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Nanosecond laser ablation modeling as support activity for LIBS measurements

Stefano CIPELLI[1,2], Domenico ACETO[3], Paolo Francesco AMBRICO[3], Irene CASIRAGHI[2], Anna CREMONA[2], Olga DE PASCALE[3], Giorgio DILECCE[3], Arshad HUSSAIN[1,3], Laura LAGUARDIA[2], Matteo PEDRONI[2], Daria RICCI[2], Dario RIPAMONTI[4], Jimmy SCIONTI[2], Andrea UCCELLO[2]

[1] CRF – Università degli studi di Padova, Padova, Italy
[2] Istituto per la Scienza e Tecnologia die plasmi (ISTP) – CNR, Milan, Italy
[3] Istituto per la Scienza e Tecnologia die plasmi (ISTP) – CNR, Bari, Italy
[4] Istituto di Chimica della Materia Condensata e di Tecnologie per l'Energia (ICMATE) – CNR, Milano, Italy

Laser-Induced Breakdown Spectroscopy (LIBS) is a promising diagnostic technique for monitoring PFCs during and after plasma exposure, enabling the assessment of elemental and isotopic composition through optical emission spectroscopy. For quantitative depth profiling and fuel retention studies, accurate knowledge of the ablation rate and thermal effects induced by a single laser pulse is essential, as these processes influence the behaviour of trapped impurities. In this context, a nanosecond laser ablation model was developed using COMSOL Multiphysics to support LIBS measurements on fusion-relevant materials.

The model solves the heat conduction equation using a heat flux with Guassian distribution in space and time, incorporating temperature-dependent material properties and phase transition through an apparent heat capacity formulation. Two materials removal mechanisms were considered – normal evaporation and phase explosion – depending on the incident fluence and ablated material. Laser energy attenuation caused by plasma shielding was implemented through an exponential attenuation term.

For model validation, a dedicated experimental campaign was carried out by irradiating tungsten and silicon samples in a low pressure chamber ($p \approx 10^{-2}$ mbar) using a 10 ns Nd:YAG laser. Ablation craters were characterized by optical microscopy, mechanical profilometry, and SEM, allowing extraction of depth, width, and volume. For tungsten, experiments in the 0.4 – 2 mJ energy range (4 – 20 J/cm^2 considering the central gaussian region of the crater) showed no evidences of phase explosion; normal evaporation was therefore assumed. The model reproduced the crater depth with good accuracy, with relative discrepancies generally below 20%. For silicon, irradiated between 4 and 20 mJ (25 – 60 J/cm^2), phase explosion was identified as the dominant mechanism, and within 20% was obtained for crater depth after accounting for a small experimental variation in spot diameter.

The model successfully predicts crater geometry, while subsurface temperature field computations allow to quantify heat diffusion, providing support for future depth-resolved LIBS fuel retention measurements.

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