Abstract: Microparticles (e.g. dust particles) in a low-temperature plasma are strongly negatively charged and are able to form regular structures, the so-called plasma crystal, due to the Coulomb interaction. The aim of the experiment is the production and investigation of the plasma crystal. The crystal structure as well as the transition to the liquid phase shall be determined.

Supervisors:

<table>
<thead>
<tr>
<th>Name</th>
<th>Email</th>
<th>Phone</th>
<th>Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prof. Dr. M. Thoma</td>
<td><a href="mailto:thoma@mpe.mpg.de">thoma@mpe.mpg.de</a></td>
<td>089/30000-3653</td>
<td>1.4.33 (X5)</td>
</tr>
<tr>
<td>Dr. Philip Brandt</td>
<td><a href="mailto:brandt@mpe.mpg.de">brandt@mpe.mpg.de</a></td>
<td>089/30000-3002</td>
<td>Building X6</td>
</tr>
<tr>
<td>Dr. Manis Chaudhuri</td>
<td><a href="mailto:chaudhuri@mpe.mpg.de">chaudhuri@mpe.mpg.de</a></td>
<td>089/30000-3007</td>
<td>Room: 1.4.50 (X5)</td>
</tr>
<tr>
<td>Dr. Peter Huber</td>
<td><a href="mailto:phuber@mpe.mpg.de">phuber@mpe.mpg.de</a></td>
<td>089/30000-3897</td>
<td>Room: 1.4.49 (X5)</td>
</tr>
<tr>
<td>Dr. M. Kretschmer</td>
<td><a href="mailto:mkr@mpe.mpg.de">mkr@mpe.mpg.de</a></td>
<td>089/30000-3610</td>
<td>Room: 1.4.49 (X5)</td>
</tr>
<tr>
<td>Chengran Du</td>
<td><a href="mailto:chengran.du@mpe.mpg.de">chengran.du@mpe.mpg.de</a></td>
<td>089/30000-3012</td>
<td>Room: 1.4.38 (X5)</td>
</tr>
<tr>
<td>Lisa Wörner</td>
<td><a href="mailto:woerner@mpe.mpg.de">woerner@mpe.mpg.de</a></td>
<td>089/30000-3834</td>
<td>Room: 1.4.49 (X5)</td>
</tr>
</tbody>
</table>

Location: MPE building X6 (former print shop)

Version 07/2012
Chapter 1

Introduction

The notation plasma crystal seems to be a contradiction. In the plasma phase no regular structures are expected. For this purpose the transition via the gaseous and liquid phase to the solid phase has to occur. Therefore a crystal formation in a usual plasma is not possible. In a complex, multicomponent plasma, however, complicated structures can appear. Inserting, for instance, plastic particles with a diameter of a few microns in a low-temperature plasma [1], these microparticles can arrange themselves in a crystalline pattern under certain circumstances. This phenomenon is known as the plasma crystal [2].

The microparticles are charged by the interaction with the electrons and ions in the plasma, predominantly negatively due to the higher mobility of the electrons. Particles of the size of a few microns can collect up to $10^5$ electron charges. The charged microparticles interact via their charge (Coulomb interaction) with each other, where the charge is screened by the positive ions of the plasma. The ratio $\Gamma$ of the (screened) Coulomb energy to the average thermal energy of the microparticles ($E_{th} \approx kT_d$) is crucial for the formation of the crystal:

$$\Gamma_{eff} = \frac{Z^2e^2}{4\pi\epsilon_0\Delta kT_d} \exp\left(-\frac{\Delta}{\lambda_D}\right).$$

Here $Ze$ is the average charge per particle, $\Delta$ the mean distance between the particles, $\lambda_D$ the Debye screening length (see below), and $T_d$ the kinetic temperature of the particles. Plasmas with $\Gamma_{eff} > 1$ are called strongly coupled. For the crystal formation a critical value $\Gamma_{eff}^c \approx 100 \cdot 1000$ has to be exceeded. Below $\Gamma_{eff}^c$ the system is in the liquid or gaseous phase. In addition, the interparticle distance has to be of the same order as the Debye screening length or smaller, i.e., $\kappa = \Delta/\lambda_D \lesssim 1$.

The plasma crystal was predicted theoretically as a new state in complex plasmas in 1986 [3] and was verified experimentally in 1994 at the Deutsches Zentrum für Luft- und Raumfahrt (DLR) in collaboration with the Max-Planck-Institut für extraterrestrische Physik (MPE) [4,5]. In the laboratory a plasma is created in a gas, mostly a noble gas, at pressures between 1 and 100 Pa within a radio-frequency discharge chamber. After the ignition of the plasma at a field strength of about 100 V/cm, where a degree of ionization between about $10^{-6}$ to $10^{-7}$ is reached, microparticles, e.g. melamine formaldehyd globules, are injected into the chamber by using a dispenser. Owing to the formation of a plasma sheath above the lower electrode the negatively charged particles are levitated against gravity\(^1\) and can arrange themselves there in a crystalline

\(^1\)At the moment plasma crystal experiments are conducted on board of the International Space Station (ISS) for
structure. The plasma crystal is observed by recording pictures from the scattered light from a laser, illuminating the particles in the chamber, by a digital CCD-camera with a computer.

Complex plasmas and plasma crystals are of interest because of various applications. First, they present an ideal model system for investigating phase transitions and crystal formation in condensed matter physics. In the case of a plasma crystal these processes can be studied in a simple way dynamically in real time at a macroscopic system. Secondly, there is a close relation to astrophysical problems: in interstellar plasmas and dust clouds, in comets, in accretion disks around stars, and in planetary ring systems the interaction between plasmas and dust plays an important role. Last but not least, for the production of microchips and other semiconductor devices the understanding of the plasma-dust interaction is of importance. During the etching process of silicon wafers in plasma reactors dust contamination can have a negative effect. For the production of thin-film solar cells, on the other hand, the carefully directed insertion of Si nanoparticles can enhance the efficiency and life-time of these solar cells.

Because of these and other applications for fundamental as well as industrial research it is no surprise that this modern research field has gained lately a lot of interest and that presently further experiments on earth and in space are conducted. On the theoretical side, great efforts are invested to improve our description and understanding of complex plasmas [6].

