Introduzione al IX meeting Campagna di Analisi di FTU

Francesco Paolo Orsitto

ENEA Aula L Pieroni

23 gugno 2025, ore 14.00

Introduzione e contesto

Le conoscenze prodotte dal lavoro svolto su FTU sono uniche e per molti aspetti ancora da sintetizzare.

Un volume di Fusion Science and Technology (Vol. 45, N.3, May 2004) è stato dedicato alle conoscenze acquisite e pubblicate tra il 1990 ed il 2004 su FTU.

Non esiste però un luogo (articolo di rivista, oppure un volume di una rivista) in cui siano sintetizzate le conoscenze prodotte da FTU dal 2005 al 2022, sebbene ci siano gli articoli di rivista pubblicati come Overviews IAEA-FEC in tale periodo.

Campagna di analisi di FTU

Il lavoro consiste nella realizzazione di un volume analogo al vol. 45 di FUSION SCIENCE and TECHNOLOGY in cui si riassumano i risultati di FTU dal 2005 al 2022 nelle varie topiche.

Per tale obiettivo è stata proposta l'organizzazione di una campagna di analisi dei dati di FTU della durata di sei mesi, definendo delle topiche con dei responsabili.

Obiettivo di tale campagna è quello di consolidare gli elementi di novità prodotte da FTU nel periodo 2005-2022 e **arrivare a una sintesi delle conoscenze prodotte su FTU.**

Topiche e gruppi di lavoro per scrittura papers di sintesi

- **RF heating systems (F Napoli, S Mastrostefano, C Castaldo, A Cardinali, V Pericoli)**
- Operation at high density **(Pucella, TBC**)
- **MHD and its stabilization/control by ECRH (E Alessi , S Nowak)**
- **Impurity seeding and Transport (C Mazzotta)**
- **Diagnostics (G Apruzzese , L Senni, E Peluso)**

Nuove topiche (introdotte successivamente al 2004) :

- Liquid Metal Limiter experiments (C Mazzotta TBC)
- Runaway Electrons studies (F Causa)
- **Operations and control (Cristina Centioli TBC, O Tudisco TBC)**
- Theory (M Falessi , TBC)

- **NUOVA TOPICA PROPOSTA : ARGOMENTI SVILUPPATI SU FTU DI IMPORTANZA PER DTT**

Metodo di lavoro

Prima parte del lavoro:

- Analisi delle OV di FTU pubblicate su Nuclear Fusion e presentazione della analisi in meetings dedicati
- Divisione del lavoro per topiche
- **QUESTA PRIMA PARTE DEL LAVORO TERMINA OGGI**

Seconda parte del lavoro:

- Scrittura dei lavori riassuntivi delle conoscenze acquisite nelle topiche

Seconda parte del lavoro

- Obiettivo : Scrittura dei lavori riassuntivi delle conoscenze acquisite nelle topiche
- Il ns modello e’ il volume gia prodotto per il periodo 1990-2004

- Meetings : NEI PROSSIMI MESI SARANNO ORGANIZZATI DEI MEETINGS DEI VARI WGs A SCADENZA MENSILE DEDICATI ALLO STATO DELLA SCRITTURA DEI LAVORI

- Date essenziali : 15 dicembre WIP su Interim Report
- Fine Marzo 2026 : LA SCRITTURA DEI VARI CAPITOLI DOVREBBE TERMINARE ENTRO i primi mesi del 2026 .

Pubblicazione

- **La sintesi delle conoscenze prodotte su FTU relative alle topiche considerate saranno inserite in articoli dedicati da pubblicare su un volume speciale di Fus Sci Tech.**

- **Tali articoli saranno raccolti in prima istanza in un volume da pubblicare a cura dell’ENEA.**

Teams

- E’ stato creato un Working Group (GdL_FTU) su Teams.
- E’ stata creata una cartella con le Overviews di FTU pubblicate su Nuclear Fusion e gli articoli del volume 45 di Fusion Science Technology dedicati a FTU per il periodo 1990-2004.
- Tale spazio su Teams potrà essere utilizzato per comunicazioni nell’ambito del WG: utilizzando la mail GdL_FTU@enea.it
- Per utilizzare tale mail è necessario essere inclusi nella mailing list del WG.

