Introduzione all’ VIII meeting Campagna di Analisi di FTU

Francesco Paolo Orsitto

Meeting Online

26 maggio 2025, ore 14.30

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 , O Tudisco TBC)**
- Theory (M Falessi , TBC)

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 OV2019

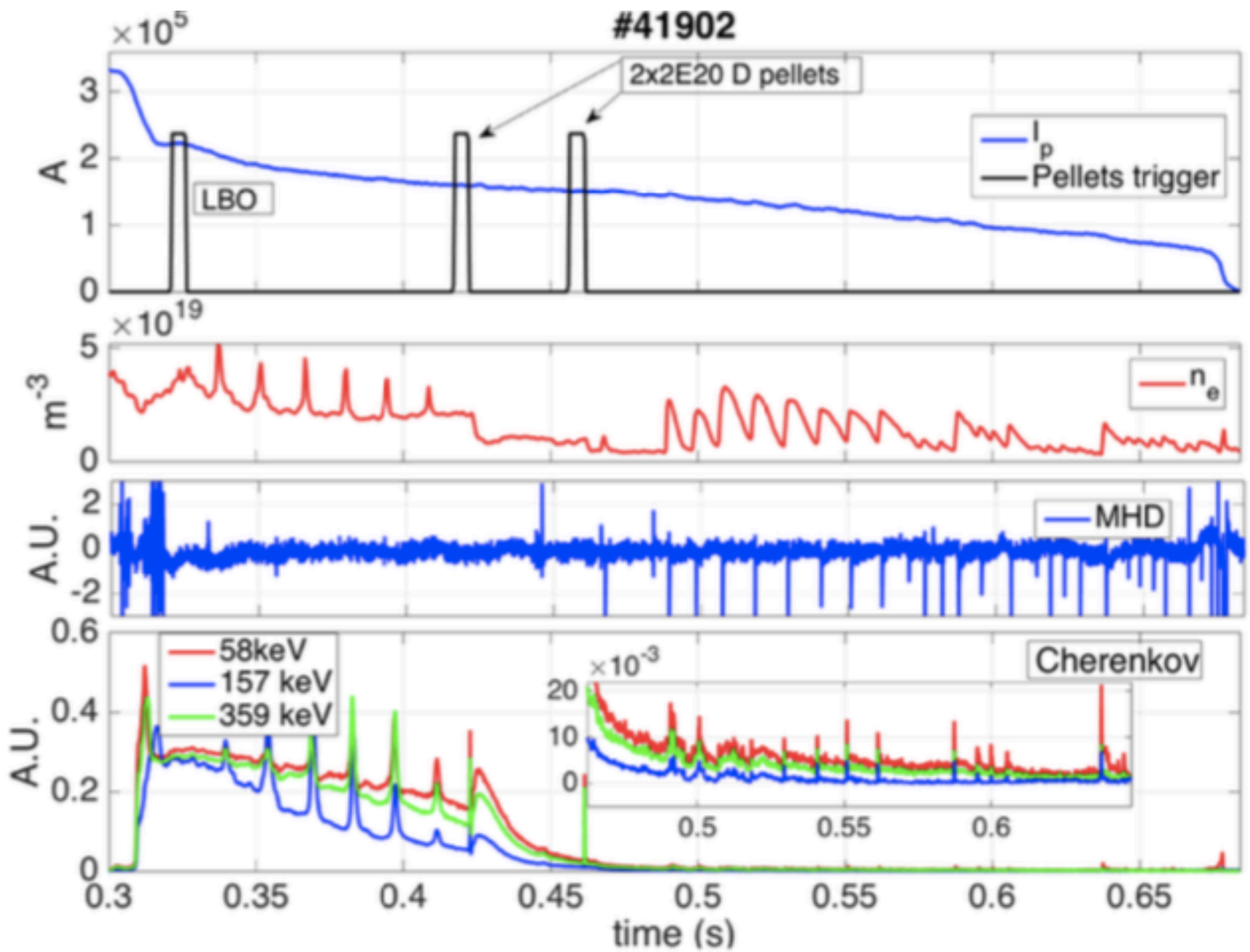
- RF heating systems
- **Operation at high density** (**High Collisional Regimes)**
- **MHD and its stabilization/control by ECRH (Tearing Mode analysis with MARS Code)**
- Impurity seeding and Transport
- **Diagnostics(REIS , CTS, Cherenkov probe, LIBS**)

Nuove topiche:

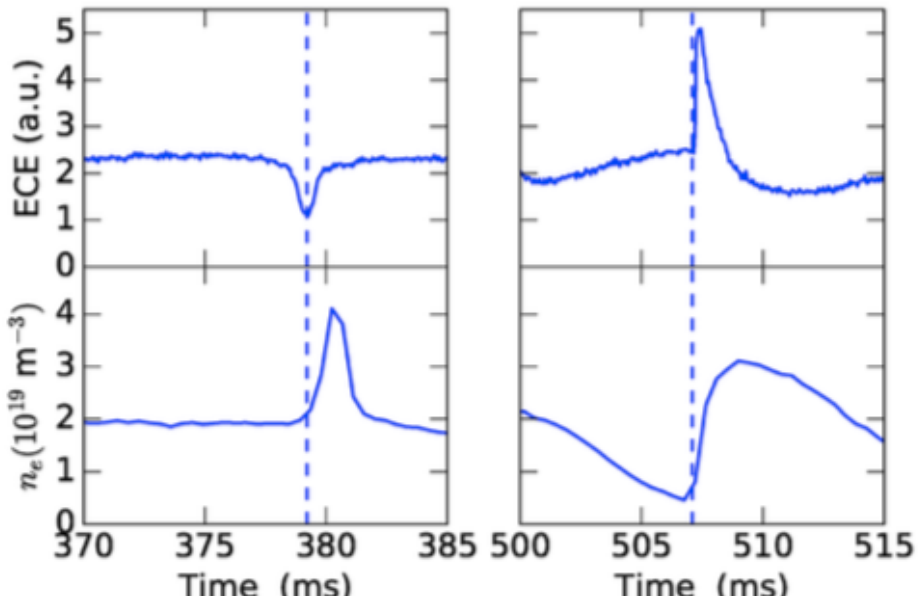
- **Liquid Metal Limiter experiments (Tin Liquid Litium Limiter)**
- **Runaway Electrons studies (RE generation and Control)**
- **Operations and control (FTU–D elongated, DUST Analysis)**
- Theory

topics	OV2005	OV2007	OV2009/11	OV2013	OV2015	OV2017	OV2019
•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
•Impurity seeding and Transport					Y	Y	
•Diagnostics	Y	Y	Y	Y	Y	Y	Y
•Liquid Metal Limiter experiments		Y	Y		Y	Y	Y
•Runaway Electrons studies					Y	Y	Y
•Operations and control					Y	Y	Y
•Theory		Y	Y				

Runaways generation and control: interaction of RE with metal injection and pellet



Two types of instabilities detected corresponding to LBO-Fe and pellet injections



The spikes in the density plot after 0.45 s could be induced by gas recycling from the wall of expelled REs impacting the wall or ionizing the surrounding inert gas.
The density spikes related to time lower than 0.45 s do not seem to be induced by known instabilities and are under study.

ECE has a fully non-thermal origin, in fact emission spectra are continuous, without any sign of the harmonics structure which characterizes thermal spectra

Diagnostics for RE

Plasma Internal RE : SXR , HXR (Ne213) , REIS

Plasma external RE : Cherenkov probe

Table 1. Summary of diagnostics used for RE studies in FTU.

Diagnostic name	RE-related measured parameter	RE diagnostic capability	Time resolution (ms)	Energy range (keV)	Real-time (Y/N)	Main features	Reference
BF_3 chambers	Neutrons	Lost	5		N	Absolutely calibrated	[3]
^{235}U fission chamber	Photoeutrons & photofissions	Lost	1		Y	Thick-target bremsstrahlung of γ-rays > ~7 MeV	[4]
NaI scintillator	HXR	Lost/ confined	1		N	Pulse mode	[5]
	HXR spectra	Lost/ confined	100	$<2 \times 10^3$	Y		[5]
NE213 scintillator	Neutrons, γ-rays	Lost/ confined	0.05		N	Current mode, no n/γ discrimination	[5]
Gamma camera	HXR radial profile	Confined	~1	>100	N	See text	[2]
Fast electron bremsstrahlung camera	HXR	Confined		20–200	N	Vertical and horizontal lines of sight	[6]
REIS	Synchrotron radiation spectra	Confined	~20	—	N	See text	—
Cherenkov probe	Lost electrons	Lost	0.001	>58	N	See text	[1]
CO_2 scanning interferometer	Electron density radial profile	Confined	0.0625	—	Y	Vertical chords at $R = (0.8965 - 1.2297)$ m	[6, 7]
						MARTe RT implementation	[8]
MHD sensors	MHD modes	—	0.002	—	Y	Poloidal field pick-up Mirnov coils	[6]

REIS
(Runaways electron imaging spectroscopy)

