Deposition of magnetic materials on dust particles levitated in vacuum arc plasmas

C. M. Ticoş, C. P. Lungu, C. Surdu-Bob, I. Mustaţă, V. Zaroschi, A. Anghel, C. Poroşnicu

National Institute for Laser, Plasma and Radiation Physics, 077125 Bucharest, Romania

Dust is a generic name for entities of matter with sizes of a few microns [1]. Dust is ubiquitous in nature. It is present in every day life, as well as in science and technology [2].

Microparticles coated with different materials such as magnetic compouds have found applications in biochemistry as catalysts/inhibitors, as chemical sensors, or as markers or tagging agents in separation of biological fluids [3]. Paramagnetic or ferromagnetic microparticles are extensively used for separation of cells in blood or bone marrow or for the isolation of cancer cells. Advanced flow cytometry methods use magnetic microparticles which target specific molecules. A flow spectrometer generates a magnetic field gradient which sorts the microspheres by their magnetic moment. The separated magnetic grains are then chemically bound to target molecules so that each species of magnetic moment is bound to a unique kind of molecule. Typical coatings for these microparticles obtained by chemical reactions are of iron oxide (paramagnetic) or CrO_2 (ferromagnetic). Our proposed vacuum arc deposition technique has the advantage of enabling the deposition of potentially any type of metal and even intermixing of different metals with magnetic properties.

In fusion plasmas, the use of microparticles as diagnostic tools which perform precise local measurements instead of giving only averages along the line of sight is gaining much interest. The harsh environment of magnetically confined fusion plasmas with charged particles densities of the order of $10^{19}-10^{20}$ m^{-3} and temperatures in the range $1-10$ keV limits the diversity of diagnostics that can be used to infer plasma properties. An important aspect during a high-beta discharge is that the topology of the magnetic field changes significantly from the vacuum field. A new method has been proposed to use injection of hypervelocity carbon microparticles [4]. Ablation at the particles surface creates a bright plume oriented in the direction of the local magnetic field, which can be then recorded by a high-resolution high-speed video camera. In principle, microspheres coated with magnetic materials and injected into the plasma can also provide insight about the magnetic field structure. Their flying trajectories would be deviated by the magnetic force which is proportional with the magnetic field gradients.

The divertor of the future International Thermonuclear Reactor (ITER) will be made of W which is a low erosion material. However, sputtered W can cause power loss in plasma. Thus, it could be desirable to test the physical and chemical behavior of tungsten under fusion plasma conditions in existing fusion devices by injecting tungsten or tungsten-coated microparticles.

Understanding of surface processes during material deposition on microparticles is of special interest to many industrial applications, for example, the use of powders in sintering processes, implantation of nanocrystallites for solar cells, hard coatings in combustion or nuclear reactors or surface protection of phosphor particles in fluorescent lamps [2, 5].

Nano/microparticles present in cold plasmas have been the subject of intense investigations in the last decades [1, 2, 4, 5]. On one hand, the particles can grow in the plasma from a few nanometers clusters to large structures having tens of microns in diameter as a result of the plasma-assisted chemical reactions between the gases used. On the other hand, seed particles made of a chosen material can be introduced in plasma for further plasma treatment. Here we propose a novel method for coating with metals of dust particles introduced in vacuum arc plasma.

Dust particles made of graphite, diamond, alumina and melamine formaldehide (MF), with sizes from 1 to 20 microns, will be injected from a dust dispenser into the plasma to study deposition onto their surface of thin layers of different materials such as Ni, Cr, Fe, Cu, Al, Sn, Ag, W, Re, Ti, and Mo. The thickness of the deposited layers, which is expected to range from a few to tens of nanometers, and their uniformity can be easily characterized by transmission electron microscopy (TEM). One of the intersecting feature of this deposition process is that the particles can become strongly coupled and form plasma crystals [1]. The coupling parameter can however change during the process as the size of the grains changes and also their charge which is proportional with the grain radius, leading to the observation of interesting phenomena. The dust-dust and plasma-dust interactions during the deposition process will be monitored with high speed imaging camera. The plasma parameters will be determined with a Langmuir probe.

One essential aspect of our proposed experiment is levitation of microparticles during plasma coating. The micoparticles can be sustained by an electric force against gravity. Charging of the microparticles present in the plasma is inherent. In steady plasma conditions, the ion and electron fluxes streaming from the plasma to the microparticle reach an equilibrium when a stationary charge is attained on the grain surface [1]. When no photo or thermionic emission is present, the grain charge is negative, of the order of $10^3 - 10^4$ elementary charges, since electrons are more mobile than ions. Thus, for a grain with 10 micrometers in diameter and an average grain material density of 3 grams/cm^3 (mass $\approx 10^{-9}$ grams), the electric fields required to levitate the grain is 50-100 V/cm, if the dust potential is of the order of 2...3 $k_B T_e$ and $T_e \simeq 1$ eV. Another important issue which needs to be properly accounted for in the balance of forces acting on grains is the thermophoretic force. Temperature gradients in the metal vapors will possibly lead to convection currents which could drag the microparticles away. Thus, optimization of the trapping technique of microparticles in the plasma based on potential wells created by biased rings or plates inserted inside the discharge is the foremost problem that needs to be resolved. The proposed experiment will benefit from our extensive expertise in the fields of thermionic vacuum arc (TVA), dusty plasmas and coating of surfaces with thin films.

