

# Contribution of Joint Experiments on Small Tokamaks in the framework of IAEA Coordinated Research Projects to mainstream Fusion Research.

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**Abstract.** Joint Experiments (JE) on small tokamaks in the framework of IAEA Coordinated Research Projects have been performed in 2005 – 2015. The paper describes background and rationale for these experiments, how they were organized and executed, main areas of research covered during these experiments, main results, contributions to mainstream Fusion research, main other outputs and discusses lessons learned from these activities. Specific outputs in education and training of young scientists and scientists from developing countries and their importance are underlined.

Keywords: small tokamak, Joint experiments, IAEA CRP, education and training

## 1. Introduction.

Small magnetic fusion devices continue to contribute to many areas of fusion research because of their compactness, flexibility, low operation costs and the high skill of their personnel. Most of the mainstream research on magnetic fusion is carried out or planned on the present and future generations of large experimental devices. At the same time, in many countries (Brazil, Canada, P R of China, Czech Republic, Egypt, Germany, India, Iran, Japan, Portugal, Republic of Korea, Russian Federation, Turkey, Costa Rica, Kazakhstan, Pakistan and USA) more than 40 small tokamaks are operational [1,2]. On small tokamaks and other small Fusion devices, research is carried out typically on the basis of domestic programmes and only in a few cases also in the frame of an international co-operation. The concept of interactive co-ordinated joint research using small devices in the scope of IAEA Co-ordinated Research Projects (CRP) was proposed in 2004 [3,4] with as overall objective to contribute to streamlining the contributions of small magnetic confinement fusion devices to mainstream fusion research by establishing a network of cooperation enabling coordinated investigations of topics of relevance to physics, diagnostics and technology issues of next step fusion devices such as ITER and DEMO.

It was suggested that these CRPs will join participants from IAEA member states, who perform experimental programmes and present results of individual and coordinated research at regular bi-annual CRP Research Coordinating Meetings (RCM), at International Conferences and in journal publications. These activities also were expected to create a platform for building long term relationships between scientists from developing and developed countries. This helps in encouraging further bilateral and/or multilateral collaborations among institutions in various member states in the field of fusion science and technology and also helps to promote fusion research in developing countries and open wider possibilities for young scientists. Work packages for the different research activities can be carried out under the supervision of the members of the CRP thus providing a clear future perspective for small tokamaks in a co-ordinated approach, improving the quality of the scientific output from the small tokamak research activities and resulting in the deeper integration of small tokamaks in national, regional, and international fusion activities and an increase in the number of the collaborative experiments.

In particular, the Joint Experiments (initially called Host Laboratory) have been proposed as very instrumental in coordinating the scientific investigations (their nature, contents, analyses and outputs) as well as in the development and application of novel diagnostics and technologies. As a result, in total eight JEs have been carried out in the framework of the IAEA Coordinated Research Projects on “Joint Research Using Small Tokamaks” (2004-2008) and on “Utilization of a Network of Small Magnetic Confinement Fusion Devices for Mainstream Fusion Research” (2011-2015) on the tokamaks CASTOR, COMPASS and GOLEM (Czech Republic), T-10 (Russia), ISTTOK (Portugal), TCABR (Brazil) and STOR-M (Canada).

These JEs have been very efficient in enabling collaborative studies of relevance to mainstream fusion research. Experimental, theoretical, and modelling activities conducted throughout the CRP lifetime have covered specific areas of physics, diagnostics and technology. Results of JEs and following independent activities on small Fusion devices utilize the flexibility of these devices, their experimental programmes, well developed diagnostics and the high skill of their personnel. The contribution of small fusion devices to the mainstream fusion research has been enhanced through advanced and structured coordinated planning and performing Joint Experiments under the CRP umbrella.

The paper presents the background, organization of JEs and describes how they have been executed, in section 2, and overviews main areas of research. Section 3 presents examples of the research activities and briefly describes main scientific results. In section 4 we discuss main outputs of JEs, both in scientific and social areas with emphasis on education and training of young scientists and scientists from developing countries. In the Conclusions we discuss the main lessons learned from these activities and provide recommendations for future similar undertakings. One of the main goals of this paper is not to repeat or overview main results achieved during JEs, as this is done in detail in the references, but to look at these activities as a whole and to overview the combined scientific, educational and social outputs.

