Ratios: (gyrofrequency/collision freq), (gyroradius/ device L)

<u>electrons</u>

(T_e ~ 2 eV, Ar)

$$\frac{\omega_{ce}}{\nu_e} \sim \frac{6 \times 10^{14} B(G)}{n_n(cm^{-3})} \gg 1$$

$$\rho_e \sim \frac{3.4}{B(G)} \text{cm} \ll L$$

Since n_n typically $10^{15} - 10^{16}$ cm^{-3} currently, need B > ~ 200 G, so electrons may already be magnetized in some expts.

<u>ions</u>

(T_i ~ .05 eV, Ar)

$$\frac{\omega_{ci}}{\nu_i} \sim 10^{12} \frac{B(G)}{n_n(cm^{-3})} \gg 1$$

$$\rho_i \sim \frac{140}{B(G)} \text{cm} \ll L$$

Since $m_i >> m_e$, $T_i << T_e$ (while $\sigma_{in} \sim 10\ \sigma_{en}$), need larger B to magnetize the ions:

B > 0.5 – 2 T with current n_n (argon)

<u>dust</u>

*($\rho_d \sim$ 2g/cc,
Ar, $T_n \sim$ 300 K)*

$$B >> \frac{R(\mu m)\, n_n\left(cm^{-3}\right)}{2\times 10^{8}\left|\phi(V)\right|}$$

$$B >> \frac{3\times 10^{5}\sqrt{T_d(eV)\, R(\mu m)}}{\left|\phi(V)\right| L(cm)}$$

Larger B needed as R↑, n_n ↑, T_d ↑, φ↓, L ↓

e.g., φ ~ - 4 V, R ~ 0.1 μm, P ~ 10 Pa, **B >> 30 T**

as above, with P ~ 0.13 Pa, **B >> 0.4 T**

Use of small dust having surface plasmon resonance?

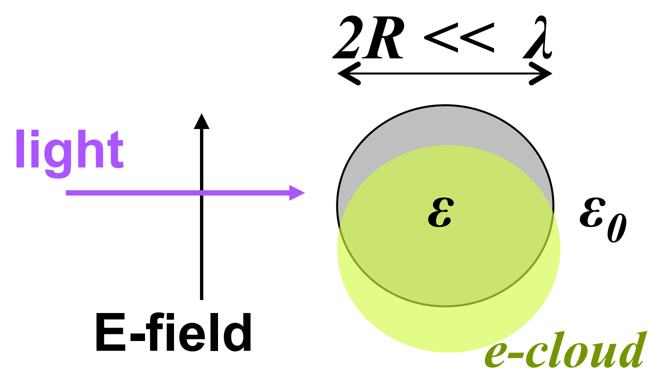
- **Background**: **Surface Plasmon (n_e wave) at interface**

Polarizability of small sphere

$$\alpha \sim R^3 \left(\frac{\varepsilon - \varepsilon_0}{\varepsilon + 2\varepsilon_0} \right)$$

resonance

Re ε = - 2 ε_0 (Im ε << 1)



surface plasmon - optical, near-UV (Au, Ag)

Possible way to see nano-sized dust in plasma

- **Absorption and scattering enhanced at SP frequency**

$$Q_{abs} \sim 4x\,\mathrm{Im}\left(\frac{\varepsilon - 1}{\varepsilon + 2}\right), \qquad Q_{scat} \sim \frac{8}{3}x^4\left|\frac{\varepsilon - 1}{\varepsilon + 2}\right|^2, \qquad x = \frac{2\pi R}{\lambda} << 1$$

- **Use of dust with SP**

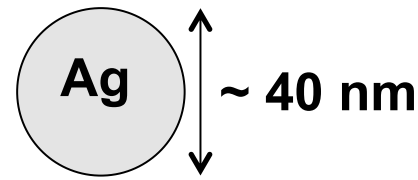
  - **'see' nanoparticle transport in plasma**

  - **'see' waves, etc. in plasma with magnetized dust (R~ 20 nm, B ~ 2T)**

Possible diagnostic for dust waves in magnetized dusty plasma

- **Nm sized dust could be magnetized**

  e.g. Ar, $T_e \sim 2$ eV, B ~ 2 T, P < 3 Pa



$$\rho_d <\sim 1 \text{ cm}, \quad \omega_{cd} > \nu_d , \quad F_{\text{Lorentz}} > F_{\text{gravity}}$$

- **'See' waves by enhanced absorption by dust with SP**

Compression - *dark*; rarefaction - *light*

$n_d \sim 10^9$ cm^{-3}

$\lambda \sim 350$ nm (Re $\varepsilon \sim -2$)