---

investigating the crystal formation in the absence of gravity (see below).
Chapter 2

Basic Facts

2.1 Fundamental Properties of Plasmas

Plasmas are many-body systems containing freely moving charge carriers. More specific, plasmas are ionized gases, e.g., in contrast to metals in which the electrons can move around freely. It should be noted that 99% of the visible matter in the Universe consists of plasmas, mainly of stars which are huge and hot plasma spheres stabilized by gravity and having such high a temperature in their center that nuclear fusion (hydrogen burning) sets in. Presently, however, there are speculations that the major part of the mass of the Universe consists of the so-called “Dark Matter”, the nature of which is not at all understood yet. Furthermore, plasmas are an everyday phenomenon. For example, neon tubes contain low-temperature plasmas, which are maintained by electric fields and which emit light by excitation of the gas atoms and continuous recombination.

Plasmas existing in nature and in the laboratory can be classified according to different features. First one can distinguish between relativistic and non-relativistic plasmas. A plasma is called relativistic if the thermal velocity of the lightest plasma component, i.e., of the electrons, assumes relativistic velocities, e.g., 30% of the speed of light. This happens at temperatures above $3 \times 10^8$ K as they are reached, e.g., in supernova explosions.

Moreover, one distinguishes between classical and quantum (or degenerate) plasmas. Quantum effects become important as soon as the de-Broglie wavelength ($\lambda_B = h/mv$) becomes larger than the distance between the particles. In the case of the electron component this occurs if the electron temperature falls short of a certain value: $T_e[K] < 1.7 \times 10^{-14}(n_e[m^{-3}])^{2/3}$ with the electron number density $n_e$.

Finally, one distinguishes between ideal and non-ideal or strongly coupled plasmas. In the case of ideal plasmas the interaction energy of the plasma particles, namely the Coulomb energy, is much weaker than the thermal particle energy. Then, for example, for electrons the relation, $e^2/(4\pi\varepsilon_0d) \ll kT_e$, holds, where $e = 1.602 \times 10^{-19}$ C denotes the electron charge, $d$ the mean distance between the electrons, and $k$ the Boltzmann constant. This relation is fulfilled as long as $T_e[K] \gg 1.7 \times 10^{-5}(n_e[m^{-3}])^{1/3}$ holds. As a matter of fact, almost all plasmas existing in nature or in the laboratory are ideal plasmas. The ratio of Coulomb energy to thermal energy (of the electrons or ions), $\Gamma = e^2/(4\pi\varepsilon_0d kT)$, which is denoted as Coulomb coupling parameter, ranges from $10^{-7}$ and $10^{-3}$ in most cases. Even in the interior of the sun with a density of $1.34 \times 10^5$ kg/m$^3$ (134 times the density of water) the plasma corresponds to an ideal gas due to
its high temperature of almost $15 \times 10^6$ K. Plasmas are called strongly coupled if $\Gamma > 1$ holds. Such plasmas are difficult to produce since in general the Coulomb energy exceeds the thermal energy only if the density is high enough and the temperature low enough at the same time. In this case, however, a strong recombination takes place and the plasma vanishes.

Important plasmas encountered in nature and in the laboratory are listed in Fig.2.1, where the temperature of the plasma (or its electron component, respectively) is plotted against the electron density (number of electrons per volume). As one can see, most plasmas are non-relativistic, classical, and ideal plasmas. We are interested in the so-called complex plasmas, which belong to the non-relativistic, classical, strongly-coupled plasmas. How such a system is produced, will be discussed in the next section.

![Figure 2.1: Plasmas in laboratory and nature](image)

A further feature of plasmas is their degree of ionization: $x = n_i/(n_i + n_a)$. Here $n_i$ denotes the ion density and $n_a$ the density of the neutral gas atoms. If $x \approx 1$, the plasma is called completely ionized or hot, as it is used e.g. in fusion experiments. In the case $x \ll 1$ we have a weakly ionized or low-temperature plasma, as it is produced, e.g., in our experiment similar as in a neon tube.

Finally, a plasma can be in an equilibrium or non-equilibrium state. For instance, in our case the electron temperature can deviate significantly from the ion temperature. Then the entire system is not in equilibrium but only the individual components.

In plasmas collective effects, in which many plasma particles participate, play an important role. For example, plasma waves can be excited or instabilities can appear. Here a central role plays the so-called Debye screening length. It follows according to the Debye-Hückel theory by inserting a test charge into the plasma. Owing to the electrostatic Coulomb interaction a cloud...
of opposite charges will be created around this particle while equal charges are expelled. The potential \( \phi(r) \) of the test charge \( Q \) is obtained in the following way: assuming that the electron density in this potential obeys a Maxwell distribution with temperature \( T_e \)

\[
n_e(r) = n_e e^{\phi(r)/kT_e}
\]

and also the density of the (single charged) ions with temperature \( T_i \)

\[
n_i(r) = n_i e^{-\phi(r)/kT_i}
\]

with the homogeneous particle densities \( n_e \) and \( n_i \), respectively, far away from the test charge. Then the charge density disturbed by the presence of the test charge is given by

\[
\rho(r) = -en_e(r) + en_e(r) + en(r) - en_i.
\]

For a sufficiently large distance from the test charge \( e\phi(r)/kT_{e,i} \ll 1 \) holds and the charge density can be linearized

\[
\rho(r) = -e^2n_{e}\phi(r)/kT_e - e^2n_i\phi(r)/kT_i.
\]

The solution of the Poisson equation

\[
\Delta\phi(r) = -4\pi\rho(r)
\]

then yields the screened potential of the test charge

\[
\phi(r) = \frac{Q}{r} e^{-r/\lambda_D}.
\]

The Coulomb potential is modified by the presence of the charged plasma particles to a Yukawa- or Debye-Hückel potential, where the screening length is given by (in CGS-units)

\[
\lambda_D = \left( \frac{4\pi e^2 n_e}{kT_e} + \frac{4\pi e^2 n_i}{kT_i} \right)^{-1/2}.
\]

In charge neutral plasmas with single charged ions \( n_i = n_e \) holds. In weakly ionized plasmas the electron temperature is generally much larger than the ion temperature. Hence the screening length is solely determined by the ions, i.e.

\[
\lambda_D \simeq \sqrt{\frac{kT_i}{4\pi e^2 n_i}}.
\]

For having a collective behavior there must be many particles inside of the screening length of a plasma particle, i.e. \( \lambda_D^3 n \gg 1 \), where \( n \) denotes the plasma particle number density.

