RUNAWAY ELECTRON BEAM CONTROL

6th Annual Theory and Simulation of Disruptions Workshop, 16-18 July 2018

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Outline

- Introduction
- The Runaway Electron Beam control architecture (FTU and TCV)
- Pellets and Laser Blow Off experiments
- Final Loss: new findings
- JET: a strategy to improve the control architecture in view of SPI experiments
- Conclusions

Motivation

Confine the RE beam for modeling and MGI/SPI dissipation experiments and provide an alternative/parallel mitigation technique (thermo-mechanical loads, penetration, diffusion).
(J. Mlynar et al. - I1.002 - Runaway electron experiments at COMPASS in support of the EUROfusion ITERphysics research)

General strategy:

- Detect the Current Quench (CQ) and plateau onset
- RE beam position confinement using PF coils while the current ramp-down is performed via central solenoid/impurity injection.

Main control issues (RE beam controllability):

- Position confinement during the CQ (solution proposed by DIII-D)
- High current decay rate and/or MHD instabilities
- Saturation of the PF coils during the controlled ramp-down
- Final loss

Standard position controllers (roughly) stabilize RE beam: robustification and performances improvements (safety).

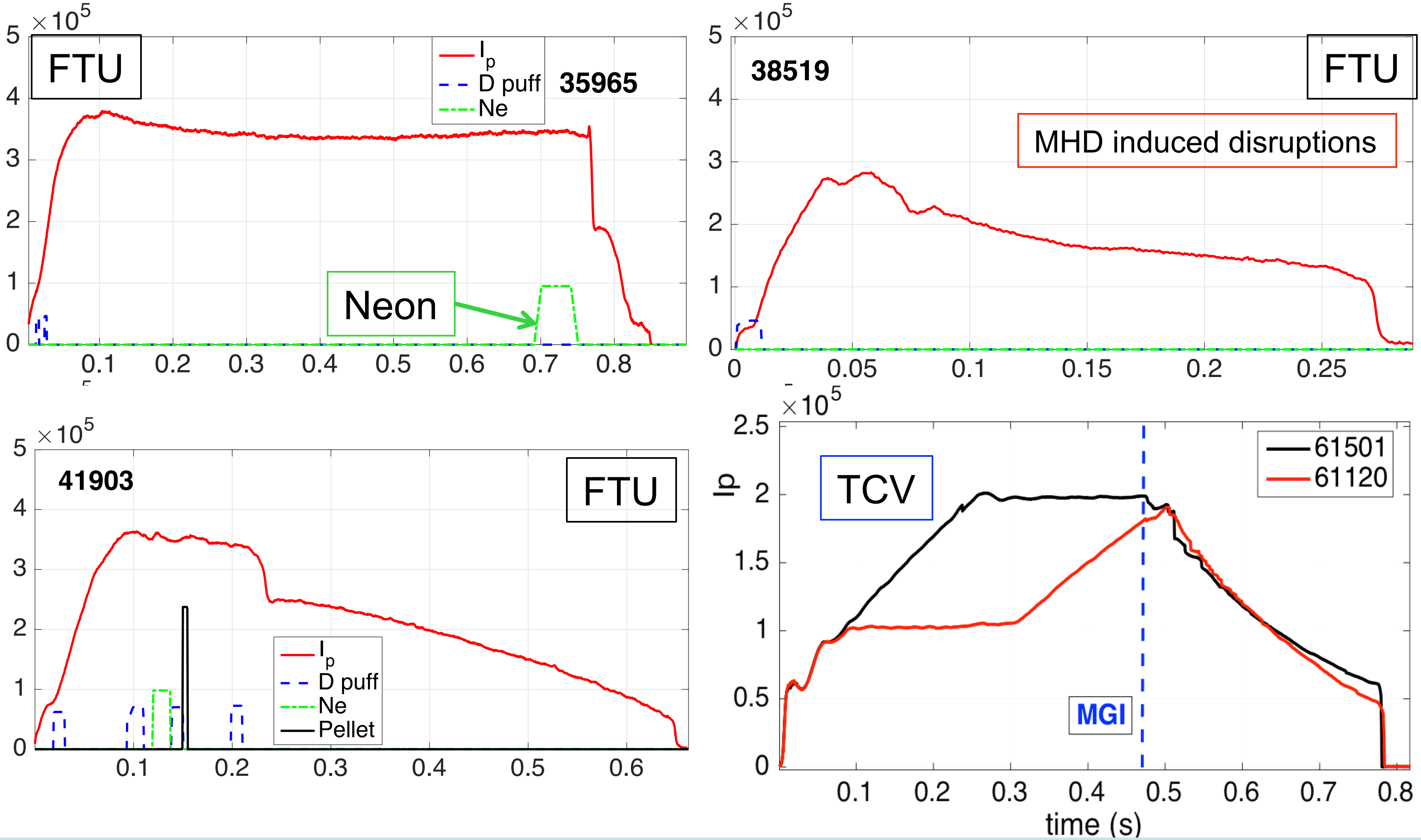
ITER: DINA simulations have shown that RE beams could be confined when the CQ is below 4 MA (coil current amplifiers limitations)
V. Lukash et al., Study of ITER plasma position control during disruptions with formation of runaway electrons ", 40th EPS, 2013

Scenarios used for RE beam control tests (FTU-TCV)

Post disruption RE beam obtained with different recipes:

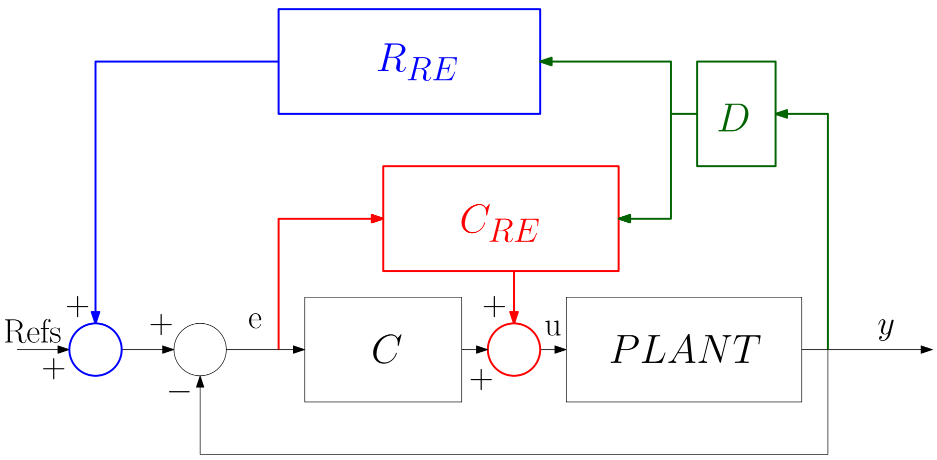
FTU (no MGI): Ne puff, natural disruptions (extremely low density), D pellets w/o Ne [circular]

TCV: single/double ramp with Ar or Ne MGI [circular/elongated]



REB-C: general scheme

- Designed to be added to the standard control system (black)
- RE plateau detector that triggers the current ramp-down
- RE beam position controller
- RE reference generator (I_p, R, Z)



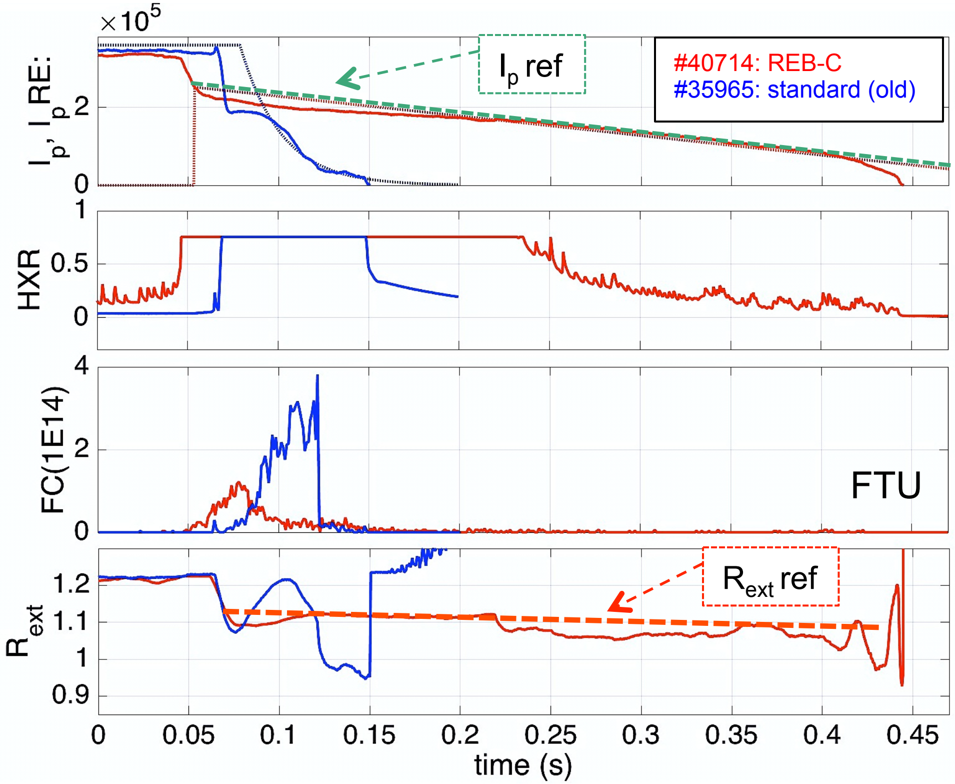
OBJECTIVE	HOW	HARDWARE/SIGNALS
Current Plateau detection	Digital Filters	I_p and/or HXR
Current control	I_p reference	Ohmic coils (central solenoid)
Position control	(R,Z) references and control input added to the standard ones	- current/voltage **request** to PF coils amplifiers - **magnetic measurements** to estimate RE beam position

Runaway Electron Beam Controller (REB-C)

A control architecture (control scheme, algorithms, code) for:

- **RE beam current ramp-down** with desired slope using the central solenoid (or in combination to SPI/MGI mitigation techniques);
- Magnetically **confinement of the RE beam** via PF coils to minimize its interaction with the vessel.

Designed as a tool for RE beam **active mitigation** and to improve RE **confinement** necessary for **modeling and mitigation (SPI/MGI) studies**.



Current ramp-down induced by central solenoid (no MGI)

RE beam confined: HXR and FC decrease down to zero
Final loss: no more high energy REs

FC: U^{235} fission chamber signal: photo fissions induced RE impact on the vessel with energy greater than 6MeV

The magnetic measurements normally used for position feedback of the plasma column can be used for RE beams (approximation).

REEB-C: Current ramp-down (1/2)

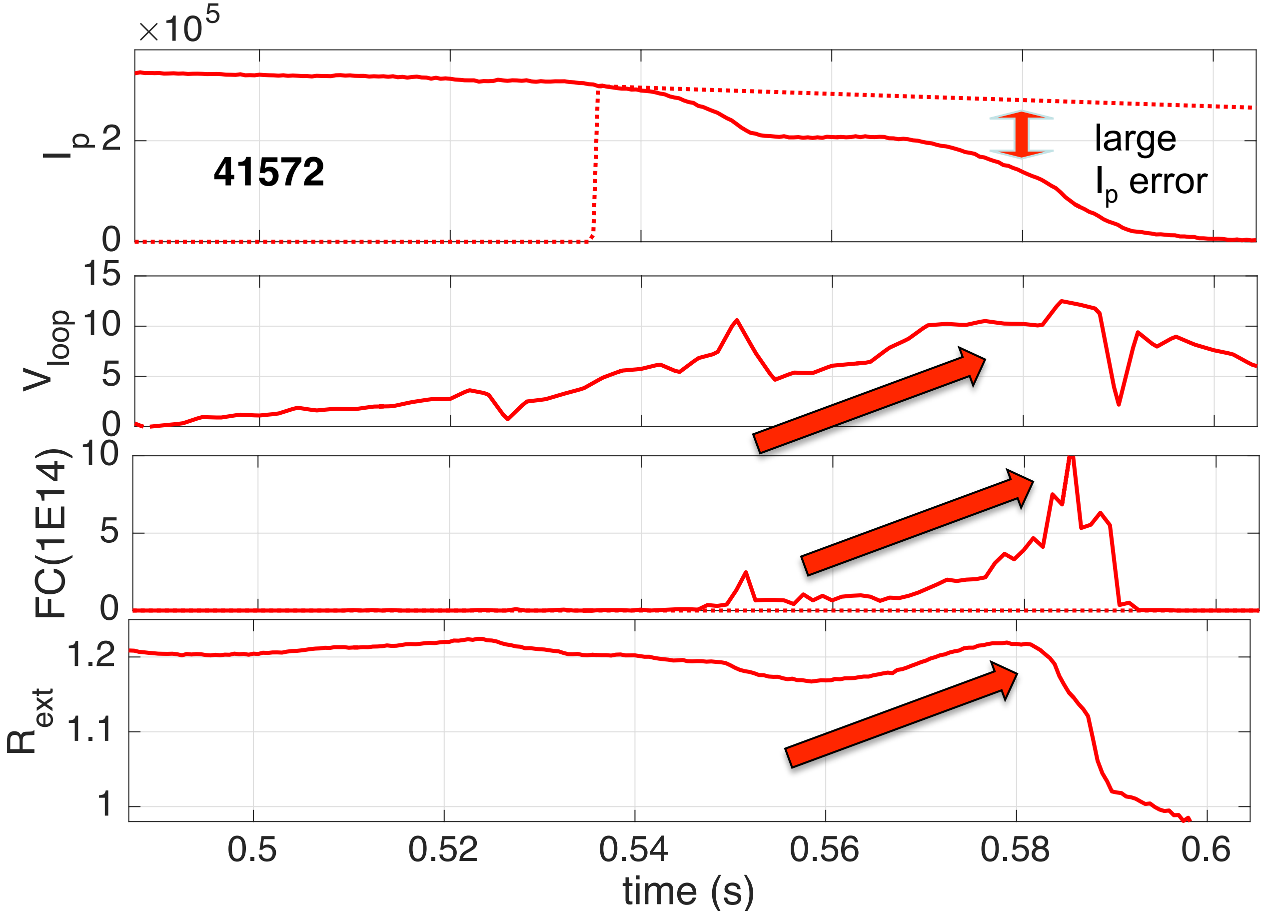
The RE beam **current ramp-down** is obtained indirectly **redesigning the I_p reference** and relying on the standard I_p controller (OH coils):