Analisi della OV2022

- RF heating systems
- Operation at high density
- **MHD and its stabilization/control by ECRH (Tearing Mode stabilization by ECRH and by pellet, MHD limit cycles; ECRH start-up)**
- **Impurity seeding and Transport** (**He doped Plasmas**)
- **Diagnostics (High Te measurements , REIS , LIBS, Diamond detectors**)

Nuove topiche:

- **Liquid Metal Limiter experiments (TIN Liquid Metal Limiter)**
- **Runaway Electrons studies (RE studies using pellets)**
- Operations and control
- Theory

topics	OV2005	OV2007	OV2009/ 11	OV2013	OV2015	OV2017	OV2019	OV2022
•RF heating systems	Y	Y		Y				
•Operation at high density	Y			Y		Y	Y	
•MHD and its stabilization/ control by ECRH	Y	Y	Y	Y	Y	Y	Y	Y
•Impurity seeding and Transport					Y	Y		Y
•Diagnostics	Y	Y	Y	Y	Y	Y	Y	Y
•Liquid Metal Limiter experiments		Y	Y		Y	Y	Y	Y
• Runaway Electrons studies					Y	Y	Y	Y
•Operations and control					Y	Y	Y	
•Theory		Y	Y					

Tin Liquid metal limiter

- FTU can be considered a pioneer as the first tokamak in the world that has performed exper-iments using a liquid lithium limiter and a liquid tin limiter
- The liquid metal limiters were inserted from a vertical port at the bottom side of the machine, and then the radial position could be moved shot by shot from the radius of the vacuum chamber wall (r = 33.5 cm) up to r = 27.5 cm
- the liquid metal has been kept confined using a capillary porous system (CPS)

Tin Liquid metal limiter

- The most relevant difference between lithium and tin is the atomic number (i.e. $Z = 3$ for lithium and $Z = 50$ for tin), which is strongly related with radiated power.
- Lithium mainly emits in the scrape-off layer, while tin also emits in the plasma core
- Several experiments on FTU suggested that if the liquid tin surface temperature was below the evaporation onset (namely below 1500 $^\circ$C), the plasma performances appeared unaffected (heat loads in excess of 18 MW m^{-2} were withstood by the liquid tin limiter for approximately 1 s)

Tin Liquid metal limiter

- a set of three shots is shown in the next slide.
- In shot 42781 (blue), the limiter was inserted 3 cm inside the vacuum chamber, whilst in shots 42783 (orange) and 42785 (green) the limiter was inserted 4 cm
- In these two shots, it acted as the main limiter and the heat flux was enough to bring the surface temperature to the upper limit value.
- When the surface temperature exceeds 1500 $\circ$C (*b*), a strong increase of the tin line integral occurs (*c*).

Tin Liquid metal limiter : assessment of limit heat load (18MW/m2) and temperature (1500celsius)

