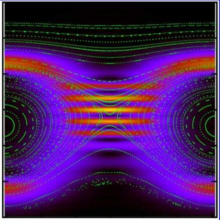
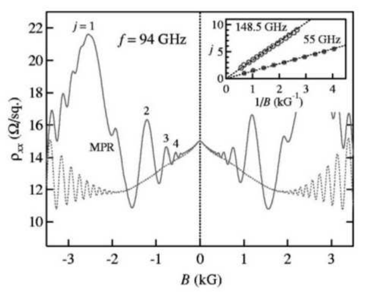
Quantum theory of polarization dependence of MIRO in 2DEG





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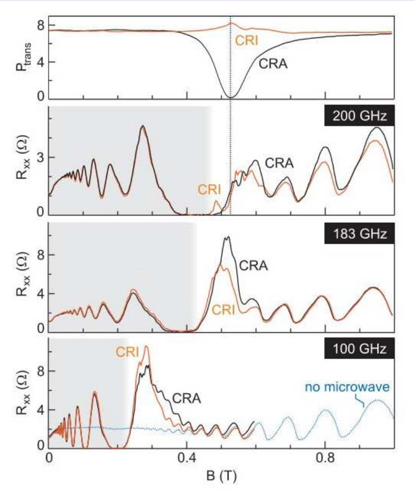
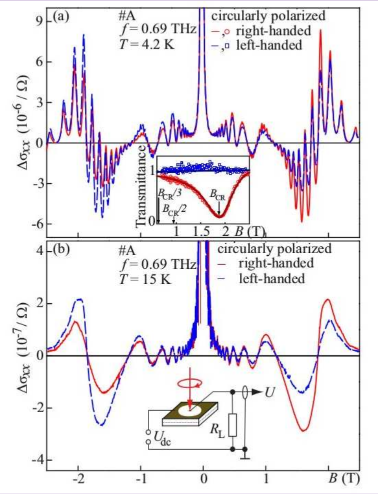
continuation of PRB 80, 241308(R) (2009); PRB 88, 035410 (2013)

MIRO discovery =>

* Zudov, Du, Simmons, Reno PRB(2001)
* Mani, Smet, von Klitzing, Narayanamurti, Jonson, Umansky Nature (2002)
* Zudov, Du, Pfeiffer, West PRL (2003)

Problem of polarization dependence





Left: Smet et al. PRL(205); Right: Ganichev-Kvon group PRB(2016)

==> "polarization dependence at low harmonics is at odds with any existing theoretical description of MIRO"

Analogy: Azbel'-Kaner effect-JETP 33,1461(1957))

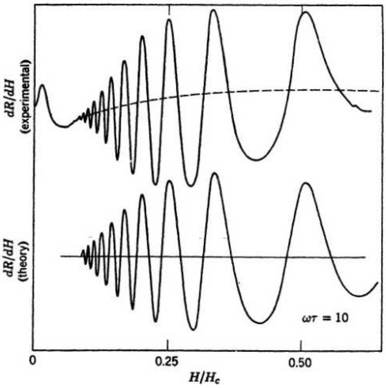


FIG. 2. Cyclotron resonance absorption in copper; comparison of calculations of the magnetic field dependence of the derivative of the surface resistivity with experimental results at 24 kMc/sec. (After Kip, Langenberg, and Moore.)

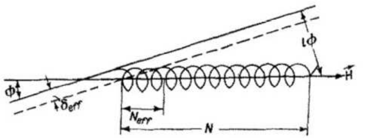


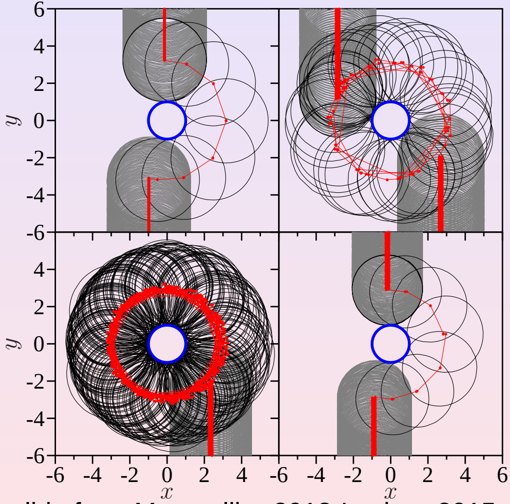
FIG. 2. Trajectory of an electron in a magnetic field at an angle ϕ to the surface of the metal. N_{eff} = effective number of turns reaching into the skin depth. N = total number of turns between collisions.

