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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 (JEs) on small tokamaks have been regularly performed between 2005 and 2015 under the framework of the International Atomic Energy Agency (IAEA) coordinated research projects (CRPs). This paper describes the background and the 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, and discusses lessons learned and outcomes from these activities. We underline several of the most important scientific outputs and also specific outputs in the education of young scientists and scientists from developing countries and their importance.

Keywords: small tokamaks, joint experiments, IAEA CRP, education and training, turbulence, geodesic acoustic mode

(Some figures may appear in colour only in the online journal)

1. Introduction

Most of the mainstream research on magnetic fusion is carried out or planned for the present and future medium and large experimental devices. However, in many countries (Brazil, Canada, People's Republic 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 currently operational [1, 2]. Small tokamaks had and can continue to provide efficient contributions to mainstream areas of fusion research benefiting from the flexibility of their experimental programmes, low operation costs and high skills of their staff. On these devices, research is carried out typically in a scope of national programmes and in some cases also in the frame of an international co-operation. The concept of co-ordinated research using small tokamaks in the scope of IAEA coordinated research projects (CRPs) was proposed in 2004 [3, 4] with an objective to increase the efficiency of the contributions of small tokamaks to the mainstream fusion research through establishing a network of cooperation, enabling coordinated advances in many topics relevant to physics, diagnostics and technology issues of next-step tokamaks such as ITER and DEMO.

It was suggested that coordinated projects under the IAEA umbrella will attract scientists who will participate in JEs and other related activities. They are expected to present results of their individual and coordinated research at International Fusion and Plasma Physics Conferences, publish in journals and report progress at CRP research coordinating meetings (RCMs). Participation in CRPs and JEs were expected to result in establishing bilateral and multilateral collaboration between scientists from developed and developing countries and encourage establishing collaborations between institutions in various member states in fusion science and technology. This will help promote fusion and plasma physics research in developing countries and open possibilities for participation of young scientists in different research activities. These activities can be supervised by the members of the CRP, providing better chances for small tokamaks to perform experimental programmes in a coordinated way, which should improve the quality of the scientific output from their research and result in the future integration of participating tokamaks and their research teams in national, regional, and international fusion activities.

The JEs have been proposed as expected to be the most efficient way in coordinating the scientific research and development activities on small tokamaks. As a result, 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), eight JEs have been carried out on CASTOR (Czech Republic), T-10 (Russian Federation), ISTTOK (Portugal), TCABR (Brazil), COMPASS and GOLEM (Czech Republic) and STOR-M (Canada).

JEs have been indeed proved to be very efficient in strengthening collaborative fusion research. Experiments, theoretical studies and computer simulations conducted during CRPs and in JEs have been performed in many specific areas of plasma physics, as well as the development of new diagnostic tools and technologies. The results of JEs and following activities within the CRP framework took full advantage of the flexibility of these small tokamaks in performing various experiments, supported by well-developed advanced diagnostics and of the high skill of their personnel. The contribution to the mainstream fusion research has been enhanced by advanced and structured coordinated detailed planning.

In section 2, the background organization of JEs is presented and how they have been executed is described, covering the main areas of fusion research. Section 3 presents examples of the research activities and a brief description of the main scientific results. The paper also addresses the main outputs of JEs here, both in scientific and social areas with an emphasis on the training and education of young researchers and scientists from developing countries. In the conclusion section, the main lessons learned from these activities are discussed and recommendations for future similar undertakings are presented. One of the main goals of this paper is not to repeat or overview main scientific 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. However, in the conclusion several important scientific outputs are underlined.

2. Background, organization and execution of JEs and main areas of research activities

JEs were organized and supported financially by the IAEA via the 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 provided to cover the 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 a common practice. Presentations of provisional results have been done either at the end of a JE, or sometimes during the experimental week. After the end of JEs, tasks for the data analysis and for the future work were typically agreed upon. Quite often some of the participants would stay after the JE to carry on research. More detailed presentations of the results were given at CRP research coordinating meetings.

The first JE was proposed at the RCM-1 of the first CRP at Lisbon, 7–10 November 2004, and organized by IAEA, ICTP, Trieste, IPP AS of Czech Republic and KFKI HAC, Hungary. It was performed in August 2005 and involved 25 scientists from 11 countries. The objective of the JE was to carry out experiments on studies of the edge turbulence and plasma confinement on the tokamak CASTOR at IPP-ASCR Prague. Biasing an electrode inserted into the edge plasma was used to modify the turbulence and transport behavior. Detailed results of JE1 are presented in [5–7].

