From Present Fusion Devices to DEMO: a Changing Role between Diagnostics and Modeling[*)]

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On present-day devices much effort is devoted to develop state-of-the-art diagnostics with a continuous drive towards higher accuracy, better spatial and temporal resolution and more diagnostic channels. Diagnostic innovations often lead to better physics insight and they are often a driver for improving theoretical models. In future fusion devices the operation of diagnostics is strongly limited by the hostile environment. In ITER many of the presently used diagnostics are still marginally applicable, but in DEMO the amount of diagnostics that can be used is severely constrained – at the one hand because of the tough environmental effects and at the other hand because access to the machine will be limited. Theoretical modeling will be very important for DEMO diagnostics. Firstly, simulations based on synthetic diagnostics should lead to the optimum choice of diagnostics and secondly, theoretical modeling should complement the rather sparse diagnostic data set that can be obtained in DEMO.

Keywords: diagnostics, burning plasma, ITER, DEMO

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1. Introduction

The tokamak is the most successful concept used in research into magnetic confinement fusion. Despite the fact that the detailed physical processes that play a role in the fusion plasma are not fully understood, it is possible to design new - and often larger - fusion machines based on extrapolations from the previous generation of smaller machines by means of so-called scaling laws. In this way one can predict with a high degree of certainty that ITER - the next generation fusion machine - will work and will meet the expectations. But if scientists succeed in better understanding the detailed physical processes taking place in the hot magnetized plasma, it may be possible to develop tools and strategies to further optimize future tokamaks, including ITER.

Within the international research focused on magnetic confinement fusion, one can distinguish two important developments. Firstly, most attention of the fusion community is devoted to the realization of ITER, the first tokamak that will produce net fusion power, and – at this moment still to a lesser extent – DEMO, the demonstration reactor and successor to ITER. Secondly, there is extensive research on the current generation of fusion devices, with the aim to understand the processes taking place in the hot magnetized plasma. In particular, much work is done in the field of turbulence research and studies of meso-scale plasma structures with the ultimate goal to find ways to control these.

In the field of plasma diagnostics one can also recognize the above two lines. The emphasis for the future generation of fusion devices (ITER, DEMO, etc.) is the development of robust and reliable diagnostics, such that the plasma parameters and machine conditions can be measured under very hostile conditions [1, 2]. However, to understand the detailed physical plasma processes in current machines, it is necessary to continue to develop diagnostic techniques with higher accuracy, better spatial and temporal resolution and with more measurement channels. New insights into the physics of hot plasmas are often the direct result of innovations in the field of diagnostics [3, 4].

Section 2 will first briefly dwell on the application of diagnostics aimed at better understanding the physical processes in the plasma. Based on a brief description of the history of research on the so-called sawtooth instability it will be illustrated how, in the course of time, innovations in the field of diagnostics have led to new physical insights. The discussion begins with the discovery of the sawtooth instability [5, 6] and ends with a short description of the most recent diagnostic developments, namely the introduction of two- dimensional (2D) microwave imaging systems that make it possible to measure certain plasma parameters in a 2D poloidal area with high spatial and temporal resolution, and with high accuracy. With these techniques detailed 2D videos can be made that are directly comparable with predictions of theoretical models. This leads to a better and deeper understanding of the underlying physics than is possible with diagnostic systems that

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have only a limited number of plasma measurement (e.g. along a chord).

Subsequently, the challenges associated with the application of diagnostics on ITER and DEMO will be discussed in Sections 3 and 4, respectively. ITER, like the current generation of machines, needs a large number of diagnostics with good spatial and temporal resolution, high accuracy and good plasma coverage (= many measuring channels). However, there are many factors that constrain the use of diagnostics on ITER. These are related to the harsh environment, with high neutron fluxes and fluences, relativistic effects, the use of tritium, etc. Most diagnostic techniques used at present devices can be applied on ITER, albeit some of them marginally. But it is very likely that many of these techniques are not suitable for application to DEMO, since this machine has an even more hostile environment for the measuring equipment. This very strong constraint will make it necessary to change the way in which diagnostics are incorporated in the machine design. It also makes it necessary to make use of theoretical models to create a coherent physics picture of the plasma from rather sparse and incomplete measurements.

