Importance of electron drag force in EUV induced pulsed plasma

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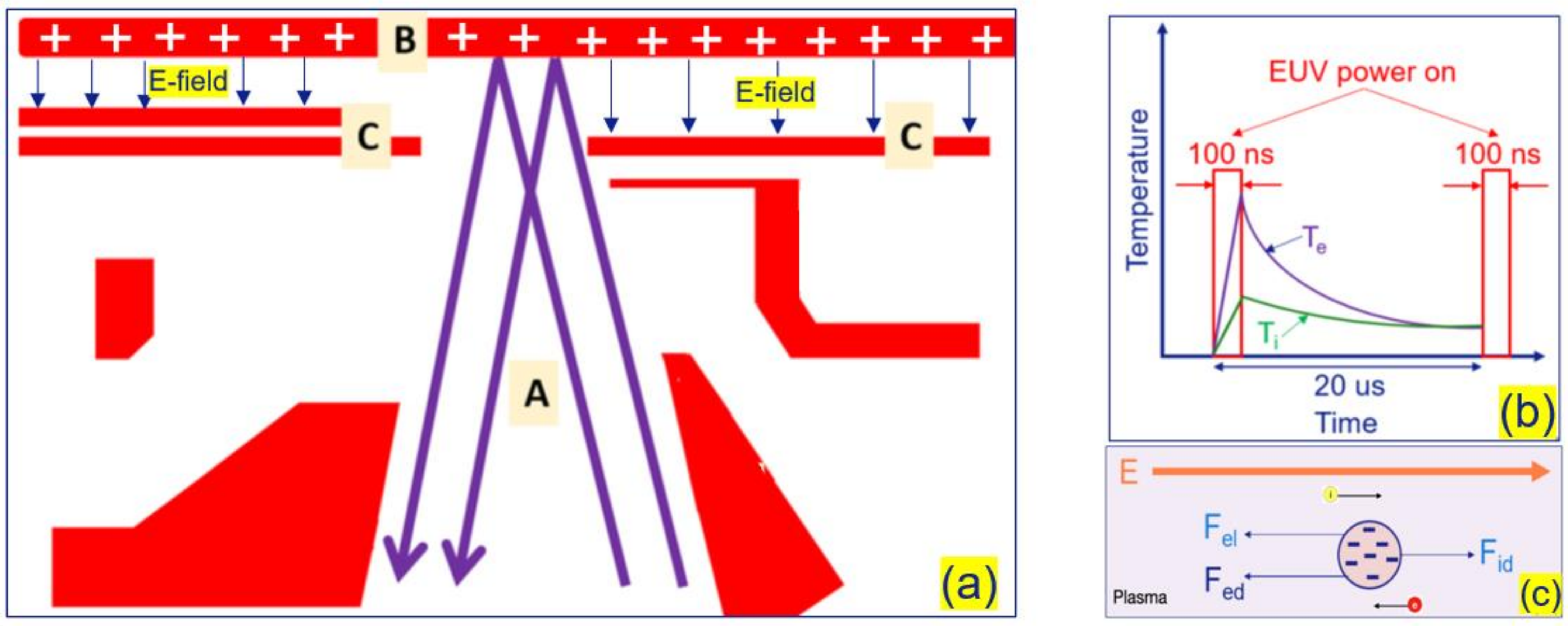
Introduction

To obtain best possible resolution of nm scale features, the extreme ultraviolet (EUV) lithography has been introduced in recent times which uses highly energetic EUV photons (energy ~ 92 eV) with shorter illumination length (13.5 nm). One of the unavoidable side effect of this technological development is the generation of EUV photon induced pulsed plasma due to the interaction of such highly energetic photons with the low pressure (~ 1 – 10 pa) background hydrogen gas. A schematic of EUV path and its interaction with hardware components along with resulting effects (E-field generation) are shown in Figure-1a. Within each pulse, the plasma switches between non-thermal state (Te >> Ti) to the thermal state (Te ~ Ti) where Te(i) is the electron (ion) temperature (Figure-1b). The relevant plasma induced forces acting on nm-µm size particles are shown (Fig. 1c)



