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Overview of the FTU results

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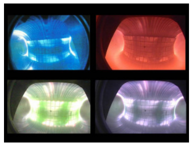
Frascati Tokamak Upgrade



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 or Tin poloidal limiter

FIG. 1 – Visible camera images of FTU plasmas.

Since the 2016 IAEA FEC Conference, FTU operations have been mainly devoted to experiments on runaway electrons and investigations about a tin liquid limiter; other experiments have involved the elongated plasmas and dust studies. The tearing mode onset in the high density regime has been studied by means of the linear resistive code MARS and the highly collisional regimes have been investigated. New diagnostics, such as a Runaway Electron Imaging Spectroscopy system for in-flight runaways studies and a triple Cherenkov probe for the measurement of escaping electrons, have been successfully installed and tested, and new capabilities of the Collective Thomson Scattering and the Laser Induced Breakdown Spectroscopy diagnostics have been explored.

Plasma Facing Components

Laser Induced Breakdown Spectroscopy

✓ LIBS is a suitable not invasive in situ diagnostic for a quantitative detection of tritium retained in the ITER vessel components, which is mandatory for deciding if the machine operation must be stopped and the exceeding tritium removed.

✓ The Multi-Purpose Deployer (a robotic arm which can be installed on ITER during maintenance) could be equipped with LIBS system to analyse a consistent area of the vessel.

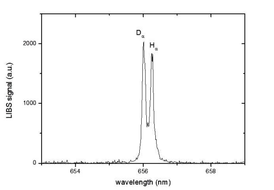


FIG. 2 – Deuterium and Hydrogen emission lines detected by LIBS on a shadowed zone in between the FTU toroidal limiter tiles, with measurements performed in vacuum.

✓ In the last year, LIBS measurements of the deuterium (used as a proxy for tritium) retained on the FTU Mo (TZM) toroidal limiter tiles have been performed from remote both in vacuum (FIG. 2) and in Nitrogen or Argon atmosphere.

✓ The experimental layout consisted of a Quantel laser “Twin BSL”, a Andor “Istar DH320T-18F-63” ICCD camera and a Jobin Ivon “Triax 550” spectrometer.

✓ Measurements carried out at atmospheric pressure showed different results depending on the used gas, Nitrogen or Argon.

Dust studies

✓ Dust remobilization in tokamaks has been long recognized to be an issue affecting normal plasma operations. Magnetic dust particles, in contrast to non-magnetic ones, could be mobilized during, or even prior to, the discharge start-up, preventing a positive evolution or leading to an inhibition of plasma discharge.

✓ Recent investigation on FTU proved the presence of dust mobilized prior to pulse start-up phase, when in the tokamak volume the magnetic field consists just of the time growing toroidal and multipole components due to the external coils.

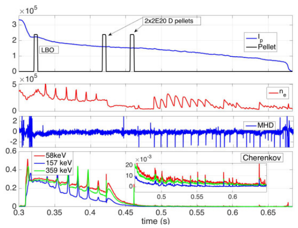
✓ An estimation of dust concentration and size based on Thomson Scattering spectra and Infrared camera images indicated an average density of the order of 10^{-3} cm^{-3} and grains size between tens of μm and few mm.

Runaway Electrons studies

Post-disruption RE beam mitigation

✓ Post-disruption RE beam mitigation is one of the main concerns for ITER operations. RE beam control algorithms for stabilization and current reduction can be combined with Shattered Pellet Injection (SPI) and Massive Gas Injection (MGI) and provide redundancy and backup in case of SPI/MGI failure.

✓ Stabilization and suppression of post disruption RE beam has been achieved on FTU, with a control architecture that allows to detect the current quench and to induce via the central solenoid a controlled RE beam current ramp-down meanwhile the beam is kept away from the vessel.



✓ Initial studies have revealed that fast changing electrical fields (via central solenoid and EC antenna) destabilize REs orbits, possibly inducing peculiar MHD instabilities growth (FIG. 3).

FIG. 3 - A post-disruption RE beam on which a first injection of iron with LBO followed by two deuterium pellets has been tested on a RE plateau. Electron density spikes are simultaneous to Cherenkov probe spikes, revealing that REs are expelled from the beam core due to instabilities. A fan-like instability take place after 0.45 s, whereas previous RE expulsions seems to have a different origin.

