OVERVIEW OF ITPA DIAGNOSTIC TOPICAL GROUP
R&D ACTIVITIES IN SUPPORT OF ITER

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Abstract

The International Tokamak Physics Activity (ITPA) Topical Group (TG) on Diagnostics has been conducting R&D activities to support an improved ITER diagnostic set and performance. In this paper, highlights of the Topical Group activity are overviewed and include: (1) integration of diagnostics and synthetic diagnostics with real-time plasma control; (2) optimization of the lifetime of first mirrors in optical systems; (3) fusion products measurements; (4) assessment of impact of in-vessel wall reflections on diagnostic performance; (5) assessment of spectroscopic diagnostic measurement techniques and (6) progress in ITER relevant laser-aided diagnostics systems.

1. INTRODUCTION

Diagnostic systems are essential for machine protection, reliable machine operation and comprehensive understanding of burning plasma behavior in ITER [1]. In order to achieve the above aims, more than fifty sub-systems are being developed for measurement of plasma and plasma facing component parameters in the harsh ITER environment, e.g. higher neutron/gamma-ray irradiation and lower accessibility/maintainability compared to that of existing fusion devices. ITPA Diagnostics TG has addressed common physics issues in diagnostics development [2] and the TG activity is mainly directed to High Priority research areas (HP);

- HP-1: Optimization of the lifetime of plasma facing mirrors used in optical systems,
- HP-2: Assessment of impact of in-vessel wall reflections on diagnostic systems,
- HP-3: Development of methods of measuring the energy and density distribution of escaping alphas
- HP-4: Plasma control system measurement requirements
- HP-5: Development of diagnostic calibration techniques/strategies compatible with the burning plasma environment.

In addition, Joint Experiments for Diagnostics (JEX-DIAG) under a framework between ITPA and the Implementing Agreement on Co-Operation of Tokamak Programs of the International Energy Agency (IEA) are being conducted in the following areas;

- JEX-DIAG-2: Environmental tests on first mirrors,
- JEX-DIAG-5: Field test of an activation probe,
- JEX-DIAG-6: Cross comparisons of Charge Exchange Recombination Spectroscopy and X-Ray Imaging Crystal Spectroscopy diagnostics,
- JEX-DIAG-7: Distributed monitoring of microwave power density,
- JEX-DIAG-8: Benchmark of Wall reflections,
- JEX-DIAG-9: Spectral MSE (MSE-LS) experiments as a design driver for ITER MSE,
- JEX-DIAG-10: Minimizing microwave absorption in vacuum windows,
- JEX-DIAG-11: Determination of the runaway electron distribution function by spectral-Bremsstrahlung measurements in the gamma-ray energy range.

Progress and plans in each HP and JEX-DIAG are reported and discussed at the TG meetings which are held twice each year. Action Items including assessments of specific subjects are launched and updated at each meeting.

2. HIGHLIGHTS

Highlighted progress based on above activities is described in following sections.

2.1. Plasma Control System Measurement Requirements (HP-4)

In ITER, PCS (Plasma Control System) [4] controls all aspects of operation and is charged with taking signals from relevant diagnostics and plant systems and using control algorithms to output signals to actuators for plasma control. Only with proper integration of diagnostic signals into PCS can optimum plasma control be achieved. Diagnostic measurements will enable model validation on which controller development is based and provide detailed understanding allowing the expansion of ITER’s operational space. It is mandatory to define correctly
the requirements for each plasma parameter and for each diagnostic. A recently launched action demonstrated the use of a synthetic diagnostic, initially for density control, in IMAS (Integrated Modelling and Analysis Suite) [5] for PCS. The Real-Time Specialists Working Group (RT-SWG) initiated the collection, development and linking to the ITER data-model, for many diagnostics, for the benefit, not only to PCS development, but also for simulations in general and in particular diagnostic simulations needed for design assessment. Progress to develop an ITER synthetic LID (line-integrated density) diagnostic in the IMAS structure to mimic the measurement in an ITER scenario that is then used to perform the control of the density during discharge ramp up, flat top, and ramp down using gas puffing was achieved.

