Stark-Zeeman spectral line shape calculations of Ne-like transitions in highly charged ions for the characterization of highly-magnetized HED plasmas

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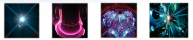
Introduction



The presence of static magnetic field is common for many types of plasmas. The experimental measurements of high magnetic fields in HED plasmas is challenging because of extreme plasma conditions. In this work, we investigate the possibility to measure high magnetic fields from Zeeman broadening of highly charged ion Ne-like transitions.

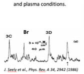
The Stark, Zeeman, natural, Doppler and instrumental broadening effects have been investigated on Ne-like Br, Kr and Xe n=3-2 and n=4-2 type transitions.

The calculations have been performed for an electron density range from 10^{24} to 10^{25} cm^{-3}, Te=2keV, Ti=1keV and the magnetic field varies from 1 to 15 kT.

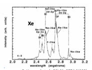
Ne-like transitions in HED plasmas

Upper level	Designation	Transition energy (eV)		
		Br^{25+}	Kr^{26+}	Xe^{44+}
$(2s_{1/2}3p_{3/2})_{J=1}$	3A	1832	1956	5041
$(2s_{1/2}3p_{1/2})_{J=1}$	3B	1818	1941	4950
$(2p^5_{1/2}3d_{3/2})_{J=1}$	3C	1730	1851	4858
$(2p^5_{3/2}3d_{5/2})_{J=1}$	3D	1686	1802	4559
$(2p^5_{1/2}3s_{1/2})_{J=1}$	3F	1590	1706	4554
$(2p^5_{3/2}3s_{1/2})_{J=1}$	3G	1543	1652	4216

Ne-like transitions are optimal for measuring the Zeeman broadening :
- intense over a broad temperature and density ranges,
- well separated from satellite transitions from neighboring charge states when recorded with high spectral resolution,
- well modeled and understood over a broad range of atomic numbers and plasma conditions.



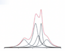
J. Seely et al., Phys. Rev. A 34, 2942 (1986)



B. Hammel et al., RSI 61, 2774 (1990)

Modelling: PPPB/MASCB

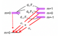
Stark-Zeeman Hamiltonian: $H = H_0 + \zeta\vec{L}\cdot\vec{S} - \vec{d}\cdot\vec{F}(t) + \mu_B\vec{B}\cdot[\vec{L}+g_s\vec{S}]$



Stark effect: $\vec{d}\cdot\vec{F}_\mu(t) = \vec{d}\cdot\left(\vec{F}_{electrons}(t) + \vec{F}_{ions}(t)\right)$
- Electrons: impact approximation using GBK model * → $-i\Phi_e$
- Ions: quasi-static approximation → $\vec{F}_i(t) = \vec{F}_i$ = constant and field distribution function $W(F)$

the ion dynamics is introduced in a latter stage within the Frequency Fluctuation Model (FFM)**

Zeeman effect: the magnetic field has three essential effects on Stark-broadened spectral lines:
- partial polarization of the emitted light: $I(\omega,\alpha) = I_\parallel(\omega)\cos^2\alpha + I_\perp(\omega)\sin^2\alpha$
- bending of the charged particles into helical path around the magnetic line of forces,
- additional splitting due to the coupling of the magnetic field to the magnetic moment of the atom
  → diagonalization of $\zeta\vec{L}\cdot\vec{S} + \mu_B\vec{B}\cdot[\vec{L}+g_s\vec{S}]$ using MASCB code ***

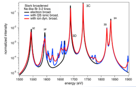


* H.R. Griem et al, Phys. Rev. A19, 2421 (1979).
** A. Calisti et al. Phys. Rev E81, 016406 (2010).
*** S. Ferri, O. Peyrusse, A. Calisti to be publisched

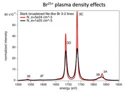
Stark broadening

N_e (cm^{-3})	Br^{25+}		Kr^{26+}		Xe^{44+}	
	3D	3C	3D	3C	3D	3C
10^{24}	1.2	0.8	1	0.86	0.7	0.6
$2x10^{24}$	2	1.8	2	1.8		
$5x10^{24}$	5.3	4.9	5.2	4.9	1.6	1.7
10^{25}	9.2	10.8				

The transitions are sensitive to Stark effect and ion dynamics.
As the Stark broadening increases, the transitions merge but the 3D and 3C are still separated.