## **2. Background, organization and execution of JEs. Main areas of research activities.**

JEs were organized and supported financially by IAEA via CRP budget and managed by the Physics Section of the Division of Physical and Chemical Sciences at the Department of Nuclear Sciences and Applications, IAEA. The financial support was mainly to cover travel expenses of participants. Other expenses were covered by organizing Institutions, sometimes also providing accommodation for participants.

Typically, JEs were organized as a one or two weeks' event. The CRP Scientific advisory committee in cooperation with the scientific officer of the IAEA agreed the main scope of a JE with the Host Institution. Each JE had a team of local topic leaders and International mentors. The first

days were devoted to introductions to hardware, diagnostics and analysis tools. Proposals for individual experiments have been collected in advance and discussed during kick-off meetings, where detailed experimental plans were presented. Experimental teams were completed and further work was carried out within these teams. Piggy-backing and combined programmes were an often practice. Presentations of provisional results have been done either at the end of the JE, or sometimes during the experimental week. After the end of JE, tasks for data analysis and future work were typically agreed upon. Quite often some of participants would stay after the JE to carry on research. More detailed presentations of results typically have been given at CRP RCMs.

The first JE was proposed at the 1st Research Coordination Meeting of the CRP on “Joint Research Using Small Tokamaks” at Lisbon, 7-10 November 2004, and organized by IAEA, ICTP, Trieste, IPP-ASCR Prague and KFKI HAC, Budapest. It was performed in August 2005 and involved 25 scientists from 11 countries. The objective of the JE was to perform studies of plasma edge turbulence and plasma confinement on the tokamak CASTOR [5-7].

The 2<sup>nd</sup> JE has been hold on T-10 at RRC “Kurchatov Institute” in Moscow, in October 2006. This experiment was aimed to continue turbulence studies of the 1<sup>st</sup> JE, now extending them to the plasma core [8-11]. As one example of investigated topics, JE on T-10 facilitated studies of Geodesic Acoustic Modes (GAM) in this device [12, 13]. T-10 is well suited for these studies, as it has a powerful ECR heating system up to 3 MW. On top of that T-10 is equipped by the Heavy Ion Beam Probe (HIBP), which is a unique diagnostic to study plasma electric potential in the core hot region of the plasma column [44]. The core plasma turbulence was studied by correlation reflectometry (CR). A combination of these features provided a unique opportunity to study core turbulences and GAM-associated oscillations of plasma potential in a wide radial interval and to investigate the temperature dependence of GAM frequency, complementing results achieved on CASTOR. More than 30 scientists from 13 countries participated in this experiment, which indicated increased interest to this activity.

The 3<sup>rd</sup> JE has been performed on ISTTOK tokamak at Lisbon, Portugal in October 2007 with the participation of 24 scientists from 13 countries and was organized by IFT Centro Fusão Nuclear, in co-operation with the IAEA. Study of the poloidal structure of the edge fluctuations with detailed characterization of the space-time structure of the edge fluctuation using different types of electrical probes, study of the influence of external biasing on the edge fluctuations structure were complimented with activities dedicated to development of new techniques and technologies: heavy ion beam diagnostics, tokamak operation in alternating current regimes, testing of the liquid metal limiter concept, plasma control, data acquisition and remote data access [15-20].

The 4<sup>th</sup> JE has been performed on the TCABR tokamak at the University of São Paulo, Brazil, in May 2009. Usual areas of research during previous JEs were complimented with the studies of the interaction of RF (Radio Frequency) electromagnetic waves in the Alfvén range with the tokamak plasmas; studies of the physics of the SOL and plasma edge in the Ohmic heating and Improved Confinement Regimes; detailed studies of the toroidal and poloidal plasma rotation profiles and a search for zonal flow and Geodesic Acoustic modes (GAMs), complementing previous studies of GAMs on T-10 and ISTTOK [21-22, 45], 21 participants represented 7 member states.

