Appl. Phys. B 73, 59–64 (2001) / Digital Object Identifier (DOI) 10.1007/s003400100590

Applied Physics B
Lasers
and Optics

Spectra of highly ionized xenon (6–30 nm) excited in W7-AS plasmas

H.H. Hacker[1], **R. Burhenn**[1,*], **K. Kondo**[4], **M. Anton**[1], **D. Assmus**[2], **S. Baeumel**[1], **C. Beidler**[1], **T. Bindemann**[2], **R. Brakel**[1], **G. Cattanei**[1], **A. Dinklage**[2], **A. Dodhy**[1], **D. Dorst**[1], **H. Ehmler**[1], **A. Elsner**[1], **M. Endler**[2], **K. Engelhardt**[1], **V. Erckmann**[2], **Y. Feng**[1], **C. Fuchs**[1], **F. Gadelmeier**[1], **J. Geiger**[1], **L. Giannone**[1], **P. Grigull**[1], **G. Gruenwald**[1], **O. Grulke**[1], **E. Harmeyer**[1], **H.J. Hartfuss**[2], **F. Herrnegger**[1], **M. Hirsch**[1], **J. Hofner**[1], **F. Hollmann**[2], **E. Holzhauer**[3], **Y. Igitkhanov**[1], **R. Jaenicke**[1], **F. Karger**[1], **M. Kick**[1], **J. Kisslinger**[1], **S. Klose**[1], **J. Knauer**[1], **H. Kroiss**[1], **G. Kühner**[1], **A. Kus**[1], **H. Laqua**[2], **R. Liu**[1], **H. Maassberg**[1], **N. Marushchenko**[1], **K. McCormick**[1], **G. Michel**[2], **F. Noke**[2], **W. Ott**[1], **M. Otte**[2], **M.G. Pacco-Duechs**[1], **F.P. Penningsfeld**[1], **E. Polunovsky**[1], **F. Probst**[1], **F. Purps**[2], **N. Ruhs**[1], **N. Rust**[1], **N.J. Saffert**[1], **A. Salat**[1], **J. Sallander**[1], **F. Sardei**[1], **F. Schneider**[1], **M. Schubert**[1], **I. Sidorenko**[1], **E. Speth**[1], **R. Suess**[1], **H. Thomsen**[1], **F. Volpe**[1], **F. Wagner**[2], **A. Weller**[1], **C. Wendland**[1], **A. Werner**[1], **H. Wobig**[1], **E. Wuersching**[1], **D. Zimmermann**[1]

[1] Max Planck Institut für Plasmaphysik, Association EURATOM-IPP, Garching, Germany
[2] Max Planck Institut für Plasmaphysik, Sub-institute Greifswald, Association EURATOM-IPP, Greifswald, Germany
[3] Institut für Plasmaforschung der Universität Stuttgart, Stuttgart, Germany
[4] Graduate School of Energy Science, Kyoto University, Gokasho, Uji, 611-0011, Japan

Received: 20 December 2000/Published online: 8 June 2001 –

Abstract. The xenon spectrum, excited in ECR- and NBI-heated plasmas with central electron densities of around $10^{20}\,\mathrm{m}^{-3}$, and central electron temperatures from 0.7 to 2.5 keV, has been studied photoelectrically with a multichannel grazing-incidence spectrometer. Besides numerous well-known lines of Zn- and Cu-like Xenon, more than 50 additional lines which have not yet been published in the literature have been found and partly identified,.

PACS: 32.30-I; 5225.Qt; 5255.Hc

Xenon is an appropriate candidate for use in studying the consequences of high-Z impurity radiation in relevant fusion plasmas. For this purpose, detailed knowledge about the line emission spectrum of highly ionized Xe, in particular in the VUV/EUV region (1–100 nm), is necessary. The identification and assignment of Xe lines, as well as the study of their emission strength under different plasma conditions, is helpful. Extended experimental and theoretical work on highly ionized Xe spectra [1–5] was carried out in the late eighties, following the paper of Hinnov in 1976 [6].

The temporary presence of Xe in Wendelstein 7-AS plasmas [7], brought about as a consequence of venting the machine with Xe for calibration of the Thomson scattering system, stimulated the reinvestigation of Xe spectra in the stellarator plasma. Moreover, for better discrimination of the Xe lines from the line spectra of other intrinsic impurity species, Xe was injected into the discharge using a short gas puff. In order to obtain line emission spectra of Xe under various plasma conditions (electron temperature and density, heating scenarios), plasmas heated using neutral beam (NBI) and electron cyclotron resonance radiation (ECR) are compared. These plasmas differ significantly in radial electron temperature and density. The observed spectra are compared with results from former studies [4, 5].

