Electrons in a microwave cavity:

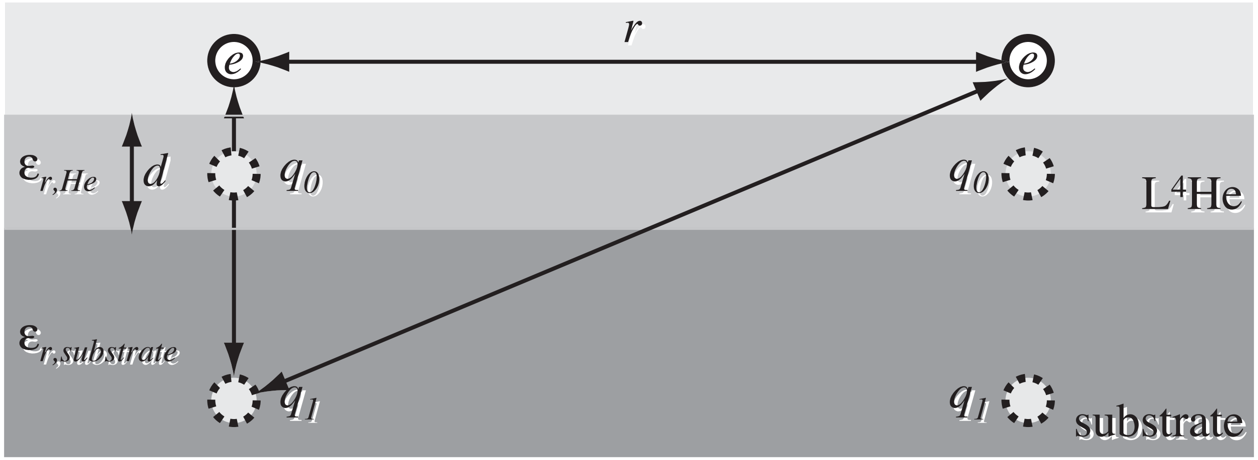
charging towards high densities, anti-crossing phenomena

Andreas Würl
Jürgen Klier
Valeri Shikin
Paul Leiderer

Overview

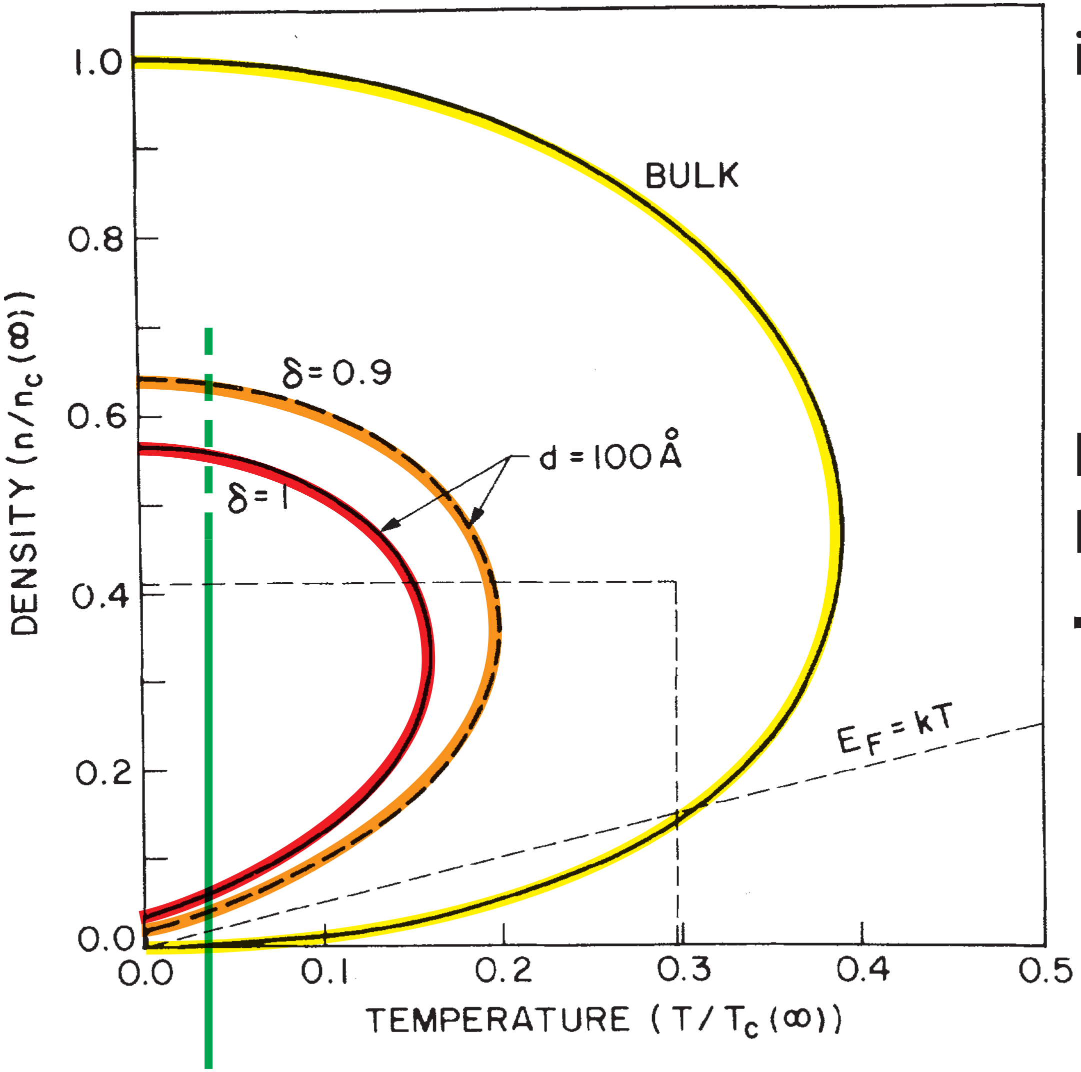
- Introduction to the system “electrons on helium“
    - Basic principles
    - Determining the electron density
- Experiment: Charging thin helium films with electrons
    - Experimental setup and methods
    - Results on lower electron densities
    - High electron densities and problems with reproducibility
- Anti-crossing phenomena in cyclotron resonance
    - General introduction
    - Looking at cyclotron resonance data
- Conclusions & Outlook

Characteristics of e⁻ on thin helium-films



- film is **stabilized** through **van-der-Waals forces**
  ➙ higher electron densities can be reached
- **interaction** between electrons gets **dipole character**
  ➙ modification of the phase diagram
- stronger **image-charge** in the polarizable substrate
  ➙ binding of electrons gets stronger
- **surface roughness** becomes important
  ➙ has to be considered in the analysis

The phase-diagram of the 2DES



experimental path

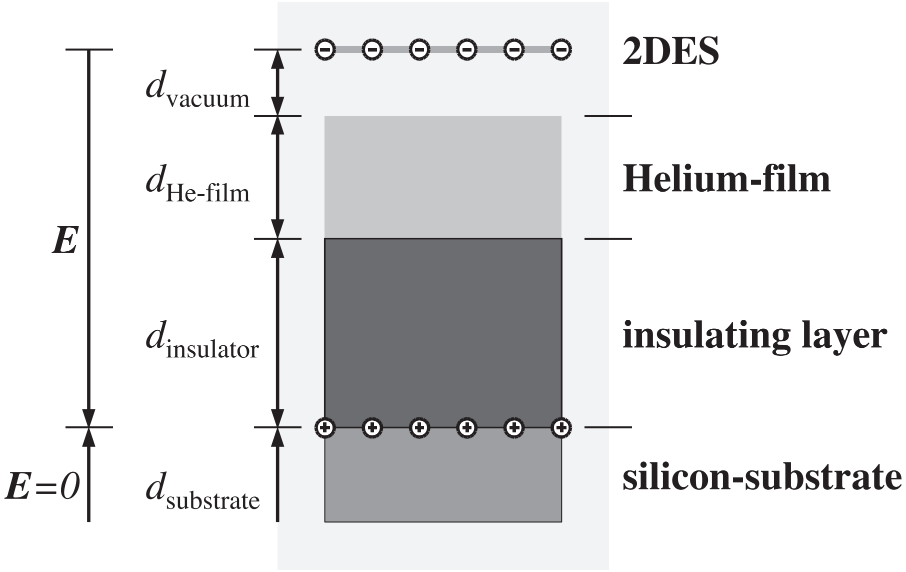
important energies:

thermal energy $\propto T$
Coulomb energy $\propto \sqrt{n}$
Fermi energy $\propto n$

