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Radioactive dust levitation and its consequences for fusion devices

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Abstract

Small particles (dust) exist in magnetic confinement fusion devices. Their origin is due to plasma–surface interactions. Dust particles may contain significant amounts of hydrogen isotopes, 50% of which will be Tritium in future devices. The radioactive decay of Tritium incorporated into carbonaceous dust may lead to its charging and to the formation of a nuclear induced plasma associated with levitation and transport of dust inside the vacuum vessel. We will discuss the experimental evidence of dust levitation and removal by appropriately shaped electric fields and we will discuss some aspects of radioactive dust in fusion devices.

Keywords: Dust; Radioactivity; Nuclear-induced plasma

1. Introduction

It is well known that small particles exist in magnetic confinement fusion devices [1,2]. In the framework of the International Thermonuclear Experimental Reactor (ITER) it became evident that for conditions of large plasma fluences (steady-state operation) the formation of dust raises serious safety problems [3,4]. ITER, as most of the present large devices, will have carbon-based wall components (graphite, carbon fiber composites). The incorporation of hydrogenic isotopes in carbon dust can be as high as 2 atoms/C atom and may yield Tritium (T) inventories of up to several kg. A dust-bound Tritium inventory is a safety issue in future reactors. Dust may become a vehicle making Tritium mobile in case of a severe accident. The radiotoxicity of such dust is a big concern. A further aspect is the explosion hazard which may exist when steam from a broken cooling line gets into contact with the highly dispersed carbon liberating hydrogen in amounts large enough to create an explosive mixture.

We will discuss the experimental evidence for charging of dust by the radioactive decay of T and for the formation of a nuclear-induced plasma in which the levitation of dust occurs. The removal of such particles can be easily accomplished by appropriately shaped electric fields. We will also briefly address the possible consequences of radioactive dust for the operation of fusion devices.

2. Experimental setup and procedure

A nuclear-induced plasma is formed by products of nuclear reactions traveling through a gas and producing electron–ion pairs in their tracks as well as exited atoms and molecules. The injection of micron-sized dust particles into a plasma may change its properties and leads to a number of new effects [5,6]. In most cases, the energy of nuclear particles is large enough to penetrate a macroparticle with a radius of several microns. As a result, the macroparticle may acquire a positive charge due to secondary electron emission. Besides, the macroparticle itself may become radioactive and emit charged particles after nuclear conversions. The dust

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particles, placed into the nuclear-induced plasma, are affected by flows of electrons and ions. Due to the different electron and ion velocities the dust particle has a negative average charge in equilibrium state. Thus a radioactive dust particle is charged by various physical processes which may change value as well as the sign of a charge.

The experimental installation presented in Fig. 1 consists of the electrode system placed in a glass tube, a source of ionizing particles, means of vacuum pumping, an electrometer and a dc voltage supply. In the first set of experiments, we used as a source of alpha-particles and fission fragments a thin layer of ^{252}Cf with an intensity of 10^5 fissions s^{-1} and 1.6×10^6 α-decays s^{-1}. The layer diameter was 7 mm. The solid angle in which ionizing particles escaped was near to 2π. The visualization of dust particles was performed with the help of a diode laser light sheet with a stretching thickness in the center of the chamber less than 150 μm. The light scattered by dust grains was imaged by a CCD–camera the output signal of which was registered by a video tape-recorder. We used spherical monodisperse melamine formaldehyde (MF) particles ($\rho = 1.5$ g/cm^3) of 1.87 and 4.82 μm diameter and polydisperse cerium oxide (CeO_2) particles ($\rho = 7.3$ g/cm^3) of 1 μm mean diameter. The experiments were performed in neon and argon at subatmospheric pressure in the range from 0.25×10^5 Pa up to 10^5 Pa. In another set of experiments, we used radioactive CeO_2 particles with a mean diameter of 1 μm instead of the ^{252}Cf layer to create the nuclear-induced plasma. The CeO_2 dust grains were activated in a nuclear fission reactor. The activation occurred according to the reaction

$$^{140}\mathrm{Ce} + \mathrm{n} \rightarrow {}^{141}\mathrm{Ce}$$

During the experiments beta-particles were emitted according to the reaction

$$^{141}\mathrm{Ce} \rightarrow {}^{141}\mathrm{Pr} + \mathrm{e}^- + v'$$

where v' is the electron antineutrino. The measured intensity of the beta-decay in the experimental chamber was about 10^9 decays s^{-1} that corresponded to an output of fast electrons from one CeO_2 particle of 0.1 decay s^{-1}. Experiments were performed in air at atmospheric pressure.

