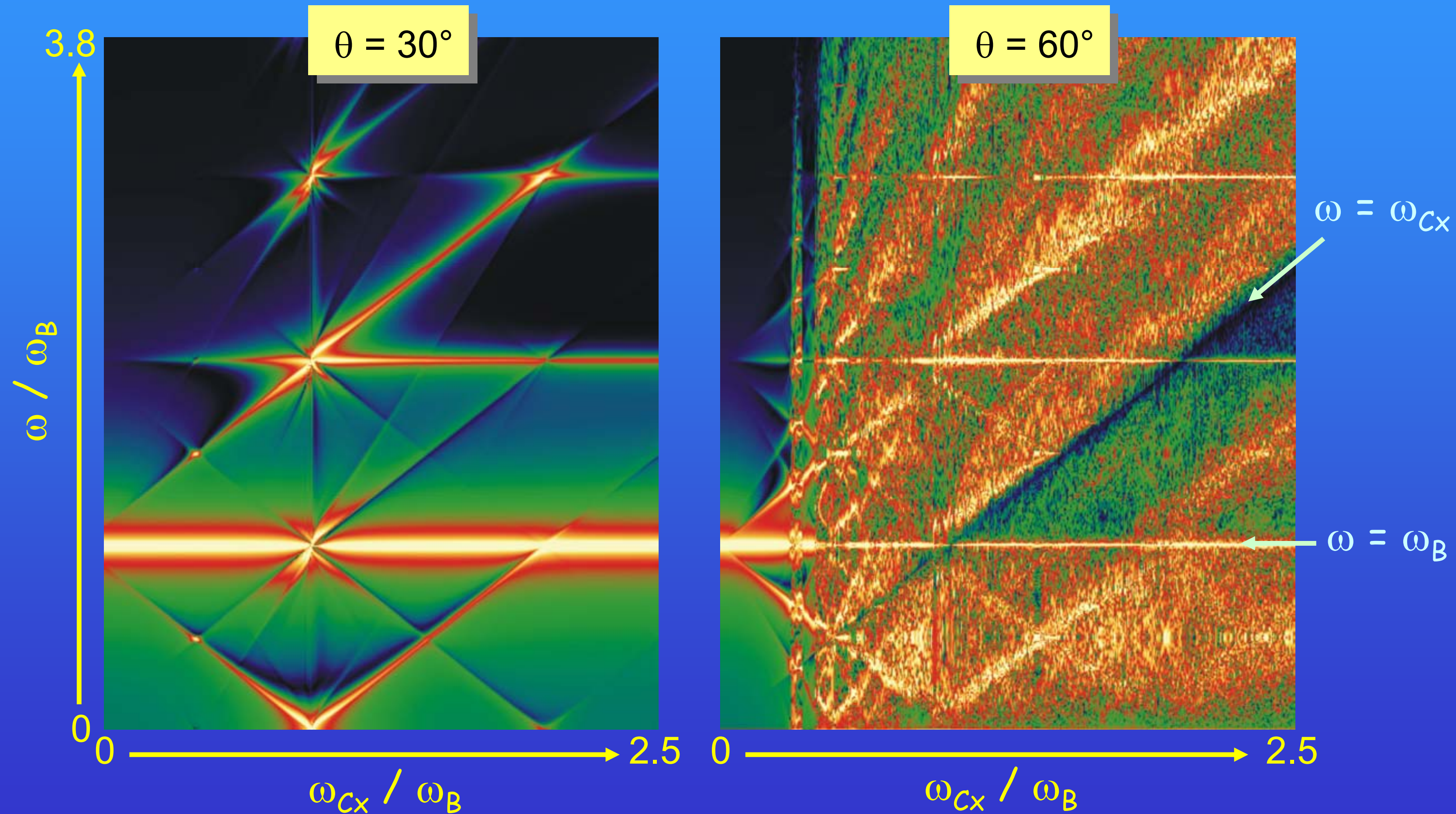
Resonant current enhancement in GaAs/AlAs superlattice at 11 T, 4.2 K