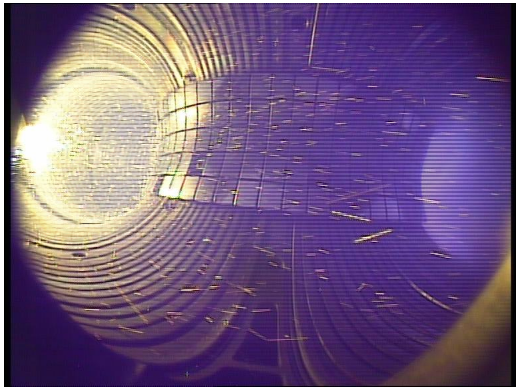
- Triggered at plateau onset, HXR threshold, fixed time
- A new I_p reference patches the standard one: start with a **constant** reference (10-30 ms) in order to provide flux (loop voltage) **reducing the radial inward displacement**.
- I_p reference converges to a straight line passing for $\mathbf{I_0}$ (current at plateau) with the desired **slope.**
- V_{loop} threshold: I_p reference modified on-line in order to **limit the maximum electrical field** during the ramp-down which is linked **to RE beam radial shift and large MHD instabilities**.
- **Electrical field oscillations during current ramp-down**: enhance RE losses via small MHD events and study RE dynamics.

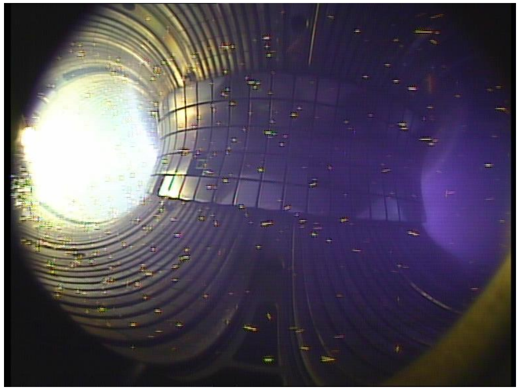
REB-C: Current ramp-down – Effects of large V_{loop}

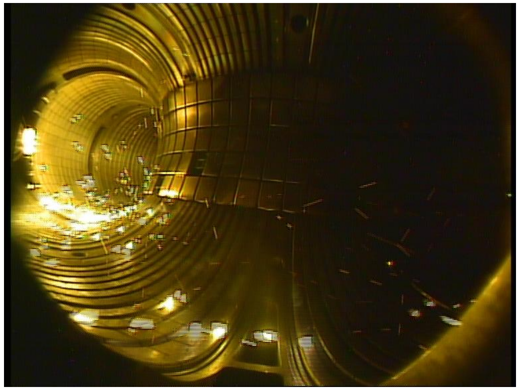
HIGH V_{loop} → RE large radial outward shift

FTU: Experiment with **fixed** ramp-down reference.









REB-C: Hybrid Fast Controller

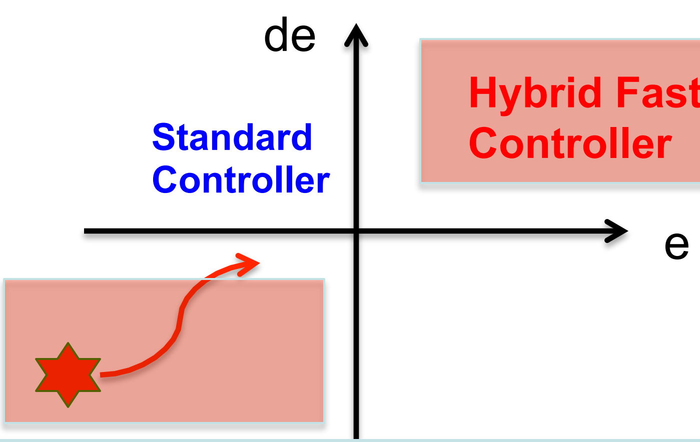
Aim: **recover fast displacements** using a **ramp-like control input**

Features:
- does not excite higher order modes like bang-bang controllers
- model free: high portability (ITER)
- adaptive gain $k_r(t)$ (ramp slope)

$$u_f(t) = -\text{sign}(e(t))k_r(t)(t-t_k), \text{ if } \{|e| > \sigma_1 \wedge |\dot{e}| > \sigma_2\} \wedge \{e\dot{e} > 0 \wedge \text{sign}(e)\ddot{e} > \sigma_3\}$$

$$\dot{u}_f = -k_d u_f, \text{ otherwise (hysteresis)}$$

Adaptive gain $k_r(t)$: the gain is increased if a number of oscillations with equal sign is detected, decreased if oscillations have alternative signs (within a time window).



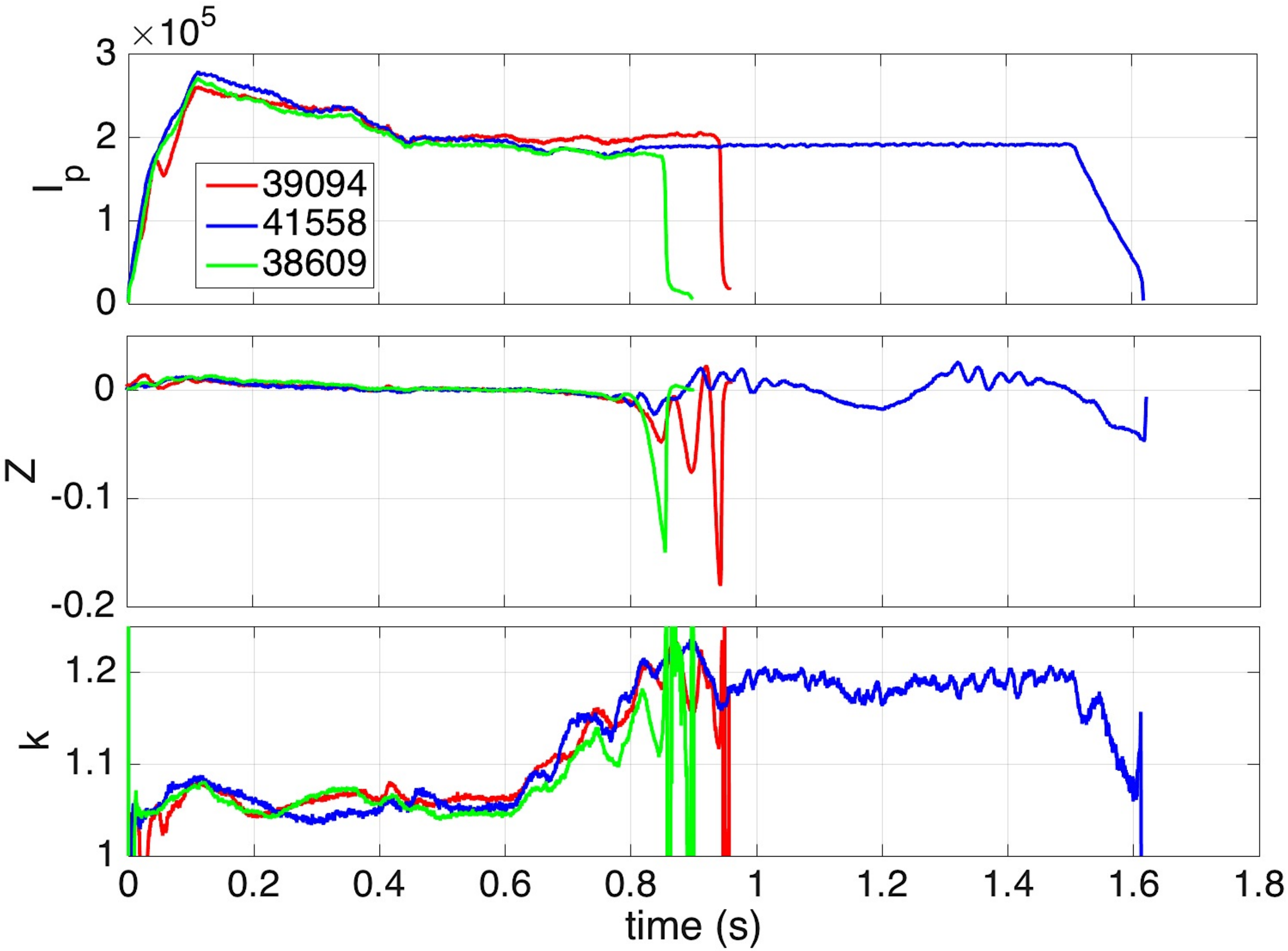
Closed loop stability relies on time scale separation principle

Easy tuning (robustness)
On FTU: 3 shots for tuning.
On TCV: 1 shot

Implementable on ITER

REB-C: Hybrid Fast Controller – FTU elongation

Fast controller: *initially* developed to cope with actuation delays of the FTU vertical control system leading to VDE on "elongated" FTU discharges.

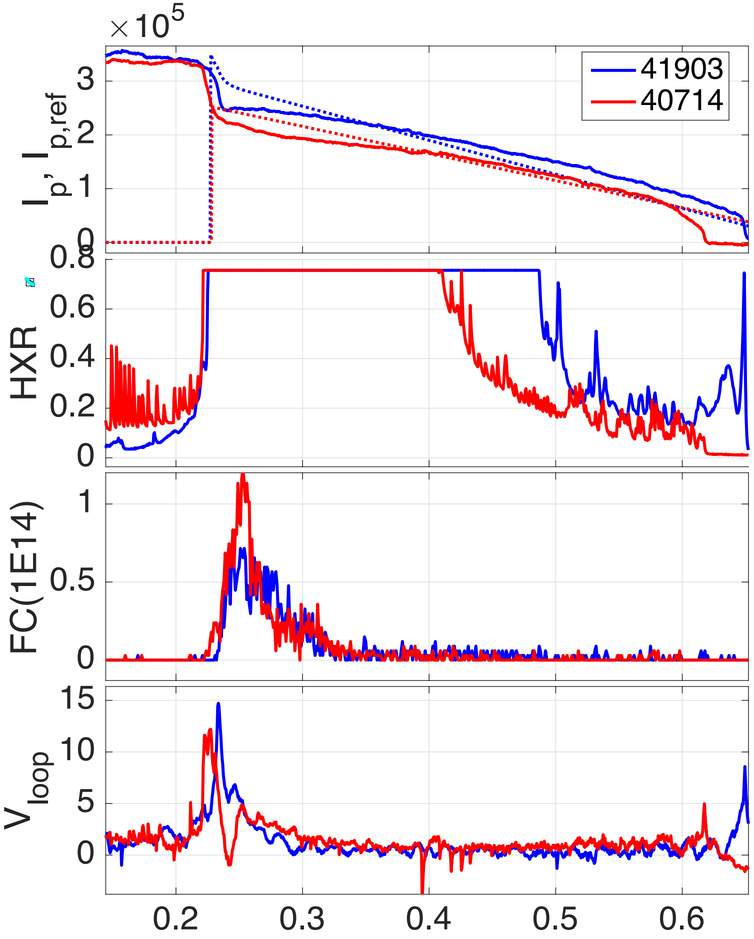


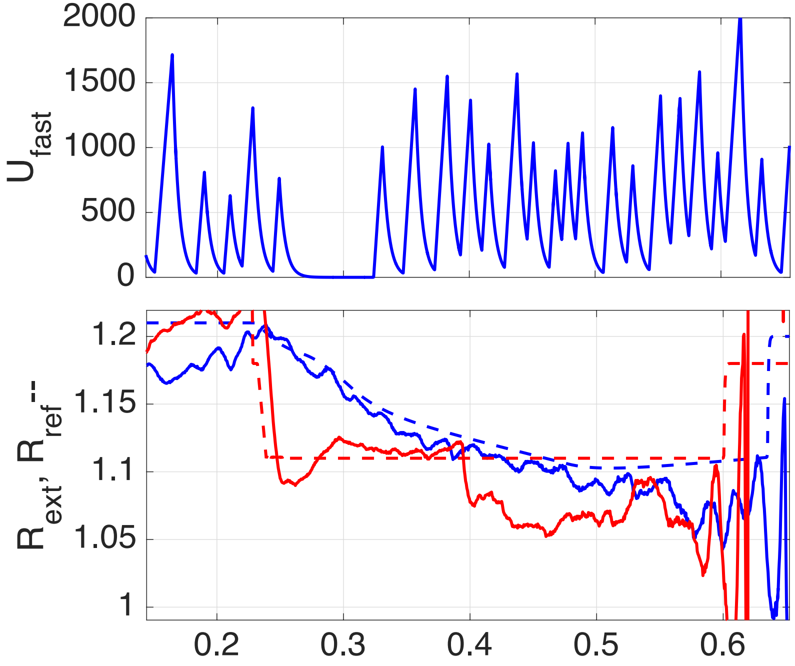
FAST CONTROLLER ACTIVE ON #41558

Control tools for plasma and RE confinement!

