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Latest results on runaway electrons experiments at FTU

FTU Experimental Campaign 2019-C1

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SUMMARY

Post-disruption RE beam scenarios: natural disruptions

- Diagnostics, additional equipment and control tools active on FTU
- Temperature increase of the background plasma: possible mechanisms
- REs instabilities observed at FTU
- Heavy metal interaction with quiescent REs and post-disruption beams
- Initial results on the use of ECRH on REs (quiescent and beam)
- REs beams trapped into MHD modes
- Long discharges
- Conclusions

RE studies: diagnostics

Plasma current: up to 1.5MA
Toroidal field: up to 8T
Major radius: 0.96m, minor radius 0.3m
Pulse duration: up to 4s

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

New release in September

New diamond detectors

RE studies: additional equipment

DEUTERIUM PELLET INJECTOR

Small D_2 pellet: $1x10^{20} \approx 1200$ m/s
Large D_2 pellet: $2x10^{20} \approx 1000$ 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 $8x10^{20}$ with I_p=1.2MA (8T) [2001]

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

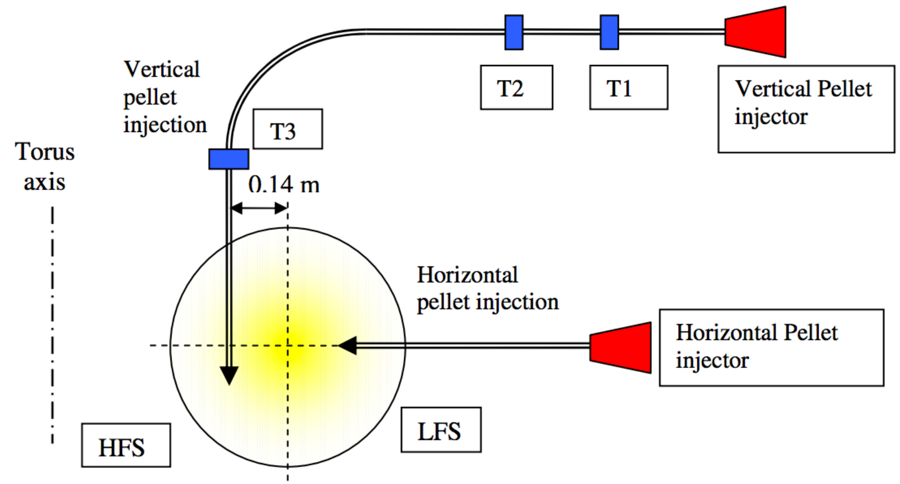


Fig. A: schematic of pellet system

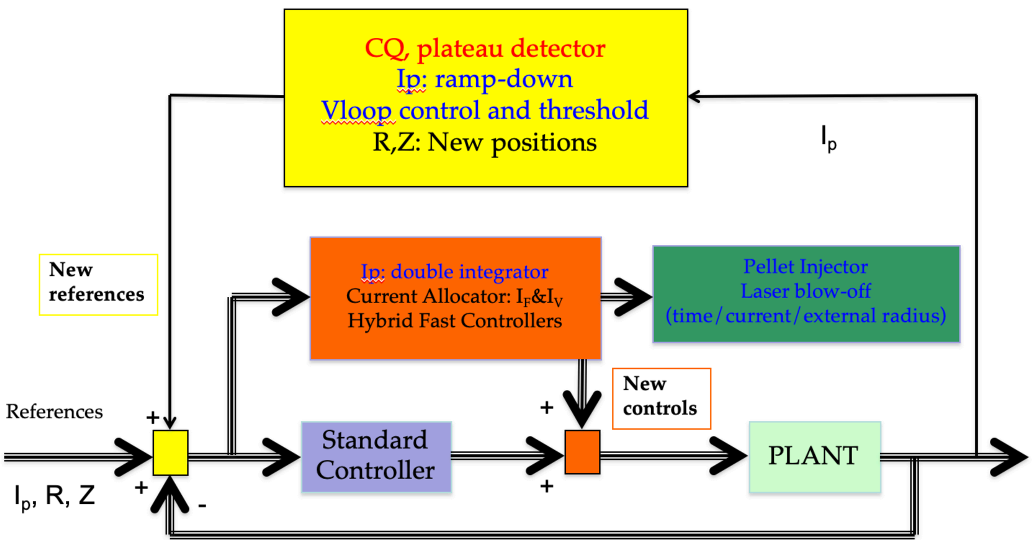
Laser Blow Off (LBO) Injector
Used in the past to trigger disruptions (E. Esposito studies on disruption mitigations)

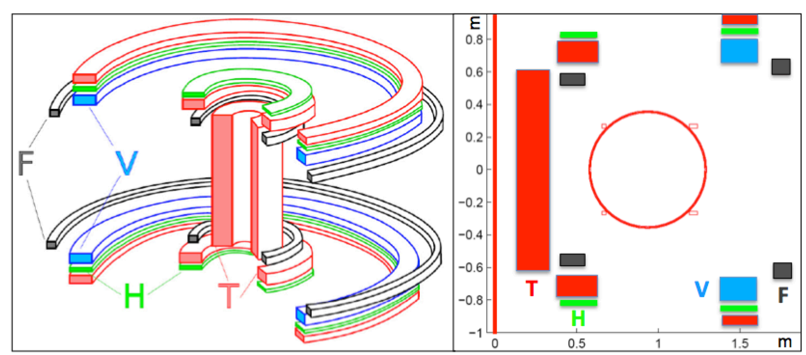
Metal impurities injector by laser ablation of deposited metals on thin layers: Molybdenum, Iron, Tungsten, Zirconium, Yttrium.

Measurements: HXR, X-VUV spectrometer Schwob, Cherenkov.

RE studies: Control tools

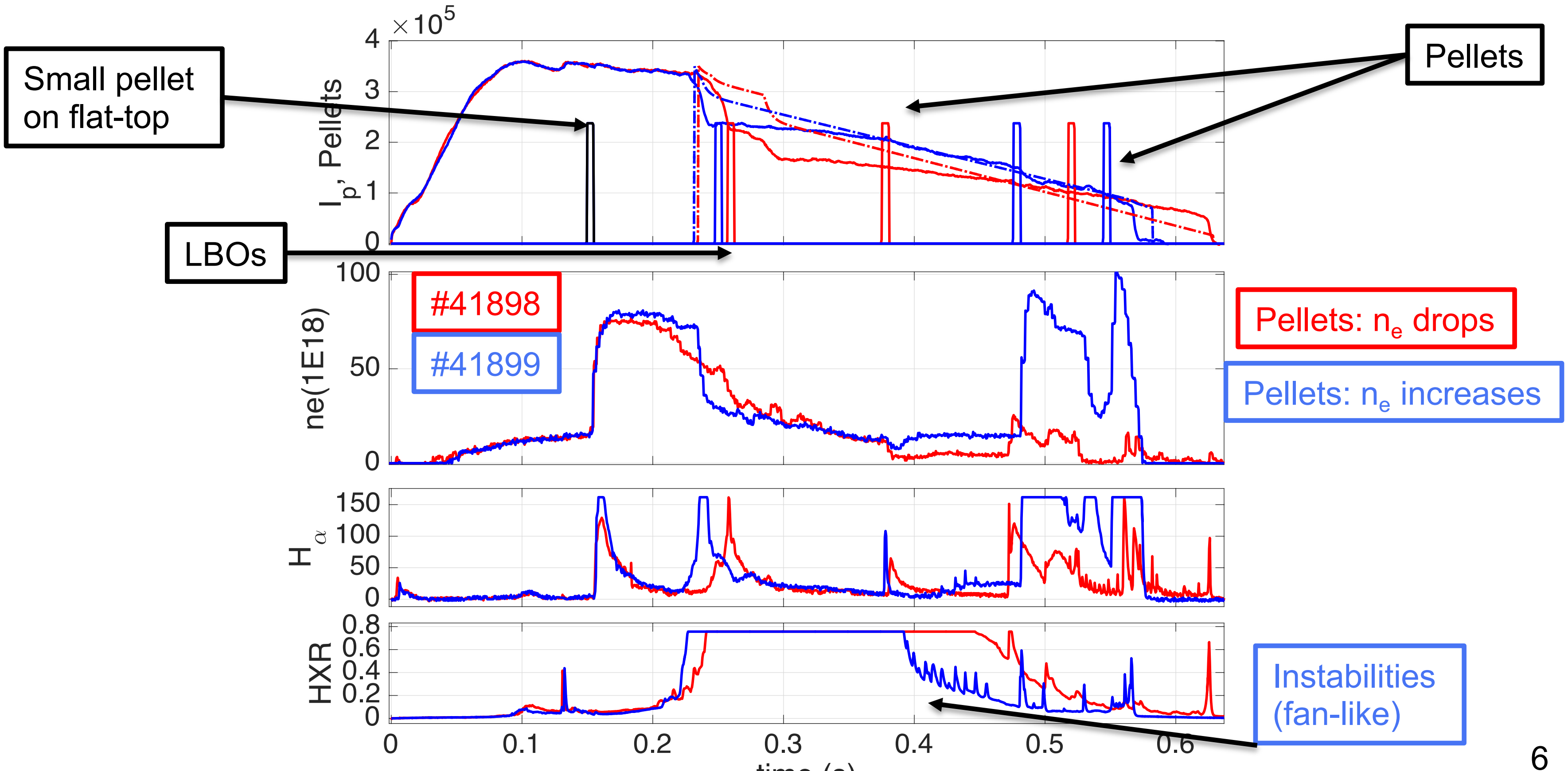
- Current Quench and Onset RE plateau **detectors** (sensing I_p)
- **Current ramp-down reference** or pre-programmed **generic waveform** (with electrical field limitations to reduce MHD instabilities and radial drift – FTU/TCV)
- **Multiple switching integrators**
- Enhanced **hybrid** (switching) **PIDs** to control the beam position (radial and vertical)
- **Fast ramp-like** controller to counteract fast events
- Newly tested **slow ramp-down controller** to improve RE beam position tracking during the non constant currents
- **Current allocation** scheme among poloidal field coils
- **Vloop controller** (used to impose loop voltage oscillations)



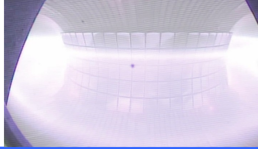


Pellets and LBO: early plateau phase (1/2)

