Introduzione al VII meeting Campagna di Analisi di FTU

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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

Main Topics: 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 (TBC))**

Nuove topiche posso essere prese in considerazione:

- Liquid Metal Limiter experiments (C Mazzotta TBC)
- Runaway Electrons studies
- **Operations and control (Cristina Centioli , da confermare)**
- 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 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

Transport : Neon seeding

- Seeding of neon impurity in FTU ohmic plasmas causes a spontaneous rise of line-averaged electron density up to a factor two associated with a significant increase of the peaking factor
- **to investigate the observed density peaking, a detailed linear micro-stability analysis of a neon-doped pulse**
- The Ne-doped pulse has higher ion and electron temperature gradients after the neon injection than the un-doped one; consequently, ITG and ETG modes turn out to be unstable, with higher values of the growth rates with respect to the similar un-doped pulse
- **the fluxes analysis shows that ETG modes drive an inward flux for all the species and everywhere, so that the sharp peaking of the density profile could be due to the inward pinch brought about by ETG modes**

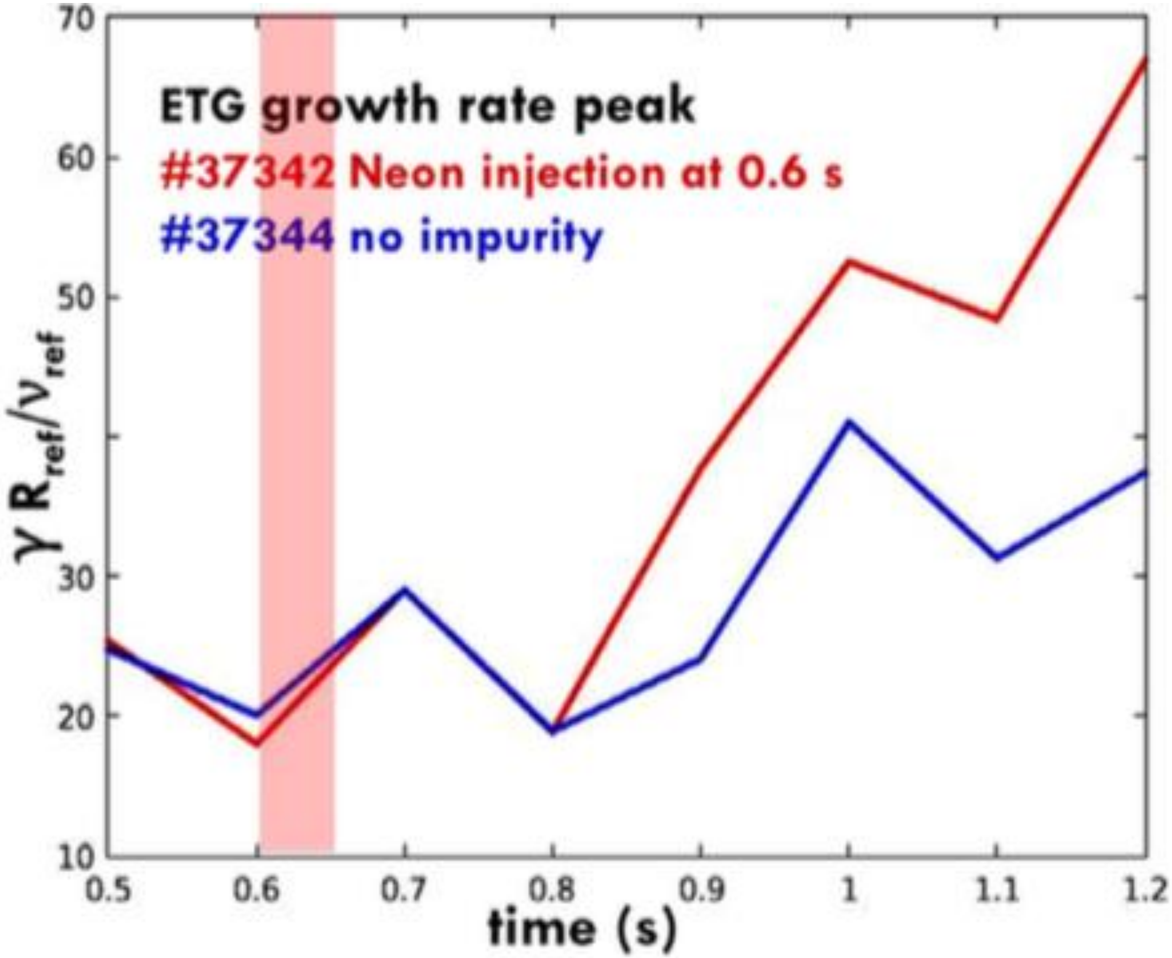


Figure 5. Time traces of the ETG growth rate peaks at $r/a = 0.5$. The red vertical box highlights the neon injection period for the pulse # 37342 (the impurity takes 150 ms to reach and to penetrate plasma).

density limits: thermodiffusion in particle transport

- In the high density regime, a sensible density peaking is observed, subsequent the formation of a strong MARFE thermal instability at plasma edge.
- The peaking of density profile is preceded by a drop of temperature in a wide peripheral region, caused by the thermal collapse at the edge which led to the MARFE formation
- the increase of peaking can be explained with a sensible increase of the total inward particle pinch between *r* /*a* = 0.5 and 0.8, and the density profile evolution is well reproduced using a particle pinch term with dependence on temperature gradients, with the expression given by Γ*p*

$$\Gamma_p = -D_{\mathrm{T}} \frac{n_e}{T_e} \frac{\partial T_e}{\partial r}$$

*D*T = 0.05 m2 s−1.