F. Peeters, numerical calculation PRL **50**, 2021 (1983):

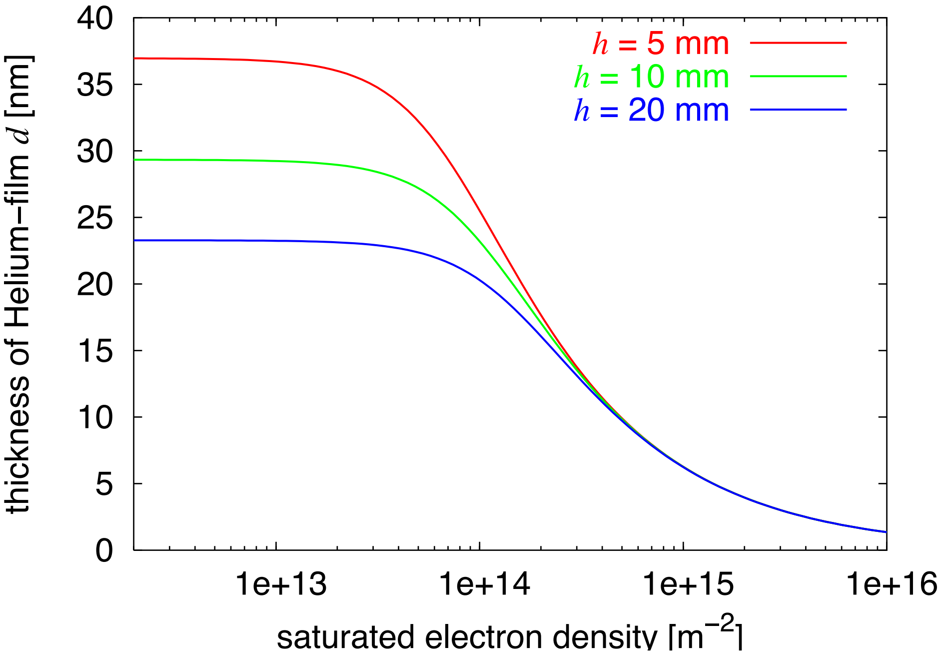
→ $T_c(\infty) = 33$ K
$n_c(\infty) = 2.4 \times 10^{16}$ m^{-2}

Determining the electron density



saturation of the 2DES:
electrical field above it vanishes

$$n_s = \frac{Q}{eA} = \frac{U_{\text{clamp}}\varepsilon_0}{e} \frac{1}{\frac{d_{\text{vacuum}}}{1} + \frac{d_{\text{He-film}}}{\varepsilon_{\text{r,He-film}}} + \frac{d_{\text{insulator}}}{\varepsilon_{\text{r, insulator}}}}$$

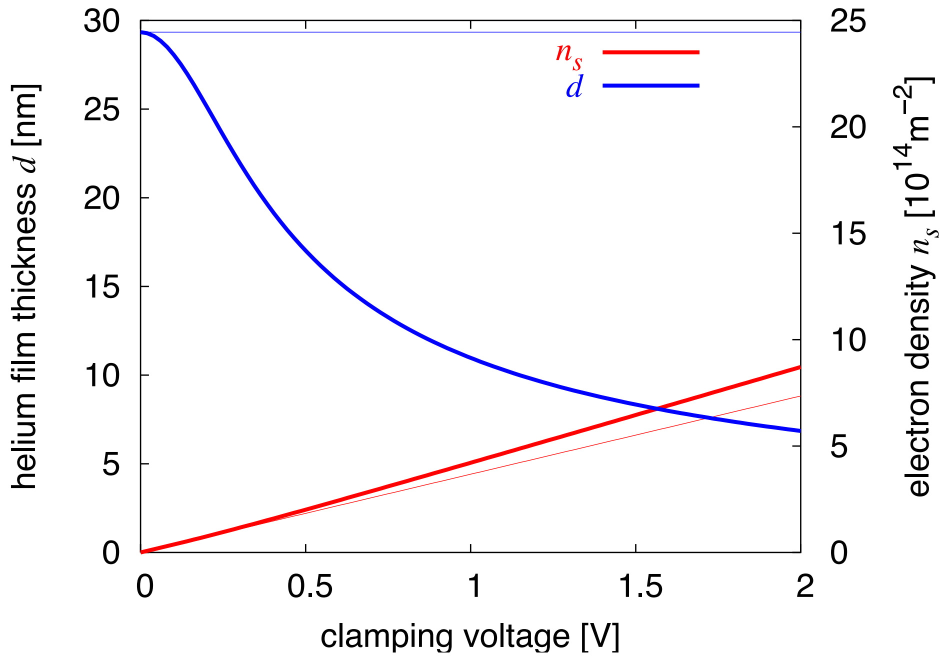


helium film thickness depends on the electron pressure:

$$d = d_0 \left(1 + \frac{n_s^2 e^2}{2\varepsilon_0 \rho g h}\right)^{-\frac{1}{3}}$$

Etz et. al., PRL **53**, 2567 (1984)

Determining the electron density



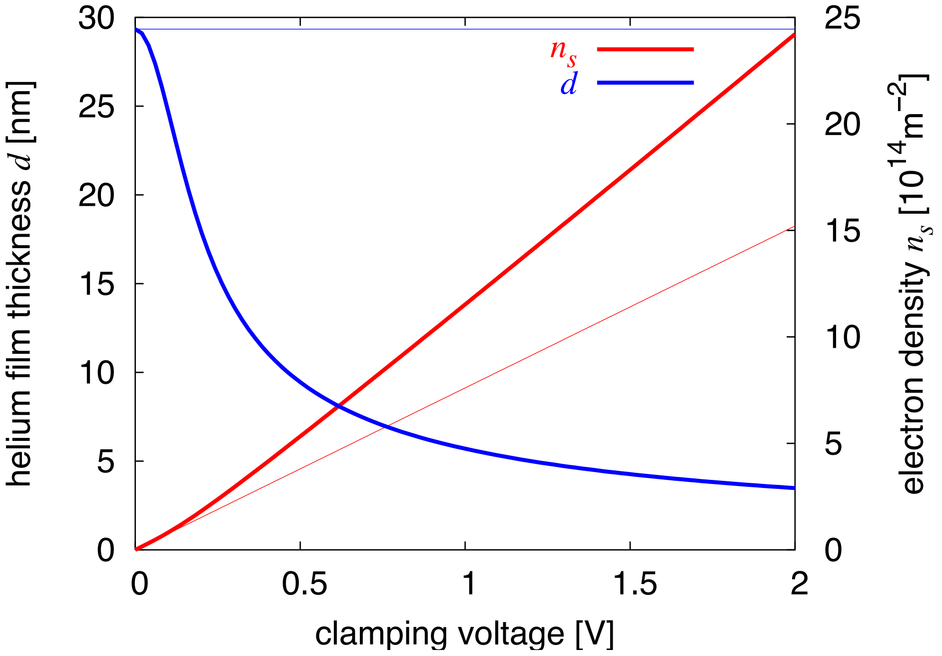
Results of the self-consistent calculations

Electrons on He on 200 nm PMMA

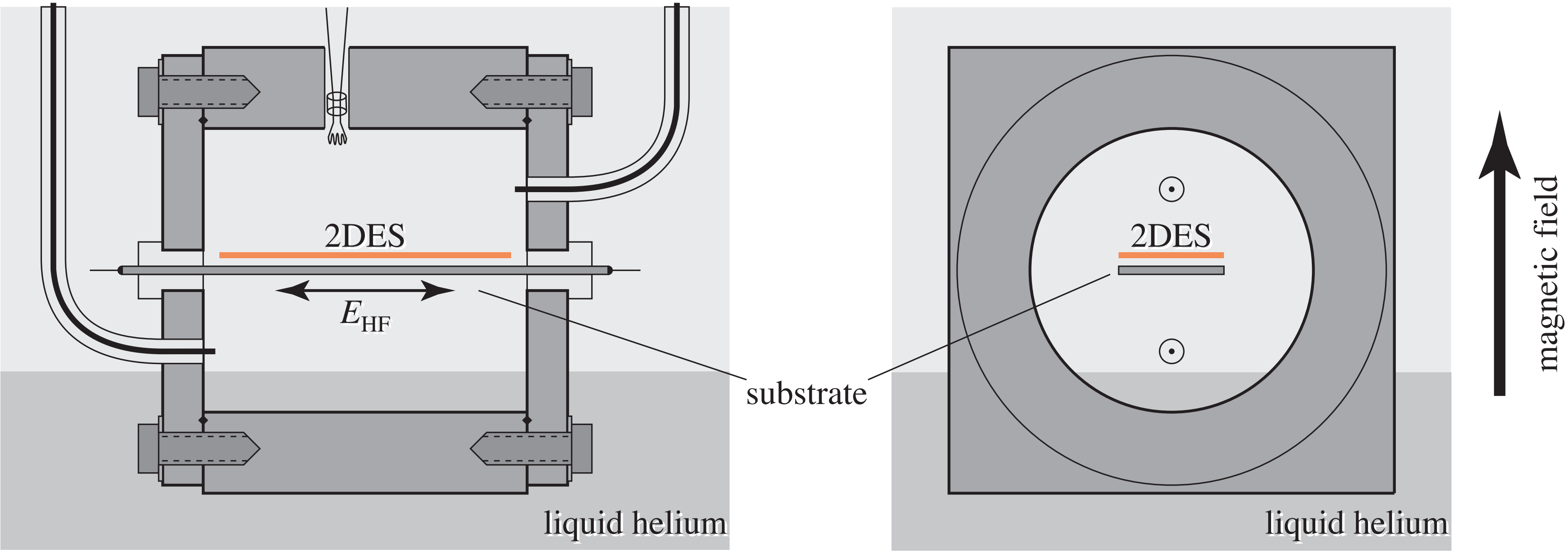
(ε = 1.7)

Electrons on He on 200 nm SiO$_2$

(ε = 5)

