Plasma Diagnostics Required for a Heliotron-Type DEMO Reactor*)

Mitsutaka ISOBE1,2), Tsuyoshi AKIYAMA1), Tokihiko TOKUZAWA1), Teruya TANAKA1,2),
Daiji KATO1), Hiroyuki A. SAKAUE1), Takuya GOTO1), Junichi MIYAZAWA1,2),
Akio SAGARA1,2) and the FFHR Design Group1)

1)*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*
2)*Department of Fusion Science, The Graduate University for Advanced Studies,*
322-6 Oroshi-cho, Toki 509-5292, Japan

(Received 8 December 2011 / Accepted 15 March 2012)

The plasma diagnostics required for a heliotron-type DEMO reactor are discussed in terms of real-time burn control and safe operation of the machine. The minimum diagnostic set having the smallest footprint are essential in DEMO. Neutron transport calculation suggests that the diagnostic components used in existing experiments will deteriorate immediately in a DEMO reactor hall if they are not protected by a neutron shield. Neutron energy spectrometry is a promising diagnostic that is expected to play an important role in diagnosing DEMO plasmas, providing a fusion energy output, fuel ion temperature, ratio of deuteron density n_{D} to triton density n_{T}, and velocity distribution of confined α particles.

Keywords: DEMO, plasma diagnostics, neutron energy spectrometry

DOI: 10.1585/pfr.7.2405053

1. Introduction

Conceptual design studies of the heliotron-type DEMO reactor force-free helical reactor d1 (FFHR-d1) have been initiated lately at the National Institute for Fusion Science (NIFS) [1]. In existing fusion devices, many superior plasma diagnostics are routinely applied for extensive physics studies. Note that the necessary and/or feasible diagnostics depend on the stage of the experiment. Many diagnostic instruments and/or methods have been greatly developed as plasma parameters increase according to practicability and/or need. Because existing critical physics issues must be solved before DEMO operation begins, measurements in DEMO are expected to be necessary only for real-time burning control, performance optimization, and safe operation. Although plasma diagnostics for ITER or ITER-relevant plasmas have been intensively considered and/or developed [2–5], discussion of diagnostics in DEMO is quite rare [6]. Reliable long-term operation of plasma diagnostics in DEMO is very challenging because the instruments must function in hostile thermal and radiation environments. The implementation of diagnostics is also challenging in that the diagnostic port and available space will be fairly limited because the reactor plasma must be surrounded by a massive blanket. In this paper, the required plasma parameters that must be diagnosed in order to support the stable steady-state operation of a heliotron-type DEMO are discussed. In addition, realistic issues and possible solution for a diagnostic set are also described.

2. What Should We Measure in Heliotron-Type DEMO?

It has been demonstrated that the world's largest superconducting heliotron device, the Large Helical Device (LHD), can provide a high beta with quasi-steady-state operation and good energetic particle confinement [7]. Here we expect that practical solutions for the remaining physics and engineering issues will be realized in existing or ITER-relevant machines before DEMO operation begins. We also assume that a heliotron-type DEMO will be operated in steady-state long-pulse mode and that measurements will be necessary only for real-time burn control, performance optimization, and safe operation. This reasoning will produce the minimum diagnostic set having the smallest footprint for the heliotron-type DEMO machine. In tokamak operation, it is indisputable that magnetic diagnostics are absolutely essential for measuring the plasma current, positioning the plasma, and identifying precursors of disruptive instabilities. In fact, the feasibility of implementing magnetic diagnostics on a tokamak-type DEMO is under intensive debate. Unlike the tokamak case, current drive, plasma position control, and disruption control are not essential to the operation of a heliotron-type DEMO reactor. Thus, such a DEMO does not rely strongly on magnetic diagnostics. This is a potential advantage of heliotron-type DEMO compared with a toka-

---

author's e-mail: isobe@nifs.ac.jp
*) This article is based on the presentation at the 21st International Toki Conference (ITC21).

Table 1 Plasma parameters and diagnostics necessary for real-time burn control and safe operation.

