Overview of Recent ISTTOK Results

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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 control and 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.

Keywords: Tokamaks, Diagnostics, Edge physics, Plasma control, Data acquisition, Plasma facing components
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INTRODUCTION

ISTTOK [1] is a large aspect ratio, limiter tokamak with an iron core transformer, in operation since 1991 at the "Centro de 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) Control and data acquisition; (iii) Diagnostics; and (iv) Edge plasma physics studies.

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.

Liquid metal limiter

The interaction of a liquid gallium jet with plasma has been investigated on ISTTOK [2, 3]. A stable, free flying liquid gallium jet has been developed with the aim of studying the relevance of liquid metals as plasma facing components. Up to now, lithium has received most of the attention of the research of liquid metals as a PFC. Gallium has been used due its better thermal properties (the gallium ebullition point is much higher than that of lithium). The main disadvantage of the use of gallium as a PFC is its high Z and the consequent risk of plasma contamination.

After the successful testing of a new damping device (to reduce the amount of gallium droplets reflected from the collector) and the latest version of the gallium injector, the gallium circuit has been installed on ISTTOK. 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. It was concluded therefore that ISTTOK can be successfully operated with a gallium limiter.

The Ga impurity behaviour has also been investigated in detail using high sensitivity photodiodes. The observations have been done at two different ports: one looking directly at the jet poloidal plane and another at a toroidally symmetric position. 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.

Due to the low power densities of ISTTOK plasmas and the small area of the jet used, it was not possible to assess the ability of liquid gallium to handle high heat loads. It is therefore important to expose a curtain of jets to plasmas with more relevant heat loads in order to fully validate liquid metals as a plasma facing component. However, the experiments on ISTTOK proved that gallium jets are compatible with tokamak operation.

Nanostructured materials

A novel material design in nuclear fusion reactors has been proposed based on W-nDiamond nanostructured composites [4]. 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 (Frascati).

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.

Bolometer tomography

A bolometer tomography diagnostic based on 3 linear 10-pixel detectors has been installed on the Portuguese tokamak [5]. 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. Several tomographic methods are available for soft X-ray or bolometric tomography, among which the Cormack and Neural networks methods stand out due to their inherent speed of up to 1000 reconstructions per second, with currently available technology. It has been found that although the Cormack based inversion proved to be faster, the neural networks reconstruction has fewer artifacts and is more accurate. Figure 1 shows an example of the reconstructed ISTTOK emissivity.

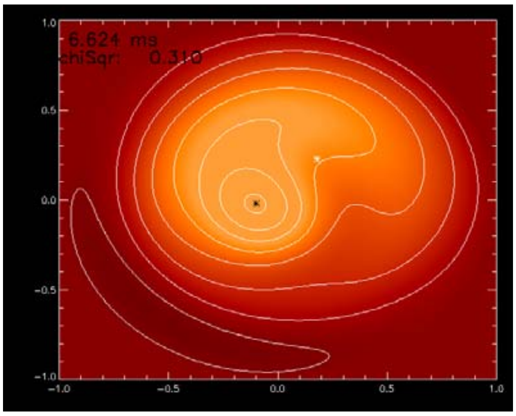

FIGURE 1. Reconstruction of the ISTTOK plasma emissivity.

Development of a retarding field energy analyzer

A retarding field energy analyzer (RFEA) has been manufactured and installed on ISTTOK with the aim of measuring the edge ion temperature [6]. The RFEA, is rather compact (D14×L23 mm^2) and it is based on the retardation of charged particles by bias potentials applied to a number of grids. Figure 2 shows a typical characteristic obtained in the ISTTOK scrape-off layer (1.3 cm outside the limiter) as well as an exponential fit to the experimental data. The derived ion temperature (T_i = 14 eV) is typically a factor of two larger than that of the electrons at the same location, which is in agreement with the results of the scrape-off layer models.