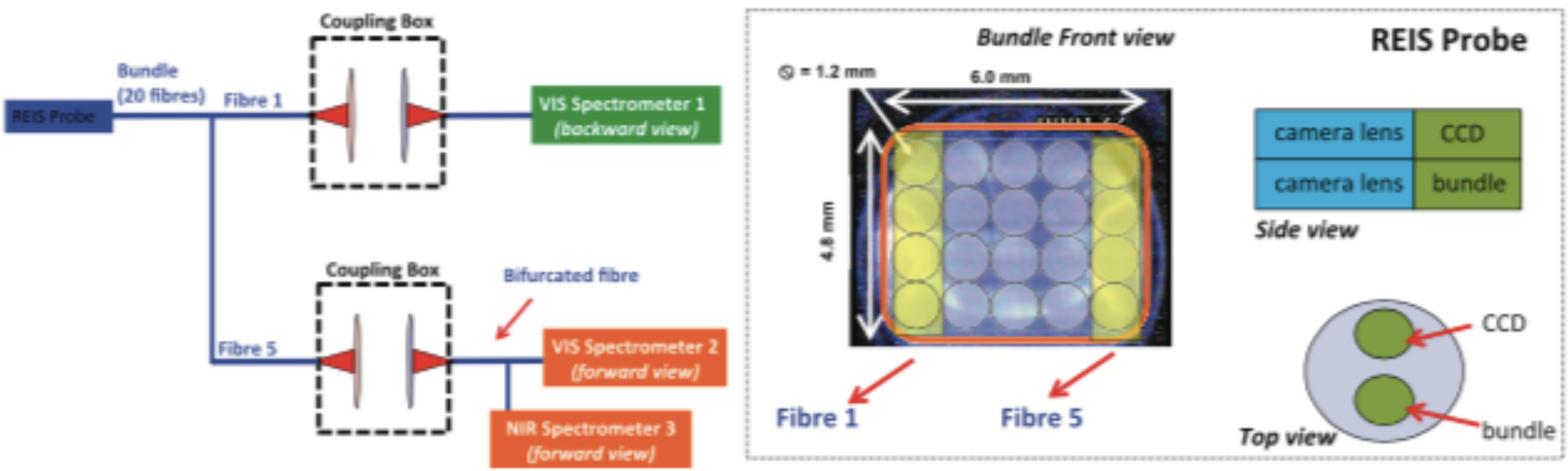


Figure 1. Layout of the runaway electron imaging and spectrometry (REIS) system. The REIS probe is composed by a wide-angle lens coupled to a CCD camera for the recording of video images (see figure 4) and a wide-angle lens coupled, through an incoherent bundle of fibres, to visible (VIS) and near-infrared (NIR) spectrometers for the acquisition of synchrotron spectra.

REIS
(Runaways electron imaging spectroscopy)

