On the theory of dust ionization waves in the gas discharge complex plasma

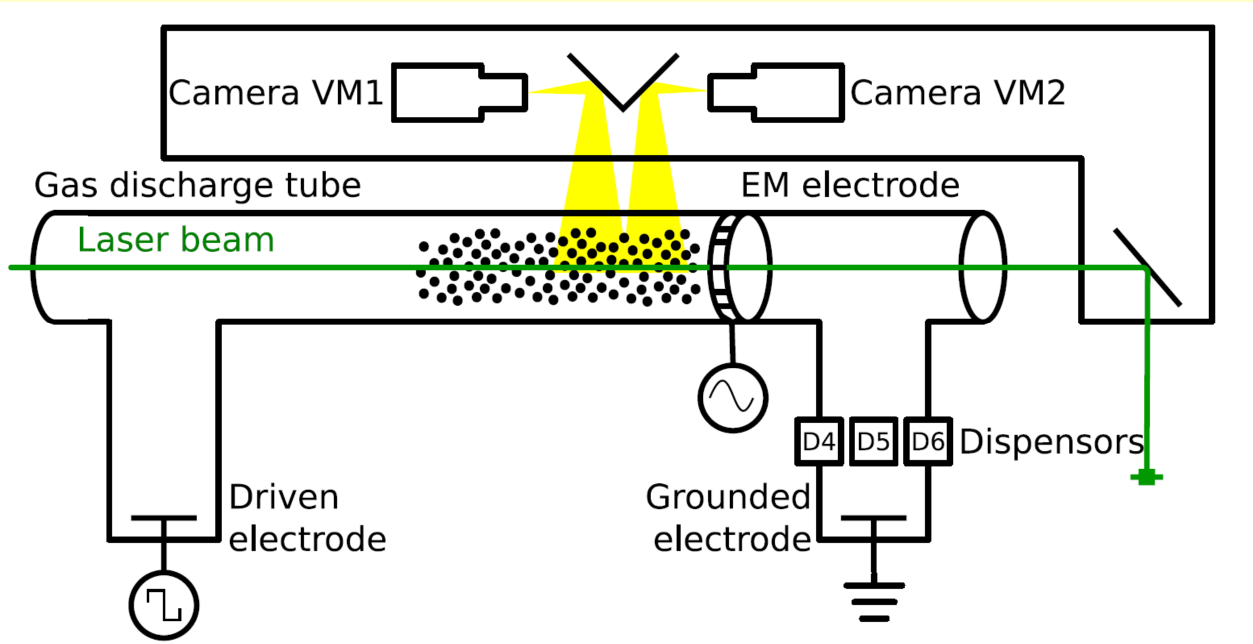
D.I. Zhukhovitskii

Joint Institute for High Temperatures, RAS,

Non-Ideal Plasma Physics, Annual Moscow Workshop
December 9-10, 2021, Moscow, Russia

Observation of the dust ionization waves (DIW) under microgravity conditions (PK-4 facility on board the International Space Station, polarity-switching dc discharge)

Naumkin V.N., Zhukhovitskii D.I., Lipaev A.M., Zobnin A.V., Usachev A.D., Petrov O.F., Thomas H.M., Thoma M.H., Skripochka O.I., and Ivanishin A.A. *Excitation of progressing dust ionization waves on PK-4 facility.* // Physics of Plasmas, 2021, vol. 28, no. 10, pp. 103704-1–103704-12.



