Overview of the FTU results

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**See Appendix of G. Pucella et al., paper OV/P-2, this Conference*

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Frascati Tokamak Upgrade

Compact high magnetic field machine

R_0	0.935	m	*major radius*
a	0.30	m	*minor radius*
B_T	2 ÷ 8	T	*toroidal field*
I_p	0.2 ÷ 1.6	MA	*plasma current*
n_e	0.2 ÷ 4.0	10^{20} m^{-3}	*plasma density*
Δt	1.5 ÷ 4.5	s	*pulse duration*
EC	140 GHz / 1.5 MW		*electron Cyclotron*
LH	8 GHz / 2.0 MW		*lower Hybrid*

- Stainless steel vacuum chamber
- High field side Mo belt limiter
- Outer Mo poloidal limiter
- Li/Tin poloidal limiter

- Liquid Metal Limiter
- Runaway electrons studies
  Plasma waves emitted by REs
- Tearing modes stabilization by ECH
  Tearing modes stabilization by pellet
  MHD limit cycles
- Behaviour of heavy metal ions
  Helium doped plasmas
- EC assisted start-up
  High temperature plasmas
- Laser induced breakdown spectroscopy
  Runaway electron imaging spectrometry
  High resolution saddle coil array
  Diamond detectors for VUV and SXR

Impurity spectroscopy and seeding

- Lines of Sn (from tin limiter) identified as emission from ionization states localized between r/a = 0.75 and 0.85 (**FIG.5-a**)
- Ion stages for W (injected by LBO technique) localized at the core/medium radius regions (coronal equilibrium calculations) (**FIG.5-b**).
- Few lines of Y (injected by LBO) clearly visible at higher wavelengths (**FIG.5-c**); no distinct lines at lower wavelengths.

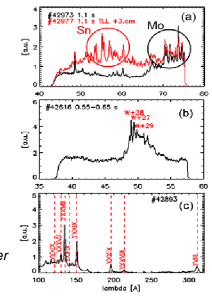

FIG. 5. Spectra of Sn (a), W (b) taken with the SOXMOS spectrometer and spectrum of Y (c) taken with the SPRED spectrometer.

- Properties of He doped plasmas studied by varying both the amount of injected He and the rate of injections. Good assessment in the estimation of the species concentrations linking effective charge, radiation losses and VUV spectroscopy.

Liquid Metal Limiters

- Liquid metal investigation as plasma-facing material on FTU: the first tokamak performing experiments using a liquid lithium limiter and a liquid tin limiter (**FIG.1**).
- Plasma performances unaffected (without core accumulation) for liquid tin surface temperatures below the evaporation onset (**FIG.1**), with heat loads up to 18 MW/m².
- Liquid Metal divertor concept design, CPS-based (WP-DTT1-LMD).

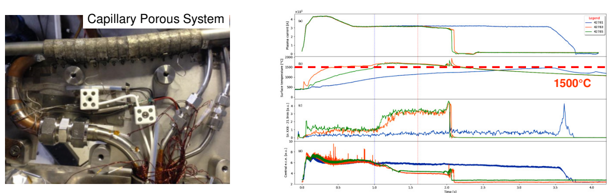

FIG. 1. (Left) Liquid Tin Limiter using a Capillary Porous System. (Right) Experiments performed by moving, pulse by pulse, the limiter towards the plasma column to increase the heat load on the liquid tin surface.

Early Electron Cyclotron injection

- Experiments on EC assisted start-up performed at reduced electric field in presence of Ne impurity, to mimic the post disruption condition in superconducting future tokamaks.
- The effectiveness of EC does not depend on polarization (**FIG.6**).
- Reduction of the internal inductance by moving the EC resonance off-axis.

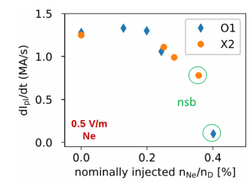

FIG. 6. Current rise as a function of impurity content in EC assisted experiments.

- Systematic disagreement between the TS and ECE temperature measurements at high temperature (**FIG.7**) in EC heated pulses on current ramp-up (distortion of the electron distribution function).