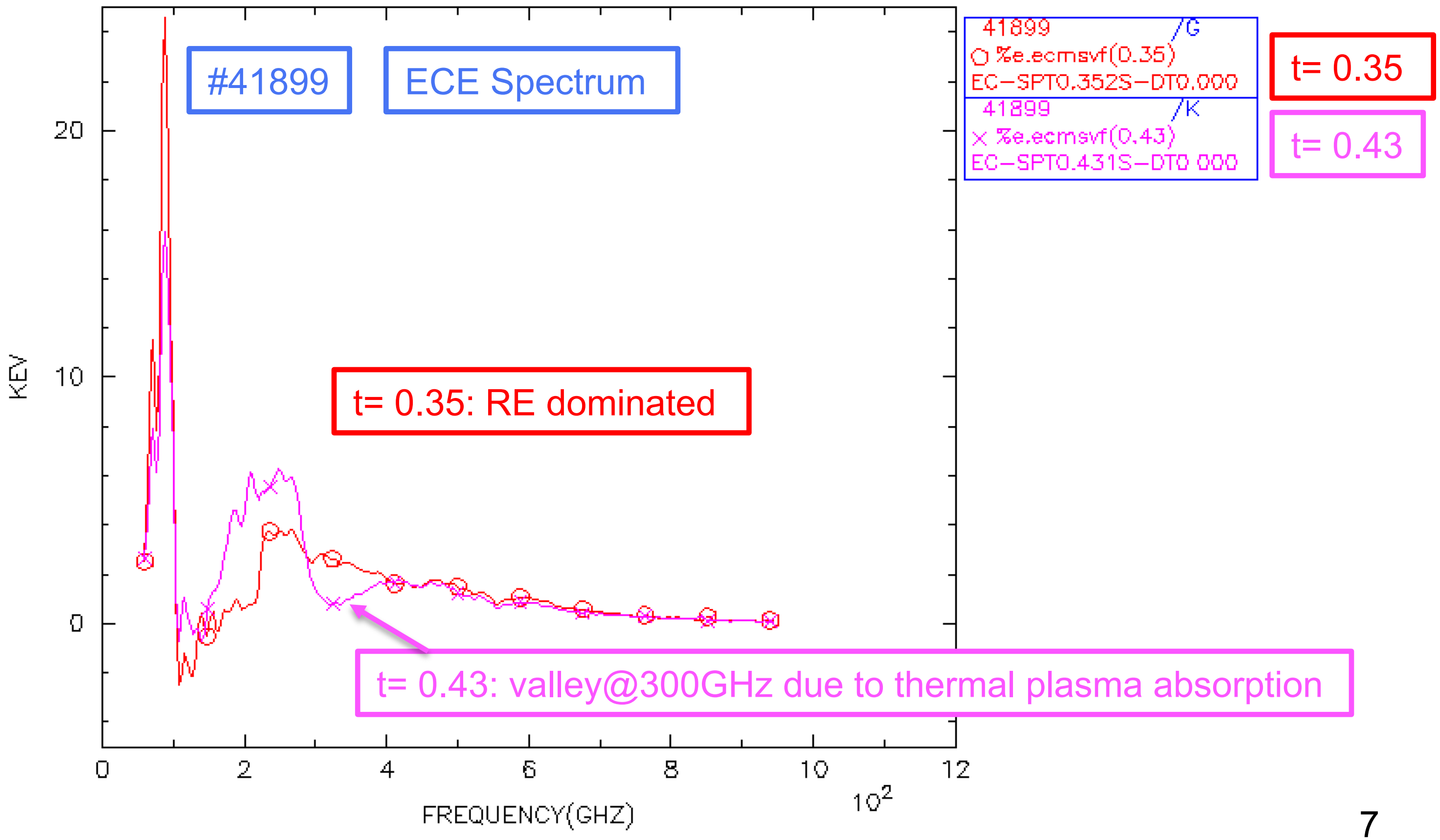
Early plateau phase: approximatively within 300ms the plateau onset
Deuterium pellets: they do ablates (H_{alpha}) but they do not ionize, on the contrary, temperature is decreased down-to recombination and density goes low. Cleaning effect.
LBO: any sensible effect with all metallic species *after* the plateau onset.



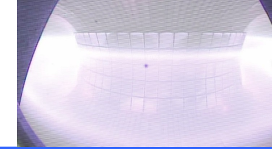
Pellets and LBO: early plateau phase (2/2)

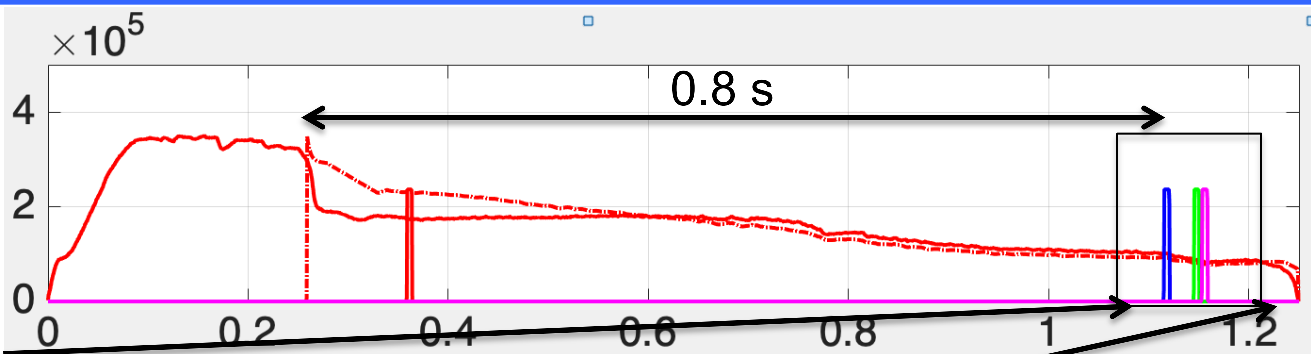


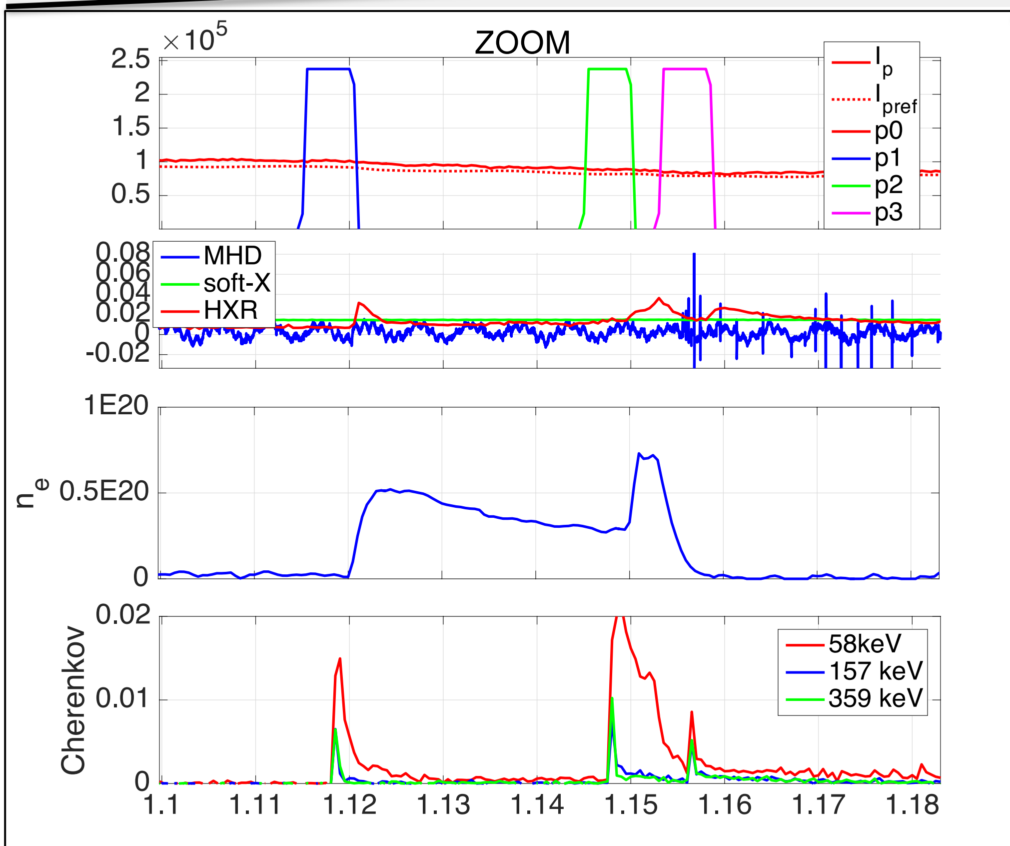
Early plateau phase: approximatively within 300ms the plateau onset
Deuterium pellets: they do ablates (H_{alpha}) but they do not ionize, on the contrary, temperature is decreased down-to recombination and density goes to zero. Cleaning effect.
LBO: any sensible effect with all metallic species *after* the plateau onset.



Pellet and LBO: late plateau phase (1/2)







Pellets injected much later in the plateau phase do increase density.

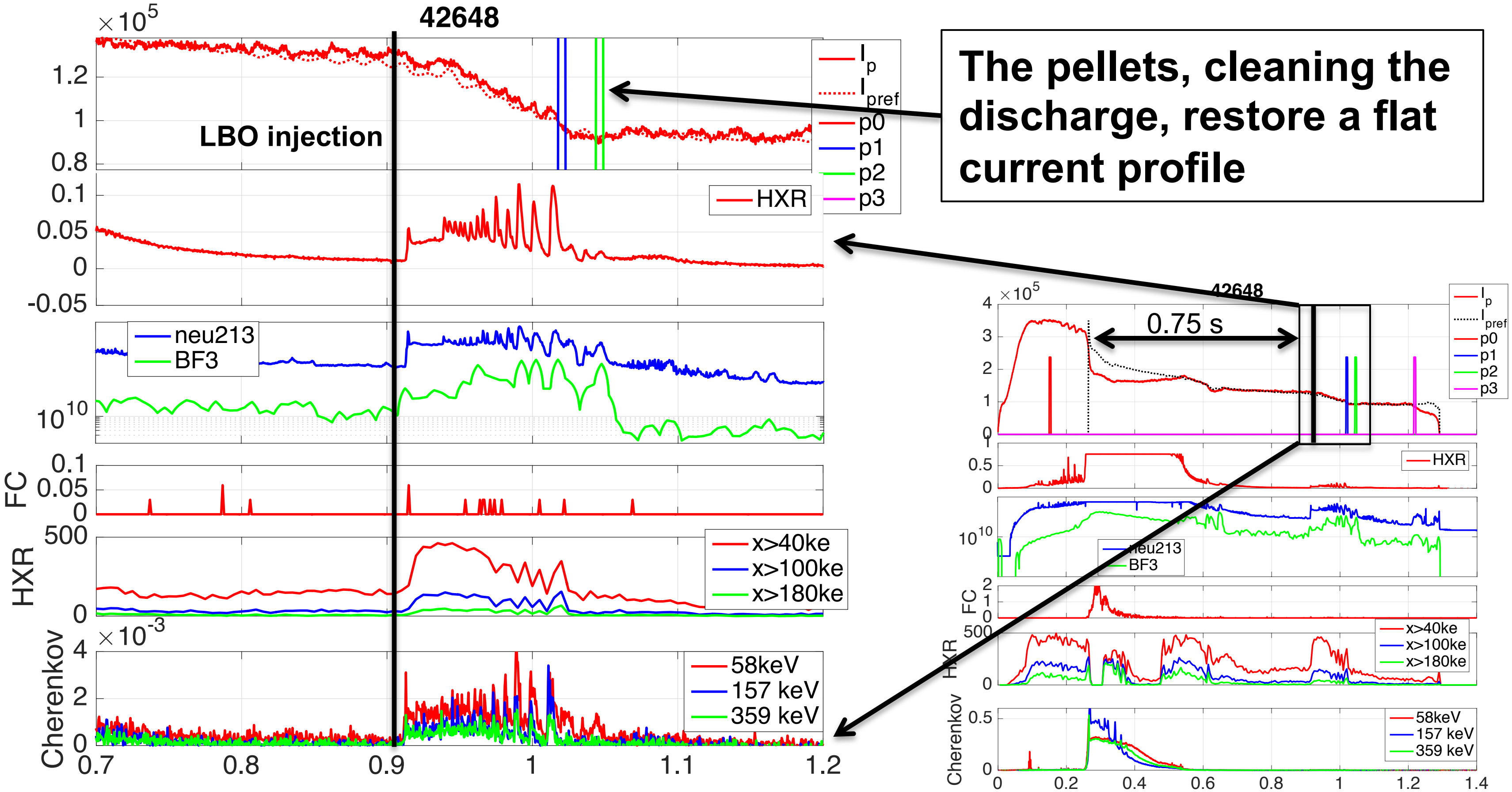
The first (small) pellet is ablated and ionized as the second (large) pellet, while the third (large) cool down to recombination the background plasma leading almost to zero the density.

