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Progress on Joint Experiments on Small Tokamaks

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1. Introduction. Small tokamaks have an important role in fusion research. Because of compactness, flexibility, low operation costs and high skill of their personnel, small tokamaks continue to contribute to many areas of Fusion research, well recognised by big tokamaks and ITER, in particular in training and educating the personnel, developing new diagnostics, testing new materials. Currently, 39 small tokamaks are operational. A new concept of interactive co-ordinated joint research using small tokamaks in the scope of IAEA Co-ordinated Research Project (CRP) "Joint Research Using Small Tokamaks" is a new step in better co-ordination of the small tokamaks collaboration and in improvements of links between small and large tokamaks. It has already resulted in more than 30 joint publications. 13 tokamaks are currently participating in the project and an overview of the present activities can be found in [1] and at www.fusion.org.uk/iaeacrp. One of the most successful activities within the CRP is the implementation of Joint Experiments gathering several experts from the fusion community on a particular device during several experimental sessions lasting about 4 to 5 days. In this paper we summarize the results obtained during the last two Joint Experiments and introduce the objectives for the third Joint Experiment organized in the frame work of the IAEA CRP on Joint Research Using Small Tokamaks.

2. 1st Joint (Host Laboratory) Experiment, CASTOR, IPP Prague, Czech Republic, 2005. The first Joint (Host Laboratory) Experiment has been carried out in 2005 on the CASTOR tokamak (R=0.4m, a=0.085m, B_t<1.5T, I_p<25kA, τ_{pulse}<50ms, 0.5<n_e(10^{19}m^{-3}) <3.0, T_e(0)<200eV) at the IPP Prague, Czech Republic [2]. It was jointly organized by the IPP-ASCR and KFKI HAC, Budapest, involved 20 scientists from 7 countries and was supported through the IAEA and the International Centre for Theoretical Physics (ICTP), Trieste. The objective of the JE was to perform studies of plasma edge turbulence and plasma confinement. During the experiments, electric fields were generated by biasing an electrode inserted into the edge plasma to modify the turbulence and transport behavior in this region. The edge plasma and the electrostatic turbulence were characterized using two rake probes with 16 Langmuir tips each (radial separation 2.5mm). From the time shift between two poloidally separated tips it was possible to measure the poloidal velocity of fluctuating density and plasma floating potential structures. From the gradient of floating potential the phase velocities were roughly estimated as v=E_r/B, where E_r is estimated as grad Φ_f However, it was found that the electron temperature gradient can not be fully neglected, if a precise comparison of the phase and ExB velocity is required. The phase velocity of potential fluctuations in the poloidal direction was measured using a poloidal array of 96 Langmuir probes arranged uniformly poloidally in one toroidal position. It was found that the phase velocity of density fluctuations was systematically lower than that of potential fluctuations. From the spatial-temporal behavior of cross-correlation functions of radially separated tips, a radial size of the fluctuating structures of about 1cm has been determined. A typical correlation plot is shown in Fig.1. The reference probe was at 33.75° relative to the equatorial plane on the LCFS. Spatial wave-like structures (electromagnetic features of turbulence) were observed in the range between ~0 and 135° (0° corresponds to the LCFS).

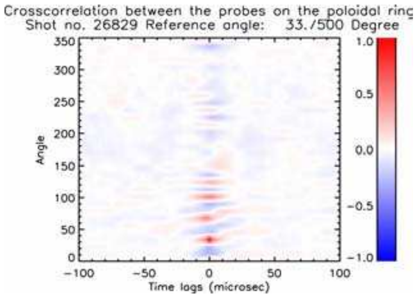

Fig.1. *Spatial-temporal correlation function along the poloidal ring of probes.*

