Dust - production and detection in tokamaks

Charles Skinner, Lane Roquemore, Henry Kugel, PPPL

12th Meeting of the ITPA Topical Group on Diagnostics,
PPPL, 26-30 March 2007

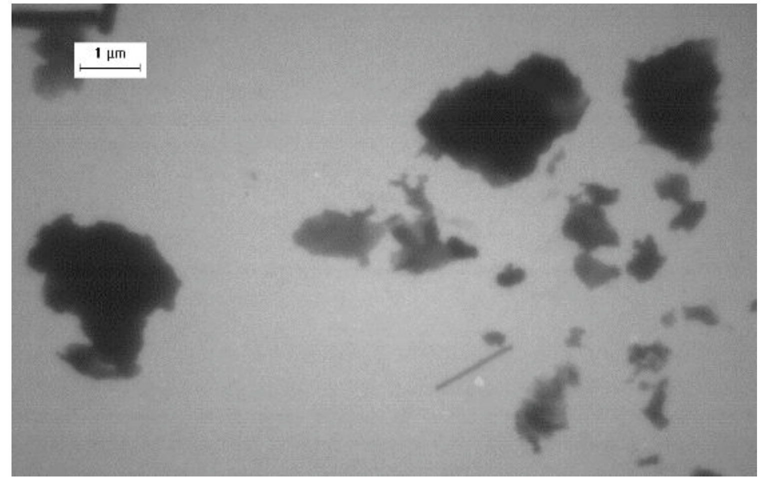
Outline:

- Dust production in tokamaks
- Dust trajectories in NSTX plasmas
- Potential dust detectors for ITER:
  - Novel Electrostatic Dust Detector
  - Capacitive Dust Detector
- R&D needed.

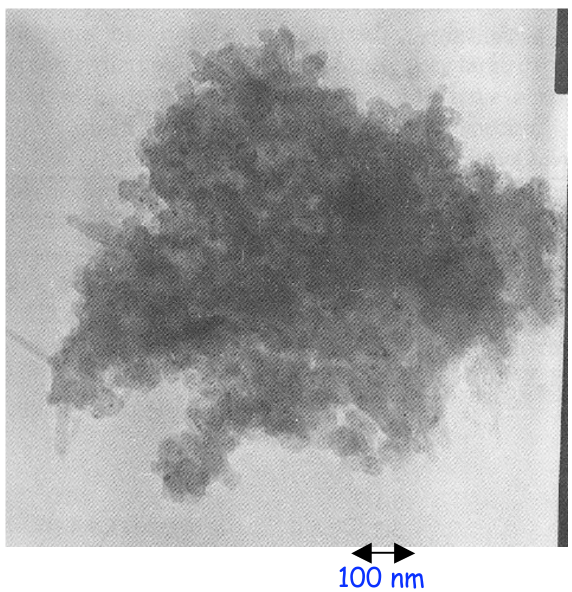
Supported by US DoE DE-AC02-76CH03073

Diverse 'flora' of dust in contemporary tokamaks

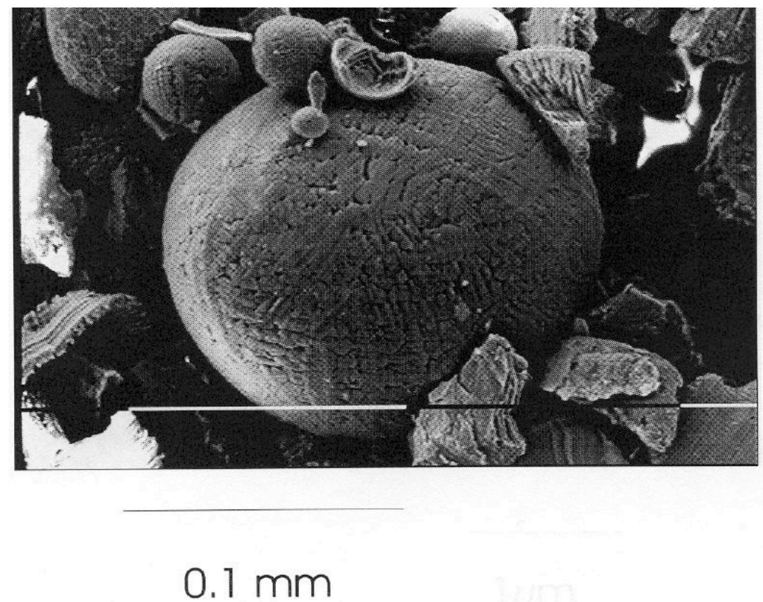
Dust in NSTX under lower divertor tile.



Dust retrieved from TFTR.



TEM image of flakes from Tore Supra: globular and elongated structures.
Ph. Chappuis et al., J. Nucl. Mater 290-293 (2001) 245

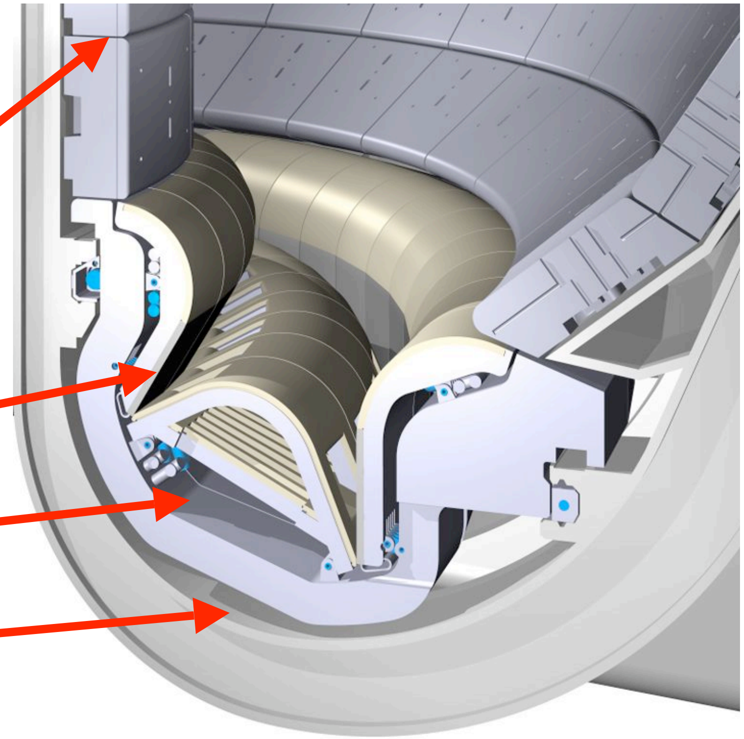


Iron spheres from TEXTOR-94 with the large sphere showing a regular surface texture
J Winter, Plasma Phys. Control. Fusion, 40 (1998) 1201

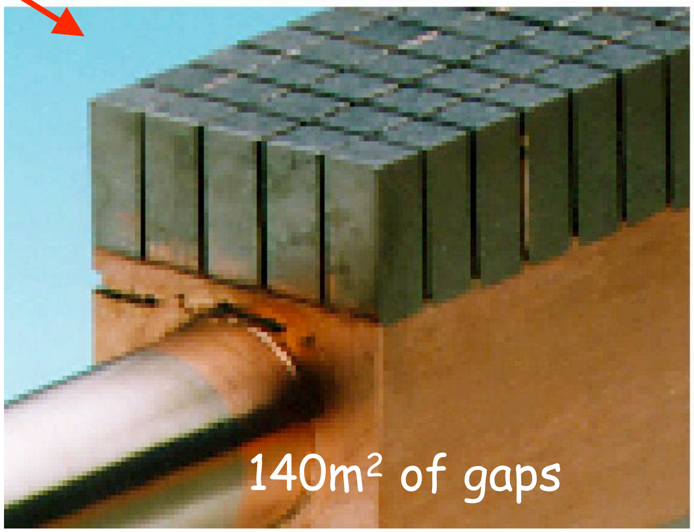
Potential dust locations in ITER

Dust typically accumulates at the bottom of a tokamak (TFTR diagnostic pipes, JET subdivertor…).

- Gaps between blanket modules
- Gaps in macrobrush
- Under divertor dome
- Under divertor cassette



Macrobrush



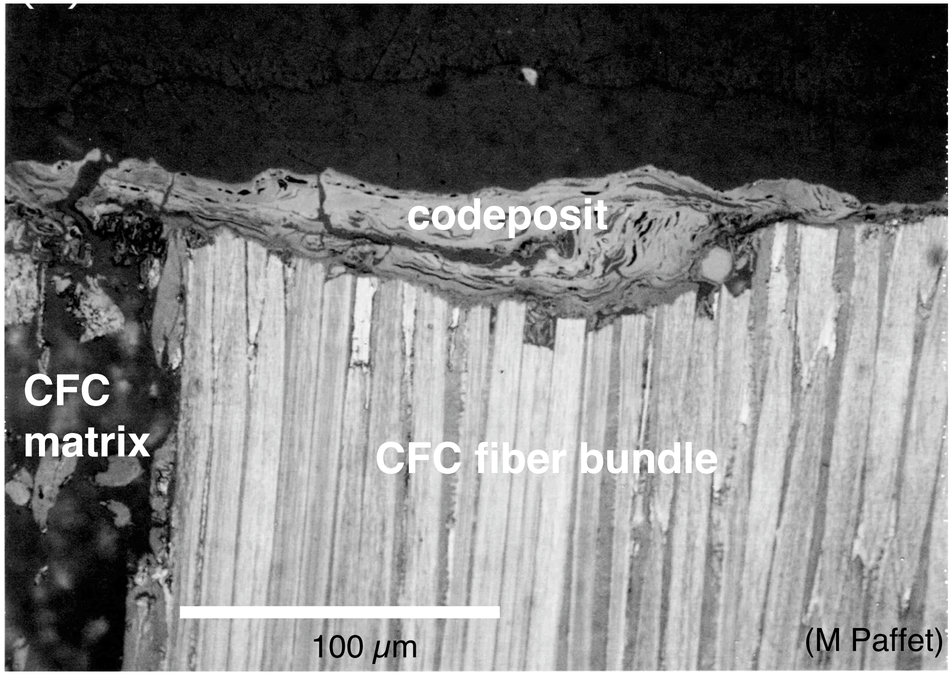
- 'Dust' is defined as particles < 100 μm (larger particles will not transport to the environment in accident scenarios).
- Dust in ITER could be carbon, tungsten beryllium or mixed materials.
- Typical count median diameter in present tokamaks is few microns.
- Fractal-nanoscale particles reported in ELM simulators (see Khimchenko IAEA'06 paper)

Dust production:

1. Thick carbon codeposits can crumble (ITER peak growth rate 40 μm / day)
2. ELMs can create aerosols of tungsten droplets or carbon 'shrapnel'.
3. Synthesis of C_nH_{2n} chains from chemical sputtering.
4. Debris from in-vessel activities or friction

Dust can also threaten 1st mirrors.