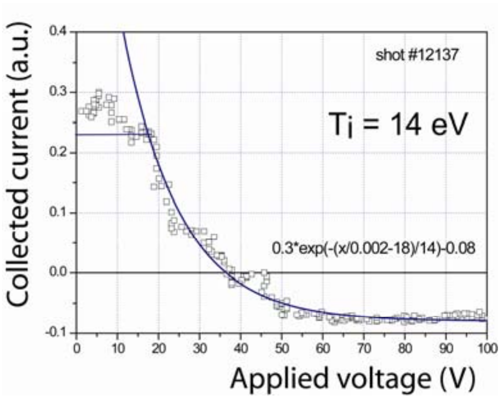

FIGURE 2. Typical ion characteristic obtained in the ISTTOK scrape-off layer

Edge plasma pressure measurement using a mechanical force sensor

A novel mechanical probe to measure the plasma pressure directly has been developed on ISTTOK [7]. It consists of two pendulums whose heads are exposed to the plasma (with no, or almost no, plasma between them), while the deflection is measured by high sensitivity semi-conductor strain gauges. The plasma pressure was successfully measured, its value being in good agreement with that derived from the electrical probe data (1–10 Pa). The pendulum has been inserted at different radial position in the plasma and the force measured. It has been observed that the plasma force increases as the pendulum is inserted into the plasma. The time evolution of the plasma force has been derived and a force pulse is clearly seen when plasma is present. Figure 3 shows the comparison of a pulse with no plasma and a normal pulse. It is clear that a force appears in the pendulum due to the plasma. The derived plasma force is shown by the dashed line.

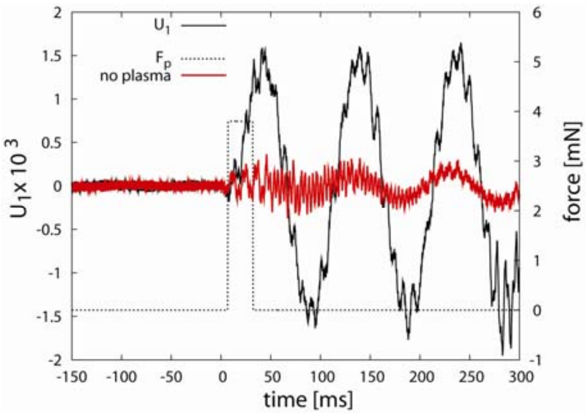

FIGURE 3. Measured (solid line) and estimated force (dashed line) signal during a plasma pulse a pulse without plasma on ISTTOK.

CONTROL AND DATA ACQUISITION

The ISTTOK control and data acquisition has been upgraded with the main objective of achieving long AC operation. The activities in this area include the migration from VME to PCI boards, the development of real-time plasma position controller and the respective power supplies and the development of remote data access tools.

Migration of the data acquisition from VME to PCI

The ISTTOK data acquisition has been migrated from VME to PCI modules (PCI-TR-256), developed at CFN [8]. The main characteristics of this module are: (i) 8 galvanic isolated channels, with 14-bit ADC @ 2 MHz; (ii) a Texas Instruments Fixed-Point DSP @ 500 MHz (TMS320C6415); (iii) a Xillinx FPGA (Spartan-IIE XC2S400E); and (iv) 512 MB SDRAM memory module. Compared with the old VME boards, the PCI units represent a major upgrade not only in the sampling rate but mainly in the memory available per channel.

Development of a real-time controller for the plasma position

A real-time controller for the horizontal plasma position was developed, which allows controlling the magnetic equilibrium field using a novel power supply [9]. This controller is based on an existing PCI module (PCI-TR-256). The software developed for this module acquires the data from 8 poloidal magnetic probes (Mirnov probes), calculates the plasma position using the current filaments method and generates a power supply control signal with a PI controller. The horizontal and vertical plasma position control system (128 μs feedback cycle) was installed. The vertical power supply allows controlled currents from -240 to 240 A with a 20 μs feedback cycle, being capable of rising from 0 to 90% of the peak current in 1ms. The horizontal power supply is similar but the current is limited to ±150 A. Feedback position control tests were performed showing that digital feedback is applicable to control the plasma of a small machine.

