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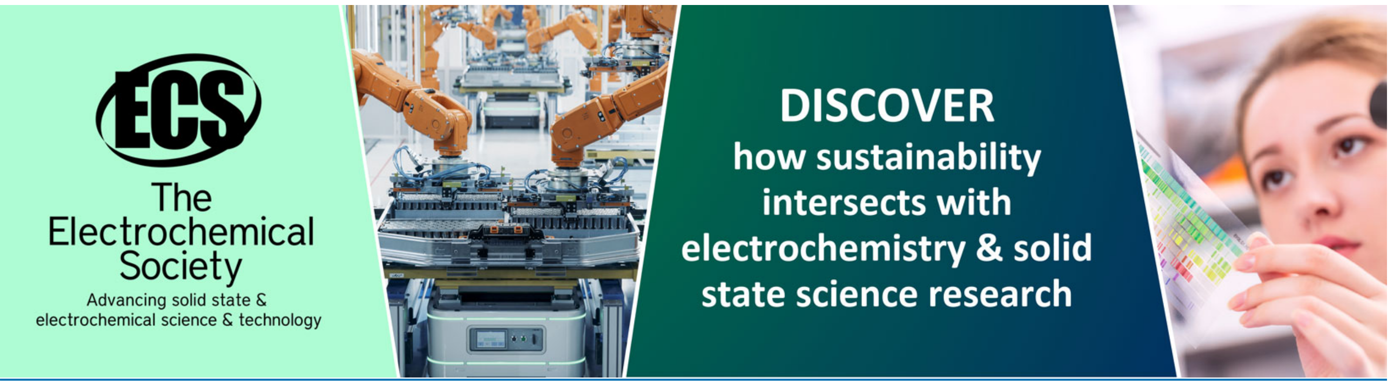

EUV spectroscopy of highly charged iron ions with a low energy compact EBIT

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Abstract. We measured extreme ultraviolet (EUV) spectra of highly charged iron ions (Fe IX - Fe XV) in the range of wavelength 130-300 Å by a new compact electron beam ion trap (EBIT) which was developed for low electron energy operation. The electron energy of this compact EBIT is controllable from 100 eV to few keV, therefore it is appropriate for spectroscopic investigation of the moderately charged ions. A slitless flat-field EUV spectrometer developed exclusively for this compact EBIT is mounted with it and high sensitivity and high resolution spectroscopic analysis of highly charged iron ions become possible. The electron energy dependence of highly charged iron ion spectra were measured in the range of electron energy of 200-1350 eV. We could get the spectral information of wide range of charge state from Fe IX to Fe XV, and moreover, various charge state ions could be selectively produced with a narrow charge state distribution by adjusting the electron beam energy.

1. Introduction

The research of highly charged ions (HCIs) with an electron beam ion trap (EBIT) [1] advanced widely in the field of atomic and molecular physics. Although it can be used as an ion source similar to an electron beam ion source [2], it is a powerful tool especially for spectroscopic studies of trapped HCIs. In particular, the spectroscopic investigation of HCIs which are moderate charge state ions attract attention not only in atomic physics but also in some research fields recently. For example, to develop an extreme ultraviolet (EUV) light source for the next-generation lithography, the atomic data of highly charged tin ions with charge states around 10 are strongly needed [3, 4]. Another example is the diagnostics of nuclear fusion and astrophysical plasmas. The spectra of highly charged iron ions with charge states around 10 are observed for diagnostics of the solar corona by the launched satellite Hinode recently [5, 6, 7, 8]. The atomic data of impurity highly charged iron ions are needed for the spectroscopic diagnostics of high temperature and density controlled plasma like a Large Helical Device (LHD) [9, 10]. For International Tokamak Experimental Reactor (ITER), which is the next-generation fusion device, the spectroscopic data of tungsten ions with moderate charge states around 20 are needed [11] because tungsten is one of the candidate of diverter materials.

We developed the compact EBIT [12] for low energy, which is named "CoBIT", and an EUV spectrometer for exclusive use. We carried out the EUV spectroscopy of such a moderate charge state ions. In this paper, we present the observation EUV spectra (130-300 Å) of highly charged iron ions in CoBIT. The electron energy range is from 200 to 1350 eV and the observed charge states of iron ions are from 8+ to 14+. The detail of the new device and electron energy dependence of highly charged iron ion spectra are discribed in this paper.