Master equations

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\frac{c_a^2}{n_d}\frac{\partial n_d}{\partial x} + \frac{Ze}{M}\frac{\partial \varphi}{\partial x},$$

$$\frac{\partial n_d}{\partial t} + \frac{\partial}{\partial x}(un_d) = 0,$$

$$\frac{\partial \varphi}{\partial x} = \frac{T_e}{en_e}\frac{\partial n_e}{\partial x},$$

$$D\frac{\partial}{\partial x}\left(\frac{T_e}{T_i}\frac{n_i}{n_e}\frac{\partial n_e}{\partial x} + \frac{\partial n_i}{\partial x}\right) = Rn_d n_i - Kn_a n_e,$$

$$Rn_{d0}n_{i0} = Kn_a n_{e0},$$

$$\frac{\partial^2 \varphi}{\partial x^2} = 4\pi e(Zn_d + n_e - n_i).$$

Linearized equations

$$\frac{\partial u}{\partial t} = -\frac{c_a^2}{n_{d0}}\frac{\partial n_d'}{\partial x} + \frac{Ze}{M}\frac{\partial \varphi}{\partial x},$$

$$\frac{\partial n_d'}{\partial t} + n_{d0}\frac{\partial u}{\partial x} = 0,$$

$$\frac{\partial \varphi}{\partial x} = \frac{T_e}{en_e}\frac{\partial n_e'}{\partial x},$$

$$D\frac{T_e}{T_i}\frac{n_{i0}}{n_{e0}}\frac{\partial^2 n_e'}{\partial x^2} = Rn_{d0}n_i' + Rn_{i0}n_d' - Kn_a n_e',$$

$$n_i' = n_e' + Zn_d' \quad \text{if} \quad kr_{De} \gg 1,\ r_{De} = (T_e / 4\pi n_{e0}e^2)^{1/2}.$$

Dispersion relation (DR)

$$\alpha^2\tilde{k}^4 - \left(\alpha^2 - 1 + \tilde{\omega}^2\right)\tilde{k}^2 + \tilde{\omega}^2 = 0 \quad \text{or}$$

$$\tilde{\omega}(\tilde{k}) = \sqrt{\alpha^2\tilde{k}^2 + 1 + \frac{1}{\tilde{k}^2 - 1}}, \qquad \tilde{k}_{\min} = \sqrt{\frac{\tilde{\omega}_{\min}}{\alpha}},$$

$$\tilde{k} = k / k_d,\ \omega = \tilde{\omega} / \omega_d,\ \alpha = \omega_a / \omega_d = c_a / c_d,$$

$$k_d^2 = \frac{H}{(1+H)^2}\frac{Kn_a}{D}\frac{T_i}{T_e},$$

$$\omega_d^2 = \frac{1+2H}{(1+H)^2} v_d^2 \frac{ZKn_a}{D}\frac{T_i}{T_e},$$

$$c_d^2 = \left(\frac{\omega_d}{k_d}\right)^2 = \frac{1+2H}{H} Z v_d^2, \quad v_d^2 = T_e / M.$$

Obtained DR corresponds to two modes, LW and SW

The phase velocity is $c_{\rm ph} = c_d \dfrac{\tilde\omega}{\tilde k} = \sqrt{\alpha^2 + \dfrac{1}{\tilde k^2} + \dfrac{1}{\tilde k^2(\tilde k^2+1)}},$

the group velocity is $c_{\rm gr} = c_d \dfrac{d\tilde\omega}{d\tilde k} = \dfrac{c_d^2}{c_{\rm ph}}\left[\alpha^2 - \dfrac{1}{(\tilde k^2-1)^2}\right].$

For LW mode, k is almost independent of ω:

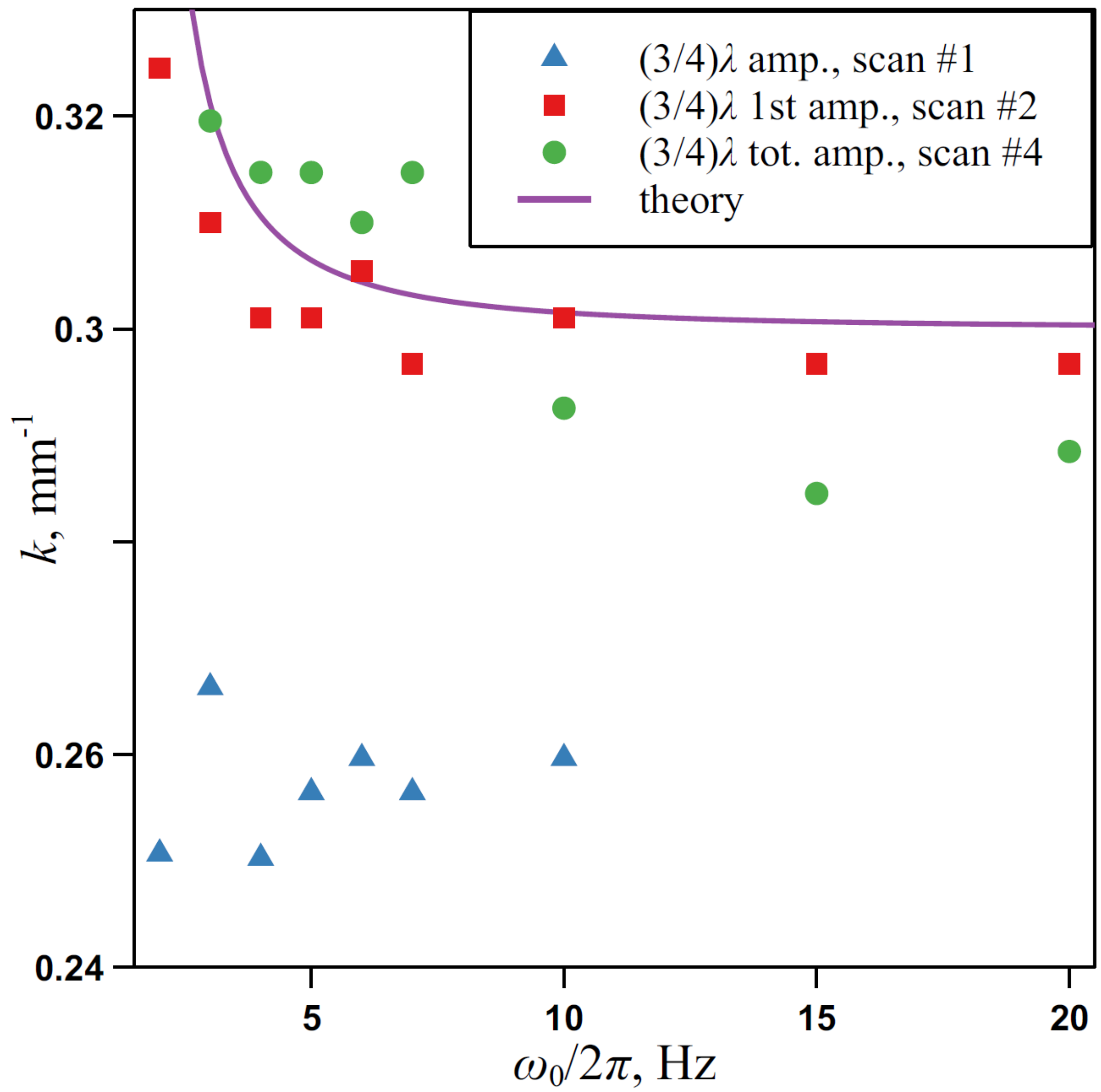
$$\tilde k \simeq 1 + \frac{1}{2}\left(\tilde\omega^2 - \alpha^2 - 1\right)^{-1}, \quad \tilde\omega \to \infty.$$

For SW mode, k is almost proportional to ω: $\tilde\omega \simeq \sqrt{\alpha^2 \tilde k^2 + 1}.$

