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Line analysis of EUV spectra from molybdenum and tungsten injected with impurity pellets in LHD

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Motivation and purposes

High-Z elements like Tungsten and Molybdenum considered as a candidate for first wall material in ITER

- ➢ Less sputtering yield and high melting point

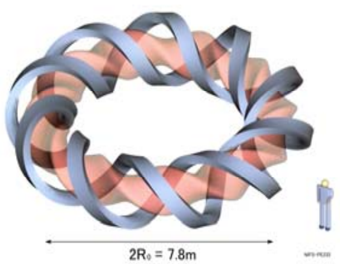
Spectroscopic studies on impurities

- To understand their production mechanism
- To find out contribution in energy loss, etc.

Line analysis of EUV spectrum

- Find out dominant charge states inside plasma
- Identification of prominent line spectra of different charge states

Experimental Set-up



LHD (Large Helical Device) parameters during experiment;

Magnetic field (B_T) – 2.64T

Average major radius (R_{ax}) – 3.75m

Average minor radius (r) – 60cm

Electron temperature ($T_{e,0}$) ~ 2.5keV

Line-average electron density

~ 1–4x10^{13}cm^{-3}

Cylindrical Carbon coated wire of W and Mo injected

Pellet size - 0.8mm in diameter and 0.8mm in length

Wire size - 0.2mm in diameter and 0.5mm in length

EUV spectrum (30Å- 500Å) monitored

Using a flat-field EUV spectrometer

Varied Line Space (VLS) laminar 1200g/mm holographic grating

Spectral resolution - 0.16Å at 70Å

CCD - 1024/255pixels, Pixel size - 26μm

Whole spectrum recorded from several discharges by moving CCD detector

- ➢ Spectrometer acquire 160Å at a time

Accurate wavelength calibration done

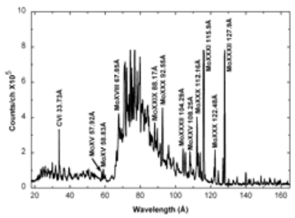
Line spectrum from carbon and other intrinsic impurities

Charge states of Mo and W ions determined

Temporal evolution of intensity of line spectrum after pellet injection and temperature decay phase at the end of discharges

EUV spectrum and analysis

Molybdenum Spectrum ⟶



1. Complicated structure at 65–90Å seen
2. Highest ionization stages MoXXXII observed (I.E. – 1.72 keV)
3. Forbidden transitions of MoXV and MoXVI observed

(e.g. 3d^{10} $^1S_0$-3d^{9}4s $^{1,3}D^2$ in the Ni-like MoXV at 57.92Å and 58.83Å)

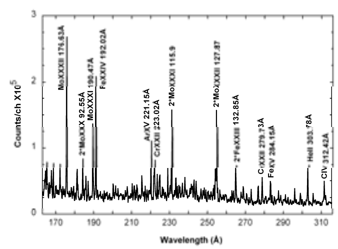
Complicated structures around 65-90Å identified and tabulated