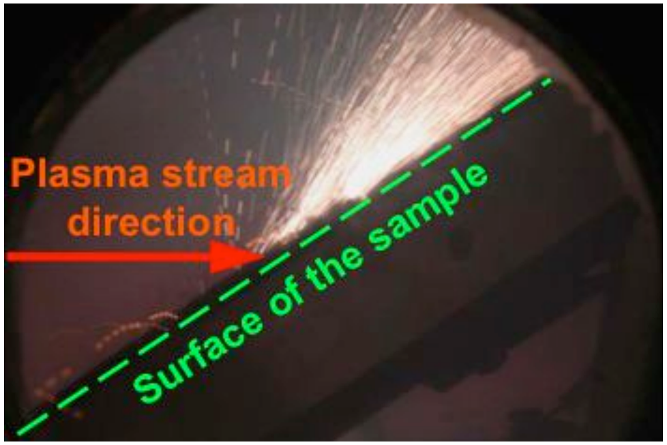
Microstructure of TFTR codeposit



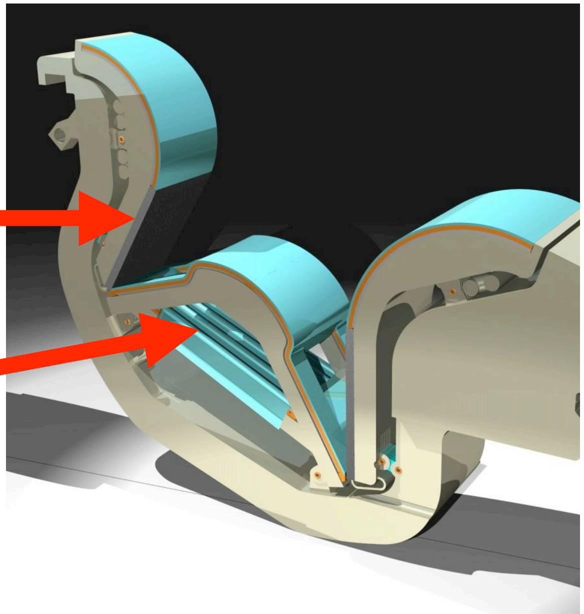
3ms after 1st pulse.

Mass loss 67 mg/pulse

Zhitlukhin PSI-17



Tungsten droplet tracks in QSPA ELM simulator at Troitsk, 1.6 MJ/m^2 first pulse



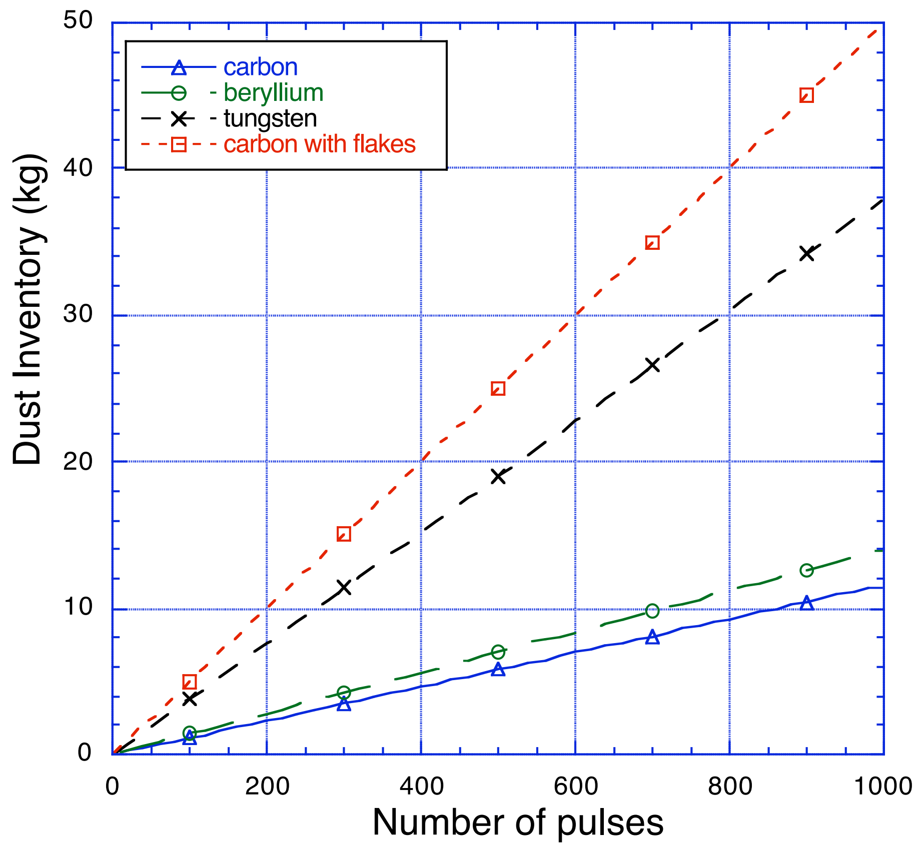
Tritiated dust can levitate by beta induced static charge

- Radioactive decay of tritium via beta emission leaves a positive charge on a dust particle.
- Tritiated particles could be uniquely more mobile than other dust.
- Movie of tritiated dust from TFTR-->
-
- D/C in TFTR dust only 0.007
  T/C in TFTR dust only 0.0003
  (TFTR D/T fueling ratio 3%)
  Low D/C indicates high temperature outgassing in dust formation.
- JET flakes D/C = 0.75
  higher value similar to codeposits.

(C Gentile, S Langish, PPPL)

ITER operations depends on limiting dust inventory

Estimated Dust Production Rate



ITER dust production crudely estimated at 10% of sputtered, 50% of evaporated material assumed + flakes for CFC
[G Federici]

Dust Hazards:

Dust	Safety Issue	Limits
Beryllium	Reactivity with steam and H_2 Toxic	100 kg
Carbon	Tritium retention Explosion with air	200 kg
Tungsten	Activation	100 kg

from J.Ph- Girard SOFT '06

- Limits for C-and Be-dust are related to an explosion (e.g., H produced by Be reactivity with steam).
- The limit for W-dust implies a containment factor > 17 to avoid evacuation in worst credible accident.

- *Independent of safety considerations: dust particles can move with high speed and could contaminate core plasmas.* *[S. I. Krasheninnikov et al., Contrib. Plasma Phys.* ***46****, 136 (2006), A. Pigarov PSI17]*

Bottom Line: Dust diagnostics and dust removal technology or other countermeasures needed to assure ITER safe operation ! (ITER issue card PFC-5)

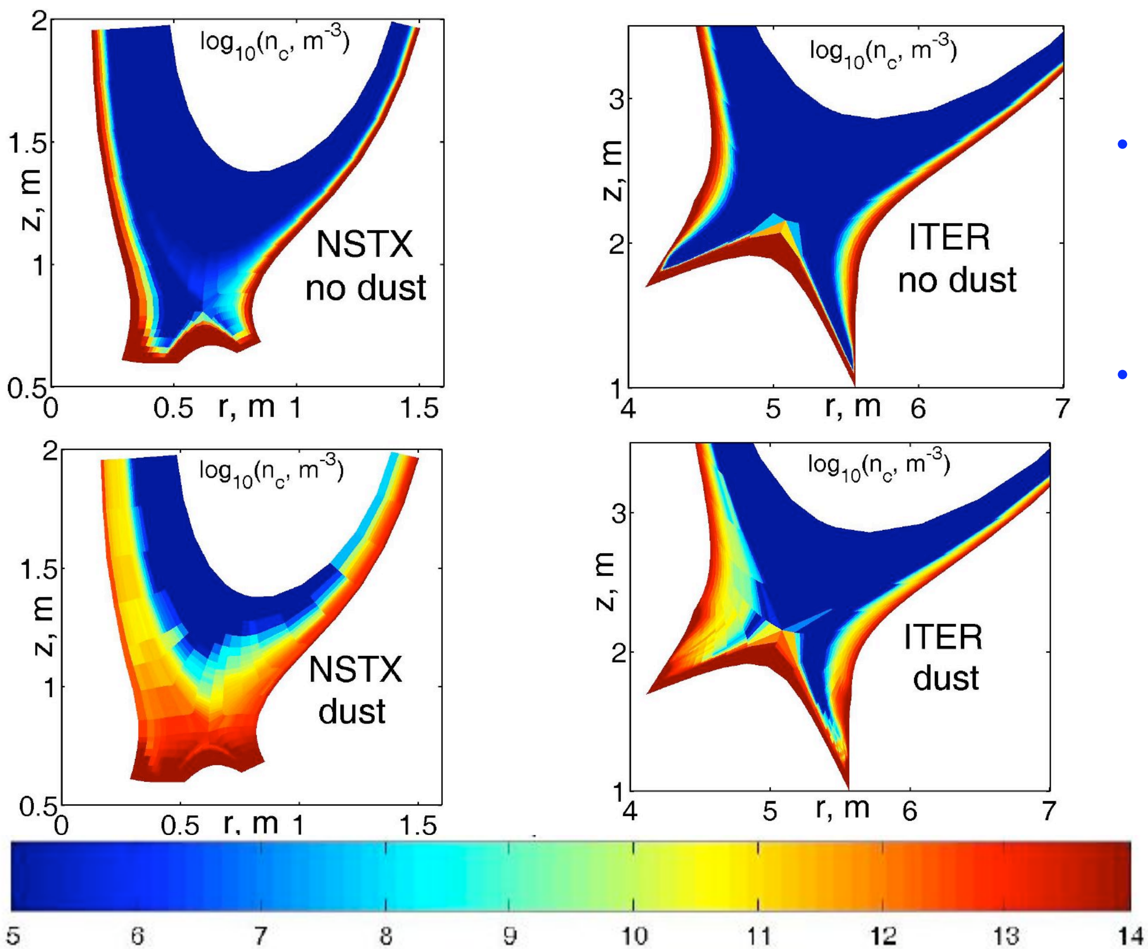
Outline:

- Dust production in tokamaks
- Dust trajectories in NSTX plasmas
- Potential dust detectors for ITER:
  - Novel Electrostatic Dust Detector
  - Capacitive Dust Detector
- R&D needed.

