Why Using Laser for Dust Removal from Tokamaks

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Abstract. During ITER lifetime, the interaction of all types of plasmas with the Plasma Facing Components (PFCs) will lead to the generation of dusts with various sizes, shapes and composition. These dusts will be activated, tritiated and potentially chemically toxic. Then, ITER has fixed a set of safety limits to manage the potential hazards which might be caused by these dusts. In this study we investigate the capability of the laser cleaning process to be applied to this specific application. The development of a laser cleaning tool for dust mobilization in Tokamak requires a full understanding of the physical mechanisms leading to the particle removal. This knowledge is necessary to select the right laser source; to anticipate the influence of both the material properties (size, nature) and the ambient conditions (access, pressure…); to determine the nature and morphologies of the ejected products in order to optimize the collection process, and to guarantee to do not damage the irradiated substrates. For carbon dust, we demonstrated that laser ablation processes lead to the dust removal at fluence lower than ablation threshold of substrates. The main part of the ablation products is composed of atoms. Experiments performed with metallic particles showed a strong influence of laser wavelength and pulse duration on process efficiency. UV or short pulse laser irradiations are suitable to remove metallic dusts. We demonstrated that electrostatic forces, due to photoelectron emission, are the main mechanism leading to particle removal. We also developed laser induced shock wave based process to remove dusts from castellation. Indeed, the focalisation of a laser beam in gas or on a surface induces the fast heating of a small volume of gas and then the generation of a shockwave. Its fast expansion allows blowing the dusts. This technique appears very efficient in this configuration to move dust towards colder areas.

1. Introduction

During ITER lifetime, interactions between plasmas and Plasma Facing Components will induce dust production [1]. These dusts are composed by walls material such as tungsten, beryllium and carbon. They are re-deposited on the reactor surfaces and they might lead to safety problem because they could be activated, tritiated and potentially chemically toxic. Thus, in the framework of the ITER (International Thermonuclear Experimental Reactor) project, a limitation of the amounts of dust in the vessel has been fixed [2]. As a consequence, a dust collection device has to be developed to keep these inventory guidelines [3].

The first step to realize such a cleaning process is the mobilization of the dusts. Indeed, before their collection, they must be moved away from the surface to reduce the surface-particle adhesion force. Laser processes have already been successfully used to clean surfaces in fields like nuclear decontamination [4], optics and microelectronics industries [5]. This technique has also been proposed in the ITER context to detritiate co-deposited carbon layer [6].

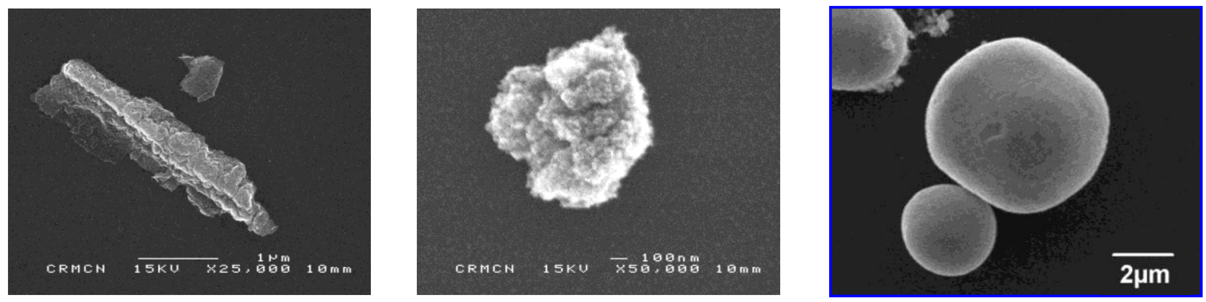
Thus, a lot of studies have already been performed on the laser-induced particle removal, and several mechanisms have been identified. For transparent particles, in low fluence regime, the removal can be due to the explosion of the humidity trapped at the interface between particle and substrate [7]. For higher fluences, the local substrate ablation due to the optical near field enhancement underneath the particles is the dominant cleaning mechanism [8]. Historically, Dry Laser Cleaning (DLC) was explained on the basis of a mechanical ejection resulting from the rapid thermal expansion of the irradiated materials [9]. Then irradiation of absorbing particles can lead to the particle ablation if laser energy is high enough.

