Overview of Recent ISTTOK Results

[a]C. Silva, [a]H. Fernandes, [a]C.A.F. Varandas, [a]D. Alves, [a]B.B. Carvalho, [a]I. Carvalho, [a]P. Carvalho, [a]P.A. Carvalho, [a]R. Coelho, [a]A. Duarte, [a]P. Duarte, [a]H. Figueiredo, [a]J. Figueiredo, [a]J. Fortunato, [a]R. Gomes, [a]B. Gonçalves, [a]I. Nedzelskij, [a]A. Neto, [a]T. Pereira, [a]V. Plyusnin, [a]D. Valcárcel, [b]P. Balan, [b]C. Ionita, [b]R. Schrittwieser, [c]J.B. Correia, [c]V. Livramento, [d]O. Lielausis, [d]A. Klyukin, [d]E. Platacis, [d]A. Sharakovski, [d]I. Tale, [e]T. Lunt, [f]M. Gryaznevich, [g]G. Van Oost, [h]M. Hron, [i]A. Malaquias, [j]N. Dreval, [k]A. Melnikov, [l]P. Khorshid, [m]C. R Gutierrez Tapia, [n]W. Sá, [o]M. Kolokoldarov, [p]A. Czarnecka, [p]L. Jakubowski, [p]J. Zebrowski, [p]K. Malinowski, [p]M.J. Sadowski

[a]Associação Euratom/IST, Instituto de Plasma e Fusão Nuclear, Instituto Superior Técnico 1049-001 Lisboa, Portugal; [b]IEPPG, Association EURATOM/ÖAW, University of Innsbruck, Austria; [c]LNEG, Departamento de Materiais e Tecnologias de Produção, Lisboa, Portugal; [d]EURATOM/University of Latvia, Institute of Solid State Physics, Riga, Latvia; [e]Humboldt-Universitat zu Berlin, Berlin, Germany; [f]EURATOM/UKAEA Fusion Association, Culham SC, Abingdon, UK; [g]Dep. of Applied Physics, Ghent Univ., Belgium; [h]Institute of Plasma Physics, Association EURATOM/IPP, Czech Rep.; [i]IAEA, NAPC Physics Section, Vienna, Austria; [j]Plasma Physics Lab., Univ. of Saskatchewan, Canada; [k]RRC "Kurchatov Institute", Moscow, Russia; [l]Plasma Physics Research Center, Teheran, Iran; [m]ININ, Mexico; [n]Institute of Physics, Univ. of São Paulo, Brazil; [o]Institute of Atomic Energy of National Nuclear Center Kazakhstan; [p]Association EURATOM – IPPLM Poland

Abstract. This paper reviews the recent work developed on ISTTOK. A wide variety of diagnostic tools, instrumentation and systems have been developed demonstrating that small tokamaks can play an important role in the fusion community. Furthermore, a physics programme has been carried out with particular emphasis on the characterization of the edge fluctuations. Recently, the ISTTOK programme has also dedicated particular attention to the development of plasma facing components being both liquid metal limiters and nanostructured materials.

1. Introduction

ISTTOK [1] is a large aspect ratio, limiter tokamak with an iron core transformer, in operation since 1991 at the "Instituto de Plasmas e Fusão Nuclear", in the frame of the Euratom Fusion Programme. ISTTOK has been very important for the creation and consolidation of the Portuguese fusion research team, its main objectives being: (i) the formation of students in fusion plasma physics and technologies; (ii) the development of new diagnostic techniques and instrumentation systems; and (iii) to carry out a tokamak physics programme. The flexibility of small tokamaks is particularly appropriate to accomplish these objectives.

In this contribution the work developed recently on ISTTOK will be reviewed with emphasis on the following topics: (i) Study of fusion relevant materials; (ii) Diagnostics; and (iii) Edge plasma physics studies.

2. Study of fusion relevant materials

Presently one of the main challenges for nuclear fusion technology is related to plasma-wall interaction. In large size devices (including ITER), plasma facing components (PFC) are submitted to high power loads under steady state operation that could even reach the GW/m^2 range during off-normal events in the divertor region. One possible solution for this issue is the use of liquid metal flow as they may provide an efficient mean to exhaust heat produced in the core plasma. Other possibility is the development of materials with high thermal conductivity compatible with fusion reactors. The use of nanostructured materials is a possible way to achieve the reactor requirements, although significant developments are still needed. Both approaches (liquid metals and nanostructured materials) are under investigation on ISTTOK, being the main achievements summarized below.