Dust can transport impurities into plasmas:

Carbon dust can penetrate deeper toward the core plasma than impurity atoms sputtered from walls and can affect divertor plasma profiles. Ambipolar effects charge up tokamak dust and ion drag then leads to core contamination.
(Pigarov/Krasheninnikov DUSTT code)

Simulated profiles of neutral carbon density



- Edge plasma profiles in tokamaks are simulated with **UEDGE**.
- Dust particle transport is calculated with **DUSTT** employing Monte Carlo method.
- The calculations are done under assumption that **1%** of carbon impurity ion flux on material surfaces is agglomerated into **1-micron** dust and transported as carbon dust particles.

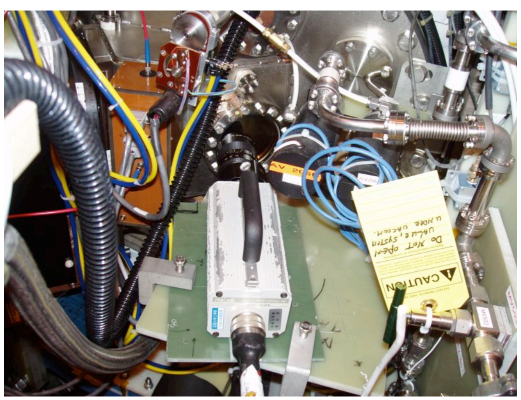
(A. Pigarov et al., Phys. Plasmas 12 (2005) 122508, PSI-17)

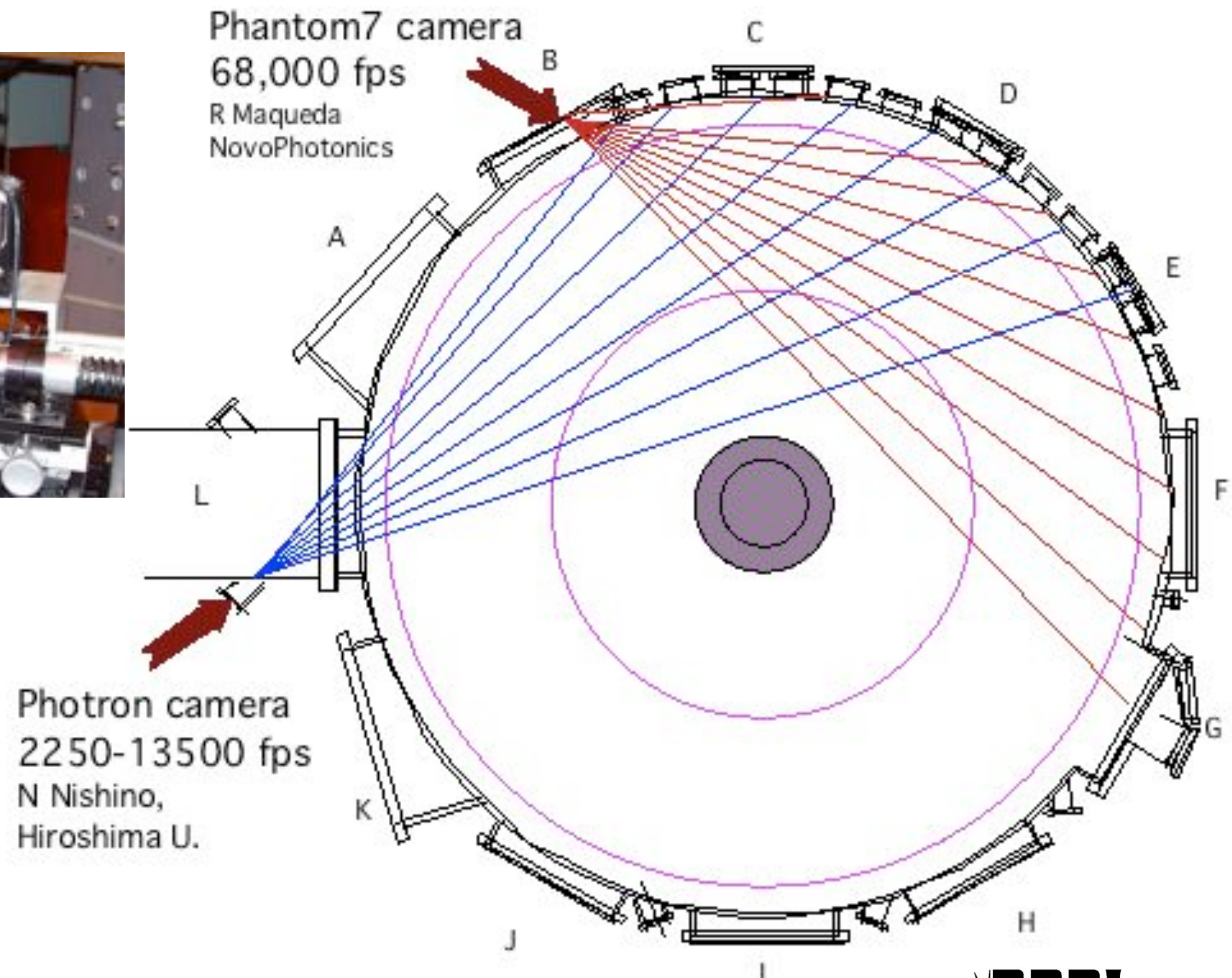
DUSTT Code Validation in NSTX in progress

NSTX

- Open geometry of NSTX ideal to track dust
- Use multiple fast cameras to measure 3D dust trajectories
- Compare data to DUSTT dust transport model.