The 2nd JE has been held in T-10 at the NRC Kurchatov Institute, in October 2006. This experiment continued turbulence studies of the JE1, now extending the edge studies to the plasma core [8–11]. As one example of investigated topics, JE on T-10 facilitated studies of geodesic acoustic modes (GAMs) in this device [12–14]. T-10 is well suited for these studies, as it has a powerful ECR heating (ECRH) system with power up to 3 MW. T-10 is equipped with the heavy ion beam probe (HIBP) [15], which is a unique diagnostic to study plasma electric potential in the hot core region of the plasma column [16]. The turbulence in the plasma core was studied also using correlation reflectometry [17]. A combination of these diagnostics 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 [18]. The edge turbulence analysis included comparison of probability density function (PDF) in the scrape-off layer (SOL) of T-10 and TCABR, showing similar features and demonstrating strong non-Gaussian PDF in the SOL while in the vicinity of the last closed flux surface (LCFS) the PDF was much closer to the Gaussian. More than 30 scientists from 13 countries participated in this experiment, which indicated increased interest to this activity. Results were presented by the T-10 team jointly with the CRP team at many conferences and meetings, and comprehensively published, see references below.

The 3rd JE has been performed on the ISTTOK tokamak in Lisbon, Portugal, in Autumn 2007. 24 scientists from 13 countries participated at this JE, which was organized by IST-IPFN, in cooperation with the IAEA. Studies of the poloidal structure of the edge fluctuations using different types of electrical probes, of the influence of the biasing on the edge fluctuations amplitude and structure were complimented with activities dedicated to the development of new techniques and technologies: heavy ion beam diagnostics, the operation of the tokamak in alternating current (AC) mode, tests of the liquid Ga/Li limiter concept, advanced plasma position control, novel approaches in data acquisition and remote data access [19–22].

The 4th JE has been performed at the University of São Paulo on the TCABR tokamak, in May 2009. Usual areas of research during previous JEs were further complemented with the studies of the interaction of RF (Radio Frequency) Alfvén range waves with the plasma in a tokamak, studies of the physics of the SOL in different confinement regimes, detailed studies of the plasma rotation profiles (toroidal and poloidal), and a search for zonal flows and GAMs, extending previous studies of GAMs on T-10 and ISTTOK [23–26]. As an example of one of the advanced diagnostics, 5-pin Langmuir probes (LPs), 6-pin double LPs for zonal flow measurements and 20-pin rake probes have been used during these experiments. 21 participants represented seven IAEA member states at this JE4.

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 the COMPASS and GOLEM teams jointly with the CRP team at many conferences and meetings, and comprehensively published [27–38], and references within. COMPASS, for the first time during JEs, implemented the neutral beam injection (NBI), which extended previous studies to new regimes with H-modes, the observation of fast particles and also was the first small tokamak to perform studies during JEs in the ITER-like divertor configuration.

GOLEM is the new name for the CASTOR tokamak and is mainly used for education and training. However, during these JEs, GOLEM was used to demonstrate, for the first time on fusion devices, feasibility of using of high temperature superconductors (HTSs) in tokamak poloidal field coils.

Studies on the COMPASS tokamak during these JEs included characterization of the turbulent transport in limiter and divertor configurations; investigations of the plasma edge in the H-mode in the ohmic heated (OH) and the NB heated discharges, detailed studies of the plasma electric potential and of the electron energy distribution function (EEDF) at the plasma edge; the edge plasma studies using microwave emission; disruption studies and in particular the toroidal asymmetry [38]; studies of GAMs [34] and NBI-induced Alfvén Eigenmodes (AEs) [35] as well as AE studies in the ohmically heated discharges and studies in several other areas [31, 32]. The width of the parallel heat flux in the scrape-off layer has been measured during the 6th JE on COMPASS, showing the decrease in the decay length with the increase in the plasma current or the average density [38] and effects of the 3D plasma distortion have been observed, increased during the pre-disruption phase. Experiments on GOLEM were dedicated to many pioneering studies in connection with the application of the HTS magnets: HTS DC and AC tests, HTS switch tests, plasma optimization with HTS coils and required modifications to the discharge scenario to reduce AC losses in HTS coils during current ramp-up, and also characterization of a quench in the HTS coil. Also, a low-power ECR pre-ionization based on a cheap commercial magnetron for plasma formation has been demonstrated on the GOLEM tokamak and was later used on other small tokamaks participating in the CRP.

