Electrons on thin helium films

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Charging the film to higher densities and characterization of the substrate quality

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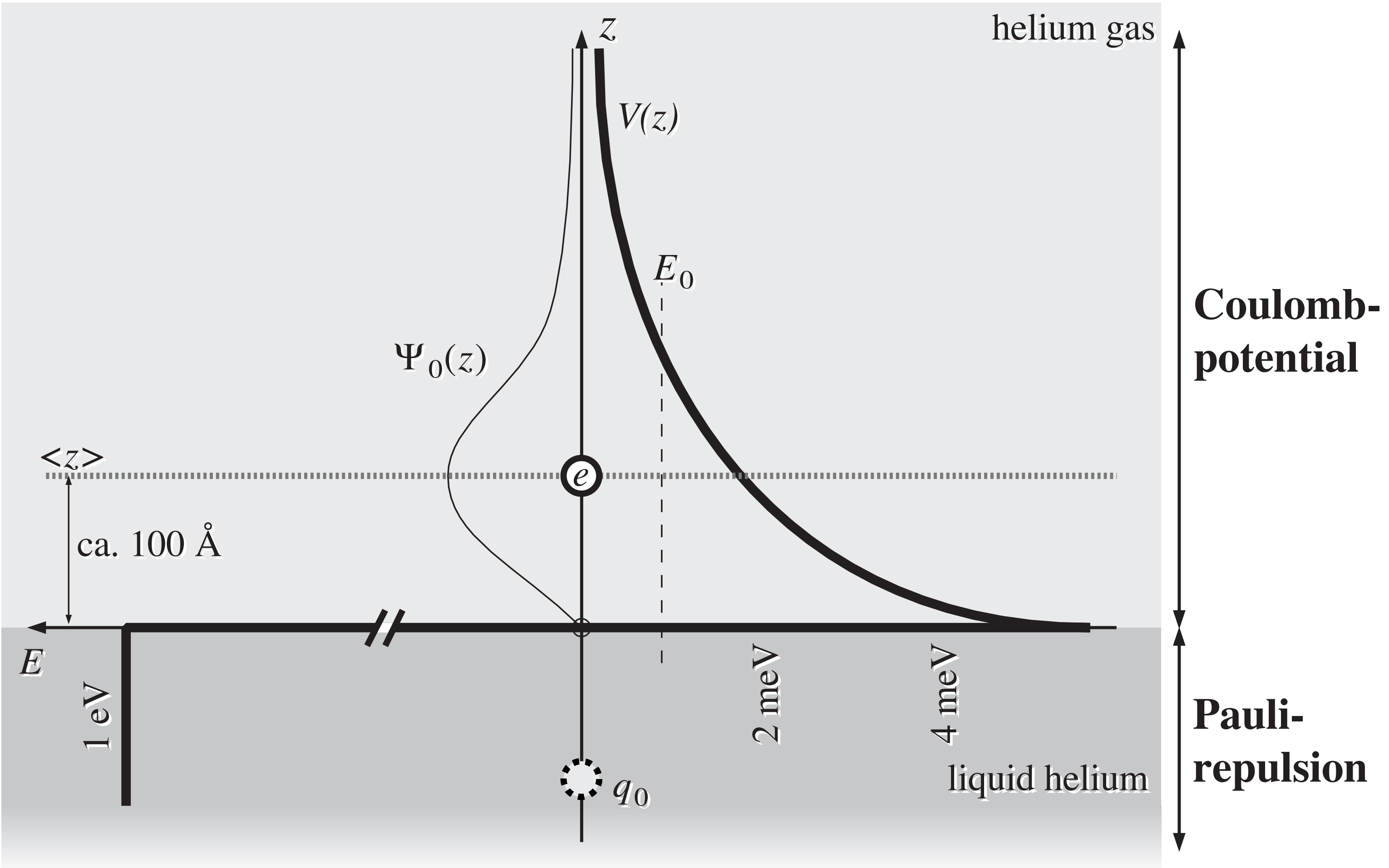
Overview

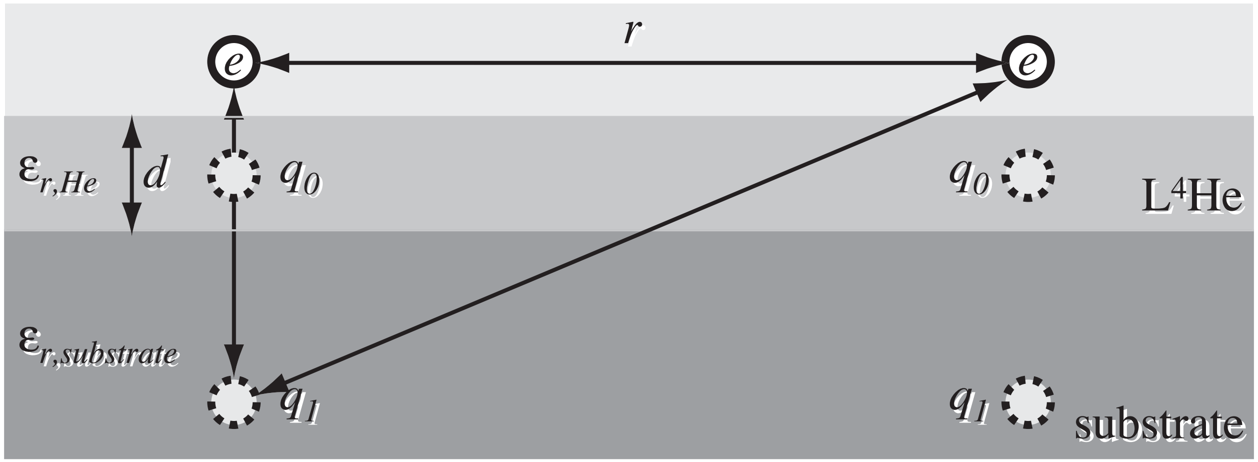
- Introduction to the system "electrons on helium"
  - Basic principles
  - Determining the electron density
- Experiment: Charging thin helium films with electrons
  - Experimental setup and methods
  - Results on lower electron densities
  - High electron densities and problems with reproducibility
- The two-fraction model of electrons
  - General introduction
  - Application to cyclotron resonance data
- Conclusions & Outlook

Electrons on liquid helium



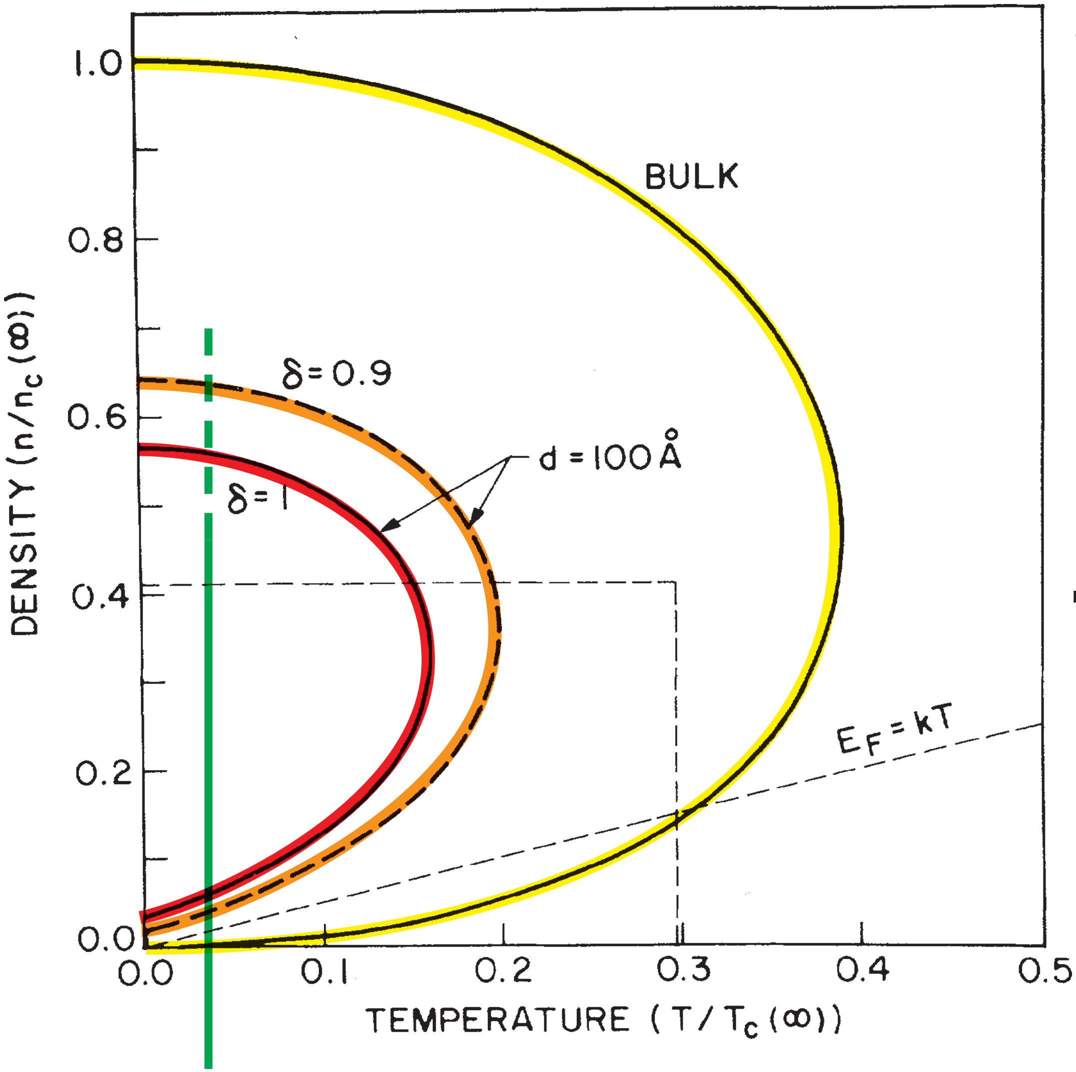
$$V(z) = \begin{cases} V_0 & z \leq 0 \\ -\frac{1}{4\pi\,\epsilon_0}\frac{q_0\,e^2}{z+\beta} & z > 0 \end{cases} \quad \text{with:} \quad \begin{aligned} V_0 &\approx 1\text{eV} \\ q_0 &= \frac{\epsilon_{L4He}-1}{4(\epsilon_{L4He}+1)} \end{aligned}$$