In the ITER burning plasma experiment, PCS controls plasma initiation, ramp-up, flattop, ramp-down, and controlled termination along with the control of all available actuators. PCS is charged with taking signals from relevant diagnostics and plant systems and uses control algorithms to output signals to actuators to control the plasma, including plasma operations related to event handling. PCS is the first line of defence for investment protection on ITER designed to operate within specified Operating Limits and Conditions (OLC) and to respond first to both plasma and plant system events in real-time to attempt to protect the ITER investment and avoid interlocks (dedicated system is in charge of the investment protection). PCS involves the real-time integration of plasma sensors (diagnostics), actuators (heating systems, etc.), and plant systems via advanced control algorithms. PCSSP (PCS Simulation Platform) and IMAS (Integrated Modelling and Analysis Suite) have been developed and can be used to aid PCS development, but require plasma models, as well as models of sensors and actuators.

Diagnostics play a crucial role in ITER plasma control and hence the operation of ITER. Only with proper integration of diagnostic signals into PCS can optimum plasma control be achieved. Diagnostic measurements will enable the validation of plasma models on which the controller development is based and provide detailed understanding allowing the expansion of ITER’s operational space. Consequently, it is mandatory to define correctly the requirements for each of the plasma parameters and for each of the diagnostic systems; requirements that not only involve the individual diagnostics capabilities but also how they are planned to work together.

The Real-Time Specialist Working Group is currently addressing specific action items related to:

1. Gathering experience on existing devices on how the (1) density measurement, (2) heat load measurements, (3) MHD instability activity (e.g.; locked modes, NTM) measurement, (4) NBI shine-through measurement, and (5) High-Z impurity content measurements are validated and treated for PCS use. This effort includes procedures to handle measurement failures and switchover processes and criteria. Data about latency should be collected as well for future discussions.
2. Collecting experience on existing devices related to feedback and control loops for breakdown.
3. Assembling a high-level risk evaluation (items) related to not meeting key control loops (e.g. limited DNB).

Interest in use of modelling for both control/event handling design and online validation, consistency or model based control:

- Analyse cases of interest.
- Comparison of performance and derive requirements.
- Synthetic diagnostic development.

Modelling efforts should be compatible with PCS Simulation Platform (PCSSP) and Integrated Modelling & Analysis Suite (IMAS)

- Allows detailed development and assessment of diagnostic/control integration.
- Use ITER standard Data Model

For PCS, models should be able, in some cases, to simulate degradation and/or failure of the diagnostic to identify solutions and strategies to be applied later during real operation. It has been decided to launch a new action related to the first demonstration of use of Synthetic diagnostic in IMAS for PCS (first demonstration will be the control of density). The RT-SWG of the ITPA Diagnostics TG initiated the collection, development and linking to the ITER data-model, for many diagnostics, for the benefit not only PCS development, but also simulations in general and in particular diagnostic simulations needed for the design assessment.

The first goal was to produce a simple use case to demonstrate density control capabilities with synthetic diagnostics, actuators and control algorithms. The RT-SWG and IO reported on the first attempts to develop an ITER synthetic LID (line-integrated density) diagnostic in the IMAS structure to mimic the measurement in an ITER scenario that is then used to perform the control of the density during ramp up flat top and ramp down of the discharge. The density waveform is taken from core profiles IDS of METIS simulation, 2.65T Hydrogen
plasma: shot 4321, run 2 in /work/imas/shared/scenarios/metis/, to be replaced later by a DINA simulation. The initial workflow employed is shown in Fig. 1. Tests were performed using 1D density code RAPdens, a density ramp-up plasma scenario, feedback using pellet injection, and a simple synthetic diagnostic. White noise was added to the synthetic measurement and then PCS computed the request for the actuators (in this case a simple gas valve or pellets). Very nice preliminary results have been reported, as shown in Fig. 2. Further development will be pursued using a more advanced workflow, as described in Fig. 3, where the exercise will be extended to include plasma shape control.

**Figure 1.** Initial workflow chart.
**Figure 2.** Control of LID during ramp up and flat top using pellet injection as actuator.

**Figure 3.** Planned future workflow.

### 2.2. Optimization of the lifetime of plasma facing mirrors (HP-1, JEX-DIAG-2)

Since all optical and laser-based mirror systems will have a mirror as their first plasma-facing optical element, minimizing mirror degradation and optimizing its lifetime are of paramount importance. First Mirror (FM)
research and development (R&D) activities are aligned with the Work Plan (WP) of the FM R&D [1], which consists of 5 main areas:

1. Performance under erosion- and deposition- conditions: material choice
2. Predictive modeling of mirror performance in ITER
3. Mirror Surface Recovery: deposition mitigation, in-situ calibration, cleaning
4. Tests under neutron, gamma and X-ray environment
5. Engineering and manufacturing of ITER first mirrors

Investigations of candidate mirror materials have been largely advanced at the Forschungszentrum Jülich (Germany). Presently, there are two primary mirror concepts, single crystal molybdenum and single crystal rhodium, envisaged for the majority of ITER diagnostics [2, 3]. A new direct comparative test of the single crystal (SC) rhodium and molybdenum mirrors revealed only a very moderate decrease of the specular reflectivity after sputtering exposure. The maximum reflectivity degradation was measured to be 9% at wavelength of 250 nm. The accumulated sputtering fluence corresponded to ~ 200 cleaning cycles.