Fifure-1: (a) Schematic of EUV path (A) close to reticle (B) which is always positive. The electric field is shown close to reticle and nearby surfaces (C) (b) An illustration of EUV pulsed plasma generation (c) An illustration of plasma induced volume forces acting on a negatively charged particle (outside of EUV beam) in presence of an external electric field (E): electric force (F_{el}), ion drag force (F_{id}) and electron drag force (F_{ed})

Force balance

The force balance determines the dynamics of the charged particle in an electric field. The direct impact of electric field on the charged particle is the electric force. The indirect effects are associated with plasma induced ion drag and electron drag forces which are the associated with the momentum transfer between flowing ions and electrons to the particle (Figure 1b). In the operational parameter regime, collision less electron drag force and weakly collisional ion drag force have been considered. The electric force dominates over the drag force in the non-thermal plasma over the particle sizes of interest (nm-µm). However, in the thermal plasma there is a competition between electric force and electron drag force (Figure-2).

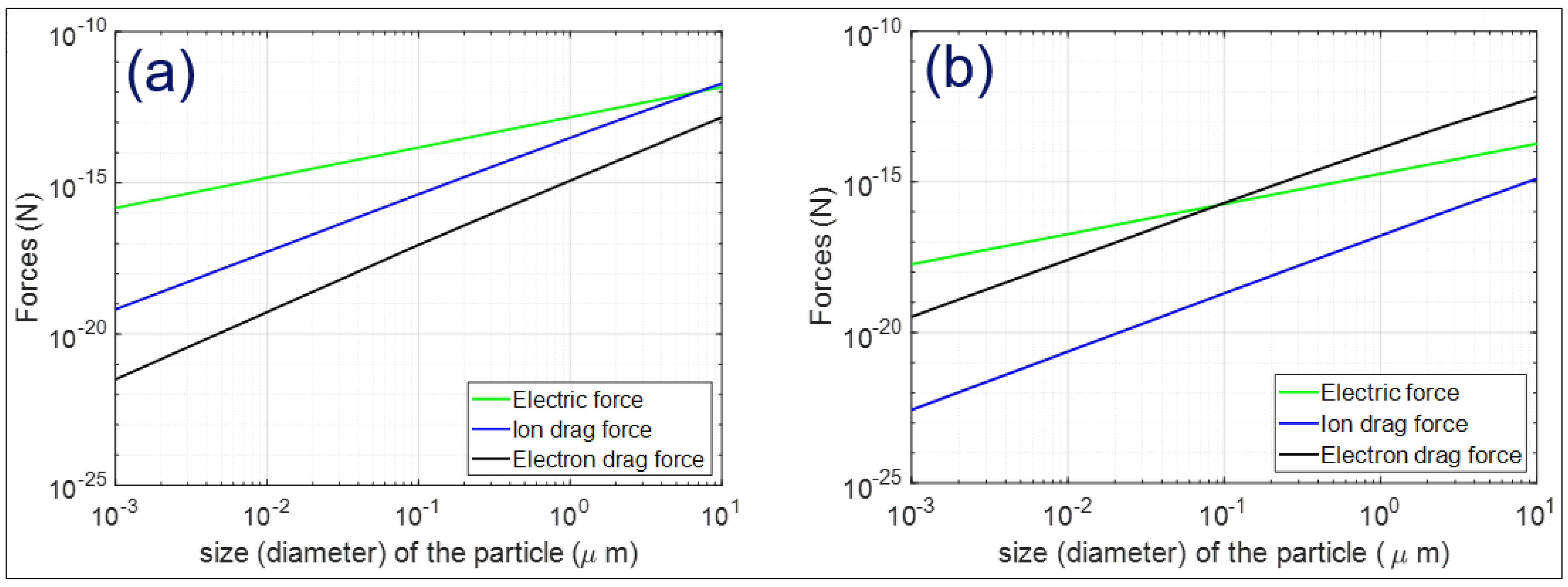


Figure-2: Force balance plots. The variation of electric force, ion drag force and electron drag force with particle size in (a) non-thermal plasma and in (b) thermal plasma. In the non thermal plasma ion drag dominates over electron drag force, but less than electric force over nm-µm particle size. In the thermal plasma, electron drag dominates over ion drag force and competes with electric force.