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 $\propto \sqrt{n}$

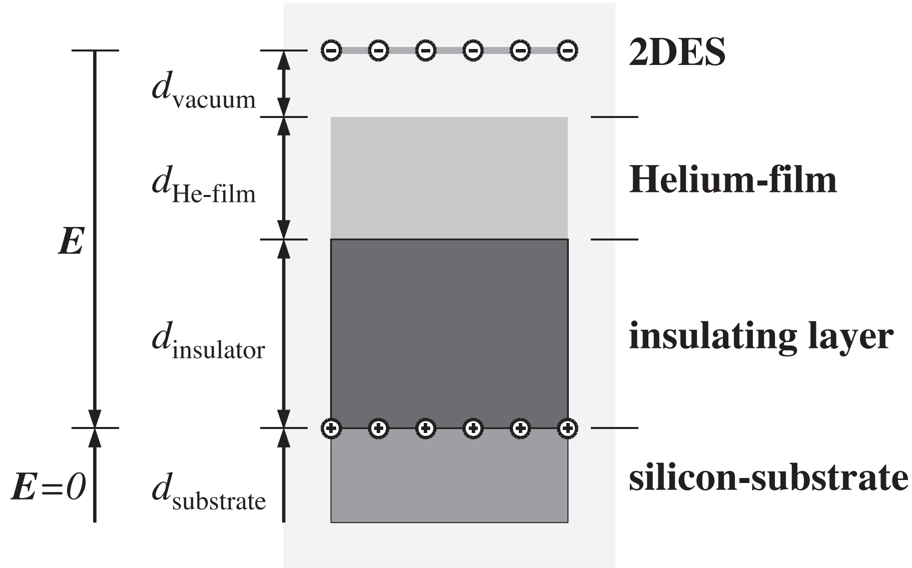
Fermi energy $\propto n$

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



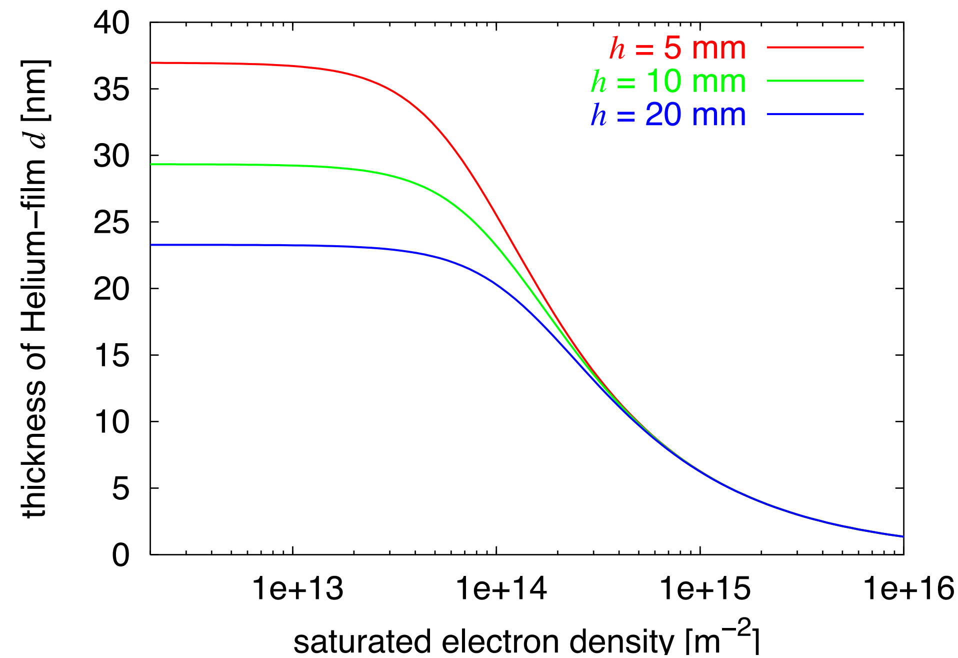
saturation of the 2DES:
electrical field above it vanishes

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

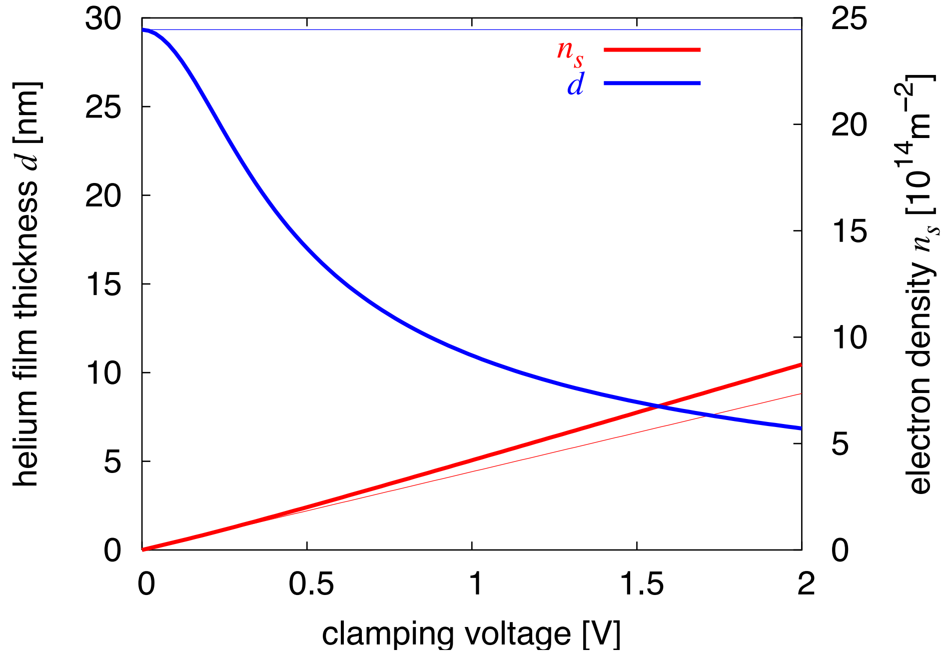
helium film thickness depends on the electron pressure:

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

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



Determining the electron density



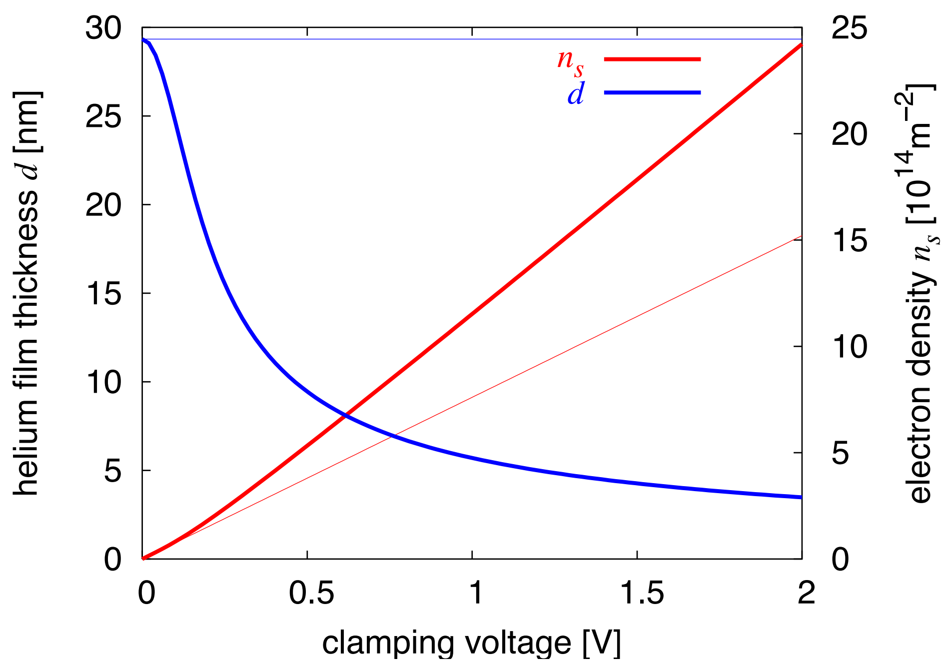
Results of the self-consistent calculations