Significant progress was attained in the series of experiments performed under ITPA-IAEA Joint eXperiment Program, Task JEX-DIAG-2; “Environmental effects on diagnostic first mirrors”. Within this task, a series of mirror- based diagnostic duct systems, with varying length and aperture, were exposed in several tokamaks: TEXTOR, ASDEX Upgrade, JET, EAST and KSTAR along with the LHD stellarator and several laboratory experiments. The aim of this JEX activity is to study the deposition of impurities on the mirrors and to suppress the deposition employing a specific duct geometry. In particular, a duct Deposition Mitigation (DeMi) system developed at the Ajou University was successfully installed and exposed in KSTAR tokamak [4]. The real-time measurement of deposition in the diagnostic duct was pioneered during this experiment. Experimental data explicitly shows the dominating contribution to the deposition inside the diagnostic duct caused by plasma wall conditioning achieved through glow discharge cleaning (GDC).

_in situ_ mirror cleaning experiments conducted with magnetic field of 1.7 T and with/without the self-bias in EAST tokamak in China were carried out in the frame of collaboration between ASIPP (China) and the University of Basel (Switzerland) [5]. The cleaning speed was at least 40 times faster in EAST with self-bias than that without the B field in the laboratory. The total reflectivity was recovered in almost all areas except those shadowed from direct cleaning plasma impact, as can be seen in Fig. 4. Efforts were invested in the physics understanding of particle environment around the mirrors both during plasma operation and during dedicated cleaning discharges. Progress was achieved in modeling of mirror cleaning as well as in the dedicated benchmarking experiments. A dedicated code was successfully applied at Kurchatov Institute (Russia) for estimates of the first mirror condition in the ITER H-alpha system. The code predicted sputtering-dominated conditions at the mirror and deposition prevailing only in the shadowed areas of the mirror. Based on modeling results, no significant degradation is expected on first mirror during a regular operation of ITER [6]. The cleaning system might be nevertheless needed in order to recover the mirrors affected by potential accidents inside the ITER vacuum vessel, i.e., water leaks. The dedicated Monte-Carlo code developed in Ioffe Institute (Russia) was able to reproduce the impurity deposition patterns formed during the benchmarking experiments [7]. At the same time, the new radiofrequency-based cleaning system developed or the US-lead Upper Port Wide Angle Viewing System was capable for removing 10-20 nm of tungsten from a single crystal Mo mirror. No mirror damage has occurred after cleaning and the surface roughness of the mirror did not increase [8].

Finally, based on established mirror concepts and solutions, intensive manufacturing of prototype mirrors for ITER diagnostics is currently underway worldwide. Among general performance, the functioning of the particular diagnostic elements is under test. In particular, the shutter system for the core Charge-eXchange Recombination Spectroscopy diagnostic was installed and tested in the laboratory. The shutter was able to make more than one million open-close cycles without catastrophic failure. At the same time, the development of a shutter for the ITER edge Thomson scattering system led by JADA was advanced [9]. The modified shutter developed at QST (Japan), survived more than 10,000 open-close cycles.

Significant progress was attained in all major areas of diagnostic mirror R&D. Among crucial results:
- Single crystal molybdenum and rhodium are prime materials for first mirrors
- Basic concept of the mirror cleaning system will be based on a sputtering plasma cleaning process.
- Critical areas of future R&D are identified and presently under investigation.

Several remaining crucial questions are yet to be resolved. These activities are largely a final development of current systems and/or prototypes. Among the necessary R&D questions for near future:
Finalizing studies of deposition mitigation by duct geometry
Investigations of scalability and uniformity of the cleaning discharge
Development of shutters and in situ reflectivity measurement system. Such a system is crucially important for operation of mirror cleaning system.

Figure 4. Cleaning of the mirrors contaminated with alumina (Al₂O₃) serving as proxy to Be, by using the RF-stimulated discharge in EAST tokamak. The blue curve represents the remote area shadowed from the direct impact of cleaning plasmas. Numbers correspond to different mirrors.

