ON THE USE OF OPTICALLY TRAPPED DUST PARTICLES AS MICRO-PROBES IN PROCESS PLASMAS

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In this paper we outline the progress in the development of an optical system for particle manipulation as a plasma diagnostics method. We demonstrate basic principles and preliminary experimental results for optical trapping of microparticles in a plasma. A counter-propagating laser beam was used to trap particles in water as well as in an RF discharge. The experiments indicate that it is possible to manipulate particles, which are levitating in the plasma sheath, to obtain information on the sheath and plasma parameters.

PACS: 42.50.Wk, 52.27.Lw, 52.70.-m, 87.80.Cc

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 [1-4]. Several experiments on the analysis of plasma sheath properties, e.g. electric field measurements or energy flux measurements, have been discussed [5, 6]. Due to the force balance of the particles in the plasma sheath, however, one is often spatially restricted and it is very difficult to change their position without changing the external and internal plasma parameters. Recently, experiments have been performed where the confined particles are affected by additional centrifugal force [7] or by laser radiation [8].

In the present study for the first time a macroscopic optical manipulation system for microparticles in plasma has been realized, which is based on the principle of laser tweezers [9]. 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 nN range) may yield information about the potential and electric field at arbitrary positions in the sheath.

1. BASICS OF OPTICAL TRAPPING

Already in the year 1619 J. Kepler assumed that the light from the sun deviates a comets tail away from the sun. The radiation pressure was deduced theoretically in 1873 by J. C. Maxwell and in 1876 by A. Bartoli. However, due to the small momentum of photons, the first experimental proofs were performed at the beginning of the 20th century. The technique of trapping and manipulating small (nm-µm) particles by radiation pressure was first shown by A. Ashkin in 1970 [10] going hand in hand with the development of lasers producing intense and coherent light.

Considering a transparent particle in a Gaussian laser beam, we can apply ray optics, when the particle is much bigger than the laser wavelength (d >> λ). Fig. 1 shows two situations in an unfocused beam. As light carries momentum, which is conserved, due to reflections and refractions a net force F_{net} acts on the bead. The lateral component is the gradient force and the scattering force is the component along the beam axis. When the particle is in the center of the unfocused beam, the lateral components compensate each other and the total force points into the beam direction resulting in an acceleration of the particle due to scattering. When the particle is displaced from the beam center, the intensity distribution leads to a larger momentum transfer from the light closer to the maximum intensity, resulting in a net force toward the center of the laser. However, the scattering component still pushes the particle in transverse direction. This principle can be already used to trap particles against gravity [10].

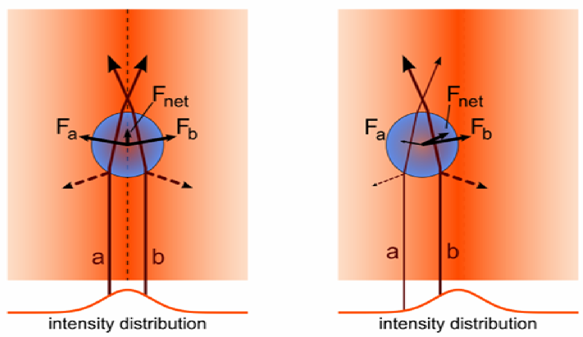

Fig. 1. Forces on a particle in an unfocused Gaussian laser beam in the ray optics regime. The force due to reflections always drags the particle in the beam direction. The lateral component of the total force is zero, when the particle is in the center of the beam (left) and is restoring the particle towards the maximum intensity, when the particle is displaced (right)

A focused beam produces an axial gradient in the intensity, which leads to an additional gradient force along the beam axis (Fig. 2). This force is always directed towards the focal point, where the intensity has its highest value. Thus, the particle is located slightly behind the focus, where the scattering force is compensated by this axial gradient force. By moving the focused laser beam the particle can be manipulated with so called optical tweezers, which are widely used in biology, medicine or life sciences, for example, under microscopes with short focal lengths in the millimeter range and with high numerical apertures [11].