The latest, 8th JE has been hosted by the STOR-M tokamak group at the University of Saskatchewan, Canada, in August 2015. 14 scientists from 8 countries have participated. Experiments included studies of the effect of resonant magnetic perturbation (RMP) on GAMs and on the plasma confinement; edge potential and GAMs under the influence of the MHD activity, investigation of the interplay between MHD and turbulence under the edge biasing, measurements of high-frequency MHD oscillations as a possibly runaway electron-driven Alfvén modes in ohmically heated plasmas, a model-measurement comparison of magnetic fields induced by image currents in the iron core of STOR-M tokamak with that on GOLEM, the study of the edge plasma behavior during the compact torus injection [39], the study of relevant timescales of a vertical displacement event (VDE) and plasma 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 of 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 from coordination and JEs.

3.1. Overview of main areas of scientific research

As shown in the previous section, the first JE studies were aimed at the characterization of the core and the edge turbulence to find correlations between the appearance of an improved confinement, transport barriers, electric fields and the electrostatic turbulence using diagnostics with sufficient temporal and spatial resolution. In the following JEs, studies have been extended to characterization of the pedestal in the ohmically and neutral beam heated H- and L-mode discharges, studies of the q-dependence and non-linear evolution of the neutral beam induced AEs, studies of the edge plasma in these regimes, studies of the microwave emission, relation between 3D asymmetries of the plasma and halo currents during disruptions, measurements of the parallel electron power flux with Langmuir and Ball-pen probes. This not only shows the extension of the covered scientific areas during JEs, but also reflects gains in the experience of the JEs team.

3.1.1. Characterization of the edge plasma using Langmuir probes. Research on small tokamaks is often restricted to specific research areas and to education/training purposes. However, some small fusion devices that participated in the IAEA CRPs and JEs, i.e. the COMPASS, T-10, Globus-M, START tokamaks, TJ-II and Uragan-2M stellarators and others, have (or had) broad and extended research programmes, they are well-equipped with advanced diagnostics and in some cases with relatively powerful heating systems. Taking advantage of the flexibility of small devices, a number of diagnostic systems (such as various types of advanced probes for the edge studies) as well as novel data analyses techniques have been successfully developed and tested.

For example, experiments that have been performed during the JE1 on studies of the edge plasma turbulence using LPs have shown that the correlation function, the spectra and the PDF, derived from the LP ion saturation current, feature complex power laws with multi-scale properties (i.e. the bi-Maxwellian electron energy distribution function (EEDF)). The experimental knowledge of the EEDF is of great importance for the understanding 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 parallel plasma heat fluxes and interactions of the plasma with neutrals and impurities. The observed non-Maxwellian tail on the EEDF results in an overestimate of the temperature measured by divertor LPs by a factor of 2–6. Detailed studies have been performed during JEs on CASTOR and then, later, on COMPASS [40–42]. Both the temperature and the density measurements show such bi-Maxwellian features in the vicinity of the LCFS while in the far SOL the EEDF is Maxwellian, similar to results of the PDF studies in the SOL of T-10 and TCABR tokamaks.

The relative entropy and discrimination (Kullback-Liebler divergence) was used to compare PDFs in T-10 and TCABR [23]. Most of the LPs 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 and on the TJ-II stellarator (Spain) [43–46].

3.1.2. Studies of the core instabilities. A good illustration of the relevance of the work conducted during JEs is that AE 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. The AE studies were an important area of the JEs research. AEs are driven by the energy of the energetic ions transferred to the electromagnetic plasma waves [47–49]. During the JE6, studies of AEs on COMPASS tokamak have been performed in the plasma heated by the 40 keV neutral beam. However, AEs have also been observed in discharges when NBI was not used [31]. These modes were observed only in the H-mode phase of the discharge [50, 51]. To check other possibilities for AEs to be induced, an attempt to find such modes has been later repeated during the 8th JE on STOR-M [43].

