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From X-Rays To Visible Photons — What Do We Learn From The Plasma Observations?

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Abstract. Photon spectroscopy from plasmas has proven to give new insights into the dynamics of the hot plasmas through multifaceted observations using absolute intensity and wavelength measurements. The spectroscopy observations have given a multitude of comparisons of theoretical modeling with experimental observations. Doppler, Zeeman and Stark effects have proven to be important ingredients in the observed spectra from the visible to the x-ray region.

Keywords: plasma spectroscopy, x-rays, Zeeman effect, motional Stark effect, Doppler effect

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INTRODUCTION

Photon spectroscopy has proven to be one of the very successful methods in plasma diagnostics. In this paper I highlight some of the great successes which have proven that photon spectroscopy can give information on the plasma properties and dynamics that had not been foreseen. Plasma spectroscopy has also proven to give synergetic effects over different fields of science such as fusion plasma physics, astrophysics [1-3], space plasmas, basic atomic physics [4-6]. Several excellent examples are given in the recent special issue of J. Phys. B, *Spectroscopic Diagnostics of Magnetic Fusion Plasmas* [7].

The successes have been carried forward by ingenious and essential progresses in the spectroscopic techniques. This paper goes through the various inventions and ideas which have brought the spectroscopic diagnostic to such a mature state as it is today.

Simultaneously with the progress in the experiments the theoretical and interpretational methods have progressed with more and more powerful models in collisional-radiative computer codes which employ extensive sets of atomic data. Here, the ADAS consortium [8] has given a substantial contribution. Also other codes deserve to be mentioned e.g. ALADDIN [9] and CHIANTI [10].

THE EARLY DAYS

Spectroscopy of highly charged ions was first brought forward by Edlén [11] who studied spectra from the sun and concluded that there were signs of highly charged iron ions. These spectroscopic observations were then verified by atomic modeling and the Lund group became a specialist group in the data on spectra from highly

charged atoms. With the observations of *forbidden lines* from the PLT tokamak [12] the first signs of different ionization and excitation mechanisms in the hot plasma were evident and called for much more elaborate models for predicting the emitted spectra from the x-ray to the visible region. Further spectroscopic observations of highly charged atoms from hot plasmas, from beam foil spectroscopy, from laboratory sources and recently from EBIT ion sources were reported [13-15]. From these observations a large bank of atomic data was collected and made available for further observations and modeling.

However, in the spectroscopic observations from the plasma other parameters were needed and here the very first x-ray spectra from PLT, Fig. 1 [16] paved the way for x-ray spectroscopy as an essential plasma diagnostic technique.

FIGURE 1. From left to right: Geometry of the crystal spectrometer at PLT. Middle: Line profiles of the Fe XXV resonance transition during time intervals of 50 msec, and to the right: ion temperature derived from Doppler broadening of the Fe XXV line at $1.85\text{\AA}$ (from ref. 16).

The Doppler-broadening of x-ray lines from these highly charged atoms are usually more than an order of magnitude larger than the natural and instrumental broadening, which make the spectroscopic diagnostics very useful for the plasma observations. The He-like ion species exist over a large range of electron temperatures and they give a nice simple spectrum which could be employed for many plasma observations. Thus, detailed knowledge of the spectra from helium-like ions was collected and further atomic calculations were performed for interpreting these spectra [17-20].

FIGURE 2. Comparison of Ohmically heated and electron-cyclotron-heated tokamak discharges. The measured electron temperatures from Thomson scattering from the two discharges are nearly identical; however the spectra are dramatically different. The ECH spectrum has notably lower intensities for the non-dipole lines, e.g. x, y, and z (from Ref.20).

One unusual example of helium-like spectra from titanium came from the DIII-D experiment where the variation in intensities of the lines in the x-ray spectrum from the plasma with electron cyclotron heating (ECH) showed the presence of non-thermal electrons [20,21], see Fig. 2.

A most successful x-ray spectroscopy program was started at the Alcator C experiment where seeding the plasma with a minute concentration of argon made the x-ray spectroscopy reliable for the many different operating scenarios, Fig.3.

FIGURE 3. X-ray spectrum from He-like ions; the left spectra of Ar XVII, from ref.[22] , the right spectra from S XV and Cl XVI from Ref.[23].

With this stable intensity in the x-ray spectra many spectroscopic observations would reveal the plasma dynamics of inherent rotation, of transitions to L and H modes as well as properties of plasmas with internal barriers [24,25]. In particular, the excellent measurements of the plasma flow through the measurements of the Doppler shifts of the resonance line of Ar XVII have given new understanding of the intrinsic rotation drive [26].

CHARGE EXCHANGE AND VISIBLE SPECTROSCOPY

With the heating beams in operation on the tokamak devices the visible charge exchange diagnostic took a quantum leap. Now, the spectroscopic observations could be performed in the visible wavelength region with fiber optics and with absolutely calibrated instruments, Fig.4. Furthermore, the impurities to be observed were usually

the light inherent ones such as carbon and oxygen and the absolute concentration of impurities could be reliably determined both with a spatial and temporal resolution.

FIGURE 4. The He II and Be IV charge exchange spectra and the passive background line spectra of C III and Be II. From ref. [30]. The left figure shows the time evolution of the spectrum.

With this successful development the charge exchange beam diagnostic became the most important spectroscopic diagnostic with which a large number of plasma parameters could be determined. Several nice reviews are given in [27-32].

The invention to include the polarization of the visible line emission measurements lead to several important discoveries for the plasma dynamics. Here, we can say that Zeeman and Stark did not foresee what applications their discoveries would have in plasma diagnostics [33-37] nor did the modeling of the atomic spectra include these effects before the observations were made.

NEW DEVELOPMENTS

I have here briefly discussed the development of spectroscopy results from the x-ray to the visible with several examples given which gave new breakthroughs in the

FIGURE 5. Ionization balance in coronal equilibrium for beryllium in the metastable resolved form and tungsten in the stage-to-stage representation. The density is fixed at 10^{19} m^{-3} and the temperature range is representative of the range of tokamak condition from the edge/divertor to the core (from ref. 40).

spectroscopic observations. With the larger fusion plasma experiments also observations of emission from high Z elements will become important and this challenging development has already started both experimentally and theoretically, see Fig. 5 [38-41].

Now the question is posed, how can we meet the requirements of detection of e.g. turbulence using spectroscopic techniques [42]? Spatial imaging as well as high temporal resolution will be needed over the full wavelength range and here a remarkable development has taken place in the new design of imaging x-ray spectrometers with 2-D detectors [22,43].

The utilization of polarization (and coherence) in the visible emission lead to many astonishing results and may still lead a way for new information of the plasma and atomic processes. The polarization of x-rays is a well-known phenomena used in high density laboratory plasma observations [44-46] and also in applications to space plasma searching for dark matter [47] but has not yet been explored for the less dense, hot tokamak plasmas. Some earlier, not yet explained observations of variations in line ratios, e.g. the x/y in He-like ions [48], could point towards a polarization dependent factor.

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