Results on quiescent and post-disruption runaway electrons mitigation experiments at Frascati Tokamak Upgrade

Theory and Simulation of Disruptions Workshop – (Virtual) - PPPL July 19-23, 2021

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ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development
ISTP Consiglio Nazionale delle Ricerche
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
SWISS PLASMA CENTER
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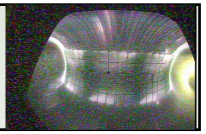
Outline



- Frascati Tokamak Upgrade:
  - main parameters
  - PF coils
  - diagnostics
  - pellet injector
  - RE quiescent scenarios

- D_2 pellet injections:
  - RE loss on on flat-top (0.5MA,4.0-5.3T) or ramp-up current (0.36-0.55MA,5.3T) discharges
  - Exponential growth of REs on (0.36MA,5.3T) discharges

- The Anomalous Doppler Instability (ADI)

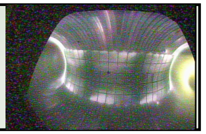
- ADI as an effective RE dissipation mechanism

- TCV and FTU comparison: full ohmic conversion of post-disruption RE beam (by ADI?)

- D_2 puffing and modulated ECRH: a possible way to pace ADI?

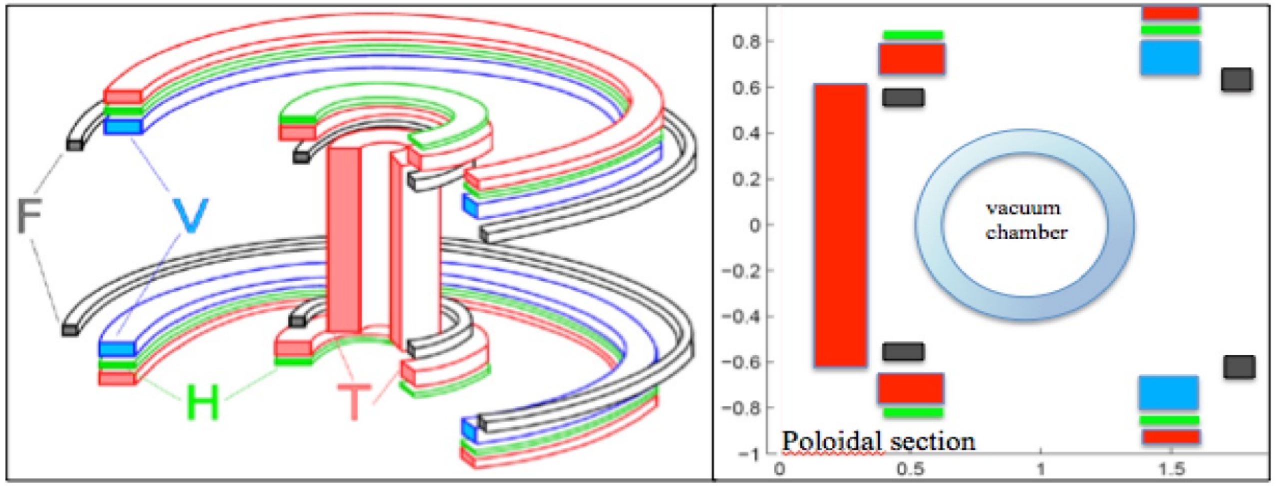
- Conclusions

Frascati Tokamak Upgrade: main parameters (final shutdown December 2019)



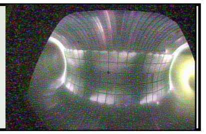
Circular section with liquid nitrogen cooled cryostat (high toroidal field - 8T). Molybdenum first tiles (limiter conf.)

IBW FTU parameters	Values
Major radius R_0	0.935 m
Minor radius a	0.3 m
Radial antenna position r_{ant}	0.33 m
Central density n_{e0}	1×10^{20} m^{-3}
Limiter density n_{ea}	1×10^{19} m^{-3}
Vessel density	3×10^{17} m^{-3}
Central temperature $T_e = T_i = T_0$	1.5 keV
Limiter temperature $T_e = T_i$ $(= T)$	50 eV
Vessel temperature $T_e = T_i$ $(= T)$	10 eV
$n_e = n_{ea} + n_{e0}(1 - x^2)$	
$T = T_a + T_0(1 - x^2)^{5/2}$	
Exponential profiles in the scrape-off plasma	$L_n, L_T \approx 1$ cm
Magnetic field on-axis B_0	7.9 T
$4\Omega_{cH}$ resonant layer location	$x = r/a = 0.31$
$9\Omega_{cD}$ resonant layer location	$x = r/a = 0.67$
Plasma current	0.5 MA



- **T coil**, central transformer: provides the main flux to induce breakdown (plasma initiation) and plasma current [±20 kA]
- **V coil**: slow (54kA/s) plasma radial confinement and secondary flux generation for I_p
- **F coil**: fast (830kA/s) radial plasma stabilization. Used also to *elongate* the plasma
- **H coil**: vertical plasma stabilization (feedback) [±1.5kA]
- **Toroidal coils**: generate the main B field.

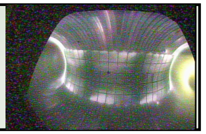
Frascati Tokamak Upgrade: RE-levant diagnostics



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

Diamond Detectors IR fast detectors ''low'' temperatures background, MHD, instabilities… [F. Bombarda et al, IAEA-FEC 2021]

Frascati Tokamak Upgrade: pellet injector



DEUTERIUM PELLET INJECTOR

Small D_2 pellet: $1\text{x}10^{20} \approx$ 1200 m/s
Large D_2 pellet: $2\text{x}10^{20} \approx$ 1000 m/s -> time to reach the plasma core ≈ 0.3ms
Injection on a single discharge (horizontal): 2 small + 2 large

Used to rise density (fueling) up to $8\text{x}10^{20}$ with I_p=1.2MA (8T)
[E. Giovannozzi et al, 2005]

Diagnostics: H_{alpha}, CO_2 scanning interferometer (65 μs), Mirnov coils (MHD)
Only horizontal pellet injector is available.

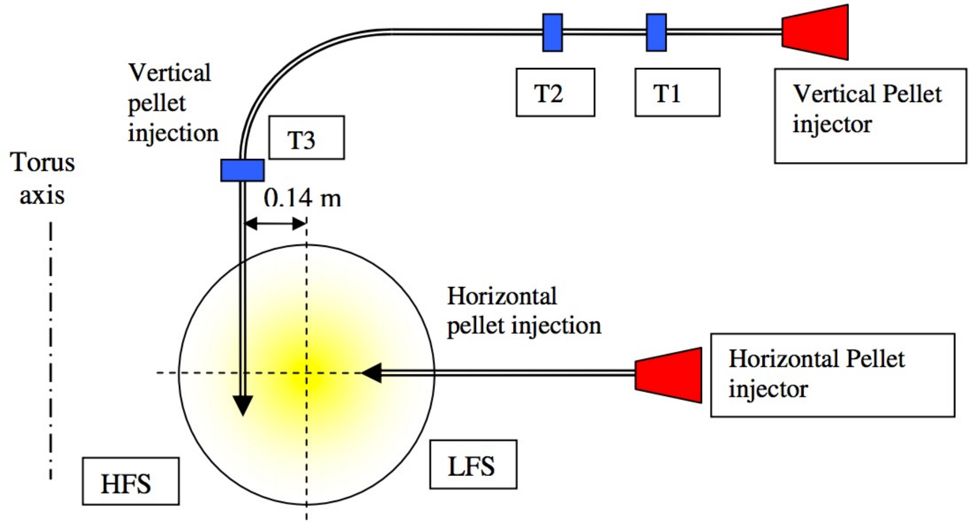


Fig. A: schematic of pellet system

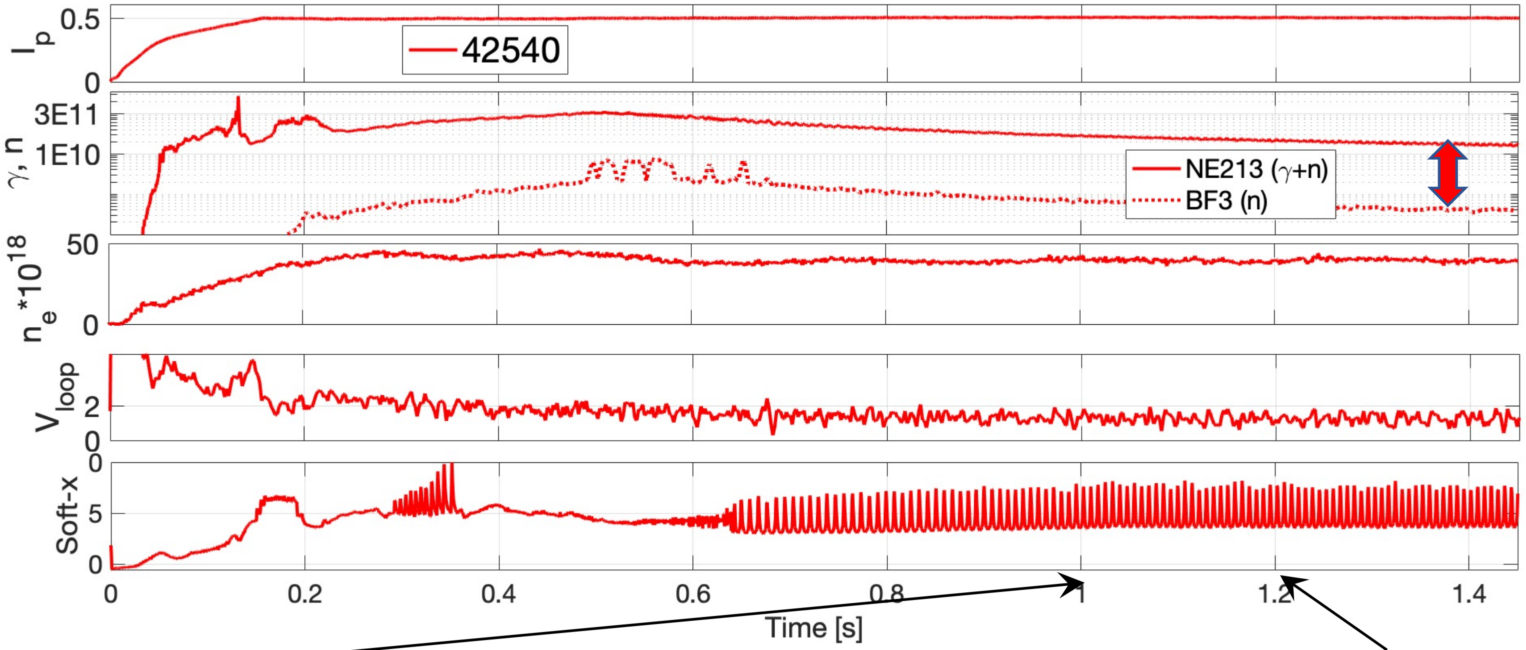
Laser Blow Off (LBO) Injector

Used in the past to trigger disruptions (B. Esposito studies on disruption mitigations)

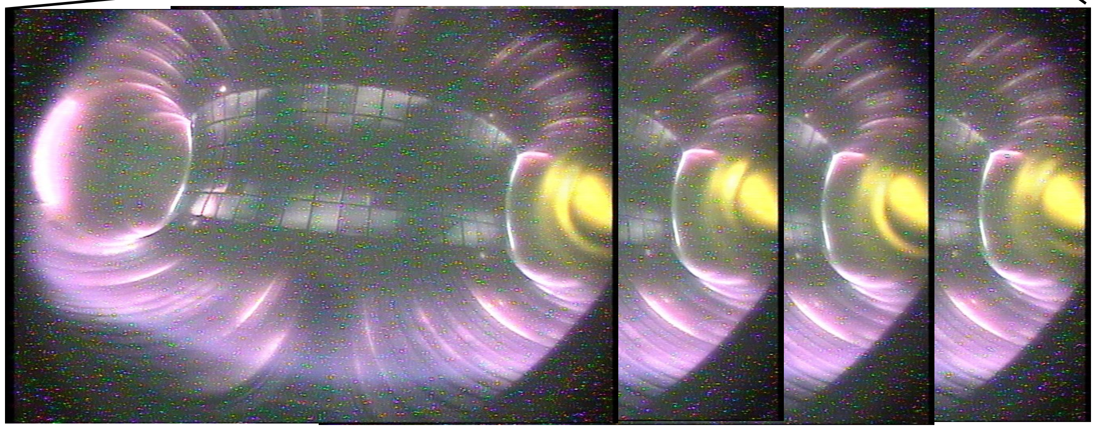
Metal impurities injector by laser ablation of deposited metals on thin layers:
Molybdenum, Iron, Tungsten, Zirconium, Yttrium.