The simplest model for a theoretical description of plasmas relies on the one-particle picture, where, however, the important collective effects are not considered. Therefore this model holds only for extremely dilute plasmas. It serves, however, as a starting point for more complicated methods (see below). In the one-particle picture it is assumed that the plasma particles move independently in a common potential. This potential can come from an external but also from
the mean field of the charges in the plasma. The equations of motion of the plasma particles with charge $e$ and mass $m$ are given by the Lorentz force (in CGS-units)

$$m \frac{dv}{dt} = e \left( E + \frac{v}{c} \times B \right),$$

(2.9)

where the external electric and magnetic fields are determined by the Maxwell equations in vacuum (assuming that the sources of the fields are outside of the plasma)

$$\nabla \times E = -\frac{1}{c} \frac{\partial B}{\partial t}, \quad \nabla B = 0,$$

$$\nabla \times B = \frac{1}{c} \frac{\partial E}{\partial t}, \quad \nabla E = 0.$$  

(2.10)

The Hamiltonian, from which the above equation of motion via

$$v = \frac{\partial H}{\partial p}, \quad \frac{dp}{dt} = -\frac{\partial H}{\partial r},$$

(2.11)

follows, reads

$$H = \frac{(p - eA/c)^2}{2m} + e \Phi,$$

(2.12)

where the vector potential $A$ and the scalar potential $\Phi$ follow from

$$B = \nabla \times A, \quad E = -\nabla \Phi - \frac{1}{c} \frac{\partial A}{\partial t}.$$

(2.13)

For numerical simulations of many-body systems, in particular for strongly-coupled plasmas, often a method called molecular dynamics is applied. Here it is not longer assumed, as in the one-particle picture, that the particles move independently of each other but the interaction between the particles is taken into account explicitly within the equations of motion. Then the Hamiltonian of a many-body system of $N$ plasma particles is given by

$$H = \sum_{i=1}^{N} \frac{p_i^2}{2m} + V.$$

(2.14)

(For simplicity only one kind of particles was assumed here and external fields were neglected.) In the case of a pure Coulomb interaction the potential reads

$$V = -\frac{e}{2} \sum_{i \neq j}^{N} \frac{1}{|x_i - x_j|}.$$

(2.15)

Hence $2N$ coupled equations of motion arise

$$\frac{dx_i}{dt} = \frac{\partial H}{\partial p_i}, \quad \frac{dp_i}{dt} = -\frac{\partial H}{\partial x_i},$$

(2.16)

Starting from given initial conditions this system of coupled differential equations is integrated numerically. From the coordinates and momenta of all $N$ particles, following in this way, mean
values such as the temperature, the free energy or correlation functions can be extracted. For instance, the temperature follows from

\[ \frac{3}{2} kT = \frac{1}{N} \sum_i^N \frac{P_i^2}{2m} \] (2.17)

An alternative approach for the theoretical description of plasmas is given by the transport theory [7,8]. Since it is only applicable to weakly coupled plasmas, we will not discuss it here.

### 2.2 Experiments with complex Plasmas

As mentioned in the Introduction, a complex plasma is a low-temperature plasma containing beside electrons, ions, and neutral gas atoms microparticles (e.g. dust). Such plasmas are present in many astrophysical systems, in the upper atmosphere but also in technological applications. Therefore, their investigation is of great interest and since a few years the topic of intense and rapidly growing experimental as well as theoretical research.

![RF plasma chamber](image)

**Figure 2.2: RF plasma chamber**

In the laboratory a complex plasma can be produced either via a radio frequency (RF) discharge or by applying a DC in a plasma chamber. So far, mostly a RF chamber has been used as it is the case also in our experiment. For this purpose, the chamber (see Fig.2.2) is filled with a gas, mostly inert noble gases (Ne, Ar, Kr), typically with a pressure between 10 and 100 Pa. By applying a RF power between 0.1 to 1.0 W via disk like electrodes at the bottom and ceiling of the chamber the plasma is ignited. The distance between the electrodes is 3 cm in our case. The frequency of 13.56 MHz leads to the fact that only the light electrons can follow the field and are accelerated. By collisional ionization further electrons are produced and a velocity distribution of the electrons appears corresponding to a temperature of \( kT_e = 1 - 3 \) eV. Since the ionization potential of noble gases is of the order of 15 eV, only electrons from the tail of the distribution can ionize the neutral gas atoms. Hence, only a small degree of ionization \( \left( 10^{-7} - 10^{-6} \right) \) results. The ions cannot follow the RF field due to their mass and their temperature agrees roughly with the one of the neutral gas, i.e. room temperature (\( kT_i = kT_n = 0.025 \) eV). The plasma emits a glow which is characteristic for the gas used and is caused by the excitation of
the neutral gas atoms. The plasma is confined in the space volume between the two electrodes by the surrounding electric field (see Fig.2.6).

![Microscopic image of the plastic particles](image)

**Figure 2.3: Microscopic image of the plastic particles**

After the ignition of the plasma $10^5 - 10^6$ plastic particles with diameters between 1 and 10 $\mu$m are injected via a dispenser. These particles have a very uniformly spherical form with a unique diameter (monodisperse) as shown in Fig.2.3. This is important for the creation of regular structures as discussed below. As we will discuss in the next section, the particles get charged negatively. The electric field above the the lower electrode in the plasma sheath (see Fig.2.6) – the bulk plasma is field free –, levitates the negatively charged particles.

The walls of the plasma chamber consists of glass. The particles are illuminated by a laser sheet and the scattered light (Mie scattering) is observed from outside via a CCD camera. The laser and the camera are mounted on a motor driven sliding carriage, which can be moved forth and back. Via a laser scan the entire plasma volume can be observed and the particle positions determined. In this way the arrangement of the particles, e.g. regular structures, but also particle trajectories can be determined. Hence microscopic processes can be observed directly. This is a unique opportunity for studying phase transitions, e.g. crystallization, on the microscopic and kinetic level. (In colloids such investigations can also be performed. However, these processes take weeks to months due to the strong damping, whereas in complex plasmas these processes occur within seconds or minutes.)

The particle charges and forces on the particles (see below) can be extracted from the trajectories. Moreover, the charges can be determined also from the oscillation frequency of the particles caused by applying a vertical electric field modulation. Depending on the particle size (see below) charges between $10^3 - 10^5$ electron charges are found.

Beside the determination of the particle arrangement (gaseous, liquid, or crystalline phase), the charge of the particles, and the forces acting on them, numerous other interesting experiments can be performed. For example, lattice and plasma oscillations can be excited, single particles can be manipulated by a Langmuir probe or a strong laser, magnetic fields can be
applied, the welding of crystals and interfaces can be observed, and shock waves can be stimu-
lated. To remove the effect of gravitation, experiments under zero gravity (see below) are
conducted beside laboratory experiments.

