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RELATÓRIO DE ATIVIDADES DE 2005 DA LINHA DE PESQUISA E DESENVOLVIMENTO EM FUSÃO TERMONUCLEAR CONTROLADA DO LABORATÓRIO ASSOCIADO DE PLASMA (LAP) DO INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS (INPE)

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Relatório de Atividades de 2005 da Linha de Pesquisa e Desenvolvimento em Fusão Termonuclear Controlada do Laboratório Associado de Plasma (LAP) do Instituto Nacional de Pesquisas Espaciais (INPE)

Introdução

A pesquisa e o desenvolvimento na área de fusão do LAP/INPE são financiados dentro do Plano Plurianual (PPA) 2004-2007 pela Ação 6228 intitulada "Manutenção do Laboratório de Plasma para Fusão Termonuclear Controlada", Programa 0461 de "Promoção da Pesquisa e do Desenvolvimento Científico e Tecnológico" do Ministério da Ciência e Tecnologia (MCT). Esta atividade também conta com suportes financeiros eventuais obtidos das agências de fomento brasileiras.

Atualmente, as atividades na área de fusão do LAP/INPE integram o projeto intitulado "Estudo do plasma de borda no tokamak esférico ETE" (Plasma edge studies in the ETE spherical tokamak). Este projeto é parte do Projeto de Pesquisa Coordenada (Coordinated Research Project - CRP) sobre "Pesquisa em Conjunto Utilizando Pequenos Tokamaks" (Joint Research Using Small Tokamaks – JRUST) da Agência Internacional de Energia Atômica (International Atomic Energy Agency – IAEA).

Este relatório lista inicialmente o objetivo geral e um resumo da execução da Ação 6228 em 2005, conforme consta do formulário de Acompanhamento da Ação submetido à Assessoria de Acompanhamento e Avaliação da Secretaria Executiva do MCT. Na seqüência, o relatório fornece um resumo das atividades na área de fusão do LAP/INPE no contexto do projeto coordenado pela IAEA. O relatório detalhado destas atividades, submetido recentemente à IAEA, encontra-se no Anexo 1. Este relatório detalhado segue a classificação de atividades estabelecida na primeira Reunião de Coordenação de Pesquisa (RCM), realizada pela IAEA em Lisboa, Portugal, de 7 a 10 de novembro de 2004, e descrita no documento IAEA F1-RC-963. Finalmente, o Anexo 2 lista todos os trabalhos realizados com a participação dos pesquisadores integrantes do projeto durante a vigência do CRP, a partir de 13 de setembro de 2004, identificando as publicações que estão diretamente relacionadas ao projeto, ou que são de interesse para os objetivos do mesmo.

Acompanhamento da Ação 6228: "Manutenção do Laboratório de Plasma para Fusão Termonuclear Controlada"

Informações gerais

Desenvolver sistemas, equipamentos, processos, recursos lógicos, instrumentos e dispositivos visando capacitar o País para a utilização futura da fusão termonuclear controlada como uma fonte primária de energia, limpa, segura e sustentável. Investigar sistemas de confinamento magnético de plasma, acompanhando os avanços internacionais na área e possibilitando a participação do País em projetos multinacionais tais como o ITER. Ampliar, atualizar e operar o toróide esférico ETE do Laboratório Associado de Plasma (LAP) do INPE, explorando as propriedades desta configuração e seu potencial como um reator de fusão de geometria compacta e alta eficiência. Desenvolver, instalar e operar sistemas de aquecimento de plasma e geração de corrente, bem como dispositivos de diagnóstico de plasma de alta temperatura nas condições dos futuros reatores de fusão.

Situação atual

Durante o ano de 2005 deu-se andamento à ampliação, no ETE, dos sistemas de diagnóstico por espalhamento Thomson no núcleo do plasma, para operação com 10 canais, e por injeção de feixe de lítio neutro na borda do plasma, para operação com 8 canais. Iniciou-se a implementação de sondas magnéticas adicionais, para reconstrução magnética do plasma, e a compra de componentes para montagem de um espectrômetro de raios-X moles. Foram realizados os testes térmicos do canhão de elétrons para acionamento de fontes de radiação de alta potência para aquecimento do plasma no ETE. Foram introduzidas melhorias nos recursos lógicos para controle de operação do ETE. Foi estabelecido um acordo de colaboração do LAP com o Instituto Superior Técnico (IST) de Lisboa, Portugal, nas áreas de diagnósticos de plasmas quentes e de controle e aquisição de dados, visando, também, uma possível co-participação em projetos do ITER. A assinatura do acordo depende da anuência final das consultorias jurídicas do Ministério da Ciência e Tecnologia (MCT) e do Ministério das Relações Exteriores (MRE). Dentro deste acordo, especificou-se e deu-se início à compra de um sistema de aquisição de dados a ser integrado pelo IST para uso no ETE. Deu-se continuidade ao projeto intitulado "Estudo do plasma de borda no tokamak esférico ETE", dentro de um programa coordenado pela Agência Internacional de Energia Atômica. Foram desenvolvidos modelos teóricos sobre o equilíbrio autoconsistente de plasma em toróides esféricos, a indução de correntes parasitas na câmara de vácuo do ETE, e o efeito de campos elétricos escalonados em tubos de microondas.

