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Development of novel fuel ion ratio diagnostic techniques[a]

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To overcome the challenge of measuring the fuel ion ratio in the core ($\rho < 0.3$) of ITER, a coordinated effort aiming at developing diagnostic techniques has been initiated. The investigated techniques are novel uses or further development of existing methods such as charge exchange recombination spectrometry, neutron spectrometry, and collective Thomson scattering. An overview of the work on the three diagnostic techniques is presented. [doi:10.1063/1.3460634]

I. INTRODUCTION

Diagnostics to measure the fuel ion ratio in magnetically confined fusion plasmas has attracted increasing attention recently. For the diagnostics currently in the ITER baseline design (such as the neutral particle analyzer), it is not clear if the fuel ion ratio can be determined in the plasma center within $\rho < 0.3$.[1] The fuel ion ratio is a Group 1a measurement, i.e., measurements for machine protection and basic control. Therefore, it is of great interest to the community to develop alternative diagnostics capable of measuring the tritium to deuterium ratio. To encounter this challenge for ITER—as well as for future magnetically confined burning plasmas—a coordinated effort to develop novel diagnostic techniques for this purpose has been initiated within Europe.

Generally, the investigated techniques are novel uses or further development of existing methods such as charge exchange recombination spectrometry (CXRS), neutron spectrometry, and collective Thomson scattering (CTS). The ongoing work encompasses modeling as well as development and testing of proof-of-principle diagnostic methods on existing devices. Here we present an overview of the diagnostic methods and the obtained results as well as an evaluation of the measurement potential of the different techniques. For ITER, a combination of diagnostic methods may be required. The progress toward proposing a potential diagnostic set for fuel ion ratio measurements on ITER is presented.

The ITER measurement requirements are described in Sec. II, and the three diagnostic techniques are described in Sec. III. In Sec. IV, a perspective on the future work in the field is given.

II. MEASUREMENT REQUIREMENTS

The fuel ion ratio is defined as the ratio of the number density of tritium to that of deuterium, n_T/n_D. For ITER, the fuel ion ratio is a Group 1a measurement. The measurement requirement on precision for n_T/n_D is 20% over the parameter range $0.01 < n_T/n_D < 10$ inside $r/a < 0.85$, where r is the distance from the plasma center and a is the minor radius of the plasma.[2] The temporal resolution is set to 100 ms. The primary diagnostic systems envisaged for this measurement is the neutral particle analyzer and, since 2009, the high resolution neutron spectrometer. Back-up systems are the radial and vertical neutron cameras, and in Ref. 2, CTS, radial gamma ray spectrometers, and vertical gamma ray spectrometers are mentioned as supplementary diagnostic systems. However, the full diagnostic potential of all these diagnostic systems have not been fully quantified.

III. DIAGNOSTIC METHODS

A. Neutron spectrometry

The principle behind neutron emission spectrometry as a fuel ion diagnostic is based on the intensity of deuterium-tritium (DT) and deuterium-deuterium (DD) reactions being proportional to the fuel density products,[3] i.e.,

$$I_1 = 0.5 n_D^2 \rho_{DD} L_1 C_1, \tag{1}$$

$$I_2 = n_D n_T \rho_{DT} L_2 C_2, \tag{2}$$

where the reactivities ρ_{DD} and ρ_{DT} are functions of the ion temperature, C_1 and C_2 are calibration coefficients, and L_1 and L_2 are effective chord lengths. I_1 and I_2 are the DD and DT neutron intensities recorded by a neutron spectrometer. In addition to the DD and DT reactions, there is a weaker neutron emission from the tritium-tritium (TT) reaction. Normally, the TT contribution can be neglected with the excep-

tion of pure tritium plasmas. By combining Eqs. (1) and (2), one obtains an expression for the fuel ion ratio,

$$n_T/n_D = 0.5(I_2/I_1)(\rho_{DD}/\rho_{DT})(L_1/L_2)(C_1/C_2). \qquad (3)$$

The possibility of neutron emission spectrometry for fuel ion ratio measurements is hampered by the adverse role of wall emission (back-scattered) neutrons. MONTE CARLO N-PARTICLE TRANSPORT CODE (MCNP) modeling of neutron scattering off a back wall shows that under normal plasma operating conditions, the order of magnitude of the wall emission neutron component under the 2.5 MeV DD peak is comparable to the peak itself. The detailed shape and intensity of the scattered neutron emission depends on the wall composition. The MCNP code was used to produce simulated scattered neutron spectra.

