Plasma sheath diagnostics by optically manipulated micro-particles

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Introduction

The idea to use microscopic test particles as electrostatic or thermal probes, respectively, in complex plasmas has been consequently developed during the last years [1-3]. Due to the force balance of the particles, however, it is very difficult to change their position in the plasma sheath without changing the external and internal plasma parameters. Recently, experiments have been performed where the confined particles are affected by additional centrifugal force [4] or by laser radiation [5].

In the present study for the first time a macroscopic optical manipulation system for micro-particles in plasma has been realized, which is based on the principle of laser tweezers [6]. The particles have been successfully trapped in the focus of a split infrared laser beam whereas the focus length was several tens of centimeters. By vertical motion of the rf-electrode the confined particles can be shifted to a certain extent through the sheath in front of the electrode or into the plasma bulk. By this non-invasive method it is possible to perform flexible investigations without changing or disturbance of the plasma and its conditions. The evaluation of the affected force balance (in pN range) may yield information about the potential and electric field at arbitrary positions in the sheath.

Experimental

Dust particles are charged and confined in a capacitively coupled asymmetric rf-plasma (13.56 MHz) above the powered rf-electrode which has a diameter of 100 mm. The cylindrically shaped vacuum chamber (40 liter volume) is equipped with several windows for diagnostics (Fig.1). The discharge is typically operated in argon at a gas pressure of 10...100 Pa and at power of 10 … 50 W. Usually the particles (MF, 10µm in diameter) are levitated in about 1cm distance in front of the electrode. In order to confine a 1D-chain of MF particles a pattern with a slit has been placed onto the electrode, see Fig.2. A particle from the chain can be picked up by the laser tweezers which is at fixed position and subsequently moved along the z-axis relatively to the plasma by moving the rf-electrode upwards or downwards, respectively. The used IR laser (1) at λ = 1070 nm (and a maximum power of 11 W) is mostly operated at 100 … 1000 mW. After passing a λ/2-plate (2) the laser beam is divided into two beams (arms) by a polarizing beam splitter (3). Afterwards, the beams are passing through beam expanders (4), 10µm-pinholes (5), mirrors (6) and collimator lenses (7). Finally the beams are focused by lenses (8) to the particle position (9) in the plasma chamber. In comparison to common laser tweezers which are used in combination with microscopes in our case the focus length is about 30 cm. Therefore, the requirements for accuracy of adjustment, alignment and particle detection in µm-range are quite high.

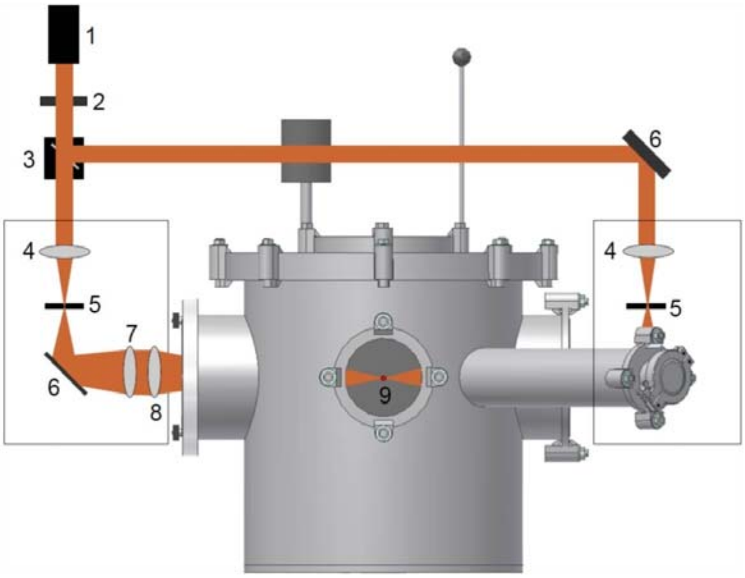

Fig.1: Schematic setup (plasma chamber and laser tweezers system) used for experiments.

