Magneto-Oscillations in intensely irradiated two-dimensional electron gas

THE UNIVERSITY OF IOWA

Maxim Khodas

<u>*Collaboration:*</u>

M.G. Vavilov U of W, Madison
M. Zudov U of Minnesota

I.A. Dmitriev,
A.D. Mirlin, D.G. Polyakov
Karlsruhe, Germany

M. Khodas, H.-S. Chiang, A.T. Hatke, M.A. Zudov M.G. Vavilov, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. 104, 206801 (2010).

I.A. Dmitriev, M. Khodas, A.D. Mirlin, D.G. Polyakov, M.G. Vavilov, Phys. Rev. B 80, 165327 (2009).

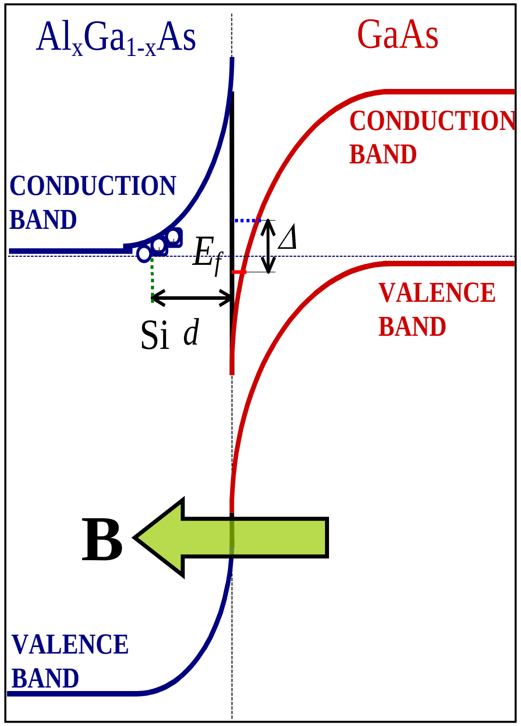
M. Khodas and M.G. Vavilov, Phys. Rev. B 78, 245319 (2008)

Outline

1. Experimental motivation
2. Hall induced resistance oscillation
3. Combined action of AC and DC excitations
4. MIRO at high power and at strong dc bias
5. MIRO: Temperature dependence
6. Conclusions

2D electron systems

- Two lattice-matched semiconductors:
  - GaAs and AlxGa1-xAs
- Realizations
  - 1). Heterostructure (HS)
    - single interface
  - 2). Quantum Well (QW)
    - double interface
    - highest mobility
- 2D electrons
  - AlxGa1-xAs: Si *d*-doping
  - *EF* << D
    - At low T, only the lowest subband is occupied

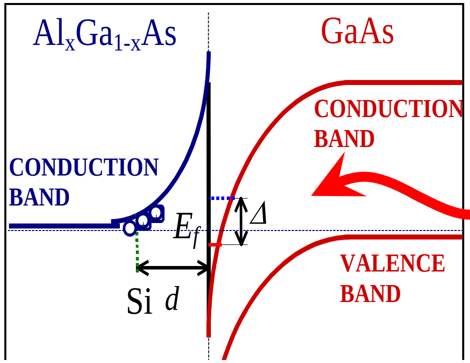


Heterostructure

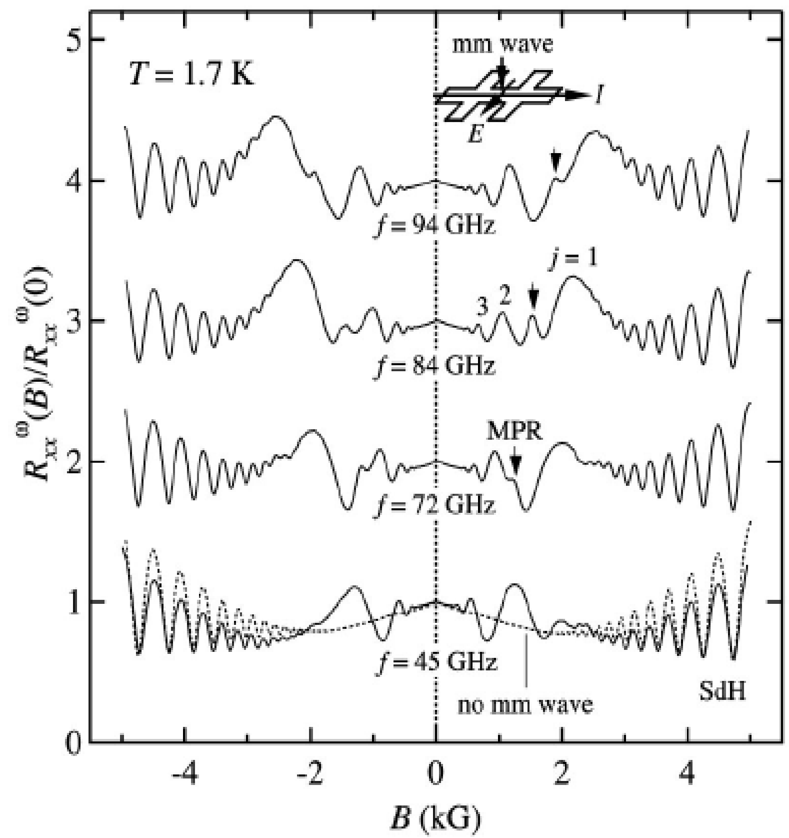
$$\boxed{1/\tau_{tr} \ll \omega_c \lesssim 1/\tau_q}$$

Hall angle $\approx\pi/2$ levels unresolved

Microwave induced resistance oscillations (MIRO)



Microwave



Novel Oscillations!

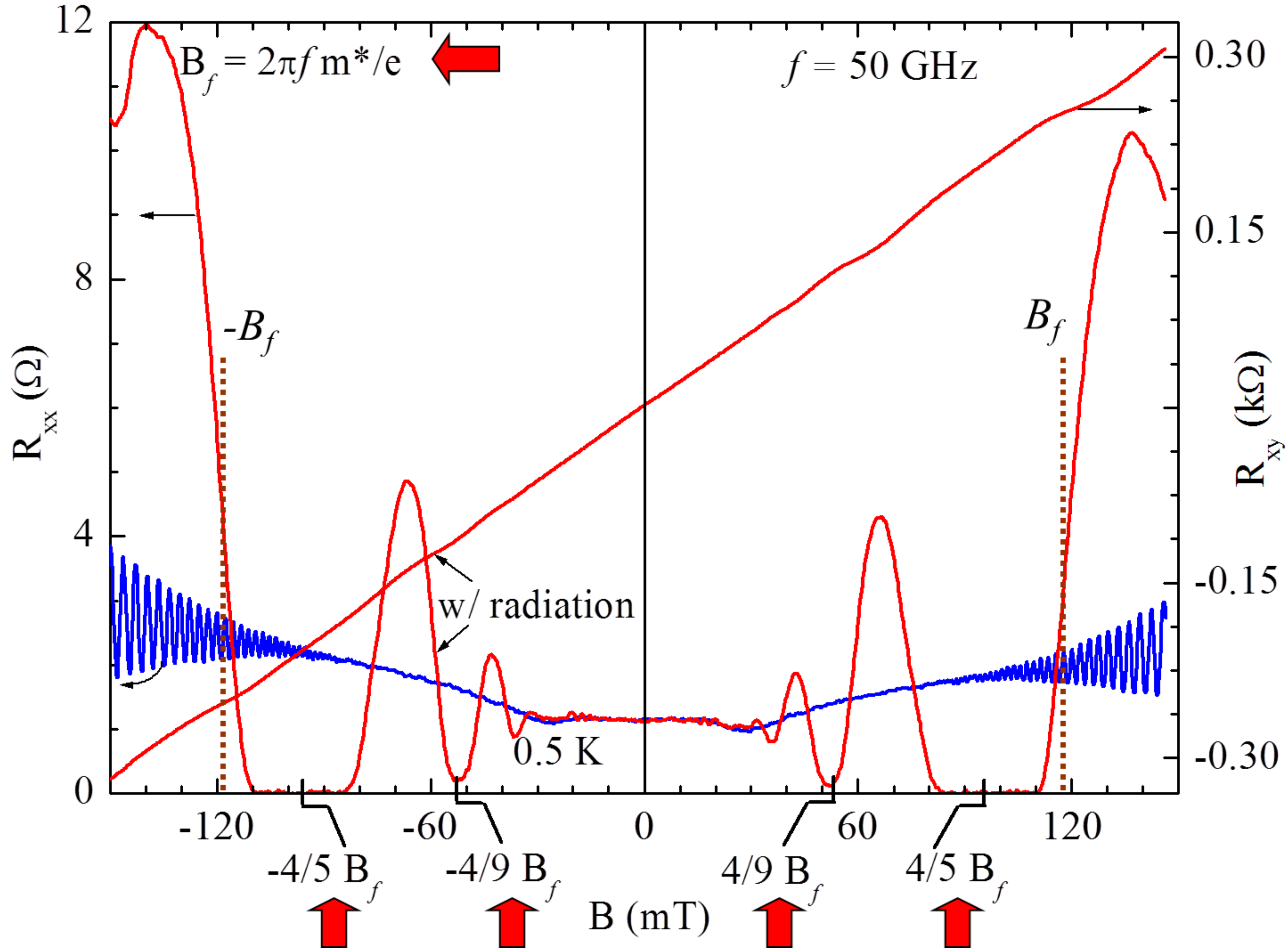
Parameter: $\epsilon_{\rm ac} \equiv \dfrac{\omega}{\omega_{\rm C}}$

(Not SdHO: ϵ_F/ω_c)

Maxima/Minima: $\epsilon_{\rm ac}^{\pm} \simeq n \mp \frac{1}{4}$

Theory: $\Delta R \propto \epsilon_{\rm ac} \sin(2\pi\epsilon_{\rm ac}),\ 2\pi\epsilon_{\rm ac} \gg 1$

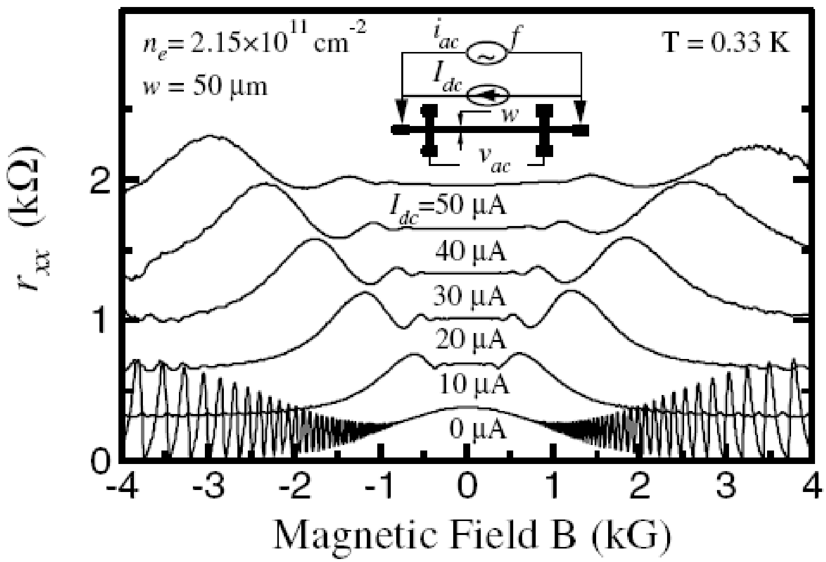
Zudov, Du, Simmons, Reno, Phys. Rev. B **64**, 201311(R) (2001)
Vavilov and Aleiner, Phys. Rev. B **69**, 035303 (2004)



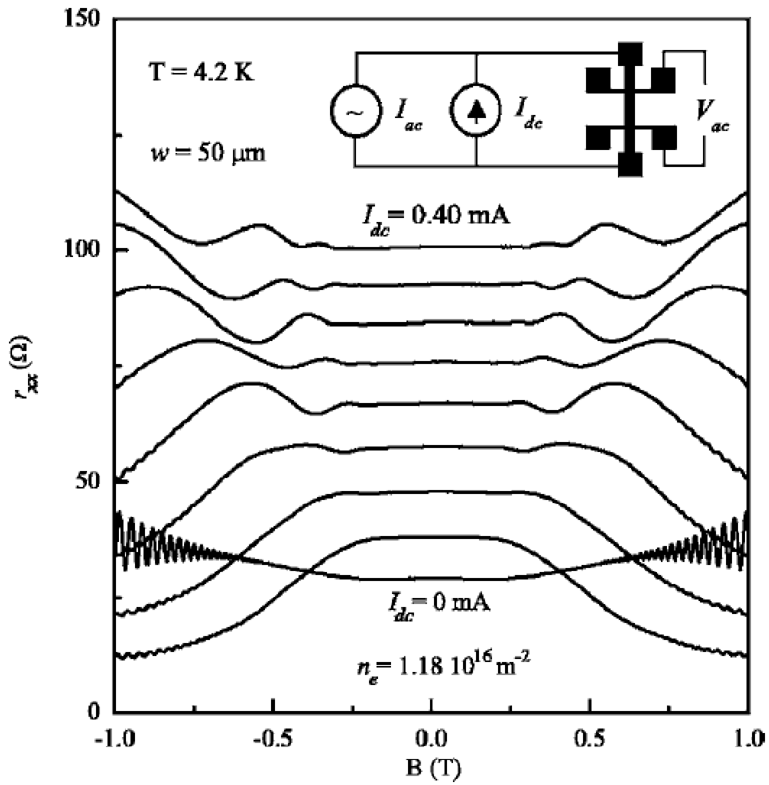
$B_f = 2\pi f m^*/e$
f = 50 GHz
$-B_f$
B_f
w/ radiation
0.5 K
R_{xx} (Ω)
R_{xy} (kΩ)
B (mT)
-4/5 B_f
-4/9 B_f
4/9 B_f
4/5 B_f
12
8
4
0
0.30
0.15
-0.15
-0.30
-120
-60
0
60
120

Hall field induced resistance oscillations (HIRO)