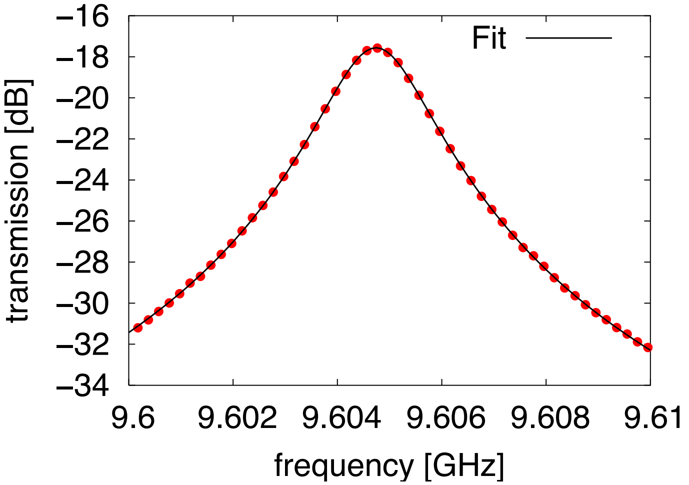


The experimental setup



microwave resonator:

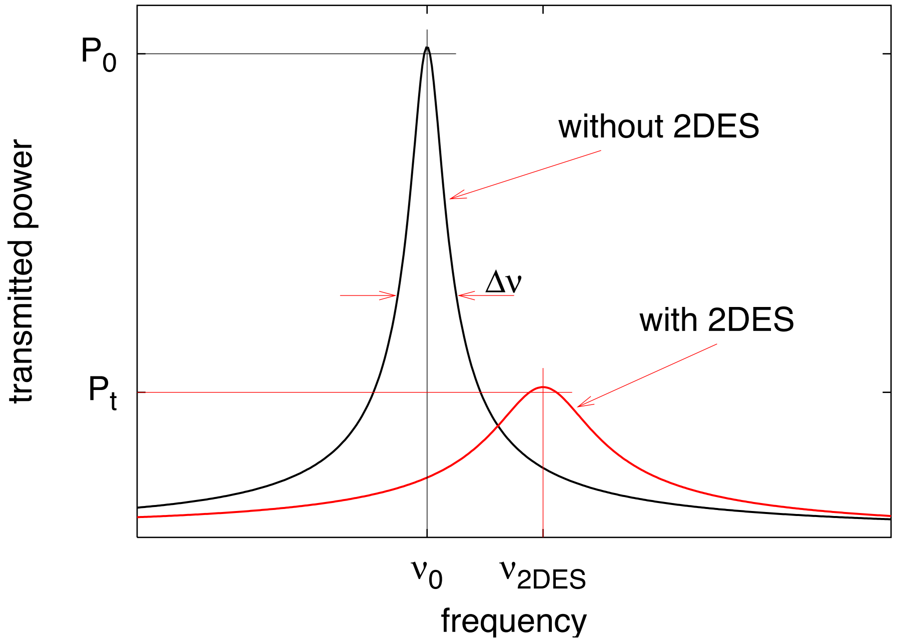
- working frequency ≈ 10 GHz
- microwave transmission is measured around the cavity’s resonance
- parameters are extracted via a curve-fit

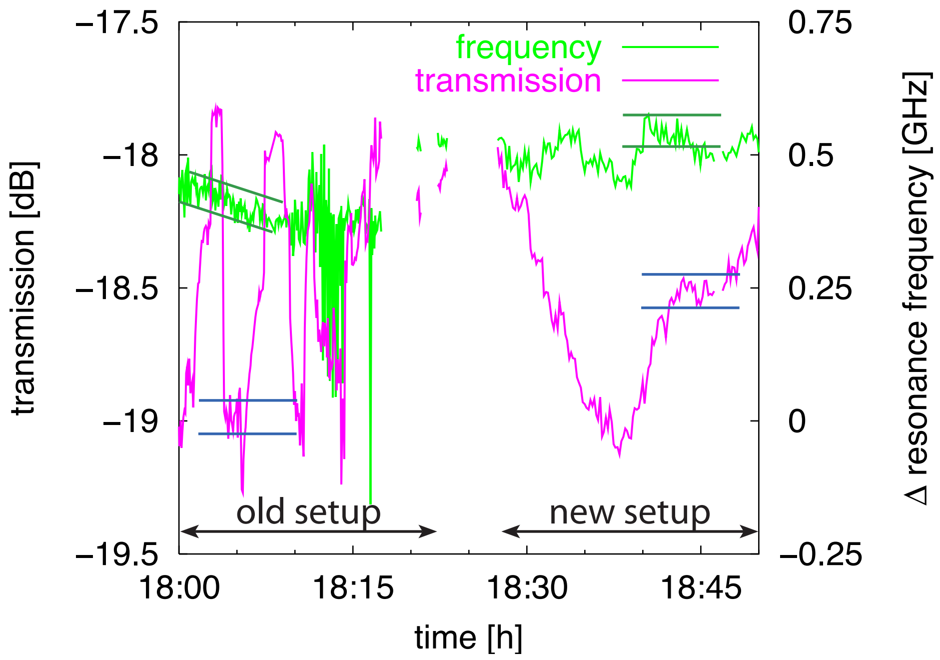


How the experiment works

The presence of a 2DES on the substrate leads to a **damping of the resonators transmission** and a **shift of the resonance frequency**.

The physical parameters of the 2DES can be extracted from this information.

