Beyond Orbital-Motion-Limited theory effects for dust transport in tokamaks

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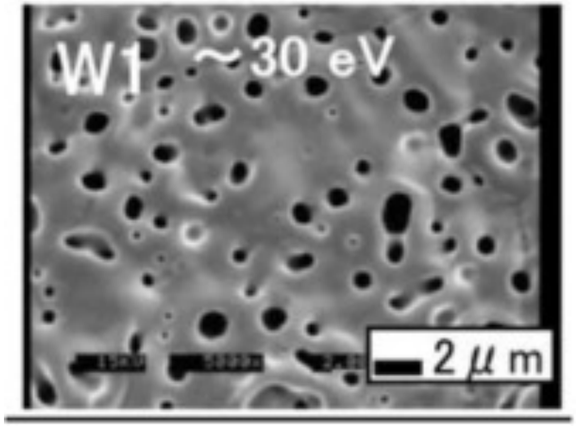
Outline

- Motivation: magnetic fusion energy
- Conventional model of dust transport in tokamaks: OML
- Thermionic emission, positively charged dust regime
  - Problems with OML
  - OML^{+} approximation
- Conclusions

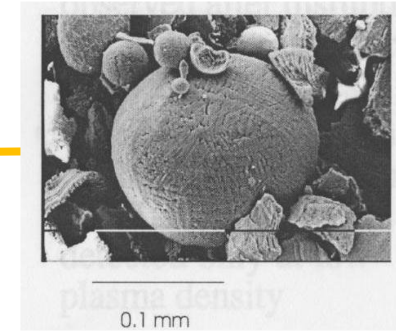
Plasma-material interaction in a fusion reactor

- Burning plasmas: intense heat/particle/neutron fluxes to the wall
- Two competing processes:
  - Erosion: TEXTOR limiter tip estimated to 1 m/year gross erosion
  - Redeposition: wall material released as neutrals, ionized and redeposited
- Steady-state fusion reactors rely on a nearly perfect balance between erosion and redeposition
- Greenwald report 07: PFCs and materials TIER 1 (most urgent) R&D challenge in fusion research!

Holes on Tungsten



Existing tokamaks produce dust

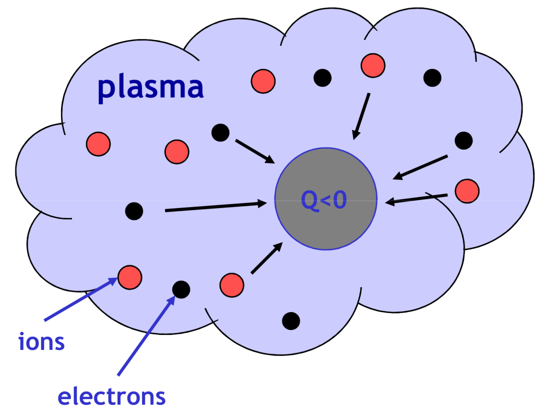


Winter, POP 00

- Presence of dust (UFOs) known for a long time
- Produced by plasma-material interaction, maintenance
- Not an issue in short-pulse tokamaks: lower heat load $q_{ref} = 1\,\mathrm{MW/m^2}$
- A problem in ITER-era: higher heat load $q_{ref} = 10\,\mathrm{MW/m^2}$
  - hundreds kgs of dust estimated for ITER
  - dust safety limits
  - Can dust survive in ITER?
- Safety issues & operational issues:
  - Dust penetration. Plasma pollution, disruptions
  - PMI. Survivability, non-local redeposition