Positive electrode edge biasing experiments have been performed to demonstrate the effects of electric fields on the main plasma parameters. Fig. 2 illustrates the influence of the positive biasing on the radial dependence of edge plasma parameters. During the biasing phase, the radial dependence of ϕ_f is strongly modified as shown in Fig.2(a), leading to a narrow positive and single-peaked E_r structure just inside the LCFS, Fig.2(b). As a consequence, a strong positive and negative E_r shear is generated inside and across the LCFS, respectively, as shown in Fig.2(c). The maximum shear rate of the $E_r \times B$ flow, $\tau_s^{-1} \propto dv_{\bar{E}\times\bar{B}}/dr$, is thus about 1-1.3×$10^6 s^{-1}$. The decorrelation rate of local turbulence scattering, τ_{c0}^{-1}, calculated from the e-folding time of the autocorrelation function of I_s fluctuation data detected before biasing, gives $\tau_{c0}^{-1} = 1.6\times10^5$ s^{-1}. Hence, the flow shear rate exceeds significantly the turbulence scattering rate and thus suppresses turbulence and turbulent transport. The reduction in I_s and ϕ_f fluctuations during biasing has been observed in the experiments. The reduced turbulent transport leads to the formation of an edge pedestal and thus steepening of the edge density profile during biasing, as shown in Fig.2(d). During initial stage of the biasing, a clear reduction in recycling indicated by a drop in H_α emission, and thus, a net increase of the ratio $\bar{n}_e/H_\alpha$ (which is roughly proportional to the particle confinement time τ_p) by a factor of 2.5 with respect to the pre-bias phase, have been observed. These results indicate an improvement of the global particle confinement induced by the electrode positive biasing, as observed earlier [3]. Flow measurements have been performed using a Gundestrup probe with 8 collectors. The time evolution of the radial profiles of

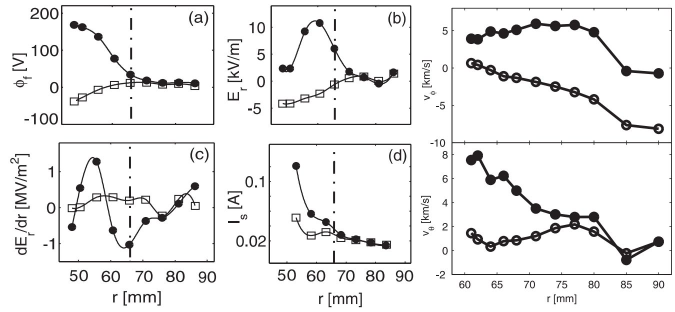

Fig.2. *Radial profiles of floating potential (a), radial electric field (b), the E_r shear, (c) ion saturation current (d), toroidal, v_ϕ, (e) and poloidal velocity, v_θ (f), averaged over 4 ms before (open symbols) and during (filled symbols) biasing The vertical line marks the position of the LCFS.*

floating potential, radial electric field, parallel and perpendicular Mach numbers were measured in the biased and ohmic phases of a single discharge. The radial flow profiles were measured by a shot-to-shot scan in reproducible discharges. It is found that not only the perpendicular flow, but also the parallel flow increases during biasing, as shown in Fig.2 e,f.

Two arrays of fast AXUV-based bolometers with 16 and 19 channels were installed in the same poloidal cross-section in perpendicular directions (from LFS and bottom side) to monitor the radiated power profile. This arrangement with temporal resolution of 1μs and spatial resolution of ~ 1cm and a very high signal to noise ratio allowed a visualization of the evolution of fine structures on the radiated power profile during biasing, as shown in Fig.3.

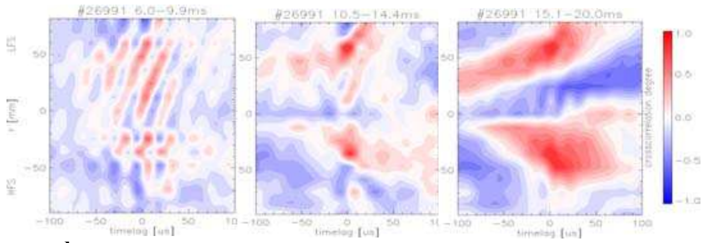

Fig.3. *Cross-correlation between horizontal chord at 40 mm against all bottom chords prior to biasing (left figure), during biasing with biasing voltage +150V (middle figure) and after biasing (right figure).*

3. 2nd Joint Experiment, T-10, RRC "Kurchatov Institute", Moscow, RF, 2006. Following the success of the 1st JE, the 2nd JE has been performed on T-10 at RRC "Kurchatov Institute" in Moscow. 30 scientists from 13 countries participated in this experiment. This experiment was aimed to continue JE1 turbulence studies, now extending them to the plasma core.

