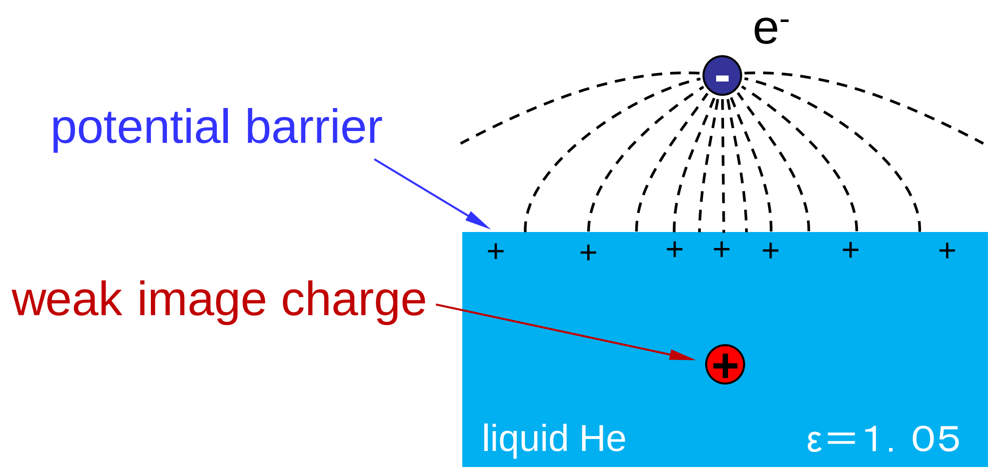
Electrons on helium under CR excitation

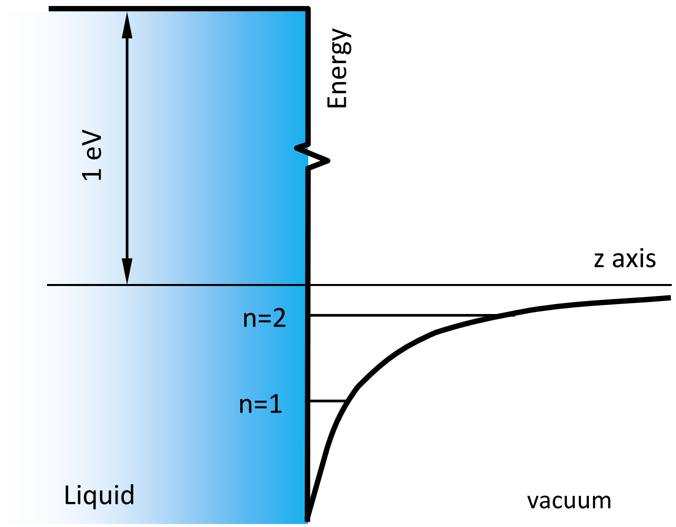
Denis Konstantinov, Alex Badrutdinov, Leonid Abdurakhimov

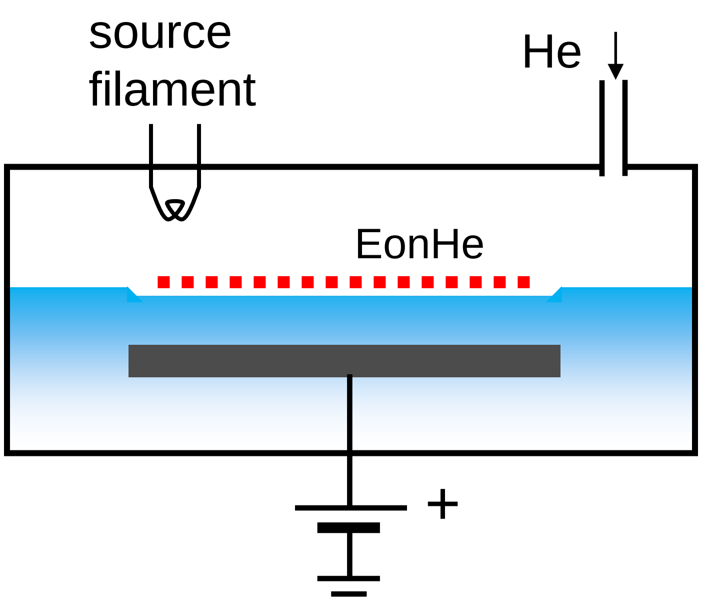
Quantum Dynamics Unit, OIST Graduate University

2D Quantum Transport, Luchon, May 2015

Electrons on liquid helium







Transverse confinement

Image potential + surface barrier

Lateral confinement

Electrostatic potential due to positively biased gate

Phase diagram

$$\Gamma_p = \frac{V_C}{E_{th}} = \frac{e^2\sqrt{\pi n_s}}{4\pi\varepsilon\varepsilon_0 k_B T}$$

Thermal fluctuations

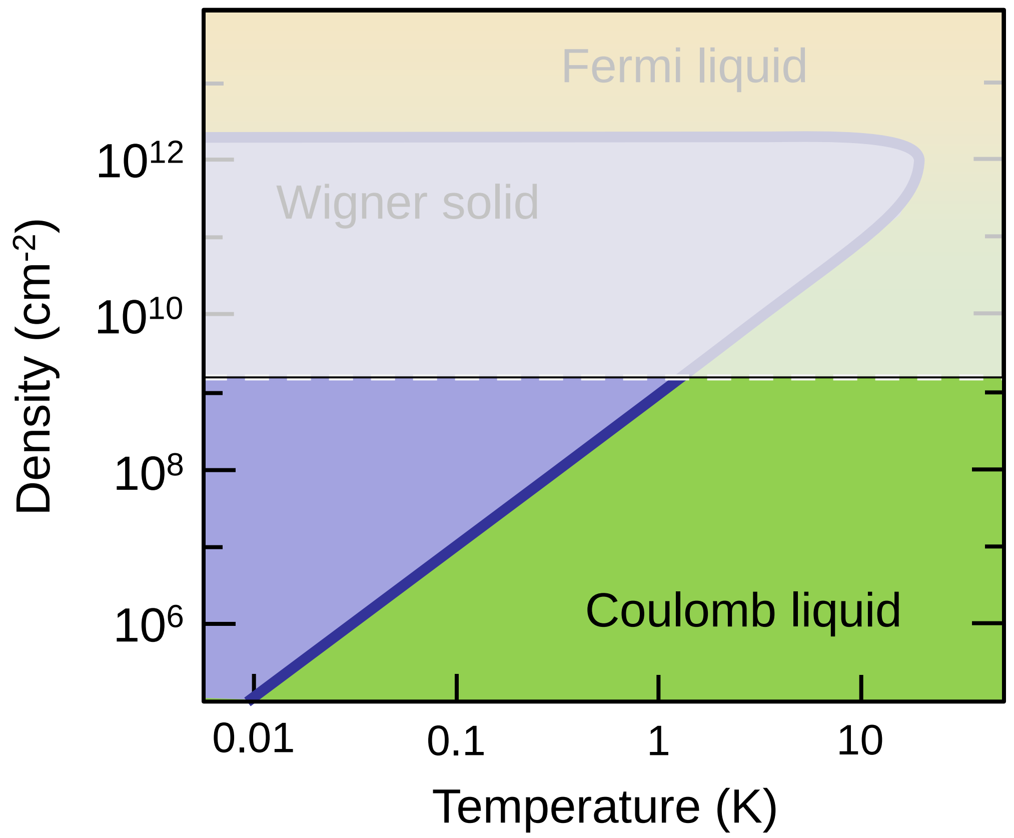
ε=1

$$r_p = \frac{E_f}{V_C} = \frac{4\pi\varepsilon\varepsilon_0}{e^2\sqrt{\pi n_s}} \frac{\hbar^2 \pi n_s}{m^*}$$