Electrons on 200 nm PMMA

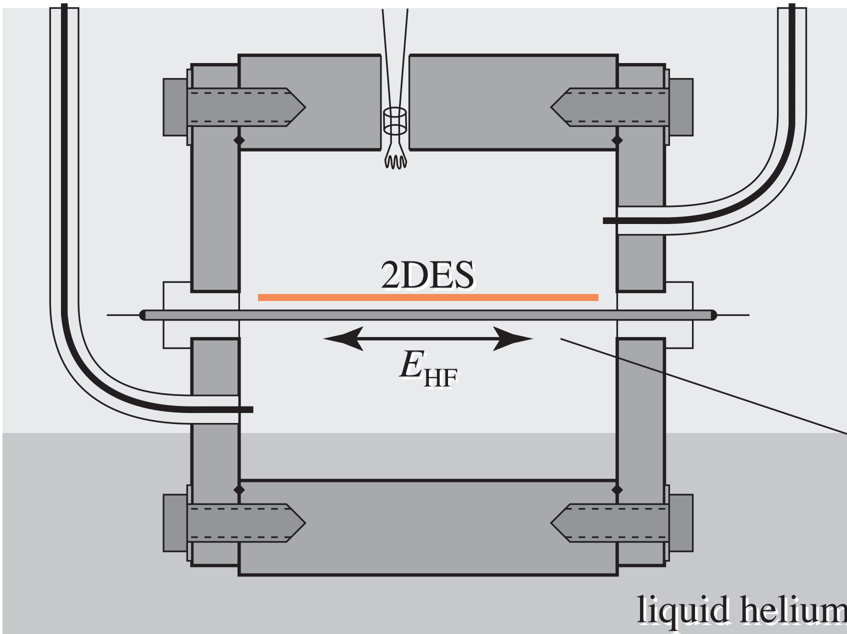
(ε = 1.7)

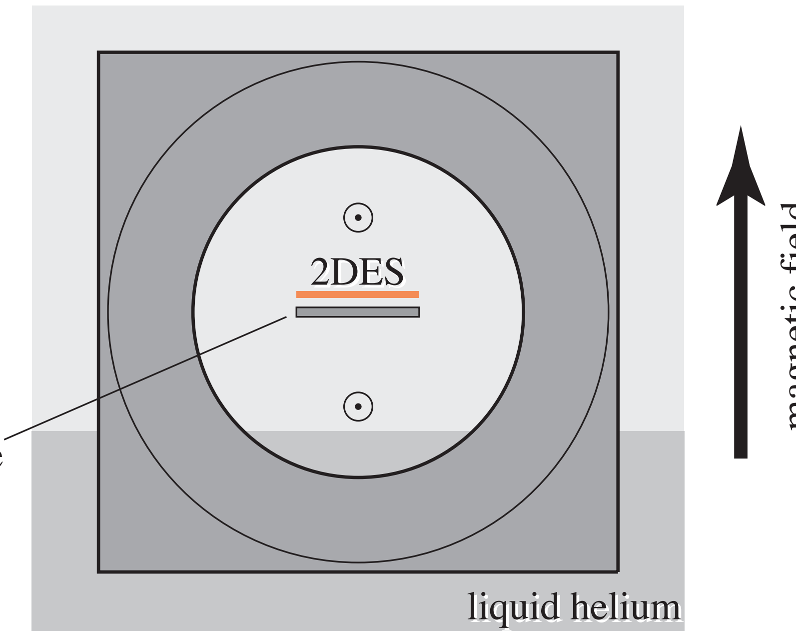
Electrons on 200 nm SiO_2

(ε = 5)



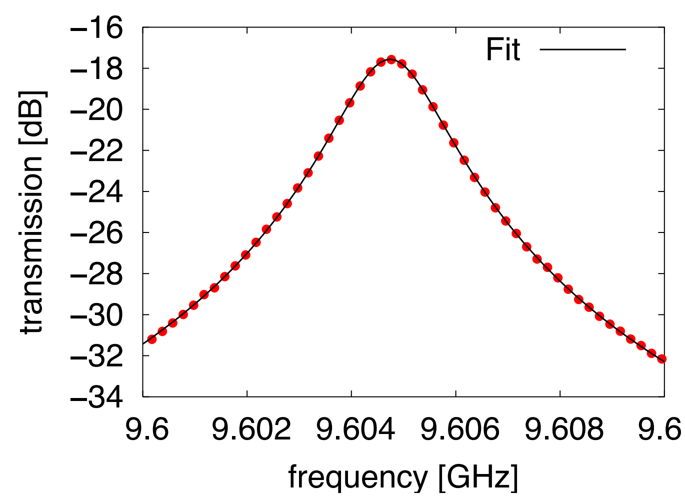
The experimental setup





microwave resonator:

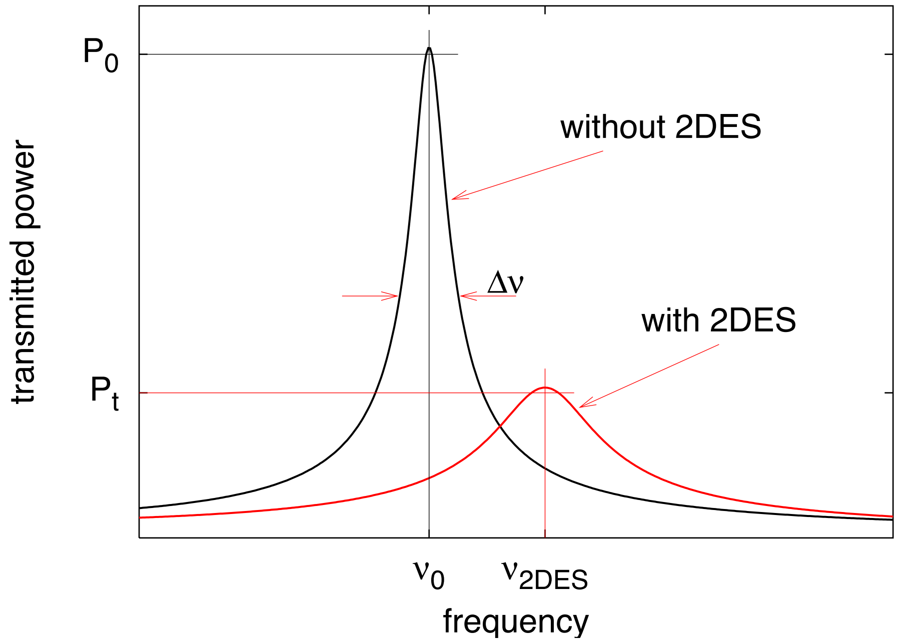
- working frequency ≈ 10 GHz
- microwave transmission is measured around the cavity's resonance
- parameters are extracted via a curve-fit

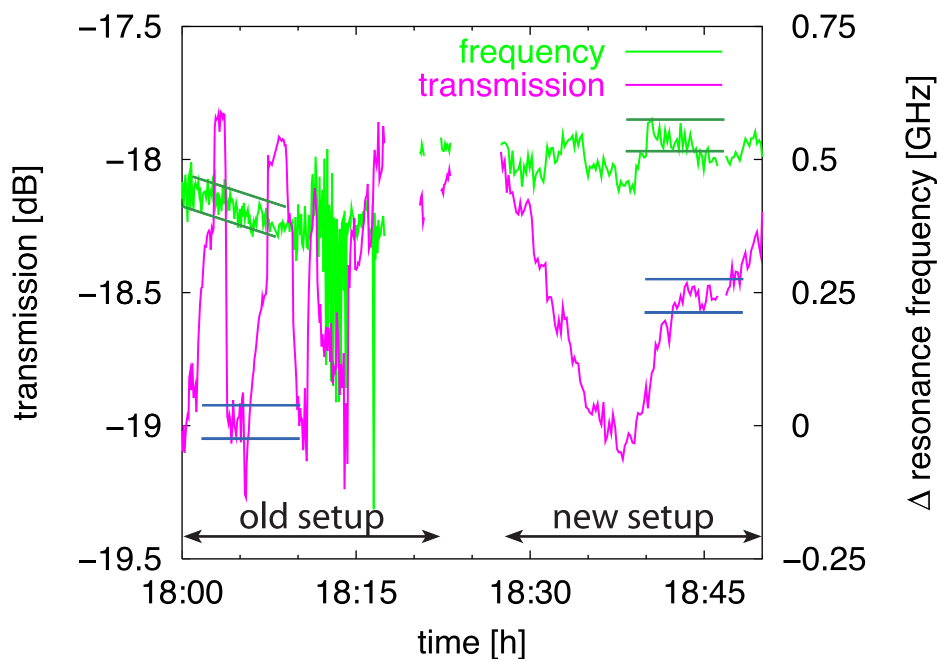


How the experiment works

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.

