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Observation of the energy transport of a fast electron beam in a high-density fast-ignition core

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Fast ignition is a promising approach for achieving inertial confinement fusion in laboratory. In this approach, the deuterium-tritium fuel shell is firstly compressed isochorically to a high areal density by nanosecond laser beams, and then a fast (relativistic) electron beam produced by an ultra-intense laser (UIL) is injected to rapidly heat the compressed core, creating a hotspot and igniting the fuel. Therefore, a high coupling efficiency from the UIL to the core is of great importance in fast ignition.

A coupling efficiency of 15-30% was reported in early experiments at Osaka university with the cone-in-shell scheme. However, it was demonstrated as an optimistic result by subsequent experiments, where lower coupling efficiencies of ~1.6% and (3.5 ± 1.0)% were respectively inferred on the same facility and on the OMEGA laser facility. Experiments on OMEGA suggested that the coupling efficiency was limited by the intrinsic properties of the fast electron source, which not only had a large divergence angle but also was far away from the core due to preplasma filling the cone.

A unique solution to improve the coupling efficiency is the super-penetration scheme, in which the guiding cone is absent in the fuel shell. It applies effects such as relativistic self-focusing, relativistic induced transparency and hole-boring to the UIL, so that it can propagate into the overcritical region, minimizing the transport distance of the fast electrons to the core and hence improving the coupling efficiency. Recent experiments on OMEGA with a planar target have demonstrated the formation of a plasma channel up to overcritical density under fast-ignition-relevant conditions and observed collimated fast electrons on the channel axis, rather promising to achieve fast ignition with this super-penetration scheme.

Here, we report on the integral fast ignition experiments with the super-penetration scheme, which are performed by injecting a short pulse UIL into a spherically compressed target (see Fig. 1). With a solid sphere target rather than a shell, a higher areal density of 0.06 g/cm^2 at peak compression is achieved, because of its better hydrodynamic performance. By doping the target with Cu tracer, the transport and energy deposition of fast electrons in the compressed core plasmas are directly observed through the excited Cu Kα emission (see Fig. 2). An energy coupling efficiency of (0.8 ± 0.3)% from the UIL to the core plasma at the time of peak compression is obtained based on the measured Cu Kα photons. Key factors for achieving higher coupling efficiency are identified with the support of 2D particle-in-cell (PIC) simulations for the future ignition experiments. It indicates that the energy coupling efficiency can be improved up to 12% by optimizing the key factors in future ignition-scale plasmas.

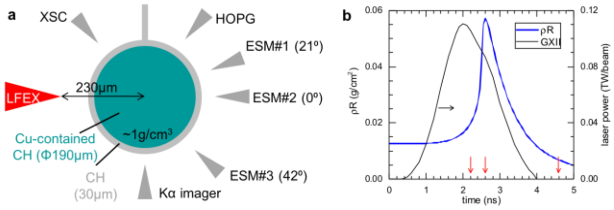

Fig. 1. (a) Experimental setup. (b) Temporal behavior of the target areal density (blue) and the pulse shape of the driver beams (black).

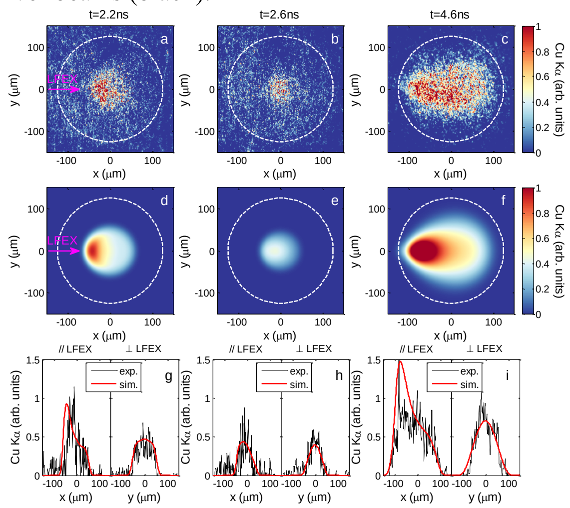

Fig. 2. Cu Kα images produced by fast electrons as a function of the injection time of the short pulse laser. Panels (a-c) are measured in experiments and panels (d-f) are from simulations. Panels (g-i) are horizontal (left) and vertical (right) lineouts across the target center from experiments (black) and simulations (red) at the corresponding times, respectively.

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