1 Experimental procedure

Xe was puffed into the plasma after the start-up phase (0.3 or 0.6 s) by means of a fast piezoelectric valve. The highly reproducible gas puff had a pulse duration of less than 20 ms. The Xe remained in the plasma until the end of the discharge (0.8 s), which was turned off by switching off the heating power. The spectra were excited in two types of currentless D_2 plasmas in a toroidal field of 2.5 T (see Fig. 1a and b):

a) NBI (neutral beam injection) heated plasma: 550 kW electrical heating power, central electron density $n_{e0} = 10^{20}\,\mathrm{m}^{-3}$, central electron temperature $T_{e0} = 500$–700 eV.
b) ECR (electron cyclotron resonance) heated plasma: 140 GHz, with max. 1 MW plasma heating power, $n_{e0} = 1$–$1.5 \times 10^{20}\,\mathrm{m}^{-3}$, $T_{e0} = 1$–3 keV.

About 250 shots before the start of the Xe experiments, the inner wall of the torus was boronized in order to reduce the concentration of impurity species intrinsically present in the plasma due to the plasma wall interaction. Therefore, apart from boron, only small amounts of C, O and sometimes Cl were found in the discharges. Even when using a short Xe puff, both types of discharges showed an increase in the Xe line radiation during the stationary phase of the discharge (Fig. 2a and b). The measured radial profiles of the average effective charge state, Z_{eff}, in the plasma revealed evidence for a radial peaking of the total Xe density during the discharge time. This behaviour is consistent with impurity transport coefficients, which have been measured in similar W7-AS discharges.

*Corresponding author. (E-mail: burhenn@ipp.mpg.de)

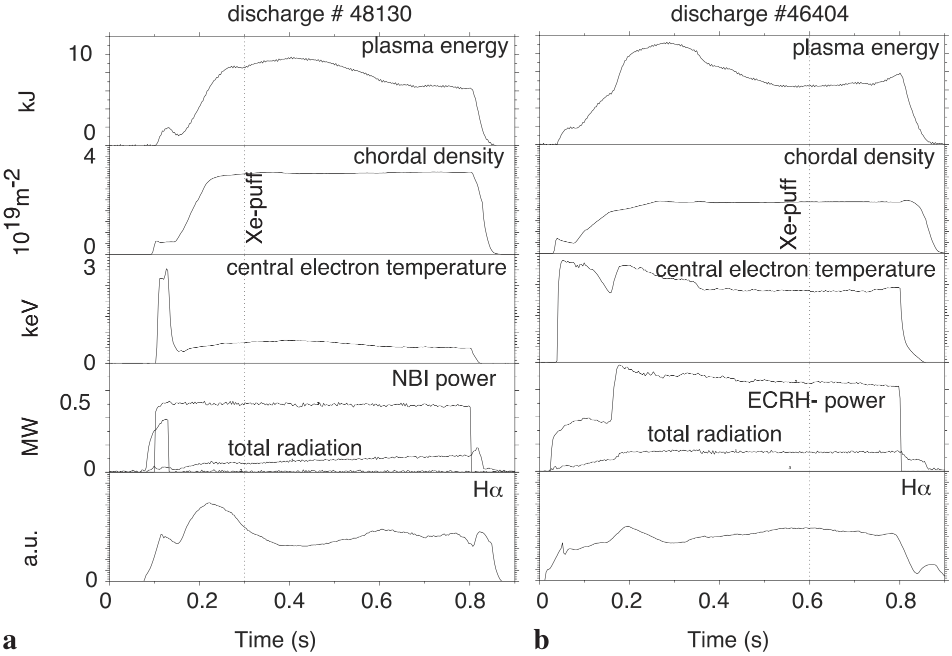

Fig. 1a,b. The two types of discharges in which most of the Xe spectra have been excited: The global parameters are displayed for **a** NBI-heated and **b** ECR-heated plasmas. The start of the Xe gas puff is marked by the *vertical line*

The absolute Xe density in the bulk of the plasma, as derived from Z_{eff} data and bolometer measurements, was about $1–2 \times 10^{17}\ \text{m}^{-3}$.