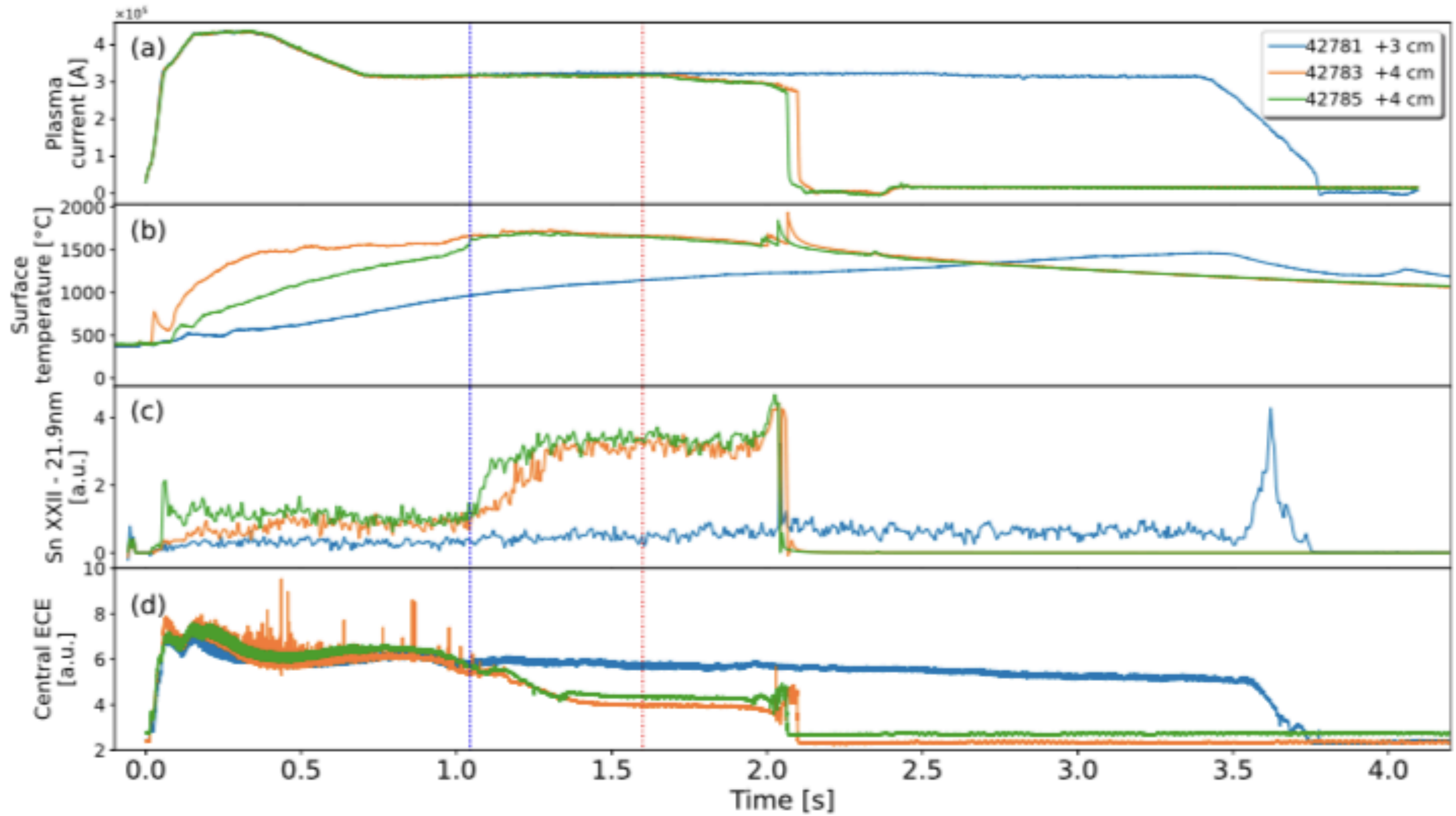


Figure 1. Liquid metal limiters. From top to bottom: (*a*) plasma current, (*b*) limiter surface temperature, (*c*) Sn XXII (21.9 nm) line integral, (*d*) central ECE. The strong increase in the plasma impurity content (see the tin line integral in (*c*)) is observed when the surface temperature exceeds the tolerable operative range (shots 42783 and 42785). The ECE drop and subsequent loss of the sawtooth activity lead to the plasma disruption.