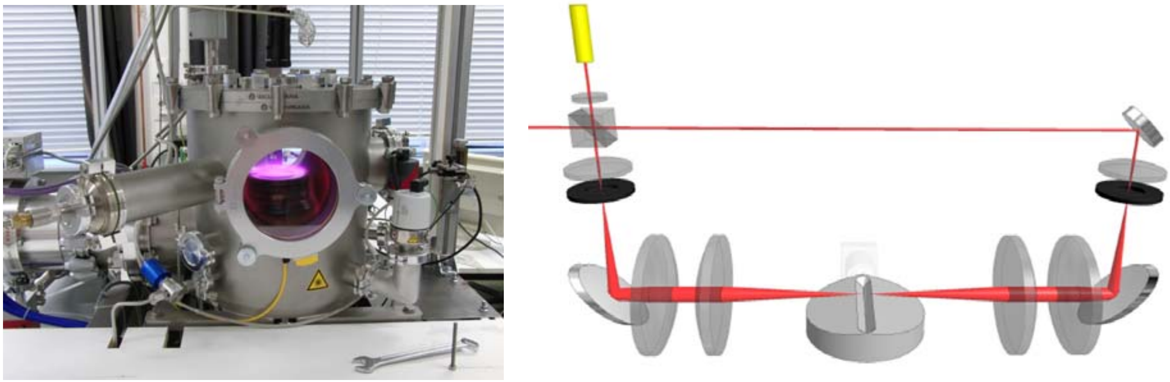

Fig.2: Vacuum chamber with capacitively coupled asymmetric rf-discharge (left). Right: Schematic view into the chamber with indicated optical components and part of the electrode for particle confinement.

In previous experiments the laser system and its handling procedure has been checked for particles which solvated in water. The cuvette was placed onto the electrode at same position where particles are usually trapped in the plasma. Due to the better damping of the particle motion in water the confinement by the tweezers was easier to achieve. After getting some routine in particle handling preliminary experiments for laser tweezing in plasma environment have been performed.

Results and Discussion

When a micro-particle in a medium with a smaller refraction index (n_m) is hit by a laser beam with power P then a force F is applied due to reflections and refractions.

$$F = Q\frac{n_m P}{c} \qquad (1)$$

In general, this force consists of two parts: (i) a gradient force, e.g. a lateral component and (ii) a scattering force, e.g. a component along the beam axis [7]. The gradient force is always directed towards the beam axis, see Fig.3. The factor Q is a quantity depending on the angle of incident and transmitted light by the particle.

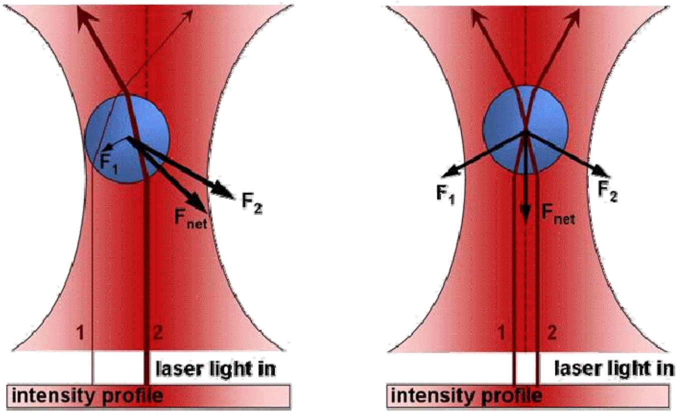

Fig.3: Forces in a laser beam acting on a particle for confinement.

A strongly focused laser beam leads to the effect that the total force is always directed towards the focal point. Hence, a single particle can be trapped due to the laser force which is balanced by the other forces acting on the particle in a plasma [8]. By a rough estimation one obtains for a small polymer particle (cross section ~ $1\mu m^2$) which is hit by a laser beam of 1W a force of about 10^{-9} N. This value is much larger than the gravitational force of about 10^{-14} N for such a particle (volume ~ $1\mu m^3$).

