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A.L. Roquemore, B. John, F. Friesen , K. Hartzfeld, D.K. Mansfield

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Techniques For Injection Of Pre-Charaterized Dust Into The Scrape Off Layer Of Fusion Plasma

A.L. Roquemore[a], B. John[b], F. Friesen[c] , K. Hartzfeld[d], D.K. Mansfield[a],

[a] *Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton New Jersey, 08543*
[b] *Swarthmore College, 500 College Avenue. Swarthmore, Pennsylvania, 19081-1390*
[c] *Grinnell College, Grinnell, Iowa 50112-1690*
[d] *Toms River High School, Toms River, NJ, 08753, USA*

Corresponding Author: lroquemore@pppl.gov

Introduction of micron-sized dust into the scrape-off layer (SOL) of a plasma has recently found many applications aimed primarily at determining dust behavior in future fusion reactors. The dust particles are typically composed of materials intrinsic to a fusion reactor. On DIII-D and TEXTOR [1] carbon dust has been introduced into the SOL using a probe inserted from below into the divertor region. On NSTX, both Li and tungsten dust have been dropped from the top of the machine into the SOL throughout the duration of a discharge, by utilizing a vibrating piezoelectric based particle dropper [2]. The original particle dropper was developed to inject passivated Li powder ~ 40 μm in diameter into the SOL to enhance plasma performance. A simplified version of the dropper was developed to introduce trace amounts of tungsten powder for only a few discharges, thus not requiring a large powder reservoir. The particles emit visible light from plasma interactions and can be tracked by either spectroscopic means [3] or by fast frame rate visible cameras [4]. This data can then be compared with dust transport codes such as DUSTT [5] to make predictions of dust behavior in next-step devices such as ITER. For complete modeling results, it is desired to be able to inject pre-characterized dust particles in the SOL at various known poloidal locations, including near the vessel midplane. Purely mechanical methods of injecting particles are presently being studied using a modified piezoelectric-based powder dropper as a particle source and one of several piezo-based transducers to deflect the particles into the SOL. Vibrating piezo fans operating at 60 Hz with a deflection of ± 2.5 cm can impart a significant horizontal boost in velocity. The highest injection velocities are expected from rotating paddle wheels capable of injecting particles at 10's of meters per second depending primarily on the rotation velocity and diameter of the wheel. Several injection concepts have been tested and will be discussed below.

Keywords: Dust, scrape-off layer, DUSTT transport, spherical tokamak

1. Introduction

Dust in future tokamak fusion devices has become a major issue from both the performance and safety aspect. Tracking of pre-characterized dust in present day devices allows verification of dust transport codes such as DUSTT to predict the impact dust will have on future devices such as ITER. Information on edge plasma flows can also be obtained from these images. To date, a number of devices have introduced dust into tokamaks either by dropping dust into the scrape-off layer from above[4] or by placing dust on the end of a probe at the bottom of a vessel and sweeping the strike-point over the probe location[1]. No method has been developed that will inject the dust horizontally into the SOL from either the midplane or divertor locations. One of the main problems with any injection device is that it must operate in a vacuum with high magnetic fields and a harsh noisy environment complicating the use of electromagnetic devices to inject or release dust. We have tested several devices based on piezoelectric transducers that perform well in the harsh environments of present day tokamaks.

In reference 2, a piezo-based particle dropper is discussed, that can supply a well-regulated stream of dust particles. This device is used in most of the concepts discussed here either as a direct injector of particles from the top of the machine or as a source of particles for other devices.

This paper discusses various concepts for introducing pre-characterized dust into the SOL by dropping from above or propelling the particles horizontally, preferably from a midplane location. Also, a method is discussed to levitate dust particles vertically upward from the divertor region without the need for sweeping the strike point. Each of the methods should be non-perturbing to the plasma. The primary diagnostic for dust studies is two fast cameras taking 2-D images of excited dust particles emitting in the visible or IR range. The 2-D images are then combined to construct 3-D trajectories of dust particles using techniques similar to those developed at Florida International University [6].

