Chapter 5

Conclusion

The aim of this work was the development and qualification of a setup for the analysis of 3D plasma crystals using FIR (far infrared) diffraction signals. During the progress of this project the realisation of several elements of the undertaking turned out to be much more challenging than initially expected. Significant design and development effort had to be invested in each part of the system starting with the FIR laser system and ending with the plasma crystals and their control procedures.

Large 3D plasma crystals had initially been produced in a stainless steel plasma chamber with four glass windows. This chamber resembles the well known GEC reference cell (GEC: Gaseous Electronic Conference) but it is smaller and has a segmented electrode which allows the application of different electric fields. These crystals had been very stable with volumes of about $3 \times 3 \times 3$ cm$^3$ containing millions of dust particles. The mono disperse micro particles used have been gold coated because of the higher refractive index of gold compared to polymer particles. This gold coating increases scattering intensities expected from these particles.

The power of the incoming radiation necessary to measure diffraction peaks from those crystals has been calculated using the scattering theory described in this work. The use of gold coated micro particles has been assumed in this calculation. A CO$_2$ laser that pumps the FIR resonator has been purchased based on this estimation and a FIR resonator has been developed. A Golay cell detector has been purchased which is operated at room temperature and has a minimum signal limit well above the diffraction intensities estimated.

However, it turned out that the gold coated dust particles could not be used in actual scattering experiments because they degenerate most probably due to an argon ion etching process. The surface of the dust particles becomes craggy and long
term stable plasma crystals could not be produced using these particles. Therefore, uncoated mono disperse melamine resin (MF) and polystyrene (PS) particles could be used only, decreasing the diffraction signal intensities below those expected.

The FIR laser system built in this work consists of a commercial CO\textsubscript{2} pump laser and a home made FIR wave guide resonator. The FIR resonator design allows an easy change of the wave guide radius, input and output stainless steel mirrors, and of the laser gas. The FIR laser provides a Gaussian beam of up to 5 mW power and a wavelength of 118.83\,\mu m and 170.58\,\mu m when using methyl alcohol as laser medium. The FIR laser system has carefully been characterised and tested. This includes e.g. the variation of input and output plane mirror roughness and their hole diameters, the variation of the resonator pipe radius, and the change from plane mirrors to concave mirrors. The wavelength selectivity and the stability of the resonator has been improved using the concave instead of plane mirrors.

The CO\textsubscript{2} laser Brewster windows got dirty after about one year of frequent operation due to oil vapour originating from the rotary vane pump and diffusing back into the CO\textsubscript{2} laser plasma. The zinc selenite (ZnSe) Brewster windows therefore had to be removed, cleaned, polished using lap foils, and reinstalled again. This procedure worked quite well but some scratches remained on the windows which could not be removed by polishing. These are probably responsible for the somewhat reduced CO\textsubscript{2} laser power after the readjustment of the laser.

The CO\textsubscript{2} laser power is stabilised by an opto–galvanic stabiliser. It measures changes of the laser current which are induced by changes of the laser power to readjust the laser resonator length. However, it turned out that the long term stability of the whole FIR laser system has to be further improved by enhancing the frequency stability of the CO\textsubscript{2} laser with a feedback system that measures directly the FIR beam intensity through a beam splitter.

The development of a new plasma vacuum chamber has been a challenging task of this project. The chamber should provide optical and FIR access to the plasma crystals—if possible roundabout. Only a few materials suitable for vacuum vessels meet the requirement to be transparent in the visible and in the far infrared region of the spectrum. Crystalline quartz windows of the z-cut type fulfil the transparency demand. But a polygon chamber does not provide roundabout access to the crystals which is necessary to assure the detection of every possible diffraction peak from plasma crystals.

The polymer poly-methylpentene (TPX) is a mechanically stable material which
meets the demand of roundabout optical and FIR transparency. Thus a plasma vacuum chamber has been built using a TPX cylinder which is glued into grooves of aluminium flanges using silicone rubber. This chamber is smaller than the one previously mentioned and it has a larger window area which means more floating walls. This changes plasma characteristics and thereby plasma crystal properties compared to the other chamber.

The material TPX turned out to be sensitive to UV radiation which is produced by the plasma. It becomes more and more opaque due to microscopically small imperfections of the material. Furthermore, TPX is elastic to a certain extent but at the same time prudish. Forces due to repetitive venting and pumping stressed the material enormously and led to failures of the chamber. Although TPX is not the perfect material for the plasma chamber it is still used because of the lack of alternatives.