Proposed measurement	Necessary and/or feasible diagnostics	Purpose
Nuclear fusion energy output	Neutron flux monitor (NFM)	Real-time burn control
β value and/or stored energy	Diamagnetic loop	Real-time burn control
Electron density, temperature	Interferometer Thomson scattering diagnostic	Real-time burn control
Fuel ion temperature	Neutron energy spectrometer (NES) for fuel ion temperature at core Spectroscopy of tungsten for edge ion temperature	Real-time burn control
n_D/n_T	NES at core Spectroscopy of Dα and Tα at edge	Real-time burn control
Radiation power	Imaging bolometer	Real-time burn control
Effective ionic charge	Spectroscopy	Real-time burn control
Confined alpha particles	NES Collective Thomson scattering diagnostic	Real-time burn control
MHD events	Mirnov coils	Real-time burn control Safe operation
Divertor detachment	Not known	Safe operation
Temperature of first wall and divertor plate	Not known	Safe operation
Plasma image	Not known	Safe operation

mak DEMO, reducing the number of diagnostics required to operate the machine and achieving the least intrusive diagnostics. The minimal plasma parameters and diagnostics necessary for the real-time burn control, and safe operation of a heliotron-type DEMO are listed in Table 1. As discussed in Sec. 4, neutron energy spectrometry (NES) will play the most important role in diagnosing core plasmas in DEMO.

3. Effect of Neutron Irradiation on Diagnostic Components

Stable, long-term operation of diagnostics is required in the strong-neutron environments of DEMO. Several questions have been raised about diagnostics in DEMO, such as 1) Is a viewing diagnostic port available? 2) Do optical fibers function? 3) What is the effect of irradiation on semiconductors? 4) Is the effect of radiation on insulators significant? Numerous efforts have been undertaken to investigate the effects of neutron and/or γ-ray irradiation on diagnostics components [8–11]. Figure 1 shows the fast-neutron flux distribution ($E > 0.1$ MeV) around the FFHR2m1 [12] calculated by the Monte Carlo neutron transport calculation code MCNP-5 [13]. The nuclear fusion output is set to 3 GW in this calculation. The fast neutron flux (> 0.1 MeV) is expected to be high where the diagnostics will be installed, ranging from 10^{10} n/cm^2/s to 10^{12} n/cm^2/s. The hardness levels of D-T neutron irradiation for representative elements or devices of the fusion diagnostics are shown in Table 2 [8]. According to Ref. 8, the hardness level to monoenergetic D-T neutrons is qualitatively defined as a performance degradation of 10%. The lifetime of quartz fibers and photomultiplier tubes is expected to be slightly greater than that of other components but it is just a matter of time. Most components will deteriorate immediately in a DEMO reactor hall if no neutron shield is provided. Note that in Table 1, several of the diagnostics require an optical fiber and/or mirror. The feasibility of those diagnostics will be carefully investigated by the diagnostics task team of the fusion engineering research project at NIFS.

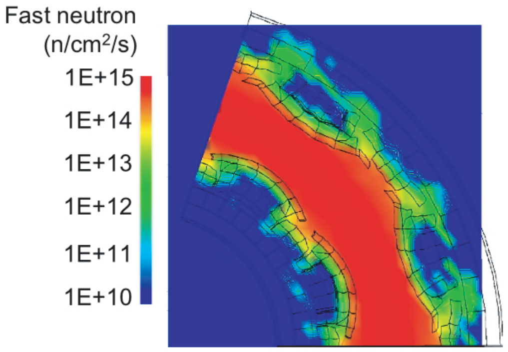

Fig. 1 Fast neutron flux distribution (> 0.1 MeV) around FFHR2m1 calculated by the MCNP code.

Table 2 Acceptable D-T neutron flux for representative diagnostics components [8].