2. Diagnostics for Research with Current Fusion Devices

To demonstrate that new physical discoveries are often a direct result of innovations in the field of diagnostics, a brief – and certainly not complete – description is given of various discoveries that have been made in the area of the so-called sawtooth instability.

Von Goeler [5] and Vershkov [6] discovered in 1974 independently of each other, the sawtooth instability on respectively the ST and the T3 tokamaks. Von Goeler observed the instability in the ST tokamak after he had installed a detector for measuring the line-integrated soft X-ray radiation through a pinhole. Measurements through the plasma centre showed a signal with a sawtooth-like behaviour: a ramp phase with a slowly increasing emissivity, followed by a very fast (100 μs) crash phase. Measurements through the outer regions of the plasma showed inverted sawteeth, with exactly the opposite behaviour.

Shortly after the discovery of the sawtooth instability - often simply called sawtooth – the full reconnection model was developed [7]. In this model, an $m/n = 1/1$ mode is driven by a pressure-driven instability that is excited by an increase in the central plasma current (such that the central value of the safety factor $q_0 < 1$). The pressure-driven instability leads to a rearrangement of the magnetic field lines (reconnection), with as consequence an influx of colder plasma from outside the sawtooth inversion radius (i.e. the radius where $q = 1$) towards the central area. This gives rise to the formation of a cold island that slowly grows and that eventually pushes the hot core in a short time out of the plasma centre (i.e. the region with $q < 1$).

About 10 years after the discovery of the sawtooth very accurate measurements of the current density profile in the TEXTOR tokamak were performed with a (then new) 9-channel far-infrared polarimeter [8]. This led to the conclusion that $q_0 < 1$ throughout the complete sawtooth period; an observation that was not consistent with the full reconnection model. This because the latter is based on the hypothesis that the sawtooth becomes unstable as soon as $q_0 < 1$ in the plasma centre, which leads to a rearrangement of the current density distribution, with the result that $q > 1$ in the entire plasma.

Roughly around the same time first measurements with a multi-channel X-ray tomography system at JET were published [9]. With this system, consisting of two cameras, it was for the first time possible to make two-dimensional (2D) movies of the X-ray emission from the plasma. The tomographic reconstructions seemed not to be in agreement with the full reconnection model and gave rise to the so-called quasi-interchange model [10]. This model is not based on magnetic reconnection, and does not require a pressure-driven instability. The idea is that the current density profile in the plasma centre is flat (with $q \sim 1$). The central part of the plasma becomes unstable by a subtle change in the magnetic field. The centre of the hot plasma thereby gradually changes into a crescent shape, while the colder part of the plasma from outside the inversion radius convectively penetrates the plasma centre, leading to a flattening of the pressure profile in the plasma centre. A few years after the measurements at JET, detailed simulations were done with numerical emission profiles [11]. This led to a falsification of the previous conclusions based on the JET measurements. Indeed, it was shown that an X-ray tomography system with only two independent cameras cannot distinguish between the topologies of the full reconnection model and the quasi-interchange model. In spite of this falsification and the fact that $q_0 < 1$ during the entire sawtooth period, the quasi-interchange model was not immediately rejected.

In the middle of the 1990's, detailed measurements were done at the TFTR tokamak with an Electron Cyclotron Emission (ECE) diagnostic [12]. By assuming that the sawtooth precursor rotates as a rigid body (i.e. the changes per rotation period are negligibly small) it was possible to convert a measurement along a horizontal chord of points to a 2D picture of the evolution of the electron temperature during the sawtooth precursor phase. It was observed that during the precursor phase a localized bulge forms in the temperature profile at the low field side of the tokamak. This gave rise to the development of the pressure-driven ballooning mode model [13]. In this model, a steep pressure gradient near the temperature bulge at the low field side of the tokamak leads to a global stochastisation of the magnetic field there, resulting in the sawtooth crash.

Late last century, a 200-channel/10-camera X-ray tomography system came into operation on TCV. The system was used for reconstruction of the 2D X-ray emissivity during the entire sawtooth period in discharges with intense electron cyclotron heating [14]. The detailed experimental data made a comparison with theoretical models possible and they were in accordance with a modified version of the full reconnection model taking into account the local heating by the microwaves [15].