2.1 Liquid metal limiter

The interaction of a liquid gallium jet with plasma has been investigated on ISTTOK [2]. A stable, free flying liquid gallium jet has been developed with the aim of studying the relevance of liquid metals as plasma facing components. A comparison of the tokamak discharges with and without the plasma-liquid gallium jet interaction has been performed [3]. It is possible to conclude that the presence of the jet does not change significantly the discharge performance and that the radiation losses do not increase. The analysis of data clearly shows that the gallium jet only influences locally the ISTTOK plasma as no gallium radiation has been observed toroidally away from the jet. Furthermore, no gallium emission is detected in discharges without the gallium jet, meaning that there is no machine contamination. The experiments on ISTTOK proved that gallium jets are compatible with tokamak operation.

Recent activities in this area have been concentrated in the study of the liquid gallium jet power removal capabilities. The response of an IR sensor intended to perform the measurements of the gallium jet surface temperature was investigated. When absolutely calibrated, this diagnostic will provide an estimate on the power extraction capability of such a liquid metal jet in tokamaks. A HgCdTe (Mercury-Cadmium-Tellurium) sensor operated at cryogenic temperature (78 K) and specially designed to measure low temperature (>150 ºC), low emissivity materials like this kind of liquid metals has been tested. Since this sensor is sensitive in the infrared region of the spectra (peak efficiency from 6 to 7 μm) the chosen optics (viewing window and collection lens) has to be transparent in this range. From the analyses of the obtained data, it has been possible to clearly identify the heating of each individual droplet (at this position the jet is already in droplets from) and also a clear shift of the jet due to electromagnetic forces (Figure 1). It is possible to

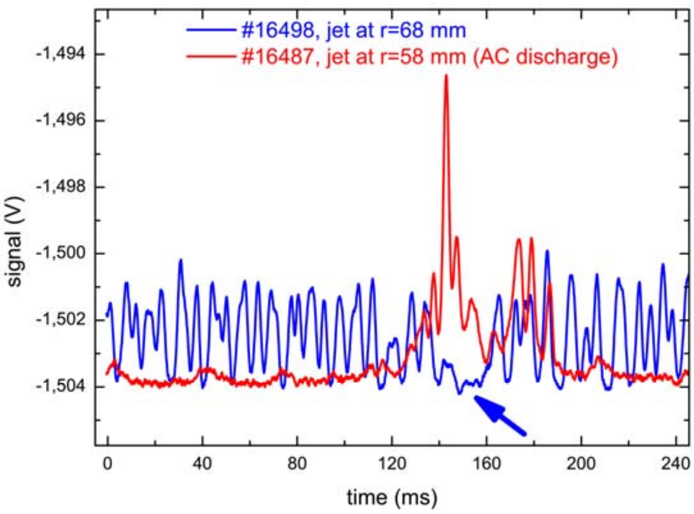

Figure 1: Signal response of the IR sensor for two different radial positions of the of the gallium injector.

observe a wavy formation corresponding to the droplet signal passing in front of the detector. The disappearance of this signal (at about 160 ms) for the jet at r=68 mm can be related to the motion of the jet that partially leaves the field of view (FOV) of the sensor. The signal for the jet at r=58 mm appears only in the detector FOV when the discharge occurs due to the influence of the forces. Measurements performed at that viewing port using a fast frame CCD camera have confirmed the displacement of the droplets, in front of the sensor FOV. These were only noticeable when a discharge occurred (no motion when no gas was injected in the chamber).

2.2 Nanostructured materials

A novel material design in nuclear fusion reactors has been proposed based on W-nDiamond nanostructured composites [3]. Generally, a microstructure refined to the nanometer scale improves the mechanical strength due to a modification of plasticity mechanisms. Moreover, a highly specific grain-boundary area raises the number of sites for annihilation of radiation induced defects. However, the low thermal stability of fine-grained and nanostructured materials demands the presence of particles at the grain boundaries that can delay coarsening by a pinning effect. As a result, the concept of a composite is promising in the field of nanostructured materials. The hardness of diamond renders nanodiamond dispersions excellent reinforcing and stabilization candidates and, in addition, diamond has extremely high thermal conductivity. Consequently, W-nDiamond nanocomposites are promising candidates for thermally stable first-wall materials. The proposed design involves the production of W/W-nDiamond/W-Cu/Cu layered castellations. The W, W-nDiamond and W-Cu layers are produced by mechanical alloying followed by a consolidation route that combines hot rolling with spark plasma sintering (SPS). Layer welding is achieved by spark plasma sintering. Long term plasma exposure experiments are planned for ISTTOK and FTU.

