Electrostatic Dust Detection and Removal for ITER

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Abstract: We present some recent results on two innovative applications of microelectronics technology to dust inventory measurement and dust removal in ITER. A novel device to detect the settling of dust particles on a remote surface has been developed in the laboratory. A circuit board with a grid of two interlocking conductive traces with 25 μm spacing is biased to 30 – 50 V. Carbon particles landing on the energized grid create a transient short circuit. The current flowing through the short circuit creates a voltage pulse that is recorded by standard nuclear counting electronics and the total number of counts is related to the mass of dust impinging on the grid. The particles typically vaporize in a few seconds restoring the previous voltage standoff. Experience on NSTX however, showed that in a tokamak environment it was still possible for large particles or fibers to remain on the grid causing a long term short circuit. We report on the development of a gas puff system that uses helium to clear such particles. Experiments with varying nozzle designs, backing pressures, puff durations, and exit flow orientations have given an optimal configuration that effectively removes particles from an area up to 25 cm^2 with a single nozzle. In a separate experiment we are developing an advanced circuit grid of three interlocking traces that can generate a miniature electrostatic traveling wave for transporting dust to a suitable exit port. We have fabricated such a 3-pole circuit board with 25 micron insulated traces that operates with voltages up to 200 V. Recent results showed motion of dust particles with the application of only 50 V bias voltage. Such a device could potentially remove dust continuously without dedicated interventions and without loss of machine availability for plasma operations.

1. Introduction

The increase in duty cycle and erosion levels in next-step devices will cause a large scale-up in the amount of dust particles produced [1,2]. This has potential safety consequences as the dust particles may be radioactive from tritium or activated metals, toxic, and/or chemically reactive with steam or air. The radiological and/or toxic hazard of dust depends on how well it is contained in accident situations and whether it is small enough to remain airborne as an aerosol and be respirable ($< \sim 10\ \mu$m). The tritium content of dust will depend strongly on whether it originates from crumbling codeposited layers, or under thermal overload of tritiated layers by off-normal events. Dust that is produced during ELMs and disruptions may be heated sufficiently to outgas tritium as T_2 reducing the radiological hazard of the dust. The D content in dust retrieved from TFTR MIRI diagnostic windows [3] was measured to be D/C $\approx 5.8\times10^{-3}$ and the T/C ratio was 26$\times$ lower, as expected from the T/D fuelling ratio. Baking of 0.24 g of flakes from TFTR codeposits at 773 K for 1 h released 0.72 Ci or 75 μg of tritium, a T/C ratio of 3×10^{-4} [4] broadly consistent with the dust results. A low H/C ratio of 0.04 was found in dust from JT-60[5] and interpreted in terms of high wall temperatures. In contrast, ion beam analysis of JET flakes showed a D/C ratio of 0.75 [6], which is about two orders of magnitude higher than the TFTR deuterium fraction.

While the tritium content of dust may be reduced from that in codeposited layers, tritium bound to metal or carbon particles can have a much longer residence time in the human body (and concomitant radiation dose) than the 10 d biological half life of HTO. A study of the dissolution rate of carbon tritide particles from TFTR in simulated lung fluid found that >90% of the tritium remained in the particles after 110 d [7]. A further complication with tritiated dust is that it can self charge through the emission of beta electrons and spontaneously levitate in electric fields [8]. Such levitation was observed experimentally in tritiated particles retrieved from TFTR [9] and adds to the challenge of confining dust in accident situations.

Typically the highest concentrations of dust in contemporary tokamaks are found in the lower part of the vacuum vessel. The particle size distribution of dust most often follows a log-normal distribution with a count median diameter ranging from 0.46 μm [10] to 9.6 μm [11], i.e. is respirable. Nano-scale particles have been observed in Tore Supra [12] and TEXTOR [13]. Particles generated by the SIRENS disruption simulator have count median diameters smaller than found in tokamaks (0.1 μm in ref. [14]) and this can be understood by modeling of the condensation of a vapor cloud [15]. The QSPA disruption simulator facility produced a significant number of nano-scale particles together with particles of $0.1 - 3$ μm [16]. The physics of dust in magnetic fusion devices has been recently reviewed in ref. [17] and techniques for dust measurements in tokamaks described in ref. [18].