Quantum fluctuations

$m^*=m_e$

$n_s < 2\text{x}10^9\ \text{cm}^{-2}$



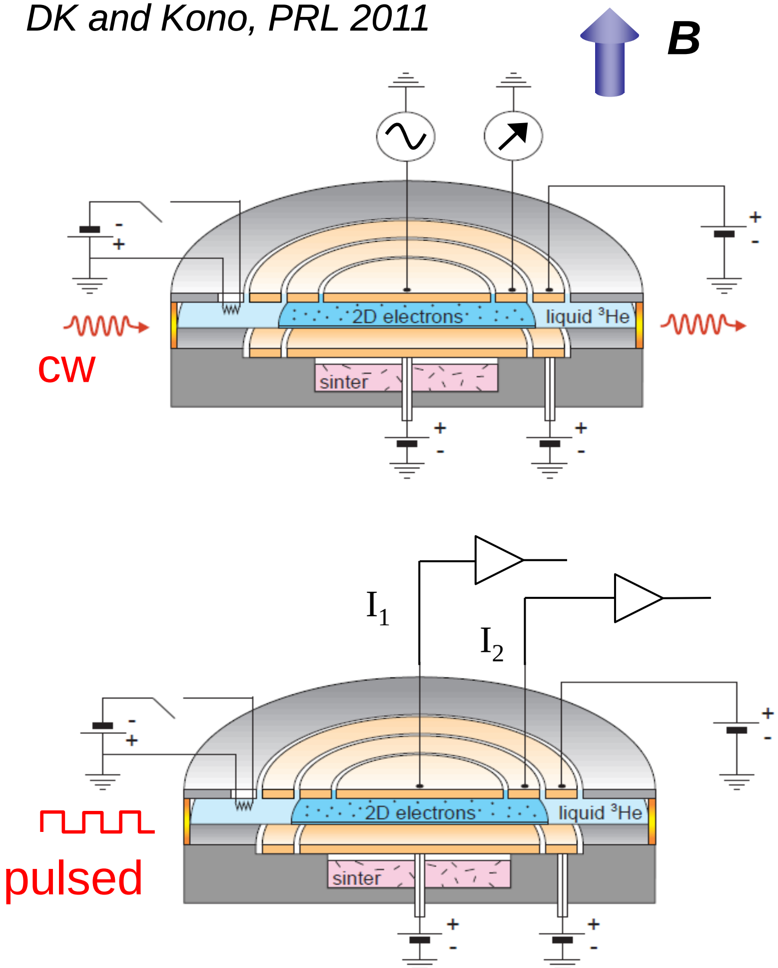
2DEG in semiconductors

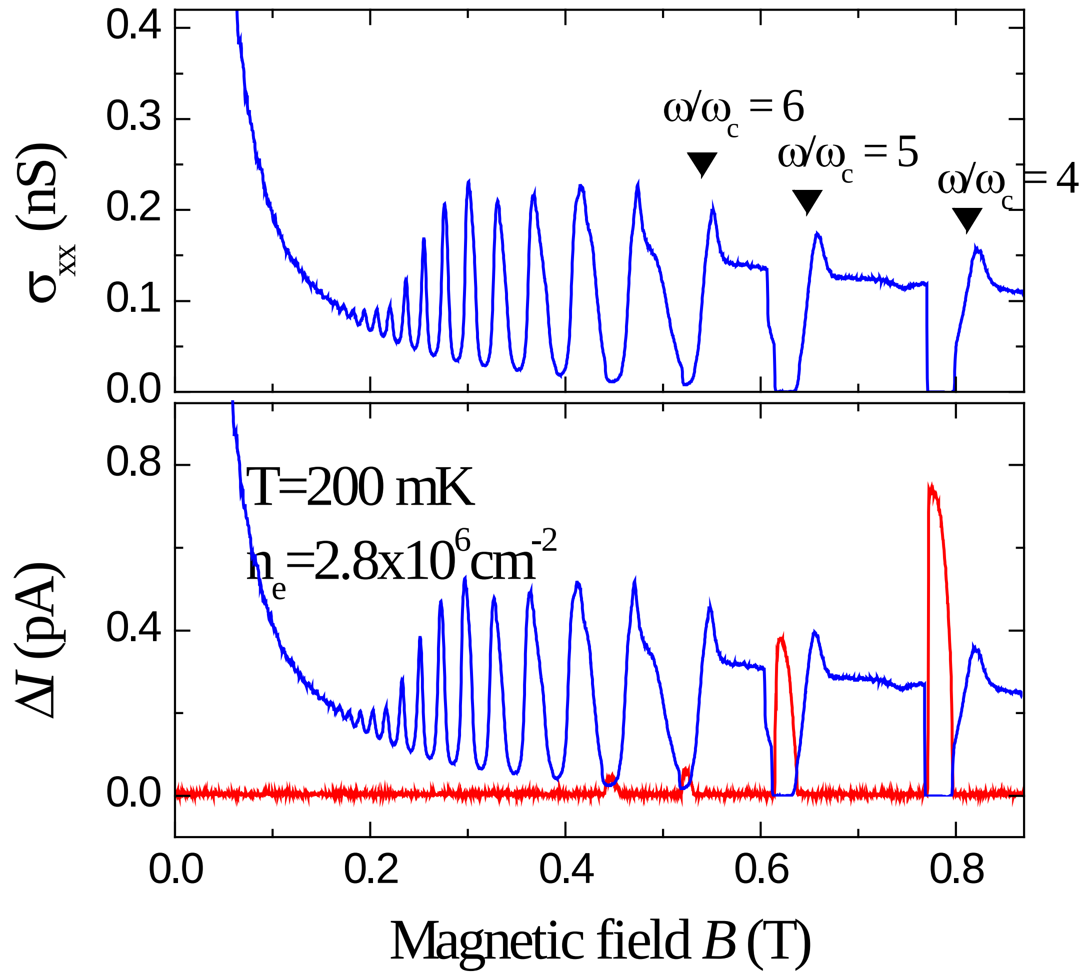
$\varepsilon \approx 10,\ m^* \approx 0.1 m_e$

$n_s > 5\text{x}10^{10}\ \text{cm}^{-2}$

MIRO and ZRS

DK and Kono, PRL 2011



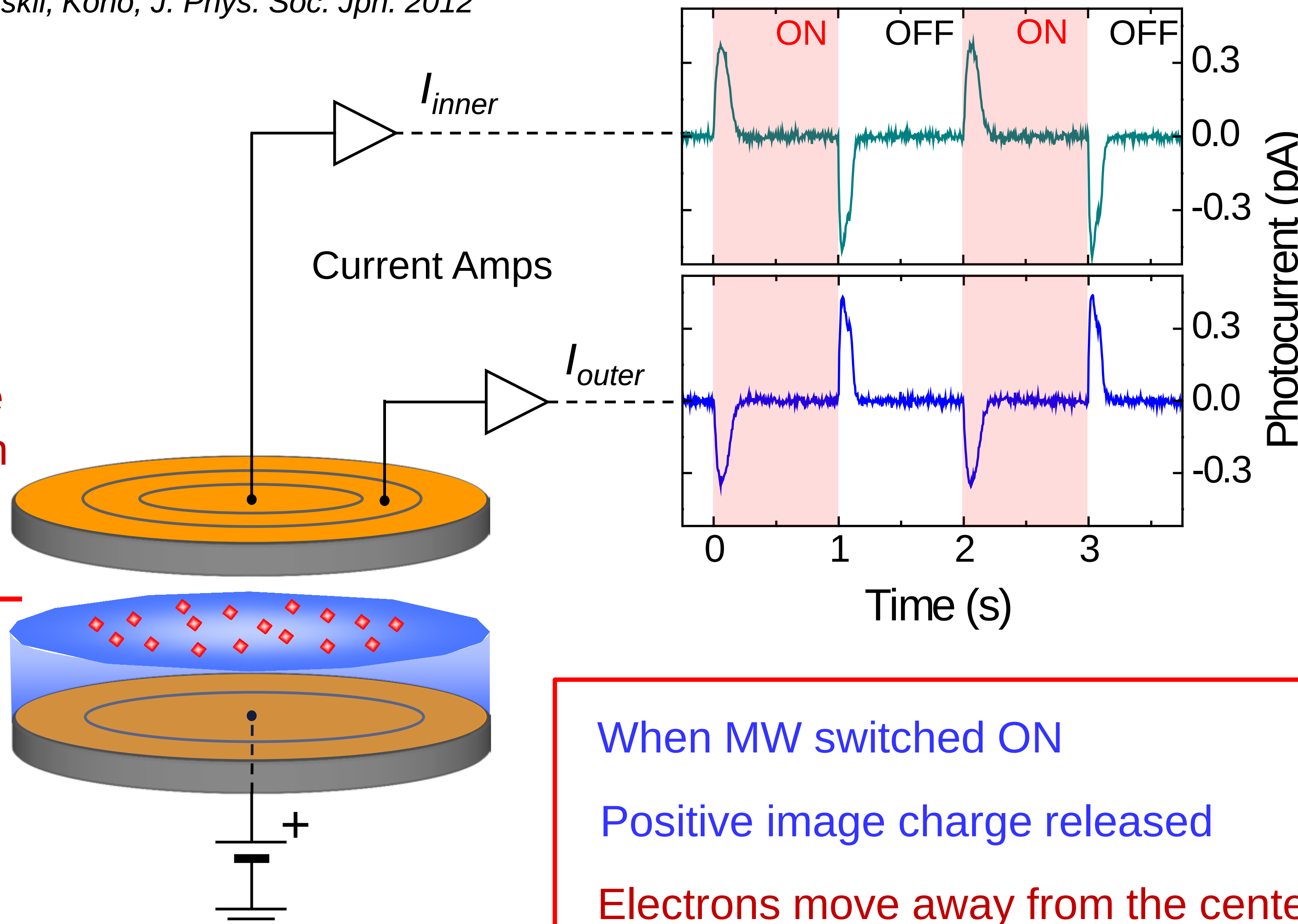


Time-resolved measurements

DK, Chepelianskii, Kono, J. Phys. Soc. Jpn. 2012

Fix *B*-field at minima of σ_{xx}

Microwave modulation ON/OFF



When MW switched ON

Positive image charge released

Electrons move away from the center

Mechanism of oscillations in EonHe

Momentum balance equation

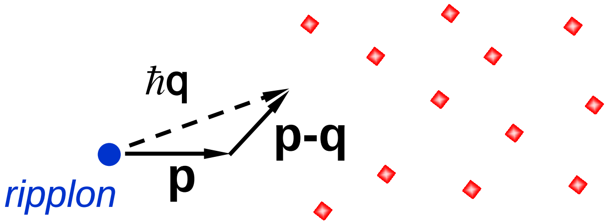
Yu. P. Monarkha

$$\mathbf{F}_{friction} = -N_e m \nu_{eff} \mathbf{u}_d$$

$$\sigma_{xx} = \frac{e^2 n_s}{m_e} \frac{\nu_{eff}}{\omega_c^2 + \nu_{eff}^2}$$

$$\mathbf{F}_{friction} = -\sum_{\mathbf{q}} \hbar \mathbf{q} \cdot P_{\mathbf{p},\mathbf{p}-\mathbf{q}} = -\frac{N_e}{\hbar^2 S} \sum \hbar \mathbf{q} \cdot U(\mathbf{q}) \cdot \mathcal{S}(\mathbf{q}, \underbrace{\omega - \mathbf{q} \cdot \mathbf{u}_d}_{})$$

Doppler shift in laboratory frame



$\mathcal{S}(\mathbf{q}, \omega)$ - Dynamical Structure Factor (DSF)

$$\mathbf{F}_{friction} = -\frac{N_e}{\hbar^2 S} \sum_{\mathbf{q}} \hbar \mathbf{q} \sum_{n,n'} \rho_n U_{n,n'}(\mathbf{q}) \left[\underbrace{(N_q + 1) S_{n,n'}(q, \omega_{n,n'} - \mathbf{q} \cdot \mathbf{u}_d)}_{\text{creation of ripplon}} - \underbrace{N_q S_{n,n'}(q, \omega_{n,n'} + \mathbf{q} \cdot \mathbf{u}_d)}_{\text{annihilation of ripplon}} \right]$$

creation of ripplon — annihilation of ripplon

$$\mathbf{F}_{friction} \sim -\sum_{\mathbf{q}} \hbar \mathbf{q} \sum_{n,n'} \chi_{n,n'}(\mathbf{q}) \cdot S_{n,n'}(q, \omega_{n,n'} + \mathbf{q} \cdot \mathbf{u}_d) \cdot \left(\rho_n - \rho_{n'} e^{-\frac{\hbar \omega_{n,n'}}{k_B T_e}} e^{-\frac{\hbar \mathbf{q} \cdot \mathbf{u}_d}{k_B T_e}}\right)$$

