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ENGINEERING ASPECTS OF THE TOKAMAK ISTTOK

EXPERIMENTAL DEVICES

KEYWORDS: *tokamaks, plasma diagnostics, data acquisition*

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The first Portuguese magnetic confinement experiment, the tokamak ISTTOK, has been in operation since 1993. This tokamak device is described and the main technological features, as well as the novel techniques of its diagnostics and control and data acquisition system, are reported. A synopsis of the experimental activity is also presented.

I. INTRODUCTION

Since 1987 a research and development program in the field of controlled nuclear fusion has been carried out in Portugal within the framework of the European Community Fusion Programme.[1] To fulfill one of its main objectives, the creation of a home laboratory, a small magnetic confinement experiment, the tokamak ISTTOK, was installed at the Instituto Superior Técnico, with the following main purposes:

1. to create an attraction pole for plasma physics postgraduate students in a university environment
2. to provide basic experimental formation in fusion-oriented plasma physics and technology to young physicists and engineers
3. to develop new diagnostic techniques, such as heavy-ion beam probing, fast swept broadband microwave reflectometry, and laser-induced fluorescence
4. to perform a scientific program based on the study of the influence on the plasma parameters of externally applied electric and magnetic signals.

These last two objectives are relevant for the fusion community since the ISTTOK plasma parameters are similar to those of the edge plasmas of large machines.

Construction of ISTTOK was started in mid-1990 reusing some parts of the former TORTUR tokamak[2] [support structure, vacuum vessel, copper shell, toroidal magnetic coils, transformer, capacitor banks, radiofrequency (rf) generator, and discharge cleaning system], which had been decommissioned by the Dutch Euratom Association. The other components of ISTTOK (the vacuum systems, the poloidal windings, and the power supply for the toroidal magnetic coils), as well as its diagnostics and control and data acquisition system, were locally designed and built.

The ISTTOK tokamak has been in operation since February 1993, and some important experimental results[3,4] have been obtained.

This paper is organized as follows. The device is described in Sec. II. Brief descriptions of the diagnostics, as well as of the control and data acquisition system, with particular emphasis on their main novel technological features, are given in Secs. III and IV, respectively. The experimental activity is summarized in Sec. V. Conclusions are presented in Sec. VI.

II. THE TOKAMAK DEVICE

The ISTTOK tokamak is a small-size, large-aspect-ratio, limiter tokamak with an iron core transformer. Its plasmas are characterized by moderate density and temperature and a circular cross section. The experiment parameters are given in Table I. The main tokamak components are described in this section.

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TABLE I

The ISTTOK Main Parameters

Parameter	Value
Vacuum vessel	
Major radius (m)	0.46
Minor radius (m)	0.085
Elongation	1.0
Aspect ratio	5.4
Electrical resistance (mΩ)	60
Maximum baking temperature (°C)	150
Toroidal magnetic field coils	
Maximum magnetic field (T)	3
Electrical resistance (mΩ)	10
Magnetic inductance (mH)	1.88
Flux swing (V·s)	0.25
Operation conditions	
Toroidal magnetic field (T)	0.5
PRECO voltage (kV)	2.0
ELCO voltage (V)	250
Working pressure (Torr)	1.0×10^{-3}
Transformer ratio	40:1

II.A. Vacuum Vessel

The vacuum vessel consists of two circular half tori, each one composed of six rigid sections, manufactured in stainless steel, separated by thin bellows, made of INCONEL alloy 625,[a] with a thickness of 0.15 mm. The two halves of the torus are joined together by means of two viton O-rings.

Connected to the rigid sections, there are 31 ports, which are used to insert the pumping and gas inlet systems, two stainless steel limiters, and the diagnostics.

II.B. Copper Shell

The vacuum vessel is surrounded by a 1.5-cm-thick copper shell, which is electrically insulated up to 12 kV by a 1-mm-thick coating on the inside. The copper shell has two main functions: to support the vacuum vessel and to suppress fluctuations of the plasma position on a timescale shorter than the copper shell skin time (2 ms). It can also be used to hold a water-cooling circuit and to apply high-voltage pulses to the plasma.

The copper shell is positioned and supported by wooden plates. It is divided into eight parts, which can be separated by insulating gaps in the poloidal as well as in the toroidal directions, in order to avoid currents that might be induced by time-varying magnetic fields.

II.C. Vacuum Systems

The main pumping system is composed of a 500 ℓ/s magnetic levitation turbomolecular pump (TMP), backed by a two-stage rotary pump. This system provides a residual pressure of $\sim 1 \times 10^{-9}$ Torr in the vacuum chamber after suitable discharge cleaning procedures. The vacuum chambers of several diagnostics are pumped by conventional TMP systems.

Pressure is measured by standard equipment (pirani and ionization heads). The residual gas composition analysis is performed by a quadrupole mass spectrometer. During a tokamak discharge, the pressure in the main vacuum chamber is measured by a capacitance manometer.

The gas inlet system consists of (a) the gas filling system, controlled by the capacitance manometer and (b) the gas puffing system, which includes a piezoelectric valve directly controlled by the vacuum controller unit described in the next paragraph. This system is used for density control during the tokamak discharge by fast (1-ms) injection of small quantities of gas.