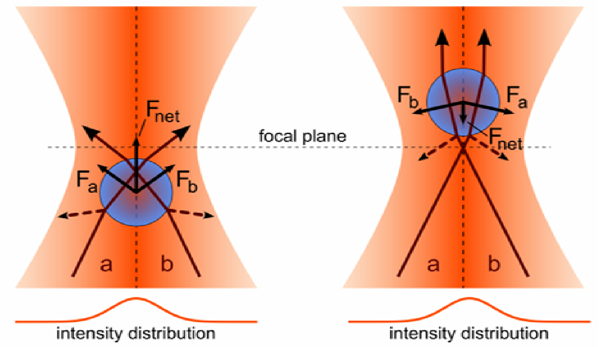

Fig. 2. Forces in a focused laser. The intensity distribution leads to an axial gradient force, which is directed towards the focus and which compensates the scattering force slightly behind the focal point

2. EXPERIMENTAL SETUP

The idea of the experiment is the manipulation of particles in plasma without changing the internal or external plasma parameters. For this purpose, dust particles are charged and confined in a capacitively coupled asymmetric RF discharge (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. 3). The discharge is typically operated in argon at a gas pressure of 10...100 Pa and at a power of 10…50 W. Usually the particles (MF, 10 µm in diameter) are levitated in about 5 mm distance in front of the electrode.

The optical trapping system in this experiment is based on the counter-propagating principle [10, 12], where the scattering forces of two laser beams compensate each other and the gradient forces fix the particle in its transversal position. In comparison to common laser tweezers which are used in combination with microscopes, this method is not restricted to high numerical apertures and short focal lengths. Nevertheless, 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 very high.

The optical components used to trap particles are shown in Fig. 3. The IR laser (1) at λ = 1070 nm is mostly operated at 100 mW…1000 mW. After passing a $\lambda/2$-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), 10 µm 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. Once trapped, the particle can be moved along the z-axis relative to the plasma by moving the RF electrode (12) in z-direction upwards or downwards, respectively. Thus, the particle can be shifted to a certain extent through the sheath in front of the electrode or into the plasma bulk. While moving the electrode or while external forces are acting on the particle, respectively, the particle position is measured with a quadrant photo detector (11) by splitting the beam with another beam splitter (10). In addition to gravity and electrostatic field force in the sheath on a charged microparticle, now the force due to the optical confinement acts onto the particle. For small vertical deviations Δz of the particle from the beam axis the force can be assumed as a spring force $F = -\kappa \Delta z$ with the stiffness κ of the trap. If 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 determine this force by these deviations and, thus, experimentally determine the field strength in the sheath. By changing 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.

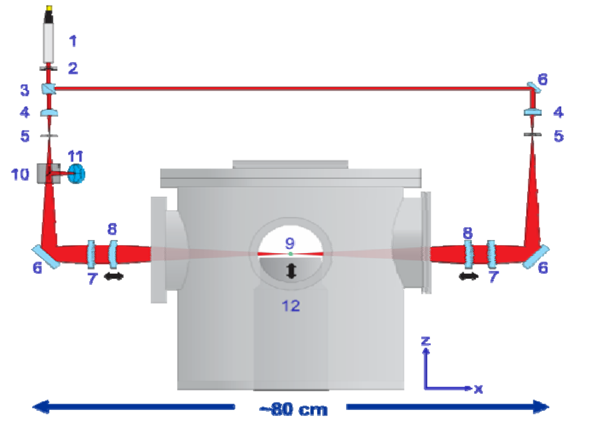

Fig. 3. Schematic setup of the plasma chamber and the laser trapping system used for the experiments

3. PRELIMINARY EXPERIMENTS

3.1. TRAPPING IN WATER

Due to the much higher damping of their motion first experimental verifications of the trapping system where performed with particles dispersed in water.

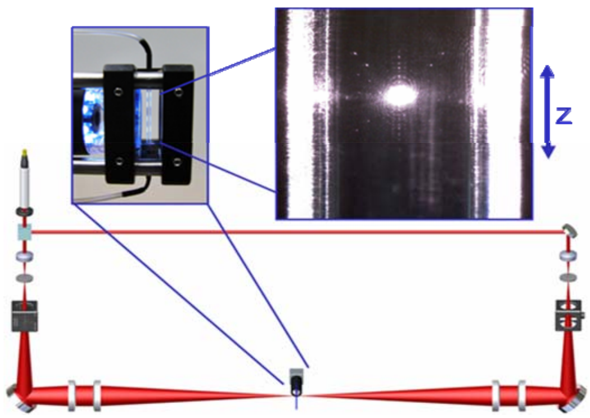

Fig. 4. Setup for particle trapping in a glass cuvette filled with water. The cuvette is moveable in xyz-direction. The laser power was less than 300 mW