2.3 Theory of Complex Plasmas

Due to the higher mobility of the electrons in the plasma (because of the smaller mass and higher
temperature) the current of the electrons onto the particle surface is larger at the beginning than
the ion current. Therefore, the particles are negatively charged. (In the presence of UV-radiation
a positive charging can be achieved by electron emission from the particle surface.) The process
of charging and the equilibrium charge of the particles are described by the so-called “Orbit-
Motion-Limited” (OML) theory. Here one calculates the currents of the electrons and ions onto
the particle surface (see Fig.2.4) and assumes that the mean free path of the ions is much larger
than the Debye screening length and the latter larger than the particle radius. This is realized
approximately at low gas pressure below about 30 Pa. Then the collisions between the ions and
the neutral gas can be neglected.

![Figure 2.4: Microparticles in a plasma](image)

Let us consider first a single particle in the plasma. As in the case of the calculation of the
Debye screening, we assume that the electron density is given by a Maxwell distribution

\[
n_e(r) = n_e \exp \left[ \frac{eV(r)}{kT_e} \right]
\]  (2.18)

in the screened potential of the microparticle with radius \(a\)

\[
V(r) = V(a) \frac{a}{r} \exp \left( -\frac{r - a}{\lambda_D} \right).
\]  (2.19)
Then the electron current onto the particle surface is given by

$$I_e = -e \pi a^2 n_e(a) \bar{v}_e$$  \hspace{1cm} (2.20)

with the geometrical cross section $\pi a^2$ and the mean electron velocity $ar{v}_e = \sqrt{8kT_e/(\pi m)}$.

For the ions with mass $M$ we assume that they approach the particles without collisions with the neutral gas (“free-fall trajectory”), starting far away from the particle with an initial velocity $v_0$, energy $E_0 = Mv_0^2/2$, impact parameter $b$, and angular momentum $J_0 = Mv_0b$ (see Fig.2.5).

Then according to energy conservation

$$E_0 = \frac{M\dot{r}^2}{2} + \frac{J_0^2}{2Mr^2} + eV(r).$$  \hspace{1cm} (2.21)

holds for a distance $r$ from the particle. From this follows that ions with an impact parameter smaller than

$$b_{coll} = a \sqrt{1 - \frac{eV(a)}{E_0}}$$  \hspace{1cm} (2.22)

will reach the particle surface. (For $b = b_{coll}$ the ions hit the surface with the velocity $\dot{r} = 0$.) Hence, the cross section for absorption of ions on the particle surface is $\sigma_{coll} = \pi b_{coll}^2$ and the ion current onto the particle surface

$$I_i = e n_i \bar{v}_i \sigma_{coll} = e \pi a^2 n_i \sqrt{8kT_i} \frac{\pi a^2}{\pi M} \left( 1 - \frac{eV(a)}{kT_i} \right),$$  \hspace{1cm} (2.23)

where we have replaced $v_0$ by the thermal velocity and $E_0$ by $kT_i$.

In equilibrium, i.e. $I_e + I_i = 0$, and in the case of charge neutrality ($n_i = n_e$) we obtain

$$\exp \left[ \frac{eV(a)}{kT_e} \right] = \sqrt{\frac{T_i m}{T_e M}} \left[ 1 - \frac{eV(a)}{kT_i} \right].$$  \hspace{1cm} (2.24)

Solving this equation numerically, we find the surface potential $V(a)$ and the surface charge $Q = Ze = 4\pi \varepsilon_0 a V(a)$. The latter can be approximated by

$$Z \approx B \frac{4\pi \varepsilon_0 a kT_e}{e^2} \ln \sqrt{\frac{T_e M}{T_i M}},$$  \hspace{1cm} (2.25)

with the material constant $B$ (Argon gas: $B = 0.73$). For particle radii from 1 - 10 $\mu$m, $kT_e = 3$ eV, and $kT_i = 0.03$ eV we obtain $Z = 5000 - 50000$. Owing to this high charge number the
microparticles interact strongly with each other, leading to the possibility of regular structures (see below). The charging time until the equilibrium charge is reached, is typically of the order of $1 \, \mu s$.

In the presence of many particles – typically the particle density is of the order of $n_d = 10^5 \, \text{cm}^{-3}$ and the ion density of the order of $n_i = 10^9 \, \text{cm}^{-3}$ – most of the electrons are found on the particles, implying a small electron density $n_e \ll n_i$ in the plasma. Charge neutrality requires then $n_e - Z n_d = n_i$. Then one has to multiply (2.24) on the left hand side with the factor $1 + Z n_d / n_i$ leading to a reduction of the surface charge on the particles.

Various forces act on the particles. First of all, there are external forces. They come from gravitation, external electric fields, the friction with the neutral gas, the interaction with the ions, and a possible temperature gradient (see Fig.2.6).

**Gravitation:** The gravitational force of particles with mass $m_d$ is given by $F_g = m_d \, g$.

**Electric field:** In the RF or DC plasma chambers used, there are electric fields present, which, on the one hand, confine the plasma and the particles, repelling each other, in a finite volume, on the other hand, can levitate the particles against gravity. These fields are small within the bulk plasma but are significant in the plasma sheath, e.g. close to the electrodes. The force on the the particles is given by $F_E = Q \, E$ with the electric field $E$.

**Neutral gas friction:** If particles move with a finite velocity through the gas or a gas flow is present, there will be friction with the neutral gas. For spherical particles and a mean free path of the atoms, which is large compared to the particle size, it will be described by Epstein friction

$$F_n = \frac{8}{3} \sqrt{2\pi k T_n M_n a^2 n_n v_{rel}}.$$  \hspace{1cm} (2.26)

Here $T_n$ is the temperature of the neutral gas, agreeing in general well with the ion temperature $T_i$, $M_n$ is the mass of the neutral gas atoms, $n_n = p/k T_n$ the neutral gas particle density, and $v_{rel}$ the relative velocity between the particles and the neutral gas. For argon gas at room temperature the neutral gas friction force can be written as $F_n[N] = 2.7 \times 10^{-16} \, (a[\mu \text{m}])^2 \, p[\text{Pa}] \, v_{rel}[\text{cm/s}]$.
**Interaction with ions:** The interaction between particles and ions results from the momentum transfer of the ions to the particles by absorption on the surface and by the Coulomb interaction of the ions passing the particles. Therefore, the force mediated by the ions on the particles can be of similar strength as the neutral gas friction, although the degree of ionization is only about $10^{-6}$. The ion drag force $F_i$ is presently still under experimental and theoretical investigation. The results (see e.g. [9]) cannot be given in analytical form. Close to the lower electrode (lower part of the plasma sheath) the velocity of the ions streaming to the negatively charged electrode can become so large that their interaction with the particles can lead to instabilities (strong fluctuations of the particle positions), in particular at low pressure.