The ISTTOK tokamak has a central vacuum control system that controls the operation of all vacuum units, as well as of some other tokamak components, such as the discharge cleaning system, the cooling system of the toroidal magnetic coils, and the charge circuits of the capacitor banks. This system (Fig. 1) is based on a commercially available vacuum controller unit[b] linked through RS232 to an MS-DOS personal computer (PC), which is also connected to the residual gas analyzer and capacitance manometer through IEEE 488 interfaces.

II.D. Transformer

The iron core transformer has a 2×20 winding primary coil around the central leg of the yoke. An alternative primary coil consists of 2×33 windings located around the torus outside the toroidal coils. The advantage of this primary circuit is that it usually creates also a suitable poloidal magnetic field for high-performance tokamak discharges. There is also an auxiliary primary coil, composed of 20 + 10 windings around the external leg of the yoke, which is normally used for the discharge cleaning operation.

The yoke allows a flux swing of 0.25 V·s. The premagnetization of the iron core is made by feeding the main primary coil with a current provided by a suitable power supply (40 V, 15 A) with a large inductance in series. To decouple this power supply during the main discharge, the current is switched off by means of a gate turn-off thyristor.

II.E. Magnetic Coils and Windings

The toroidal magnetic field is obtained with 24 conventional water-cooled coils, which may generate a maximum B field of ~ 3 T. Because of power limitations, ISTTOK is being operated at lower magnetic

[a]INCONEL is a trademark of the Inco family of companies.

[b]Edwards Controller 2032.

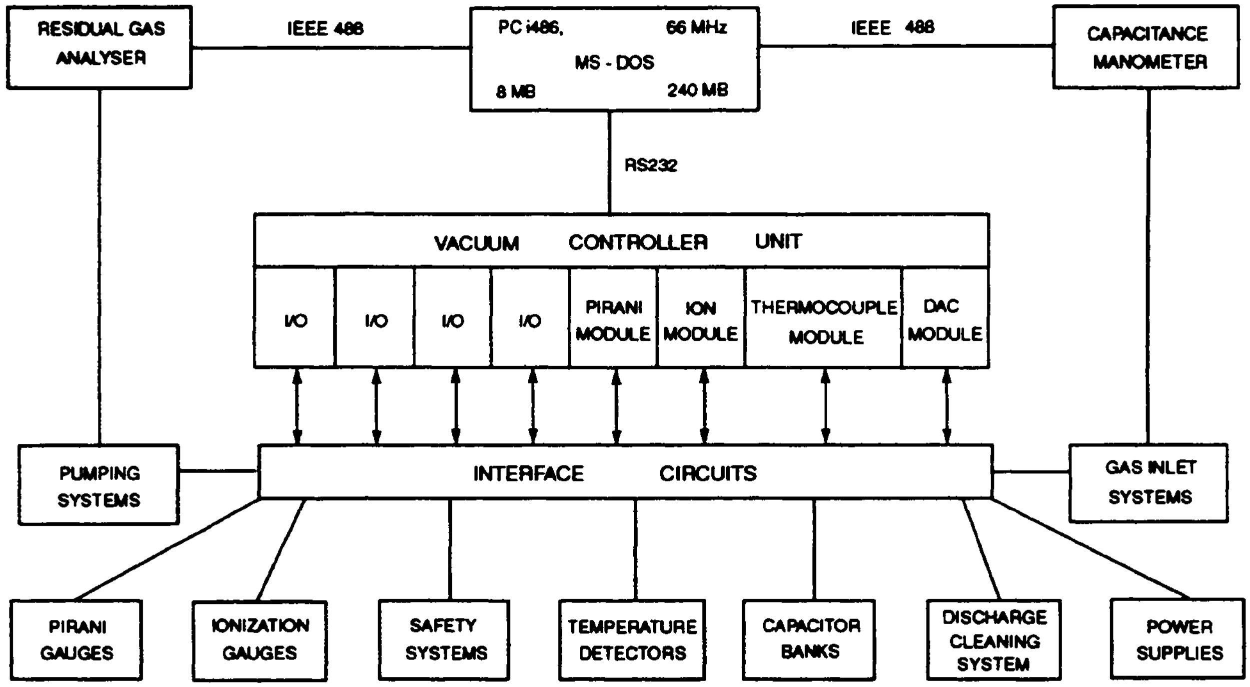

Fig. 1. Block diagram of the central vacuum control system.

fields (0.45 to 0.6 T) produced by currents obtained from the power supply described in the next section.

The external poloidal magnetic field is created by 2×6 windings (horizontal field) and by 4×8 windings (vertical field) inserted between the toroidal coils and the copper shell. As these fields must be proportional to the plasma current, the windings are connected to a section of the electrolytic capacitor bank, hereafter referred to as ELCO, with a set of resistors in series to control the currents. The current for the vertical field is typically on the order of 10% of the primary current.

II.F. Power Supplies

The ISTTOK inductive operation is performed with an rf generator (1.7 MHz, 300 W) for the pre-ionization of the gas, a 1-MW direct-current (dc) power supply for feeding the toroidal magnetic coils, and two capacitor banks: the high-voltage bank (1 mF, 5 kV), hereafter referred to as PRECO, for the predischarge and the ELCO (0.5 F, 500 V) for the control of the discharge duration as well as of the plasma current shape and intensity.