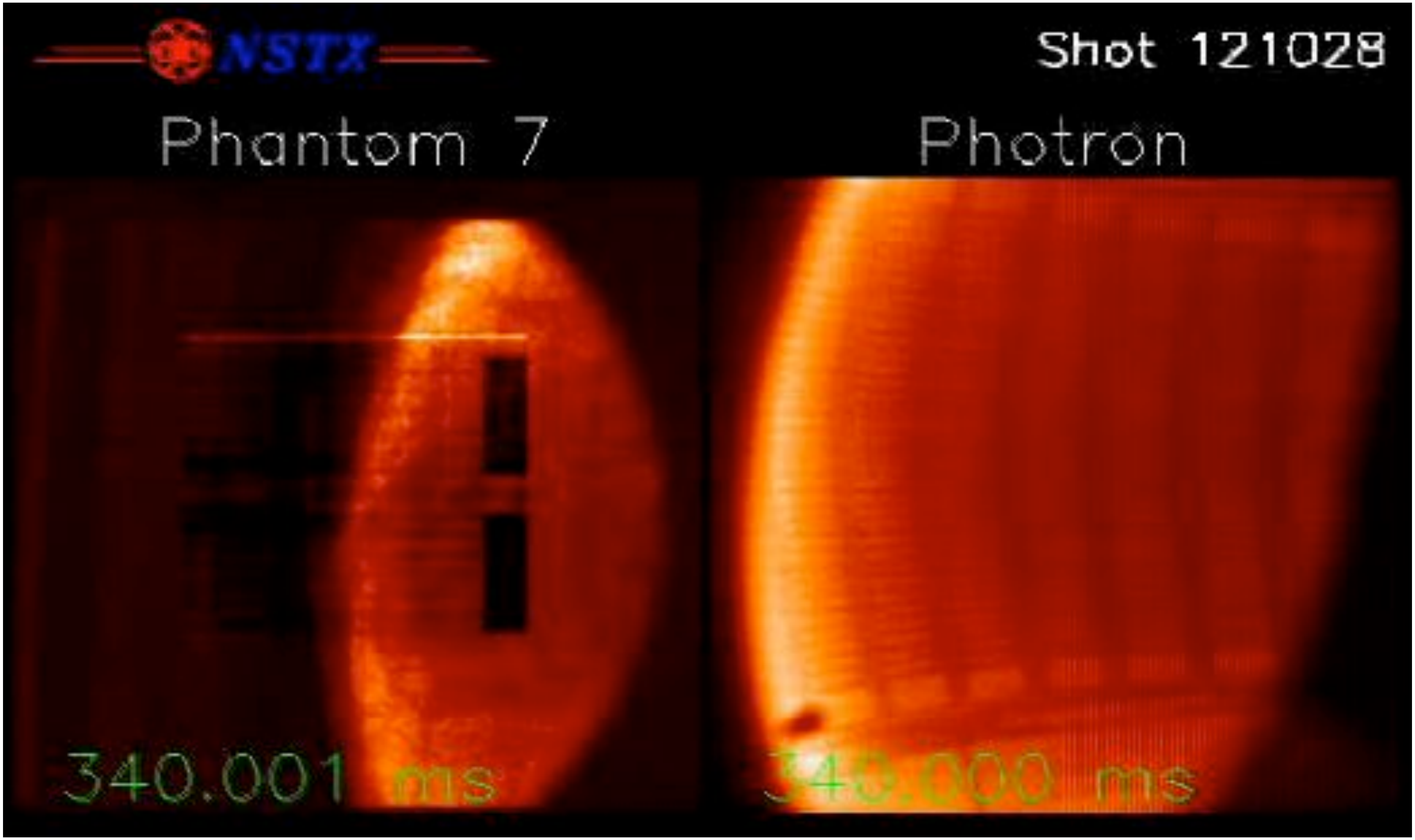
Lane Roquemore



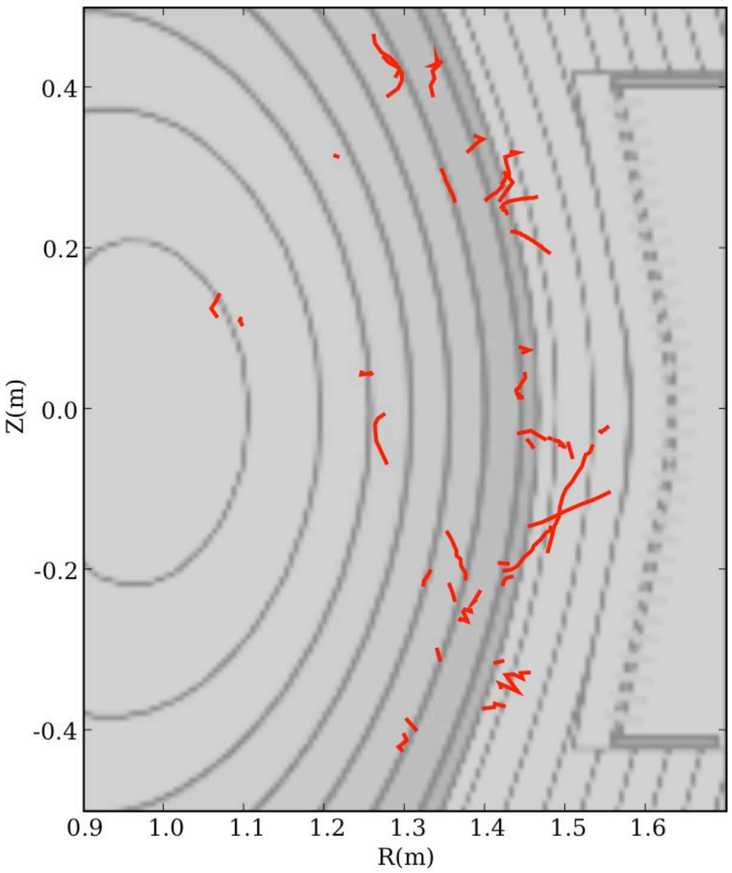


Steroscopic view of dust in NSTX plasma

356 ms

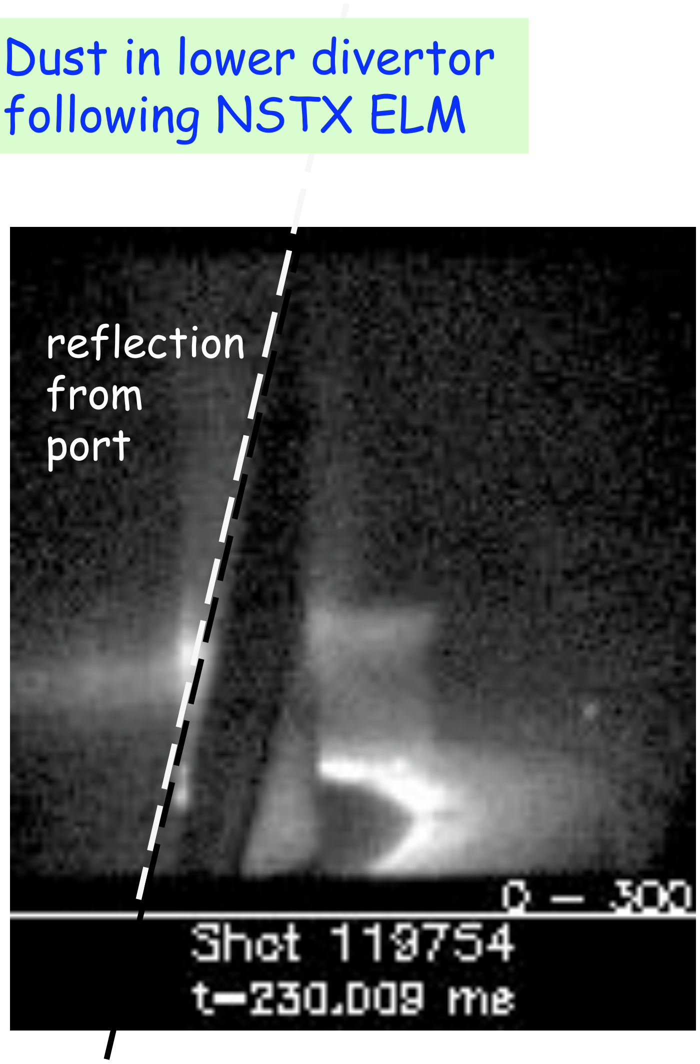


3D trajectories (red) are derived for comparison to theory



W. Boeglin, R. Maqueda, L. Roquemore

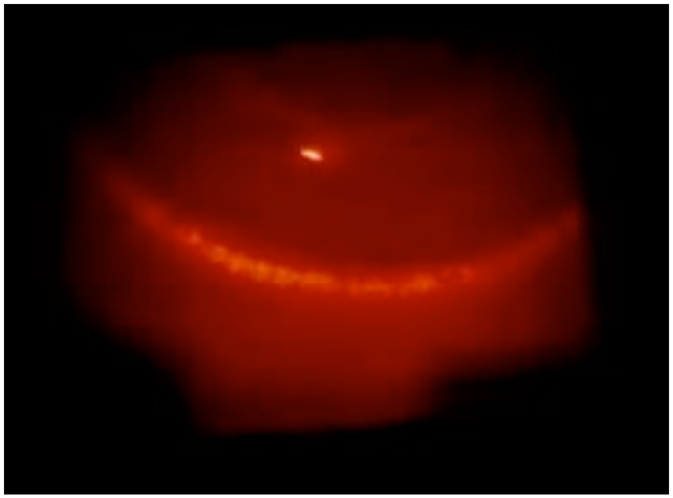
Dust in lower divertor following NSTX ELM



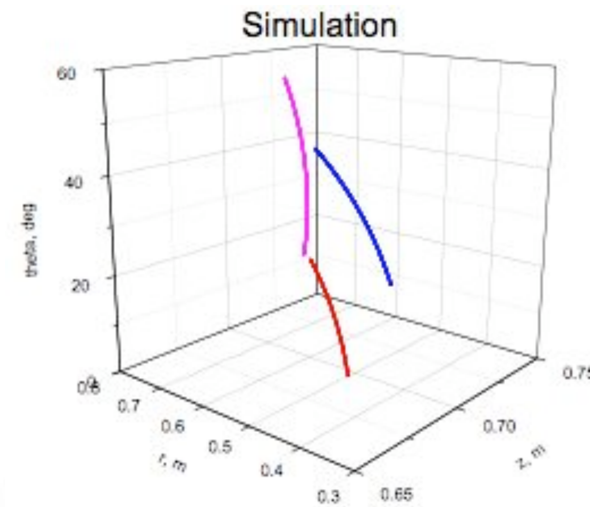
What are implications for 1st mirrors ?

Comparison of observed particle trajectories with simulations from DUSTT code

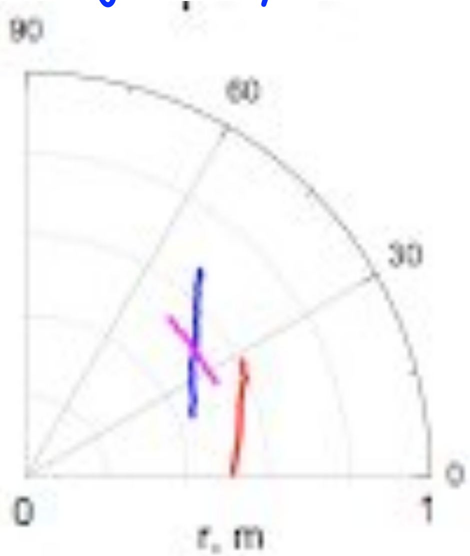
Fast camera view of NSTX lower divertor



Results from DUSTT code



Derived Trajectory



See Roquemore et al.,
PSI-17 proceedings
J. Nucl. Mater.

Outline:

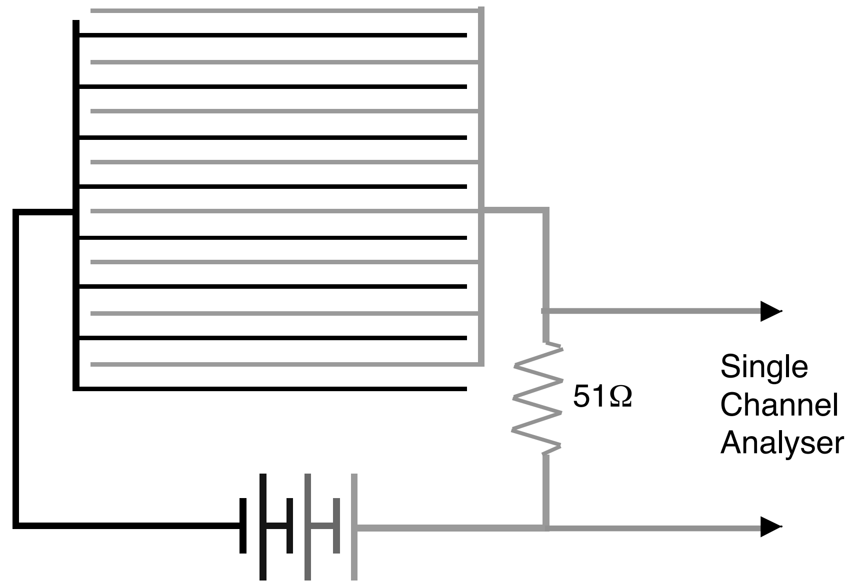
- Dust production in tokamaks
- Dust trajectories in NSTX plasmas
- Potential dust detectors for ITER:
  - Novel Electrostatic Dust Detector
  - Capacitive Dust Detector
- R&D needed.