Conventional model of dust transport: OML

- Dust charging: $$\frac{dQ_d}{dt} = I_i + I_e + I_{se} + I_{th}$$



- Dust motion: $$\frac{d\mathbf{x}_d}{dt} = \mathbf{V}_d$$ $$m_d\frac{d\mathbf{V}_d}{dt} = Q_d\left(\mathbf{E} + \mathbf{V}_d \times \mathbf{B}\right) + \mathbf{F}_{i,drag} + \mathbf{F}_{n,drag} + \mathbf{F}_{rocket}$$
- Dust grain heating: $$\frac{d}{dt}\left(C_d m_d T_d\right) = q_e + q_i + q_n - q_{sec} - q_{th} - q_{rad}$$
- Dust mass loss: $$\frac{dm_d}{dt} = \frac{q_{net}}{H_{evap}} \xrightarrow{\text{spherical dust}} 4\pi r_d^2 \rho_d \frac{dr_d}{dt} = \frac{q_{net}}{H_{evap}}$$

- Coupled with the background plasma model
- Currents, ion drag and heat fluxes modeled by the OML theory
- Standard model used by many groups: DUSTT, DTOKS, MIGRAINE, …

Checking OML applicability

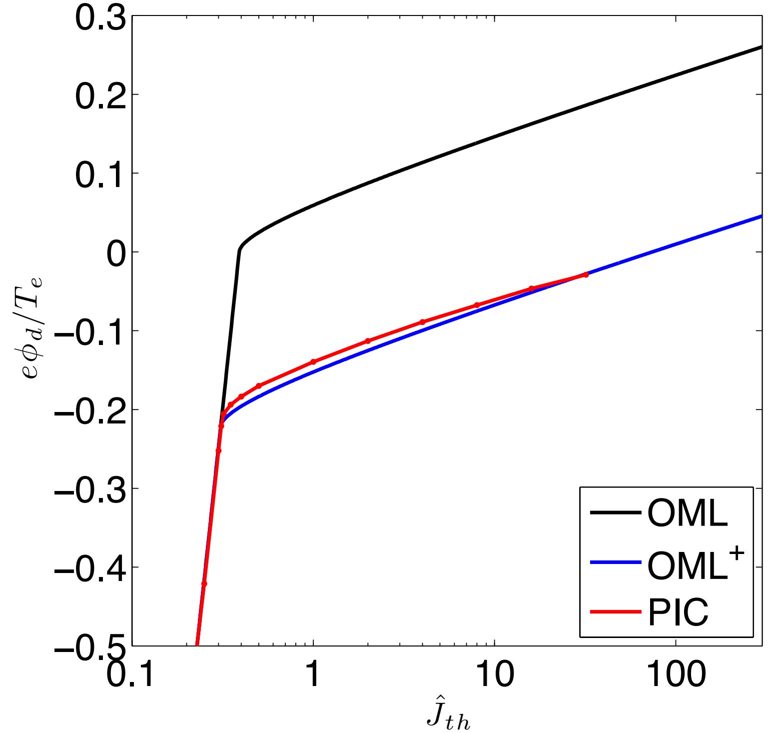
- PIC simulations: spherical dust grain in a plasma + thermionic emission. $r_d = \lambda_{De}$, $T_d/T_e = 0.03$

Richardson-Dushman current:

$$\hat{J}_{th} = \frac{J_{th}}{e n_0 v_{th,e}} = \frac{4\pi m_e T_d^2}{n_0 v_{th,e} h^3} \exp\left(-\frac{W}{T_d}\right)$$

Thermionic current [Sodha&Guha, 71]:

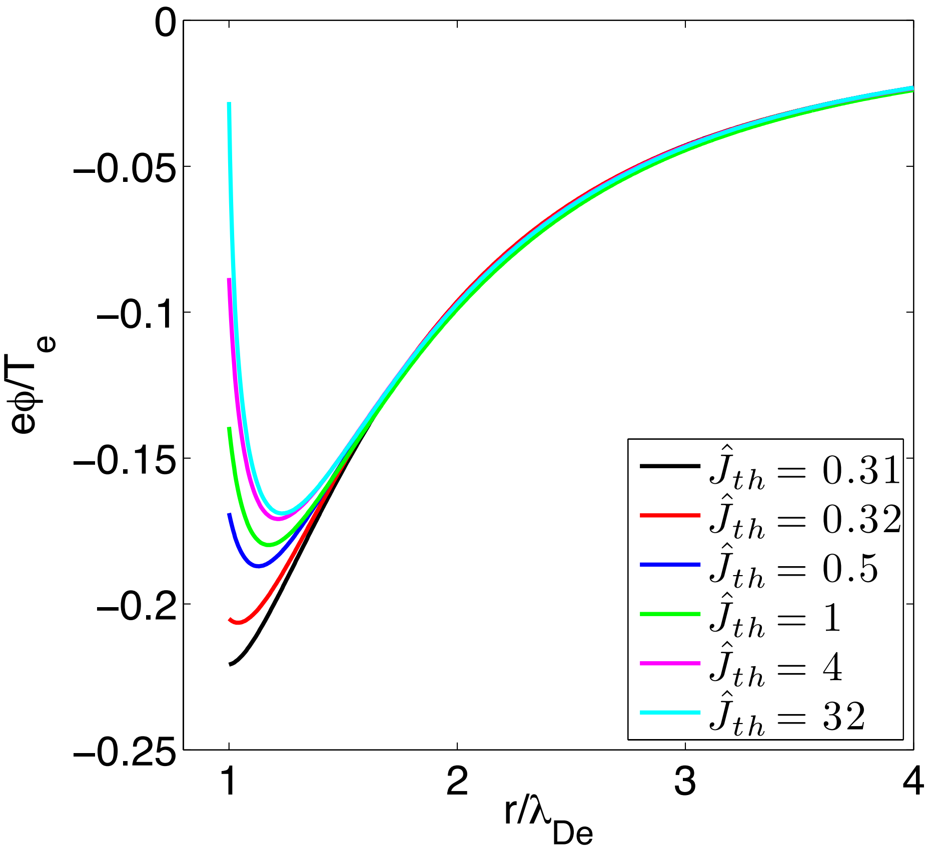
$$I_{\rm th} = (4\pi a k T_d)^2 \times \frac{m_e e}{h^3} e^{-W/kT_d} \begin{cases} 1 & \text{if } \phi_d < 0 \\ (1 + \frac{e\phi_d}{kT_d}) e^{-e\phi_d/kT_d} & \text{if } \phi_d > 0 \end{cases}$$



Theory and simulations disagree in the positively charged regime. Good agreement for negatively charged

The disagreement is due to a non-monotonic potential near the dust grain

- In the positively charged regime, a trapped particle thermionic electron population exists



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Delzanno et al, PRL 04; POP 05; PRL14

Understanding the disagreement: orbital motion

- Steady state of a collisionless plasma in a central force field

$$v_r^2 + v_\theta^2 - \frac{2e}{m_e}\phi_d = v_r'^2 + v_\theta'^2 - \frac{2e}{m_e}\phi(r),$$ Cons. energy

$$m_e r_d v_\theta = m_e r v_\theta',$$ Cons. angular momentum

+ Liouville's theorem

- Equivalent to radial motion in effective potential

$$v_r^2 - U(r, v_\theta) = v_r'^2$$

$$U(r, v_\theta) \equiv \underbrace{\frac{2e}{m_e}\left[\phi_d - \phi(r)\right]}_{\text{Electrostatic force}} - \underbrace{\left[1 - \left(\frac{r_d}{r}\right)^2\right] v_\theta^2}_{\text{Centrifugal force}}$$

