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Measurements of temperature and density in magnetic confinement fusion devices

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Elsevier use only: Received date here; revised date here; accepted date here

Abstract

Controlled thermonuclear fusion can fulfil the demand of mankind to have an inexhaustible source of energy that does not cause any serious environmental pollution. The aim of fusion research is to build a continuously operating reactor in which the energy released by the fusion reactions is sufficiently high to keep the plasma hot and to produce more fusion reactions. The knowledge of the plasma temperature and density, together with the energy confinement time, is therefore very important for the effective control of the self-sustained fusion reactor. Various methods and diagnostics for measurements of the plasma temperature and density in present experimental fusion devices, as well as requirements for the future fusion reactors, will be discussed. A special attention will be given to the temperature and density diagnostics in ITER tokamak, which is presently under construction by several international partners at Cadarache in France. Development of these diagnostics is a major challenge because of severe environment, strict engineering requirements, safety issues and the need for high reliability in the measurements.

Keywords: fusion; plasma; diagnostics; ITER; temperature; density

1. Introduction

At the present time, the most of the world's energy is produced by burning fossil fuels, which are limited to some hundreds years of use. Already in 50 years from now, the world population will rise to about 10 billion, and the energy use is estimated to rise to approximately three times higher than present consumption [1]. Continuing to burn fossil fuels, therefore, could pose a serious problem already in 50 years from now. Also, the substantial use of fossil fuels might lead to the release of extreme quantities of CO_2 into the atmosphere and thus contribute to the greenhouse effect. That is why the renewable energy sources, such wind, solar, geothermal, tidal and others are important. However, the renewable energy

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sources can only provide tenths of the world energy need and therefore it is important to explore also other forms of electricity production.

One option is given by nuclear energy. Fission power plants do not contribute to the greenhouse effect, but they do produce a radioactive waste that needs to be isolated or reprocessed. Controlled thermonuclear fusion neither contributes to greenhouse gas inventory nor produces radioactive ash and could therefore fulfil the demand of mankind to have an inexhaustible source of energy that does not cause any serious environmental pollution.

To fuse, two light nuclei must be brought close enough together to overcome the Coulomb barrier. In the nuclear reaction, a portion of mass is released in the form of energy. The highest yielding fusion reaction, with non-radioactive ash is that of heavy hydrogen isotopes deuterium (D) and tritium (T):

$$D + T \Rightarrow {}^{4}He + n + 17.6\ \text{MeV}, \quad (1)$$

where n is a neutron. The ***temperature*** (which is a measure of the interaction energy) required for nuclear fusion should exceed a hundred million degrees K. At this temperature electrons are detached from the nucleus, atoms are ionised and form a 4th state of matter called plasma.

A star (and our Sun in particular) shines when, under the gravity, the matter inside it attains sufficiently high ***temperature*** and ***density*** to set off fusion reactions. On Earth, gravitational confinement of plasma is not possible. Two options are currently under the study to generate fusion energy: inertial confinement, in which a small volume of matter is being raised to very high density and temperature in a short time, and magnetic confinement, in which hot plasma is confined by a force from external magnetic fields. A criterion for a self-sustained fusion reactor has been derived by Lawson from the energy balance, taking into account energy sources and losses in the plasma [2]. It gives the value of the product of plasma ***density*** n_p, the energy confinement time τ_E and the plasma ***temperature*** T_p to attain a given amplification factor, Q, between energy put in the plasma to keep it hot and the energy released by fusion. For Q = 1 (break-even) one gets:

$$n_p\, T_p\, \tau_E > 10^{21}\ \text{keV s m}^{-3} \quad (2)$$

for T_p typically of tens of keV (1 eV = 11600 K). In other words, to be able to produce energy from fusion reactions, sufficiently hot and dense plasmas must be confined effectively. The plasma temperature and density are common products of their respective electron and ion components, as well as of contribution from neutrals which remain in the fusion plasma. That is why methods to measure and to control temperature and density in fusion plasmas are of a great importance for experimental devices and for the future fusion power plant. In future fusion reactors, the electron and ion temperatures will be almost equal.