3. Diagnostics

One of the main activities of the ISTTOK team is the development and optimization of diagnostics. Some of the recent diagnostic developments are summarized in this contribution.

3.1 Bolometer tomography

A bolometer tomography diagnostic based on 3 linear 10-pixel detectors has been installed on the Portuguese tokamak [4]. One of the main objectives of this diagnostic is to supply the required feedback to the control system as the plasma position determination during AC operation based on magnetic probes system has been found to be inadequate during the current inversion due to the reduced plasma current. The Fourier-Bessel (FB) and Neural networks (NN) tomographic methods stand out due to their inherent speed necessary for real-time control. The performance and reliability of these methods have been compared. It has been found that although the FB based inversion proved to be faster, the NN reconstruction has fewer artifacts and is more accurate (Figure 2). The real-time tomographic algorithm based on the FB method has been implemented and tested on the computer acquiring the tomographic data. This computer is running the Real-Time Application Interface (RTAI) layer in Linux, so as to ensure that the algorithm is always run with the maximum priority. Off-line tests showed that each tomographic reconstruction is generated in about 40 μs;

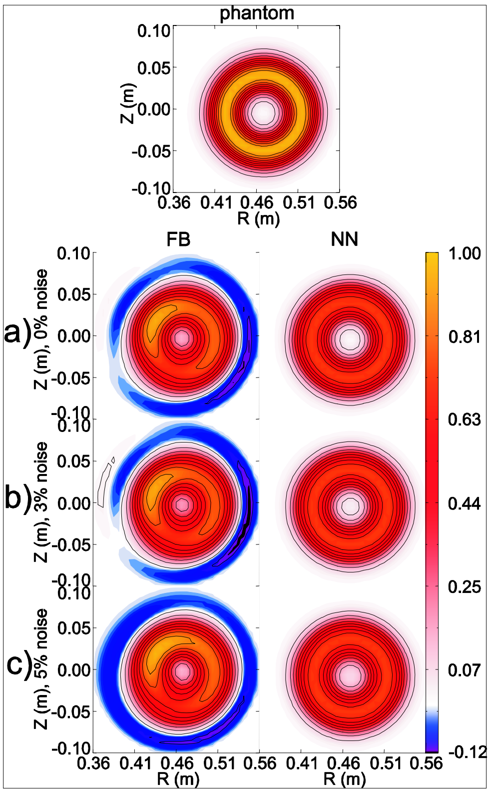

Figure 2: Comparison of the reconstructions using Fourier-Bessel and Neural Networks algorithms for different ranges of measurement noise - a) has no noise, b) has 3% noise and c) has 5% noise. Clearly, the NN reconstructions are superior to the FB in any of the cases presented.

3.2 Heavy ion beam upgrade

The use of a multi-cell array detector offers unique capabilities to the Heavy Ion Beam Diagnostic (HIBD) as it allows simultaneous measurements across the plasma column. New pre-amplifiers for the HIBD have been successfully tested with a bandwidth of 400 kHz, allowing the use of this diagnostic for fluctuations studies. Broad band (<100 kHz) fluctuations at plasma periphery associated with turbulent transport as well as quasi-coherent fluctuations in bulk plasma at frequencies between 100-200 kHz have been identified. The localization and frequency of the latter fluctuations correlate well with the MHD activity of the plasma.

3.3 Detection of runaway electrons using Cherenkov-type detectors

A new detector for the measurements of Cherenkov radiation emitted at the interaction of energetic electrons (super-thermal and runaways) with AlN crystal was designed, manufactured and installed on the ISTTOK tokamak. Using this Cherenkov-type detector the runaway generation regimes have been identified in the low-current ISTTOK discharges confirming previous results obtained by the numerical analysis of macroscopic plasma parameters. The population of the runaway electrons with energy higher than 80 keV has been recorded. Their energy is obviously higher than the critical energy for the runaway process in ISTTOK. The numerical evaluation of the experimental data has revealed that such electrons can be generated at the vicinity of the plasma centre and can be detected at the probe position [5].

4. Edge plasma physics studies

Recently, the plasma physics studies on ISTTOK were concentrated mainly on the characterization of the edge turbulence. ISTTOK is equipped with two probe systems that allow the investigation of the edge fluctuations: (i) a 8-pin radially movable poloidal array of Langmuir probes with a resolution of 2 mm, installed in an equatorial port; and (ii) a 8-pin radial array of Langmuir probes with a spatial resolution down to 3 mm toroidally located at about 120º from the poloidal array and installed near the top of the poloidal cross-section. Such an experimental arrangement allows the investigation of the three dimensional characteristics of the edge fluctuations.