ECE spectral absorption and pellet ionization support plasma background temperature increase *(and/or runaway energy decrease)*

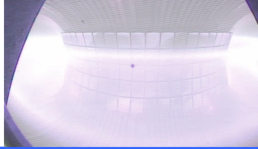
157 keV Cherenkov probe got damaged

Pellet and LBO: late plateau phase (2/2)

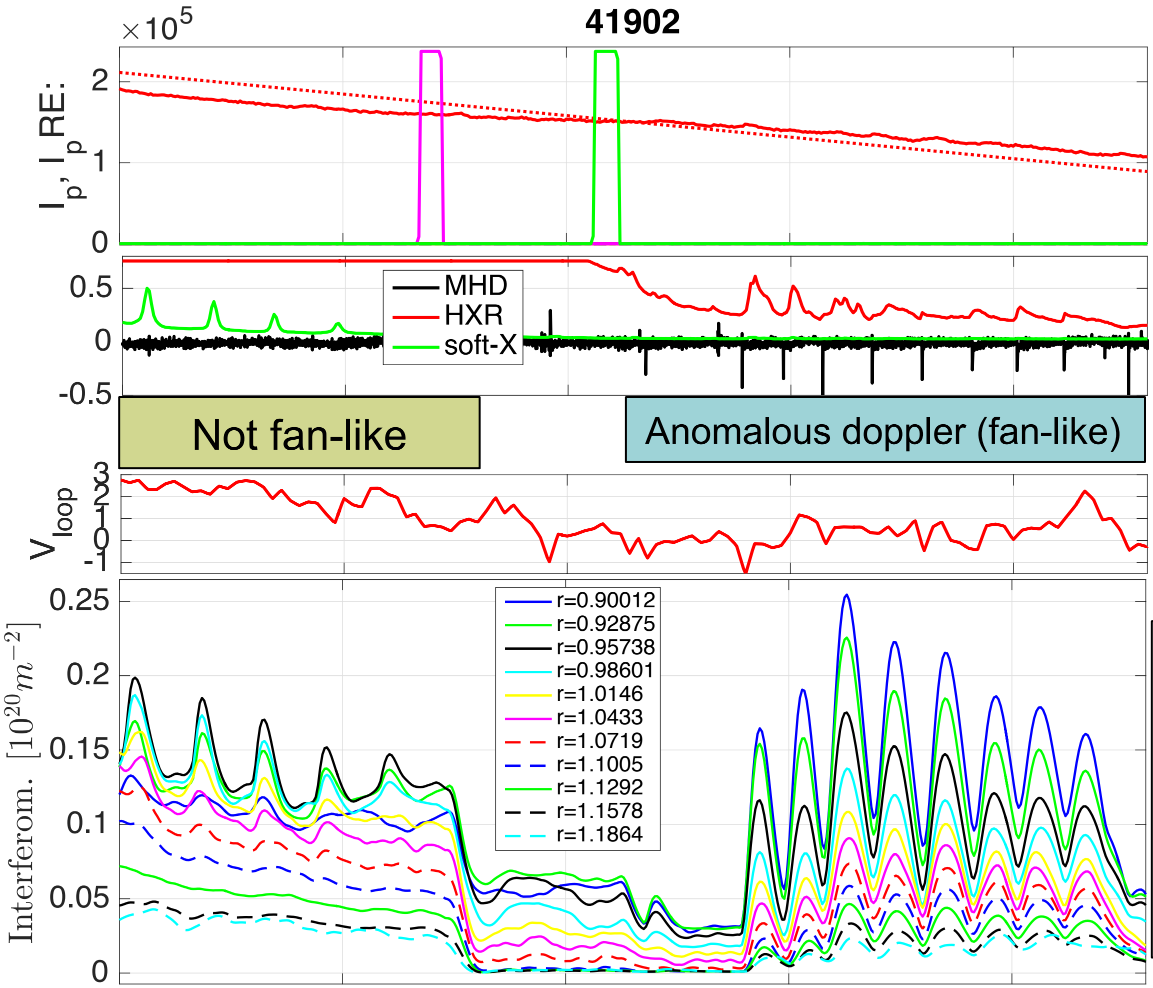
Fe LBO has been used on a post-disruption RE beam undergone a current ramped-down. The OH coils does not sustain the current and instabilities have **increased the background plasma temperature** enough to ionize iron yielding increased I_p decaying rate due to **increased collisionality by high-Z particles**.



Plasma background heaters: instabilities (1/2)



There are different instabilities that are capable of heating the surrounding plasma in different ways.



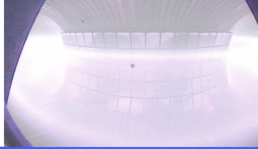
Each time the Ohmic coil starts inverting current derivative (almost null flux or slightly negative provided to REs) anomalous doppler appears (at different frequency)

Slower frequency instabilities (involving higher energy REs - FC) do not seem to be fan-like, no clear MHD signs and inverted ECE signal wrt fan-like.

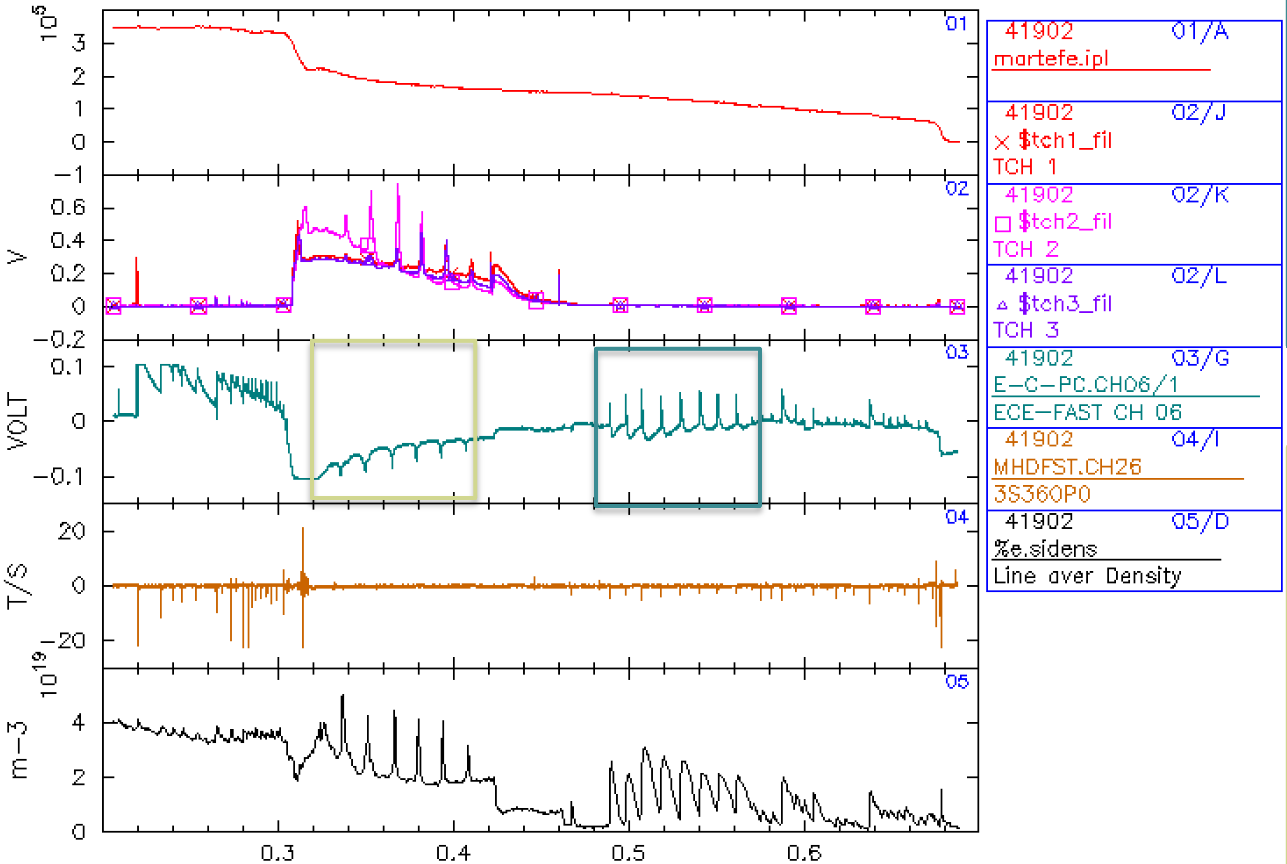
Note that the ''not fan-like'' induces vertical line density changes only on the middle (radial) part.
The fan-like involves all of them.

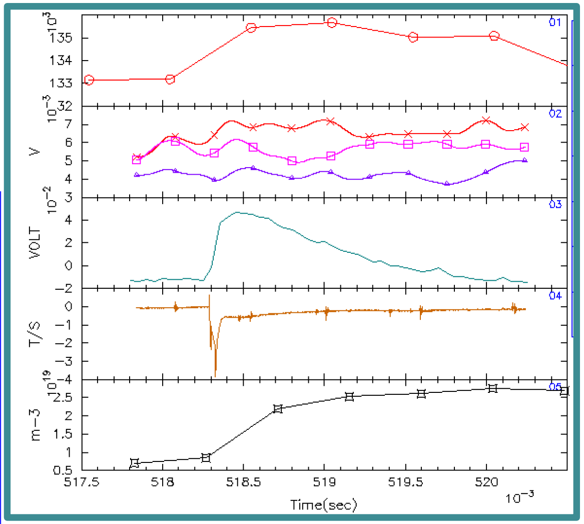
Interferometer: vertical line density of mainly "cold" background plasma.

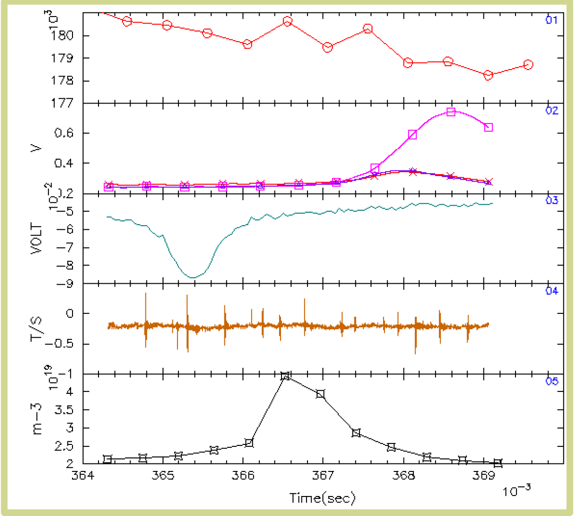
Plasma background heaters: instabilities (2/2)



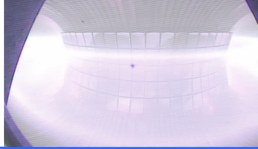
Check differences between fan/not fan-like instabilities (ECE raw signal is E-C-PC.CH06)