2. Experiments

The experimental apparatus consists of the CoBIT, which is highly charged ion source, and the EUV spectrometer. A schematic drawing of the CoBIT and the EUV spectrometer are shown in Figure 1. The EBIT mainly consists of an electron gun, an ion trap (drift tube), an electron collector, a superconducting coil, and liquid nitrogen tank. We used the same electron gun as the Tokyo-EBIT [13, 14, 15] which had a good performance. The perviance of the gun is about 0.4 μperviance, so that an electron current of 10 mA can be obtained with an anode voltage of 1 kV. At the CoBIT, it is possible to decelerate the electron beam between the anode and drift tube. The electron beam current is about 20mA in electron energy 400 eV by such a decelerating operation. The high critical temperature superconducting Helmholtz coil which can be used at the liquid nitrogen temperature is mounted around the drift tube. The electron beam emitted from the electron gun is accelerated (or decelerated) toward the drift tube and compressed by the magnetic field produced by the superconducting Helmholtz coil. The maximum central magnetic field produced by the present coil is about 0.2 T with a maximum current of 50 A. This magnetic field 0.2 T is enough to produce the HCI of moderate charge state. The trap consists of three drift tubes (DTs). DTs are generally cylindrical electrodes, however, for high accessibility to the trap center, we employed DT2 which consists of six poles surrounding the electron beam. For example, by surrounding the trap by a parabola, ellipse or Wolter mirror, the visible, EUV and x-ray spectroscopy can be performed with high efficiency. After passing through the drift tube, the electron beam is collected by the electron collector which has a cooling system. All the electrodes in this CoBIT are fixed in the liquid nitrogen tank with ceramic insulators (Shapal M-soft) which have high thermal conductivity to keep them at low temperature. The electron collector, at which 10 W is consumed at the maximum, is also cooled through this thermal conductivity and so the present EBIT is compact. The operating electron current is 10-20 mA at electron energy 200-2000 eV, and very stable operation is possible during a long exposure time (several hours). When we operate the CoBIT, the background pressure in it is very important parameter. It is necessary to keep the pressure of the CoBIT less than 10^{-8} Pa during the measurement, however, the pressure of spectrometer which connected to the CoBIT is about 10^{-7} Pa. Therefore, the quadrate pipe (6W×26H×60L mm) was installed between the CoBIT and spectrometer for differential pumping.