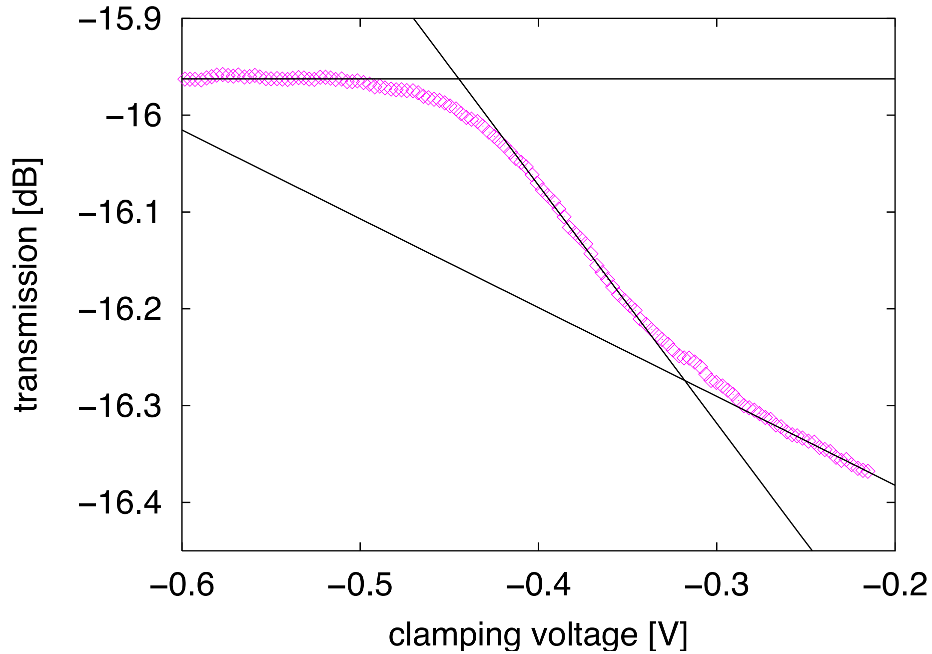


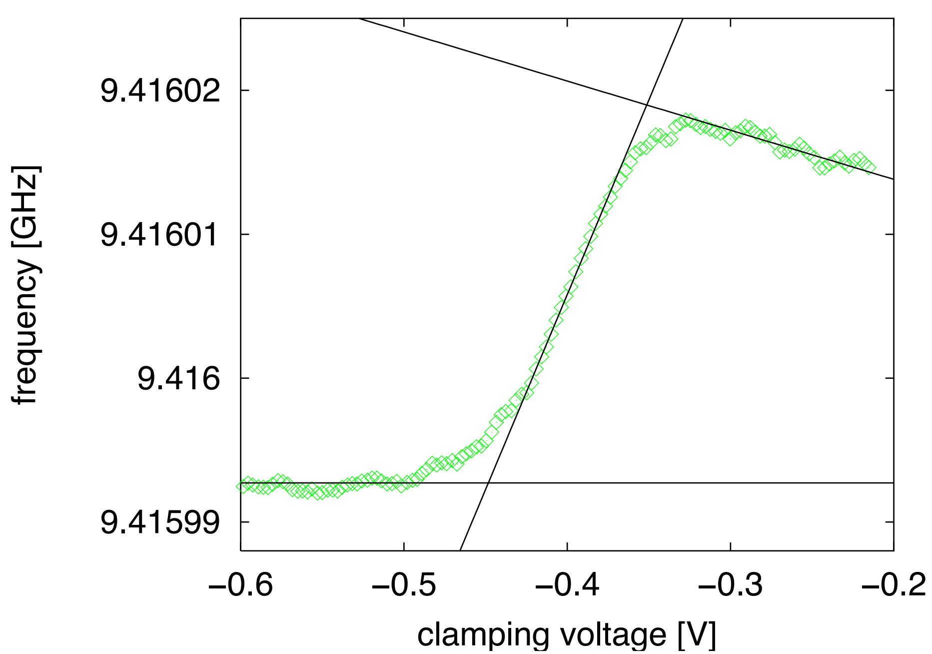


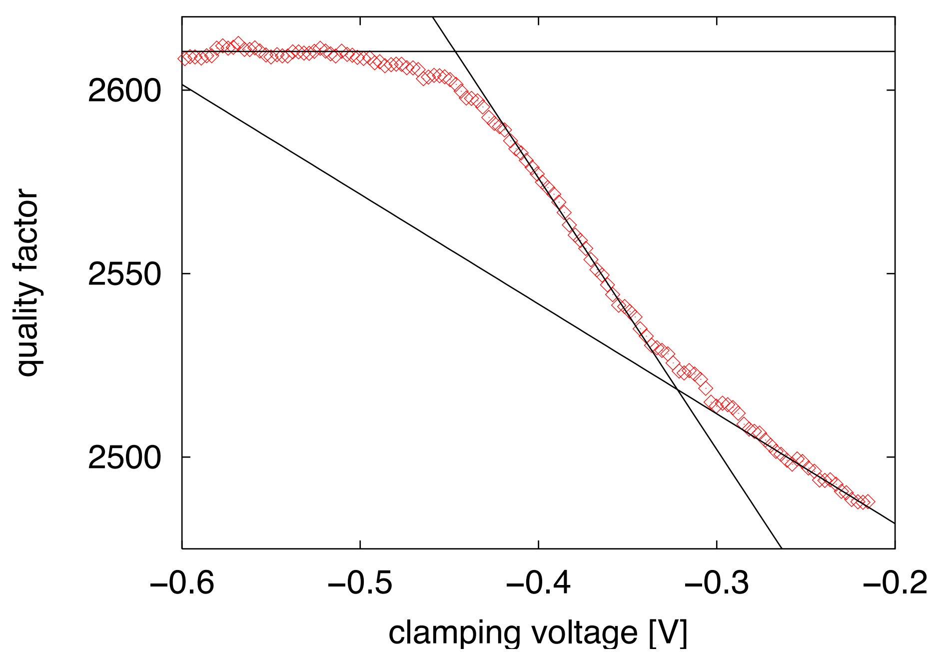
Comparison between the formerly used setup and the new network analyzer method.

➞ The noise level is compareable.

Charging the helium film on PMMA







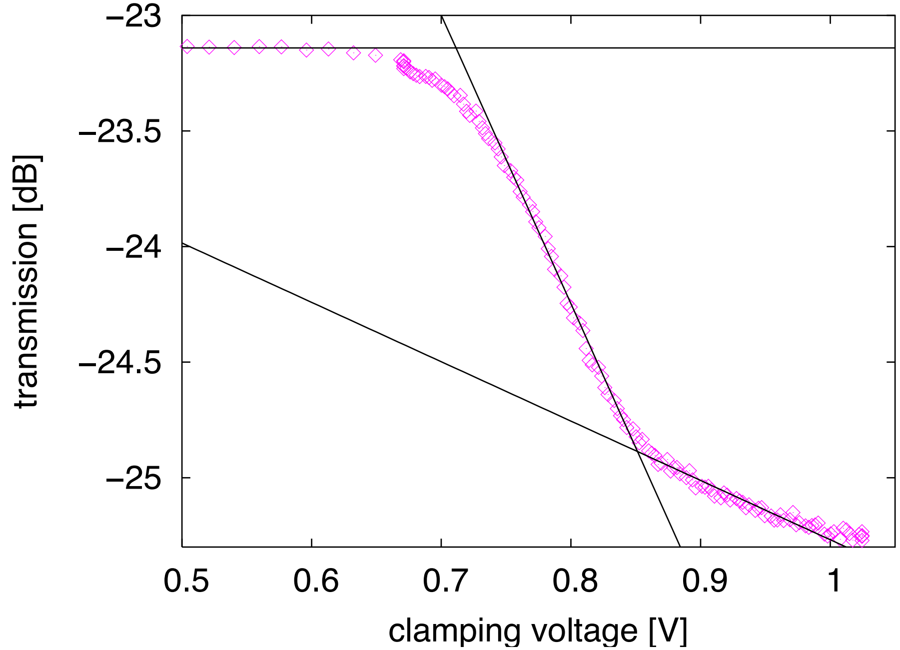
substrate: 200 nm PMMA on silicon

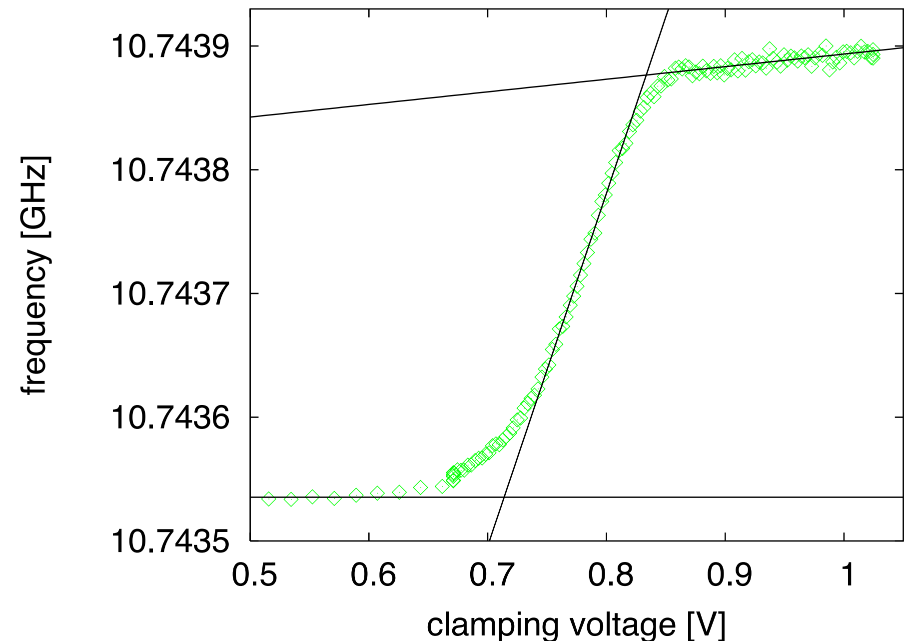
T = 1.29 K

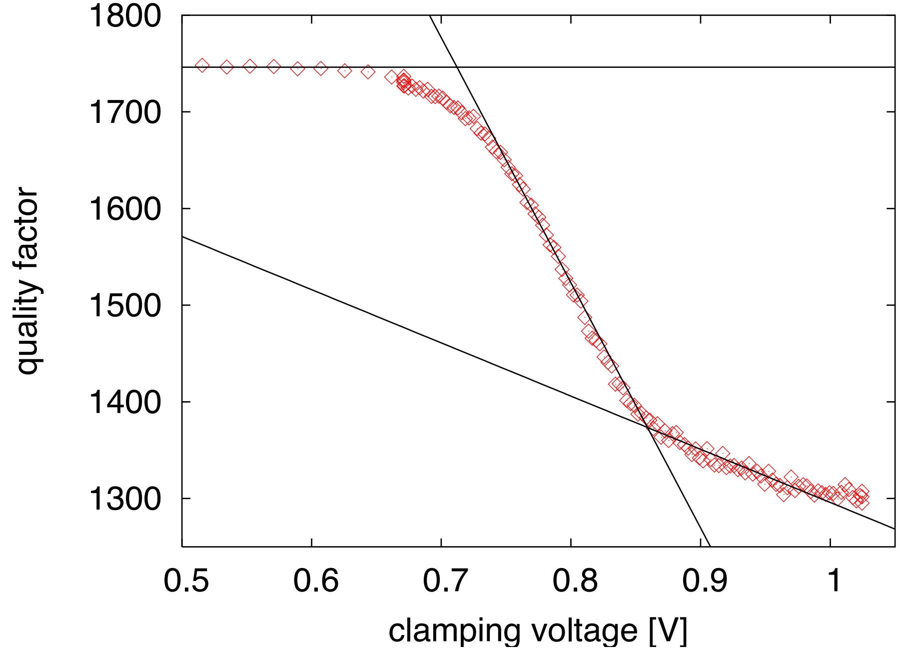
h = −7 mm (d_0 = 33 nm)