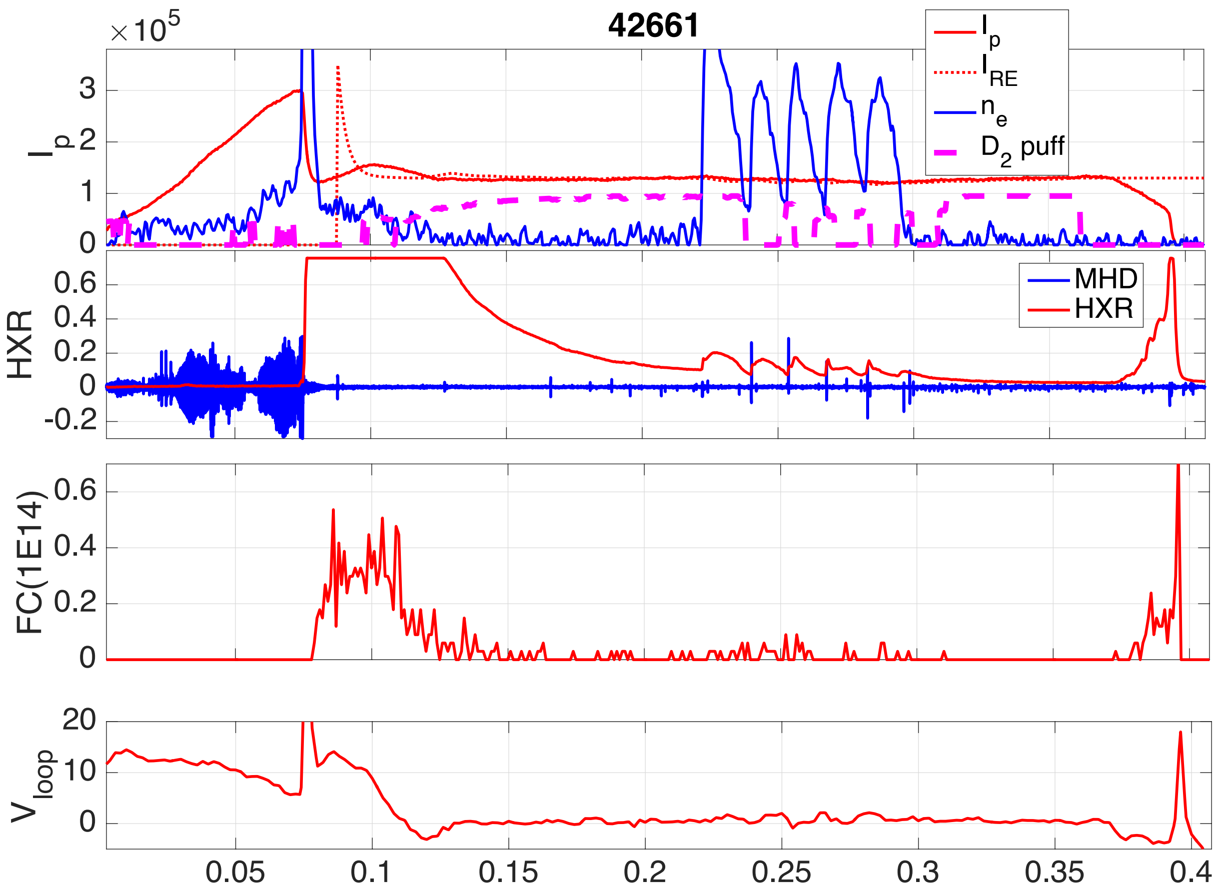




REs current decay induced by fan-like inst.



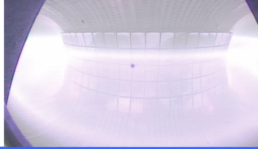
Continuous **deuterium puff**, similar to D_2 pellets, wipes out heavy particles and given the extremely low temperature during the RE plateau phase, recombination takes place yielding to negligible densities and almost **null drag**: the **REs current evolves almost freely** (T coil current constant before 0.24s).

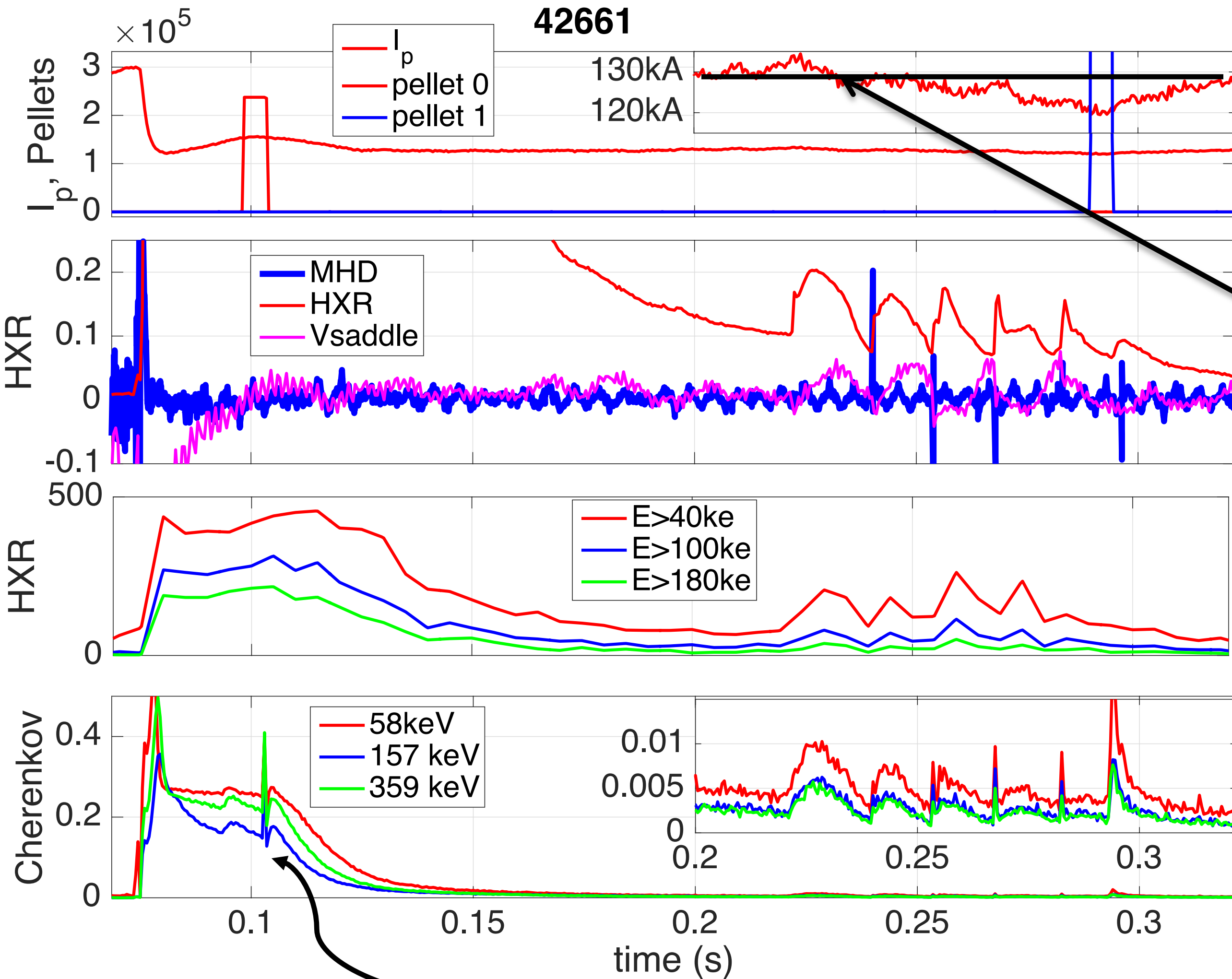


Being the **voltage non negative**, the **REs do not loose their energy** and when a quick current shut down is imposed at 0.37 s (pulse program error), the **beam energy is released against the vessel**.

FC signal is practically zero during the plateau phase (except when fan instability sets in) since the beam is well confined.

REs current decay induced by instability





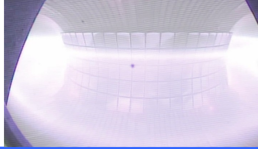
Instability sets in at about 0.22 s increasing the REs losses as marked by Cherenkov and HXR detectors.

Total current I_p shows a mild decrease only due the instability ().

A **second pellet destroys the instability** and losses disappear (not unique). Do pellets affects RE beams instabilities similarly to MHD instabilities on plasma discharges?

Pellets usually induce prompt REs loss.

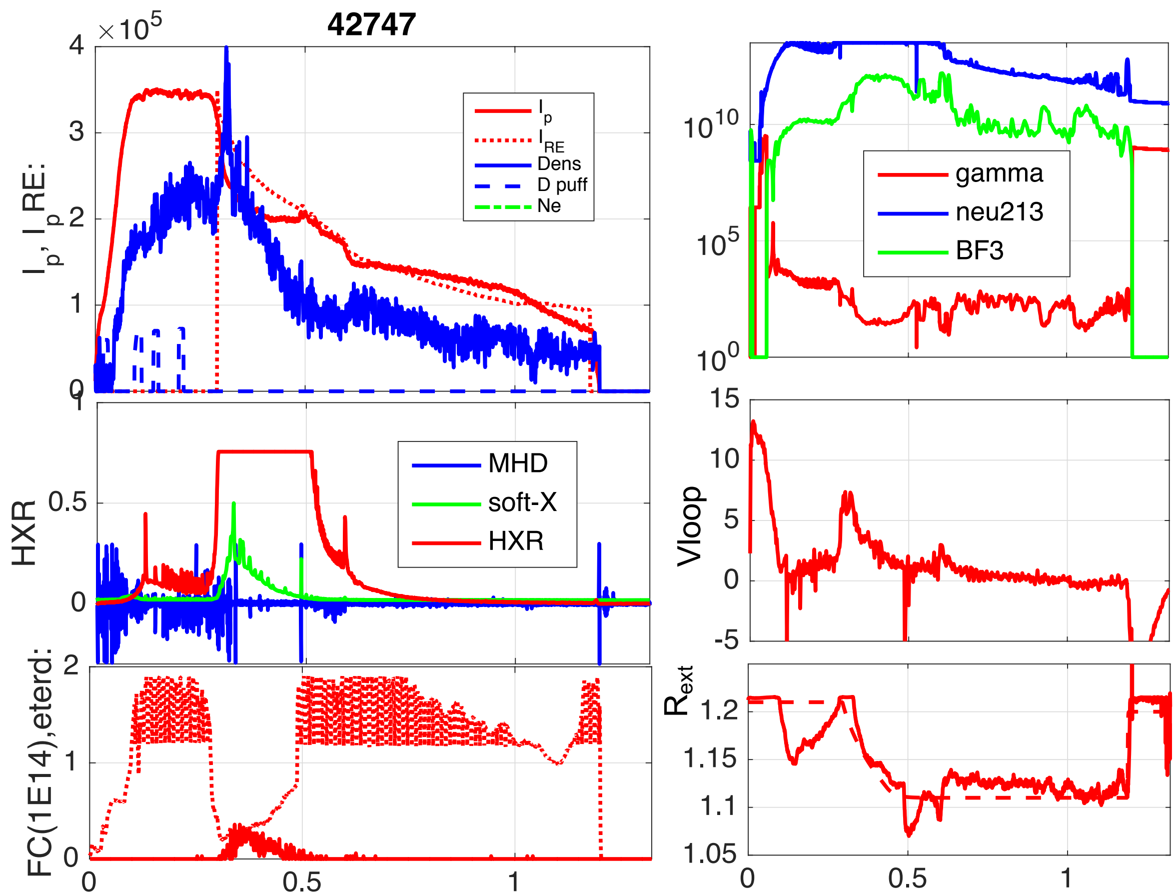
Long lasting plateau: RE energy suppression



On long lasting RE beams the energy is:

- **Dissipated (drag, instabilities, error fields)**
- **Transferred to the background plasma (instabilities)**
- **Reduced (via central solenoid)**

Harmless final loss
(position control has limited capability on ITER, backup and/or simultaneous to others)

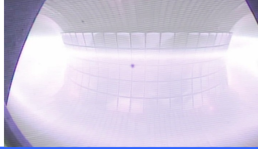


Remark:
There are a series of peculiar marks that seems to reveal the start of fast energy *release/conversion (RE thermalization):*