Novel Electrostatic Dust Detector

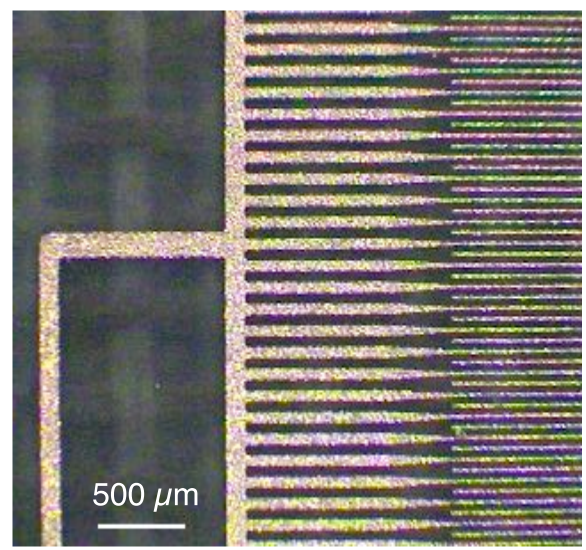
with National Undergraduate Fellows:
Aaron Bader, now at MIT; Chris. Voinier, College of New Jersey; Colin Parker, now at Princeton U.; Robert Hensley, Embry-Riddle Aeronautical Univ

- A 30-50v bias is applied across a grid of interlocking traces on a circuit board.
- Impinging carbon dust creates a short circuit and current pulse.
- Current pulse is input to nuclear counting electronics and converted to counts.
- Number of counts is proportional to mass of dust.
- Current also vaporizes or ejects dust from the circuit board restoring an open circuit.
- Device works in air or vacuum.

Schematic



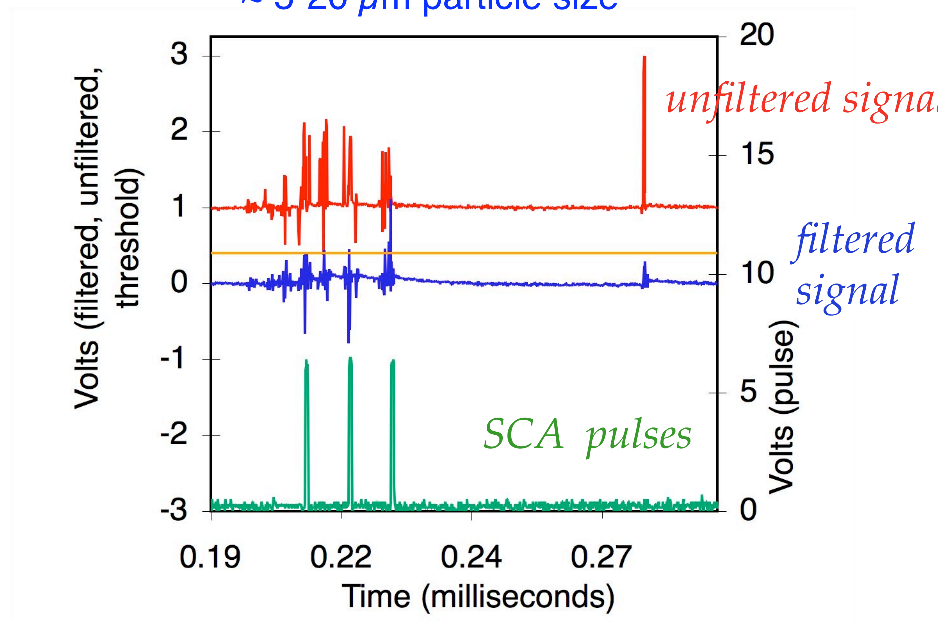
Grid with 25 micron spacing

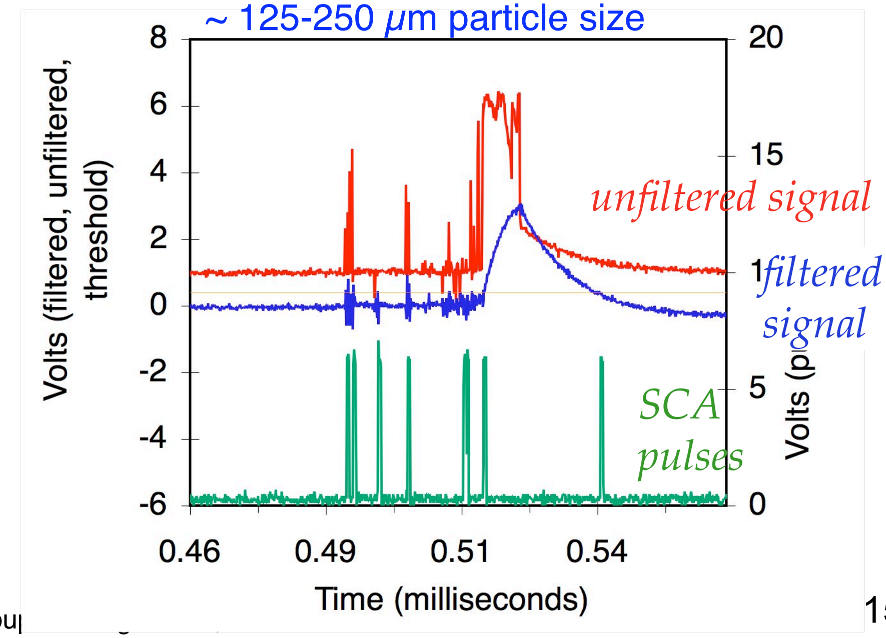


100 μm dia. of human hair

Electrostatic Dust Detector in action

Waveform contains information on dust size

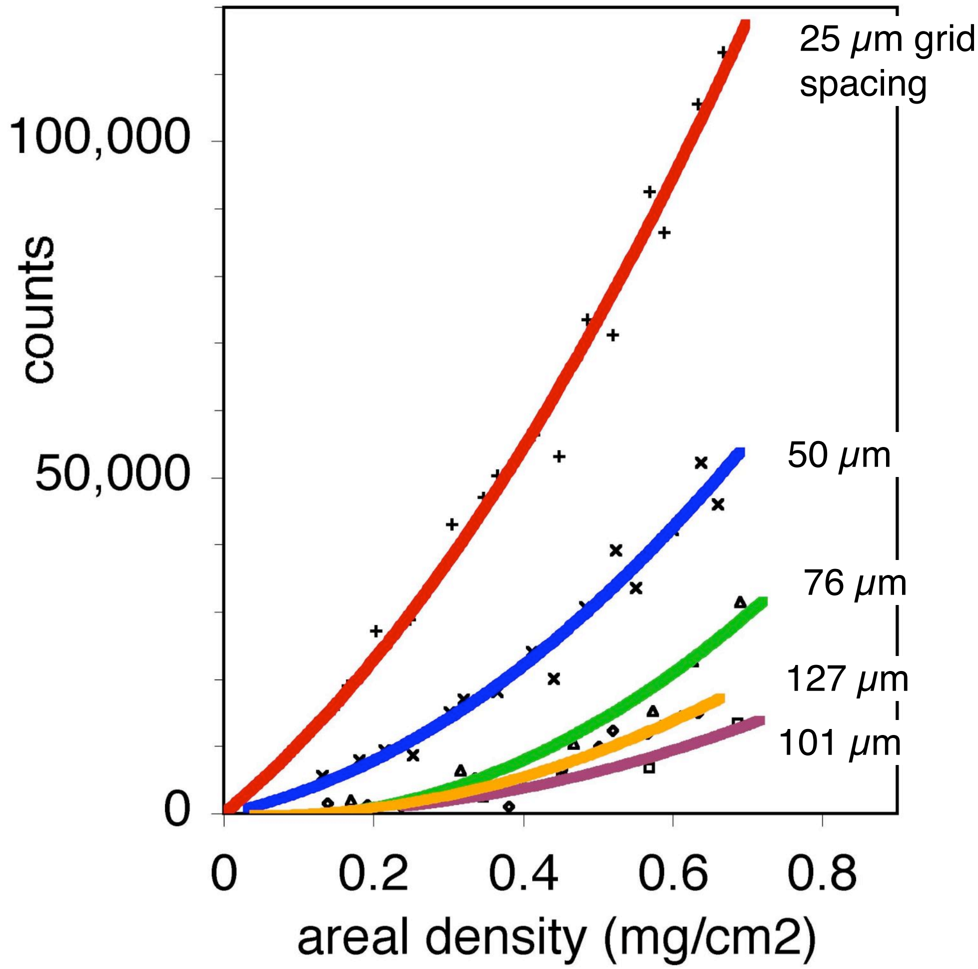




- Larger dust particles take longer to vaporize and create signals with higher voltage and longer duration.

Sensitivity increased 30x with finer grids

Grid response with different spacing



C. H. Skinner ”12th Meeting of the ITPA Topical Group on Diagnostics, PPPL 26-30 March 2007”.

Is response due to a few large particles or many small particles ?