RE quiescent scenario in FTU

Low D_2 prefill, low density (n_e<0.4E20 m^{-3}) discharges.



The presence of REs is provided by the difference between NE213 and BF3



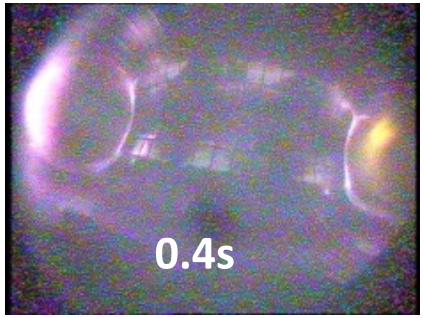
Example of quiescent RE scenario: *Trapped REs with rotating synchrotron emission spot highlighting a ("locked") slowly rotating (m/N)=(2/1) mode.*

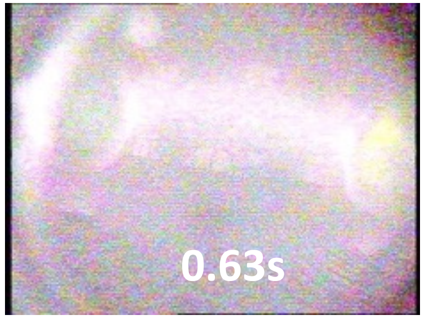
Pellet injections expel REs in (I_p = 0.5MA, B_T=5.3) RE quiescent discharges

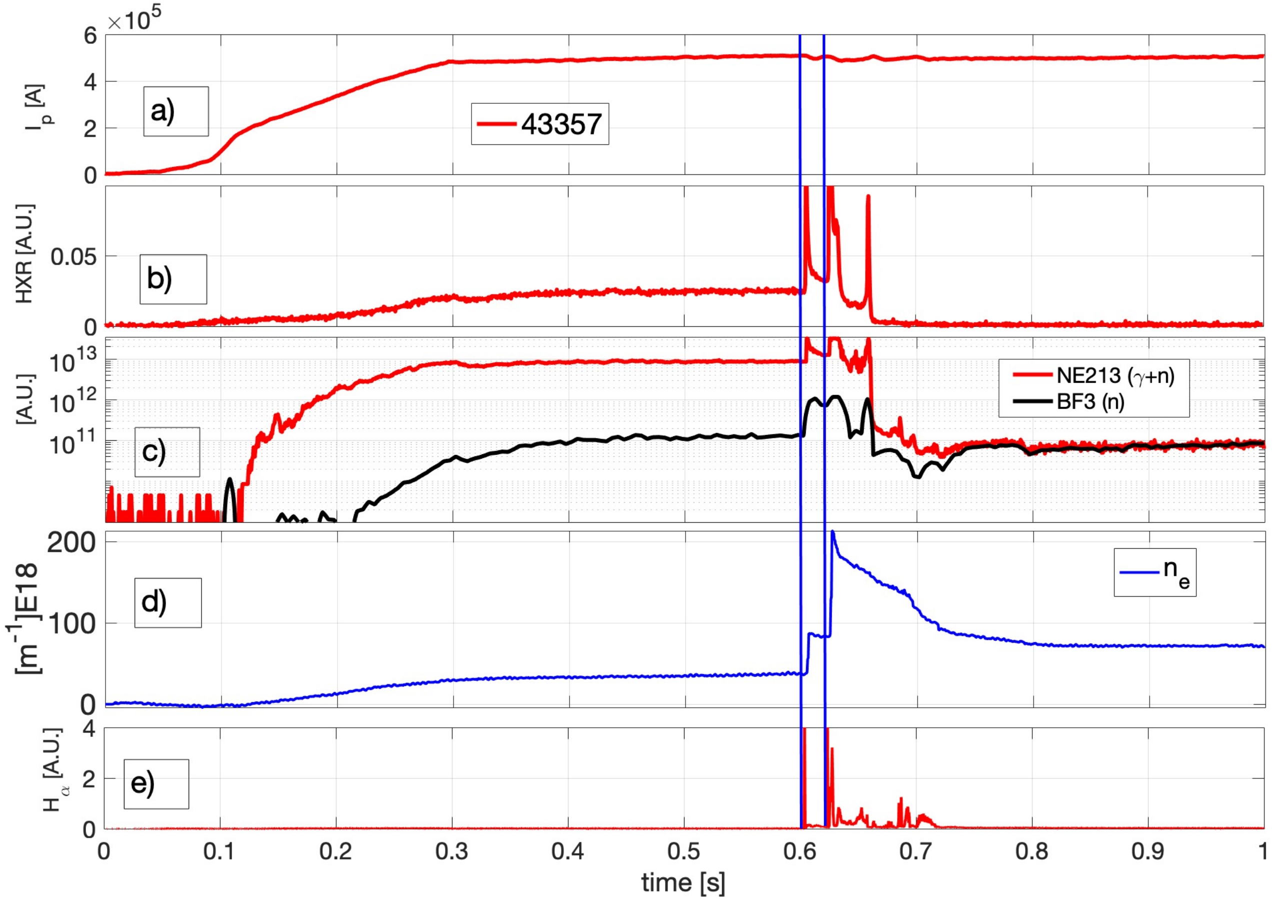
Single or multiple pellet injections (small/big) induce **burst MHD activity** completely expelling RE population within (8ms,100ms) - [10 discharges, no disruption induced].

FTU volume is about 1.6 m^3 , with n_e approx. 0.4E20 m^{-3} , the small pellet (complete ablation) contains about 1.5 times the total particles.

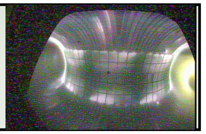
Discharge #43357: 1E20 (small) D_2 pellet at 0.6s + 2E20 (big) D_2 pellet at 0.62s: complete loss of RE population.







Pellet injections expel REs during ramp-up current (I_p = 0.36-0.55MA, B_T=5.3)



Target: test the effect of pellet with a “larger” electrical field.

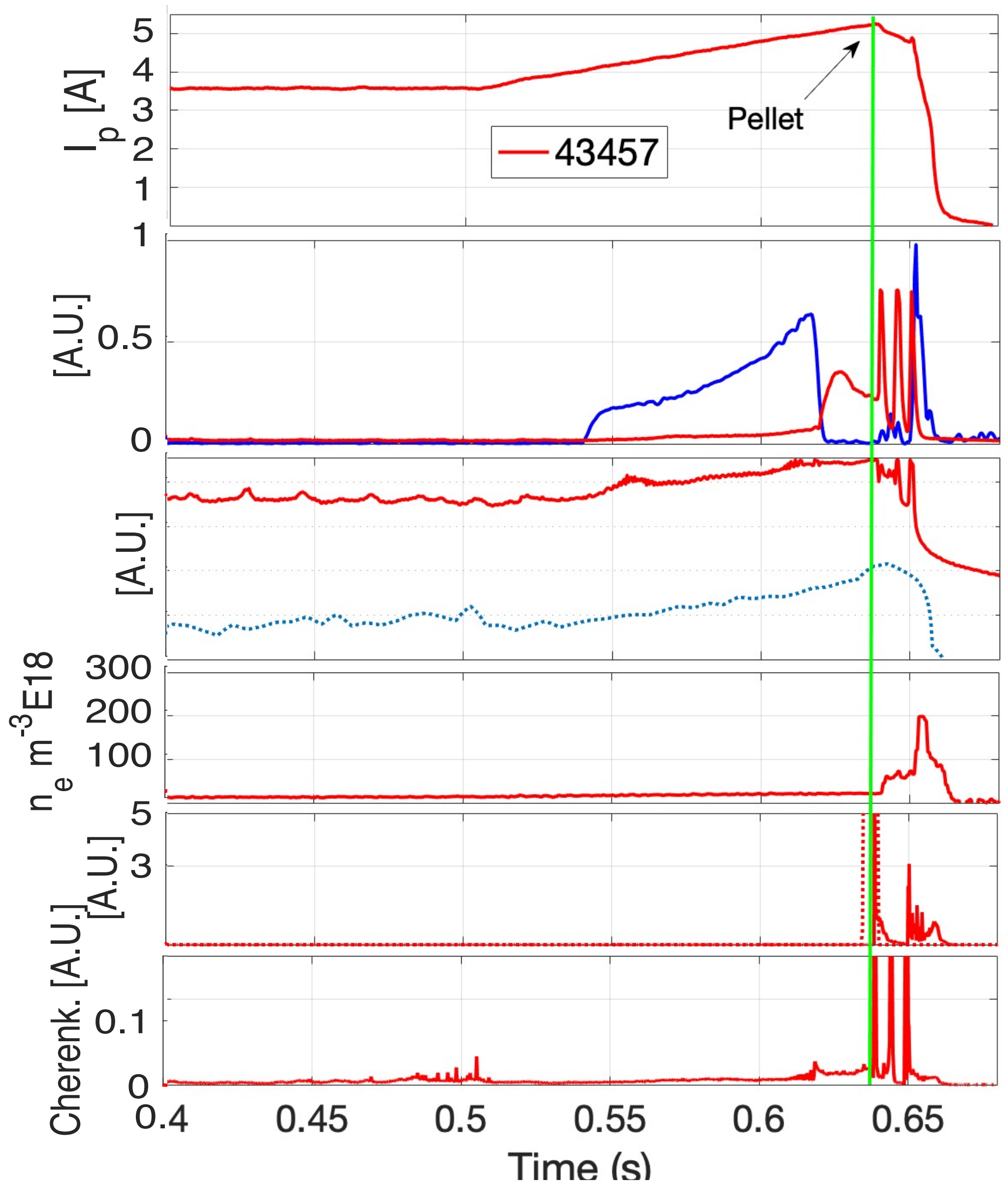
All discharges in which a single/mutilple pellets have been injected during a **current ramp-up** disrupted with complete loss of REs.

Pellets induced intense MHD burst activity.

No evidence of kink instabilities [q_{edge}>4.5].

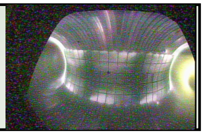
No RE-regeneration observed.

Discharge #43457: An example of pellet injection at 0.623s (green vertical line) during current ramp-up when the electrical field is above 2.5V
and a (m/n)=(2/1) is “locked” (slow rotation).



LOCKED MODE

Pellet injections expel REs during ramp-up current (I_p = 0.36-0.55MA, B_T=5.3)



Target: test the effect of pellet with a “larger” electrical field.