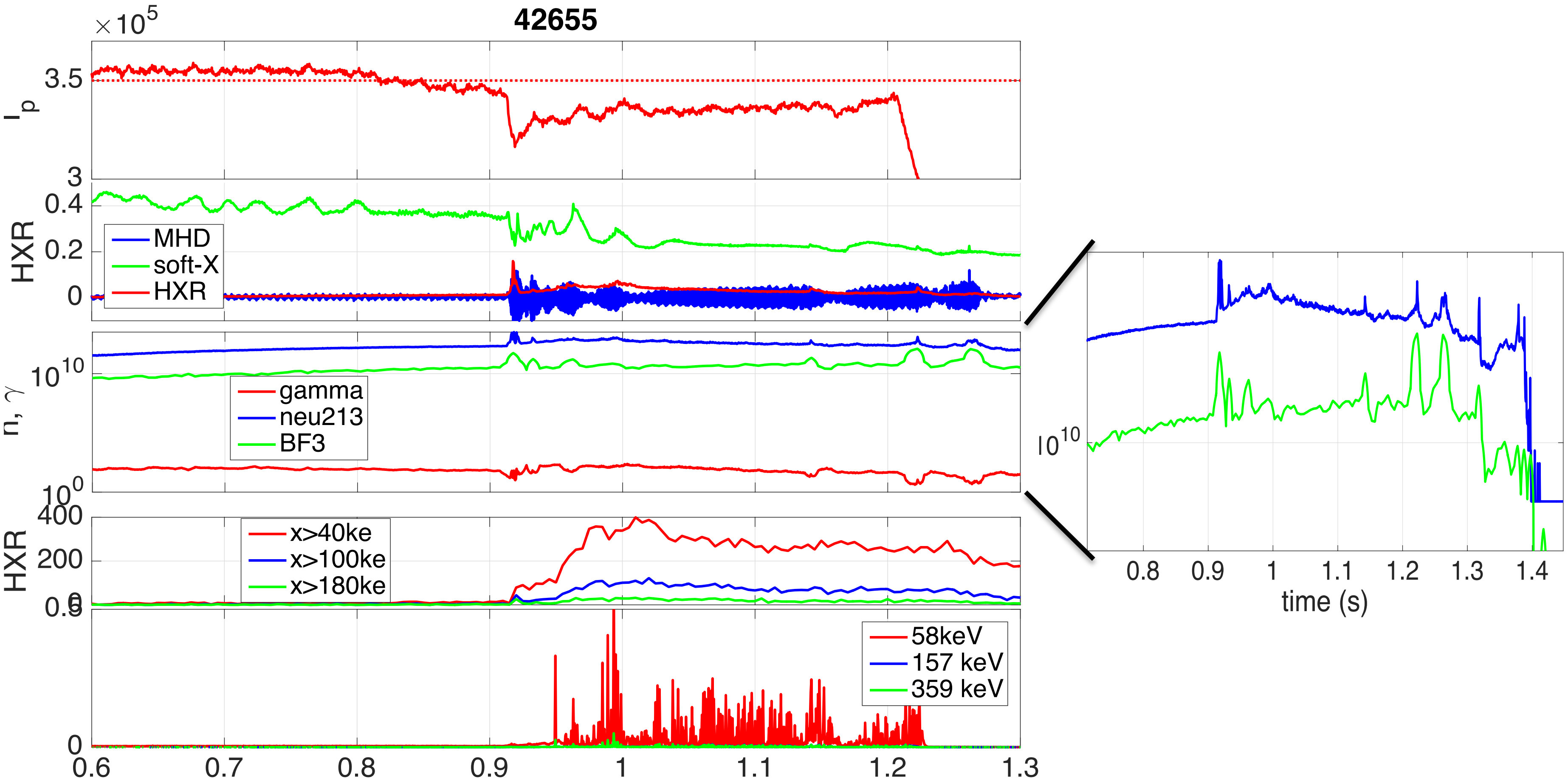
- HXR, NEU213 begin to decrease
- Radial flick.
- Spike in the Vloop
- ECE emission shows a non-cold background plasma
- HXR spectra peaks

Interestingly, similar marks have been found on two unique discharges at TCV where full conversion has been obtained (Electrical Field oscillations).

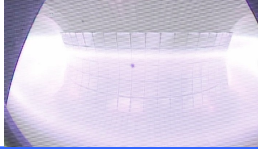
LBO: continuous expulsions



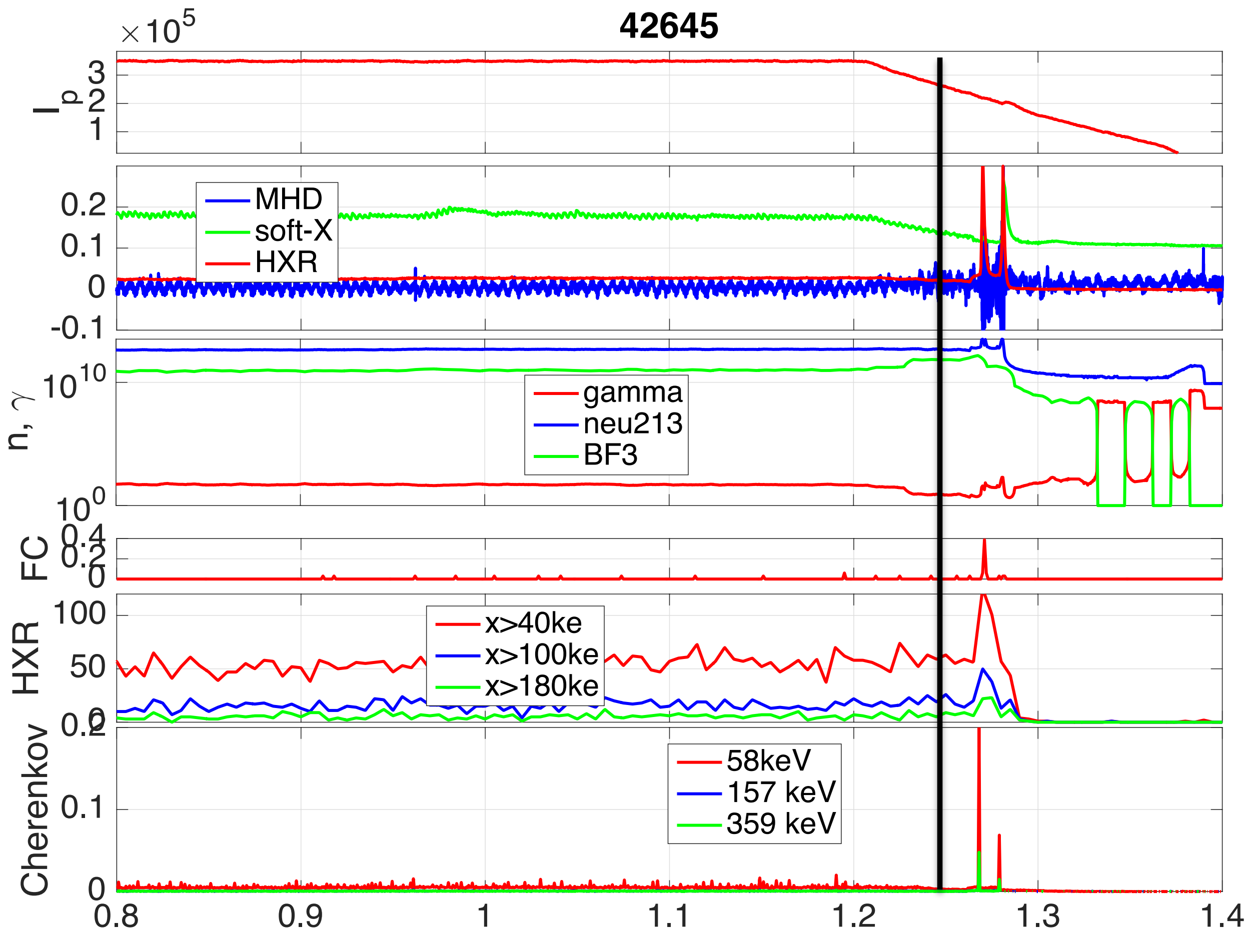
In the shot #42655 a LBO injection of Fe at 0.9 s induced MHD instabilities that seem to continuously expel REs.



LBO on quiescent runaways at ramp-down



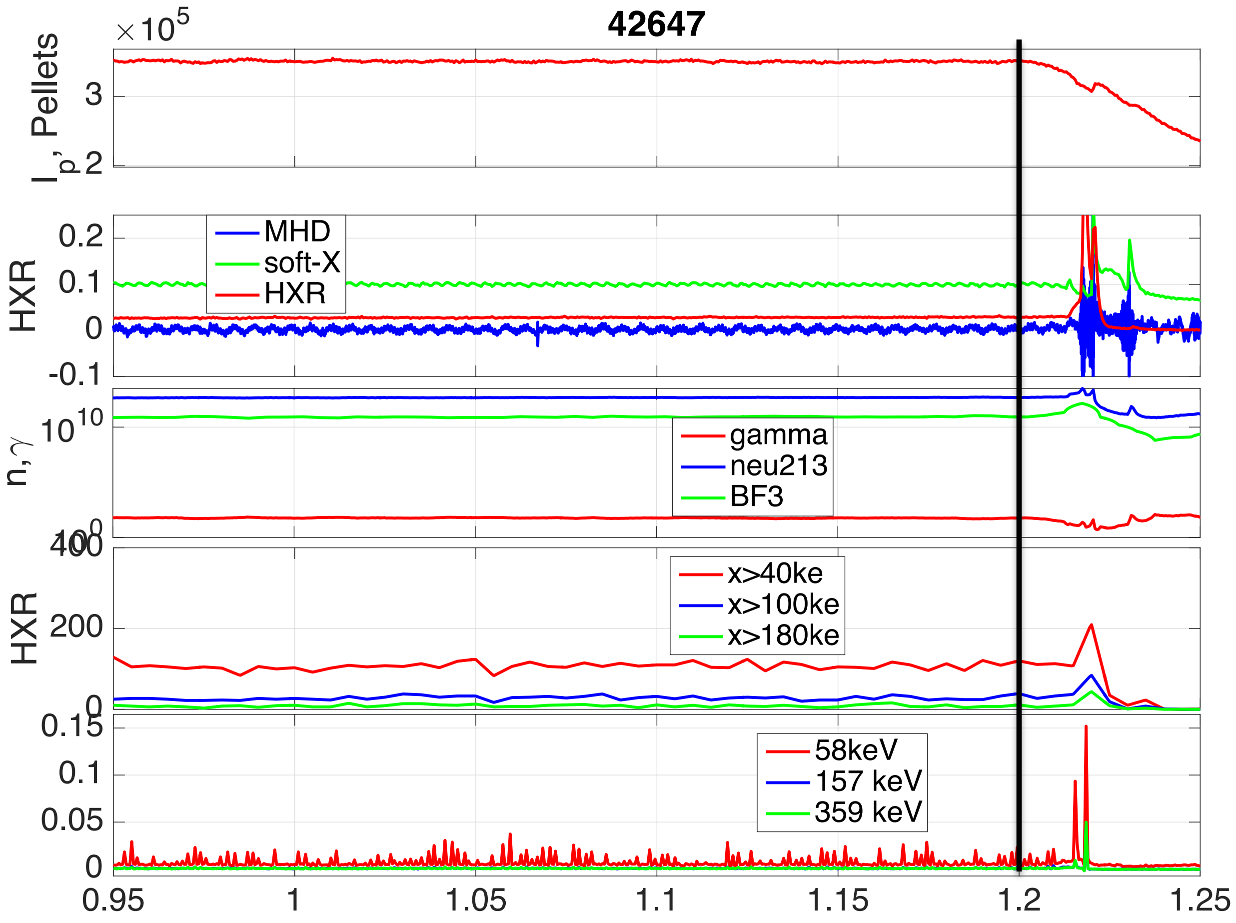
Low density discharge with REs (quiescent) in current flat-top: LBO injection at 1.24 s of Fe.



Fe induces large MHD instability burst leading to RE expulsion.

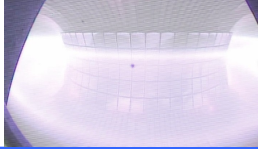
LBO on quiescent runaways at ramp-down

Low density discharge with REs (quiescent) in current flat-top: LBO injection at 1.2 s of Fe.



Fe induces large MHD instability burst leading to RE expulsion.

LBO: considerations



LBO seems to be able to induce "small" disruptions expelling REs in flat-top (quiescent) as well as ramp-down and post-disruption: abruptly or continuously.

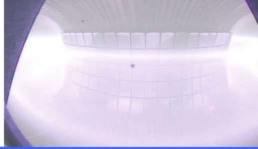
The main key parameter seems to be the level of (background) **plasma temperature** that allows for **ionization**.