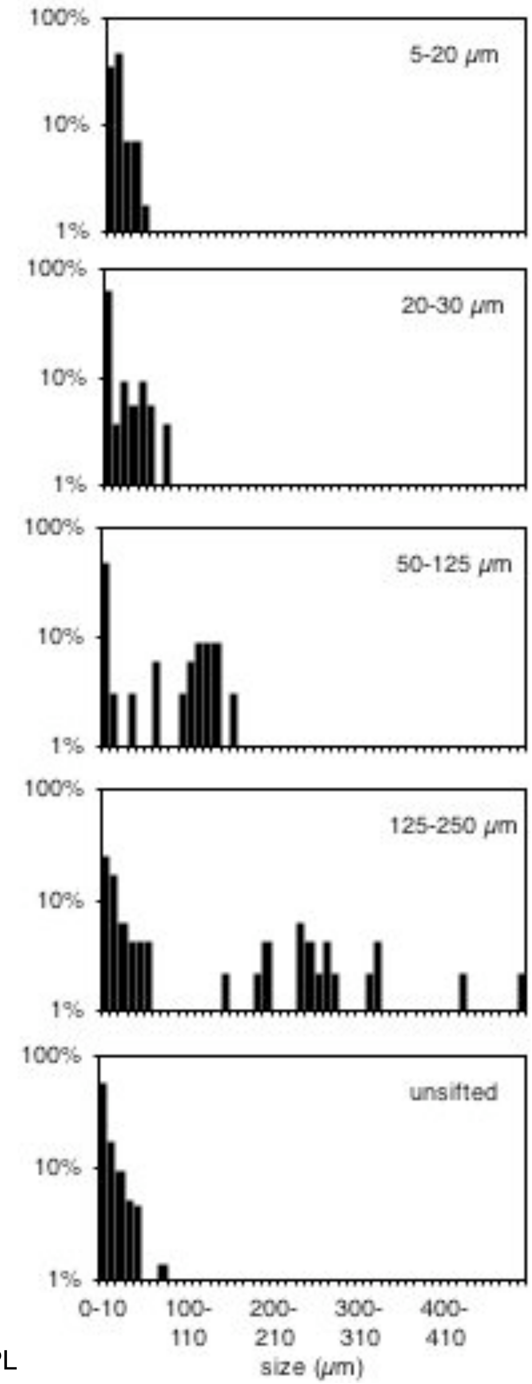
Sift carbon test particles in the “Sonic Sifter”…

Unsifted Dust

Viewing Area: 2.5 x3.4 mm

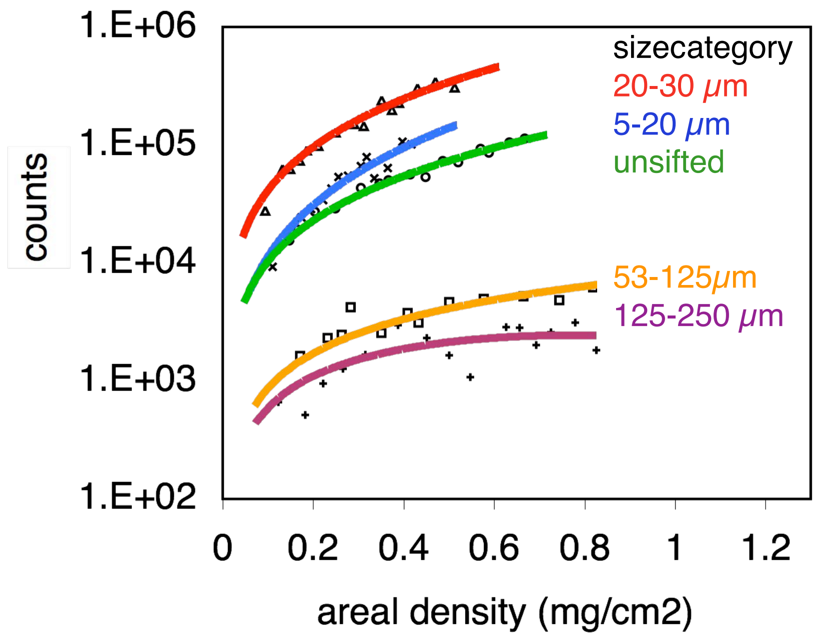
Size distribution as measured in microscope after sifting through various sieves.
(50 - 125 μm means dust passed through 125μm sieve but was stopped by 50 μm sieve).

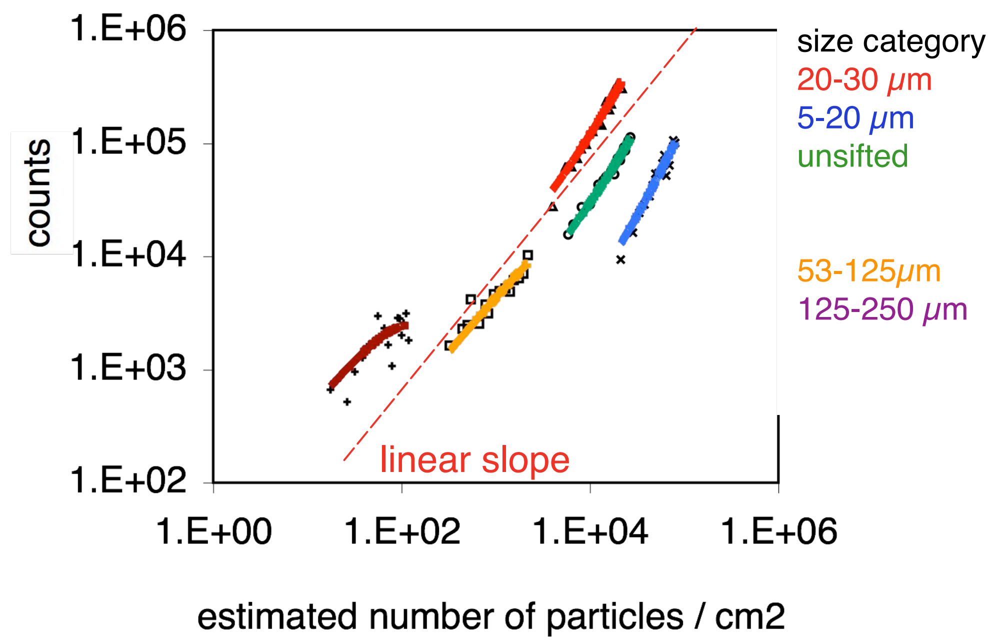
‘Size’ is for equivalent spherical particles of same projected area. Filtering is incomplete.



Counts depend on number of particles / cm^2

Response of 25 μm grid in air to different particle size categories.





Size category 20 - 30 μm means particles transmitted by 30 μm sieve but retained by 20 μm sieve.

Much stronger response to small particles
-favourable for tokamak dust as most is
1-micron scale.

Data on left replotted vs. estimated number of particles

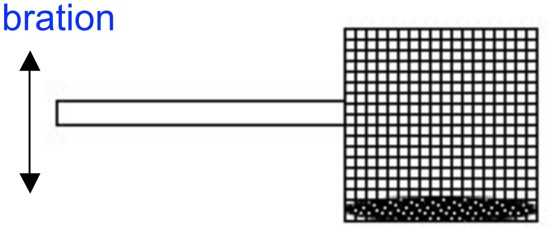
Analysed microscope images give list of areas of individual particles.

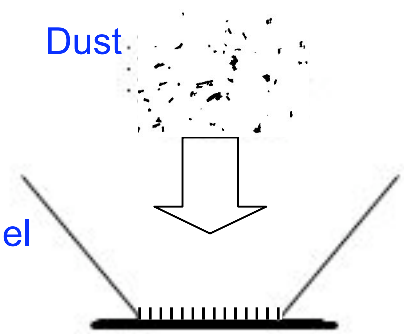
Assume volume = area$^{(3/2)}$ (cubic particles) and unit density to derive mass of imaged particles

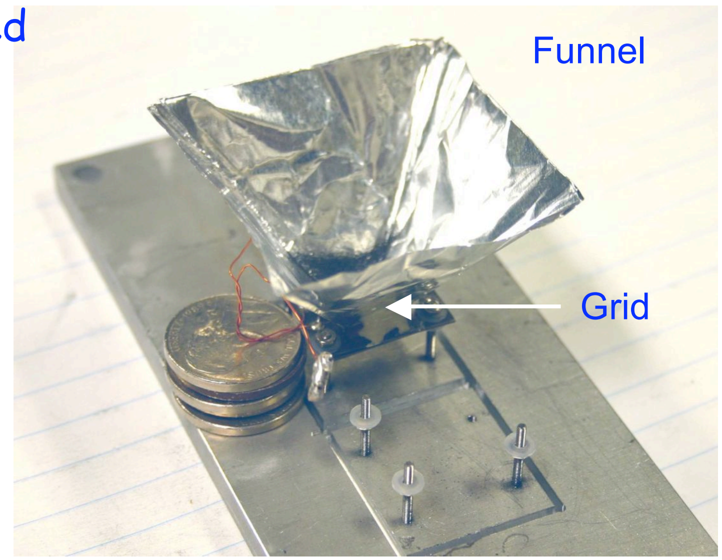
particles / cm2 = mg/cm2 X # particles / mg

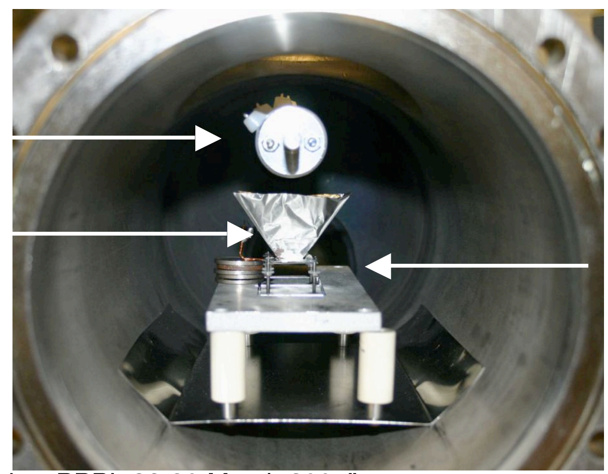
Could this device be used to control the dust inventory ?