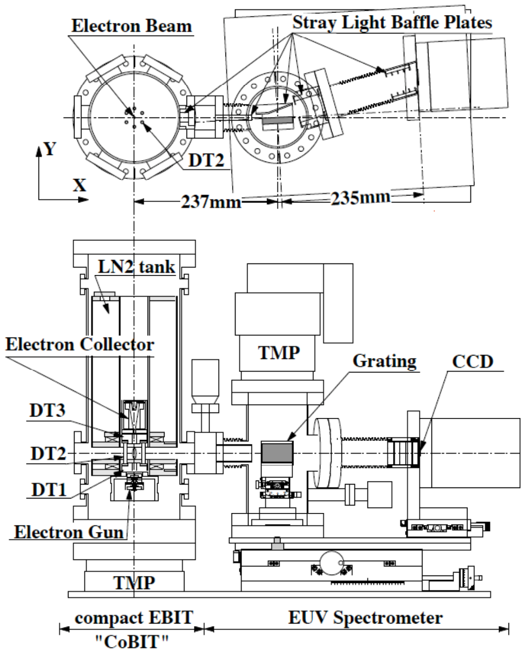

Figure 1 Cross sectional view of compact EBIT and EUV spectrometer

We developed an slitless EUV spectrometer which was exclusive use of CoBIT. In general, it is necessary to install a entrance slit in front of the diffraction grating, but we designed the spectrometer of slitless type because an EBIT represents a line source with a width of about 0.1 mm. Therefore, high efficient spectroscopic measurement became possible. On the other hand, we paid attention enough for a stray light countermeasure because of the slitless spectrometer. The designed spectrometer is flat-field grazing-incidence (87deg.) spectrometer with a 1200 grooves/mm laminar-type replica diffraction grating (30-002, Shimadzu Corporation). The diffraction grating is installed in the chamber center precisely and can be moved to the X,Y axis directions at minimum resolution 0.01 mm and be adjusted it to the design position. The spectrometer is mounted with the rotary table whose the axis of rotation agrees with the diffraction grating central axis. Then the rotary table is adjustable with precision of turning angle +/- 0.02 deg. to set a spectrometer to angle-of-incidence 87 deg.. In addition, the diffraction grating holder has an adjustment mechanism which adjust the blast angle by αβ-axis goniometers. The position and angle adjustments of spectrometer are possible while measuring a spectrum by these adjustment mechanisms and we can perform optimization smoothly. The detector is the back-illuminated CCD camera (Princeton Instruments PIXIS-XO: 400B). This camera has 1340×400 pixels whereby the dimension of each pixel is 20× 20 μm^2. The CCD camera installed in 235 mm from the diffraction grating position is movable on the focusing plate and fixed on the position of the measuring wavelength area. The wavelength range by this grating is from 50 to 300 Å. The high resolution EUV spectroscopy is possible at wavelength range from 10 to 60 Å by only changing the another diffraction grating (30-003:2400 grooves/mm, grazing-incidence 88.65 deg.).

3. Results and Discussion

EUV spectra of highly charged iron ion are shown in Figure 2. The electron energy dependence of highly charged iron ion spectra were measured in the energy range 200-1350 eV and the wavelength range 130-300 Å. The broad emission lines around 190-200 Å are 2nd order lines from an impurity HCI of Ba evaporated from the cathode. It is called UTA (Unresolved Transition Array), and the impurity HCIs of O and N were observed. At the electron energy range 600-1350 eV, the emission lines were not observed at all in the measurement wavelength range of 130-300 Å. The strong emission line of Fe XV (284.16 Å) were observed at 500 eV. As electron energy decreases from 500 to 300 eV, the dominant emission lines transfer from Fe XV to Fe IX successively. The emission lines of highly charged iron ion were almost not confirmed in this wavelength region at 200 eV. In spectrum of each electron energy, only emission lines from two or three kinds of charge states of iron HCI are observed. We could measure the EUV spectra with a narrow charge state distribution of HCIs at each electron energy in this way. This narrow charge state distribution of HCIs is very sensitive to the pressure in ion source, therefore it is

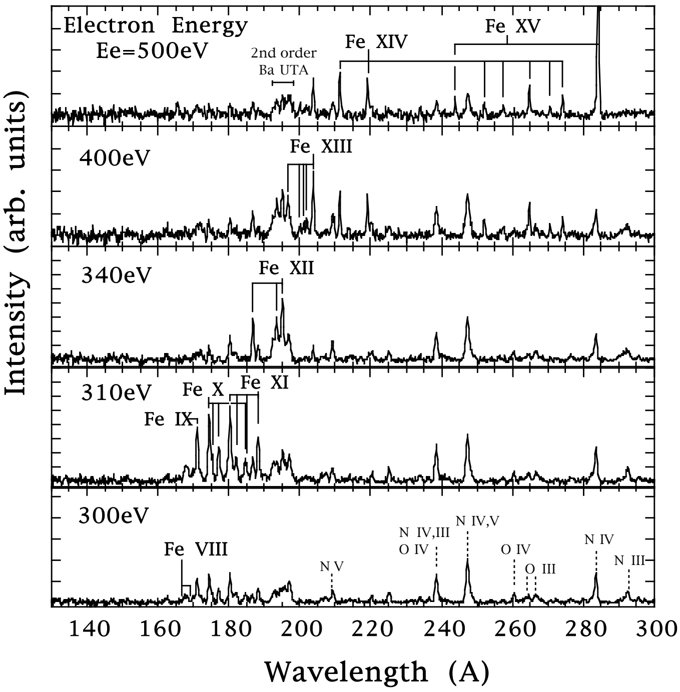

Figure 2 EUV spectra of highly chargd iron ions obtained with the compact EBIT. For all the spectra, the exporsure time were about 20 minutes.

Table 1 configurations of observed lines.

