World's fastest water heater—100,000 degrees in under a 10th of a picosecond

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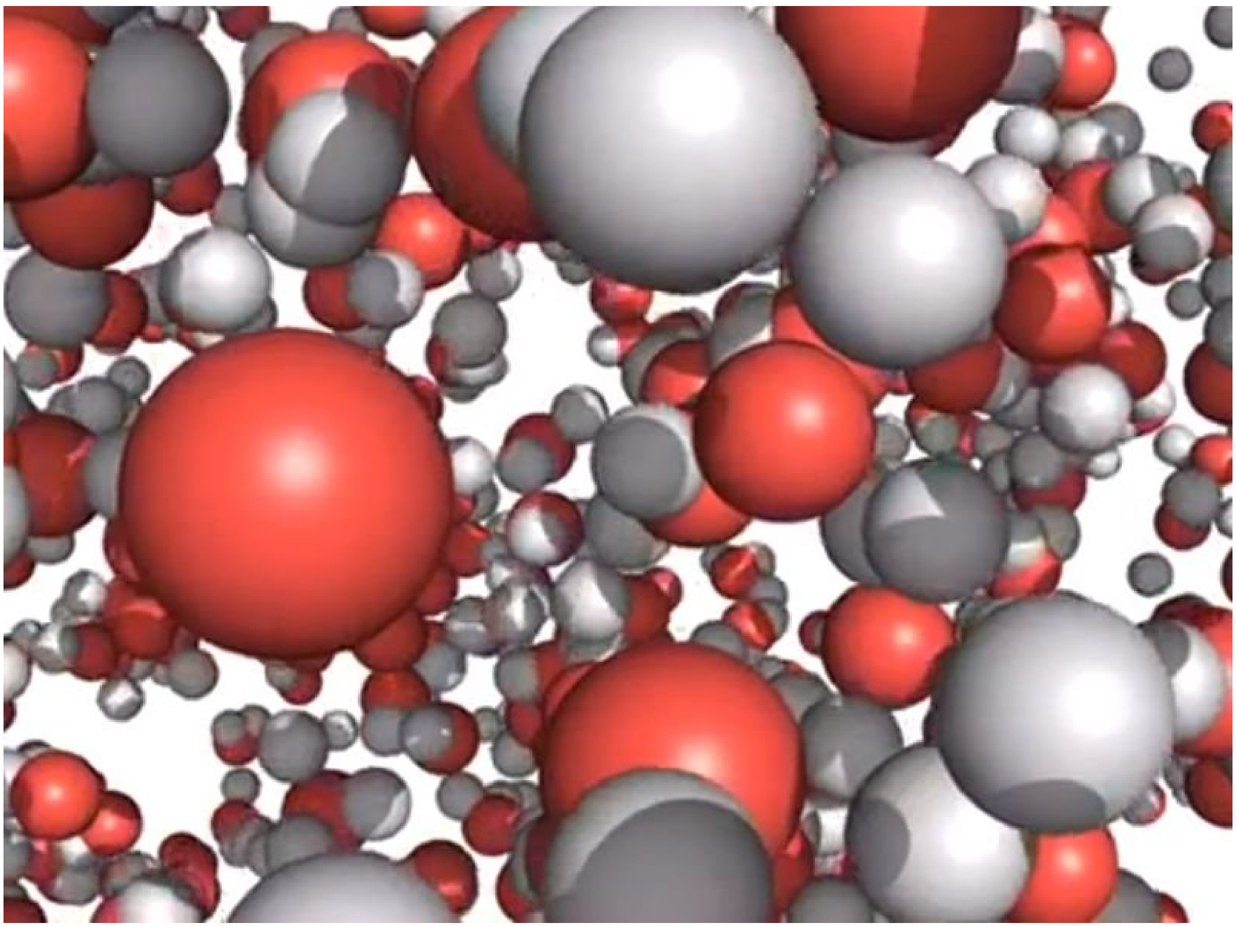

Scientists have used a powerful X-ray laser to heat water from room temperature to 100,000 degrees Celsius in less than a 10th of a picosecond (millionth of a millionth of a second). The experimental setup, which can be seen as the world's fastest water heater, produced an exotic state of water from which researchers hope to learn more about the peculiar characteristics of water. The observations also have practical use for the probing biological and many other samples with X-ray lasers. The team of Carl Caleman from the Center for Free-Electron Laser Science (CFEL) at DESY and Uppsala University (Sweden) reports its findings in the journal *Proceedings of the National Academy of Sciences* (*PNAS*).

