Dusty wall or dust wall

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Magnetized sheath

- Magnetized plasma sheath, from wall to interior plasma, is made of three parts
  - Debye sheath: λ_D
  - Chodura Layer (magnetic presheath): ρ_i
  - Plasma presheath: plasma size
- Electric field and plasma flow:
  - Plasma presheath: ambipolar electric field accelerates ion flow to sonic speed parallel to B.
  - Chodura layer: $E_C \sim k_B T / e\rho_i$ plasma flow deflected from B and form normal ion flow to ion sonic speed. ExB and parallel flow lead to sonic poloidal and toroidal ion flow parallel to the wall.
  - Debye sheath: $E_D \sim k_B T / e\lambda_D$ ion flow reaches supersonic speed in all directions.

A reference DEMO plasma

- A tokamak DEMO with one GW fusion output and Q=20.
  - R = 7 m, B = 6 Tesla
  - Wall heat load: $P_{\rm wall} = 250\ {\rm MW},$
- Divertor surface area: $A \approx 2 \times 2\pi R_0 L,$
- If all heat goes to divertor with heat flux $\Gamma_{\rm H} = 10\ {\rm MW/m^2},$

$$L = \frac{P_{\rm wall}}{\Gamma_{\rm H}} \frac{1}{4\pi R_0} = 0.3\ {\rm m}$$

- Plasma parameter near the divertor:

$$T_e = T_i = 10\ {\rm eV}, n_0 = 3 \cdot 10^{20}\ {\rm m^{-3}}.$$

Dust motion near the wall

- Dust particles are negatively charged:

$$Q_d = 2 \cdot 10^4 \frac{T}{10\text{eV}} \frac{r_d}{1\mu\text{m}} e,$$

- Lorentz force and gravity are negligible for micron-size or smaller dust particulates.
- Normal to the wall: electric force and ion flow drag force equilibrium position in the Chodura layer and Debye sheath for micron-size dust particulates.
- Parallel to the wall: ion flow drag is unbalanced.

$$\mathbf{F}_d = \frac{m_d}{\tau_d}(\mathbf{V}_i - \mathbf{v}_d). \qquad \tau_d = \frac{m_d}{10\pi r_d^2 m_i n_i v_{\text{thi}}} = 0.12 \frac{r_d}{1\mu\text{m}} \frac{3 \cdot 10^{20}\text{m}^{-3}}{n} \; s,$$

- Equation of motion parallel to the wall

$$\begin{aligned}
\frac{dR}{dt} &= v_{dR} \\
\frac{dv_{dR}}{dt} &= \frac{V_{iR} - v_{dR}}{\tau_d} + \frac{v_{d\varphi}^2}{R} \\
\frac{dv_{d\varphi}}{dt} &= \frac{V_{i\varphi} - v_{d\varphi}}{\tau_d} - \frac{v_{dR} v_{d\varphi}}{R}.
\end{aligned}$$

What happens to the dust particle

- Divertor poloidal transit time:

$$\tau_t(\gamma = 0) = \bar{\tau}_t = \sqrt{2L\tau_d/V_{iR}} = 1.8 r_{d1\mu\mathrm{m}}^{1/2} \ \mathrm{ms}.$$

$$\gamma \equiv \frac{V_{i\varphi}}{V_{iR}}\sqrt{\frac{L}{3R_0}} = \frac{V_{i\varphi}/V_{iR}}{\sqrt{70}} \ll 1,$$

$$v_{dR}^{\mathrm{exit}} = V_{iR}\tau_t/\tau_d \sim 3 \cdot 10^2 \ \mathrm{m/s}.$$