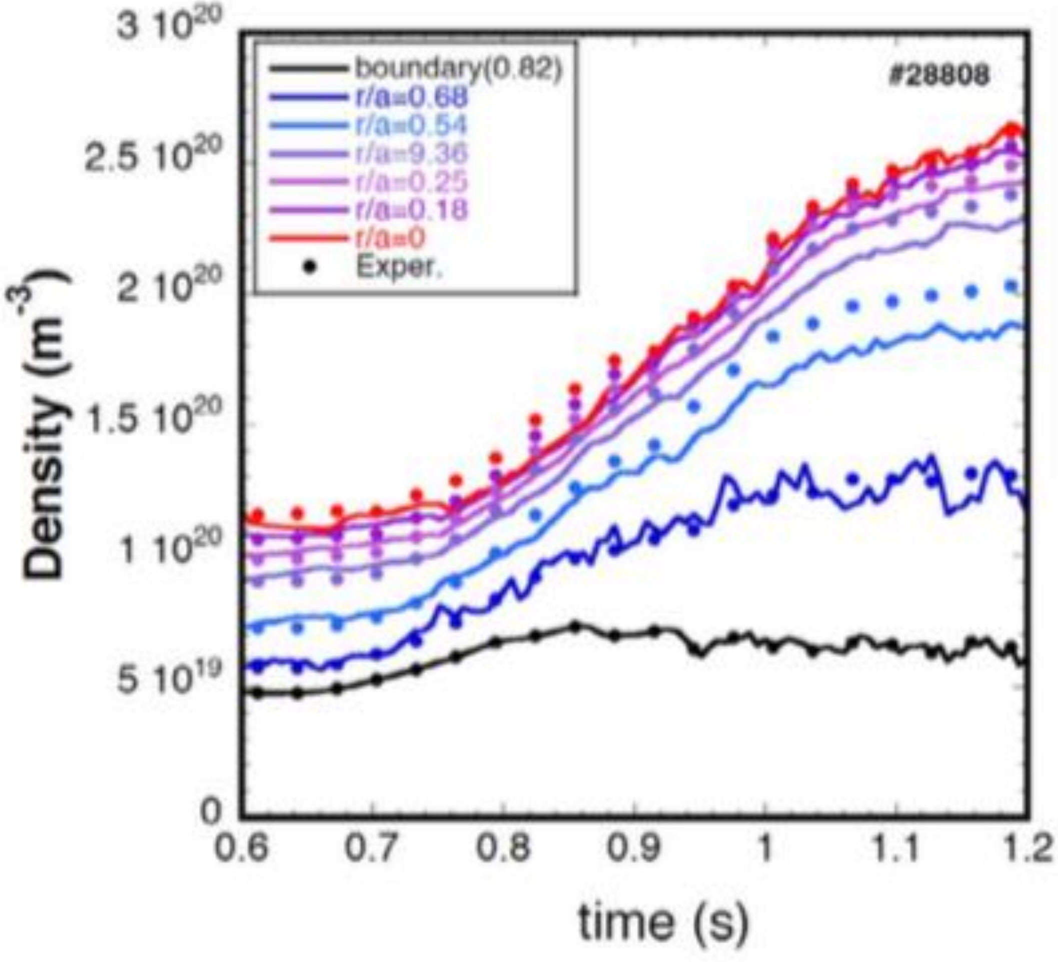


Figure 6. Density evolution at different normalized plasma radii for a pulse in the high density regime; simulated densities (lines) are well in agreement with experimental data (dots).

Density limit

- obtained results confirmed the edge nature of the density limit, as a Greenwald-like scaling was obtained for the maximum achievable line-averaged density along a peripheral chord with normalized radius $r/a = 0.8$
- **a clear scaling of the maximum achievable line-averaged density along a central chord with the toroidal magnetic field only was found:**
- interpreted as due to interplay between the Greenwald edge limit and the specific density profile behavior when approaching the density limit, with the density peaking linearly depending on the edge safety factor at the density limit