A large number of magnetic configurations for confining plasmas have been devised: z- and theta-pinches, magnetic traps, stellarators and some other. The most efficient magnetic configuration so far is a toroidal helix of the tokamak which has rapidly replaced many other magnetic configurations in the research of controlled nuclear fusion. Today, only stellarators are still considered as a possible alternative to the tokamaks, albeit that their present performance is significantly lower than that of tokamaks. In this manuscript, diagnostics for temperature and density measurements only in tokamaks and stellarators will be discussed.

This paper is organised as follows. In Section 2, overview of techniques and achievements in measurements of temperature and density in present experimental devices is described. In Section 3, various diagnostics for ITER and challenges involved in their development are discussed. Finally, outlook and summary are given.

2. Measurements of temperature and density in existing magnetic fusion devices

There are various diagnostic techniques for measuring electron and ion temperature and density which have been developed since the beginning of controlled fusion research in 1950-s. One of the main demands from experiments is the knowledge of temperature and density profiles, their averaged values and fluctuations. The constraints imposed on diagnostics for measurements of temperature and density can be quite strict. Temperature range can span from several eV in the scrape-off layer up to tens of keV in the plasma core, and the density range can vary between $10^{17} – 10^{20}$ m^{-3}. Several techniques, depending on different physical principles, are being used to extract the required information. Also, diagnostics can be distinguished between active, which involve injecting laser beam, particles or microwaves into the plasma, and passive ones. In this paper, a subdivision according to the underlying techniques is used.

2.1. Microwave diagnostics

Microwave (or mm-wave) diagnostics are routinely used in many magnetic fusion devices. They operate in the range from 1 GHz up to 1 THz. ***Electron Cyclotron Emission (ECE)*** diagnostic principle is based on emission of electromagnetic radiation by electrons gyrating around the helical magnetic field lines of the tokamak or stellarator. Since the electron gyration is periodic, it emits the radiation in a series of harmonics. In case of a Maxwellian energy distribution of the electrons the intensity of the emitted radiation is related to the electron temperature T_e. Nowadays, several ECE diagnostic types are being used; most advanced are heterodyne radiometers [3-4] and Michelson interferometers [5-6]. The latter gives measurement of the emitted microwave radiation over a large frequency ranges (e.g. 1st – 4th harmonics). The ability of heterodyne ECE radiometers to provide the high temporal and spatial resolution measurements is being used to follow evolution of MHD phenomena [7], as well as to study plasma turbulence by quantifying the fluctuations of electron temperature [8-9].

Reflectometry is used to measure the electron density profiles, fluctuations, as well as to identify the plasma position by launching the wave below the cut-off frequency into the plasma [10-13]. The wave is then reflected from the critical density layer. The position of this critical layer is deduced from the measurement of the phase shift between the probing wave and a reference wave or by measuring the time-of-flight of a short pulse to the reflecting layer and back. Reflectometry does have a problem, however, diagnosing the central part of the plasma where density gradients are small.

Microwave ***interferometry*** [14] is used to measure the line-averaged electron density by comparing the phase change of two waves, one travelling through the plasma, and another traveling through the vacuum or air. Several viewing chords allow obtaining the profiles across the plasma. Often, a laser beam is being used for interferometry/polarimetry diagnostics, and these diagnostics are being regarded as laser-aided [15].

Collective Thomson scattering [16] is usually employed to measure the electron density fluctuations or the velocity distribution of fast ions. This diagnostic requires an additional microwave radiation to be injected into the plasma, for example, from a gyrotron.

2.2. Laser-aided diagnostics

Laser-aided plasma diagnostics operate in a wide wavelength range, typically between 100 nm and 100 μm. They make use of the interaction between light and matter, which refer to the following processes: absorption/emission, phase shift, change of polarization and scattering. Incoherent ***Thomson scattering*** is now a routine diagnostic in almost every tokamak and stellarator [17-18]. It is based on the scattering of electromagnetic waves by free electrons of the plasma. When the laser wavelength is much smaller than the plasma Debye length, the scattering spectrum gives a measure of the electron velocity distribution. This diagnostic technique can therefore be used to derive the local values and profiles of electron density and temperature. ***Laser-induced fluorescence*** makes use the absorption and re-emission measurements, from which the neutral density of a certain species in the plasma can be determined [19].