C.L. Yang, J. Zhang, R.R. Du, J.A. Simmons, J.L. Reno; PRL 89, 076801



A.A. Bykov, J-q Zhang, S. Vitkalov, A.K. Kalagin,A.K. Bakarov PRB 72, 245307

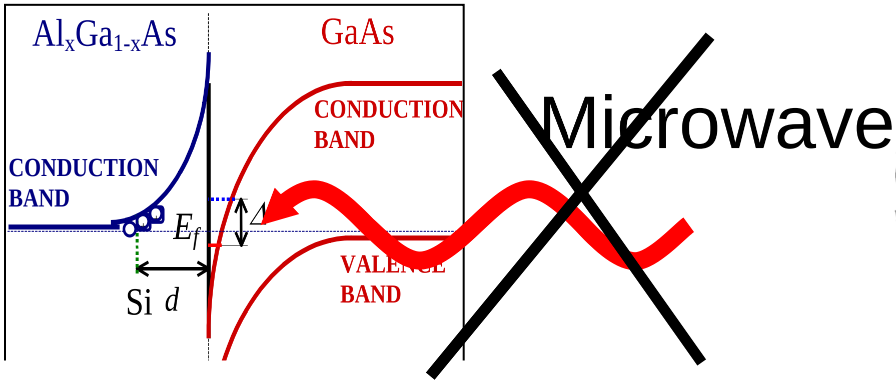


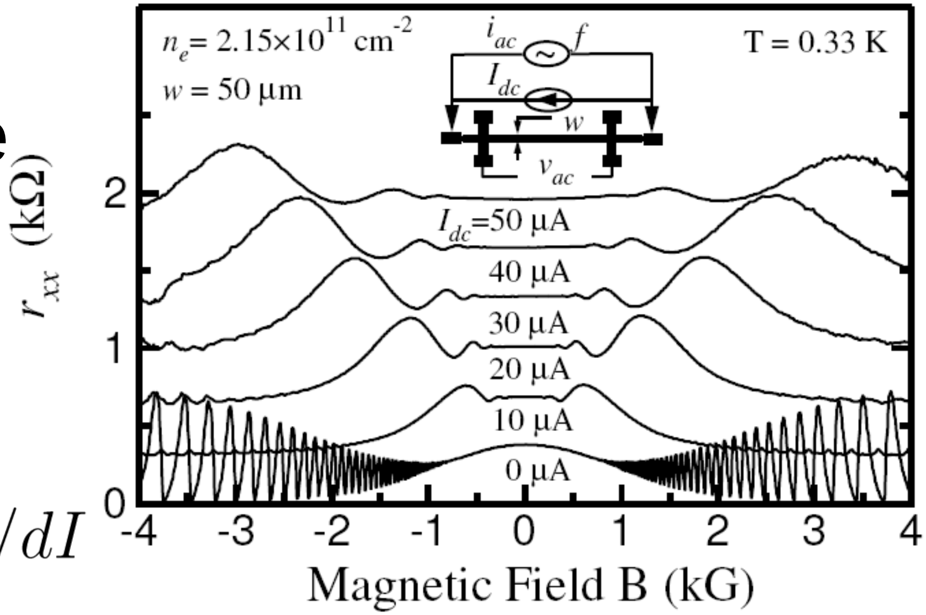
As current increases:

1. SdH oscillations are suppressed
2. New oscillations develop

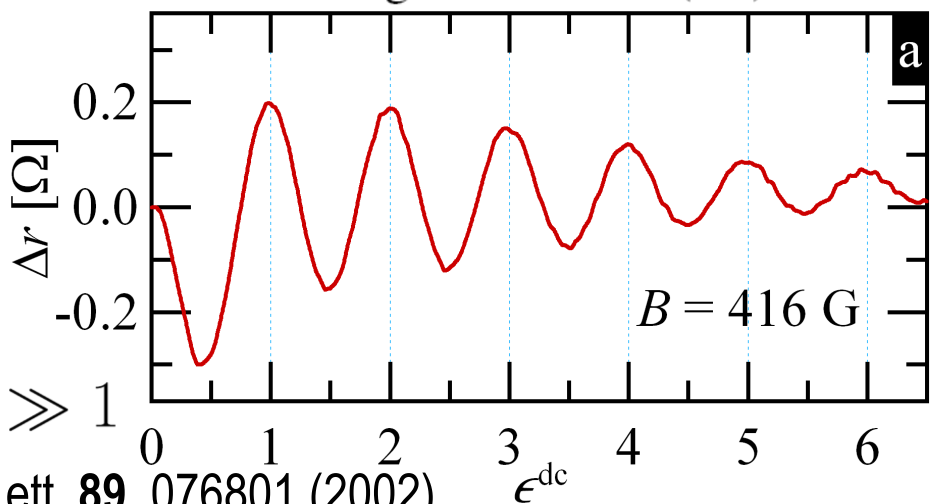
$$E \approx \rho_H j$$

Hall field induced resistance oscillations (HIRO)





- Differential resistance: $r = dV/dI$
- Parameter: $\epsilon^{\mathrm{dc}} \equiv \dfrac{eE(2R_{\mathrm{C}})}{\hbar\omega_{\mathrm{C}}}$
- Maxima: $\boxed{\epsilon^{\mathrm{dc}}_{+} \simeq n}$
- Theory: $\Delta r \propto \cos(2\pi\epsilon_{\mathrm{dc}}),\ 2\pi\epsilon_{\mathrm{dc}} \gg 1$



Yang, Zhang, Du, Simmons, Reno, Phys. Rev. Lett. **89**, 076801 (2002)
Zhang, Chiang, Zudov, Pfeiffer, West, Phys. Rev. B **75**, 041304(R) (2007)
Vavilov, Aleiner, Glazman, Phys. Rev. B **76**, 115331 (2007)

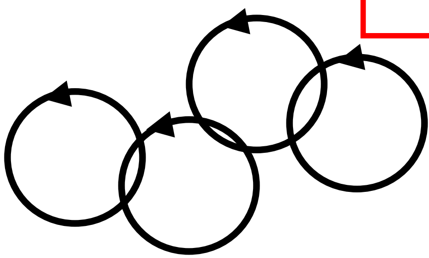
Outline

1. Experimental motivation
2. Hall induced resistance oscillations (HIRO)
3. AC and DC excitation: low power
4. AC and DC excitation: high power
5. MIRO: Power dependence
6. Conclusions

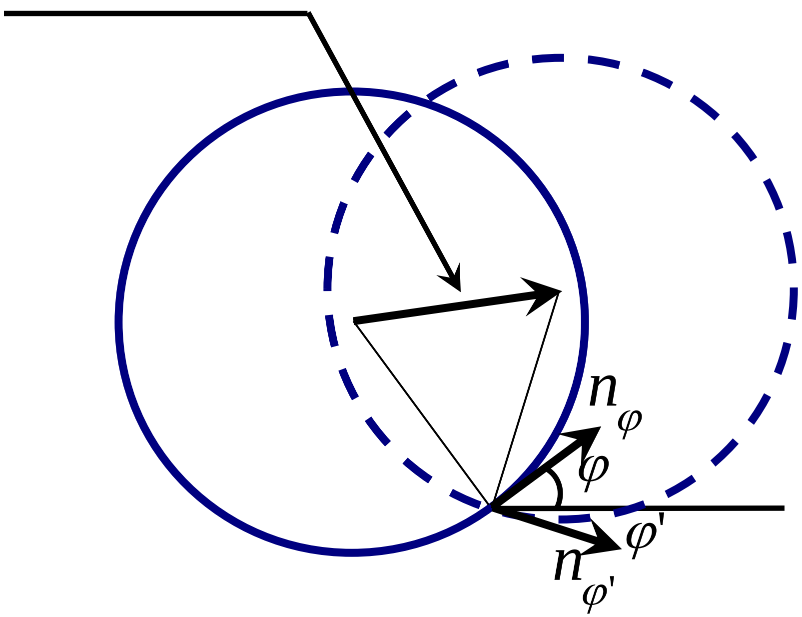
Classical picture

$\mathbf{B}\odot$

$$\boxed{\omega_c \gg 1/\tau_{tr}}$$



$$\Delta\mathbf{R}_{\varphi\to\varphi'} = R_c\widehat{\mathbf{B}}\times(\mathbf{n}_\varphi - \mathbf{n}_{\varphi'})$$



Diffusion of guiding centers

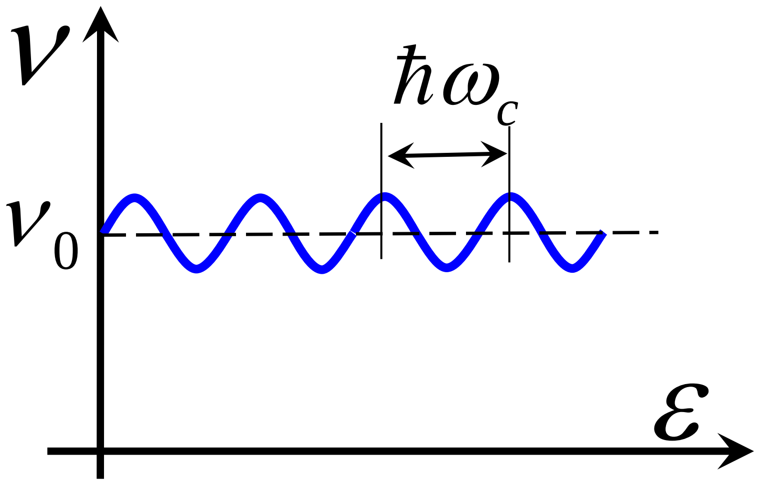
$$\sigma_{xx} = e^2 2\nu_0 D$$

$$D \approx \frac{\left(\sum_i \Delta R_i\right)^2}{2T}$$

$$D = \left\langle \frac{\Delta\mathbf{R}^2_{\varphi\to\varphi'}}{\tau_{\varphi\to\varphi'}} \right\rangle_{angles}$$

$$\boxed{\sigma_{\mathrm{D}} = e^2\nu_0 \frac{R_c^2}{\tau_{\mathrm{tr}}}}$$

Quasi-classical picture



$$E_F/\omega_c \sim 100$$

$$1/\tau_{tr} \ll \omega_c \lesssim 1/\tau_q$$

Probability to make a circle

$$\nu(\varepsilon) = \nu_0\left(1 - 2\lambda\cos\frac{2\pi\varepsilon}{\omega_c}\right)$$

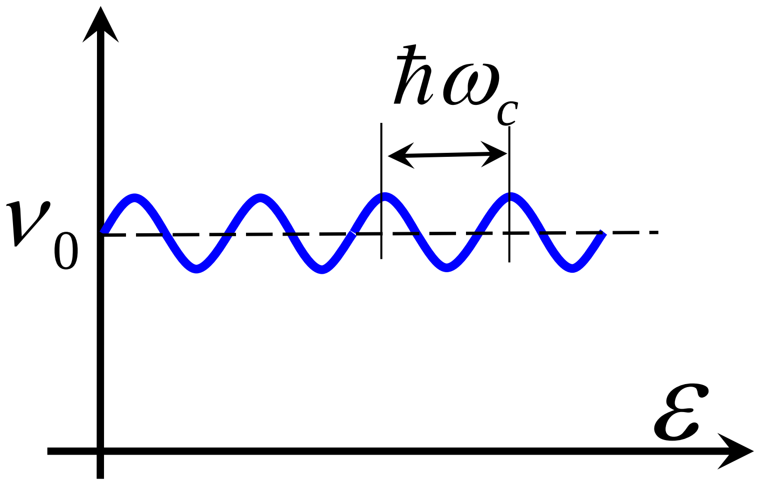
$$\lambda = \exp(-\pi/\omega_c\tau_q) \lesssim 1$$

Add constant electric field $\quad \varepsilon \to \varepsilon + eEx$

Energy and space dependent DOS $\quad \nu(\varepsilon) \to \nu(\varepsilon + eEx)$

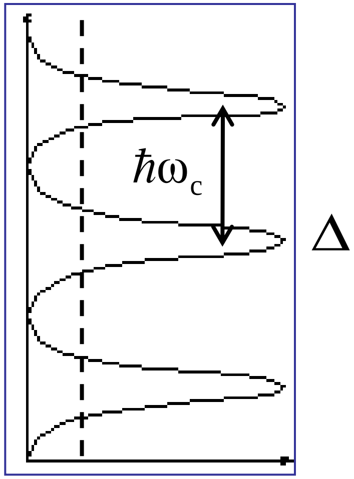
Dissipative current ?

Contact with electrons on He (M.J. Lea)



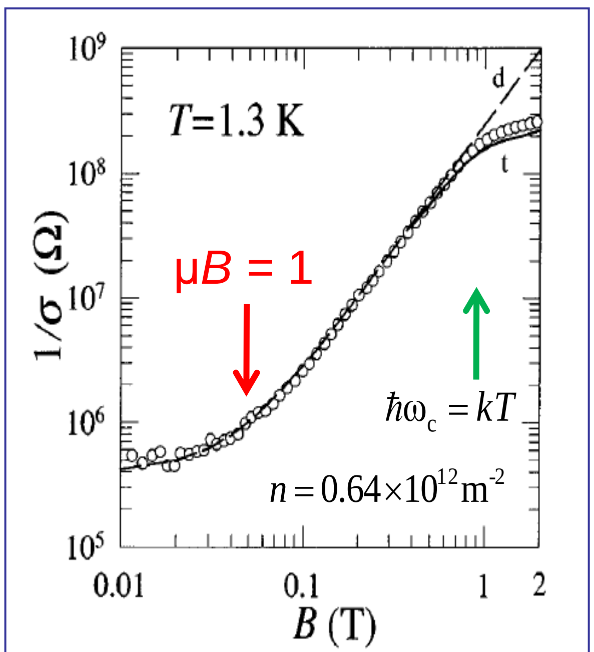
$$\frac{\tau_0}{\tau_B} \approx \frac{\hbar\omega_c}{\Delta}$$

$$\frac{\tau_0}{\tau_B} \approx \frac{\hbar\omega_c}{\hbar/\tau_B} = (\omega_c\tau_0)^{1/2} = (\mu B)^{1/2}$$

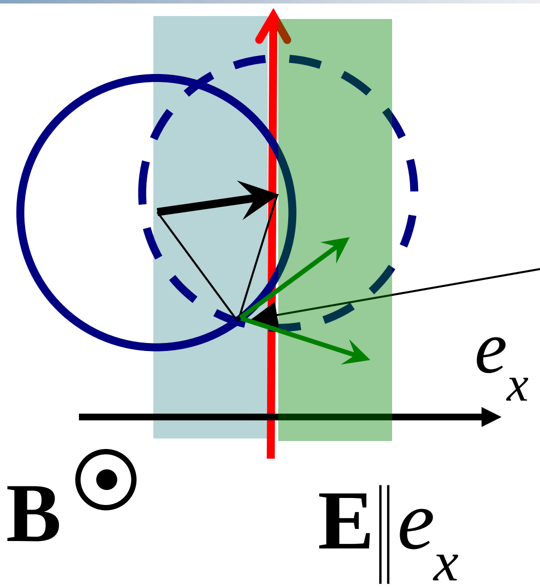


$$\nu(\varepsilon) = \nu_0\left(1 - 2\lambda\cos\frac{2\pi\varepsilon}{\omega_c}\right)$$

$$\lambda = \exp\left(-\frac{\pi}{\omega_c\tau_0}\right) \to \frac{\hbar\omega_c}{\Delta}$$



