Introduzione al VI meeting Campagna di Analisi di FTU

Francesco Paolo Orsitto

ENEA C.R. Frascati, Aula B. Brunelli

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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

La proposta 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.**

Main Topics

(per ogni topica un gruppo di lavoro)

- Le topiche seguenti, estratte dall'analisi delle Nuclear Fusion Overviews (NFO) di FTU dal 2005 al 2022, sono prese come riferimento per il lavoro della campagna di analisi:

- RF heating systems
- Operation at high density
- MHD and its stabilization/control by ECRH
- Impurity seeding and Transport
- Diagnostics

Nuove topiche posso essere prese in considerazione:

- Liquid Metal Limiter experiments
- Runaway Electrons studies
- Operations and control
- Theory

Metodo di lavoro

- Nella stesura del volume 45 di FUS SCI TECH 2004 dedicata a FTU, il lavoro dei vari capitoli è stato fatto usando solo le pubblicazioni fatte nel periodo 1990-2004.

- Il lavoro era stato strutturato con un responsabile per capitolo.

- **Il lavoro relativo alla Campagna di analisi di FTU si può organizzare seguendo tale esempio: ogni capitolo ha un titolo tratto dalle topiche elencate, con un responsabile.**

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

Seconda parte del lavoro:

- Scrittura dei lavori riassuntivi delle conoscenze acquisite nelle topiche

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 OV 2005

- 4.La analisi del testo della OVFTU del 2005 (Angelini et al , Nuc Fus 2005) ha condotto alle seguenti osservazioni:
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- Le topiche rilevanti incluse in tale OV2005 sono :
- i**) RF physics**: argomento fondamentale la fisica del riscaldamento e di generazione di corrente con LH ed ECRH, lo studio delle barriere di trasporto interne ;
- ii) **RF Technology** : la nuova antenna LH /PAM e l'upgrade della antenna ECRH;
- iii) **la fisica della alta densita** con pellets ;
- iv) **lo studio della MHD** con gli electron fishbones ;
- v) le **diagnostiche**
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Analisi della OV 2007

- 3.La analisi del testo della OVFTU del 2007 (V Pericoli et al et al , Nuc Fus 2007) ha condotto alle seguenti osservazioni:

- Le topiche rilevanti incluse in tale OV2007 sono :
  1. **RF:** Physics and technology of RF heating systems
  2**. Liquid Litium Limiter**
  3**. MHD** and its Stabilization by ECRH, disruption control by ECRH
  4.**Theory** and measurements of electron fishbones
  5.**Diagnostics**

Analisi OVs 2009/2011
(A A Tuccillo et al Nuc Fus 49(2009)10413 and ibid. 51(2011)094011)

- Argomenti:
- **Liquid Litium Limiter**: improved performance in high density discharges with lithized wall
- **MHD /Theory : Electron Fishbones** , theory and modelling of experimental observations
- ECRH control of disruptions
- Dust dynamics in tokamak plasmas
- **Diagnostics**: oblique ECE measurements

Analisi della OV 2013

Dall’analisi del testo della OV FTU del 2013 (P. Buratti et al, Nuclear Fusion 53 (2013) 104012) risulta che le topiche rilevanti incluse nella OV 2013 sono:

1. **RF:** Physics and technology of RF heating systems (LHCD coupling at high density and new ECRH launcher)

2**. Operation at high density (density limit)**

3**. MHD** and its stabilization by ECRH (ST stabilization)

4. **Theory** and measurements of electron fishbones and simulations by MHD-gyrokinetic XHMGC code

5. **Diagnostics** (refractometer)

Analisi della OV2015

- RF heating systems
- Operation at high density
- **MHD and its stabilization/control by ECRH (RTC of MHD instabilities, EC assisted plasma start-up, MHD as disruption precursors)**
- **Impurity seeding and Transport (desnsity peaking by Neon seeding, Tearing Mode Instability by Ne inj)**
- **Diagnostics (Cherenkov probe , gamma camera , LIBS**)

Nuove topiche posso essere prese in considerazione:

- **Liquid Metal Limiter experiments (Cold LL oper)**
- **Runaway Electrons studies (RE generation and Control)**
- **Operations and control (FTU –D)**
- Theory