Runaway Electrons Imaging and Spectroscopy

✓ The REIS system is a wide-angle optical diagnostics collecting RE synchrotron radiation from two plasma cross sections (corresponding to RE backward and forward views) and transmitting it to visible/infrared spectrometers via an incoherent bundle of fibers.

✓ The system was calibrated and commissioned as a portable diagnostic for operation in medium sized tokamak. First operated in FTU, after design and construction of suitable interfaces, the REIS was installed in AUG and TCV and exploited in RE generation and control experiments.

✓ In FIG. 4 are shown images of the RE beam on FTU from the visible camera (left) correlated with the measured synchrotron radiation intensity at several wavelengths (right top) and the measured synchrotron radiation visible spectra (right bottom). The spectra are fitted (black solid lines) assuming a mono-energetic RE distribution.

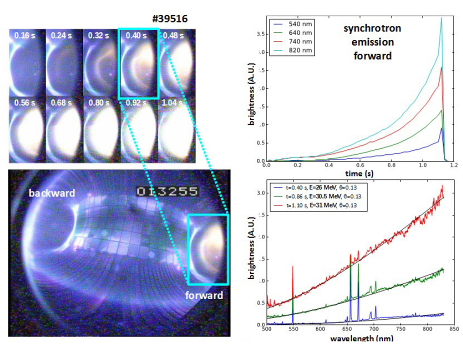


FIG. 4 – Pulse #39516. Visible camera images of the RE beam (left): the bottom image (corresponding to frame 013255, t = 0.4 s) shows both RE backward and forward views, while the top image is a time sequence of the forward view for the same pulse. Note the temporal correlation of the visible images with the measured synchrotron radiation intensity at several wavelengths (right top) and synchrotron radiation visible spectra (right bottom): the spectra are fitted (solid lines) assuming mono-energetic distributions (energy and pitch angle values in the insert).

Liquid Metal Limiters

Tin Liquid Limiter

✓ In future fusion reactors, the divertor plates must not be subjected to average powers greater than 10 MW/m^2, with slow transients below 20 MW/m^2.

✓ Liquid tin may prove a good candidate as a Plasma Facing Components material, with a large operating window (300 < T < 1300 ° C) before vaporization, low or negligible activation, and low H retention.

✓ The Tin Liquid Limiter (TLL) installed on FTU (FIG. 5) is based on the innovative concept of the Capillary Porous System. It consists of a Mo tube around which strips made of tungsten felt filled with tin are wrapped. The TLL can be cooled by flowing air and atomized water in a copper pipe inserted inside the Mo tube.

✓ The TLL (without active cooling) was tested with standard FTU pulses (B_T = 5.3 T, I_p = 0.5 MA). The maximum thermal load deduced by the Langmuir probes was about 15 MW/m^2 for almost 1 s, without any degradation of the plasma performance.

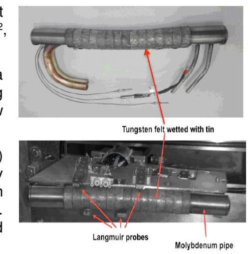
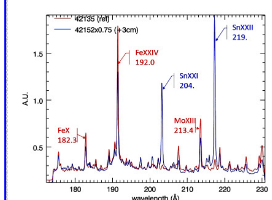


FIG. 5 – Tin liquid limiter installed on FTU. The limiter is equipped with several thermocouples and four Langmuir probes, two on each side. The surface temperature of the limiter is recorded with a fast Infrared camera observing the whole surface from the top of the machine.

Schwob-Fraenlel XUV spectrometer



✓ A 2 m grazing incidence Schwob-Fraenkel XUV spectrometer was installed on FTU observing the plasma emission in the range from 20 to 340 Å, to identify the spectral lines of Sn, with high spectral resolution (FIG. 6), during the TLL experiments.

FIG. 6 – Comparison of one segment of the spectrum observed by the Schwob-Fraenkel XUV spectrometer for two discharges, one with the TLL fully retracted (in red), and the other with the TLL at +3 cm (in blue). The blue curve is normalized to the same background level.