Restrições e Providências

1. **Restrição Financeira** – o orçamento liberado em 2005 (R$225.000,00) corresponde a cerca de 10% do originalmente solicitado e necessário para execução plena da ação. **Providência** – a continuidade da ação requer, para o ano de 2006, um aporte de R$1.200.000,00 (50% capital, 50% custeio).
2. **Restrição de Pessoal** – a ação tem sofrido redução de pessoal ao longo dos anos, acompanhada de um aumento das atividades e responsabilidades. **Providência** - há necessidade da contratação urgente de 3 pesquisadores doutores e 1 tecnologista de nível superior.
3. **Restrição de Licitações** – as regras e exigências para compras e licitações nas instituições públicas federais são incompatíveis com atividades de pesquisa e desenvolvimento. **Providência** – reformular o processo de compras e licitações para atender as necessidades de instituições de pesquisa e desenvolvimento tecnológico.

Resultados Obtidos

Os resultados da pesquisa realizada aparecem principalmente na forma de publicações. Durante o ano de 2005 foram publicados oito trabalhos em revistas internacionais indexadas e seis trabalhos completos em anais de conferências.

Comentários da execução

O desenvolvimento tecnológico e as campanhas experimentais encontram-se prejudicados pelas restrições orçamentárias e de pessoal. Desta forma, os resultados científicos estão em grande parte limitados a trabalhos teóricos, com contribuição experimental inferior às possibilidades. Apesar disso, os trabalhos realizados durante o ano de 2005 ultrapassam a meta acordada de cinco publicações.

Contrato de Pesquisa BRA-12932: "Estudo do plasma de borda no tokamak esférico ETE"

Introdução

O Projeto de Pesquisa Coordenada (CRP) sobre "Pesquisa em Conjunto Utilizando Pequenos Tokamaks" da Agência Internacional de Energia Atômica (IAEA) reúne os esforços de nove laboratórios mundiais. A participação do LAP neste projeto coordenado teve início em 13 de setembro de 2004 quando entrou em vigor o Contrato de Pesquisa BRA-12932 firmado entre o INPE e a Agência. O contrato foi renovado por mais um ano a partir de 15 de outubro de 2005, permitindo a participação, com suporte parcial da IAEA, em conferências e reuniões de trabalho para apresentação de resultados técnicos e científicos, com forte incentivo a publicações e atividades realizadas em parceria pelos grupos contratados.

A primeira Reunião de Pesquisa Coordenada (Research Coordination Meeting - RCM) promovida pela IAEA dentro deste CRP teve lugar de 7 a 10 de novembro de 2004, em Lisboa, Portugal. Nesta reunião foram apresentadas as atividades de pesquisa propostas em cada projeto submetido à Agência, classificados os tópicos de pesquisa, identificados os interesses comuns de pesquisa, e preparado o plano final de trabalho. Assim, as atividades na área de fusão do LAP/INPE passaram a ser conduzidas de acordo com o plano coordenado pela Agência, com forte incentivo à colaboração internacional.

Resumo da Pesquisa Proposta

Medidas e estudos sistemáticos dos parâmetros do plasma de borda serão realizados no Experimento Tokamak Esférico (ETE), atualmente em operação no Laboratório Associado de Plasma (LAP) do Instituto Nacional de Pesquisas Espaciais (INPE). O projeto inclui a implantação e/ou atualização de diagnósticos (espalhamento Thomson, sonda de feixe de lítio neutro, sondas eletrostáticas, espectroscopia óptica, medidas magnéticas, espectrômetro de raios-X moles, entre outros) que serão utilizados em conjunto para estudar as propriedades do plasma de borda. Vários aspectos da física da borda serão considerados, incluindo-se questões de reposição e controle da densidade do plasma, condicionamento da parede e efeitos de impurezas, e manipulação de partículas e energia. Além disso, a capacitação e as instalações do LAP na área de plasmas tecnológicos serão utilizadas no desenvolvimento e caracterização de novos processos de tratamento da superfície de componentes em contato com o plasma a serem testados no ETE. Finalmente, será realizado um esforço na modelação teórica de alguns fenômenos associados com o contorno do plasma.

