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Tokamak Research at University of São Paulo

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The main results obtained in the small tokamak TBR-1 of University of São Paulo (USP) are reviewed. The main effort has been concentrated on the characterization and external control of MHD activity, plasma edge phenomena and diagnostic development. The design of a small-aspect-ratio tokamak, TBR-E, and the research program to be carried out in TCA, to be transferred from Lausanne to São Paulo, are also briefly described.

KEY WORDS: Tokamak; plasma edge phenomena.

1. INTRODUCTION

Research in Plasma Physics is a relatively recent activity in Brazil. Although some sporadic work was carried out already in the fifties,[(1)], the first research groups were organized in the mid-seventies. The Plasma Physics Laboratory of USP was founded in 1977 by a group of experimental nuclear physicists interested in starting fusion research in Brazil. The strategy to initiate the group and attract graduate students was to design and construct a small research tokamak that could provide a good opportunity to get acquainted with the main experimental techniques relevant for fusion research. With the collaboration of a plasma physicist from the State University of Campinas and another from the University of Sydney, Australia, the group completed in 1978[(2)] the design of a small tokamak, TBR-1, and obtained the first shots in the device in April 1980.[(3)]

The initial plan was to carry out experimental work in TBR-1 for 2–3 years, mainly to train graduate students and get experience on tokamak operation, and then design and construct a middle size tokamak in which a more scientifically ambitious research program could be pursued. Unfortunately, although the activities developed around TBR-1 were rather successful, with training of many graduate students and publication of some scientific papers in international journals, it was not possible to get financial support for the next device TBR-2. We have then decided to improve the performance of TBR-1 and establish a fusion-relevant research program that could be carried out in such a small tokamak. The main improvements in the device were to elongate the pulse, add a system of external helical widings, and develop a feedback system for the vertical equilibrium field and a PC-based data acquisition system. The research program concentrated mainly on the characterization and control of MHD activity and study of plasma edge phenomena.

A few years ago, the Plasma Physics Laboratory of USP received financial support to conduct the conceptual design of a middle-size tokamak, to be built in Brazil. After completing the design of a standard device, TBR-2[(4)] with aspect ratio $R/a = 2.5$, major radius $R = 0.56$ m, the group decided to work on the design of a more ambitious device, in which the aspect ratio could be varied in the range $1.5 \leq R/a \leq 2.0$, to test the concept of the spherical tokamak put forward by Martin Peng.[(5)] The conceptual and basic engineering design of the device, named TBR-E, was finished in 1991, in collaboration with the State University of Campinas and the National Institute for Space Research.[(6)] Unfortunately,

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once again it was not possible to obtain financial support to actually build TBR-E. We have then decided to accept an offer of Professor Francis Troyon, from École Polytechnique Fédérale de Lausanne, to transfer the TCA tokamak to São Paulo. The machine is scheduled to arrive in Brazil by the end of 1993 and it will take at least one year to put it back into operation. Although Alfvèn heating and current-drive has not yet been convincingly demonstrated in TCA or any other tokamak, it is obvious that this auxiliary scheme can be very important in a fusion reactor.(7) We plan therefore to carry on the research on this topic in TCA, exploiting new ideas on antenna design, impurity control, and synergetic effects with electron cyclotron heating.

2. DESCRIPTION OF TBR-1

The main parameters of TBR-1 (Tokamak Brasileiro - 1) are listed in Table I and a picture of the device is shown in Fig. 1. The ohmic heating transformer and the toroidal and vertical field coils are powered by capacitor banks. The toroidal field coil system is divided into eight sectors, each with 14 turns.

The vacuum vessel is made of four 304L stainless steel elbows of 3.2 mm wall thickness. Eighteen access ports are available, including a pair of straight line-of-sight tangential ports, providing a total area of 410 cm^2 for diagnostic and pumping. Viton O-rings are used for seals and to provide two voltage breaks in the toroidal direction. A base pressure of 5×10^{-7} Torr is attainable with a 450 ℓ/s turbomolecular pump. The time evolution of the main parameters in a typical discharge is shown in Fig. 2a. The filling pressure is usually around 10^{-4} Torr and there is no active control of the plasma density, which decays with time from its peak value at breakdown, as shown in Fig. 2b. Recently a feedback control system that keeps the horizontal plasma position within ± 2 mm has been installed.