Mechanism of oscillations in EonHe

Yu. P. Monarkha

$$\nu_{\mathrm{inter}} \sim \sum_{\mathbf{q}} \hbar \mathbf{q} \sum_{n>n'} \chi_{n,n'}(\mathbf{q}) \cdot \underbrace{S_{n,n'}(q,\omega_{n,n'})}_{\text{DSF}} \cdot \left(\rho_n + \rho_{n'} e^{-\frac{\hbar\omega_{n,n'}}{k_B T_e}}\right) +$$

$$+ \frac{\hbar}{k_B T} \sum_{\mathbf{q}} \hbar \mathbf{q} \sum_{n>n'} \chi_{n,n'}(\mathbf{q}) \cdot \overbrace{S'_{n,n'}(q,\omega_{n,n'})}^{\text{derivative of DSF}} \cdot \underbrace{\left(\rho_n - \rho_{n'} e^{-\frac{\hbar\omega_{n,n'}}{k_B T_e}}\right)}_{\text{non-zero for nonequilibrium population}}$$

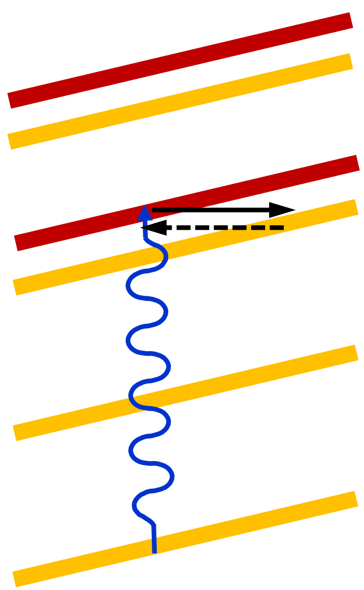
DSF

derivative of DSF

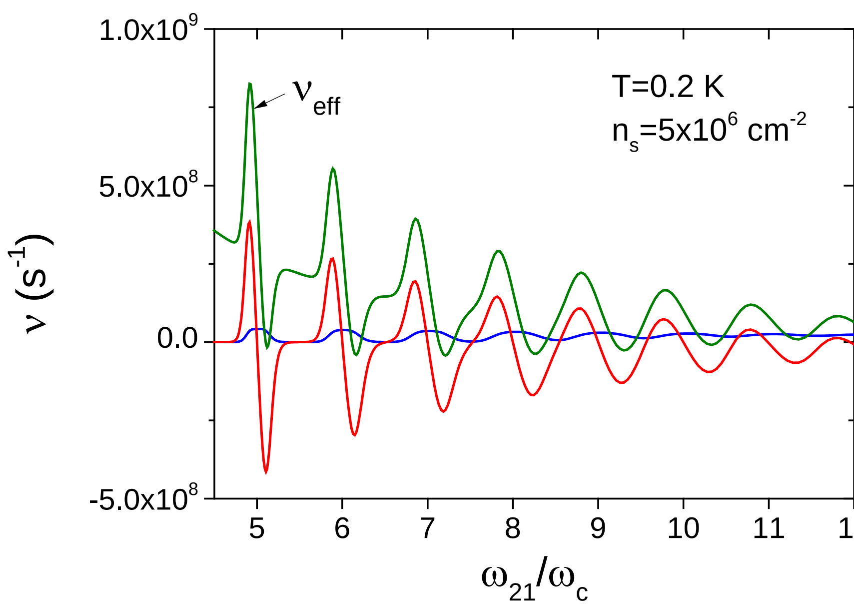
non-zero for nonequilibrium population

Tilted LLs in dc E-field

Excited subband

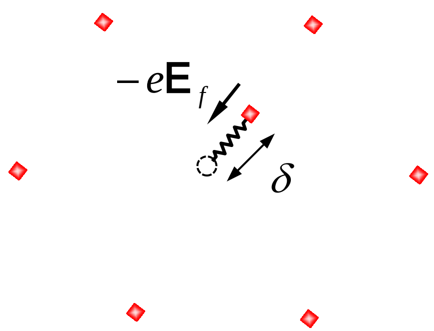


Ground subband



Coulomb effects

Dykman, Khazan 1979



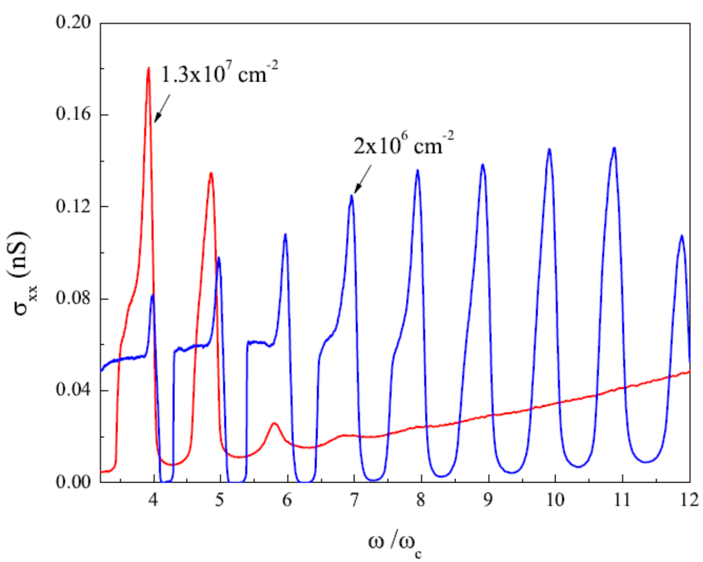
$$\boxed{\frac{k\delta^2}{2} \approx k_B T_e} \quad \Rightarrow \quad \boxed{\left\langle E_f \right\rangle \approx n_s^{3/4}\sqrt{4\pi k_B T_e}}$$

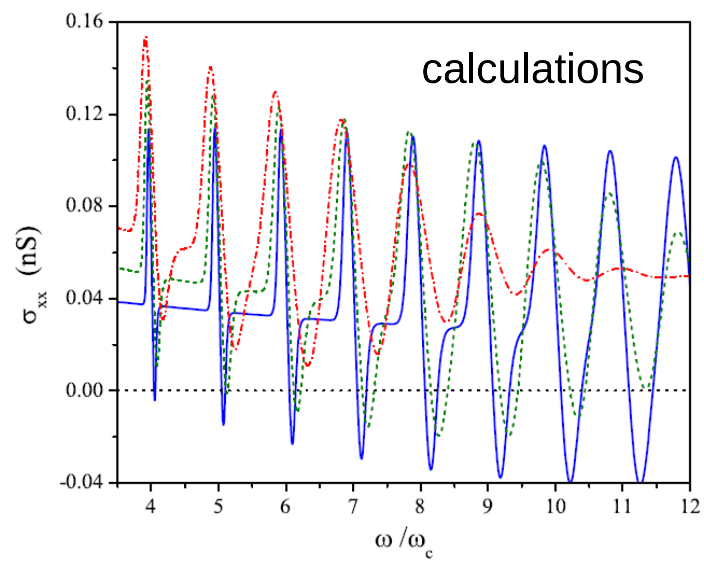
$$\mathbf{u}_d \to \mathbf{u}_f$$

$$S^{(me)}(q,\omega) = \left\langle S(q, \omega - \mathbf{q}\cdot\mathbf{u}_f) \right\rangle$$

Coulomb broadening of DSF

DK, Monarkha, Kono, PRL 2013

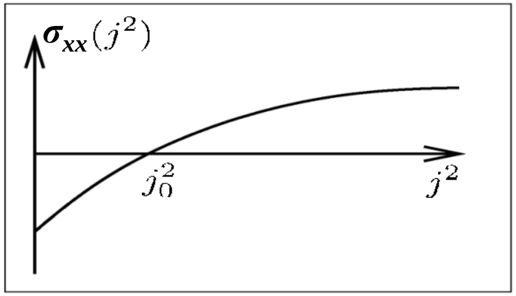




Zero-resistance states

There exists (some) mechanism

leading to absolute negative σ_{xx}



$$\frac{\partial \rho_s}{\partial t} = -\nabla \vec{j} = \sigma \nabla_r^2 V$$

$$\nabla^2 V = -\rho_s \delta(z)$$

$$\rho_k \sim \exp\left(-\frac{\sigma k}{2} t\right) \to \infty$$

Instability and formation of current domains

Andreev, Aleiner, Millis, PRL 2003

Other explanations are proposed, e.g. Entin and Magarill: arXiv: 1504.03422

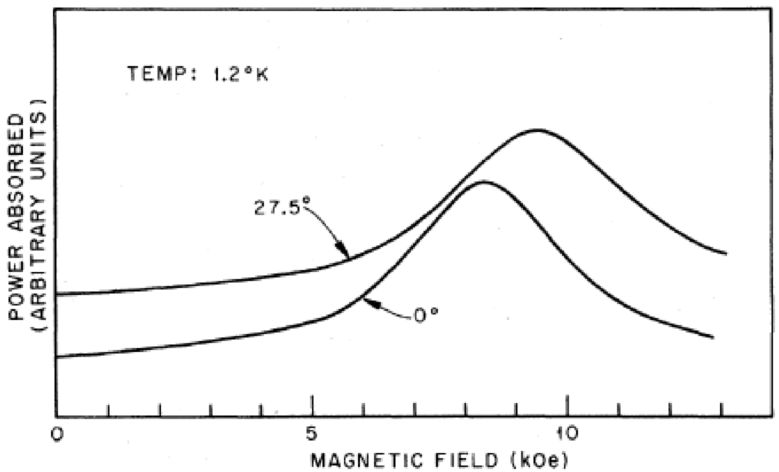
ZRS in electrons on helium have interesting properties

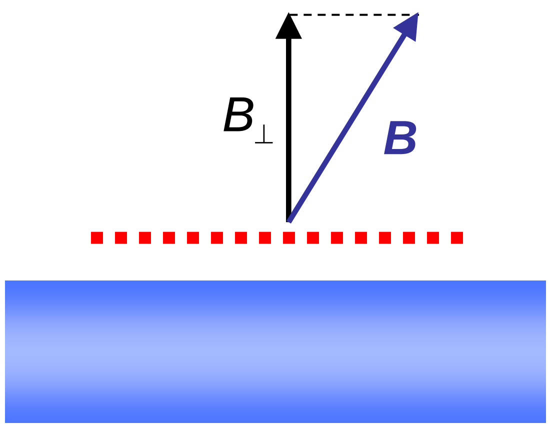
- self-organized oscillations (previous talk)
- incompressibility (next talk)