O programa de pesquisa delineado não esgota as atividades que poderão ser realizadas no tokamak ETE. Porém, forma a base de um esforço dedicado à instalação de diagnósticos e ao desenvolvimento de ferramentas teóricas no ETE durante os próximos anos. O investimento no projeto ETE estará essencialmente limitado pelo orçamento aprovado institucionalmente. Espera-se ampla colaboração internacional.

Pesquisadores participantes

1. Gerson Otto Ludwig (teoria – investigador principal).
2. Edson Del Bosco (operação da máquina, diagnósticos eletromagnéticos e de raios-X moles).

3. Júlio Guimarães Ferreira (sistema de potência, sondas eletrostáticas, condicionamento do vácuo).
4. Luiz Angelo Berni (sistema de espalhamento Thomson, espectroscopia óptica).
5. Rogério de Moraes Oliveira (diagnóstico por feixe de lítio neutro, sistema de aquisição de dados).
6. Carlos Shinya Shibata (aquisição, tratamento e visualização de dados).
7. Maria Célia Ramos de Andrade (teoria – efeitos neoclássicos, equilíbrio magnetoidrodinâmico).
8. Joaquim José Barroso de Castro (teoria – microondas de alta potência, monotron).
9. Pedro José de Castro (desenvolvimento do monotron, medidas de microondas).

Auxílios de instituições internacionais

Auxílios parciais obtidos em 2005 da Agência Internacional de Energia Atômica (IAEA, Viena) e do Centro Internacional de Física Teórica (ICTP, Trieste) para participação em Reuniões de Trabalho (1 e 3), Experimento Conjunto (2) e para o projeto ETE (4):

1. *Second IAEA Technical Meeting on the Theory of Plasma Instabilities: Transport, Stability and their Interaction*, Miramare, Trieste, Italy, 2-4 March 2005 (~US$1,200.00).
2. Host Laboratory Experiment in the CASTOR Tokamak, Institute of Plasma Physics, Prague, Czech Republic, 29 August-9 September 2005 (~US$2,000.00).
3. *Joint Meeting of the 3rd IAEA Technical Meeting on Spherical Tori and the 11th International Workshop on Spherical Torus*, St. Petersburg, Russia, 3-6 October 2005 (~US$2,300.00).
4. Research Contract BRA-12932, "Plasma edge studies in the ETE spherical tokamak", Co-ordinated Research Project on *Joint Research Using Small Tokamaks* – International Atomic Energy Agency (~US$2,000.00).

Anexo 1. Relatório de atividades submetido à Agência Internacional de Energia Atômica ao final do primeiro ano de vigência do contrato de pesquisa BRA-12932.

Progress Report: Research Contract BRA-12932/R0
Plasma edge studies in the ETE spherical tokamak

Summary of the Proposed Research

Systematic measurement and study of plasma edge parameters will be performed in the ETE (Experimento Tokamak Esférico) spherical tokamak currently in operation at the Associated Plasma Laboratory – LAP of the National Space Research Institute – INPE in Brazil. The project includes the implementation and/or upgrade of diagnostics (Thomson scattering, neutral lithium beam probe, electrostatic probes, spectroscopic and magnetic measurements, ultra soft X-ray photodiode arrays, among others) that will be used conjunctly to study the plasma boundary properties. Several aspects of the edge physics will be considered, including issues of plasma fuelling and density control, impurity effects and wall conditioning, and power and particle handling. Also, the facilities and capability of LAP in the area of plasma technologies will be used in the development and characterization of new surface treatment processes for plasma facing components to be tested in ETE. Finally, an effort in the area of theoretical models related to plasma boundary phenomena will be carried out.

The research program outlined does not constitute the sole activity that will be performed in the ETE tokamak. Nevertheless, it will form the basis of an effort concerning the installation of diagnostics and the development of theoretical tools in ETE during the next few years. The budget reflects what can be reasonably expected for total investment in the ETE program. Wide international collaboration is expected.