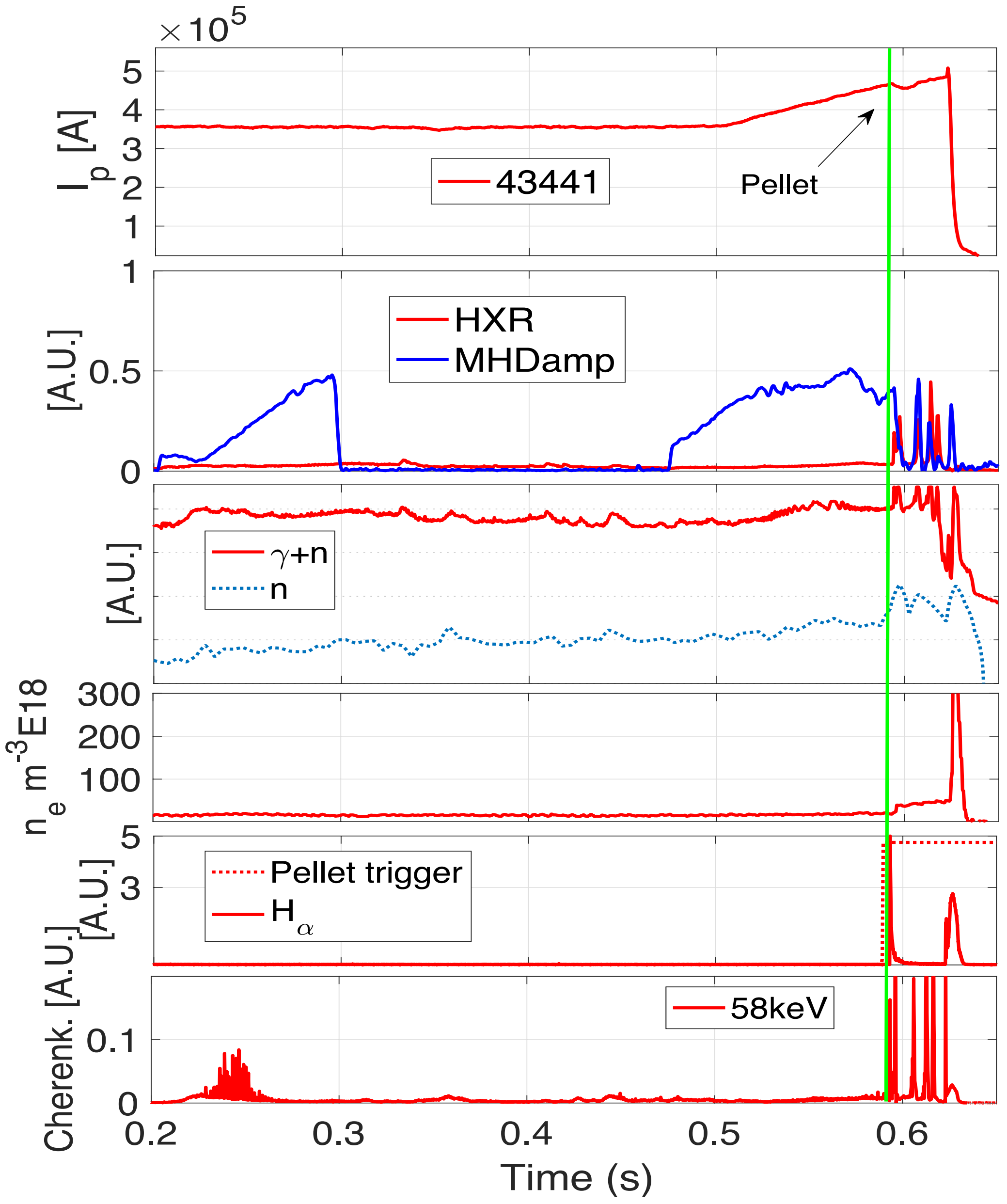
All discharges in which a single/mutilple pellets have been injected during a **current ramp-up** disrupted with complete loss of REs.

Pellets induced intense MHD burst activity.

No evidence of kink instabilities [q_{edge}>4.5].

No RE-regeneration observed.

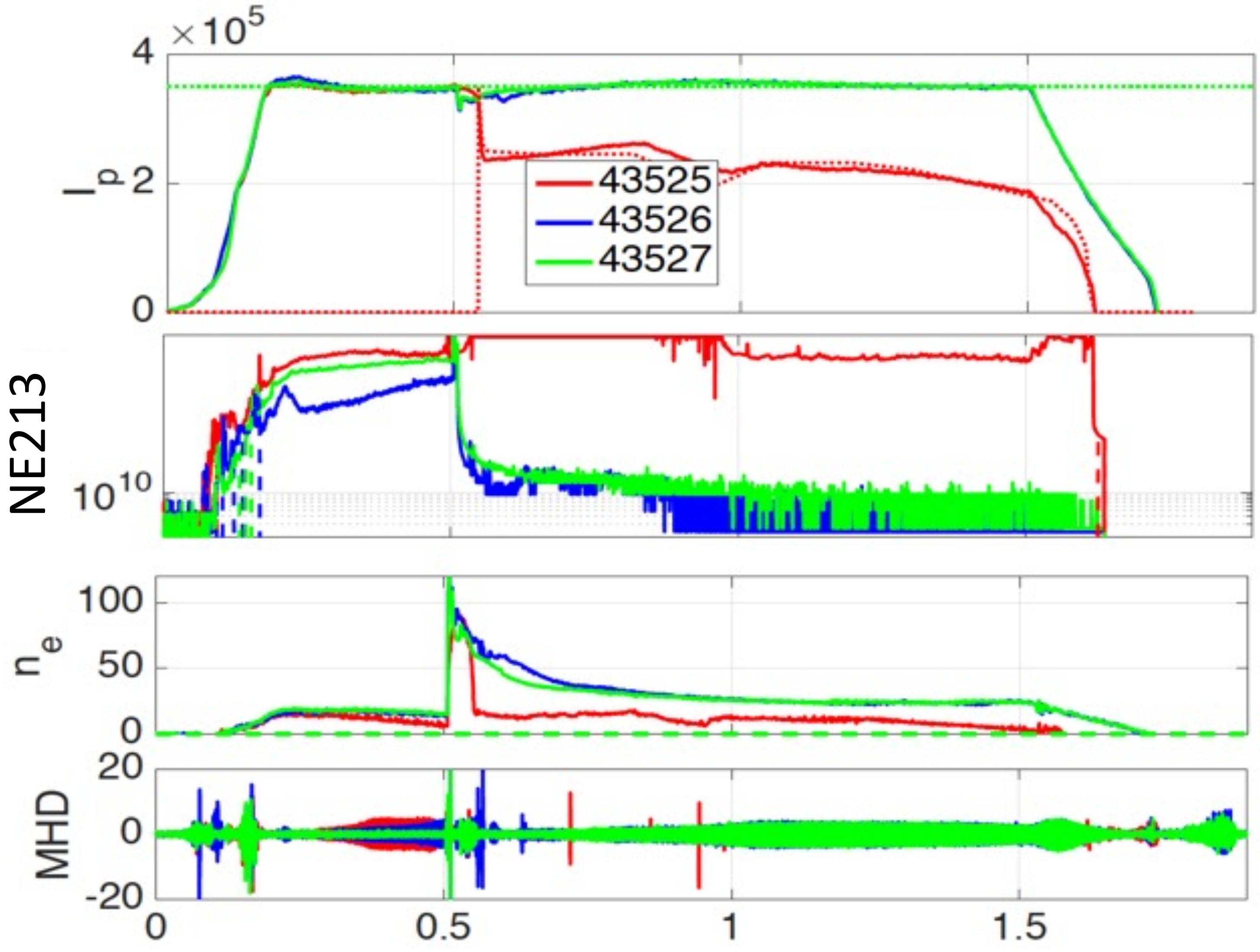
Discharge #43441: An example of pellet injection at 0.59s (green vertical line) during current ramp-up when the electrical field is above 2.5V and there is a large MHD mode.



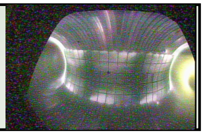
Runaway electrons growth after pellet injections (I_p = 0.36MA, B_T=5.3)

Pellet injected on RE quiescent discharges with (I_p = 0.36MA, B_T=[4.0-5.6]) have **complex** evolution.

High probability (about 85%) of expelling REs if $\gamma + n$ < 1E13 counts (NE213). Above this level growth of REs can be generated, yielding RE post-disruption beams.



Exponential growth of REs and post-disruption RE beam (I_p = 0.36MA, B_T=5.3)

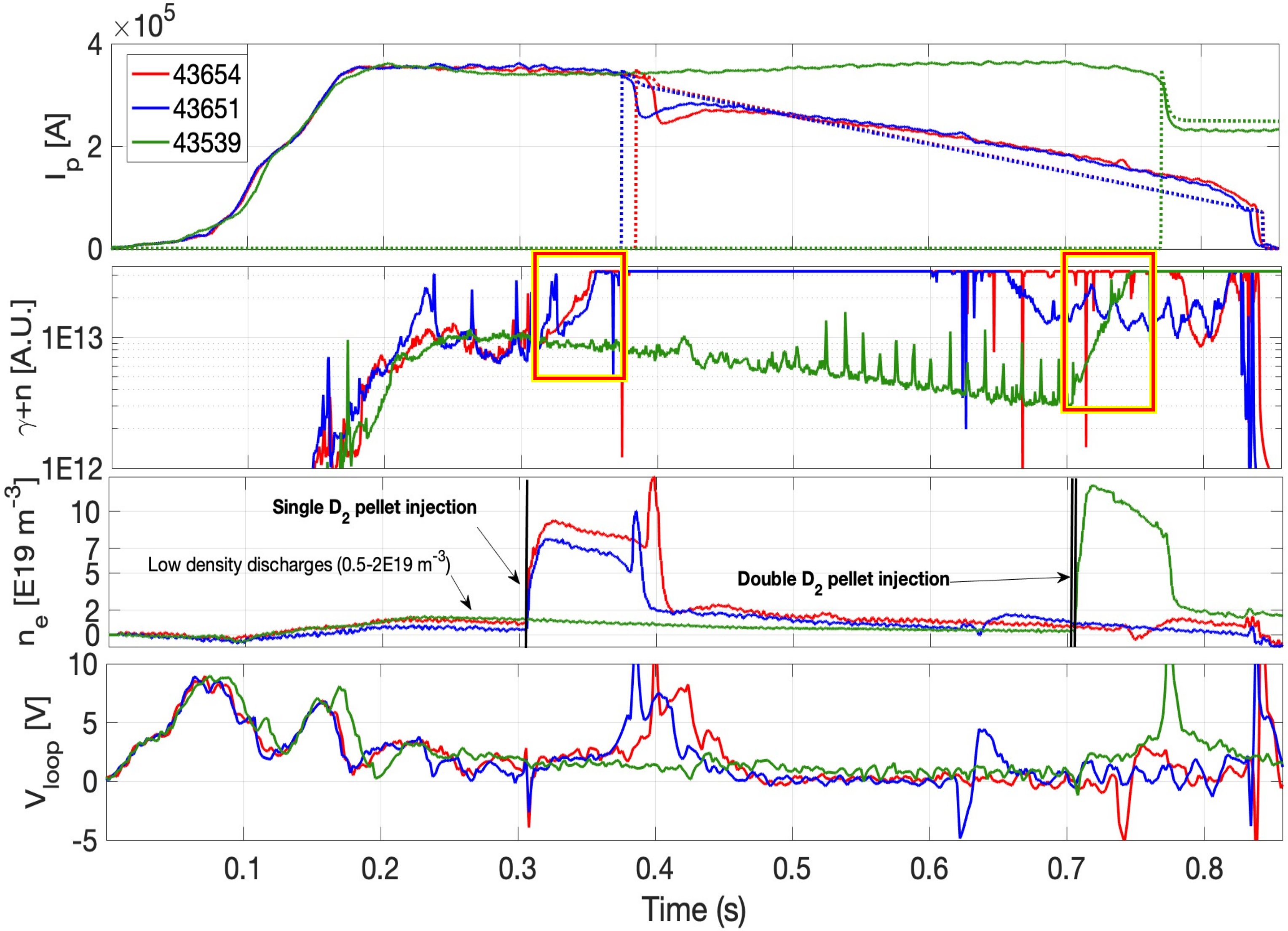


Pellet injections on quiescent REs leading to post-disruption RE beam formation.