In May 2006, three publications were published on sawtooth observations in the TEXTOR tokamak [16–18]. The first two of these articles describe observations of sawteeth with an advanced 2D Electron Cyclotron Emission Imaging (ECEI) system, with 128 measurement channels arranged in a matrix form with 8 (radial) × 16 (vertical) channels. With this system it was for the first time possible to make direct 2D movies of the temperature variations during the sawtooth instability (without having to use an Abel inversion, tomographic reconstruction or any other assumptions). This led to new insights. First of all, it was observed that during the sawtooth crash a restricted orifice is formed in the $q = 1$ surface (the sawtooth inversion radius), so that the plasma pressure from the central part of the plasma can rapidly escape in a collective manner. The orifice can occur anywhere along the inversion radius (i.e. not preferably at the low field side of the tokamak as was concluded from the measurements on TFTR). Detailed comparisons with 2D models [18] have shown that the onset of the sawtooth crash is best described by the ballooning mode model, albeit with the caveat that this model only predicts crashes starting at the low field side of the tokamak, while the measurements show that they can occur everywhere. The later stages of the crash are instead better described by the full reconnection model. The quasi-interchange model is not at all supported by the measurements.

More than 39 years after the discovery of the sawtooth instability, the underlying physics is still not fully understood. But our understanding has gradually improved considerably; often thanks to the introduction of new and more innovative diagnostics. 39 years is a remarkable long time span. The first diagnostics that were used to observe the sawtooth instability were rather course and did not give very detailed information. Moreover, many diagnostics that were subsequently implemented in later years measured only one or a few parameters related to the sawtooth instability, and in many cases only in a limited spatial region. Therefore, it has not yet been possible to come to a full understanding of the physics underlying the sawtooth instability. It is anticipated that in the coming years our understanding of the sawtooth will continue increase. Recently, a number of highly advanced ECEI systems came into operation on DIII-D [19], ASDEX-UG [20], K-STAR [21] and EAST [22]. The systems on DIII-D, KSTAR and EAST have about 400 measuring channels and can simultaneously monitor a large part of the plasma cross section with high spatial and temporal resolution. It is now possible to observe the entire area around the $q = 1$ surface at once, such that it can be expected that soon even better comparisons can be made with theoretical models. Recently, for instance, it has been observed in KSTAR that the sawtooth precursor in ECR heated discharges can break up in two or more individual flux tubes, that merge again after a number of rotations [23]. At the same time methods are developed to control the sawtooth period, and amplitude. Especially methods based on electron cyclotron heating and current drive are very capable in this [24]. However, to really understand the details of the sawtooth instability it is probably needed to measure all relevant plasma parameters simultaneously with multiple diagnostics at the same cross section. This is still well beyond our present day possibilities.

The aim of this Section was to demonstrate that there is an on-going innovation in the diagnostics used to study fusion plasmas (i.e. more measurement channels, higher spatial and temporal resolution, better accuracy). This is an absolute necessity to better understand the very detailed and often complicated processes that take place in a hot magnetized plasma. Ultimately, this should lead to better tools and algorithms for actively controlling the various processes and, hence, optimizing the operation of the fusion reactor. Although many experimental and theoretical publications have appeared on the sawtooth instability, it was impossible within the limits of this paper to present a complete and exhaustive overview. Instead, only a limited number of examples has been given.

3. Diagnostics for ITER: the Next Generation

As was indicated in Section II, the knowledge gained at contemporary fusion devices is often directly linked to the capacity of the diagnostic equipment. That will certainly also apply for ITER, the next step in fusion research. But unlike present-day fusion devices, the application of diagnostics on ITER is not as straightforward.

The aim of ITER is to show that fusion is scientifically feasible. ITER will generate 500 MW of fusion power while having an input power of about of 50 MW. This will initially take place in pulses which are 400 s long. In a second phase, ITER will be operated with non-inductive techniques; the pulse duration will stretch to 1000 s, and ultimately to about 1 hour. ITER is not designed to generate electricity. However, it will feature Test Blanket Modules to examine whether the required tritium for fuelling the fusion reactor can be produced in the reactor wall. ITER is the first machine with dominant heating by alpha particles. When operating at full performance ($Q = P_{\mathrm{fusion}}/P_{\mathrm{in}} = 10$), the power carried by the alpha particles is twice as large as the externally added power. The alpha particles interact with all kinds of instabilities in the plasma, and the underlying physics has not yet been studied in detail.