Electrostatic force   Centrifugal force

The potential determines the orbit around the grain

- Maxima of the effective potential depend on v_θ

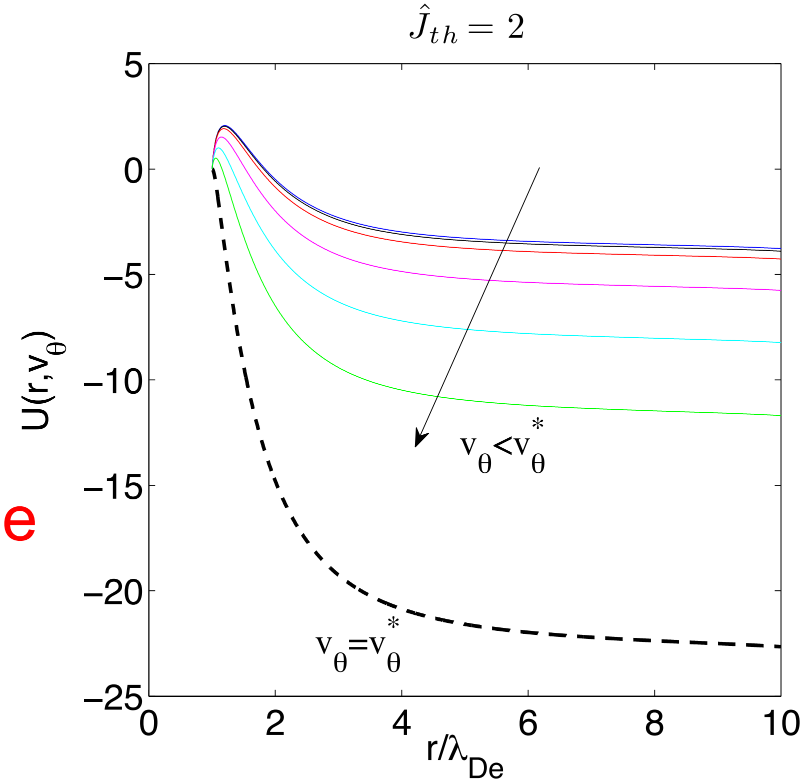
$$-\frac{e}{m_e} r_m^3 \phi'(r_m) = r_d^2 v_\theta^2$$

Potential well: only 1 solution for $r_d \le r_m \le r_{min}$

- Critical tangential velocity

$$v_\theta^* = \sqrt{-\frac{e}{m_e} r_d \phi'_d}$$

- $v_\theta > v_\theta^*$ monotonic U-> passing
- $v_\theta < v_\theta^*$ non-monotonic U-> can be trapped!



OML misses the emitted electrons trapped/ passing boundary …

- Full OM trapped/passing boundary of the emitted electrons

$$v_r^2 = U(r_m(v_\theta), v_\theta)$$

- Approximation: slow emitted electrons, see the potential barrier at the minimum of the electrostatic potential r_{min}

$$v_r^2 + \left[1 - \left(\frac{r_d}{r_{min}}\right)^2\right] v_\theta^2 = \frac{2e}{m_e}(\phi_d - \phi_{min})$$