It has been found that the ISTTOK fluctuations have distinct characteristics for r > a (SOL) and r $\lesssim$ a (edge plasma). Figure 3 shows the V_f cross-correlation for pins poloidally separated by 4 and 8 mm, measured in the SOL and in the edge plasma regions, as well as the V_f autocorrelation. In the SOL, fluctuations are characterized by short correlations both in space and time (poloidal correlation length, λ_c~10 mm and autocorrelation time, τ_c~3-4 μs). However, in the plasma edge, the autocorrelation time is significantly larger, τ_c~10 μs, and the poloidal cross-correlation only shows a very small reduction across the 14 mm extension of the poloidal array (λ_c >> 14 mm).

Poloidal wavenumbers in the range of $k_\theta < 3$ cm^{-1} and a broad frequency spectrum are observed in the SOL. Assuming a poloidally uniform structure, these wavenumbers correspond to poloidal mode numbers up to $m = 25$. In the edge plasma the wavenumbers are smaller, $k_\theta < 1.0$ cm^{-1}, and the spectrum is dominated by low frequency components (10-25 kHz). Furthermore, k_θ is close to zero for frequencies below 50 kHz consistent with a poloidally symmetric structure.

The I_{sat} fluctuations have also been investigated and comparable results obtained. However, contrary to the observed with V_f, the I_{sat} fluctuations are not dominated by the low frequency fluctuations. The relative magnitude of the low frequency fluctuations (ratio of the spectrum amplitude in the range 10-25 kHz to the total spectrum amplitude) is significantly smaller for I_{sat} than for V_f. As a consequence, the I_{sat} fluctuations in the edge plasma show evidence of both turbulent and low frequency scales, clearly visible in the cross-correlation.

Results indicate that the characteristics of the potential fluctuations in the SOL are consistent with the typical broad band turbulent fluctuations while in the edge plasma they are dominated by low frequency oscillations consistent with a symmetric structure in the poloidal direction, characteristic of the geodesic acoustic mode, which for the ISTTOK edge plasma is expected to have a frequency of ~20 kHz ($T_i = T_e = 20$ eV). Furthermore, the amplitude of the density fluctuations in the 10-25 kHz range is significantly smaller than that of the potential as expected from the GAM theoretical predictions [6]. Results suggest therefore the existence of GAM-like modes in the edge plasma region of the ISTTOK tokamak.

Potential signals measured simultaneously at different toroidal locations show a striking similarity, particularly at low frequencies. To quantify the similarity between potential fluctuation probe signals the toroidal cross-correlation has been computed. Raw data for potential signals evolution, frequency spectra as well as toroidal cross-correlation (between potential signals measured by both probe arrays) are shown in figure 4. As illustrated in figure 4a, a clear similarity is observed between floating potential signals measured in the edge plasma by the two probe systems toroidally apart. Signals are dominated by a ~20 kHz oscillation with time varying amplitude (figure 4b). As shown in figure 4c, a high toroidal cross-correlation (up to .9) is found. As no significant phase shift is observed between signals measured by the probe systems poloidally and toroidally separated, results suggest that the potential has a $m = 0$, $n = 0$ structure compatible with GAM. Figure 4c also shows the amplitude of the V_f power spectrum in the range 15-25 kHz. Both long-range correlations and low frequency components show a significant degree of intermittency and a good correlation between them is found. The lifetime of the GAM is estimated to be $\lesssim$ 100 μs, which is compatible with the spectral width of the GAM peak, ~10 kHz. These findings show direct evidence of (intermittent and low frequency) long-range correlations for potential fluctuations in the plasma edge region.

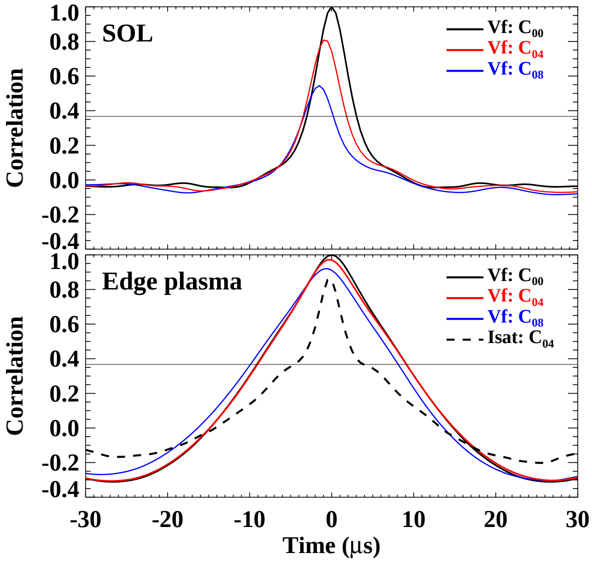

Figure 3: Floating potential cross-correlation for pins poloidally separated by 4 (C_{04}) and 8 mm (C_{08}) measured in the SOL and in the edge plasma. The V_f auto-correlation is also shown (C_{00}) as well as the I_{sat} cross-correlation in the edge plasma.