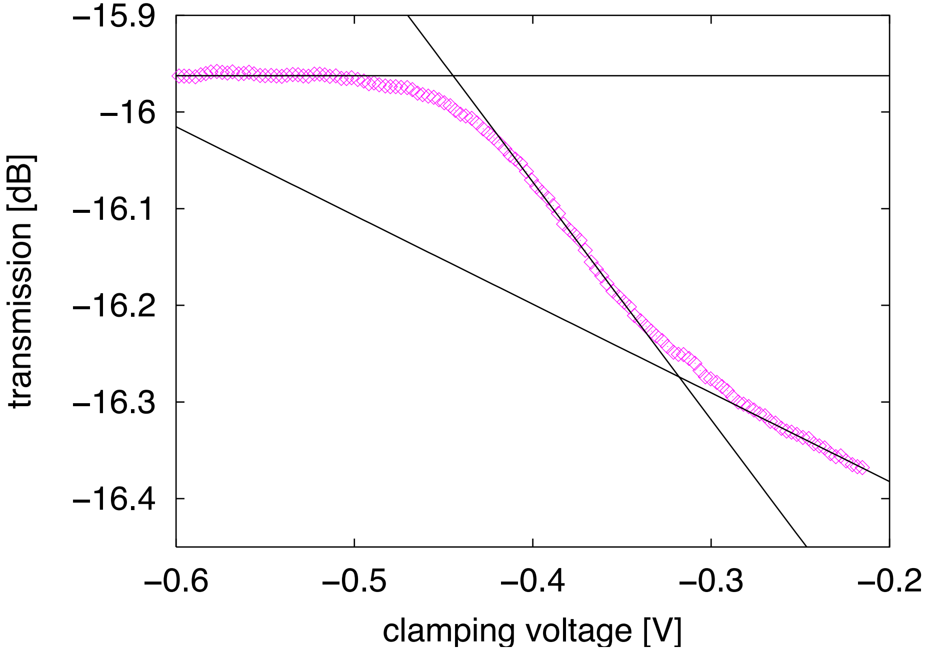


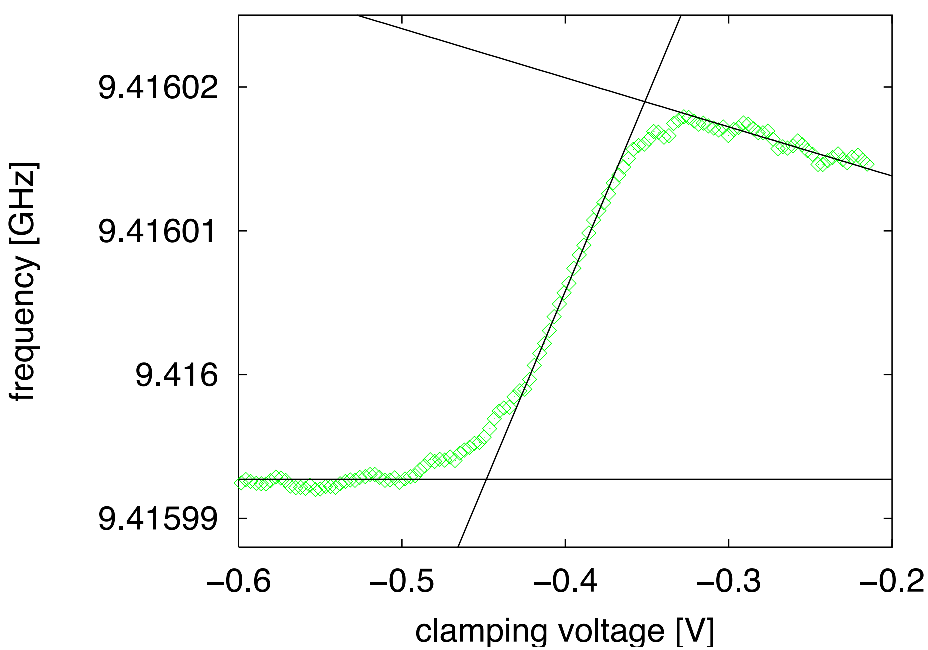


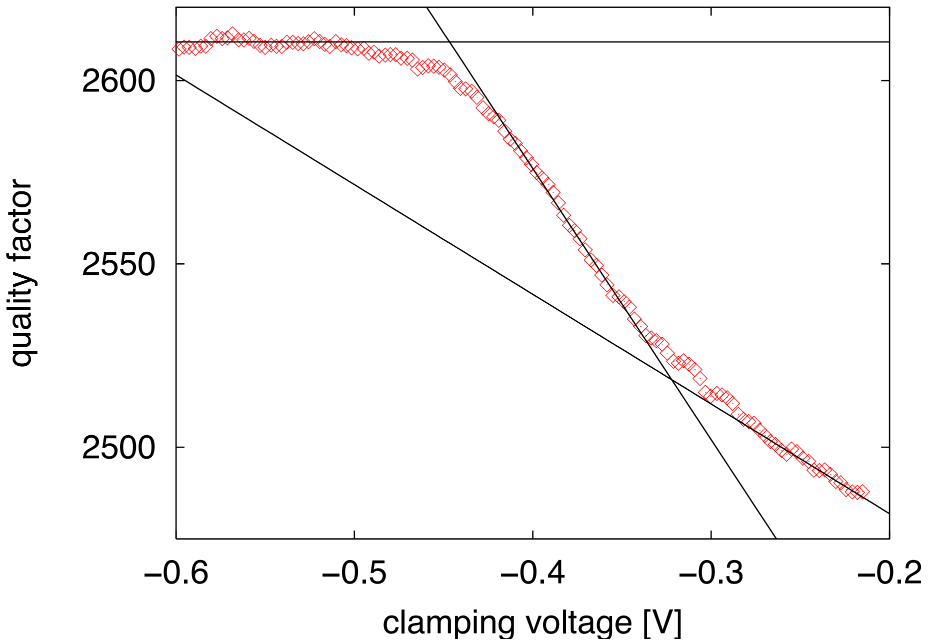
Comparison between the formerly used setup and the new network analyzer method.

➞ The noise level is compareable.

Charging the helium film on PMMA







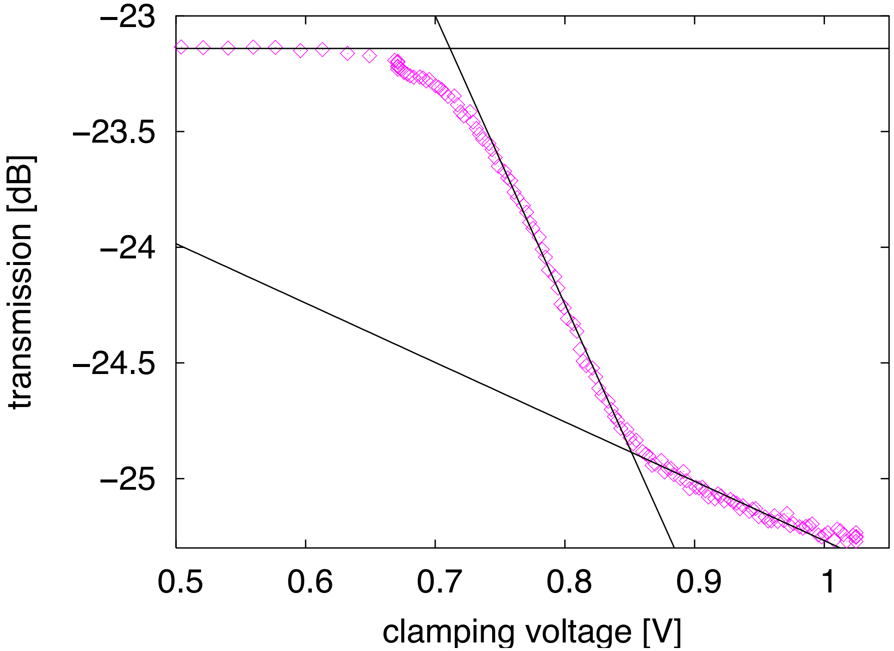
substrate: 200 nm PMMA on silicon

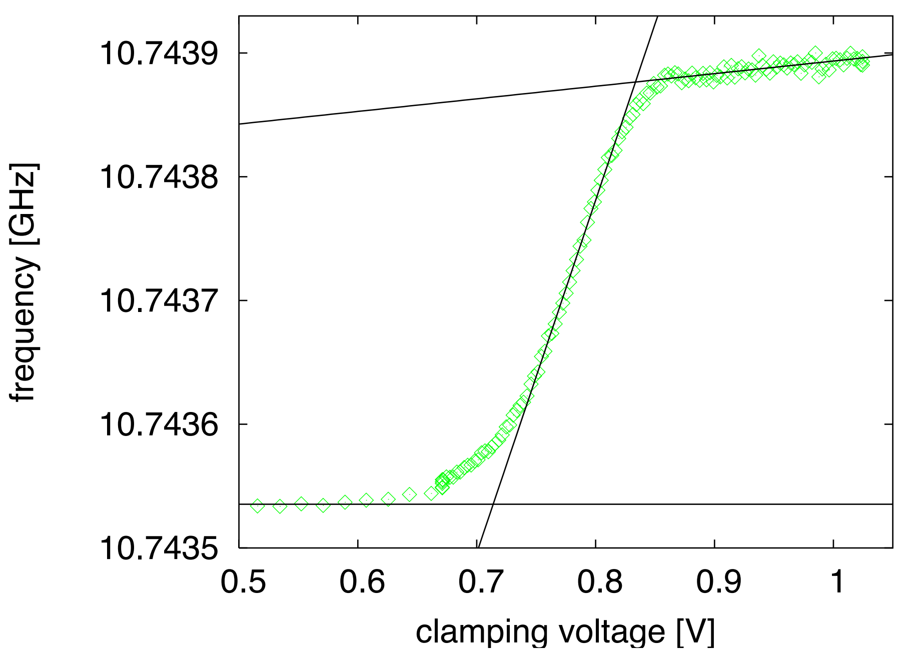
$T = 1.29$ K

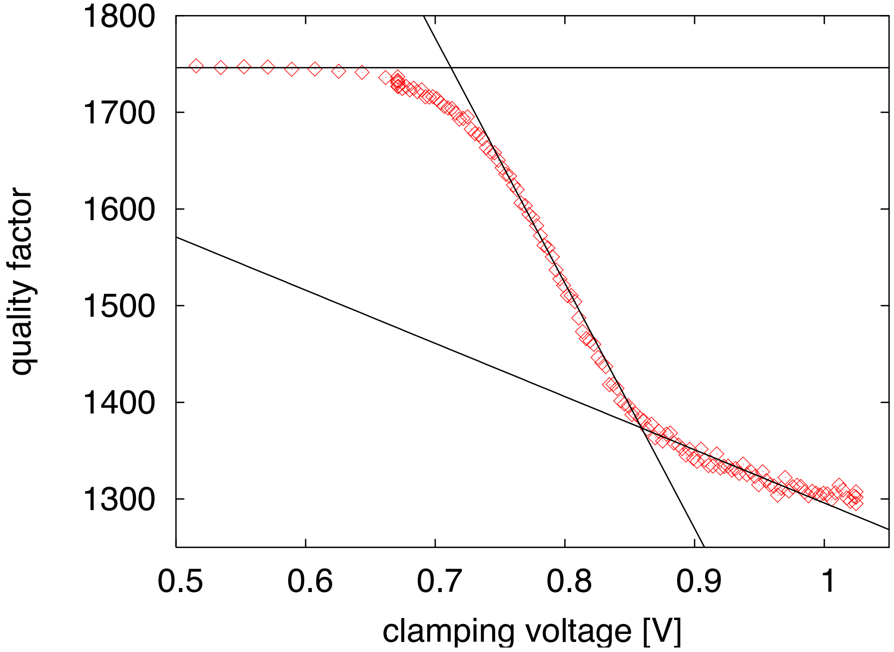
$h = -7$ mm ($d_0 = 33$ nm)

data: mw0205d4 #41

Charging the helium film on SiO_2







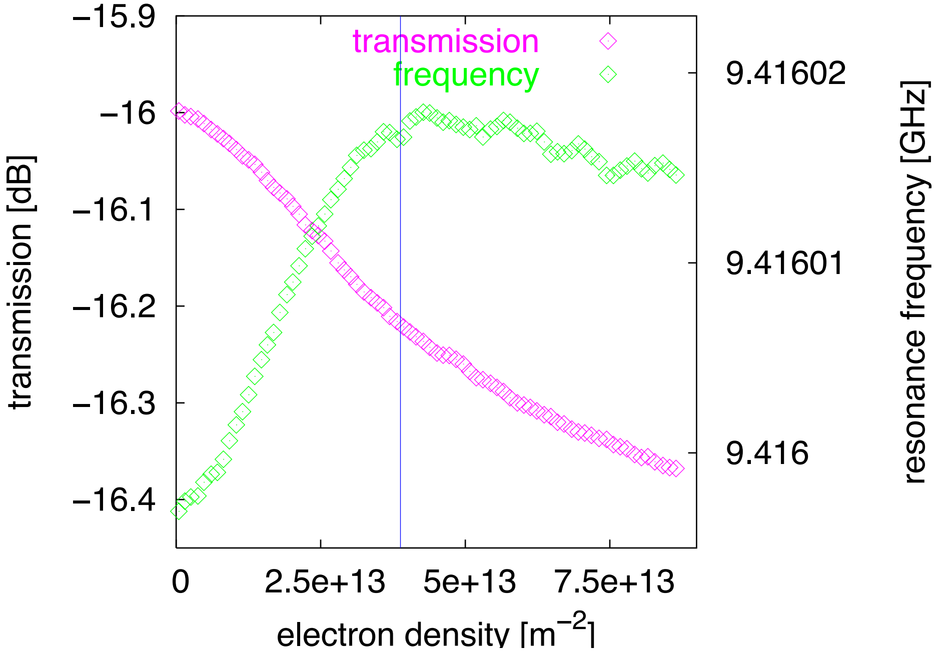
substrate: 200 nm SiO_2 on silicon

$T = 1.30$ K

$h = -9.7$ mm ($d_0 = 30$ nm)