The charge procedures of the two capacitor banks are supervised by the vacuum controller unit. Local automatic units maintain the voltages at the preset values. The discharge circuits are switched on by an ignitron in PRECO and by thyristors in ELCO, which are triggered by optical signals from the central timing system. Both banks have safety circuits for dumping and parking.

The power supply for the toroidal magnetic coils[5] is a 1-MW, 12-pulse, thyristor converter, from 10-kV, 50-Hz, three-phase input provided by the public net to dc currents continuously ranging from 4 to 8 kA. This power supply is operated in a pulsed regime: 4 s on, 3 min off. The system architecture for dodecaphasic rectification is based on the parallel association, through the interphase reactor L_1, of two three-phase double star rectifiers. Each one of these components is provided with one transformer that supplies, through the interface coil L, two three-phase half-wave rectifiers. This power supply was locally developed and relies on a new control concept, which improves the response time and assures global safety. The control of the output current is achieved by comparison with the reference value (I_{ref}) by means of two proportional integral regulators, each one controlling the output current of one double star rectifier (I_Y and I_Δ). Hall effect transducters are used for current measurements, allowing isolation between power and control circuits.

The ripple of the output current is $<1\%$ and the global distortion in the public net is $<1.5\%$. The dc current has a pulsation index on the order of 12 while the harmonics with significant amplitudes at the network side have order numbers >12.

II.G. Discharge Cleaning System

The ISTTOK tokamak is provided with a discharge cleaning system (Fig. 2) for the conditioning of the vacuum chamber by conversion of low-Z impurities (oxygen, carbon) into pumpable components (H_2O and

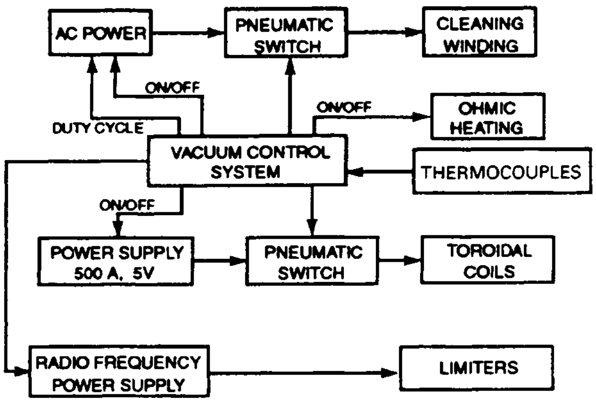

Fig. 2. Block diagram of the discharge cleaning system.

CH_4). Baking of the vacuum vessel up to 150°C is made by (a) external dissipative heating by electrical resistors surrounding its rigid sections and (b) heating by glow or pulsed discharges, in a very low magnetic field (0.0375 T), obtained with an auxiliary power supply (500 A, 5 V). The glow discharges are produced by rf signals applied to the limiters. The pulsed discharges are made by 50-Hz electric current through the auxiliary primary winding of the transformer, using an electronic unit for control of the duty cycle duration.

Usually the discharge cleaning system works (a) 1 or 2 h before the production of tokamak plasmas and (b) during 2 to 5 days after an opening of the vacuum chamber. In the first phase of the discharge cleaning procedure, the chamber is filled with H_2. In the last phase, the gas used is helium because the wall must not act as a reservoir of too much hydrogen, to avoid density limit problems during the tokamak discharges.

III. DIAGNOSTICS

The ISTTOK tokamak is equipped with the following diagnostics (Fig. 3): magnetic and electric probes, a microwave interferometer, a Thomson scattering system, a microwave reflectometer, a spectrometer and a photodiode array for the visible light, and a heavy-ion beam probe. A CO_2 scattering diagnostic, a laser-induced fluorescence system, and three X-ray diagnostics are being commissioned.

Two *Rogowski coils* (each one with 500 windings of 3.25-mm diameter), a set of *sin-cos coils* (each one with 300 windings of 3.2-mm diameter), a *loop*, a set of *magnetohydrodynamic (MHD) coils* [8 in the toroidal direction (101 to 168 deg) and 10 in the poloidal direction (313 deg)], and a radially movable *Langmuir probe* make up the standard diagnostic equipment.

The *one-channel interferometer*[6] has an improved detection system based on a differential quadrature phase concept in a heterodyne configuration (100 and 99.15 GHz are, respectively, the launching signal and the local oscillator frequencies), allowing measurements of the phase variation of less than 1 deg.

The *Thomson scattering diagnostic*[7] was developed aiming at performing simultaneous multipoint, high-resolution measurements in low-density, low-temperature plasmas, along two vertical lines of sight with a single laser pulse. This diagnostic includes the following:

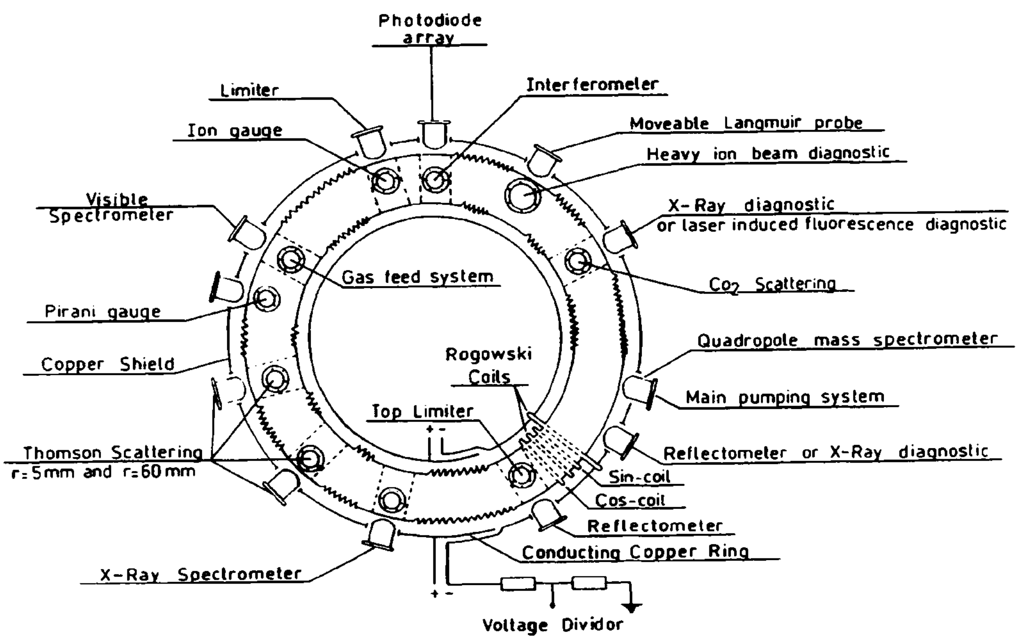

Fig. 3. Schematic drawing of the diagnostic implementation.

1. Two special collection optics, based on combinations of spherical and aspheric lenses, optimized for maximum light throughput.

2. Two stacks of four different length monofibers for sequential transmission of the collected light to the polychromators. The utilization of monofibers instead of fiber bundles is due to the large etendue provided by the aspheric lenses and leads to the increase of the spatial resolution and accuracy of this diagnostic.

3. Two multimonofiber input polychromators, each one with three narrow band dielectric interference filters. Detection is done by high quantum efficiency silicon avalanche photodiodes, placed behind each filter.

4. Specially designed low-noise preamplifiers and amplifiers mounted close to the detectors.

5. A high-power (1-GW) pulsed (25-ns) neodymium:glass laser ($\lambda = 1054$ nm), providing an acceptable signal-to-noise ratio.

6. A data acquisition system based on a digitizing oscilloscope (2 channels, 1 giga sample per second, and 500-MHz bandwidth), controlled by an MS-DOS personal computer, through an IEEE 488 interface.

The three output signals of each polychromator are given, after suitable delays, to the vertical amplifier of the oscilloscope. This unit is triggered by a signal provided by a photodiode placed before the first polychromator filter.

The *microwave reflectometer*[7] operates in the *K* band (16 to 25 GHz), using O-mode wave propagation, in broadband swept frequency for plasma density profile measurements and fixed frequency for the study of radial correlation parameters of density fluctuations. The main technological features of this diagnostic are as follows (Fig. 4):

1. A single antenna for transmission and reception, which has a reduced far field distance to enable measurements in the plasma edge region. The antenna and the directional coupler are placed inside the tokamak vacuum vessel to avoid contributions to the reflected signals from reflections in the vacuum window and from the walls of the access port. The sealing of the