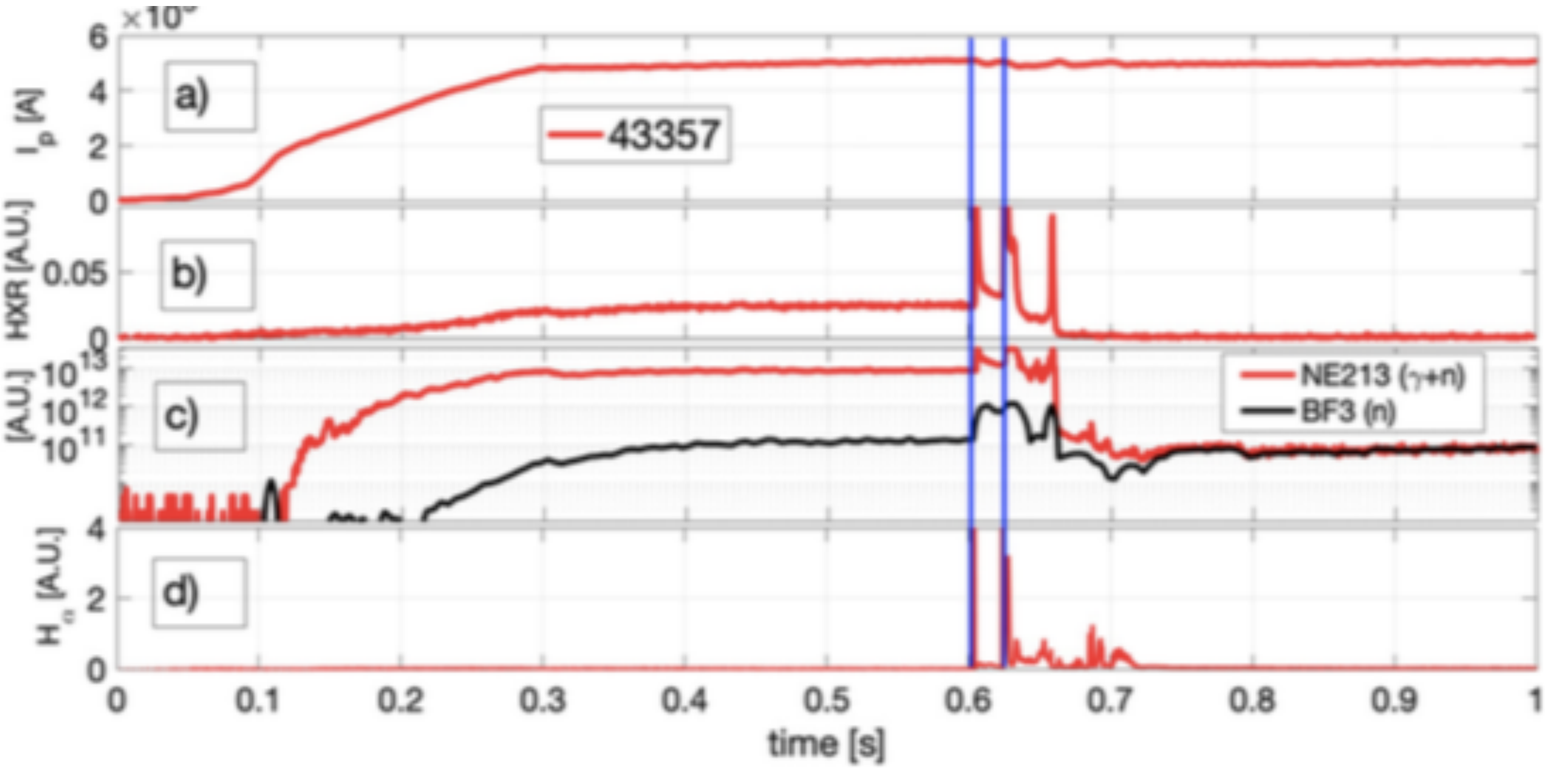
Runaway Electron Studies

- Runaway electrons (REs) beam generated during disruptions are considered one of the main concerns for large tokamaks such as ITER.
- Different strategies are currently investigated, mainly hinging on RE suppression before the RE beam formation, i.e. injecting high-*Z* particles via shattered pellet injections and/or massive gas injection to dissipate RE energy by collisions.

Runaways Electron Studies

- studied the effects of $D2$ pellet injections on RE quiescent discharges.
- single or multiple pellet injections on 0.5 MA current discharges lead to complete suppression of RE seeding by triggering bursts of MHD activity, which expel REs

Runaway Electron Studies



Anomalous doppler instabiity linked to RE generation

- The anomalous Doppler instability is driven by anisotropy of the momentum distribution function, a naturally occurring condition for RE electrons.
- Unstable waves with frequency falling in the observed spectral range (0.4–3.0 GHz) can be either whistlers or magnetized plasma waves
- The latter are favored at the high ω_{ce}/ω_{pe} values explored in FTU, for which whistlers can only resonate with RE at high-energies (> 15 MeV typical);
- however, further studies and multimachine comparisons are required to assess the relative importance of involved wave branches.

Anomalous Doppler Instability

Threshold on RE current vs plasma density

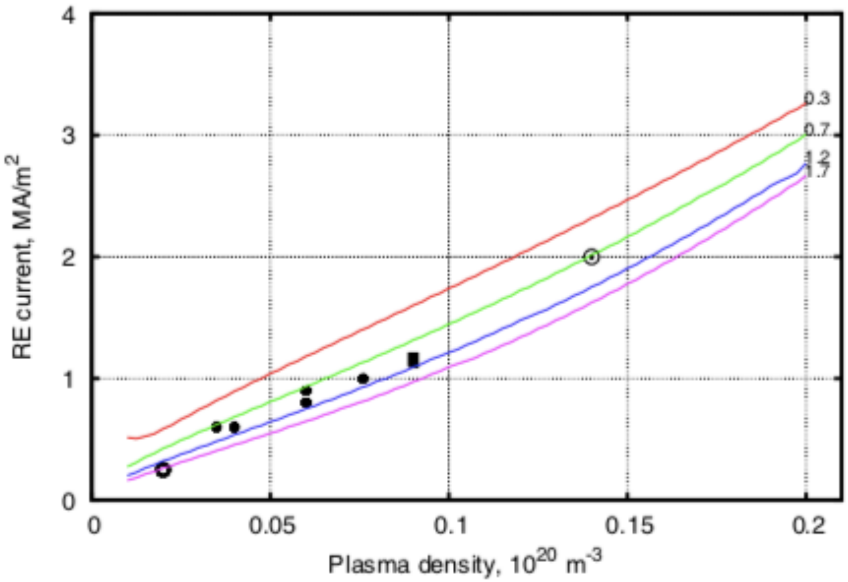


Figure 4. Calculated and experimental instability threshold. The lines represent calculations for different average energies of the REs (in MeV) indicated next to the lines. The instability exists above the line. The points represent experimental data [2]; empty circle—T-6, dots—TM-3, filled rectangle—TFR, circle with dot—T-10.

Two branches of the ADI : Magnetized plasma Mode(green) and Wistler Mode (Red)