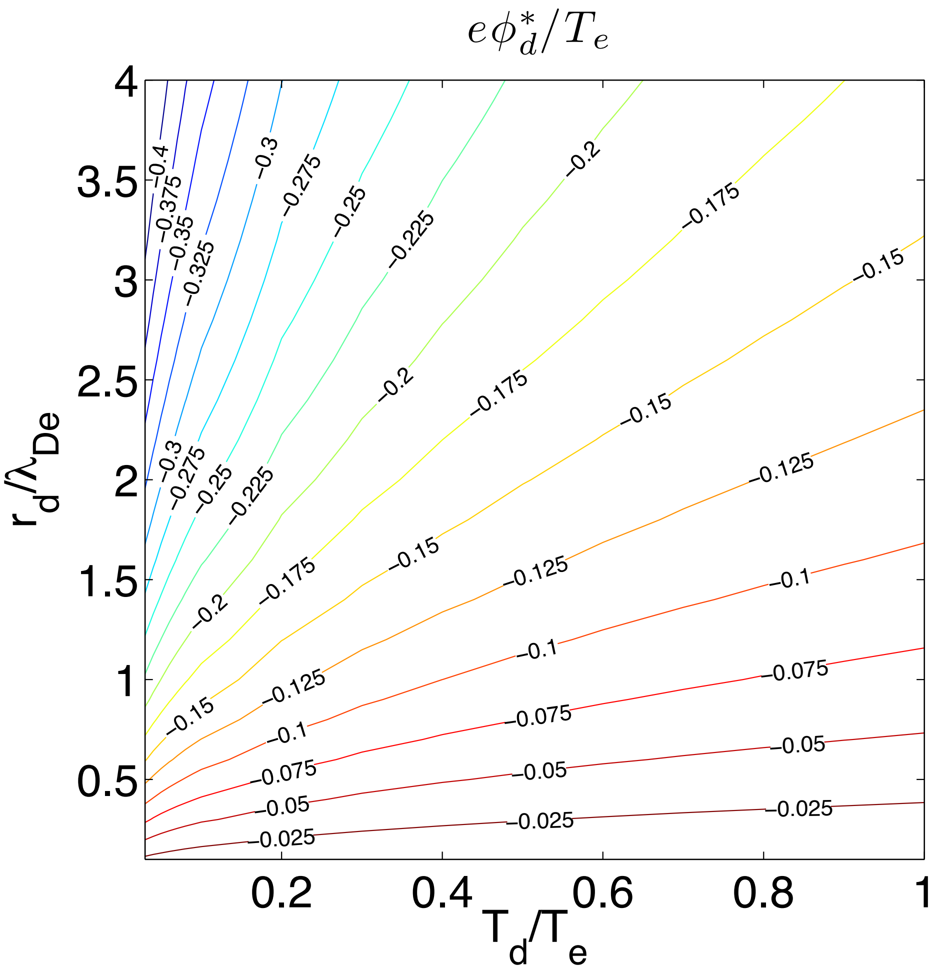
- OML trapped/passing boundary [Sodha&Guha, 1971]

$$v_r^2 + v_\theta^2 = \frac{2e}{m_e}\phi_d$$

… when the potential well is deep and localized!

Potential well effects are important for large grains and small dust temperatures

- Solve OML Poisson's equation to calculate the transition from negatively to positively charged dust grain: $J_{th} \rightarrow Q_d=0$



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Can we develop an OML-like theory when potential well effects are important? OML$^+$

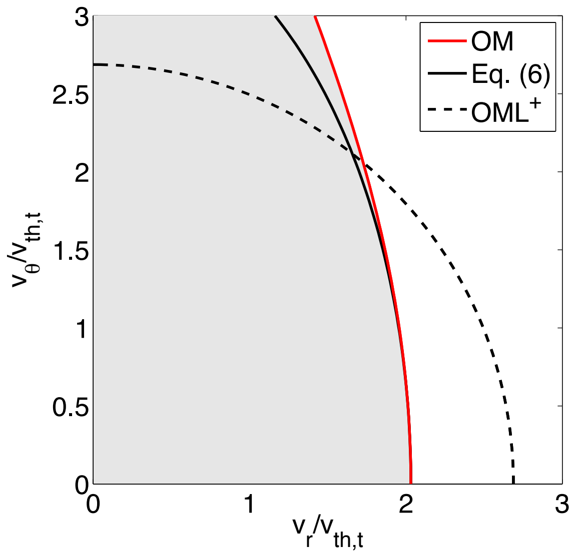
- Challenging because OML does not solve Poisson's equation
- Approximate emitted e$^-$ T/P boundary

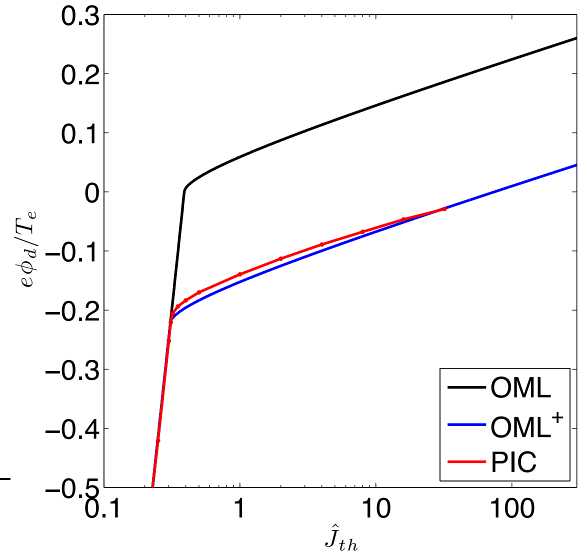
$$v_r^2 + v_\theta^2 = \frac{2e}{m_e}\left(\phi_d - \phi_d^*\right)$$