Dust issues came under scrutiny in the 2007 ITER design review and a task force was formed to develop a strategy for managing in-vessel dust and tritium in ITER. The resulting integrated approach to dust and tritium inventory control is described in ref. [19]. A 1000 kg inventory of dust inside the ITER vacuum vessel is used as a basis for safety assessments. Dust inventory measurement will be based on global erosion measurements, coupled with local dust measurements. The actual dust inventory will be maintained below 670 kg taking into account measurement uncertainties, estimated to be 330 kg. In addition, smaller quantities of dust on hot surfaces are important in potential chemical reactions that could lead to vessel overpressure events. Significant quantities of hot dust are 6 kg of Be, C, and W dust, or, if carbon is not present, 11 kg of Be and 77 kg of W dust. A full strategy for hot dust has not yet been completed as these levels of dust are quite low and the uncertainties in measurements high. Vacuum cleaning with a remote handling tool is foreseen for periodic dust removal.

Diagnostics to provide assurance that ITER is in compliance with its dust inventory limits need development. A separate challenge is demonstrating techniques that could remove dust from the tokamak, once the limits are approached. We present some recent results on the application of microelectronics technology to provide innovative solutions to these issues.

2. Electrostatic Dust Detector:

A novel device to detect the settling of dust particles on a remote surface has been developed in the laboratory. A grid of two closely interlocking conductive traces on a circuit board is biased to $30 - 50$ V. Miniature sparks appear when test particles, scraped from a carbon fiber composite tile, land on the energized grid and create a transient short circuit. Typically the particles vaporize in a few seconds restoring the previous voltage standoff. The transient current flowing through the short circuit creates a voltage pulse that is recorded by standard nuclear counting electronics and the total number of counts is related to the mass of dust impinging on the grid. The device works well in both atmosphere and in vacuum environments. The sensitivity has been enhanced by more than an order of magnitude by the
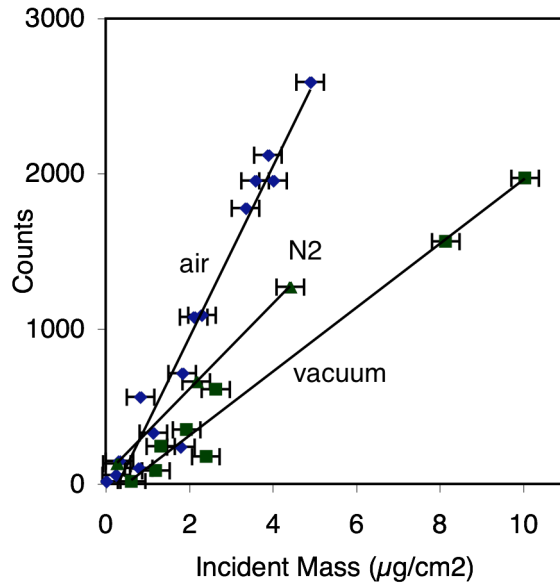
Fig. 1. Response of 51 x 51 mm grid in air
(diamond), nitrogen (triangle) and vacuum
(square points). The lines are least squares
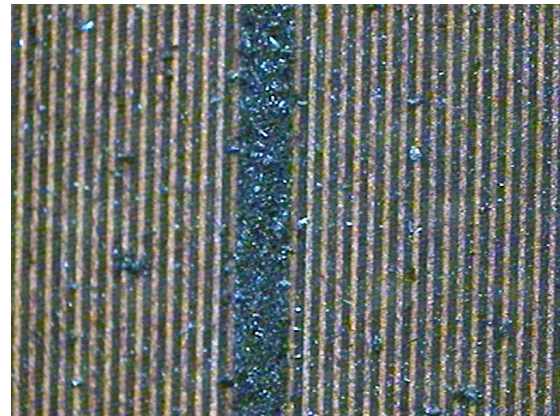fits to the data (from Ref. [21]).

Fig. 2. Image of circuit grid with one trace
open circuit. Incident dust particles are
largely absent from the energized traces, in
contrast to the high density of dust remaining
along the open circuit trace. The trace width is
50 μm (from Ref. [20]).

use of ultrafine grids with 25 μm spacing between the traces (Fig. 1). The response to particles of different size categories was compared and the sensitivity, expressed in counts / areal density (mg/cm^2) of particles, was maximal for the finest particles. This is a favorable property for tokamak dust which is predominantly of micron scale. Larger particles produce a longer current pulse, providing qualitative information on the particle size. The short circuit is temporary and the fate of the dust particles has been tracked by measurements of mass gain / loss. Heating by the current pulse caused up to 90% of the carbon particles to be ejected from the grid or vaporized (Fig. 2) [20]. Further work is needed to increase the ruggedness of the device for particles of refractory metals.