data: mw0205d4 #41

Charging the helium film on SiO_2







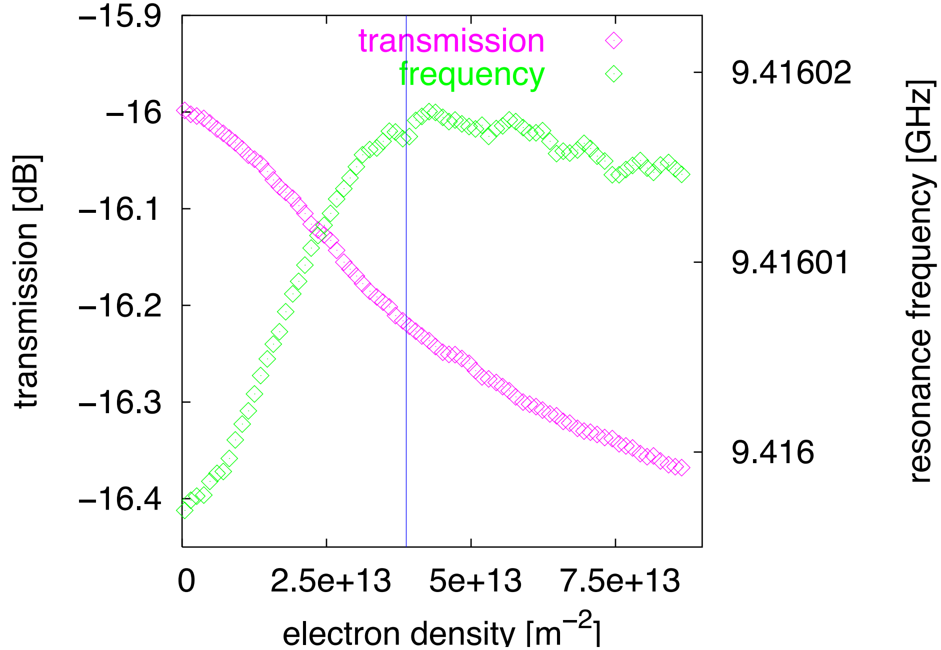
substrate: 200 nm SiO_2 on silicon

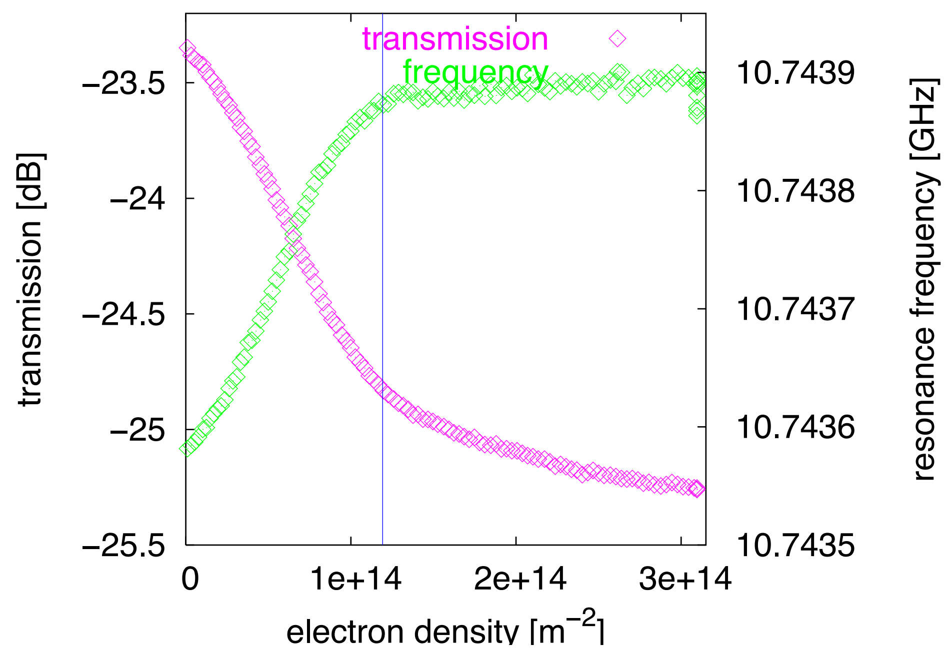
T = 1.30 K

h = –9.7 mm (d_0 = 30 nm)

data: mw0205d4 #41

Data analysis





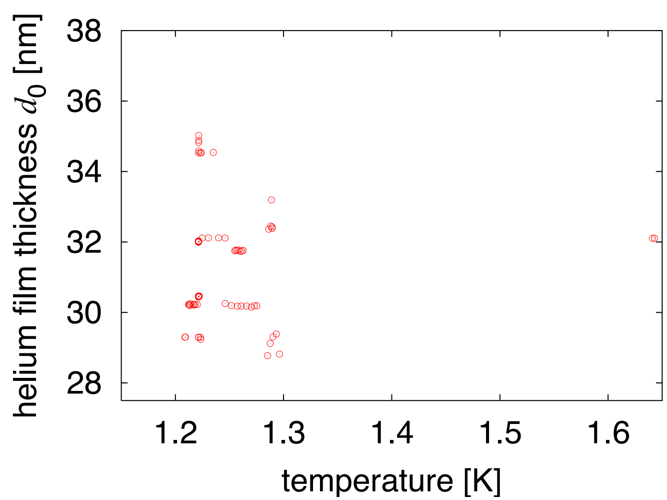
PMMA/silicon substrate, T = 1.29 K

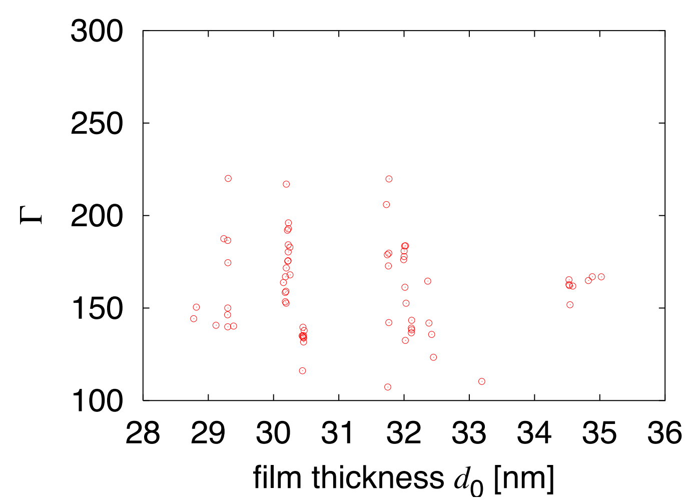
$n_{WC} = 3.9 \times 10^{13}\ m^{-2}$

SiO_2/silicon substrate, T = 1.30 K

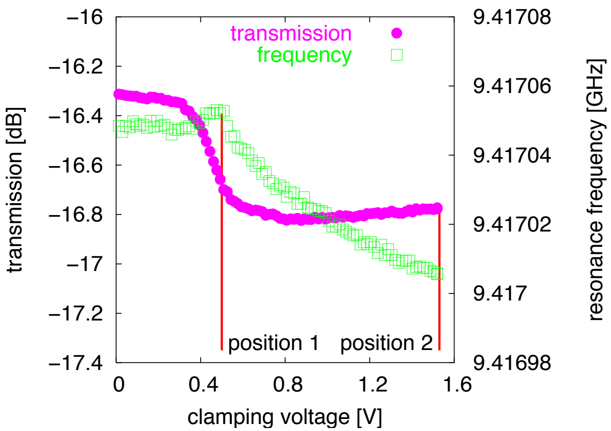
$n_{WC} = 1.2 \times 10^{14}\ m^{-2}$

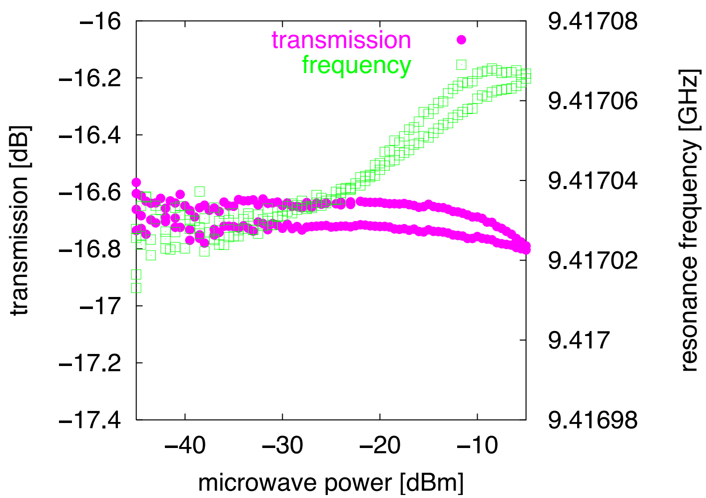
but: experimental results for Wigner-crystallization scatter over a wide range