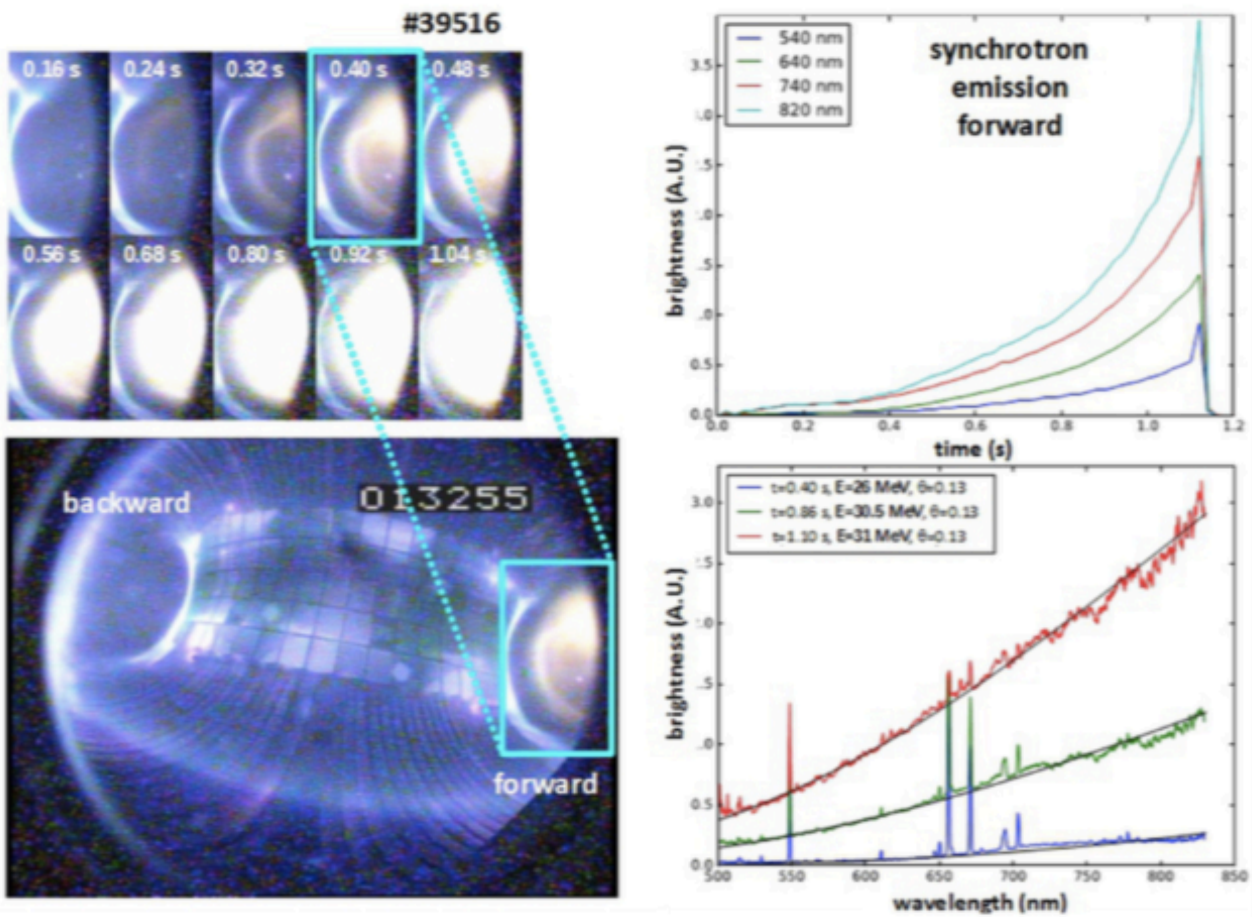


Figure 9. Pulse #39516. Visible camera images of the RE beam (left): the bottom image (corresponding to frame 013255, $t = 0.4$ s) shows both RE backward and forward views, while the top image is a time sequence of the forward view for the same pulse. Note the temporal correlation of the visible images with the measured synchrotron radiation intensity at several wavelengths (top right) and synchrotron radiation spectra (bottom right). In particular, the spectra are fitted (solid lines) assuming mono-energetic distributions (energy and pitch angle values in the insert).

Cherenkov probes:Diamond detectors Measuring fast electrons escaping from plasma

Electrons impinging on the probe emit Cherenkov radiation in the diamond ,
this radiation is routed through a fiber optic to a PMT operating at 1kV with a
Detectable range of 185-850nm.

Triple probe has three diamond detectors with three different energy threshold
E=58,187, 359 keV , able to perform energy scan .

Each diamond detector is mounted on a Titanium Zirconium Molibdenum head in vessel ,
and Coated with a Ti/Pt/Au inter-layer filtering the Dalpha line

In the triple probe two of them have a Mo layer thick 56micron and 164micron to get
Different energy thresholds.