**Thermophoresis:** In the presence of a temperature gradient the microparticles are transported from the hot to the cold side. This process is known as thermophoresis. Small temperature gradients ($\Delta T/\Delta z \sim 1$ K/cm) are mostly present due to different ionization densities (Ohm heating) in the plasma chamber. Externally applied temperature gradients of the order of 10 K/cm can be used in order to levitate particles of a given size against gravity, also in locations where no strong enough electric field exists. The thermophoretic force in noble gases is approximately given by [10]

$$F_{th} = -3.33 \frac{k a^2}{\sigma} \frac{\Delta T}{\Delta z}, \quad (2.27)$$

where $\sigma$ is the cross section for collisions between the neutral gas atoms (argon: $\sigma = 4.2 \times 10^{-19}$ m$^2$).

A particle assumes a stable equilibrium position in the plasma, if the sum of the external forces on the particle vanishes: $F_g + F_E + F_n + F_i + F_{th} = 0$. The gravitational force is proportional to the particle mass and thus to $a^3$, the electric force to $Q \sim a$ and all other forces to the particle cross section, i.e. to $a^2$. Therefore, gravity dominates for large particles and the electric force (in the plasma sheath) for small ones. Consequently large and small particles are found at different equilibrium positions.

![Figure 2.7: Attraction by shadowing](image)

The interaction of the particles with each other is determined by the Yukawa interaction. Since the particles are negatively charged, it is repulsive. A stable interparticle equilibrium
distance originates from the fact that the system is confined to a finite volume in the plasma chamber by an external electric field. Due to polarization of charge distribution on the particles an induced dipole moment \( p \) can be generated, which leads to an additional interaction potential \( V(r) \sim r \cdot p/r^3 \). Furthermore, shadowing of the bombardment by atoms and ions between neighboring particles (see Fig. 2.7) can lead to an attractive force between these particles. Finally, often it is observed that especially larger particles arrange in vertical chains in the plasma sheath. This is caused by the deflection of the ions streaming to the lower electrode. This leads to a positive charge cloud underneath the particle (distortion of the Debye sphere, see Fig. 2.8) which favors the localization of the next particle underneath the upper one resulting in the formation of chains. In most cases, however the Yukawa force is the most important force between the particles and other forces (dipole moment, shadowing) can be neglected.

![Distortion of the Debye sphere by ion streaming](image)

Figure 2.8: Distortion of the Debye sphere by ion streaming

Further theoretical investigations deal with phase transitions, e.g. crystallization (see below), with the excitation of plasma oscillations, with instabilities etc. These investigations will not be discussed here since they play, apart from crystallization presented in the next section, no role in our experiment.

### 2.4 Plasma Crystal

Owing to the strong charging of the particles under the strong interaction between the particles caused in this way, a regular structure of the particles, the plasma crystal, can show up under certain conditions. If we regard the particles as a further plasma component beside ions and electrons, complex plasmas are strongly coupled plasmas. As mentioned above, such plasmas have a Coulomb coupling parameter \( \Gamma = Q^2/(4\pi\varepsilon_0 dkT) > 1 \). Calculating the free energy of the system using molecular dynamics and Monte-Carlo simulations in the liquid and crystalline phase, one finds in the case of a one-component plasma with pure Coulomb interaction that the crystalline phase is energetically favoured over the liquid phase above the critical Coulomb coupling parameter \( \Gamma_c = 172 \) [11]. In realistic systems with Debye screening, additional interparticle forces, and external forces (gravity, neutral gas friction, ion drag, etc.) a value of \( \Gamma_c > 1000 \) is required for crystallization. For most of the plasmas existing in nature or in the laboratory, however, \( \Gamma \) lies only between \( 10^{-7} \) and \( 10^{-3} \) corresponding to a disordered (gaseous)
phase. Due to the high charge of the microparticles \((Q = 10^3 - 10^5)\) and the fact that \(\Gamma \sim Q^2\), large values for \(\Gamma\) can be achieved in complex plasmas.

Because of Debye screening of the particle charge in the plasma, however, the effective Coulomb coupling parameter

\[
\Gamma_{\text{eff}} = \frac{Q^2}{4\pi \epsilon_0 \Delta k T_d} e^{-\Delta/\lambda_D}
\]  

(2.28)

with the interparticle distance \(\Delta\) and the kinetic particle temperature (not surface temperature) \(T_d\) has to be considered. For getting a large \(\Gamma_{\text{eff}}\) the distance between the particles has to be of the order of the Debye length or smaller, i.e. \(\kappa = \Delta/\lambda_d \leq O(1)\). Therefore, beside the Coulomb coupling parameter \(\Gamma\) the distance parameter \(\kappa\) is relevant for crystallization. A small value of \(\kappa\), however, implies a large particle density. Then there might be not enough electrons in the plasma available to get a high particle charge. Therefore, one has to select an appropriate window in the particle and ion density, for the particle size, pressure, etc. for the formation of a crystal.

After Ikezi predicted in 1986 that crystallization might occur in a complex laboratory plasma [3], scientists at the Deutsches Zentrum für Luft- und Raumfahrt (DLR) in collaboration with the MPE in Garching succeeded for the first time [4,5] to produce and observe a plasma crystal. Almost at the same time a plasma crystal was produced by two research groups in Taiwan and Japan. Since then the plasma crystal became an important research topic which is investigated by numerous groups world wide.

![Figure 2.9: Plasma crystal: top view (left) and side view (right)](image)

In the first experiments it was possible to produce only relatively small crystals with less than 10 layers in vertical direction. The particles \((a > 3 \, \mu m)\) were arranged in vertical chains due to the interaction with ions streaming downwards (see above). In the horizontal planes, however, perfect hexagonal structures were found corresponding to (quasi) 2-dimensional crystals. A picture (Fig.2.9) taken of the crystal from the side and from above exhibits the vertical and horizontal structures, as they were observed in these experiments. In the present experiment, conducted in the plasma chamber discussed above, only the side view of the crystal is available. Hence the horizontal structure has to be deduced from a laser scan (see below).