The next three JEs have been performed in Prague, Czech Republic, in September 2012, November 2013 and November 2014 on two tokamaks, COMPASS at IPP ASCR, Prague and GOLEM at the Technical University of Prague. All three experiments had common areas of studies and so were much more focused and coordinated. The number of participants significantly increased, exceeding 50 scientists from 13 countries. Experiments have been performed in shifts, and sometimes in parallel on two devices. Results were presented by COMPASS and GOLEM teams at many conferences and meetings, and comprehensively published [23-34, 47 and references within]. COMPASS, for the first time during JEs, implemented Neutral Beam Injection (NBI) which extended

previous studies to new regimes with H-modes, fast particles and also was the first small tokamak to perform studies during JEs in the ITER-like divertor configuration. The scrape-off layer width of parallel heat flux has been measured during 6<sup>th</sup> JE. GOLEM is the new name for CASTOR and mainly is used for education and training. However, during these JEs, GOLEM was used to demonstrate, for the first time on Fusion devices, the use of High Temperature Superconductors (HTS) in tokamak magnets.

Studies on COMPASS included: characterization of edge turbulent transport in limiter and divertor configuration; characterization of the pedestal in ohmic and NB heated H-mode discharges; evaluation of the plasma potential and electron energy distribution function (EEDF) at the plasma edge; edge plasma studies using microwave emission; disruption studies and in particular the toroidal asymmetry [47]; studies of GAMs and NBI-induced Alfvén Eigenmodes as well as AE studies in ohmically heated discharges and studies in other areas. Experiments on GOLEM were dedicated to many pioneering studies in connection with application of HTS magnets: HTS DC and AC tests; HTS switch tests; plasma optimisation with HTS coils and required modifications to the discharge scenario to reduce AC losses in HTS coils during current ramp-up; characterization of quench in HTS coil. Also, low-power ECR pre-ionization based on a cheap commercial magnetron for plasma formation has been demonstrated on GOLEM tokamak.

The latest, 8<sup>th</sup> JE has been hosted by STOR-M tokamak group at the University of Saskatchewan, Canada in August 2015. 14 scientists from 8 countries have participated and publications are in preparation [i.e. 38]. Experiments included studies of the effect of biasing on GAM and on plasma confinement edge potential and GAM under the influence of MHD activity; investigation of the interplay between MHD and turbulence under edge biasing; measurements of high-frequency MHD oscillations as a possibly of runaway-electron driven Alfvén modes in ohmically heated plasmas; model-measurement comparison of magnetic field by image currents in the iron core of STOR-M tokamak with that on GOLEM; study of the edge plasma behavior during the compact torus injection; study of relevant timescales of VDE and current quench.

Overall, about 50 experimental days joined nearly a hundred scientists representing 16 countries in this coordinated research.

### **3. Main scientific outputs of JEs.**

Main results and outputs if JEs are presented in detail in references and here we only mention some of them as prominent examples illustrating how research on small tokamaks benefit of coordination and JEs.

As was shown in the previous Section, in the first JEs, experimental programs were aimed to diagnose and characterize the core and the edge plasma turbulence in a tokamak in order to investigate correlations between the occurrence of transport barriers, improved confinement, electric fields and electrostatic turbulence using advanced diagnostics with high spatial and temporal resolution. In the following JEs, studies have been extended to characterization of the pedestal in ohmically and NB heated H-mode discharges,  $q$ -dependence and non-linear evolution of the NBI-induced Alfvén Eigenmodes, edge plasma studies and microwave emission, relation between halo currents and 3D asymmetries of  $I_p$  during disruptions, evaluation of the parallel electron power flux density using Langmuir and Ball-pen probes, investigation of RF pre-ionisation, and investigation of the use of high-temperature superconductors in PF coils of a tokamak. This not only shows the extension of the covered scientific areas during JEs, but also reflects gains in experience of the JEs team.

Research on small Fusion devices is typically restricted to specific areas and education/training purposes. However, several small devices, i.e. COMPASS, Alcator C-Mod, T-10, Globus-M, START, RTP, TEXT, TJ-2, Uragan-2M, Uragan-3 and others have (or had) extended

research programmes, well-equipped with sophisticated diagnostics and in some cases with powerful heating systems. Taking advantage of the flexibility of small devices a number of diagnostic systems (such as HIBP for core plasma studies and various types of advanced probes for edge studies) as well as novel data analyses techniques have been successfully developed and tested on small Fusion devices.