A (1.5x1.5) mm^2 squared glass cuvette was placed in vertical direction into the focal plane of the two laser beams on a xyz-translation stage (Fig. 4). The cuvette was observed with a microscope camera. Two syringes were used to pump the water with the particles through the cuvette. After some adjusting procedures stable trapping with 300 mW and less laser power was achieved. Fig. 4 shows a trapped particle in the cuvette. By moving the cuvette in z-direction the particle was moved relative to it.

3.2. TRAPPING IN PLASMA

The use of the optical trapping system is much difficult to handle and to align under plasma conditions. Due to the low pressure (~30 Pa) resulting in a weak damping by the surrounding gas, the particles are much more unstable in their position in the plasma sheath as in water.
For easier handling of the particles an additional electrode with a 6 mm slit was placed on the RF electrode with the slit perpendicular to the beam axis. This alignment formed a shaped electrostatic potential, which damped the transverse movement of the particles resulting in a 1D-particle chain confined in the plasma sheath along the slit. Fig. 5 shows a top view of the electrode with the particle chain in the plasma sheath. The bright spot in the center is a particle in this chain optically trapped by the laser beams. This was proved by electrostatically moving the particle chain along the slit. The trapped particle remained at the same position while the other particles moved and passed around the fixed one.

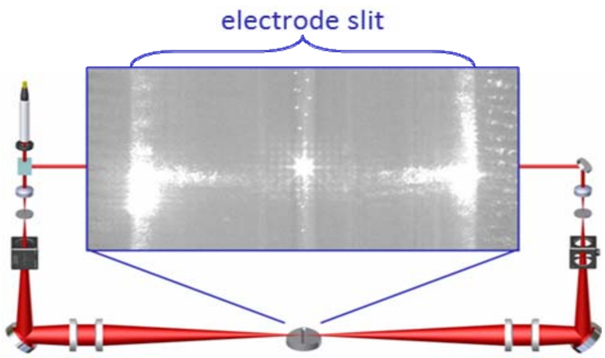

Fig. 5. Setup for particle trapping in plasma. An additional electrode with a slit confines the particles in a 1D-chain in the plasma sheath. The bright spot is an optically trapped particle. Although the trapping laser is in the NIR the CCD sensor is sensitive at this wavelength

The next step was to change the electrode in its vertical position. For this, a particle was optically trapped as described above and the electrode was lowered. Fig. 6 shows this principle: One MF particle out of the chain of confined particles is picked up by the laser tweezers (Fig. 6 left) and the RF electrode is moved downwards, e.g. the fixed particle is moved upwards in the sheath (Fig. 6 right). It is still confined despite the electric field force is different at the new equilibrium position. When the particle suddenly escapes at a certain position the force balance is not anymore fulfilled and the external forces at this position can be estimated by the maximum trapping force.

Due to the force balance a trapped and charged particle can be moved against the electric field force in the sheath to higher positions above the electrode if the laser power increases, see Fig. 7. The displacement is almost linearly proportional to the optical force of the trap.

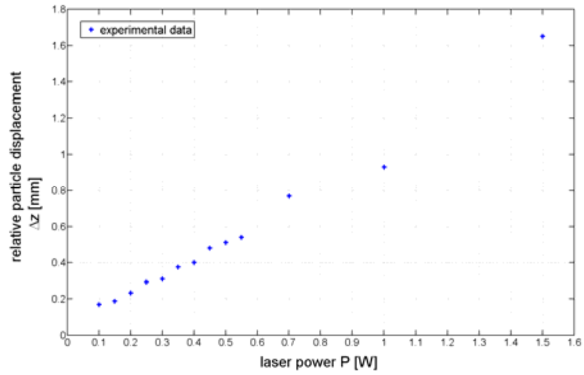

Fig. 7. Relative particle displacement of a particle from its original position in the sheath by laser manipulation in dependence on the applied laser power

CONCLUSIONS

An optical trapping system for microparticles based on a two beam counter-propagating principle has been designed and build. The "laser tweezers" is proposed to be a tool for manipulating particles in plasma and its sheath as a suitable diagnostic tool. This method is non-invasive referring to the plasma and its parameters and it allows a long-term particle manipulation. Compared to other experiments, where particles have also been manipulated by lasers [13-15], in this experiment it is possible to move particles in both directions, e.g. into the plasma sheath or into the plasma bulk, and over longer distances and timescales.