HIRO: Current



Red line crossings rate

$$j = \overrightarrow{j}^{+} - \overleftarrow{j}^{-}$$

Golden Rule:

$$j = \left(\overrightarrow{\int d\varphi d\varphi'} \int dx - \overleftarrow{\int d\varphi d\varphi'} \int dx \right) \int d\varepsilon$$

$$\times \nu(\varepsilon, x) f(\varepsilon, x)(1 - f(\varepsilon, x + \Delta X))\Gamma_{\varphi \to \varphi'}$$

Scattering rate: $\Gamma_{\varphi \to \varphi'} = \dfrac{1}{\tau_{\varphi \to \varphi'}} \dfrac{\nu(\varepsilon, x + \Delta X)}{\nu_0}$

HIRO: Current (cont)

$$j \propto \int dx \int d\epsilon \, [f(\epsilon, x) - f(\epsilon, x + \Delta X_{\varphi \to \varphi'})] \frac{1}{\tau_{\varphi \to \varphi'}}$$

$$\times \, \nu(\epsilon, x) \nu\left(\epsilon, x + \Delta X_{\varphi \to \varphi'}\right)$$

$$\left(1 - 2\lambda \cos \frac{2\pi\epsilon}{\omega_c}\right) \times \left(1 - 2\lambda \cos \frac{2\pi\left(\epsilon + eE\Delta X_{\varphi \to \varphi'}\right)}{\omega_c}\right)$$

Classics

SdHO

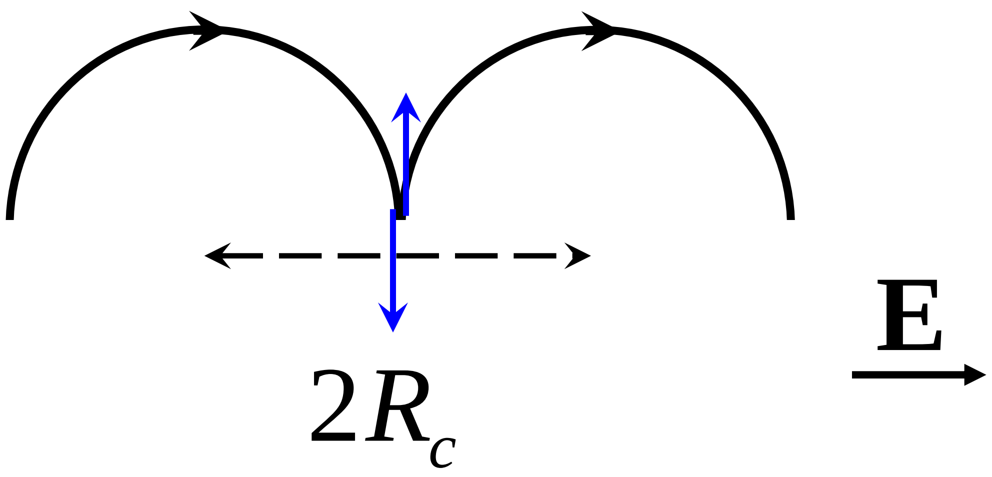
small: $T >> \omega_c$

?!

HIRO: Current (cont)

Scale separation $T \gg \omega_c$

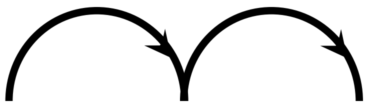
$$j \propto \lambda^2 E \left\langle \frac{\Delta X^2_{\varphi\to\varphi'}}{\tau_{\varphi\to\varphi'}} \cos\left[2\pi\epsilon_{dc}(\sin\varphi - \sin\varphi')\right] \right\rangle_{\text{angles}}$$



$$\epsilon_{dc} = \frac{eE(2R_c)}{\hbar\omega_c} \geq 1$$

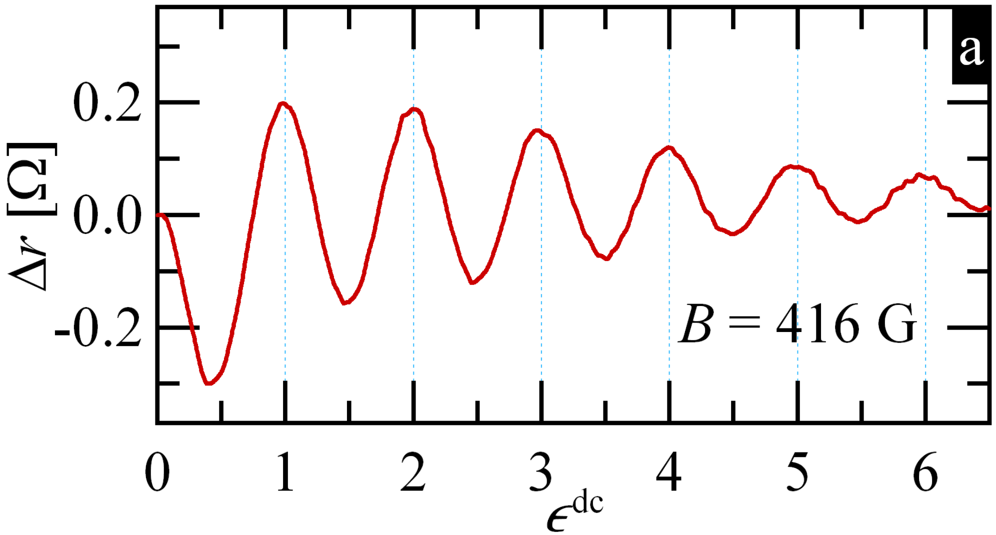
HIRO: Current (cont)

Backscattering



$$\epsilon_{dc} = \frac{eE(2R_c)}{\hbar\omega_c} \geq 1$$

$$\Delta r \propto \lambda^2 \frac{\cos 2\pi\epsilon_{dc}}{\tau_{\pi}}$$



Parameter: ϵ_{dc}

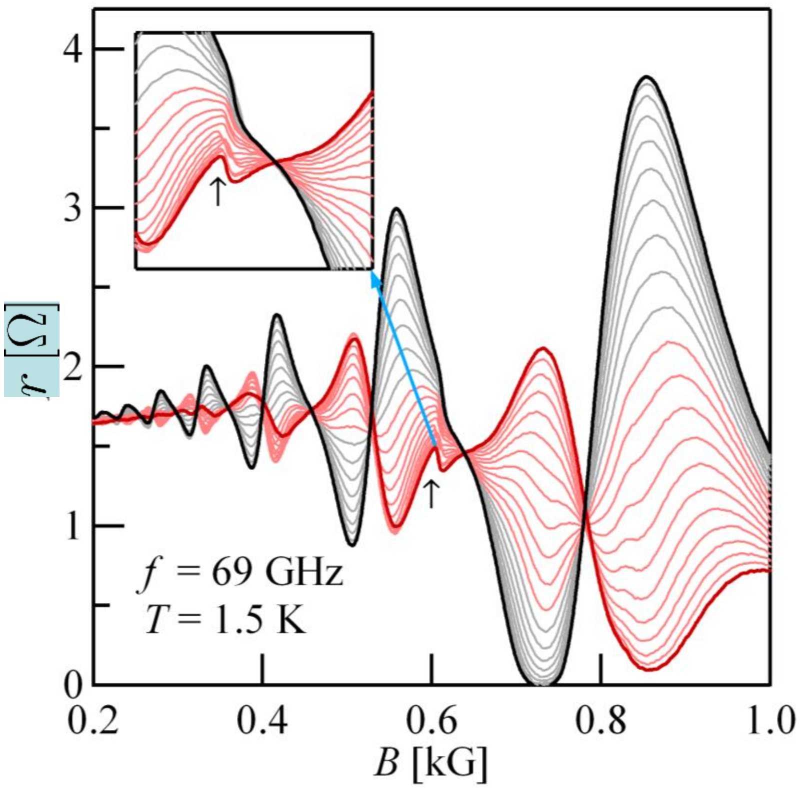
M.G. Vavilov, I. Aleiner, L.I. Glazman, 2007

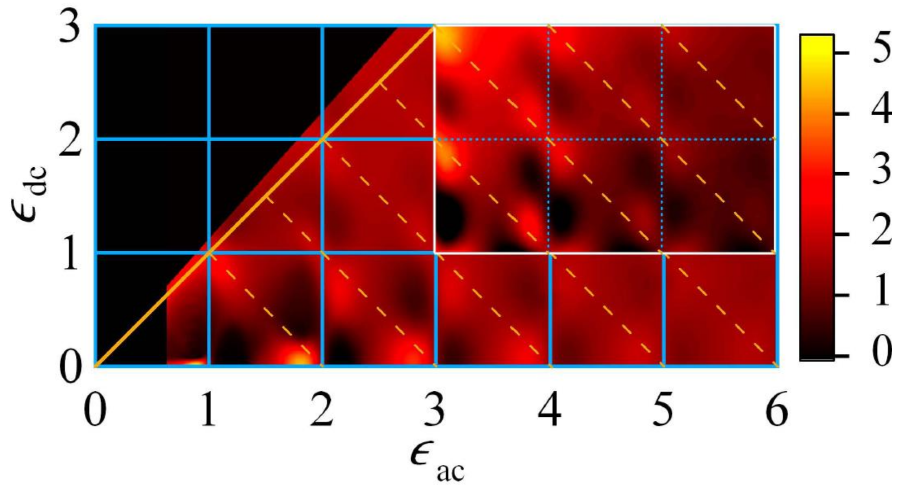
Outline

1. Experimental motivation
2. Hall induced resistance oscillations (HIRO)
3. AC and DC excitation: low power
4. AC and DC excitation: high power
5. MIRO: Power dependence
6. Conclusions

AC+DC

Combined (dc) current and (ac) excitation





Strong effect of current excitation

Zhang, Zudov, Pfeiffer, West, Phys. Rev. Lett. **98**, 106804 (2007)
Zhang, Zudov, Pfeiffer, West, Physica E **40**, 982 (2008)

AC+DC

Hall Field DC parameter

$$\epsilon_{dc} = \frac{eE(2R_c)}{\hbar\omega_c} \geq 1$$

Microwave AC parameter

$$\epsilon_{ac} = \frac{\omega}{\omega_c}$$

$$\Delta r_{xx} \propto \left(1 - 2\mathcal{P}_\omega\right)\cos\epsilon_{\rm dc}$$

$$+\mathcal{P}_\omega \frac{\epsilon_{\rm dc} + \epsilon_{\rm ac}}{\epsilon_{\rm dc}} \cos(\epsilon_{\rm dc} + \epsilon_{\rm ac}) + \mathcal{P}_\omega \frac{\epsilon_{\rm dc} - \epsilon_{\rm ac}}{\epsilon_{\rm dc}} \cos(\epsilon_{\rm dc} - \epsilon_{\rm ac})$$

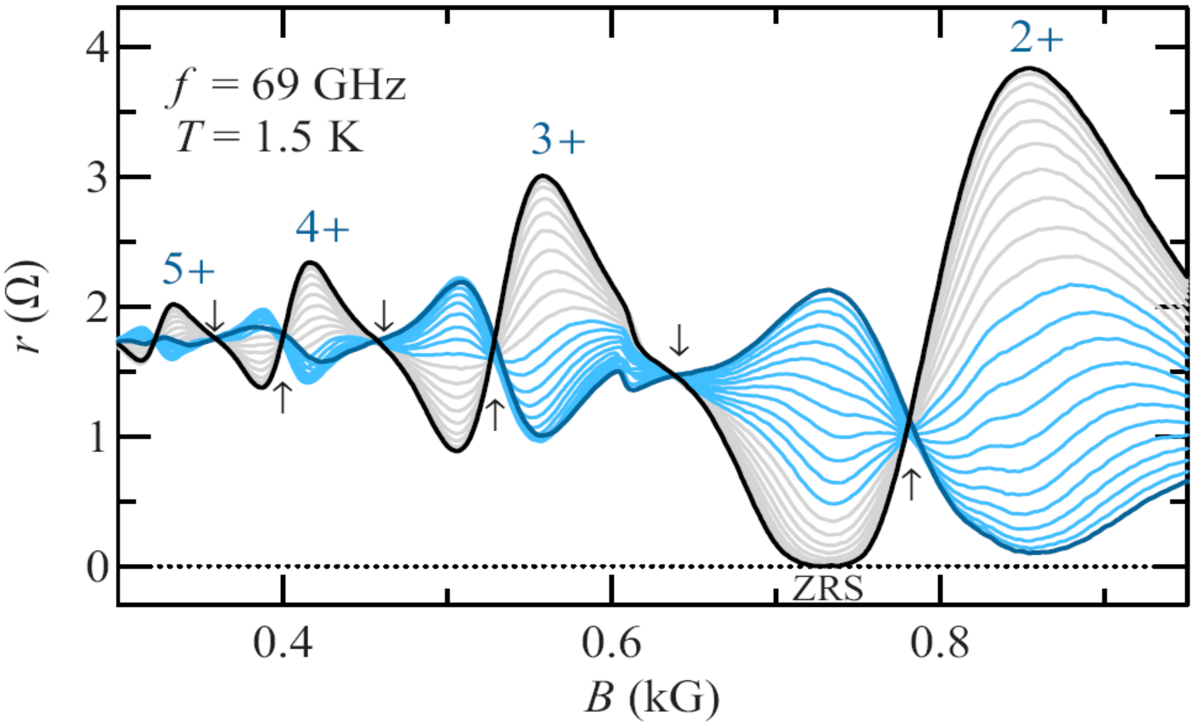
Absorption

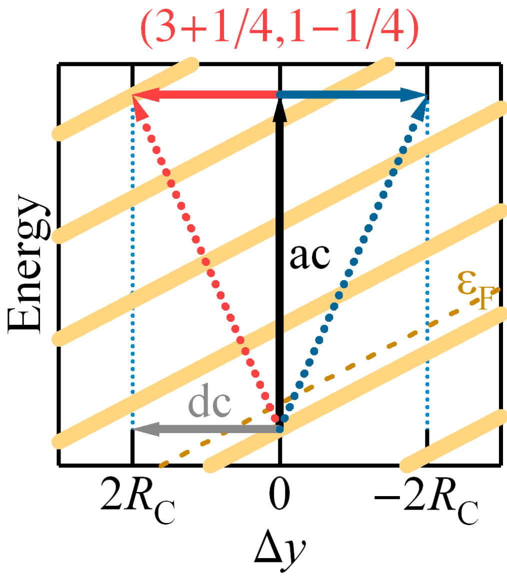
Emission

$$\mathcal{P}_\omega = \frac{v_F^2 e^2 E_\omega^2}{\omega^2 \left(\omega \mp \omega_c\right)^2}$$