2.3. Fusion Products Measurements (HP-3, JEX-DIAG-5)

ITER is designed to produce a burning plasma dominated by alpha-particle heating with a fusion power amplification factor, Q ≥ 10. Good alpha-particle confinement is therefore of paramount importance for the ITER project. Although several diagnostics for confined fast-ions are being proposed for ITER, a lost alpha diagnostic has not yet been approved. The harsh environment in ITER places a number of constraints on standard fast-ion loss detection techniques unprecedented in present tokamaks with easier access and more tolerable conditions. A Fast Ion Loss Detector (FILD) has been identified as a diagnostic that is capable of measuring losses with time resolution <<10 ms for physics studies [10,11,12]. Plans for a new JEX to support development of a FILD for energetic particle measurements in ITER is currently under consideration. The goal of this JEX will be to test components, calibration and critical simulations related to application on ITER.

ITER is expected to generate (and sustain for several hundreds of seconds) thermonuclear fusion based on either deuterium-deuterium (DD) or deuterium-tritium (DT) fusion reactions in a burning plasma. For this reason, neutron measurements have been considered to be one of the major diagnostic methods to determine crucial plasma parameters, such as fusion power, power density, temperature and energy of fast ions, fuel ion ratio and ion spatial distributions in the plasma core. Measuring confined alpha particles, another fusion product, is important because collective effects and the interaction of plasma particles with alpha particles can affect the physics of ignition. Additionally, the neutron flux on the first wall and the loss location of alpha particles should be measured for protection of the ITER device and for the design of future thermonuclear reactors. In order to demonstrate the possibility of measuring fusion products with high accuracy and high reliability under the difficult environmental conditions of ITER, several issues related to the proper measurement of a thermonuclear product are considered.

The influence of coupled electric and magnetic fields on the properties of electron drift in the fission chambers is presented in reports [13,14]. CVD Diamond detectors dedicated to neutron measurements and placed into the In-Port should operate under the following environmental conditions:

- Operating Pressure ≥ 100 Pa and temperature ~100-200°C
- Maximum temperature during baking (no operation of the sensor) ~ 240°C
- Dwell time at max. temperature ~100 hours
- Temperature ramp-up rate ~50°C/hour and cooling rate ~70°C/hour
- Max number of Baking Cycles during lifetime ~ 500 cycles
- Neutron fluence ~ 8x10¹⁶ n/cm² and Neutron flux (14 MeV) ~ 2x10⁹ n/cm²/s
- Ionising dose deposition estimate(silicon equivalent) ~ 6 MGy
Based on these tests, the following conclusions are reached:

- Spectrometric properties of the tested diamond detectors (CIVIDEC) did not change after completing eleven full heating cycles (Phase2) in the TCT scenario (i.e. 33 mini-cycles) nor after two long heating cycles in the STT scenario.
- Values of the total counts from both detectors did not change and remain on a satisfying order of magnitude. Small differences in the energy peak positions for both detectors are slightly visible. However, the value of this difference is counted in single energy channels and is less than 1 %.
- The most important spectrometric parameter monitored during the tests, FWHM, remained constant during the tests at an excellent value of 45 keV – 60 keV.

2.4. Assessment of impact of in-vessel wall reflections (HP-2, JEX-8)

First Wall Specialist Working Group efforts have been mainly concentrated on the quantification of radiated power in the presence of reflection by metal walls, including wall components, in close connection with JEX-8. The final goal of FW-SWG activities is full 3D modelling and experimental validation of radiated power measurement with metal walls with stray light due to reflections. The activity consists of several action items such as the measurement of reflectance, imaging of visible light pattern and its reconstruction by modelling and the measurement of radiated power, and modelling of SOL radiation pattern by edge modelling codes such as SOLPS or EDGE2D. The results from edge modelling codes can be cross-checked by edge plasma diagnostics such as Langmuir probes. One example of reflection modelling by Raysect simulation of JET tested against in-vessel lighting and benchmarked against LightTools modelling of ITER CXRS is shown in Fig. 5. No modelling of Divertor/SOL nor Raysect reflection modelling for H-alpha in JET is done yet.