==> "This [cyclotron] resonance differs basically from the well-known deamagnetic resonance in semiconductors in two respects: (1) Cyclotron resonance occurses not only when the imposed frequency ω is equal to the cyclotron frequency ω_C, but also at the multiple frequencies $\omega \approx \omega_C, 2\omega_C, \ldots$, whether the metal is isotropic or not. (2) Cyclotron resonance in metals is possible only when the constant magnetic field B is strictly parallel to the metal surface."

==> short orbit interval of interaction with microwave

==> similar effect works for MIRO eliminating polarization dependence

Microwave induced scattering on disk (classical dynamics)

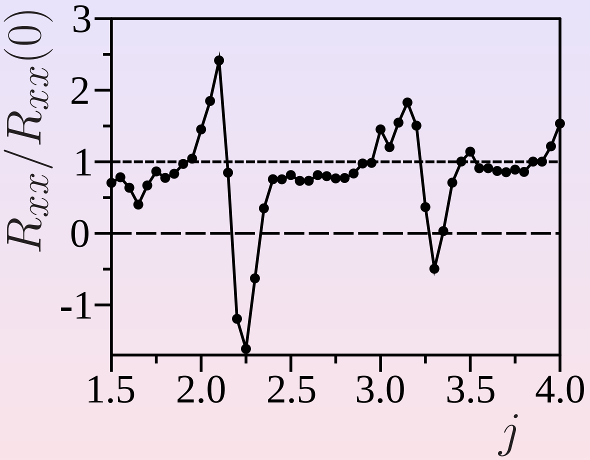


Disk radius $r_d \sim r_c$
Top left: $\epsilon = 0$,
$J = omega/\omega_c = 9/4$;
top right: temporary captured path at $\epsilon = v_{osc}/v_F = qE/(m\omega v_F) = 0.04$, $j = 9/4$;
bottom left: path captured forever at $\epsilon = 0.04$, $j = 9/4$;
bottom right: no capture at $\epsilon = 0.04$, $j = 2$;
dissipation at disk collisions $\gamma_d = 0.01$ Zhivov, Chepelianskii, DS (arxiv-2013).

slide from Montpellier-2013-Luchon-2015

Classical dynamics description: Beltukov, Dyakonov PRL (2016)

Classical conductivity computations



R_{xx} dependence on $J = \omega/\omega_c$, minimum at $j = n + 1/4$
Zhirov,Chepelianskii, DS PRB 88, 035410 (2013)

Circular polarization: Quantum/classical theory

Hamiltonian in the rotating frame ($e = m = 1$):
$H = {p_r}^2/2m + {p_\phi}^2/2mr^2 + p_\phi \omega_c/2 + m{\omega_c}^2 r^2/8 + U_d(r) - Er\cos\phi - \omega p_\phi$

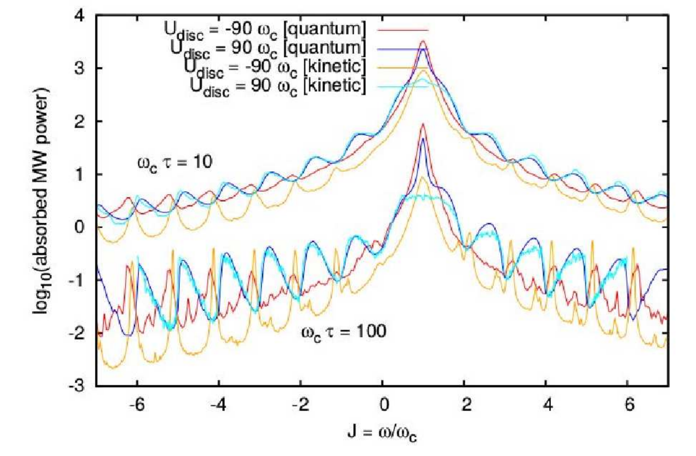
Approximate symplectic map (bar marks new value):
$\bar{\chi} = \chi + R_J(\alpha)$
$\bar{\alpha} = \alpha + 2\bar{\chi} - 2\pi j + \pi$
$R_J(\alpha) = \arg[1 + \eta \exp(-i\alpha)[\exp(2\pi i|J|) - 1]] \propto \mu$
$\eta = eE/(m\omega^2 r_d)$

velocity angle α is analog of impact angle β; $p_\phi \sim \sin\chi$ is analog of impact parameter b