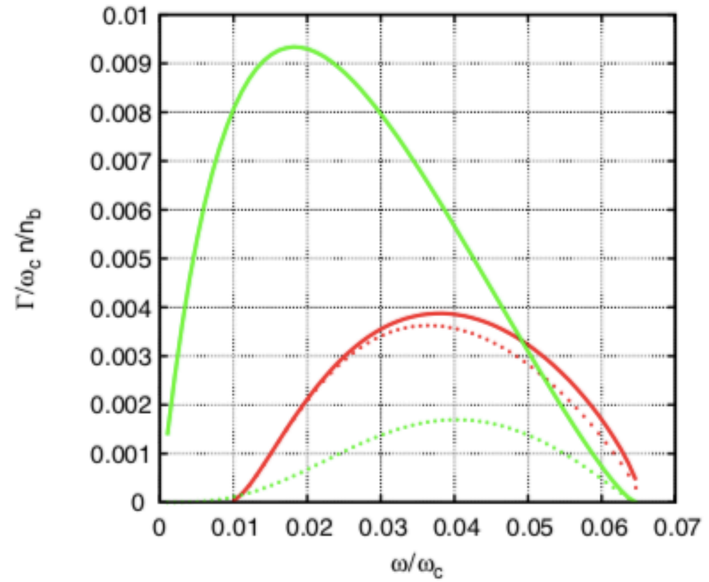


Figure 3. Normalized kinetic drive and suppression of the magnetized plasma mode by finite Larmor effects. Magnetized plasma mode (green/light curves); whistler mode (red/dark curves). The solid curves denotes the growth rates in the zero Larmor radius limit. The dotted curves are the growth rates for a beam with $\theta_0 = 0.1$. The ratio of ω_p/ω_c is 0.5 and $\gamma = 25$.

Measurements of wave emitted by Runaway electrons

- Evidence of anomalous Doppler Instability

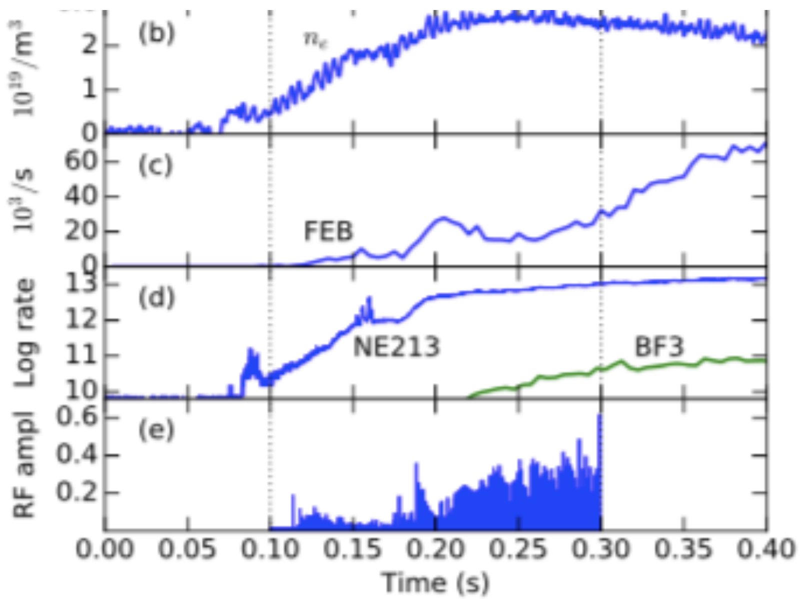


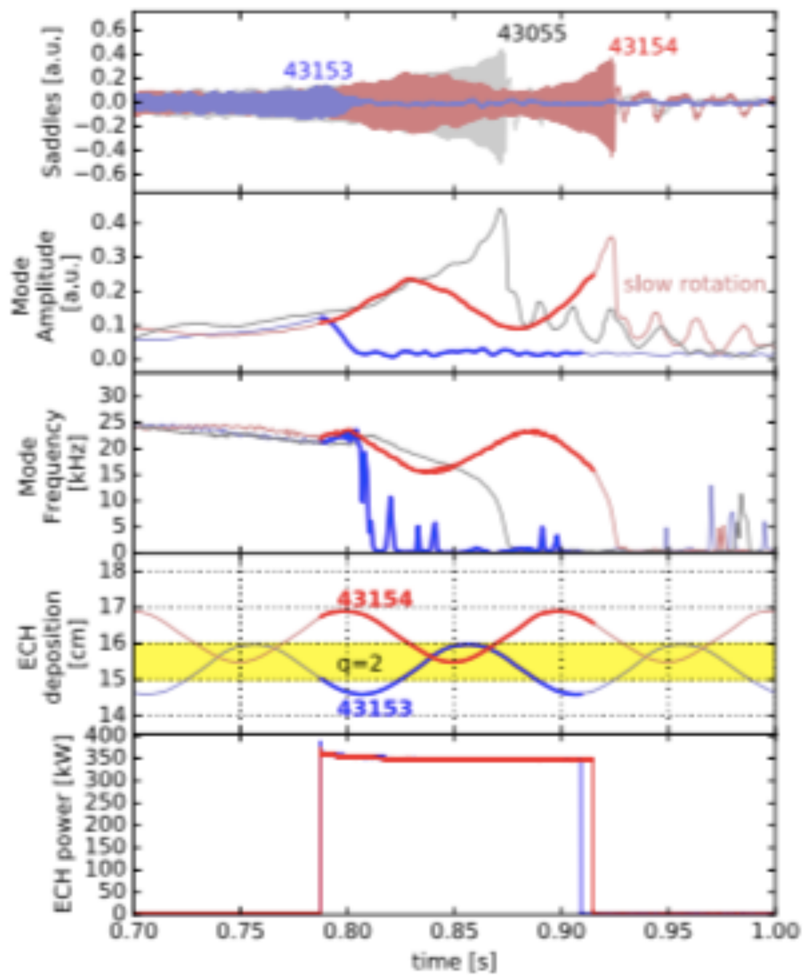
Figure 3. Measurements of plasma waves emitted by runaway electrons. FTU pulse 43649 at 5.3 T. (*a*) Plasma current. (*b*) Line-averaged density from the central chord of a CO_2 laser interferometer. (*c*) HXR count rate from an equatorial channel of the fast electron bremsstrahlung camera. (*d*) Log_{10} of HXR and neutron count rate from a Nuclear Enterprises liquid organic scintillator (NE213) sensitive to both HXR and neutrons; the neutron