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

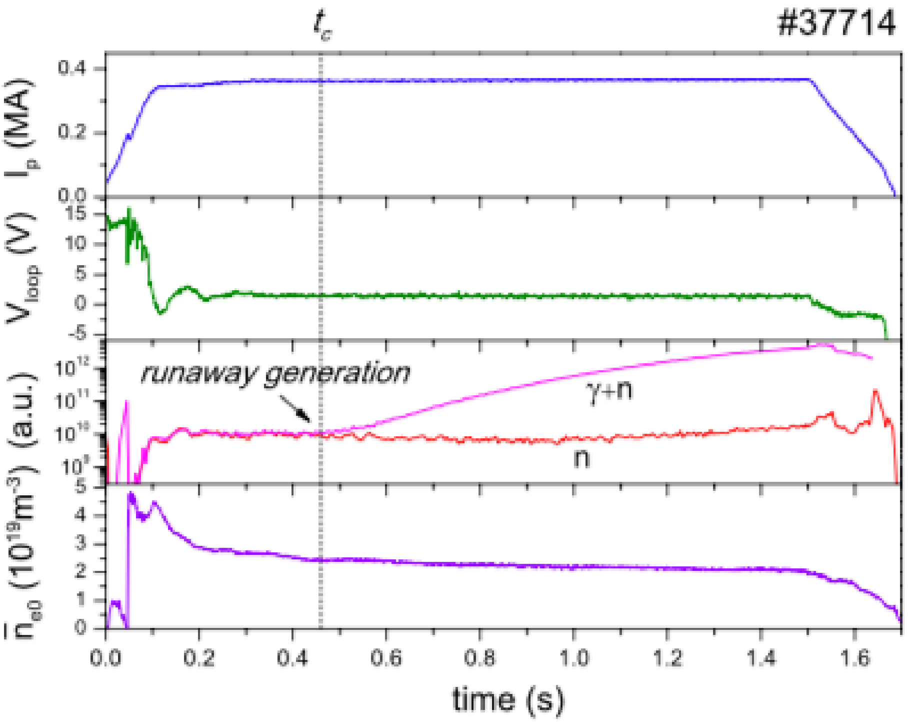
Runaway electron generation and suppression

- The determination of the threshold density value to be achieved by means of massive gas injection for RE suppression in ITER relies on the relativistic collisional theory of RE generation which predicts that, below a critical electric field (E_R), no RE can be generated.
- Experiments had shown that RE suppression is found to occur at electric fields substantially larger than those predicted by the relativistic collisional theory of RE generation.
- This was found to be consistent with an increase of the critical electric field due to the electron synchrotron radiation losses, which lead to a new electric field threshold (E_R^{rad})

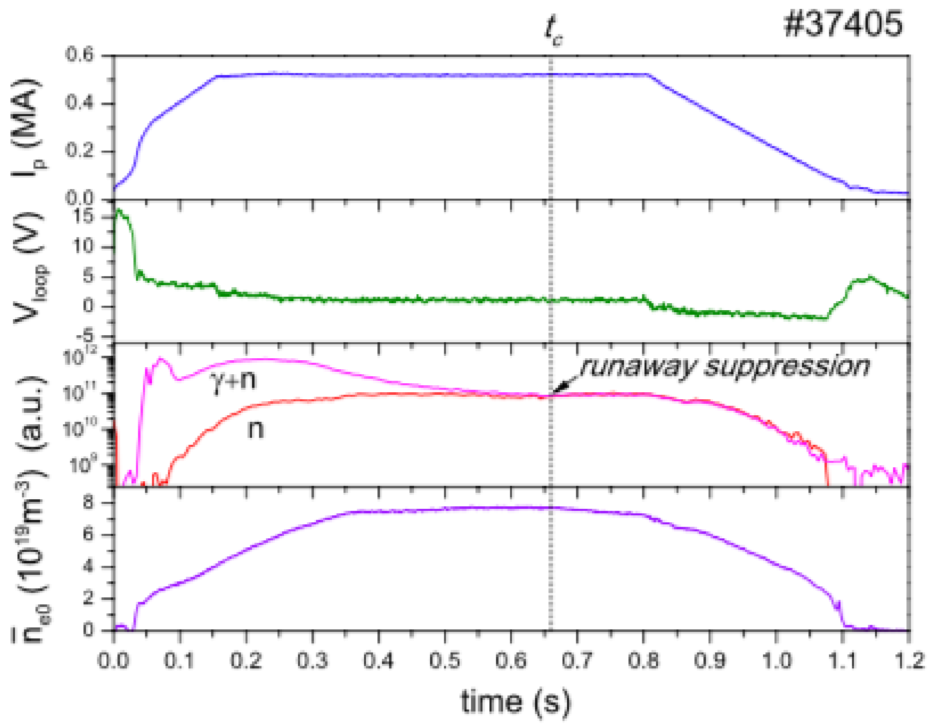
RE in FTU : two types of experiments

- The conditions for RE generation was systematically investigated for ohmic discharges: toroidal magnetic field (BT = 3.0–7.2T), plasma current (Ip = 0.35–0.50MA) and effective charge (Zeff = 1.5– 15).
- The threshold electric field for RE generation was measured in two different types of experiments (RE onset and RE suppression), in the first using feed-forward gas programming to obtain a decreasing electron density until RE are generated and in the second creating a RE population during the Ip ramp-up that is then suppressed by the density increase.