Project Personnel

1. Gerson Otto Ludwig (theory – chief scientific investigator)
2. Edson Del Bosco (machine operation, electromagnetic and soft X-rays diagnostics)
3. Júlio Guimarães Ferreira (power system, electrostatic probes, vacuum conditioning)
4. Luiz Angelo Berni (Thomson scattering system, optical spectroscopy)
5. Rogério de Moraes Oliveira (fast neutral lithium beam diagnostic, data acquisition)
6. Carlos Shinya Shibata (data acquisition-storage-visualization)
7. Maria Célia Ramos de Andrade (theory – neoclassical effects, MHD equilibrium)
8. Joaquim José Barroso de Castro (theory – high-power microwaves, monotron)
9. Pedro José de Castro (monotron development, microwave measurements)

Progress report of proposed activities under the CRP framework: as classified in the first Research Coordination Meeting, Lisbon, 7 – 10 November 2004, IAEA document F1-RC-963

Topic 2. Edge physics, plasma surface interaction and technology

Subtopic 2.8. Fuelling, recycling, wall conditioning
Proposed activity:

Improvement of ETE vacuum conditioning by increasing the baking temperature and optimization of glow discharge operation accompanied by a systematic study of the effects produced on plasma temperature and impurity lines.

Progress report:

Auxiliary vacuum conditioning such as glow discharge, which cleans the walls by ion bombarding, and baking that boosts wall outgassing by running the vacuum system with vessel walls at sufficiently high temperatures, are now routinely used in the ETE spherical tokamak. A feedback control circuit developed in our laboratory keeps the baking system running at wall temperatures around or above 100°C over periods of a few days. The system can go up to 200°C, but is still limited by the use of a few viton seals. Besides the ionization gauge used to read the total pressure, the main tool available in ETE to diagnose vacuum quality is a residual gas analyzer to identify and follow the composition of the remaining gas mixture over the whole baking period. After a vacuum break and a few days of pumping, water becomes the main residual gas component in ETE, as usually observed in similar vacuum systems. Therefore, typical pre-conditioning mass spectra have the main line at mass 18 (H_2O), with around 50% partial pressure, and also a non negligible line at mass 17 (OH). Other important components under such conditions are nitrogen, oxygen and hydrogen, the gas used in basically all tokamak discharges in ETE. The other gas largely used in ETE glow discharges and in the calibration of the lithium beam diagnostic system is helium, an easily pumped inert gas which is therefore always a relatively small component. When baking is applied up to around 100°C, the partial pressure of the light masses (H_2, He) increases two or more orders of magnitude to reach a peak after a few hours before it starts decreasing slowly. The partial pressure of water components increases much less and also in a longer timescale, although it still raises more than an order of magnitude. The effect on masses over 20 is even smaller and so the basic role of a long baking, over a period of two to three days, is to attenuate the lower end of mass spectra, the main benefit being reduction of water proportion in the residual gas. After an additional period of about 50 hours of glow discharge cleaning with helium at 2.4×10^{-3} mbar, the base pressure drops to 8×10^{-8} mbar.

Topic 3. Heating, current drive and plasma formation

Subtopic 3.1. Heating power source development

Proposed activity:

Work will be carried out on the design and construction of a high-power 6.7 GHz monotron and also on the study of advanced concepts of corrugated waveguides and cavity resonators, looking for plasma heating applications in the future.

Progress report:

The simplest of the microwaves tubes, the monotron is a transit-time oscillator consisting of a circular cylindrical cavity driven by a linear electron beam. For transit angles close to $2\pi(N+1/4)$, with N integer, velocity modulation and bunching take place in the cavity, leading the beam to interact unstably with a cavity mode which, in turn, grows at the expense of the DC beam's energy. While considering a spatially-uniform electric field, past studies have indicated that the monotron operating in a circularly symmetric TM mode reaches the maximal conversion efficiency of 20% at weakly relativistic energies. But, recent work carried out by our group demonstrates that the monotron interaction can achieve conversion efficiency as high as 57% by considering a stepped axial electric-field profile along the electron stream. The model uses two circular TM cavities coupled capacitively by an annular slit. Both cavities are carefully tailored so that the smaller cavity pre-modulates the beam with the second and larger resonant cavity providing the main interaction space. Such axial electric field profiles are analytically described by Tanh[z] functions and a cold-beam;

one-dimensional analysis discusses how the beam energy and cavity dimensions should be interrelated to give maximum efficiency. A detailed calculation example relates to a 4.0 GHz, TM_{010}-mode cavity driven by a 20 keV, 10 A hollow electron beam. The operation of the two-cavity monotron thus synthesized is examined through a particle-in-cell (PIC) simulation which indicates a conversion efficiency of 47% inferred from the energy distribution of the beam electrons collected in the downstream end of the cavity. Departure of the theoretically predicted efficiency from the simulation results is explained by beam-thickness effects.