Absorption coeff. ~ 0.1 /cm

Rosenberg & Shukla, *APL* 86, 2005

Theory has been done for dust wave instabilities under the following conditions, but not aware of experiments to test these :

Unmagnetized dust, magnetized ions

e.g. Hall current (E x B) driven instabilities
drift instabilities

Magnetized dust

e.g. electrostatic dust cyclotron instability (higher harmonics too)
waves in plasma crystals

Possible constraint related to Electrostatic Dust Cyclotron waves

EDC wave: in long λ limit, $k_\perp \rho_d << 1$,

$\omega \sim \omega_{cd}(1+\Delta)$, $\Delta \sim k_\perp^2 c_{sd}^2 / 2\omega_{cd}^2 << 1$,

where the dust acoustic speed $c_{sd} \sim \lambda_{Di}\omega_{pd}$ (for $T_e >> T_i$)

$$k_\perp\left(cm^{-1}\right) < 0.01 \; B(G)\left(\frac{T_i(eV)\, n_d m_d}{n_i m_p}\right)^{-1/2}$$

e.g. $T_i \sim 0.2$ eV, $n_d/n_i \sim 10^{-4}$, $m_d/m_p \sim 2 \times 10^9$ (R ~ 0.1 μm),

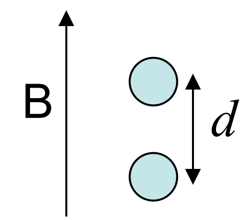
B ~ 2 T ➡ **$\lambda_\perp >$ 7 cm** ($\lambda_\parallel > \lambda_\perp$) , **larger device ?**

Estimates of B for controlling motion of paramagnetic dust

Induced magnetic moment $$M = R^3\left(\frac{\mu-1}{\mu+2}\right)B$$

Ratio of forces: attractive magnetic dipole-dipole to repulsive Coulomb

$$\frac{F_M}{F_e} \sim \frac{6M^2}{d^4}\frac{d^2}{Z_d^2 e^2} \sim 0.005\left(\frac{R^2(\mu m)B(G)}{d(\mu m)\phi(V)}\right)^2\left(\frac{\mu-1}{\mu+2}\right)^2 \propto \frac{R^4 B^2}{d^2}$$



Tune grain interactions via F_M, using superparamagnetic grains

e.g., φ ~ - 4 V, R ~ 5 μm, d ~ 100 μm, μ ~ 3 , **B ~ 200 G** , **$F_M/F_e \sim 0.1$**

as above with R ~ 0.3 μm, **$F_M/F_e \sim 0.1$ requires B ~ 5 T**

as R ↓ , B ↑

Magnetic packing force: magnetic grains move to regions of max. B

Ratio of forces: magnetic packing to attractive magnetic dipole-dipole

$$\frac{F_{MP}}{F_M} \sim \frac{\nabla(MB)}{6M^2 / d^4} \sim \left(\frac{d}{R}\right)^3 \left(\frac{\mu+2}{\mu-1}\right) \frac{d\nabla B}{6B}$$

e.g., as in previous example, R ~ 5 μm, d ~ 100 μm, μ ~ 3, B ~ 200 G,

$F_{MP}/F_M > 1$ if $\partial B/\partial z \sim 6$ G/cm

Levitate [1] **:** **F_{MP}, grav. force both proportional to R^3**

$$B\nabla B \sim \left(\frac{\mu+2}{\mu-1}\right) \frac{4\pi\rho_d\, g}{3}$$

e.g., μ~ 3, **B ~ 1000 G, $\partial B/\partial z \sim 20$ G/cm**, $\rho_d \sim$ 2g/cc

[1] Samsonov et al, NJP, 2003

Some physics issues that could be studied at large B ~ T

Charging: Debye sphere, anisotropic, E x B of electrons ($\rho_e \sim R$) ?

Forces: effect of magnetized ions ($\rho_i \sim 200\ \mu m$) on ion drag?

Fusion: how does B affect structure of ablation cloud around large grain?

Waves: observe EDC waves and instabilities?

Crystal: how do magnetized ions & electrons affect structure and waves?
(e.g., $\rho_i \sim$ lattice spacing, E x B motion in sheath)

Crystal: can crystal form if dust is magnetized (smaller R, lower Z_d) ?

Some physics issues that could be studied at B < T

(magnetized ions and/or electrons, unmagnetized dust)

Waves: observe dust wave instabilities driven by electron or ion cross –field drifts, including Hall current instabilities, and drift wave instabilties?

Paramag. dust: tune behavior of dust acoustic waves (attractive force along B, repulsive perpendicular to B)?

Paramag. dust: tune spacings and structure in a plasma crystal by changing magnitude and orientation of B?

Paramag. dust: use $F_M + F_e$ force to levitate one type of grain, F_e to levitate other type, form binary crystal?