The demands on the ITER diagnostics are rather tough. Many of the ITER plasma and machine parame-

Table 1 Overview of the main parameters of ITER and DEMO as compared to the best/highest achieved values in present devices (derived from [27]).

Parameter	**Parameter**	**ITER**	**DEMO Steady state**[a]	**Best achieved individual parameter**
Plasma volume	V (m^3)	850	900 – 2700	80 (JET)
Pulse length	(s)	400 - 3000	c.w.	390 (Tore Supra)
Fusion power	P_{fus} (MW)	~500	2500 – 5000	16 (JET)
Power multiplication	$Q = P_{\mathrm{fus}}/P_{\mathrm{in}}$	10	15 – 35	0.8 (JET)
Total number of neutrons	(n/s)	1.4×10^{21}	$1.4 – 7 \times 10^{21}$	1.2×10^{19}
Neutron flux on first wall	(n/m^{2}s)	3×10^{18}	$3 – 10 \times 10^{18}$	3×10^{17} (JET)
Neutron load on first wall	(MW/m^2)	~0.5	1 – 3	~0.05 (max) (JET)
Neutron fluence	(MWyear/m^2)	0.3	5 – 15	negligible
Neutron fluence	(n/m^2)	$\sim 3 \times 10^{25}$	$50 – 150 \times 10^{25}$	$\sim 3 \times 10^{21}$ (JET)
Displacements per atom in first wall	(dpa)	~3	50 – 150	0

[a] Since there is not yet a single steady state DEMO design, ranges of values are given here, covering the various options.

ters (and even profiles of parameters) will have to be actively controlled with sometimes complicated control systems. This means that many diagnostics must be able to provide real-time data, that are automatically evaluated to subsequently drive various actuators. However, applying diagnostics on ITER is nowhere as straightforward as in the present tokamaks, especially because of the harsh environment (Table 1). In particular, the high fluxes of neutrons and gammas (~ 10 times as much as in JET) and long pulses, with related to this the high neutron fluences (~ 10^4 times as much as in JET), give rise to many effects that are new to fusion diagnostics and which can result in serious limitations for the operation of those diagnostics [1, 2, 25, 26]. Examples are radiation induced conductivity (RIC) and radiation induced electromotive force (RIEMF) in electrical conductors, and radiation-induced absorption (RIA) and radioluminescence (RL) in optical materials. There are at least ten of these effects that potentially play an important role and that modify the physical properties of materials used in the reactor in a negative sense: they can lead to ghost signals, degradation of signals, contact degradation and/or finite lifetime of the diagnostic components. Also, the material itself can be permanently changed by transmutation. Some radiation induced effects are prompt and are only present during the plasma pulse, but many of the effects are cumulative in time.

In addition to the above effects, which have a direct impact on the components themselves, the diagnostic design needs to take into account the specific nuclear environment. For example, there are strict requirements for working with tritium: all diagnostics have to be fitted with a double vacuum barrier that can withstand a possible high-pressure wave in the event of an emergency. Further, with a very few exceptions, diagnostics may not have direct line of sight to the plasma to reduce neutron streaming as much as possible. The signals to and from the plasma need to be channelled through complicated labyrinths in the diagnostic ports. Activation should be avoided where possible by choosing proper materials and one has to design all diagnostics in such a way that components installed in the port plugs can be replaced by remote handling.

In ITER the particle fluxes and fluences will be much higher than in present devices, leading to much more pronounced effects of erosion and deposition on plasma facing diagnostic components as mirrors [2, 28]. For this purpose much effort is presently being put on methods to mitigate the erosion and deposition effects and/or to clean the mirrors at regular intervals [29].

The high temperatures in ITER (up to 40 keV) will lead to strong relativistic effects that must be taken into account in the design and utilization of diagnostics. For instance, the relativistic downshift of the electron cyclotron emission (ECE) frequency strongly restricts the part of the plasma that can be viewed with ECE techniques. Relativistic effects should be explicitly included in the analysis of many different diagnostics.