New features: * kick amplitude is proportional to $\eta = [eE/(m\omega^2 r_c)][r_c/r_d]$; with the enhancement factor $r_c/r_d \gg 1$; * kick amplitude is zero at $J = integer$

Quantum: Numerical solution of master equation for density matrix with relaxation:
$\partial\hat{\rho}/\partial t = -i[\hat{H(t)}, \hat{\rho}]/\hbar - (\hat{\rho} - \hat{\rho_{eq}})/\tau$
Classical: numerical solution of Vlasov kinetic equation:
$\partial f/\partial t + \{f, H\} = -(f - f_{eq})/\tau$

Microwave power absorption

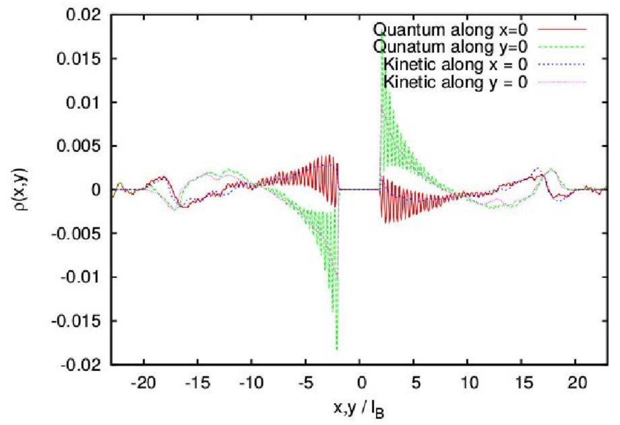


Absorption power $\mathcal{P} = \mathrm{Tr}(\hat{\rho}\mathbf{v} \cdot q\mathbf{E}_{ac})$ (in arbitrary units) is shown as a function of $J = \omega/\omega_c$ for $r_d/\ell_B = 2$ at $qE_{ac}\ell_B/\hbar\omega_c = 0.1$ and $\epsilon_F/\hbar\omega_c = 60$. Data are shown for two relaxation time scale with $\omega_c\tau = 10; 100$; numerical simulations with the master equation and classical kinetic.

Similarity to I.Dmitriev et al PRB 70, 163505 (2004) for repulsion

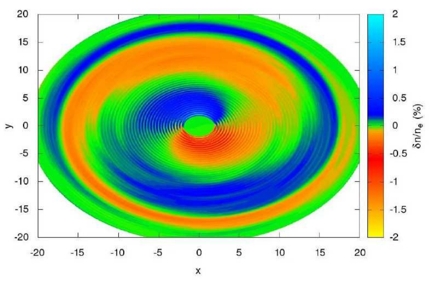
Charge density distribution in (x, y)

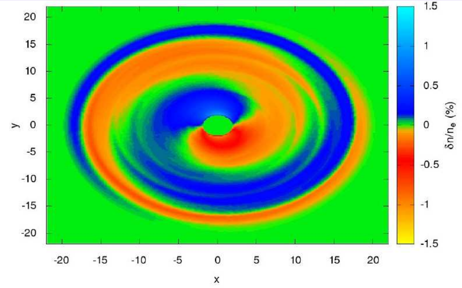
In the laboratory frame microwave driving creates a significant rotating charge redistribution with a rotating dipole moment.



parameters of previous Figure and $J = 2.7$

Charge density distribution in (x, y)





quantum (left) - classical (right) simulations ($\delta n / n_e$ in percent)
$J = 2.7$