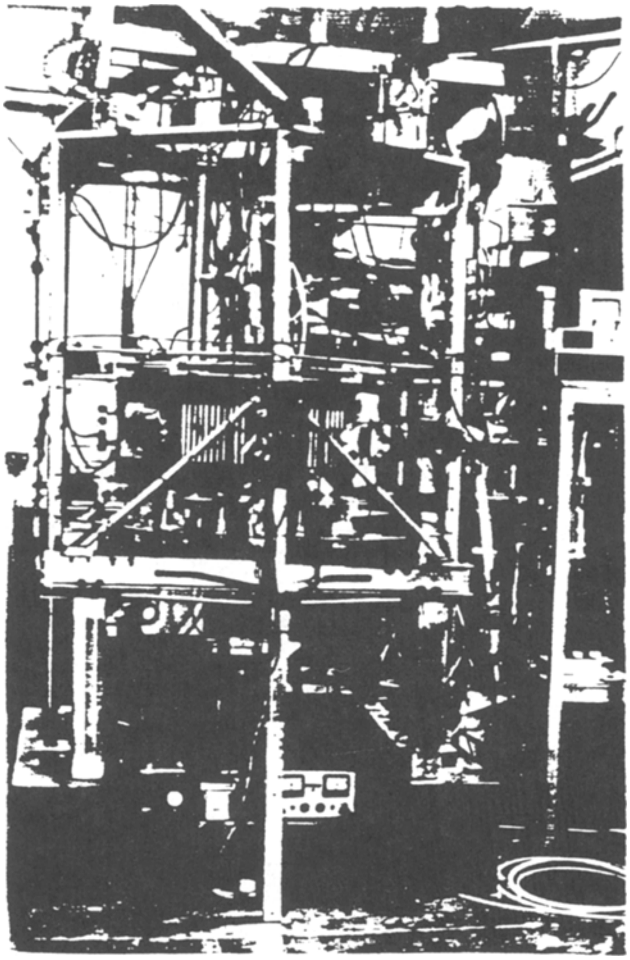
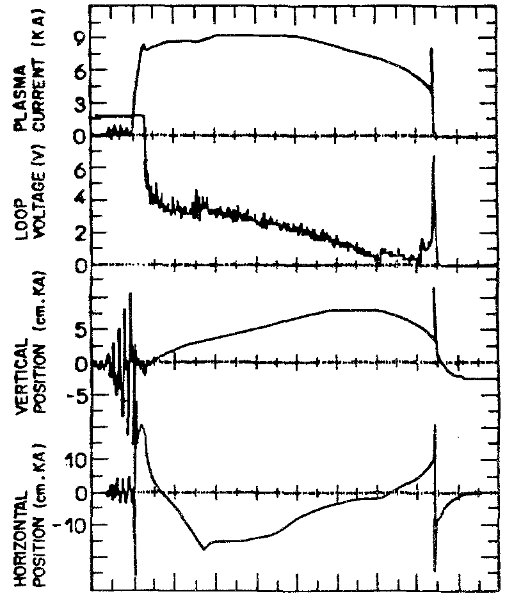


Fig. 1. Picture of the TBR-1 device.

Table I.

