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Single-Pulse Measurements of Ultrabright Xe(L) X-Ray Pulses from Optimized Relativistic Channels

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A novel technique to significantly increase the brightness of 4.5 keV Xe(L) hard x-ray pulses from optimized stable ultra-powerful relativistic channels has been developed and experimentally verified. The relativistic channel formation in plasmas with an appropriate gradient in the longitudinal electron density profile optimizes the stability of the self-channeling, the power compression, and the x-ray source brightness. The experimental measurements of Xe(L) 4.5 keV pulses from optimized ultra-powerful stable relativistic channels have produced the first direct single-pulse observation of strong multi-keV amplification of Xe^{35+} (2p ← 3d) transition at $\lambda \cong 2.86$ Å and demonstrated a solid correlation between the strong amplification of Xe^{35+} line and the formation of long stable ultra-intense relativistic channels.

The relativistic and ponderomotive self-channeling [1-10] is the first rank method for the controlled power compression of ultrashort multi-TW and PW laser pulses in plasmas. The performed detailed analysis of the transverse stability of relativistic channel formation in initially uniform plasmas [5] has revealed three main stability modes of the relativistic self-channeling: (1) the stable mode resulting in the formation of the single stable ultrapowerful channel, (2) the highly unstable mode of the small-scale filamentation resulting in the formation of multiple peripheral channels containing power in the order of one critical power, and (3) the bifurcation mode of relativistic self-channeling characterized by the splitting of the beam into two or more ultrapowerful channels. The developed stability maps [5,8-10] indicating the ranges of the laser and plasma parameters corresponding to stable, highly unstable, and bifurcation modes of the self-channeling have demonstrated that simultaneous increase of laser power and electron density results in deep penetration into the zone of highly unstable self-channeling. It has been demonstrated that the unstable mode of the relativistic self-channelling of ultra-powerful laser pulses in high-density plasmas can be converted into the formation of single stable channels using a two-stage process of the self-channelling, with the initial phase involving an appropriate gradient in the longitudinal electron density profile [8-10]. The resulting stable channels typically produce extremely narrow zones of 4.5 keV Xe(L) emission since the diameter of the ultra-powerful core is small and the intensity of weak peripheral field is below the intensity threshold for Xe(L) production. Our recent numerical modelling and experimental studies have revealed the existence of a new mode of stable ultra-powerful relativistic channel formation optimized to significantly increase the volume of the Xe(L) emission zone and the brightness of Xe(L) x-ray pulses. The switch from the typical to the optimized mode of self-channelling has been achieved by the proper adjustment of the longitudinal electron density profile and the parameters of the laser pulse. We note that the established dual-stage self-channeling (1) extends the stable mode of self-channeling into the zone of ultra-high power and high electron density (stability control); (2) minimizes energy losses due to channel formation (optimization of power compression); and (3) significantly increases the brightness of the Xe(L) 4.5 keV hard x-ray source (x-ray source optimization). The ability to control the channel stability and minimize energy losses due to the channel formation using the initial buffer zone with a gradient in the electron density has been experimentally verified [10].

Stable relativistic self-channeling of ultra-powerful laser pulses in plasmas is one of the key processes for the recently developed ultra-bright multi-keV coherent x-ray source from gaseous cluster targets. The observed (1) strong ($\sim 10^6$) enhancement and (2) sharp spectral narrowing of certain Xe(L) lines in the $\lambda \sim 2.71$-2.93 Å region indicate the strong amplification of these lines in stable relativistic channels [11-15]. Additional experimental evidence of the hard x-ray amplification includes (3) the detection of a spatially narrow directed beam ($\delta\theta_x \cong 100$–200 μrad) [11,13], and (4) the observation of deep spectral hole-burning [12,14,15] on the inhomogeneously broadened spontaneous emission profile at wavelengths correlating exactly with the amplified transitions.

Our latest experimental measurements of Xe(L) pulses from optimized ultra-powerful stable relativistic channels have produced the first direct single-pulse observation of strong multi-keV amplification of Xe^{35+} transition at $\lambda \cong 2.86$ Å and demonstrated a solid correlation between the strong amplification of Xe^{35+} line and the formation of long stable ultra-intense relativistic channels [15]. The measured diameter of the observed x-ray beam matches the calculated width of the Xe(L) emission zone from optimized stable relativistic channels. The estimated peak brightness of the 4.5 keV Xe(L) hard x-ray source exceeds 10^{30} photons s^{-1} mm^{-2} $mrad^{-2}$ / (0.1% bandwidth) [11].

The recently obtained experimental data demonstrated (1) a solid correlation between the strong amplification of Xe^{35+} line and the formation of long stable ultra-intense relativistic channels, (2) a precise match between strongly amplified lines from single-pulse and time-integrated Xe(L) spectra, and (3) a significant increase in the brightness of 4.5 keV Xe(L) hard x-ray pulses from optimized stable ultra-powerful relativistic channels [15].

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