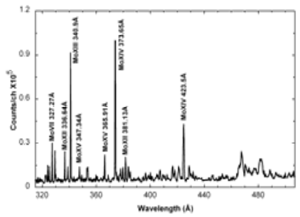
Ionization stages	Transitions	Wavelengths (Å)			
		Present experiment	Previous experiment	Calculated	Predicted
MoXXIV	$3p^6 3d\ ^2D_{3/2}-3p^5 3d^2(^3F)\ ^2D_{3/2}$	70.83±0.02	70.8 [3]	68.9 [4]	
	$3p^6 3d\ ^2D_{5/2}-3p^5 3d^2(^3P)\ ^2P_{3/2}$	71.34±0.03	71.24 [3]	70.1 [4]	
	$3p^6 3d\ ^2D_{5/2}-3p^5 3d^2(^3F)\ ^2D_{5/2}$	72.22±0.02	72.12 [3]	70.2 [4]	
	$3p^6 3d\ ^2D_{3/2}-3p^5 3d^2(^1S)\ ^2P_{1/2}$	73.50±0.05	73.300 [2]		
	$3p^6 3d\ ^2D_{3/2}-3p^5 3d^2(^3F)\ ^2F_{5/2}$	75.17±0.02	75.0 [4]	74.1 [4]	
	$3p^6 3d\ ^2D_{5/2}-3p^5 3d^2(^3F)\ ^2F_{5/2}$	77.38±0.05	77.354 2]		
MoXXV	$3p^6\ ^1S_0-3p^5 3d\ ^1P_1$	74.40±0.02	74.2 [3]	73.1 [4]	
MoXXVI	$3p^5\ ^2P_{3/2}-3p^4(^1D)3d\ ^2P_{3/2}$	72.61±0.04	72.7 [4]	69.5 [4]	
	$3p^5\ ^2P_{3/2}-3p^4(^3P)3d\ ^2P_{3/2}$	75.82±0.06	75.2 [4]	72.8 [4]	
	$3p^5\ ^2P_{3/2}-3p^4(^3P)3d\ ^2D_{5/2}$	76.85±0.05	76.73 [3]	73.4 [4]	
	$3p^5\ ^2P_{3/2}-3p^4(^1D)3d\ ^2S_{1/2}$	78.16±0.05	78.4 [4]	75.7 [4]	
	$3p^5\ ^2P_{3/2}-3p^4(^1S)3d\ ^2D_{5/2}$	79.34±0.06	79.3 [4]	76.5 [4]	
	$3p^5\ ^2P_{1/2}-3p^4(^3P)3d\ ^2P_{1/2}$	84.29±0.02	84.069 [2]		
MoXXVII	$3p^4\ ^3P_2-3p^3(^2P)3d\ ^3P_2$	79.74±0.02	79.761 [2]		
	$3p^4\ ^1D_2-3p^3(^2D)3d\ ^1F_3$	80.67±0.06	80.403 [2]		
	$3p^4\ ^3P_2-3p^3(^2D)3d\ ^3D_3$	81.20±0.04	81.302 [2]		
MoXXVIII	$3p^3\ ^4S_{3/2}-3p^2(^3P)3d\ ^4P_{5/2}$	81.87±0.04	Not observed		81.947 [5]
	$3p^3\ ^2D_{3/2}-3p^2(^1D)3d\ ^2D_{3/2}$	82.54±0.06	82.773 [2]		82.821 [5]
	$3p^3\ ^2D_{5/2}-3p^2(^3P)3d\ ^2F_{7/2}$	83.21±0.05	83.308 [1]		
	$3p^3\ ^4S_{3/2}-3p^2(^3P)3d\ ^4P_{3/2}$	83.89±0.03	83.756 [1]		
	$3p^3\ ^2P_{3/2}-3p^2(^1D)3d\ ^2P_{3/2}$	84.67±0.05	84.771 [2]		

MoXXVIII 3p^3 $^4S_{3/2}$-3p^2(^{3}P)3d $^4P_{3/2}$ transition at 81.947Å observed newly and presented as 81.87 in the table

Strong isolated Mo line visible along with other impurities line

- One of 3s–3p doublet (127.9Å, 176.63Å, 3s $^2S_{1/2}$-3p $^2P_{3/2,\ 1/2}$) in Na-like MoXXXII apparent
- Li-like FeXXIV at 192.02Å (2s $^2S_{1/2}$-2p $^2P_{3/2}$) appeared
- Be-like ArXV (2s^2 $^1S_0$-2s2p $^1P_1$), 221.15Å observed



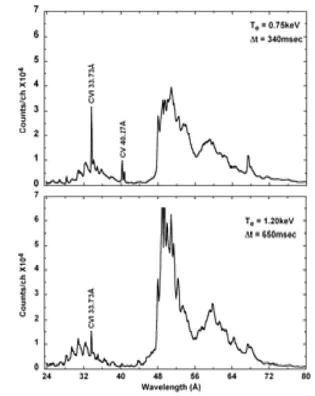


Strong isolated lines of Zn-like MoXIII (340.91Å, 4s^2 $^1S_0$-4s4p $^1P_1$) and Cu-like MoXIV (373.65Å, 423.5Å 4s $^2S_{1/2}$-4p $^2P_{3/2,\ 1/2}$) observed

EUV spectrum and analysis

Tungsten Spectrum ⟶

1. Three well separated bands appeared
2. Peak of band around 30Å shifted from 34Å to 31Å when plasma temperature raised 0.75keV to 1.2keV after pellet injection
3. Many Isolated lines on top of pseudo-continuum of the band around 50Å identified