Ion	lower	Upper	Wavelength(Å) [16]	
Fe XV	$3s3p\ ^1P_1$	$3s3d\ ^1D_2$	243.794	
	$3s^2\ ^1S_0$	$3s3p\ ^1P_1$	284.164	
Fe XIV	$3s^23p\ ^2P_{1/2}$	$3s^23d\ ^2D_{3/2}$	211.331	
	$3s^23p\ ^2P_{3/2}$	$3s^23d\ ^2D_{5/2}$	219.136	
	$3s^23p\ ^2P_{1/2}$	$3s3p^2\ ^2P_{3/2}$	252.188	
	$3s^23p\ ^2P_{1/2}$	$3s3p^2\ ^2P_{1/2}$	257.377	
	$3s^23p\ ^2P_{3/2}$	$3s3p^2\ ^2P_{3/2}$	264.785	
	$3s^23p\ ^2P_{3/2}$	$3s3p^2\ ^2P_{1/2}$	270.511	
	$3s^23p\ ^2P_{1/2}$	$3s3p^2\ ^2S_{1/2}$	274.203	
Fe XIII	$3s^23p^2\ ^1D_2$	$3s^23p3d\ ^1F_3$	196.525	
	$3s^23p^2\ ^3P_1$	$3s^23p3d\ ^3D_2$	200.021	
	$3s^23p^2\ ^3P_1$	$3s^23p3d\ ^3D_1$	201.121	
	$3s^23p^2\ ^3P_0$	$3s^23p3d\ ^3P_1$	202.044	
	$3s^23p^2\ ^3P_2$	$3s^23p3d\ ^3D_3$	203.826	
Fe XII	$3s^23p^3\ ^2D_{3/2}$	$3s^23p^2(^3P)3d\ ^2F_{5/2}$	186.856	*1
	$3s^23p^3\ ^2D_{5/2}$	$3s^23p^2(^3P)3d\ ^2F_{7/2}$	186.880	*1
	$3s^23p^3\ ^4S_{3/2}$	$3s^23p^2(^3P)3d\ ^4P_{3/2}$	193.509	
	$3s^23p^3\ ^2D_{3/2}$	$3s^23p^2(^1D)3d\ ^2D_{3/2}$	195.119	*2
	$3s^23p^3\ ^4S_{3/2}$	$3s^23p^2(^3P)3d\ ^4P_{5/2}$	195.119	*2
Fe XI	$3s^23p^4\ ^3P_2$	$3s^23p^3(^4S)3d\ ^3D_3$	180.407	*3
	$3s^23p^4\ ^3P_1$	$3s^23p^3(^4S)3d\ ^3D_2$	182.173	
	$3s^23p^4\ ^1D_2$	$3s^23p^3(^2D)3d\ ^1D_2$	184.800	
	$3s^23p^4\ ^3P_2$	$3s^23p^3(^2D)3d\ ^3P_2$	188.219	
Fe X	$3s^23p^5\ ^2P_2$	$3s^23p^4(^3P)3d\ ^2D_3$	174.534	
	$3s^23p^5\ ^2P_1$	$3s^23p^4(^3P)3d\ ^2D_2$	175.266	
	$3s^23p^5\ ^2P_2$	$3s^23p^4(^3P)3d\ ^2P_2$	177.243	
	$3s^23p^5\ ^2P_1$	$3s^23p^4(^3P)3d\ ^2P_1$	180.450	*3
	$3s^23p^5\ ^2P_2$	$3s^23p^4(^1D)3d\ ^2S_1$	184.542	
Fe IX	$3s^23p^6\ ^1S_0$	$3s^23p^53d\ ^1P_1$	171.075	

*1,*2,*3 blend

necessary to keep it the low pressure stably even when iron atom is injected. The configurations of ions and wavelength of observed lines are listed in Table 1. Almost all observed lines are transitions to the ground states of each highly charged iron ion. The intensity of emission lines which are transition to the upper level of fine structure *J* in ground states is depend on the electron density strongly. These emission line are studied especially for diagnostics of nuclear fusion and astrophysical plasmas. Moreover, the spectra obtained with CoBIT are useful for testing atomic codes in plasma diagnostics since an EBIT is a simple plasma source consisting of trapped HCIs and a quasi-monoenergetic electron beam whose the energy and current are controllable.

In summary, for the HCIs spectroscopic studies of moderate charge states, we developed the compact EBIT and an EUV spectrometer for exclusive use of it. Then high efficiency and high resolution EUV spectroscopic measurement become possible. Moreover, there is an advantage of this apparatus at HCIs spectroscopy, because various charge state ions can be selectively produced with a narrow charge state distribution by adjusting the electron beam energy in this CoBIT. In addition, the study of electron density dependence of the highly charged ion spectrum is possible by changing an electron beam current. This CoBIT will become the powerful and versatile tool for studying HCIs of moderate charge states.

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