Elongated plasmas

✓ A new vertical controller has been designed to stabilize vertically elongated plasmas in FTU, where Vertical Displacement Events (VDE) have been observed. In the latest experimental campaigns, experimental results showed its capability of stabilizing plasma up to the FTU record elongation of 1.23.

✓ A comparison between the standard Proportional Integral Derivative PID controller and the new hybrid controller is reported in FIG. 7.

✓ Elongated plasmas pulses using the liquid metal limiters (lithium or tin) as primary limiter is the subject of on-going research.

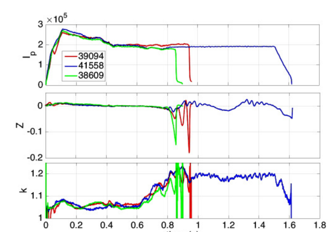


FIG. 7 – From top to bottom: plasma current I_p, vertical displacement z, and elongation k. In the pulses #39094 (red) and #38609 (green) the standard PID controller is considered and the pulses have been vertically lost. When the hybrid controller has been introduced, in the pulse #41558 (blue), the vertical confinement has been evidently improved.

MHD instability and Transport studies

Tearing Mode onset

✓ A detailed study on tearing modes has been carried out in the contest of high density regimes, where the magnetic perturbation associated to the mode can increase up to disruption.

✓ When the density increases, an increase of the radiation losses is also observed which leads to contraction of the temperature profile and so to shrinkage of the current profile. Because the TM is driven by the radial gradient of the current, as the current shrinks, TMs appear in the experimental pulse.

✓ The onset of the TMs in a good number of different pulses (B_T=4-8T, I_p=0.5-0.9 MA) has been analyzed by means of the MARS code, which is a global, resistive, spectral code for full MHD linear stability analysis. The onset of the TMs established by the MARS code has been compared with the one observed experimentally from pick-up coil signals and a good agreement can be claimed (see **FIG. 8** for the analysis of a specific pulse).

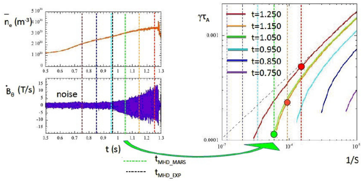


FIG. 8 – FTU pulse #34769. B_T = 8 T, I_p = 0.9 MA. (Left) Line-averaged central density and perturbed poloidal magnetic field evolution. (Right) MARS output for different times (equilibria) during the density ramp-up. The effective values of the experimental inverse Lundquist number in FTU are shown as vertical dotted lines.

Highly collisional regimes

✓ In literature an inverse linearity between the electron density peaking and the effective collisionality ν_{eff} is found for most tokamaks devices (**FIG. 9**, grey symbols).

✓ On FTU, at high values of the collisionality (obtained thanks to the capability to operate up to very high electron density values) such inverse linearity does not occur, but, instead, an increase of the density peaking with the collisionality is found (**FIG. 9**, red symbols).

✓ This behavior seems to be related to an edge phenomenon, as the MARFE instability presence and ameliorated conditioning of wall by using the Li limiter.

✓ Another interesting effect is associated to the Neon injection: keeping the same collisionality, an impressive increase of the density peaking is obtained for doped pulses with respect to the un-doped ones.

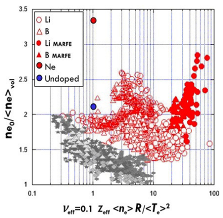


FIG. 9 – Density peaking as a function the effective collisionality. Red symbols for FTU data; grey symbols for other devices. The behavior of a Ne doped pulse on FTU is also reported.

Diagnostics

Collective Thomson Scattering

✓ The CTS diagnostic allows the investigation of ion populations in fusion plasma devices, studying the characteristic emissions, stimulated by the injection of a powerful microwave probing beam. From the shape of the emitted spectrum, plasma parameters such as ion temperature, drift velocity and ion composition can be inferred

✓ The availability in FTU of a CTS diagnostic system at 140 GHz and the possibility of "non-resonant" plasma scenarios, i.e. scenarios in which the EC layer (and harmonics) resonant with the probe frequency is out of the plasma region, allow carrying out studies on ions characteristics. In fact, in presence of EC resonances, the ECE background (at probing frequency) can significantly overwhelm the signals due to thermal CTS.