The thermionic vacuum arc is a novel arc method in metal vapors proposed by our team over two decades ago for deposition of metallic films on different substrates [6, 7, 8, **?**]. The thermionic arc is a DC discharge produced between two electrodes placed in vacuum, as shown in Fig. 1. The cathode consists of an electron gun. A few grams of the metal which will be deposited is placed in a crucible at the anode. Intense bombardment of the anode by an electron beam generated by a hot filament heats up the crucible and melts and vaporizes the metal. Simultaneously, a high voltage of the order of $1-5$ kV applied between the electrodes ionizes the metallic vapors creating a bright plasma. Currents of $0.1-5$ A and running voltages of $\sim$ 1kV are typical for this type of discharge. Some of the important advantages of the thermionic vacuum arc compared to other deposition methods such as plasma enhanced chemical vapor deposition (PECVD) are multiple: TVA can practically work with any type of metal, including those with high melting temperatures ($\geq$ 3000 K) such as Mo, W, without heating the substrate [6, 7, 8, 9, 10]. Since TVA is produced in plasma vapors, it combines the advantages of ion acceleration in the sheath separating the substrate and ion flux uniformity, without relying on rate enhancement induced by chemical reactions .

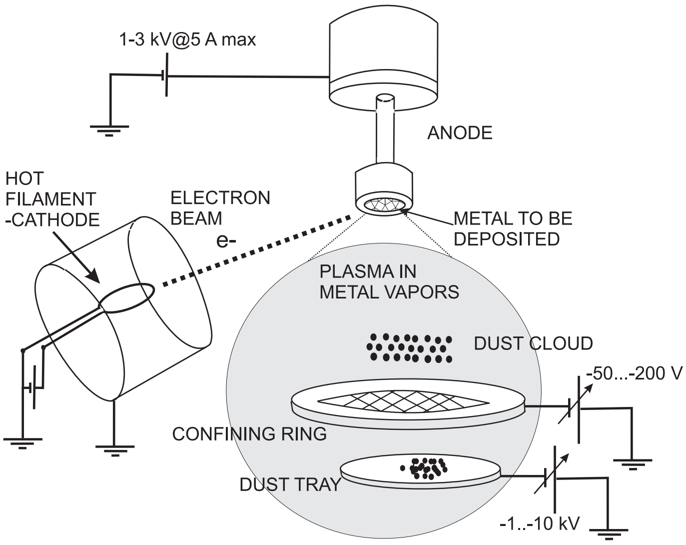

Figure 1: Proposed set-up for dust coating in vacuum arc plasma

Externally introduced microparticles in plasma for coating with different materials is a new field of research [2, 5]. Several approaches have been successfully employed which involved the use of PECVD methods in combination with rf and/or dc magnetron enhanced plasmas. In each of them gas or aluminium-organic precursors such as CH_4 , SiH_4, and $Al(i\text{-}OH_3H_7)_3$, respectively, have been introduced in the vacuum chamber. Our proposed method is much simpler since it requires only the use of materials that need to be deposited and circumvents the use of gas precursors and their complex chemistry.

Microparticles with selective coatings or tailored surface roughness can be very useful in a wide range of applications. Here we propose to generate them in vacuum arc plasmas by taking advantage of several techniques from different areas of plasma physics and embed them into a unique task.

References

[1] P.K. Shukla, A.A. Mamun, Introduction to Dusty Plasma Physics, Bristol, IOP 2002.

[2] Dusty Plasmas, Physics, Chemistry and Technological Impacts in Plasma Processing, Editor A. Bouchoule, Wiley 1999.

[3] M. Espy et al., Bioassay with magnetic microspheres in flow: a method for highly parallel molecular separations of complex biological systems, Nano-Microgadgets Workshop, Santa Fe 2005, New Mexico, USA.

[4] Z. Wang, C. M. Ticos, et a.l, IEEE Trans. Plasma Sci. **34**, 242 (2006); Z. Wang et al., Physics of Dust in Magnetic Fusion Devices, New Aspects of Plasma Physics, Proceedings of the 2007 ICTP Summer College on Plasma Physics Abdus Salam International Centre for Theoretical Physics, Trieste, Italy 30 July - 24 August 2007, p. 394-475, World Scientific (2008); C. M. Ticos, et al., Rev. Sci. Instrum. 77, 10E304 (2006); C. M. Ticos et al., Phys. Rev. Lett. **100**, 155200 (2008) ; Z. Wang, C. M. Ticos, G. A. Wurden, Phys. Plasmas 14, 103701 (2007).

[5] G. S. Selwyn et al., Appl. Phys.Lett. 57, 1876 (1990); H. Kersten et al., New J. Phys. 5, 93-1 (2003).

[6] C. P. Lungu, I. Mustata , et al., Phys. Scr. T128, 157 (2007).

[7] G. Musa, A. Baltog, A. Popescu, N. Betiu, I. Mustata, Contrib. Plasma Phys. 26, 171 (1986).

[8] C. P. Lungu et al., J. Optoel. Adv. Mater. 8, 74 (2006).

[9] T. Akan et al.., Plasma Sci. Technol. 9, 280 (2007).

[10] C. P. Lungu, I. Mustata, et al., Surf. and Coat. Technol. 200, 399 (2005).