X-ray spectroscopy and spectropolarimetry of high energy density plasma complemented by LLNL electron beam ion trap experiments

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X-ray spectra of high energy density (HED) Z-pinch plasmas have been analyzed by means of a comprehensive kinetic modeling. A new diagnostic, x-ray spectropolarimetry, was applied to study anisotropy of Z-pinch plasma. This diagnostic is based on theoretical modeling of polarization-dependent spectra measured simultaneously by spectrometers with different sensitivity to polarization. Specifically, K-shell emission from Ti X-pinches was recorded simultaneously with identical LiF crystal spectrometers with the dispersion plane perpendicular and parallel to the discharge axis. Spectroscopic results from seven Ti X-pinch shots have been analyzed. Similar K-shell Ti polarization-dependent spectra generated by a quasi-Maxwellian electron beam at the LLNL EBIT-II electron beam ion trap have been studied. Further, the EBIT-II M-shell W spectra have proved to be important in the development of M-shell diagnostics of HED Z-pinch plasma. The advantages provided by electron beam ion trap data in the interpretation of HED Z-pinch spectra will be presented. © 2003 American Institute of Physics. [DOI: 10.1063/1.1535277]

I. INTRODUCTION

Polarization-sensitive experiments on the 1 MA pulsed power Z-pinch device at the Nevada Terawatt Facility (NTF) provide the experimental evidence of the existence of strong electrons beams in Ti X-pinch plasmas and motivate the development of a new diagnostic, x-ray spectropolarimetry, for investigating the level of anisotropy of such plasmas, as first reported in Refs. 1 and 2. Further development of x-ray spectropolarimetry based on the results of more X-pinch shots with improved diagnostics is presented. This diagnostic requires a sophisticated theoretical modeling of polarization-dependent spectra simultaneously measured by spectrometers with different sensitivity to polarization. To develop such modeling and to study the effects of plasma electron energy distributions on the spectra, experiments at the LLNL EBIT-II device have been performed.3 To this end, K-shell Ti spectra similar to the NTF spectra were gathered while the electron beam energy was swept through a carefully synchronized pattern to replicate a Maxwellian. The results of the analysis of the K-shell Ti spectra are presented in Sec. II. Further, the EBIT-II M-shell W spectra, which proved to be important in the development of M-shell diagnostics of HED Z-pinch plasma are discussed in Sec. III.

II. K-SHELL X-RAY SPECTROSCOPY AND SPECTROPOLARIMETRY OF TI PLASMAS AT THE NTF AND LLNL EBIT

Ti plasmas have been produced at the NTF from a wide variety of pinches including single wires and X-pinches. The distinct feature of X-pinches is an existence of a strong electron beam, which results in polarization of emitted line radiation. It makes them attractive objects for spectropolarimetry. A planar-loop X-pinch configuration with a 20 mm anode–cathode gap was employed, which produces a bright, small-sized x-ray source, with a well-defined location. The polarization-dependent spectra of K-a line radiation generated by Ti X-pinches were recorded simultaneously by horizontal (H) and vertical (V) spectrometers (see the scheme and discussion of the experimental setup in Refs. 1–3). H spectrometer provides resolution along the Z-pinch symmetry axis and has a dispersion plane perpendicular to the discharge axis, whereas V spectrometer has a dispersion plane parallel to the discharge axis. H spectrometer records almost a pure parallel polarization state, whereas V records almost a pure perpendicular polarization state. Both spectrometers are identical LiF (2d = 4.027 Å) convex crystal spectrometers. The LiF crystal has a spacing corresponding to the nominal Bragg angle of 40° at the wavelength of 2.6 Å and is sensitive to polarization of the resonance line and other lines with larger wavelength up to the cold K-a line.

Time-integrated images of selected two X-pinch and two single wire shots are shown in Fig. 1. The anode is at the top of all images. The diameter of Ti wires varies from 30 μm to 76.2 μm for X-pinches and from 30 μm to 177.8 μm for single wires. The left-hand side image in each picture was recorded through the filter providing the maximum of radiation at λ<2.6 Å, whereas the central and the right-hand side images were recorded through the filter providing the maximum of radiation at softer wavelengths. Figure 1 shows
that an X-pinch is a small, almost point source for radiation with $\lambda \approx 2.6$ Å. A structure of an X-pinch includes energetic electron beams directed toward the anode and along the wires.\(^{1,2}\) The single wire images indicate a chain of numerous hot spots on the discharge axis, which make single wires a difficult object for spectropolarimetry.