Cherenkov probes measurements

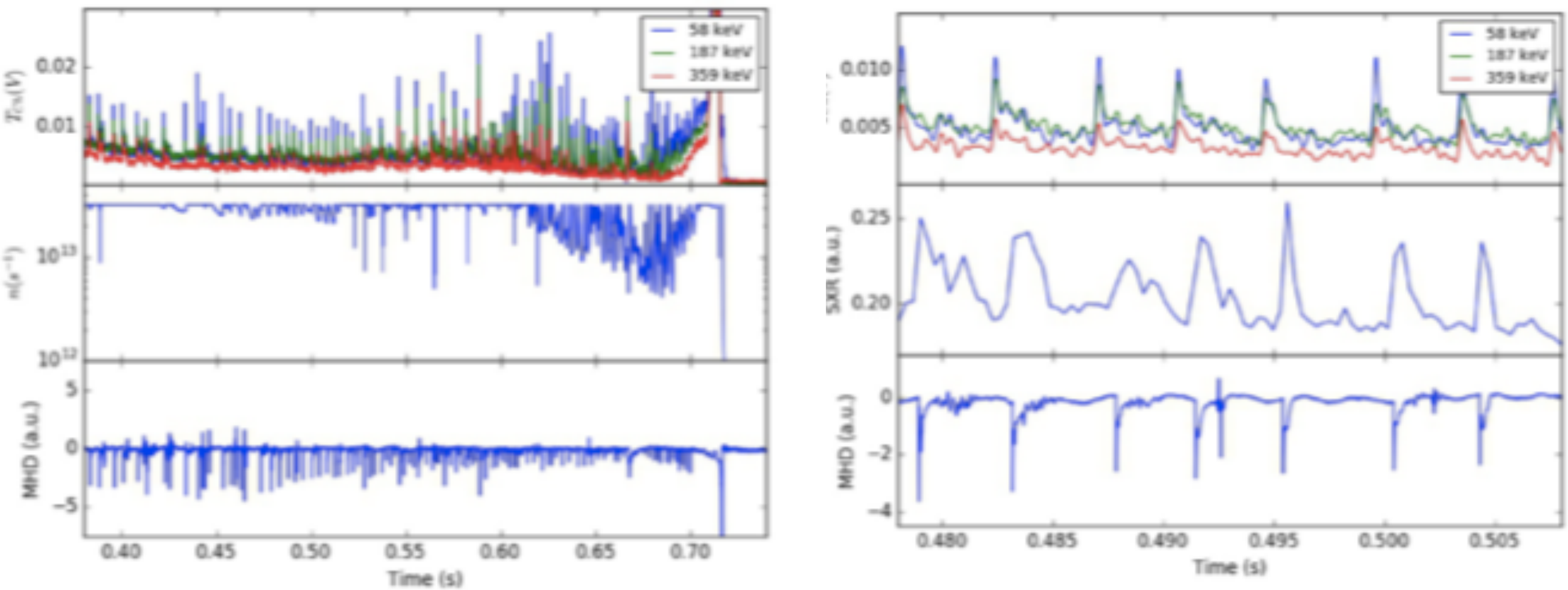


Figure 10. (Left) Correlation between triple Cherenkov probe signal, gamma-ray count rate and MHD activity. (Right) Triple Cherenkov signal, soft x-rays and MHD activity. Pulse #41146.

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

More than 90% of the power will be radiated in the center and/or
In the SOL and the plasma will be partially detached

liquid tin may prove a good candidate
as a plasma facing component material,
with a large operating window ($300 < T < 1300$ ◦C)
before vaporization, low or negligible activation,
and low H retention

Tin Liquid limiter experiments

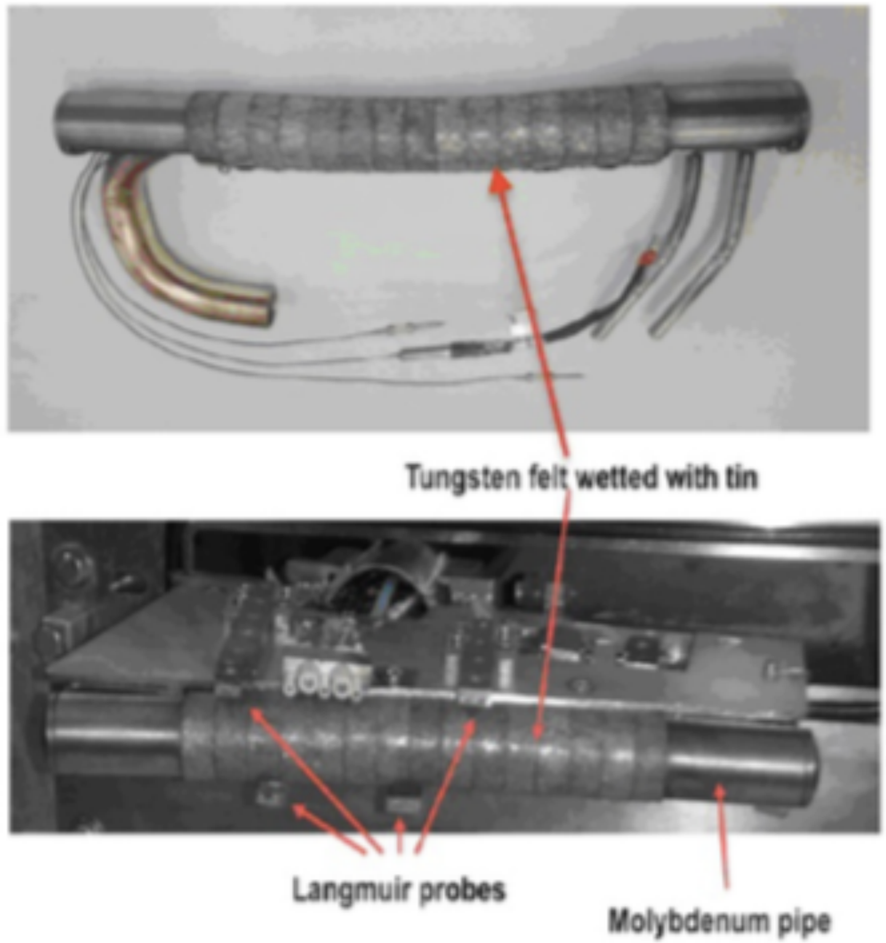


Figure 3. TLL installed on FTU. The TLL is equipped with several thermocouples and four Langmuir probes, two on each side.

Diagnostics of Tin Liq Limiter(TLL)

- Thermocouples
- 4 langmuir probes
- A fast Infrared Camera observing the whole TLL From top
- A Schwob-Fraenkel XUV spectrometer observing The range 20-340 angstrom to identify the spectral lines of Tin.

Max temperature 1700 Celsius, reached up to 18MW/m^2 heat load

B = 5.3T ,
Ip=500kA .