RE generation and suppression

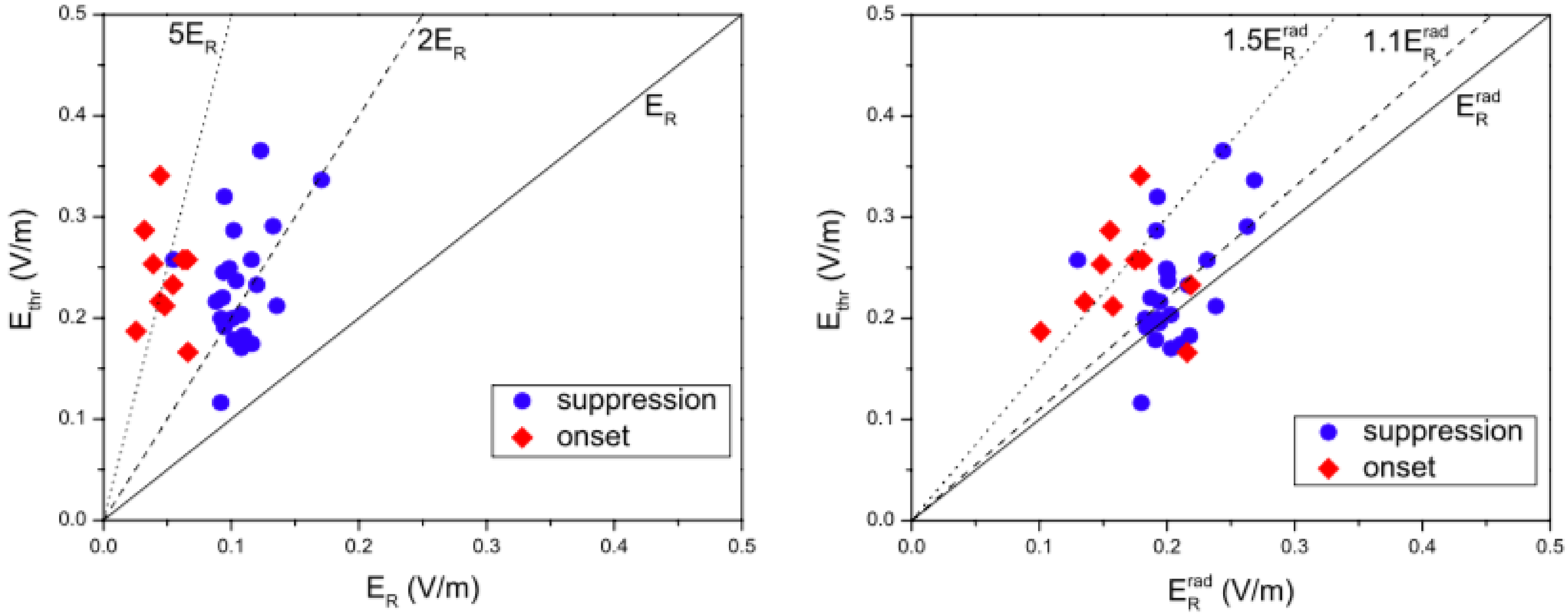


RE Generation



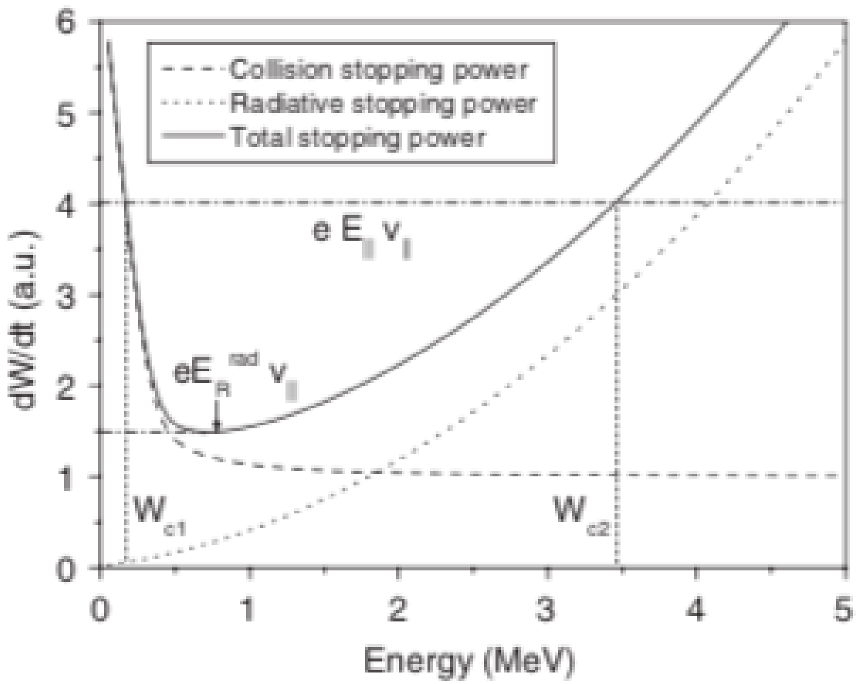
RE Suppression

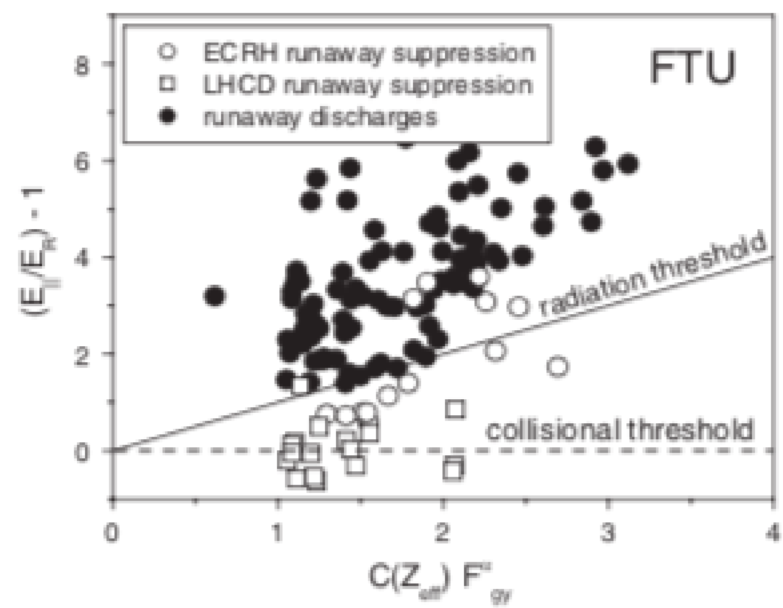
Threshold Electric field for RE generation and suppression