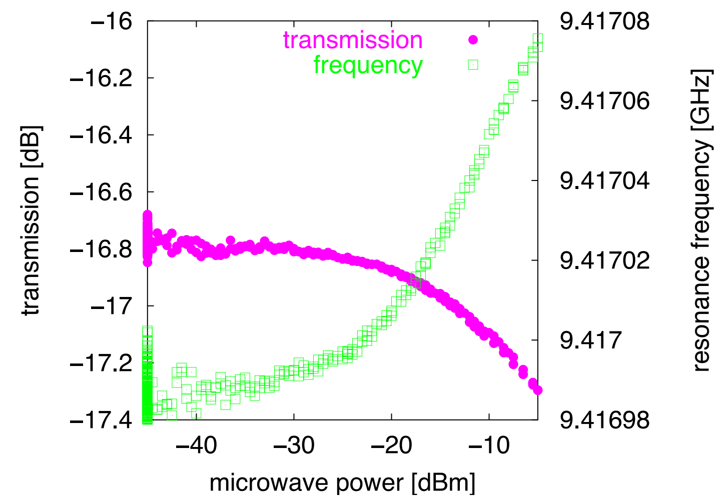




Changing the excitation power

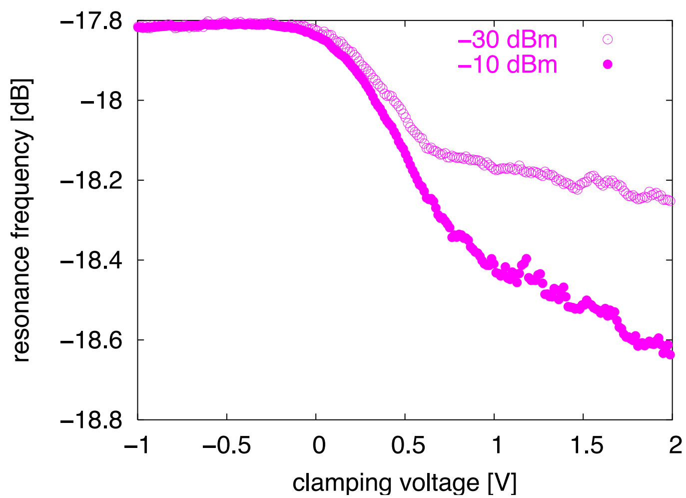


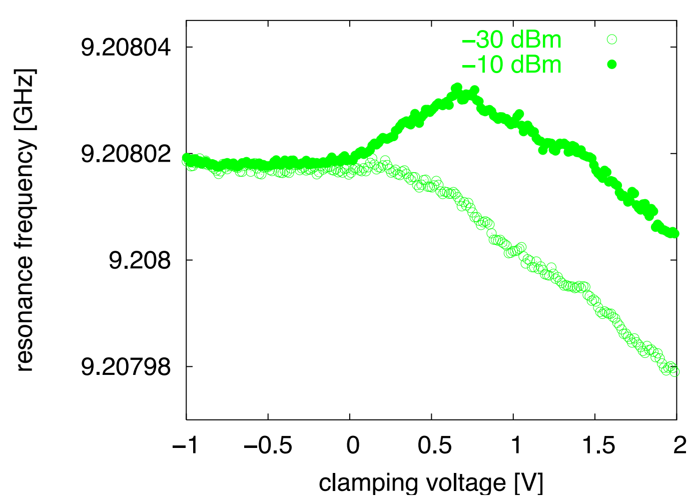




two excitation power sweeps in the liquid and crystalline phase

charging simultaneously with two different excitation powers

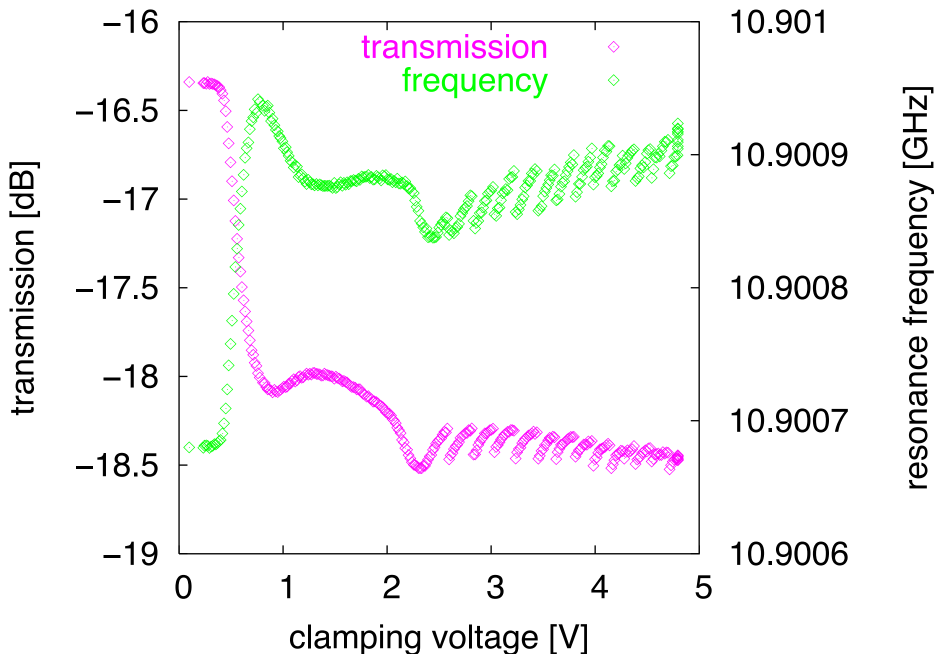




Charging the helium film to high e⁻ densities

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

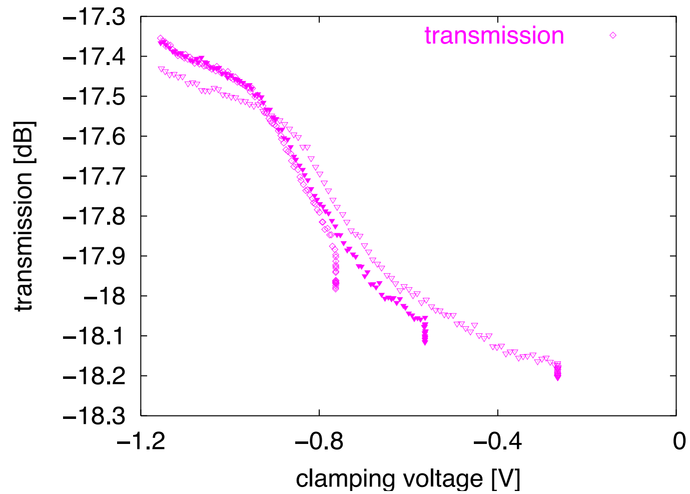


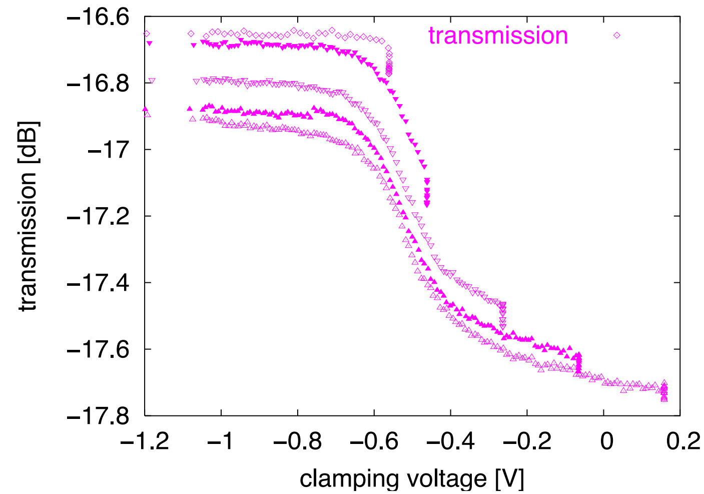
to detect these phenomena, repeated charging sweeps were done

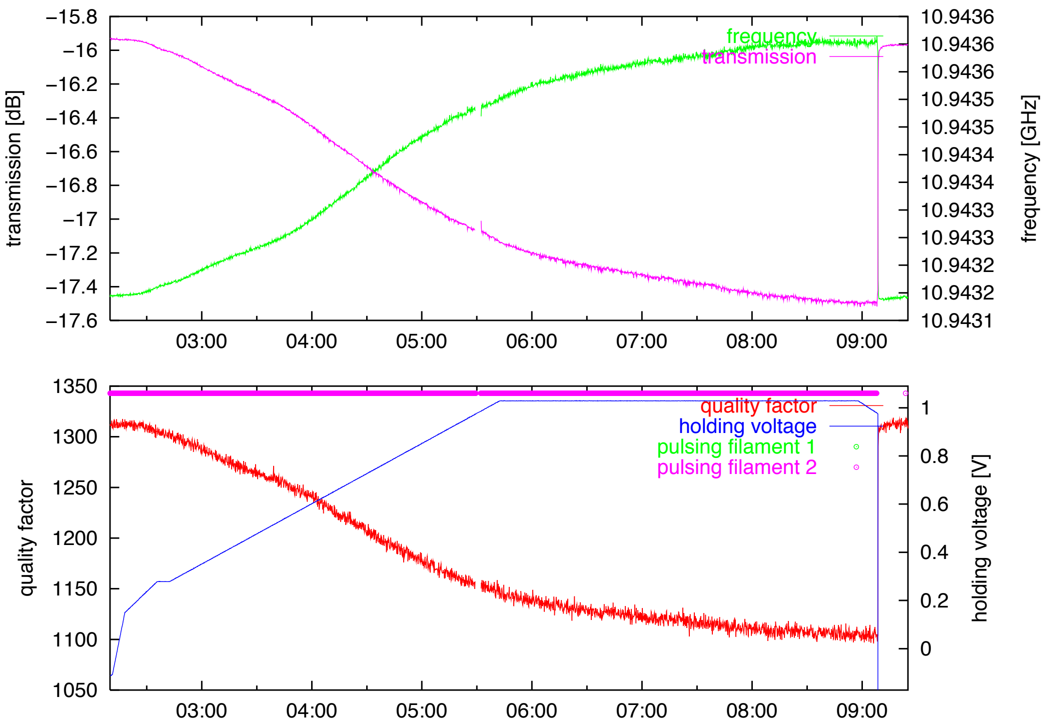
- **breakthrough** and **tunneling** of electrons shift the on-set of charging to more positive voltages
- **localized electrons**, which lead to enhanced absorp-tion cannot be removed after the charging process
  → absorption does not go back to the initial value