Ultrafast scattering prevents full development of orbits

Frequency Spectra of v_x

Variation of magnetic field for weak damping



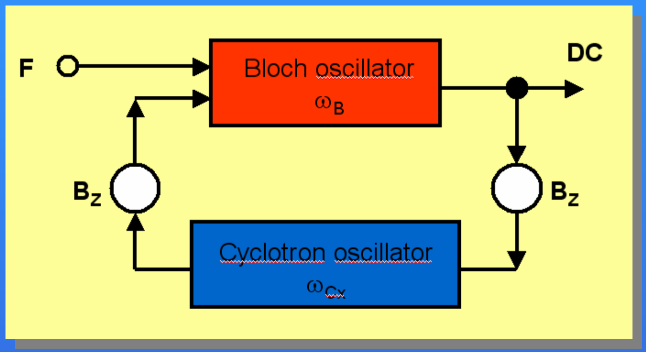
Origin of Resonant DC Current

In case of a scattering event:

Velocity of electron changes

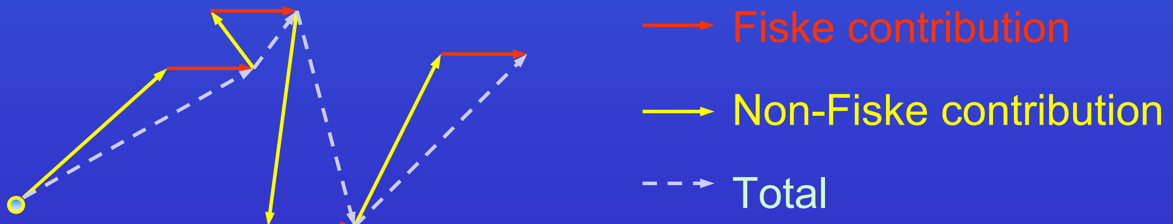
↓

Lorentz force resets phase and direction of in-plane cyclotron oscillation such that the rectified current doesn‘t change its direction



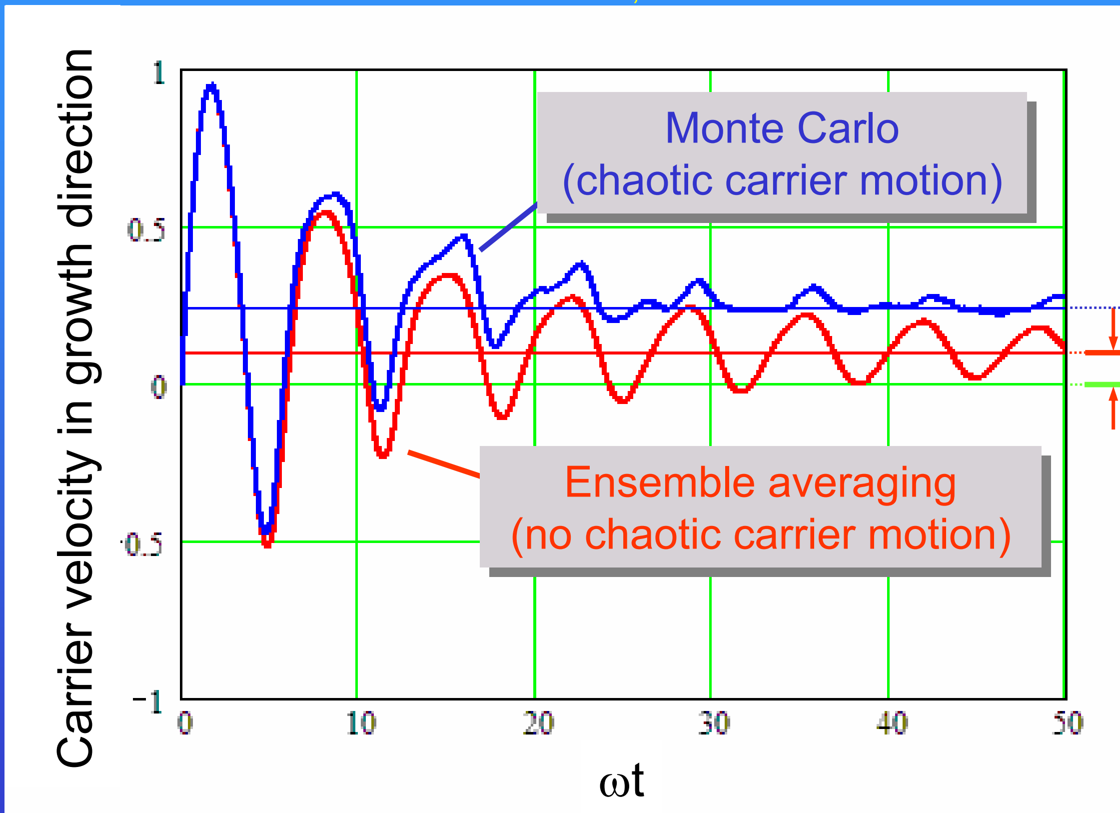
Relationship between DC current of Fromhold et al. and the ultrafast Fiske effect (Fiske carrier displacement) observed by us:

DC current is the sum of unidirectional Fiske displacements between scattering events:



Simulation of Electron Velocity $v_x(t)$

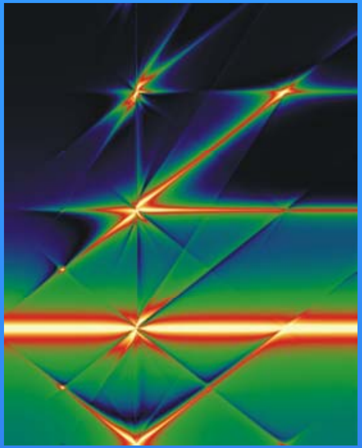
$\theta = 30°$; resonance ($\omega_B = \omega_{C,x}$); $\Gamma_B = 0.1$; $\Gamma_C = 0.07$



$t \to \infty$: Esaki-Tsu current plus continuous Fiske current

$t \to \infty$: Esaki-Tsu current (the usual scattering-induced forward current in a superlattice)

Summary



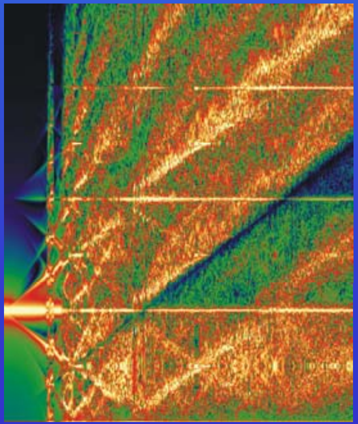
- Semiconductor superlattice in tilted electric and magnetic fields:
  Ultrafast Fiske effect, a self-induced quasi-DC current

  → Analogous to Fiske effect of superconductor Josephson junctions in a magnetic field

  → Existence of Fiske effect is closely related with the occurrence of chaos in the electron motion

  → Ultrafast Fiske effect and DC current enhancement in I/V measurements reflect the same physics

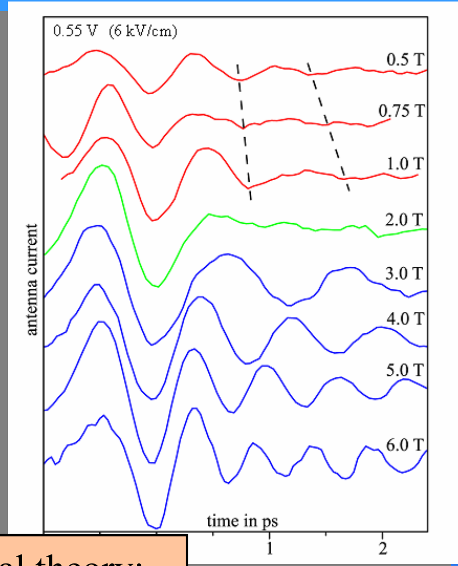
  → Manifestation of chaos in ultrafast measurements is not well understood