E_R is the threshold evaluated using collisional relat model ; E_R^{rad} includes the radiation
the experimental threshold is consistent with the evaluations done including Syncrothron radiation

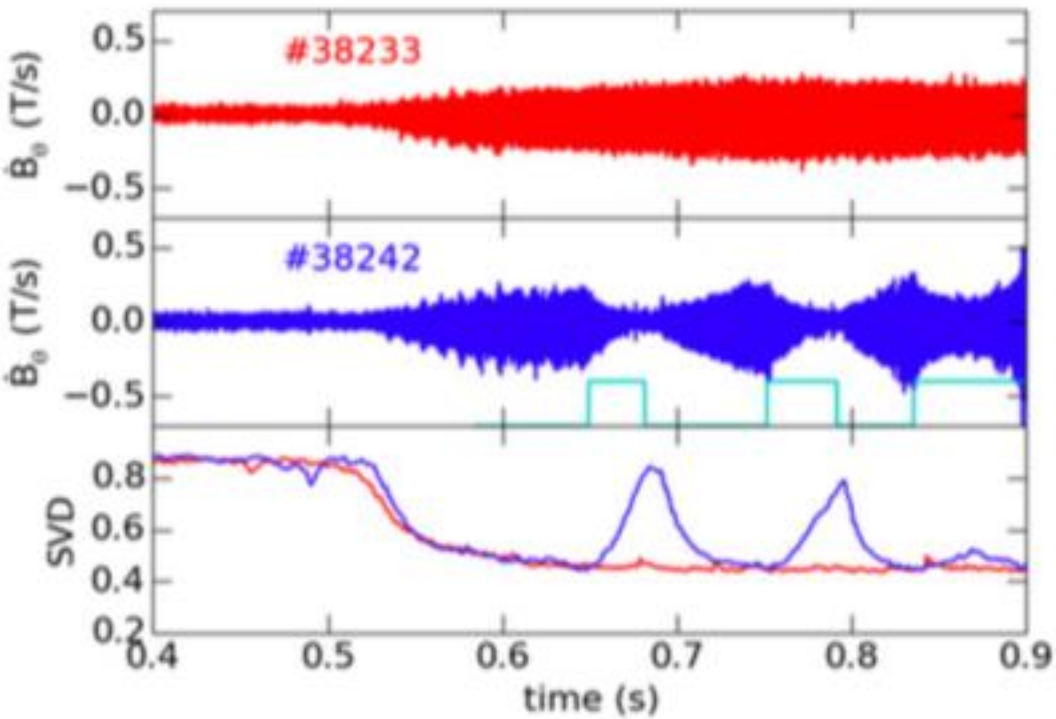
Dynamics of RE stopping power including synchrotron radiation