✓ The CTS diagnostics was used also for investigations on Parametric Decay Instability excitation by EC beams in correlation with magnetic islands induced by neon injection and in resonant scenarios. Parasitic emissions from the gyrotron were observed, while other spectral emissions have been observed and analyzed with very high time and frequency resolution. To determine the emissions mechanism and locate the plasma volume originating them, an independent receiving line has been recently installed.

Cherenkov probe

✓ Measurements of fast electrons produced in the plasma core and escaping from it are of interest to study processes occurring inside the plasma itself. Cherenkov diagnostic is a good candidate to perform these studies and a triple Cherenkov probe was installed on FTU and its performances have been under investigation.

✓ The probe has three diamond detectors with three different energy thresholds (58, 187 and 359 keV), thus it is able to perform a first energy scan. Each diamond detector is mounted on a TZM head inserted into the vessel, and it is coated with a Ti/Pt/Au interlayer filtering out visible light. Electrons impinging on the probe emit Cherenkov radiation in diamond, and this radiation is routed, through a visible/ultraviolet optical fibre, to a PMT operating at 1 kV with a detectable range of 185÷850 nm.

✓ As an example, REs expulsion due to Anomalous Doppler Effect is shown in **FIG. 10**. The most notable thing is the correlation of each peak from X-rays and Cherenkov signals to those from the MHD activity. Moreover, the Cherenkov peaks are clean and more distinct than those from the X-ray signals, due to the better time resolution of the probes.

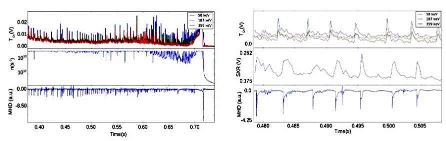


FIG. 10 – (Left) Correlation between triple Cherenkov probe signal, gamma-ray count rate and MHD activity. (Right) Triple Cherenkov signal, Soft X-rays and MHD activity. Pulse #41146.

Conclusions

✓ LIBS measurements of the deuterium retained on the FTU Mo toroidal limiter tiles have shown that LIBS is a suitable not invasive in situ diagnostic for a quantitative detection of tritium retained in the ITER vessel components.

✓ Recent investigation on FTU proved the presence of dust mobilized prior to pulse start-up phase, when in the tokamak volume the magnetic field consists just of the time growing toroidal and multipole components due to the external coils.

✓ Stabilization and suppression of post disruption RE beam has been achieved on FTU, with a control architecture that allows to detect the current quench and to induce via the central solenoid a controlled RE beam current ramp-down meanwhile the beam is kept away from the vessel.

✓ The REIS diagnostic has allowed to provide simultaneously the image and the visible/infrared spectrum of the forward and backward radiation from in flight REs.

✓ The Tin Liquid Limiter was tested with standard FTU pulses (B_T = 5.3 T, I_p = 0.5 MA). The maximum thermal load deduced by the Langmuir probes was about 15 MW/m^2 for almost 1 s, without any degradation of the plasma performance, proving liquid tin to be a good candidate as a Plasma Facing Components material.

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✓ A new vertical controller has been designed to stabilize vertically elongated plasmas in FTU, where Vertical Displacement Events have been observed. Experimental results showed its capability of stabilizing plasma up to the FTU record elongation of 1.23.

✓ The onset of TMs in the high density regime has been analyzed by means of the MARS code, which is a global, resistive, spectral code for full MHD linear stability analysis. The obtained onset times have been compared with the ones observed experimentally from pick-up coil signals and a good agreement can be claimed.

✓ An increase of the density peaking with the effective collisionality ν_{eff} has been found on FTU at high values of ν_{eff}. This behavior seems to be related to an edge phenomenon, as the MARFE instability presence and ameliorated conditioning of wall by using the Li limiter.

✓ The CTS diagnostics was used for investigations on Parametric Decay Instability excitation by EC beams in correlation with magnetic islands induced by neon injection. Parasitic emissions from the gyrotron were observed, while other spectral emissions have been observed and analyzed.

✓ A triple Cherenkov probe was installed and tested on FTU, confirming the Cherenkov prove to be a valid diagnostic system to study and monitor plasma scenarios involving REs.

Members of the FTU Team

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