Elements or devices for fusion plasma diagnostics	Hardness level (n/cm^2) (performance degradation of 10%)
Pure silica core fiber	1×10^{15} ~ 3×10^{15}
Plastics core fiber	1×10^{11} ~ 5×10^{11}
Photomultiplier tube	3×10^{14} ~ 1×10^{15}
CCD camera	1×10^{10} ~ 1×10^{11}
Photodiode	1×10^{11} ~ 1×10^{12}
Operational amplifier	5×10^{10} ~ 2×10^{11}

4. Consideration of DEMO Diagnostics

Neutron diagnostics will play the most important role in the monitoring and real-time burn control of DEMO plasmas because they have several great advantages over other existing diagnostics. First, the detector does not need to connect with the main vacuum and can be placed away from the DEMO machine. Moreover, a viewing port is not essential. Because fast neutrons can penetrate thin metal with no interaction, only a 3-4-mm-thick blank metal port having a straight duct is needed to guide unscattered, direct neutrons produced in burning plasmas to the neutron detector. Neutron measurements yield information on the nuclear fusion energy output, fuel ion temperature, $n_\mathrm{D}/n_\mathrm{T}$ ratio, and velocity distribution of confined α particles. Note that in existing experiments, only the Joint European Torus is equipped with a comprehensive set of neutron and γ-ray diagnostics [14–16]. To evaluate the fusion energy output in DEMO using a neutron flux monitor, a startup-range neutron monitor consisting of a ^{235}U fission chamber and pulse/Campbelling modes [17], and a power-range neutron monitor consisting of a ^{235}U fission chamber and a direct current mode based on field-programmable gate array technique [18] employed in advanced boiling water reactors can be applied without modification. Note that a γ-ray diagnostic is also useful for evaluating the D-T reaction rate if 16.6 MeV γ-rays emitted from D-T reactions are measured by a high-Z, neutron-insensitive scintillator with a large volume, such as BGO [19].

NES can be a powerful tool for diagnosing DEMO plasmas. It can provide information on the fuel ion temperature. NES of fusion experiments was originally proposed for evaluating the fuel ion temperature diagnostic by measuring the Doppler broadening of the neutron energy spectrum [20]. The fuel ion temperature can be evaluated if fuel ions form a Maxwellian velocity distribution. The Doppler broadening of the neutron spectrum can be approximately expressed by ΔE (keV) = 82.5 [T_i (keV)]$^{0.5}$ for D-D reactions and ΔE (keV) = 177 [T_i (keV)]$^{0.5}$ for D-T reactions at the full-width at half-maximum of the spectrum [21]. Unlike the case in a tokamak, neutral beam injection (NBI) is not essential in the power range of heliotron-type DEMO plasmas because current drive is not required to confine fusion plasmas. In a heliotron-type DEMO, NBI will act as a sort of match to ignite a target plasma. Therefore, a substantial amount of energetic fuel ions will not be present. Once the heliotron-type DEMO plasma is ignited, it will be maintained only by α particle heating. Note that in existing fusion experiments, the velocity distribution of fuel ions differs significantly from a Maxwellian distribution, exhibiting significant energetic fuel ion tails. The reason is that intensive auxiliary heating, such as NBI and/or ion cyclotron resonance heating, which produce substantial amounts of suprathermal fuel ions is used. Consequently, NES is not applicable to the fuel ion temperature measurement because most of the fusion neutrons are produced by beam-plasma reactions. In this case, neutrons originating in bulk thermal plasmas overlap with those produced by beam-plasma reactions, and NES provides the velocity distributions of the energetic-ion tails [22]. As an alternative for ion temperature measurement in DEMO, diagnostics involving visible forbidden lines of highly charged heavy impurity ions have been proposed [23–25]. Spectroscopy of light impurity atoms such as carbon and argon, which is regularly conducted in existing experiments, cannot be used as an ion temperature diagnostic in DEMO because these atoms will be fully ionized even in the plasma edge region. Note that the magnetic-dipole (M1) transition of highly charged ions falls into the visible range. Therefore, the Doppler broadening measurement of highly charged ions can be applied to an impurity ion temperature diagnostic, although a question about the transfer of this visible line from the DEMO plasma to the measurement section remains. To check the potential of this method, the measurement of the visible line spectra of highly charged tungsten ions has been undertaken using an electron-beam ion trap called EBIT and the LHD [26, 27].

