SAFETY ISSUES THE DUSTS IN TOKAMAK MAKE
A NEW TYPE OF ELECTRIC DISCHARGE: THE STREAMER DISCHARGE

Research Laboratory, General Electric Co., Schenectady, N. Y.
Irving Langmuir, C. G. Found, A. F. Dittmer

Science [Vol. LX, No. 1557 October 31, 1924]

Thus we must conclude that the inside of a detached globule is negatively charged and that this is surrounded by a positive ion sheath. The tungsten is imprisoned inside the globule in the form of solid particles which are concentrated particularly at the boundary of the regions of positive and negative charge.
Dusts in plasmas

- From lab to the universe

Wave propagation

Instability induced by dusts

Vortex formation

Killer particles in semiconductor industry

Eva Kovacevic, DPG Tagung in Kiel, 2004
Dusts in tokamaks

ITER definition: solid particles/debris of size about 10 nm-100 µm

Flakes (Tore Supra)

Mobilized dusts (Tore Supra)

Nanoparticles (Tore Supra/JET)

Droplets from arcing (AUG)

Neutraliser deposit (2002)

TEM micrograph
Dusts in tokamaks

Flake formation

Deposition → Erosion → +Redeposition → Thick films on surface → + internal stress, shock

Melting / splashing

high heat flux / run away impact → Melting/brittle destruction of PFCs → Splashing

Spontaneous nanoparticle formation from super-saturated vapor

Presence of critical density of materials in unit volume → spontaneous nucleation → Coagulation, agglomeration → Accretion

Suk-Ho Hong, IAEA Divertor Concept TM, 29th Sept.-2nd Oct. 2015, Vienna, Austria
What are the problems dusts brings in?

- Degradation of plasma performance as “uncontrolled pellet injection“ from LFS SOL
- Damage of in-vessel components by high speed collision or by high temperature
- Stress relaxation of layers by incorporated dusts
- Tritium retention and Radioactivity
- Explosion

Main question = “Amount of dusts or how often events occur”
Degradation of plasma performance as “uncontrolled pellet injection” from LFS SOL

- Impurity influx
  - Radiative power loss
  - Fuel dilution
  - Disruption (such as killer pellet)

- Dust influx after plasma touches the wall at JET (captured by high speed camera)

S. Hong et al., “Temporal evolution and spatial distribution of dust creation events in Tore Supra and in ASDEX Upgrade studied by CCD image analysis”, Nucl. Fusion 50 (2010) 035002
Degradation of plasma performance as "uncontrolled pellet injection" from LFS SOL

- To study influence of dusts on the plasma performance and to simulate W splashing event in ITER, a gun-type injector has been designed, developed, and fabricated.
  - Aimed to inject various powder form particles into edge plasmas
  - For W injection: W 12 \( \mu \text{m} \) in diameter.
  - Initial velocity \( \sim 1.5-4.0 \text{ m/s} \) in air, up to a factor \( \sim 2 \) in vacuum.
  - 2-3 mg per single injection
- First injection of W has made at KSTAR.
- International collaboration is ongoing: EAST, WEST, AUG will perform similar experiments.
Degradation of plasma performance as "uncontrolled pellet injection" from LFS SOL

- "Splashing" of ~3 mg W droplets from LFS SOL would not be a problem in current machines. Only transient effects of W influx into the discharge were observed (no influence of W on discharge after 0.5-1 sec, also on next shot). "Splashing" from divertor will be performed in next campaign.

- More detailed, quantitative analyses and comparison with SANCO modelling are ongoing (will be reported in next PSI).

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I_p = 600 kA, P_{NBI} = 5 MW, H-mode discharge

Damage of in-vessel components by high speed collision

- Hyper velocity dust impact on PFCs and diagnostics can cause severe damages.

- Runaway impact at Tore Supra (captured by high speed camera)

**FIG. 2** - Electron microscope analysis of the surface of the unexposed probe (left) and probe used in the measurements (right).
Damage of in-vessel components by high speed collision

- Quantitative measurement of in-vessel dust velocity and its correlation with toroidal rotation of plasmas

Damage of in-vessel components by high speed collision


\[ V_{\text{tungsten}} = \sqrt{\frac{m_{\text{carbon}}}{m_{\text{tungsten}}}} \cdot V_{\text{carbon}} \]

- Impact of carbon dust with a velocity of 316 m/s on Beryllium wall is equivalent to an impact of a tungsten dust with a velocity of 100 m/s.

