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THE RESEARCH LABORATORY OF THE PHYSICS OF ADVANCED TOKAMAKS OF THE ST. PETERSBURG STATE POLYTECHNICAL UNIVERSITY

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ЛАБОРАТОРИЯ ФИЗИКИ УЛУЧШЕННОГО УДЕРЖАНИЯ ПЛАЗМЫ ТОКАМАКОВ САНКТ-ПЕТЕРБУРГСКОГО ГОСУДАРСТВЕННОГО ПОЛИТЕХНИЧЕСКОГО УНИВЕРСИТЕТА

Within the Research Laboratory of the Physics of Advanced Tokamaks, which has been founded in 2011 on the basis of a MEGA-Grant, the two groups from the University and the Ioffe Institute cooperate on the three tokamaks, Globus-M, TUMAN-3M and FT-2. The research of both partners benefitted from the means of the MEGA-Grant. The laboratory has given itself a transparent governing structure and its annual outcome is assessed by an international advisory committee. A graduate school has been founded to ensure proper education. The Laboratory could serve as a model for integrated research and education centre in Russian thermonuclear program. The urgent need to modernize the Russian fusion devices has become obvious.

RESEARCH LABORATORY, THERMO-NUCLEAR FUSION, TOKAMAK DEVICES, PLASMA CONFINEMENT, PLASMA DIAGNOSTICS, PLASMA HEATING, THEORY AND EXPERIMENT, EDUCATION WITHIN RLPAT.

В рамках Лаборатории физики улучшенного удержания плазмы токамаков, организованной в 2011 на основе МЕГА-гранта, две группы из Университета и из ФТИ имени А.Ф. Иоффе РАН объединили свои усилия в работах по трем токамакам: Глобус-М, ТУМАН-3М и ФТ-2. Исследования обоих партнеров обеспечиваются из средств МЕГА-гранта. Лаборатория сформировала прозрачную структуру управления. Результаты ее работы ежегодно оцениваются Международным консультативным комитетом. Была создана школа для обеспечения выпускников Университета специальным образованием. Лаборатория может служить моделью интеграции исследований и образования, необходимых в Российской термоядерной программе. Кажется очевидной настоятельная необходимость модернизации российских установок термоядерного синтеза.

ИССЛЕДОВАТЕЛЬСКАЯ ЛАБОРАТОРИЯ, ТЕРМОЯДЕРНЫЙ СИНТЕЗ, ТОКАМАКИ, УДЕРЖАНИЕ ПЛАЗМЫ, ДИАГНОСТИКА ПЛАЗМЫ, НАГРЕВ ПЛАЗМЫ, ТЕОРИЯ И ЭКСПЕРИМЕНТ, ОБУЧЕНИЕ В РАМКАХ RLPAT.

I. Introduction

The Research Laboratory of the Physics of Advanced Tokamaks (RLPAT, www.rlpat.ru) has been founded in 2011 at the St. Petersburg State Polytechnical University on the basis of a MEGA-Grant from the Russian government (Agreement No. 11.G34.31.0041). The grant has been awarded for 2 years and terminates 31.12.2013. The mission of the RLPAT is: «to organize a scientific laboratory in the University for investigating experimentally and theoretically regimes with improved plasma confinement; to provide it with equipment for such investigations; to actively involve graduate and post-graduate students in the scientific work». The speciality of the organization of the laboratory is that it strengthens the traditional cooperation between SPbSPU and the Ioffe Physical-Technical Institute of the Russian Academy of Sciences in the field of fusion research. Russian science enjoys an extremely fruitful history in fusion research; the development of the tokamak confinement concept is one of the science legacies of Russia. The culmination of this effort is the realization of the experimental fusion reactor ITER based on the tokamak concept. Russia is one of the seven ITER partners and contributes within 10 % of the costs. The great history of fusion research of Russia is the background of our efforts and represents strong responsibility and commitment.

II. Organization of the RLPAT

The laboratory comprises about 100 members with nearly equal parts from SPbSPU and the Ioffe Institute. It is structured into 7 scientific groups, 4 from SPbSPU and 3 from the Ioffe Institute:

1. Group of «Plasma fuelling and exhaust and related diagnostics», headed by Prof. V. Sergeev of SPbSPU;
2. Group of «Theory and modeling of edge plasma of tokamaks», headed by Prof. V. Rozhansky of SPbSPU;
3. Group of «Tokamak plasma turbulence», headed by Prof. V. Bulanin of SPbSPU;
4. Group of «RF plasma heating», headed by Prof. G. Sominski of SPbSPU;
5. «Globus-M» – group headed by Dr. V. Gusev from the Ioffe Institute;
6. «FT-2» – group headed by Prof. E. Gusakov from the Ioffe Institute;
7. «TUMAN-3M» – group headed by Prof. S. Lebedev from the Ioffe Institute.