The functionality of the trapping system was successfully demonstrated in water due to better damping of the particle motion as well as in plasma at low pressure. By moving the electrode and the plasma, respectively, relative to the optically held particle it was possible to move the particle through the sheath either into the direction of the bulk or the electrode. Preliminary measurements showed an almost linear dependence of the relative displacement of the microparticle on the applied laser power.
The next step will be the installation of the quadrant sensors with an increased position detection. The measured particle position in the trapping beams will be used to determine the trap stiffness parameter κ and hence, the external force acting on the microparticle.

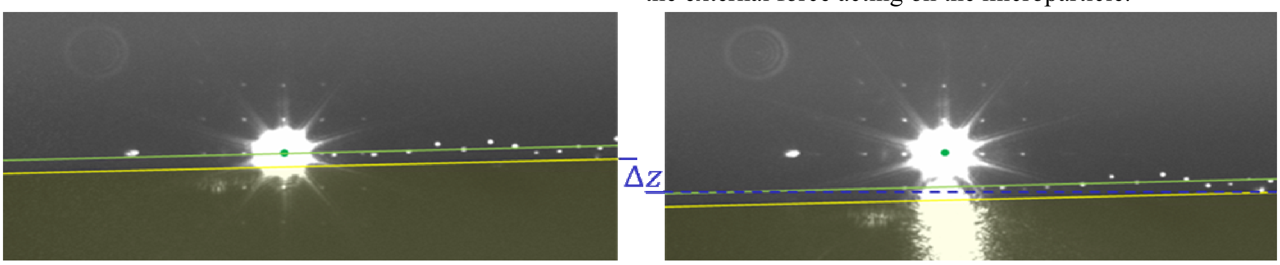

Fig. 6. Side view of the electrode (yellow area) and the microparticles in the plasma sheath. Left: A particle (bright spot with a green dot in the center) is taken from the particle chain (green line) by the laser tweezers. Right: By lowering the RF electrode the particle is transferred to another position Δz in the plasma sheath. Note that the rest of the particles move with the electrode

ACKNOWLEDGEMENTS

This work was supported by the Deutsche Forschungsgemeinschaft DFG in the framework of the SFB-TR24 Greifswald Kiel, Project B4. We also would like to thank the group of Prof. Pavel Zemánek from the ISI of ASCR in Brno, Czech Republic, for the development and construction of the optical trapping system.

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Article received 24.12.12

ИСПОЛЬЗОВАНИЕ ОПТИЧЕСКИ ЗАХВАЧЕННЫХ ЧАСТИЦ ПЫЛИ КАК МИКРО-ЗОНДОВ В ПЛАЗМЕННОМ ПРОЦЕССЕ

V. Schneider, H. Kersten

Описывается прогресс в развитии манипуляционных частиц оптической системы, как метода плазменной диагностики. Описываются основные принципы и предварительные экспериментальные результаты при оптическом захвате. Для распространяющихся волн был использован лазерный луч, который улавливал частицы в воде, а также в РФ-разряде. Эксперименты показывают возможность манипулирования частицами, которые находятся в состоянии левитации в плазменной оболочке, чтобы получить информацию про саму оболочку и плазменные параметры.

ВИКОРИСТАННЯ ОПТИЧНО ЗАХОПЛЕНИХ ЧАСТИНОК ПИЛУ ЯК МІКРО-ЗОНДІВ У ПЛАЗМОВОМУ ПРОЦЕСІ

V. Schneider, H. Kersten

Описується прогрес у розвитку маніпуляційних частинок оптичної системи, як методу плазмової діагностики. Описані основні принципи і попередні експериментальні результати при оптичному захопленні мікрочастинок в плазмі. Лазерний пучок, що зустрічно поширювався, був використаний для захоплення частинок у воді, так само як і у РЧ-розряді. Експерименти показують можливість маніпулювання частинками, які знаходяться в стані левітації у плазмовій оболонці, щоб отримати інформацію про саму оболонку і параметри плазми.