Clearly, the wall emission and other scattering contributions can undermine the possibility of neutron emission spectrometry for fuel ion ratio measurements: they provide a background around 2.5 MeV that can exceed the signal peak. Under these conditions, a determination of n_T/n_D requires good statistics in the measurement and good stability of the background shape. The influence of statistical errors on the measurement is described briefly below and investigated in detail in Ref. 4. Systematic errors are also of some concern since they cannot be quantified easily. Among the systematic errors, there are other contributions to n_T/n_D besides scattered neutrons as seen in Eq. (3). For example, at $T_i = 20$ keV, a 10% error in T_i gives a 5% error in n_T/n_D because of the different temperature dependence of the DT and DD reactivities.

The magnetic proton recoil (MPR) type spectrometer can satisfy the ITER requirements over part of the operating space. The calculations have been done for two diameters of the aperture in the ITER wall: 10 and 30 cm, respectively. The aperture size is a key parameter for the spectrometer performance. The calculation results presented here rely on the bigger aperture. Two limits arise from the calculations. At low T_i (<6 keV), an insufficient number of neutrons is detected to give a spectrum, which is analyzable in the required time interval. At high n_T/n_D, the background from DT neutrons drowns out the DD signal. A larger first wall aperture results in higher neutron fluxes at the detector and pushes the 20% precision boundary higher in n_T/n_D and lower in T_i. Further work needs to be done on incorporating more realistic emissivity profiles, the determination of line integration effects, the effect of errors in certain assumed quantities, and the possibilities offered by including TT and NBI components in the analysis.

B. Charge exchange recombination spectrometry

The principle behind determination of the fuel ratio from charge exchange measurements relies on observation of the Balmer-α spectrum. The spectrum consists of active and passive CX components from all present hydrogen isotopes as well as neutral line radiation from the nonconfined region for each hydrogen isotope. In addition, a background level from bremsstrahlung is observed.

In order to assess CXRS spectra, a simulation code, SIMULATION OF SPECTRA (SOS), has been developed. SOS gen-

erates artificial spectra for a given set of input parameters, such as density, temperature, geometry, beam specifications, vessel conditions, etc. The code includes present day known effects impacting charge exchange measurements, such as atomic cross-section effects or, for instance, consequences of the given beam and observation geometry. These spectra can then be analyzed with common code suites, such as the CXSFIT suite provided by the Atomic Data and Analysis Structure (ADAS) consortium, not only to extract the quantities of interest, such as ion temperature, rotation, but also the intensity or density of the individual radiating ion. This SOS code is adapted to many experimental setups on different devices as well as on the ITER geometry. Several different spectral CXRS lines for different ions can be simulated, including Balmer-α.

In order to validate the simulation package measurements have been made on Tokamak EXperiment for Technology Oriented Research (TEXTOR) and the results compared to synthetic spectra. The first results showed a variation over the radial profile, effectively confirming that the passive Balmer-α light from the edge cannot be used to determine the fuel ratio in the plasma. The statistical error-bars on the individual data points, as resulting from the minimization routine, were below the 2% level. This is predicted by the simulation code as well. Although this is not regarded as a full validation of the code, it increases the confidence in the predicted results of the code when extrapolating to ITER.

For ITER, the input to the simulations where specifications of the envisaged CXRS system on the diagnostic neutral beam, i.e., a high throughput spectrometer with an étendue of 1 mm^2 sr, a spectral resolution of 0.2 nm, and a time resolution of 10 ms. The radial resolution of this system is more than adequate ($a/30$ over the full profile) for the requirements on the fuel ion ratio ($a/10$). The simulations predict an unacceptable high inaccuracy of the determination of the fuel ion ratio in the plasma core (error-bars up to 100%) from the complete Balmer-alpha D/T spectrum. This seems understandable due to the low signal intensity compared to the passive Balmer-alpha emission, the large Doppler broadening of the lines, and the spectral distortions due to the cross-section effects. Beam modulation will certainly improve the situation drastically because one can get rid of the first uncertainty effect (the passive emission) as well as improve on some other effects influencing the spectra (e.g., the bremsstrahlung emission, the fast beam ion contribution from the heating beams, etc.). Error-bars down to 20% in the plasma center are predicted for the high performance case (i.e., high density, for lower electron densities the signals will increase and result in an improved accuracy). Nevertheless, it should be noted that this is the ideal case (complete subtraction of passive lines, no halo effect included, no hydrogen, parametric description of cross-section effect, no fast beam ions, etc.)., Therefore an exact statement on the accuracy cannot yet been made and depends primarily on the validation of the simulation code on data of present devices.