M.K., M.G. Vavilov 2008

ac/dc-induced oscillations in differential resistivity



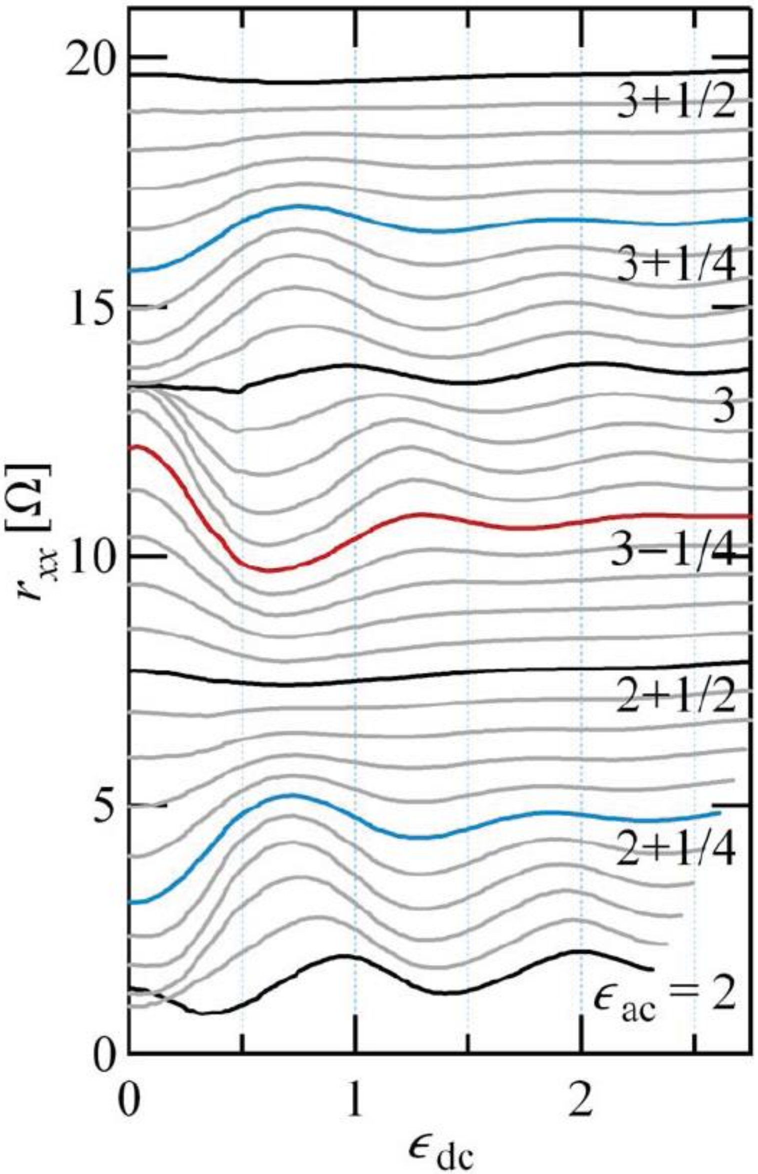


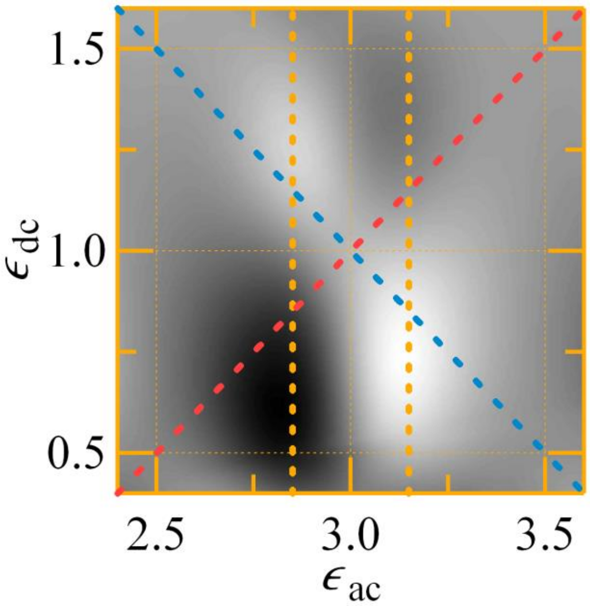
- Explained by a **single-photon** "displacement" mechanism:

$$\boxed{\Delta r \propto \epsilon_{\rm dc}^{-1}\left[(\epsilon_{\rm ac}+\epsilon_{\rm dc})\cos(\epsilon_{\rm ac}+\epsilon_{\rm dc})-(\epsilon_{\rm ac}-\epsilon_{\rm dc})\cos(\epsilon_{\rm ac}-\epsilon_{\rm dc})\right]}$$

Zhang, Zudov, Pfeiffer, West, Phys. Rev. Lett. **98**, 106804 (2007)
Hatke, Chiang, Zudov, Pfeiffer, West, Phys. Rev. B **77**, 201304(R) (2008)
Khodas and Vavilov, PRB (2008)

Experiment (closer look)





Theoretical prediction

$$(\epsilon_{\rm ac}, \epsilon_{\rm dc})^{+} \simeq (n \pm 1/4, m \mp 1/4)$$
$$(\epsilon_{\rm ac}, \epsilon_{\rm dc})^{-} \simeq (n \pm 1/4, m \pm 1/4)$$

Outline

1. Experimental motivation
2. Hall induced resistance oscillations (HIRO)
3. AC and DC excitation: low power
4. AC and DC excitation: high power
5. MIRO: Power dependence
6. Conclusions

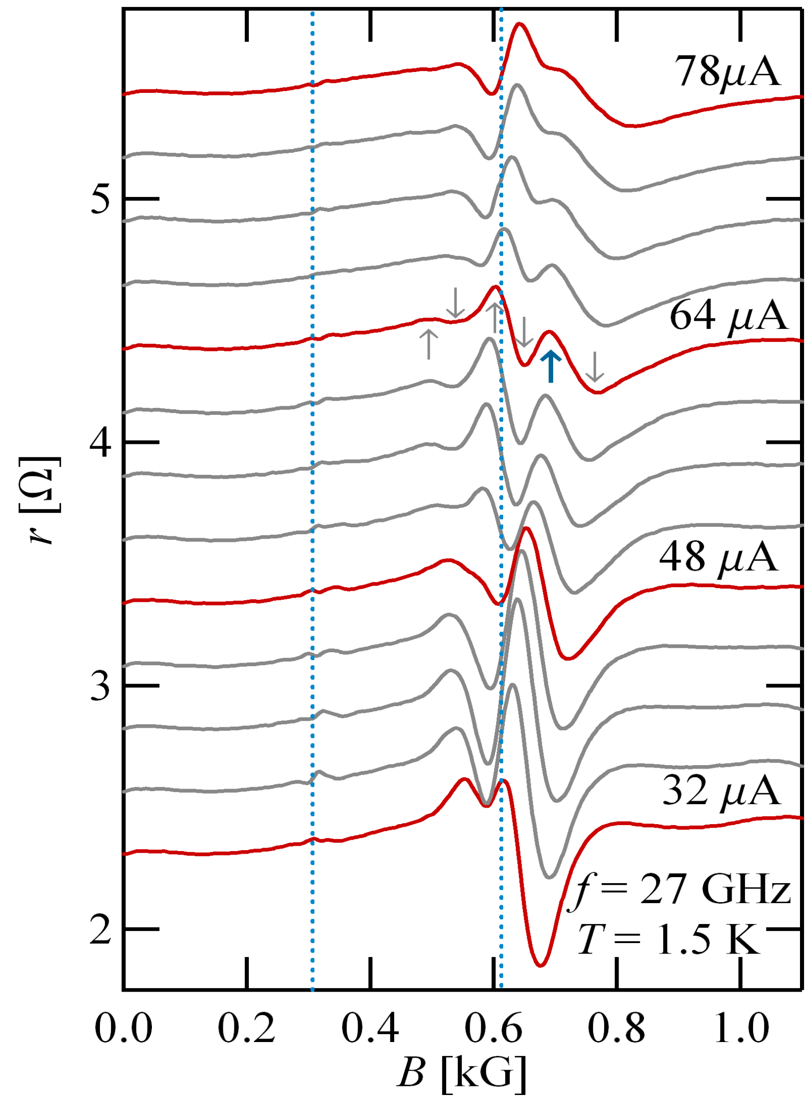
High power: new oscillations

- <u>Non-zero</u> current:

  new oscillations!

  – ***Multiple*** maxima and minima in the narrow range around cyclotron resonance which move to higher *B* with increasing *I*

- ***Qualitatively different*** from all magneto-resistance oscillations reported earlier!

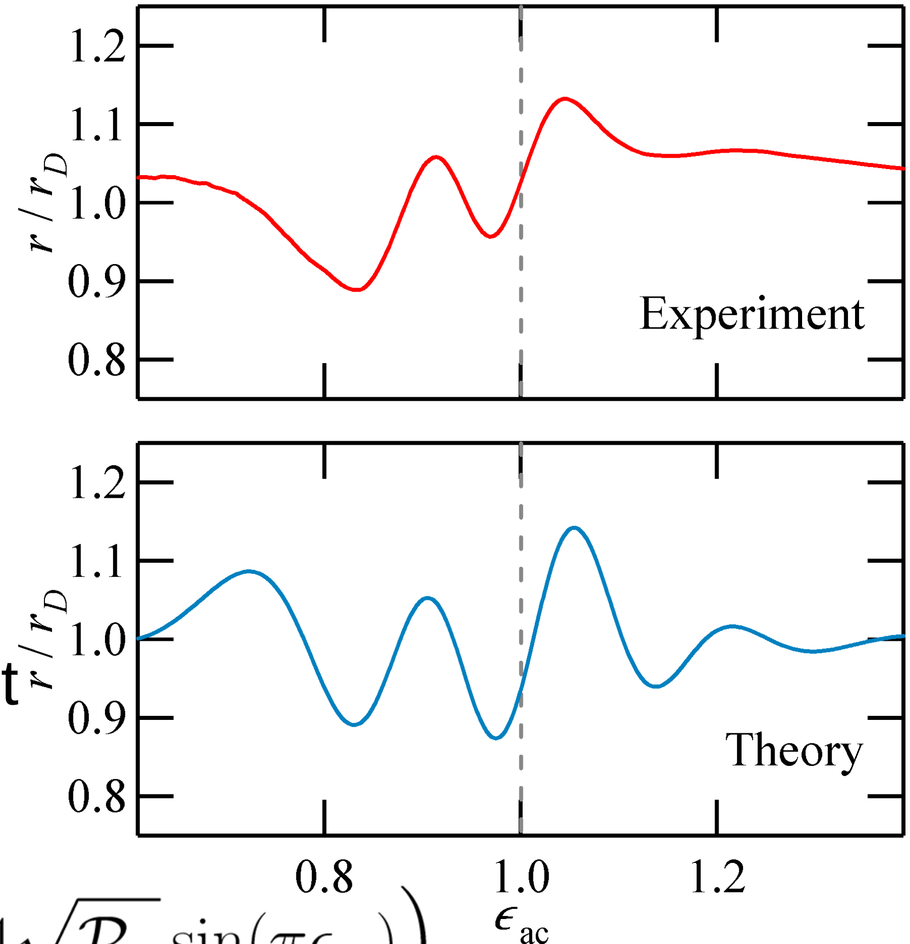


M. K., H.-S. Chiang, A.T. Hatke, M.A. Zudov M.G. Vavilov, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. 104, 206801 (2010).

Experiment vs. Theory

- Qualitative agreement
  - Number of oscillations and their positions

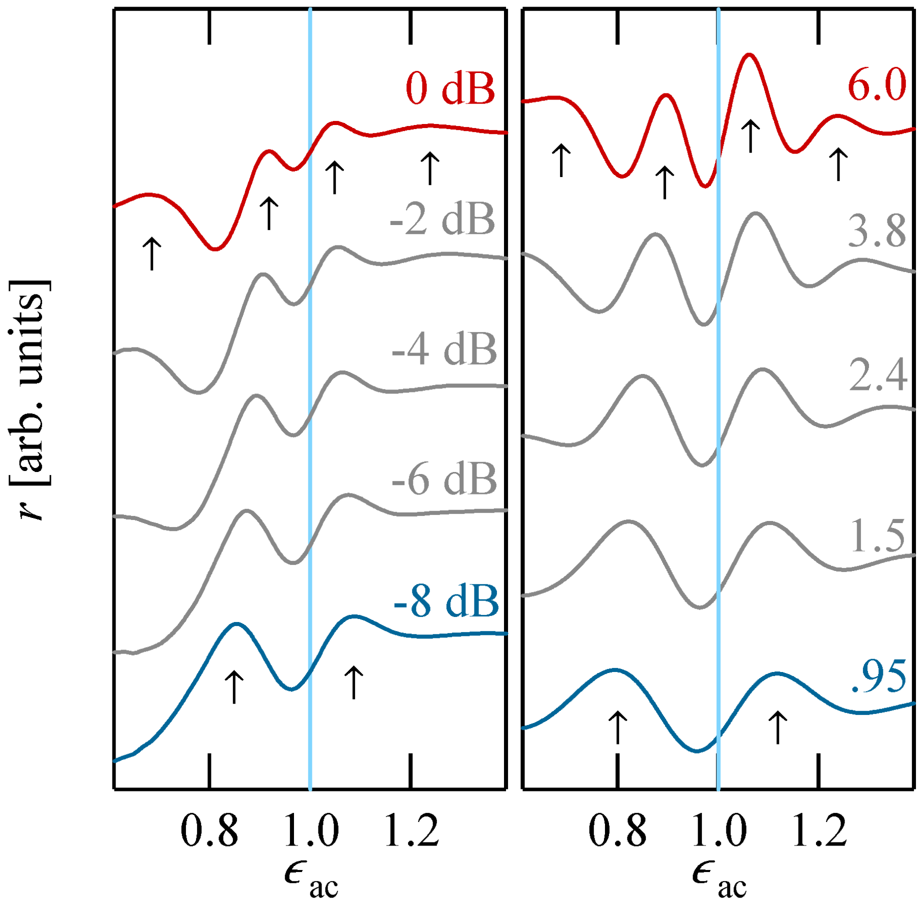
- Quantitative agreement
  - Amplitude of oscillations
    - We use $\tau_{tr}/\tau_{\pi} \approx 0.18$ obtained from Dingle plot analysis of HIRO



$$\frac{\delta r}{r_D} = \frac{(4\delta)^2 \tau_{tr}}{\pi \tau_{\pi}} \left[\cos(2\pi\epsilon_{dc}) J_0 \left(4\sqrt{\mathcal{P}_\omega} \sin(\pi\epsilon_{ac}) \right) - \frac{2\epsilon_{ac}}{\epsilon_{dc}} \sqrt{\mathcal{P}_\omega} \sin(2\pi\epsilon_{dc}) \cos(\pi\epsilon_{ac}) J_1 \left(4\sqrt{\mathcal{P}_\omega} \sin(\pi\epsilon_{ac}) \right) \right]$$

M. K., H.-S. Chiang, A.T. Hatke, M.A. Zudov M.G. Vavilov, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. 104, 206801 (2010).