Charging series on thin helium films

charge series which show the typical behaviour

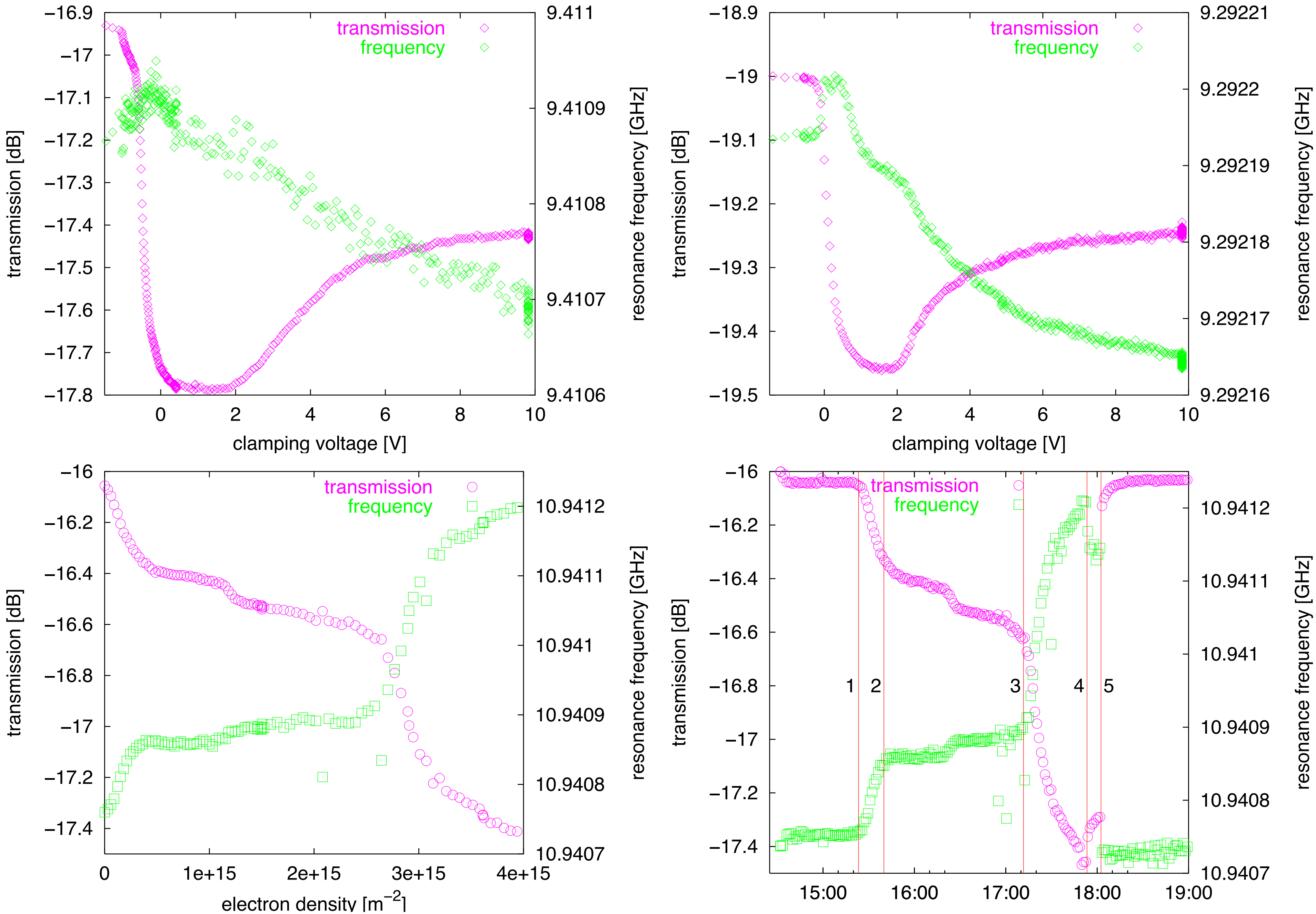




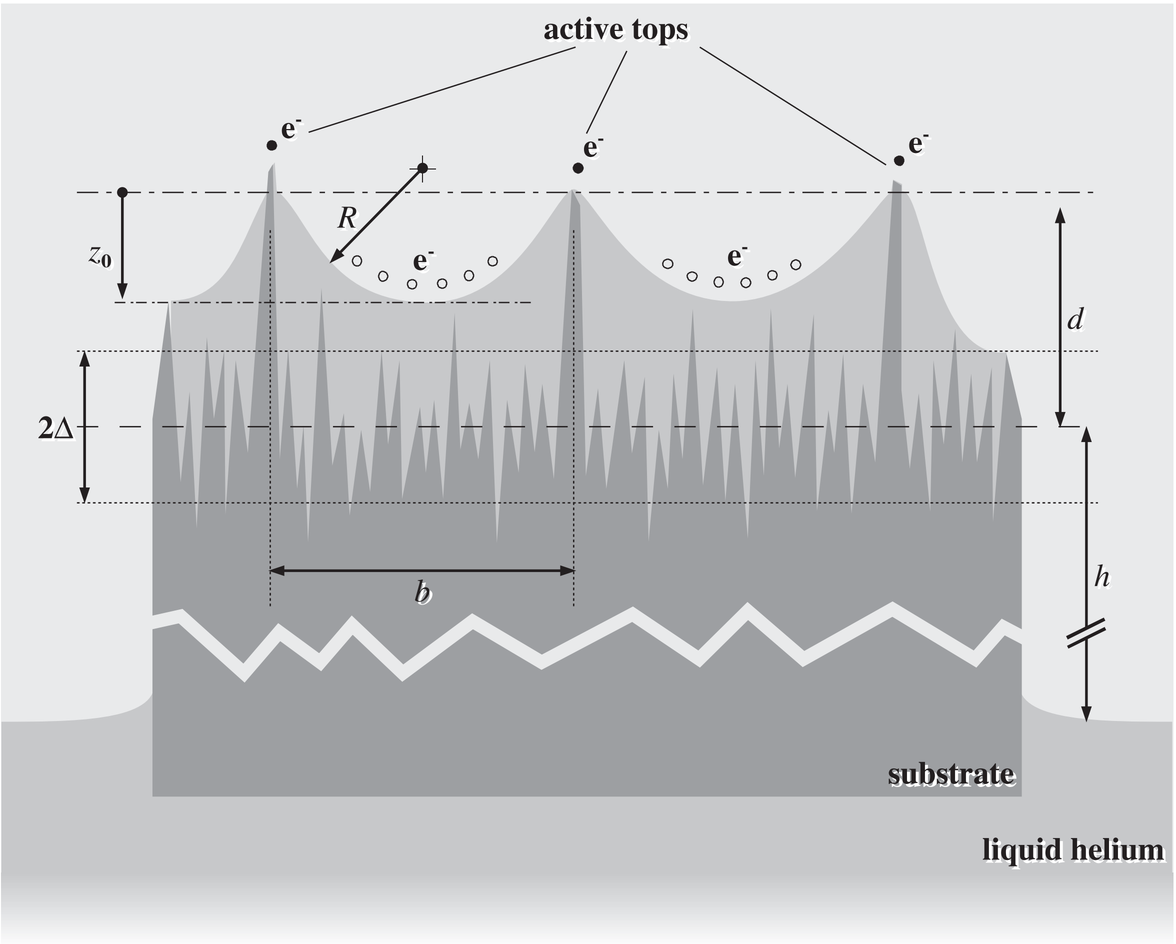


charging in the time domain

High electron densities



The two-fraction model of e⁻ on thin He films



- free and localized electrons contribute to the signals.
- the substrate roughness and the form of the helium film surface are modelled

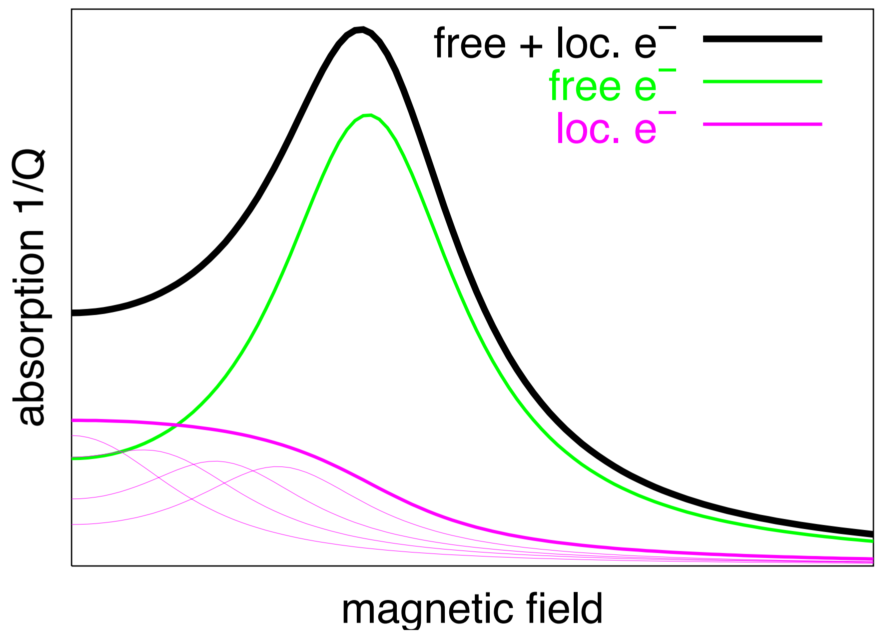
Application of the two-fraction-model in the case of cyclotron resonance