The main purpose of this study is the understanding of the laser removal mechanisms of particles generated in Tokamak-like conditions. This step is essential to have the initial knowledge to apply and optimize the laser process for the ITER project. In this purpose, the removal of two kinds of particles is studied, carbon aggregates, and tungsten droplets for several irradiation conditions. Thanks to this work, we have established that although both are absorbing particles, their removal mechanisms are very different and the influence of the laser beam parameters could not be neglected to select the appropriate laser source for this application.

2. Experimental Setup

2.1. Tokamak-like dust generation

The first issue of this study was to produce dusts which can simulate tokamak particles. Thus, the particles used in these experiments were produced by excimer laser ablation of targets in ambient air. We irradiated graphite, or Carbon Fiber Components (CFC) from Tore Supra tiles, and tungsten targets because they are representative of materials eroded in Tokamak. A detailed description of this experimental setup can be found elsewhere [10]. The high energy deposition which can be achieved by short pulse laser irradiation in a substrate leads to the melting vaporization of this material. This induces the formation of plasma containing neutral and excited atoms and molecules. In this plasma, many processes, such as aggregation and sticking, occur which are responsible of the formation of particles and particle aggregates. Laser-induced particles have already been used to simulated dust collected in Tokamaks [11] with very good accuracy [1, 12]. Droplets can also been ejected from liquid layer formed at the surface during the irradiation, leading to the production of smooth particles of micrometer size. These ejected particles are collected on silicon substrate (100) from commercial wafers or UV silica substrate from Laser Components. The following figure shows the typical features of the laser induced particles with some comparison with dust collected in Tokamaks.



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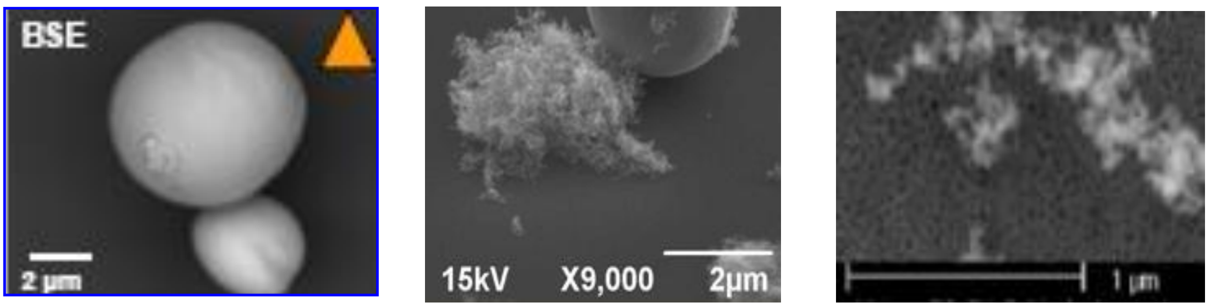


d e f

FIG. 1. SEM images of laser induced particles compared with dusts collected in Tokamaks. Carbon fiber (a), carbon nano-aggregates (b), Tungsten droplets (c) to be compared with W droplets collected in Tokamak (d), Tungsten aggregates (e) to be compared with W foam collected in tokamak (f).

Two kinds of tungsten particles are produced by laser ablation, very thin particles which look like foam, and droplets with size of about 1 to 5µm with very smooth surfaces.The corresponding images of figure 1 show clearly the ability of laser ablation process to simulate both the plasma-induced wall erosion leading to the formation of thin aggregates (fig 1.e and 1.f), and the generation of liquid droplets occurring in Tokamaks during ELMs (fig 1.c and 1.d).

2.2. Particle Removal Efficiency measurement

The understanding of removal mechanisms requires the investigation of the influence of the irradiation conditions on the process efficiency. Then, we performed particles removal efficiency measurements with various lasers: two Nd-YAG sources with 50 ps (Continuum - 1064 nm) and 4 ns (Quantel - 266 nm, 355 nm, 532 nm, 1064 nm) pulse duration, Ytterbium source with 450 fs at 1025 nm (Amplitude System). A metallic mask is imaged by a lens to obtain a near-uniform irradiation of the substrate, set perpendicularly to the beam, beyond 800×800 µm². The characteristics of lens focal, mask and irradiation spot vary with the different source used. All the removal efficiency experiments were performed in ambient air with 5 shots at 1 Hz. The sample is fixed on a long-range motorized translation stage that allows a precise repositioning of the irradiated zone in front of an optical microscope. Then, we can take pictures, before and after the laser irradiation, and determine the number of removed particles (imaging software) to calculate the particle removal efficiency (PRE): PRE $= 1-N/N_0$, with N the number of removed particles and N_0 the initial number of particles. This setup has already been described in [10].