Our laboratory is currently testing an electron gun used to accelerate and inject a hollow electron beam into a cylindrical cavity to generate high-power microwaves at 6.7 GHz, a frequency suitable for plasma heating, communications, medical and industrial applications. With inner and outer diameters of 2.6 cm and 3.0 cm, respectively, the hollow beam is emitted from an annular nickel strip with surrounding electrodes tipped at 67.5 degrees (Pierce angle) toward the anode to counterbalance the mutual repulsion between electrons to keep the flow paraxial. The circular nickel strip is coated with a (Ba, Sr, Ca)O film, which at the operation temperature of 800°C provides a pulsed emission current density of 3.0 A/cm^2. The heater is made of a 0.5 mm-diameter pure tungsten wire tightly wound, with the resulting helix bent to take the shape of a toroid that is placed on the back of the cathode to heat the emitting strip radiatively. This electron gun will be used in a 6.7 GHz monotron, which operates with a 5.0 A beam current at 10 kV in connection with the design and operation characteristics of the gun.

Subtopic 3.5. Startup

Proposed activity:

A microwave RF power system based on a 9.5 GHz, 40 kW/500μs pulsed magnetron is being devised to assist the startup phase of the ohmic discharge by using microwave power at the electron-cyclotron (EC) frequency range as a means of preionizing and preheating the plasma.

Progress report:

Because of severe cuts in the financial support available for ETE, it was not possible to purchase the components of the microwave RF power system for preionizing the plasma in ETE. This activity was postponed pending the return of finances to the requested level.

Proposed activity:

Theoretical work will be undertaken in the area of plasma startup simulation applied to the ETE conditions.

Progress report:

The absence of a toroidal gap in the vacuum vessel of ETE allows the appearance of a relatively high toroidal induced current, of the order of the plasma current, generating stray magnetic fields inside the vessel and consuming volt-seconds of the ohmic heating system, mainly during the plasma formation phase. A model to calculate eddy currents in the vacuum vessel due to the poloidal coils has been developed. In this model the vacuum vessel of ETE is divided in three sectors of different thickness, according with the actual fabrication. Then, the integro-differential equation that governs the evolution of the surface current density induced in a thin axisymmetric shell is solved for each sector, taking into account all the external flux sources, plus the eddy currents induced in the central column of ETE and the proximity effect in the ohmic heating solenoid. The total electromotive force calculated with this model is in very good agreement with the voltage measured in loop voltage sensors placed along the poloidal perimeter of the vacuum vessel of ETE. This effort is the first step for simulating the startup conditions in ETE. Next, the plasma will be inserted in the model and its evolution simulated using the same basic formalism of the present model.

Topic 4. MHD and control

Subtopic 4.8. MHD instabilities

Proposed activity:

Theoretical work will be undertaken in the formulation of edge plasma models, particularly looking into effects of plasma viscosity at the boundary.

Progress report:

The interface between the plasma edge and its surroundings affect both the structure of plasma instabilities and the quality of confinement. According to well established procedures in MHD theory, the boundary conditions for the analysis of free-boundary instabilities is set by the flow of energy, mass, or flux across the boundary. However, ideal MHD disregards the role of viscosity in fluid motion. Even considering that viscosity effects are negligible for large scale instabilities in the core of high temperature plasmas, the viscous stresses have a strong influence on high-order modes of oscillation near the plasma edge. Work has been carried out in two instances where edge viscosity may be important in the behavior of natural as well as laboratory plasmas. In the first example the turbulence associated with the Rayleigh-Taylor instability, which is driven during the contracting stage of the decaying return stroke of a lightning discharge, creates anomalous viscosity that defines the spatial structure of bead lightning. In the second example the kink modes in circular cylindrical plasmas are examined by taking into account the effect of viscosity in the boundary. It is shown that the $m = 1$ kink mode is barely changed, but the higher order $m \geq 2$ modes are significantly damped if the collisionality is high. This has interesting implications for magnetic fusion, since the ballooning modes, which set a limit to the maximum pressure that can be confined in a tokamak, could be strongly affected. One may conjecture that anomalous ion viscosity associated with drift wave turbulence increases the viscous stresses thus leading to improved confinement if plasma flow is also taken into account. Since the anomalous viscous stress has a non-Newtonian character, one would have eventually a situation of bifurcation, allowing for drastic changes in the equilibrium. These topics are presently under investigation.