Several electrode geometries and electrical wirings have been examined to produce plasma crystals. These include the powering of upper, lower, and parts of the lower electrode as well as the application of different DC and AC electric fields to the powered as well as to parts of the grounded electrode. Two different plasma crystal types have thereby been found: extended and flat crystals. The extended crystals have volumes up to $3 \times 3 \times 2 \text{ cm}^3$ and are not fully stationary. They still show relatively high mean particle velocities of e.g. $0.36 \text{ mms}^{-1}$. The flat crystals are produced using higher power or by powering the lower electrode. They consist of three to four layers only but are extended over almost the whole electrode area of 10 cm in diameter. They are more stable (mean particle velocity e.g. $0.13 \text{ mms}^{-1}$) and exhibit a better defined crystal with less structural domains.

Various control procedures have been developed to stabilise the crystals and to optimise their structure by reducing their defects and the structural domain density. The crystal temperature could be reduced through lifting the plasma crystal to about two centimetres above the lower electrode by applying DC voltages to the electrodes. This lifted crystal position is not only advantageous for the crystal quality but also for the diffraction experiment. It eases the FIR beam adjustment and disturbing reflections from the lower electrode can easily be minimised.

A scattering arrangement has been developed to guide the FIR laser beam into the plasma chamber and to record diffraction peaks. It consists of a Yolo telescope, several tilted mirrors, and a motorised circular positioning system to move mirrors and detector around the chamber. All mirrors and mirror holders have been made
of aluminium and they have been manufactured and polished by the in house workshop.

The Yolo telescope is composed of two spherical mirrors and focusses the FIR beam. Two tilted mirrors deflect the beam from the laser table to the plasma chamber table where it can straightly reach the plasma chamber. Incoming beam and plasma crystal are not moved and diffraction signals are expected from single structure domains of the crystals.

A second diffraction method is an analogy to the rotating crystal recording. But since 3D plasma crystals can not easily be rotated in a well defined way, the incoming laser beam has to be rotated around the crystal together with the detector. A mirror system consisting of four mirrors mounted on a circular rail way accomplishes this beam rotation around the chamber and the detector is placed on a separate waggon.

Several computer programs have been written e.g. the program “Cockpit” by which it is possible to control the plasma parameters like pressure and power, to move the detector waggon and monitor its position, to calculate diffraction peak positions for different crystal structures and lattice plane distances, and to do the complete data storage. The program “Beam calculator” has been developed to calculate beam diameters of the FIR beam on its way along the scattering arrangement. Position and focal distances of the Yolo telescope mirrors have been determined using this program which applies the formulae of Gaussian beam optics.

A significant effort has been put into the design, the improvement, and the testing of the video analysis software. Existing procedures have been adapted, refined, and customised to ensure the correct analysis of videos taken by laser sheet illumination and a CCD (Charge Coupled Device) camera. The production of plasma crystals has been evaluated and refined by judging structure and stability with the video analysis software.

A 2D mesh that consists of about 2090 golden squares with edge lengths of 40 $\mu$m and distances of 200 $\mu$m has been deposited on a GaAs wafer (courtesy of Nadine Vitteriti, Chair for Applied Solid State Physics, Prof. Dr. A. D. Wieck, Ruhr–University Bochum). Diffraction signals from this golden mesh have successfully been recorded and the influence of the TPX wall and chamber structure has been analysed. Detailed estimations have been given for the diffraction peak intensities expected from real plasma crystals on the basis of these results. They suggest that a more sensitive and fast germanium detector should be used in diffraction
experiments and that the number of different domains within a plasma crystal has to be minimised to achieve enough intensity in one diffraction peak.

The presence of several structural domains within the extended 3D plasma crystals remains an unsolved problem. It prevented the recording of a diffraction peak of an actual plasma crystal. Flat crystals consisting of only three or four planes may be an alternative to large 3D crystals. They are located nearer to the lower electrode, however. The adjustment of the FIR beam becomes more critical when using flat crystals because beam reflections from the near electrode may increase the incoherent background.

The basis for FIR diffraction experiments on plasma crystals has been developed in this work. Further refinements of the FIR laser system and the plasma crystal production and control are necessary to obtain diffraction signals.