2.3. Particle collection and analysis

A specific setup has been used to collect, on silicon substrate, the ejected particles during the laser removal process. Then, the characterization of the particles morphologies is performed by means of collection substrate observations with scanning electronic microscope. The incident angle between the laser beam and the sample is 45°, and the collector substrate is set parallel, in front of the sample. The substrates are set in a vessel to control the ambient pressure, and the collection distance i.e. the distance between the sample and the collector substrate. Scheme of this setup can be found in [13]. For high resolution analyses of particles and irradiated material, scanning electron microscopy (SEM-JEOL JSM-6390) was employed.

3. Results and discussion

3.1. Removal of carbon dust

Figure 2 shows that carbon dust pollution is efficiently removed by laser irradiation for a large range of wavelengths, from UV to IR, (Fig.2.a) and pulse durations, from few ns to fs, (Fig.2.b). Whatever the irradiation conditions, fluences higher than 450mJ/cm² induce a removal of more than 80% of the particles. In this case, thermal ablation has already been suggested as the removal mechanism because of their absorption of the laser energy [5, 10]. These results confirm this hypothesis.

The optical absorption properties of carbon do not significantly change with wavelength, and, as shown in figure 2.a, this parameter has no influence on the cleaning efficiency. The carbon particle removal occurs when the temperature reached in the particle is sufficient to damage or vaporize it. Thus, when the irradiation intensity (W/cm²) is high enough to induce such temperature increase, the cleaning process becomes efficient. The pulse duration must be short enough to limit the thermal diffusion length L_D and then the fluences required to ablate carbon dust. Irradiations with pulse durations longer than few hundreds of nanosecond can't guarantee a safe cleaning. Ultra-short pulse lasers can't be used for cleaning applications in Tokamak, but they are of interest to study the physical mechanisms. In such ablation regime, the gap between efficient cleaning and substrate damage is small. This limits the fluence range investigated in ps and fs regime. In conclusion, laser with from nanosecond to tens of nanosecond pulse durations are well adapted for the carbon particles removal

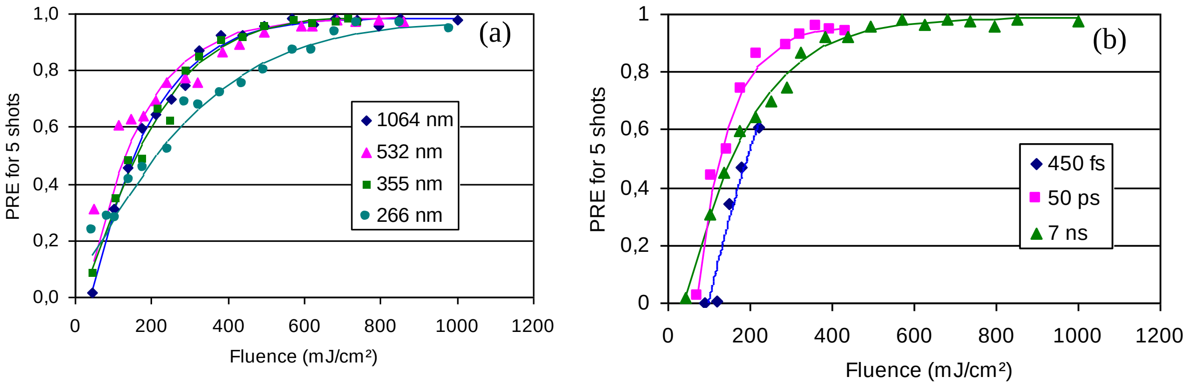


FIG. 2: Removal Efficiency (PRE) of carbon particles, deposited on Si substrate, for 5 shots as a function of laser fluence, for 4 ns pulse duration for different wavelengths (a) and for irradiation in infrared range with different pulse durations (b)

Collection experiments also confirmed that particle ablation is the removal mechanisms for carbon particles. Indeed, almost no intact carbon particles have been collected with the collector setup. We performed these experiments in the most favorable conditions to collect particles on the substrate: we used fluences as low as 380mJ/cm², the ambient pressure was decreased down to 0.1Pa, and collection distance was reduced to 5mm. Despite these conditions, the SEM analysis did not permit to observe any carbon particles on the collection substrate. This is consistent with the thermal ablation process which vaporizes particles, leading to gas phase products and very small nanoagregates (> 10 nm). To avoid their redeposition, these ablation products have to be collected; a suction device seems to be the best solution for our application.