OIST

CR in electrons on helium

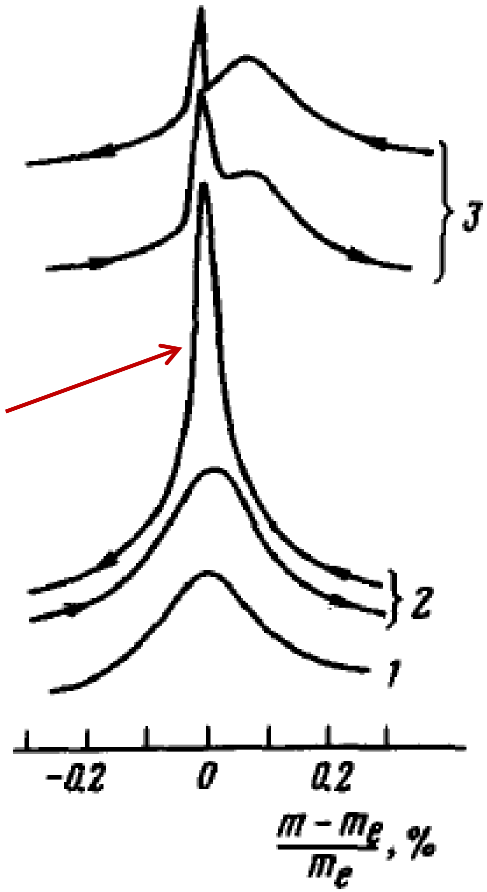
Brown, Grimes 1972





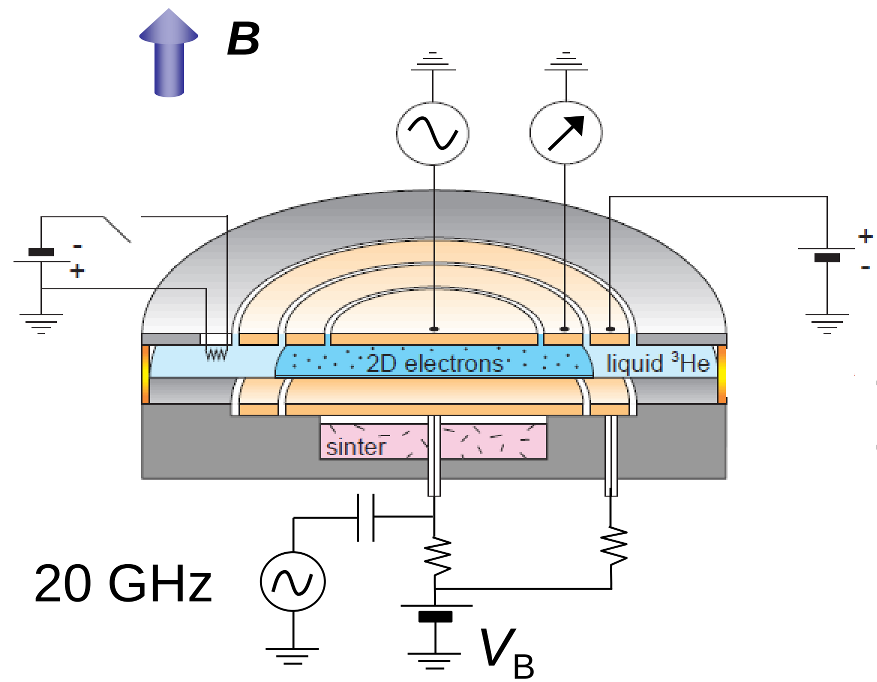
Edelman 1972

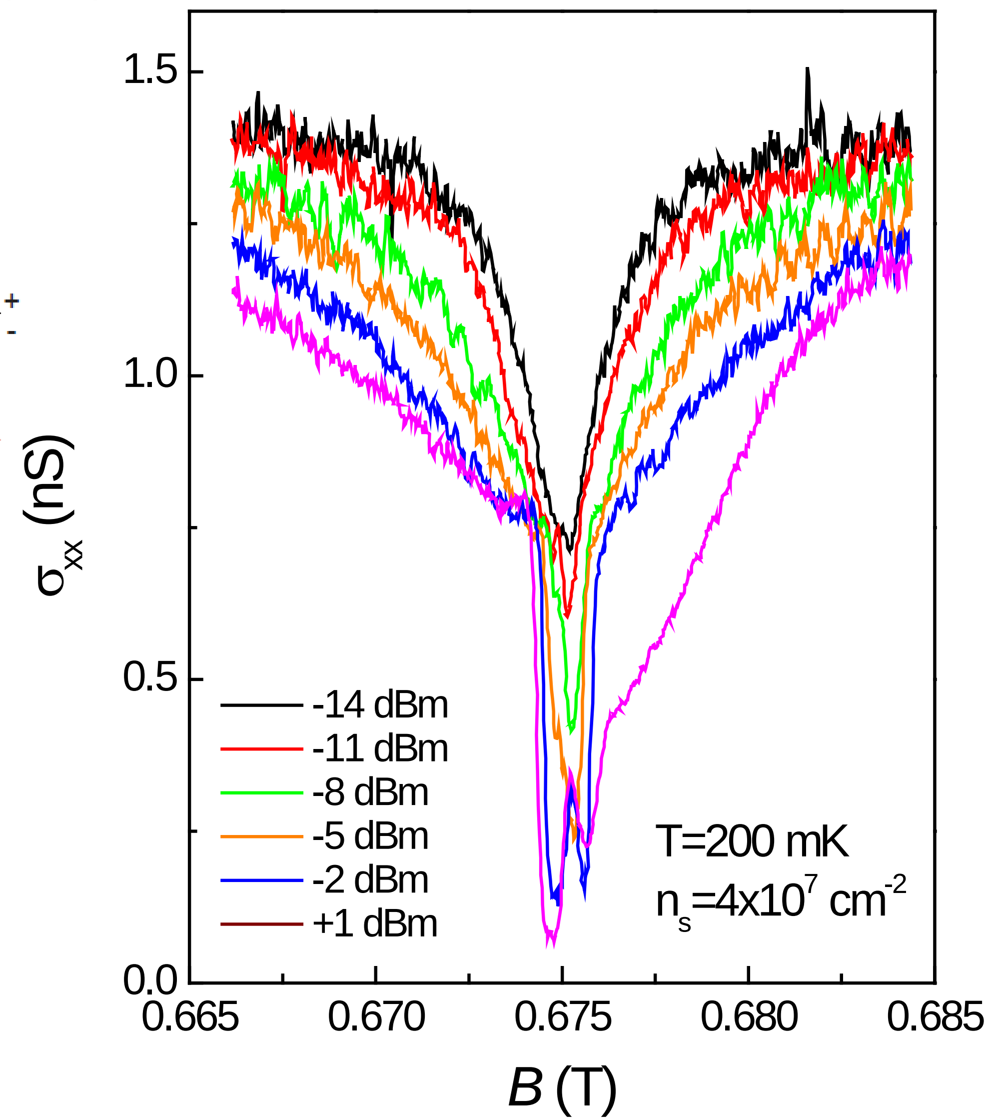
quasy-3D



Experiment I

Badrutdinov , Abdurakhimov, DK, PRB 90, 075305 (2014)



