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Behavior of Heavy Metal Ions in FTU Plasmas

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The high field, high density tokamak FTU closed its 30-years of operation at the end of 2019. FTU is a circular machine (R0=0.93 m, a=0.29 m) with an Inconel Vacuum Vessel, Ni and Fe being its dominant elements, and Mo poloidal and toroidal limiters. The relatively high plasma densities, in combination with baking and boronization conditioning techniques, have ensured the possibility of producing plasmas characterized by an extremely low level of impurities of any kind, thus making FTU especially well-suited for investigating non-intrinsic impurities and the performances of liquid metal limiters under high thermal loads (up to 18 MW/m2). Initial tests were performed with a Lithium Liquid Limiter, while the more recent experiments have explored the plasma behavior with a Tin Liquid Limiter (TLL). Both are based on the innovative Capillary Porous System [1]. Lithium contamination was considerable, and traces can occasionally still be seen on various spectroscopic diagnostics. Oxygen is hardly present, and C is also low; N is detected at times, while He, Ne and Argon are detected when injected for diagnostic purposes.
Besides the exploration of the spectral features of Tin, the injection of Tungsten and Yttrium by means of the Laser Blow Off technique has allowed the observation of spectra emitted in more transient conditions, offering the opportunity of comparing similar ionization stages of these elements. For both of them, experimental data from high temperature plasmas are scanty; for this reason, our first goal was the identification of the main spectral features, to support further studies of the possible influence of heavy metals in the plasma core, and to complement previous observation regarding vaporization and plasma contamination by Fe, Ni, and Mo. Tungsten, in particular, is considered the main candidate for plasma facing components in future reactors and extensive work is being carried out also in other devices to characterize its behavior. The W emission bands result from overlapping of the emission from several ionizations states, therefore a well resolved identification of W spectrum in those spectral regions would be of great interest in order to increase the confidence on the atomic physics models [2]
Our interest in Yttrium arises from its application to inertial fusion experiments. The X-ray radiation emitted by laser-produced plasmas has many interesting characteristics, making it suitable for a wide range of applications. The ABC experiment at Frascati used Yttrium targets to produce intense radiation sources that were analyzed both in low (2-50 Å) and high spectral resolution (5.2-5.8 Å) [3]. The Y emission spectra can yield valuable information about the plasma parameters but, as for the other heavy elements, very little information is available in literature. Its observation in well diagnosed tokamak plasmas can thus help filling some gaps.
Over the past three years, a 2 m grazing incidence Schwob-Fraenkel XUV spectrometer [4], was installed on FTU to observe the plasma emission in the range from 20 to 340 Å, to complement the EUV survey spectrometer SPRED. The XUV spectrometer is equipped with interchangeable 600 g/mm or 1200 g/mm gratings, providing very good spectral resolution (Δ⊠/⊠~100), and a typical time resolution of 6 ms. An absolute wavelength calibration is normally carried out relying on well known, isolated lines; nevertheless, a residual estimated uncertainty of the order of 1/100 Å is present, which makes it difficult, in certain cases, to identify lines from different ions whose theoretical values are also affected by relatively large errors. A good deal of effort was devoted to providing the best possible experimental estimates for line positions.
The spectrum of Tin was recorded across the full spectral range of the Schwob spectrometer, in a series of discharges with similar plasma conditions. A good number of lines were identified as being emitted by Sn IX through XXII. The region below 100 Å initially did not appear to display well resolved spectral features, but rather a continuum; the same range was later re-scanned in different plasma conditions and with additional ECRH heating, and a host of Sn lines were observed to emerge between 50 and 70 Å. At lower wavelengths, no evidence emerged of any line from the higher ionization stages that were reported in literature [5].
Previous experiments on PLT, ASDEX-U, LHD, JET, WEST, and RFX-mod by LBO, recorded quasi continuum bands of Tungsten in the spectral regions of 20-40 Å and 45-65 Å [6]. These expected emission features have been extensively identified with high spectral resolution on FTU in the course of the 2019 experimental campaign. W transport properties can be qualified from time history and space distribution of its emission (line radiation, emitted power, Soft-X continuum), but here will report only the spectroscopic analysis of the experiments carried out. Standard Ohmic discharges at 500 - 700 kA/5.3 T at low density (0.6⊠1020 m-3) and with ECRH heating were chosen in order to reach the highest possible electron temperatures in reproducible conditions. The main problem was to find the optimal injection condition to obtain significant signals on the

Soft-X and bolometer diagnostics without causing at the same time a drastic change in the plasma temperature. Both gratings were used to explore the regions of interest, but there was not enough experimental time to carry out a full spectral scan as in the case of Sn.
Yttrium injection could benefit from an even more limited number of Ohmic discharges, and in this case the search for clear spectral features was almost blind. The plasma temperature varied between 1.7 and 2.0 keV, with densities ne = 0.6-0.7⊠1020 m-3. Few lines clearly associated with the Y LBO injection were visible on the survey spectrometer SPRED between 100 and 200 Å, while more lines and broad band signal increases were observed with the Schwob spectrometer in the range 70-100 Å and below 40 Å. Their identification is more difficult due to the presence of complex spectral features associated with Mo in the same range. However, these provide the indication of the minimal plasma perturbation cause by the LBO injection, confirmed also by a barely visible increase in the Soft-X and bolometer signals, and no appreciable lines appearing in the visible range. Overall the range from 20 to 120 Å was explored with the 600 g/mm grating. Once again, the correspondence with theoretical and EBIT experimental data [7] was not confirmed, but it is still under investigation.
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