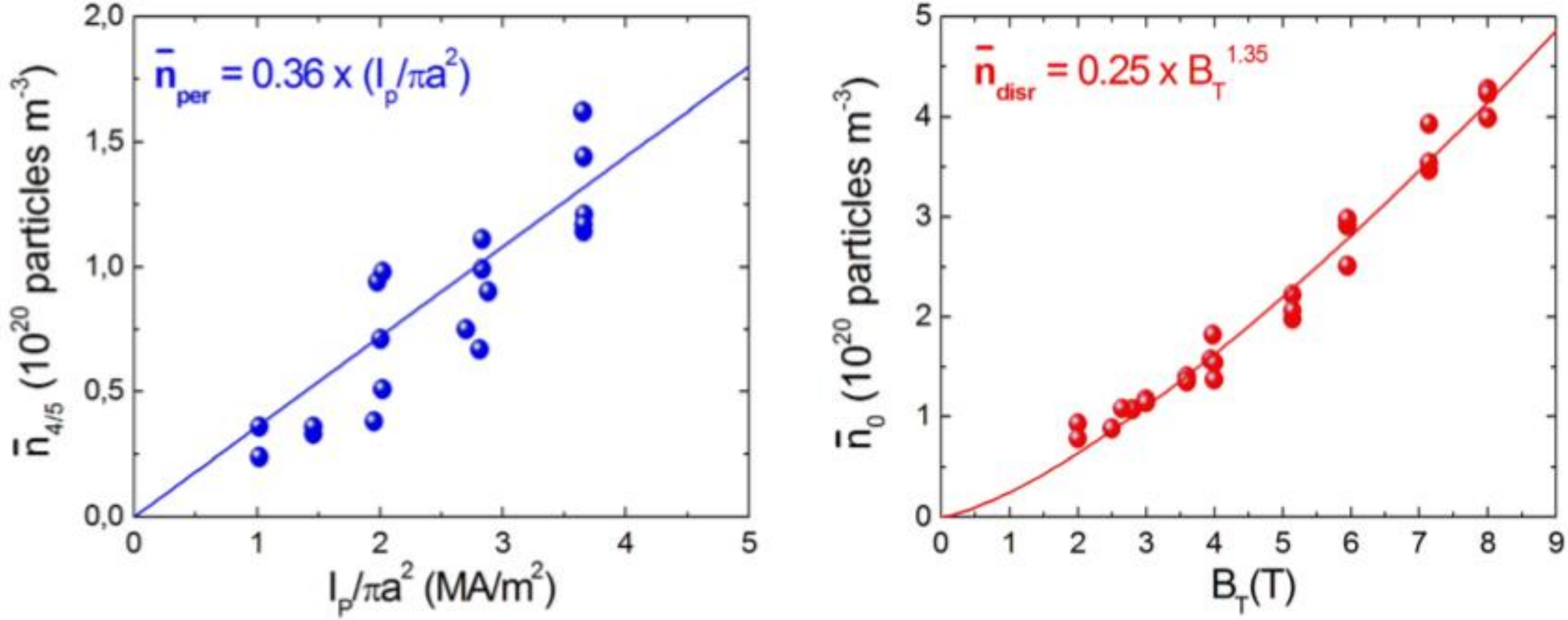


Figure 8. Left side: line-averaged density for a peripheral chord ($r/a = 4/5$) at the disruption versus the plasma current density. Right side: line-averaged density for a central chord ($r/a = 0$) at the density limit disruption versus the toroidal magnetic field.

Density limit : MHD

- Density limit disruptions are usually ascribed to a thermal instability occurring when the radiation loss near the edge region overcomes the heat flux emerging from the core.
- The contraction of the temperature profile leads to a shrinkage of the current profile driving unstable a global MHD mode, such as the tearing mode, leading to disruption if the density continues to grow

Tearing mode behaviour

- tearing modes develop during the pre-programmed plasma density ramp-up up to the density limit on FTU: the evolution of the magnetic islands shows a complex behavior which is not observed in the low density regime.
- In the first phase, the magnetic island grows smoothly at constant rotation frequency.
- Second phase : amplitude and frequency feature oscil-lations with larger and larger excursion. Finally, the island grows quickly to large amplitude and locks: this stage ends in a disruption