Some efficiency measurements have also been done with carbon particles originating from the scratching of Tore Supra CFP. These dusts are larger (up to 20 µm) than our home-made particles. However, laser irradiation allows reaching more than 80% of removal efficiency. Large particles are first fragmented, and then these fragments are completely ablated.

3.2. Removal of tungsten dust

In this study, we only investigated the removal of tungsten droplets of few micrometers of diameter. Figure 3 presents the PRE measurements for such particles as a function of wavelength and pulse duration. Unlike the results obtained with carbon, these irradiation parameters have a strong influence on the process efficiency. In UV range, the PRE reach 85% whereas in infrared range the maximum PRE value is about 20%. The absorption coefficient and the absorbtivity ($A = 1\text{-}R$, R is the reflectivity) of tungsten slightly decrease with the wavelength but this decrease is too weak to explain this difference observed in figure 3.a. This suggests that the removal mechanism of the tungsten droplets is not the particle ablation. This is also confirmed by numerical simulations of laser ablation, based on the resolution of heat equation, which demonstrate that UV irradiation at fluences leading to the particle removal cannot induce a sufficient temperature increase to vaporize the tungsten particles [14]. The SEM observations of ejected particles show that tungsten droplets are removed from the substrate without any modifications of their morphology. These results confirm that thermal ablation is not the removal mechanism of tungsten droplets.

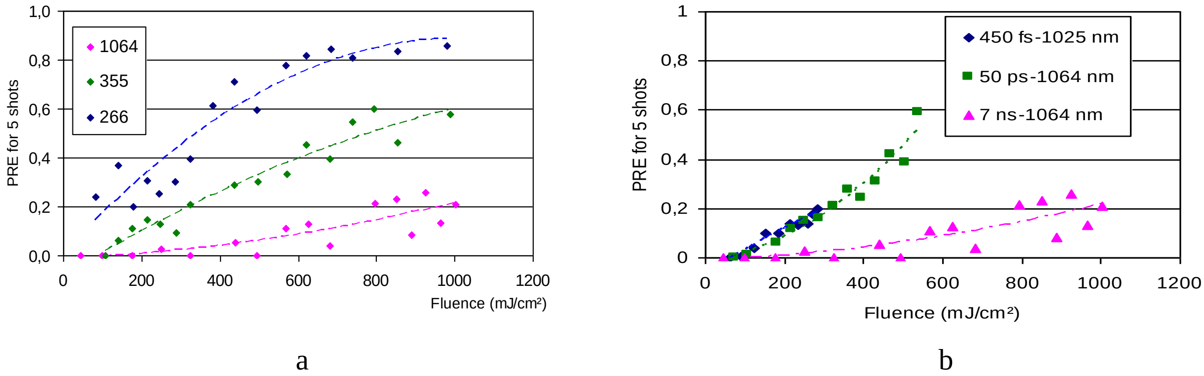
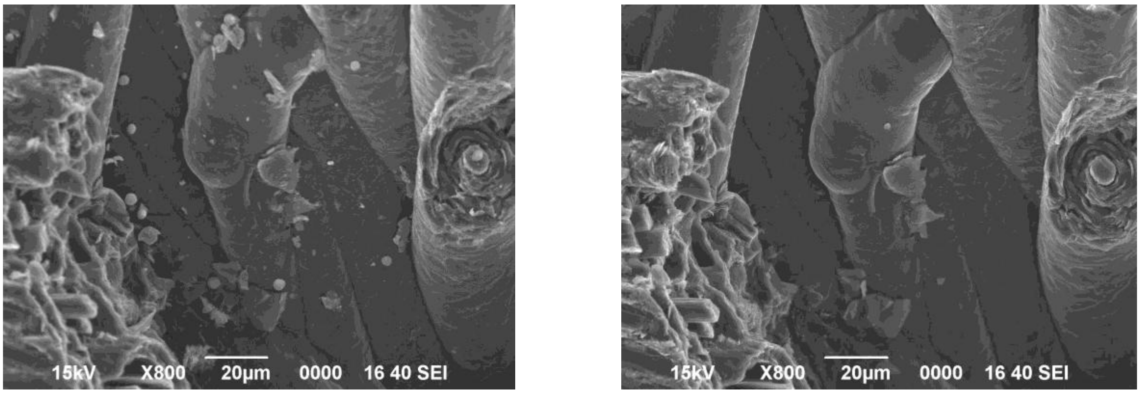


