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X-ray lasers

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The advent of x-ray free-electron lasers providing femtosecond x-ray pulses of unprecedented high intensities opened the field of nonlinear x-ray science and the study of collective x-ray matter interaction. In this tutorial I will give an overview over the development of inner-shell x-ray lasers based on superfluorescence of K-α emission. The concept of single-pass x-ray laser amplifiers based on stimulated emission on transitions involving inner-shell electronic levels has been developed by Duguay and Rentzepis [1] soon after the invention of the optical laser. The idea is relatively simple: tuning x-rays with frequencies tuned above K-shell ionization edges predominantly promotes electrons from this shell to the continuum. The resulting inner-shell hole decays on a femtosecond timescale predominantly via Auger decay (for atoms with $Z < 21$) or K-α fluorescence decay (for atoms with $Z > 20$). For intensities achievable at XFELs, the K-shell ionization rates are comparable to these decay rates, resulting in a sizable, transient population inversion, that can be exploited for stimulated K-α emission. The first proof-of principle experiment on inner-shell x-ray amplification has been performed in 2010 on the K-α transition in neon gas [2], in a cylindrical gain medium of large aspect ratio, in which a short XFEL pulse creates a channel of population inverted ions propagating through the sample in swept gain geometry. Spontaneously emitted photons propagating in the forward direction of the propagating XFEL pulse meet ions in an inverted state, eventually resulting in an avalanche of stimulated emission processes (superfluorescence, or amplified spontaneous emission). Exponential gain of stimulated x-ray emission has been demonstrated over four orders of magnitude, with small signal gains of ≈ 20. This concept of inner-shell x-ray amplification has been also established in the hard x-ray spectral range on K-α transitions in solid Cu [3], and Mn, and on Mn atoms in solution [4]. Interestingly, it has been demonstrated that the spectroscopic information on the oxidation state of the metals – the chemical shift of K-α emission – is preserved in the stimulated x-ray emission [4], thereby opening the pathway towards stimulated emission spectroscopy [5]. Theoretical modeling [6,7] predicts that the emitted x-ray superfluorescence can result in almost transform limited femtosecond x-ray pulses, despite the process starting from spontaneous emission. Being pumped with a stochastic XFEL source, also phase-stable pairs of fs pulses can be generated, as recently demonstrated [8]. Currently, concepts of x-ray laser oscillators based on the inner-shell x-ray lasing are investigated [9], potentially providing fully coherent x-ray pulses of unprecedented spectral brightness with properties comparable to x-ray free-electron laser oscillators

Further Reading

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