Main Parameters of TBR-1		
Major radius	R(m)	0.30
Vessel radius	a_v(m)	0.11
Plasma radius	a(m)	0.08
Toroidal field	B_T(T)	0.5
Plasma current	$I_{p,MAX}$(kA)	12
Cylindrical safety factor	q_c	4.4
Central electron temperature	T_{eo}(eV)	200
Central electron density	n_{eo}(m^{-3})	7×10^{18}
Pulse duration	τ_p(ms)	7 − 9
Filling pressure	p(Torr)	10^{-4}

Besides the standard electromagnetic signals (Rogowskii coil, voltage loop, in-out position coils, Mirnov coils etc.), the basic diagnostic systems in the device are a one-channel 4 mm microwave interferometer, soft and hard X-rays, and spectroscopy. The central electron temperature is only approximately evaluated using the absorber filter method for soft X-rays.(8) The data acquisition system is based on CAMAC modules and personal computers.(9) Raw data are stored and the main traces are pre-processed between shots. The plasma equilibrium configuration is reconstructed using a hybrid technique. First the plasma boundary is obtained from the magnetic signals in pick-up coils by modelling the plasma as current filaments. The position of the current centroid is initially determined minimizing the modulus of the difference between the measured fields and the field pro-



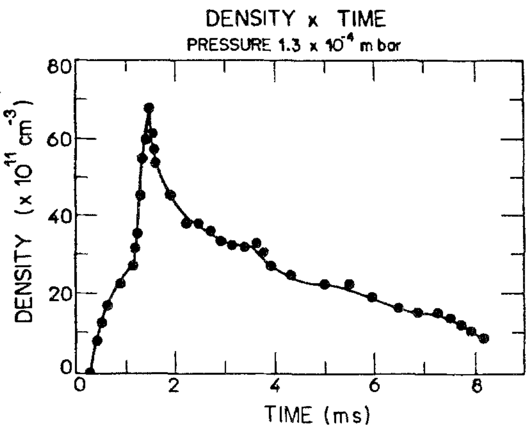


Fig. 2. Time evolution of the plasma current, loop voltage and vertical and horizontal position of a typical discharge in TBR-1 (a); time evolution of the plasma density (b).

duced by a single current filament with the total plasma current. Having the current centroid, the positions and the current in two other filaments with zero total current are determined minimizing the residual differences. The plasma boundary is then identified with the last closed field line, produced by the current filaments, that touches the limiter in one point. The magnetic flux surfaces are obtained solving the Grad–Shafranov equation with fixed boundary subject to the constraints of fixed total current and maximum plasma pressure obtained from other diagnostic systems. A more sophisticated system, based on function parametrization,[10] is currently being developed.

3. CHARACTERIZATION AND CONTROL OF MHD ACTIVITY

The disruptions caused by MHD modes are one of the major problems for the tokamak approach to fusion reactors. Minor disruptions in the discharge lead to enhanced particle and energy transport and major disruptions may lead to serious mechanical damage to the vacuum vessel and support structure. Therefore, the discharges in large devices are usually programmed to avoid disruptions which, however, can be rather safely investigated in small devices. In TBR-1 there is a set of external helical windings wound around the vacuum vessel in such a way that, by combining different windings, helical perturbed fields with toroidal mode number $n=1$ and poloidal mode number $m=2,3$, or 4 can be produced. The windings can be used to excite or to detect perturbed magnetic fields. The Fourier spectra of each m/n helical winding arrangement is given in Ref. 11. Using the Mirnov coils and the helical windings, a thorough study of the MHD activity and its control has been carried out in TBR-1.

Since most of the discharges in TBR-1 have $q(a) > 4$, there are many rational surfaces inside the plasma. We have verified that the minor disruptions are due to partial island overlap of the modes excited at different rational surfaces.[12,13] In Fig. 3 we show the traces of a discharge with a series of minor disruptions before the major disruption. A Fourier analysis of the oscillations of the poloidal magnetic field indicated that the $m/n = 2/1$ and $3/1$ were the dominant precursor modes associated with the minor disruptions. The amplitudes of these components were measured 50 μs before and at the moment of the minor disruption indicated in Fig. 3e. The associated Poincaré maps were obtained by integrating the field line equation, representing the perturbed field as a linear superposition of the equilibrium and 2/1 and 3/1 perturbing fields created by helical surface current densities localized on the corresponding unperturbed rational surfaces and distributed according to the measured mode numbers. It is clear that although the 2/1 and 3/1 islands are not entirely destroyed, there is a great enhancement of the stochastic region, giving rise to a partial relaxation of the discharge.