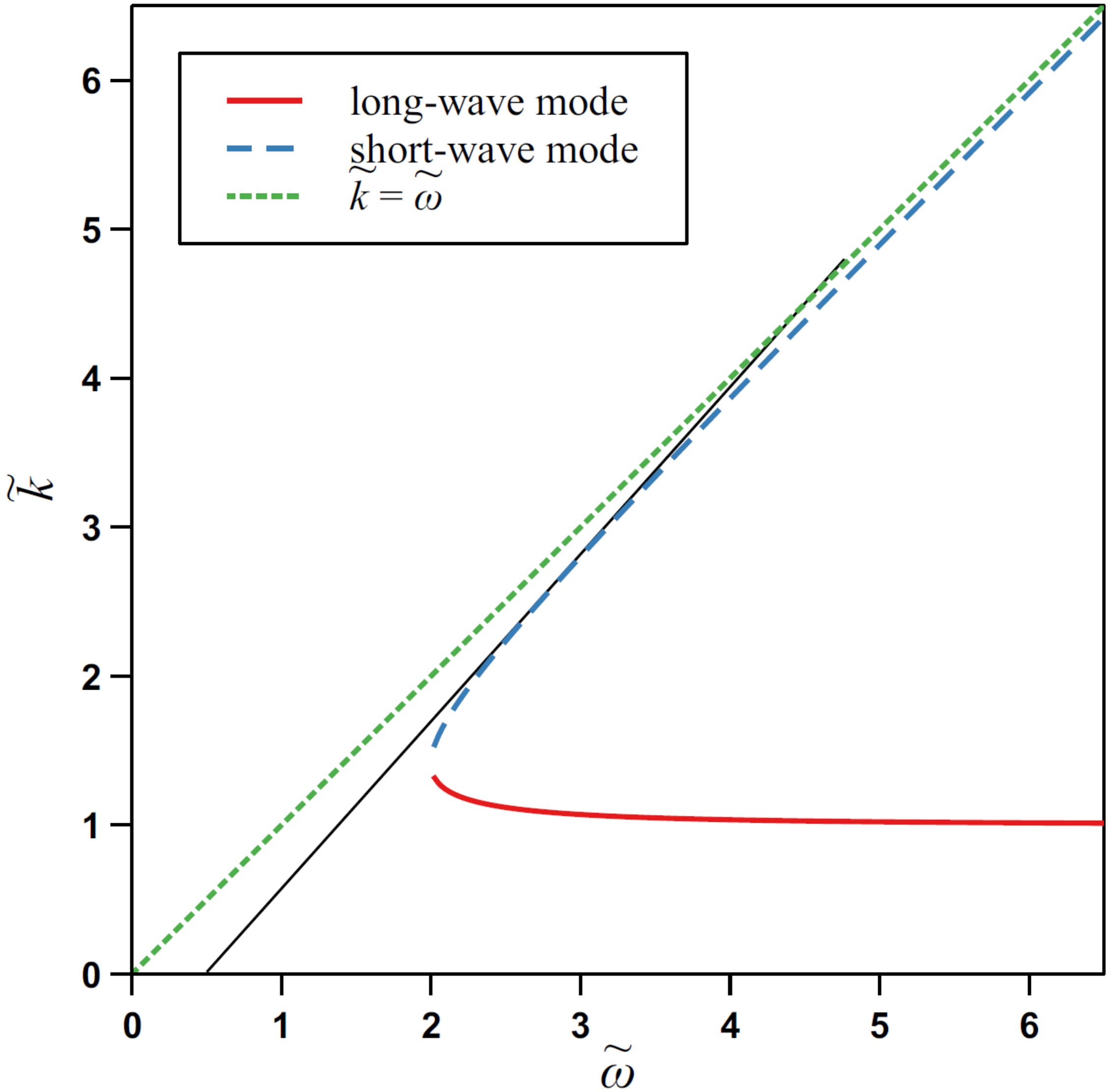
The LW group velocity is $c_{\rm gr} = -c_d(\omega/\omega_d)^3 = -\omega^3/c_d^2 k_d^3,$