Production of new power supplies

A new concept of switched power supplies (57 kHz) were designed and produced with an embedded microcontroller, for the necessary current drive of the vertical and horizontal magnetic fields [10]. This option allows a direct implementation of PID algorithms with a faster response time. Each power supply allows a maximum current of 100 A, with a very compact design and bipolar capabilities. A hybrid control algorithm has been developed and tested successfully. Results show the improvements in the current ramping towards a far setpoint and in the time necessary for a current inversion compared with the previous algorithm (PID). The new hybrid algorithm allows faster current inversions in the ISTTOK tokamak and allowed a more precise control of the plasma position. These improvements made in the power supply controller allowed better results in plasma discharges, especially in alternate discharges.

Development of a SCAD – a cooperative software for shared tokamak operation

A multi-user platform, based on standards like CORBA, XML and JAVA, has been developed for remote control and data acquisition experiments [11]. The main objective of this tool is to detach the machine operation from a single computer, allowing hardware configuration, following experiments and data share by all connected users. Among the main features it has a built-in chat, profile saving, remote sharing and remote calculation invocation. Since it was developed in JAVA and deployed with JAVA Web-Start technology, it can run in all the most common operating systems and computer platforms like PCs, Solaris and Mac in a very intuitive way. The software is plugin based, providing an easy way of adding new hardware, data viewers and data calculation algorithms. As any hardware is described in a XML file, the program automatically creates configurators to the hardware. Every time a configuration is changed, the information is sent to hardware controller so that in the next discharge the hardware is programmed accordingly.

Development of remote data access tools

Each laboratory uses different data store schemes making it difficult for scientists to access the different device data. To solve these problems a common software layer between end-users and laboratories has been developed [12]. The library allows data retrieval using the same methods for all laboratories and has been tested in some of the most common data analysis programs such as MatLab and IDL. The system is already being used in ISTTOK, CASTOR and ETE. These tools are also particularly relevant for working groups as integrated tokamak modelling where data access to different databases is essential.

PLASMA PHYSICS STUDIES

Recently, the plasma physics studies on ISTTOK were concentrated mainly on the characterization and control of the edge turbulence and on the investigations of the MHD activity.

Influence of emissive electrode bias on the E×B flow profile

Emissive electrode biasing experiments have been described in detail before [13]. Recently, the work in this area was concentrated on the detailed characterization of the modifications induced in the edge profiles with the aim of understanding the different plasma behaviour with positive and negative bias. It has been observed on ISTTOK that the line-averaged density increases substantially for both polarities. However a significant improvement in particle confinement has only been observed for negative bias.

To better characterize the modifications introduced by the electrostatic biasing at the plasma periphery, the radial electric field, E_r, and the E×B flow shear, $\gamma_{ExB}=dv_{ExB}/dr$, radial profiles have been measured using the rake probe (figure 4).

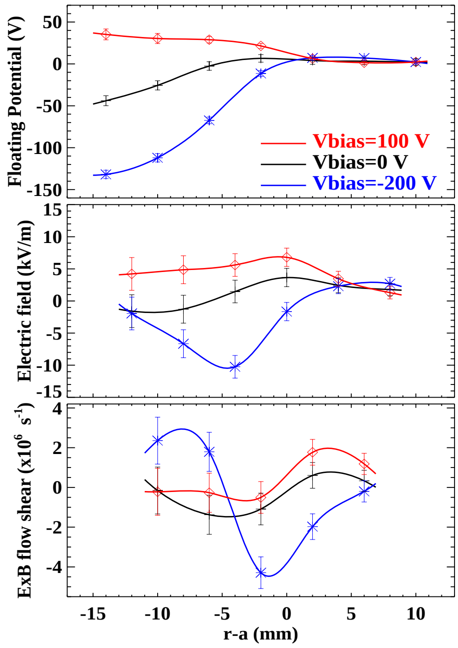

FIGURE 4. Radial profiles of the floating potential, radial electric field and E×B flow shear for positive, negative and without bias.

As the bias is applied, a large electric field is observed for both polarities, associated with a strong E_r shear. In the region just inside the limiter position the E_r magnitude and more importantly, the magnitude of the E×B flow shear are larger for negative bias. For positive bias, a significant γ_{ExB} is only observed near the last close flux surface (LCFS).