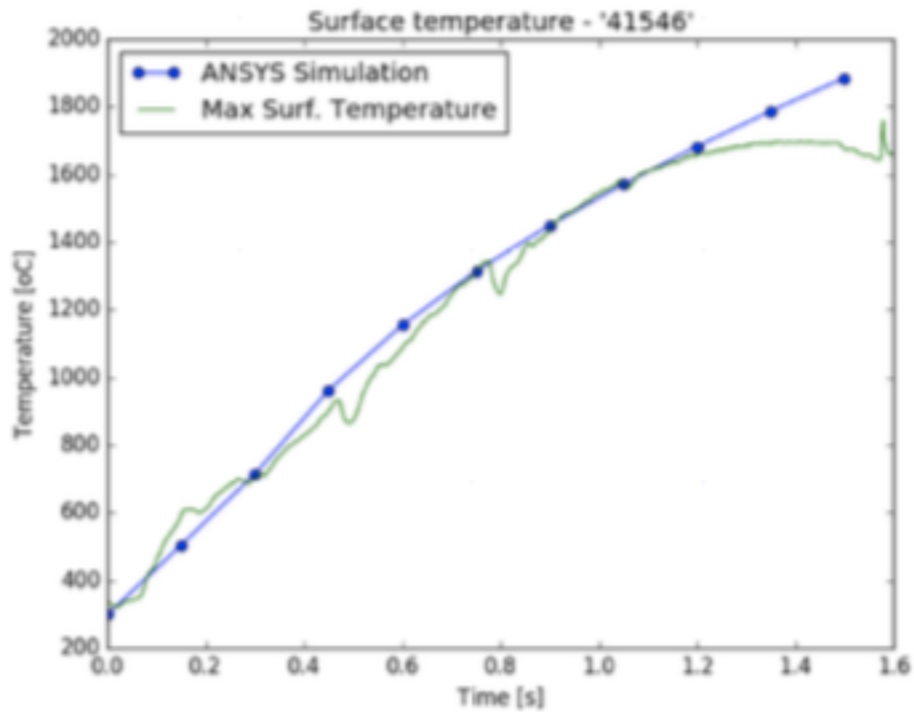


Figure 5. Experimental surface temperature compared with the ANSYS model. The flattening of the surface temperature can be linked to the evaporation phenomena.

Highly Collisional Regimes

inverse linearity between the electron density peaking and the effective collisionality veff is found for most tokamak devices

FTU offers the unique opportunity to explore regimes of high collisionality (up to ~100), thanks to the capability to operate up to very high electron density values.

at high values of collisionality such inverse linearity does not occur, but, instead, an increase of the density peaking with the collisionality is found