Quantitatively the lattice structure can be investigated by construction of the Wigner-Seitz cells (in coordinate space, not in momentum space!) by determining the perpendicular bisectors...
Figure 2.10: Wigner-Seitz cells of a 2D plasma crystal

between to neighbours (see Fig. 2.10). Of course, there are also defects, e.g., cells with 5 or 7 sides, as in the case of real crystals.

By lowering the pressure the electron temperature is reduced, e.g., from 3 eV at 42 Pa to 1 eV at 10 Pa. This causes a reduction of the particle charge. At the same time, the friction of the particles in the gas decreases, leading to an increase of the kinetic temperature of the particles. Both effects cause a reduction of the Coulomb coupling parameter. Hence the system starts to melt and can even go into the gas phase. Quantitatively this process can be described by measuring the pair correlation function

\[ g(r) = \left\langle \frac{1}{N} \sum_{i \neq j} \delta(r - (r_i - r_j)) \right\rangle. \]  

(2.29)

Here \( r_i \) und \( r_j \) are the coordinates of two particles and \( N \) the total particle number. In the case of a crystal the correlation function shows several peaks corresponding to the distance between next neighbours, next-to-next neighbours, etc. Then the system is ordered at close as well as far distances, characterizing the crystal state (see Fig. 2.11).

The height of the peaks decreases exponentially with increasing \( r \), i.e., on average \( g(r) \sim \exp(-\eta r) \) holds. In the liquid phase only one pronounced maximum is found corresponding to the next neighbour distance. This corresponds to an ordering at small distances, i.e., the distance and orientation to the next neighbours are still preserved, an ordering at far distances, however, does not exist any longer due to the flow in the system. In between the solid and liquid phase there is a mixed or transitional phase, in which crystalline areas float in the surrounding fluid (“floe-and-flow phase”). In the liquid phase the particle oscillations around their equilibrium position increase significantly compared to the crystalline phase. In the solid phase these oscillations are given by the thermal lattice excitations at room temperature (corresponding to a typical particle velocity of 0.2 mm/s). In the gaseous phase, finally, the particle velocities are about 200 times faster. Hence no regular structure exists anymore and the system becomes
chaotic. The parameter $\eta$ of the pair correlation function increases from the solid via the liquid to the gaseous phase continuously as shown in Fig.2.12. Therefore it can be used for a characterization of the phase under consideration. In Fig.2.12 is, beside the parameter $\eta$, decreasing with increasing pressure, also shown the the orientational correlation function, which can also be used for characterizing the phases. However, it will not be used here further on.

In recent experiments, using smaller particles (e.g. $a = 1.7 \, \mu m$), larger 3 dimensional crystals with up to 20 horizontal lattice layers could be produced. Since for smaller particles the ion drag force is smaller, the particles do not arrange in vertical chains any longer but exhibit already a lattice structure in the side view (see Fig.2.13).

Due to the pressure exerted by the upper layers, the structure of the lower layers is more
pronounced (less defects), the lattice planes are more accurately defined, and the lattice distance is smaller (see Fig.2.14).

The lattice structure of the 3 dimensional crystal can be determined by superimposing three lattice planes. Although each horizontal plane shows a hexagonal structure, the 3D structure of the crystal can also be, e.g., fcc if the horizontal layers correspond to the (111) plane of this crystal. As shown in Fig.2.15, these structures (fcc or hcp) can be distinguished by a superposition of three layers [12].

In general one finds that the entire crystal has not a unique structure but domains of fcc and hcp, separated by 2 to 3 lattice distances, coexist. Molecular dynamic calculations of Yukawa systems (without gravity) yield the phase diagram in Fig.2.16 [13]. By comparing the percentage of fcc structure observed in the experiments with this phase diagram a Coulomb coupling parameter between $10^3$ and $10^4$ and $\kappa \simeq 1 - 2$ is inferred.

### 2.5 Microgravity Experiments

The gravitational force on the particles is of the same order as the other external as well as the interparticle Yukawa force. Therefore it has a strong influence on the system. For example, it causes the restriction of the plasma crystal to the plasma sheath, where the electric field is strong enough to compensate gravity. Consequently only quasi 2 dimensional crystals instead of 3 dimensional are produced. Furthermore, gravity influences the crystal structure and could be responsible, e.g., that hcp structures show up in laboratory experiments in contrast to theoretical predictions in which gravity is neglected. Therefore, it is very desirable to perform experiments under zero gravity conditions.

The MPE conducted various experiments with complex plasmas under zero gravity, to be more precise, under microgravity conditions ($F_g \simeq 10^{-6} m_{dg}$). First complex plasmas were studied in parabolic flights in airplanes in the absence of gravity for about 20 s. However,
Figure 2.14: Dependence of the crystal quality on the height. Above: lower plane, middle: middle plane, below: upper plane.
Figure 2.15: Superposition of lattice planes for determining the crystal structure. Above: fcc structure, below: hcp structure.
Figure 2.16: Phase diagram predicted by theory.

References:

Figure 2.17: Complex plasmas with gravity (left) and without (right).
20 s are not sufficient for the formation of a stable plasma crystal. After all, parabolic flight experiments are still performed nowadays for testing experiment devices developed for space experiments. Later complex plasmas were investigated in sounding rockets, in which zero gravity exists for about 6 minutes. Since 2001 complex plasma experiments on the International Space Station ISS take place in cooperation with Russian scientists and cosmonauts. This experiment, PKE-Nefedov, has provided already many interesting results. In 2006 PKE Nefedov was terminated after 13 experimental runs and dozens of publications in refereed journals (one of the mostly used and published experiments onboard the ISS!) and PK-3 Plus took over and continued the successful story of plasma crystal experiments of MPEE in space. Further experiments (PK-4, PlasmaLab) aboard the ISS are in preparation at the moment with an expected launch of PK-4 in 2011. The long-term facility ”PlasmaLab” (formerly known as ”International Microgravity Plasma Facility” (IMPF)) for investigating complex plasmas within fundamental research but also technological aspects is presently planned.

Indeed, under microgravity conditions it is possible to fill the entire plasma chamber with particles (see Fig.2.17). But surprisingly a void with a sharp boundary is formed in the center. The cause and dynamics of this void is not yet understood completely. Presumably the void is produced by the interaction of the particles with ions, which are generated in the center of the chamber and stream to the walls. Beside the void, crystal formation is found below and above the void and convection eddies in the corners of the chamber (see Fig.2.18). Thus, complex plasmas, produced in a RF chamber under zero gravity exhibit new and interesting non-equilibrium properties and structures.