Demonstrations of real time measurements of dust on surfaces in contemporary tokamaks are challenging because of the comparatively low dust levels. For example, the average flux of dust in the National Spherical Torus Experiment (NSTX) that accumulated on a glass slide was 5.6 ng/cm^2/discharge, a level below the first detector sensitivity of 36 ng/cm^2/count [20]. Experiments with microgram quantities of dust and a large area (51 x 51 mm) grid showed a doubling of sensitivity and linear response down to the lowest measurable masses[21]. Most recently we have optimized the detection electronics by removing a low pass RC filter and lowering the setting of a single channel analyzer from 400 mV to 50 mV and this has further increased the sensitivity of the detector by two orders-of-magnitude [22].

3. Tokamak application.

As with many diagnostics there are challenges in the transition from the laboratory to the routine application of this device in a tokamak. There are a wide variety of potential sources of dust particles in a tokamak – particles and fibers from tiles, glass fibers used to insulate wires, particles of insulation and debris from maintenance activities. The electrostatic dust detector was installed on NSTX and large signals were obtained that correlated with
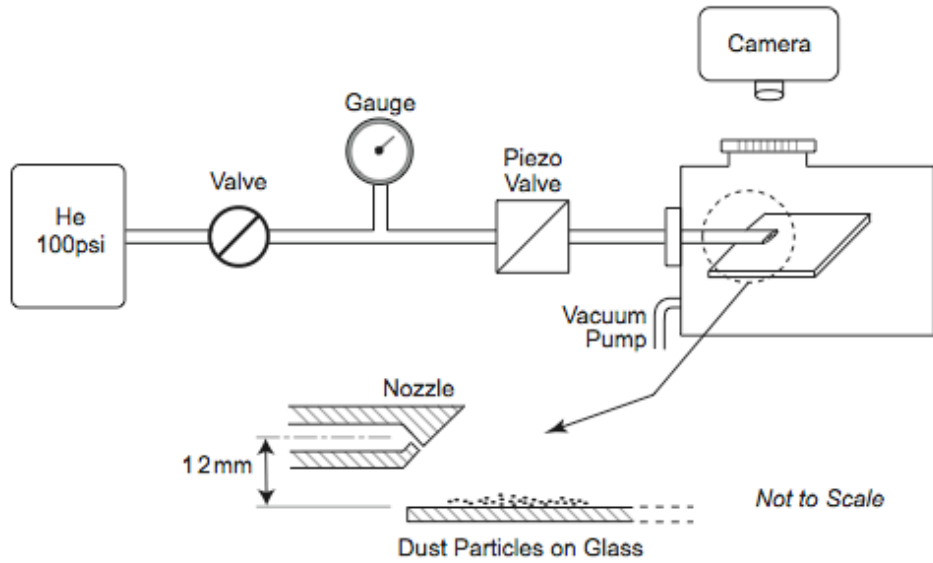
Fig. 3 Gas puff system (not to scale).

observations of visible dust by fast cameras following transient plasma contact with the RF limiter. However unambiguous identification of the signals as being due to dust needs further work to discriminate against potential electrical pickup by the high sensitivity detector. A second issue is that in NSTX some particles were incident on the grid that were not ejected or vaporized causing a long term short circuit. In some cases these could be cleared by repeatedly connecting and disconnecting the voltage bias, presumably because the capacitors in the power supply can deliver a transient high current pulse that can vaporize or eject the particles. After retrieval from the tokamak some residual particles were observed remaining on the grid. To facilitate a more rapid recovery we have developed a gas puff system that will be applied to clear these particles in the tokamak.