To take account of all these effects a systematic and holistic approach to the design and implementation of the entire diagnostics park for ITER is required. In comparison to present devices, much more thought needs to be given to in-situ calibration of the diagnostics to compensate for the degradation of components that are placed close to the plasma that suffer from the various radiation and particle-induced effects mentioned above. For measuring most plasma parameters in ITER still the same techniques may be used as on current machines; but often only after adaptations to make the diagnostics suitable for the specific nuclear environment. Only a few parameters in ITER cannot be measured with existing diagnostics. For this purpose completely new techniques need to be developed. This is especially the case for measuring alpha particles and the related fast particle instabilities. Much effort is presently being put on rather new techniques as fast-ion collective Thomson scattering [30], fast-ion D-alpha measurements [31], fast-ion loss detection by activation probes and scintillator detectors [32], antennas to detect toroidal Alfvén eigenmodes [33], etc.

Parallel to the development of specific diagnostic systems for ITER attention should be devoted to the integration of those systems in port plugs. In contrast to current machines, in which each diagnostic is installed on a separate viewing window, it is necessary to integrate approximately 5-10 ITER systems into a complex diagnostic port plug. The design of each individual port plug is comparable to the design of a space satellite: the different diagnostic systems need to be put together as a sort of Chinese puzzle. Care should be taken that the diagnostics don't influence each other.

The development of diagnostics for ITER is a nice example of extreme engineering. First, there is a need for a wide range of rather advanced diagnostics, while simultaneously strong constraints are imposed on the use of diagnostics by the hostile environment. The dilemma here is to measure as many as possible parameters of the ITER plasma as accurately as possible (preferably as part of real-time control loops), while at the same time the access to the plasma is strongly limited. A recent example of an advanced control system for stabilizing magnetic tearing modes is the so-called in-line sight ECE/ECRH system, in which the diagnostic system and the actuator are fully integrated, so that the required number of ports in ITER can be limited [34]. An important additional advantage of this system is that no assumptions need to be made about the magnetic equilibrium of the plasma to relate the position of the measurements to the ECRH deposition location.

4. Diagnostics for Burning Fusion Plasmas

DEMO is the machine scheduled after ITER. It is the demonstration reactor aimed to show that effective electricity can be generated from nuclear fusion, in a commercially cost-effective way. DEMO will a higher capacity than ITER ($\sim 2\,\mathrm{GW}$) and will also have much longer plasma pulses [35]. Therefore, the neutron and gamma fluxes, neutron fluence, nuclear heating and high-energy particle fluxes are higher than in ITER. In particular, the neutron fluence in DEMO is about 50 times higher as in ITER. The consequence is that many diagnostics that can be marginally used in ITER, will no longer be applicable in DEMO [36]. This is the case for many of the sensors inside the vacuum vessel (eg cables, magnetic coils, bolometers), where the prospects to be applied in DEMO, even after further developments, are poor. The particle fluxes in DEMO will be approximately twice as high as those in ITER. This seems to be a small increase, but it may prevent the use of diagnostics that feature mirrors with a large opening angle. Instead, systems are required with a small opening angle and with mirrors at a great distance from the plasma. Optical diagnostics might probably still be possible in DEMO, but with a very limited number of lines of sight. Approaches that are likely to be applicable to DEMO without too many modifications with respect to their current applications are microwave and fusion product diagnostics (neutron and x-ray diagnostics).

Mainly because the neutron fluence in DEMO is higher than in ITER (rather than the neutron flux), it are not the prompt but the time integrated effects that are of interest. Perhaps it is still possible to utilize diagnostics, such as magnetic coils, and bolometers within the vacuum vessel if one finds suitable ways to regularly replace these components (for example, by means of a pneumatic tube transport system), without leading to too long a machine shutdowns. The same goes for mirrors and other components at close vicinity to the plasma. If these diagnostics with related components are essential for the operation of DEMO, approaches must be developed to make frequent exchanges possible. It is evident that this has a significant impact on the design of the DEMO machine. New diagnostics or diagnostic components should be developed to replace techniques that no longer work under DEMO conditions. In Ref. [36] and references therein, a number of new and promising developments have been summarized, as free standing metallic gratings, photonic sieve metallic lenses and photonic hollow fibres. For diagnostic components that are used outside the vacuum vessel, the situation is less critical, but there will still an intensive test and development program to be implemented, including the testing of components in fission reactors, in the DT phase of ITER and in the International Fusion Materials Irradiation Facility [37]. It should be noted that radiation testing involves much time (to reach the DEMO fluence levels) and resources, so it is important to start the diagnostic strategy for DEMO already at this stage, and not wait until the end of the ITER exploitation phase. The research in ITER can help to guide the further selection of the optimal techniques for DEMO. During ITER exploitation experience must be gained with real-time data processing and control of multiple parameters, automatic validation of large data streams, in-pulse calibration techniques, etc. [38].