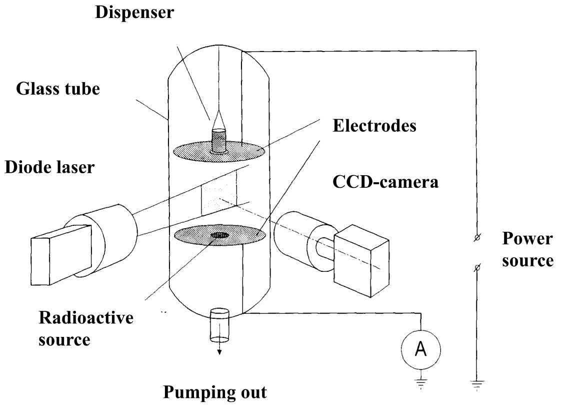

Fig. 1. Experimental setup.

3. Results

The experiments revealed the formation of conical structures of CeO_2 particles near a hole in the upper electrode when this electrode has a positive polarity. Fig. 2 presents a video image of the conical structure. Charges of the levitating dust grains were estimated from a balance of the gravitational force and the electric force to be in the range from 200 to 400 **e**. The conical structures were observed for MF particles with 1.87 μm diameter as well. The experiments demonstrate that it is possible to control the position of charged dust particles near the electrode. In the case of the reactor-activated CeO_2 particles, we observed broad regions with levitating dust part in the central part of the interelectrode space when an electric field was less 30 V/cm. The estimate of the particle charge from a balance of the gravity and the electric force gave a value of $(3–5) \times 10^2$ **e**.

4. Plasma vacuum cleaner

To remove charged dust grains from a volume of the experimental chamber we developed a electrostatic probe, the so-called 'plasma vacuum cleaner' (Fig. 3). It is a probe consisting of two electrodes: the main elec-

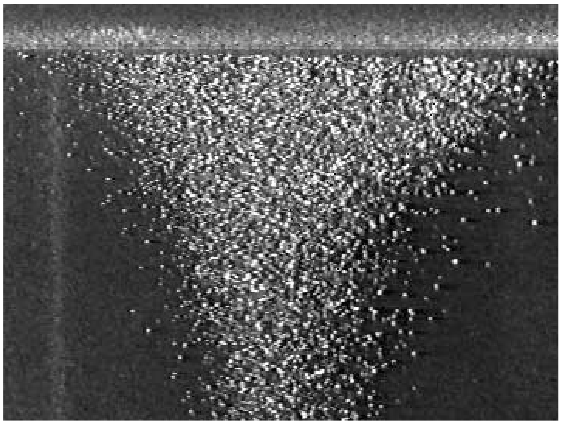

Fig. 2. Video image of the conical structure for CeO_2 particles, neon, $p = 0.5 \times 10^5$ Pa, U_e is +160 V. Image size is 9×10 mm^2, vertical section.

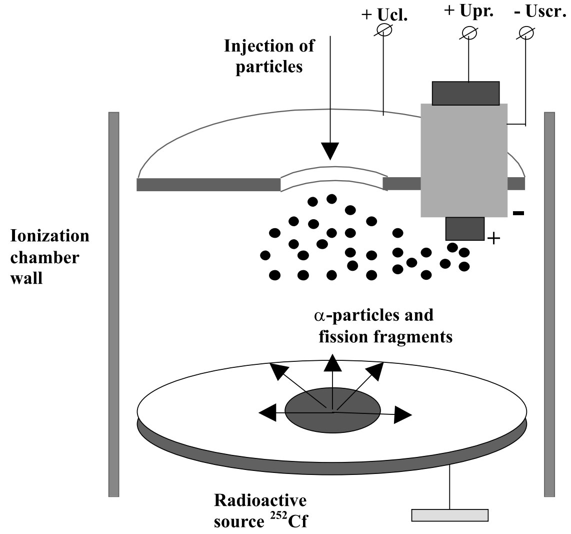

Fig. 3. Scheme of the experiment for removing dust grains in the nuclear-induced plasma.