Ionization stages	Transitions	Wavelengths (Å)			
		Present experiment	Previous experiment	Calculated	Predicted
WXXVIII	$4d^{10}4f\ ^2F_{5/2}-4d^9 4f(^3P)4f\ ^2G_{7/2}$	52.31±0.03	52.35 [7]		52.35 [9]
	$4d^{10}4f\ ^2F_{5/2}-4d^9 4f(^3P)4f\ ^2G_{7/2}$	51.42±0.02	51.457 [9]	51.245 [9]	51.455 [9]
	$4d^{10}4f\ ^2F_{7/2}-4d^9 4f(^3P)4f\ ^2G_{9/2}$	50.87±0.02	50.895 [9]	50.7 [9]	50.891 [9]
	$4d^{10}4f\ ^2F_{5/2}-4f(^1P)4f\ ^2D_{3/2}$	49.44±0.02	49.4 [6], 49.403 [9]	48.919 [9]	49.405 [9]
	$4d^{10}4f\ ^2F_{7/2}-4f(^1P)4f\ ^2D_{5/2}$			48.874 [9]	49.402 [9]
	$4d^{10}4f\ ^2F_{5/2}-4d^9 4f^2\ ^2F_{5/2}$	48.02±0.02	47.94 [7]		47.94 [9]
WXXIX	$4d^{10}\ ^1S_0-4d^9 4f\ ^3D_1$	59.88±0.02	59.852 [8]	59.736 [8]	59.851 [8]
	$4d^{10}\ ^1S_0-4d^9 4f\ ^1P_1$	49.00±0.02	48.9 [6], 48.948 [8]	49.295 [8]	48.944 [8]
WXXX	$4d^9\ 2D_{5/2}-4d^8(^3G)4f\ ^2P_{3/2}$	49.99±0.03	49.938[10]	50.034 [10]	49.936 [10]
	Not identified	67.96±0.05			
		65.87±0.05			
		64.53±0.04			
		62.13±0.05			
		61.19±0.05			
		59.17±0.04			
		57.54±0.03			
		56.73±0.04			
		53.32±0.04			

Ionization stages	Transitions	Wavelengths (Å)			
		Present experiment	Previous experiment	Calculated	Predicted
WXXII	$4d^{10}4f^7-4d^9 4f^7 5p$	38.13±0.07	Not measured	37.57 [11]	
	$4f^7-4f^6 5g$			37.95 [11]	
WXXIII	$4f^6-4f^5 5g$	35.86±0.07		35.93 [11]	
	$4d^{10}4f^6-4d^9 4f^6 5p$			36.21 [11]	
WXXIV	$4d^{10}4f^5-4d^9 4f^5 5p$	34.90±0.06		34.85 [11]	
	$4d^{10}4f^5-4f^4 5g$	34.12±0.06		34.06 [11]	
WXXV	$4f^4-4f^3 5g$	32.50±0.05		32.43 [11]	
WXXVI	$4d^{10}4f^4-4d^9 4f^4 5p$	32.50±0.05		32.37 [11]	
	$4d^{10}4f^4-4f^3 5g$	30.90±0.03		30.94 [11]	
WXXIX	$4d^{10}\ ^1S_0-4d^9 5p\ ^1P_1$	29.51±0.03			29.40 [12]
	Not identified	28.32±0.05			
		26.87±0.04			
		25.36±0.05			

4. Band around 30Å mainly transition from WXXII-WXXVI at Δt=340ms and from higher states when Δt=650ms
5. Band around 60Å likely from from triplet transitions of WXXIX 4d^{10}-4d^{9}4f and WXXVIII 4d^{10}4f-4d^{9}4f^2

Summary

- EUV spectrum from Mo and W investigated
- Carbon coated Mo and W wire injected into LHD plasma
- Molybdenum spectrum observed in 30–500Å
- Lines around 65-90Å identified and listed in table along with previous work
- Three blended spectrum bands observed for tungsten in 24-80Å
- Line spectra around 34Å identified as Δn=1 transition of WXXII–WXXVI having 4d^{10}4f^k-4d^{9}4f^{k}5p and 4d^{10}4f^k-4d^{9}4f^{k-1}5g, where k=3–7
- Isolated lines on top of the pseudo-continuum in 50-70Å identified as Δn=0 transitions of WXXVIII–XXX

Future study - Detail analysis on EUV spectrum below 50Å using an EUV spectrometer with better spectral resolution

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