The major disruptions in TBR-1 are sometimes connected with a coupling between the $m/n = 1/1$ (detected by soft X-rays) and 2/1 modes. The precursor 1/1 and 2/1 modes grow in amplitude and lock their frequence just before the major disruption.[13] A similar mechanism has been observed more recently in large devices[14] and modeled theoretically.[15]

The partial control of major disruptions by external

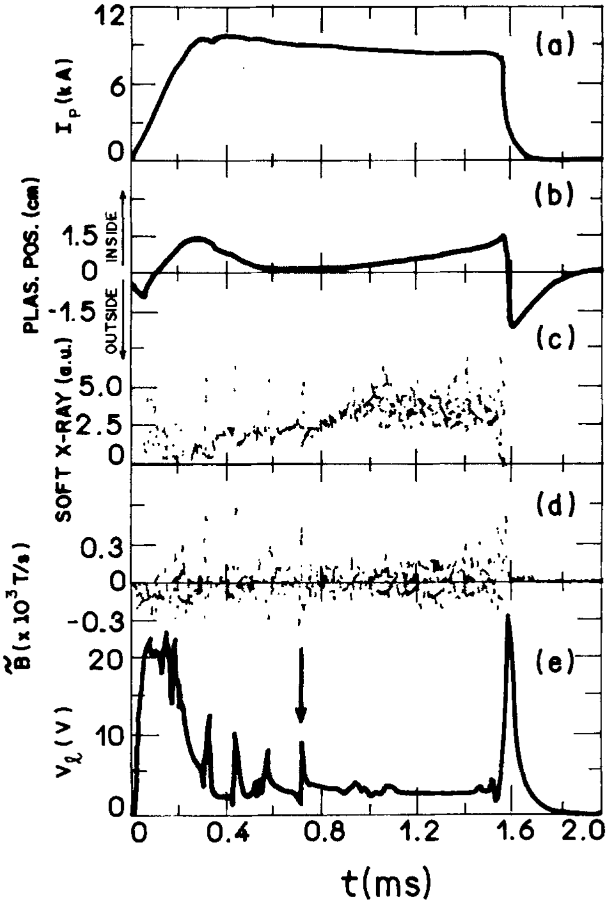


Fig. 3. Discharge with a sequence of minor disruptions observed in the soft X-ray emission (c), magnetic loop (d), and loop voltage (e) signals. The arrow indicates the disruptive event discussed in the text.

helical windings was first achieved by Karger and collaborators in Pulsator.[16] We have carried out a detailed investigation of the influence of the external helical windings on the MHD activity for different plasma conditions and mode numbers. In Fig. 5 we show a 11 kA discharge with the activation of a 2/1 helical winding with 400 A for 50 μs. After a time delay of a few microseconds, due to finite penetration time through the vacuum vessel, the amplitude of the 2/1 Mirnov oscillations is considerably attenuated. Soon after the current in the helical winding is switched off, the amplitude of the Mirnov oscillations recovers its original level. Using an innovative analysis based upon the wavelet transform, we have also determined how the amplitude of the side band modes are attenuated and the correlation between different modes.[17]

Discharges with an ergodic magnetic limiter can also be produced in TBR-1 by having a value of $q(a)$ slightly below six and exciting the $m/n = 4/1$ external helical winding. We observe that there is a reproducible decrease in the absolute value of the (negative) floating potential at the plasma edge of the order of 15–20%, which can be explained by an enhancement of the outward flux of particles in the enlarged scrape-off layer.[18]

The perturbed magnetic field in tokamaks is an example of almost integrable dynamical systems, with resonances in several rational magnetic surfaces. Thus, theoretical concepts such as perturbed average KAM surfaces,[19,20] and onset of chaos[21] have been applied to interpret TBR-1 experiments on natural or externally induced MHD activity.

4. PLASMA EDGE STUDIES

The characteristic parameters and transport properties of the plasma at the edge of the discharge column in TBR-1 have thoroughly been also investigated. The toroidal field ripple is quite large in this region and therefore our attention was initially concentrated on ripple-induced collisional transport.[22] However, we soon found out that turbulent transport was more relevant and most of our recent activity has been on this topic.