The relativistic effects in DEMO will be very similar (or a little stronger) to those in ITER. Dedicated experiments in ITER should lead to a full understanding of these effects. In current machines at high temperatures a discrepancy is observed between the measured electron temperatures by Thomson scattering and ECE. This could be related to the fact that the electron velocity distribution is no longer maxwellian, which implies that one has to reconsider the concept of temperature. The effects resulting from the dominant heating by alpha particles in DEMO are even more pronounced than in ITER, and therefore research in ITER must lead to an understanding of the underlying physics and the consequences this has for the control circuits of the reactor.

Unlike ITER, DEMO is no longer a research machine, but a device to demonstrate the economic viability of fusion. DEMO therefore does not have to be as flexible in design. While ITER should enable a large number of different plasma scenarios, DEMO operation will be based on one or at most two different plasma scenarios. The choice of the optimum scenario(s) needs to be made during full DT operation of ITER. The very limited number of plasma scenarios foreseen in DEMO implies that fewer measurements and diagnostics are required. Namely one needs

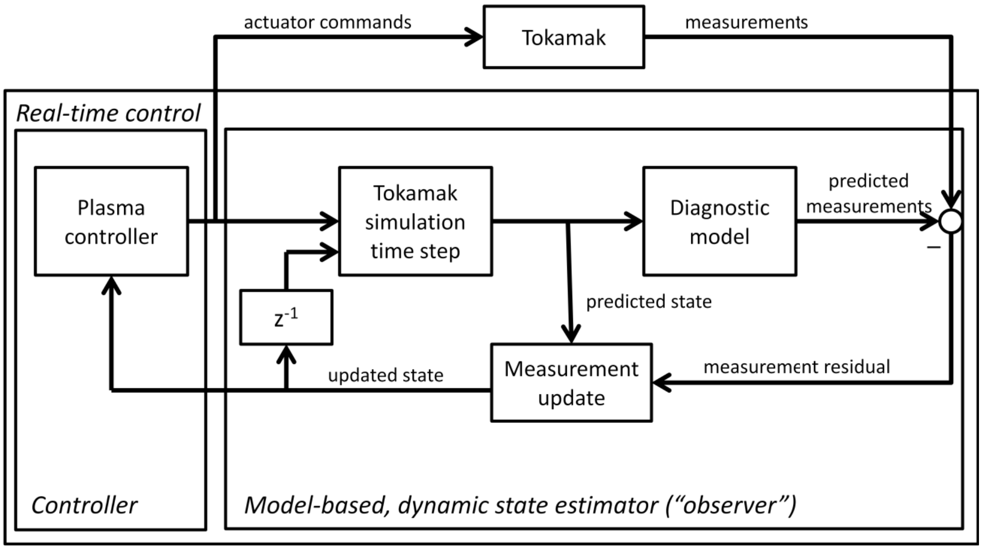

Fig. 1 Real-time control of a tokamak involving dynamic state observers. Simulation models are utilized to predict the behaviour of the tokamak plasma as well as to predict the measurements from synthetic diagnostics. The measurement residual is used to both feedback on the plasma controller as well as to fine tune the tokamak simulation model. The diagnostic model can provide many more synthetic signals than are available as actual measurements in the tokamak and thus compensate for the general lack of real diagnostics in DEMO. Courtesy F. Felici.

only to establish that the plasma in DEMO meets certain requirements. During DT operation of ITER it needs to be determined which diagnostics are essential for proper operation of DEMO and which diagnostics are superfluous. One must, of course, have constantly in mind that the use of diagnostics on DEMO is extremely limited. Probably analysis in DEMO is based on a very small number of measurements and therefore, one must rely on highly sophisticated computer models to still draw relevant conclusions. These computer models should be tested in detail on ITER. A way to do this is by running a full fledge ITER-discharge on one of the foreseen DEMO scenarios with all available diagnostics. After that the same discharge can be repeated in a computer model, but each time with a more limited set of diagnostics, to judge which diagnostics are essential and which are superfluous.

