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量子分子動力学計算に基づくレーザー駆動パルス磁場拡散の数値解析
Numerical analysis of laser-driven pulsed magnetic diffusion based on quantum molecular dynamics

森田 大樹[1], Tadashi Ogitsu[2], S. X. Hu[3], Frank R. Graziani[2], 藤岡 慎介[1]
Hiroki Morita[1], Tadashi Ogitsu[2], S. X. Hu[3], Frank R. Graziani[2], Shinsuke Fujioka[1]

[1]阪大レーザー研, [2]LLNL, [3]UR LLE
[1]OU ILE, [2]LLNL, [3]UR LLE

The spreading of relativistic electrons generated by a short-pulse laser is a problem for fast-ignition inertial confinement fusion studies with energetic electrons because a large spread angle of a relativistic electron beam (REB) reduces the heating efficiency from the incident laser to the fuel core. To overcome this problem, an external magnetic field can be applied in fast-ignition fusion studies: this scheme is known as magnetized fast ignition (MFI). A proof-of-principle experiment of the MFI scheme was conducted at the GEKKO-XII and LFEX using a laser-driven coil [1], with efficient core heating achieved [2].

However, there is no direct confirmation in these experiments that the magnetic field inside the cone was sufficiently strong to guide the REB to the fuel core. In the fast ignition scheme, a gold guiding cone is usually attached to the fusion fuel target to exclude ablation plasma from the path of the heating laser pulse to the fuel. The duration of the applied magnetic field should be sufficiently longer than the diffusion time of the magnetic field into the guiding cone so that the magnetic field sufficiently soaks into conductive materials such as the guiding cone. The time scale of this magnetic diffusion must be determined to guarantee the REB guiding by the applied magnetic field.

The intense magnetic pulse causes induction heating inside materials and greatly changes their electrical and thermal conduction. Under the assumption that a 1-ns Gaussian magnetic pulse of 600 T soaks into 10-µm-thick gold, the temperature increase is approximately 20.7 eV. The state with solid density and a temperature of several electron volts is referred to as warm dense matter (WDM). The theoretical modeling of this state is limited and experimental data are lacking in the WDM regime. The diffusion time of a magnetic field is proportional to the electrical conductivity of the material. We must therefore take into account the temperature dependence of electrical conductivity in a wide range (0.01 eV - 100 eV), including the WDM state, to evaluate the magnetic diffusion time.

In this study, we have developed a numerical analysis method of magnetic field generation and its diffusion into the gold guiding cone valid for laser-driven coils. For the generation process, we calculate the temporal evolution of the coil current and magnetic field in the laser-driven coil using a self-consistent circuit model which allows a conventional circuit model to include current diffusion and Joule heating [3]. For the diffusion process, we calculate the electrical conductivity of warm dense gold over a wide temperature range (300 K - 100 eV) using a combination of the Kubo-Greenwood formula based on the quantum MD simulation [4] and the modified Spitzer [5] model to estimate the magnetic diffusion into the guiding cone target with consideration of the temperature dependence of the electrical conductivity.

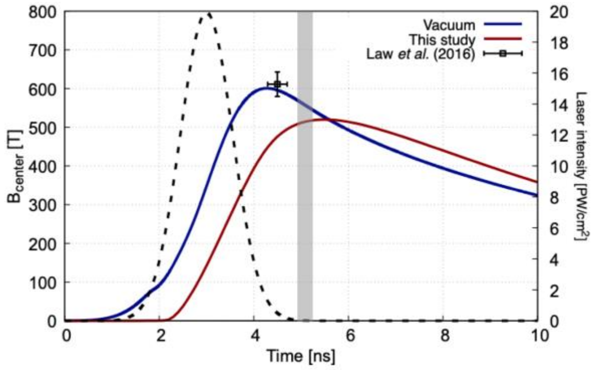

Fig. 1. Temporal evolution of generated and penetrating magnetic fields. A square point shows the experimental data of the magnetic field measured in a plastic [6]. The shaded area (4.8-5.2 ns) represents the time window in the arrival times of several shots of a short-pulse laser to heat the fuel core in a previous MFI experiment [2]

Our numerical investigation shows the magnetic field that penetrates the gold cone reaches a maximum strength of 530 T delayed by 2.5 ns with respect to the laser peak shown in Fig. 1. In the MFI experiments performed by Sakata *et al.* and Matsuo *et al.*, a heating laser was irradiated 1.88 - 2.22 ns after the incident laser peak of the laser-driven coil, and the maximum coupling efficiency was observed at 2.2 ns after the incident laser. At this timing, our calculation shows that the field strength at the tip of the gold cone is 385 T, which is sufficiently strong to guide the REB to the fuel core.

References

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