Another example of studies performed during several JEs is the study of the GAMs [12], the high-frequency branch of the zonal flows, which is considered now as a turbulence self-regulating mechanism, affecting the anomalous energy and the particle transport. The study of GAM, originated on T-10 and performed during the JE2, with a set of core and edge diagnostics, and then extended to ISTTOK, COMPASS and STOR-M tokamaks during the following JEs, was later extended on T-10 and brought a lot of important results. As mentioned above, T-10 is equipped with the HIBP, which is a unique diagnostic to study plasma electric potential in the plasma core region. Figure 1 shows variation of the plasma potential at the mid-radius of T-10 as a function of the line-averaged electron density $\bar{n}_{\mathrm{e}}$ and/or the effective collisionality, $\nu_{\mathrm{eff}} = 0.1RZ_{\mathrm{eff}}\bar{n}_{\mathrm{e}}/T_{\mathrm{e}}(0)^2$ [52]. HIBP data is taken from both initial and flat-top phases of different ohmically heated and ECRH shots. Here R is the major radius of a torus, Z_{eff} is plasma effective charge, $T_{\mathrm{e}}(0)$ is central electron temperature.

An example of a GAM is presented in figure 2. It demonstrates the important features of the GAM and quasi-coherent mode (QC) [53, 54]: the GAM is highly pronounced in the plasma potential oscillations, see figure 2(b), while it is marginally visible in the plasma density PSD, where QC is dominating, see figure 2(c). Both GAM and QC mode shows high ($0.6 < \mathrm{Coh} < 1$) coherences and the finite cross-phases $\theta_{\mathrm{GAM}}(\varphi, n) = -\pi/2, |\theta_{\mathrm{QC}}(\varphi, n)| < 1$.

Bi-spectral analysis of the HIBP data from figure 2 shows the presence of the three-wave coupling between GAM and ambient turbulence, as demonstrated in figure 3. From the figure, it is shown that statistically the significant value of the

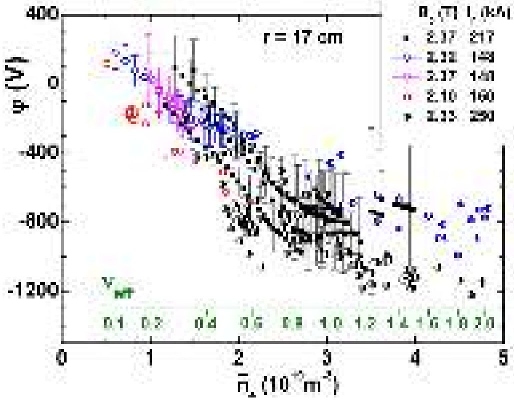

Figure 1. Variation of the plasma potential at the mid-radius of T-10 as a function of line-averaged electron density $\bar{n}_e$ and/or effective collisionality. Adapted courtesy of IAEA. Figure from [52]. Copyright (2013) IAEA.

bicoherence coefficient $b^2_{\varphi,\,n,n}$, calculated for the triplet φ, n, n—potential, density, density, at $f = f_{\mathrm{GAM}}$ extends over the whole available frequency range under study up to the Nyquist frequency 350 kHz (see figure 3(a)). This data is supported by the finite values of bi-phase (see figure 3(b)). Importantly, the value of b^2 is not uniform over the whole frequency range but has the local maxima at the QC mode frequency domain (see figure 3(a)).

Long-range correlations were also shown with a symmetric structure in the poloidal and toroidal directions and the radial uniformity of the frequencym suggesting a global GAM [55]. The theoretically predicted square root T_e dependence and uniform poloidal structure ($m = 0$) were confirmed experimentally during JEs and later [56]. A more detailed analysis, based on the abilities of the advanced diagnostics on T-10 and COMPASS has shown new GAM features—eigenmode structure, not predicted by the local theory [57]. The radial uniformity of the GAM frequency, found first during the JE2 on the circular cross-section tokamak T-10, was then confirmed on the D-shaped COMPASS [41]. The magnetic component of a GAM was first observed during the JE2 on T-10 [13] and then also confirmed on COMPASS along with the three-wave coupling between GAM and broadband turbulence [43].

The studies of AEs and GAMs 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 [58].

3.2. Development of tools and technologies

One of the challenges on the path to fusion power is connected with the advances in the development of materials for the first wall, divertor and for magnets. The JEs have been successful in pursuing various fusion technology activities. Major achievements include the development and testing of high-temperature superconducting magnets on tokamak devices. High-temperature superconductors (HTS) have the potential to provide higher magnetic fields in comparison with the currently used low temperature superconductors. Figure 4 shows results of the first measurements of the critical current (measured at the increase of the resistivity) in different turns of the poloidal field HTS coil on GOLEM. Measurements of the voltage over each turn of the coil and over each joint also helped to identify the most probable locations of quenches. The critical current was around 300 A, however the quench did not result in a coil failure. After the first use of the HTS in poloidal field tokamak magnets has been successfully demonstrated on a small tokamak GOLEM at the Technical University of Prague, and many following experiments have been performed during and after JEs [8, 28, 29, 37].