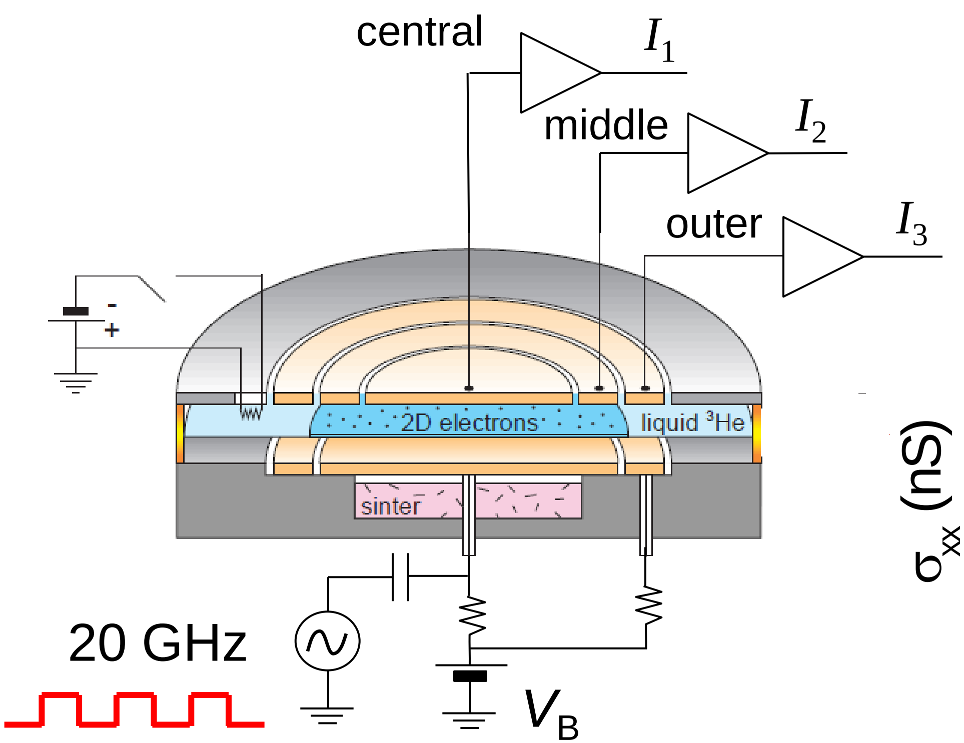


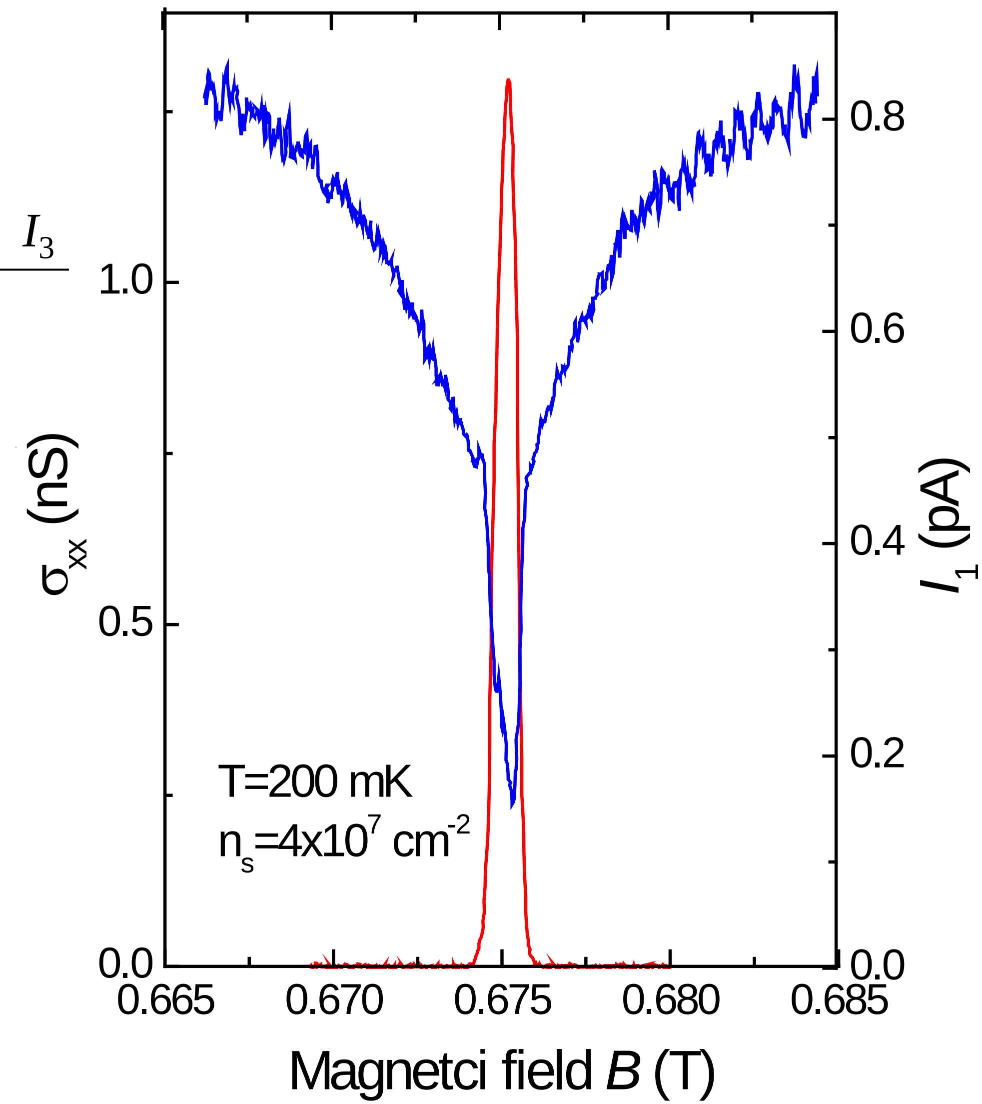
Irreversable loss of electrons

at high MW power

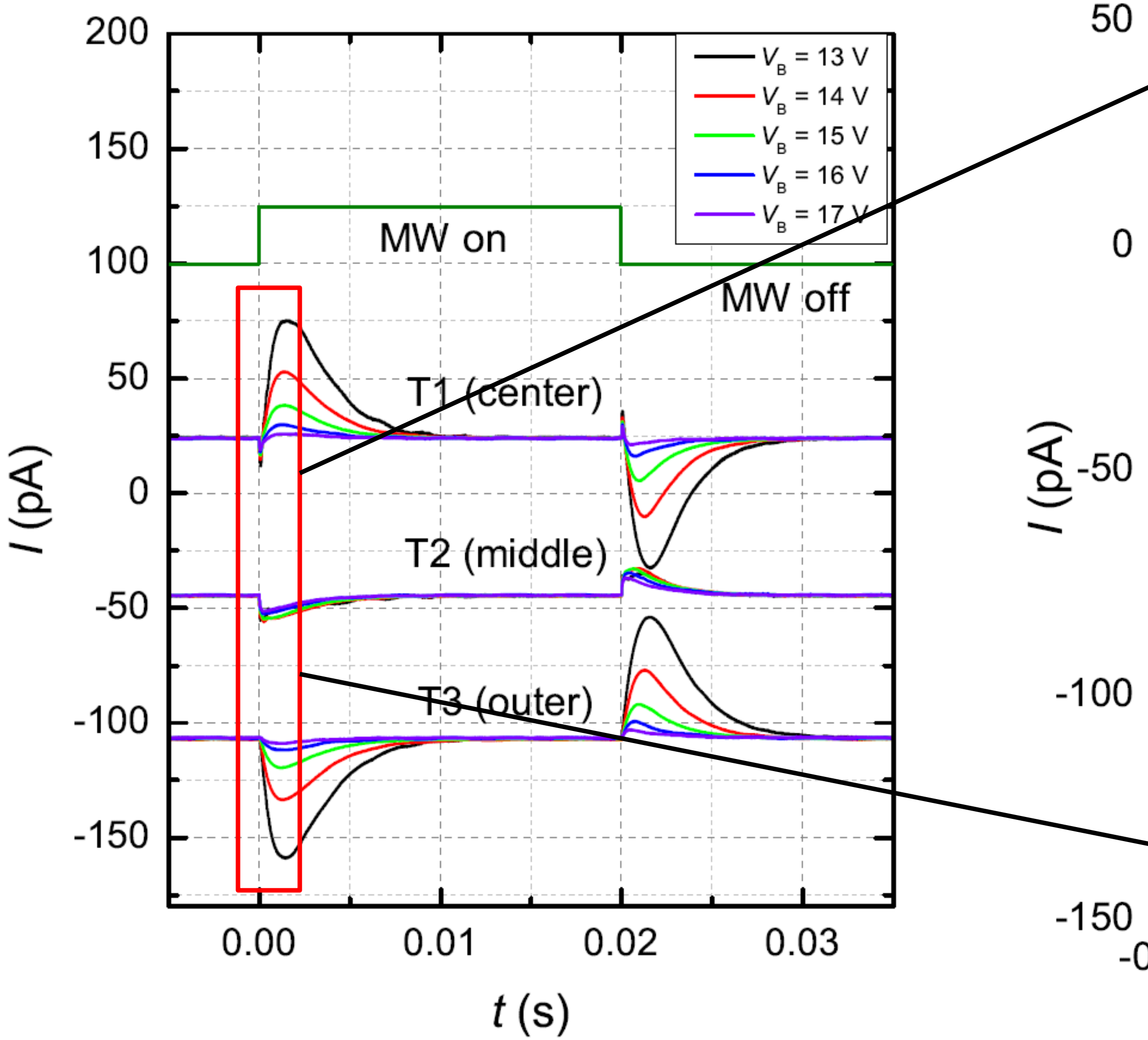
Experiment II

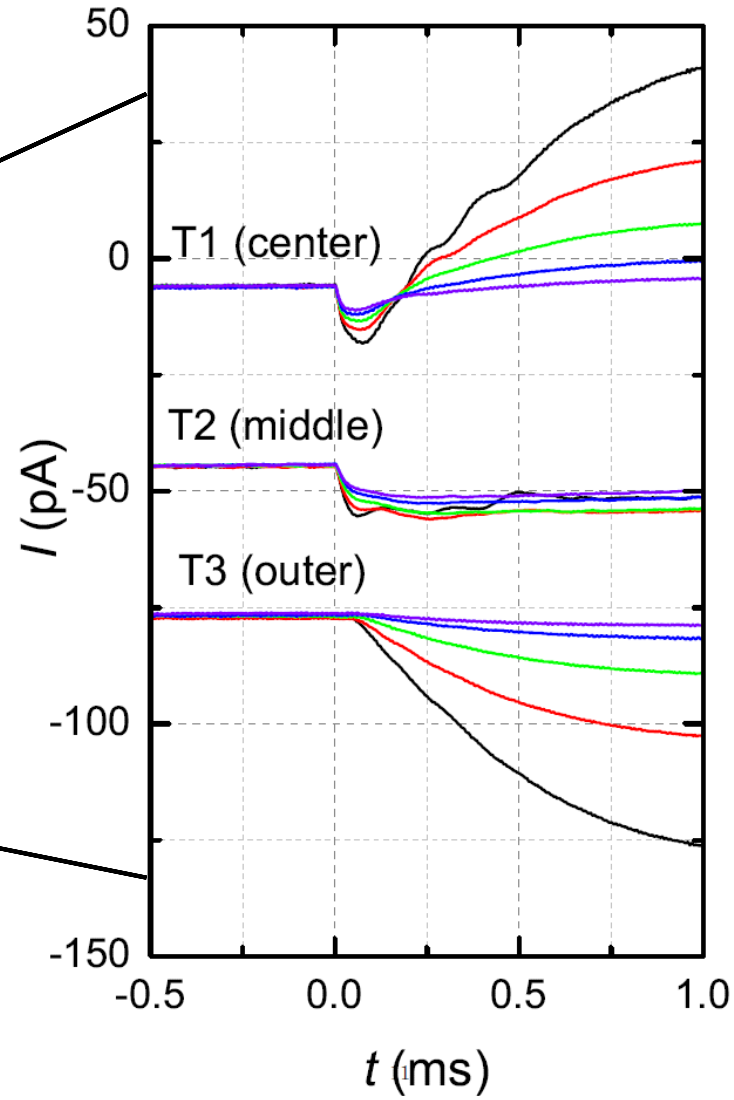
Badrutdinov , Abdurakhimov, DK, PRB 90, 075305 (2014)