Groups 1, 2 and 5 are the only ones in Russia with experience in divertor tokamak physics. Groups 3 and 5 are the only ones working in Russia in the field of turbulence and flow interaction with spontaneous H-mode – the operational regime of ITER; Groups 6 and 7 also contribute to the understanding this important topic. Group 4 specializes in the technology of gyrotrons – an important way to heat a future fusion reactor by electron-cyclotron-resonance heating. Russian industry is also very strong (GYCOM company) in gyrotron development. Groups 5 and 6 study non-inductive current initiation and current drive – again in a field of relevance for ITER and a fusion neutron source, FNS. Groups 5 and 7 are involved in fast ion confinement issues.

The RLPAT has given itself a governance structure based on the postulate that all executive and scientific decisions should be carried out in a transparent form after thorough discussion within the Executive Committee or the Scientific Committee, respectively. The Executive Committee has four members from SPbSPU and Ioffe Institute and is chaired by the «Leading Scientist», F. Wagner, or his deputy, V. Sergeev. The Scientific Committee is formed by the group leaders of the RLPAT. The governance structure of the RLPAT is such that its leadership can easily be transferred to someone from the University or the Ioffe Institute. It does not require the presence of the Leading Scientist forever.

To ensure regular progress control along international standards, an International Advisory Committee (IAC) has been formed. Its members are W. Morris (chair, UK), H. Wilson (UK), S. Kaye (USA), B. Kuteev (Russia), A. Litvak (Russia). The foreign members come from the field of spherical tokamaks which Globus-M also belongs to. The IAC has had two meetings up to now, one in 2012, and one in 2013. It operates along specific «Terms of References» defined by the Executive Committee and it summarizes its findings and recommendations in a report which is sent to the heads of university, the Ioffe Institute and to the RF ministry of education and science.

If properly financed, e. g. in an institutional form as it is necessary for fusion with its long-term objectives, the RLPAT represents a structure which formalizes the cooperation between SPbSPU and an Academy institute. This cooperation is supposed to ensure filling two gaps in the Russian fusion program – participating in new devices like the upcoming Globus-M2 tokamak and educating young people in fusion physics. There is a tremendous need in performing the both tasks.

II. Research of the RLPAT

With the MEGA-Grant, the tokamak devices of the Ioffe Institute could not be modernized, but the diagnostics and heating periphery with which the SPbSPU staff cooperates with could be improved. According to the Russian fusion program which aims at a fusion energy source in the cooperation with ITER and at a fusion neutron source as a national goal, the research of RLPAT centers around the needs of ITER and the FNS. The programmatic guideline for the work within the RLPAT is the scenario to use the potential of spherical tokamaks in terms of creating a neutron source. This development would be carried out with strong partners in Europe and the USA. The strategy of the Ioffe Institute is to replace, in near future, the present spherical tokamak, Globus-M, by the upgrade into Globus-M2 and finally to aim at Globus-M3, a non-nuclear device which could accompany a nuclear one to be built elsewhere, where the corresponding nuclear licensing is possible. Globus-M2 and more so Globus-M3 could explore the physics of anisotropic, strongly beam-driven plasmas.

The major topics where the RLPAT can contribute at present to such a strategy are:

the study of plasma confinement, specifically the conditions for this and the transition physics of the H-mode. The most successful paradigm to explain the H-mode transition is the non-linear interaction of turbulent eddies which adopt sufficient anisotropy between radial and poloidal flow components so that the Reynolds stress develops at the plasma edge whose induced zonal flow adds to the L-mode background mean flow. As a consequence of sheared flow, the turbulence is ultimately quenched, the local confinement improved and a large ion pressure gradient appears at the plasma edge. Its related electric field stabilizes the new boundary conditions of low turbulence. In all the three tokamaks of the Ioffe Institute, the oscillatory form of the zonal flow (local ExB plasma poloidal flow), so called GAMs, due to the background turbulent field, are observed [1, 2]. The recent discovery of GAMs in Globus-M [1] has been achieved by the new microwave Doppler reflectometry system from the MEGA-Grant.