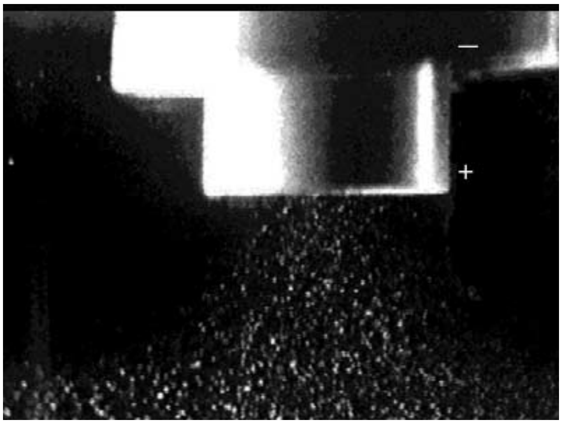

Fig. 4. Video image of the removing dust grains, neon, $p = 0.5 \times 10^5$ Pa, CeO_2 particles, vertical section.

trode and the screening one. Positive potential was applied to the main electrode and the negative potential was applied to the screening electrode. Both electrodes generate the electric field which induces a flow of negatively charged dust grains from the plasma into the probe. Fig. 4 presents the video image of a frame demonstrating the removal of dust grains from the plasma volume.

5. Possible effects of radioactive dust on the operation of fusion devices

In the following rough estimate a carbonaceous particle of 1 μm thickness with a diameter of 5 μm is considered with a total concentration of hydrogen isotopes of 0.4 per C atom of which 50% is Tritium. The mean density of such a type of redeposited carbon film in tokamaks has been measured to be of the order of 1.5 g cm^{-3}. The number of T decays in the carbonaceous particle is about 5×10^2 s^{-1}. It is assumed that all electrons leave the particle into the vacuum. The steady-state positive charge on the particle depends on the effective neutralization rate. If we assume for the tritiated carbonaceous dust no secondary electron emission and in the evacuated torus a mean charge lifetime of 1 s, an equilibrium charge of $Q = 5 \times 10^2$ elementary charges accumulates. The particle would levitate at an electric field strength $E = 38$ V cm^{-1}.

During break down and the initial current ramp phase of a fusion plasma rapidly varying eddy currents are flowing in the vessel. They cause electric fields whose strength and direction is difficult to predict. The electric field strength may easily be large enough to levitate the charged dust particles. If these particles get into the main volume of the vessel before a significant current is established, burnthrough of the plasma becomes difficult. The dust particles will be vaporized, the partially ionized carbon atoms radiate power out of the plasma and make a significant contribution to plasma resistivity. This, in turn, requires larger loop voltages for plasma startup. However, particularly low loop voltages (of the order of 1 V) are required for devices with superconducting coils for technical reasons. In this case the presence of dust is critical.

There exists another possibility for levitation due to the formation of a nuclear-induced plasma. When the gas pressure in the vessel is increased to about 10^{-3} mbar for plasma breakdown, the fast electrons from the T-decay will ionize the gas along their track. The range of the electrons is of the order of 10^3 m at this pressure. Due to the toroidal magnetic field the electrons have gyroradii which are very small compared to the vessel dimension and they may ionize the gas efficiently. Assuming a mean value of 35 eV per ion–electron-pair and full stopping of the fast electrons about 500 ion–electron pairs per emitted β-particle are formed. It is assumed that the inner tokamak surface (of the order of 10^3 m^2) is covered to 50% with dust and redeposited films of the type discussed above. Under the assumption that 50% (2π solid angle) of the β particles out of an escape depth of 1 μm leave the film towards the main vessel volume, a total flux of about 1.2×10^{19} electrons and ions per second results. Assuming a confinement time for electrons of 0.5 s and considering a vessel volume of 10^3 m^3 an electron density of this nuclear-induced plasma of the order of 5×10^9 cm^{-3} results. Levitation of dust may occur as shown in the previous sections. It thus appears to be important to consider dust charging by nuclear decay and the nuclear-induced plasma.

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