REB-C at FTU: Current ramp-down improvements

- Fast ramp control active in: #41903
- New external radial reference depending on I_p (to maintain inner limiter configuration)
- V_{loop} active threshold: I_p reference is dynamically changed to limit V_{loop}.

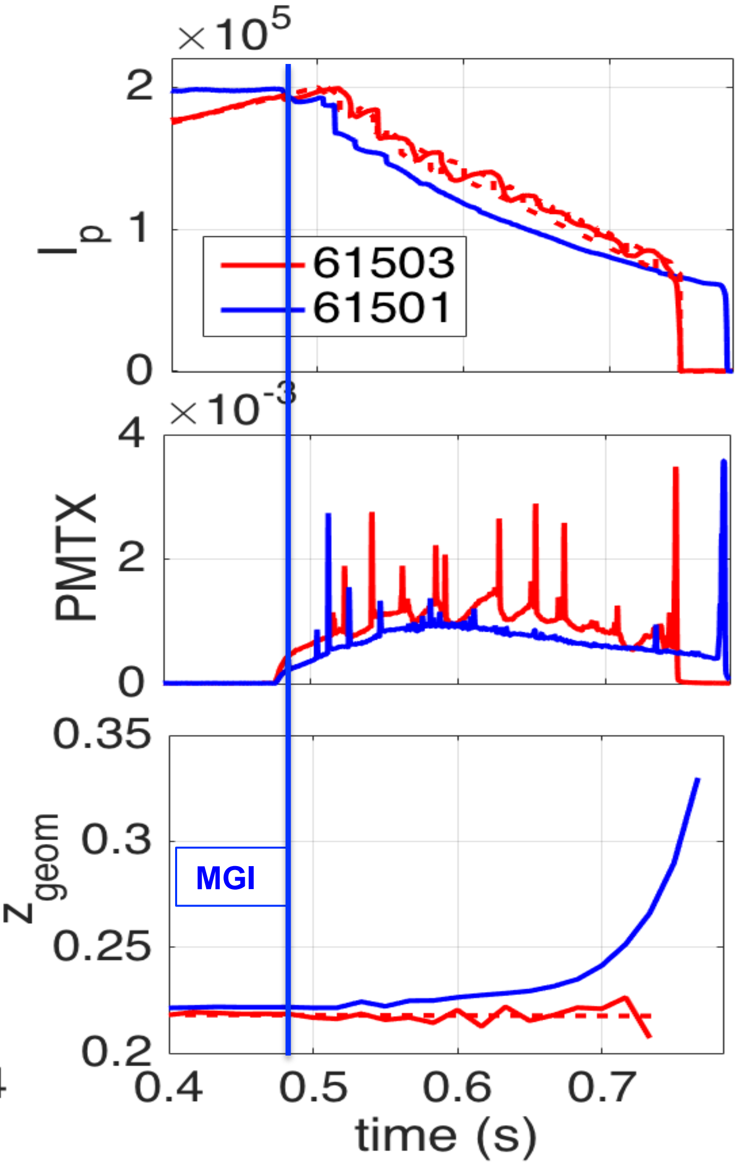




Fast control: the ramp slope adaptively increases or decreases based on the tracking error

Tracking error improved with the hybrid fast control

REB-C at TCV: improved stability

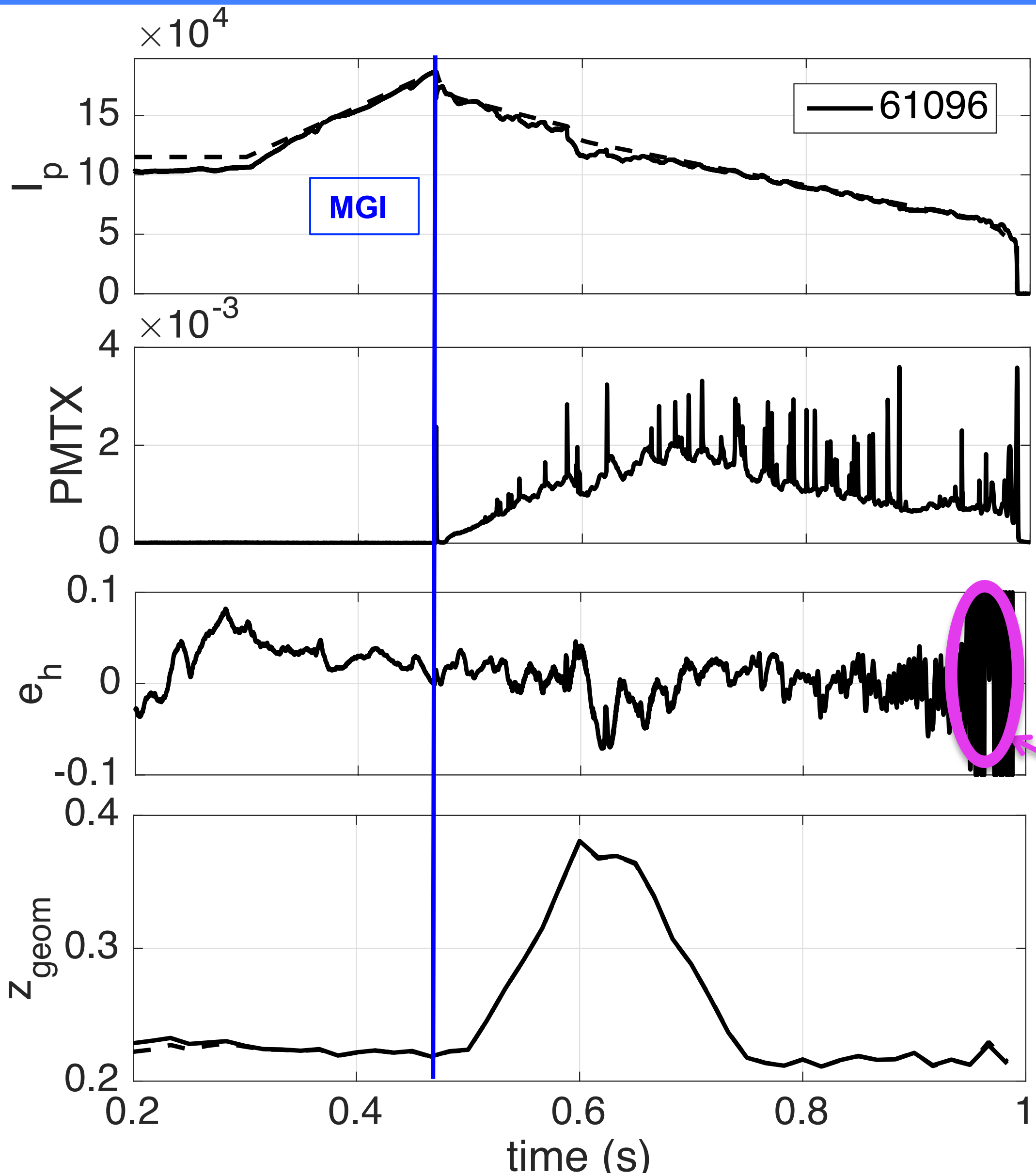


#61501: standard controller
#61503: REB-C

Current oscillations: hard time for the controller... not a fair comparison

VDE with the standard controller (not every time....)

REB-C at TCV: Current ramp-down with vertical sweeping



Ramp down triggered by CQ (usually forced at TCV)

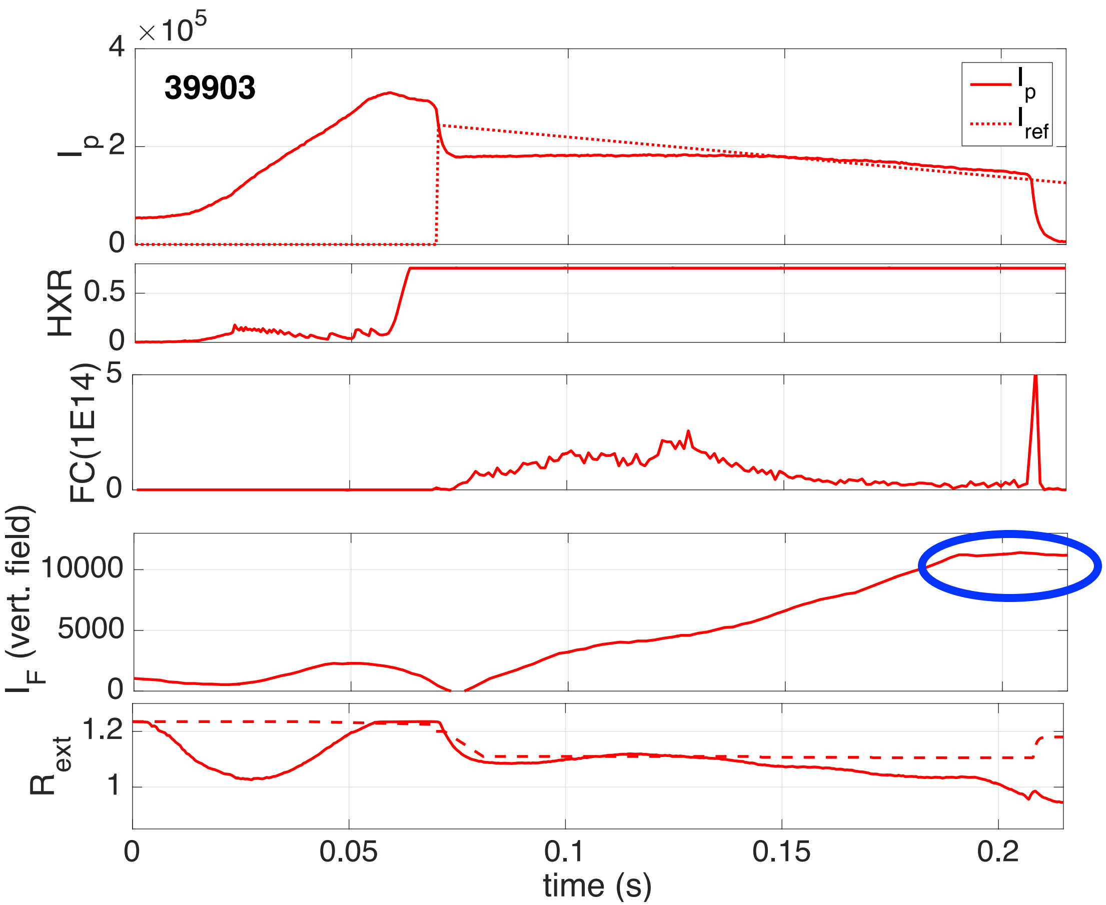
Good vertical(radial) confinement

Final loss due to amplifiers delay at current inversion (zero crossing voltage switch)