As the GAM frequency depends on the ion mass, the study of GAMs has been linked to that of the isotopic effect on confinement. This is an important field because this effect forces ITER to operate during the non-nuclear phase with helium, as the H-mode is not expected in hydrogen. RLPAT has an excellent potential for further exploring the inherent physics of the H-mode: Globus-M operates with a spontaneously developed H-mode but does not show an isotopic effect on confinement [4]; TUMAN-3M can operate with an induced H-mode [5] and displays an isotopic effect [unpublished]. Both devices show GAMs which disappear – as expected – when the H-mode sets in. FT-2 can develop an alternative good confinement regime to compare with and has specific diagnostic means to explore the non-linear relation of turbulence and GAMs, and has interesting observations regarding the isotopic effect [6]. This is an ongoing research field.

Other important areas of confinement research are the strong density dependence of an energy confinement time τ_E in case of Globus-M compared to the saturation effects observed in the other two devices, and the trade-off between strong plasma current I_p scaling of τ_E in case of larger aspect ratio and strong toroidal magnetic field B_t scaling in case of spherical tokamaks [7, 4, 9]. In this context, the density profile shape may play a significant role (e. g. for the stabilization of so-called η_i-turbulence). The new pellet injector purchased from the MEGA-Grant and mounted onto TUMAN-3M will help clarifying these issues.

Another important issue for both ITER and the FNS is fast ion confinement. This can be studied in Globus-M and TUMAN-3M. In TUMAN-3M, the classical aspects of ion confinement and slowing down can be explored in the future with a new NPA from the MEGA-Grant. Critical for ion confinement is the radial plasma location [8]. The aspects of the toroidal field ripple have to be investigated in more details. In Globus-M, the heating ions are not well confined owing to the low current and magnetic field [9]. This is clearly shown by neutron and by spectrally resolved charge exchange measurements. Though, this is a strongly negative aspect for plasma heating; it seems, on the other hand, that this condition renders the beam confinement to respond sensitively to the MHD properties of the discharge. Both, sawteeth and Alfven Eigenmodes, lead to fast ion redistribution and losses. This sensitivity can be used to understand better how the mode-fast particle interaction happens on a microscopic scale and causes ion losses. These studies are of utmost importance both for ITER and an FNS because beam current drive is essential and necessitates perfect beam ion confinement also during MHD active periods.

Steady-state operation is even more mandatory for an FNS aiming more at large fluences than at pure fusion. Therefore, all current drive issues are of highest relevance. The theory group of the Ioffe Institute and the groups of both Globus-M and FT-2 tokamaks are well prepared to study lower hybrid current drive. An exciting period is ahead of Globus-M because a novel antenna arrangement which allows poloidal wave launch will be operated soon [10]. New klystrons, provided by the MEGA-Grant, will improve the conditions of Lower Hybrid heating and current drive in this device.

In FT-2, the onset of ion heating by LH waves which stops the bulk electron interaction and diminishes the current drive efficiency has been shown to be shifted to larger density values by replacing hydrogen with deuterium. This is a highly relevant experimental verification of the theoretical expectation. It will be interesting to see to what extent this aspect also affects non-inductive current build-up. This technique is mandatory for spherical tokamaks operated without explicit ohmically heating system. Advancement in this area requires a close cooperation between the three teams: Globus-M, FT-2 and the theory group.

A highlight in the fusion related research of SPbSPU is edge and divertor modeling. The working horse for this purpose is the B2SOLPS code series [11]. This code is the world-wide standard for edge modeling thanks to its advanced physics e. g. its including the effects of drifts. Because the Russian fusion program does not possess a powerful divertor device, most of the modeling and advancements of the code are driven by external interests. The latest step in this development is the cooperation with ITER and the development of a custom-made code version B2SOLPS-IO. Thanks to the increasing diagnostic possibilities of Globus-M to study the edge and divertor plasmas, also some of the modeling activities are concentrating on this device now and, starting from it, on modeling the next step, Globus-M2.

In order to improve modeling, the diagnostic capabilities for the plasma edge were improved thanks to the MEGA-Grant support and will be further improved. The most crucial edge parameter is the scrape-off layer width in the plasma mid-plane. The existing data predict a width in the mm-range for ITER. This is a tremendous threat for the safe and steady-state operation of a fusion device and more research is urgently needed in this field. In the frame of the RLPAT, the first power deposition profiles at the Globus-M divertor target have been measured [12]. These studies will be complemented by a new diagnostics, a supersonic He beam which allows the simultaneous measurement of the density and electron temperature in the divertor chamber of Globus-M.