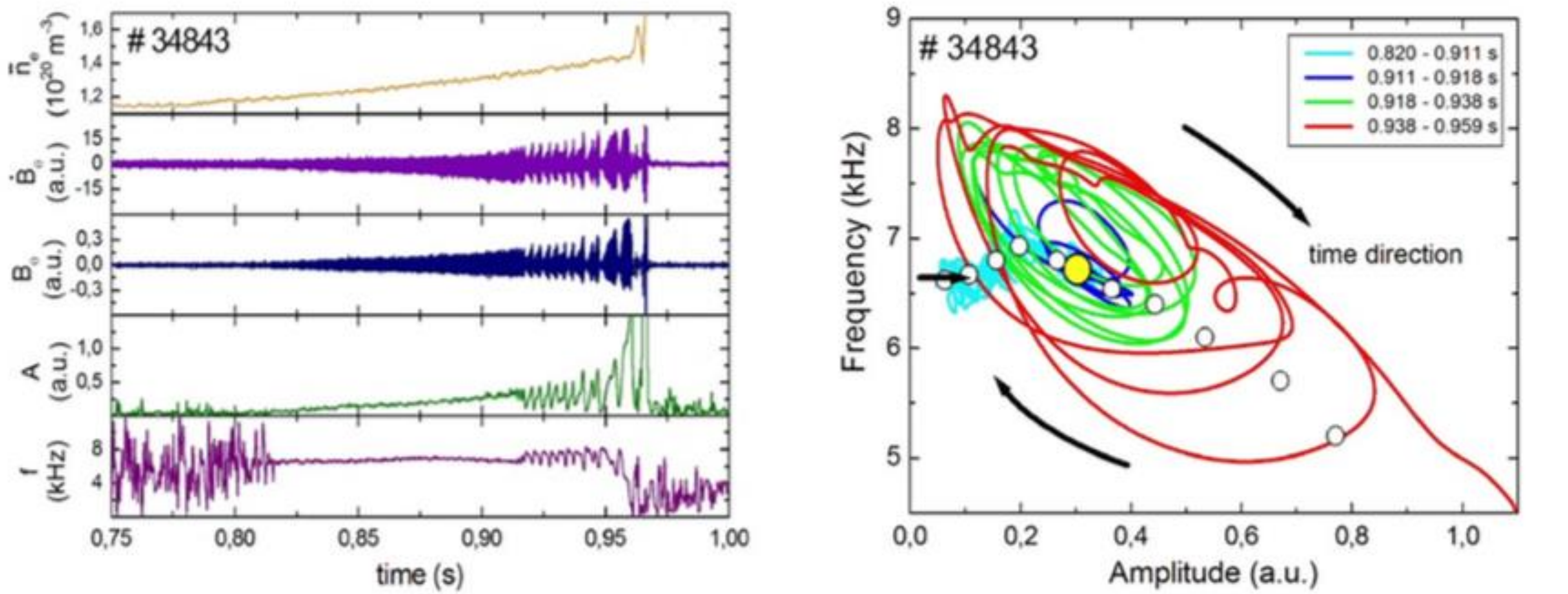


Figure 10. Left side: time traces of some relevant quantities for the MHD activity in a high density pulse (central line-averaged density, output from the pick-up coil, poloidal magnetic perturbation, mode amplitude, mode frequency). Right side: mode evolution on the amplitude/frequency plane; the evolution of amplitude and frequency envelopes is also reported as open circles (the yellow corresponds to the critical mode amplitude for transition from smooth to cyclic behavior).

LLL liquid litium limiter

- Research on liquid metals is pursued as a viable solution to solve the power exhaust problem. The experiments on FTU aim at testing a cooled liquid lithium limiter (CLL) and sub- sequently a cooled liquid tin limiter (TLL) under reactor relevant thermal loads up to 10 MW m^{-2} in stationary conditions.
- the tests performed on the LLL in the latest experimental campaign are extremely encouraging, showing heat loads on the LLL up to 6 MW m^{-2}, as derived by means of the plasma edge parameters measured by Langmuir probes for pulses with B_T=4T and I_p=500kA,with no damage of the exposed surface

