Research on atomic physics of highly charged ions; development of highly charged ion sources

Nobuyuki NAKAMURA Laboratory

Nobuyuki NAKAMURA

Summary of Research

Research on the Atomic Physics of Highly-Charged Ions and on Developing Highly-Charged Ion Sources

Our laboratory seeks to elucidate the phenomena associated with the essential properties of highly-charged ions from the perspective of atomic physics and to develop highly-charged ion sources that enable such research.

Atoms consist of a nucleus and surrounding electrons. Highly-charged ions refer to atoms in an unstable state that have been stripped of some of their electrons. When highly-charged ions collide with other particles, the vacancies in the electron shells act as powerful attractive forces, resulting in what are sometimes called “electrostatic black holes”. The physics of these highly-charged ions is not yet fully understood; even quantum electrodynamics (QED), the most precise physical theory conceived to date, might appear incapable of adequately accounting for this phenomenon.

Collaborative Research Projects with Astronomical Observatories and Nuclear Fusion Research Facilities

Highly-charged ions do not occur naturally on Earth but are common in high temperature regions of outer space, such as the Sun. An understanding of the properties of highly-charged ions should help clarify the phenomena observed in the Sun, making information on highly-charged ions important for astrophysical research.

Here on Earth, highly-charged ions play a vital role in the next-generation power generation systems since they can be found in extreme high temperature conditions inside thermonuclear experimental reactors. Our laboratory maintains close ties with astronomical observatories and nuclear fusion research facilities and pursues collaborative research projects whose goal is elucidate the properties of highly-charged ions. These research projects also encourage dialogue and the exchange of information.

Applications of Highly-Charged Ions

Highly-charged ions have received a lot of attention in recent years from the light source development field for next-generation lithography systems. To advance the state of integration in today’s lithography systems, light sources of progressively shorter wavelengths are required to increase processing accuracy. A prime candidate for this is a light source utilizing the emission in the extreme ultraviolet range from highly-charged ions within a plasma. Since the wavelength and intensity of emission from highly-charged ions depends on both the element and the number of electrons stripped off, these factors can be adjusted to produce light of the desired wavelength.

Tokyo-EBIT (Electron Beam Ion Trap)

Conventional experiments involving highly-charged ions require dedicated instruments. Producing highly-charged ions generally requires large accelerators that create collisions between high-velocity ions and thin films or thermonuclear reactors in which highly-charged ions are generated by plasma. However, both accelerators and reactors are gigantic instruments, posing significant obstacles to research on and the development of applications for highly-charged ions.

In 1997, Professor Ohtani and Associate Professor Nakamura in the Institute for Laser Science at the University of Electro-Communications built the Tokyo-EBIT, one of the world’s largest, highest-performance, highly-charged ion sources.

The Tokyo-EBIT can produce ions with any charge state of any element, expanding the scope of research to a remarkable degree. The Tokyo-EBIT is indisputably a high-performance highly-charged ion source. At the same time, it measures more than 3 meters in height and requires liquid helium to cool its superconducting coils, generating high running costs.

Keywords

Highly charged ion, atomic physics, astrophysics, quantum electrodynamics, nuclear fusion, plasma physics, Tokyo-EBIT, CoBIT, EBIT (electron beam ion trap)

Affiliations	The Atomic Collision Society of Japan; The Physical Society of Japan; The Forum for Atomic and Molecular Data and Their Applications
Member	Nobuyuki Nakamura, Associate professor

CoBIT

To overcome the problem of size and the running costs, our group subsequently built a compact highly-charged ion source called CoBIT, which measures a mere 50 cm in height—or nearly one-sixth the size of the Tokyo-EBIT—while retaining its fundamental structures. Despite certain limitations on the charge state of the ions that can be studied, the device is capable of producing highly-charged iron ions with the charge states of 10 to 20, characteristic of the most abundant components of the solar atmosphere. This performance is sufficient for experiments involving highly-charged ions abundant in a variety of plasmas. This achievement demonstrates a balanced approach typical of the R&D efforts at our laboratory—in this case, a balance between research on highly-charged ions on the one hand and the development of an efficient experimental device for ion production on the other.

Advantages

A Compact, Highly-Charged Ion Source CoBIT Based on Knowledge and Experience Accumulated with the Tokyo-EBIT Development Project

In developing the Tokyo-EBIT, our laboratory gathered knowledge and experience that contributed immeasurably in building the new highly-charged ion source. Our laboratory handled the process of developing the compact highly-charged ion source CoBIT from design to assembly. The CoBIT system retains the essence of the mechanism used in the Tokyo-EBIT, which irradiates and traps ions with electron beams compressed by the magnetic field to strip off electrons, while incorporating a new technique using a high-temperature superconducting wire to generate the magnetic field. This allows us to build a device of compact dimensions that does not require a large laboratory for deployment and eliminates the need for liquid helium to achieve low operating costs.

