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Overview of the FTU results

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Since the 2018 IAEA FEC Conference, FTU operations have been devoted to several experiments covering a large range of topics, from the investigation of the behaviour of a liquid tin limiter to the runaway electrons mitigation and control and to the stabilization of tearing modes by pellet injection and electron cyclotron heating. Other experiments have involved the spectroscopy of heavy metal ions, the electron density peaking in helium doped plasmas, the electron cyclotron assisted start-up and the electron temperature measurements in high temperature plasmas. The effectiveness of the Laser Induced Breakdown Spectroscopy system has been demonstrated and the new capabilities of the Runaway Electron Imaging Spectroscopy system for in-flight runaways studies have been explored. Finally, a high resolution saddle coil array for MHD analysis and UV and SXR diamond detectors have been successfully installed and tested on different plasma scenarios.

§ Liquid Tin Limiters. FTU can be considered a pioneer and leader device in the liquid metal investigation as plasma-facing material and it was the first tokamak in the world that has been performed experiments using a liquid lithium limiter and a liquid tin limiter. The allowed temperature ranges have been investigated and the impact of the two elements on the plasma performances has been well assessed. Recently, soft x-ray cameras and electron cyclotron emission have been analysed to extend the core plasma characterization on MHD internal activity. The experience gained during the FTU experiments is the basis of the design chooses of the liquid metal divertor within the framework of the WP-DTT1-LMD. **§ Runaway Electrons studies.** The conditions in which solid D2 pellets can be used on a low density pulse to completely wipe out the RE population have been identified. These results would help to define a possible recipe for pre-emptive actions in ITER to mitigate the RE formation before and during the current quench. Studies on pellet ablation, useful for ITER prediction, are carried out even for pellet injected in the early phase of RE beam formation. Further results have been obtained with LBO injections in quiescent and post-disruption RE beams, modulated ECRH pacing fan-like instabilities and on optimized RE beam controlled ramp-down. Finally, new interesting observations have been performed concerning the interaction between REs and large magnetic island. **§ Waves excitation by Runaway Electrons.** A measurement chain has been realized to detect radiofrequency waves generated by runaway electrons. Intense and intermittent fluctuations have been detected. Amplitude peaks are generally coincident with the occurrence of pitch angle scattering instability events. Amplitude peaks can be analyzed with 100 ns time resolution, which provides unprecedented information on the time development of the instability. Fluctuations spectra are broadband in most cases, with frequency span of some GHz; line spectra have been found in a minority of cases. **§ Tearing Modes stabilization by pellet injection.** In saw-tooth free low density pulses, magnetic islands formed by Tearing Mode (TM) instabilities around the q=2 surface can saturate at large amplitudes. A fast mode stabilization has been observed after a pellet injection in presence of a rotating magnetic island, possibly providing a new MHD stabilization strategy, while a pellet injected in presence of a "quasi-locked"magnetic island has induced an increase of the rotation frequency, preventing a dangerous total locking. Linear stability analysis are planned with the MARS code to get some insight in the stabilization process. **§ Tearing Modes stabilization by Electron Cyclotron Heating.** TM stabilisation by ECH has been performed in saw-tooth free scenarios at low density. The ECH deposition has been varied in real time (RT) around the q=2 surface, with a "sweeping"strategy, allowing to relax the resolution on the position of the O-point, and in certain cases to accelerate the stabilisation. The efficiency of the method has been compared with results from experiments at fixed antenna position both in case of rotating modes and of quasi-locked modes. **§ MHD limit cycles.** A peculiar MHD activity was discovered in the past on FTU, with a 2/1 TM characterized by "limit cycle" in the island amplitude/frequency plane. New observations have been performed, starting with saw-tooth free low density pulses characterized by a one-to-one relation between amplitude and frequency. In these pulses, a transition to "limit cycles"behaviour has been obtained by Neon injection, with the corresponding appearance of saw-tooth activity, suggesting an interaction between the two kinds of instability. **§ Behaviour of heavy metal ions.** The high-resolution spectrometer SOXMOS and the survey spectrometer SPRED have allowed the identification of new, or better resolved, spectral features of Tin (originated from the Tin Liquid Limiter), Tungsten and Yttrium (injected by the LBO technique). Tungsten is obviously a material of interest for Plasma Facing components, but experimental data for such a heavy element are not yet exhaustive and the atomic data are difficult to calculate. Yttrium is used as targets in the inertial fusion experiment ABC at Frascati to produce intense radiation sources, but very little information is available in literature about the Y emission spectra, so that its observation in well diagnosed tokamak plasmas

can thus help filling some gaps. **§ Helium doped plasmas.** Helium doped plasmas have been realized, varying both the total amount of Helium injected and the speed of the injection. High electron density peaking was found and a JETTO transport code analysis added interesting consideration about particle transport and improvement in confinement. **§ Electron Cyclotron assisted start-up.** Experiments have been performed at reduced electric field (about 0.5V/m) in presence of Ne impurity (both X2 and O1 polarizations) and moving the EC resonance off-axis with fixed poloidal magnetic configuration. In the first case the impurity influences plasma resistivity making the ECRH necessary to pass the burn-through, while in the second case a reduction of the internal inductance is found, with respect to the on-axis case, with a reduction of the MHD activity. **§ High temperature plasmas.** Electron temperature up to 14 keV was obtained in ECRH heated pulses on current ramp-up and a systematic disagreement between the Thomson Scattering and ECE measurements was found and explained in terms of distortion of the electron distribution function. **§ Laser Induced Breakdown Spectroscopy.** A LIBS in-situ chemical analysis of the FTU first wall components has been performed by using a compact LIBS system installed on a robotic arm. Measurements were performed on the TZM tiles of the toroidal limiter and on the stainless steel components of the first wall, showing their main chemical elements and the presence of superficial contaminants. **§ Runaway Electron Imaging Spectrometry system.** An upgrade of the REIS system has been carried out recently. The range of the measured synchrotron radiation spectra emitted by runaway electrons is now from 0.4 up to 5 micron. The new system has been commissioned in FTU runaway discharges in 2019. The diagnostic is portable and its use is foreseen in AUG and COMPASS during 2020. **§ High resolution saddle coil array.** The signals coming from a poloidal and toroidal array of saddle coils have been acquired at 250 kHz, without temporal integration, showing the capability to perform the toroidal and poloidal mode number analysis of TM in a large range of frequencies. **§ Diamond Detectors for fast VUV and SX-Ray Diagnostics.** Two photo-detectors based on synthetic single crystal diamonds and optimized for extreme UV and SX detection, respectively, were installed on FTU and tested on different plasma scenarios during the latest experimental campaign. Beautiful examples of plasma fast events have been collected and compared with other diagnostics. The preliminary measurements have opened the possibility of a much wider range of application for this diagnostic.

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