Dependence on Microwave Intensity



Microwave power affects:

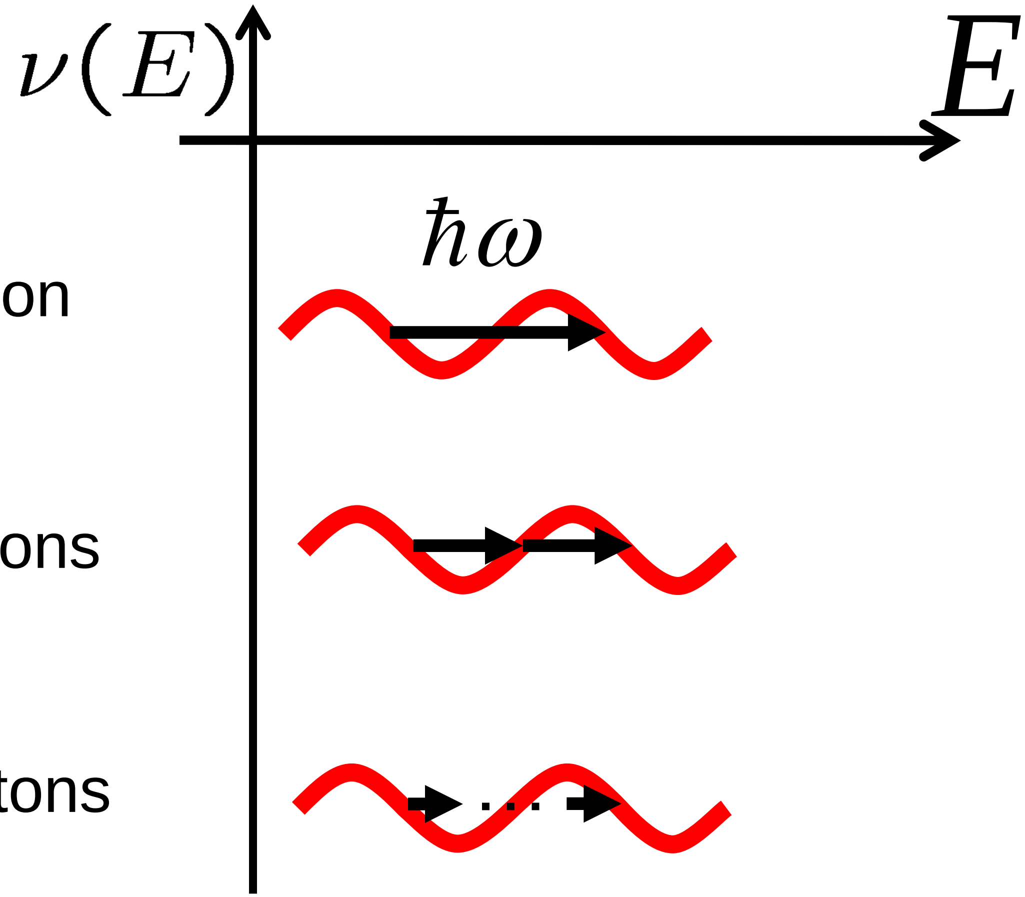
- Number of oscillations
- Period of oscillations
- Position of oscillations

Theory captures all three reasonably well!

M.K., H.-S. Chiang, A.T. Hatke, M.A. Zudov M.G. Vavilov,
L.N. Pfeiffer, K.W. West,
Phys. Rev. Lett. 104, 206801 (2010).

Multi-photon processes

Why multi-photon ?



1: photon $\quad \epsilon_{\mathrm{ac}} = 1$

2: photons $\quad \epsilon_{\mathrm{ac}} = 1/2$

N: photons $\quad \epsilon_{\mathrm{ac}} = 1/N$

Experimental motivation

- High power, near CR: $\epsilon_{\rm ac} = 1+\delta,\ \delta \ll 1 \Rightarrow \sin(\pi\epsilon_{\rm ac}) \simeq -\pi\delta$

$$\frac{\delta r}{r_D} \propto \cos\left(4\sqrt{\mathcal{P}_\omega}\sin(\pi\epsilon_{\rm ac}) - \frac{1}{4} - 2\pi\epsilon_{\rm dc}\right) \simeq \cos\left[2\pi\left(2\sqrt{\mathcal{P}_\omega}\delta + \frac{1}{8} + \epsilon_{\rm dc}\right)\right]$$

- Maxima positions:

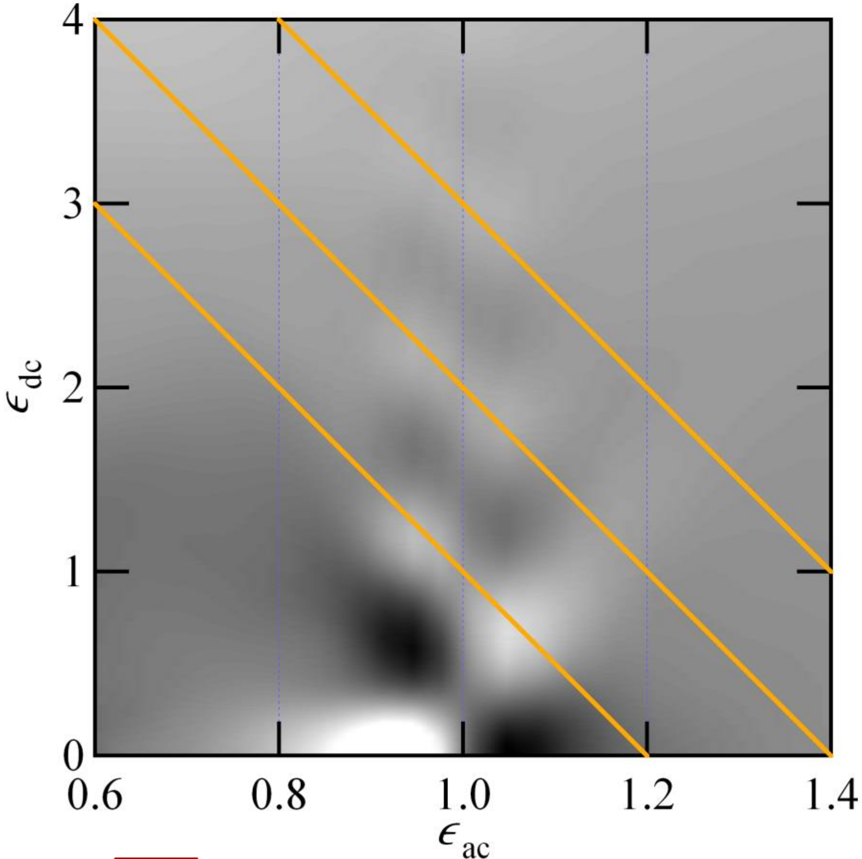
$$2\sqrt{\mathcal{P}_\omega}\cdot\epsilon_{\rm ac} + \epsilon_{\rm dc} \simeq n + \text{const}$$

- Effective number of participating photons:

$$N^* \simeq 2\sqrt{\mathcal{P}_\omega}$$

  – Low power (single photon):

$$\epsilon_{\rm ac} + \epsilon_{\rm dc} \simeq n$$



$$2\sqrt{\mathcal{P}_\omega} \simeq 5 \Rightarrow \mathcal{P}_\omega \simeq 6.3$$

Theory: approach

$$\hat{H} = \frac{1}{2m}\Big[\underbrace{-i\nabla - e\mathbf{A}}\, - e\mathbf{A}_{\mathrm{el}}(t)\Big]^2$$

$$\Downarrow$$

$$\hat{U}_t = \exp\left(-i\hat{\mathbf{p}}\zeta_t\right) \rightarrow \text{Guiding center trajectory}$$

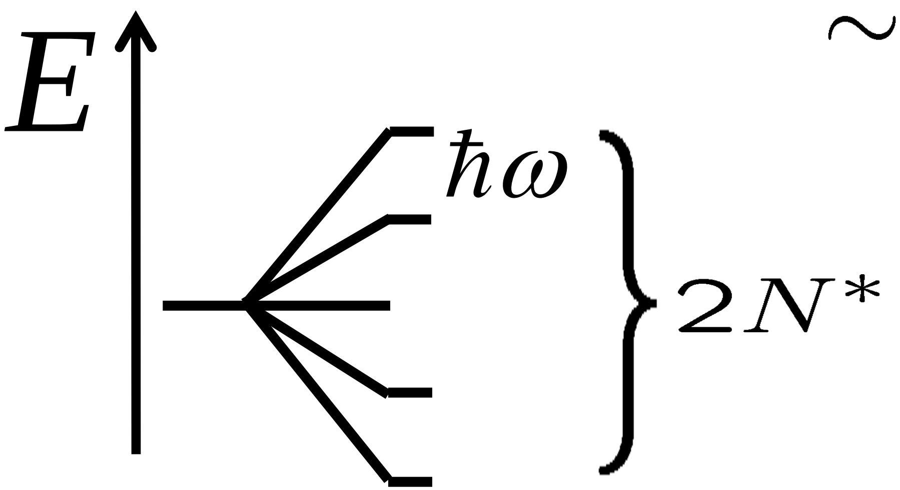
$$\downarrow$$

$$\hat{H}' = \frac{\mathbf{p}^2}{2m}$$

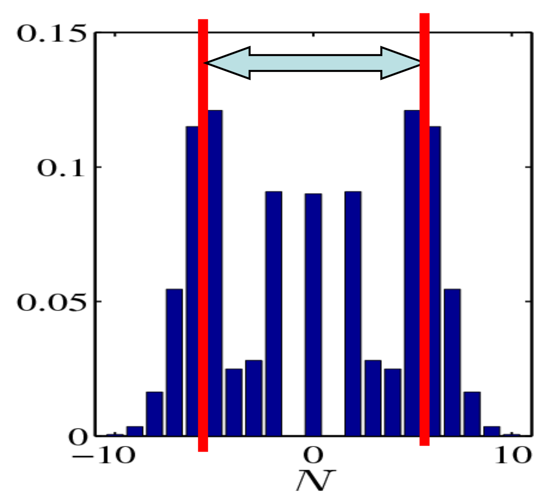
Floquet subbands

$$\omega_c \ll E_F \longrightarrow \text{Quasi-classics}$$

$$\psi_F = \psi_{\mathbf{p}} e^{\underbrace{-ip\mathbf{n}_\varphi \zeta_t - iEt}_{\sim \sum_N J_N(\sqrt{\mathcal{P}_\omega}) e^{-iN\omega t}}}$$



$$N^* \sim \sqrt{\mathcal{P}_\omega} \propto \frac{e\mathcal{E}_{ac} l}{\hbar\omega}$$



N^*

Impurity potential as a perturbation

1) Add impurity potential

2) Floquet basis

$$\psi = \sum_{\mathbf{k}} c_{\mathbf{k}}(t)\psi_{k,\varphi} e^{-iEt-ik\mathbf{n}_{\varphi}\zeta_t}$$

3) Transition amplitudes

$$i\hbar\dot{c}_{\mathbf{k}} = \sum c_{\mathbf{k}'}\hat{V}_{\mathbf{k}\mathbf{k}'} e^{i(E-E')t+ik(\mathbf{n}'_{\varphi}-\mathbf{n}_{\varphi})\zeta_t}$$

Impurity potential = perturbation

Impurity potential as a perturbation (cont)

1) Transition *probability*

$$\overline{\left|c_{\mathbf{k}}(t_f)\right|^2} = n\sum_{\mathbf{k}} |V_{\mathbf{k}'\mathbf{k}}|^2 \int_{t_i}^{t_f} dt' \int_{t_i}^{t_f} dt\, e^{i(E-E')(t'-t)}$$

$$\times\, \overline{e^{ip(\mathbf{n}'_\varphi - \mathbf{n}_\varphi)\zeta_{t',t}}} \Longrightarrow \sum_N a^{(N)}_{\varphi\varphi'} e^{-iN\omega(t-t')}$$

2) Transition *rate*

$$\frac{d}{dt}\overline{|c_{\mathbf{k}}|^2} = \sum_N \int \frac{d\varphi'}{2\pi} a^{(N)}_{\varphi\varphi'} \frac{\nu(\epsilon + N\omega)}{\tau_{\varphi\varphi'}}$$

Golden rule
(in disguise)

Kinetic equation

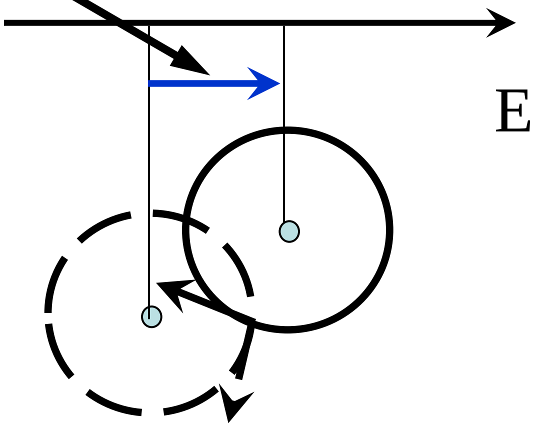
$\omega_c \ll E_F$ → Quasi-classics

$$\omega_c \partial_\varphi f_{\varepsilon;\varphi} = \mathrm{St}\{f\}_{\varepsilon;\varphi}$$

N-photon processes

$$\mathrm{St}\{f\} = \sum_N \int \frac{d\varphi'}{2\pi} \Gamma^{(N)}_{\varphi\varphi'} [f_{\varphi'}(\varepsilon + \boxed{W_{\varphi\varphi'}} + \boxed{N\hbar\omega}) - f_\varphi(\varepsilon)]$$