The absolute core plasma potential was measured by Heavy Ion Beam probing (HIBP) using Tl^+ ions with energy 220-260 kV [4]. The core plasma turbulence was studied by correlation reflectometry. In the Ohmic plasma (I_p=180kA, n_e=1.3–1.5x10^{19}m^{-3}) the potential profile presents linear-like function with the lowest absolute value φ(0.17m)= -900V. The slope of the potential profile gives the estimation of the mean radial electric field E_r~ -7.5kV/m. In the ECR off-axis heated plasma (P_{EC}=0.4–0.8MW), the depth of the potential well becomes smaller, φ(0.17m)= –720V, and the electric field decreases to E_r~ -5.5kV/m. In the studied region the plasma column rotates not as a rigid body with $V_{[E\times B]}$~3km/s. The turbulence rotation velocity obtained by the correlation reflectometry [4] has been compared with this data, Fig.4.

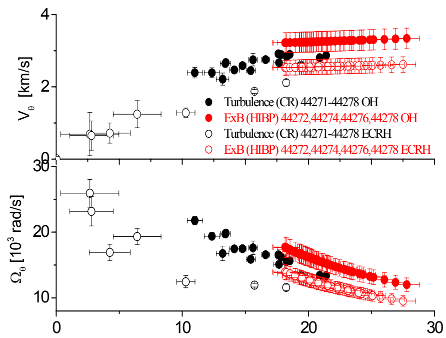

Fig. 4. *Comparison of rotation velocities of density perturbations (black) with core plasma rotation (red) in OH (filled) and ECRH (open) plasma.*

Geodesic Acoustic Modes (GAM) were investigated on the T-10 tokamak using HIBP and Correlation Reflectometry [5]. Ohmic heating and on- and off-axis ECRH regimes were studied (B_t=2.2–2.5T, I_{pl} =180-330kA, n_e =1.3–2.5x10^{19}m^{-3}). The result of the correlation measurements of the two diagnostics will allow determination of the toroidal and poloidal mode structure of the GAM [5]. It was shown that the GAM may have a complex structure, (not similar to conventional periodical oscillations with a single frequency), which is mainly manifested in the plasma potential and not much pronounced in the plasma density fluctuations. The GAM have an intermittent character presenting the stochastic sequence of the wave packages with a "lifetime" of a package in a range of 0.5 - 2ms. The GAMs are more pronounced in the ECRH plasmas with typical frequencies of the wave packages in a narrow interval 22-27 kHz in the outer one third region of the plasma column.

With a direct link to the experiments performed during the 1st JE, studies of edge plasma turbulence using Langmuir probes have been performed and the results have been compared with those obtained on the TCABR tokamak [6]. The analysis of probe signals has shown that the spectra, the correlation functions and the probability density functions (PDF), derived from probe ion saturation current, Fig.5, demonstrate complex power laws with multi-scale properties. Relative entropy and discrimination (Kullback-Liebler divergence) was used to compare PDF in T-10 and TCABR [6].

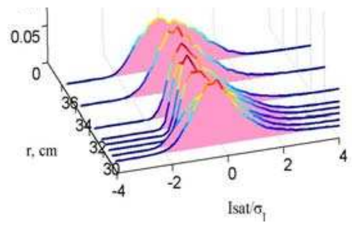

Fig.5. *PDF in the SOL of T-10*

4. Future plans: the 3rd JE, ISTTOK, ICT CFN, Lisbon, Portugal, 2007. The 3rd JE will be carried out in October 2007 on ISTTOK at IST CFN, Lisbon. The main goals of this experiment will be: tokamak operation in alternating current regimes; testing of the liquid metal limiter concept; study of the influence of external biasing on the plasma confinement and stability and study of the fluctuation induced transport and their driving mechanisms. Other activities will include familiarisation with the use of the ISTTOK control, data acquisition and remote data access systems; improvement of the remote access tools by adding new features based on user experience on ISTTOK and in other laboratories; implementation of a real-time plasma position control system based on bolometer tomography; studies of plasma-material interaction. The development and implementation of remote participation tools is very important for supporting Joint Experiments and to allow remote collaboration. It is expected that the solutions implemented and being tested among the small tokamak community can provide useful clues for the development of a reliable standard supporting the future remote operation of large fusion devices.

5. Conclusions. These first 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 programmes. The contribution of small tokamaks to the mainstream fusion research such as edge turbulence, improved confinement, and diagnostics development in the present case can be enhanced through coordinated planning. The activities under this IAEA Coordinated Research Project are already paying visible dividends both in increased number of publications and improved collaboration between participating tokamaks. Another important output of joint experiments is improvement in understanding and communications between scientists from different countries, creating efficient team work both during experiments and data analysis.

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