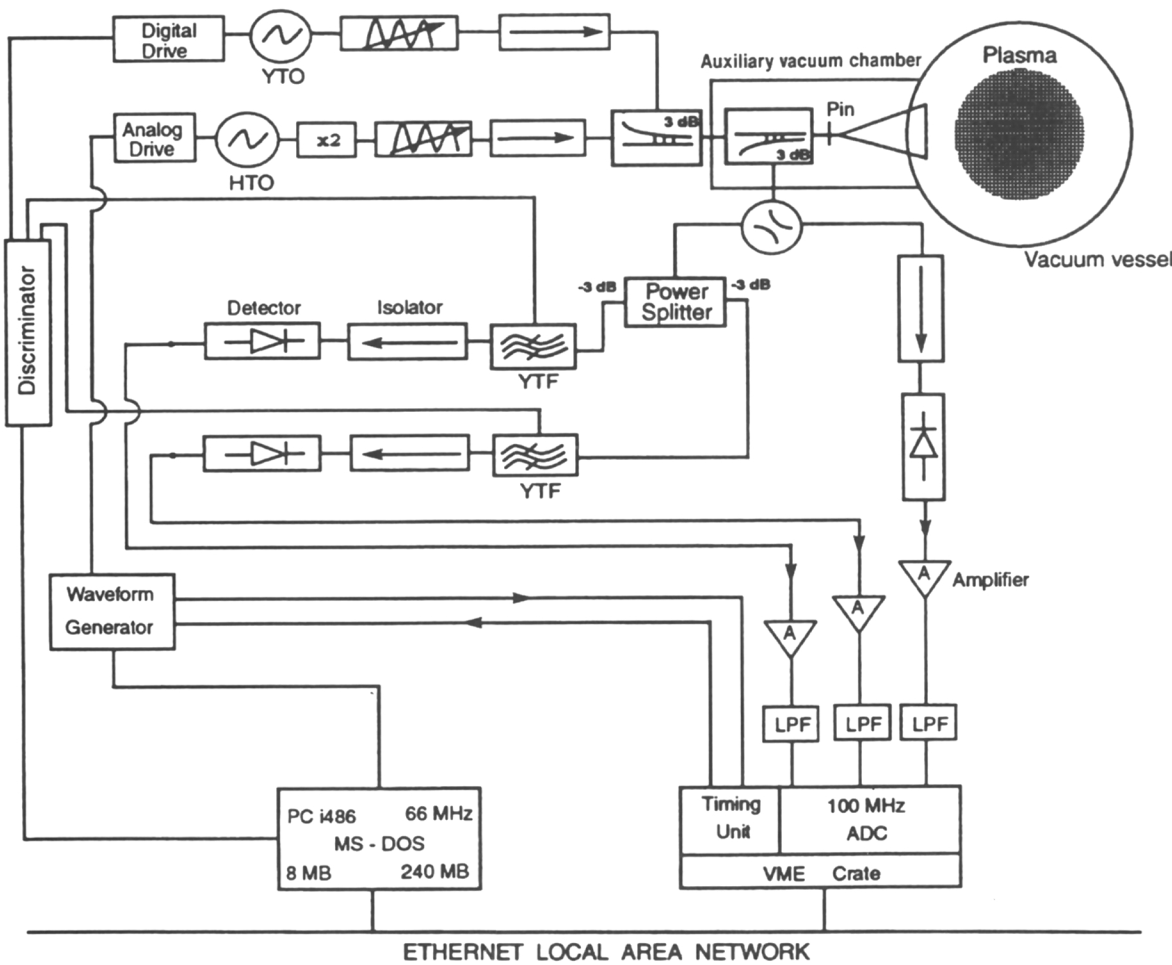

Fig. 4. Block diagram of the microwave reflectometer.

waveguides is made by standard vacuum windows using mica disks with typical attenuation of 0.1 dB.

2. Locally developed analog drives for the hyperabrupt tuned oscillators (HTOs), admitting very fast sweeping times (10 μs), which are important to reduce the influence of plasma density fluctuations. This oscillator is rather insensitive to the magnetic field, allowing its installation close to the tokamak in order to ensure low losses and circuit simplicity.

3. In fixed frequency operation, two signals with different frequencies, provided by an HTO and by a YIG tuned oscillator (YTO), are mixed in a directional coupler, and the resulting signal is launched into the plasma. The reflected signal is divided in two parts: each one is filtered around the incident wave frequency by YIG tuned filters.

4. A homodyne detection system, based on Schottky diode broadband detectors. The reference signal is obtained by reflection of the incident wave in a metallic pin, partially inserted in the waveguide before the antenna.

5. A dedicated control system for the remote choice of the operation mode, signal frequencies, HTO sweeping velocity, and central frequency of the tuned filters. This system is composed of an MS-DOS personal computer connected through RS232 interfaces to (a) an arbitrary waveform generator (AWG), which provides output signals for the control of the HTO analog drive and of the versatile module Europe (VME) digitizers, ensuring the maximum synchronism between the AWG and the analog-to-digital convertors (the AWG is triggered by a signal generated by a VME timing unit) and (b) a discriminator, through an 8031 input/output (I/O) module. The discriminator is linked to a commercially available YTO digital drive and to the tuned filters.

The *spectrometer* for visible light consists of a 1-m Mc Pherson monochromator containing a grating of 1200 line/mm, supplied with an optical multichannel analyzer with temporal resolution of 5 ms and spectral resolution of 0.0117 nm/pixel. This corresponds to a linear dispersion of the monochromator of 0.833 nm/mm and a horizontal pixel dimension of 14 μm. With a suitable optical arrangement, this diagnostic allows measurements of, for example, the central impurity temperatures through the Doppler broadening of the spectral lines (C^{III} at 464.7 nm) and the average intensity of the H_α radiation at the plasma edge.

The *heavy-ion beam diagnostic*[8] has been developed for performing spatial and temporal resolved measurements of the electron density, poloidal magnetic field, and plasma potential. This diagnostic consists of the following parts (Fig. 5):

1. An ion gun,[9] based on a new type of high-density cesium plasma source, connected to a top flange of the tokamak vessel. It provides a thin, low-divergence, elliptical Cs^+ primary beam, with transverse dimensions of 2.0 × 2.7 mm at the injection point and 1 μA at 25 keV.