The ExB flow shear necessary to suppress turbulence, γ_{ExB}^{crit}, is given by the inverse of the fluctuations autocorrelation time. We find that this time for both I_{sat} and V_f in the SOL (r-a=6 mm) is typically 3-4 μs and therefore $\gamma_{ExB}^{crit} \approx 3\times10^5$ s^{-1}. For negative bias, the E×B flow shear exceeds largely the necessary value for turbulence suppression across the whole region sampled by the probes, while for positive bias this is only clearly true for r-a>-2 mm. This difference may explain the distinct behaviour of the particle confinement for positive and negative bias.

Edge plasma biasing strongly modifies the fluctuations in the boundary plasma, the changes being distinct in the SOL and in the core periphery. Figure 5 shows the evolution of I_{sat}, V_f and Γ_{ExB} for a discharge with negative bias (#11752, V_{bias}=-150 V) and another with positive bias (#11729, V_{bias}=100 V). The parameters have been measured with the turbulent transport probe located 6 mm outside the LCFS. Without bias, the density and the cross-field particle flux in the boundary plasma are characterized by intermittent events with duration up to 0.1 ms. These oscillations are more evident after the bias is switched off as their amplitude tends to be larger at high densities. As illustrated, emissive electrode bias is very effective in modifying the SOL fluctuations and turbulent transport for both polarities. A strong reduction in I_{sat} and V_f fluctuations is observed associated with a reduction in the cross-field turbulent transport. Furthermore, the time-averaged I_{sat} is also reduced in the SOL, suggesting that a particle transport barrier is induced for both polarities.

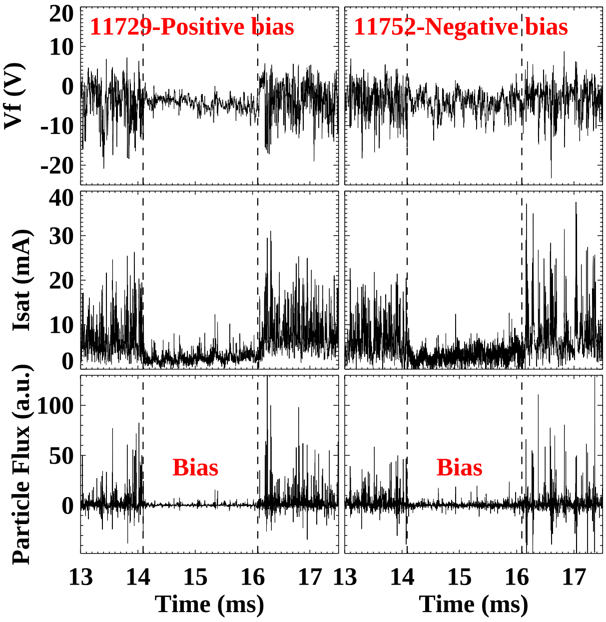

FIGURE 5. Time evolution of V_f, I_{sat} and Γ_{ExB} in the SOL (r-a=6 mm) for positive and negative bias. The vertical dashed lines indicate the biasing period.

Observations are therefore consistent with a reduction of the anomalous particle flux, as a result of a reduced electrostatic turbulence. In addition, figure 5 indicates that bias reduces the fast radial propagation of the intermittent events, which contributes also to the narrowing of the SOL density profile.

Poloidal structure of the ISTTOK edge fluctuations

The poloidal structure of the fluctuations has been investigated using a poloidal array of Langmuir probes consisting of 7 pins poloidally separated by 1.5 mm. Pins can be individually set to measure the floating potential or the ions saturation current. It has been observed that the ISTTOK edge plasma is characterized by low frequency (< 100 kHz), small wavenumber (k_θ< 3 cm^{-1}) fluctuations. Large poloidal structures are clearly visible in the probe signal (figure 6) having a poloidal velocity around 1-2 km/s, a correlation length around 10 mm and a typical duration of 10 µs, resulting in an estimated structure poloidal size of 1-2 cm.

The cross-correlation between the signals from different pins has also been investigated as a function of the frequency. It was observed that the correlation length is very large for frequencies between 50 and 150 kHz (>10 mm), the correlation being roughly constant across the 7 pins in this range. This frequency range corresponds to time scales of ~10 µs, which is the typical time scale of the large events observed. On the contrary, the correlation length is small at high frequencies. These results show evidence of multi-scale structures with different properties. The high frequencies are dominated by small-scale structures while the intermediate frequencies are dominated by large structures with long correlation lengths.