Laser-aided interferometry/polarimetry principles are very close to those used in microwave interferometry, except that the laser beam is used to propagate through the plasma [15]. This diagnostic provides information on line-averaged electron density and (when multi-chord system is enabled) on current density profile and, thus, on q-profile.

2.3. Spectroscopy and particle diagnostics

Spectroscopic measurements of line intensities, broadening and shifts in the visible, VUV, XUV and soft X-ray ranges can yield useful information on ion densities, temperature and plasma rotation. ***Soft X-ray tomography*** proves to be very useful in studying MHD phenomena with a high degree of space and time resolution [20]. The SXR radiation is proportional to the cross-product of electron density and temperature.

Charge eXchange Recombination Spectroscopy (CXRS) is a combination of a particle and a spectroscopy diagnostic. It gives valuable information not only on the impurity ion temperature and density, but also on the plasma rotation velocity and electron density fluctuations [21].

Neutral particle analysis (NPA) diagnostics are used to measure the energy spectrum of neutral particle fluxes from the plasma [22]. From the data analysis, information on the plasma ion temperature, ion energy distribution function, plasma isotope ratios and other plasma characteristics can be obtained.

2.4. Diagnostics for temperature and density measurements at the plasma edge

At the plasma edge, temperatures are an order of magnitude lower than in the plasma core. Direct contact with the edge of the plasma with physical probes is required to obtain the local measurements of temperature and density. However, temperatures are in order of magnitude or more lower than in the core. The most famous are active diagnostics called ***probes***; in particular, ***Langmuir probes*** which extract information on the local electron temperature from their current-voltage characteristics [23].

3. ITER, the next big step in diagnostic advances

The knowledge gained with the present fusion machines is being used to design the diagnostics for ITER tokamak, which is presently under construction by several international parties in Cadarache, France. Development of these diagnostics is a major challenge of environmental aspects, such as electromagnetic forces during disruptions, containment of Tritium, plasma purity as vacuum integrity, and high levels of neutron flux and fluence on front end diagnostic components [24-25]. An integrated view of all ITER diagnostics access is seen in Fig. 1.

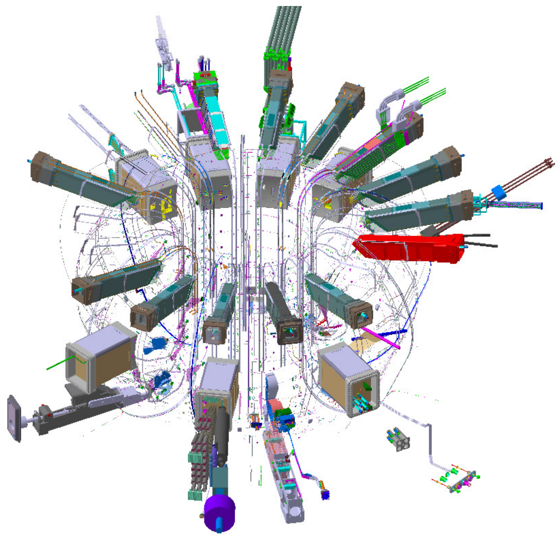

Fig. 1. An integral view of all ITER diagnostics, with the vacuum vessel and tokamak systems removed from the drawing. The plasma is inside the magnetic diagnostics, which are located inside of the vacuum vessel of the tokamak.

3.1. Overview of diagnostics for temperature and density measurements in ITER

Measurements of electron temperature and density are very important not only for physics study, but also for the plasma control and operation [25]. In the plasma centre, the electron temperature and density values will vary between 0.5 – 40 keV and 10^{19} – $5x10^{20}$ m^{-3}, respectively. The core Thomson scattering, operating on the time-of-flight (LIDAR) principle, and ECE system which consists of Michelson interferometer and heterodyne radiometer, are designed to provide accurate measurements of electron temperature profiles with a spatial resolution of less than 10 cm (< a/30), as well as high-frequency instabilities such as magnetohydrodynamic (MHD), toroidicity-induced Alfven Eigenmodes (TAEs) and fluctuations (turbulence). Oblique ECE line-of-sight will enable the study of moderately energetic electrons distribution function. Reflectometers for the main plasma (Fig. 2), toroidal interferometer/polarimeter and LIDAR core Thomson scattering will provide information on electron density profiles, line-averaged density and fluctuations with the same spatial resolution as electron temperature profile diagnostics.