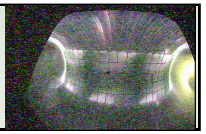
Single D_2 pellets (1E20) have been injected at 0.3s in the discharges #43651 and #43654, whereas two D_2 pellets (1E20+2E20) have been injected at 0.7s in #43539.

Note the **exponential growth** of REs ($\gamma + n$) after the pellet injections.

Exp. growth in RE quiescent scenarios has been found on DIII-D and EAST but with different plasma parameters.



Exponential growth of REs and post-disruption RE beam (I_p = 0.36MA, B_T=5.3) (cont'd)



From classical theory the critical electric field is

$$E_r = \frac{n_e e^3 ln\Delta}{4\pi\varepsilon_0{}^2 m_e c^2}, \quad (1)$$

$$\bar{V}_{loop} = V_{loop}/2\pi R_0 \;,\; R_0 = 0.96\text{ m.}$$

In FTU REs are generated (not suppressed) when $\boldsymbol{\bar{V}_{loop} \geq \sigma E_r}$, with **20** $\geq \boldsymbol{\sigma} \geq$ **5**.

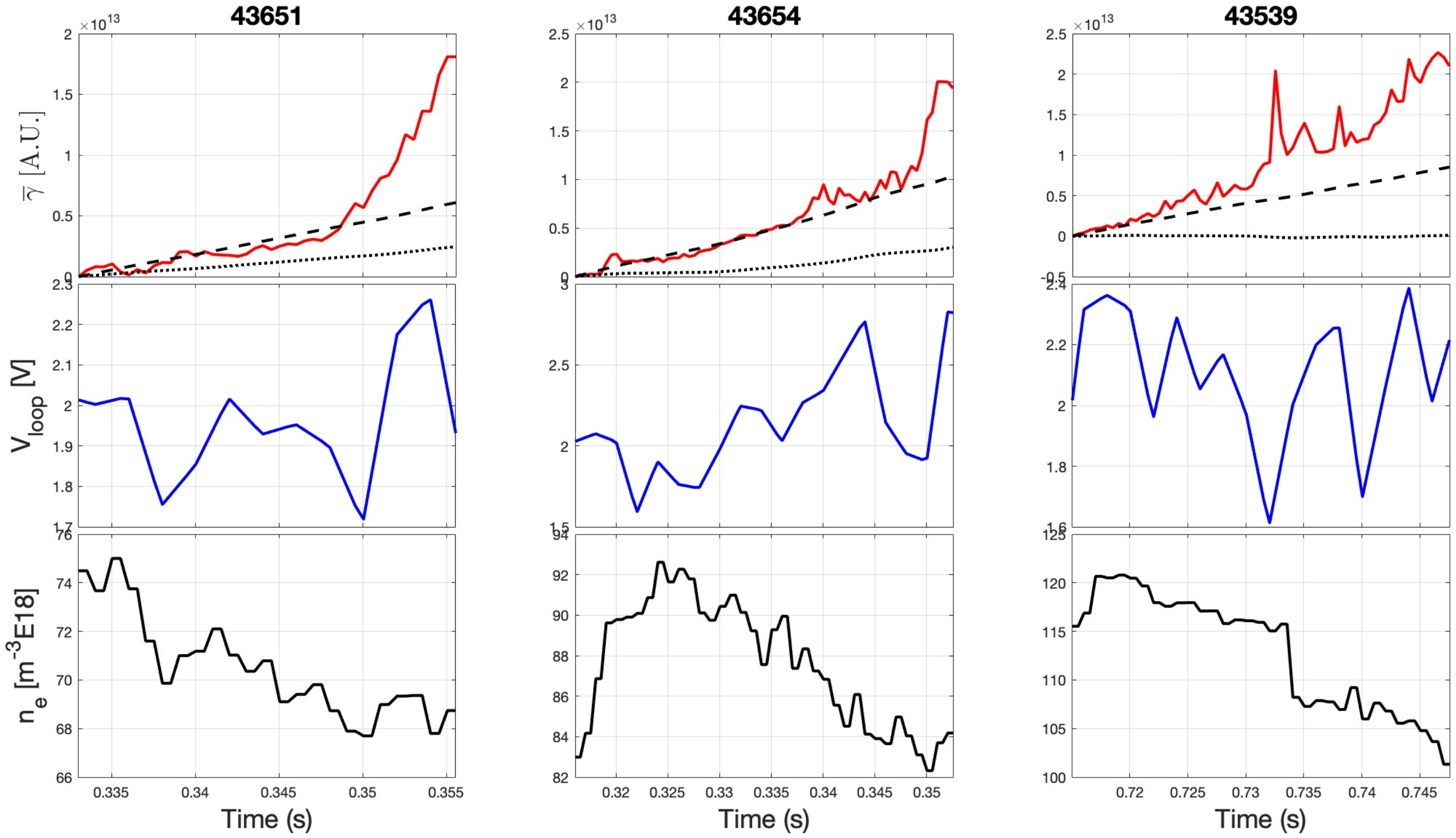
A rough estimation of γ is provided by

$$\hat{\gamma}_{Dreicer,\sigma} = \int \theta(\bar{V}_{loop} - \sigma E_r) \qquad (2)$$

with $\theta = 1\text{E}15$.

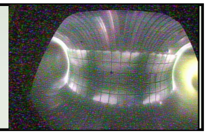
Selecting $\boldsymbol{\sigma = 1}$, $\hat{\gamma}_{Dreicer,1}$ should provide an **upper-bound of γ** : on the contrary, experimental growth of γ overcome $\hat{\gamma}_{Dreicer,1}$ (dashed black lines).

Selecting $\sigma < 4$ yields RE quick suppression ($\sigma = 4$ dotted black lines, *to be deleted?*).

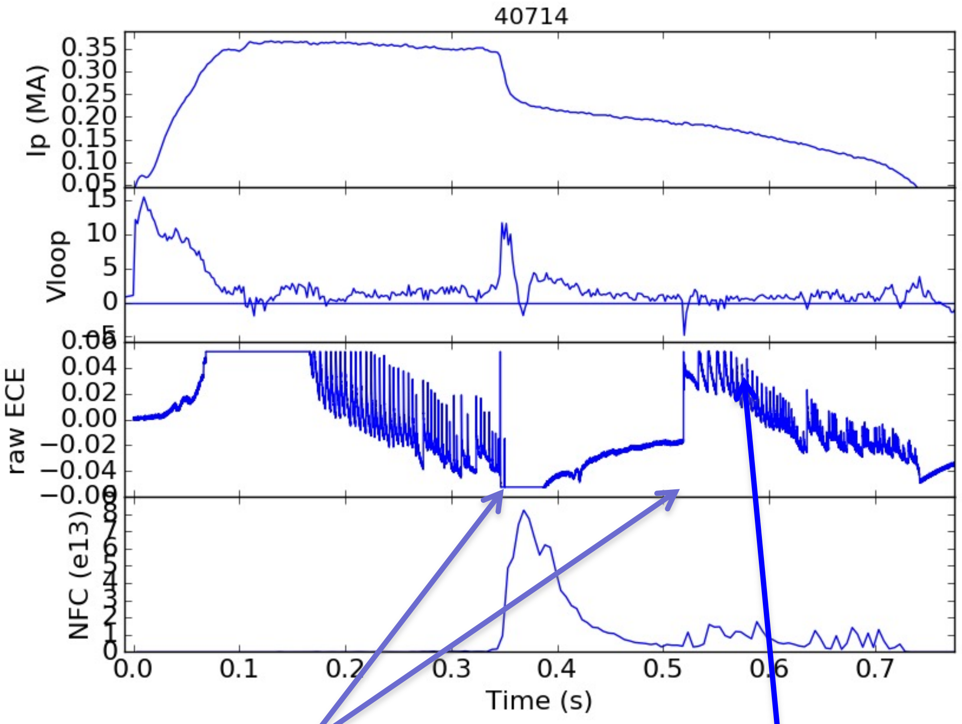


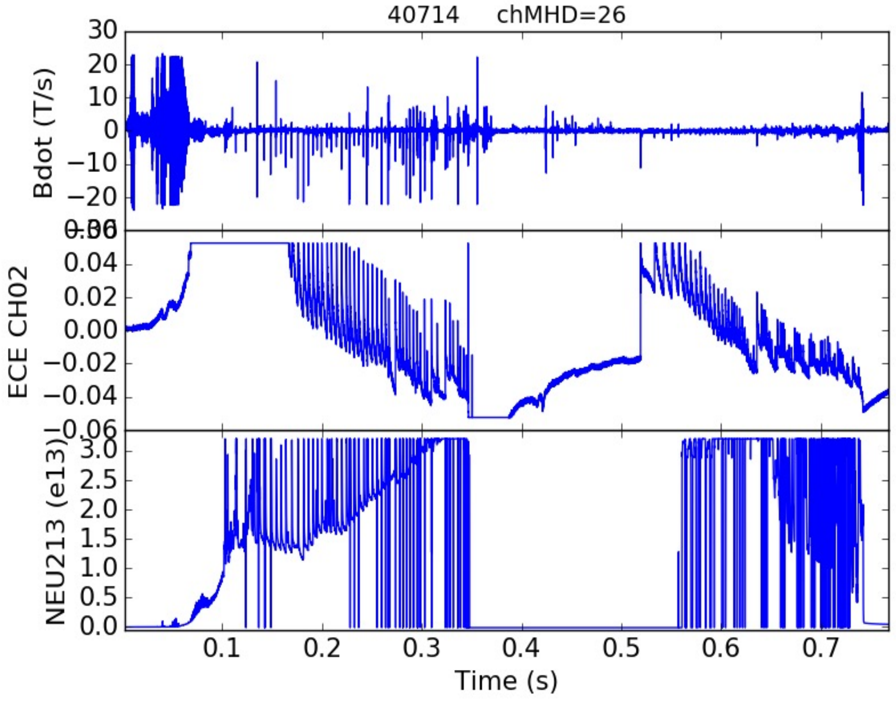
After pellet injections densities are unusually high for RE quiescent scenarios

Anomalous Doppler Instabilities (ADI – fan-like instabilities)



Correlations with Electron Cyclotron Emission, HXR from NE213 scintillator and Mirnov coil (MHD26) .