Highly Collisional Regimes

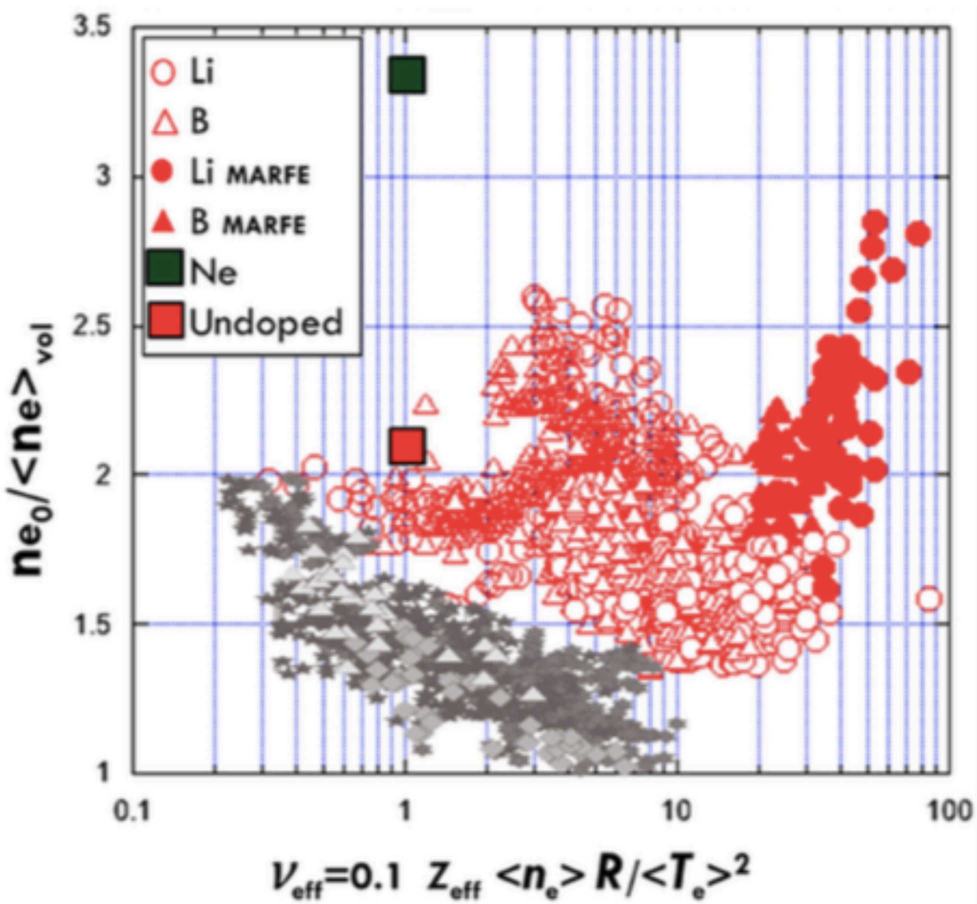


Figure 8. Density peaking as a function of the effective collisionality. Red symbols for FTU data; grey symbols for other devices. The behaviour of a neon doped pulse on FTU is also reported (green square).

Highly Collisional Regimes

From the comparison between pulses with and without the MARFE instability and with lithium or boron wall conditioning,

The increase of the density peaking is related to edge phenomena

These effects are particularly evident in Neon seeded discharges

System LIBS (Laser Induced breakdown spectroscopy)

- Quantel Nd YAG and Andor Charge Coupled Intensified camera coupled to a Jobin-Yvon spectrometer 1/2m focal length
- The collinear transmission of the laser beam and detection of emitted visible lines was done through the 2 inches window of an equatorial port by using a dielectric mirror

LIBS (Laser Induced breakdown spectroscopy)

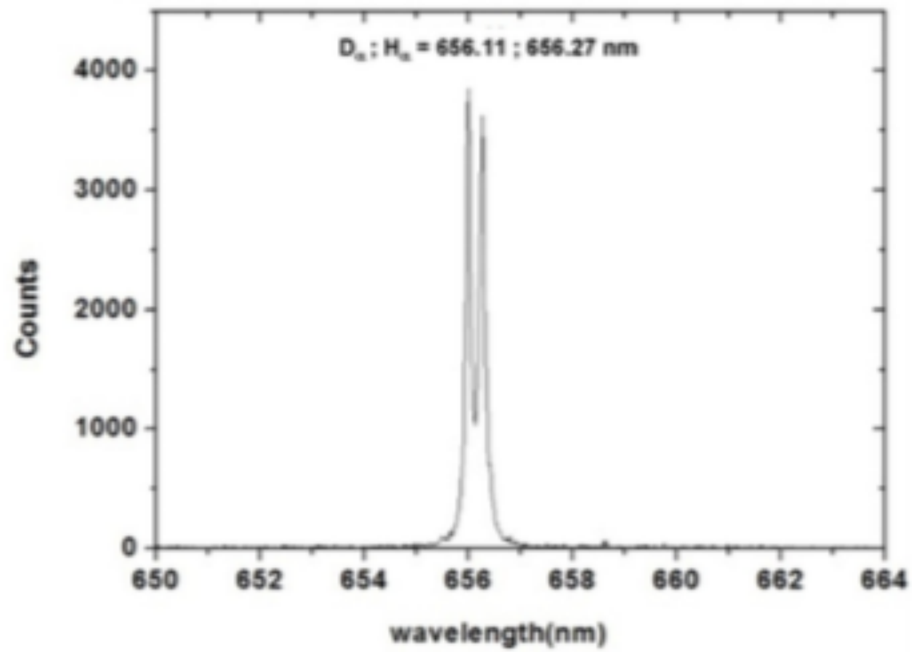


Figure 11. Deuterium and hydrogen emission lines detected by LIBS on a shadowed zone in between the FTU toroidal limiter tiles.

Collective Thomson Scattering

The measurements of Parametric Decay Instabilities of the EC pump wave were Attempted .