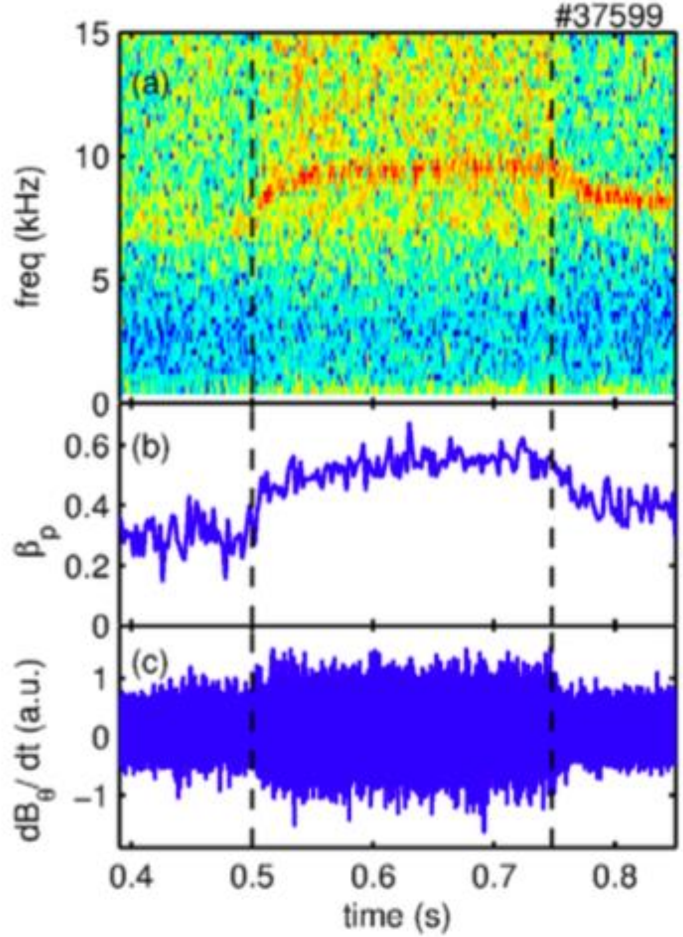
Martin-Solis , Sanchez, Esposito PRL 2010

ECW experiments : MHD and its stabilization/control by ECRH



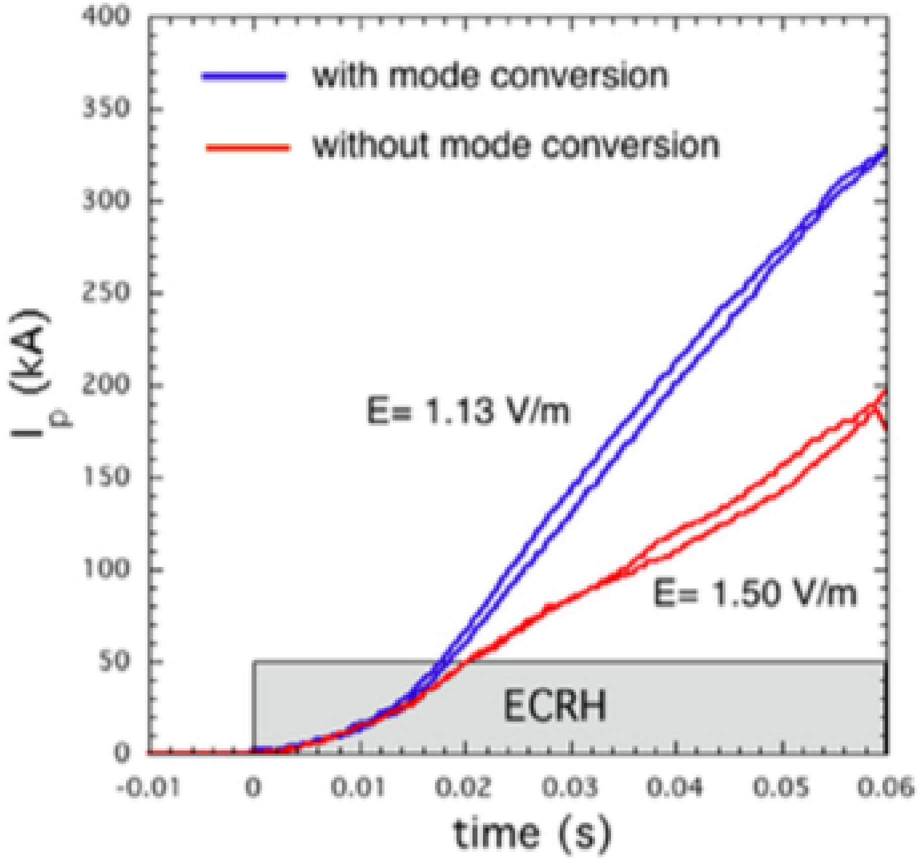
Stabilization of m/n=2/1 tearing mode by ECRH
The mode is generated by injection of Neon
And it is stabilized by ECRH heating in the position
Of the mode