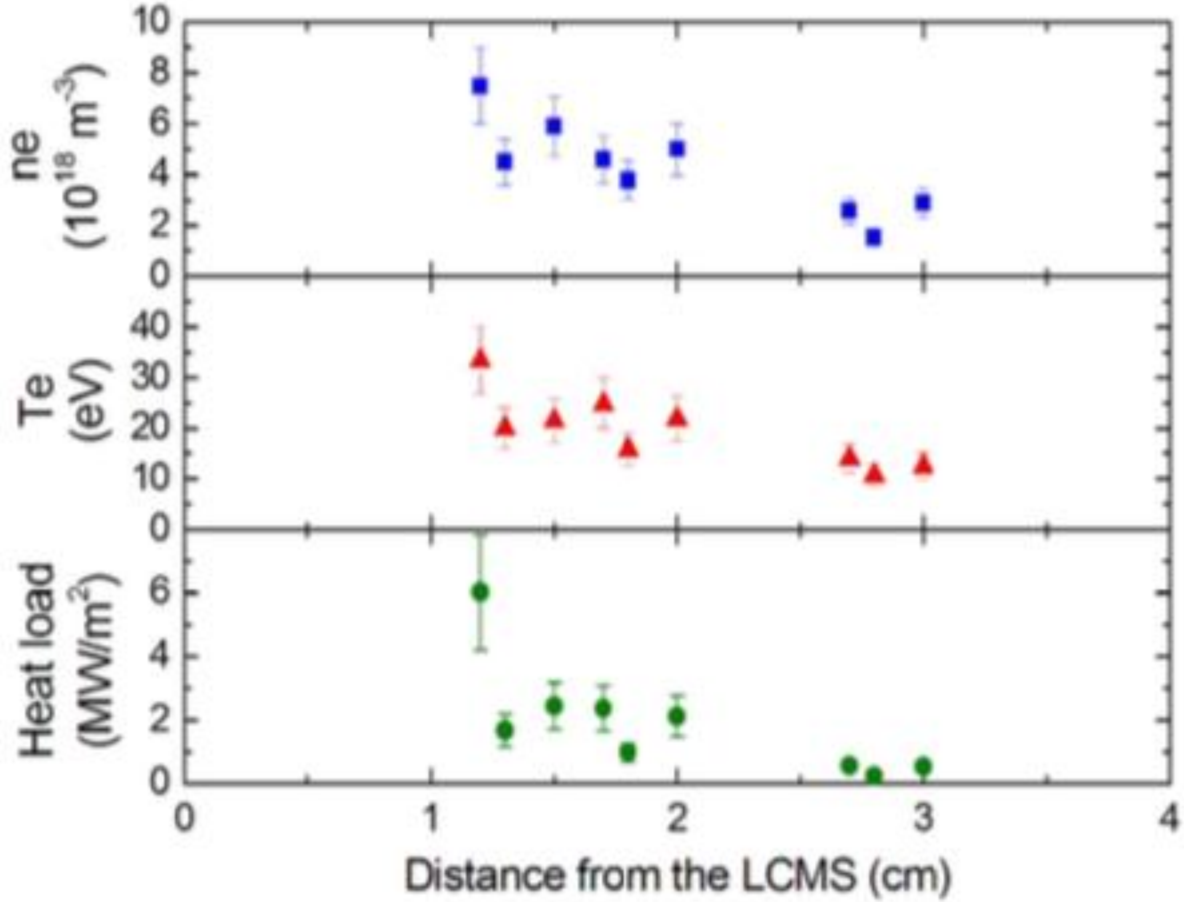


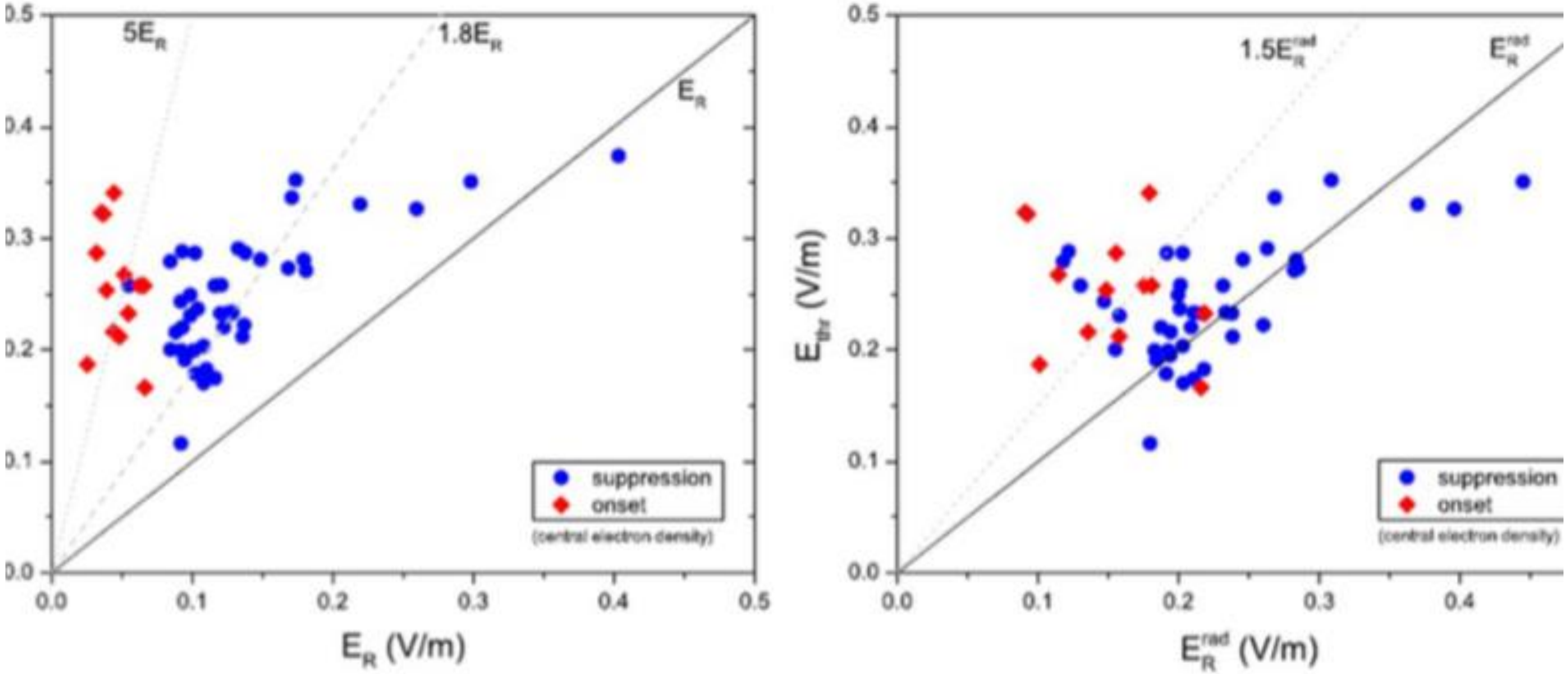
Figure 11. Electron density, electron temperature and averaged heat loads on LLL in stationary conditions for pulses with different distance from the last closed magnetic surface (LCMS).

Runaways

- The RE onset is obtained through a decreasing electron density in the plasma current flat-top
- the RE suppression is achieved by starting a pulse with low gas pre-fill thus creating a RE population subsequently suppressed by a feedback-con- trolled phase of increasing electron density.
- The time of RE onset/ suppression is determined through the comparison of the time traces of a set of absolutely calibrated neutron detectors (BF3chambers) with those of a liquid organic scintillator (NE213), which is sensitive to both neutrons and γ-rays.
- In the RE onset experiments, during the pre-RE phase the NE213 signal overlaps the BF3 signal, while, as soon as the REs are generated, the two time traces diverge.

- **the use of the RE onset and suppression experiments provide upper and lower bounds for the critical electric field, respectively**

Runaways: threshold electric field



omparison of measured E_{thr} with relativistic collisional (left) and collisional + synchrotron radiation (right) theory
:d electric fields have been evaluated using the local central electron density instead of the line-averaged central der
ally generated in the plasma core.

Diagnostics: runaway electron imaging and spectroscopy (REIS)

- The system permits the simultaneous detection of forward and backward image and VIS/NIR spectra of synchrotron radiation from in-flight RE
- a wide-angle visible camera and an incoherent bundle of optical fibers coupled to 2 visible light spectrometers and 1 near-infrared spectrometer.
- The prototype was tested in FTU during the 2015 experimental campaign in several runaway pulses at 4 T and 5 T (figure 13), obtaining useful spectra in the visible 350–850nm and infrared 900–2100nm range.