The diagnostic of the plasma edge is based upon electrostatic probes, spectroscopy, and measurement of H_α light emission from the limiter. A reliable electrostatic probe has been developed which allows simultaneous measurement of the electron and ion temperatures in the scrape-off layer.[23] We find that in all shots the ion temperature is larger than the electron temperature; the ratio T_i/T_e is as large as 2.2 ± 0.6. The electron density and temperature decay exponentially at the plasma edge with characteristic lengths given respectively by $\lambda_n = 1.4$ cm and $\lambda_T = 2.6$ cm. Using the scrape-off model of Stangeby[24] we find that the cross-field particle diffusion coefficient is $D\perp \approx 5.8\ m^2/s$ and the electron thermal diffusivity is $\chi\perp \approx 8.3\ m^2/s$.[25] The value of the diffusion coefficient is somewhat above the value predicted by the Bohm model, i.e., $D_B \approx 1.3\ m^2/s$ but quite close to the value predicted by the ALCATOR-INTOR scaling[26] $D\perp \approx 10^{19}/\bar{n} \approx 4.5/m^2/s$.

The particle confinement time was also measured using two other independent techniques: measuring with probes the flux to the limiter and vacuum vessel and measuring the H_α radiation from the limiter and three other regions equally spaced in the toroidal direction. We obtain $\tau_p = 1.4 \pm 0.4$ ms for a density $\bar{n} \approx 3 \times 10^{18} m^{-3}$. Varying the density, the particle confinement time first increases to this value and then decreases

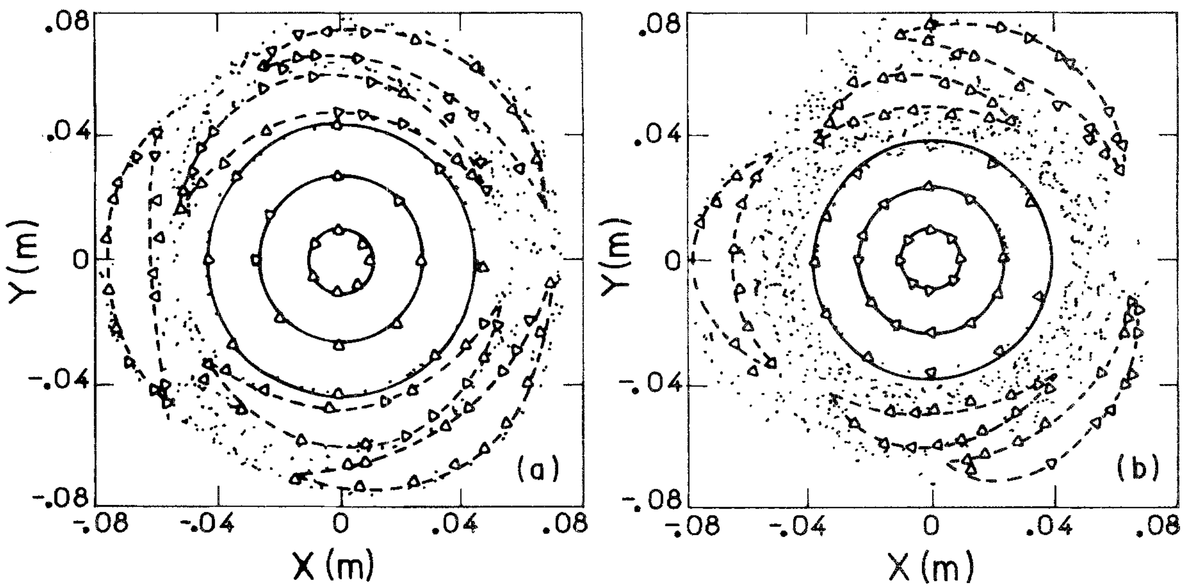


Fig. 4. Intersection of the magnetic field lines with a poloidal plane 50 μ (a) and at the instant (b) of the minor disruption indicated in Fig. 2.