- The short circuit is temporary suggesting the device may be useful for the removal of carbon dust from specific areas.
- The fate of the dust particles has been tracked by measurements of mass gain / loss.



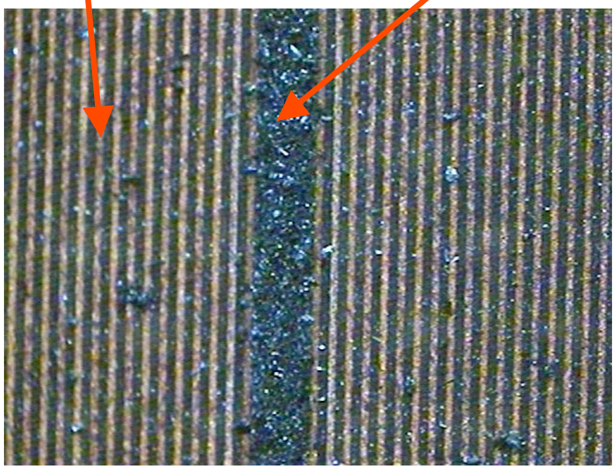




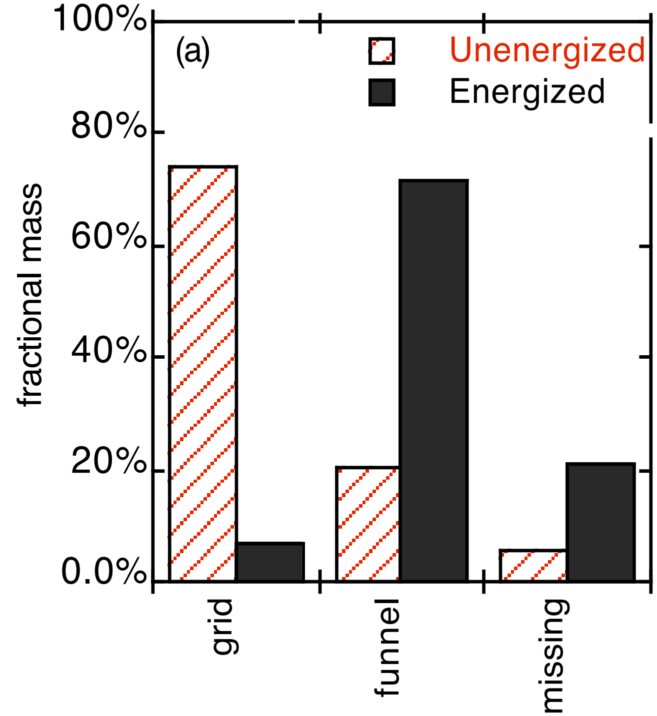


C. H. Skinner ”12th Meeting of the ITPA Topical Group on Diagnostics, PPPL 26-30 March 2007”.

Tests showed 91% of dust removed from board in vacuum

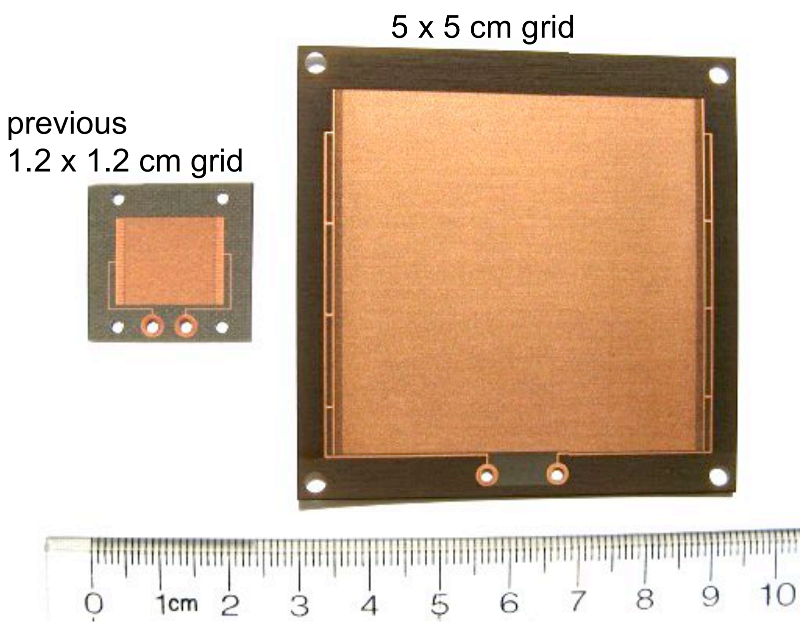


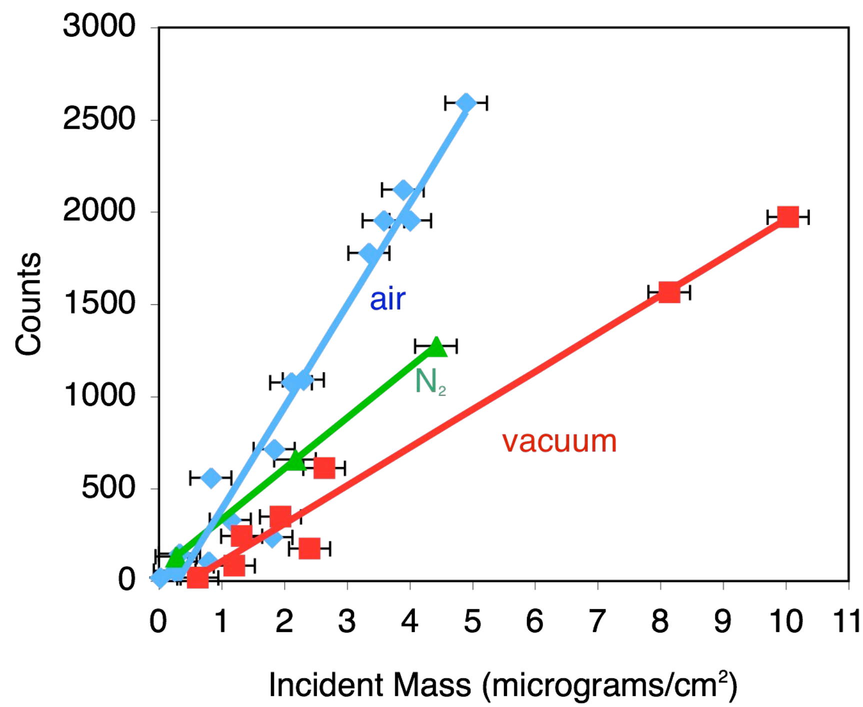
Dust left on one board from an open trace, trace widths are 50 μm



- We tracked the dust weight in the trough, funnel, and board.
- ~91% of dust is removed in vacuum.
  - ~21% eliminated (in addition to missing mass)
  - ~70% relocated onto funnel
- Some of the remaining dust is in a furrow due to a single open trace

Lab Tests with large area detector:





- 5x5 cm grid has 17 times larger area
  (credit IPP Garching)
- 100 times more sensitive balance
  - 5 gram capacity with
    0.000 001 gram readability
- 25 μm trace spacing
- 30 volts max
  - (spontaneous breakdown at 50 volts)
- Extreme precautions needed
  - (fingerprint weighs 40 μg)

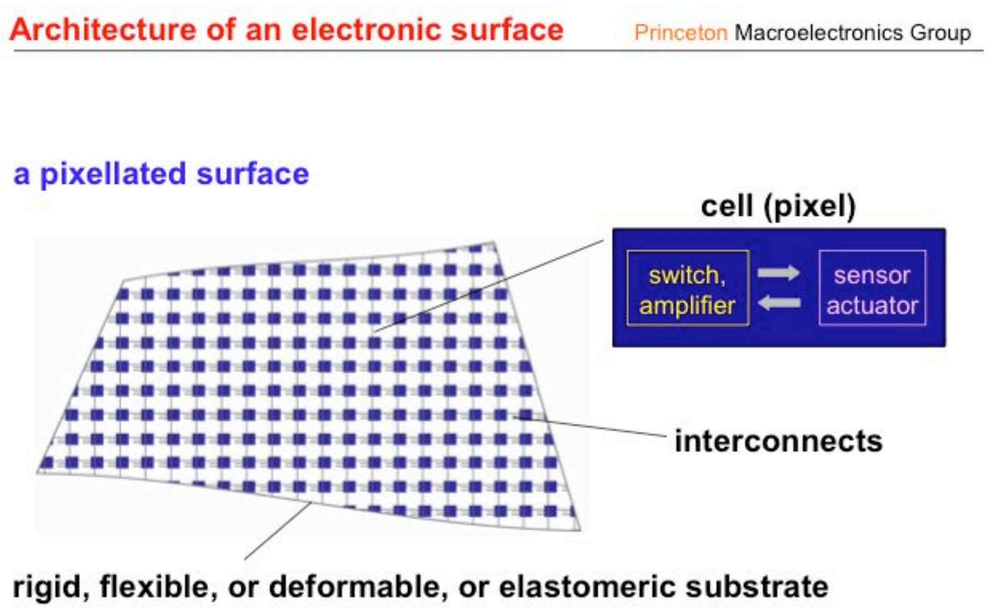
Preliminary Results:

- Response linear down to
- ≈1 μg/cm^2
- ITER anticipates 60 mg/cm^2
- (dust levels in NSTX still lower than grid sensitivity)

C. H. Skinner "12th Meeting of the ITPA Topical Group on Diagnostics, PPPL 26-30 March 2007".

Application to ITER:

- Device is relatively cheap.
  a mosaic of these devices could cover large areas.
- Would use low activation substrate such as SiO_2
- Would detect and eject dust settling on surfaces
- Nanotechnology is a rapidly evolving area.
- Propose to apply advances in large area display microelectronics to develop mechanical and/or electrostatic dust detector/ transporter for industrial and fusion applications.