2. Introducing dust into the upper SOL

Lithium introduced into tokamak plasmas was first shown to enhance plasma performance on TFTR [7]. A recent innovation in the manufacturing of micron-size stabilized Li powder [8] spurred the development of a piezo-based powder dropper at PPPL, which has successfully been used to introduce Li powder into the SOL of NSTX. Only a brief description of the instrument is given here since it is described in reference 2. A 63.5 mm diameter piezoelectric disk with a 2.5 mm diameter aperture in the center, is mounted at the bottom of a reservoir containing up to 50 grams of the desired powder. AC voltage typically, from 1-20 Volts and at a resonance frequency of 2.25 kHz, is applied across the disk, causing it to vibrate. The vibration dislodges the particles and causes the powder to fall through the aperture. By controlling the amplitude of the vibration, the amount of powder that falls can be regulated from a few tens of particles per second up to the saturation point of the disk aperture where the amount of powder dropped is limited by the diameter of the aperture. A throttle, consisting of a cylindrical skirt just above the aperture helps to regulate the amount of powder that is dropped. In the case of Li powder, it was necessary to drop amounts of Li in excess of 120 mg per discharge to enhance the plasma performance. This constitutes approximately $5.0X10^{-6}$ Li spheres, a number far too large to track with cameras successfully. Also, large amounts of dust have been predicted to affect the edge parameters [10]. This has been verified in recent Li experiments on NSTX and will be the topic of a future publication.

For dust studies, only a very small number of particles need to be deposited into the SOL to prevent affecting the edge parameters. Though the Li dropper as developed is capable of introducing very small numbers of particles and has been used to do so, a far simpler device was recently developed that utilizes the same vibrating disk but only has the total capacity of ~ 0.5 – 1.5 grams. This amount far exceeds the required inventory. Fig. 1 shows the assembly of the simplified dropper. The piezo disk is sandwiched between two larger disks of PEEK each 6.3 mm thick with clamping o-rings securing the transducer edge. A fine mesh screen over the transducer aperture is used to support the desired powder. The mesh size is dependant on the size of particles injected. Our goal was to inject tungsten particles with a mean diameter of 10 μm. This required the testing of a range of mesh sizes looking for an amount that inhibits the particle flow when the disk was at rest, but freely passed the particles when the disk vibrates. We tested a range of mesh sizes with openings from 12-40 μm for the 10 μm particles. We found that the larger 40 μm opening was required for the tungsten particles. This is due in part to the irregular shape of the particles that more easily form clogs at the aperture. We assume that spherical particles would require smaller relative mesh sizes to arrest the particle flow when the transducer is at rest. This compact powder dropper was successful in dropping a stream of 10μm particles continuously throughout an NSTX discharge. Both Li and tungsten particles were tracked with two fast cameras and the results are discussed in reference 4.

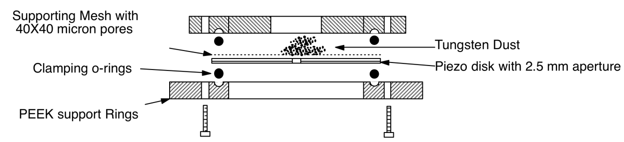

Fig. 1 Impurity dust injector used to release trace quantities of tungsten dust into the SOL of NSTX

Each of the powder droppers on NSTX are located ~1 m above the plasma SOL and have proven to be an excellent way to introduce a vertical stream of particles into the plasma edge. At the end of one of the flight tubes an angled 45° deflector plate was included which imparted a horizontal component to the particles driving them inboard toward the NSTX center column.

3. Piezo fans

Piezo fans are often used to cool electronic components. These fans provide simple forward-backward oscillation. We have tested in the lab, a commercial variety operated by standard 110V AC line voltage from Piezo Systems to determine if this could impart significant horizontal velocity to dust particles.

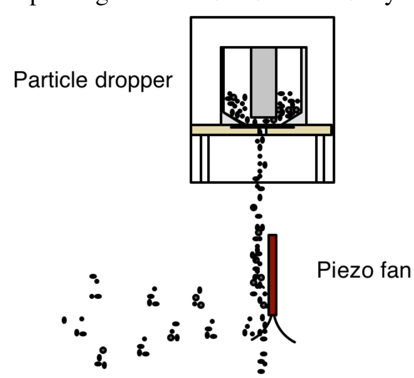

Fig. 2 Schematic of the piezo fan and particle dropper

This unit has a transducer that is 1.5 mm thick by 12 mm wide by 40 mm long. A mylar extension is epoxied to the transducer to increase its length to 75 mm. The piezo fans is plugged directly into a standard 110V outlet and will oscillate at the standard AC frequency of 60Hz. The tip of the mylar has a range of motion of ± 12.7 mm at full voltage. Experiments with glass beads have confirmed that the piezo fan will launch particles at