In addition, NES is potentially capable of providing the $n_\mathrm{D}/n_\mathrm{T}$ ratio [28, 29]. The neutron emission rates from the D-D and D-T reactions are expressed by S_DD = $1/2 n_\mathrm{D} n_\mathrm{D} <\sigma v>_\mathrm{DD}$ and S_DT = $n_\mathrm{D} n_\mathrm{T} <\sigma v>_\mathrm{DT}$, respectively. Thus, $n_\mathrm{D}/n_\mathrm{T}$ can be estimated as follows if the D-D and D-T neutron rates and ion temperature T_i are measured.

$$\frac{n_\mathrm{D}}{n_\mathrm{T}} = 2\frac{S_\mathrm{DD}}{S_\mathrm{DT}}\frac{\langle\sigma v\rangle_\mathrm{DT}}{\langle\sigma v\rangle_\mathrm{DD}}.$$

S_DD and S_DT are measureable. In addition, $<\sigma v>_\mathrm{DD}$ and $<\sigma v>_\mathrm{DT}$ are approximately expressed as a function of T_i [20]. This method faces several challenges because S_DD is expected to be much lower than S_DT (by approximately 1%). Therefore, pure D-D neutrons must be distinguished from partially thermalized scattered neutrons originating in the D-T reaction. In D-T discharges of the Tokamak Fusion Test Reactor, $n_\mathrm{D}/n_\mathrm{T}$ was evaluated by measuring the intensity ratio of the Dα emission light to Tα emission light in the edge region [30].

The measurement of the energetic knock-on tails resulting from α particle-fuel ion collisions has been proposed to obtain information on the spatial and energy distributions of fast confined αs in fusion plasmas [31, 32]. The presence of α particles in a D-T fusion plasma will produce energetic tails on the velocity distributions of both the deuterium D$'$ and tritium T$'$ fuel ions due to high-energy transfer or knock-on elastic scattering collisions between the αs and those fuel ions. The energy E picked up by the fuel ion after collision with an α particle of energy E_a is

$$E = 4E_\alpha\frac{m_\mu}{m_\mathrm{c}}\sin^2\theta/2,$$

where θ is the α particle's center-of-mass frame-scattering angle, $m_\mathrm{c} = m_\mathrm{i} + m_\alpha$, and $m_\mu m_\mathrm{i} m_\alpha/m_\mathrm{c}$. The maximum energy gain E_max is produced by a head-on backscatter (θ

$= \pi$). Suprathermal D′ or T′ will yield a visible, distinct knock-on signal in the neutron energy spectrum that can be used as a confined α particle diagnostic. Note that the fraction of the knock-on tail is expected to be small, and it will not contaminate the energy spectrum of thermal neutrons, which contains information on the fuel ion temperature.

Next, we describe our effort to develop advanced diagnostics toward DEMO at NIFS. Electron density measurements are thought to be indispensable for fueling control in the DEMO reactor. Although a conventional interferometer works successfully in many existing fusion devices, it has intrinsic disadvantages such as errors due to mechanical vibrations and fringe jump errors in the high-density range. Because effective steps have been taken against these weaknesses, a conventional interferometer works well in existing experiments, but an interferometer robust against those weaknesses is required in DEMO. One solution is a dispersion interferometer (DI) [33]. The DI is characterized by lower sensitivity to mechanical vibrations and no fringe jump; therefore, it is promising for high-density, large, and steady-state fusion devices. The fundamental principle of the DI is as follows. The probe beam of the DI is a mixture of the fundamental and second harmonics. The phase of the interference signal between two second harmonics is measured. While the phase due to the vibrations is canceled, that due to a plasma, i.e., dispersion, remains. This decreases the sensitivity to mechanical vibrations. A DI will be applied in LHD experiments to prove the principle. At the same time, performance degradation in the first mirror and optical fibers should be examined in detail.