The control of the intrinsic impurities, as well as the proper adjustment of the size of the Xe gas puff, was done using a VUV SPRED (Survey Poor Resolution Extended Domain) spectrometer [8] in the wavelength region from 10 to 100 nm. The radiation in the EUV region from 2 to 30 nm was diffracted by means of a McPherson Mod 247M22 grazing incidence spectrometer (Schwob-Fraenkel-type) with 2217-mm focal length, 2-degree grazing angle and a gold-coated grating with 600 grooves/mm (standard mode). Two simultaneous spectra (width 2 to 4 nm) in different spectral regions were registrated by two MCPs (CsJ-coated, on carriages moving along the Rowland circle) coupled to Reticon CCD cameras by means of fiber guides. The minimum experimental exposure time of 4 ms was identical with the highest possible time resolution of the two cameras. The wavelength resolution with the 600 g/mm grating was around 160, depending on slit width and Rowland circle position. The absolute wavelength calibration accuracy that could be achieved by interpolation between neighboring C and O impurity lines varied from 0.005 to 0.01 nm, depending on spectral range, line intensity and distance from calibration lines. The lines of sight of the two spectrometers passed horizontally through the W7-AS plasma center.

2 Xe spectrum from 2 to 30 nm

All the lines unambiguously identified as those of Xe, by means of artificial enhancement of Xe radiation using a Xe gas puff, are presented in Table 1. In the first column, an averaged peak intensity ($n_{e0} = 10^{20}\ \text{m}^{-3}$) in cts/s is given, as observed during the stationary phase ($T_e = \text{const.}$) after Xe puffing. Absolute values for volume brightness were not derived due to the lack of absolute calibration of the spectrometer below 20 nm and also the absence of space resolved measurements. The assignment of different ionization stages to transitions has been achieved using their different temporal behaviour after the Xe pulse. The total number of Xe atoms launched into the torus was kept small enough so that the global plasma parameters, e.g. electron temperature and electron density profiles, were not perturbed by the Xe puff. Those lines showing an abrupt increase of intensity, usually within 150 ms following the gas valve trigger, have been assigned to Xe transitions. In Fig. 2b, some typical time histories of intrinsic impurity and Xe lines are shown, and are easily distinguished by their different behaviour during and after the gas puff. In a further step, those lines still unidentified were assigned to their corresponding ionization states by comparison of their time evolutions with those of known transitions of different ionization states. In this way, all the reported lines were labeled to the ionization states "<XXIV, "XXV, "XXVI and "XXVII in Table 1, column (c). For lines with the label "<XXIV, a clear assignment to Ga-, Ge-, As-like ionization states was not possible because their temporal behaviour was not distinguishable within the error bars.

In columns (d) and (e), the result of this study is compared with identifications already published in the literature [4]. Generally, the wavelengths of the lines agree with the published values within the experimental uncertainty. Discrepancies were found around the spectral positions 11.9, 13.0 and 13.5 nm. As a benefit of steady-state and clean discharges (free of impurities like Fe etc.), numerous weak Xe lines in the region 14–16 nm, mostly assigned to "<XXIV, could be identified The right column shows the wavelengths predicted by Seely and Bar-Shalom [5] for those transitions among the type $4l4l'$ configurations which could be easily correlated to most of the observed lines. No line was found for the transitions $4s4d\ {}^1D_2$–$4s4f\ {}^1F_3$ and $4s4p\ {}^3P_2$–$4s4d\ {}^3D_1$ (blended with Xe XXVI 13.835 nm?). The time behaviour of the weak spectral lines assigned to $4s4d\ {}^1D_2$–$4s4f\ {}^1F_3$ and $4s4p\ {}^3P_2({}^3P_1,\ {}^3P_2,\ {}^1P_1)$–$4p^2\ {}^1D_2({}^3P_0,\ {}^1D_2,\ {}^1D_2)$ is more similar to that of lower ion stages, so the identification is tentative.