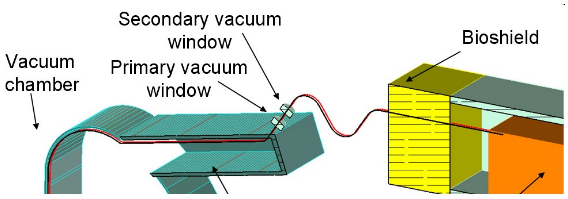

Fig. 2. Schematic view of ITER plasma position and high field side reflectometers.

For the plasma edge (r/a > 0.85) with typical temperatures and densities of 0.05 – 10 keV and $5x10^{18}$ – $3x10^{20}$ m^{-3} respectively, edge Thomson scattering, main plasma reflectometers (LFS) and toroidal polarimeter/interferometer are being designed to meet the measurement requirements. In the divertor region ($T_e < 200$ eV, $n_e < 10^{22}$ m^{-3}), dedicated diagnostics, such as divertor Thomson scattering, divertor interferometer (Fig. 3) and Langmuir probes, are planned.

Ion temperature profile will be observed by the core and edge CXRS based on the diagnostic neutral beam injector (DNBI) with energy of about 100 $keVamu^{-1}$ and power of 2.2 MW injected radially into the plasma. The same CXRS diagnostic will allow monitoring core He density. X-ray crystal spectrometer is planned to deliver high-resolution core T_i profiles. H-alpha and visible spectroscopy are designed to monitor the density of neutral particles between the plasma and the first wall. The high resolution neutron spectrometers and neutron cameras for tomographic reconstruction will deliver information on the ion temperature profile from the profile of neutron emission, n_t/n_d fuel ratio profile and fast ions population.

Not all of the ITER diagnostic set have been described here. Other diagnostics for measuring temperature and density in ITER, for example, VUV spectroscopy or collective Thomson scattering, are discussed in [25].

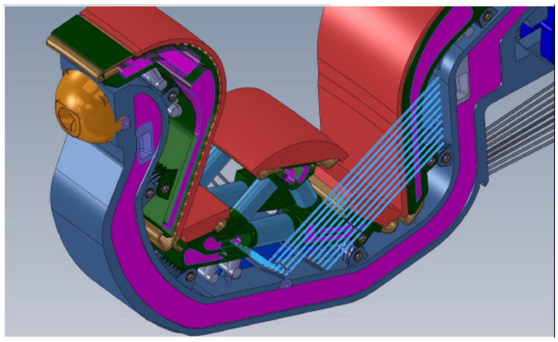

Fig. 3. An ITER divertor cassette with interferometer (based on 10.6 micron technology for the lasers, optics, and detectors) lines-of-sight across the outer divertor plasma leg.

3.2. Engineering aspects and challenges

The components of the diagnostic systems in ITER will be installed in the vacuum vessel, the vacuum vessel inner wall, the cryostat, the upper, equatorial and divertor ports, and in the divertor cassettes (Fig. 1). The design basis conditions for the front end of the diagnostics include the following conditions and events: temperature up to 350 C in divertor cassette bodies and applied 240 C elsewhere in the vessel excluding temperature increases due to radiation and neutron loading; accelerations due to disruption forces; strong magnetic field; radiation environment. Diagnostic components that are placed in a high radiation environment are required to be sufficiently reliable to not require maintenance. Maintenance will only be possible when there is a planned service period and a dismantling of the machine equipment with the diagnostic component is therefore enabled. This applies, for example, to in-vessel reflectometry waveguides. Integration of diagnostics in the tokamak is a very important task which requires consideration of physical and functional interfaces with other systems, like vacuum vessel, blanket or remote handling. The remote transport of port plugs and divertor components, refurbishment and testing outside the tokamak, in the hot cell facility, drive some of the design of the diagnostic components. Furthermore, some diagnostic calibration equipment will have to be remotely handled, too.