Figure 2.18: Convection, void and plasma crystal under zero gravity.

In another experiment under zero gravity particles were injected without igniting the plasma. It turned out that the particles build very rapidly large agglomerates. The coagulation occurred much faster than expected since the particles were charged positively and negatively by friction and polarization effects and therefore attracted each other due to the electrostatic interaction. Similar effects could have played a central role in planet formation because neglecting electrostatic effects the formation of planets from the dust cloud around the sun occurs much too slow.
Chapter 3

Experiment Set-up, Run, and Aims

3.1 Aim of the experiment

The aim of the student experiment is to produce and investigate a plasma crystal. First the dimensions of the crystal and the lattice distances in vertical and horizontal direction shall be determined. Afterwards static and dynamic properties of the system, in particular a possible phase transition, during a reduction of the pressure shall be studied (measuring of the pair correlation function). Finally the particle positions in a finite volume of the crystal shall be extracted and the crystal structure in the horizontal layers (2 dimensional Bravais lattices, see e.g. [14]) and in 3 dimensions shall be determined from these positions.

3.2 Experiment set-up

The experiment set-up consists of the following components

- Plasma chamber and dispenser
  Electrodes on top and bottom, capacitively coupled to RF generator (13.56 MHz); windows for observation; particle injection by a dispenser (Melamine formaldehyd globules) with a diameter of 3.4 µm from above (see Fig.2.2).

- Gas fill system and vacuum pump
  Argon gas as working gas (Ionization energy: 15.7 eV, degree of ionization: $10^{-7} - 10^{-6}$); vacuum pump for evacuating the chamber.

- Laser
  Diode laser, cylinder optics for producing a laser sheet in a vertical plane.

- Digital camera
  Recording of the laser light scattered off the microparticles, motor driven translation stage for camera and laser (in z-direction) for scanning the crystals; micrometer gauge for adjusting the camera position in x-direction.
• Electronics rack
  Control of various experiment components (laser, RF, pressure, etc.)

• Computer
  Experiment computer: experiment control,
  Data PC: recording and analyzing of the pictures.

3.3 Experiment conduction

The day before the experiment the pump should be switched on by the supervisor. At the day of
the experiment first the control PC will be switched on and the program Krilab will be started
with the command “krilab”. On panel 6 under “3-way-cock” at “Direct” click on “Ein”.

Starting the experiment:
1. Gas filling: Under 3-way-cock” at “Control” click on “Ein” for closing the chamber and to
  finish pumping.
2. Software-Control “Ein”, Setpoint to desired value (e.g. 10) for adjusting the nominal value
  of the pressure at the electronics insert (valve switch in the middle of the insert).
3. Click on “Cycle” as many times as necessary to reach the nominal pressure (see electronics
  insert).
4. Change to panel 5 and increase the electrode voltage under “Operating Voltage” in steps by
  10 until plasma ignites. Afterwards return to about 20 V.
5. Switch on laser at the electronics insert.
6. Start program “Grabit” at the data PC and click on symbol “camera”.
7. Inject particles by clicking on “Ein” at “Dispensor” on panel 5. Repeat 1 to 2 times until
  desired particle amount is reached.
8. The gas pressure can be reduced by lowering the “Setpoint” (panel 6). This works automatic-
  ally. To increase the pressure increase the setpoint and fill in gas (“Cycle”) until the desired
  pressure is reached (check instruments in the electronics rack).

Laser-Scan:
1. Start program “SM32” at the data PC.
2. Setup: Step Width = 1, Switch Mode = 43.
3. Run: Motor #1 “on” (double click). Select the desired velocity under “F”, e.g. 300 (cor-
  responding to 0.3 mm/s during scanning, away from chamber center) or -1000 (laser/camera
  drive (fast) towards center of chamber). After selecting the velocity click on this field or press
  RETURN to start the motor. Note: Usually, camera and laser are positioned at the end of the
  translation stage, imaging the center of the cloud. During the scan both are moved from the
  center outwards. There are off-switches at both ends of the translation stage.
4. Before starting the scan click on “sequenz neu” under “File” at the program “Grabit” and
  choose number of pictures (e.g. 100). Then start the motor and click on “rec” at “Grabit”. 
  Note: Try to accomplish this task as quick as possible for not losing to many ’good’ frames in
the center of the crystal!
After recording switch motor “off” and click on “Bilder speichern” in “Grabit” and save images as tif-files on the data acquisition PC (create a new folder on volume D). These files can be used for the analysis via IDL (see IDL instruction below). Note: Don’t forget to drive back the camera towards the center for the next exercise.

3.4 Safety Instructions

The laser used for the illumination of the microparticles belongs to the laser class 3B (Classification according to EN 60825-1). Therefore it is a potential hazard for the eye. Owing to the widening of the laser beam into a sheet the laser intensity is significantly reduced. Furthermore the beam direction is fixed and the laser light cannot exit the plasma chamber due to a cover. After all, a direct contact of the laser light with the naked eye has to be avoided in any case. The scattered laser light, however, is not dangerous. The participants on this experiment are requested to sign a form for recognizing this safety instruction before conducting the experiment!

3.5 Sicherheitsbelehrung (deutsch)

Der zur Beleuchtung der Mikropartikel verwendete Laser gehört zur Laser-Klasse 3B (Klassifizierung nach EN 60825-1) und stellt somit ein mögliche Gefahr für das Auge dar. Durch die Auffächerung ist allerdings die Intensität des Lasers deutlich reduziert. Ausserdem ist der Strahlengang fixiert und das Laserlicht kann durch eine Abdeckung aus der Plasmakammer nicht austreten. Trotzdem ist ein direkter Augenkontakt mit dem Laserlicht unter allen Umständen zu vermeiden. Das Streulicht dagegen ist ungefährlich. Die Praktikumsteilnehmer werden gebeten, die Kenntnisnahme dieser Sicherheitsbelehrung durch Unterschrift auf einem Formblatt vor der Versuchsdurchführung zu bestätigen!

3.6 Experiment tasks

0. Determine the imaging scale of the camera system. Use the micrometer gauge at the camera platform (Unit: Inch! 1 inch = 2.54 cm) to translate the camera by a certain value. By measuring the travelled distance of a prominent feature on the lower electrode on the screen in pixels in two saved TIFF images (by using the program ”XnView” on the desktop) calculate the scaling factor in µm/pixel. Check out this value with the supervisor!

1. Produce and observe crystal: How does it form? How long does it take? How does the structure look like? What happens at the edges?