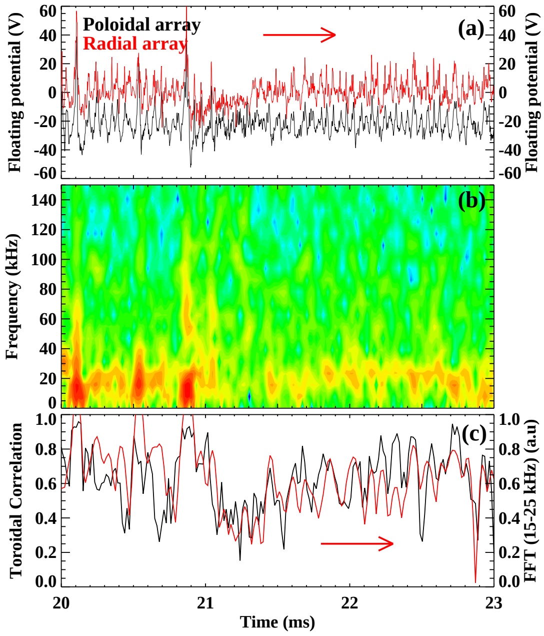

Figure 4: Time evolution of: (a) V_f measured simultaneously in two toroidal positions at r-a= -10 mm; (b) V_f spectrogram; and (c) toroidal correlation between V_f signals together with the amplitude of the V_f power spectrum in the range 15-25 kHz.

5. Joint Experiments

IPFN has organized in October 2007 the Host Laboratory Experiment on the tokamak ISTTOK. The Joint Experiment was organized in cooperation with the IAEA in the framework of the IAEA Coordinated Research Project (CRP) on "Joint Research Using Small Tokamaks" with the participation of 24 scientists from 13.

Taking into account the ISTTOK scientific programme and the feedback from the pre-registered participants the following areas were explored during the ISTTOK JE: (i) Study of the poloidal structure of the edge fluctuations; (ii) Tokamak operation in alternating current regimes; and (iii) Testing of the liquid metal limiter concept. These activities were successfully carried out being distributed in 5 experimental sessions. Other areas related with plasma engineering and diagnostics were also investigated, although with no dedicated experimental sessions attributed. These areas, organized in small workshops, included: (i) plasma diagnostics; (ii) plasma control; (iii) data acquisition; and (iv) remote data access.

Remote experimental sessions in the following weeks were also organized to complement the experiments performed during the JE in ISTTOK. The participants could run experiments using the ISTTOK remote participation tools. Working groups have been formed for data analysis and remote meeting regularly organized to plan experiments and discuss results.

Transverse areas to ISTTOK-JE were data acquisition, signal processing and remote access tools where CFN has a long experience. These systems have been successfully used for data management on several tokamaks and they may serve as a platform for a unified environment for data exchange and processing in the framework of small tokamak activity (IAEA CRP).

6. Summary

This paper reviews the work recently developed on ISTTOK. The highlights of this work can be summarized as follows:

- Study of fusion relevant materials: An important research area on ISTTOK has been the study of the liquid metals as plasma facing components. A gallium jet limiter has been developed and installed at ISTTOK. Successful plasma operation with a jet interacting with the plasma demonstrated that gallium is compatible with fusion plasmas. Furthermore, the ISTTOK plasma has also been used to test fusion relevant plasma facing materials based on tungsten, copper and nano-diamond alloys;
- Diagnostics: Several diagnostics have been installed or upgraded recently on ISTTOK, like for instance a bolometer tomography diagnostic, heavy ion beam upgrade and detection of runaway electrons using Cherenkov-type detectors;
- Edge plasma physics: The physics programme has been based mainly in the characterization of the edge fluctuations at different scales (local versus long-range correlations).
- Joint Experiments in the framework of the IAEA Coordinated Research Project (CRP) on "Joint Research Using Small Tokamaks" have also been carried out on ISTTOK in October 2007 with the participation of 24 scientists from 13 countries. The ISTTOK achievements demonstrate that small tokamaks can play an important role in the fusion plasma physics community as a result of their flexibility, high availability and good opportunity for the development of sophisticated diagnostics and technology tools.

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