Characterization of dust and its dynamics in LHD, JT-60U and TRIAM-1M

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Thanks for LHD, JT-60U and TRIAM-1M groups
Plasma Facing Materials in LHD and JT-60U

LHD

Divertor by Carbon
First wall by Stainless Steel

JT-60U
Carbon machine (mainly)
TRIAM-1M Tokamak

Bird’s-eye view of TRIAM-1M

M. Sakamoto

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<table>
<thead>
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<tbody>
<tr>
<td>Major radius</td>
<td>0.84 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>0.12 m</td>
</tr>
<tr>
<td>Toroidal field</td>
<td>8 T (Steady State)</td>
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TF coils: Nb$_3$Sn (superconductor)
PF coils: Cu (normal conductor)

Plasma facing components: High Z

Wall Conditioning:
(1) Baking of extension ports and then
(2) ECR discharge cleaning for PFCs
Variation of dust particles

LHD:

Carbon dust

Metal dust

TRIMA – 1M

Mo dust
Connection of nano-order carbon dust produces larger dust (by TEM analysis) in LHD
Size distribution of dust particles in LHD

Many small size of dust is observed using both analysis of SEM and TEM

Under 1 μm... small spherical shape
Over 1 μm... mainly Fe, Cr, irregular shape
Collected mass density in LHD

![Graph showing collected mass density over time.](Image)

J.P. Sharpe et al. / Journal of Nuclear M

Fig. 4. Distribution of surface mass density of dust collected from LHD.
Dust collection results

Dusts were collected in one poloidal (P10) section (1/36 toroidal area) in 2003, and they have been deposited in W-shaped divertor operation (1997-2002).


Dusts were cumulated on lower PFCs:
• **not only tile surface** (2.1mg on the first wall and 4.1mg on the divertor plates) **but also under tiles of the outer baffle** (10.5mg). (⇒ fig.)

• **larger number of dusts were cumulated under the divertor plates.** (⇒ next page)
Number of dusts were found under divertor (shadow area)

- Collected dust was 170 mg (for 1/36 toroidal area): 95% was on the lower VV, 90% (150mg) was under the divertor plates: most dense area was under outer (Low-Field-Side) divertor and dome, i.e. on the exhaust route of gas flow by divertor pumping in experiments.
Dust production was smaller than C erosion at LFS divertor

Extrapolation to total dust weight in the whole VV is 7 g
⇒ averaged Dust production rate is estimated to $\sim 0.2 \text{mg/s} (1.1 \times 10^{19} \text{C/s})$

(7g is divided by NBI period of $3 \times 10^4 \text{s}$ in 13000 shots)

Dust production rate is small, such as 3-7% of net-erosion rate at the outer divertor surface.

Time-averaged C ionization flux at the outer divertor ($2.3 \times 10^{21} \text{C/s}$) was 6 times larger than er.rate ($\sim 4 \times 10^{20} \text{C/s}$). Time-averaged C influx at the inner divertor ($7.4 \times 10^{20} \text{C/s}$) was comparable to dep.rate ($6 \times 10^{20} \text{C/s}$).

C mass density of the deposition layers is $\sim 1/2$ of CFC ($1.7 \text{g/cm}^3$)

N. Asakura, K. Masaki
Comparison of Plasma strike point around divertor region

Particle size distribution is quite different. In LHD large size carbon was not observed.
Dust movement in TRIAM-1M from limiter

Visible camera 30 to 4500 frames per second (fps) in the full frame. In this case, 4500 frames is used.

full complement of pixels (256 x 256 pixels).

Velocity is observed from 10 to 50 m/s
Dust movement in JT-60U @ divertor region

• Visible fast camera of 2 kHz (1024x1024 pixs, 3s) - 8 kHz (256x256 pixs, 8s) was measured from tangential port.

• Dust from outer divertor is moving towards the main plasma(#46953).

• Many dusts were removed from deposition layer near INNER strike-point after ELMs

• Toroidal /poloidal movements are 0.2-0.5km/s

• The toroidal movement was mostly ion drift direction. it is consistent with SOL flow measurement

N.Asakura
Advantage in LHD:

Magnetic field is steady state during plasma discharge

Phoenix (FILR)
-0.025K@30 °C
-InSb 3-5μm
-Time resolution 5.29ms (320x256 pixels)

Diameter of dust
LHD: 8 nm – 10μm (Carbon and Stainless steel)
Infrared images

Directions of moving heated dusts are not uniform
The observed velocities of dust particles are about 1–20 m/s.
Comparison of moving direction of dust and magnetic field line (same dust, different time)

Blue: dust movement, Red: magnetic field line

A difference is observed mainly at vertical direction
**Dust Dynamics using theoretical model**