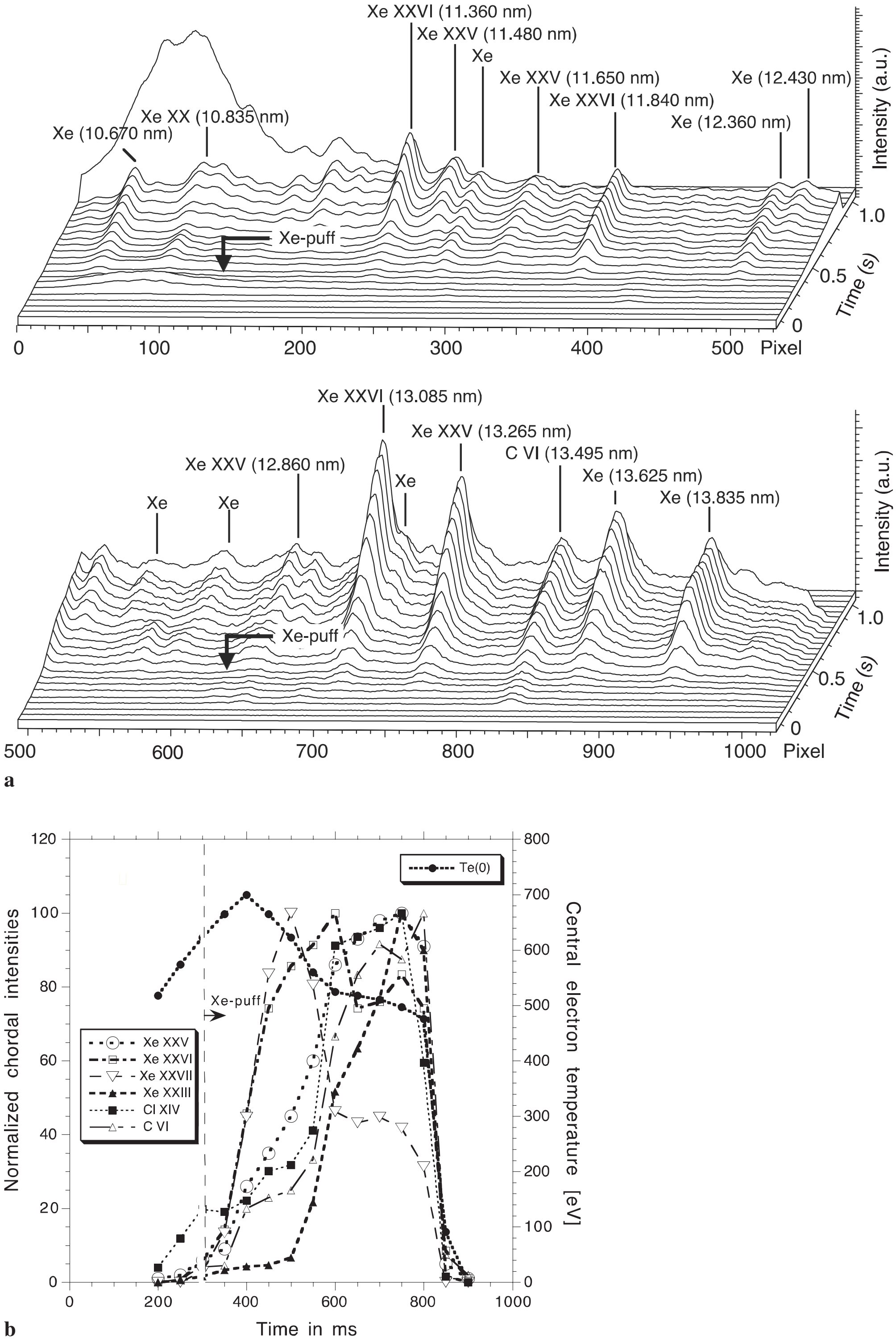

Fig. 2. **a** Time evolution of surface brightnesses [a.u.] of Xe lines in the 10.5–14.0 nm-region. The spectrum was excited in a discharge of type **a**. The gas puff was started electrically at 0.3 s. **b** Time behaviour of Xe lines of different ionization stages and intrinsic impurity ions observed in discharges of type **a**. T_e was varied from 500 to 700 eV. The gas puff starting point is marked

In good agreement with the observations of Breton et al. [4], the broad and intense band centered at 10.8 nm was observed just after the gas puff entered the plasma and was even more pronounced (peak intensity about 800 cts/s) when the central electron temperature dropped below 450 eV. A similar but weaker band (3–20 cts/s) at 21.7 nm (0.3 nm wide) was found for $1000\,\text{eV} > T_e > 100\,\text{eV}$ with some isolated lines (listed in Table 1) of Xe ions with ionization states below Xe XXIV.