MHD equilibrium and neoclassical effects: additional activities not classified

A detailed study of the bootstrap current fraction and bootstrap current profile upon some plasma profile parameters and its consequences on plasma equilibrium quantities such as internal plasma inductance, normalized and poloidal beta values, loop voltage and central safety factor, among others, has been performed in the framework of a self-consistent equilibrium calculation in tokamak plasmas. The components of the total plasma current are represented by the diamagnetic, Pfirsch-Schlüter, and the neoclassical ohmic and bootstrap currents. The loop voltage used to determine the ohmic component is calculated consistently in order to give the prescribed value of the total current. The behavior of the bootstrap component is then analyzed according to the variation of the central and peaking factors of the electron and ion temperature profiles, as well as the central and peaking factor values of the pressure profile or, in other words, of the density profile since temperature parameters are fixed while varying the pressure profile parameters. Variations of the effective charge in the plasma are also carried out. We considered only cases where the bootstrap current is generated by thermal particles. This study was performed for the conditions of ETE and our results are compared to a general empirical scaling law established for machines of large aspect ratio and circular cross-section. Despite this, our calculations show a reasonable agreement with those predicted by the scaling law, with possible deviations that are under investigation.

An estimate of the plasma resistance in ETE was performed in a self-consistent equilibrium calculation where the total plasma current is supposed to have contributions of the diamagnetic, Pfirsch-Schlüter, and the neoclassical ohmic and bootstrap currents. This estimate was obtained both for the neoclassical (R_{neo}) and Spitzer (R_{Sp}) resistances in two ways: from the calculated loop voltage or from the total ohmic power dissipated in the plasma. The intrinsic plasma resistance R_{neo} takes into account neoclassical effects due to the presence of the bootstrap current and of the trapped particles (that modify the classical Spitzer value), while in the Spitzer case, these effects are not taken into account. In other words, R_{neo} is calculated from the neoclassical ohmic toroidal current provided by the self-consistent equilibrium calculation when neoclassical effects are taken into account, while for the Spitzer evaluation we take the Spitzer ohmic toroidal current when such effects are not accounted. These resistances are in general significantly different from the usual experimental value obtained from the measured loop voltage and the total toroidal plasma current. This experimental value is in fact an apparent plasma resistance since it includes effects of the bootstrap, diamagnetic and Pfirsch-Schlüter currents not properly associated with dissipative effects in the plasma. A method is being proposed to relate the neoclassical and Spitzer resistances to the experimental value without having to solve a self-consistent equilibrium. It is interesting to remember that from the knowledge of the Spitzer resistance it would also be possible to obtain a fast estimate of the plasma temperature. Different plasma parameters in parabolic temperature profiles are used as examples in this work.

Topic 5. Diagnostics improvement and development

Subtopic 5.1. Core diagnostics

Proposed activity:

For the first year of the project, the single-channel Thomson Scattering (TS) diagnostic will be upgraded to 10 channels applying a time-delay technique. This multiplexing technique uses different lengths of optical fibers to relay the scattered signals to the same polychromator. The density and temperature measurements obtained with the TS system will be extended as far as possible into the edge, overlapping the measurements obtained with the FNLB (cf. Subtopic 5.2) and Langmuir probes.

Progress report:

Thomson scattering (TS) is a well-established diagnostic for measuring electron temperature and density in fusion plasma experiments with high spatial and temporal resolutions. Presently, the one-channel TS system of the ETE spherical tokamak is being upgraded to a multipoint system based on the time delay technique of the collected scattered light from the plasma. This technique allows the utilization of one polychromator to collect the light of several points in the plasma core in one single shot reducing the cost of the conventional multipoint TS system. The technique was already successfully tested on ETE for four channels. In order to explore the maximum capability of the available polychromator a ten-channel system was designed and assembled in our laboratory. The scattered light is imaged by a collection lens set (numerical aperture NA = 0.07) on ten large core monofibers (diameter = 0.8 mm, NA = 0.39, attenuation = 7 dB/km) of different lengths (fiber 1: 8 m and fiber 10: 134 m) to relay the light signals to the same polychromator. Between the collection lens and each monofiber a microlens (focal length = 15 mm) was placed to match the numerical aperture of the optical system and to enlarge the observation length inside the plasma to 4 mm. The ten-channel Thomson scattering diagnostic is presently being prepared for tests in the ETE tokamak.

Subtopic 5.2. Edge diagnostics

the electron temperature with high time resolution. The present data acquisition system based on the CAMAC standard will be replaced by a new 64-channels system based on the PCI standard. This new system will be used mostly in the magnetic reconstruction of the plasma equilibrium. Work has been initiated to develop a model describing the plasma evolution including eddy current effects, as reported in Subtopic 3.5. It is expected to use this original model as the main equilibrium reconstruction tool for ETE.