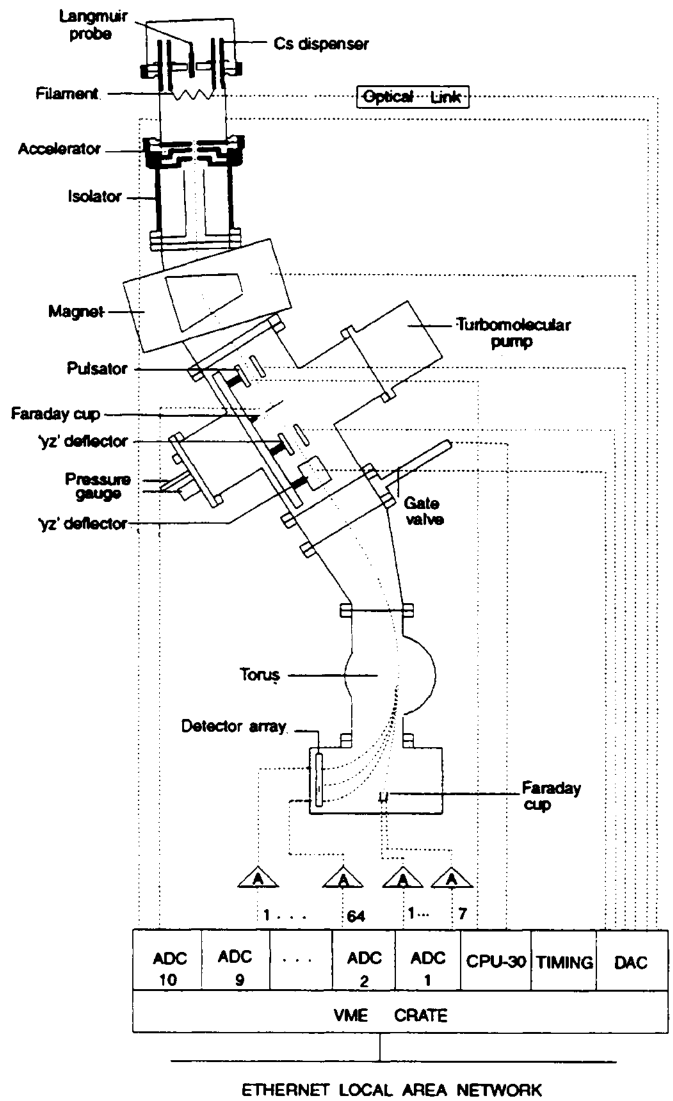

Fig. 5. Block diagram of the heavy-ion beam diagnostic.

2. The detection system, mounted in an auxiliary differentially pumped vacuum chamber connected to the corresponding bottom tokamak flange. It is composed by a Faraday cup set, which collects the primary ions for centering and global attenuation measurements, and by a continuous multiple cell detector for the secondary ions. Each element of the Faraday cup set was built in a stainless steel tube with a 3-mm internal diameter and a length of 15 mm. The multiple cell detector was built as an array (16 × 4) of adjacent copper plates, each one with 2.5 × 5.0 mm^2.

3. A fast control and data acquisition system based on a Motorola 68030 processor as well as on VME timing, waveform generator and digitizer modules.

The *X-ray diagnostic set* consists of the following:

1. one X-ray spectrometer, based on an UltraLeGe detector with good efficiency in the range from 300 eV to 300 keV and high resolution (150 eV to 6.4 keV), for impurity analysis and runaway detection by multichannel analysis
2. two X-ray systems for electron temperature measurement and MHD activity analysis, based on recently developed passivated implanted plasma (PIP) silicon detectors.

A *diagnostic using a dye-laser* is being commissioned for the measurement of spatially resolved ion temperature and plasma rotation velocity, by laser-induced fluorescence, and line-integrated impurity densities, via enhanced stimulated emission in the beam direction.[10]

A new configuration of a *CO_2 scattering diagnostic* is being developed to determine the spectrum of the plasma density fluctuations in the region of low wave numbers.[11] The main technological feature of this diagnostic is an optical arrangement called dual waist, which creates two parallel laser beams. Information about structure with wavelength of the order of the distance between the observed points is taken from the detector current, which is proportional to the scattered fields from the two different plasma volumes.

IV. CONTROL AND DATA ACQUISITION SYSTEM

The control of the ISTTOK operation, as well as the acquisition of the signals from the engineering and physics diagnostics, is carried out by a fully computerized system (SCAD), designed complying with the requirements of the ISTTOK operation and research program, in a distributed, modular, multivendor, integrated, and transparent approach.[12] Interfacing between the computers and the tokamak components is accomplished using, as much as possible, locally developed VME instrumentation (Table II).

Figure 6 shows a block diagram of the current configuration of the SCAD hardware. Connections between the control and data acquisition units and the ISTTOK operation components and diagnostics are also depicted.

The computer system consists of two 80486 PCs, two 80386 PCs, two CPU-30 (Motorola 68030) boards, and one workstation, linked by an ethernet local area network, physically implemented by thin-wire cables and by a NOVELL server. The multivendor character of the SCAD hardware leads to the existence of the following operating systems: MS-DOS (PCs), OS-9 (MC68030), and UNIX (workstations). The following standardized protocols were adopted for transparent communications: IPX/SPX, between PCs in a NOVELL environment and TCP/IP, for integration of UNIX and OS-9 computers. At a higher level, the compatibility of all systems is obtained by common network file system services.

Control is performed by the vacuum controller unit referred to in Sec. II.C, as well as by digital I/O, timing, and waveform generator VME modules. The tokamak components and the control units are connected by optical fibers. Data acquisition is provided by VME instrumentation, as well as by PC-based modules and by a digitizing oscilloscope.

Software, which has been developed mainly in C language, includes the central database and three main programs, which provide the operator interface and the ISTTOK general operation, the operation of each subsystem, and the access to the central database.

V. EXPERIMENTAL ACTIVITY

The highest plasma parameters obtained so far in independent discharges are the following: plasma current $I_p \simeq 11$ kA, discharge duration $\tau_d \simeq 70$ ms, central

TABLE II

The ISTTOK VME Modules

Type	Channels Number	Channels Type[a]	Resolution (bit)	Frequency (MHz)	Total Memory (k words)
Timing	16	I	1 μs	1	---
Waveform generator	8	I	12	1	64
Digitizer	2 × 32	M	12	0.333	32
Digitizer	4	I	12	20	64
Digitizer	8	I	12	0.333	32
Digitizer	4	I	8	100	16
Multichannel analyzer	4096	---	---	0.08	64+64

[a]I = independent, and M = multiplexed.