Time-resolved response

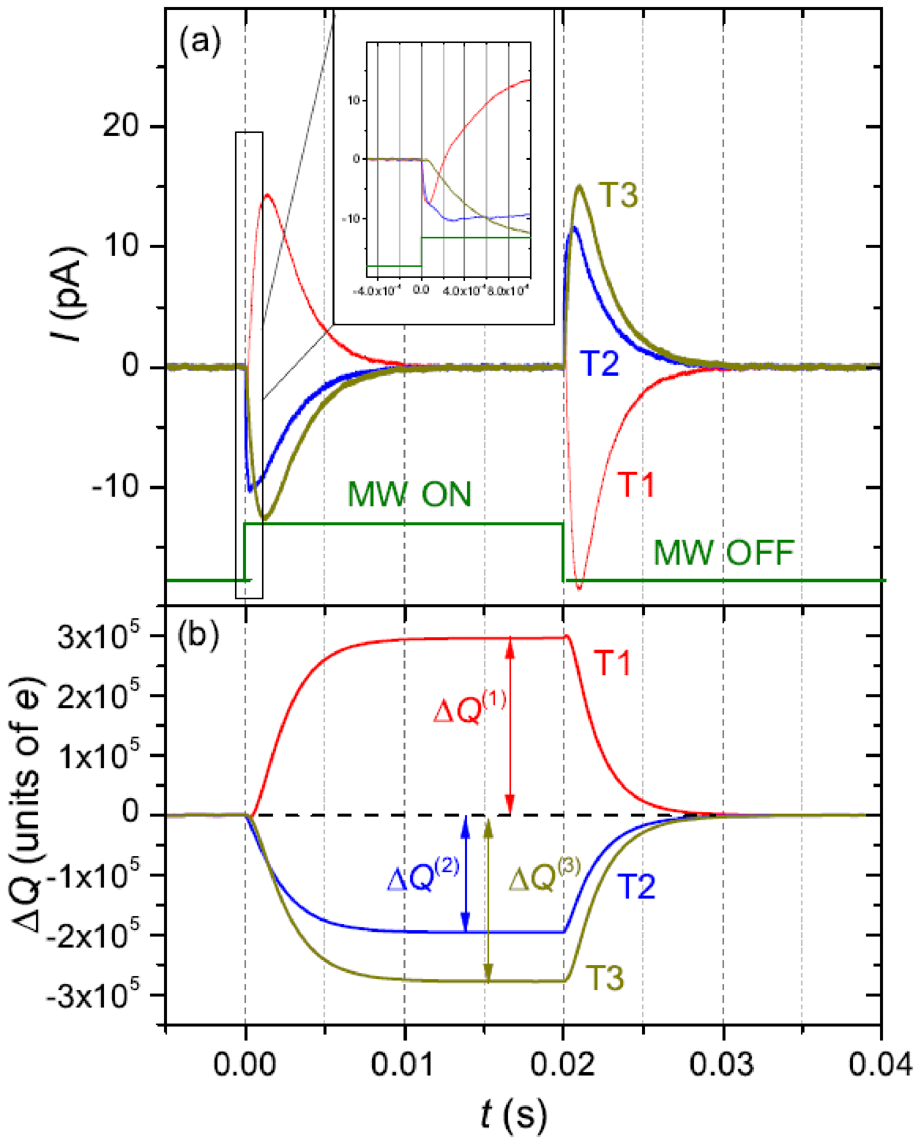




OIST

Analysis

Badrutdinov , Abdurakhimov, DK, PRB 90, 075305 (2014)



Extraction of $\Delta Q^{(i)}_{\mathrm{perp}}$ and $\Delta Q^{(i)}_{\mathrm{in-plane}}$ from data:

$$\Delta Q^{(i)} = \Delta Q^{(i)}_{\mathrm{in-plane}} + \Delta Q^{(i)}_{\mathrm{perp}}$$

$$\Delta Q^{(1)}_{\mathrm{in-plane}} + \Delta Q^{(2)}_{\mathrm{in-plane}} + \Delta Q^{(3)}_{\mathrm{in-plane}} = 0$$

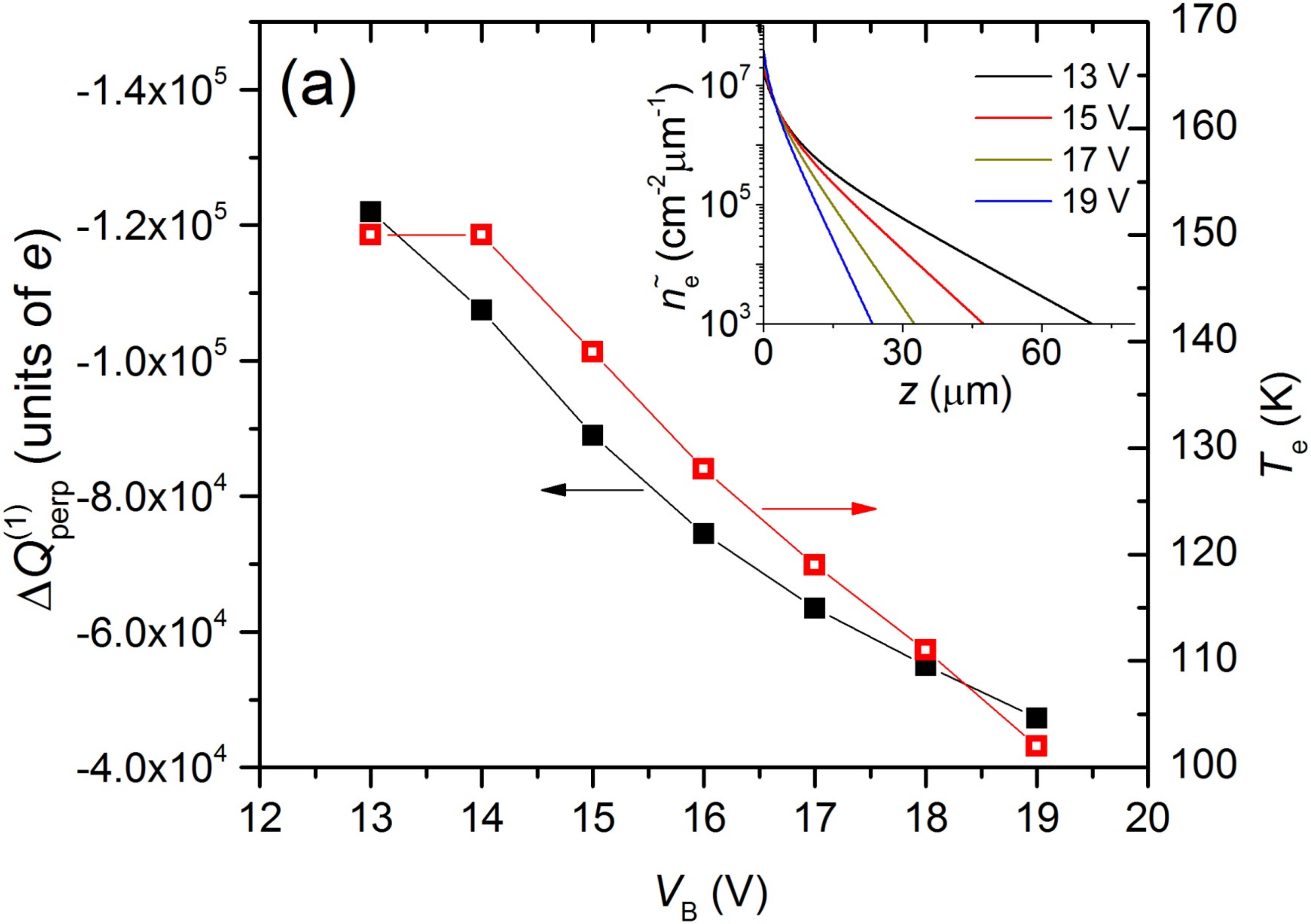
$$\Delta Q^{(1)}_{\mathrm{perp}} = \Delta Q^{(2)}_{\mathrm{perp}}$$

$$\Delta Q^{(3)}_{\mathrm{perp}} = 0$$

V_B (v)	$\Delta Q^{(1)}_{in-plane}$	$\Delta Q^{(2)}_{in-plane}$	$\Delta Q^{(3)}_{in-plane}$	ΔQ_{perp}
13	-1338000	55000	1283000	122000
14	-736500	109500	627000	107500
15	-385000	107000	278000	89000
16	-184500	72500	112000	74500
17	-95500	46500	49000	63500
18	-56800	32000	24800	55000
19	-38600	23700	14900	47300