Vertical sweep of about 11 cm

REB-C at FTU: **Current Allocation** during ramp-down

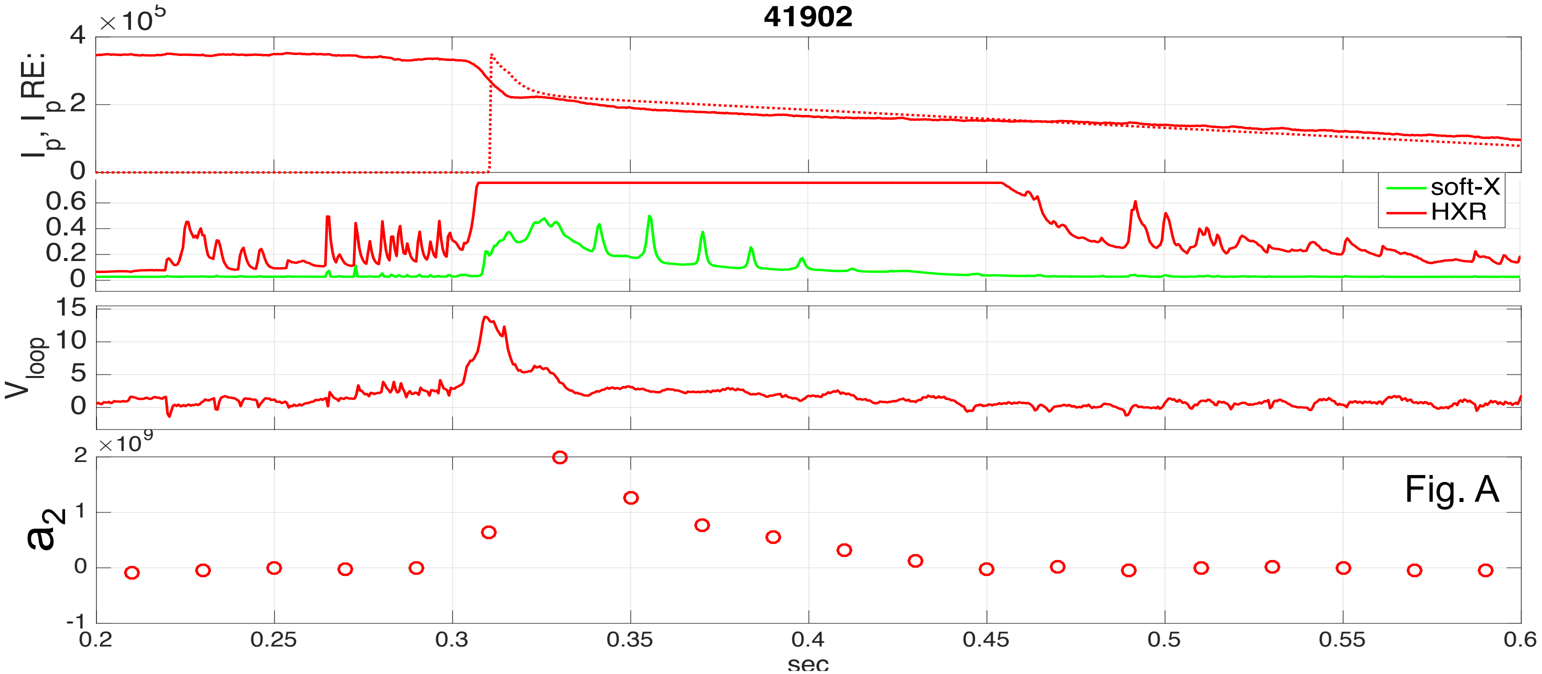
Current allocator: the currents of the PF coils are reallocated in real-time to minimize a cost function weighting currents saturation proximity and beam displacement.



FC decreases due to RE beam confinement, when the beams hit the vessel there are large spikes on FC.

I_F reaches the saturation level: RE beam radial loss

REIS: RE energy reduction



Runaway **E**lectron **I**maging and **S**pectroscopy **S**ystem

REIS spectra (blue curves in Fig. B) fitted with a second order polynomial $a_2x^2+a_1x+a_0$ (red curves) at different times: time evolution of the coefficient a_2 is shown in Fig. A.

The peak of the energy distribution shifts toward high energies from 0.3s up to 0.33 s (TQ and CQ) and then smoothly decreases: **the energy of the REs after the CQ decreases.**

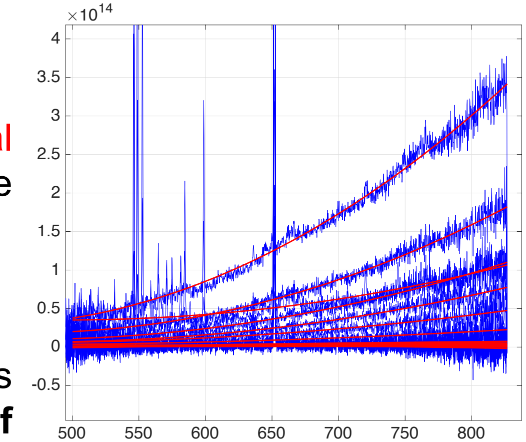
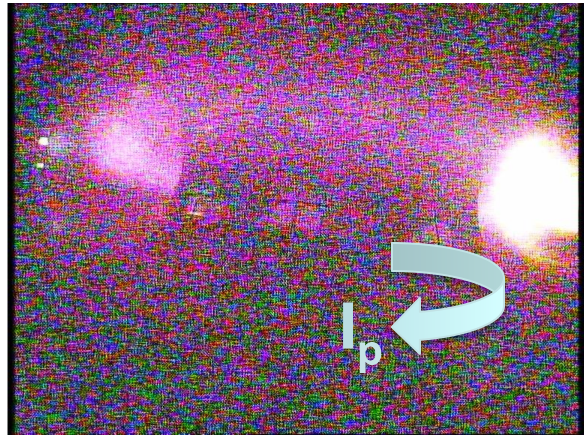
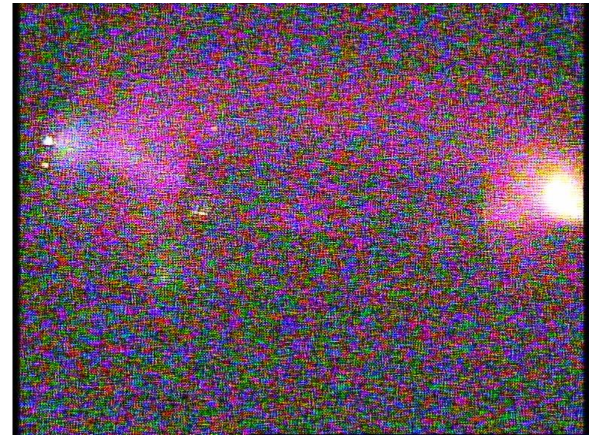


Fig. B : visible spectra of synchrotron emission

REB-C: Controlled ramp-down

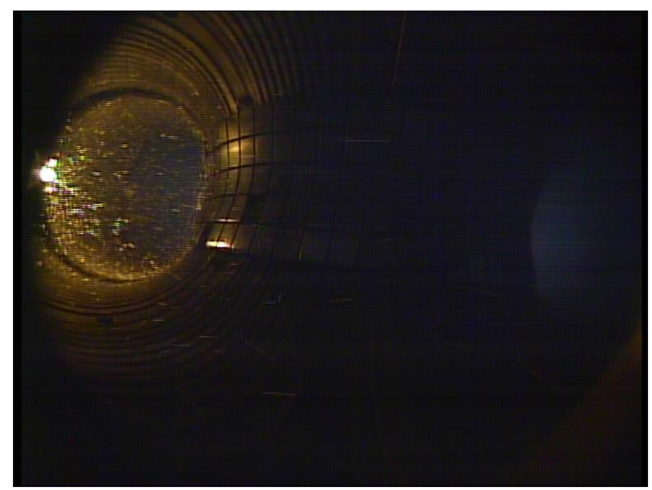




current plateau onset (onset of the current ramp-down)

Current ramp-down (synchrotron radiation)

Reduction of the RE beam current (energy)



Final loss: RE beam pushed on the outer limiter when the current is below 60kA (loss of controllability).

ITER: foreseen possible final loss events with 2MA

Deuterium Pellets injections and Laser Blow Off

Pellet Injector

D_2 pellets: 2xSmall ($1x10^{20} \approx 1200$ m/s) and 2xLarge ($2x10^{20} \approx 1000$ m/s), equatorial.
Diagnostics: H_{alpha}, CO_2 scanning interferometer (65 μs), Mirnov coils (MHD).

A single small pellet on flat-top discharge with RE: n_e increases and RE increase (50%) or RE sudden loss (50%)

Large/small pellets on RE beam (no MGI):
n_e drops (low temperature). No visible effects on dissipation rate (no MGI). Only in one case (of about 20) n_e largely increases.

Laser Blow Off injector

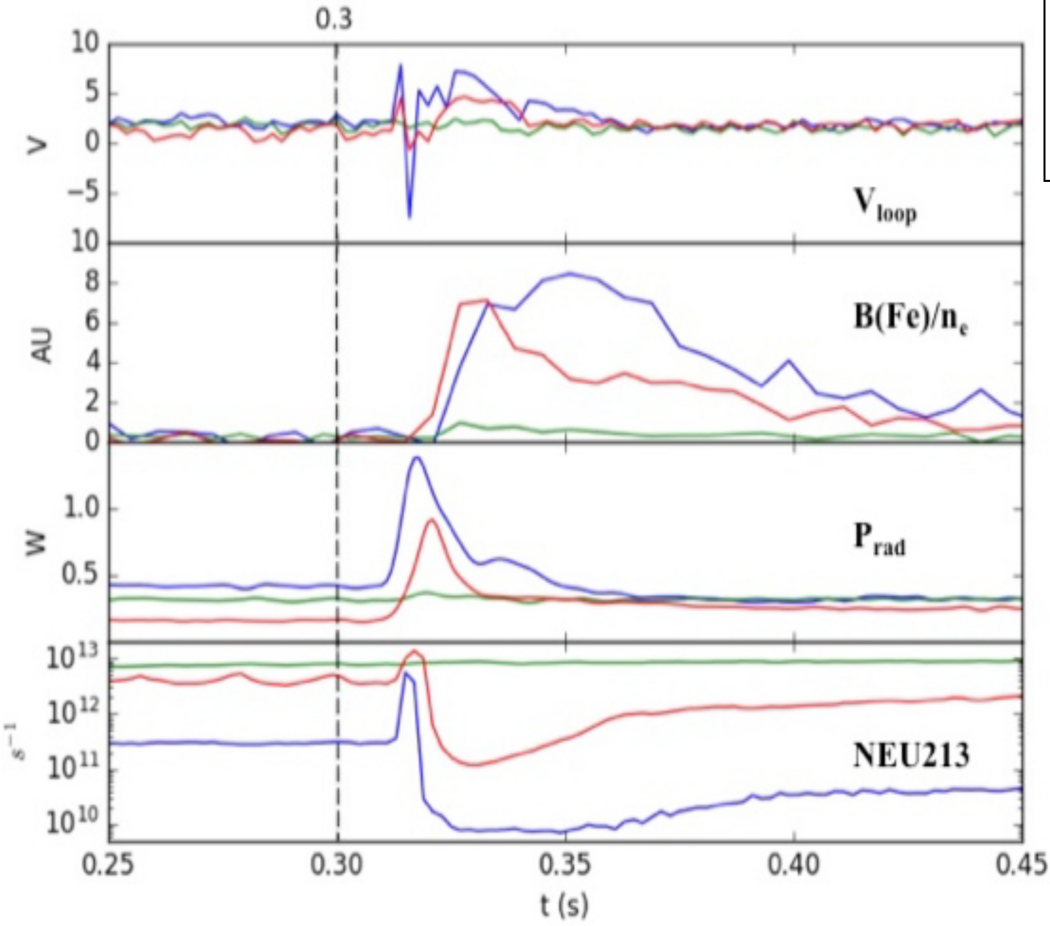
Impurities: Molybdenum, Tungsten, Iron (3E18 atoms), Zirconium

Flat-top discharge with RE: Depending on the material ionization (plasma temperature) RE losses are induced by small instabilities.

LBO on RE beam: ionization do not take place, consequently there are not effects.
LBO injections have also performed right after D_2 pellets injection to clear off cold background plasma and allow RE beam penetration.

Accompanying poster: A. Romano et. al. "Effects of pellets and impurity injection on runaway control experiments on FTU", P5.1053

Laser Blow Off: flat-top I_p with RE expulsion



LBO on flat-top discharge with RE: depending on the material ionization (plasma temperature) RE losses are induced by small instabilities.

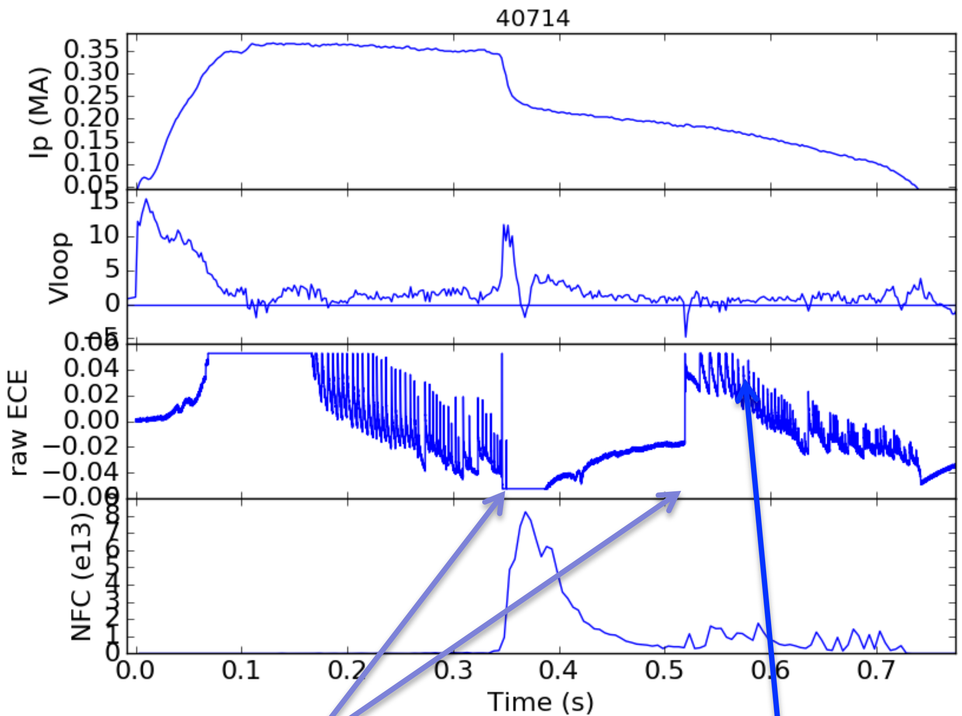
X-VUV spectrometer Schwob: time evolution of Fe XXIII (135.80 Å) line brightness normalized to the electron density.