These are generated inside a MHD island

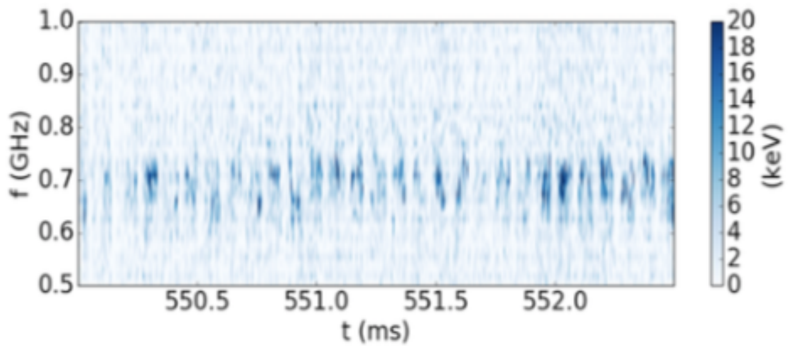
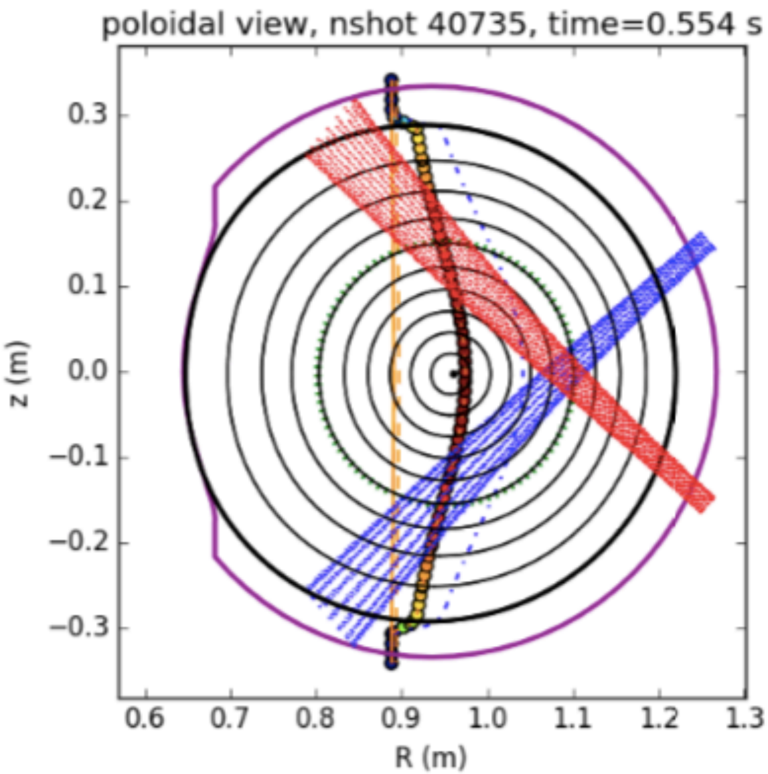


Fig. 13. Example of line-emission of Type 7 (shot #40735).



ig. 15. Plasma reconstructed equilibrium and resonances for shot #40735 with symmetric launch: receiving beam crosses the probe beam close to the q=3 rational surface (dotted circle in green) where a MHD island exists. Before reaching the EC resonance (thin vertical line) the beams intersect again the q=3 surface, in the proximity of the UH resonance (dots in colour).

GRAZIE PER LA ATTENZIONE

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 e' organizzato seguendo tale esempio: ogni capitolo ha un titolo tratto dalle topiche elencate, con un responsabile.**

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

Analisi della OV 2005

- 4.La analisi del testo della OVFTU del 2005 (Angelini et al , Nuc Fus 2005) ha condotto alle seguenti osservazioni:
-
- 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**
-

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

Analisi della OV2017

- RF heating systems
- **Operation at high density** (**density limit studies extended to low field and current**)
- **MHD and its stabilization/control by ECRH (EC assisted plasma start-up and MHD vs disruption)**
- **Impurity seeding and Transport (density peaking by Neon seeding, Tearing Mode Instability by Ne inj, MARFE dynamics vs density peaking)**
- **Diagnostics (Visible/IR detector for runaways studies, IR camera for thermografic analysis of plasma facing components , triple GEM detector for Xray diagnostics, New capabilities of CTS and Cherenkov probe**)

Nuove topiche:

- **Liquid Metal Limiter experiments (operation extended to 10 MW/m2)**
- **Runaway Electrons studies (RE generation and Control)**
- **Operations and control (FTU –D elongated configuration obtained for 3.5s, DUST Analysis , Plasma facing components)**
- Theory

Runaways control

- RE beam current ramp-down policies using the central sole-noid have been implemented on FTU in order to confirm the possibility of RE beam mitigation without the use of massive gas injection.
- The control system acts on the central solenoid to induce RE beam current ramp-down meanwhile the beam is kept away from the vessel
- The study has revealed that the decay rate during RE beam current ramp-down is a key parameter for runaway current suppression.
- experimental findings suggest that post-disruption RE beam suppression is mainly achieved when the decay rate is of about 1 MA s^{-1},

Runaways generation during EC assisted plasma start-up

- The results show the generation of REs even at moderate EC power injection (400 kW), in conditions of toroidal electric field *E*Loop well below the Dreicer field threshold *E*Dreicer for primary generation,
- evidencing that EC waves moderately increase the energy of electrons, which may be further accelerated by the toroidal electric field to runaway.
- The database has been analyzed in order to find a possible parameter controlling RE generation, assuming that the electric field is not the only relevant parameter.
- **The exploration has evidenced a dependency on the pre-filling pressure more than on the plasma density during the EC pulse**