For example, experiments performed during the 1<sup>st</sup> JE on studies of the edge plasma turbulence using Langmuir probes have shown that the spectra, the correlation functions and the probability density functions (PDF), derived from probe ion saturation current demonstrate complex power laws with multi-scale properties (i.e. bi-Maxwellian EEDF). The experimental knowledge of the EEDF is of great importance to understand the underlying physics processes that occur at the edge of tokamak plasmas, such as turbulence and the formation of the edge transport, the interaction of the plasma with the tokamak wall, etc. The non-Maxwellian tail of the EEDF strongly affects plasma diagnostics, parallel plasma heat fluxes and plasma-neutral and plasma-impurity interactions. An elevated non-Maxwellian tail into the plate results in an overestimate of the temperature estimation by divertor Langmuir probes by a factor of 2–6, using classical probe techniques. Detailed studies have been performed during JEs on CASTOR and then later on COMPASS [35-38]. Both temperature and density measurements show bi-Maxwellian features in the vicinity of the LCFS while in the far SOL the EEDF is Maxwellian.

Most of the LP and other diagnostics and techniques developed and tested during JEs are now routinely used on different devices within the network of small tokamaks, and some are being implemented on larger devices such as the WEST (France) and ASDEX-Upgrade (Germany) tokamaks as well as the TJ-II stellarator (Spain). The relative entropy and discrimination (Kullback-Liebler divergence) was used to compare PDFs in T-10 and TCABR [17].

A good illustration of the relevance of the work conducted during JEs is that Alfvén Eigenmode studies on the COMPASS tokamak during JEs have been an integral part of the International Tokamak Physics Activity (ITPA) on Energetic Particles in support of ITER. Alfvén Eigenmode (AE) studies was an important area of the JEs research. Instabilities driven by energetic ions have been observed in many fusion devices of various size, i.e. in small, medium and large size tokamaks and stellarators. The induced modes, AEs, are driven by the energy transfer from energetic ions to the waves. During the 6<sup>th</sup> JE, studies of AE modes on COMPASS tokamak have been performed in the plasma heated by the 40keV neutral beam. However, AEs have also been observed in discharges when NBI was not used. It is important to mention that the modes were observed only in H-mode phase of the discharge [30]. To check other possibilities for AEs to be induced, an attempt to find such modes have been later repeated during 8<sup>th</sup> JE on STOR-M and the analysis of results is on-going.

Another example of studies performed during different JEs are studies of the Geodesic Acoustic Modes (GAM) [11-13], the high-frequency branch of the Zonal Flows, which is considered now as a turbulence self-regulating mechanism, affecting anomalous energy and particle transport. The study of GAM, originated on T-10 and performed during the 2<sup>nd</sup> JE, with a set of core and edge diagnostics, and then extended to ISTTOK, COMPASS and STOR-M tokamaks during following JEs, have shown long-range correlations with a symmetric structure in the toroidal and poloidal directions and radial uniformity of frequency suggesting a global GAM. The theoretically predicted square root  $T_e$  dependence and uniform poloidal structure ( $m=0$ ) were confirmed experimentally during JEs. A more detailed analysis, based on the abilities of the advanced diagnostics on T-10 and COMPASS have shown new GAM features - eigenmode structure, not predicted by the local theory [39]. The radial uniformity of the GAM frequency, found first in JE on the circular cross-section tokamak T-10, was then confirmed on the D-shaped COMPASS [32]. The magnetic component of a GAM was first observed during JE on T-10 and then confirmed on COMPASS [32].

The studies of Alfvén Eigenmodes and Geodesic Acoustic modes present an example of the JEs contribution to fundamental plasma physics, putting the bridge from high-temperature plasma physics to astrophysics by AE studies and to physics of planet's atmosphere by GAM/Zonal Flows studies [46].

One of the major risks on our path to Fusion power is connected with the desire to rely on fast progress in the development of materials, both for the first wall/divertor and for magnets, and on the current drive technologies. Small Fusion devices can provide significant contribution to resolving some of the relevant issues. The JEs have also been successful in pursuing fusion technology activities. Major achievements include the development and testing of high temperature superconducting magnets on tokamak devices. High temperature superconductors have the potential to provide higher magnetic field in comparison with the currently used low temperature superconductors. The first application of HTS in poloidal field (PF) magnets has been demonstrated on a small tokamak GOLEM at the Technical University of Prague and many following experiments have been performed during JEs [23, 25-29].

Studies of ECR pre-ionisation system have been performed during 5-7<sup>th</sup> JEs on GOLEM using 2.45GHz 1kW magnetron taken from a standard microwave oven, first proposed on GUTTA tokamak [40]. The use of commercial magnetrons allowed the pre-ionisation system to be very cheap and so affordable for small tokamaks, and later has been implemented on the GLAST tokamak in Pakistan [28, 29].