the total absorption of the system follows from the sum of the absorption of free and localized electrons

$$Q^{-1} = Q_e^{-1} + Q_l^{-1}$$

the free electron part is given by the Drude law

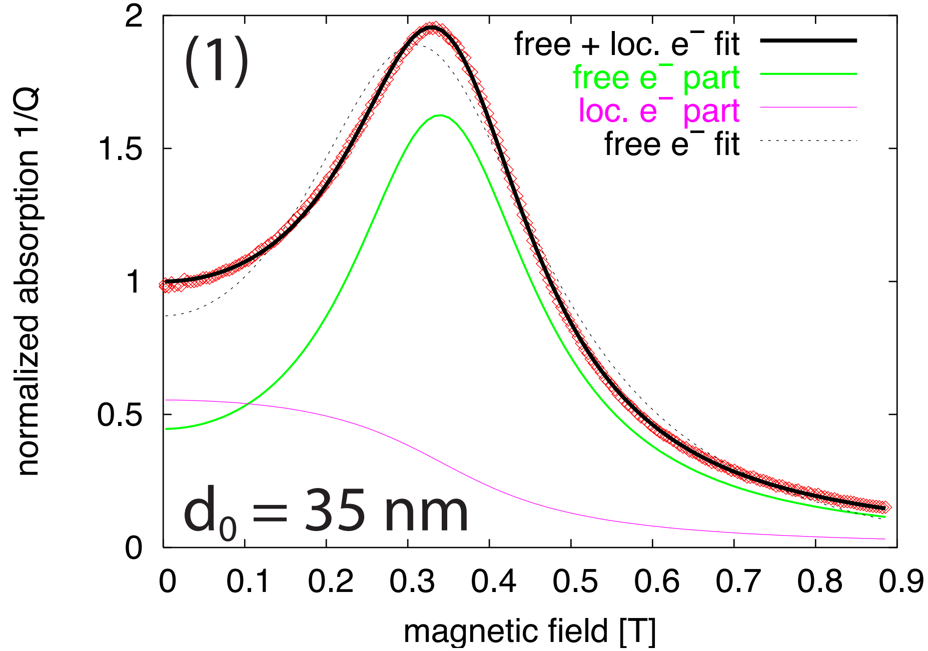
$$Q_e^{-1} \propto n_e \frac{1+z+x}{(1-z+x)^2+4z}$$



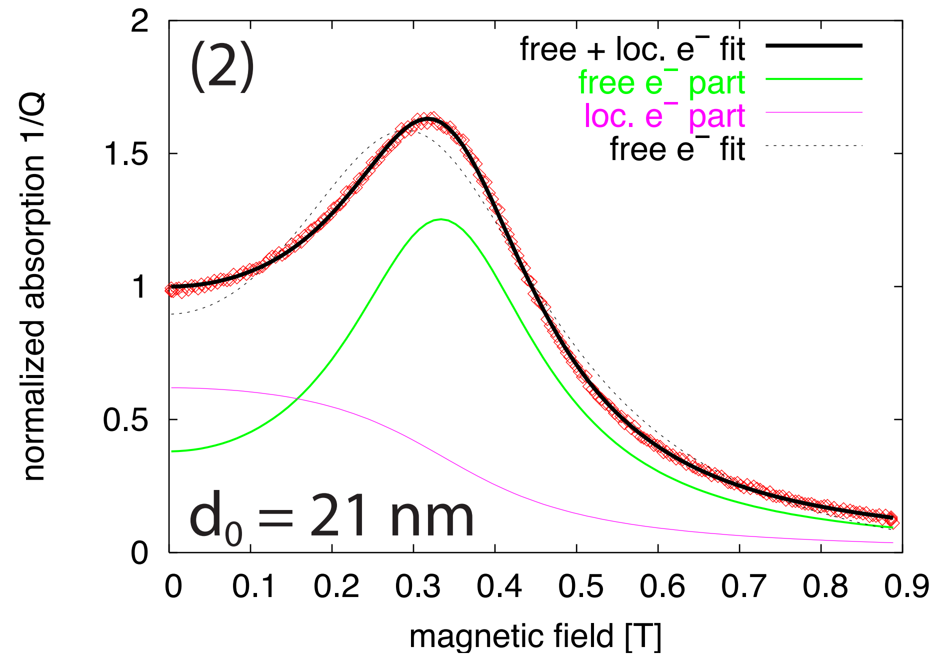
the localized electron part results from the calculated distribution of the localized electrons' potential

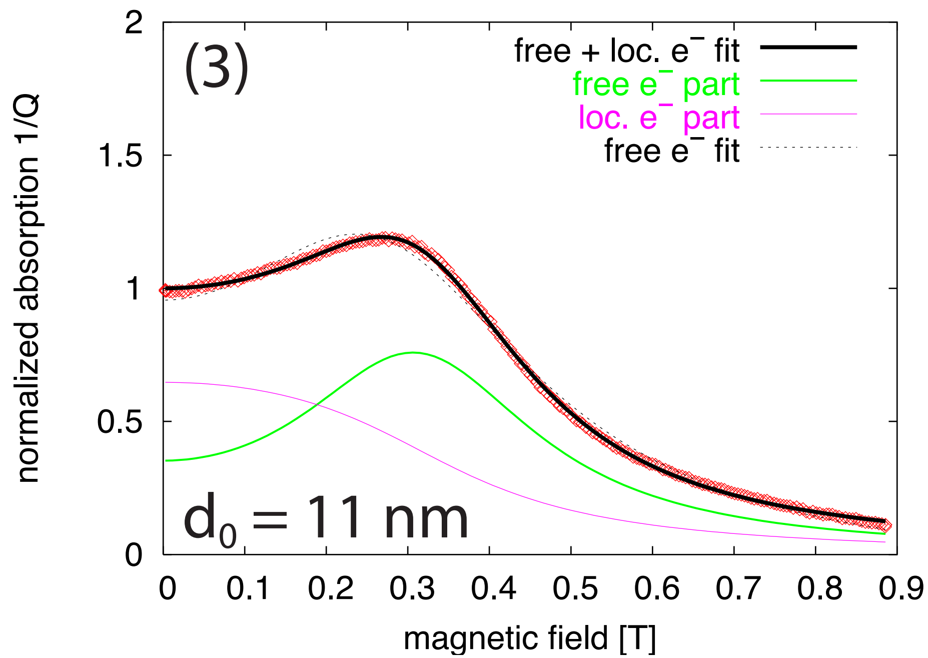
$$Q_l^{-1} \propto n_l \frac{\arctan \frac{\sqrt{z}}{1+x+\sqrt{xz}} + \arctan \frac{\sqrt{z}}{(1+x)\sqrt{z}-z\sqrt{x}} + c(z,x)}{2\sqrt{z}}$$

Cyclotron resonance measurements



decreasing film-thickness





Analyzing the results

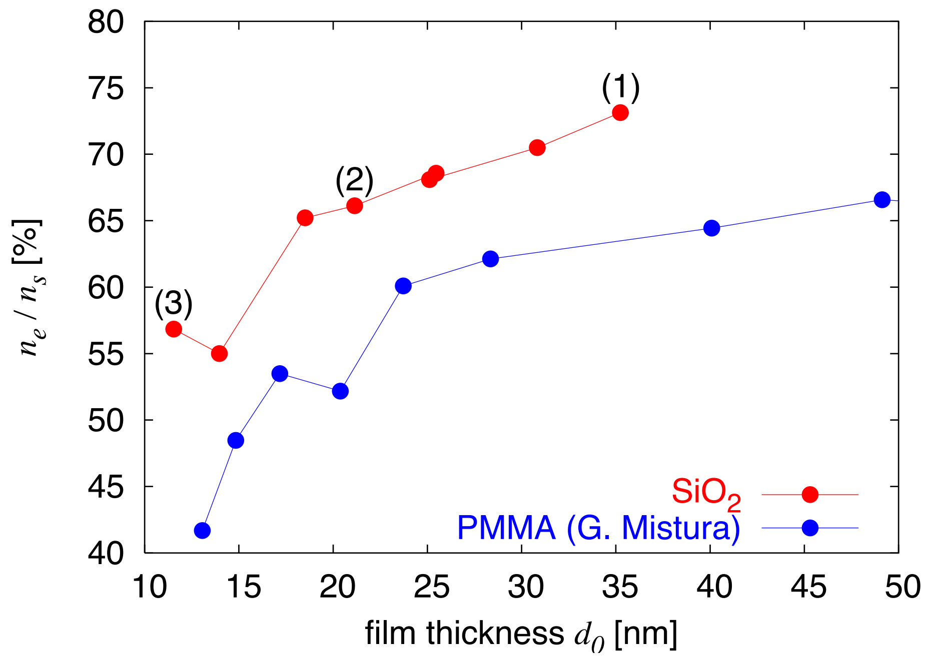
fitting the absorption signal

$$Q^{-1} = A Q_e^{-1}(\omega, \omega_c, \tau) + A_l Q_l^{-1}(\omega, \omega_c, \tau) + c_0$$ free parameters

the fractions of the free and localized electrons results from the ratio be-ween Q_e^{-1} and Q_l^{-1}:

Qualitative analysis:

- SiO_2 is smoother than PMMA
- model-roughness is in the expected range
- sign of the dip-effect?



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