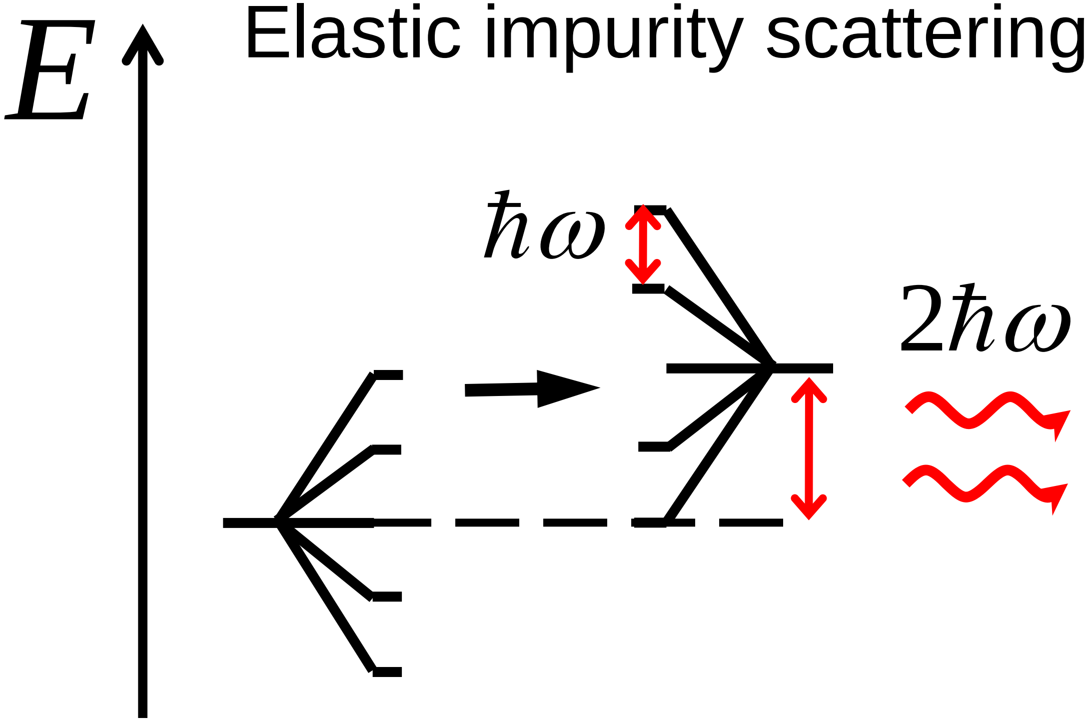
$$\Gamma^{(N)}_{\varphi\varphi'} = a^{(N)}_{\varphi\varphi'} \frac{\nu(\epsilon + W_{\varphi\varphi'} + N\hbar\omega)}{\tau_{\varphi\varphi'}}$$



# of photons ??

Multi-photon processes

Elastic impurity scattering



$$\Delta N \approx 2\sqrt{\mathcal{P}_\omega}$$

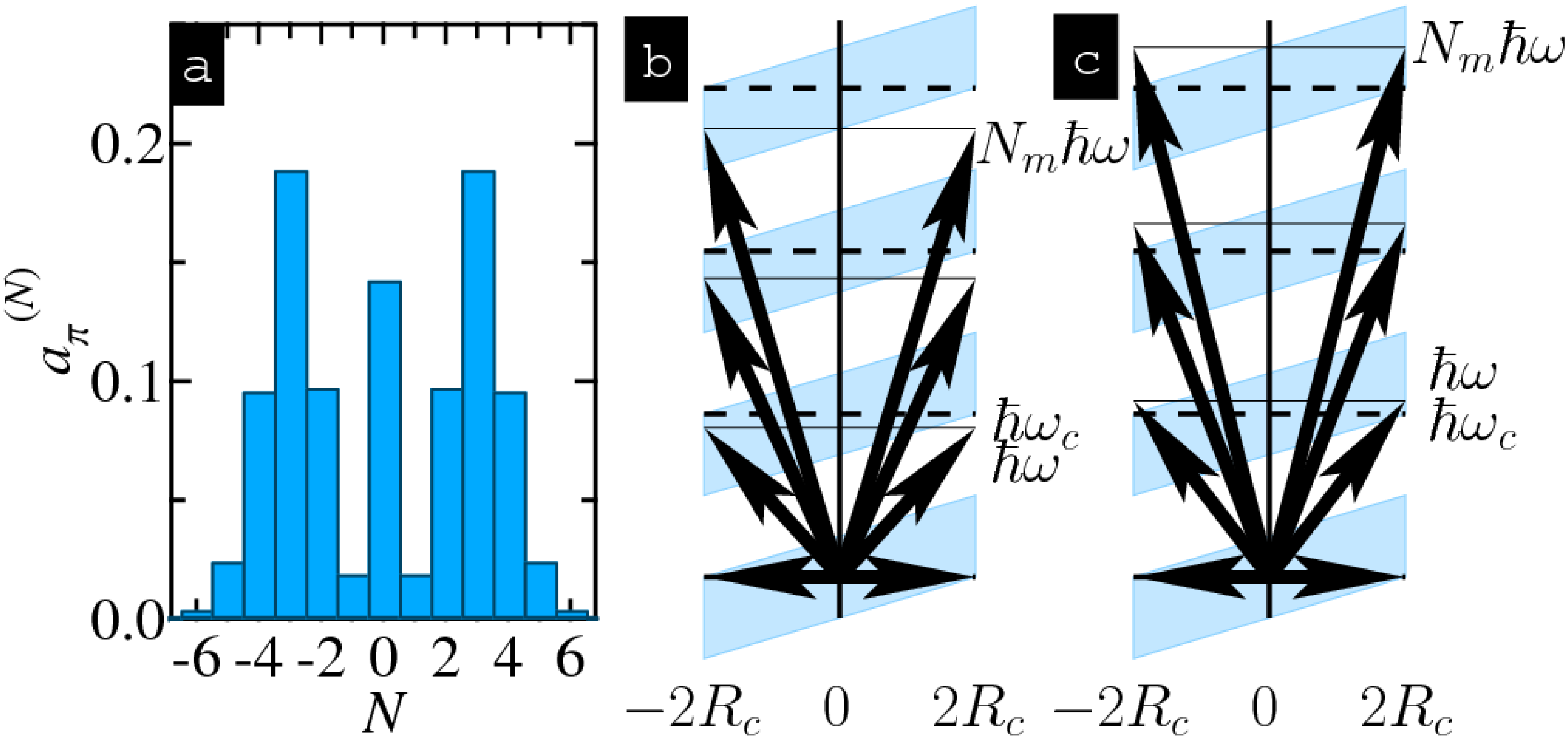
$$\sqrt{\mathcal{P}_\omega} \propto \frac{e\mathcal{E}_{ac} l}{\hbar\omega}$$

Sharp cut-off ??

$$a_{\varphi\varphi'}^{(N)} = J_N^2(\sqrt{\mathcal{P}_\omega}(1-\cos(\varphi-\varphi')))$$

Yes !!

Multi-photon processes at work



# of photons

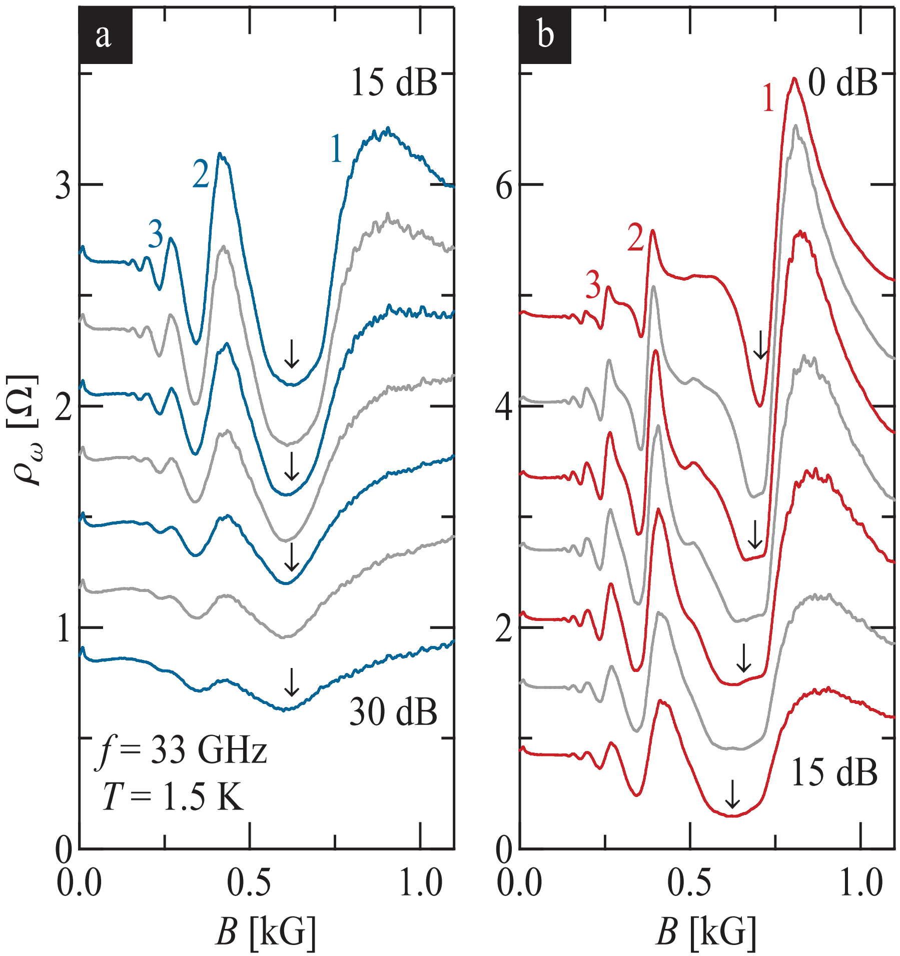
Maximal resistance

Minimal resistance

Outline

1. Experimental motivation
2. Hall induced resistance oscillations (HIRO)
3. AC and DC excitation: low power
4. AC and DC excitation: high power
5. MIRO: Power dependence
6. Conclusions

MIRO: Power dependence



MIRO:
Both amplitude and phase are affected by power increase

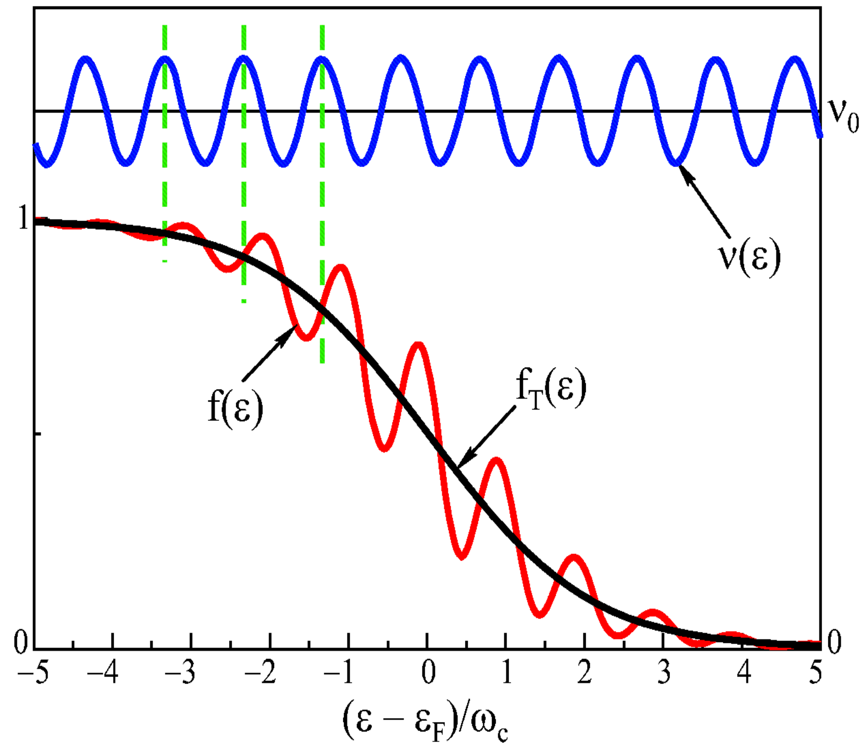
Displacement mechanism is insufficient

Inelastic mechanism

I.A. Dmitriev, A.D.Mirlin, and D.G. Polyakov, Phys. Rev. Lett. **91**, 226802 (2003)
I.A. Dmitriev, M.G. Vavilov, I.L. Aleiner, A.D. Mirlin, and D.G. Polyakov, Phys. Rev. B **71**, 115316 (2005)

MIRO: Inelastic Mechanism

Non-equilibrium occupation isotropic

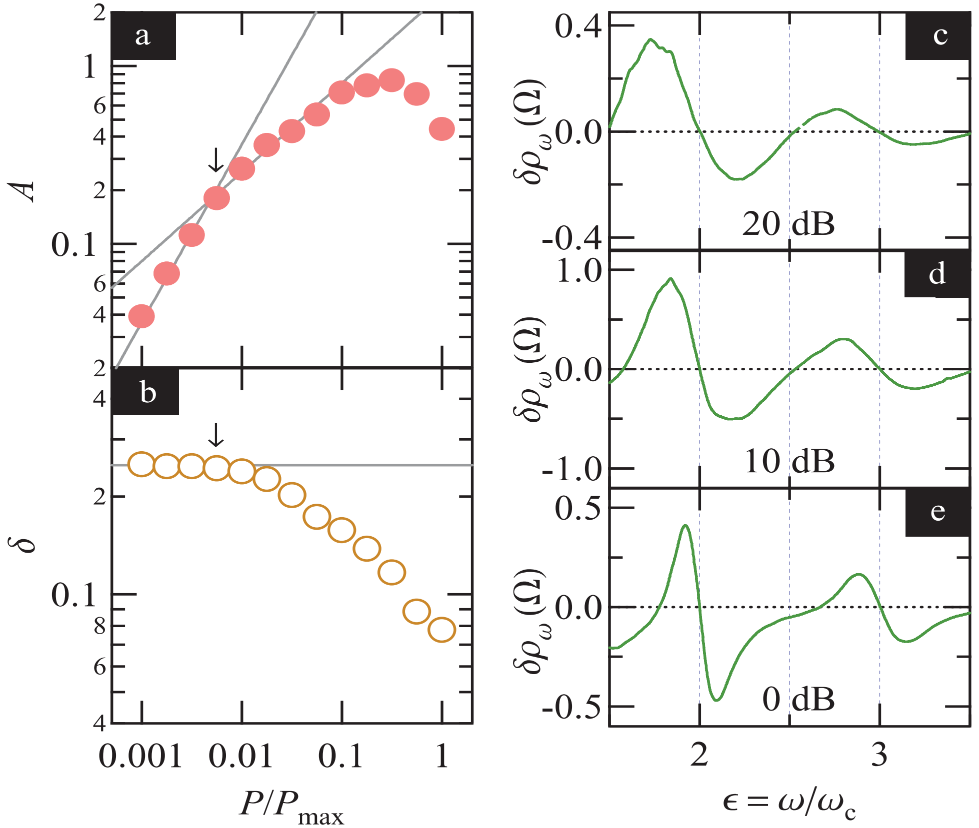


Stabilized by *inelastic* processes

$$\Delta r \propto \frac{\tau_{inelastic}}{\tau_{tr}}$$

Dominates at low T

MIRO: Power Crossover



Maxima found at

$$\epsilon^{+}_{ac} = n - \delta$$

phase

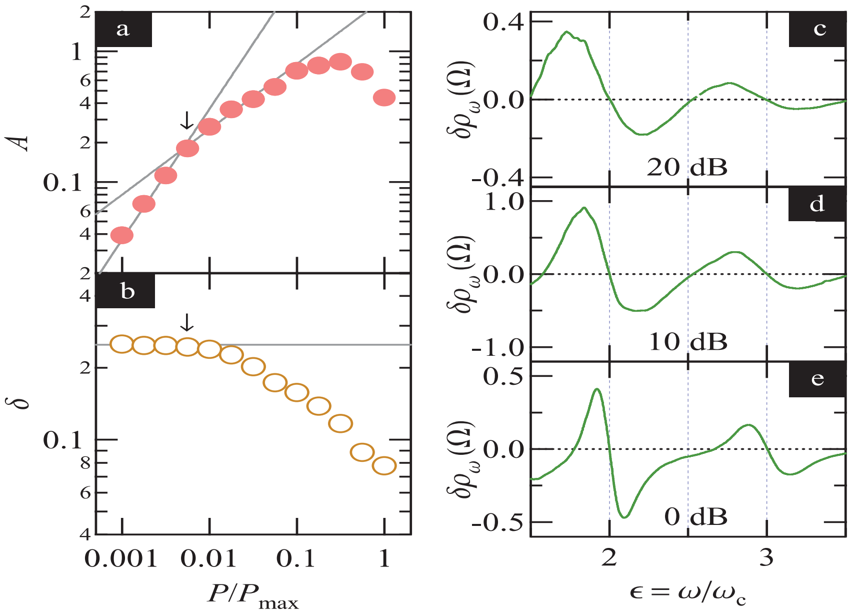
$$A \propto \frac{\delta\rho(\epsilon^{+}_{ac})}{\lambda^2 \epsilon^{+}_{ac}}$$

