Local Versus Global: Rethinking Incubation in Ultra-Short Pulse Laser Ablation

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In recent decades, ultrashort pulse (USP) laser ablation has evolved into a cornerstone technique for precision material processing. This advancement has been driven by experimental and theoretical studies focusing on the fundamental ablation dynamics with single-pulses, as well as multiple pulses. With the latter, the incubation effect stands out, which manifests in a decrease in the ablation threshold with an increasing number of applied pulses. While most studies model this effect with a heuristic power-law model introduced in 1988 [1], some other works have recently refined this concept. However, the existing attempts to date deal with global (across the ablation crater) averaged properties, such as increased absorption coefficients [2], material weakening or defect densities [3]. To the best of our knowledge, the consequences of local field effects, although crucial in laser irradiation of edges or rough surfaces, have not yet been investigated in this context.

Our research aims to understand incubation on a pulse-by-pulse basis for two distinct metals, aluminum (Al) and stainless steel AISI 304, each exhibiting unique single-pulse crater morphologies. To achieve this, we employ a comprehensive methodology that includes ablation experiments with a USP laser (1040 nm, 500 fs), pulse-integrated self-reflectance measurements, precise surface metrology via confocal microscopy and scanning electron microscopy paralleled with simulations of the local electrical fields via Finite-Difference Time-Domain method.

In contrast to the conventional picture, that increasing global absorption or material alteration is the primary mechanism of incubation, our results suggest that incubation may not be seen as uniform process. Rather, it can be markedly influenced by local field enhancements, especially at the crater edges. This is evidenced by the emergence of selective ablated Laser-Induced Periodic Surface Structures adjacent to the first pulse's crater edge, which are associated with simulated surface plasmon polariton excitations. Notably, for AISI 304, unlike Al, we also observed no straightforward relationship between incubation and increased total absorption.

Through these insights, we challenge the traditional picture of incubation, which primarily considers averaged or global material alterations, and highlight the necessity of accounting for local field effects to attain a more nuanced understanding of this process.

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