C. Collective Thomson scattering

CTS measurements of ion Bernstein waves (IBW) provide an alternative way to determine the fuel ion ratio. Previously, a feasibility study concluded that a CTS based fuel ion ratio diagnostic system can meet the ITER measurement requirements.[5] It would need to be operated as a separate system in conjunction with the enabled fast ion CTS diagnostic system on ITER. A demonstration of the principle on current devices is the next natural step, which will test numerical predictions and provide valuable experience for the development of a CTS based fuel ion ratio diagnostic for ITER.

The method relies on the following: IBWs are electrostatic hot plasma waves, which are inherently present in fusion plasmas. IBWs are virtually undamped for $k_\parallel = 0$ but are strongly damped when $k_\parallel$ increases. IBWs will thus affect the CTS spectrum when the resolved direction is close to perpendicular to the magnetic field. The IBW modulated CTS spectrum is dependent on the cyclotron frequencies ω_{ci} of the different ion species in the plasma as well as the relative number densities of the species. The ability to diagnose the fuel ion ratio by CTS relies on the fact that the IBW signatures are particularly sensitive to the ion composition in the plasma. Calculations of CTS spectra for different values of $R_H = n_H/(n_H + n_D)$ and for different scattering geometries, e.g., the angle ϕ between the magnetic field and the resolved wave vector component, show that the peaks of the IBW modulated CTS spectrum only appear in the spectrum for ϕ near $90°$ ($\pm \sim 5°$) and that they depend strongly on the value of R_H.

In the recent feasibility study, the aim was to determine the optimal geometry and plasma parameters for CTS measurements of IBWs on TEXTOR. Furthermore, the sensitivity to other parameters was investigated as well as the sensitivity to uncertainties in the scattering geometry. The feasibility study was completed successfully, and it is predicted that in principle it should be possible to measure IBW signatures in the CTS spectrum at TEXTOR.

The work toward measurements of the fuel ion or isotope ratio by the CTS diagnostic on TEXTOR is described in detail in Ref. 6. In the future work beyond the proof-of-principle measurements on TEXTOR the work will focus on evaluating the diagnostic capability of a CTS fuel ion ratio diagnostic for ITER.

IV. CONCLUSIONS AND FUTURE WORK

The status of the present work is that all three diagnostics show some potential within certain constraints. It is foreseen that not one single diagnostic can fulfill the measurement needs for ITER providing the fuel ion ratio for both high and low values of n_T/n_D, with high spatial and temporal resolution, and for parameters at both low and high temperatures and densities. Hence, a set of two or more diagnostic systems could be necessary. In the future work, it is planned to define the limitations of the individual diagnostic systems for the ranges of relevant plasma parameters for ITER. The final aim is then to propose a potential diagnostic set that could provide the required measurement. Other potential diagnostic systems have been mentioned, such as fast wave reflectometry (FWR). However, it has not been investigated in the present work.

The ultimate test and benchmarking of the diagnostic systems would involve installing a CTS fuel ion ratio diagnostic system at JET, which is already equipped with ITER-like CXRS and MPR and time-of-flight optimized for high count rate neutron spectrometer diagnostic systems. Furthermore, by a subsequent tritium campaign, the simulation codes for the three diagnostics could be benchmarked, and the diagnostic potential could be well established. This plan would be quite demanding, but it would form the optimum basis for selecting a diagnostic set for ITER.

An important topic in the future work is the real time determination of the fuel ion ratio. It is a concern in relation with all the three described diagnostic systems. The fuel ion ratio is—as mentioned—a Group 1a diagnostic for control, and the temporal resolution is set to 100 ms. For all three diagnostics, the fuel ion ratio is normally determined after detailed analysis using codes taking several minutes/hours to run. We consider this topic to be a challenge for future development and believe that the challenge could be met by the development of the analysis tools. One could easily imagine a fast determination of an approximate value for the fuel ion ratio to be used for the control, whereas an exact value to be used for physics interpretation could be found after thorough analysis.

We point to the fact that the development in technology can prove essential for the performance of the fuel ion ratio ITER diagnostic systems. In the future work, we will include expected improvements in technology performance in the outlining of a diagnostic set for ITER.

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