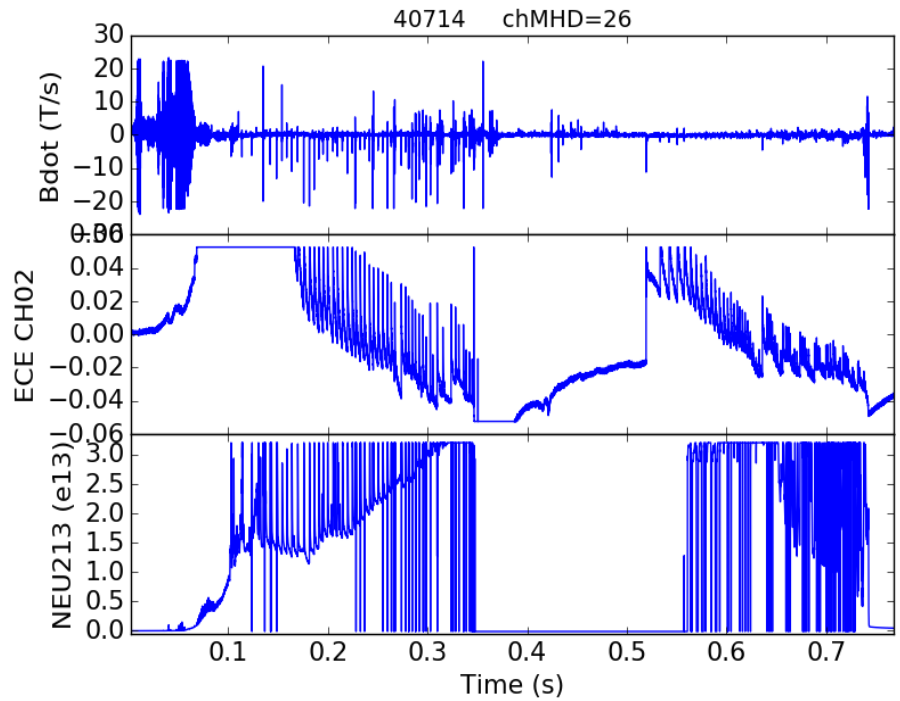
gamma+neutrons

LBO on RE beam: ionization do not take place, consequently there are not effects.

RE losses: Fan instability

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





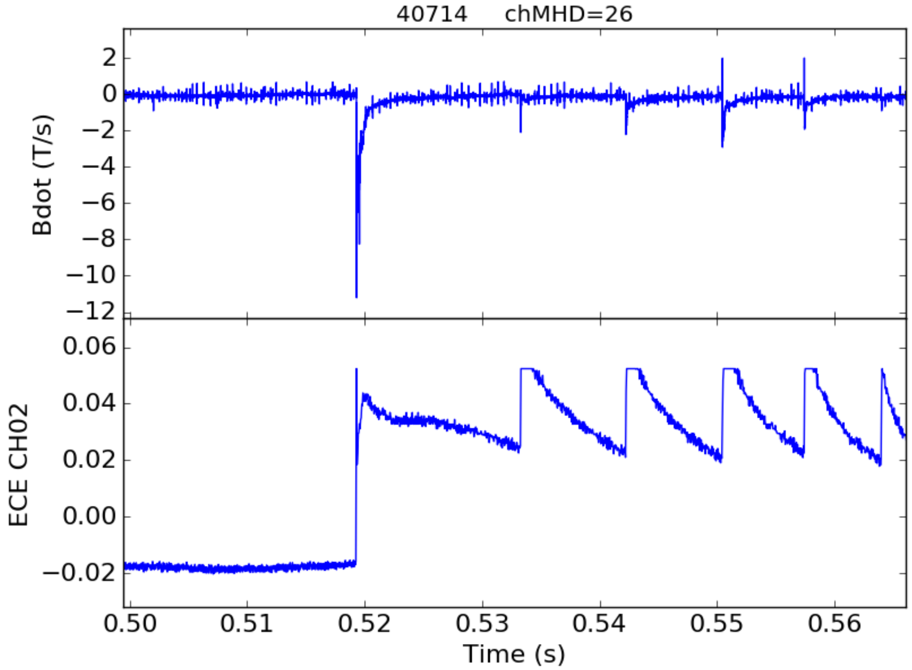
Latency after disruption (large photo-neutron signal)

ECE spikes

ECE spikes are correlated with MHD and NE213

RE losses: Fan instability

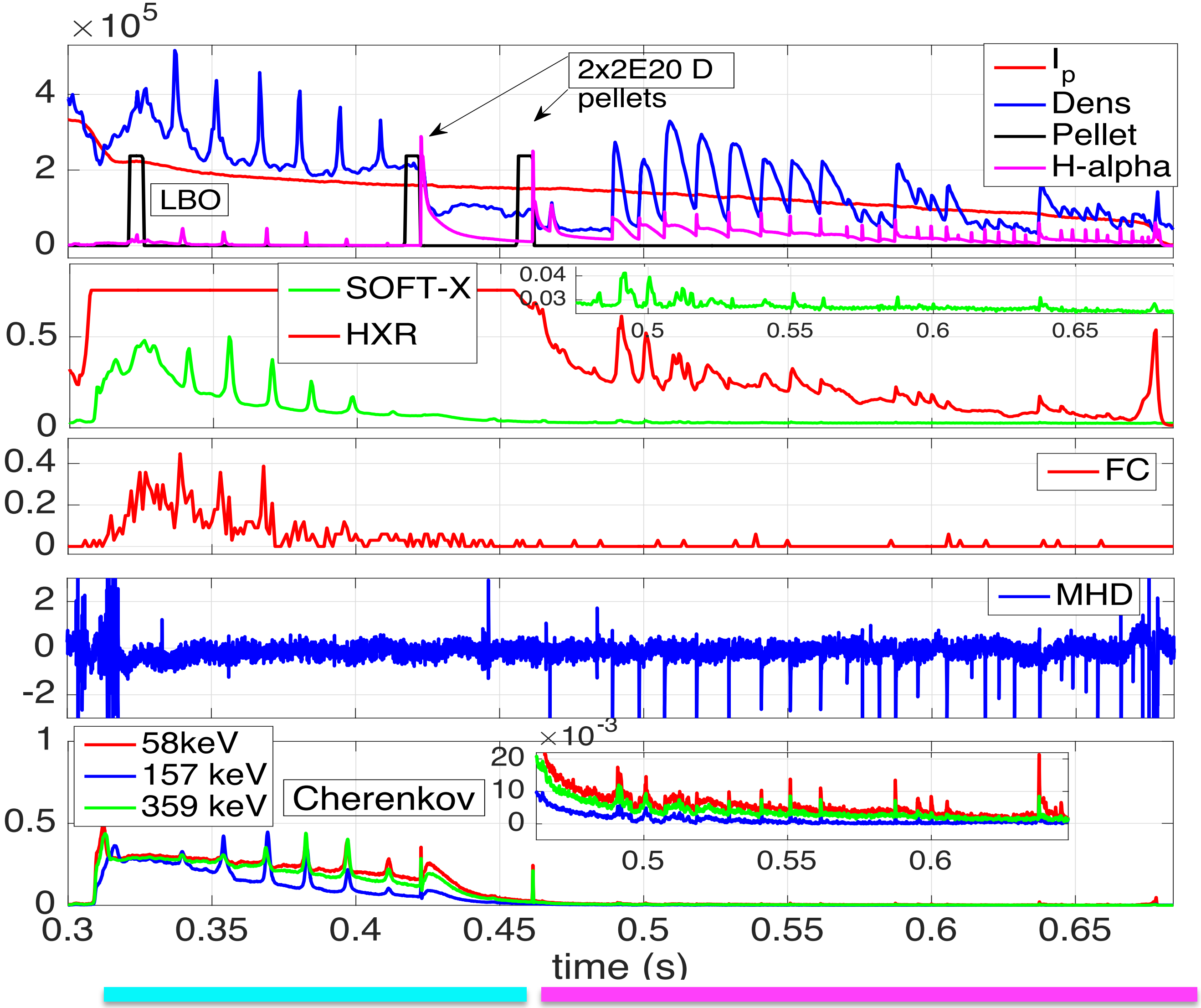
- ECE: not the usual thermal emission, it is the **low-frequency tail of synchrotron emission by RE**.
- **ECE increase at microsecond time scale** can only be due to **anomalous pitch angle scattering**.
- Anomalous pitch angle scattering due to the "*fan instability*" is well known (Vlasenkov 1973, 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.**

RE beam: a new instability?



Instability with high REs energies: no MHD signs, sharp n_e spikes with density peaked at the magnetic axis (quite peaked), spikes on FC, Cherenkov and soft-x. **[new type of instability?]**

Instability with low REs energies and after the injection of two D pellets (2x2E20): MHD signs, large n_e spikes (quite peaked), low spikes on FC, Cherenkov and soft-x as well as heterodyne peaked oscillations. [Fan instability]

41902

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** have shown sudden loss of all REs, **radial inner movement** (T increase, L_i decrease) and Ohmic plasma since then: **never seen before**.

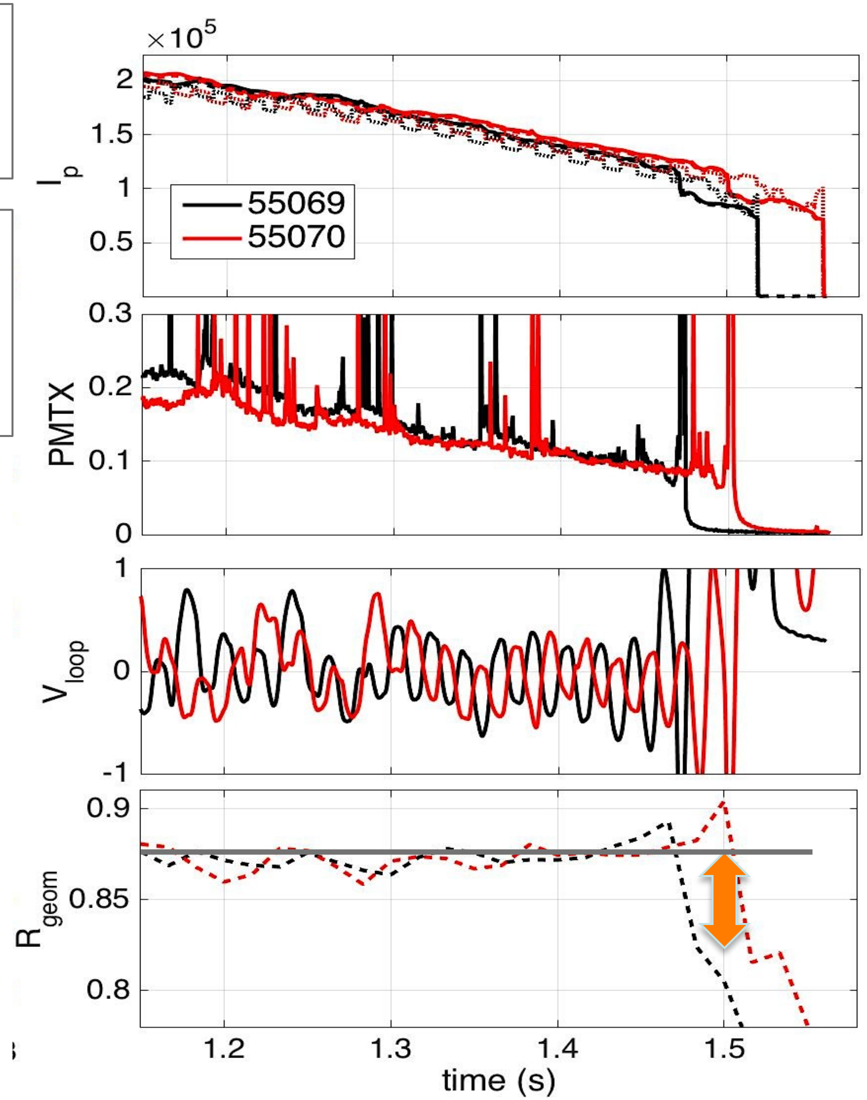
Radial shift approx.