Amplification of Neoclassical Tearing Mode by ECRH heating



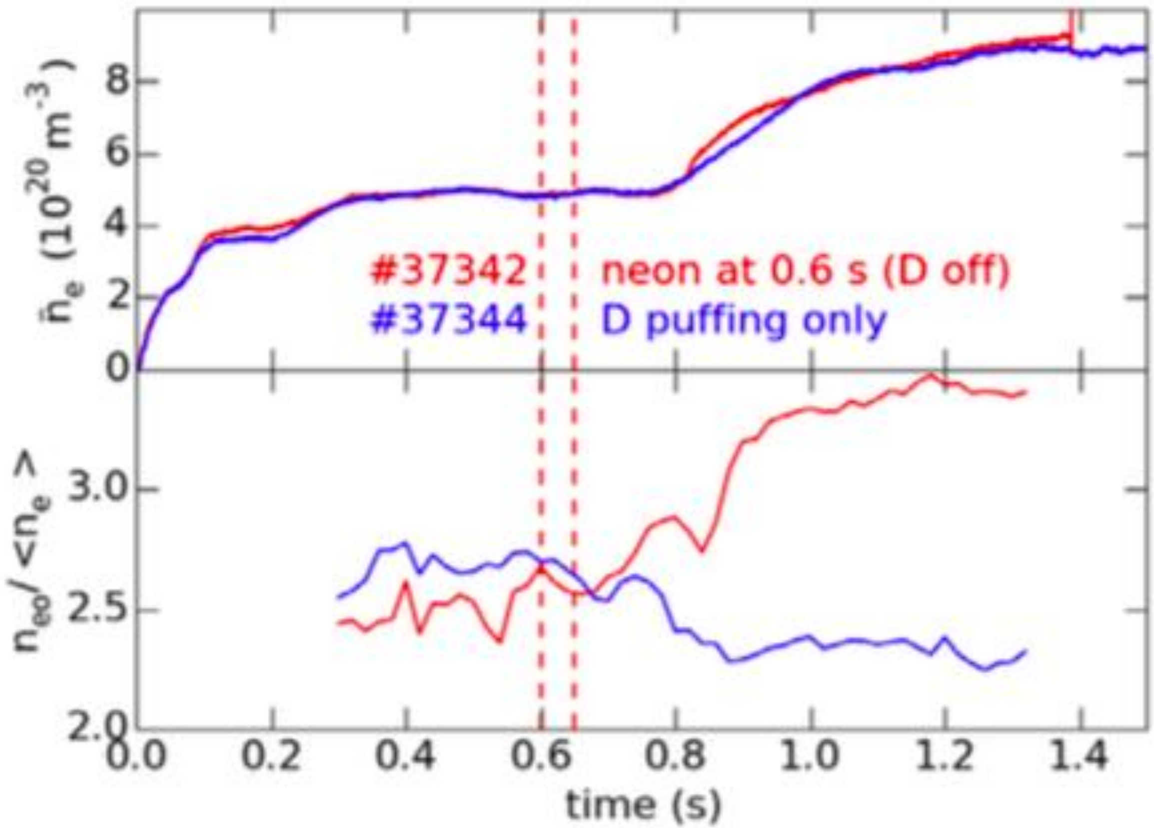
Amplification of NTM by
Co-ECCD
Increasing the bootstrap current
Inside the island

EC assisted plasma startup



Oblique injection of ECRH allows the mode conversion from O to X
On the wall to get improved absorbtion of the wave
The plasma start up al lower loop voltage

Neon seeding : density peaking



Comparison of two discharges with and without NEON :
at the same density The discharge with NEON
has a strong density peaking

Cherenkov probe

The Cherenkov probe consists of a **diamond detector** mounted on a titanium–zirconium–molybdenum (TZM) head inserted in the FTU vessel (in the limiter shadow).
The Cherenkov radiation emitted within the diamond by electrons escaping from the plasma is coupled to a VIS/UV fibre connected to a high-gain photomultiplier tube.

evidence of loss of confinement of fast electrons in presence of high-amplitude magnetic islands and demonstrating that the modulation of the Cherenkov signal is due to the rotation of the magnetic island

