Relativistic interaction of ultra-high contrast femtosecond laser pulses with core-shell nanostructures

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Abstract

We report experimental results on the relativistic interaction of intense ultra-short laser pulses with arrays of composite nanowires using complex diagnostics including X-ray and particle spectra. The low-Z (Silicon), ≥5 μm wire length, 150 nm diameter, 400 nm regular spacing core nanowires were etched into a 50 μm thick Si membrane and subsequently coated by a 25 nm thick layer of Titanium dioxide (high-Z cladding) using the atomic layer deposition (ALD) technique. The experiments were conducted at the multi-terawatt Ti:Sapphire laser system JETI 40 delivering 0.7 J, 30 fs laser pulses at 0.8 μm wavelength and 10 Hz repetition rate. To ensure high temporal contrast, the laser pulses were frequency doubled with an efficiency ≈20% providing ~40 fs pulses with central wavelength of 400 nm and a temporal contrast $\leq 10^{-12}$. The second harmonic beam was focused by an Al off-axis parabolic mirror under 90º incidence angle onto the focal spot with a diameter of ≈2 μm on the target reaching intensities above 3×10^{19} W/cm^2 ($a_0 \approx 2$).

Two crystal spectrometers with X-ray CCD cameras as detectors were used for high resolution measurements of X-ray line emission from high charge states of Si and Ti. A flat KAP crystal was used for measurements of X-ray spectra emitted from Si in the spectral range 1.7-2.5 keV (covering K-line emissions from neutral Si to Si^{13+}) and an imaging crystal spectrometer by using a toroidally bent GaAs crystal with 111 reflection and CCD detection. This provides a spectral resolution of 3500 and a spatial resolution of 5 micron for measurements of Ti lines in the energy range 4.5-4.95 keV (covering K-line emissions from neutral Ti to Ti^{21+}). The spectral analysis of K-shell X-ray emission lines revealed strong emission from Ti^{20+} (He-like) and weak emission from Ti^{21+} (H-like) ions, as well as strong emission from Si^{12+} (He-like) and Si^{13+} (H-like). Comparison to the reference flat targets (50 μm thick Ti foil and 50 μm thick Si substrate coated by 25 nm Ti layer) show an order of magnitude increase in the intensity of the line emission from He- and H-like ionic states of Ti achieved with nanowire arrays. Comparing the

measured Ti X-ray emission with simulations using the collisional-radiative code FLYCHK predicts for the plasma an electron temperature of 1.6 keV and an electron density of 1×10^{24}, meaning that our generated plasma is very hot and dense. Moreover, 1D imaging of the X-ray emission from the Ti plasma shows that, in addition to the main source of the He-like emission localized at the target surface, a weak He-like emission with the spatial extension up to 1 mm from the target surface is detected from the nanowire array targets (but not from the reference flat targets!). Such spatially extended He-like emission was observed before in experiments with high energy nanosecond laser pulses irradiating flat targets. Here, we observe this phenomenon for femtosecond pulse duration. Considering extremely short (tenses of femtoseconds) radiative lifetime of the excited electronic states in He-like Ti^{20+} ions, this observation suggests an anomalously long lifetime of the relatively dense and hot plasma. Additionally, our FLYCHK simulations also predict that He-like (w) line needs solid density plasma and temperature about 1 keV!!!

Finally, our particle diagnostic consists of electron and proton spectrometers based on permanent magnets with image plates as a detector, located at the front and at the rear sides of the targets along the direction of the laser beam and in the backward direction. The measured spectra of protons ejected from the front side of the nanowire array targets show 3× increase in the effective proton temperature as well as >3× increase in the cutoff energy as compared with protons generated from the reference target. On the other hand, measured electron spectra at the front and at the rear sides of the targets demonstrate 4× increase in the intensity and almost equal effective hot electron temperature ($\boldsymbol{T_{hot}}$) as compared with reference target.

More details on the measurements will be presented at the seminar.