maximum horizontal velocities of ~2m/s. It is used in conjunction with the powder dropper as a particle source as shown in Fig 2., where the stream of particles are aligned to pass in close proximity to the front of the fan.
Because of the parabolic curvature of the fan blade, the particles are actually dispersed in a fairy broad range of angles and velocities. Because of the broad range of particle paths, it would be best to locate the fan arrangement as close to the plasma edge as possible. A distance of 30 cm appears be optimal. One of the funnel arrangements described in section 5 would reduce the spread considerable.

4. Particle levitation

Probes have been used on several tokamaks to insert dust into the divertor region. Typically, dust is preloaded onto a probe head and inserted into the divertor. The strike point of the plasma is then swept across the probe head, dislodging the particles and transporting them into the divertor SOL. The dust will readily ablate and if atoms in the ablation cloud are ionized, spectroscopic techniques are used to detect the ions in the core. This is an excellent method to study particle transport from the divertor into the plasma core.

A variation on the technique is being developed whereby the probe head is replaced with a vibrating piezo disk identical to the one used in the powder dropper but without the central aperture. Laboratory tests with 40 μm diameter glass beads placed on top of the disk have confirmed that the vibrating disk is capable of levitating the particles up to at least 30 cm above the surface. A fast camera was employed to determine a crude distribution of particle heights above the disk as a function of applied voltage to the transducer as shown in Fig. 3.

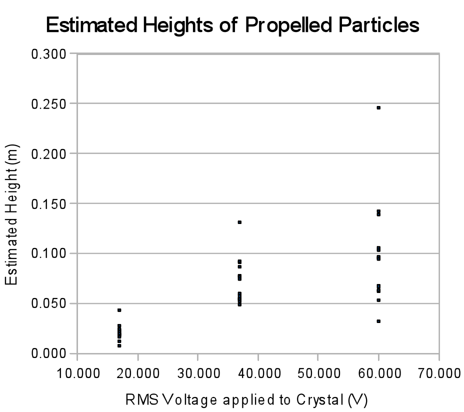

Fig. 3 Height distribution of particles levitated above the transducer surface as a function of applied voltage.

For the medium voltages of 60 Volts, the majority of particles were propelled from 5-10 cm above the transducer and about 1% of the particles were elevated up to 30 cm. The transducer can be used at voltages up to ±180 volts. At the highest voltage, the transducer is specified to deflect approximately ±0.5 mm. This concept has only been tested to ±60 volts but we estimate that at maximum voltage, the majority of particles should attain heights of 15-20 cm. Note that in these experiments, very few particles remain on the disk after the initial full second of operation.

Utilizing this technique to supply particles into the divertor SOL requires having a port in the desired region as well as a probe capable of introducing the instrument to within a few millimeters of the surface of the divertor tiles.

5. Rotary Paddle wheel

To date, dust has not been introduced horizontally into the midplane SOL in any machine. Horizontal dust injectors based on electrostatic acceleration have been proposed [8] but the velocities of these have been typically too high to make measurements in the SOL. In addition, a gas is introduced with the particles into the plasma edge that may affect the edge region being diagnosed.

A rotary paddle wheel injector that works in conjunction with the powder dropper to inject particles horizontally at fairly high velocities has been developed. The dust velocity is a function of the paddlewheel diameter and rotation velocity. With a fairly compact wheel of 14 cm and a rotary motor capable of at least 20 revolutions/sec, velocities of 7.5 m/s can be easily achieved. Much higher velocities have been obtained but are not required and are considered to be unnecessary for studying the behavior of intrinsic dust in the SOL.

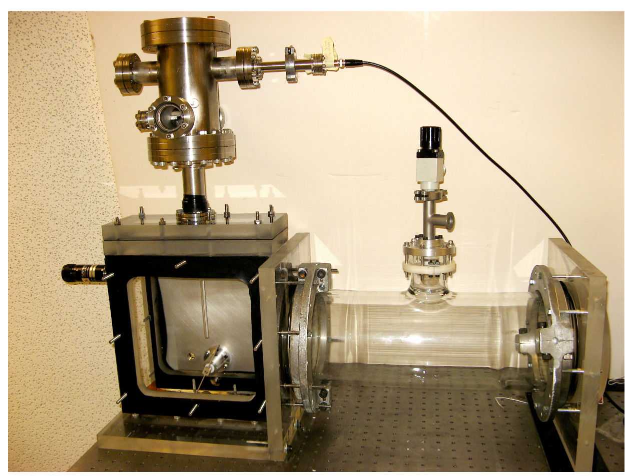

Fig. 4 Photo of paddle wheel enclosure and target chamber. The dropper releases dust approximately at the axis of the wheel.