No lines of Xe XXVI to Xe XXX were detected, although the spectral range from 2.0 to 6.0 nm was investigated in detail in discharges with increased Xe densities and maximum $T_e = 2.5\,\text{keV}$. This may be explained by the reduced sensitivity of the detection system compared to the photographic (100 shots accumulated) registration of spectra by Wyart et al. [2]. Unfortunately, in the present work the strongest resonance lines are hidden by the strong lines of the intrinsic impurities B and C.

Table 1. List of all Xe lines in the 6–26 nm region, observed in the present work

Experimental data			Identification	Predicted wavelength and transition
Wavelength [nm] (a)	Intensity [$\times 10^3$ cts/s] (b)	Xe ion stage (c)	from Breton et al. [4] [nm] (d)	from Seely and Bar-Shalom [5] [nm] (e)
6.640	25	"XXVI		
6.670	35	"XXV		
6.835	5	"XXV		
6.98	5	"XXIV		
7.820	5	"XXVI/XXVII		
8.070	15	"XXIV		
8.290	15	"XXVI		
8.370	10	"XXIV/XXV		
8.99	< 15	"XXVII		
9.115	15	"XXVI		
9.240	10	"XXIV/XXV		
9.365	150	"XXVI		
9.525	5	"XXV/XXVI		
9.60	10	"XXVII		
9.820	10	"XXV/XXVI		
9.895	5	"XXVII		
9.985	60	"XXV	9.978	
10.166	30	"XXV		
10.230 bl	25	"XXIV		
10.275	10	"XXVII		
10.430	20	"XXV/XXVI		
10.510	20	"XXVI/XXVII		
10.630	< 5	"<XXIV	10.637, XIX	
10.680	200	"XXV	10.679	
10.730	10	"<XXIV	10.724, XX	
10.760	< 5	"<XXIV	10.757, XX	
10.835	150	"<XXIV	10.835, XX	
10.885	50	"XXV/XXVI	10.884	
10.905	< 5	?		
10.945	50	"XXV	10.950	
11.01	5	"<XXIV		
11.045	20	"XXVII		
11.090	50	"<XXIV	11.084	
11.170	120	"<XXIV	11.192	
11.240	20	"<XXIV	11.240	
11.285	10	"<XXIV	11.280	
11.33	5	"XXVII		
11.360	200	"XXVI	11.363	
11.395	5	"XXVII		
11.480	100	"XXV, bl<XXIV	11.484, XXIII	
11.525	45	"XXV		11.4947, XXV, $4s4p\,^3P_0$–$4s4d\,^3D_1$
11.650	40	"XXV	11.645, XXV, $4s4p\,^3P_1$–$4s4d\,^3D_2$	
11.670	10	"XXV	11.685, XXV, $4s4p\,^3P_1$–$4s4d\,^3D_1$	
11.960	10	?		
11.850	80	"XXVI	11.870/94, XXVI, $4p_{1/2}$–$4d_{3/2}$	
12.020	10	?	12.05	
12.360	40	"XXVI		
12.430	30	"<XXIV		
12.54	20	"<XXIV		
12.590	20	"XXVII		
12.690	30	"XXIV/XXV		12.6690, XXV, $4s4d\,^3D_1$–$4s4f\,^3F_2$
12.860	50	"XXV/XXVI		12.7887, XXV, $4s4d\,^3D_2$–$4s4f\,^3F_2$
12.920	30	"<XXIV		
13.03	5	"XXVI		13.0220, XXV, $4s4d\,^3D_3$–$4s4f\,^3F_4$
13.085	200	"XXVI	13.045, XXVI, $4p_{3/2}$–$4d_{5/2}$	
13.140	25	"XXV	13.166	13.0779, XXV, $4s4d\,^3D_3$–$4s4f\,^3F_3$
13.265	160	"XXV	13.253, XXV, $4s4p\,^3P_2$–$4s4d\,^3D_3$	13.6311, XXV, $4s4p\,^1P_1$–$4s4d\,^1D_2$
13.325	30	"XXV	13.485, XXVI, $4d_{5/2}$–$4f_{7/2}$	13.7705, XXV, $4s4p\,^3P_2$–$4s4d\,^3D_1$
13.39	10	"<XXIV	13.505/13.585	
13.625	150	"XXV	13.625/13.637/13.660	
13.835	120	"XXVI	13.842, XXVI, $4d_{3/2}$–$4f_{5/2}$	
13.920	10	"XXVI	13.925	
13.980	10	"XXVII		
14.040	10	"<XXIV		
14.360	20	"XXIV		
14.395	10	"<XXIV		
14.405	10	"XXVI		

Table 1. Continued.