Size dependency

The force balance plots between different forces with particle size provides an impression of the charged particle dynamics in plasma environment. In this work, there is a cross-over particle size (dc) below which electric force dominates over electron drag force and above which electron drag dominates. The variation of dc with pressure and electron-to-ion temperature ratio (Te/Ti) is shown in Figure 3. Within the low-pressure regime as mentioned above, dc varies between 50-200 nm. For non-thermal plasma, dc ~ 100 nm and it increases with increasing Te/Ti

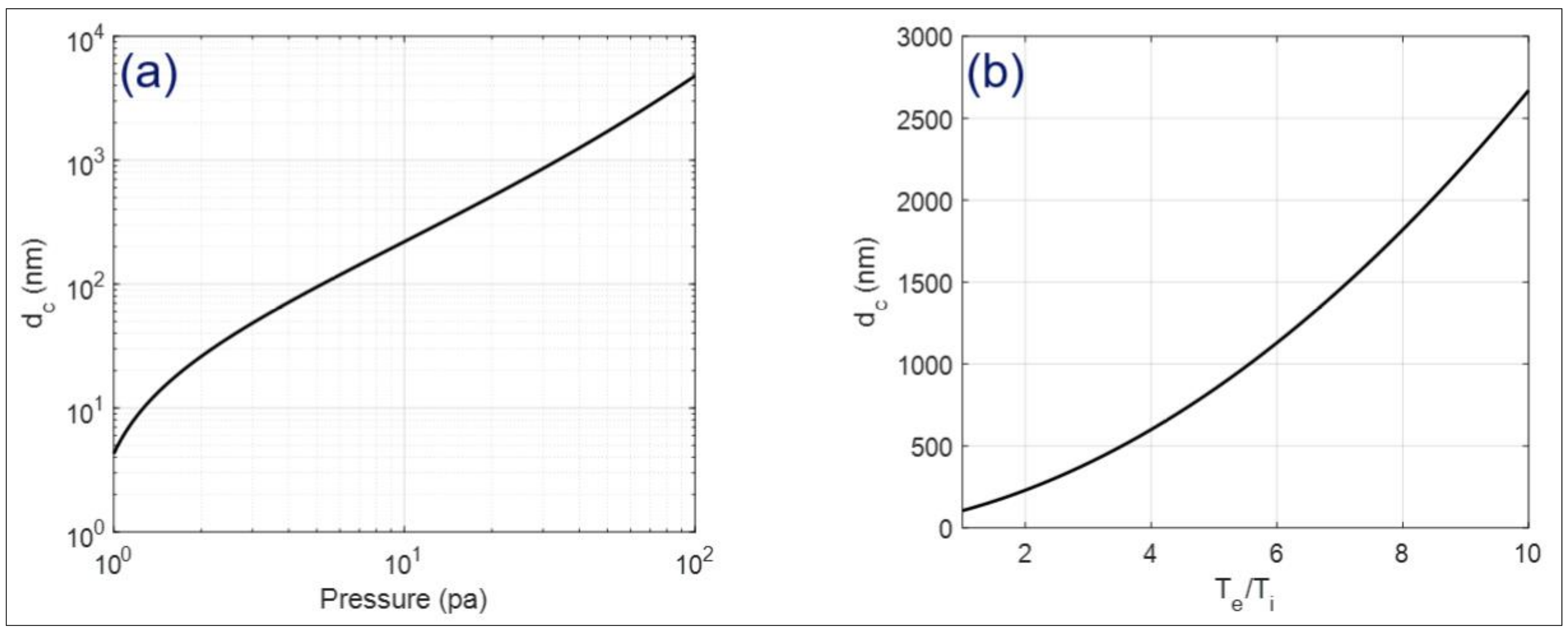


Figure-3: The variation of the cross-over particle size , dc (when Fel = Fed) with (a) pressure and (b) electron-to-ion temperature ratio (Te/Ti)

Conclusion and outlook

It is shown that particle transport within each EUV pulse strongly depends on the plasma regime. In case of multiple pulse scenario, residual charge may play an important role and its role on the steady state charge as well as drag force estimations should be performed self-consistently. Experimental realization of this theoretical prediction would be useful and is kept as future work.

Reference

M. Chaudhuri, A. M. Yakunin, M. van de Kerkhof and R. Snijdewind, “Electron drag force in EUV induced pulsed hydrogen plasma”, Plasma Sources Sci. Technol., 31, 045019 (2022).