Initial testing of two candidate paddle wheels has been performed. One is a commercial fan wheel with 10 flat blades each 7.3 cm long as measured from the axis of rotation. The second is a two bladed paddle made of PEEK with the same overall dimensions. A Plexiglas vacuum chamber 30cm high x 30 cm long by 7.5cm wide was constructed. A cylindrical glass target chamber is attached to the front that is 50 cm long and 15 cm diameter. The paddle wheel is located in the Plexiglas section so that the top of the wheel is just below the center of the chamber. A powder dropper is located on top of the chamber just above the axis of the wheel so that dust contacted by the wheel would, on average, travel in a horizontal direction. A photo of the chamber and the two-bladed paddle are shown in Fig. 4. A stepper motor and multiplying gear train were utilized in conjunction with a high-speed vacuum feed through, to achieve initial rotation results. When rotated at 20 rev/s, horizontal dust velocities equal to the blade velocity, of 7.5 m/s are achieved as measured by a fast framing camera. By adjusting the position of the particle stream with respect to the wheel axis, a position has been found where the majority of particles are launched in a predominantly horizontal direction, though significant scatter occurred. If the particles must be launched for a distance of ~1m it is important to reduce this scatter. In order to be propelled forward, the particles must not collide with each other as the paddle wheel contacts them. In order to minimize inter-particle collisions, the stream of particles should be in the shape of a vanishingly thin sheet. Since a true monolayer is unattainable, the thinnest possible sheet is sought. The dropper creates a column of particles with a circular cross section of ~ 4mm, which induces inter-particle collisions. Two separate devices were constructed and tested to constrict the falling column into a thin sheet.

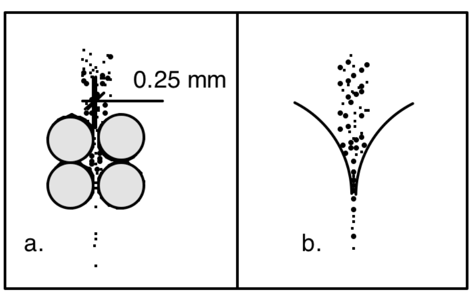

Fig 5. Panel a. shows 4 each 10 mm diameter by 50 mm long cylinders with a 0.25 mm spacing for dust particles to flow through. Panel b. shows a stainless sheet curved to form a funnel also with 0.25 mm spacing at the bottom.

The first, as shown in Fig 5a is comprised of two pairs of solid cylinders, with the particles falling through the narrow opening in the middle of each pair. The optimum spacing of the cylinders that would prevent particle jams using the 40μm glass beads was about 0.25 mm. The second device shown in Fig 5b was made from two thin stainless steel sheets also separated by 0.25 mm at the bottom and bowed outwards at the top to form a funnel. Measurements confirmed that the cylinders created a slightly thinner sheet and thus should allow the paddle wheel to hit more particles in the desired forward direction. The improvement in scatter from the paddle wheel must await the availability of the fast framing camera.

6. Conclusion and future work

A number of concepts have been investigated that inject dust into the SOL of plasmas to study dust behavior with the primary goal of verifying dust transport codes. Two versions of the dust particle droppers have been successfully employed on NSTX and hundreds of trajectories using fast cameras have been obtained. Additional injection techniques discussed above have been verified to work in the laboratory and are viable candidate dust injectors. Two devices are capable of horizontal midplane particle injection. Also under design, is a more compact particle dropper that employs a 3 cm diameter disk as opposed to the 6.3 cm diameter transducer currently utilized. The present model only requires ±20 volts out of the ±180 volt specified limit and has an associated displacement of order ±40μm. This same displacement is well within the range of the smaller piezoelectric transducers. A more compact version of the dropper could greatly increase the versatility of the dust injector techniques where space limitations are and issue.

7. Acknowedgments

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Princeton Plasma Physics Laboratory
P.O. Box 451
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