Compared to the Tokyo-EBIT, CoBIT has certain limitations in the charge states it can produce. Nevertheless, CoBIT will be more efficient for measurements of the highly-charged ions with moderate charge states important for research on plasma atomic processes at nuclear fusion research facilities and in astrophysical research at astronomical observatories. It is the only instrument in Japan that does not require a large-scale laboratory and is capable of spectroscopically observing and extracting highly-charged ions with high degrees of freedom. This flexibility reflects one of the great strengths of our laboratory.

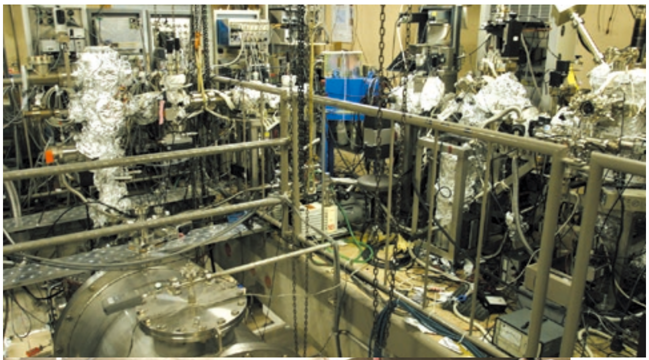
Future Prospects

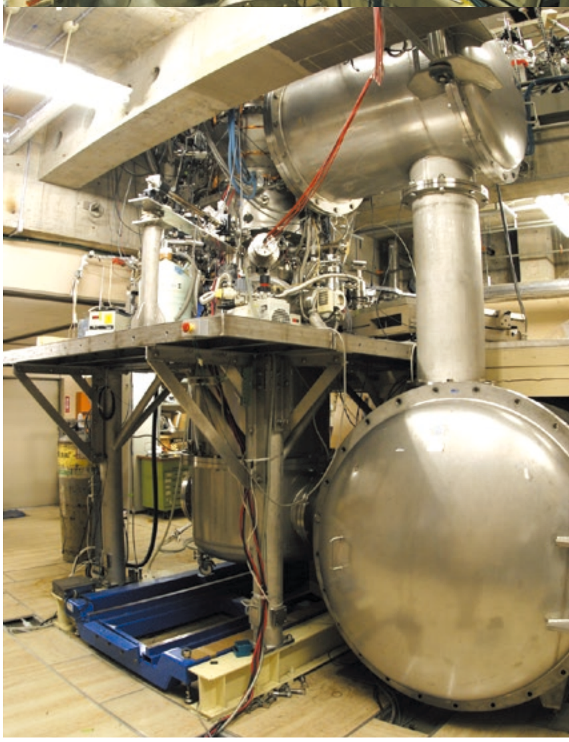
Developing a More Compact, Higher-Performance Highly-Charged Ion Source to Promote Highly-Charged Ion Research

Our research on elucidating the nature of highly-charged ions, our first theme, remains incomplete, and much work lies ahead. At the same time, we will strive to continue refining our highly-charged ion source technologies.

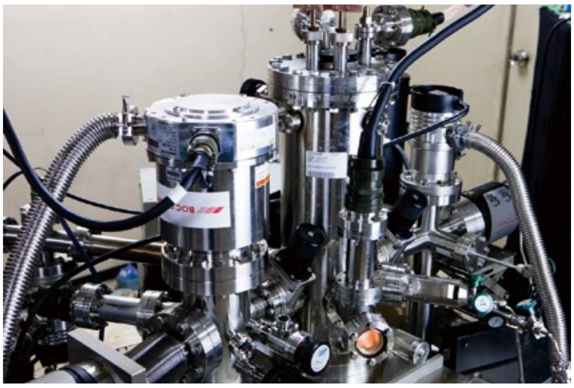
Our efforts to develop CoBIT have proven successful in the sense that they resulted in a compact device incorporating functions comparable to full-scale instruments. Nevertheless, considerable room for progress remains. It is our pledge to all prospective commercial partners willing to engage in joint projects with our laboratory to strive to build still more compact highly-charged ion sources that will make it possible to obtain more intense, higher charged ions, based on our experience and expertise in the development of highly-charged ion sources.

Without question, more compact, higher-performance highly-charged ion sources will expand the boundaries of source deployment and use, provide access to researchers at various research facilities, and expand use in product development and analysis by commercial entities.





Tokyo-EBIT (high-energy electron beam ion trap)



CoBIT (compact low-energy electron beam ion trap)

We believe such progress will promote research involving highly-charged ions worldwide and lead to new discoveries and new applications. At our laboratory, our goal is to make highly-charged ions more accessible to an ever wider circle of researchers.