FIG. 3: Removal Efficiency (PRE) of tungsten particles, deposited on Si substrate, for 5 shots as a function of laser fluence, for 4 ns pulse duration for different wavelengths (a) and for irradiation in infrared range with different pulse durations (b)

The numerical model we developed to calculate the tungsten temperature when a particle is irradiated, also shows that in our conditions the temperature of the bottom part of the particle, and then the surface underneath the particle, does not exceed 600 K. This increase is not high enough to induce a fast expansion of the surface, and then, this mechanism cannot explain the droplet ejection. The SEM observations of the sample after the irradiation show that the substrate under the particles is not affected by the laser beam. That means that local ablation of the substrate due to near field enhancement under the particle is not the origin of the removal. This has also been confirmed by FDTD optical simulations. The droplet protects the interface of any thermal or optical interactions. Consequently, all the interface mechanisms can be eliminated as removal mechanisms because the amount of energy in this interface is not significant enough to expand materials, or ablate the substrate or induced the explosive evaporation of the trapped humidity.

All the removal mechanisms previously observed in other studies cannot explain the ejection of tungsten droplets. Then, we have to find out other mechanism to interpret our results. The role of laser parameters on removal efficiency provides information about the removal mechanism. We have seen that the wavelength has a great influence on the droplet removal efficiency (Fig. 3.a), then we can assume that photon energy is primordial in the removal mechanism of tungsten droplets: high photon energy is required to eject metallic droplets. On figure 3.b, we can see that in infrared range, the use of ultra-short pulse durations significantly increases the removal efficiency. This shows that multiphotonic processes, which appear in these ultra-short regimes, have beneficial effects on the removal. Both observations suggest that the removal mechanism is linked with photoelectrons. Indeed, in both cases, the energy of the photons transferred to the electrons of the material before the electronic relaxation, is high enough to overcome the work function of tungsten, and then to extract photoelectrons. These photoelectrons are slow down and stop in surrounding gas (in our case ambient air) in the first few hundred of nanometers (mean free path ~ 130 nm). They could produce negative oxygen ions and generate an electrostatic force between the particles, positively charged and the plasma above it containing negative species. This phenomenon seems to be at the origin of an electrostatic force stronger than the adhesion forces (Van der Walls), and then induces the particle ejection. Numerical simulations and experiments with others metal, with different work functions, have confirmed these hypotheses [15].

Laser cleaning experiments have also been performed with tungsten droplets deposited on a CFC tiles from Tore Supra reactor. The purpose is to validate first that dust can be ejected from complex surfaces like carbon fibers, and then that the process does not damage such substrates used in Tokamak. Tungsten dusts have been deposited on CFC tiles by laser ablation. We can seen on figure 4.a both W droplets and some other small particles, probably carbon. The sample has then been irradiated with five shots of a KrF laser beam (λ=248nm, τ=27ns) at 500mJ/cm². Figure 4.b presents the same area after the irradiation. We can see that most of the particles have been removed, whatever their position of the fiber based substrate (edge or bottom). We can also notice that within the accuracy of the SEM measurements, no substrate damage can be observed.



a b

FIG. 4: SEM pictures of tungsten dust on CFC tile from tore Supra reactor before (a) and after (b) laser irradiation with KrF laser (5 shots, 500mJ/cm²).

3.3. Removal of dust from castellation

A second laser-based physical process has been investigated in the frame of this study to mobilize the dust. This technique exploits the ability of the pulsed laser to generate a shock wave. It is currently named Laser-Induced Shock Wave Cleaning (LSC), and has been previously used to remove particles from microelectronic compounds by focusing the laser beam in air above the surface [16]. Indeed, the focalisation of a short laser pulse in gas or on a surface induces the fast heating of a small volume of gas and then the generation of a shockwave. Its fast expansion allows blowing the dusts. The divertor is a castellated surface with grooves of about 1mm width and 10mm deep. The plasma achieves a strong erosion of this divertor and the dust fall down into these grooves. Particle removal from these castellations is one of the major concerns for the ITER safety.