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohmic</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>L-mode</td>
<td>0.51%  (5 events)</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>H-mode</td>
<td>0%</td>
<td>0.66%  (4 events)</td>
<td>1.89%  (14 events)</td>
</tr>
<tr>
<td>NBI power</td>
<td>1.3 MW</td>
<td>1.5 MW</td>
<td>3.2 MW</td>
</tr>
</tbody>
</table>

Probability and the number of dusts over 316 m/s

- Number of dust with speed higher than 316 m/s increases as a function of input power

Suk-Ho Hong, IAEA Divertor Concept TM, 29th Sept.-2nd Oct. 2015, Vienna, Austria
Damage of in-vessel components by hot dust

- Modeling of dust behavior in conventional operation range of a tokamak shows that the temperature of a dust can reach several 1000 K.
- Such hot dust can cause melting of metal PFCs.

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Diagram showing temperature of a spherical carbon dust particle at thermal equilibrium in a deuterium plasma with temperature $T_e = T_i$ and with fraction $\gamma_c = 1\%$ of carbon impurity ions.

Damage of in-vessel components by hot dust

Primary dusts impact on lower passive stabilizer, cause second generation, are that impinging on fast reciprocating Langmuir probe (FRP) in KSTAR.

Melted Mo probe head
With a crater

Broken BN cover

The same type probe used for the campaign afterwards. Broken BN cover after plunging, but not melted.

Melted spot of a quartz window nearby FRP due to hot dusts

Suk-Ho Hong, IAEA Divertor Concept TM, 29th Sept.-2nd Oct. 2015, Vienna, Austria
Stress relaxation of layers by dusts

- Layers deposited on a substrate build internal stress.
- Once the stress overcome adhesion, layers peel off resulting in mobilization, become dusts.
- If dusts are incorporated in layers, they actively relax the stress, leading to thick layers up to several hundred μm. (by a factor 4 in figure)
- Such layers with incorporated dusts inside are observed in KSTAR, Tore Supra, TEXTOR.
- This might be one of reasons why redeposited layers in tokamaks have no ‘well defined” critical thickness before they peel off.

- This is universal, the same for metal layers.
Tritium retention and Radioactivity

- Retention in co-deposited layers and dusts cannot be separated, since “mobilized” layers will become automatically dusts (dust conversion factor).
- T inventory in metal machines, e.g. JET with ITER-like wall, is very low, and main retention mechanism is long term retention via co-deposition in Be layers (S. Brezinsek et al., Nucl. Fusion 53 (2013) 083023).
- Concentrate on retention in tungsten nano- to micron-size dusts.
Tritium retention and Radioactivity

Tritium release: with Temperature, air flow

- **Filtration by impaction**
  - Large quantity produced (g), Pure W
  - mono-disperse, 2 types: centered at 0.7µm or at 2.9µm
  - Low Surface Specific Area (SSA)
  - apparent low defects density

- **Laser production**
  - Low production rate
  - Large SSA (to be measured)
  - Mono disperse (80 nm)

- **T release** with SSA
  (high discrepancy depending on dust design)

- **Release of T in HTO form mainly due to moisture (H₂O) in the carrier gas**

- **T** inventory varies with type and size of dust.
- Smaller dusts have trapped much more tritium than larger ones.
- Tritium trapping in powder triggered by surface effects (rough and defected surface).

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C. Grisolia et al., “Tritium absorption and release from relevant tokamak tungsten dust”, ISFNT-12, 14-18 Sept., Juju, Korea

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Suk-Ho Hong, IAEA Divertor Concept TM, 29th Sept.-2nd Oct. 2015, Vienna, Austria
Tritium retention and Radioactivity


S. -H. Hong et al., ITPA div/SOL meeting, Aachen, Jan 2012

V. Rohde et al., dust CRP, IAEA, Vienna, Dec 2011
Tritium retention and Radioactivity


Movies document technician experience of mobilizability of tritiated particles - dust can levitate, fly across fume hoods and climbs walls!