ITER: current quenches of hundred of milliseconds would possibly allow continuous LBO injections to limit REs formation (particularly second mechanisms) - provided enough temperature for ionization.

ECRH:

- Increase the temperature of the background plasma
- Provide extra free electrons ionizing puffed deuterium during CQ to absorb flux and to possibly limit the maximum RE energy
- Do heated electrons by ECRH possibly reduce the CQ drop?

ECRH on REs: initial results

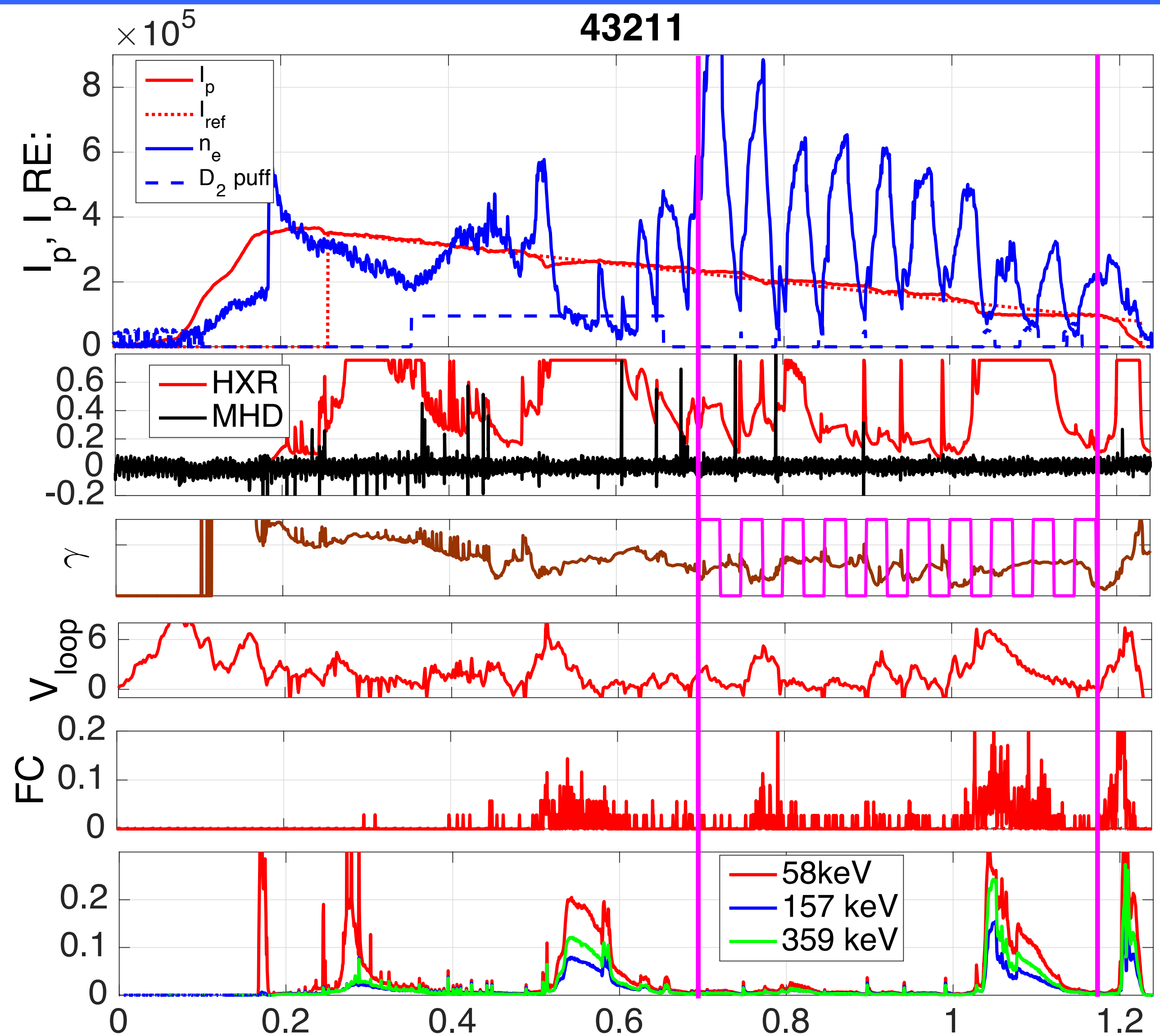


ECRH is configured as for plasma **current assisted break-down** experiments**:**

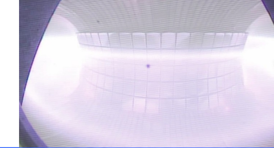
- Continuous ECRH on early RE beam phase: no clear effects on density.

- On RE Soft-stop (ramp-down triggered due to high HXR) with D_2 puff, the **RE expulsion synchronizes with ECRH pulse modulation (20Hz).**

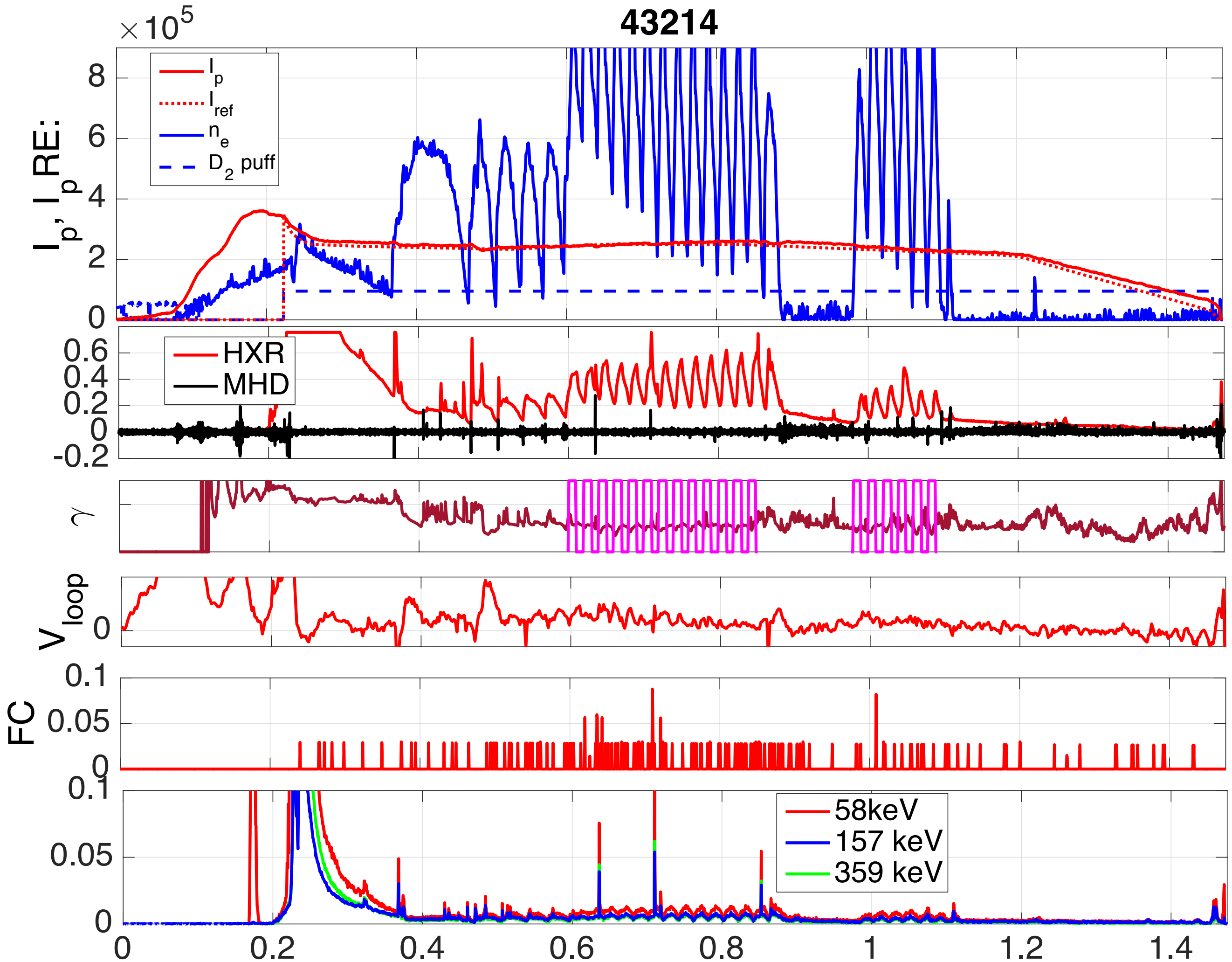
Note the multiple small CQs (0.5s, 0.75s, 1.05s): reduced CQ drop?



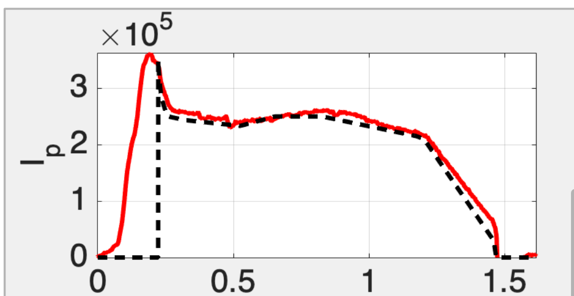
ECRH on REs: initial results



- On quite low energetic post-disruption REs with continuous D_2 puffing, the **RE expulsion synchronizes with** **ECRH pulse modulation (50Hz): with higher frequency no exact correspondence with MHD spikes, no multiple plateaus…**

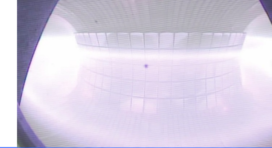


Note that current reference profile is not a simple ramp-down:



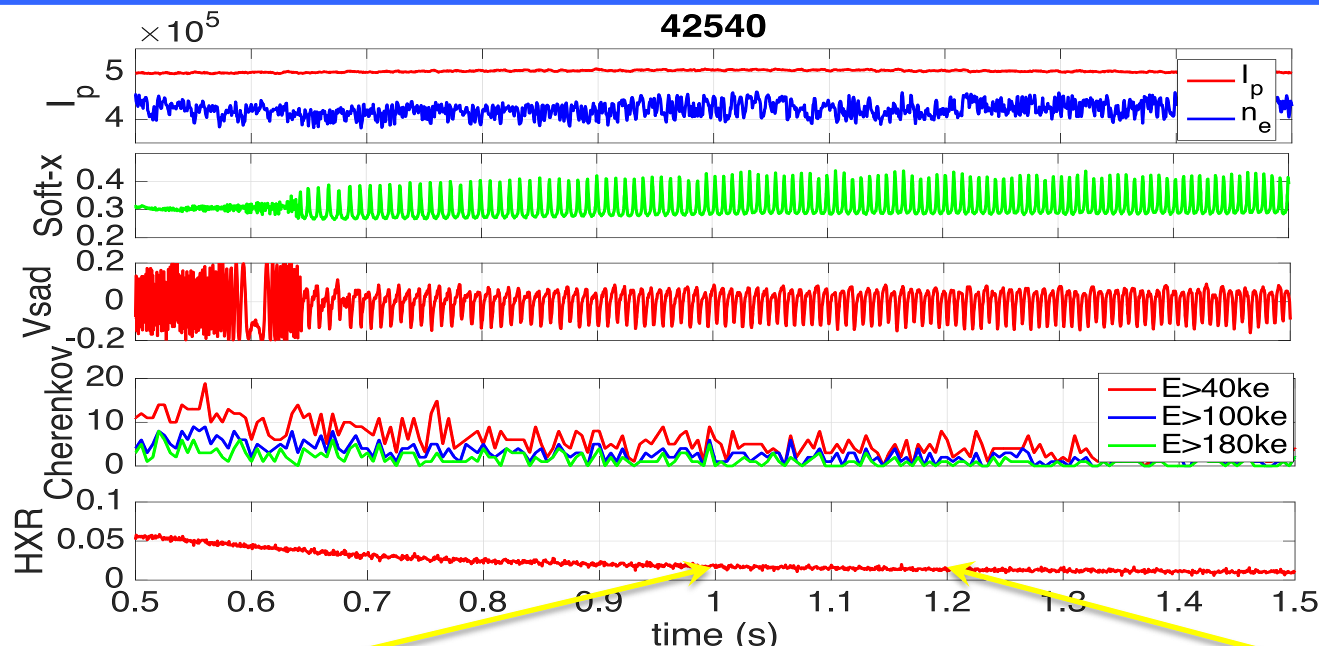
AIM: Increase the current to measure the fraction of flux absorbed by REs and heated background plasma (energy limiting).