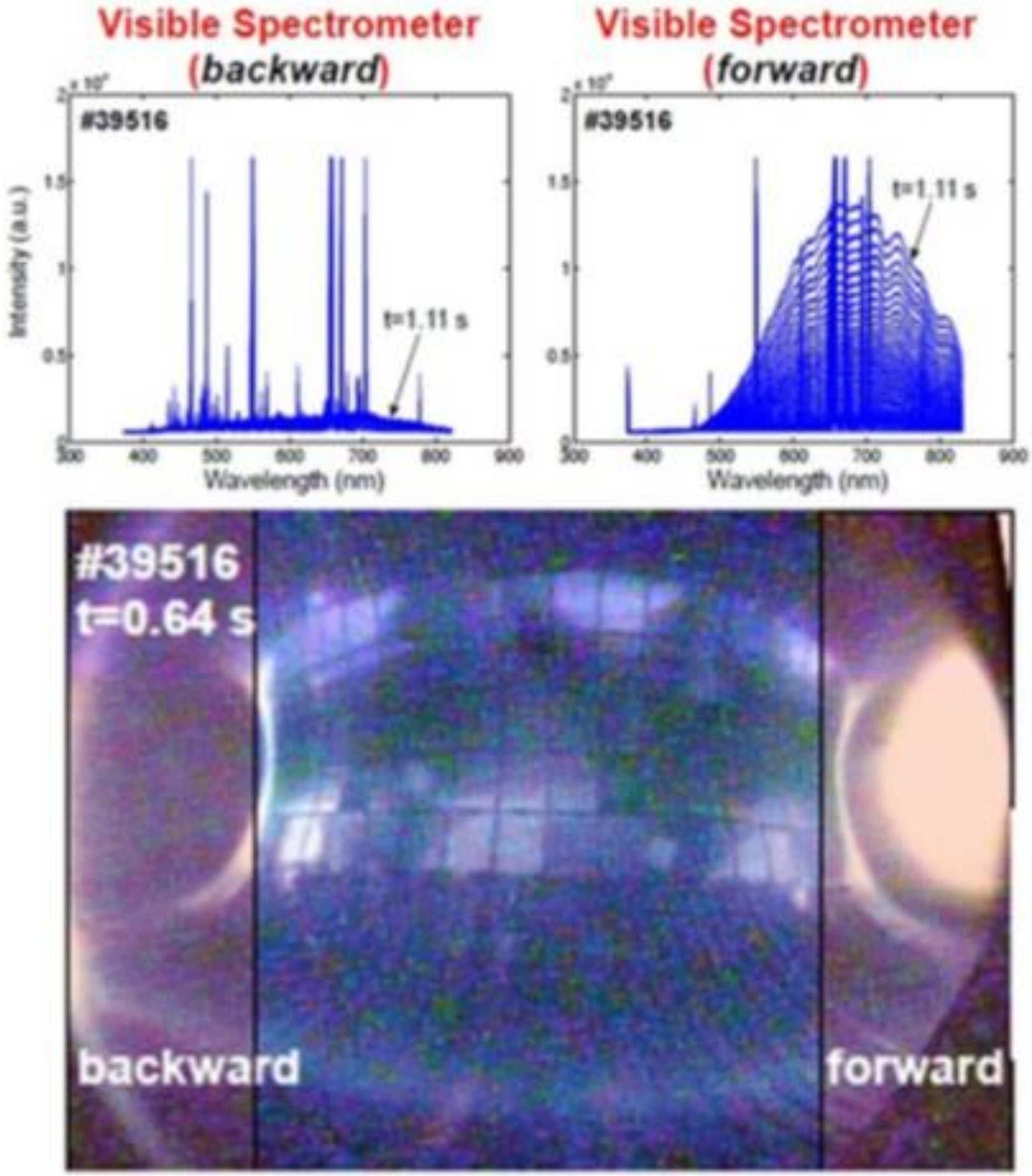


Figure 13. Visible camera image and visible spectra (raw data) for a runaway pulse in FTU (the visible spectra show also the impurity spectral lines).

GRAZIE PER LA ATTENZIONE

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

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**