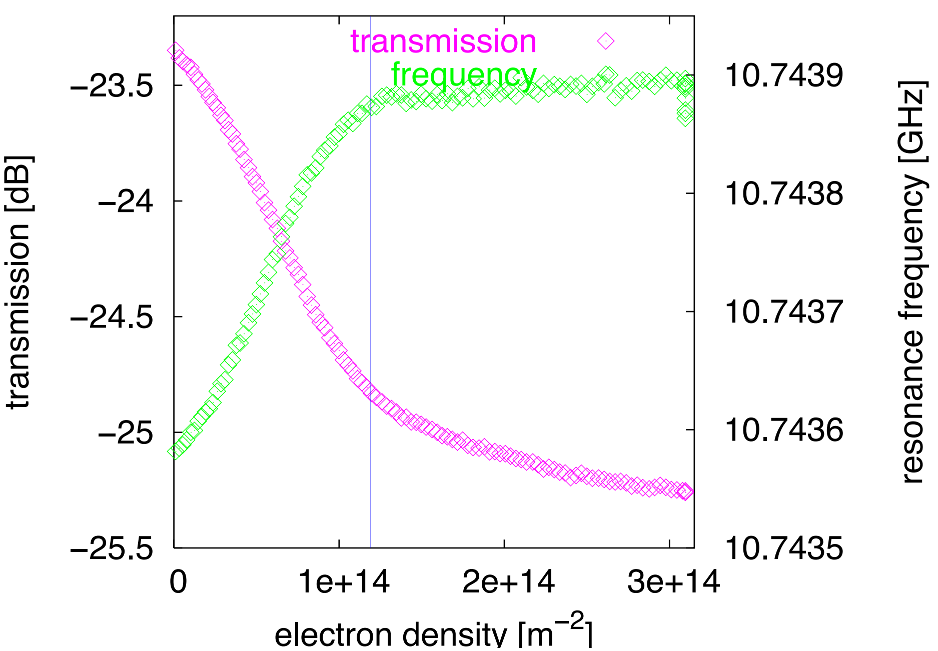
data: mw0205d4 #41

Data analysis



PMMA/silicon substrate, T = 1.29 K

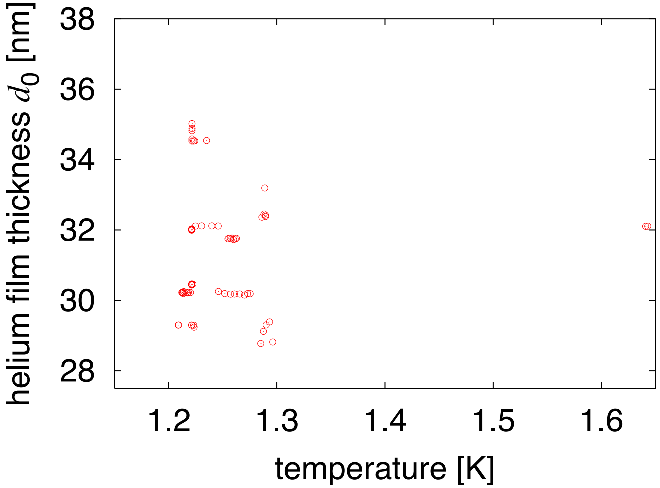
$n_{WC} = 4.1 \times 10^{13}$ m^{-2}, Γ=125

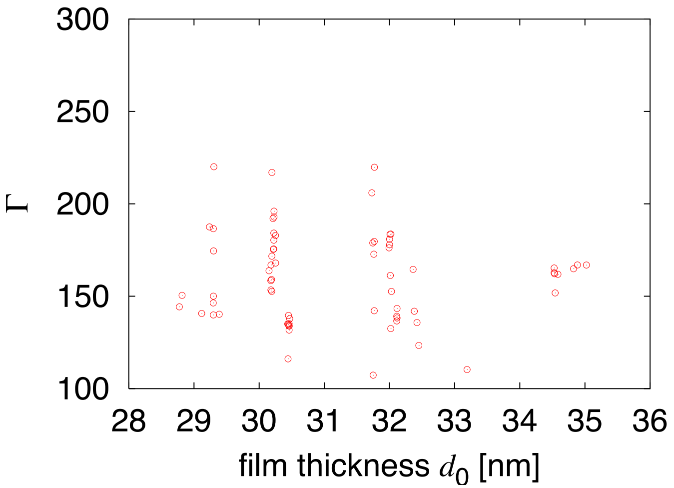


SiO$_2$/silicon substrate, T = 1.30 K

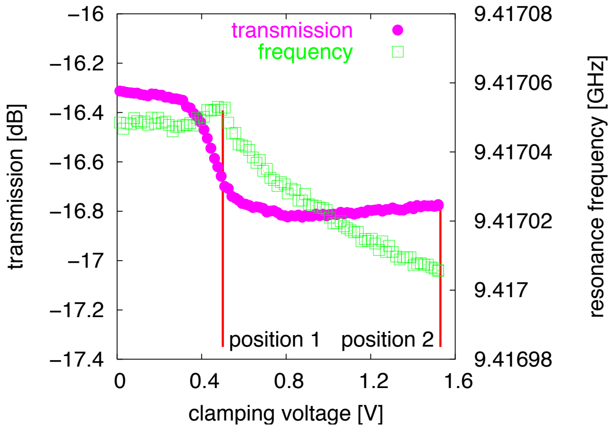
$n_{WC} = 1.2 \times 10^{14}$ m^{-2}, Γ=165

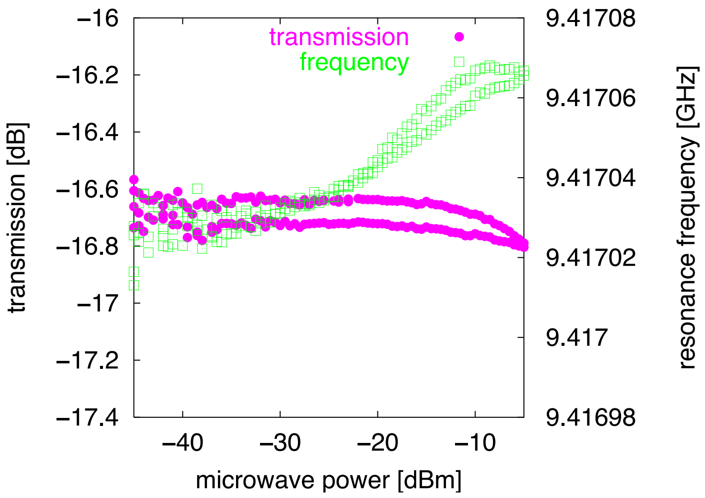
but: experimental results for Wigner-crystallization on PMMA scatter over a wide range