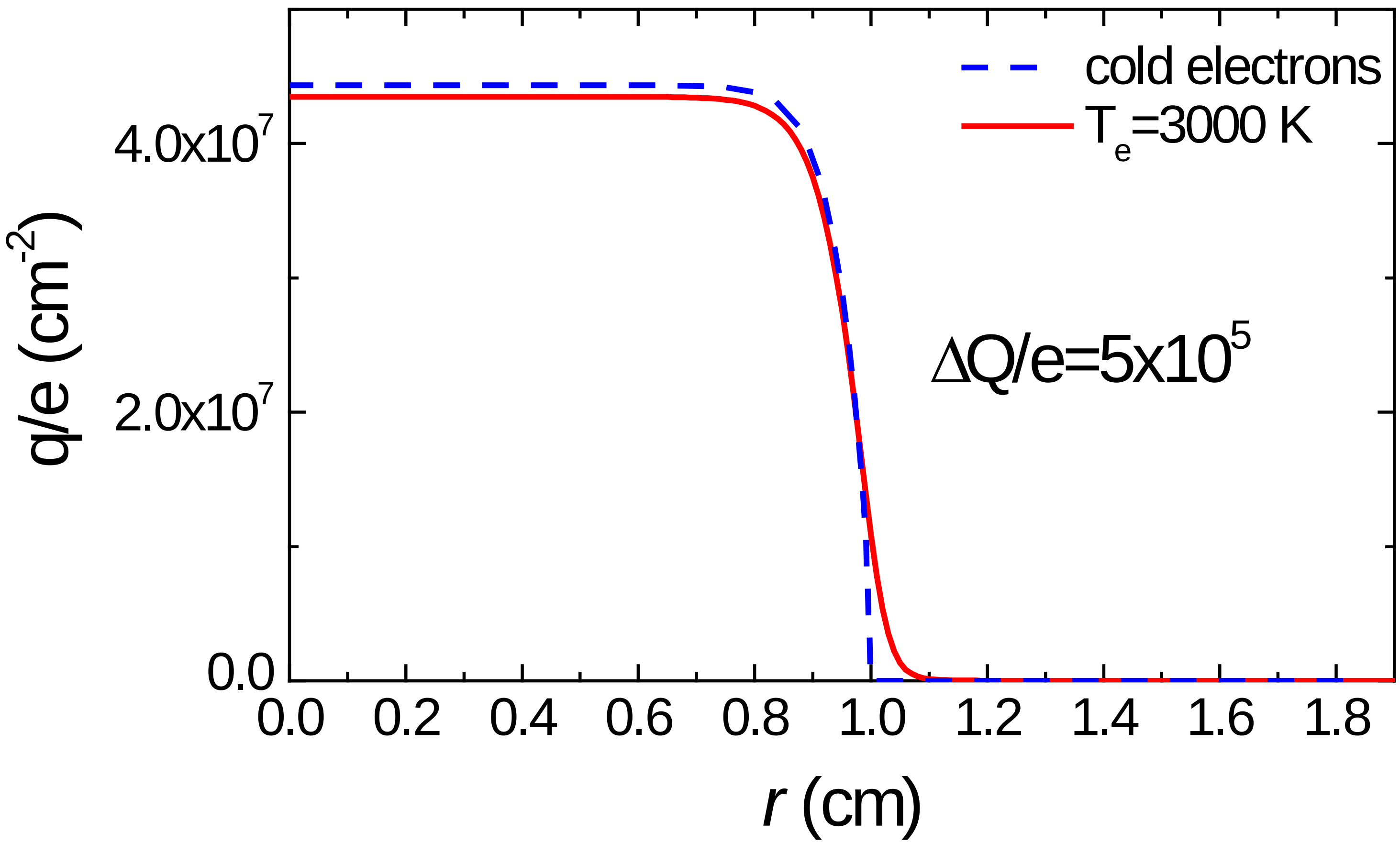
$$Q_0 = 1.35 \cdot 10^8$$

Effective electron temperature



Effective electron temperature

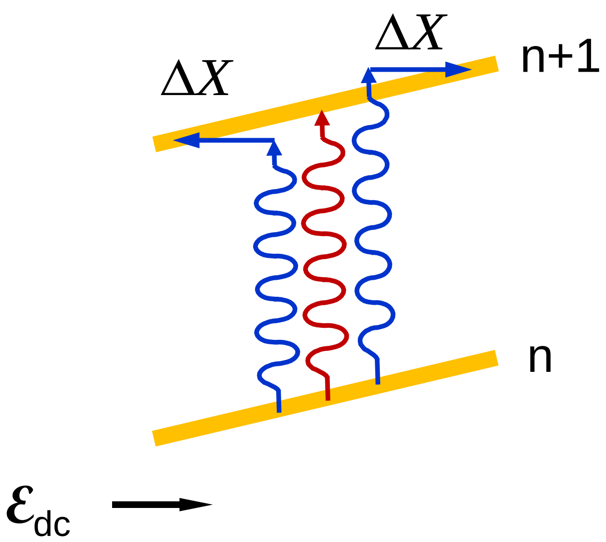
Simultaneous solution of Poisson and Boltzmann equation gives estimate of 3,000 K for electron temperature

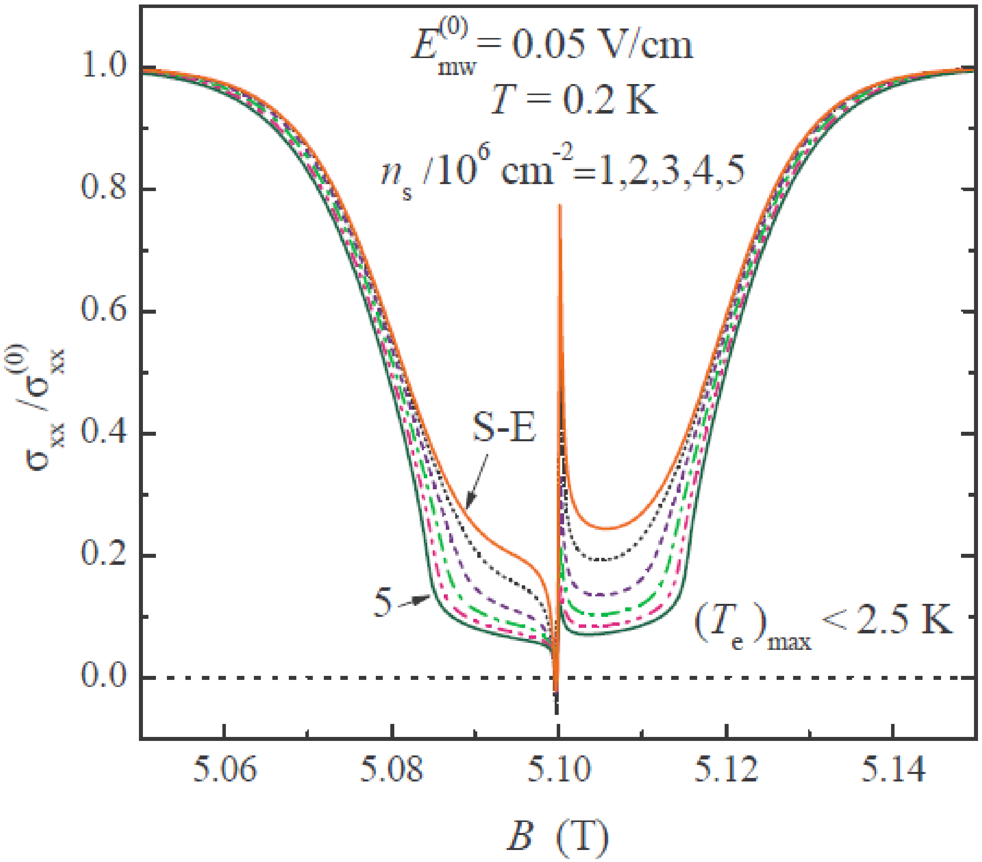


Possible scenarios

Breakdown of the effective electron temperature approximation?

Yu. Monarkha, PRB(R) 2015





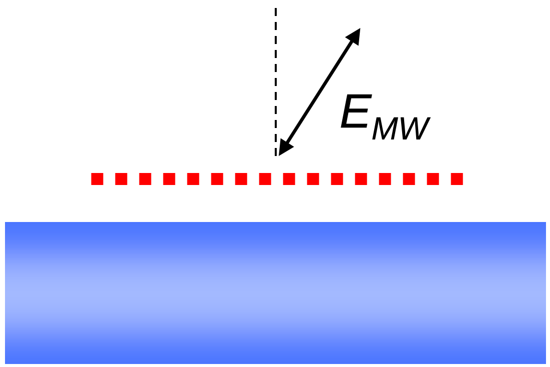
Predicts negative σ_{xx} and instability

on the low-field side of CR

OIST

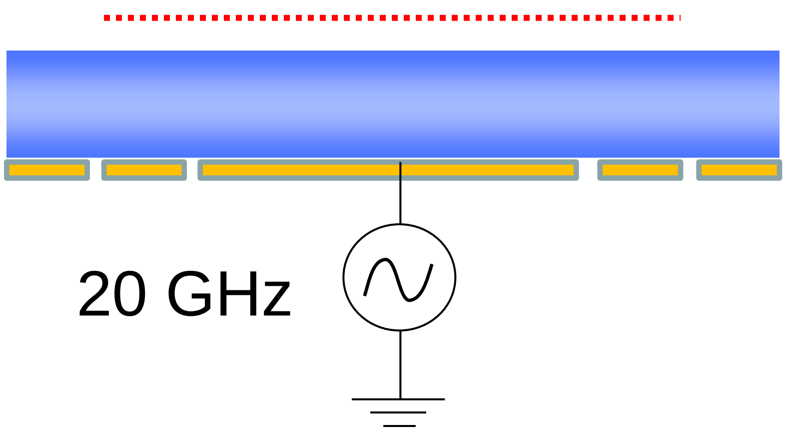
Possible scenarios

Magarill and Entin, arXive:1504.03422



$$j_x = \left\langle e n_s \sum_{\beta'} (X_{\beta'} - X_{\beta}) w_{\beta \to \beta'} \right\rangle$$

Second order perturbation theory



Would expect radial photocurrent

in our geometry

OIST

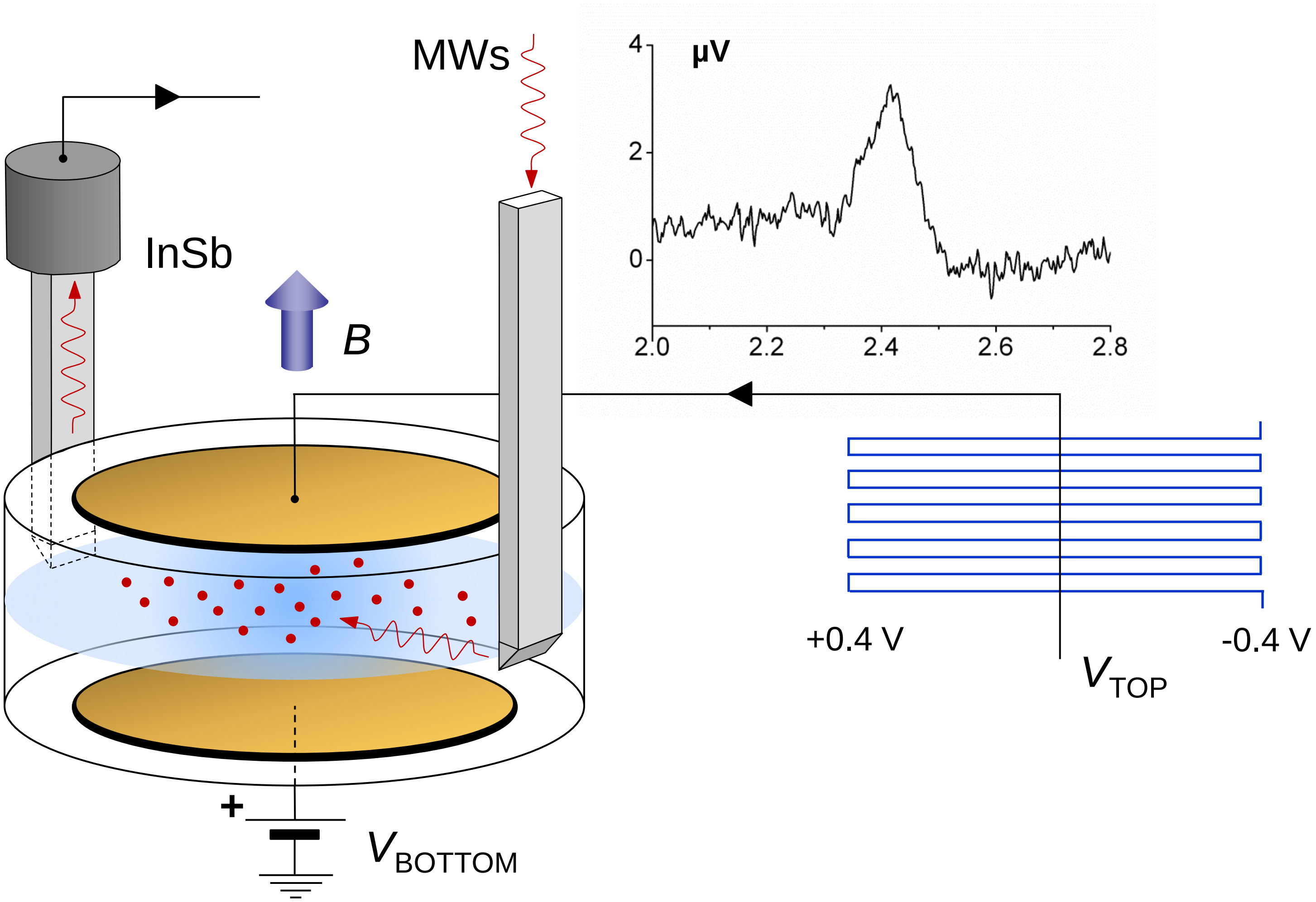
Summary

- In principle, our observation is consistent with formation of a quasy-3D electron system speculated earlier.