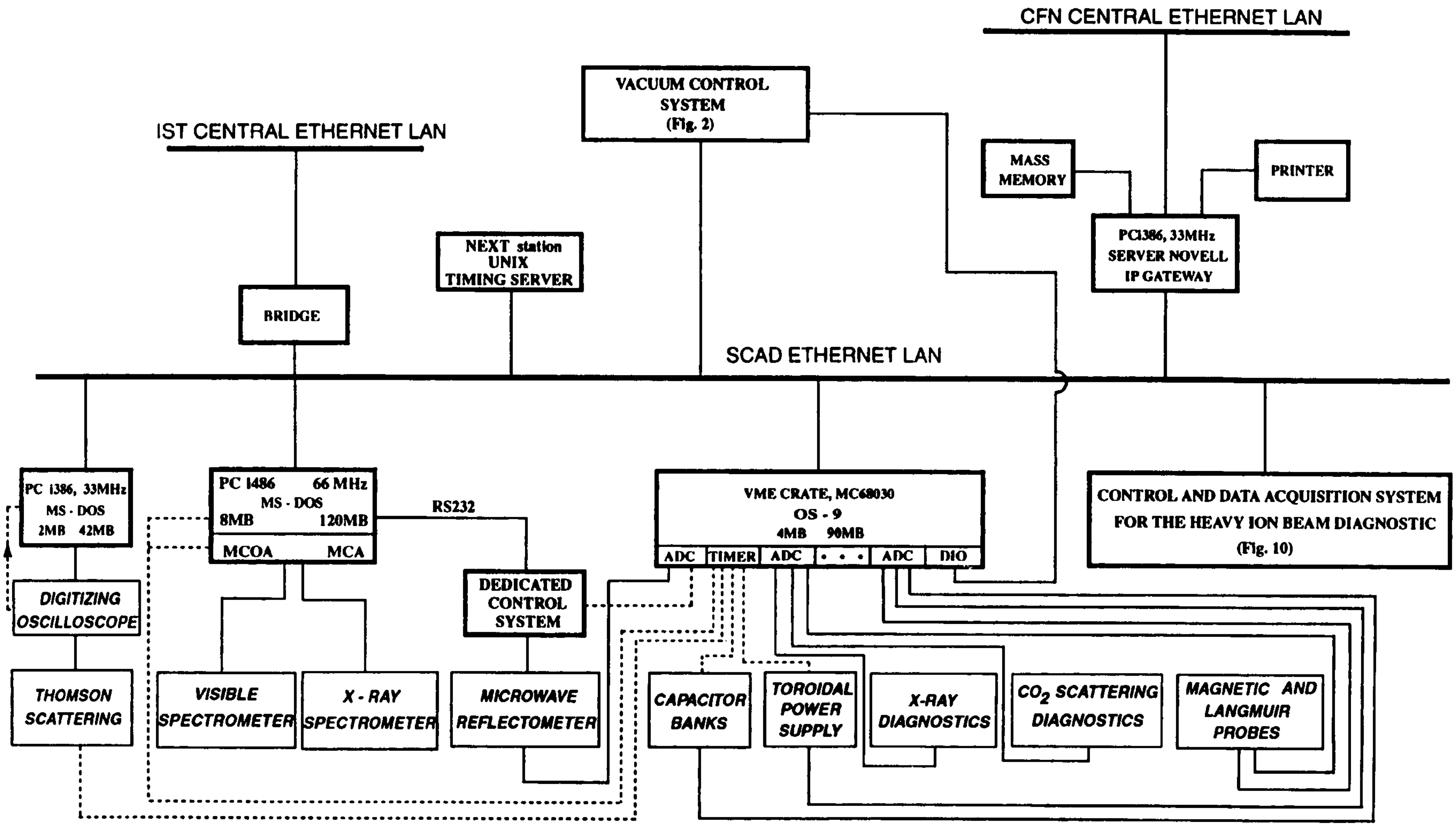

Fig. 6. Block diagram of the current configuration of the SCAD hardware. Connection between the control and data acquisition units and the ISTTOK operation components and diagnostics are also depicted. Dashed lines represent trigger connections.

plasma density $n_e(o) \simeq 1.2 \times 10^{19}\ m^{-3}$, central electron temperature $T_e(o) \simeq 250$ eV, central ion (C^{III}) temperature $T_i(o) \simeq 400$ eV, energy confinement time $\tau_E \simeq 1.5$ ms, $\beta = 0.6\%$, and safety factor $q(o) \simeq 0.95$ and $q(a) = 3.0$.

The main experimental results already obtained are (a) the observation in rather stable discharges ($I_p \simeq 7$ kA, $\tau_d \simeq 50$ ms) of a kind of ohmic H mode when the limiter is positively biased and of confinement degradation with negative biasing[3] and (b) the determination of the temporal evolution of the plasma density profile with the heavy-ion beam diagnostic in sawtooth-like discharges. Flattening of both n_e and T_e profiles were observed two confinement times after the sawtooth crash within the so-called mixing radius.[4]

For the future, the following activities are foreseen:

1. analysis of the detailed temporal evolution of the poloidal magnetic field profile by heavy-ion beam probing
2. study of the nonlinear space-time evolution of vortices produced in the plasma periphery
3. control of the $m = 2$, $n = 1$ MHD mode
4. study of the plasma confinement in alternating discharges
5. analysis of transport phenomena by laser-induced fluorescence techniques.