the DAW velocity is $\tilde\omega \simeq \sqrt{\alpha^2 \tilde k^2 + 1}.$

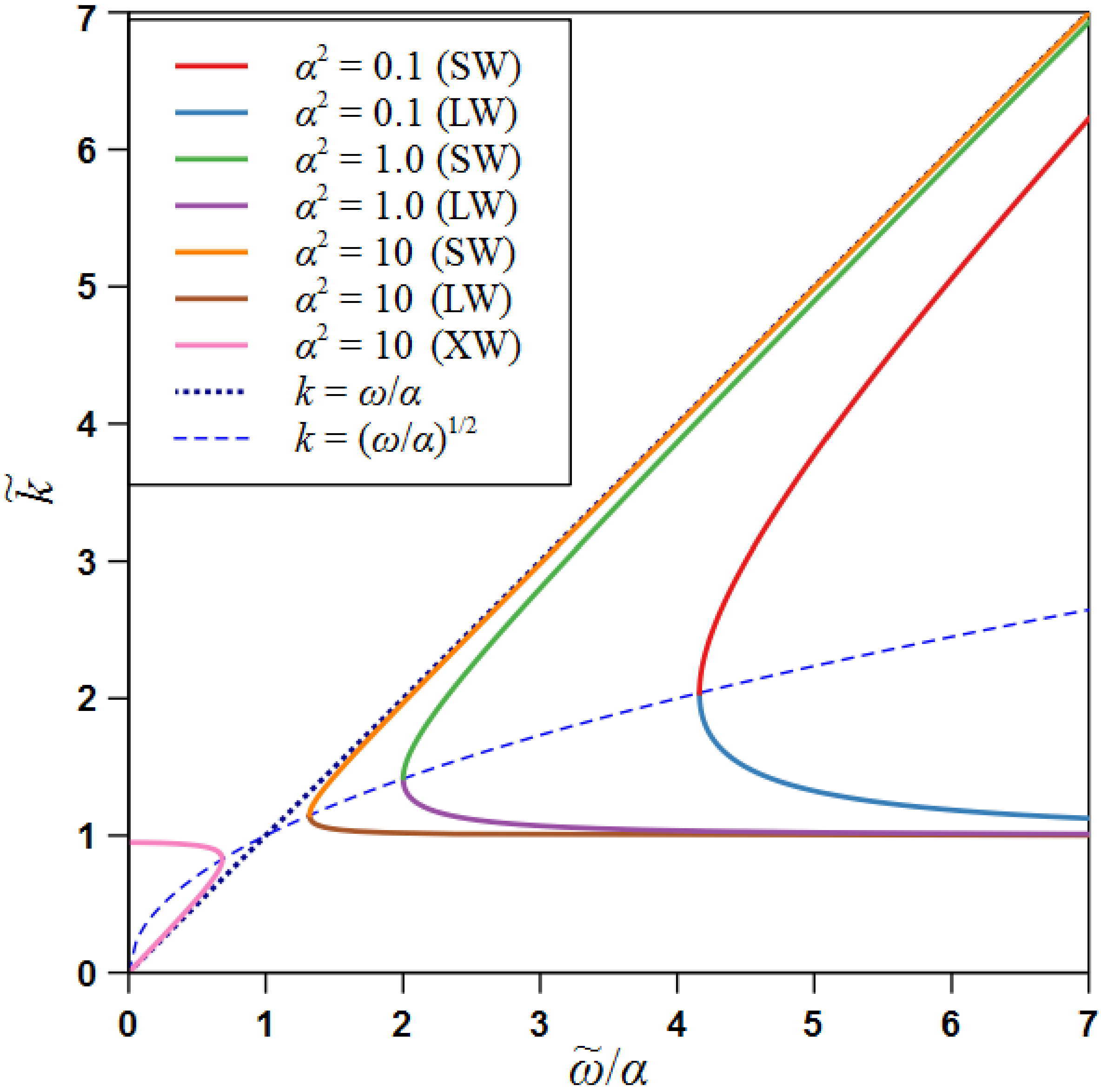
Wave number vs. the excitation frequency for the DIW (long-wave) mode
(experiment and theory)



Wave number vs. the excitation frequency for the dust acoustic waves (DAW, short-wave mode)



Wave number vs. the excitation frequency for the DIW and DAW (LW and SW modes)



Thank you for your attention!

For more details, visit
http://oivtran.ru/dmr