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Advanced Ultrabright X-Ray Sources for the Study of Superenergetic States of Matter

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12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

A class of ultrabright multikilovolt x-ray sources has been developed that can serve an array of new measurements and applications concerning the properties of all forms of condensed matter. In comparison to presently available synchrotron technology, the experimentally demonstrated superiority in performance (peak brightness per unit cost) is approximately a factor of 10^{10}. An important characteristic of these sources is the intrinsic capability to produce coherent energy at an intensity for which the electric field magnitude exceeds an atomic unit (e/a_o^2). A leading consequence of this property is the introduction of new nonlinear modalities of electromagnetic coupling into the x-ray spectral region that are applicable to all classes of materials.

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FINAL PROGRESS REPORT
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Advanced Ultrabright X-Ray Sources for the Study of Superenergetic States of Matter
Award End Date: November 22, 2004

(1) FOREWORD

The Xe(L) source at $\hbar\omega_x \sim 4.5$ keV, a system of exceptional peak brightness, whose properties are documented above in Sections I-IV, can be applied immediately to the experimental study of the coupling of intense femtosecond x-ray pulses to all classes of materials.

(2) NA

(3) NA

(4) STATEMENT OF PROBLEM STUDIED

Attainment of Xe(L) Scaling Limit and Multiple Inner-Shell Vacancy Production

In order to apply the Xe(L) source to the study of material interactions, the brightness scaling must be verified. The estimated brightness scaling limit for the Xe(L) system indicates that it would produce an intensity of $\sim 10^{19}$ W/cm^2 without the use of a focusing element. For a pulse length $\tau_x \sim 1$ fs, this gives a flux of $\sim 10^4$ J/cm^2, a magnitude that would saturate reaction channels with cross sections greater than $\sigma_\gamma \sim 3.6 \times 10^{-20}$ cm^2. The K-shell cross sections σ_K for Ar, K, Ca, and Sc are above this value, so it should be possible to produce selectively multiple K-shell vacancies in these systems.

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(5) SUMMARY OF THE MOST IMPORTANT RESULTS

The Xe(L) system at $\lambda \sim 2.9$ Å exhibits all of the canonical attributes of a saturated amplifier. The key observables are (1) sharp spectral narrowing, (2) the detection of a narrow directed beam ($\delta\theta_x \cong 200$ μrad), (3) an increase in the amplitude of the emission and the development of an intense output ($\geq 10^6$ enhancement), and (4) the observation of deep spectral hole-burning on the inhomogeneously broadened spontaneous emission profile. Experimentally determined by two methods, (a) line narrowing and (b) signal enhancement, the observations for several single-vacancy 3d→2p transitions indicate a range of values for the effective linear gain constant given by $g_L \cong 25–100$ cm^{-1}. It is shown that this result stands in clear conflict with the corresponding upper bound estimated with conventional theory from prior spectroscopic studies of $g_L \cong 40–80$ cm^{-1}. Overall, the observed values deviate substantially from expectations scaled to the spectral density of the measured Xe(L) spontaneous emission profile; they are systematically too high. The most extreme example is the strongly saturated Xe^{32+} transition at $\lambda = 2.71$ Å, a case that fails to reconcile the measured signal strength with the corresponding theoretically predicted value by a factor exceeding 10^3. The paradox is resolved with the Ansatz that the amplification is governed principally by the saturated gain g_s, not the conventionally described small signal (linear) value g_L. This interpretation is supported by the observation of deep spectral hole-burning, the signature of strong saturation, that occurs uniformly across the spectrum of the spontaneous emission profile; the effective amplification exhibits an anomalously weak dependence on the spectral density. One clear manifestation of the saturation is the recording of high spectrally resolved x-ray yields that cause gross structural damage to material in the film plane of the spectrometer. The behavior of the amplifier can be best described as a system that undergoes explosive supersaturated amplification. The source of this exceptionally strong amplification can be traced to the dynamically enhanced radiative response of the excited Xe hollow atom states located in the clusters that are mode-coupled to the plasma waveguide forming the amplifying channel.

(6) LIST OF PAPERS

Published

"Ultrabright Multikilovolt Coherent Tunable X-Ray Source at $\lambda \sim 2.71 – 2.93$ Å," Alex B. Borisov, Xiangyang Song, Fabrizio Frigeni, Yevgeniya Koshman, Yang Dai, Keith Boyer, and Charles K. Rhodes, *J. Phys.* B 36, 3433 (2003).

"Saturated Multikilovolt X-Ray Amplification with Xe Clusters: Single-Pulse Observation of Xe(L) Spectral Hole Burning," Alex B. Borisov, Jack Davis, Xiangyang Song, Yevgeniya Koshman, Yang Dai, Keith Boyer, and Charles K. Rhodes, *J. Phys.* B 36, L285 (2003).

"Amplification of Multikilovolt Xe(L) Hollow Atom Transitions with Xe Clusters in Confined Plasma Channels," Alex B. Borisov, Xiangyang Song, Yevgeniya Koshman, Jack Davis, Yang Dai, Keith Boyer, and Charles K. Rhodes, Ultrafast Optics IV: Selected Contributions to the 4th International Conference on Ultrafast Optics, Vienna Austria, Springer Series in Optical Sciences, Volume 95 , ed. Ferenc Krausz, Georg Korn, Paul Corkum, and Ian A. Walmsley (Springer-Verlag, New York, April, 2004) p. 343.

"Ultrabright Multikilovolt Coherent Tunable X-Ray Source at ~ 2.71 – 2.93 Å for Biological Microimaging," Alex B. Borisov, Xiangyang Song, Ping Zhang, Jonas Moses, Jeremy Callner, Maria Vogrinc, Keith Boyer, and Charles K. Rhodes, ed. Hironari Yamada, in AIP Proceedings of the International Symposium on Portable Synchrotron Light Sources and Advanced Applications (Shiga, Japan, January 13–14, 2004).

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"Optimization of Power Compression and Stability of Relativistic and Ponderomotive Self-Channeling of 248 nm Laser Pulses in Underdense Plasmas," J. Davis, A. B. Borisov, and C. K. Rhodes, *Physical Review* E 70, 066406 (2004).

Pending

"High-Intensity Applications of Excimer Lasers," Alex B. Borisov, Jack Davis, Keith Boyer, and Charles K. Rhodes, in *Excimer Laser Technology*, G. Marowsky, ed. (Springer-Verlag, Berlin, in press).

"The Nuclear Era of Laser Interactions—New Milestones in the History of Power Compression," Alex B. Borisov, Xiangyang Song, Ping Zhang, Keith Boyer, and Charles K. Rhodes, eds. J. Magill and H. Schwoerer, in *Laser & Nuclei: Applications of Ultra-high Intensity Lasers in Nuclear Science*, Springer-Verlag, Heidelberg, in press.

"Quadratic Reciprocity, the Higgs Mass, and Complexity," Y. Dai, A. B. Borisov, J. W.Longworth, K. Boyer, and C. K. Rhodes, *ACSM*, in press.

(7) PARTICIPATING SCIENTIFIC PERSONNEL

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(8) INVENTIONS

NA

(9) BIBLIOGRAPHY

See bibliographies of attached papers in (5) above.

(10) NA