- Emitted current

$$I_{th} = 4\pi r_d^2 J_{th} \exp\left[-\frac{e\left(\phi_d - \phi_d^*\right)}{T_d}\right]\left[1 + \frac{e\left(\phi_d - \phi_d^*\right)}{T_d}\right]$$

- Recovers OML when potential well effects are unimportant
- Good agreement with PIC





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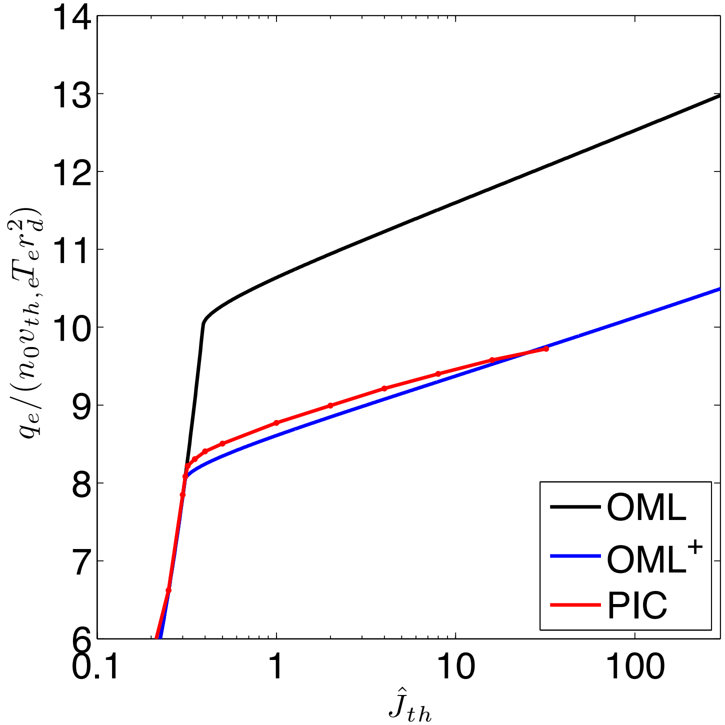
OML overestimates the power collected by the dust grain from background electrons

- Important for dust survivability
- Positively charged dust grains are heated mostly by background electrons [Smirnov et al., PPCF 07]



$$\hat{q}_e = q_e / \left(n_0 v_{th,e} T_d r_d^2 \right)$$

TABLE I: Parametric study increasing the dust radius for $\hat{J}_{th} = 2$ and $T_d/T_e = 0.03$ ($R/\lambda_{De} = 20$ for $r_d/\lambda_{De} > 1$).

r_d/λ_{De}	$e\phi_d^{PIC}/T$	$\hat{q}_e^{PIC}$	$\hat{J}_{th}^*$	$e\phi_d^*/T_e$	$e\phi_d^{OML^+}/T_e$	$\hat{q}_e^{OML^+}$
1	-0.113	9.0	.31	-0.22	-0.125	8.8
2	-0.208	8.1	.27	-0.33	-0.228	8.0
3	-0.268	7.7	.26	-0.39	-0.292	7.5
4	-0.309	7.4	.24	-0.44	-0.336	7.2

$q_e^{OML} \sim 11$

Conclusions

- Dust transport in tokamaks is very important for ITER
  - Can we really accumulate many kgs of dust? Can dust survive?
- Conventional dust transport model is based on OML
- OML can break in the limit where the dust grain becomes positively charged due to electron emission processes
  - Overestimates the dust collected power
- An OML^{+} approximation of the emitted electrons trapped/passing boundary is shown to be in good agreement with PIC simulations