![Simulation (Raysect) Camera image](image)

**Figure 5. Raysect modelling of JET tested against in-vessel lighting.**

For the surface characterization, University of Basel has developed an automated goniometer called BULGO (Basel University Laboratory Goniometer) which measures the Bidirectional Reflectance Distribution Function (BRDF) [15], see Fig. 6. BRDF describes how the light rays reflect when they are incident upon a surface depending on the angle of incidence and reflectance of the surface including roughness. Surface roughness of samples are characterized by ellipsometry, atomic force Microscopy (AFM). Furthermore, a high-performance UV-visible spectrometer will be used to obtain total and diffuse reflectance. BULGO is calibrated and the measurement accuracy was cross-checked by comparison with another setup in Zürich for a JET Inconel tile measured in 2008. BRDF of tungsten coated samples from CEA and Beryllium samples from JET were measured, and results will be implemented in the Monte Carlo ray tracing code SPEOS developed at CEA [16].

Radiated power can be measured by bolometry. An imaging bolometer based on the IR technique measuring total radiated power absorbed by a thin foil was proposed, and is installed on KSTAR. Significant progress has been made: The Pinhole aperture change has been made for better S/N ratio. The results from phantom tests as well as experimental tests reveal that 3.5 mm by 3.5 mm would be the best choice for the measurements. After the change of the aperture, measurements have been performed for impurity injection experiment in KSTAR. A reasonable measurement of radiated power during the Kr injection was obtained.
2.5. Assessment of spectroscopic measurement techniques (HP-5, JEX-Diag-6)

Cross-calibration of X-ray crystal spectrometer with Charge-Exchange spectroscopy: The comparison of ion temperature profiles measured with CXRS and XICS on EAST and KSTAR tokamaks are found in good agreement. A JEX proposal was made for using Xenon lines for ITER XICS (core) with identified markers for in-situ wavelength calibration of the spectrometer. A work plan for experimentally observing the xenon spectrum with XICS diagnostics and verifying the tolerable limit of xenon injection, which do not affect the plasma performance, was discussed for JET, KSTAR, EAST.

EUV spectroscopy of W plasma in KSTAR: The newly developed compact advance extreme ultraviolet spectrometer reported spatiotemporally varying tungsten spectra measured in fusion plasma of KSTAR. Spatially-resolved W spectra in EUV range were successfully observed under injection condition: 2 – 3 mg of 12 µm W powder. Significant changes in spatiotemporal distribution of EUV: 4 – 6 nm emission increased after W injection (quasi-continuum) and poloidal asymmetry was also observed by the GEM camera and IRVB after the W injection.

Survey of calibration method for ITER XRCS Survey spectrometer: Outline of a procedure for absolute calibration of ITER XRCS Survey was reported having made an extensive survey of calibration procedures relevant for XRCS Survey systems. The survey of procedures from spectrometer installations on Tokamak Fusion, Magnetic Fusion, Space Mission, Synchrotron Beam Lines etc. showed that the calibration is usually achieved two ways, (1) Measured and calculated: Calibrate individual components (diffractors, detectors, Window, filters etc.) and then calculate calibration factors for full spectrometer, (2) Measured: Fully integrated spectrometer is calibrated. This is most accurate as it takes into account exact geometry of the spectrometer and condition of the components. Variety of X-ray sources have been employed for testing and calibrating systems, including laboratory source like X-ray tube(s), Radioisotope(s) - (mostly used in direct or fluorescence methods) and Large machines like Synchrotron, EBIT, (Laser, Plasma) etc. Also, in-line X-ray sources have been deployed where impact of operational environment on spectrometer performance is observed and access to the spectrometer is restricted, e.g. conventional source in JET Survey spectrometer, Radio-XRF source in XICS on C-Mod.

2.6. Progress in ITER-relevant Laser-Aided Diagnostic Systems

A full scale ITER TIP prototype with 96m round trip path length, including automated feedback alignment, was successfully tested in the laboratory and on DIII-D [18]. The 2-color DIII-D TIP prototype uses a 10.59 micron CO2 laser and 5.22 micron QC (quantum cascade) laser. The system includes a matching 96 m reference leg and the beams are fully enclosed along path. The active alignment system was able to compensate for movement up to ±25mm during a tokamak discharge. Structural stabilization, reducing movement to <2nm, allowed the alignment system to perform to expectations. Overall system noise levels, time response and phase resolution exceeded the ITER specifications. Effectiveness and necessity of realtime feedback control on the laser beam position is demonstrated in Fig. 7.
In addition, poloidally-viewing polatimeter-interferometer systems on EAST and DIII-D tokamak have demonstrated capabilities to provide non-inductive measurement magnetic axis position [19] and internal magnetic fluctuations at frequencies up to 1 MHz [20].

Figure 7: TIP prototype density measurement on DIII-D. Blue: Active alignment off; Black: Active alignment on; Red: Partially “locked” active alignment.

Disclaimer
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