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

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.**

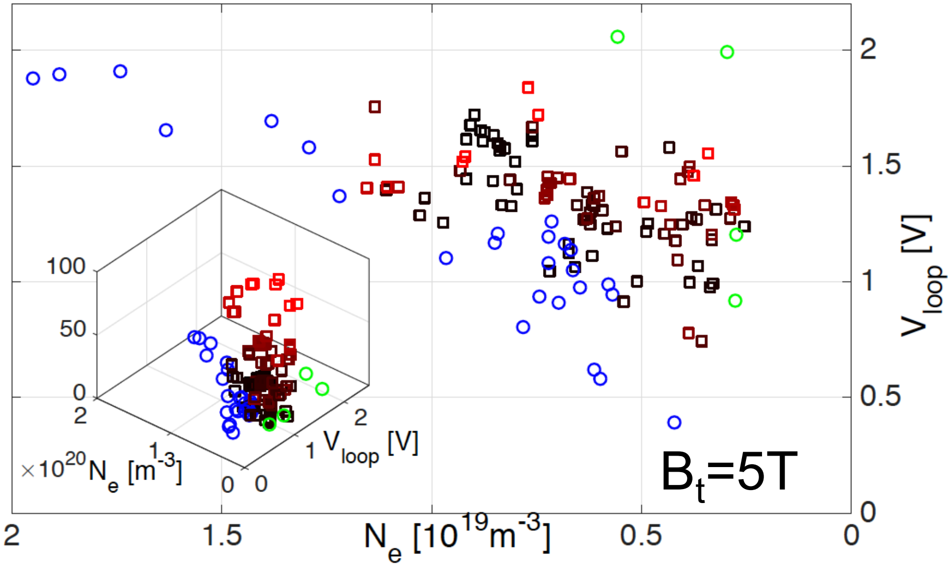
Final Loss at TCV: why did it happen ?

Why on discharges with V_{loop} oscillations having negative mean?

Hysteresis in RE generation/suppression dynamics might be the explanation

Flat-top current discharge with RE on FTU: **steady state** is assumed if all signals (I_p, V_{loop}, n_e , gamma, neutrons) and their derivatives are within bounded values for 120ms.

- Green circles: generation
- Blue circles: suppression
- Black to red: from low to high values of RE.

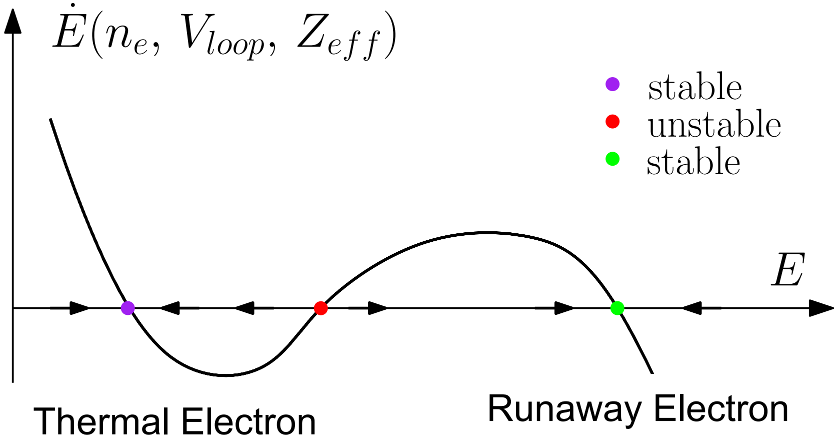


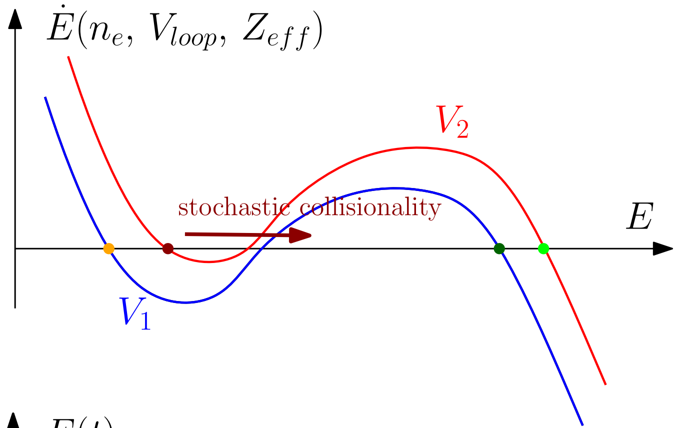
Different levels of REs coexist on same plasma parameters (V_{loop},n_e): created at previously (ramp-up) remain then steadily.

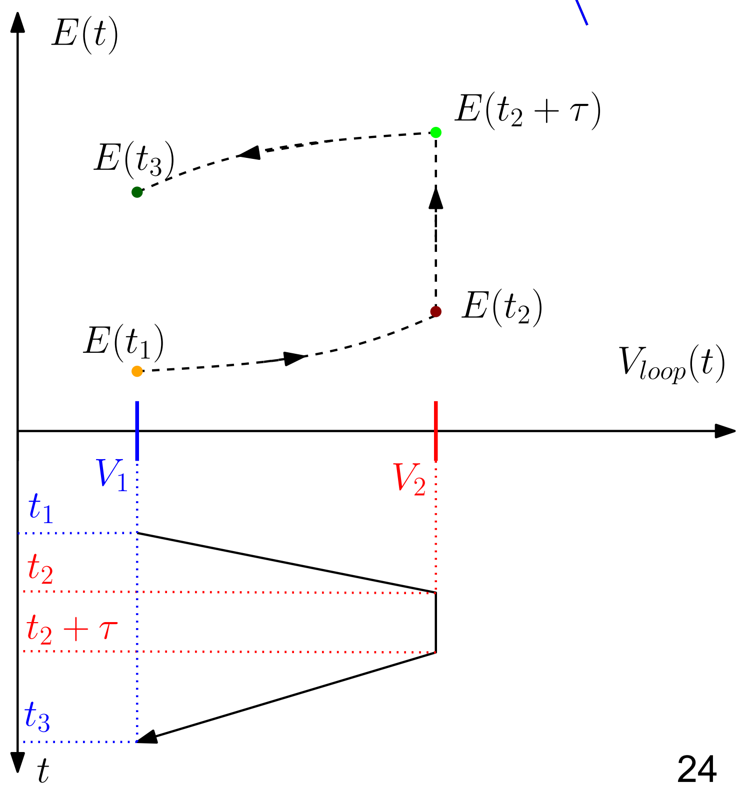
Final Loss: explanation and a possible strategy

The differential equation of the electron energy dynamic posses three equilibrium points:

$$\dot{W}_e = P_{gain} - P_{coll} - P_{sync} + P_{\text{th}} = e\frac{V_{\text{loop}}}{2\pi R} v\cos(\theta) - \frac{n_e e^4 ln(\Delta)}{4\pi\varepsilon_0^2 m_e v} - \frac{2}{3} r_e m_e c^3 \left(\frac{v}{c}\right)^4 \gamma^4 \left\langle \frac{1}{R^2(t)} \right\rangle + P_{\text{th}}(v)$$





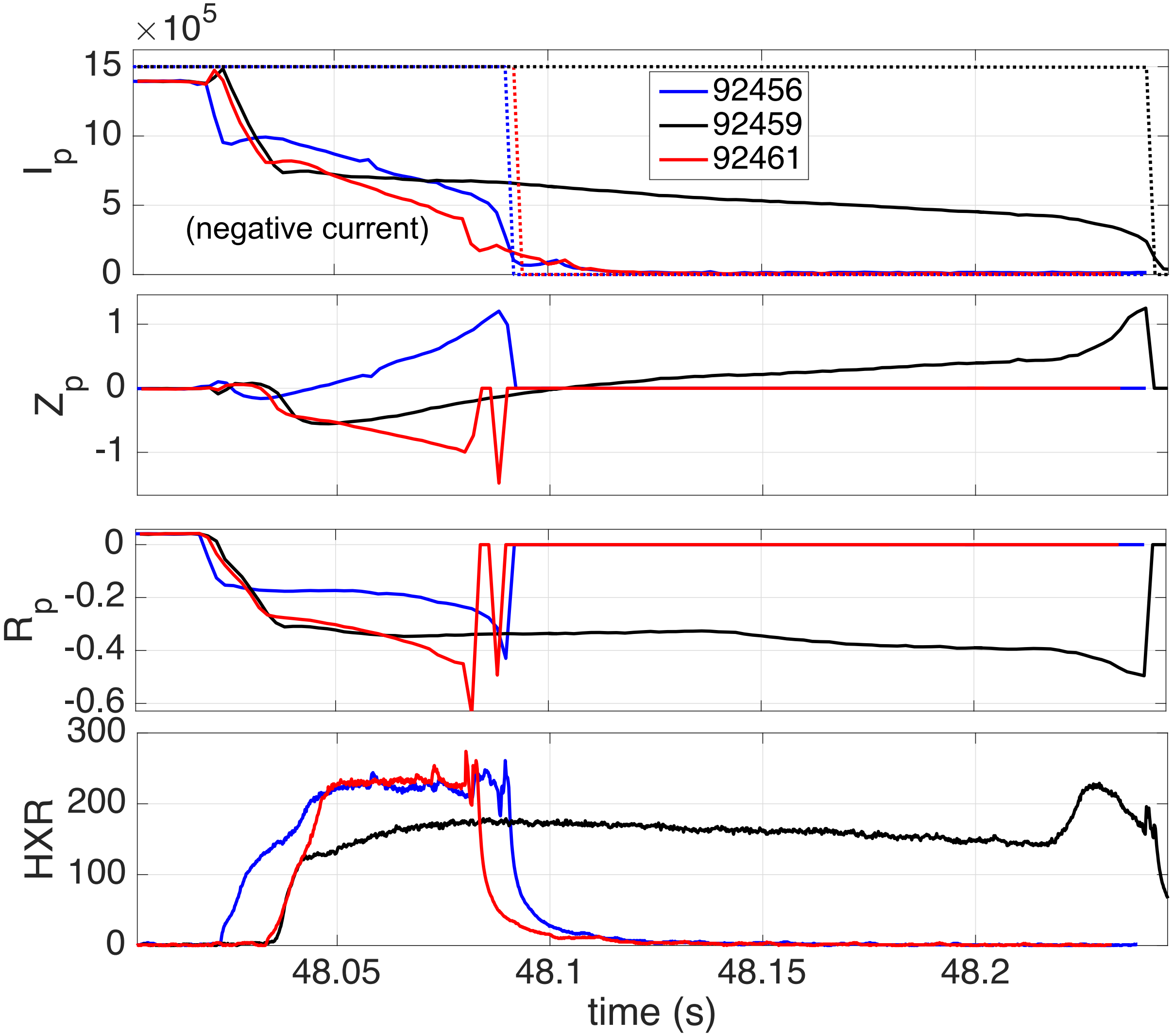


IF the hysteresis effect will be confirmed we might have a possible strategy to reduce the magnetic to kinetic RE conversion.
Impose a mean V_{loop} the current ramp-down (*safe controllability constraint*) then add oscillations in order to anticipate ohmic conversion when the RE energy is below a threshold (oscillation can induce phase transition).

NEW CONTROL TOOLS FOR **JET** EXPERIMENTS ON RE BEAMS (SPI)

JET: past experiments (1/2)

Past experiments 3: pre-quench plasma position (z,r) = (**0.01**,**0.4**)

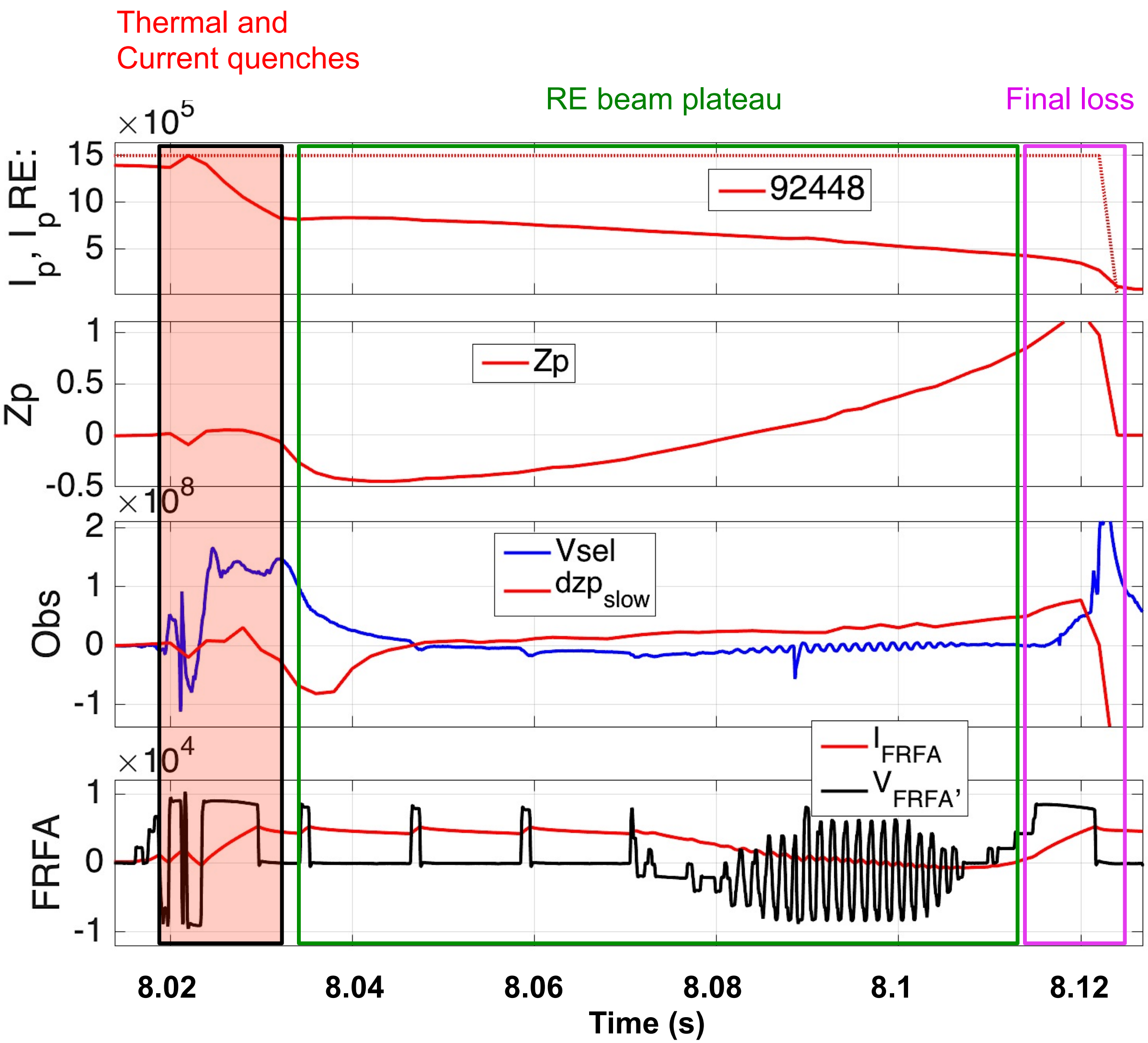


With optimized initial position a RE beam survived more than 200 ms

The central solenoid is sustaining the RE beam current (MGI)