#### **4. Main outputs of JEs**

Joint Experiments within the IAEA Coordinated Research Projects activities are paying visible dividends and have resulted in a substantial number of joint presentations and publications. Combined and coordinated efforts within a network of small fusion devices enhance the contribution of small devices to mainstream nuclear fusion R&D. Joint Experiments have clearly demonstrated that small tokamaks are suitable and important for broad international cooperation, providing the necessary environment and manpower to conduct dedicated joint research programs.

However, research on small devices has obviously some limits. Small tokamaks typically can't compete with medium size and large facilities neither in availability of comprehensive diagnostics and plasma parameters, although COMPASS, Alcator C-Mod, START and some other small tokamaks have demonstrated extraordinary performance and made or making visible contribution. As examples, we can remind beta record on START [41] and achievement of record pressure in tokamaks on Alcator C-Mod [42]. Joint experiments on COMPASS have demonstrated how an international team can advance utilization of capabilities of well-equipped experimental device [29, 31-37, 47]. Contribution of JEs on small tokamaks is not limited by scientific results obtained during these experiments. In many cases JEs played a role of a trigger for a following-up research and brainstorming during JEs provided ideas and plans for future experiments. The team building also can't be not noticed, as discussed above.

The JEs have also proven to be a conducive environment for providing opportunities to students and young researches from participating members of CRPs to gain knowledge and experience that can later be used in domestic programmes. Experimental work on small devices is very appropriate for education of students, scientific activities of post-graduate students and for training of personnel for larger experimental facilities. Overall, the JEs have substantially contributed to capacity building and human resource development in various institutions in IAEA member states, and in particular, in developing countries, such as Brazil, Mexico, Pakistan, Iran, China, Kazakhstan, Costa Rica, Egypt [1, 2, 28, 29, 43]. This represents an important asset in the provision of future skilled experts that will make possible the implementation of next steps in fusion energy development,

which show at present significant advances in the developing countries and in particular in Asia where most of recently built tokamaks are operating.

## 5. Conclusions

Joint Experiments (JE) on small tokamaks in the framework of IAEA Coordinated Research Projects have been performed in 2004 – 2015 and described in this paper. The background and rationale for these Joint Experiments, how they were organized and executed, main areas of research covered during these experiments, main results, contributions to mainstream Fusion research, main other outputs and lessons learned from these activities are discussed. Specific outputs in education and training of young scientists and scientists from developing countries already demonstrated significant advances through broadening the geography of the Fusion research. An important output of JEs is also in the demonstration of a possibility to organize joint experimental activities under the IAEA umbrella, efficiently and on a regular basis. However, the future of JEs depends on activity of participated and new institutions and on utilization of the established network.

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## References

- [1] Gryaznevich M.P. *et al* 2005 Joint Research Using Small Tokamaks. *Proc. 20th IAEA Fusion Energy Conference, 1-6 November 2004, Vilamoura, Portugal, 1-6 November 2004. IAEA Vienna (2005) IAEA-CSP-25/CD OV/P6-15*
- [2] Gryaznevich M.P. *et al* 2005 *Nuclear Fusion* **45** S245
- [3] Van Oost G., E. Del Bosco, M. P. Gryaznevich, A. Malaquias, G. Mank 2006. Proposals for an influential role of small tokamaks in mainstream fusion physics and technology research. *AIP Conf. Proc.* **875**, 142 <http://dx.doi.org/10.1063/1.2405918>. *Proceedings of 16th IAEA TM on Research Using Small Fusion Devices, 30 November-2 December 2005, Mexico City, Mexico (Vienna, Austria, 2006, 060-15491) IT-03*
- [4] M. P. Gryaznevich, *et al* 2006 Recent Activities on the Experimental Research Programme Using Small Tokamaks. *AIP Conf. Proc.* **875**, 120 <http://dx.doi.org/10.1063/1.2405914>. *Proceedings of 16th IAEA TM on Research Using Small Fusion Devices, 30 November-2 December 2005, Mexico City, Mexico (Vienna, Austria, 2006, 060-15491) IT-01*
- [5] Van Oost G. *et al* 2007 Joint experiments on small tokamaks: edge plasma studies on CASTOR. *Nuclear Fusion* **47** 378
- [6] Van Oost G. *et al* 2006 Joint Experiments on Small Tokamaks. *IEAEA FEC Preprints. (IAEA), 2006. Proc. IAEA Fusion Energy Conference. Chengdu (CN), 16.10.2006-21.10.2006 EX/P4-34*
- [7] Van Oost G. *et al* 2007 Joint experiments on small tokamaks. *Iranian Physical Journal*, **1** 1
- [8] Gryaznevich M. *et al* 2007 Characteristics of the core and edge plasma turbulence in small Tokamaks. 2008 *Iranian Physical Journal*, **2-3** 1
- [9] Gryaznevich M. *et al* 2007 Progress on Joint Experiments on Small Tokamaks. *34th EPS Conference on Plasma Phys. Warsaw, 2 - 62 July 2007, P-1.070*