ADI quickly increases the RE pitch angle reducing the anisotropy in the momentum space (perpendicular momentum increase)

Latency after disruption (large photo-neutron signal)

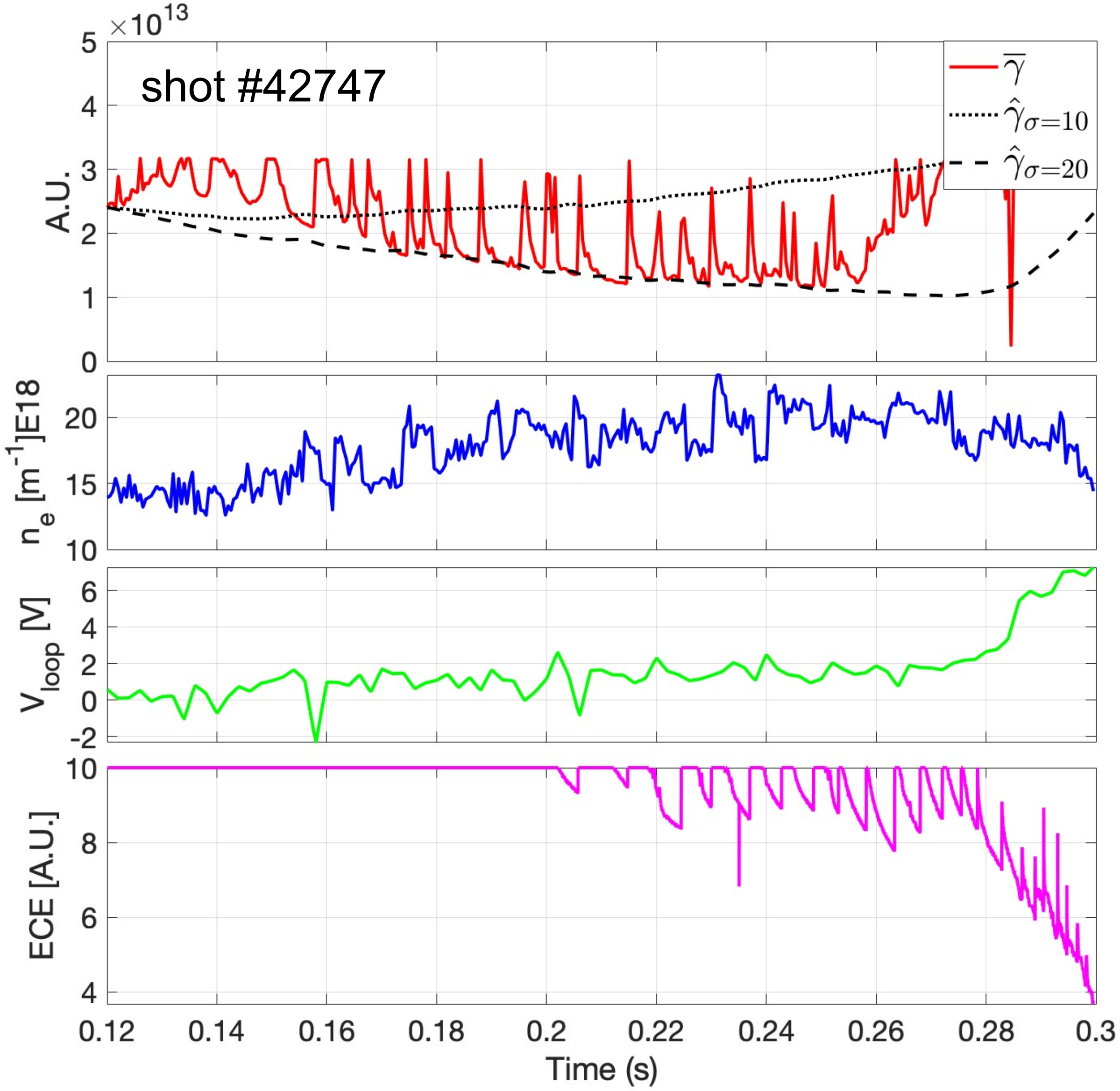
ECE spikes

ECE spikes are correlated with MHD and NE213

- Buratti P et al. Fast dynamics of radiofrequency emission in FTU plasmas with runaway electrons, *Plasma Phys. Control. Fusion (2021)*
- Causa F, Buratti P, FTU Team, Analysis of runaway electron expulsion during tokamak instabilities detected by a single-channel Cherenkov probe in FTU. Nucl Fusion 59:046013 (2019)

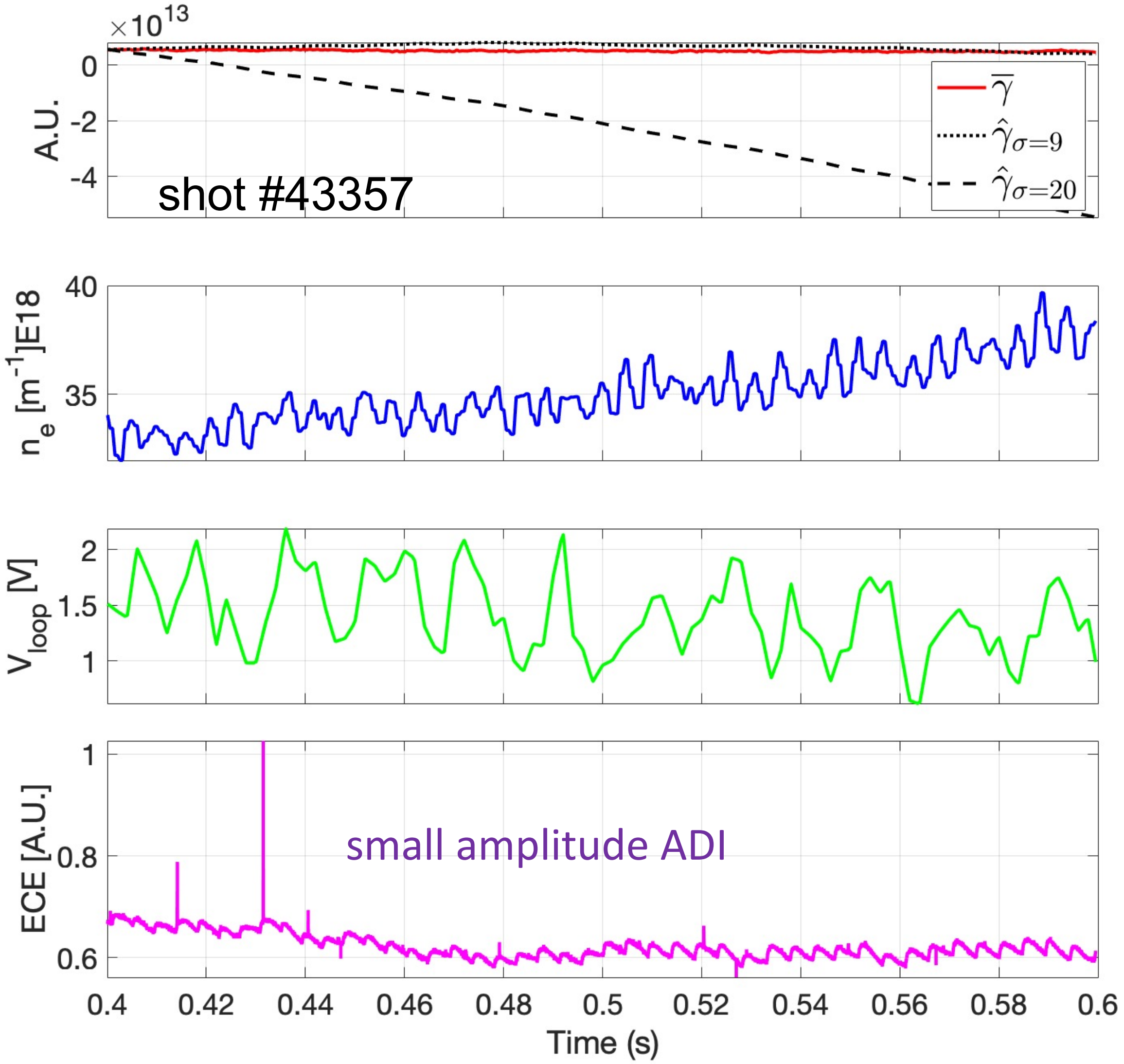
RE suppression in presence of significative amplitude ADI

To provide an estimation of the dissipative effects on the RE growth we show again consider $\hat{\gamma}_{Dreicer,\sigma} = \int \theta(\bar{V}_{loop} - \sigma E_r)$ with $\boldsymbol{\sigma = 10}$, $\hat{\gamma}_{Dreicer,10}$ (black dots) and with $\boldsymbol{\sigma = 20}$, $\hat{\gamma}_{Dreicer,20}$ (dashed line) that should provide a **lower bound** for typical FTU discharges.



RE suppression in presence of very small amplitude ADI

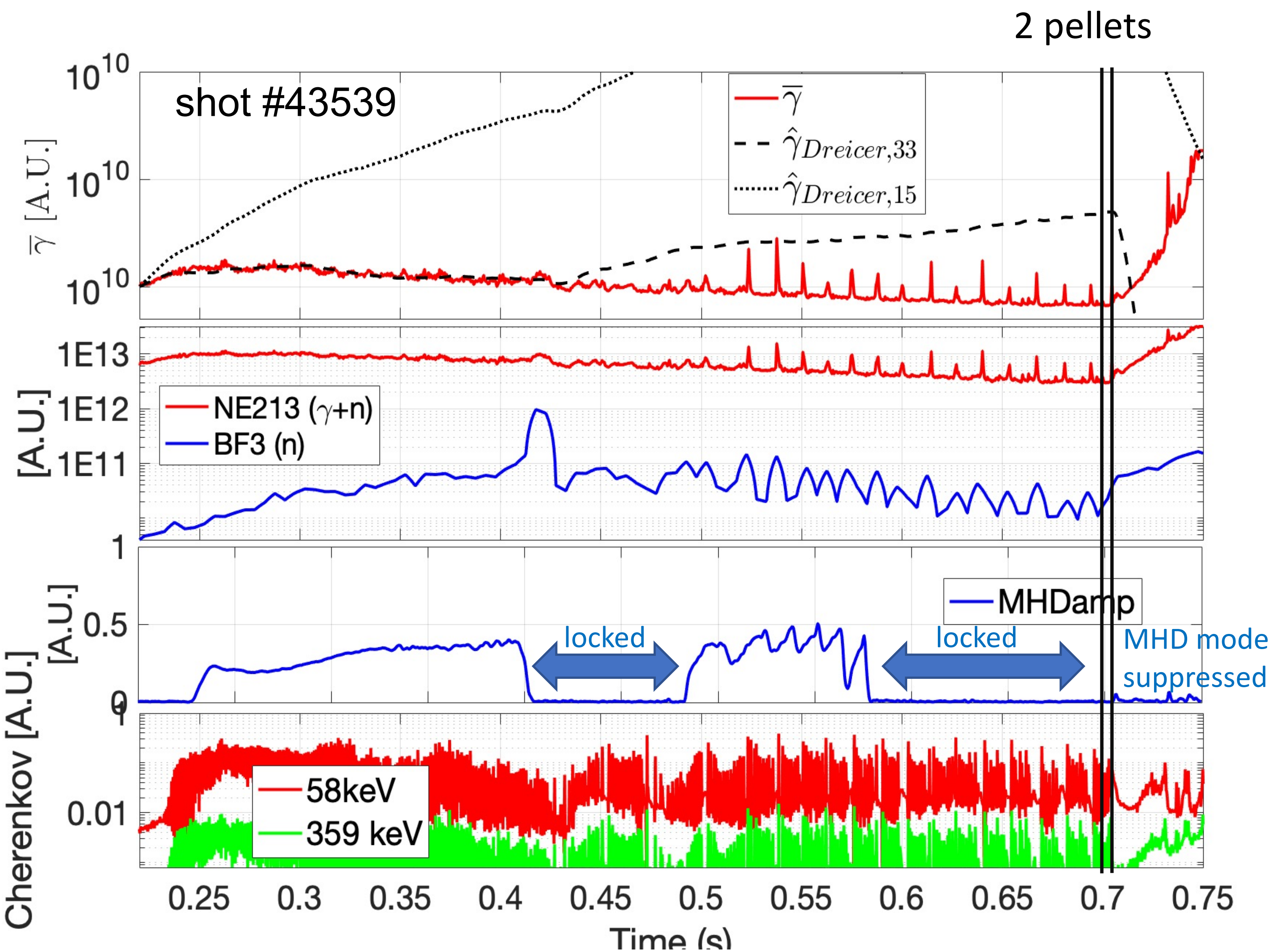
To provide an estimation of the dissipative effects on the RE growth we show again consider $\hat{\gamma}_{Dreicer,\sigma} = \int \theta(\bar{V}_{loop} - \sigma E_r)$ with $\boldsymbol{\sigma = 9}$, $\hat{\gamma}_{Dreicer,10}$ (black dots) and with $\boldsymbol{\sigma = 20}$, $\hat{\gamma}_{Dreicer,20}$ (dashed line) that should provide a **lower bound** for typical FTU discharges.