**Motivation:** an understanding dynamics of dust particles

![Life of Dust Diagram](image)

**Production** → **Movement** → **Deposition**

**Modeling supports difficult regions of time, space by diagnostics**

":"Estimation of dust diameter": Camera measurement is difficult due to relation between spatial channel and dust size. And then, a modeling estimate this diameter based on experimental results."
I) Model

1) **1D analysis**; along magnetic field $\xi$

2) **spherical dust** with charge $Q_d = -Z_d e < 0$

3) small dust: $R_d << l_D \sim \text{few tens } \mu\text{m}$

4) stationary after-glow plasma
   
   plasma decay time $>>$ dust dynamics

5) plasma flow in collisional presheath (CPS)
   
   and neutral plasma
   
   $\rightarrow$ ambipolar flow to wall
   
   along magnetic field

6) uniform oblique magnetic field
2) Estimation of forces

\[ F_{iab} = \pi R_d^2 n m_i V^2 (1 - Q_d e / 2 \pi \varepsilon_0 R_d m_i V^2) = 2.17 \times 10^n TR_d^2 \]

: drag force due to ion absorption

\[ F_{isc} = n Q_d^2 e^2 \ln \Lambda / 4 \pi \varepsilon_0^2 m_i V^2 = 1.14 \times 10^2 nTR_d^2 \]

: drag force due to Coulomb scattering

\[ F_E = Q_d E = 1.7 \times 10^9 nTE \]

: electrostatic force

For the case of effective force direction of dust particle is along the magnetic field lines, and then, electrostatic force is removed

- Plasma parameter at dust
  - a low density plasma a order of \(10^{17} \text{ m}^{-3}\)
  - \(T_e\) and \(T_i\) are a few eV.

- Stationary charge of dust: \(Z_d / R_d T_e = 1.06 \times 10^{28}\)
3) Force of dust particle

\[ F_\xi = F_{iab} + F_{isc} = 1.35 \times 10^2 \ nTR_d^2 \]

- acceleration: experimental data

- dust mass: \[ m_d = 4\pi R_d^3 \rho_d / 3 \]

\[ m_d \frac{dV_d}{dt} = F_\xi = F_{iab} + F_{isc} = 1.35 \times 10^2 \ nTR_d^2 \]

Dust diameter \( R_d \) is determined

\* \( \rho_d \) is density of dust. In LHD, carbon and stainless steel are considered.
Dust experiment in LHD; to compare modeling and experimental results

Starting a brightness signal from the holder. Carbon dust is injected to the plasma direction. One of injected dust is reflected on the wall. Moving direction is not uniform.

This data supports our theoretical model in future works.
Estimation of thermal intensities is difficult

Temperature is discussed about lifetime of dust particles on modeling

- Diameter of dust is smaller than one spatial channel of field of view from infrared camera (as one order)
- Diameter of dust is constant during one frame
- Relationship between wavelength and diameter of dust (micron order)

Detection

1 Frame

Intensity

Temperature (K)
Carbon dust measurement by Mie scattering using YAG laser system in JT-60U

At SOL region, strong intensities are observed after disruption

N. Asakura
Removal method; ICRF discharge cleaning in LHD

In LHD hydrogen removal rate by GDC is 10 times larger than ICC.

170Pa m³ (H₂) 8550 sec

2180 Pa m³ (H₂) 10900sec

N.Ashikawa et al., FED
Material probes on ICWC

- From experiences (LHD, AUG, others), effective cleaning area by ICRF conditioning is considered smaller than by glow discharge.
- From damages area of material probes, effective cleaning area by ICRF conditioning was estimated.
- Material holder was installed at the first wall level.
- It have three kinds of facing.

1. Plasma Facing Area
2. Vertical direction
3. Gap (slit 1.5mm)
   Demonstration between divertor tiles

Plasma

<table>
<thead>
<tr>
<th>Vacuum Vessel</th>
<th>4.5L-Port</th>
<th>Probe Head</th>
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<tbody>
<tr>
<td>Helical Coil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material Probe System</td>
<td>4.5L-Port</td>
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## Transmission Electron Microscopy (TEM) Analysis

**Bright field images, SS316L**

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<tr>
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<th>Plasma facing</th>
<th>Vertical</th>
<th>Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ICRF conditioning</strong> (about 4000s)</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Number of damages</strong> is depend on direction - it is suggested effective charge exchange particles to the wall straight. ICWC is cleaning only plasma facing area.</td>
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### Damages with He bubbles are observed only plasma facing area
- Vertical : small
- Gap : non
Future work

Multi machine experiment of injecting dust with known-particles