- [10] Melnikov A.V. *et al* 2007 The study of GAM properties in the T-10 tokamak. *34th EPS Conference on Plasma Phys. Warsaw, 2 - 62 July 2007, P-1.096*
- [11] Perfilov S.V. *et al* 2007 Absolute plasma potential, radial electric field and turbulence rotation velocity measurements in low-density discharges on the T-10 tokamak. *34th EPS Conference on Plasma Phys. Warsaw, 2 - 62 July 2007, P-2.058*
- [12] Melnikov A.V. *et al* 2006 *Plasma Phys. Control. Fusion* **48** S87
- [13] Melnikov A.V. *et al* 2015 *Nuclear Fusion* **55** 063001
- [14] Van Oost G, *et al* 2008 Joint experiments on the tokamaks CASTOR and T-10. *AIP Conf. Proc., 996 24. Plasma and Fusion Science: 17th IAEA Technical Meeting on Research Using Small Fusion Devices, 22-24 October 2007 Lisbon, Portugal*
- [15] M Gryaznevich, *et al* 2009. Results of Joint Experiments and other IAEA Activities on Research Using Small Tokamaks. *CD-ROM file. Fusion Energy 2008. Proceedings of the 22nd IAEA Conference, Geneva, 13-18 October 2008, OV/P1-1 (IAEA, 2009)*
- [16] Gryaznevich M. *et al* 2009 *Nuclear Fusion* **49** 104026
- [17] Budaev V.P. *et al* 2007 The Characterization of Edge Plasma Intermittency in T-10 and TCABR Tokamaks. *Proceedings of 34th EPS Conference on Plasma Phys. Warsaw, 2 - 62 July 2007, P-1.088*
- [18] Van Oost G, *et al* 2008 Overview of results from the IAEA-CRP 3rd International Joint Experiment on the tokamak ISTTOK. *35th EPS Conference on Plasma Physics, Hersonissos, Crete, Greece, June 9-13, 2008, P-2.040 (European Physical Society, 2008) Vol 32D*
- [19] Silva C. *et al* 2008 *Fusion Energy 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland, 2008)* (Vienna: IAEA) CD-ROM file EX/P4-11 <http://www-naweb.iaea.org/napc/physics/FEC/FEC2008/html/index.htm>
- [20] Fernandes H. *et al* 2009. The International Joint Experiment ISTTOK. *Plasma Physics Reports* **35** 841
- [21] Severo J.H.F. *et al* 2009 *Nuclear Fusion* **49** 115026
- [22] Kuznetsov Yu.K. *et al* 2012 *Nucl. Fusion* **52** 063004
- [23] Gryaznevich M. *et al* 2012 *First Results from Tests of High Temperature Superconductor Magnets on Tokamak*. Proc. 39th EPS Conference & 16th Int. Congress on Plasma Physics, Stockholm, 2 - 6 July 2012, Europhysics Conferences Abstracts, Vol. **36F** P2.052, <http://ocs.ciemat.es/EPSICPP2012ABS/html/>
- [24] Bromová E. *et al* 2012 Recent results from the GOLEM tokamak. 'Indeed, you can teach an old dog some new tricks.' *Proc. 39th EPS Conference & 16th Int. Congress on Plasma Physics, Stockholm, 2 - 6 July 2012, Europhysics Conferences Abstracts, Vol. 36F* P2.059 <http://ocs.ciemat.es/EPSICPP2012ABS/html/>
- [25] Gryaznevich M. *et al* 2012 Progress in application of High Temperature Superconductor in Tokamak Magnets. *Proc. of 27th Symposium on Fusion Technology September 24-28 2012, Liege, Belgium* P2.81 <http://www.soft2012.eu/papers-and-contributions>
- [26] Gryaznevich M. *et al* 2013 First Results from Tests of High Temperature Superconductor Magnets on Tokamak. *Fusion Energy 2012. Proceedings of the 24th IAEA Conference, San Diego, October 8-13, 2012, (IAEA, 2013) FTP/P7-26*
- [27] Gryaznevich M. *et al* 2013 *Fusion Energy and Design* **88** 1593