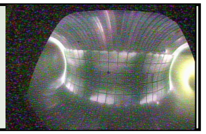
RE evolution in presence of large MHD activity and ADI

RE dissipation seems to be increased by large MHD (locked) mode coexisting with ADI.

To provide an estimation of the dissipative effects on the RE growth we show again consider $\hat{\gamma}_{Dreicer,\sigma} = \int \theta(\bar{V}_{loop} - \sigma E_r)$ with $\boldsymbol{\sigma} = \mathbf{15}$, $\hat{\gamma}_{Dreicer,15}$ (black dots) and with $\boldsymbol{\sigma} = \mathbf{33}$, $\hat{\gamma}_{Dreicer,33}$ (dashed line) that should provide a **lower bound** for typical FTU discharges.



Large post-disruption ADI dissipating REs

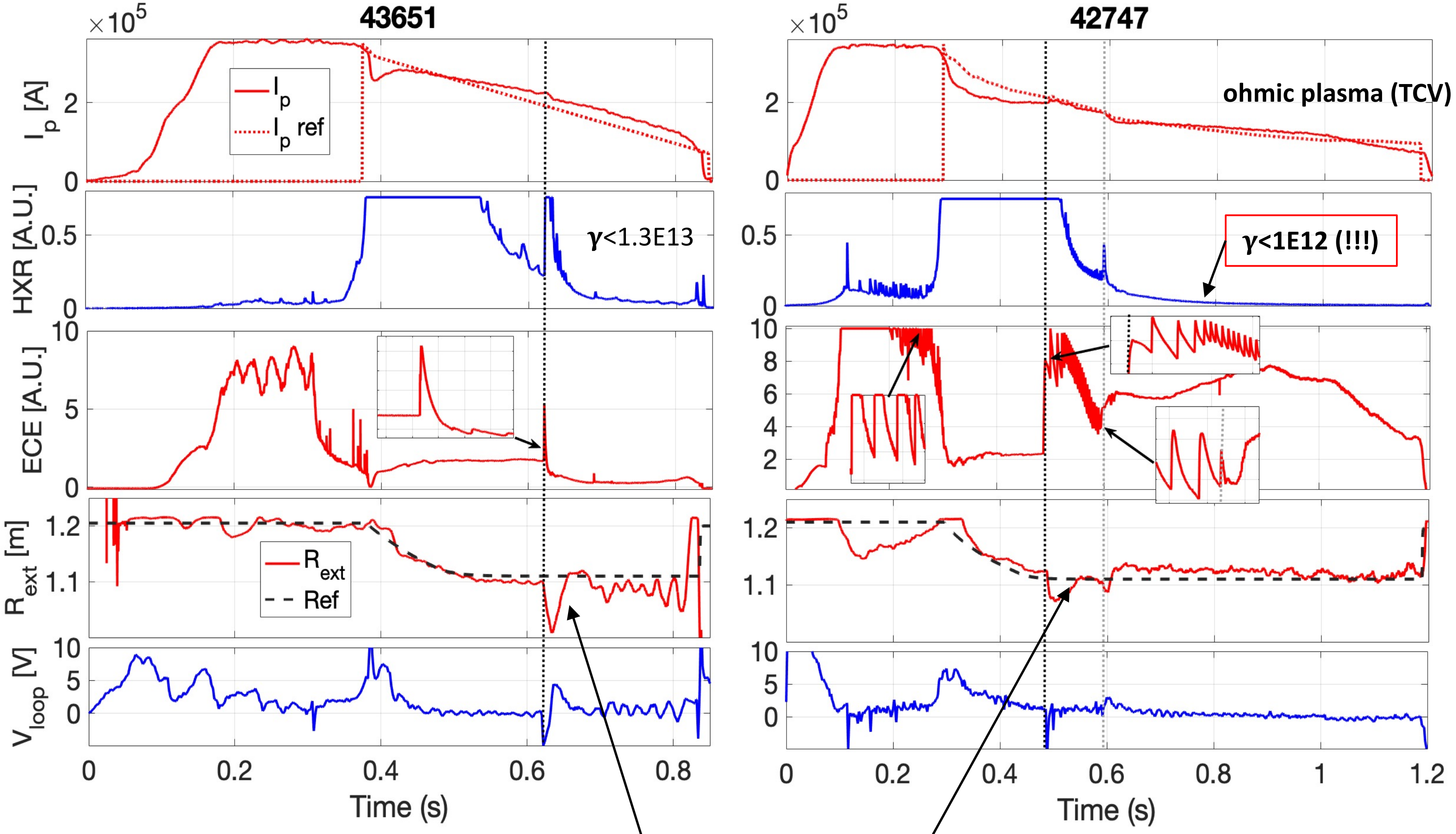


On post-disruption RE beam extremely **large ADI** have been found (TFTR) a certain amount of time (70ms-280ms) after the CQ that seem to be correlated with RE energy reduction (CS brake).

Marks of large ADI:

- ECE increase (isotropization),
- V_{loop} negative spike (magnetic energy reduction)
- Radial inner shift
- Enlarged synchrotron radiation spot from visible camera

It seems that large ADI are seen when RE energy has been decreased since the plateau onset (low loop voltage/flux provided by CS). This should be the reason why are not seen on discharges where CS continue to transfer energy to REs (e.g. JET).



After the ADI, the control system moves the beam outward to track the desired radial position.

Large post-disruption ADI dissipating REs (cont'd)

On post-disruption RE beam extremely **large ADI** have been found (TFTR) a certain amount of time (70ms-280ms) after the CQ that seem to be correlated with RE energy reduction (CS brake).

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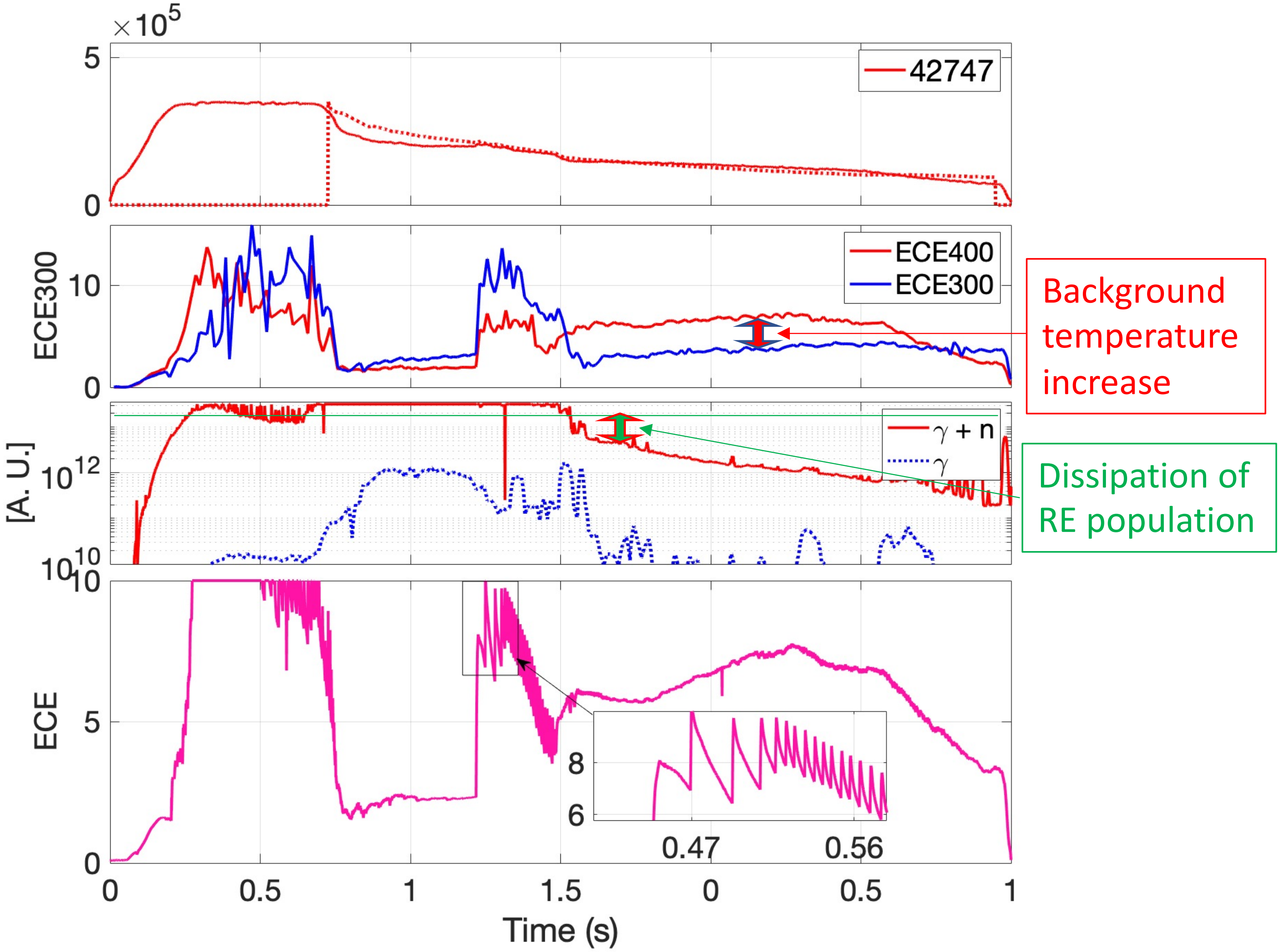
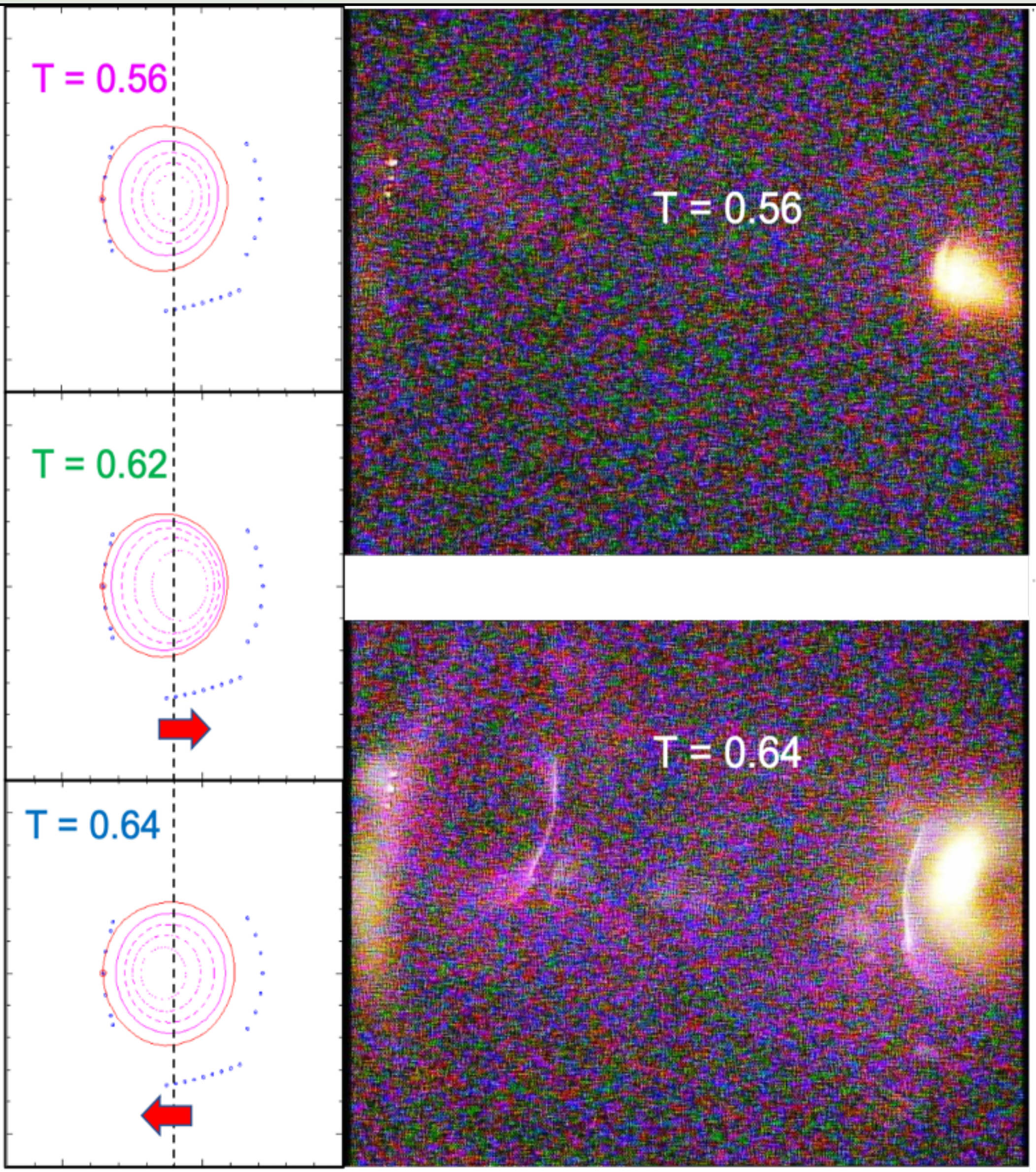