REs trapped by MHD in quiescent REs

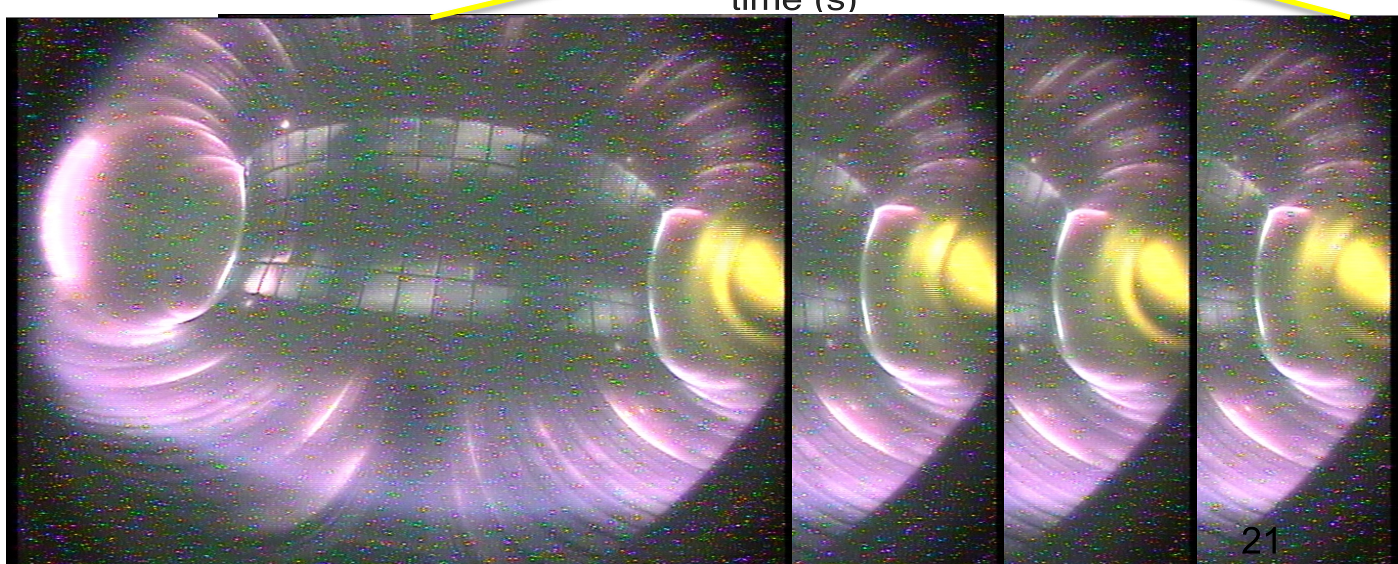


On flat-top low density discharges large rotating MHD modes marked by voltage oscillations of the saddle coil (Vsad) trap REs.

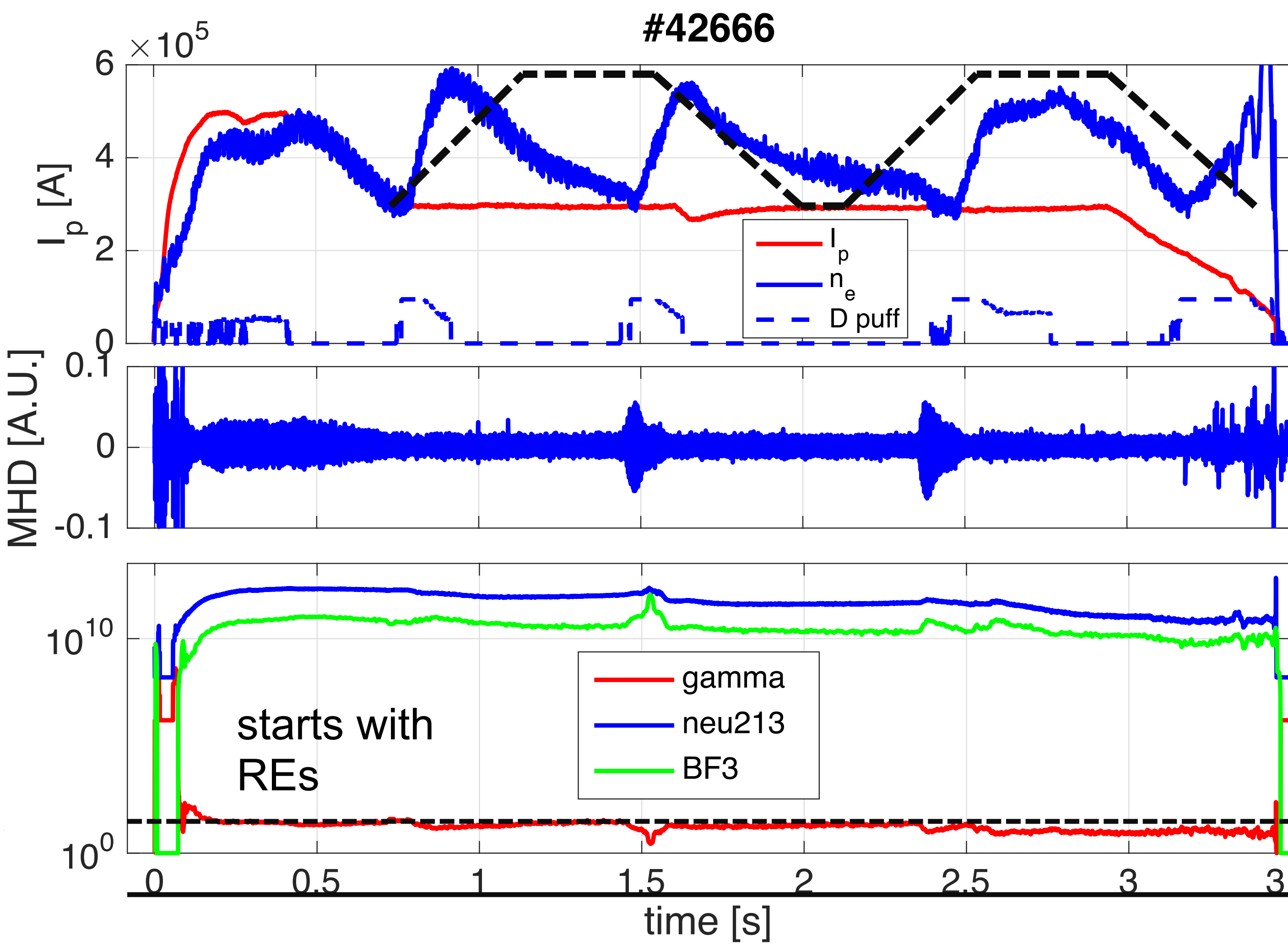
Cherenkov probes level confirm REs confinement.



Images of the visible camera, sampled at 50Hz, shows peculiar REs marks trapped by MHD modes.



Long discharges: density cycles

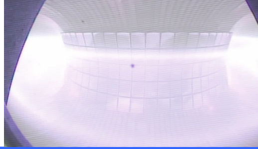


Long discharges density cycles obtained by feedback action resulted not smooth and reached to low values triggering mode growth.

In the next experiments we will provide a pre-programmed reference (dashed black) to smoother the density evolution and avoid MHD growth.

Density cycles with constant current on quiescent plasma and the REIS should provide good data for RE energy models validation.

Conclusions



- **Long lasting RE beams with almost no residual energy** (more than 1.1s, extendable)
- **Temperature increases again: RE phase transitions and/or energy transfer to background plasma.**
- **Dissipation effects of RE losses due to fan-like/MHD instabilities on quiescent and post-disruption RE beams.** ***Plasma waves emissions by REs are studied, waves in the 400-800 MHz range have been detected.***
- **LBO can increase/induce RE dissipation/losses**
- **Pellets seem to stabilize instabilities on post-disruption RE beams**
- **Quantifiable effects of RE losses due to fan-like instability on a RE beam**
- **REs orbits trapped by MHD large modes on quiescent REs**
- **ECRH initial results on quiescent REs, post-disruption and Soft-Stop (w/o modulation)**

Control dream/obsession: inject the minimum amount of materials for thermo-mechanical loads, reduce the current drop (more current curriers provided by ECRH and less drag thanks to D_2 pellets/puff cleaning effect) and the REs peaking energy (flux absorption by many electrons and larger interaction with higher temperature background plasma)…improved controllability for ITER!!!

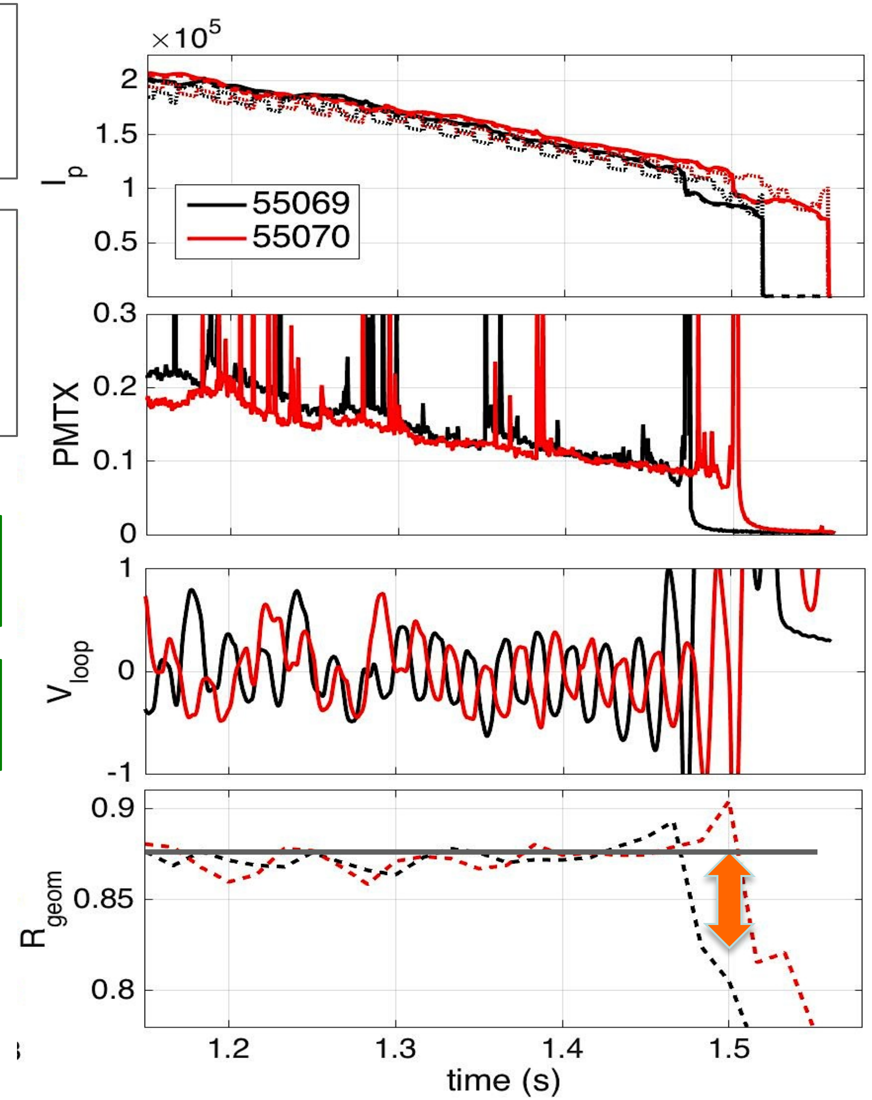
FTU (almost certainly) conclusive campaign: are you interesting to participate?!