To simulate carbon dust trapped in castellations, we built a small plexiglass cell with a groove similar to those used in a divertor (1 mm x 10 mm) and we filled it with carbon particles of micrometer sizes (courtesy of Toyo Tanso). The height of the particle deposit was 3mm and the bottom of the groove was a SiO_2 plate. The laser was operated at 10Hz and the beam irradiated the groove with an angle of incidence of 45°. A mirror was used to move the beam along the surface. Figure 5 shows six pictures illustrating the removal process generated by the laser-induced shock waves. On Fig 5.a, we can observe the cell and the carbon dust through the Plexiglas wall of the groove. Laser beam is indicated on the right hand side of the cell. The following images show that, as soon as the laser reaches the beginning of the groove, the shock wave is guided into it and blow the particles out of the castellation. Some of the carbon dust flew over the cell, but the largest part fall down at the other end of the groove. The particle motion is clearly induced by the shock wave because there is no direct interaction of the laser beam with dust. On the Figure 5.f, we can observe that all the particles are blown away from the castellation before the laser beam reaches the third of the groove length. Due to the particular shape of a gap, all the shock wave energy is concentrated into this groove. In this specific geometry, such process is then, very efficient and well adapted to move dust from hot to cold area.

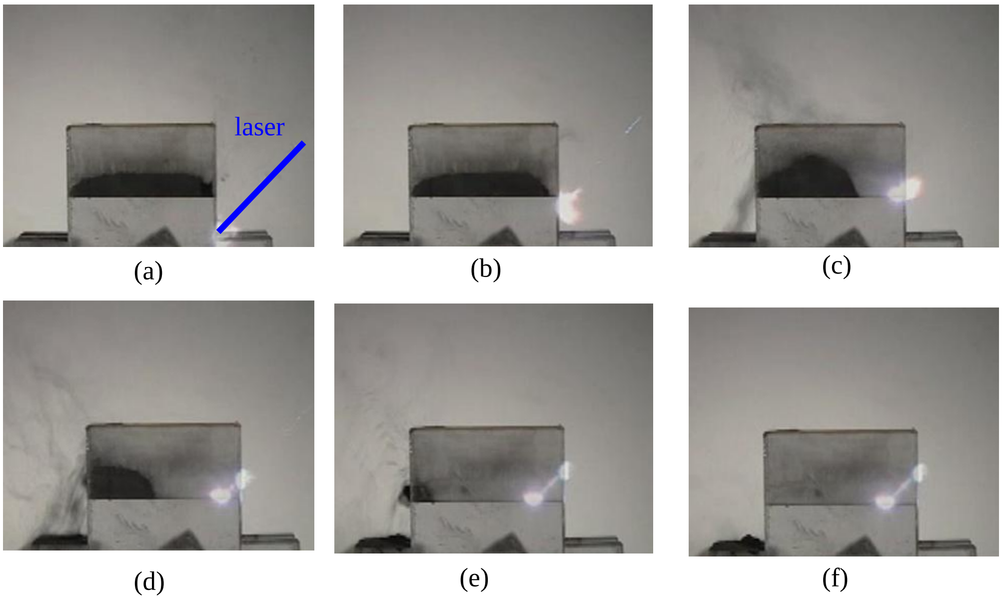


FIG 5. Images of the removal of C particles from castellation (1mm width, 10mm deep, 20mm long).

4. Conclusion

In this paper, the DLC and LSC techniques have been described and investigated to evaluate their ability to be applied in a fusion reactor context for dust mobilization. The removal mechanism of carbon particles is confirmed to be the particle ablation due to the direct beam absorption. A new mechanism is proposed to explain the ejection of metallic particles, as tungsten, without modification of their morphologies. High energetic photons or multiphotonic processes strongly improve the removal efficiency, and we assume that electrostatic forces induce by photoelectrons emission is the origin of this mechanism.

Both laser cleaning processes appear to be very effective at the laboratory scale. DLC unsticks more than 80% of W dust when using an UV laser at short pulse duration (<10ns) associated with a suction system, and it could be a reliable collection tool to control the dust in vessel inventory. Using LSC technique permits to clean easily castellations from carbon particles which are blown from one place to another. However, their integration in a fusion device seems to be rather complex. This is due to the fact they need to use a scanning system not easily implementable in a port plug. In order to treat large and complex surfaces as it is foreseen in ITER, it seems judicious to embark the laser cleaning tools in a Remote Handling system able to carry and protect the laser and the collection system.

5. Acknowledgements

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