Studies of the ECR pre-ionization have been performed during JE5–JE7 on GOLEM using a 2.45 GHz 1 kW magnetron taken from a standard microwave oven, first proposed on the GUTTA tokamak [59]. Such use of commercial magnetrons makes it possible for the pre-ionization system to be not expensive and so quite affordable for small devices, and later has been implemented on the GLAST tokamak in Pakistan [30].

3.3. Specific outputs of JEs and their role in the mainstream fusion research

JEs within the IAEA CRP activities have resulted in a number of joint publications and presentations. Coordinated research within a network of small fusion devices plays a visible role in enhancing their contribution to the mainstream nuclear fusion R&D. These experiments have clearly demonstrated that small tokamaks can be used for a broad international cooperation, providing manpower and an environment to conduct joint research programmes.

However, research on small devices has obviously some limits. Small tokamaks typically cannot compete with medium-sized and large facilities in the availability of comprehensive diagnostics and plasma parameters, although COMPASS, Alcator C-Mod, START and some other small tokamaks have demonstrated an extraordinary performance and made or making visible contribution. As examples, we can remind of the beta record on START [60] and the achievement of record pressure in tokamaks on Alcator C-Mod [61]. Joint experiments on COMPASS have demonstrated how an international team can advance the utilization of capabilities of a well-equipped experimental device [30, 32–35, 37–40]. 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 clearest example of such an influential role of the JE on the scientific program of the hosting device is the study of GAM on T-10, where GAM was studied in its link to the plasma broadband turbulence and confinement. A number of experiments were performed during JE2 and later during the period of CRPs. The results were presented in a number of the IAEA TM on Research Using Small Fusion Devices (RUSFD), IAEA-FEC conferences [62–67], EPS Conferences on Plasma Physics [9–11, 68–82], and other conferences like