Cherenkov probe vs MHD island rotation

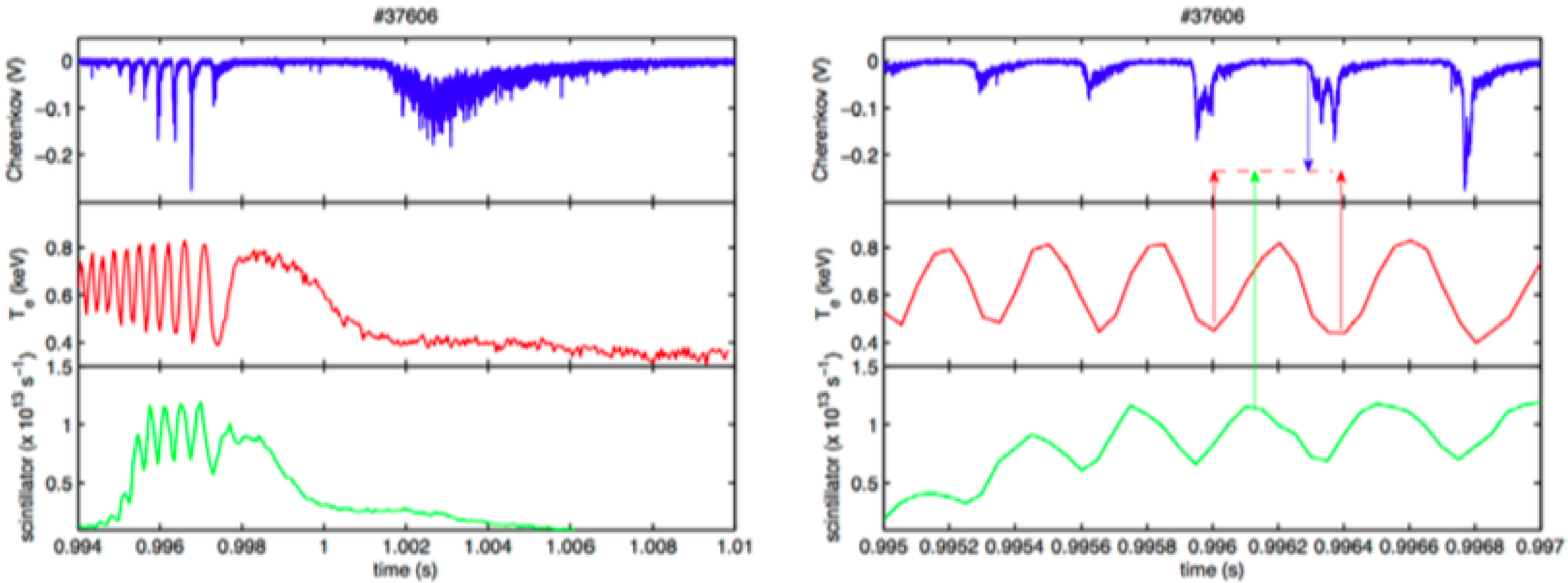


Figure 11. Left side: data acquired from Cherenkov probe (top panel), ECE (middle panel), liquid organic scintillator (lowest panel) over the duration of the MHD activity, showing the modulation of the Cherenkov probe signal during magnetic island rotation. Right side: detail showing the time delay of the Cherenkov signal and of the signal of the liquid organic scintillator with respect to the electron temperature signal (from ECE), due to the relative positions of the detectors (FTU discharge 37606).

X-ray detection by Gamma camera

- A digital upgrade of the analogue electronics of the FTU neutron camera has been carried out in order to enable studies on REs by measuring the HXR produced in the bremsstrahlung interactions between RE and plasma ions.
- The gamma camera system is based on six radial lines of sight equipped with liquid organic scintillators (NE213) capable of n/γ discrimination also in conditions of very high count rate (MHz range)
- thanks to the spectrometric and neutron/gamma (n/▯) discrimination capabilities of its detectors can also provide radially resolved measurements of hard X-rays (HXR) emitted perpendicularly to the magnetic field and produced by RE through bremsstrahlung in the plasma.
- **HXR are measured through Compton scattering (rather than photoelectric absorption used in a similar system at JET) of RE-generated photons with energies above ∼100 keV.**