- However, it is difficult to understand why different motional degrees of freedom do not thermalize.

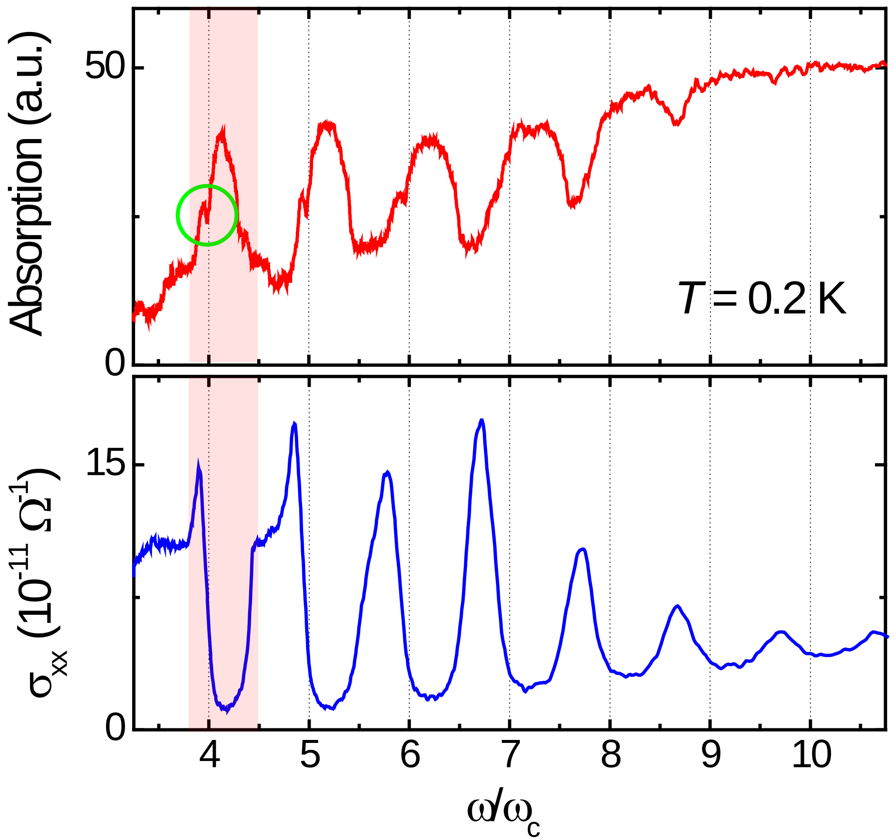
- Other theoretical proposals might be relevant but require examination

MW absorption measurements



OIST

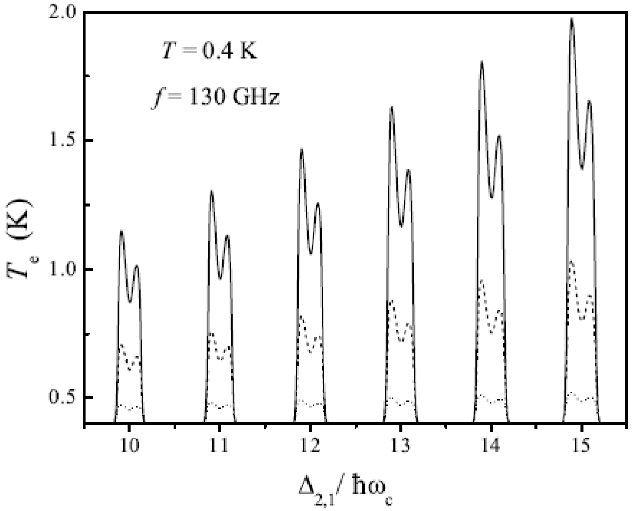
Absorption and electron heating



Energy balance equation:

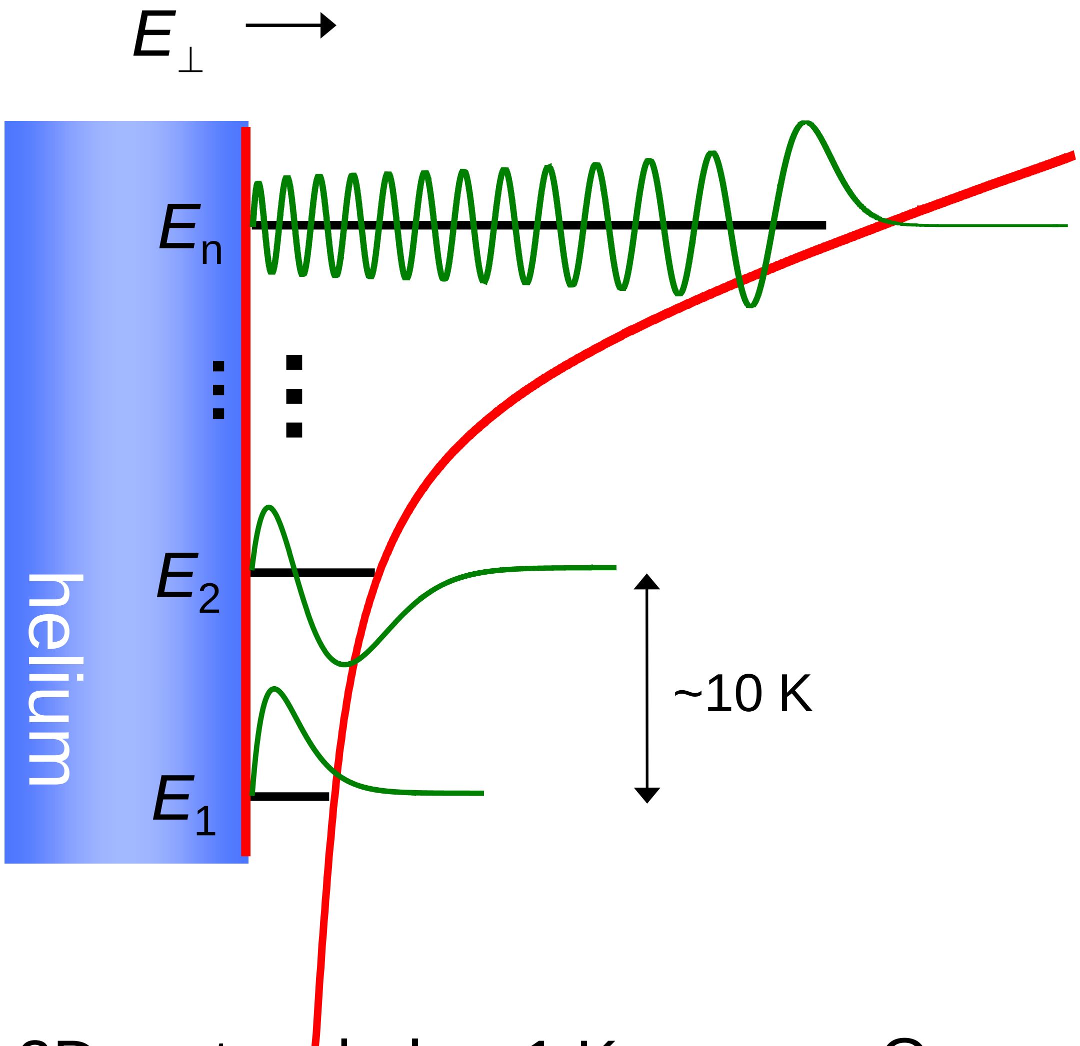
$$\text{Absorption} = \nu_E \cdot (T_e - T)$$

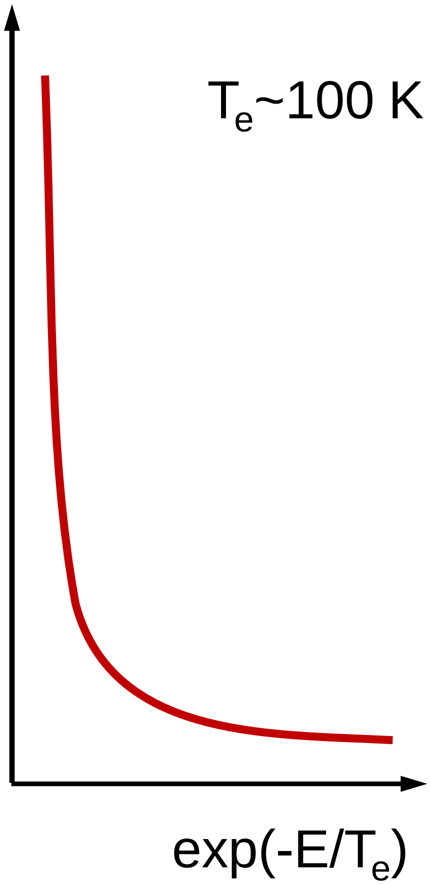
Heating of electrons:



DK and Kono J. Phys. Soc. Jpn. 2013

Subband population





2D system below 1 K

Quasy-3D hot electron system