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High-resolution X-ray spectroscopy of highly charged tungsten EBIT plasma

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ABSTRACT

Highly charged tungsten transitions can be used as a diagnostic tool for investigating performance of the fusion device. Systematic spectroscopic investigations of the radiative decay channels of the tungsten charge states allow for extending the fundamental understanding of highly charged ions and can serve as a diagnostic tool to improve applied plasma research. Electron beam ion traps (EBIT) offer the ability to generate emission from highly charged tungsten ions because of their charge state and excitation selectivity due to their quasi-monoenergetic electron beam. In this work, we report the current experimental capabilities of the EBIT at the National Institute of Standards and Technology (NIST). High-resolution measurements of EUV and x-ray transitions from tungsten charge states are shown, demonstrating our ability to produce and identify the spectral features of highly charged tungsten plasma. While the experimental results were limited by the lack of an absolute calibration of the spectrometer, we present approximate transition energies of two strong transitions from the Ti-like W^{52+} and Sc-like W^{53+} charge states. Our estimates agree quite well with the results of FAC simulations, where these strongest transitions were identified to originate from 3d-4f transitions. This decay channel has been shown to be the strongest transition for surrounding charge states.

1. Introduction

Spectroscopy of highly charged tungsten ions has garnered considerable interest due to its relevance in fusion plasma research. Tungsten has a considerable amount of favorable properties for being a primary plasma-facing material in fusion reactors, such as ITER and the ASDEX Upgrade tokamak devices. This provides impetus for understanding the properties of the various charge state distributions of highly charged tungsten plasma via accurate atomic data and spectral line identification measurements from spectroscopy experiments. This has been extensively discussed and highlighted by numerous research groups for over a decade in attempt to improve the current state of fusion reactors. An excellent review of these recent efforts was compiled by Kramida [1].

Erosion of tungsten into the fusion plasma is well documented, where the charge state distribution in the ITER plasma is expected to range from Ag-like W^{27+} at the outer edges of the plasma to F-like W^{65+} in the core of the plasma [2,3]. The core plasma of the ASDEX Upgrade device produces Kr-like W^{38+} to Ni-like W^{46+} ions, while lower charge states Sn-like W^{24+} to Rb-like W^{37+} are produced in the outer edge of the plasma [3]. Inevitably, tungsten ions will contaminate the fusion-plasma through interactions with the plasma, generating a wide range of tungsten ion charge states. Pütterich et al. (2008) compiled a comprehensive report on the effect of tungsten from experimental data from the ASDEX Upgrade, producing predictions for effects within the ITER plasma [3]. The presence of such tungsten charge states significantly enhances the power loss of the fusion-plasma device via emitted radiation, a serious issue that substantially degrades the performance of tokamaks [3]. The impurities due to tungsten can result in reductions in the fusion reactions that are required for energy production and potentially increasing the difficulty in confinement [3]. It is thus essential to understand the characteristics of highly charged tungsten plasma in order to develop a means for mitigating their effect on the fusion-plasma device [3].

Determining the tungsten charge state distribution within the fusion-plasma requires accurate atomic data (atomic transitions with identified wavelengths, transition intensities, ionization, excitation and recombination cross sections for many tungsten charge states) [4]. Many fusion-plasma devices utilize spectroscopic equipment to probe the fusion plasma to infer information about the plasma state. Observations of tungsten transitions from the fusion plasma can be and have been used to diagnose the state of the fusion device. For the anticipated ITER project, Peacock et al. (2007) provided theoretical estimates of x-ray and VUV spectroscopic data expected from the device along with outlining the various diagnostic instrumentation planned to help aide the reactor [2]. The core imaging x-ray spectrometer (CIXS)

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represents a crystal x-ray spectrometer experiment designed to diagnose the ITER plasma state, one of many diagnostic systems planned for the ITER project [5]. Such projects require fundamental laboratory measurements of spectral features of the various charge states of tungsten through spectroscopic line identification measurements. Spectroscopic observations of highly charged tungsten plasma produced in an electron beam ion trap (EBIT) help aide in fusion-plasma research (and general plasma research) as the EBIT can produce and confine nearly all tungsten charge states while offering charge state selectivity. Skinner (2008) provided a report on the importance of contributions from EBIT devices pertaining to improving fusion devices [6]. Such measurements of the highly charged extreme-ultraviolet tungsten spectra have been extensively studied and discussed [see for example, [7–11]].