The hardware for the new data acquisition system will be integrated by the Centro de Fusão Nuclear, Instituto Superior Técnico in Lisbon, Portugal, within the scope of a mutual cooperation agreement with LAP-INPE. This upgrade requires a significant update of the data acquisition-storage-visualization procedure for ETE as reported next.

The original computational code for the control system of the ETE tokamak was conceived in our laboratory. This code, written in C, is composed of several routines responsible for plasma discharge and data acquisition procedures via CAMAC modules. The operation is monitored from a web page, written in Hypertext Markup Language (HTML) and comprising JavaScripts, where shot parameters (e.g. capacitor bank charging voltages, plasma current etc.) and data acquisition parameters (e.g. channel sampling rate, memory size etc.) are provided by means of Common Gateway Interface (CGI) scripts. At the present stage, experimental data acquired by Analog to Digital Converter (ADC) cards after each discharge cycle are stored in three ASCII-format files, identified by a sequential shot number, and analyzed using the Origin software. The visualization of these signals is also being adapted for an Interactive Data Language (IDL) code. The operator can request the last shot data or the files corresponding to an older shot by using a graphical console. Despite the relatively low amount of data collected per discharge, we are now doing some modifications to improve the reliability of the system. In this scenario, all the information from the experiment will be stored in a Structured Query Language (SQL-standard) database. The IDL Dataminer routines will connect this database through the Open Database Connectivity (ODBC) interface plus a specific driver (e.g. for MySQL). Again, a friendly-interface will permit to choose the signals to be processed, now based not only on the shot number but on all the selection rules available in SQL. The update in the data acquisition-storage-visualization procedure, based on an integrated C+SQL+IDL architecture, is motivated not only by reasons of the integrity of the machine historical series data, but also by the expected volume increase of the data generated in each shot.

Topic 8. Expertise exchange

Proposed activities:

Visits to other laboratories and participation of visiting scientists are a traditional practice in ETE related activities. It is planned to carry out this policy in future activities, mostly involving the institutions mentioned in the proposal (NIFS, IST, USP, Ioffe). However, getting funds for completing these visits or for participating in conferences is one of the main difficulties in carrying out the research program in ETE. It is expected to use the budget requested from the Agency in such visits.

Progress report:

The IAEA Coordinated Research Project on "Joint Research Using Small Tokamaks" has motivated the establishment of a mutual cooperation agreement between the Laboratório Associado de Plasma – LAP of the Instituto Nacional de Pesquisas Espaciais – INPE in Brazil and the Centro de Fusão Nuclear – CFN of the Instituto Superior Técnico – IST in Portugal. Within the scope of this agreement a data acquisition system will be integrated by the CFN for use in the ETE spherical tokamak, including visit of a specialist and support for installation. The agreement also covers the development of diagnostics for fusion plasma research. Informal discussions have been initiated to establish similar agreements with the

Proposed activity:

The present single-channel optical detection system of the fast neutral lithium beam (FNLB) probe allows the measurement of the density and its fluctuations on the edge region of the plasma in ETE, with reasonable spatial and temporal resolutions, of the order of 1.5 cm and a few nanoseconds, respectively. For the first year a multi-channel photomultiplier will be implemented in the optical detection system of the FNLB, coupled to an objective lens, plus fiber optics and interference filters that will allow the processing of up to 64 signals in parallel. Several arrangements can be made with the 64 cells of this photomultiplier, which act like 64 independent photomultiplier tubes. Initially, an array of 8 x 8 will be implemented to probe 8 radial points of the discharge, allowing gain amplification by a factor of eight, in comparison with the case of using just one cell for each observed radial position.

Progress report:

After successful measurements of the temporal evolution of plasma density in discharges of the ETE tokamak with a fast neutral lithium beam (FNLB) probe, an upgrade of the system is being performed. The main modification concerns the replacement of the old one-channel optical detection system by a new eight-channel system. The high spatial (1 cm) and temporal (order of nanoseconds) resolutions achieved before will be retained, while the plasma density spatial profile will be obtained in a single shot, by either using a density reconstruction code or a calibration method for plasma density determination. The new vacuum window that will be used for observations of the light emitted from the plasma as a result of interaction with the lithium beam allows visualizing a 15 cm radial length of the plasma from the edge. In the old setup, only one spatial point (1 cm length) in the plasma could be probed because of the limited observation angle. The new multi-channel photomultiplier composes a frame of 8 x 8 cells. Furthermore, a narrow 1 nm pass-band interference filter substitutes the old 10 nm one, separating the measuring wavelength of interest (670.8 nm) from the background light. A set of nine optical fibers, each one with a 1.5 mm diameter single encapsulation, and 99.8% transmission rate per meter at 670.8nm, will substitute the old single-fiber optical system. In summary, the upgrade of the FNLB device will allow probing all the edge region of the ETE discharge with high temporal and spatial resolutions, bringing relevant edge plasma information to present research performed in spherical tokamaks. Presently, the various components are being assembled to be installed and tested in ETE.