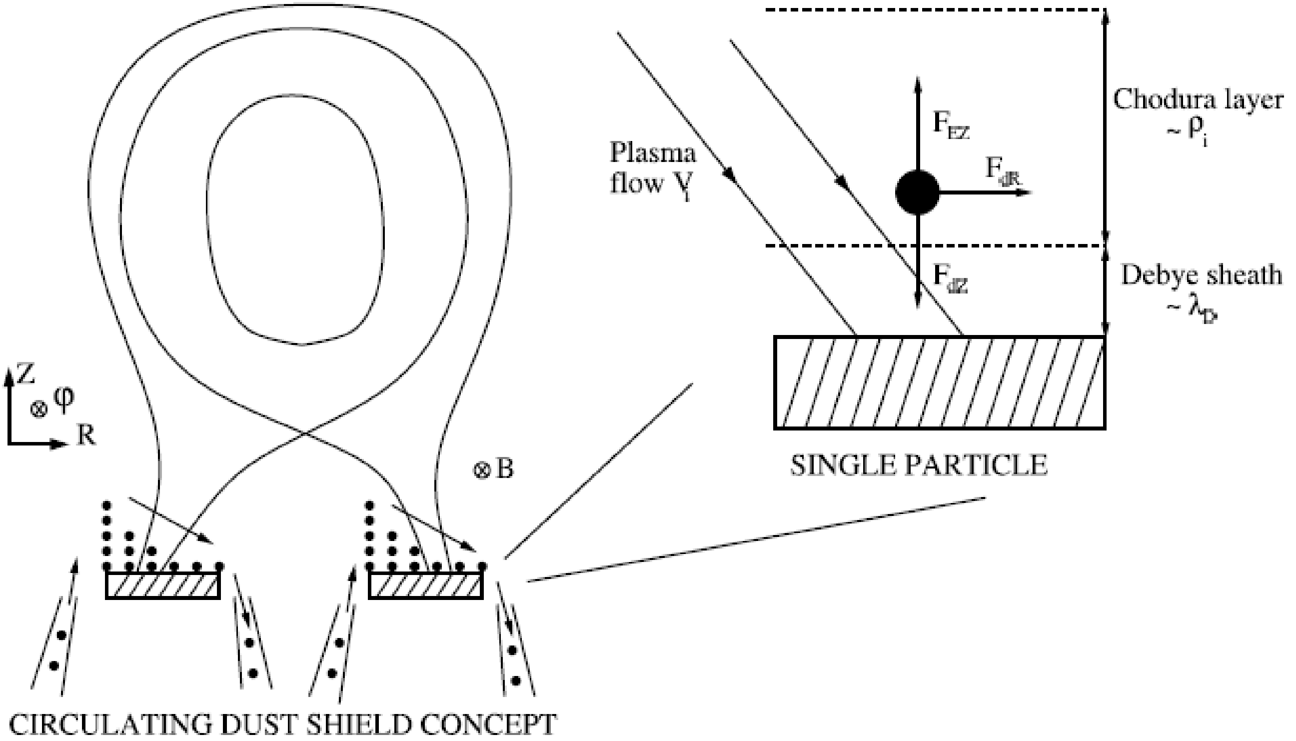
- Heating of the tungsten dust particle:

$$m_d C_d \frac{dT_d}{dt} = \Gamma_{\mathrm{H}} A_d = \pi r_d^2 \Gamma_{\mathrm{H}},$$

$$\tau_m = \frac{m_d C_d}{\pi r_d^2 \Gamma_{\mathrm{H}}}(T_m - T_0) = \frac{4 r_d \rho_d C_d}{3\Gamma_{\mathrm{H}}}(T_m - T_0).$$

$$\tau_m \approx 1.8 \times 10^{-3} \frac{r_d}{1\mu\mathrm{m}} \frac{10\mathrm{MW/m}^2}{\Gamma_{\mathrm{H}}} \ \mathrm{s}.$$

Dust wall (divertor) concept



Dust divertor parameters

- Dust surface density:

$$\sigma_d^{\text{exit}} = 1/\pi r_d^2 = 3 \cdot 10^{11}\ \text{m}^{-2}.$$

- Power consumption on the ion flow drag

$$P_{\text{drag}} = \sigma_d^{\text{exit}} 2\pi R_0 v_{dR}^{\text{exit}} (m_d v_d^2/2) \approx 28\ \text{MW}.$$

- Dust mass pump rate for the dust divertor

$$\Gamma_d^{\text{mass}} = \sigma_d^{\text{exit}} 2\pi R_0 v_{dR}^{\text{exit}} m_d \approx 3 \cdot 10^2\ \text{kg/s}.$$

- Total dust mass in the divertor

$$M_d = \sigma_d^{\text{exit}} m_d \cdot 4\pi R_0 L \sim 0.6\ \text{kg}.$$

- Dust pumping power

$$P_{\text{pump}} = \sigma_d^{\text{exit}} \pi R_0 v_{dR}^{\text{exit}} m_d (v_{dR}^{\text{source}})^2 \approx 0.28\ \text{MW}.$$

- Dust charge density

$$n_d Q_d \approx Q_d \sigma_d^{\text{source}} / H_d^{\text{source}} \sim 6 \cdot 10^{19} e\ \text{m}^{-3}$$

What can we do on NSTX?

- Sheath measurement: (near term)
  - Sheath electric field in Chodura layer and Debye sheath
  - Ion flow (normal, poloidal, and toroidal) in the Chodura layer and Debye sheath.
  - Neutral flow
- Single dust motion measurement: (mid-term)
  - Size dependence of the equilibrium position normal to the wall
  - Shape dependence on charging and drag
  - Poloidal and toroidal transit motion parallel to the wall
  - Dust heating
- Dust shield measurement: (long term)
  - Field a dust injection and collection system
  - Dust shield modification of magnetized sheath
  - Dust-dust interaction.