TM stabilization by ECH in sawtooth-free scenarios at low density

- The study of the tearing mode (TM) stability is an important issue for tokamak fusion devices, because the development of the magnetic islands characterizing the instability can deteriorate the confinement, leading to a decrease of the plasma energy content and sometimes to a plasma disruption.
- In sawtooth-free low-density regimes, magnetic islands formed by tearing instabilities around the $q = 2$ surface can appear and saturate at large amplitudes
- This behaviour is common to most tokamak fusion devices, so it is important to improve the possible stabilization strategies

TM stabilization by ECH in sawtooth-free scenarios at low density

- In pulse 43153 (Blue Trace) , the launcher antenna is steered to cover the foreseen island O-point location, and slightly inward from the *q* = 2 surface. When the mode amplitude overcomes the set threshold, and gyrotron is triggered, the antenna is aiming at the O-point and then ECH power provides very fast stabilisa-tion of the mode in 20 ms, that is 60% less than in pulses with fixed antenna.
- in 43154 (red) ECH is injected in the outer proximity of the magnetic island



TM Stabilization by Pellets

- the effect of *D*2 pellet injection on the temporal evolution of the magnetic island characterizing the sawtooth-free low-density regimes on FTU has been studied.
- A single pellet, containing around 1 10^{20} *D*2 atoms, has been injected at about 1.2 km s−1 from the low field side mid-plane, with most of particles deposited in the core plasma.
- A mode stabilization in a few milliseconds has been observed after a pellet injection in presence of a fast rotating magnetic island
- Instead, a pellet injection in the presence of a quasi-locked magnetic island has induced a reduction of the mode amplitude and an increase of the rotation frequency