14.540	15	"XXV		
14.70	20	"<XXIV		
14.81	10	?		
14.85	15	?		
15.195	25	"<XXIV		
15.24	10	"<XXIV		
15.440	15	"XXVII		
15.595	20	"XXVII	15.226/15.287	
15.610	200	"XXVI/XXVII	15.629	
15.70	10	"<XXIV		
15.98	20	"XXVI	15.993	
16.045	150	"XXVI	16.058	
16.250	170	"XXVI	16.252	
16.440	930	"XXV	16.440, XXV, $4s^2\,^1S_0$–$4s4p\,^1P_1$	16.4398, XXV, $4s^2\,^1S_0$–$4s4p\,^1P_1$
16.545	30	"XXVI, bl XXV		16.5739, XXV, $4s4p\,^3P_0$–$4p^2\,^3P_1$
16.645	5	"XXV	16.630	16.6514, XXV, $4s4p\,^3P_2$–$4p^2\,^3P_2$
16.776	< 5	?	16.740	
16.815	< 5	"<XXIV		
16.960	15	"XXV	17.160	17.0667, XXV, $4s4p\,^3P_1$–$4p^2\,^1D_2$
17.34	10	bl. by OVI 17.3	17.323	17.3322, XXV, $4s4p\,^1P_1$–$4p^2\,^1S_0$
17.385	950	"XXVI	17.391, XXVI, $4s_{1/2}$–$4p_{1/2}$	
17.530	50	"XXVII		
18.815	80	"XXV		
19.230	40	"<XXIV	19.240	19.6536, XXV, $4s4d\,^1D_2$–$4s4f\,^1F_3$
20.13	< 5	"<XXIV		
20.70	5	"<XXIV		
20.775	< 5	"<XXIV		
21.11	5	"XXIV/XXV		21.4922, XXV, $4s4p\,^3P_2$–$4p^2\,^1D_2$
21.65	7	"<XXIV		21.6970, XXV, $4s4p\,^3P_1$–$4p^2\,^3P_0$?
21.755	5	"<XXIV		21.7778, XXV, $4s4p\,^3P_2$–$4p^2\,^3P_1$?
21.970	< 5	"<XXIV		
22.040	< 5	"<XXIV		
22.110	30	"<XXIV		
22.175	20	"<XXIV		
22.38	< 5	"<XXIV		
22.48	< 5	"<XXIV		
22.85	5	"<XXIV		
23.08	5	"XXV		
23.395	110	"XXVI	23.392, XXVI, $4s_{1/2}$–$4p_{1/2}$	
23.495	< 5	"XXVII	23.506	
24.370	10	"<XXIV		
24.585	5	"XXV		
24.920	40	"XXVI		
25.105	20	"XXVI		
25.245	120	"XXV	25.244, XXV, $4s^2\,^1S_0$–$4s4p\,^3P_1$	
25.485	10	"XXVII		
25.650	25	"XXVI		
25.860	25	"XXVI	25.840	
26.165	10	"XXVI		
26.345	30	"XXV		
26.565	10	"<XXIV		26.7477, XXV, $4s4p\,^1P_1$–$4p^2\,^1D_2$
26.96	5	"<XXIV		
27.25	10	"XXV		

(bl: line blended by other transition)

3 Summary

In W7-AS plasmas with $n_{e0} = 10^{20}\,\mathrm{m}^{-3}$ and $T_{e0} = 0.7$–$2.5\,\mathrm{keV}$, the spectra of Xe ions around the Zn- and Cu-like ionization states has been excited and photoelectrically registered with a wavelength accuracy of ± 0.005 to ± 0.01. Studying the time behaviour of the line-integrated fluxes of the spectral lines after the Xe gas puff turned out to be a useful tool for identifying Xe lines and the ionization states of the emitting ion. The numerous lines of Xe XXV and XXVI listed and assigned in literature could be confirmed. For the first time, more than 50 Xe lines are presented. A dozen of them have been assigned to transitions among $4s^2$, $4s4p$, $4p^2$, $4s4d$ and $4s4f$ configurations of Zn-like Xe.

Acknowledgements. The authors like to thank the W7-AS Operations Group for expertly running the stellarator.

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