The experimental setup is shown in Fig. 3. A plenum volume of 31 cm^3 was pressurized with helium. A Veeco PV10 piezo valve was then actuated and the helium flowed to a further volume of 10 cm^3 that was terminated by a nozzle. The resulting gas puff was incident on particles on a 7.5 cm x 7.5 cm glass plate that was either in air or in a vacuum chamber that was evacuated to 1 mTorr. Trials with varying backing pressures (40 – 100 psi), piezo valve operating voltage (up to 170 V) and pulse duration (250-1000 ms), nozzle diameter (0.34 – 1.0 mm), angle of incidence (0, 45° 90°) and distance (6.4 mm – 38 mm) from the nozzle to the plate showed that a single 170 V 500 ms pulse applied to the valve with a 0.34 mm diameter nozzle, 12 mm from the plate and aimed at a 45° angle was the most effective in clearing the carbon, tungsten, glass and sand trial particles. The amount of helium used was
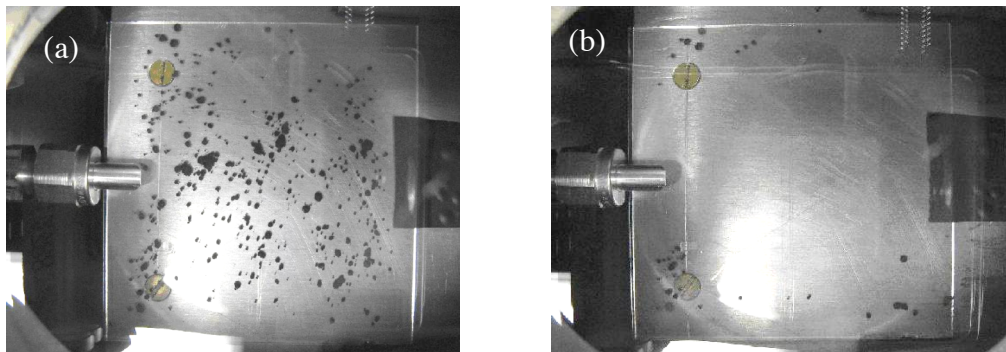

Fig. 4 Top view of 7.6 cm square glass plate with carbon particles (a) before and (b) after application of a single helium puff in vacuum. An area of 4 cm x 4 cm was cleared.
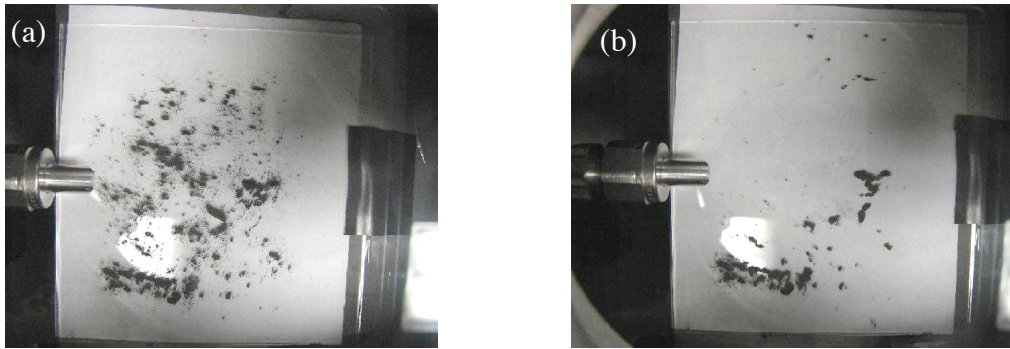
Fig. 5 Top view of 7.6 cm square glass plate with 12 μm tungsten particles (a) before and (b) after application of a single helium puff in vacuum. An area of 3 cm x 3 cm was cleared.

63 torr-liter (8.4 Pa m^3), similar to that used to fuel NSTX. The carbon particles were scraped from a carbon tile and were in the 5-20 μm sieve category as described in ref. [23]. Images before and after helium puffing in vacuum were taken through a viewport with a digital microscope (high resolution) and a digital camera (large field of view). Fig. 4 shows a 4 cm x 4 cm area of carbon particles cleared. Some adhesion of the available 12 μm tungsten particles to the glass was experienced, but nevertheless a 3 cm x 3 cm area of tungsten particles was cleared (Fig. 5).

4. Electrostatic Dust Transporter System

Once dust levels approach the maximum allowed value, dust removal will be necessary before plasma operations can continue. Vacuum cleaning with a remotely operated multipurpose deployer tool is an obvious possibility, however access to hidden areas and the loss of machine availability for plasma operations during cleaning are concerns. Clearly a system that could remove dust without venting the vessel would be very advantageous. Dust particles are typically charged by frictional forces (triboelectric effect) and this charge enables their transport by electrostatic fields. An 'electrostatic curtain' for transporting dust particles was considered in early work at NASA [24] and is being developed for dust removal in future lunar missions [25]. A large-scale electrostatic dust transport system was developed during the ITER EDA [26,27]. This was based on and utilized discrete electrodes biased to ~22 kV and demonstrated the transport of ~1 g dust / min in vacuum. Tests showed that the dust motion was unaffected by a 0.15 T magnetic field. However this system was not implemented on ITER because of its large spatial requirements.