- [28] M Gryaznevich, G Van Oost, J Stöckel, B N Kuteev, R Kamendje, and the IAEA CRP teams. 2014 Contribution to Fusion Research from IAEA Coordinated Research Projects and Joint Experiments. *CD-ROM file. Fusion Energy 2014. Proceedings of the 25th IAEA Fusion Energy Conference*, IAEA 2014 OV-P04
- [29] Gryaznevich M. *et al* 2015 *Nuclear Fusion* **55** 104019
- [30] Melnikov A. V. *et al* 2015 *Plasma Phys. Control. Fusion* **57** 065006
- [31] Loureiro J. *et al* 2014 Scrape-off layer width of parallel heat flux on tokamak COMPASS *Plasma Physics and Technology* **1** 121
- [32] Seidl J. *et al*, 2015 Observation of geodesic acoustic mode-like oscillations on COMPASS, *42nd EPS Conference on Plasma Physics, Lisbon, Portugal, 22-26 June 2015*. P4.103
- [33] Markovic T. *et al* 2015 Alfvén-wave character oscillations in tokamak COMPASS plasma *42nd EPS Conference on Plasma Physics, Lisbon, Portugal, 22-26 June 2015*. P4.104
- [34] Adamek J. *et al* 2017 *Nucl. Fusion* **57** 022010
- [35] Dimitrova M. *et al* 2014 "Plasma Parameters on COMPASS Divertor during Ohmic D-Shaped Plasmas" *Contrib. Plasma Phys.* **54** 255
- [36] Popov T. K. *et al* 2014 "Langmuir Probe Evaluation of the Plasma Potential in Tokamak Edge Plasma at non-Maxwellian EEDF" *Contrib. Plasma Phys.* **54** 267
- [37] Popov T. K. *et al* 2015 "Bi-Maxwellian electron energy distribution function in the vicinity of the last closed flux surface in fusion plasma", *Plasma Phys. Control. Fusion* **57** 115011
- [38] Xiao C. *et al* 2016 Modification of toroidal flow velocity through momentum injection by Compact Torus Injection into the STOR-M tokamak discharge. *Presentation at 26<sup>th</sup> IAEA FEC 17-22 October 2016, Kyoto, Japan*. EX/P7-39
- [39] Zenin V.N. *et al*, 2014 Study of poloidal structure of geodesic acoustic modes in the T-10 tokamak with heavy ion beam probing. *Problems of Atomic Science and Technol, Ser: Plasma physics.* **6** 269
- [40] Vorobyov G. M. *et al* 2006 Experiments of the small Spherical Tokamak Gutta. *AIP Conf. Proc.* **875** 53 (2006); <http://dx.doi.org/10.1063/1.2405902>
- [41] M Gryaznevich, *et al* 1998 *Phys. Rev. Lett.* **50** 3972
- [42] Marmor E.S. *et al* 2016 Overview of high-field divertor tokamak results from Alcator C-Mod. *Presentation at 26<sup>th</sup> IAEA FEC 17-22 October 2016, Kyoto, Japan*. OV/2-5
- [43] Gryaznevich M. 2008 Capacity Building in Nuclear Fusion: Fusion Research using Small Tokamaks. *Proc of the 1st NILES Workshop on Lasers and Plasmas and 10th Plasma Easter Meeting, 16-18 March 2008, University of Cairo, Egypt*
- [44] Melnikov A. V. *et al* 2017 "Heavy ion beam probing – diagnostics to study potential and turbulence in toroidal plasmas". Accepted for publication in *Nuclear Fusion*, 2017
- [45] Silva C. *et al* 2008 Structure of the ISTTOK edge plasma fluctuations, *Proc. 35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA* **Vol.32D**, P-1.021
- [46] Melnikov A. 2016 *Nature Physics* **12** 386.
- [47] Gerasimov S.N. *et al* 2015 *Nuclear Fusion* **55** 113006