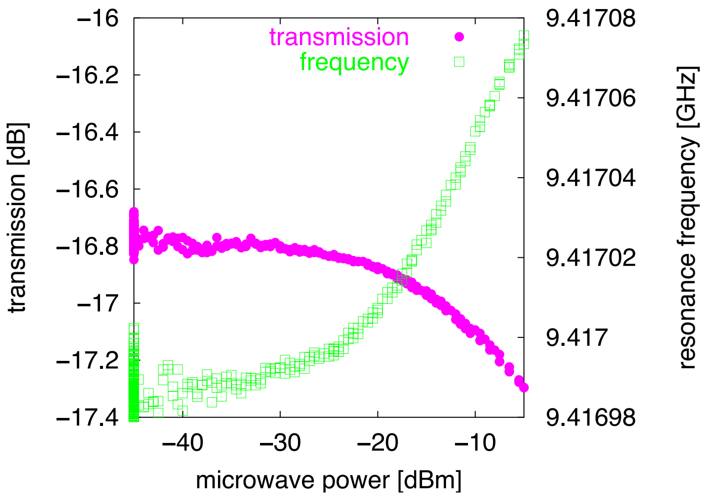




Changing the excitation power

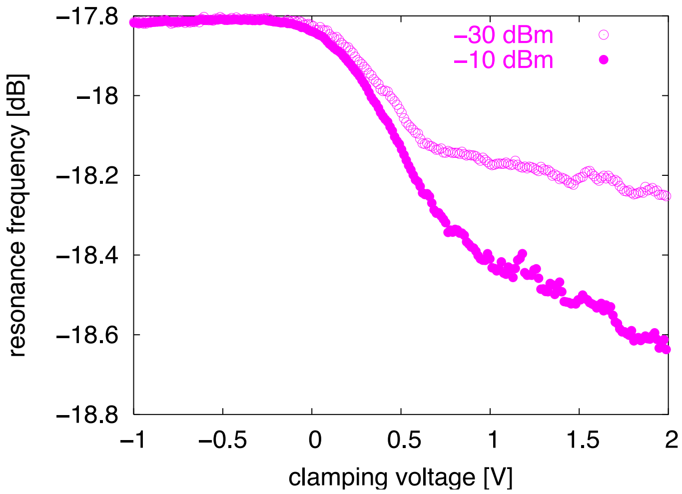


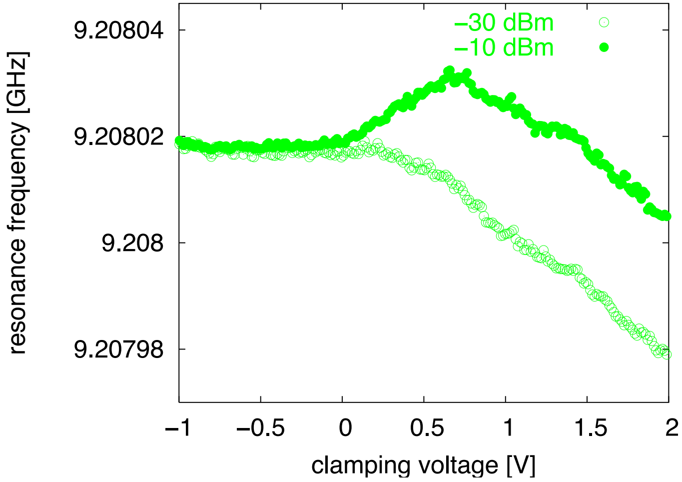




two excitation power sweeps in the liquid and crystalline phase

charging simultaneously with two different excitation powers

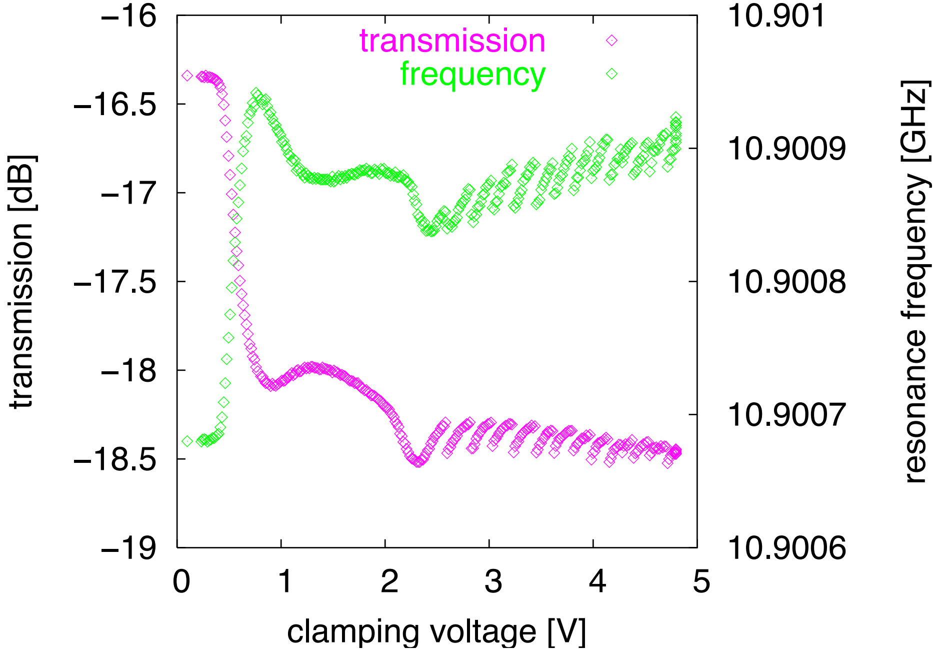




Charging the helium film to high e⁻ densities

problems which arise:

- sudden **breakthrough** of electrons
- **tunneling** at small film thicknesses
- increased absorption due to **localized electrons**



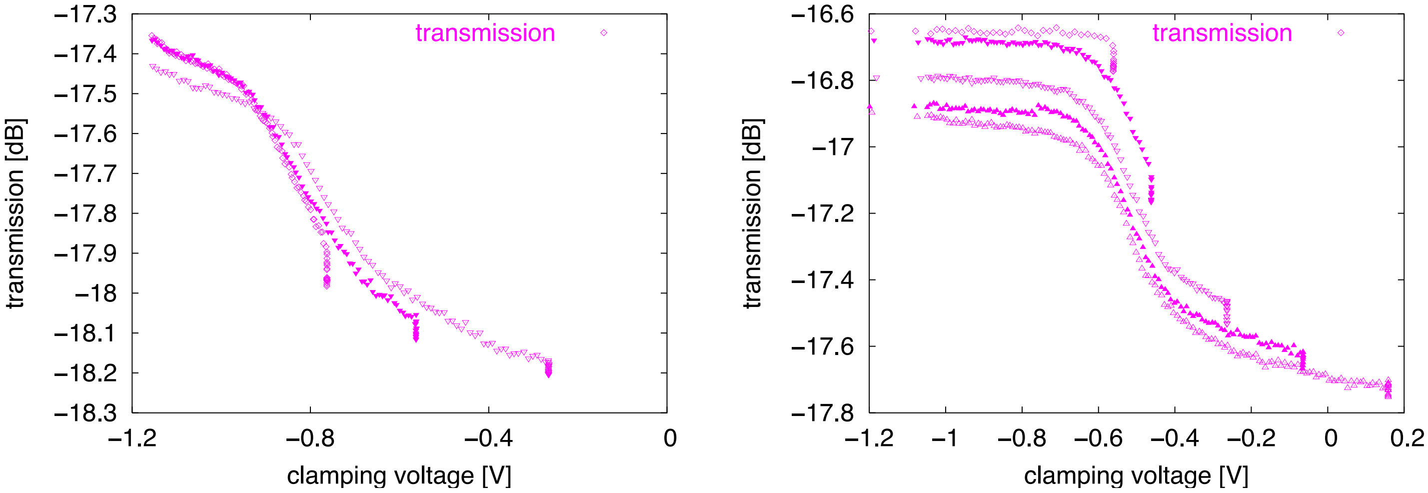
- **no saturation** because of competition beween loss and gain of electrons

to detect these phenomena, repeated charging sweeps were done

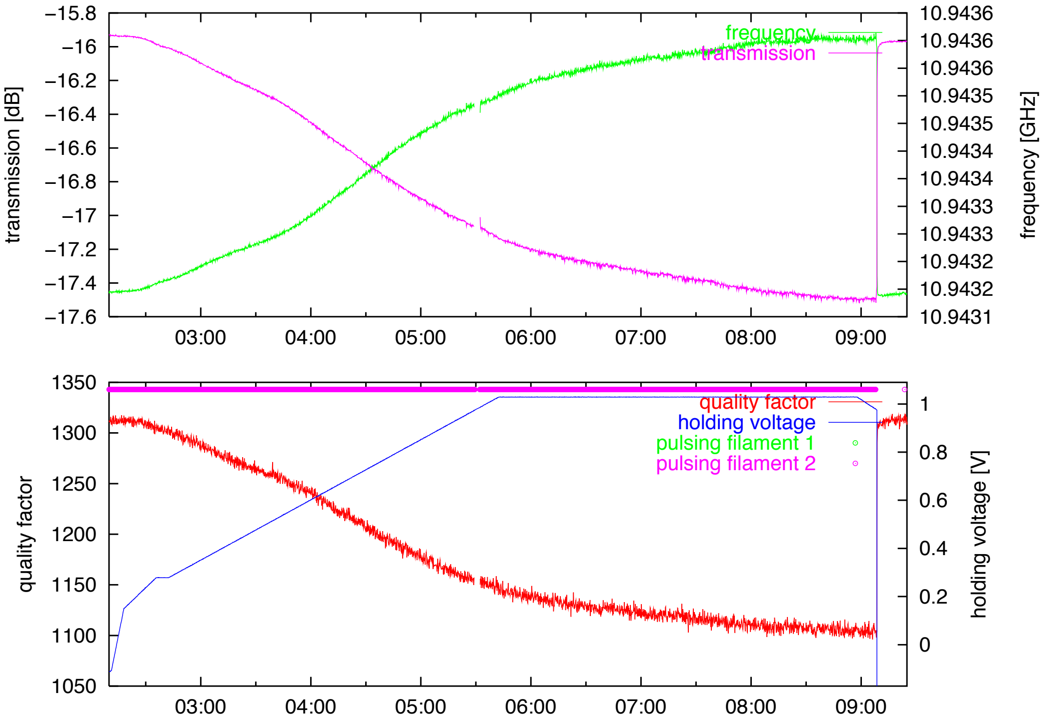
- **breakthrough** and **tunneling** of electrons shift the onset of charging to more positive voltages
- **localized electrons**, which lead to enhanced absorption cannot be removed after the charging process
  → absorption does not go back to the initial value