Rapid progress in large-area electronics is opening up new vistas for large scale devices with features that are an appropriate scale length for the electrostatic manipulation of dust. The technology, e.g. flat panel displays, X-ray imagers, solar panels has become ubiquitous. These are made on large surfaces of up to 10 m^2 by microcircuit fabrication technology. The typical micron-scale feature size of microcircuits is ideally suited to manipulating and measuring micron sized dust particles. The fine scale and large area of modern macroelectronics allows a modest applied voltage to create high local electric fields. Switching the voltages generates a traveling electrostatic wave over large areas that could convey dust to suitable 'drain' for removal from the vacuum vessel.

Figs. 6 and 7 shows the schematic of such a surface, over which a lateral potential gradient is established by driving electrodes with three different voltages that are of the order of 10 – 100 V. Each set of traces (V_a, V_b, V_c) is biased at either +V, zero or –V and the voltage is switched sequentially between the sets to create a miniature electrostatic traveling wave.
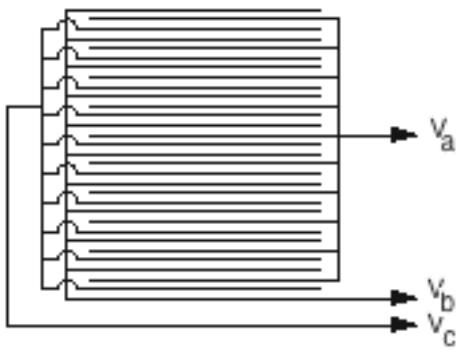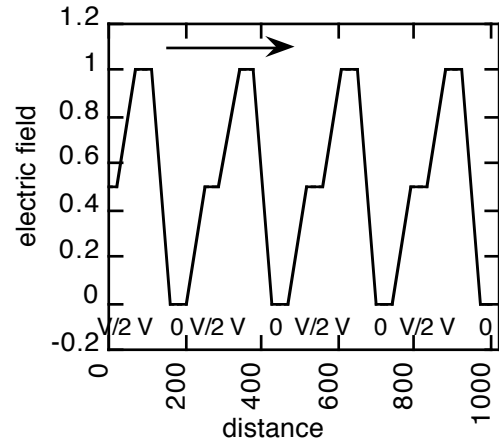
Fig. 6 Schematic of tripolar grid.

Fig. 7 Traveling electrostatic wave generated by sequentially switching voltages between the electrodes on a tripolar grid.
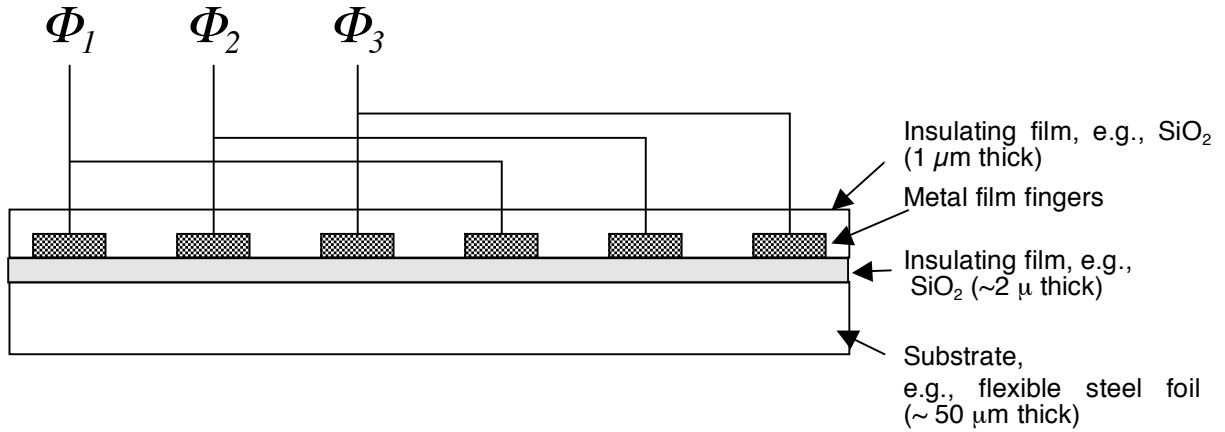
Φ_1 Φ_2 Φ_3