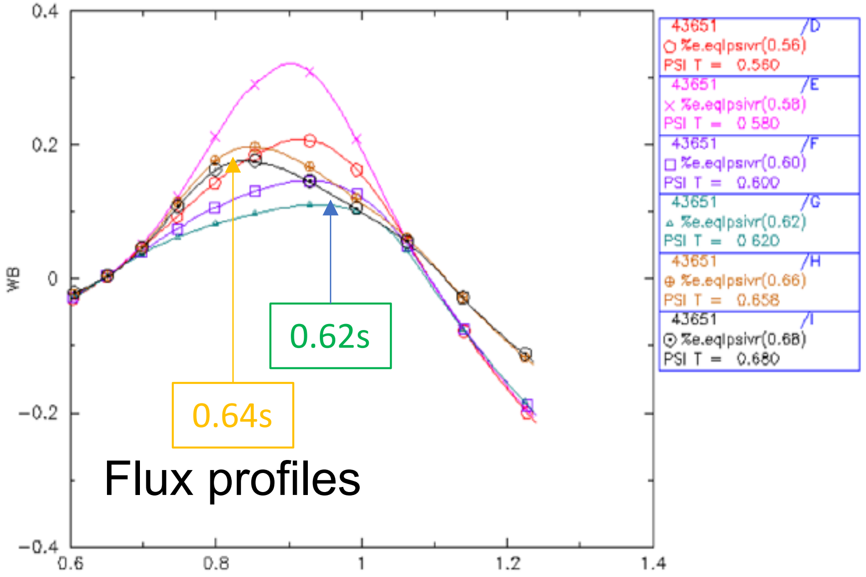
Large post-disruption ADI dissipating REs (cont'd)

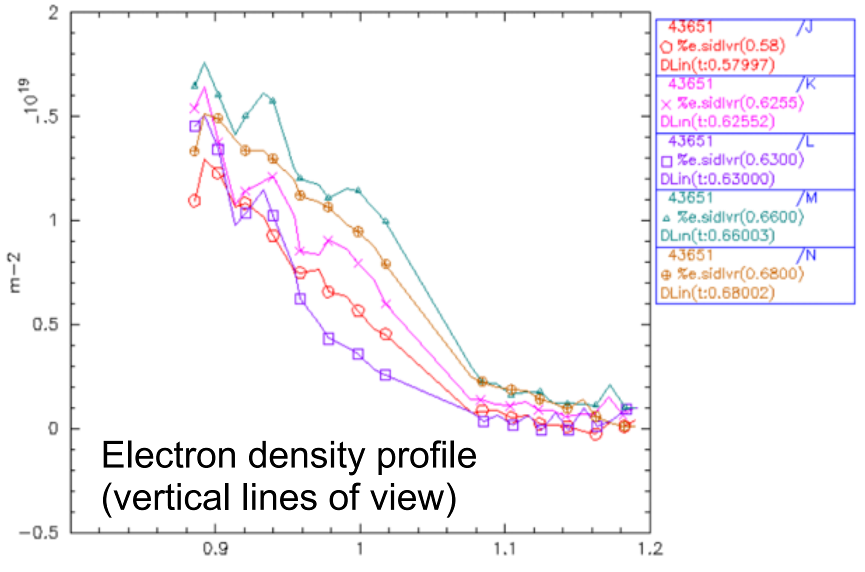
Before ADI sets in the flux surface peak has a large outward shift (0.98m) and visible synchrotron radiation spot is small.

ADI sets in at 0.621s:

- increasing the REs pitch angle
- then the flux surface peak moves inward (0.83m) due to reduction of L_i (larger and hollow profile) and the unchanged vertical field produced by PF coils.
- Larger synchrotron radiation spot (*annular distribution*).







Large post-disruption ADI dissipating REs: where does the energy go?

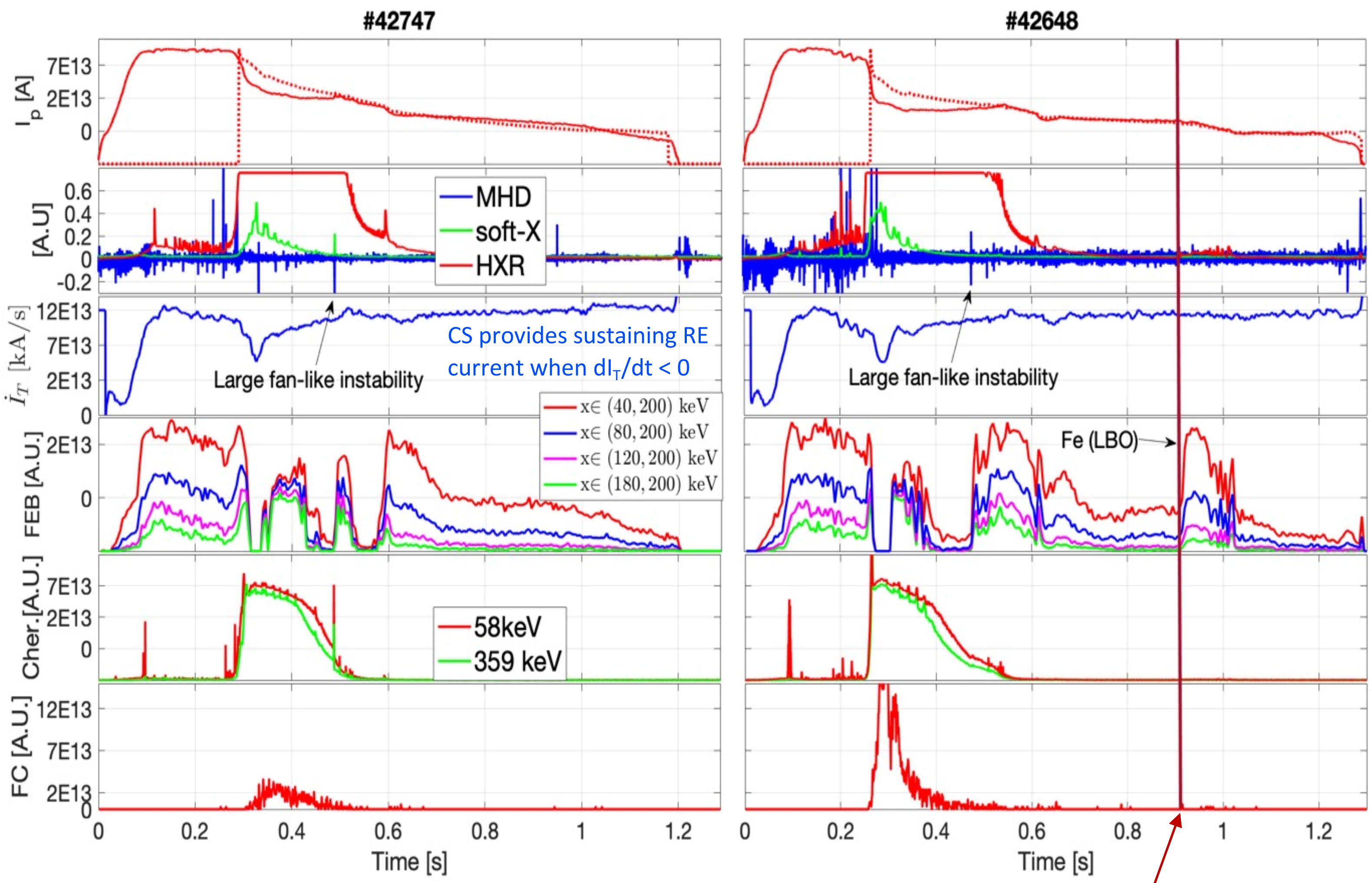
ADI reduce the magnetic RE beam energy (negative spike and current distribution reconfiguration)

$$E_{RE,mag} \approx \mu_0 l_i R_{RE} {I_{RE}}^2/4$$

Does it transform into RE kinetic energy?

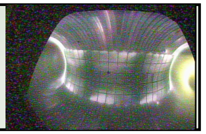
- Background plasma increase its energy
- Increased pitch angle yields increased synchrotron radiation losses
- Experimental data (γ, HXR) reveals that after ADI, RE population seems to (sensibly) decrease…

Spike/increase REs are usually detected by Cherenkov probe at the onset of ADI: RE direct loss.