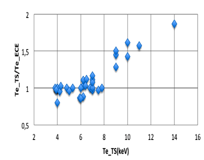

FIG. 7. Ratio Te_TS / Te_ECE versus Te_TS for FTU pulses.

Runaway electrons

- D2 pellets injected on flat-top current pulses with different RE population, by varying pellet size, number and inter-times, to study the capability of REs dissipation/mitigation (**FIG.2**) and the ablation rate of pellets, useful for ITER.
- Lower energy and higher current for post-disruption RE beams in case of pellets launched closely to the current quench.

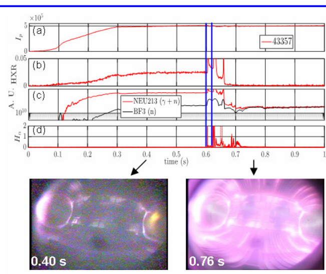

FIG. 2. Multiple D_2 pellet injections on quiescent REs inducing complete RE loss, healing the discharge.

- Emission of radio waves (0.4-3.0 GHz) in pulses with significant RE signatures. Multi-machine comparison are required to assess the relative importance of involved wave branches (whistler, magnetized plasma waves).

Diagnostics

The effectiveness of the Laser Induced Breakdown Spectroscopy system (**FIG.8**) has been demonstrated and the new capabilities of the Runaway Electron Imaging Spectroscopy system (**FIG.9**) for in-flight RE studies have been explored. A high resolution saddle coil array for MHD analysis has been utilized (**FIG.10**) and UV and SXR diamond detectors have been successfully installed and tested on different plasma scenarios (**FIG.11**).

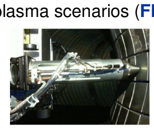

FIG.8. The LIBS device measuring inside the vacuum vessel on a tile of the toroidal limiter.

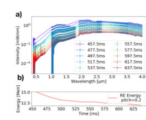

FIG.9. RE energy reconstruction based on camera and spectrometers data.

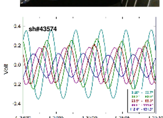

FIG.10. Signals from different saddle coils in presence of a 2/1 tearing mode.

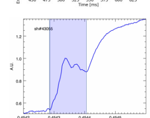

FIG.11. Ablation process of a pellet as recorded by a diamond detector.

MHD stability and control

- Tearing modes stabilization by ECH in sawtooth free scenarios at low density (**FIG.3**), with a "sweeping" strategy, allowing to relax the accuracy on the estimates of the island O-point position.
- Complete/partial TM stabilization after a pellet injection in presence of a fastly/slowly rotating magnetic island (**FIG.4**).

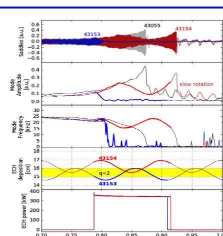

FIG. 3. Experiments of TM stabilization by ECH.

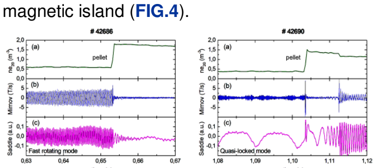

FIG. 4. Experiments of TM stabilization by pellet injection.

- Transition from smooth to limit-cycle behaviour for a 2/1 TM in correspondence with the appearance of ST activity.

Conclusions

- Liquid tin limiter used for the first time in a tokamak.
- Complete RE loss induced by multiple pellet injection.
- Emission of radio waves in pulses with significant RE signatures.
- Tearing modes stabilization by ECH with a "sweeping" strategy.
- Fast tearing modes stabilization by pellet injection.
- Transition from smooth to limit-cycle behaviour for a 2/1 mode.
- High resolution spectroscopy of heavy metal ions.
- Properties of Helium doped plasmas.
- EC assisted start-up in presence of Ne impurity.
- Disagreement between TS and ECE Te in EC heated pulses on current ramp-up.
- Effectiveness of the LIBS system mounted on the FTU robotic arm.
- Reconstructions of RE energy evolution based on camera and spectrometers data.
- Mode number analysis with high resolution saddle coil array.
- UV and SXR diamond detectors successfully tested on plasma scenarios.

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