5. Summary

The plasma parameters and related diagnostics required for a heliotron-type DEMO operation were discussed. Judging from the fast-neutron flux distribution around the DEMO torus, most diagnostic components such as optical fibers, and semiconductors will deteriorate immediately in a reactor hall if a neutron shield is not provided. A heliotron-type DEMO will be operated in a steady-state long-pulse mode, and measurements will be needed only for control and performance optimization, not for extensive physics studies. These considerations suggest a minimum diagnostic set that adds the fewest complications to the machinery. NES is promising and is expected to play the most important role in diagnosing DEMO plasmas. It can potentially provide the fuel ion temperature, n_D/n_T, and the velocity distribution of confined α particles. In ongoing development work, a DI characterized by lower sensitivity to mechanical vibration and no fringe jump is being developed by the diagnostics task team of the fusion engineering research project at NIFS for the DEMO reactor.

Acknowledgment

The authors thank Prof. M. Sasao of Doshisha University for fruitful discussion of plasma diagnostics at DEMO.

[1] A. Sagara *et al.*, International Symposium on Fusion Nuclear Technology (ISFNT-10), 11-16 September 2011, Portrand, US. O38.
[2] ITER Physics Expert Group on Diagnostics, Nucl. Fusion **39**, 2541 (1999).
[3] A.J.H. Donné *et al.*, Nucl. Fusion **47**, S337 (2007).
[4] M. Sasao, Tran. Fusion Sci. Technol. **51**, 40 (2007).
[5] K.M. Young, Fusion Sci. Technol. **53**, 281 (2008).
[6] K.M. Young, Fusion Sci. Technol. **57**, 298 (2010).
[7] H. Yamada, Nucl. Fusion **51**, 094021 (2011).
[8] T. Iida, Radiation **17**, 57 (1991) (in Japanese).
[9] T. Nishitani *et al.*, JAERI-Research 98-053 (1998).
[10] T. Nishitani *et al.*, JAERI-Research 2002-007 (2002).
[11] G. Vayakis *et a*l., Fusion Sci. Technol. **53**, 699 (2008).
[12] T. Tanaka *et al.*, Nucl. Fusion **48**, 035005 (2008).
[13] J.F. Briesmester, Los Alamos National Laboratory Report LA-12625-M.
[14] O.N. Jarvis, Plasma Phys. Control. Fusion **36**, 209 (1994).
[15] A. Murari *et al.*, Rev. Sci. Instrum. **81**, 10E136 (2010).
[16] V.G. Kiptily *et al.*, Nucl. Fusion **42**, 999 (2002).
[17] Y. Endo *et al.*, IEEE Tans. Nucl. Sci. **NS-29**, 714 (1982).
[18] H. Abe *et al.*, J. At. Energy Soc. Jpn. **37**, 628 (1995) (in Japanese).
[19] V.G. Kiptly *et al.*, Plasma Phys. Control. Fusion **48**, R59 (2006).
[20] H. Brysk, Plasma Physics **15**, 611 (1973).
[21] J. Scheffel, Nucl. Instrum. Methods **224**, 519 (1984).
[22] H. Tomita *et al.*, Rev. Sci. Instrum. **81**, 10D309 (2010).
[23] U. Feldman, P. Indelicato and J. Sugar, J. Opt. Soc. Am. **B8**, 3 (1991)
[24] P. Indelicato, Phys. Scr. **T65**, 57 (1996).
[25] H.A. Sakaue *et al.*, J. Vac. Soc. Jpn. **48**, 483 (1995).
[26] H. Watanabe *et al.*, Phys. Rev. **A 63**, 042513 (2001).
[27] A. Komatsu *et al.*, Phys. Scr. **T144**, 014012 (2011).
[28] K. Okada *et al.*, Rev. Sci. Instrum. **77**, 10E726 (2006).
[29] K. Okada *et al.*, J. Plasma Fusion Res. SERIES **8**, 666 (2009).
[30] C.H. Skinner *et al.*, PPPL-2878 (1993).
[31] J. Källne and G. Gorini, Fusion Technol. **25**, 341 (1994).
[32] R.K. Fisher *et al.*, Nucl. Fusion **34**, 1291 (1994).
[33] T. Akiyama *et al.*, Plasma Fusion Res. **7**, 2402013 (2012).