Enhanced renormalized field near impurity

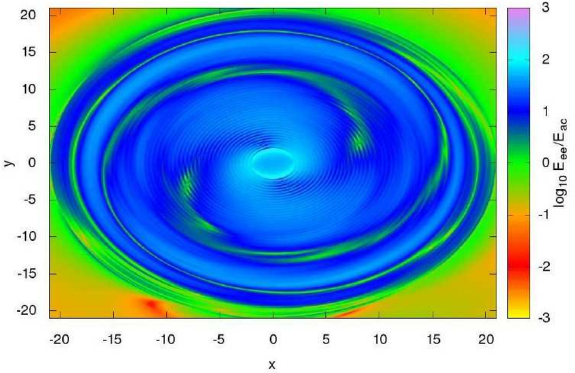
$$V_{ee}(\mathbf{x}) = -\frac{e\ell_B n_0}{4\pi\epsilon}\int \frac{d^2x'}{\ell_B^2}\frac{\ell_B}{|\mathbf{x}-\mathbf{x}'|}\frac{\delta n_e(\mathbf{x}')}{n_0}$$

$$E_{ee}(\mathbf{x}) = \frac{en_0}{4\pi\epsilon}(\ell_B\nabla)_{\mathbf{x}}\int \frac{d^2x'}{\ell_B^2}\frac{\ell_B}{|\mathbf{x}-\mathbf{x}'|}\frac{\delta n_e(\mathbf{x}')}{n_0}$$

$$\frac{e\ell_B E_{ac}}{\hbar\omega_c} = \epsilon_{ac}$$

$$\frac{|E_{ee}(\mathbf{x})|}{E_{ac}} = \frac{e^2 n_0 \ell_B}{4\pi\epsilon\epsilon_{ac}\hbar\omega_c}\left|(\ell_B\nabla)_{\mathbf{x}}\int \frac{d^2x'}{\ell_B^2}\frac{\ell_B}{|\mathbf{x}-\mathbf{x}'|}\frac{\delta n_e(\mathbf{x}')}{n_0}\right|$$

$\frac{e^2 n_0 \ell_B}{4\pi\epsilon\hbar\omega_c} = 230$ for $B = 0.1$ Tesla, $n_0 = 3.5\times 10^{11}$ cm^{-2}, $\epsilon = 10\epsilon_0$.



$J = 2.7$

Collision with impurity (map)

Original microwave field:
$$\delta I_z = \frac{\delta H_0}{\omega} = \frac{1}{\omega}\int_0^{2\pi/\omega_c} q\mathbf{E}_{ac}(t)\mathbf{v}(t)dt = \frac{qv_F E_{ac}}{\omega(\omega-\omega_c)}\left[\sin\alpha_R - \sin(\alpha_R - 2\pi J)\right]$$

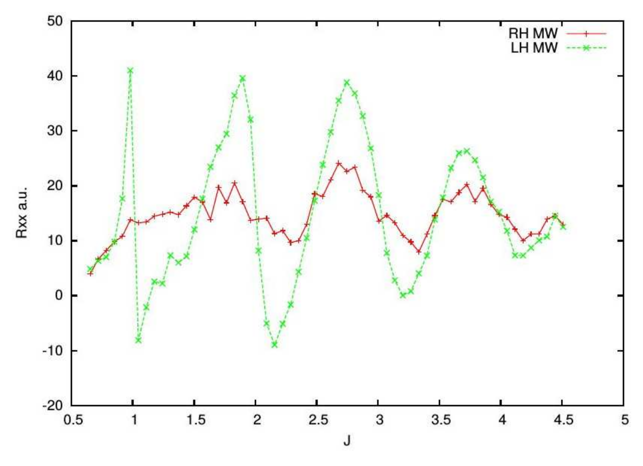
Map over orbital period:

$$\begin{cases} \bar{I}_z & = I_z + F\left[\sin\alpha_R - \sin(\alpha_R - 2\pi J)\right] \ , \\ \bar{\alpha}_{\mathcal{R}} & = \alpha_{\mathcal{R}} + \sigma(\bar{I}_z) - 2\pi J \ , \ \ F = qv_F E_{ac}/[\omega(\omega-\omega_c)] \ . \end{cases}$$

Numerical simulations with map description reproduce results of Newton dynamics.