ADDIONAL SLIDES

Final Loss: new findings

FTU: approximately 150 ms after the CQ the beam exhibits (80%) a sudden **radial inner movement** (HXR drop below saturation) .

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



Radial shift approx.

$$\Delta R_{RE} \approx \overline{q} W_{RE} / ecB$$

W_{RE} is the RE energy

FTU: lost/conversion of high energetic REs

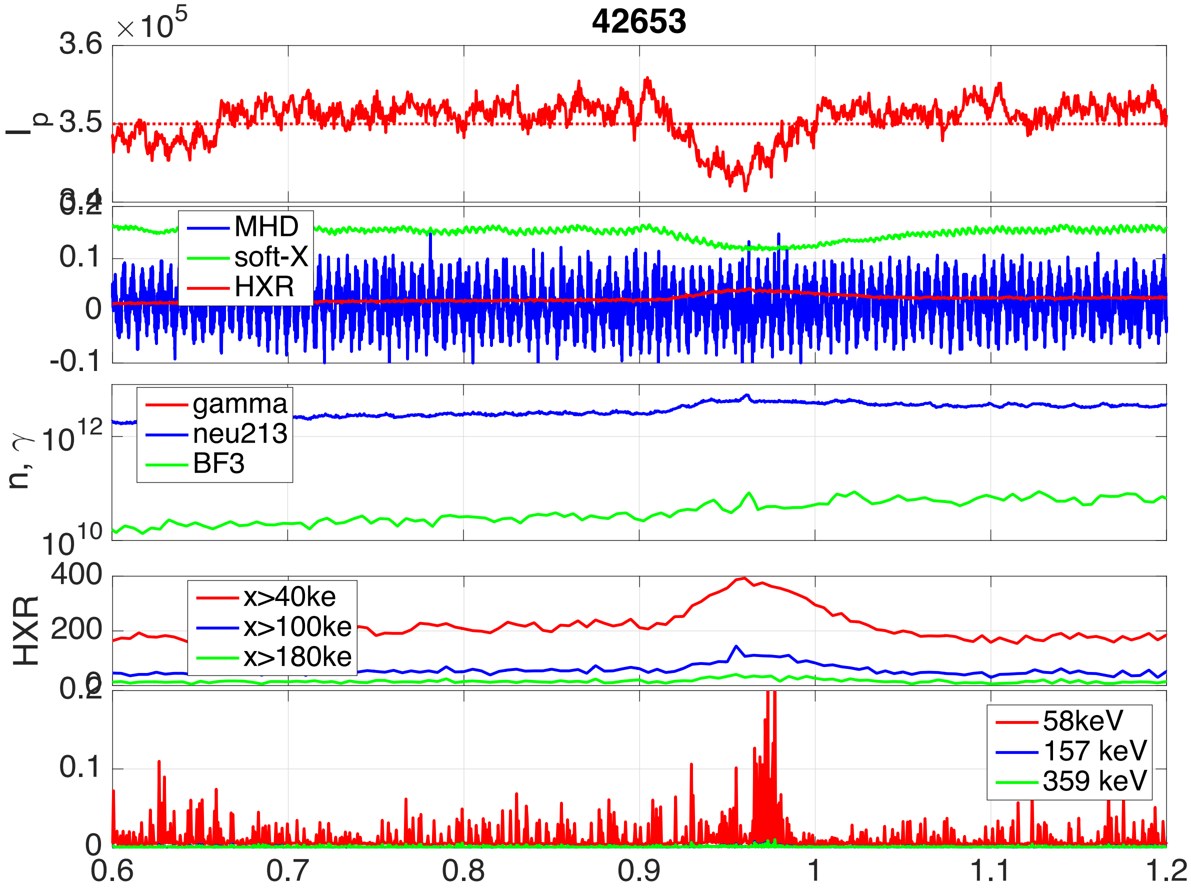
TCV: lost/conversion of **all** REs

RE dynamics are affected by **hysteresis**: oscillations of V_{loop} might enhance the RE conversion (overcrossing the hysteresis threshold) into thermal electrons.

A new possible **strategy to limit magnetic to kinetic RE energy conversion at final loss.**

LBO: W on low level of quiescent REs

A small effect of LBO injection of W at 0.9 s has been observed on the shot #42653. Probably, given the low level of REs, the temperature was high enough to ionize the W and its effect is slightly visible.



RE losses: Fan instability

EUROfusion

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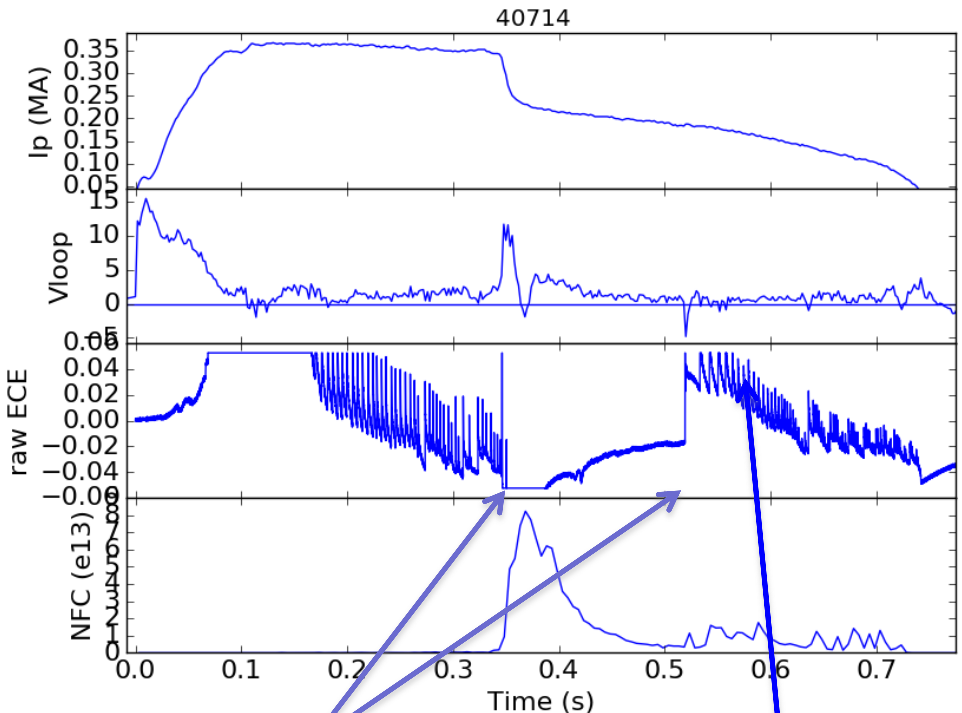
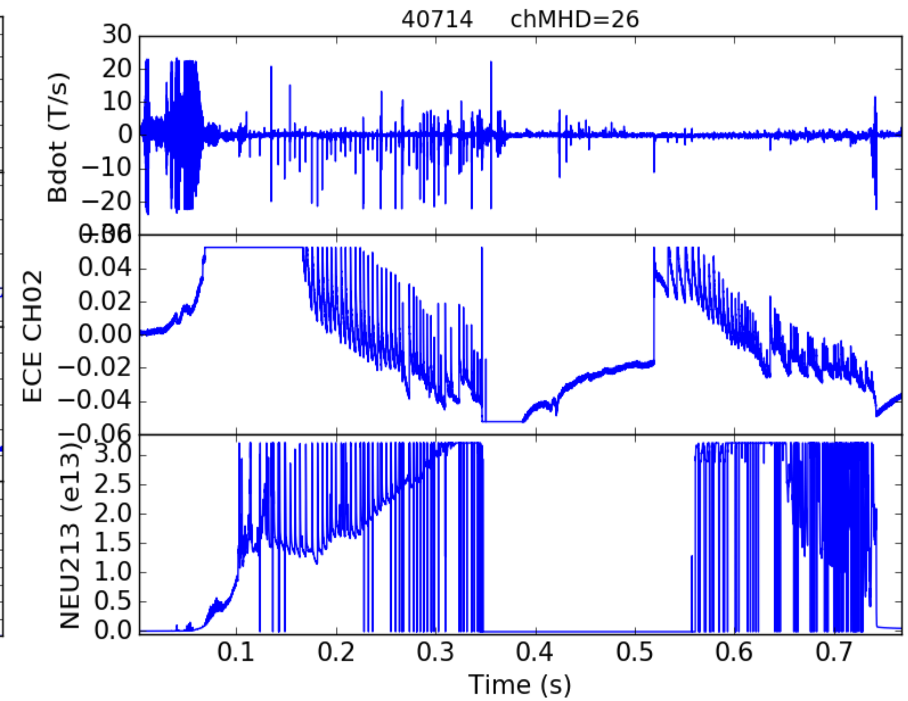
Study of correlations with Electron Cyclotron Emission and HXR from NE213 scintillator.





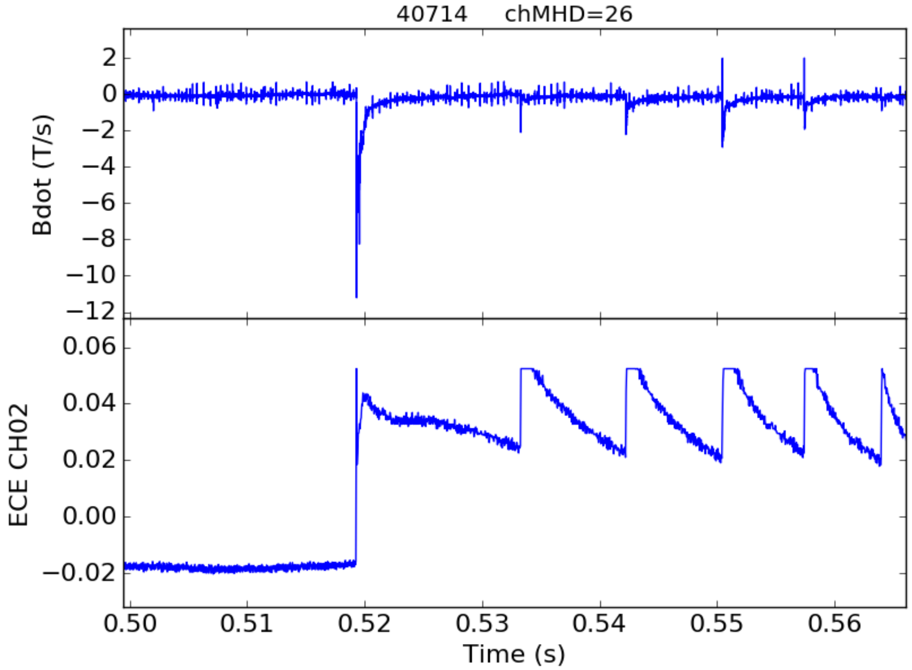
Latency after disruption (large photo-neutron signal)

ECE spikes

ECE spikes are correlated with MHD and NE213

RE losses: Fan instability

- ECE: not the usual thermal emission, it is the **low-frequency tail of synchrotron emission by RE**.
- **ECE increase at microsecond time scale** can only be due to **anomalous pitch angle scattering**.
- Anomalous pitch angle scattering due to the "*fan instability*" is well known (Vlasenkov 1973, Parail 1976, Coppi 1976).
- **NOT MHD but kinetic instability**, driven by momentum space anisotropy of RE.
- HXR increase due to larger diffusion at larger pitch angle
- MHD spike due to increase of perpendicular beta.



Importance:

- **Anomalous pitch angle scattering** can play an important role in RE beam dynamics. In fact, with an increase of the pitch angle **synchrotron losses increase** and the **maximum RE energy decreases.**