Charging series on thin helium films

charge series
which show the
typical behaviour

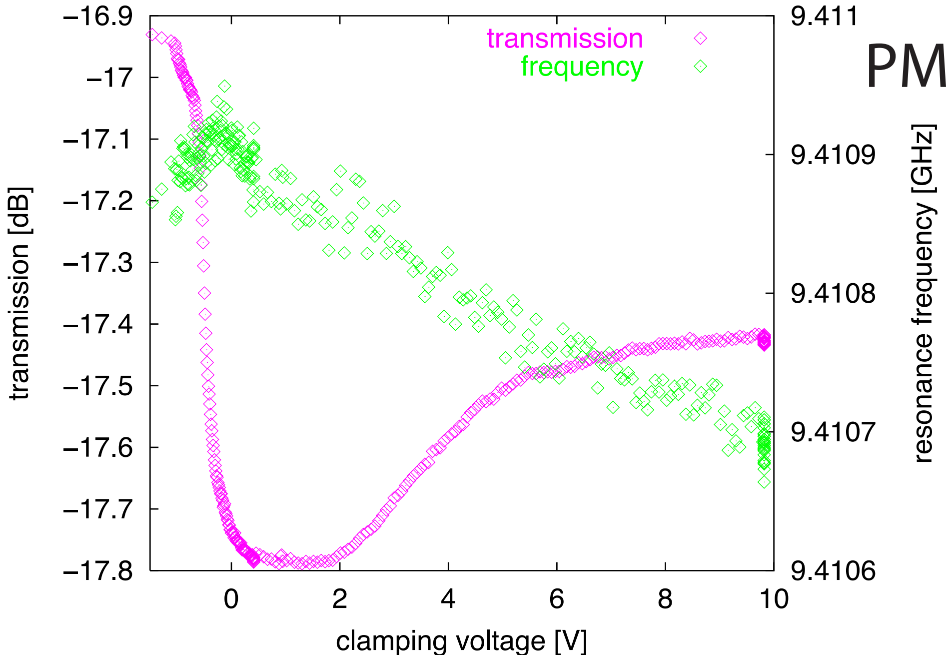


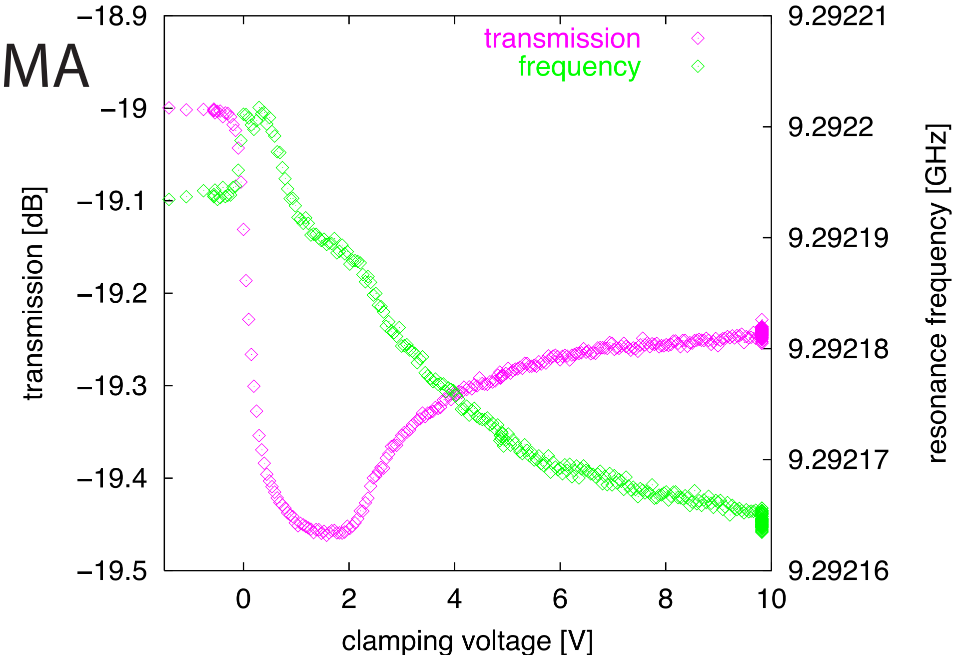
charging in the time domain



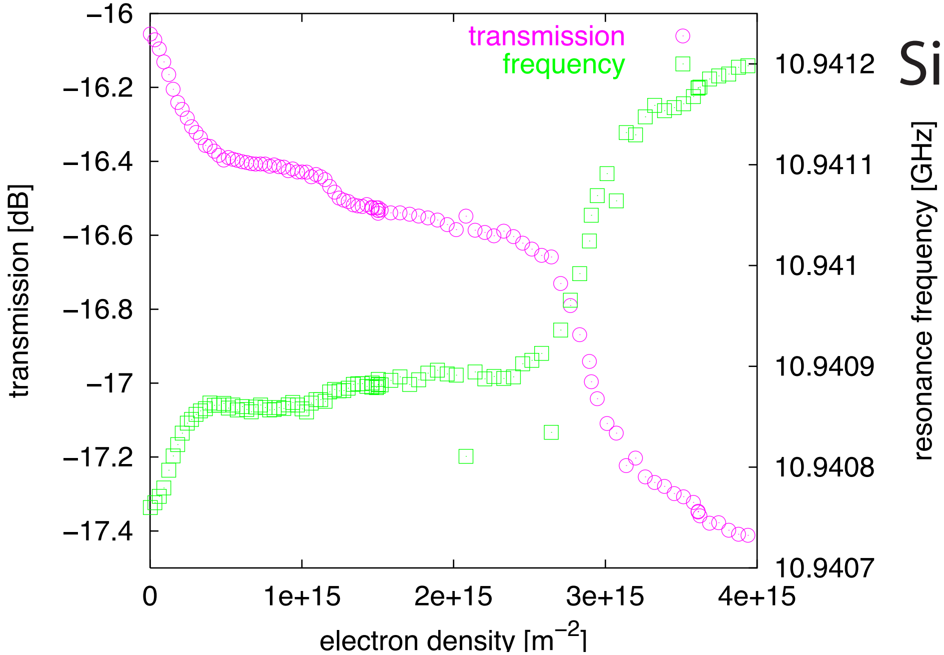
High electron densities

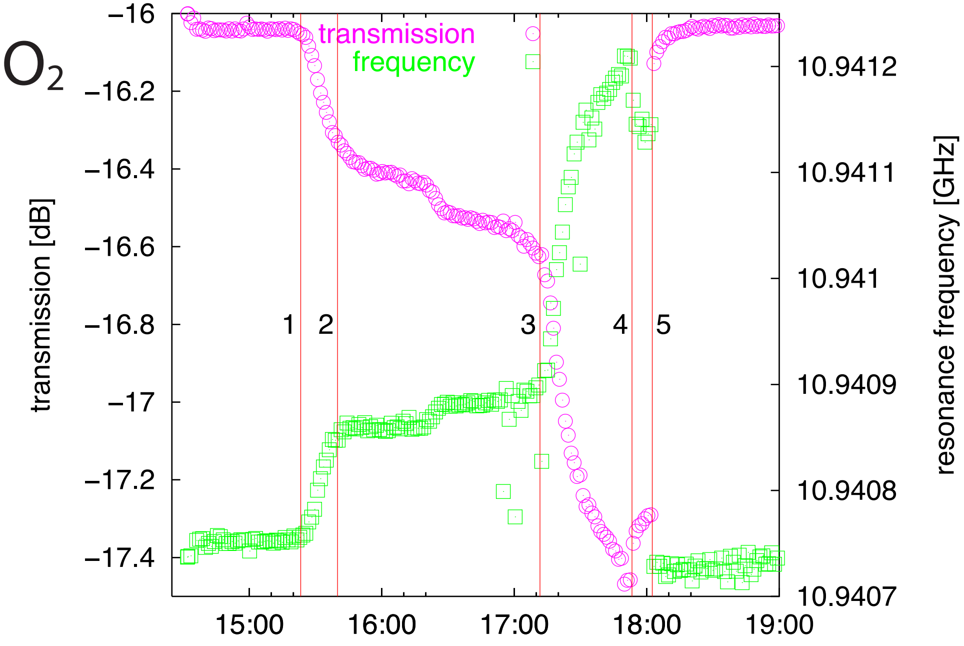
PMMA





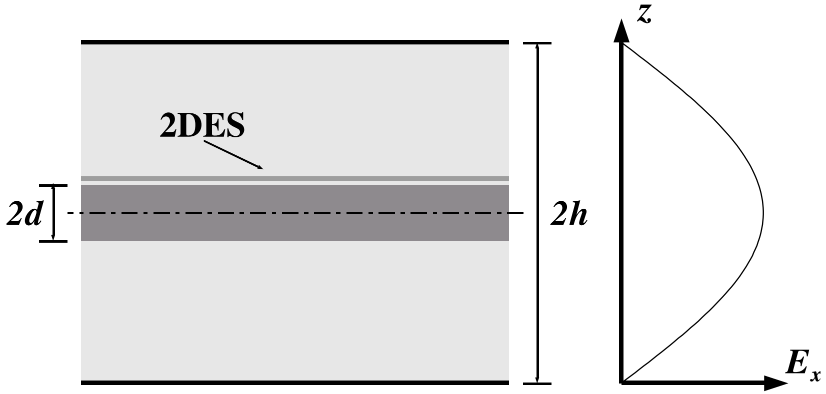
SiO$_2$





Anti-crossing phenomena in a resonator

Eigenmode of resonator vs. cyclotron frequency $\omega_0 = \omega_c$



$$\delta\omega = \omega_e - \omega_0 = \delta\omega_\sigma + \delta\omega_p$$

If $B \to 0$ and $B \to \infty$, $\delta\omega_\sigma$ is a linear function of n_s

Dispersion law of resonator:

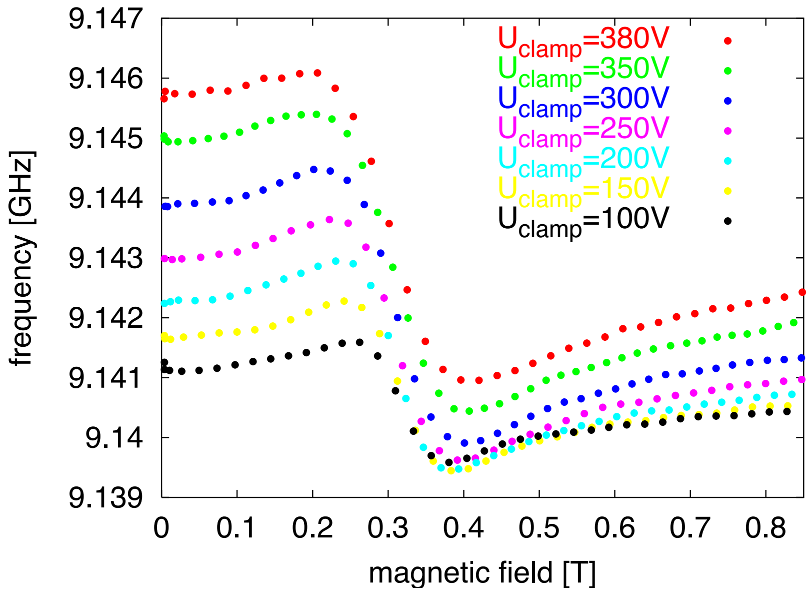
$$\tan(q_0 d) - \frac{\sin(k_0 d) + \cos(k_0 d)\cot(k_0 h)}{\cos(k_0 d) - \sin(k_0 d)\cot(k_0 h)} = \frac{4\pi i}{c}\sigma_{xx}$$

For small coupling ($\sigma_c \ll 1$):

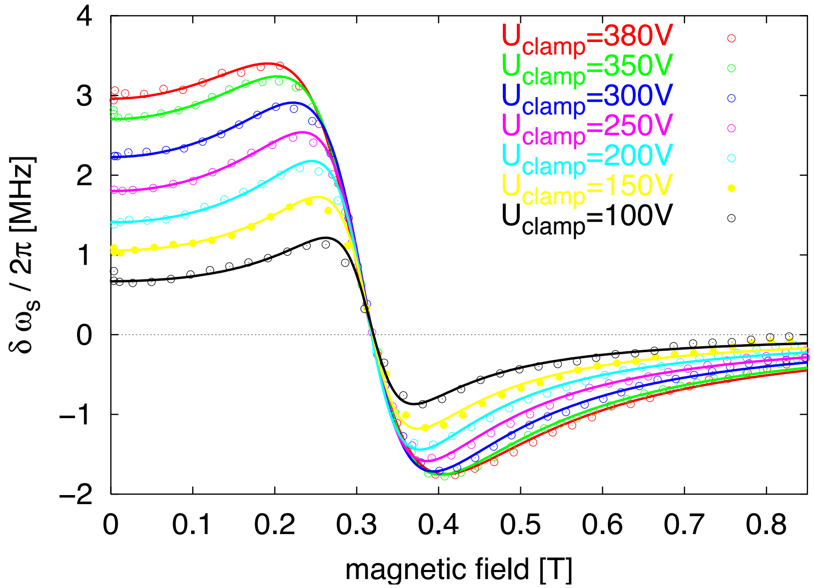
$$\omega_e - \delta\omega_p = \omega_0 + \delta\omega_\sigma$$

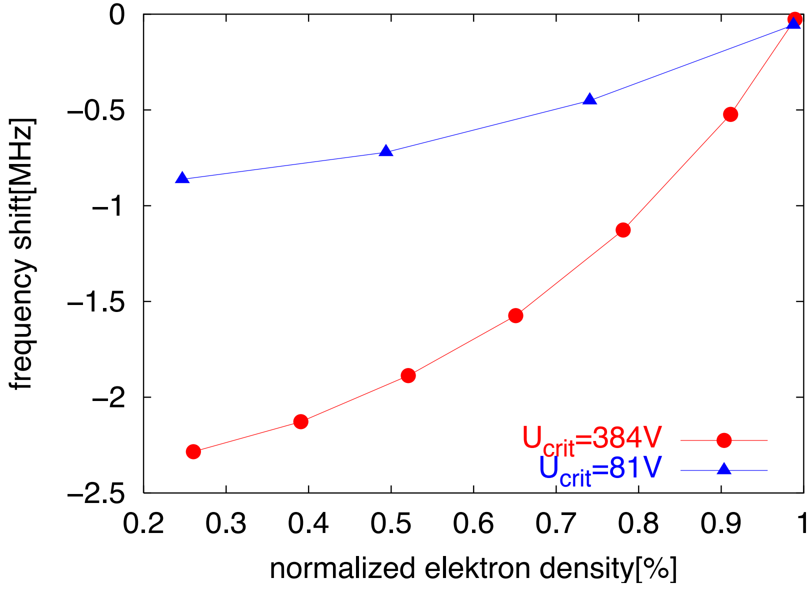
Extracting the data

raw data



frequency offset substracted

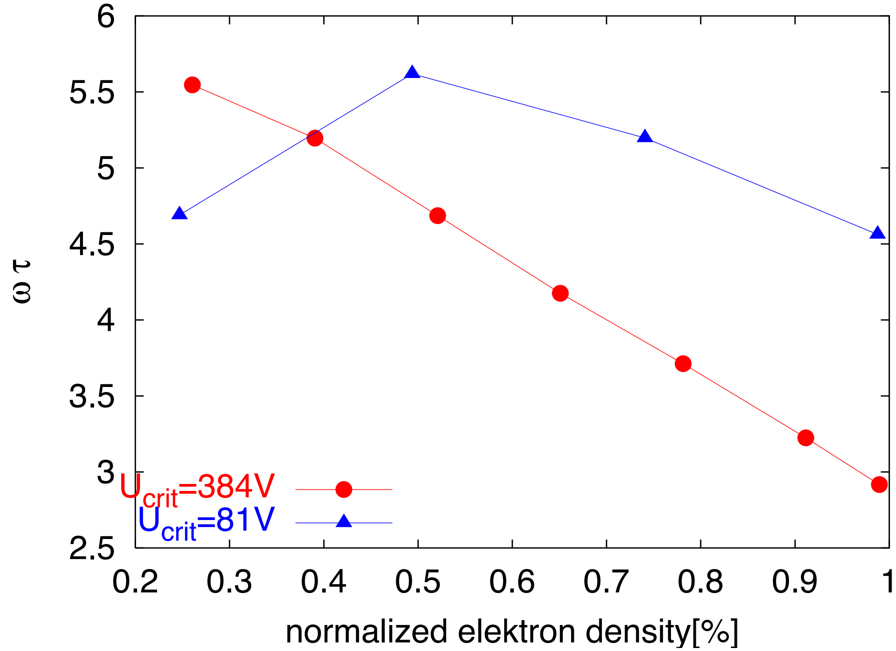




$$(e\,n_{s,\mathrm{sat}})^2 = \frac{\rho_{\mathrm{He}}\, g\, \left(d_{0,\mathrm{He}} - d_{\mathrm{He}}\right)}{4\pi}$$

helium depression ➙ frequency shift

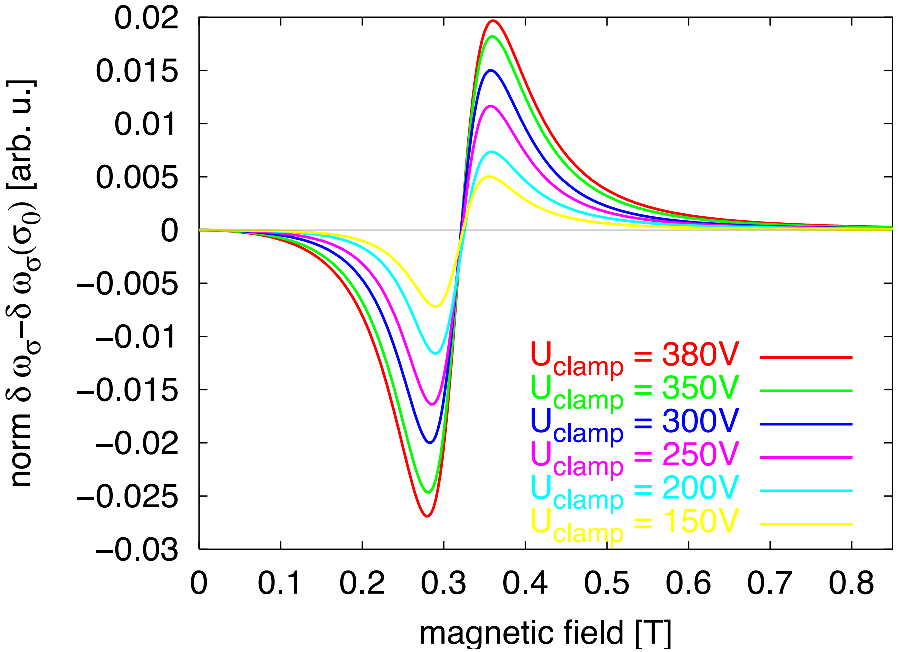
Analyzing the CR data



linewidth has maximum

deviation from linear scaling

$$\delta\omega \;\propto\; \mathrm{Im}(j_x(\omega, \omega_c, \tau)) \;\propto\; n_s$$



Conclusion

It is easily possible to charge thin helium films with electron densities up to the order of 10^{14} m^{-2}.

One can even reach higher densities, but has to be very careful with the measurement and the analysis, as a lot of problems can happen here.

Very smooth substrates are necessary for good S/N ratio.

The presented two-fraction model in combination with cyclotron resonance measurements provide a tool for surface characterization.

Outlook

- use new substrates, like "pure" silicon or carbon films
- try to explore the behaviour of the system in a wider parameter range
- further improve process of charging and discharging the system