TM stabilization by pellet

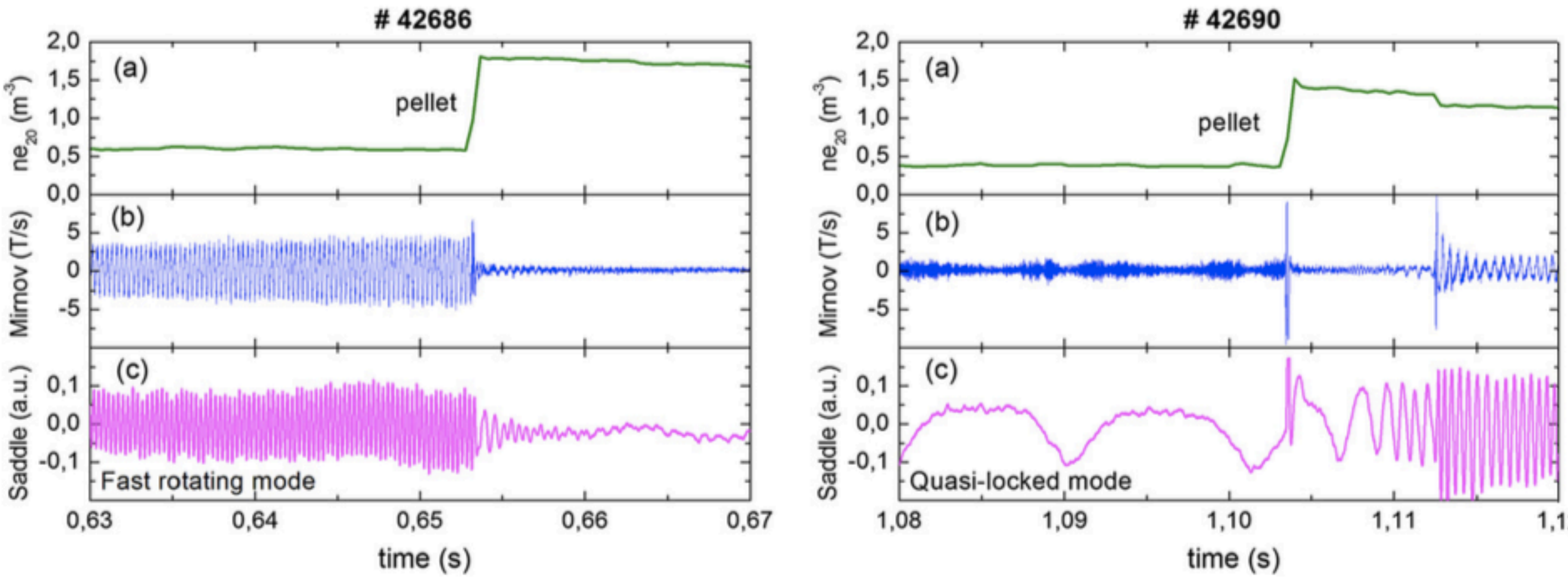
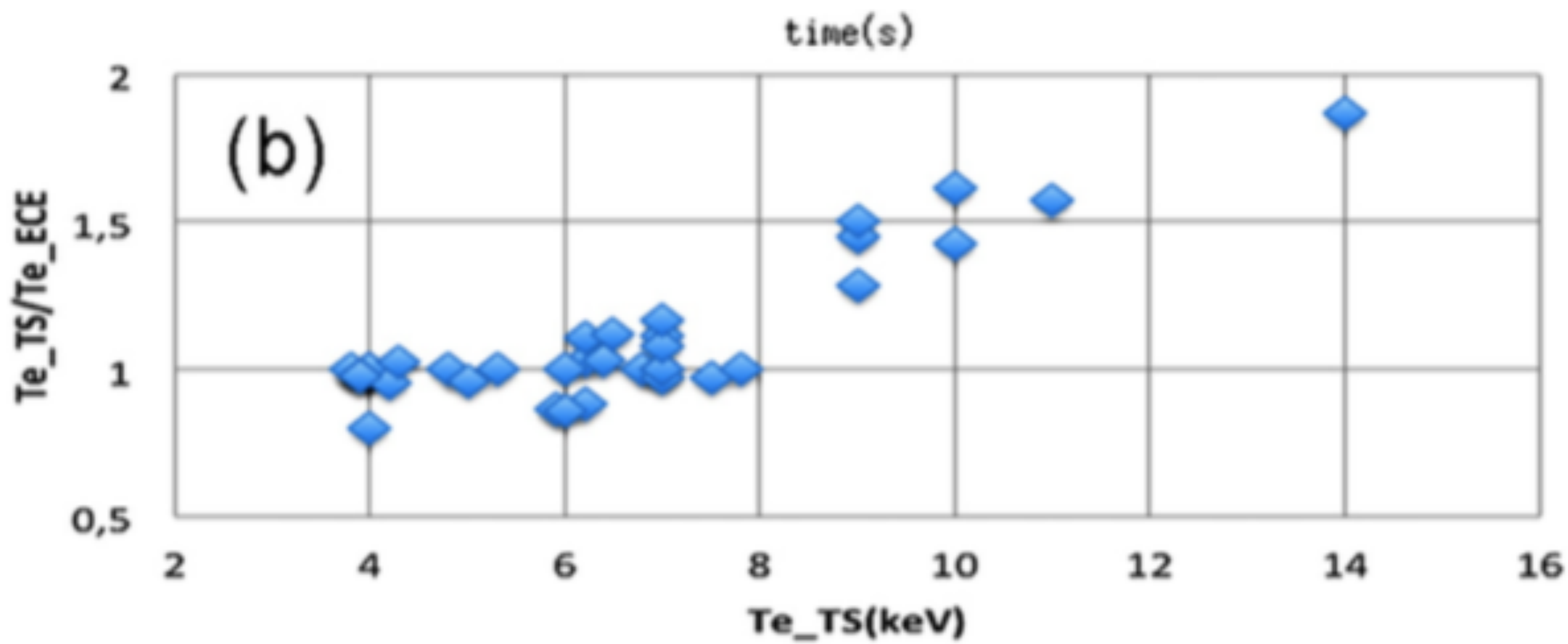


Figure 5. Tearing modes stabilization by pellet injection. FTU pulses ($B_T = 6$ T, $I_p = 0.50$ MA) with a fast rotating mode (left) and with a quasi-locked mode (right), respectively. From top to bottom: (*a*) line-averaged density for a central chord, (*b*) derivative of the poloidal magnetic perturbation from a Mirnov coil, (*c*) derivative of the radial magnetic perturbation from a saddle coil. The pellet injection corresponds to the rapid increase in density.

