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The urgent quest for new energy sources has led developed countries, representing over half of the world population, to collaborate on demonstrating the scientific and technological feasibility of magnetic fusion through the construction and operation of ITER. Data on high-Z ions will be important in this quest. Tungsten plasma facing components have the necessary low erosion rates and low tritium retention but the high radiative efficiency of tungsten ions leads to stringent restrictions on the concentration of tungsten ions in the burning plasma. The influx of tungsten to the burning plasma will need to be diagnosed, understood and stringently controlled. Expanded knowledge of the atomic physics of neutral and ionized tungsten will be important to monitor impurity influxes and derive tungsten concentrations. Also, inert gases such as argon and xenon will be used to dissipate the heat flux flowing to the divertor. This article will summarize the spectroscopic diagnostics planned for ITER and outline areas where additional data is needed.

1. Introduction

Increasing evidence for climate change has lent new urgency to the development of alternatives to fossil fuels. Magnetic fusion offers the prospect of energy production without CO_2 emission and without any possibility of accidental meltdown or long lived actinide waste. Substantial fusion power has been generated in two large magnetic confinement devices: TFTR (10.7 MW)[1] and JET (16 MW)[2]. Following this success, a next-step burning plasma device, the International Thermonuclear Experimental Reactor (ITER) will be constructed in Caderache, France by the European Union, China, India Japan, Republic of Korea, Russian Federation and the United States, representing over half of the developed world. The objective is to demonstrate the scientific and technological feasibility of fusion power with a goal to produce ten times more power (500 MW) that needed to heat the plasma [3]. During 2006-2007 there was an extensive review of the ITER design by the international plasma physics community that will result in an updated baseline design in 2008. Construction will then begin and the first plasma is scheduled for 2016. Fundamental atomic physics data will play a crucial role in ITER's performance, specifically in assessing the plasma purity and controlling impurity influx[4].

The ITER core plasma is expected to have an electron density of about 1×10^{20} m^{-3} and electron temperature about 25 keV at the center. The interaction of a burning plasma with a material wall produces heat fluxes that challenge material limits. The selection of armor materials for plasma facing components is a compromise between multiple requirements derived from the unique features of burning plasmas[5].The wall has to withstand the intense heat load and particle flux from the core plasma over years of operation with little or no maintenance. The influx of material from the wall to the plasma needs to be controlled to avoid diluting the hydrogen isotope fuel and to avoid excessive radiation losses. In the ITER design beryllium is planned for the main chamber wall. This has low-Z and low radiation losses and is an oxygen getter, but it has a low melting temperature and limited heat handling capabilities.

The ITER divertor will reduce impurity contamination by localizing the major plasma wall interaction away from the core plasma. The heat flux onto the divertor target plate is high however, similar to a rocket engine. Carbon and tungsten are proposed as plasma facing materials. Carbon is ideal in many ways as does not melt and carbon radiation in the divertor plasma reduces the incident heat flux to a manageable level. There is a serious difficulty however as tritium codeposition with eroded carbon leads to high levels of tritium retention[6]. The tritium inventory in the ITER vacuum vessel is limited for safety reasons and calculations indicated that this limit could be reached in a few weeks operations. Continued plasma operations would not be possible until the tritium was removed. The lack of a high confidence, proven solution to quickly and efficiently remove tritium led to a recent decision by the ITER organization to exclude carbon from the tritium phase of operations. The divertor material will be completely tungsten during tritium operations and impurities such as argon will be introduced to radiate ~75% of the heat flux. The divertor plasma is higher density and lower temperature than the core plasma and will have an electron density in the range $N_e = 10^{20}$-10^{21} m^{-3} and electron temperature $T_e = 0.1 – 100$ eV.

Tungsten has a high melting temperature with low erosion and low tritium retention, however it is an efficient radiator at high temperatures and tungsten influx needs to be controlled so that core plasma concentrations are much less than 10^{-4}[7]. Experience at Alcator C-mod[8] and at ASDEX-U[9] has shown that high-Z materials can be acceptable in fusion devices with divertors that have low edge plasma temperatures (~10eV or less). To gain further experience with these materials in a large tokamak the main limiter and protection tiles on JET will be replaced with bulk beryllium and the divertor tiles will be replaced by bulk tungsten and tungsten coated carbon-fiber-composite in 2009.

2. ITER spectroscopic diagnostics

ITER will have an extensive array of diagnostic systems that will function as the ‘eyes and ears’ for the engineers operating the machine and for the physicists studying the first high gain burning plasmas. Expected impurities are carbon, beryllium, tungsten and copper as well as gasses such as neon, argon, krypton or nitrogen that are introduced to dissipate the heat flowing to the divertor. Spectroscopic diagnostics for ITER have been reviewed in ref. [10]. Measurements of both the concentration in the plasma and the influx rate are needed.