When the current decreases the beam moves inward (high-field side) due to unbalanced high vertical field (produced by the active coils)

JET: past experiments (2/2)



Slow drift (radially and vertically): not a fast VDE

Vsel : **dI_p/dt affects the actual vertical velocity estimator.**

$dZ_{p,slow}$: derivative of the vertical plasma/beam center

Temperature issue: redesign the **ERFA** current reference for the slow control loop

JET: proposed strategy

Constraint: the real-time control code (core) can not be changed.

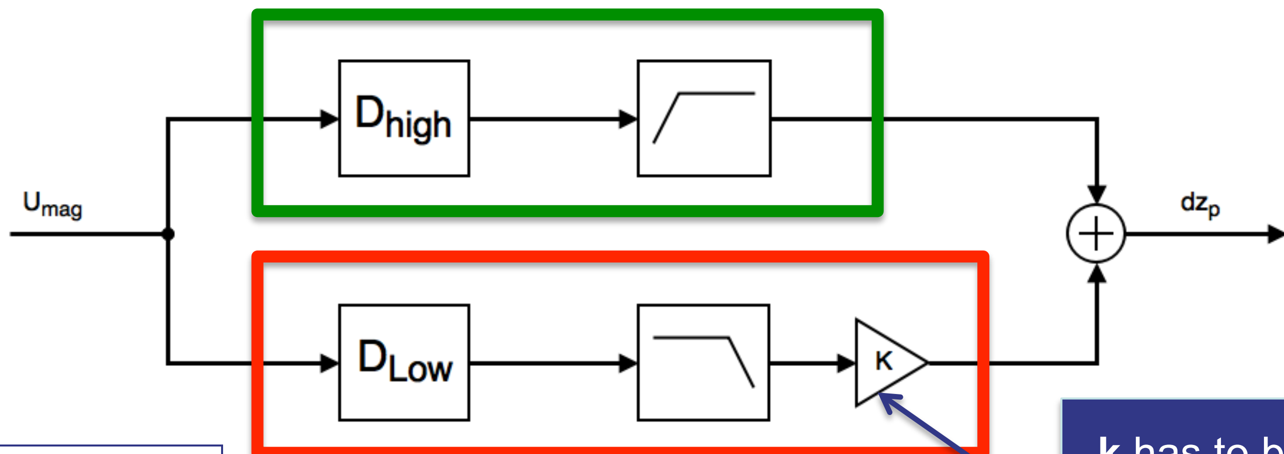
1. Current Quench and Plateau onset detector (I_p)
2. Current ramp-down (I_p patched reference)
3. Controller tools:
   a. Observer to weight the **slow drift** (acting on the VDE controller)
   b. **Shape Controller** (Z_p feedback / preprogrammed Imbalance current)
   c. Selection of (feedforward) *optimized* current profiles ($I_{ref,ERFA}$,Vertical/Radial field coils)

***Target**: improve RE beam confinement for SPI experiments*

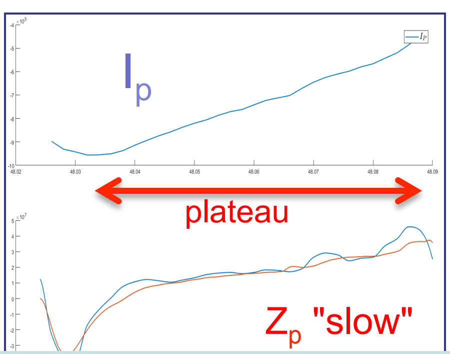
JET: RE beam plateau observer

The beam did not show "fast" VDE → The actual observer might help: its **high-frequency** behavior might be maintained

The beam slowly drift vertically (r) → The **low-frequency** response of the actual observer it is not sufficient to force reacting the control system



k has to be tuned in order to force a control action and limit the vertical drift (VS simulation)



Optimization of the observer parameters and initial condition

JET: PF current profiles optimization

Optimization of the feed-forward current profiles based on past data (and shot by shot): **how**?
Dynamic reliable models (control oriented) are not available.
Next experiments: work space only partially covered by past data.

New graph control theory
(RRT - Rapidly exploring Random Trees)

Experimental/Simulation Data
↓
Control Graph (local models)
↓
Numerical optimization
↓
New feed-forward

Node: state of the system (e.g. $\{z_p, dz_p\}$) with a second order dynamical model)
Arches: control value to pass from one state (node) to another one.

The control problem may be reduced into an optimal path planning problem.

The algorithm, updating the graph shot by shot, will suggest PF coils feed-forward currents.

Conclusions (1/2)

Post-disruption RE beam can be controlled: improved confinement performances, RE energy/current dissipation confirmed (*not only REs*).

Hybrid fast controller: model free, robust and easy to tune (ITER implementation in case a controllable RE beam forms!)

Next: tests on elongated RE beam discharges with a further "slow" controller

Impurity injections: pellet and LBO not effective on RE beams (get rid of MGI shielding cold background plasma or reduce Z_{eff} as seen by DIII-D and AUG)

LBO can be considered to provide **small disruptions expelling RE seeding** (electrical field oscillations – FTU/COMPASS)

JET: implemented tools to improve RE beam confinement without RT code changes (observer, SC and feed-forward) for future SPI experiments.

Final Loss: a new possible strategy (to be confirmed) to reduce the magnetic to kinetic RE energy conversion that is an important issue for ITER (2MA)

Conclusions (2/2)

RE beam can be controlled (DIII-D, TCV, FTU, COMPASS, ASDEX, JET?) if it is within the **controllable region ($I_{RE,CQ}/I_{p,TQ}$, dI_{RE}/dt).**

Solution bifurcation: **prompt RE dissipation** (no RE beam formation) or **$I_{RE,CQ}/I_{p,TQ}$ >1/3** and **dI_{RE}/dt** as low as possible (D_2 to decrease Z_{eff})

From a control point of view: the larger the initial RE current, the safer its confinement (no large destabilizing instabilities have been reported).

If the beam is formed and initially confined (ITER): use MGI/SPI to mitigate its energy and induce a controllable current ramp-down (less than 0.5MA/s in ITER), again, the slower current decay rate, the safer (Halo currents...)

What can be done for RE beams with CQ larger than 4MA ($I_{RE,CQ}/I_{p,TQ}$>1/3) in ITER? Is it possible to have MGI reducing initial VDE during CQ (DMV location)?

BACKUP SLIDES

Deuterium Pellets and Laser Blow Off

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.

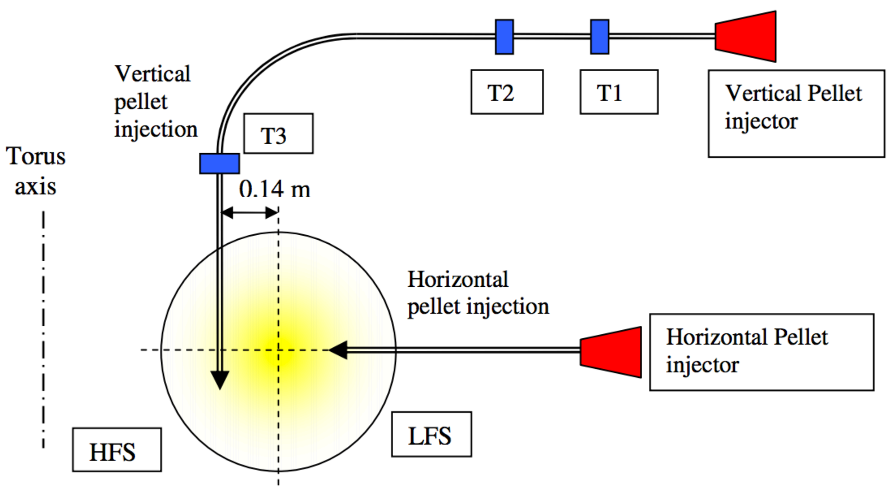


Fig. A: schematic of the pellet injector system

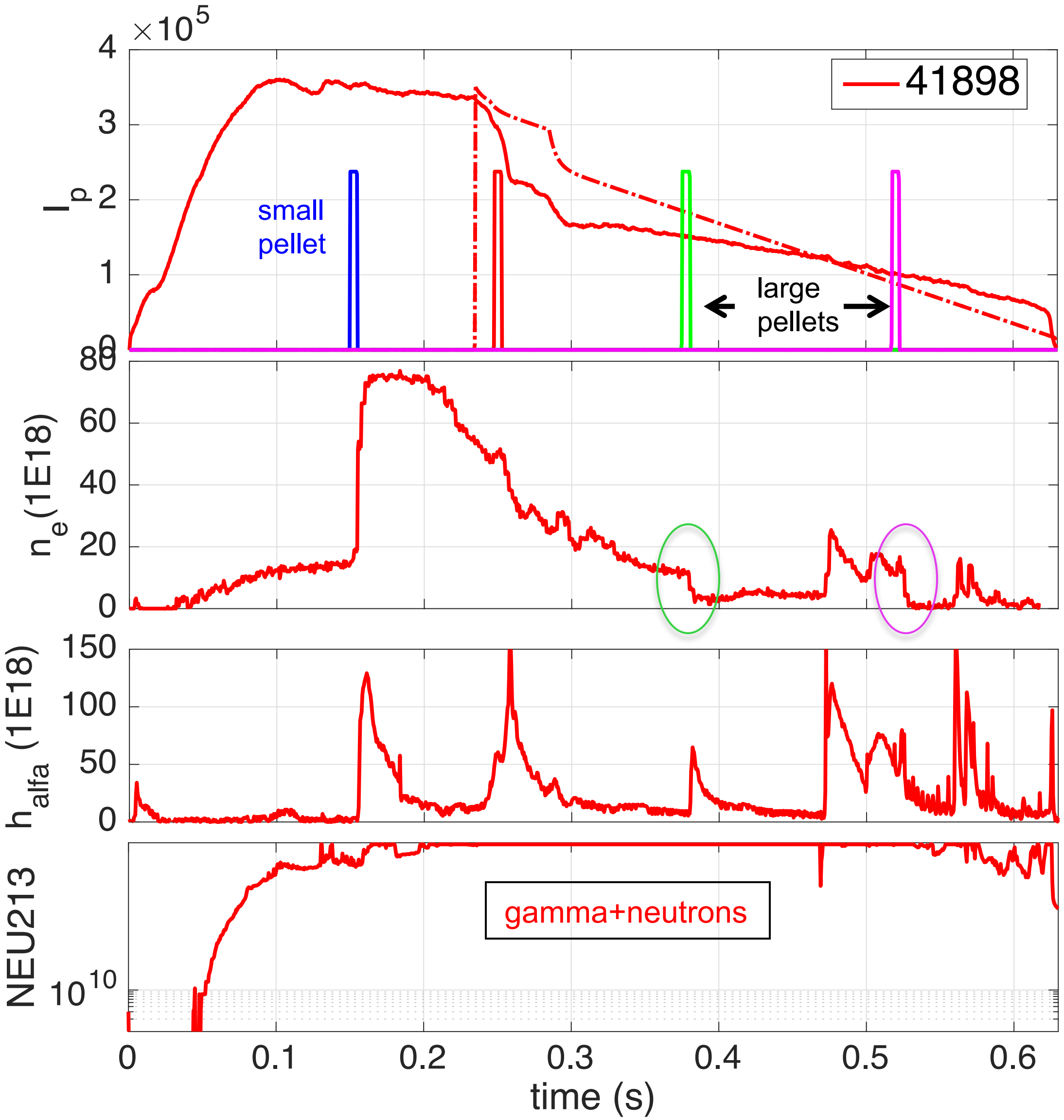
Laser Blow Off injector

- Molybdenum
- Tungsten
- Iron
- Zirconium

Iron example: 3E18 atoms are ablated by the laser (impurity upper bound)

Accompanying poster: Afra et. al.