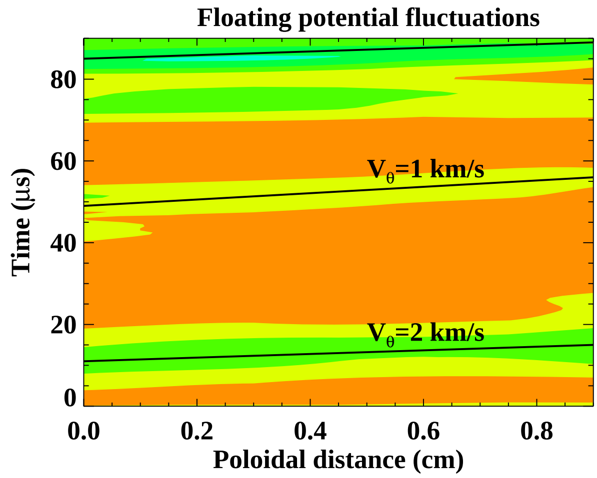

FIGURE 6. Time evolution of the floating potential fluctuations measured by the poloidal probe array.

Investigation of the MHD Activity

The Empirical Mode Decomposition method (EMD) was applied to the analysis of the time-frequency characteristics of both Mirnov and turbulence data from negative electrode biasing experiments carried out on ISTTOK [14]. This rather new technique proves to be particularly suited for the typically bursty activity, both MHD and turbulence, which characterizes ISTTOK pulses. Mirnov signals evidencing the destabilisation of a m=2 resistive mode (identified by cross-correlation with a poloidal arrays of 8 coils) have been observed and their non stationary spectrum using the Hilbert Huang Transform obtained. Figure 7 presents the instantaneous frequencies of the dominant 3 IMFs providing the signal support.

Analysis of the plasma density fluctuations via HHT revealed an average increase in the frequency of the turbulence spectra related to the biasing, in agreement with MHD activity spectra. Floating potential oscillations were also analyzed with EMD, revealing intrinsic mode functions with clear growing oscillations that might be correlated with MHD activity (although with a frequency mismatch).

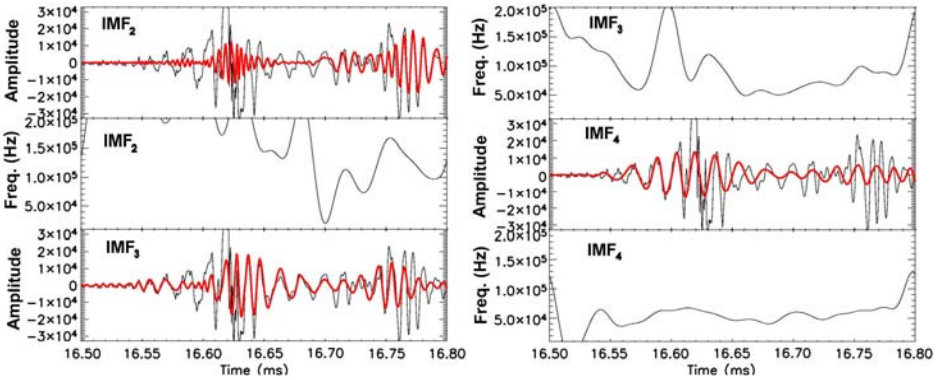

FIGURE 7. Instantaneous frequencies of the dominant 3 IMFs

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 and a pendulum for plasma force measurements;
- Control and data acquisition: The data acquisition system and the real-time plasma position control system have been upgraded to allow long AC operation. ISTTOK is operating with state of the art data acquisition technology, which is now being installed in other devices such as JET. Furthermore, remote data access tools have been developed to facilitate the exchange of information and the collaboration between physicists located around the world;
- Edge plasma physics: The physics programme has been based mainly in the characterization of the edge transport using different types of probes and on the turbulent transport control using electrode biasing.

The ISTTOK achievements demonstrate that small tokamaks can play an important role in the fusion plasma physics community as a result of their flexibility.

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