The researchers used the X-ray free-electron laser Linac Coherent Light Source LCLS at the SLAC National Accelerator Laboratory in the U.S. to shoot extremely intense and ultra-short flashes of X-rays at a jet of water. "It is not the usual way to boil your water," said Caleman. "Normally, when you heat water, the molecules will just be shaken stronger and stronger." On the molecular level, heat is motion—the hotter, the faster the motion of the molecules. This can be achieved, for example, via heat transfer from a stove, or more directly with microwaves that make the water molecules swing back and forth ever faster in step with the electromagnetic field.

"Our heating is fundamentally different," explained Caleman. "The energetic X-rays punch electrons out of the water molecules, thereby destroying the balance of electric charges. So, suddenly the atoms feel a strong repulsive force and start to move violently." In less than 75 femtoseconds, that's 75 millionths of a billionth of a second or 0.000 000 000 000 075 seconds, the water goes through a phase transition from liquid to plasma. A plasma is a state of matter where the electrons have been removed from the atoms, leading to a sort of electrically charged gas.

"But while the water transforms from liquid to plasma, it still remains at the density of liquid water, as the atoms didn't have time to move significantly yet," said co-author Olof Jönsson from Uppsala University. This exotic state of matter is nothing that can be found naturally on Earth. "It has similar characteristics as some plasmas in the sun and the gas giant Jupiter, but has a lower density. Meanwhile, it is hotter than Earth's core."

The scientists used their measurements to validate simulations of the process. Together, the measurements and simulations allow to study this exotic state of water in order to learn more about water's general properties. "Water really is an odd liquid, and if it weren't for its peculiar characteristics, many things on Earth wouldn't be as they are, particularly life," Jönsson emphasised. Water displays many anomalies, including its density, heat capacity and thermal conductivity. It it these anomalies that will be investigated within the future Centre for Water Science (CWS) planned at DESY, and the obtained results are of great importance for the acivities there.

Apart from its fundamental significance, the study also has immediate practical significance. X-ray lasers are often used to investigate the atomic structure of tiny samples. "It is important for any experiment involving liquids at X-ray lasers," said co-author Kenneth Beyerlein from CFEL. "In fact, any sample that you put into the X-ray beam will be destroyed in the way that we observed. If you analyse anything that is not a crystal, you have to consider this."

The measurements show almost no structural changes in the water up to 25 femtoseconds after the X-ray pulse starts to hit it. But at 75 femtoseconds, changes are already evident. "The study gives us a better understanding of what we do to different samples," explained co-author Nicusor Timneanu from Uppsala University, one of the key scientist developing the theoretical model used. "Its observations are also important to consider for the development of techniques to image single molecules or other tiny particles with X-ray lasers."

More information: Ultrafast non-thermal heating of water initiated by an X-ray Free-Electron Laser; Kenneth R. Beyerlein, H. Olof Jönsson, Roberto Alonso-Mori , Andrew Aquila, Saša Bajt, Anton Barty, Richard Bean, Jason E. Koglin, Marc Messerschmidt, Davide Ragazzon, Dimosthenis Sokaras, Garth J. Williams, Stefan Hau-Riege, Sébastien Boutet, Henry N. Chapman, Nicusor Tîmneanu, and Carl Caleman; *Proceedings of the National Academy of Sciences*, 2018; http://www.pnas.org/cgi/doi/10.1073/pnas.1711220115

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