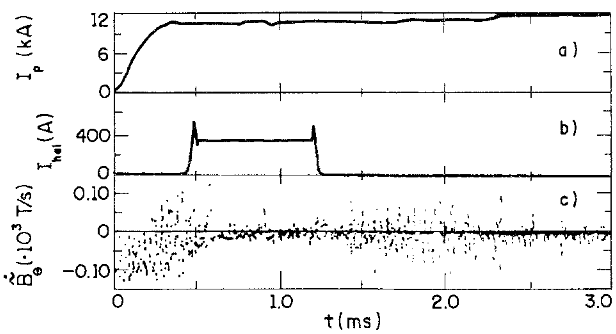


Fig. 5. Temporal profiles of the plasma (a), and 2/1 helical windings (b) currents during a discharge in TBR-1. The MHD activity in the same discharge is shown (c).

slowly and monotonically, reaching a value $\tau_p = 0.7$ ms at $\bar{n} \approx 5 \times 10^{18}$ m^{-3}.[27]

The ratio $\chi_\perp/D_\perp \approx 1.4$ estimated from the measurements based upon a diffusive model suggests that the turbulent transport at the plasma edge is mainly electrostatic. Therefore a careful study of the electrostatic fluctuations and the induced cross-field transport has been carried out in TBR-1. The radial profiles of the relative density, $\tilde{n}/\bar{n}$, and the floating potential, $e\,\tilde{\phi}\,/kT_e$, fluctuations are shown in Fig. 6a.[28] It is clear that these fluctuations do not follow the adiabatic hypothesis $\tilde{n}/\bar{n} \approx e\,\tilde{\phi}\,/kT_e$. The fluctuations were measured with a set of four single Langmuir probes (separated both toroidally and poloidally by 2 mm, allowing therefore good space resolution) located at the top of the tokamak along the plasma centerline. To obtain $\tilde{n}$ and $\tilde{\phi}$, the temperature fluctuations were neglected. The diffusion coefficient estimated from the nonlinear flux, $\Gamma = \langle \tilde{n}\tilde{v}_r \rangle$, is also above the value predicted by the Bohm model, in agreement with the diffusive measurements. The particle transport spectrum at $r/a = 0.99$ is shown in Fig. 6b. High-frequency magnetic oscillations were also measured with magnetic probes which detect modes with poloidal mode number $m \leq 30$. The relationship between the electrostatic and magnetic fluctuations has been investigated by computing the cross-correlation and coherence γ between the corresponding signals. The coherence is small, $\gamma \leq 0.3$, but presents a peak around 50 *kHz* indicating that high-frequency MHD activity may modulate the density and floating potential fluctuations at the plasma edge of TBR-1.[28]

5. TBR-E AND TCA

The small size and the low densities and temperatures achievable in TBR-1 severely restrict the options for a relevant research program. Furthermore, although it has been aging rather graciously, the effects of many years of continuous operation are quickly showing up in