The typical X-pinch and single wire spectra recorded by H spectrometer are presented in Fig. 2. For X-pinches, they include the He-like resonance line He\(_{\alpha}(w)\), the most intense line in all K-shell Ti spectra, the intercombination He-like line (y), the Li-like satellite line peak (q), the Be-like satellite line peak, the H-like resonance line Ly\(_{\alpha}\) with satellites, the He-like resonance line He\(_{\beta}\) with satellites, and the He-like resonance line He\(_{\gamma}\). For single wires, the spectra mostly lack Ly\(_{\alpha}\) line with the satellites, which indicates a lower temperature compared with X-pinch plasma. Also, at the right-hand side of the Be satellite peak, x-ray spectra include satellite structures due to B-, C-, N-, and O-like Ti ions and the most prominent peak at the right, a cold K\(_{\alpha}\).

The ratios of intensities of different lines to the resonance line (y/w, q/w, Be/w, and Ly\(_{\alpha}/w\)) from H (a) and V (b) spectra are presented in Table I associated with different polarization states $I_{\parallel}$ and $I_{\perp}$, respectively, for various X-pinch shots. In addition, the same ratios measured in the spectra of single wire shots recorded by the H spectrometer are given. To estimate polarization, first the value of $I_{\parallel}/I_{\perp}$ should be determined. From all shots, the largest deviation from 1 was observed for the shots 39 and 47. In particular, the ratio for the resonance and intercombination lines is $<1$, which indicates negative polarization, whereas the ratio for most of the satellite lines is $>1$, which indicates positive polarization. Second, the H/V (or a/b) ratios from Table I should be analyzed for each line ratio for X-pinch shots. For example, the H/V value of y/w is close to 1 for all shots, which indicates the same polarization for $y$ and $w$ lines. The H/V values for the satellite line ratios is larger than 1 for most of shots. In general, the analysis indicates positive polarization of dielectronic satellite peaks produced by a low energy electron beam (3–5 keV) and negative polarization of resonance and intercombination lines produced by an electron beam with a much higher energy (>30 keV). X-ray spectral lines of B-, C-, N-, and O-like Ti ions in the spectral region above 2.6 Å may be also polarized; relative intensities of corresponding peaks differ in H and V spectra.

A collisional-radiative atomic kinetic model has been developed to diagnose the electron temperature $T_e$ and electron beam characteristics (hot electron fraction $f$) of various emitting regions of Ti plasmas produced at the NTF. A detailed description of the model is given in Refs. 3 and 4. The NTF Ti plasmas are taken to have two regions: a hot, dense region with hot electrons that contributes all of the H-like and most of the He-like radiation and a cooler, less dense region that contributes satellite radiation from lower ionization stages. It was found that the effects of hot electrons are similar to the effects of increasing $T_e$. But if $T_e$ and $f$ are chosen such that the increase in the Ly\(_{\alpha}\) intensity is the same in both cases, the

### Table I

<table>
<thead>
<tr>
<th>Shot</th>
<th>30</th>
<th>36</th>
<th>37</th>
<th>38</th>
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<th>40</th>
<th>47</th>
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<td>0.62</td>
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<tr>
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<td>0.23</td>
<td>0.33</td>
<td>0.33</td>
<td>0.35</td>
<td>0.29</td>
<td>0.43</td>
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<tr>
<td>Ly(_{\alpha}/w)</td>
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<td>0.16</td>
<td>0.26</td>
<td>0.31</td>
<td>0.30</td>
<td>0.24</td>
<td>0.30</td>
<td>0.24</td>
<td>0.19</td>
</tr>
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</table>

![FIG. 1. NTF time-integrated x-ray pinhole camera images of Ti X-pinches and single wires with a different wire diameter $\phi$. (a) X-pinch shot 39 ($\phi=30$ µm); (b) X-pinch shot 47 ($\phi=76.2$ µm); (c) single wire shot 42 ($\phi=30$ µm); (d) single wire shot 46 ($\phi=177.8$ µm).](image1)

![FIG. 2. Typical NTF K-shell Ti spectra of X-pinch (shot 47) and single wire (shot 42) plasmas.](image2)
Li-like satellites will be more intense with hot electrons than with higher $T_e$. By matching both the Ly$_\alpha$ satellites to the experimental He$_b$ line, both $T_e$ and $f$ of the hot region can be estimated. The best fits of He$_g$, He$_b$, and satellites, and Ly$_\alpha$ and satellites in all experimental cases indicate the presence of hot electrons in the hot plasma regions with $T_e \approx 2-3$ keV. The analysis of single wire spectra indicates lower temperatures around 1–1.5 keV. Further improvements of the model require including Ti K$_\alpha$ and opacity effects.