Diagnostics : gamma camera

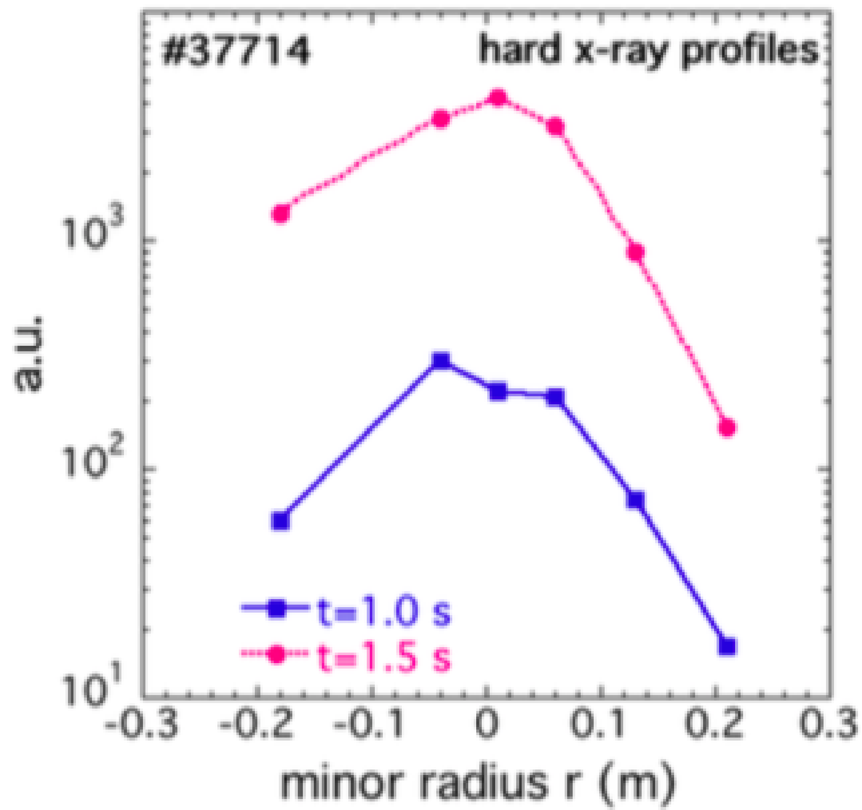


Figure 12. HXR profiles for a standard FTU discharge.

Laser Induced Breackdown Spectroscopy (LIBS)

- LIBS measurements have been performed on FTU, by focusing the radiation of a Q-switched Nd–YAG laser to tungsten samples, coated with thick Al–C–W mixed layers, and collecting the light emitted by the plasma plume generated by the laser pulse.
- Experiments were carried out under vacuum, with a toroidal magnetic field up to 4 T .
- the Al and W spectral lines from the Al–C–W mixed sample are shown as an example. These experiments have demonstrated the feasibility of *in situ* LIBS diagnostic

LIBS

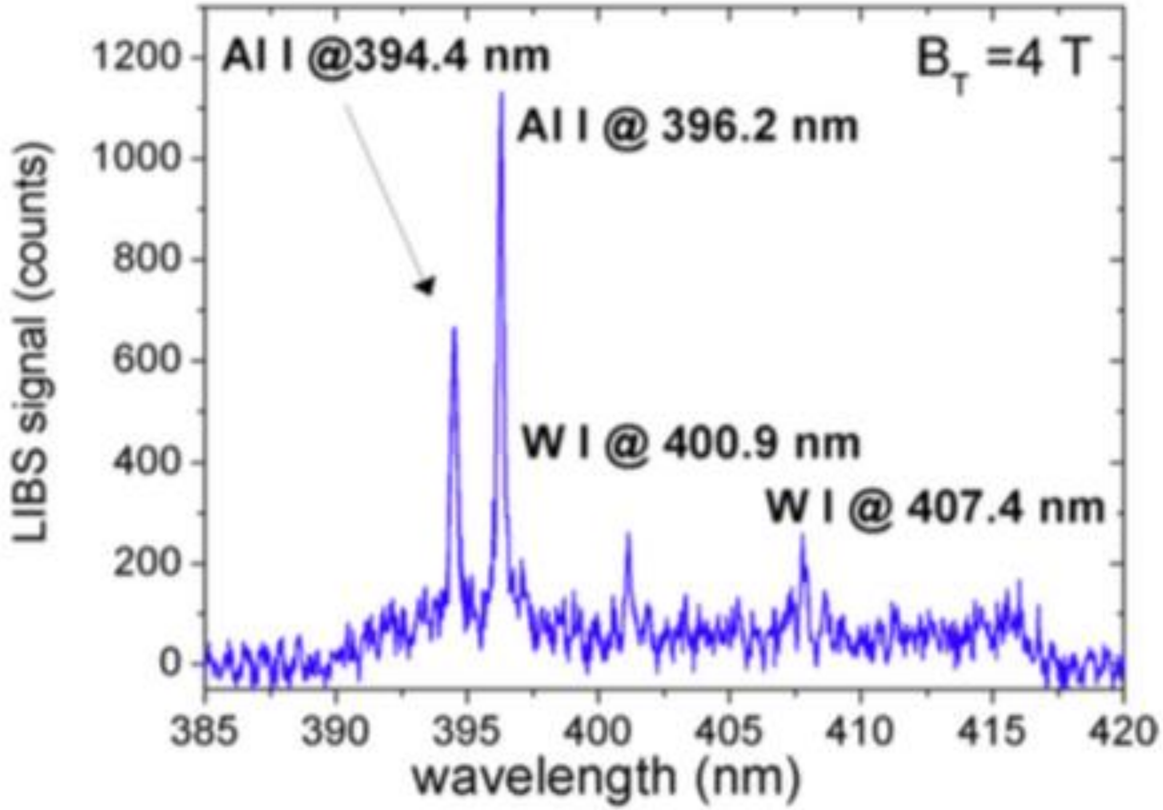


Figure 13. LIBS spectrum from Al–C–W mixed sample.

Thank You for the attention

Elongated plasmas