High Te Plasmas



LIBS (Laser Induced Breackdown spectroscopy)

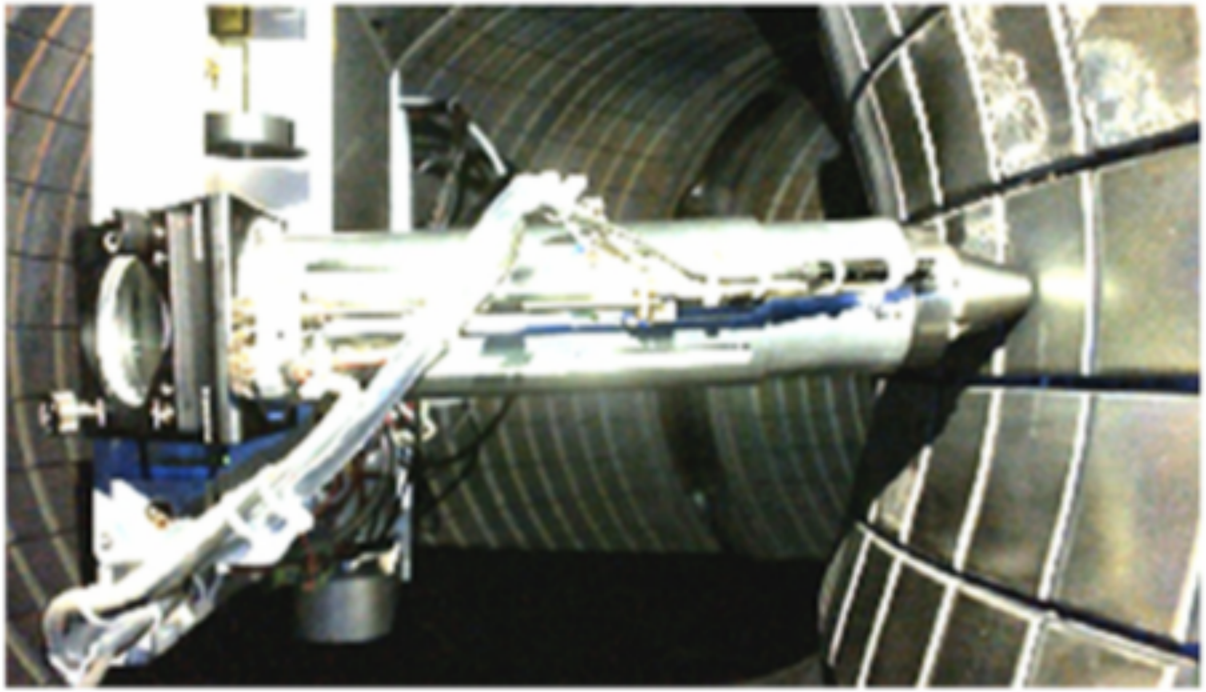


Figure 11. Laser induced breakdown spectroscopy. The LIBS device measuring inside the FTU vacuum vessel on a tile of the toroidal limiter.

Diamond detector

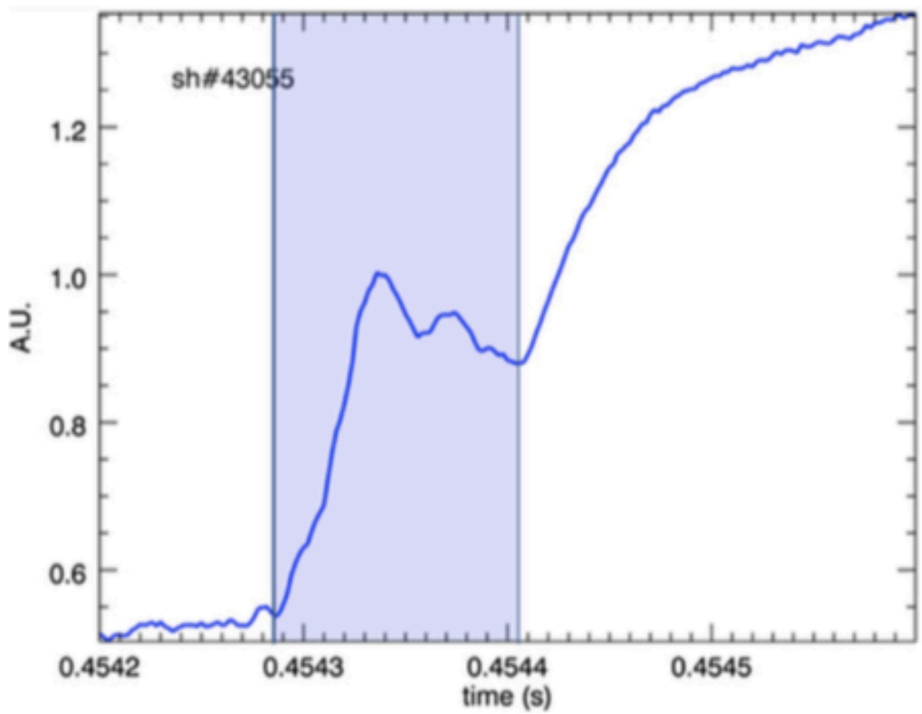


Figure 14. Diamond detectors for fast VUV and SXR diagnostics. Time evolution of the ablation process (shaded area) of a pellet injected into an FTU plasma from the low field side, as recorded by the diamond detector.

GRAZIE PER LA ATTENZIONE