VI. CONCLUSIONS

The ISTTOK successful operation for 2 yr has shown the reliability of the tokamak components, diagnostics, and control and data acquisition systems. The results already obtained allow us to conclude that the design requirements, established with regard to the research program, have been met.

Among the novel technological aspects of the ISTTOK design, we mention the development of the following:

1. a 1-MW, 12-pulse, two-quadrant, thyristor converter for feeding the toroidal magnetic coils
2. a differential quadrature phase detection system in an heterodynic configuration on the 100-GHz microwave interferometer
3. special homemade drivers for the microwave reflectometer oscillators, allowing full band sweeping in 10 μs
4. a compact three-channel Thomson scattering diagnostic, based on a time-delay technique using monofibers and special collection optics
5. a data acquisition system for the output signals of the Thomson scattering polychromators based on digitizing oscilloscopes and time-delay techniques
6. a 1 μA–25 keV cesium ion beam source and a multiple cell detector for the secondary ions of the heavy-ion beam diagnostic
7. a new configuration of a CO_2 scattering diagnostic based on a dual waist optical arrangement
8. a safety and slow control system based on a commercial vacuum controller unit
9. innovatory timing, waveform generator, and digitizer VME modules for the interface between computers and technical as well as physics diagnostics.

ACKNOWLEDGMENTS

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REFERENCES

1. C. A. F. VARANDAS, J. A. C. CABRAL, M. E. MANSO, and F. SERRA, "The Portuguese Research Programme in Controlled Nuclear Fusion," *J. Fusion Energy* (accepted for publication).

2. H. DE KLUIVER, C. J. BARTH, and A. J. H. DONNÉ, "Current Driven Turbulence and Microturbulent Spectra in the TORTUR Tokamaks," *Plasma Phys. Control. Fusion*, **30**, *6*, 699 (1988).

3. J. A. C. CABRAL et al., "Limiter Biasing Experiments on the Tokamak ISTTOK," *Proc. 20th Conf. Controlled Fusion and Plasma Physics*, Lisbon, Portugal, July 26–30, 1993, Vol. 17C, Pt. III, p. 147, European Physical Society, Geneva (1993).

4. J. A. C. CABRAL, A. MALAQUIAS, A. PRAXEDES, and C. A. F. VARANDAS, "Plasma Density Profile Evolution by Heavy Ion Beam Probing on the Tokamak ISTTOK," *Proc. Int. Conf. Plasma Physics*, Foz do Iguaçu, Brazil, October 31–November 4, 1994, Vol. 1, p. 265, INPE/Sector de Eventos, São José dos Campos, São Paulo, Brasil (1994).

5. J. SANTANA, V. L. MONTEIRO, V. ANUNCIADA, J. C. LAMEIRA, and C. A. F. VARANDAS, "A 1 MW Power Supply for the ISTTOK Toroidal Coils," *Electricidade*, **309**, 94 (1994) (in Portuguese).

6. S. VERGAMOTA et al., "The Microwave Interferometer for the Tokamak ISTTOK with Differential Quadrature Phase Detection," *Rev. Sci. Instrum.* (accepted for publication).

7. C. A. F. VARANDAS et al., "Technological Features of Some ISTTOK Diagnostics," *Proc. 17th Symp. Fusion Technology*, Rome, Italy, September 14–18, 1992, Vol. 2, p. 1532, Elsevier Science Publishers, Amsterdam (1992).

8. J. A. C. CABRAL, A. MALAQUIAS, A. PRAXEDES, W. VAN TOLEDO, and C. A. F. VARANDAS, "The Heavy Ion Beam Diagnostic for the Tokamak ISTTOK," *IEEE Trans. Plasma Sci.*, **22**, *4*, 350 (1994).

9. J. A. C. CABRAL et al., "Development of a New Type of Cs Plasma Ion Gun for Application in a Heavy Ion Beam Tokamak Diagnostic," *Plasma Sources Sci. Technol.*, **3**, *1* (1994).

10. P. H. M. VAESSEN, C. A. F. VARANDAS, and J. A. C. CABRAL, "Ion Temperature Diagnostic by Means of Laser Induced Fluorescence; Line Integrated Impurity Content by Means of Directionally Enhanced Stimulated Emission," *Proc. Int. Conf. Lasers*, Lake Tahoe, California, December 6–9, 1993, p. 334 (1993).

11. R. GUERRA, J. A. MENDANHA DIAS, P. H. M. VAESSEN, and J. T. MENDONÇA, "Spatial Correlation Techniques Using Scattering of CO_2 Laser Beam," *Proc. 21st Conf. Controlled Fusion and Plasma Physics*, Montpellier, France, June 27–July 1, 1994, p. 394, European Physical Society, Geneva (1994).

12. C. A. F. VARANDAS et al., "A Fully Computerized and Distributed VME System for Control and Data Acquisition on the Tokamak ISTTOK," *Nucl. Instrum. Methods Phys. Res., Sec. A*, **349**, 547 (1994).

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