Explosion

- ITER Design Basis Accidents include potential for:
  - H₂ explosion
    - Dust on hot surfaces will produce H₂ with air ingress and can react with air.
    - Hot ≥ 400 °C for Be and W.
    - H limited to 2.5 Kg in ITER.
    - Quantities of hot dust that could produce 2.5 Kg of H in steam reaction during ITER accident are 6 kg of Be, C, and W dust, or, 11 kg of Be and 77 kg of W dust, if carbon is not present.
  - Dust explosion triggered by H₂ ignition.
  - Dust explosion by oxidation.
A. Denkevits and S. Dorofeev have studied dust explosion (FZKA 6987, 2004 May).

- 0.6-0.9 μm, 5 μm, 12 μm tungsten, 4 μC carbon, and mixture of W+C were tested in pressurized dry air.

- Max overpressure, max rate of pressure rise, lower explosion concentration are measured.

- 5 μm and 12 μm tungsten dusts do not appear to explode under standard test condition in the concentration range 250 to 6000 g/m$^3$ (12 μm) and 300 to 7000 g/m$^3$ (5 μm).

- Fine tungsten dust is able to explode in the concentration range from 450 g/m$^3$ (lower explosion limit) to 7500 g/m$^3$.

- Maximum over pressure increases with concentration, has maximum at 5.7 bar at 5000 g/m$^3$.

- Pressure rise rate increases with concentration as well, and has maximum at 300 bar/s.

- Graphite/tungsten dust mixtures are able to explode faster than its constituents.
Pre-requisites for the safety analysis

- Physical properties
  - Size and shape distributions
  - Material density
  - Radioactivity

- Chemical properties
  - Chemical composition
  - Bonding state
IAEA dust CRP and dust database

- IAEA CRP on characterization of size, composition and origin of dust in fusion devices by B. Braams and H. Chung.
- After the meeting, “standard procedure” for dust collection and analysis methods has been set by S. Hong.
IAEA dust CRP and dust database

- Infra structure of IAEA dust database has been developed by S. Hong, installation and test are ongoing.
- Initial database from KSTAR and ASDEX Upgrade will be available soon.
Summary

- Dust in plasmas is an old issue and well known phenomena since the beginning of the plasma research.
- Dusts causes safety issues in tokamaks.
  - Degradation of plasma performance as “uncontrolled pellet injection“ from LFS SOL
    - Splashing of 3 mg tungsten dusts shows only transient effect on plasma performance.
    - Behavior of solid and liquid tungsten would be different, R & D needed.
  - Damage of in-vessel components by high speed collision or by high temperature dusts
    - As input power increases, portion of high velocity dusts will be increased.
    - Need to quantify number of events and the damage (crater formation, melting…)
  - Stress relaxation of layers by incorporated dusts
    - No data in tokamak. R & D needed.
    - Might be one of reasons why redeposited layers in tokamaks have no ‘well defined” critical thickness before they peel off.
Summary

- Dusts causes safety issues in tokamaks.
  - Tritium retention and Radioactivity
    - T inventory varies with type and size of dust.
    - Charge on tritiated dust has to be considered seriously.
  - Explosion
    - Small dusts have chance to explode.
    - Dusts of mixed material would be important to monitor.

- Larger dusts have low T retention, less explosive.
- Smaller dusts have large T retention, more explosive, easily incorporated into layers.
- House-keeping for small dusts in ITER will be very important, and removal of them during the shot has to be seriously considered.
Summary

Transport of dust

Collection/extract of dust

- Powder: Al$_2$O$_3$, 5um
- Operation pressure: $2.5 \times 10^{-1}$ Torr
- RF Power: 7W


(Courtesy of B. Annaratone, C. Godde)
Thank you for your attention!
Impurity Transport Control: Impurity Source

- Performance test under atmospheric pressure
- Amount of powder per single shot
  - W (5μm) : ~0.2 mg // W (12μm) : ~2.8mg // W (24μm) : ~1.6mg
  - Mo (2~4μm) : ~0.07 mg // Fe (6~10μm) : ~0.1mg
- Flight distance : W (12μm) shows the longest distance \( \text{(Max 9cm)} \)
- Flight speed : 1.0m/s \(-\) 4.0m/s

S. Hong, KSTAR PAC meeting, 27. April 2015, Daejeon, Korea