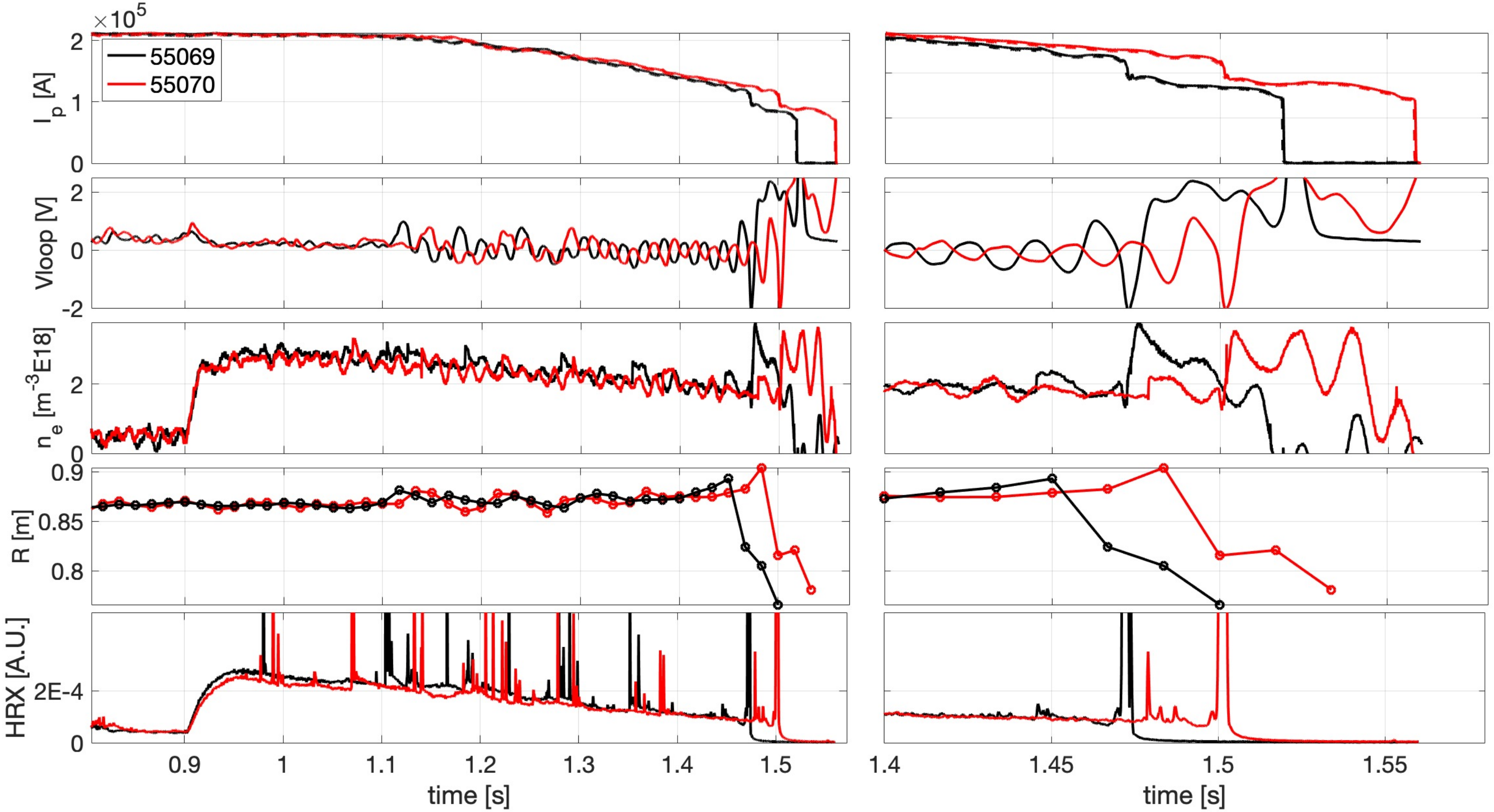


Fe Laser Blow Off injection: Fe particles find a sufficiently hot background plasma

Comparison among FTU and TCV discharges

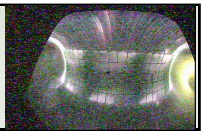


TCV: two ramp-down with V_{loop} oscillations shown **sudden loss of all REs**, **radial inner movement** (T increase, L_i decrease), negative V_{loop} spike, and ohmic plasma since then: **never seen before**.



ADI seems again to be the cause of such full conversion.

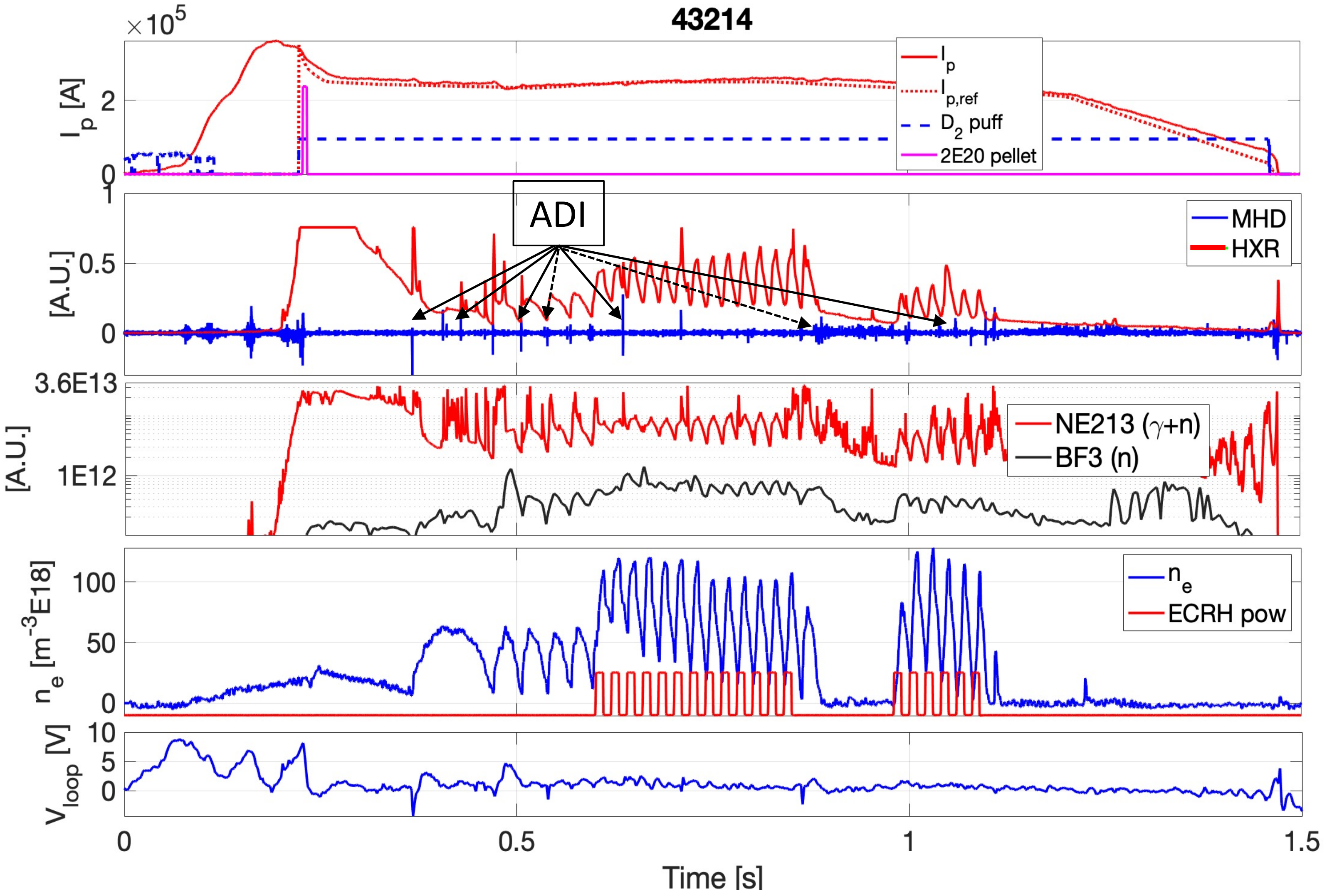
Rationale of Vloop oscillations: RE dynamics are affected by **hysteresis** [D. Carnevale et al., Plasma Phys. Control. Fusion 61 014036 (2019)]: oscillations of V_{loop} might enhance the RE conversion (overcrossing the hysteresis threshold) into thermal electrons.



A self-generated RE beam: sudden decrease of reference current (top plot, red dotted), large pellet injection during CQ might have correlated with one of the lower energy RE beam on FTU.

Continuous D_2 puffing in view of ECRH: it seems that ADI are correlated with n_e drop (below…) [RE decreased energy]

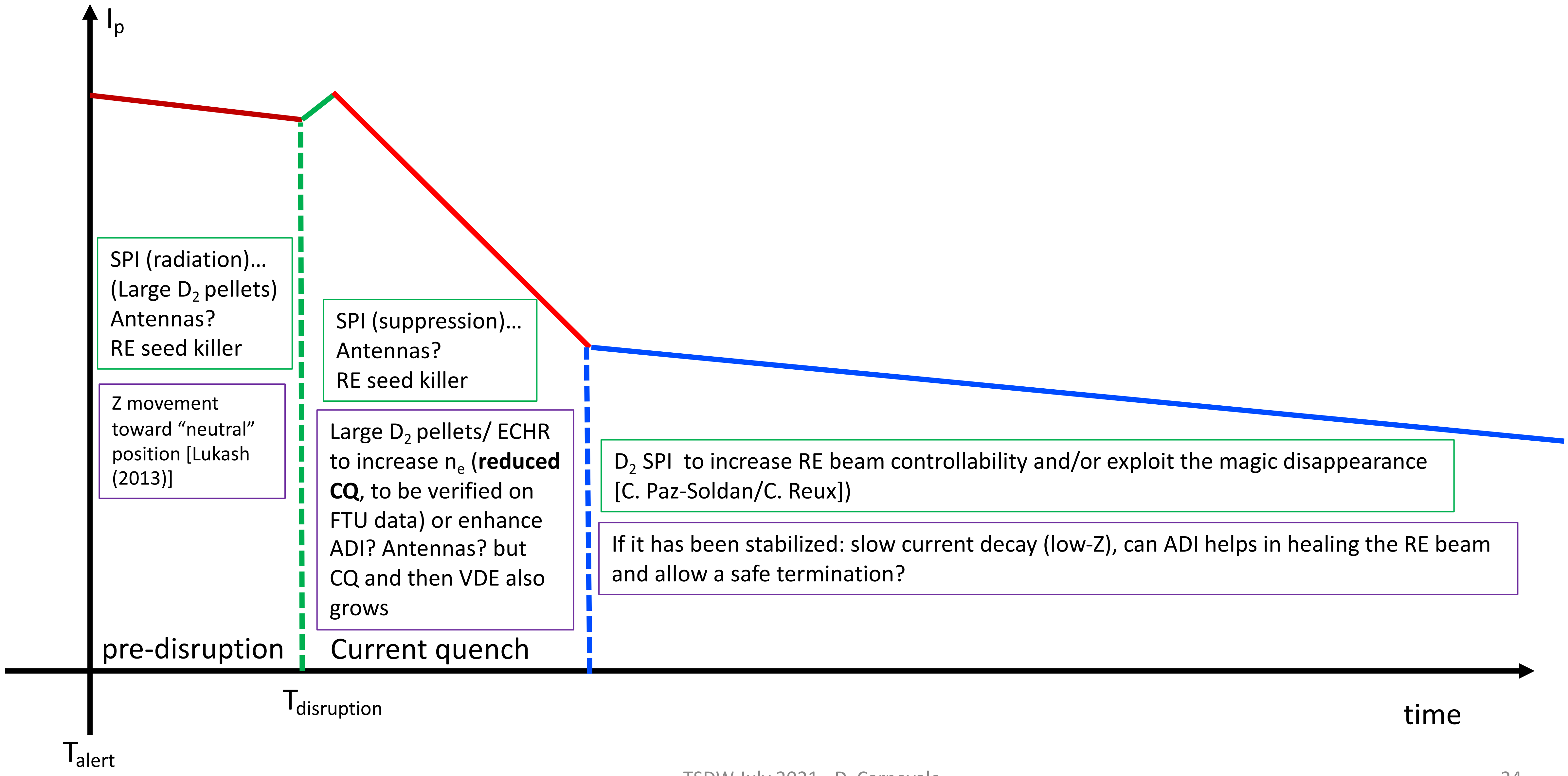
Can ECRH can be used to trigger ADI?



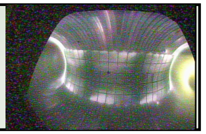
smaller ADIs

Reduced CQ providing n_e (ECRH+D_2 pellet)?

Map of tools for RE energy dissipation



Conclusions



Analysis:

- Exponential growth of REs on (0.36MA,5.3T) discharges
- Role of ADI instabilities as a dissipative mechanism in pre and post-disruption RE discharges

RE dissipation strategies:

- D_2 pellet injections: complete RE loss on flat-top (0.5MA,4.0-5.3T) or ramp-up current (0.36-0.55MA,5.3T); RE beam possible generation with RE exponential growth on (0.36MA,5.3T)
- Slow ramp-down and try to exploit ADI for energy dissipation (fast current ramp-down before ADI, i.e. low L_i, can generates strong electrical field (re)generating REs, to by deeply analysed)
- D_2 puffing and modulated ECRH: a possible way to pace ADI?