Insulating film, e.g., SiO_2 (1 μm thick)

Metal film fingers

Insulating film, e.g., SiO_2 (~2 μ thick)

Substrate, e.g., flexible steel foil (~ 50 μm thick)

Fig. 8 Schematic physical layout and connection scheme for a three-phase electrostatic "bucket brigade" that serves to move particles that land on it to a gravimetric dust detector.
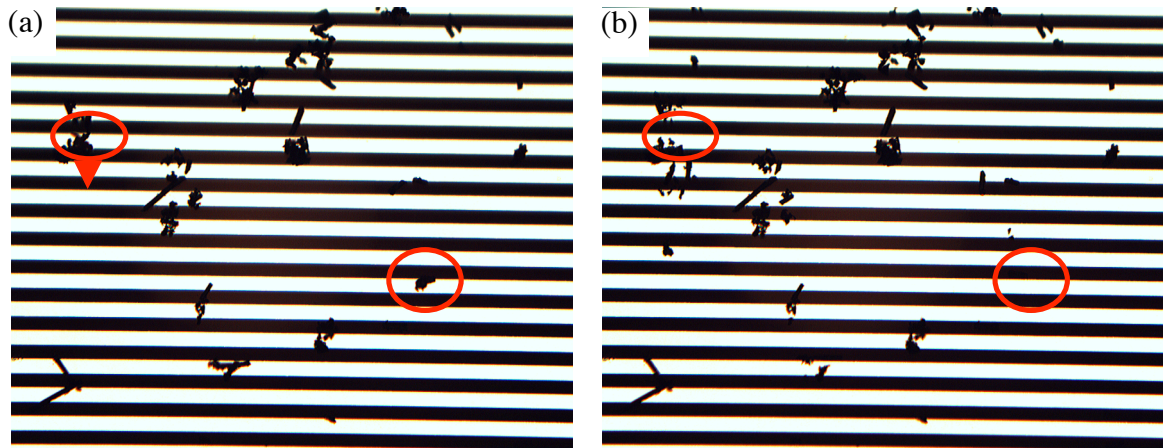

(a)

(b)

Fig. 9 Microscope images of carbon particles on the surface of the tripolar grid (a) before and (b) after the switching of ± 50 V to two of the three electrodes. The trace spacing is 25 microns and the circles are a visual aid.

These form an electrostatic "bucket brigade". An insulating top film allows setting up electric fields of over 10^6 V/cm at its free surface. At such field strengths particles with mass/charge ratio m/z of up to ~ 1 ng/z (size of 1 μm to 10 μm for z=1) that come to rest on the surface, can be levitated, detached, and moved.

Very recently we have fabricated the first prototypes of an electrostatic circuit grid (Fig. 8). It has interdigitated chromium traces 25 μm wide and 25 μm apart. The traces are insulated with a 300 nm layer of silicon nitride. The circuit is fabricated on glass and a rotary switch allows the sequential application of up to 200 v to the electrodes. The location of the particles on the grid was recorded with a digital microscope before and after voltage changes. Unfortunately, the third trace in the first available grids was open circuit, due to fabrication issues. However the switching of a bias of ± 50 V between just two of the electrodes clearly caused motion of some test dust particles as seen in Fig. 9. We anticipate that in future devices with three working electrodes directed motion will be achieved by a traveling wave generated by the rotary switch.

In summary, dust measurement and removal are vital for the safe operation of ITER and any long pulse fusion device, however suitable techniques have not been proven to date in a tokamak environment. We have taken advantage of the remarkable recent advances in macroelectronics (or large-area electronics) in innovative approaches to these issues. The typical micron-scale feature size of microcircuits is ideally suited to manipulating and measuring dust particles. We have developed an innovative dust detector for inaccessible surfaces in tokamaks and are adapting it to a tokamak environment. We have presented results from a more advanced 3-pole grid that is aimed at generating a miniature electrostatic traveling wave to convey dust to an exit port. Such devices can potentially remove dust continuously without dedicated interventions and without loss of machine availability for plasma operations. A mosaic of these devices based on a low activation substrate such as SiO_2 could be envisaged for remote inaccessible areas in a next-step tokamak to ensure that these surfaces remained substantially dust free.

5. Acknowledgements:

6. References

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