Earlier, x-ray line polarization of K-shell Ti ions excited by a monoenergetic electron beam at LLNL EBIT was measured by Beiersdorfer et al. The x-ray spectrum of He-like Ti was measured at the energy just above the electron-impact excitation threshold $\approx 4800$ eV. The measured intensities recorded by the spectrometers with a Si (220) crystal (almost a pure parallel polarization state, $I_3$) and a Ge (111) crystal (mixture of both polarization states, $I_4$) were $I_3 = 0.212$, $I_4 = 0.335$ for $z/w$; $I_3 = 0.068$, $I_4 = 0.145$ for $x/w$; and $I_3 = 0.113$, $I_4 = 0.153$ for $y/w$. In Fig. 3, theoretical modeling of He-like Ti lines with Gaussian and quasi-Maxwellian electron distribution functions is presented to match data $I_3$ and $I_4$. The theory describes well the ratios and differences in spectra between monoenergetic and quasi-Maxwellian beams, specifically the fact that the ratio $z/w$ does not change, while the $x/w$ ratio decreases from 0.191 to 0.145 and the $y/w$ ratio decreases from 0.235 to 0.153.

In Fig. 4, the experimental polarization-sensitive spectra ($I_3$ and $I_4$) are shown which include the most prominent He-like resonance line $w$ at $\lambda = 2.6105$ Å together with other lines excited by electron impact, such as He-like lines $z$, $x$, and $y$ and Li-like inner-shell satellites of Ti ions, produced...
by a quasi-Maxwellian electron beam. The comparison of polarization-sensitive ratios \( I_1/I_2 \) and \( I_3/I_4 \) for the \( z, x, \) and \( y \) lines proves that the ratio decreases for the lines \( z \) and \( x \) and they become more negatively polarized and the ratio increases for the line \( y \), which become more positively polarized. This agrees well with theoretical predictions. Future work will focus on the estimation of contribution of unresolved dielectronic satellites due to transitions \( 1s^23l-1s2l'3l'' \) into intensities of polarized \( w, x, \) and \( y \) lines and calculation of polarization of the \( q \) line.

**III. M-SHELL X-RAY SPECTROSCOPY OF W PLASMAS**

Tungsten wire explosions are being intensively studied at Sandia National Laboratories and results have been published elsewhere (see, for example, Ref. 6). High-resolution x-ray spectral data have been accumulated in tungsten experiments on the SNL-Z,\(^7\) which require a development of appropriate theoretical modeling. The spectra are immensely rich and the majority of line emissions in the spectral region from 4.5 Å to 7.5 Å is composed of \( 3l-4l' \) and \( 3l-5l' \) transitions. We have begun a series of experiments to study \( M \)-shell transitions of W ions at the LLNL EBIT-II. These studies will allow us to break down this very complicated spectrum into spectra produced by separate W ions to benchmark advanced atomic structure and ionization balance calculations. The most intense lines in the spectral range from 5 to 6 Å have been studied. \( M \)-shell W spectra have been produced at LLNL EBIT-II by a monoenergetic electron beam at electron energies from 2.4 keV up to 4.6 keV. To calculate atomic data of all needed isoelectronic sequences matching this spectrum two codes have been used: Cowan and MBPT codes. The Cowan code is a well-known MCHF code,\(^8\) and the MBPT code is a fully relativistic code based on a many-body perturbation theory and includes the Breit interaction.\(^9\) The distribution of the line intensities inside some ionization stages can be described quite well by radiative mechanisms. For example, Fig. 5 illustrates the comparison of theoretical calculations of Zn- and Ga-like W with the experimental results produced by the electron beam at 2.4 keV and 2.8 keV.

The collisional-radiative atomic kinetic model has been developed to calculate the ionization balances of W ions and includes the ground states of every ionization stage of W from the bare ion with no electrons to neutral W with 74 electrons. Detailed atomic structure is included for ionization stages from Cr-like to Se-like W. Preliminary results of this model describes well the appearance of Cu-like to V-like W ions, the dominance of Ni-like ions from 2.8 keV up to 4.2 keV, and the difference in ionization balances for monoenergetic electron beam and Maxwellian electron distribution functions.

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\(^7\) J. Bailey (private communication).