Prof. S. Wagner,
Princeton University
Macroelectronics Group

Capacitive dust detection:

- Alternative method - gravimetric principle
- Ceramic capacitive diaphragm manometer adapted to be a microbalance for dust detection.
- Prototype tests of prototype show sensitivity of 0.5 mg/cm^2 and dynamic range of 10^3.
- Can be controlled from 30m.

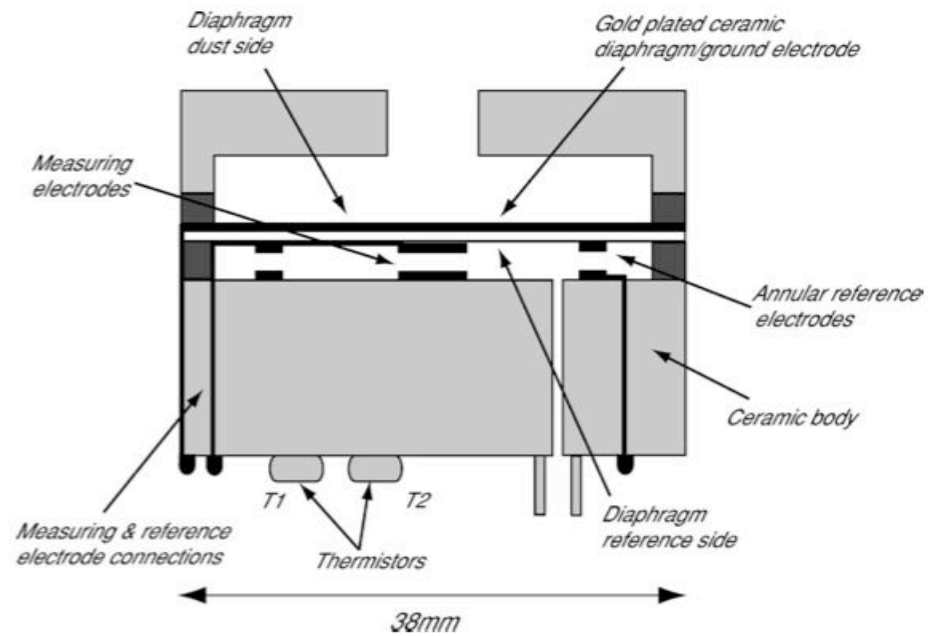


FIG. 5. Hybrid design of dust sensor showing the measuring and reference electrodes together with the ground Faraday shielding.

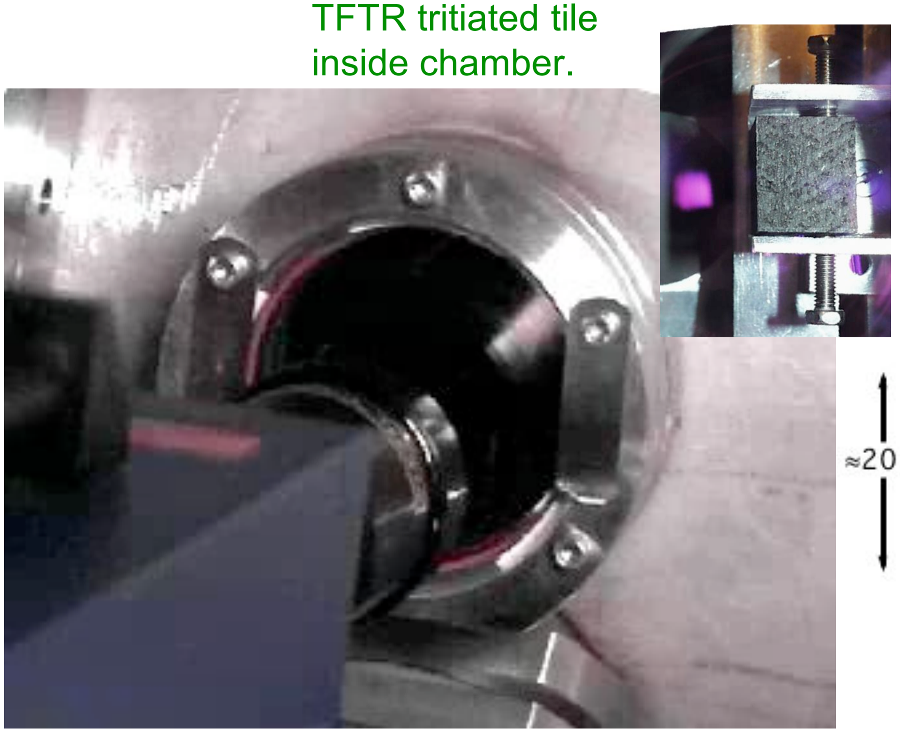
Glenn Counsell et al.,
Rev. Sci. Instrum. 77 (2006) 093501

Dust could also coat diagnostic mirrors

Divertor target plate will be eroded ~1 cm at strike point over 3 year lifetime.

Material will go somewhere !

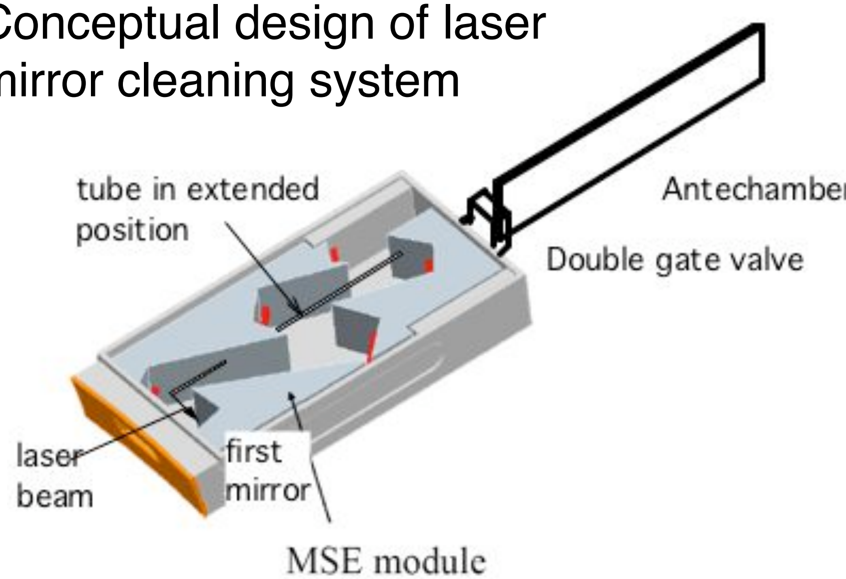
7/8” cube cut from TFTR tritiated tile inside chamber.

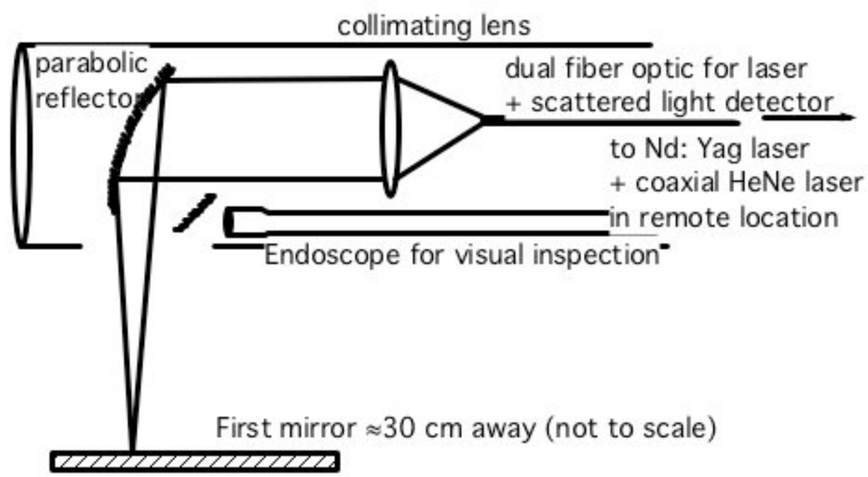


≈20 mm

From prior laser detritiation work

Conceptual design of laser mirror cleaning system





C. H. Skinner ”12th Meeting of the ITPA Topical Group on Diagnostics, PPPL 26-30 March 2007”.

Dust removal from ITER ?

Proposed techniques:

- Oxidizing plasmas might ‘burn up’ carbon dust
  - issues with collateral damage, DTO processing, access to hidden areas. [Counsell, Hu..]
- Laser ablation [Skinner, Counsell, Grisolia…]
- Vibrating conveyor [Counsell Phys. Scr. T91 (2001) 70.]
- Liquid wash-and-flush [Counsell]
- Microelectronics technology [Skinner]

None of these are on a funded development path to my knowledge.

Time is running out…..

Summary and R&D needs:

Dust will decide ITER's ability to operate.

- Dust diagnostics needed to assure compliance with ITER safety limits.
- Dust removal required if limits are approached.
- Dust can threaten diagnostic 1st mirrors.
- R&D is only means to mitigate risk.

  - each funded experiment is worth 1,000 committees.

ITER should not pioneer unproven technology so….

Serious R&D effort needed (and funding)

- Optical diagnostic requirements should include dust mitigation measures.
- Mirror tests in disruption facilities needed.
- HEIGHTS code could be applied to model melt/splashed W from ELMs with diagostic mirrors in dome.
- Mirror cleaning tests in ITER scale mockups with Be/C/W deposits needed.
- BET measurements of dust accumulation in tile gaps in disruption facilities.
- Need program to test dust diagnostic and removal techniques.
- Potential dust removal technology should be included in 2007 design base.
- The hour is late, will there be time for this R&D ?
- Who 'owns' (is responsible for solving) this issue ?