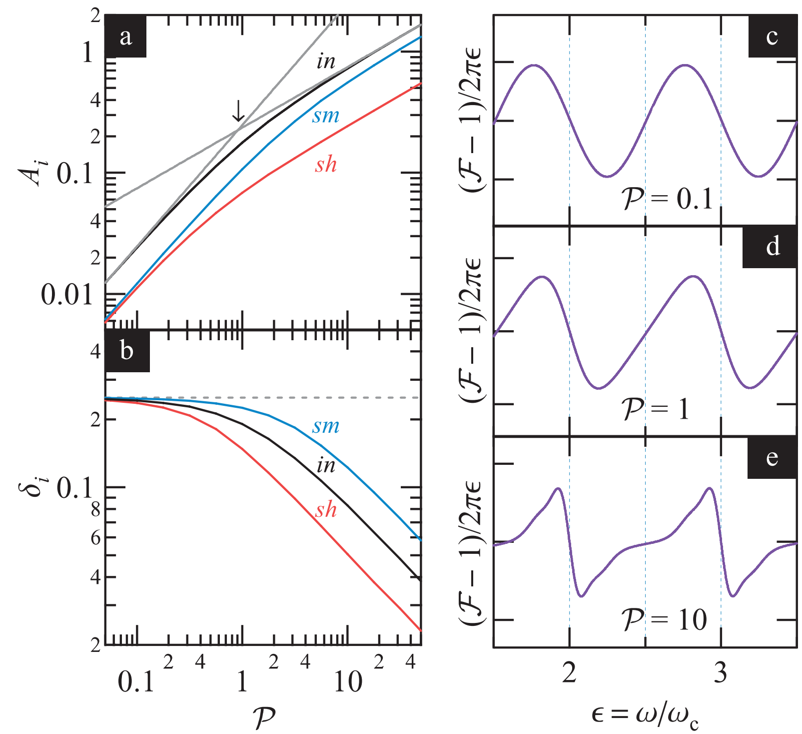
Amplitude

$$\mathcal{P} \ll 1 \xrightarrow{\text{Crossover}} \mathcal{P} \gg 1$$

MIRO: Power Crossover (cont)

	$\mathcal{P} \ll 1$	$\mathcal{P} \gg 1$
$\delta \sim$	$1/4$	$1/\sqrt{\mathcal{P}}$
$A \sim$	$\mathcal{P}$	$\sqrt{\mathcal{P}}$





Inelastic and Displacement mechanisms

Similar behavior

Conclusions

- Quasi-classical transport theory: migrating guiding centers
- Strong currents favor backscattering and displacement mechanism
- High power increases the number of emitted photons and leads to crossover in amplitude and phase of oscillations
- MIRO: inelastic mechanism is as important as displacement and is expected to dominate at low T
- The amplitude for both mechanisms cross over from linear to sublinear in power concomitantly with the decrease in phase

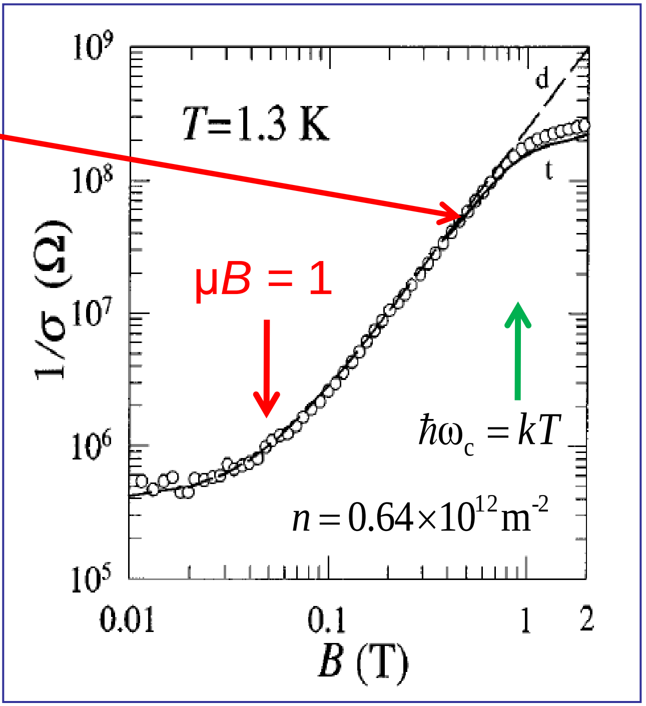
Thank you!

Thank you!

Drude model

$$\frac{\sigma_0}{\sigma_{xx}} = 1 + \mu^2 B^2$$

$$\sigma_0 = ne\mu = \frac{ne^2\tau_0}{m}$$



$$\mu B = \omega_c \tau_0$$

$$\omega_c = \frac{eB}{m}$$

Einstein relation
Diffusion

$$\boxed{\sigma_{xx} = \frac{ne^2}{kT}\frac{L^2}{\tau_B} \cong \frac{\sigma_0}{\mu^2 B^2}\frac{\tau_0}{\tau_B}}$$

$$R_c = \frac{(2mkT)^{1/2}}{eB} \qquad \frac{\tau_0}{\tau_B} = 1$$

Classical cyclotron orbit

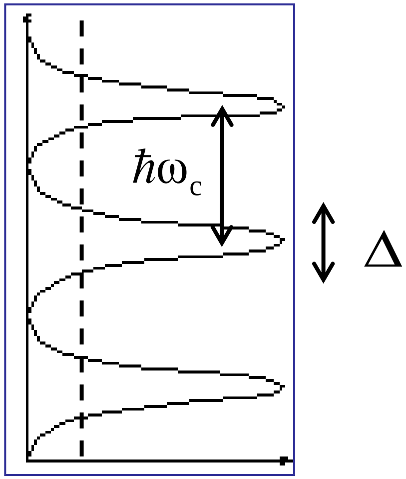
Non-degenerate

BUT $\omega_c \tau_0 = \mu B >> 1$

Landau levels $E_N = (N + 0.5)\hbar\omega_c$

$$\frac{\tau_0}{\tau_B} \approx \frac{\hbar\omega_c}{\Delta}$$

$$\frac{\tau_0}{\tau_B} \approx \frac{\hbar\omega_c}{\hbar/\tau_B} = (\omega_c\tau_0)^{1/2} = (\mu B)^{1/2}$$



Single particles
Collision broadened
(SCBA):
Enhanced scattering?

AC+DC (cont)

$$f \approx f_{FD} \; ?$$

Inelastic processes?

$$\omega_c \partial_\varphi f = \mathrm{St}_{\mathrm{dc}}\{f\} + \mathrm{St}_{\mathrm{mw}}\{f\} + \mathrm{St}_{ee}\{f\}$$

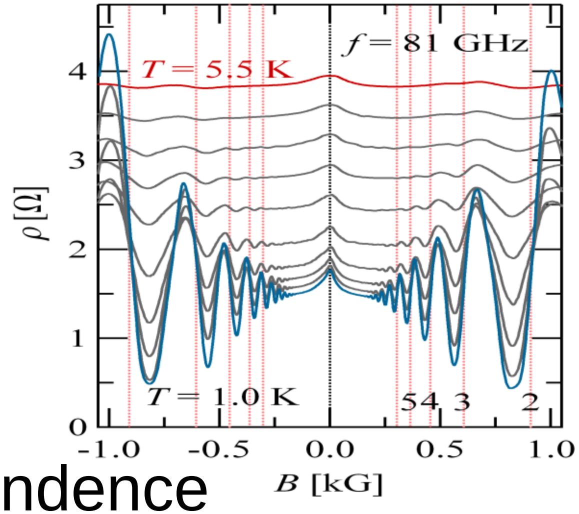
$$\frac{\Delta r_{in}}{\Delta r_{disp}} \approx \frac{\tau_0}{\tau(\pi)\varepsilon_{dc}} \leq 1$$

$$\varepsilon_{dc} = \frac{eE(2R_c)}{\hbar\omega_c} \geq 1$$

Displacement mechanism dominates

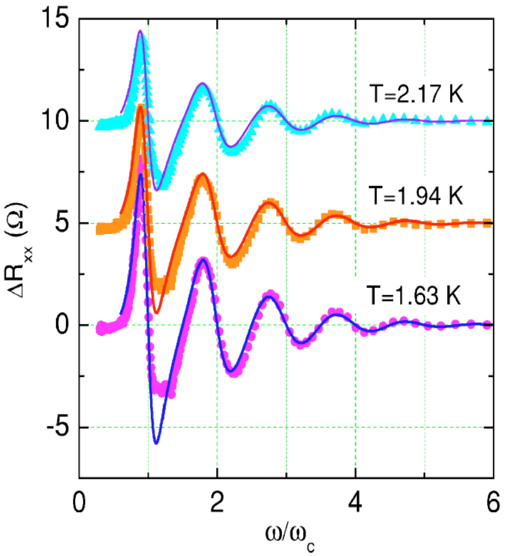
MIRO: Temperature dependence

$$\delta\rho \simeq A(T)\epsilon_{ac}\exp\left[-2\pi/\omega_c\tau_q\right]$$



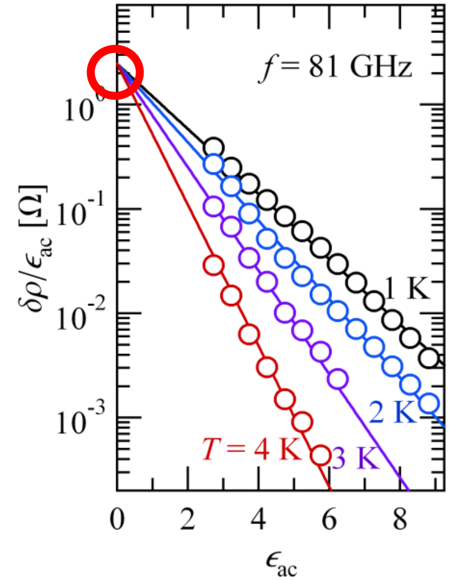
stronger *T* dependence

weak *T* dependence



S.A. Studenikin, PRB 2005

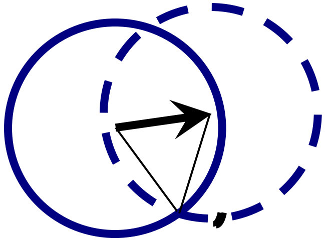
$$\boxed{A(T)\ ?}$$

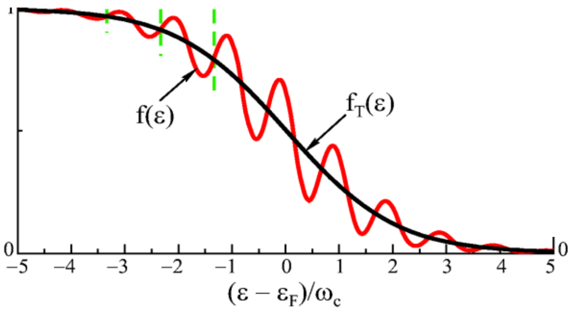


A.T. Hatke, PRL 2009

Results: mechanisms of MIRO

$$\delta \mathbf{j} \propto \mathbf{E}_{\mathbf{dc}} E_{mw}^2$$





$E_{dc} + E_{mw}$ ⇨ **<u>Time dependent</u>** occupation

E_{mw} ⇨ **<u>Second angular</u>** harmonics of distribution function

Results (cont): Displacement

$$\delta\rho \simeq A(T)\epsilon_{ac} \exp\left[-2\pi/\omega_c \tau_q\right]$$

Displacement

$$\boxed{A \propto \frac{\tau_{tr}}{\tau^*}}$$

$$\frac{1}{\tau_{tr}} = \left\langle \frac{1-\cos\varphi}{\tau_\varphi} \right\rangle_\varphi$$

$$\frac{1}{\tau^*} = \left\langle \frac{(1-\cos\varphi)^2}{\tau_\varphi} \right\rangle_\varphi$$

MW assisted scattering

$$\frac{1}{\tau_{\text{assisted}}} \propto E_{mw}^2 \frac{1-\cos\varphi}{\tau_\varphi}$$

Kohn's theorem

Results (cont)

$$\delta\rho \simeq A(T)\epsilon_{ac}\exp\left[-2\pi/\omega_c\tau_q\right]$$

Inelastic $\boxed{A \propto \frac{\tau_{\text{inel}}}{\tau_{tr}}}$ Temperature dependence

Photovoltaic, Quadrupole

$\boxed{A \propto \frac{\tau_q^{\text{dis}}}{\tau_{tr}}}$ Disorder Quantum Time

$$\frac{1}{\tau_q^{\text{dis}}} = \left\langle \frac{1}{\tau_\varphi} \right\rangle_\varphi$$

Results (cont)

$$\delta\rho \simeq A(T)\epsilon_{ac}\exp\left[-2\pi/\omega_c\tau_q\right]$$

Displacement

$$A \propto \frac{\tau_{tr}}{\tau^*}$$

Inelastic:

$$A \propto \frac{\tau_{\mathrm{inel}}}{\tau_{tr}}$$

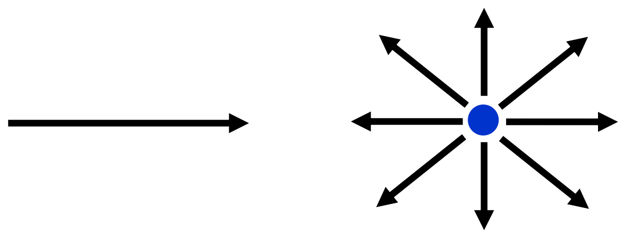
Photovoltaic Quadrupole

$$A \propto \frac{\tau_q^{\mathrm{dis}}}{\tau_{tr}}$$

Dominant ?