For small deviations of the particle from the beam axis the force can be assumed as a spring force $F = -\kappa\Delta x$ with the stiffness κ of the trap. If the other forces – e.g. especially the electrostatic field force on the charged particle due to the E-field in the sheath – are acting on the particle causing a change in position, one can measure this force by these deviations and, thus, experimentally determine the field strength in the sheath. By varying the laser power (e.g. optical force) it is possible to repeat the measurements at different positions in the sheath where stronger or weaker forces may occur. Fig.4 illustrates the principle of the measurement: One MF particle in the chain of confined particles is picked up by the laser tweezers (Fig.4 left) and the rf-electrode is moved downwards, e.g. the fixed particle is moved upwards in the sheath (Fig.4 right). It is still confined despite the field force is different at the new equilibrium position. When the particle suddenly escapes at certain position the force balance is not anymore fulfilled and the field can be estimated by the maximum trapping force.

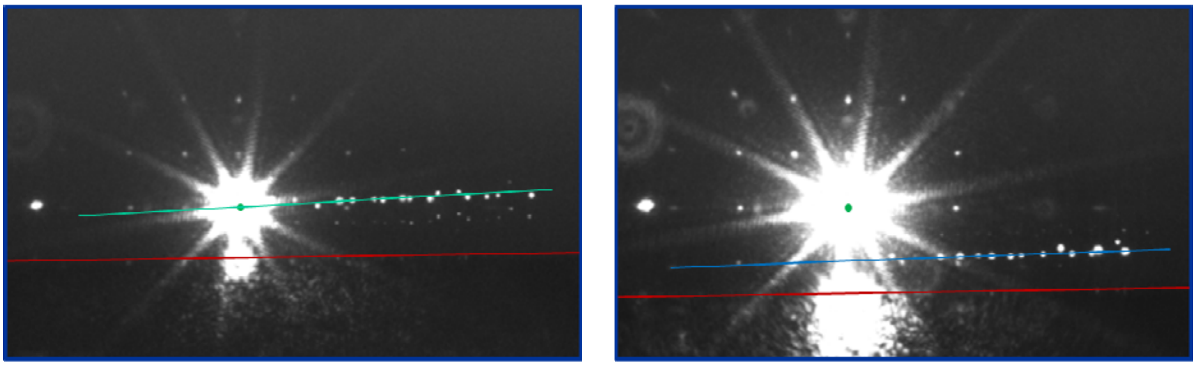

Fig.4: A particle (bright) is taken from the chain (green line) by the laser tweezers (left). By moving the rf-electrode (red line) the particle is transferred to another position in the sheath.

Conclusions

So far, positions of microscopic test particle could rarely be affected without changing the plasma parameters. In the present experiment laser tweezers have been applied as a tool for particle manipulation and, thus, for plasma diagnostics. However, extended and detailed measurements should be performed in the future to give a more quantitative description and comparison with related models.

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References

[1] B.M. Annaratone, M. Glier, T. Stuffler, M. Raif, H.M. Thomas and G.E. Morfill, NJP 5, 92 (2003)
[2] H.R. Maurer, V. Schneider, M. Wollter, R. Basner, T. Trottenberg and H. Kersten, Contrib. Plasma Phys. 51, 218 (2011)
[3] G. Schubert, R. Basner, H. Kersten and H. Fehske, Eur. Phys. J. D 63, 431 (2011)
[4] J. Beckers, T. Ockenga, M. Wolter, W.W. Stoffels, J. van Dijk, H. Kersten and G.M.W. Kroesen, Phys. Rev. Lett. 106, 115002 (2011)
[5] A. Piel and A. Melzer, Adv. Space Res. 29, 1255 (2002)
[6] A. Ashkin, IEEE J. Selected Topics Quant. Electr. 6, 841 (2000)
[7] A. Ashkin, Biophys. J. 61, 569 (1992)
[8] R. Basner, F. Sigeneger, D. Loffhagen, G. Schubert, H. Fehske and H. Kersten, NJP 11, 013041 (2009)