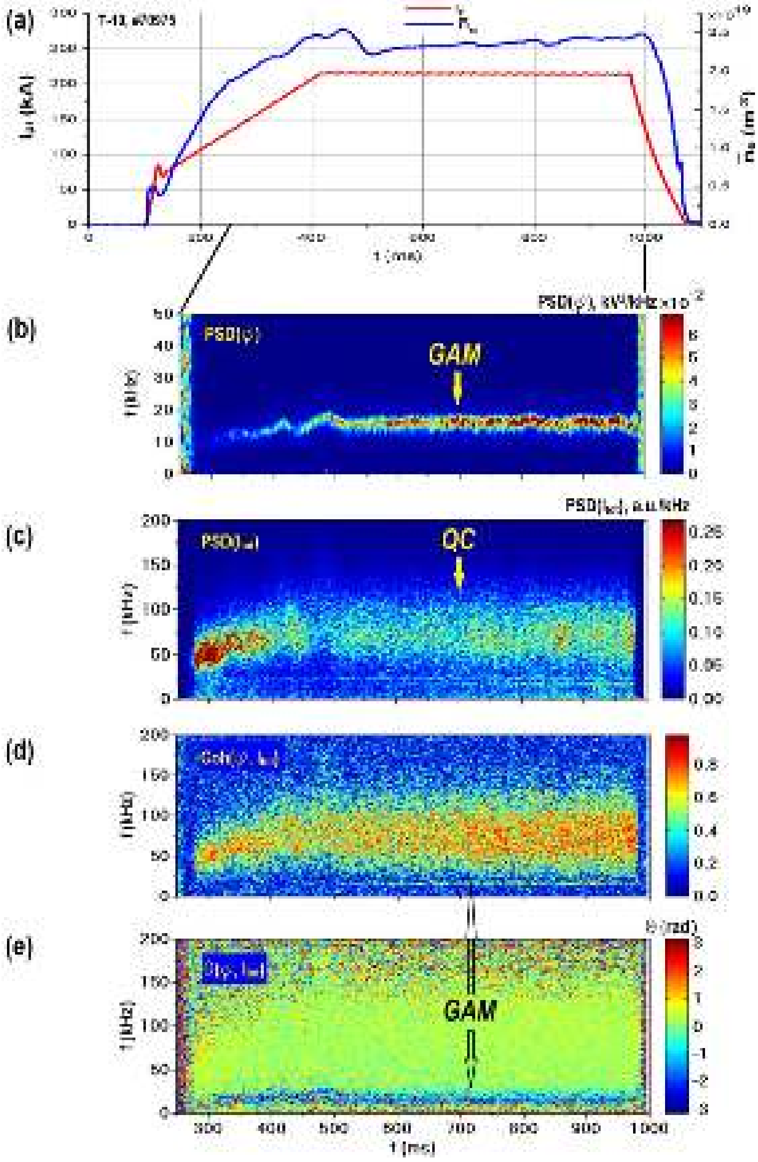

Figure 2. Plasma potential and density turbulence time-evolution in the ohmic discharge of the T-10 tokamak, measured by HIBP. (a) Time traces of the plasma current I_{pl} and the line-averaged density $\bar{n}_e$ of the shot #70975, (b) power spectrogram of the plasma potential. GAM is visible as a quasi-monochromatic oscillation with the frequency $f_{\mathrm{GAM}} = 15$ kHz, dominating over the ambient turbulence. (c) Power spectrogram of the plasma density. QC mode is visible as coherent oscillations in the frequency range of 50–120 kHz with the peak frequency $f_{\mathrm{QC}} \sim 75$ kHz, dominating over the ambient turbulence. Spectrograms of coherence (d) and cross-phase (e) between the plasma potential and density.

ICPP [83], and published in the main IAEA journal Nuclear Fusion [14, 84–87] and other refereed journals [88–92]. These results were recognized by the mainstream plasma researchers and included in the multi-machines review papers [93–95]. The summary of the main results of the electric fields and plasma turbulence, including GAM, was recently published as a monograph [96].

After JE2, GAM studies were established in other machines inside the CRP community, and the topic was included in the research plans of the following JEs and the attempts were made to detect GAMs in other machines. These attempts were successful during JE4 in ISTTOK [22], JE5, JE6 and JE7 in COMPASS [33], JE8 in STOR-M [97]. On top of that, the GAM studies were stimulated on the TEXTOR tokamak [98] and TJ-II stellarator [99, 100], indicating the link of the CRP to the mainstream fusion research. The experiments also stimulated the theoretical studies of the GAM properties and turbulence [101–103].

The diagnostic that has made the major contribution to the JE2 was HIBP [15]. The necessity to overlap the observation area of HIBP with that of correlation reflectometry and Langmuir probes during JE2 stimulated the development of the diagnostic capabilities, i.e. an increase of the probing beam current [104, 105]. On top of that, the correlation technique used during JE2 stimulated the experiments on the test-bench [106] and the creation of the multichannel version of HIBP on T-10 [16, 107, 108] and also on TJ-II [109, 110]. The capability of the HIBP diagnostic to study plasma

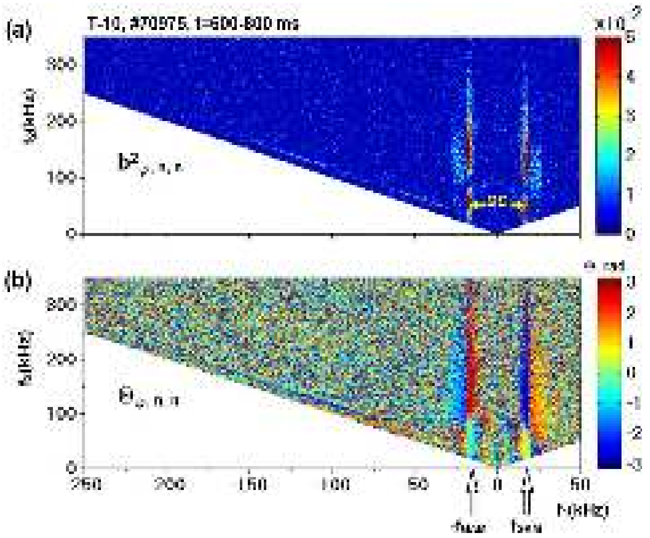

Figure 3. Three-wave coupling between GAM and ambient turbulence represented by squared bicoherence coefficient b^2 (a) and bi-phase (b). The color bar for bi-phase is in radian. The coupling is shown by statistically significant $b^2_{\varphi,\,n,n}(f_{\mathrm{GAM}}, f)$ and finite bi-phase for $\theta_{\varphi,\,n,n}(f_{\mathrm{GAM}}, f)$. Bi-spectral analysis was done for the steady state phase of the shot #70975, $t = 600$–800 ms.