Similarly, the EBIT has been used to measure transitions in the soft x-ray regime for a range of tungsten charge states, where we highlight a small sample of such observations related to the charge states of interest here [12–19]. An x-ray microcalorimeter was used to measure and identify energetic x-ray emissions for the Cu-like W^{45+} and Ni-like W^{46+} charge states providing accurate benchmarks for confirming the performance of dynamical plasma models and spectroscopic diagnostic tools of non-Maxwellian plasmas [13]. *M*-shell transitions, also recorded by an x-ray microcalorimeter array detector, were identified for the Zn-like W^{44+} through Co-like W^{47+} charge states [14]. Another measurement using a high-resolution crystal spectrometer reported identification of *M*-shell x-ray transitions of tungsten ions in the 5 Å–6 Å wavelength region from the Se-like W^{40+} to the Cr-like W^{50+} charge states, where the majority of the spectral lines were assigned to transitions from the 3d-4f and the 3p-4d shells [15]. Soft x-ray spectral features around 5.6 Å from Cu-like W^{45+} to Cr-like W^{50+} charge states were investigated in another measurement using a flat-crystal Bragg spectrometer, assigning the origin of these spectral lines to 3d-4f transitions [4]. A high-resolution grazing incidence spectrometer was used to observe 3s-3p and 3p-3d transitions between 19 Å and 24 Å arising from the K-like W^{55+} through Ne-like W^{64+} charge states [16]. This instrument also observed 3p-3p and 3p-3d transitions between 27 Å and 41 Å due to the *M*-shell tungsten ions from Al-like W^{61+} through Co-like W^{47+} [17]. *L*-shell x-ray transitions of Ne-like W^{64+} including few inner-shell collisional satellite lines arising from Mg-like W^{62+}, Na-like W^{63+}, F-like W^{65+}, and O-like W^{66+} charge states were recorded with a von-Hámos-type crystal spectrometer [18]. Dominate transitions from Si-like W^{60+} through Ne-like W^{64+} ions were also investigated with a crystal spectrometer in the 1.0 Å–1.6 Å wavelength region [4]. A detailed theoretical study aimed at providing accurate atomic data and theoretical spectra for comparison to the existing experimental data was performed for 10 tungsten charge states, from Ge-like W^{42+} through V-like W^{51+} [19]. This study identified the strongest transition to be consistently from a $3d_{3/2}$-$4f_{5/2}$ transition for all the ten charge states. They note that this particular transition from Ni-like W^{46+} to be very strong in their simulations, where the 3d-4f transition in all 10 tungsten spectra fall within a 300 eV region centered on the strong Ni-like W^{46+} feature. This interval should be well suited to infer the tungsten charge state balance in moderate-temperature tokamak plasmas [19]. These reports demonstrate the necessity of spectroscopic measurements of highly charged tungsten plasma as a means for diagnosing the plasma state of a fusion device, where all studies included comparisons to model simulations relevant to the particular experiment.

To our knowledge, measurements of the 3d-4f tungsten transitions have not been performed for the V-like W^{51+} through P-like W^{59+} charge states in the x-ray regime below 10 Å, representing one of the motivating factors of this work. In this report, we highlight our capability of producing high-resolution, x-ray observations of highly charged tungsten ions up to Sc-like W^{53+} as a means for line identification, allowing for further diagnosing the highly charged tungsten plasma, using the EBIT located at the National Institute of Standards and Technology (NIST). A high-resolution Johann-type curved crystal x-ray spectrometer was used to record the x-ray spectra [20]. Transitions in the EUV regime are also presented for validation and verification of the plasma species using a flat field EUV spectrometer, with additional broad-band x-ray spectra from a solid-state high-purity germanium (HPGe) x-ray detector for further corroboration [21].

The instruments used in this exploratory experiment are described in detail in Section 2. Section 3 outlines the experimental procedure used in the experiment. The results of the experiment are provided in Section 4, demonstrating the production of highly charged tungsten, the EUV spectra, and the high resolution x-ray spectra. The experimental high resolution x-ray spectra reported here were limited by the lack of an absolute reference for proper line identification. This report is aimed at demonstrating our current capabilities of producing proper spectroscopic measurements, in particular, those associated with x-ray transitions of highly charged tungsten ions. We were able to produce an approximate energy calibration to estimate the energy of the strongest 3d-4f transition of the tungsten charge states present in the EBIT, comparing these estimates to the predicted photon energies calculated by the Flexible Atomic Code (FAC) [22]. This is discussed in Section 5, where we also include the results of those in [19] to illustrate our capabilities as well as to provide additional spectroscopic tools for diagnosing hot plasmas.

2. Instrumentation

Highly charged tungsten ions were created and trapped using the NIST EBIT that consists of three main axially aligned components: the electron gun, the trapping region consisting of the drift tube electrodes, and the collector assembly [23]. Electrons forming the quasi-mono-energetic electron beam emanate from a Pierce-type electron gun, capable of producing a maximum electron beam current of 150 mA. Compression of the electron beam by an axial 3T magnetic field, produced by a pair of liquid-helium-cooled superconducting Helmholtz magnets, provides a minimum electron beam width of approximately 60 μm at the center of the trapping region.

The NIST EBIT is capable of producing electron beam energies from a few hundred eVs to 30 keV. The beam energy is controlled by a cylindrical shield electrode that surrounds the drift tube electrodes. The three drift tube electrodes located inside the shield electrode are electrically floated on top of the applied voltage to the shield electrode, where each drift tube electrode can be independently controlled to provide the proper axial trap potential for the ion species. The beam energy is proportional to the voltage applied to the trap electrodes and corrected for the space charge potential produced by the electron beam itself, which depends on the electron beam energy and current [24]. For this experiment, the space charge is on the order of a few hundred eV. The trapped ions are radially trapped by the axial magnetic field and also by the space charge produced by the electron beam.

Once exiting the drift tubes, the electron beam spreads out along the magnetic field lines and contacts the liquid-nitrogen-cooled collector. A metal vapor vacuum arc (MeVVA) ion source attached to the top of the EBIT chamber was used to generate singly charged tungsten ions that travel to the EBIT trapping region along the axial magnetic field lines [25].

The NIST EBIT has potential observation ports, allowing for simultaneous operation of the spectroscopic instruments. A flat-field variable-line-grating extreme ultraviolet spectrometer is currently attached to one of these observation ports [21]. This customized high-resolution spectrometer consists of a gold-coated spherical focusing mirror that images the radiation onto the entrance slit of the monochromator. A dispersive flat-field grazing-incidence reflection grating disperses the photons onto a liquid-nitrogen-cooled high spatial resolution charge-coupled device (CCD) camera sensitive to the energy of the EUV photons. Adjustment of the detector position allows for observations of wavelengths between approximately 1 nm–40 nm,