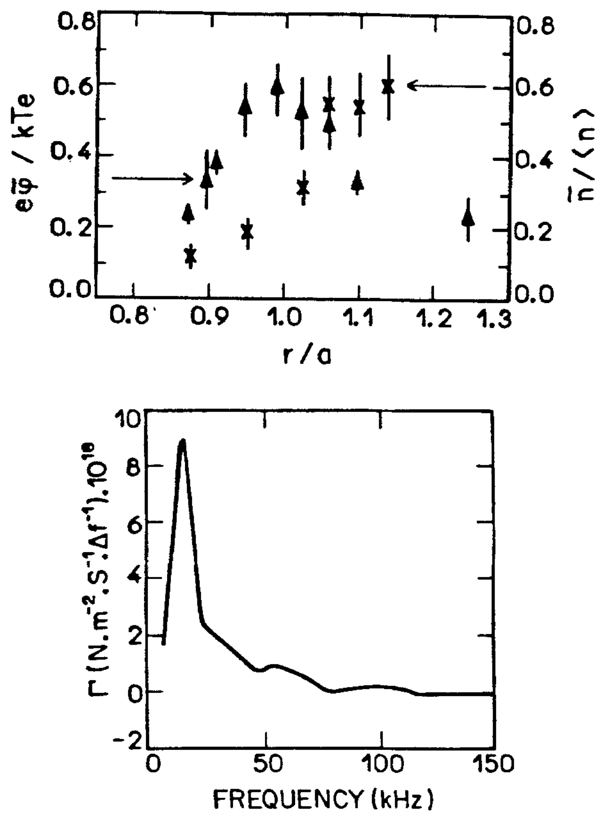


Fig. 6. Radial dependences of the normalized rms fluctuating amplitudes of potential and density (a) and the corresponding particle transport spectrum at $r/a = 0.99$ (b).

Table II.

Main Parameters of TBR-E

		Aspect ratio	
		1.5	2.0
Major radius	R(m)	0.39	0.50
Half width	a(m)	0.26	0.25
Elongation	b/a	1.6	1.7
Triangularity	δ	0.3	0.3
Plasma volume	V_p(m^3)	0.8	1.0
Maximum toroidal field	B_T	0.8	0.63
Plasma current	I_p(kA)	240	140
Cylindrical safety factor	q_c	2.3(B_T = 0.36 T)	5.1
Power requirements:			
Ohmic heating system	P_{OH}(MW)	20.6	20.6
Toroidal field system	P_{TF}(MW)	14.3	14.3
Poloidal field system	P_p(MW)	2.0	2.0

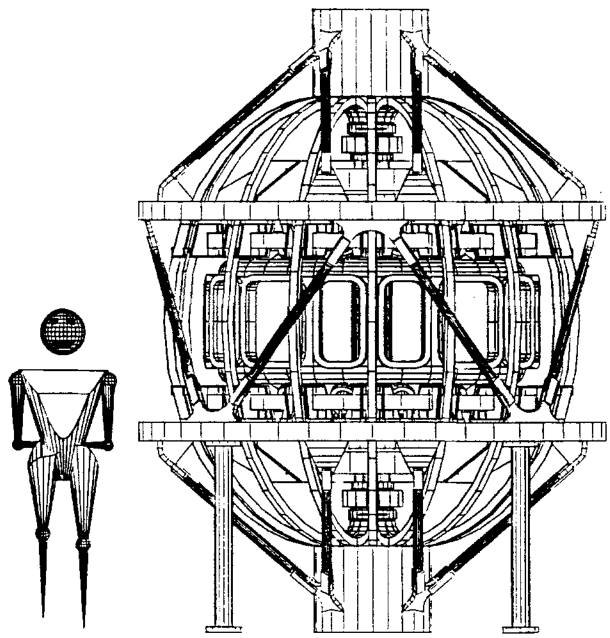


Fig. 7. Computer sketch of the TBR-E device produced with the KATIA CAD system.

TBR-1. Therefore, in the last 4 years we have been working on the design of a device to substitute TBR-1.

After working on the design of a standard tokamak, we decided that to produce relevant results with our limited resources we should follow a more bold approach. We have then developed, in collaboration with the plasma groups of the University of Campinas and the National Institute for Space Research, the design of a compact tokamak in which the aspect ratio could be varied from $R/a = 1.5$–2.0, with almost fixed elongation and constant toroidal field.[6] The main objective of the experiment would be the characterization of the equilibrium, stability, and energy confinement performance of the discharges as a function of the aspect ratio. The main parameters of TBR-E (Tokamak Brasileiro, Esférico) are listed in Table II, and a computer sketch of the device, designed using the KATIA CAD system is shown in Fig. 7.