It is not yet clear whether DEMO will have neutral heating beams. If that is not the case, this means that measurements (such as T_i, V_rot, B_p, etc.) that are nowadays obtained by means of active spectroscopy, are no longer in the same way available. New techniques need to be developed. The question is whether it is possible, for example, to control the helium ash (i.e. the thermalised helium) by measurements of the amount of helium at the plasma edge. It is evident that the development and demonstration of new and improved diagnostics for DEMO is a time consuming process that should be started already at this stage. This certainly applies to test a variety of materials because sometimes months of irradiation in a reactor are needed to reach the relevant number of displacement per atom (dpa). However, new techniques have a long development time and often have to be tested extensively on current facilities and ITER in order to ensure that they are sufficiently robust and reliable for use on DEMO. Most important is to realize that diagnostics components can no longer be conceived after the construction of the machine is complete. Diagnostics need to be an integral part of the machine as they have great impact on the exact design of the machine and, hence, they must be incorporated in the DEMO conceptual design from day 1. Compared to ITER and current machines, DEMO will have a relatively small number of diagnostics, mostly with a limited number of measuring channels. In the coming years, extensive research is needed to establish the minimum set of diagnostics for DEMO, such that the machine can still be adequately operated. All efforts should be put on the realization of exactly these diagnostics.

Most likely measurements in DEMO will be not very precise and sparse. Sharpening of the data by means of forward modelling is needed [39,40], or alternatively automatic consistency checks should be incorporated between multiple independent, but imprecise, data types. One could also consider rather unconventional approaches, like using calorimetry to measure the global energy balance of the discharge [36, 41]. This, of course, requires state-of-the-art theoretical models that describe the plasma behaviour. A successful strategy is to use so-called "dynamic state observers" [42, 43], which is in essence a real-time simulation of a theoretical model of the plasma, running parallel to the physical evolution of the plasma in the tokamak (see Fig. 1). The model predictions are continuously compared to the available diagnostic measurements, yielding improved estimates and/or leading to slight adaptations in the model. The actual control then uses the state estimate from the observer, on a timescale independent from (and often faster than) the diagnostic measurements. Recently, it was demonstrated that dynamic state observers based on Unscented Kalman Filters outrank phase-locked loops when it comes to tracking of phase, frequency and amplitude of sinusoidal noisy measurements as is needed for real-time tracking of magnetic islands in plasmas [44].

Much preparatory work can be done on ITER. Once it is clear what plasma scenarios will be used for DEMO, one can do all developments for this scenario in ITER. One can then after successful plasma discharges, study which diagnostics and which diagnostic channels are an absolute necessity to support a specific plasma scenario, and also which diagnostics are not needed. Much developments can be done with synthetic diagnostics: starting from a given plasma scenario, the plasma diagnostic signals are generated in a synthetic way. These are then used in turn to determine what can be known about the plasma scenario from the synthetic diagnostic. In this way one must eventually come to an optimum set of diagnostics for DEMO. It is evident that modelling will play very important role in preparing the diagnostics for DEMO.

5. Summary

Scientists working on diagnostics for high temperature fusion plasmas (often known as diagnosticians) are often simultaneously engaged in diagnostic development for doing physics experiments on existing devices, but also in the development of diagnostics for ITER. Moreover, they are already considering how machines as DEMO and subsequent reactors can be diagnosed. Of course this seems a huge dilemma, because on the one hand, much attention is devoted to perfecting the present diagnostics to perform better, faster, and more accurate measurement in order to test and challenge theoretical models. On the other hand, it should be investigated in a systematic way how the future generation of fusion devices can be operated with a minimal set of diagnostics. Here the modelling (a.o. models with synthetic diagnostics) is at the basis of the selection of diagnostic techniques, while during operation modelling should be incorporated in order to be able to properly steer the actuators based on rather sparse data from the limited set of diagnostics. In both cases the diagnosticians are dealing with a very complex scientific challenge that requires the utmost of their imagination, dedication and scientific qualities.

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