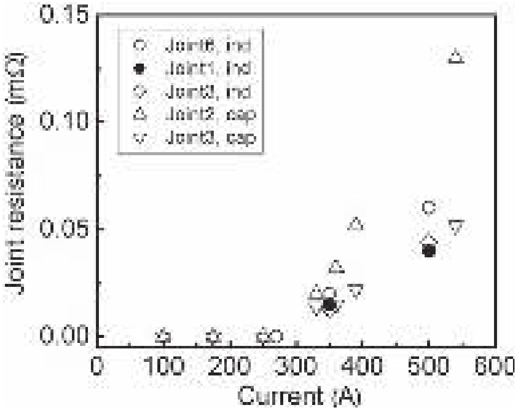

Figure 4. First measurements of the critical current in different turns of the HTS coil on GOLEM.

potential and turbulence in toroidal plasmas, demonstrated during JE2, was widely recognized. The conceptual designs and projects of the HIBP application were performed for the CRP community like TCABR [111], and also for other machines like WEGA [112, 113] and the larger machines like TCV [114] MAST [115] and W7-X [116, 117]. On the WEGA stellarator, the HIBP was build and the initial results were obtained [113] before the shut-down of the WEGA project.

The team building also cannot be not noticed, as discussed above. The bilateral collaboration between the CRP members from T-10 and TCABR [118, 119], T-10 and IST-TOK [120], T-10 and COMPASS [31, 41], T-10 and STOR-M [121] was established. Finally, a tri-lateral collaboration of T-10–TCABR–STOR-M [14, 122] was created.

The JEs have also proven to be a driving environment for providing opportunities to students and young researchers from participating members of CRPs to gain knowledge and experience that can later be used in the execution of the domestic programmes. Performing experiments on small devices is very efficient for the education of students, for various scientific activities of postgraduate students and for the training of personnel for larger experimental facilities. Overall, the JEs have already substantially contributed to capacity building and scientific 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, and Egypt [1, 2, 30, 123]. This represents the important role of JEs in the provision of skilled experts that will support and advance the implementation of next steps in fusion energy development, which shows at present significant advances in the developing countries and in particular in Asia where most of the recently built tokamaks are operating.

4. Conclusions

In this paper, we overview JEs on small tokamaks that have been performed during the period of 2004–2015 in the framework of IAEA coordinated research. The background and rationale for these JEs, 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.

The main scientific outputs of JEs are covered in detail in the references and the full overview will be given in a following paper. The scientific value of outputs of these experiments varied in some cases and results were not always necessarily novel and comprehensive, for example when experiments had training and educational goals. However, we underline here some specific outputs, highlighting its multi-machine nature.

- Studies and detailed characterization of the core and the edge turbulence on different small tokamaks have shown correlations between the appearance of improved confinement, transport barriers, electric fields and electrostatic turbulence.
- Detailed studies of the edge plasma on several tokamaks have shown strong non-Gaussian PDF in the SOL (i.e. bi-Maxwellian), while in the vicinity of the LCFS the PDF was much closer to the Gaussian.
- It was found during JEs on COMPASS and STOR-M that AEs could be present in discharges when NBI was not used.
- Studies on several small tokamaks during JEs demonstrated the important features of GAM and quasi-coherent mode (QC): GAM is highly pronounced in the plasma potential oscillations while it is marginally visible in the plasma density PSD, where QC is dominating. Both GAM and QC mode shows high coherences and the finite cross-phases. A more detailed analysis, based on abilities of advanced diagnostics on T-10 and COMPASS has

shown a new GAM feature—eigenmode structure, not predicted by the local theory. The magnetic component of a GAM was first observed during JE2 on T-10 and then confirmed on COMPASS.
- An important result of JEs is the development and testing of several novel diagnostics and technologies (i.e. HTS and the use of industrial-based magnetrons for pre-ionization).

Specific outputs in the 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. The new CRP on 'Network of Small and Medium Size Magnetic Confinement Fusion Devices for Fusion Research' has started in 2018 and four JEs are foreseen. However, the future of JEs depends on the activity of participated and new institutions, and on utilization of the established network.

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