2. Measure the dimensions of the crystal (preferably in µm):
   a) Horizontal (x) and vertical (y) lattice distances. (Measurements at 4 different locations: center/bottom, center/half height, half-radius/bottom, and half-radius/half height. Use several particles to improve accuracy, where possible.)
b) Width and height of the crystal; (use appropriate approximation to a rectangle.)
c) Total particle number (use the dimensions you got in \( x \) and \( y \) direction. Assume simply a cubic lattice and that \( z = x \). Hint: you see the middle cross section of the cylindrical particle cloud).

Have the numbers checked by the supervisor on-site!

3. **Homework:** Estimate the particle charge \( Q \) (neglecting particle density \( n_d \); give value in Coulomb and elementary charges!), the electric field \( E \) necessary for levitation of the particles, the Debye length \( \lambda_d \), the Coulomb coupling parameter \( \Gamma \), and the effective parameter \( \Gamma_{\text{eff}} \). (Hint: Use the equations given here (note the cgs units!)) Use \( a = 1.64 \, \mu m, \ kT_e = 3 \, eV, \ kT_i = 0.03 \, eV, \) density of plastic spheres 1.51 g/cm\(^3\), \( F_n = F_i = F_{th} = 0, T_d = 300 \, K, n_i = 10^9 \, \text{cm}^{-3} \).

4. Perform a Laser scan: determine the horizontal lattice structure (using IDL, see App. A). The lattice type can be extracted by superimposing three consecutive planes (like shown in this manual). Try to identify two different lattice types. Determine the pair correlation function \( g(r) \) of one appropriate plane. What does it tell us?

5. a) Pressure dependence of the crystal: structure and dynamics, in particular phase transition to liquid phase (scan at low pressure: particle arrangement and pair correlation. How do they change?).

b) Change of the structure with changing voltage (increase in steps of 10). At one higher voltage measure again lattice distances. Do they reflect the overall change of the crystal? Go back to 20 and decrease in single steps? What happens and when does the plasma disappear?

**After finishing the experiment** please set ”Operating Voltage” to 0 and ”three way cock” to ”Direct” for evacuating the chamber.

Take along the data and pictures on an appropriate carrier (300 - 500 MB; a CD-R can be provided). Send the completed report (pdf format preferred) to your supervisor via e-mail (see title page) and suggest a date for the colloquium.

**Good luck!**
3.7 Literature

Appendix A

Instruction: Data analysis with IDL

Program start-up

- Load Praktikum_IDL program on the desktop by double clicking.

- Type “@praktikum” in the command line (bottom) and press Enter. The program code is compiled and started.

- Should the program stop unexpectedly (Message: “Execution halted”, windows don’t react anymore) start over again with the same command.

Now a small window with the name “Plasmakristallanalyse” appears. First we want to read in the particle positions from the pictures made in the experiment. For this purpose, we select the button “read data”. A new window appears: “Read Plasmakristalldata”.

Converting the image format

First convert TIFF images into PNG format: Click on button “Convert...” (top left). Select the first .tif file, normally containing the number [1] in its name. The images which are to be converted appear and the conversion progress is indicated beside the button (unless covered by the images).

As soon as all images are converted, the line “Files converted: 100” appears.

The path of the first PNG image (now with the ending _000.png) is shown automatically after the conversion. (If other PNGs shall be read in, the path should be given here.)

Choice of mask

In order to disregard uninteresting regions of the image, we build a mask. For this purpose, click on the button “View/Edit Mask”. A new window will be opened in which the first image of the sequence is shown.

If one wants to use an already existing mask, one can open it at the bottom left and apply it to the image via the button “Apply Mask”. However, usually a new mask is created:

- Select the check box “Create new mask” at bottom right. For your convenience you may also select “Show mask while selecting it” (bottom).
• Now the actual cursor position on the image is shown in the value fields in normalized coordinates. By **a single click on the desired position in the image** the lower left corner of the mask (= the region of interest) is selected.

• The mask should have 2/3 of the crystal’s height (including the lowest plane) and a width of double the height, roughly. Select the **upper right corner** by another click on the **image**. Now the mask is shown in the image.

• Test the mask using the button **“Test mask”**.

• If the mask shall be changed, use the “Reset” button and select a new mask (start again at point 2).

• Save the mask with **“save new mask”** (preferably in your folder).

• Close the window via the button **“done”**. The path of the new mask is transferred automatically to the previous window.

**Read-out of particle positions**

Eventually, parameters such as the scan velocity, etc. have to be adjusted.

Afterwards push button **“Get Positions”**, opening a window which shows the image under investigation and the particles found by the program. The particle positions are written into the file “(name)_{3d}.data.dat”.

As soon as all images have been processed, the line “Output files created. Ready.” is shown in the “Read Plasmakristalldata” window beside the button. Now close the window using the button **“Done”**.

**Analysis of data**

Select the button **“analyse data”** in the first window (“Plasmakristallanalyse”). The window “Analyse Plasmacrystal” will open.

If one has read in the data with the program the path has been transferred. Otherwise select the file “(name)_{3d}.data.dat” (bottom left). For **reading in the data** click on button **“Read Data”**.

For an **automatic read-out** of the horizontal lattice planes use the button **“Find horizontal planes”**. A histogram of the suggested planes is shown. For determining these planes the program counts the particles in a given y-interval (which size is fixed by \texttt{binsize}). As soon as the number of particles exceeds a given offset, a new plane begins. If the number drops below the offset and exceeds it afterwards, this will be the next plane.
For a manual adjustment of these planes choose “Modify borders”. Here, the offset and binsize can be changed. Moreover, using the appropriate check boxes and clicking on the desired position in the histogram, new plane borders can be added or old borders can be shifted or deleted. Via “Reset” the original settings can be restored. If the plane borders are satisfying, close the window using “Done”.

To view individual planes click on “View Planes”. Then select the desired plane by marking its plane number (right side, 0 = lowest plane) and clicking on “View Plane No.” Then you will get a top view of one plane: The width corresponds to the width of your mask (x) and the height to the scanned depth (z).

By marking 3 planes the superposition of theses planes is shown, allowing the analysis of the crystal lattice type: hcp or fcc (see fig. 2.15).

Note! If you forget to select a plane number and click on ”view planes” the program will crash! Re-start by entering ”@praktikum” in the command line.

In order to show the pair correlation function of a given plane, use the button “View g(r)”.

Then select the plane by marking its number and click on “View for Plane No.”

Note: the most recent graphic can be stored to disk as PS file by pressing the button “Save current plot”.