Some diagnostic equipment will require shielding or protection from neutron flux, erosion, gamma radiation, high-power microwaves (such as ECRH) and impurity deposition. For example, the divertor Thomson scattering will face the technical challenge of collection of sufficient light, alignment issues and mirror protection. The collection optics views the plasma through a narrow gap of 20 mm between divertor cassettes. The mirrors in the divertor diagnostic rack are supported by the vessel port, while the laser and external optics will be supported by the building; therefore, there are consequently two frames of reference for one optical path. Because of the need to collect large cones of light, the mirrors are vulnerable to the large amounts of impurity deposition occurring in the divertor. For this reason, the development of techniques to prevent the deposition on the diagnostic mirrors and/or to mitigate their consequences will be one of the priorities in the ITER R&D programme.

Safety and vacuum considerations prescribe stringent requirements. In particular, two confinement barriers are given by a window assembly arrangement and a building that is detritiatable. Diagnostic windows might be required to withstand the irradiations up to 100 MGy (fast neutrons) and temperatures up to 240 C without adversely limiting the performance of a diagnostic or the safety confinement functions.

4. Summary and outlook

Measurements of temperature and density are of a fundamental importance for present magnetic fusion devices and for the planned experimental and operational programme of ITER. The knowledge and experience gained from diagnostic development and operation in ITER will aid the future fusion devices, such as, for example, the fusion energy demonstration plant reactor (DEMO), and for the development of fusion in general. This will include the optimum set of measurements needed to support the operation scenarios and for the plasma control, use of predictive and analysis codes together with experimental results to minimize the number of measurements, and, of course, engineering ideas and procedures for integration and service of diagnostics in the fusion device [25]. All together, development of diagnostics for ITER will shorten the path towards the future fusion power plant and, thus, will aid the mankind in getting inexhaustible and reliable source of energy production.

Acknowledgments

Author is thankful to all ITER Diagnostic Division members for their continuous support and help in preparation of this paper.

References

[1] "World Population Prospects: the 1994 Revision", UN Population Division, New York (1994)
[2] JD Lawson, Proc Phys Soc B 70, 6 (1957)
[3] HJ Hartfuss et al., Plasma Phys Control Fusion 39, 1693 (1997)
[4] J.L. Ségui et al., Rev Sci Instrum.76, 123501 (2005)
[5] E de la Luna et al., "Recent Development of ECE Diagnostics at JET", Proc. EC-13 Workshop, N. Novgorod, Russia (2004)
[6] O. Tudisco, "Studies of Electron Temperature Characteristic Length in FTU", Proc. EPS Conf. on Plasma Phys., Hersonissos, Greece, P4-032 (2008)
[7] VS Udintsev et al., Nucl Fusion 43, 1424 (2003)
[8] G Cima et al., Phys Plasmas 2, 720 (1995)
[9] AE White et al., Phys Plasmas 15, 056116 (2008)
[10] ME Manso et al., Plasma Phys Control Fusion 43, A73 (2001)
[11] T Estrada et al., Plasma Phys Control Fusion 43, 1535 (2001)
[12] VA Vershkov et al., Instrum Exp Tech 47, 54 (2004)
[13] A Krämer-Flecken et al., Plasma Phys Control Fusion 51, 015001 (2009)
[14] R Prentice et al., Rev Sci Instrum 66, 1154 (1995)
[15] HR Koslowski et al., Fusion Eng Design 34-35, 143 (1995)
[16] H Bindslev et al., Plasma Phys Control Fusion 49, B551 (2007)
[17] H Yoshida et al., Japan J Appl Phys 43, L1038 (2004)
[18] A Loarte et al., Phys Plasmas 11, 2668 (2004)
[19] Ph Mertens, Proc. 8th LAPD, Doorwerth, Netherlands (1997)
[20] G Turri et al., Plasma Phys Control. Fusion 50, 065010 (2008)
[21] B. Schweer, Trans Fusion Technol 37, 368 (2000)
[22] Ch Schlatter et al., Plasma Phys Control Fusion 48, 1765 (2006)
[23] JG Watkins et al., J Nucl Materials 290-293, 778 (2001)
[24] AE Costley et al., Fusion Eng Design 74, 109 (2005)
[25] AJH Donné et al., Nucl. Fusion 47, S337 (2007)