Results: mixed disorder

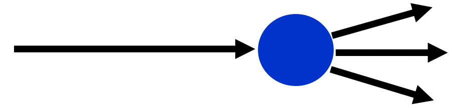
Sharp disorder:



$$\frac{1}{\tau_{tr}} \approx \frac{1}{\tau_{sharp}}$$

<<

Smooth disorder:



$$\frac{1}{\tau_{q}} \approx \frac{1}{\tau_{smooth}}$$

What if $\frac{1}{\tau_{sharp}} \ll \frac{1}{\tau_{inel}(T)} \ll \frac{1}{\tau_{smooth}}$?

$$\boxed{A_{disp} \approx 1} \gg A_{inel} \approx \frac{\tau_{inel}}{\tau_{sharp}} \gg A_{quadr,phot} \approx \frac{\tau_{smooth}}{\tau_{sharp}}$$

Temperature independent MIRO !!!

Results: smooth vs. sharp disorder

Smooth disorder:

Inelastic contribution is dominant

⇓

Strong *T* dependence

Sharp disorder:

Displacement contribution is dominant

⇓

Weak *T* dependence

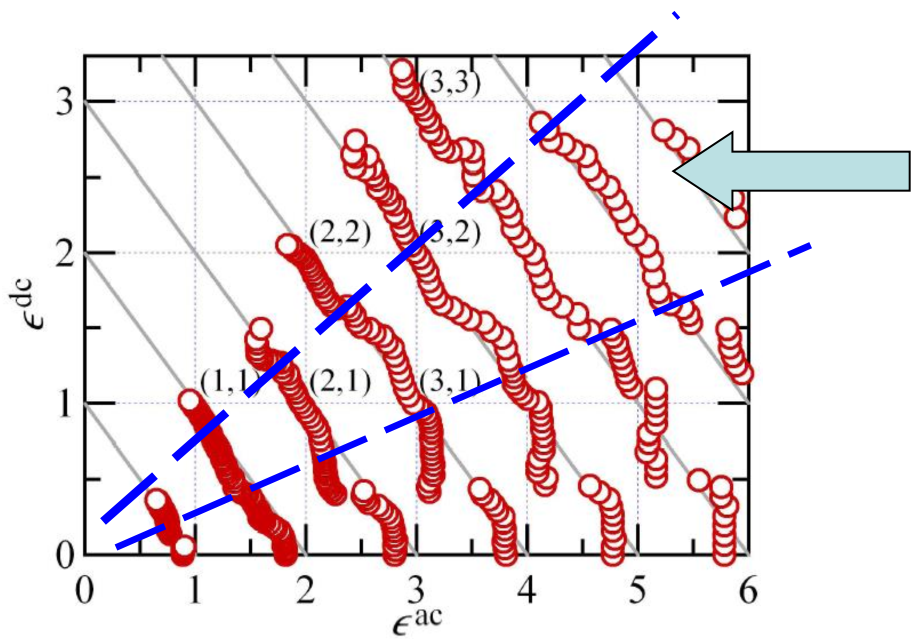
Results

Differential magnetoresistance

$$\rho_{xx} \propto (1 - 2\mathcal{P}_\omega)\cos\epsilon_{\mathrm{dc}} + \mathcal{P}_\omega \frac{\epsilon_{\mathrm{dc}} + \epsilon_{\mathrm{ac}}}{\epsilon_{\mathrm{dc}}}\cos(\epsilon_{\mathrm{dc}} + \epsilon_{\mathrm{ac}}) + \mathcal{P}_\omega \cancel{\frac{\epsilon_{\mathrm{dc}} - \epsilon_{\mathrm{ac}}}{\epsilon_{\mathrm{dc}}}\cos(\epsilon_{\mathrm{dc}} - \epsilon_{\mathrm{ac}})}$$

Condition of maxima:

$$\boxed{\epsilon_{\mathrm{ac}} + \epsilon_{\mathrm{dc}} \simeq n}$$



Results (closer look)

Differential magnetoresistance maxima

$$\rho_{xx} \propto (1 - 2\mathcal{P}_\omega)\cos\epsilon_{\rm dc} + \mathcal{P}_\omega \frac{\epsilon_{\rm dc} + \epsilon_{\rm ac}}{\epsilon_{\rm dc}} \cos(\epsilon_{\rm dc} + \epsilon_{\rm ac}) + \mathcal{P}_\omega \frac{\epsilon_{\rm dc} - \epsilon_{\rm ac}}{\epsilon_{\rm dc}} \cos(\epsilon_{\rm dc} - \epsilon_{\rm ac})$$

$$\epsilon^{\rm ac} > \epsilon^{\rm dc}$$

Maximize

Minimize

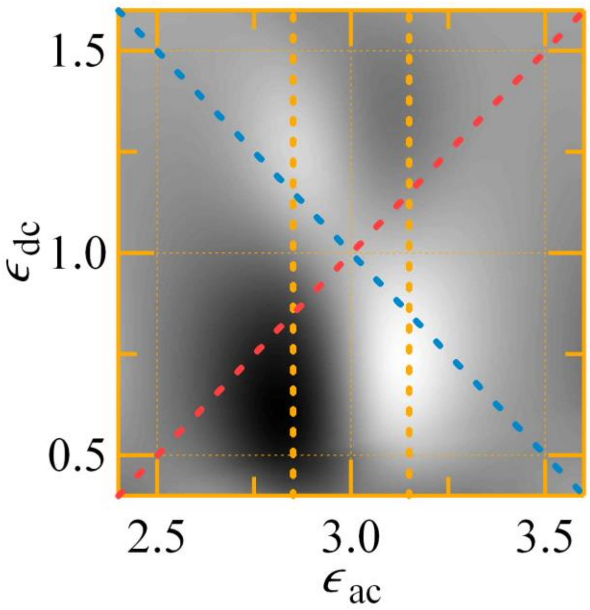
Condition for global maxima

$$\boxed{\begin{aligned} \epsilon_{\rm ac} + \epsilon_{\rm dc} &\simeq n \\ \epsilon_{\rm ac} - \epsilon_{\rm dc} &\simeq m + 1/2 \end{aligned}} \Longleftrightarrow \boxed{\begin{aligned} \epsilon^{dc} &= n \pm 1/4 \\ \epsilon^{ac} &= m \mp 1/4 \end{aligned}}$$

Experiment (closer look)

- Minima are found along:

$$\epsilon^- = \epsilon_{\mathrm{ac}} - \epsilon_{\mathrm{dc}} = 2$$



- Maxima are found along:

$$\epsilon^+ = \epsilon_{\mathrm{ac}} + \epsilon_{\mathrm{dc}} = 4$$

- Max (+) and min (–) are symmetrically offset by ~1/4-cycle from $(\epsilon_{\mathrm{ac}}, \epsilon_{\mathrm{dc}}) \simeq (n, m)$
- Equations for the global extrema:

$$(\epsilon_{\mathrm{ac}}, \epsilon_{\mathrm{dc}})^+ \simeq (n \pm 1/4, m \mp 1/4)$$
$$(\epsilon_{\mathrm{ac}}, \epsilon_{\mathrm{dc}})^- \simeq (n \pm 1/4, m \pm 1/4)$$

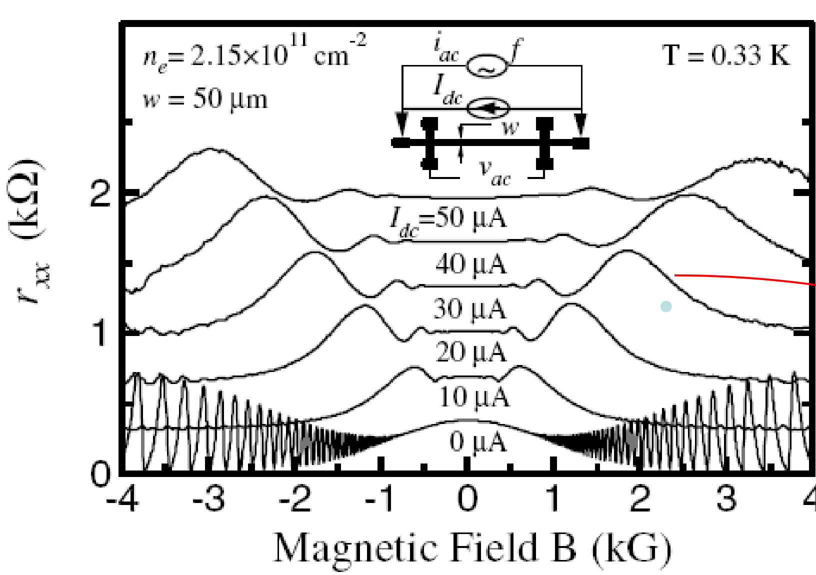
Conclusions

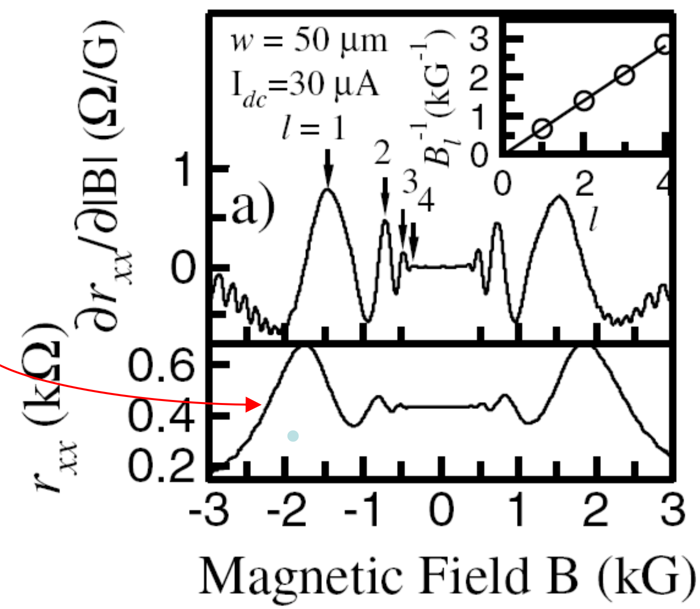
1. The theory of MIRO is constructed
2. Four different mechanisms were identified
3. The temperature dependence of magneto-resistance determined by the relative role played by the smooth and sharp part of the disorder potential
4. Understanding of the temperature dependence of MIRO in recent experiments (partial)

Thank you!

Oscillatory Differential DC Conductivity

C.L. Yang, J. Zhang, R.R. Du,
J.A. Simmons, J.L. Reno;
PRL 89, 076801



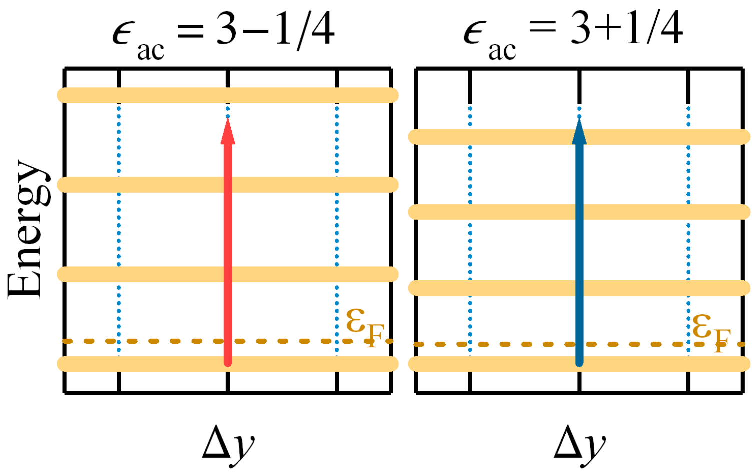


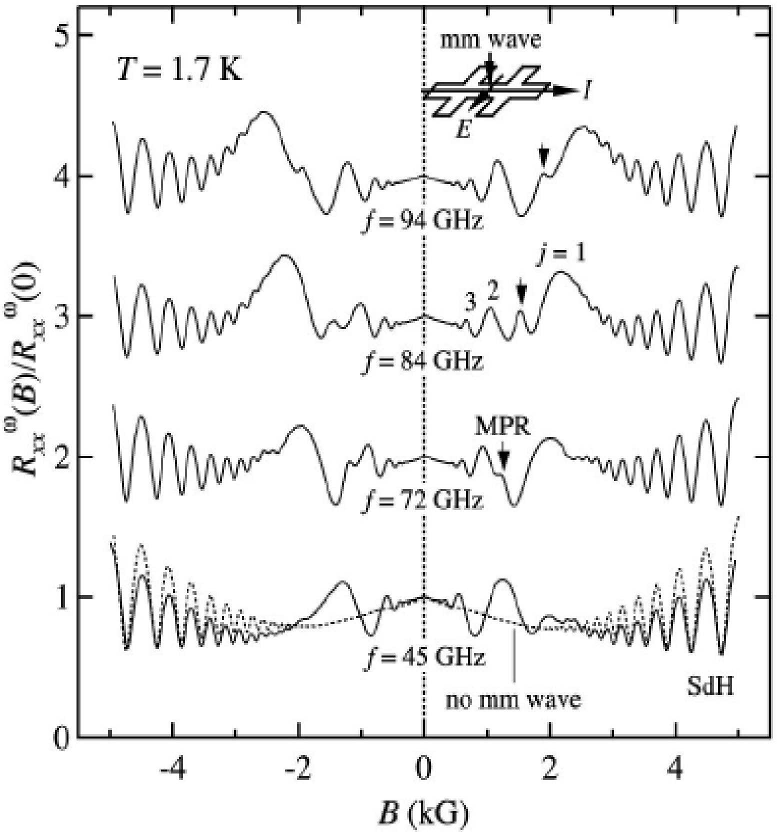
As current increases:

1. SdH oscillations are suppressed (heating?)
2. New oscillations develop

Oscillations in r_{xx} as a function of $\frac{2R_c eE}{\hbar\omega_c}$.

Microwave induced resistance oscillations (MIRO)





- Parameter: $\epsilon_{ac} \equiv \dfrac{\omega}{\omega_C}$
- Maxima and minima: $\epsilon_{ac}^{\pm} \simeq n \mp \frac{1}{4}$
- Theory: $\Delta R \propto \epsilon_{ac} \sin(2\pi\epsilon_{ac}),\ 2\pi\epsilon_{ac} \gg 1$

Zudov, Du, Simmons, Reno, Phys. Rev. B **64**, 201311(R) (2001)
Vavilov and Aleiner, Phys. Rev. B **69**, 035303 (2004)