Four visible survey spectrometers will monitor 12 lines of sight in the divertor legs and X-point region and 2D reconstructions will be achieved by combining these measurements with observations from the equatorial port and the upper port. Filter spectrometers will also cover almost 300 lines of sight and be able to monitor 12 spectral lines for every line of sight simultaneously. Spectrometers for the wavelength region below 450 nm will be located just behind the biological shield to minimize fiberoptic loss. Spectrometers for the region above 450 nm will be located remotely to minimize neutron noise and aid accessibility.

Vacuum ultraviolet spectrometer systems will be installed in an equatorial port and an upper port for spatially resolved measurements of the outer 1 m of the plasma. An additional system will view the inner leg of the divertor. Wide range crystal spectrometers at the equatorial and upper ports will measure impurity emission in the 0.05 – 10 nm range. New developments in curved crystals and 2D detectors are emerging that will enable tomographic reconstruction with improved spectral resolution[11,12,13]. A high resolution X-ray spectrometer will be used to determine ion temperature from Doppler broadening.

3. Atomic data on tungsten

The allowable concentration of tungsten in the ITER plasma is the most restrictive of any inpurity because of its high radiative efficiency. In this section we briefly review the available atomic data for tungsten and identify areas where more data is needed. In the early days of high temperature laboratory plasmas a quasi continuum feature at 5 nm was observed on PLT[14] and ASDEX-U[15].

The capability of the Electron Beam Ion Trap (EBIT) to produce and selectively excite specific ionization stages was crucial in identifying the emission as due to $4d^n$ configurations from W^{29+} to W^{35+}. This result was supported by calculations using the relativistic HULLAC code together with a collisional-radiative model. EBIT was also applied to investigate the energy and temperature dependence of spectral features between 4.5 and 6 nm from W^{39+} - W^{45+} [16]. A comprehensive identification of many spectral features of M-shell transitions in W^{37+} - W^{50+} was produced by the Livermore EBIT-II [17,18]. A magnetic dipole transition in the convenient air wavelength range was identified in Ti-like W^{52+} at 362.713 nm [19].

3.1. Atomic data needs

ITER plans include a spectroscopic diagnostic system operating in the visible region (450 – 1000 nm) in an upper port with sight lines of the divertor region that cross the plasma core[10]. The wavelength of the magnetic dipole transition in Ti-like W^{52+} at 362.713 nm is too short to be transmitted by the long ITER fiberoptics. Identification of longer wavelength magnetic dipole transitions from highly ionized tungsten are needed and would facilitate the measurement of the temperature and density of core tungsten.

Tungsten is sputtered from the plasma wall as a neutral, and a neutral W transition at 400.87506 nm has been identified and its photon efficiency (tungsten ion per photon) measured at the Berlin Plasma Simulator[20]. The intensity of the W 400 nm emission may be used to estimate W influx. One complication is that there is a coincident W^{+} line at 400.8753 nm[21]. A second complication is that sputtered high-Z metal atoms, such as tungsten, have a lower ionization potential and relatively low velocity. They are quickly ionized close to the surface and most ions are promptly redeposited onto the target near their point of origin. Estimates of the tungsten influx rate to the core plasma will depend on a calculation of transport from the wall surface through the scrape-off layer (SOL). SOL convective/blob transport is an active area of research and its effect on the transport of wall sputtered ions is unclear. Three phemonological models that simulate the range of possible physics are described in [22]. Use of emission lines from tungsten ions would minimise these complications, but there is very little atomic data for the lower charge states. The identification of emission lines from W^{+} to W^{26+} would greatly aid modeling of the important plasma edge and SOL transport and aid the determination of net tungsten influx rates.

The maximum routine electron temperature on Asdex-U is 5 keV however the ITER core will be in the 25 keV temperature range and tungsten will be ionized to L-shell charge states. Identification of emission lines from neon-like tungsten is needed. This information would also be highly useful to the JET ITER-like wall experiment as in parallel with the change in wall materials to include tungsten, there will be an upgrade of neutral beam heating to 35 MW that will raise the core electron temperature to new levels.

The tungsten ionization balance in Asdex-U was compared in detail to code predictions. Ionization rates using configuration average distorted wave calculations resulted in good agreement from W^{40+} to W^{46+}, but ad-hoc adjustments to recombination rates were needed to bring the calculations into agreement with the data for lower charge states[7]. New measurements would be helpful to resolve these discrepancies. In general more identified lines are always desirable to improve capabilities to measure tungsten densities, gradients and transport barriers in tokamaks.

4. Summary

Future fusion devices with high-Z plasma facing materials such as tungsten, will require stringent control of impurity influx. Atomic data is vital for the identification and interpretation of spectroscopic data from next-step tokamaks. Specific suggestions of areas where new data for tungsten is needed have been provided.

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