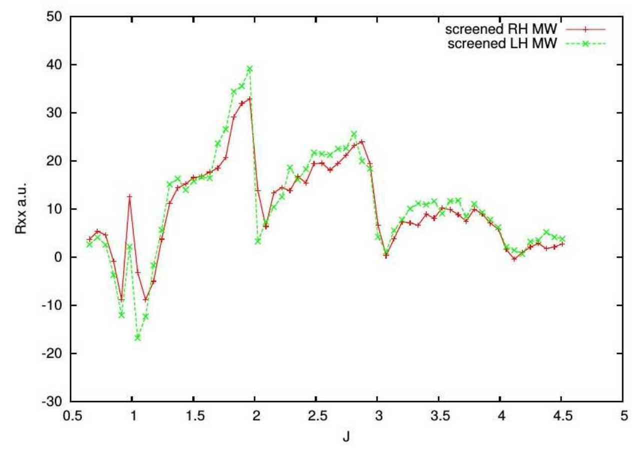
Short range screened field:
$$\delta I_z = \frac{\delta H_0}{\omega} = \frac{1}{\omega}\int_0^{2\pi/\omega_c} q\mathbf{E}_{eff}(\mathbf{r},t)\mathbf{v}(t)dt \approx [qv_F E_{ac}\delta t/\omega][\sin\alpha_R - \sin(\alpha_R - 2\pi J)]$$
with $\delta t = r_{eff}/v_F \ll 2\pi/\omega_c$.

R_{xx} for initial homogeneous field



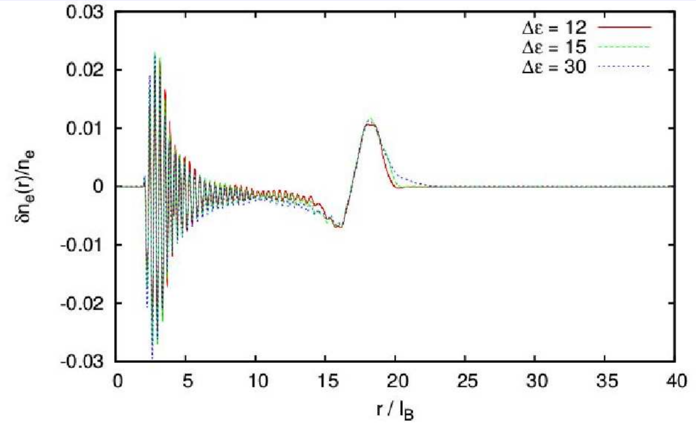
classical simulations (á la Beltukov-Dyakonov => no dissipation, Gaussian potential, distance between disks is about $3r_c$)

R_{xx} for screened field



classical simulations (á la Beltukov-Dyakonov), screening length is about $r_c/3$

For ZRS: Global charge density redistribution



Relative variation of radial electron charge density $\delta n_e/n_e$, induced by a microwave irradiation, as a function of radial distance r from impurity; results of master equation at $qE_a c\ell_B/\hbar\omega_c = 0.2$, $r_d/\ell_B = 2$, $E_F/\hbar\omega_c = 40$, $\omega_c\tau = 100$. This variation mainly takes place on a distance r_{eff} comparable with the disk radius $r_{eff} \sim r_d$; a charge variation (number of electron charges) is $\Delta Q \sim \delta n_e \pi r_{eff}^2 \sim 2$.

Discussion

Microwave creates enhanced renornamized field in a vicinity of impurity with a short range intercation on a distance r_{eff} comparable with the size of impurity. This distance is small compared to a cyclotron orbit radius ($r_{eff} \ll r_c$) and due to that an interaction of electron with renormalized (screened) microwave field takes place only near impurity so that the ramaining part of cyclotron orbit does not contribute to this interaction. Due to that left and right hand polarizations acts approximately in the same way on R_{xx}.

A similar situation appears also for the Azbel'-Kaner effect (1957) where an interaction with a microwave takes place only inside a skin layer which size is small compared to the cyclotron radius.

The developed quantum and classical theories are in good adreement with each other and they explain the puzzeling results of Smet et al. (2005) and Ganichev-Kvon group (2016) on absence of polarization dependence for MIRO.

Origin of ZRS phase => vortex quantization ?