Subtopic 5.3. Magnetic diagnostics, equilibrium reconstruction

Proposed activity:

Magnetic measurements coupled to equilibrium modeling (EFIT) will be used to define the plasma edge location. The purchase of a fast CCD camera is also envisaged to provide optical imaging information about the plasma edge location.

Progress report:

Several diagnostics are already implemented in ETE, such as electromagnetic sensors, one-channel Thomson scattering (TS) system, visible spectrometer, one-channel fast neutral lithium beam (FNLB) probe, photomultipliers, fast CCD camera, hard X-ray detector and movable electrostatic probe. As reported in Subtopics 5.1 and 5.2 above, the existing one-channel TS system is being upgraded to ten channels and the one-channel FNLB probe is being upgraded to eight channels. The available CCD camera records 30 to 500 frames per second with a frame speed setting of 1/500 to 1/20,000 s. The planned upgrade to 10,000 FPS, which would allow detailed imaging of the plasma edge evolution, was postponed pending additional financial support. A new set of electromagnetic sensors (pick-up coils, Rogowski coil, total flux coils) is being developed for magnetic measurements and equilibrium reconstruction studies, as well as a two-foil soft X-ray spectrometer for the determination of

Ioffe Physico-Technical Institute in Russia and the Institute of Plasma Physics in the Czech Republic.

The support from the International Atomic Energy Agency – IAEA and the International Centre for Theoretical Physics – ICTP has been fundamental for participation in the following meetings and activities:

1. *20th IAEA Fusion Energy Conference*, Vilamoura, Portugal, 1-6 November 2004.
2. *First Research Coordination Meeting, Coordinated Research Project on "Joint Research Using Small Tokamaks"*, Lisbon, Portugal, 7-10 November 2004.
3. *Second IAEA Technical Meeting on the Theory of Plasma Instabilities: Transport, Stability and their Interaction*, Miramare, Trieste, Italy, 2-4 March 2005.
4. Host Laboratory Experiment in the CASTOR Tokamak, Institute of Plasma Physics, Prague, Czech Republic, 29 August-9 September 2005.
5. *Joint Meeting of the 3rd IAEA Technical Meeting on Spherical Tori and the 11th International Workshop on Spherical Torus*, St. Petersburg, Russia, 3-6 October 2005.

Anexo 2. Trabalhos realizados com participação dos pesquisadores durante a vigência do Projeto de Pesquisa Coordenada (CRP) sobre "Pesquisa em Conjunto Utilizando Pequenos Tokamaks".

As publicações diretamente relacionadas ao projeto, ou de interesse aos seus objetivos, encontram-se indicadas com um asterisco (*).

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3. FONSECA, T.R.; NONO, M.C.A.; **CASTRO, P.J.** "Processamento e caracterização de cerâmicas de SrO-Nb_2-$Ba_2Ti_9O_{20}$ para aplicação como ressoadores dielétricos em microondas". *Seminário de Iniciação Científica do INPE* – SICINPE 2005 (Programa Institucional de Bolsas de Iniciação Científica – PIBIC/CNPq/INPE, São José dos Campos, SP, 03-04 Agosto 2005).
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16. **CASTRO, P.J.; BARROSO, J.J.**; LEITE NETO, J.P.; AGUIAR, O.D. "Reentrant cylindrical cavities for gravitational wave detection". 8^{th} *Brazilian Meeting on Plasma Physics* – 8EBFP, Niterói, RJ, 27-30 November 2005 (São Paulo: Sociedade Brasileira de Física, Program and Abstracts) p. 46.
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19. (*) **DEL BOSCO, E.; LUDWIG, G.O.; BERNI, L.A.; FERREIRA, J.G.; OLIVEIRA, R.M.; SHIBATA, C.S.** "Advances in the diagnostic system of the ETE spherical tokamak". 8^{th} *Brazilian Meeting on Plasma Physics* – 8EBFP, Niterói, RJ, 27-30 November 2005 (São Paulo: Sociedade Brasileira de Física, Program and Abstracts) p. 11, Invited Talk.
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