The operational regimes for TBR-E equilibria were investigated using the SELENE-J transport code.[29] The collisionality parameter and the ratio between the neoclassical and Spitzer resistivity for a typical equilibrium with $A = 1.5$ and $\langle T \rangle = 600\ eV$ are shown in Fig. 8. It is clear that even for this low temperature most of the plasma is expected to be in the low collisionality regime. Therefore results obtained in TBR-E, in particular the confinement scaling, would extend the tokamak data basis to low aspect ratio in conditions physically equivalent to the ones achieved in large tokamaks. On the other

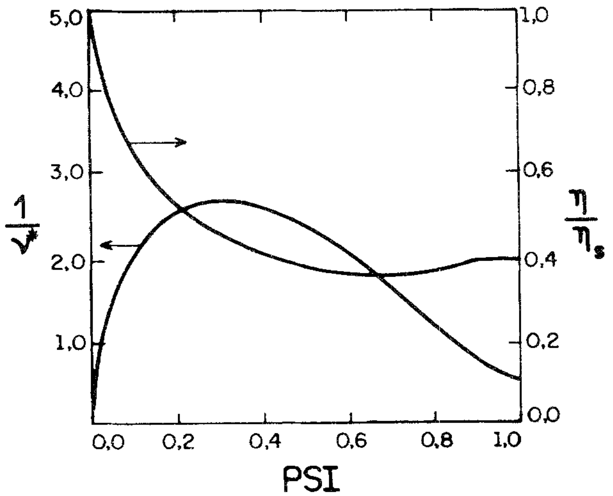


Fig. 8. Inverse of the electron collisionality parameter ν^* and the ratio between the neoclassical and Spitzer resistivity for a typical equilibrium configuration in TBR-E with $A = 1.5$ and $\langle T \rangle = 600$ eV.

hand, the low aspect ratio and the requirement of high plasma current gave rise to difficult technical problems which have been solved with some innovative concepts. For example, the central post, which includes the main solenoid of the Ohmic heating transform wound around the central legs of the toroidal field coils, is a very critical component of the overall design. The toroidal field coils are very light one-turn D-shaped coils; the external segments are connected to the central post by a specially-designed *"crown"* that also allows a up-down symmetric transfer of the current between coils, including the compensating return loops.[6] The conceptual and basic engineering design of the device was analysed and approved by a review committee of international experts gathered together in São Paulo in December of 1991. A Brazilian engineering company specialized in fission reactors became interested in carrying out the detailed engineering design of device and supervise its construction in Brazil. The proposal for building TBR-E was technically approved; however, because of its cost (around $5 million in 3 years), the actual budget commitment by the Ministry of Science and Technology will not be considered before recovery of the Brazilian Economy.

An economically feasible alternative to TBR-E has appeared with the possibility of tranferring TCA[30] (Tokamak Chauffage Alfvèn) from Ecole Polytechnique Fédérale de Lausanne to our Laboratory. With the construction of TCV (Tokamak a Configuration Variable) in Lausanne, the interesting work on Alfvèn wave heating and current drive in TCA has been discontinued. The device is however in good condition and shall be rebuilt in São Paulo with some minor modifications, mainly to adapt to our local power supplies. The research program includes carrying on the work on Alfvèn heating and current drive and investigating other interesting topics such as electron cyclotron heating and current drive, plasma edge phenomena, ergodic magnetic limiter, helicity injection, and diagnostic development. To assemble TCA and carry out that ambitious research program, we intend to have the collaboration of the plasmas groups of University of Campinas and the National Institute for Space Research and of foreign experts. In particular, we shall have the collaboration of Russian scientists, for diagnostic development and impurity control, of Georgian scientists, for antenna design, and of Chinese scientists, from the Plasma Physics Laboratory of Academia Sinica at Hefei, for machine upgrade. A special collaboration program with the Institute for Fusion Studies at Austin, Texas, to investigate innovative ideas on Alfvèn heating, is presently being discussed. Finally, it is our intention to turn our laboratory in a regional tokamak facility for scientists from Latin-America.

6. CONCLUSION

A brief review of the activities on tokamak research developed at the "Instituto de Física da Universidade de São Pauló" has been presented. In spite of the modest installations and budget and manpower limitations, serious and relevant work has been carried out. Obviously Brazil has not the economical resources to launch an independent fusion program. However, with a realistic and well-balanced research program we can maintain a group of scientists that are able to collaborate significantly in the international effort, raise the scientific level of the country, and provide the motivation and the means for the local development of advanced technology.

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