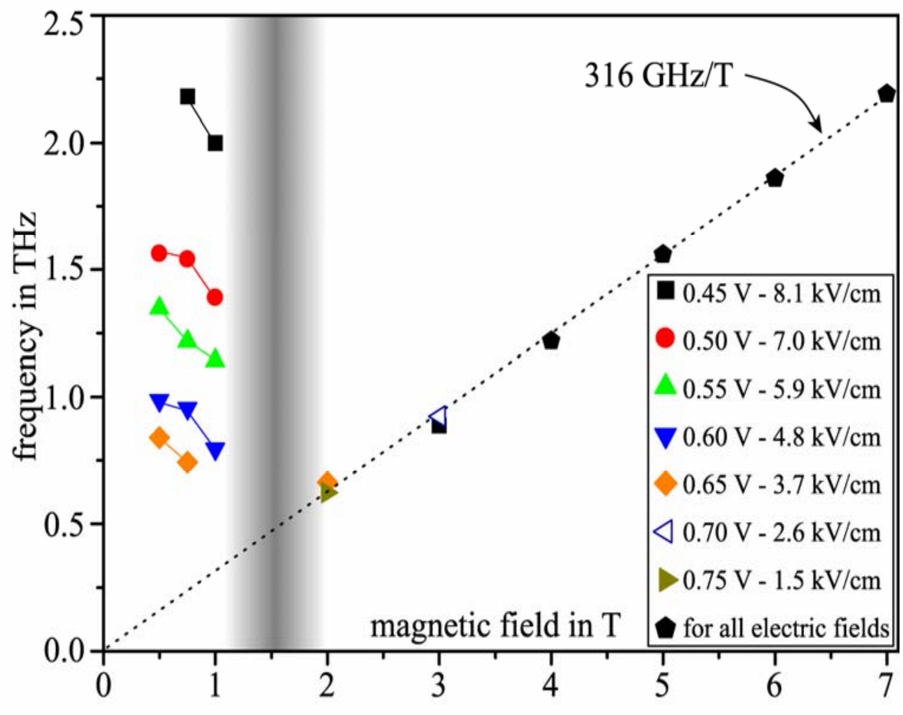
Y. A. Kosevich, A. B. Hummel, H. G. Roskos, and K. Köhler, Phys. Rev. Lett. **96**, 137403 (2006).

Y. A. Kosevich, A. B. Hummel, H. G. Roskos, and K. Köhler, phys. stat. sol. (b) **243**, 2405 (2006).

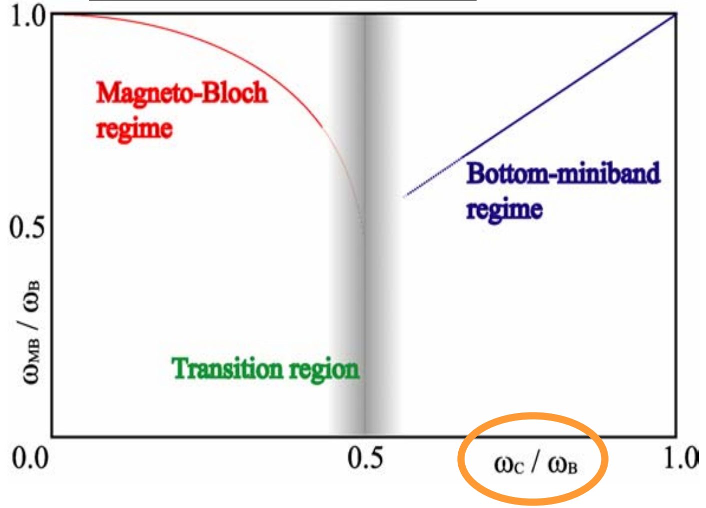
F ⊥ B: Coherent Hall Effect



Experimental frequencies evaluated by fitting a cosine or by Fourier transformation



Semiclassical theory: Calculated frequencies



~ F/B