The group «RF plasma heating» of the RLPAT deals with the improvement of gyrotron technology. Gyrotrons are used for ECRH. This is a sophisticated technology used both in tokamaks and stellarators and also foreseen for ITER. ECRH allows heating without complex plasma-antenna matching as well as current drive and MHD control. The RLPAT group is engaged in improving the electron beam quality and enhancing gyrotron efficiency [13], developing electron beam diagnostics [14] cold field emitters [15]. It works in close cooperation with the developers and manufacturers of high-power gyrotrons from IAP RAS and Gycom (Russia), and Karlsruhe Institute of Technology (KIT, Germany). Of specific interest is the diagnostics of the helical electron beam, which allows to understand better the physical processes possibly leading to higher efficiency gyrotrons [13, 14]. Without a suppressed collector and without space-charge oscillations, a record efficiency of 46 % has recently been obtained with multi-sectional control electrodes and high uniformity and emission efficiency of the thermionic cathodes. Another area of applied research is the development of cold field emitters for mm-wave and THz gyrotrons [14].

IV. Education within RLPAT

A Graduate School has been founded with full recognition by the university. It embraces about 25 graduates. In regular meetings, they present the progress of their work to their supervisors as well as to other professors of the school who are available. Presentations and discussions are held in English. The advantage of training via a Graduate School is that the graduates benefit from the knowledge, experience and contributions of all the professors of the school. In addition, the students train themselves in soft skills like presentation techniques and language capability. Deficiencies in supervision are more easily detected in such a cooperative structure. The student members of a graduate school are more ready to form a scientific community, which allows the better integration of newcomers. The graduate school invites external speakers who cover special topics. This year, five lecturers were invited covering topics like ITER physics, diagnostic techniques, stellarator and mirror machine physics. The lectures are available via the RLPAT Web page. Successful students of the graduate school have been singled out to present their material at international conferences. A separate budget has been set aside for this purpose.

V. The Russian Fusion Program and the Need for RLPAT

For a long time, Russia was leading in tokamak fusion research. In the last decades, Russia has lost its leading role at least in experimental work. The devices of the Russian tokamak program are old and do not contribute to the solutions of present and urgent problems as they are internationally defined and tackled, e. g. in the frame of the ITPA activity. As an outsider, one can recognize the existence of a fusion program in Russia – the participation in ITER and the development of a fusion neutron source. However, it is difficult to recognize, however, a clear national strategy: how to implement an experimental program, which would allow tackling the open scientific issues in broad front or an administrative structure, which would allow implementing such a strategy.

From the seven ITER partners, Russia has the lowest ratio of expenses for the national program to those of ITER. The Russian figure is 0.35; the average value of the other six partners is 0.93. The threat is that Russia will not provide sufficient number of people trained in the most relevant fusion issues and being able to nationalize sufficiently the know-how gained with ITER. The consequence of the present scientific infrastructure situation is that the scientific presence and visibility of Russian fusion scientists – at least in experimental research – is strongly limited. In the last IAEA Fusion-Energy-Conference in 2012 in the USA, Russia was on position #6 among 7 ITER partners, in terms of their contributions and oral papers, and it was only followed by India. Two out of 4 oral papers were given by RLPAT members.

Summarizing, there is a tremendous need of the Russian fusion program to expand the scientific activities in the fusion research and to educate a new generation of scientists capable of working within the national fusion program and with ITER. It is also necessary to broaden the capability to transfer the know-how gained by the operation of ITER into the national program as it is the original intension connected with a commitment to ITER. For these goals, the RLPAT is the proper organizational form to strengthen the cooperative fusion research in St. Petersburg area. The first period of the MEGA-Grant has improved strongly the research possibilities of the SPbSPU to do research in the field of high-temperature fusion plasma physics in cooperation with the experimental teams of the three tokamaks of the Ioffe Institute. RLPAT meets all criteria of a modern institution for research and education. It is structured in such a way that it can contribute to the advancement of fusion research along the major development branches: (1) basic fusion research, (2) preparation of the Ioffe Institute device Globus-M2, (3) contributions to the physics basis of the Russian project of the fusion neutron source and (4) to contribute to the identical physics needs of ITER.

VI. Outlook

The IAC of the RLPAT wrote in its first report: «In summary: the RLPAT presents a very special opportunity for fusion research in Russia, and it has made an excellent start». This was sufficient encouragement to apply for the prolongation of the RLPAT functioning beyond the present two funding years. Fusion is a long-term effort and therefore, the institutions working in this field need long-term support institutionalized by national research priorities. Since Chernobyl and Fukushima, the attractiveness of fission as an energy source has reduced. At a power capacity based on the renewable wind and photovoltaic energies which add up to 25 % of the electric load at the end of 2012, Germany presently experiences the limitations of intermittent electricity supply. Then, there only remains fusion.

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