Br^{25+} plasma density effects



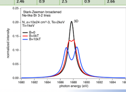
Zeeman broadening

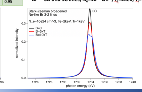
Zeeman splitting between the two σ components (eV) (ref. MASCB)

B (kT)	Br^{25+}		Kr^{26+}		Xe^{44+}	
	3D	3C	3D	3C	3D	3C
1	0.16	0.05	0.16	0.05	0.19	0.05
5	0.8	0.3	0.8	0.3	0.9	0.3
10	1.64	0.6	1.65	0.56	1.78	0.63
15	2.46	0.9	2.5	0.9	2.66	0.95

The 3D transitions are more sensitive to the Zeeman effect than the 3C transitions.

Br^{25+} 3D and 3C lines, $N_e=10^{24}$ cm^{-3}, T_e=2keV, T_i=1keV



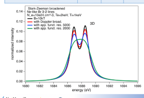


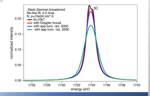
Doppler and instrumental broadening effects

Doppler and instrumental broadening (eV) ; T_e=2keV ; T_i=1keV

	Br^{25+}	Kr^{26+}	Xe^{44+}
Doppler	0.47	0.48	1
Instrumental resolution 5000	0.34	0.36	1
Instrumental resolution 2000	0.84	0.9	2.3

- For Br^{25+}, Zeeman patterns can be observed for a 5000 resolution power, but for Xe^{44+} they are completely masked.
- For a 2000 resolution power, Br^{25+} 3D lines appear much broader than 3C lines because of Zeeman effect.





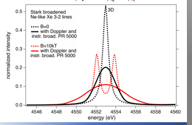
Br^{25+} 3D and 3C lines, $N_e=10^{24}$ cm^{-3}, T_e=2keV, T_i=1keV, B=10kT

Caution

Even if the Doppler and instrumental broadenings mask the Zeeman patterns, the resulting lineshape is broader than the lineshape calculated neglecting the Zeeman effect.

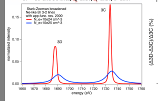
The use of those lines to infer the electron density can then lead to an over estimation of the latter if the Zeeman broadening is neglected.

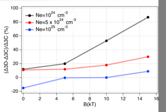
Xe^{44+} 3D lines, $N_e=10^{24}$ cm^{-3}, T_e=2keV, T_i=1keV



3D/3C widths as diagnostics tool

Br^{25+} 3D and 3C lines, T_e=2keV, T_i=1keV, B=10kT





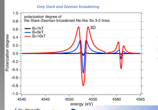
The difference in the Br^{25+} 3D and 3C line widths is significant with 2000 resolving power.

Polarization degree as diagnostics tool

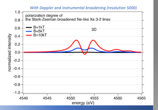
By setting polarizers along the line of sight, polarization degree could be measured : $P(\omega) = \frac{I_\sigma(\omega) - I_\pi(\omega)}{I_\sigma(\omega) + I_\pi(\omega)}$
The latter can lead to the B-fields diagnostics even if the Zeeman patterns cannot be resolved.

Polarization degree of the Stark-Zeeman Xe^{44+} 3D lines at Ne=10^{24} cm^3 for different magnetic fields.

Only Stark and Zeeman broadening



With Doppler and instrumental broadening (resolution 5000)



Concluding remarks

- Br, Kr and Xe 3-2 lines have been investigated for HED plasma Stark, Zeeman, Doppler and instrumental broadening effects have been calculated by the means of the PPPB/MASCB line shape code.
- We have focussed on the 3D and 3C lines as they are the most intense and quite isolated.
- The 3D lines are more sensitive to the Zeeman effect than the 3C lines.
- As the density increases, the Stark effect rapidly masks the Zeeman patterns.
- Caution has to be taken into account if those lines are used to infer the electron density. An additional broadening could come from Zeeman effect.
- A minimum resolving power of 5000 is required to distinguishes the Zeeman patterns among the other broadening mechanisms.
- But, the measure of magnetic fields can be done by the analysis of the 3D/3C widths even for a 2000 resolution power.
- The polarization degree (up to 80% for the 3D Ne-like Xe for Ne=10^{24} cm^{-3} and B=10kT) could be measured. It can lead to the B-fields diagnostics even if the Zeeman patterns cannot be resolved.

Acknowledgments: this work has been done by the impulsion of John Seely, NIST