Deuterium Pellets: results (1/3)



Small pellet on flat-top I_p:

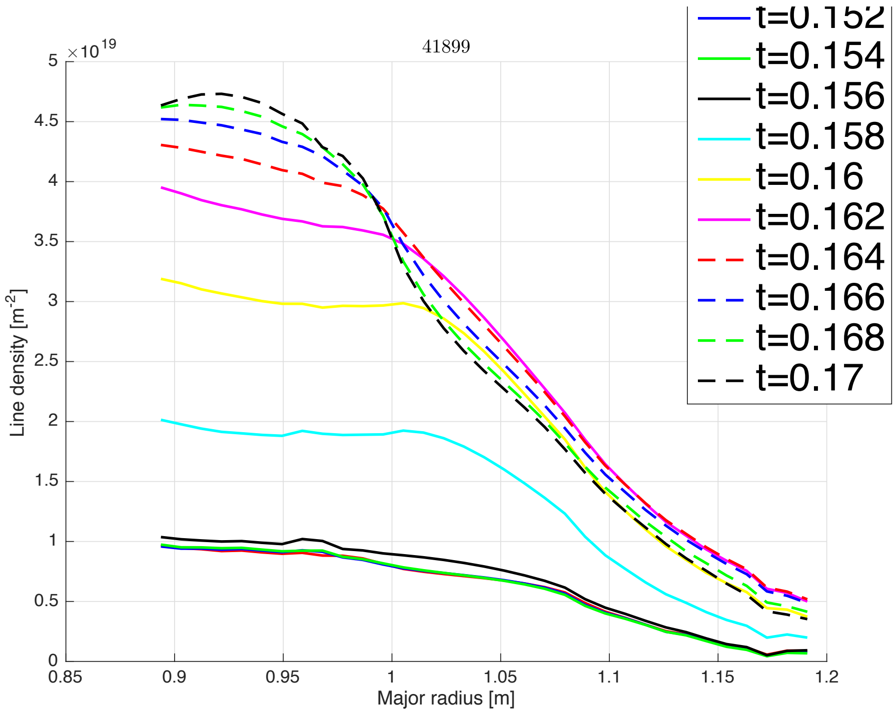
- n_e increase, RE increase
- RE sudden loss

Large/small pellets on RE beam: n_e drops (recombination due to low temperature). No visible effects on dissipation rate (no MGI).

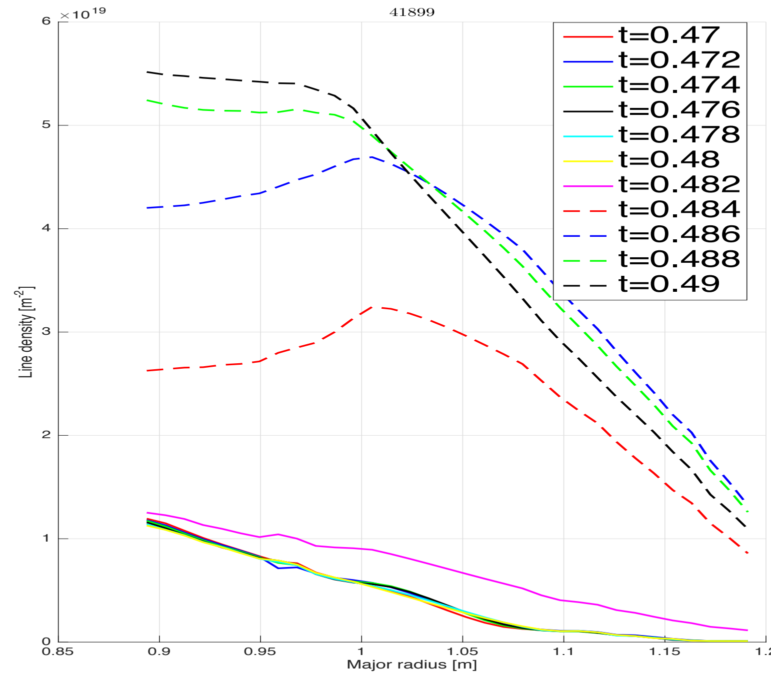
Only in one case (of about 20) the n_e largely increases

Spikes on n_e are induced by RE (filaments) hitting the vessel (recycling).

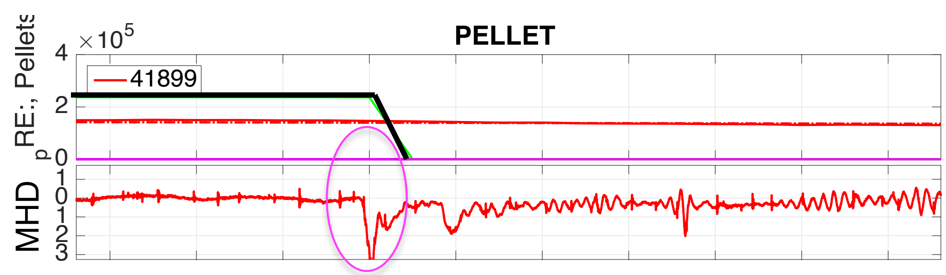
Deuterium Pellets: results (2/3)



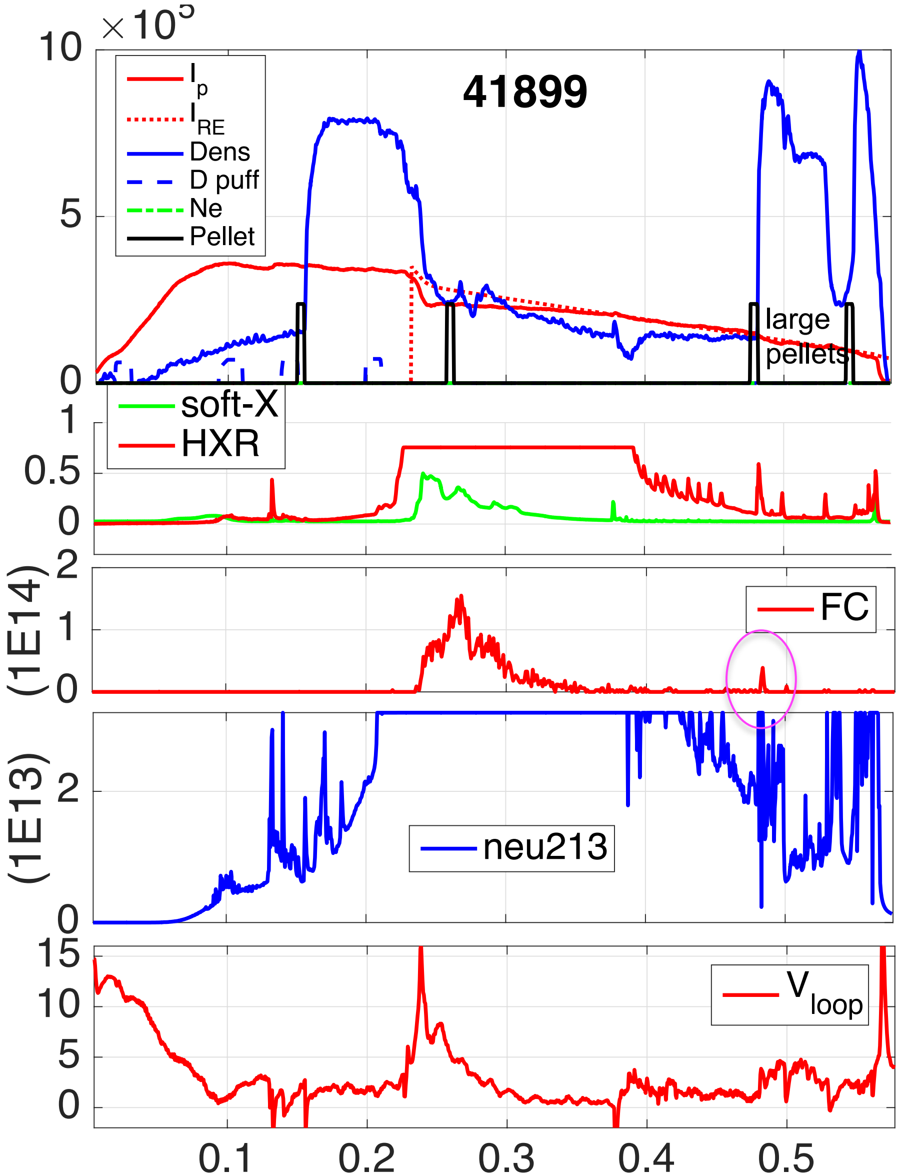
Density profiles Vs major radius at different time for the first small pellet in **the flat-top discharge**.



Density profiles Vs major radius at different time for the first large **pellet on RE beam.**



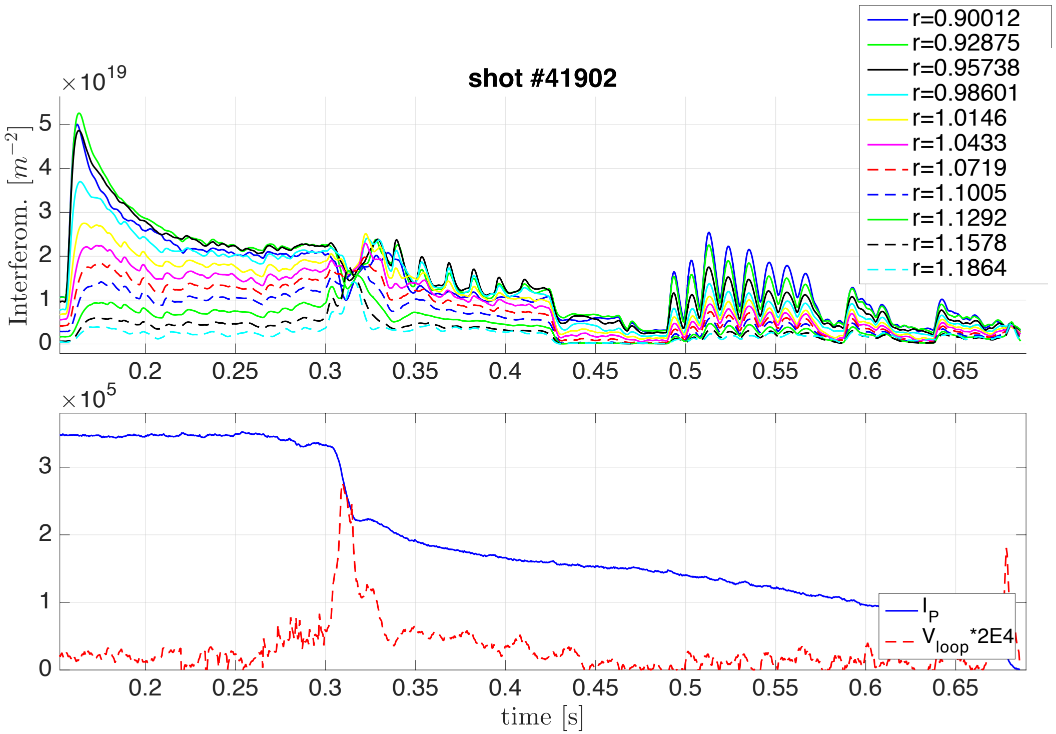
Deuterium Pellets: results (2/3)

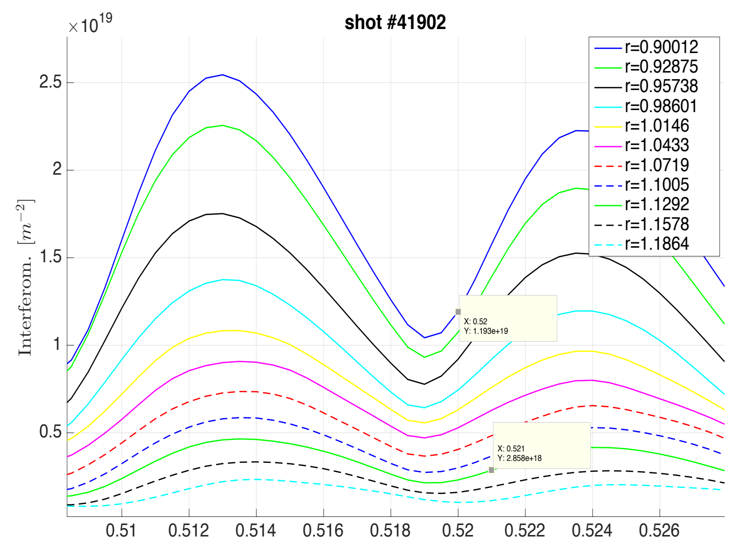


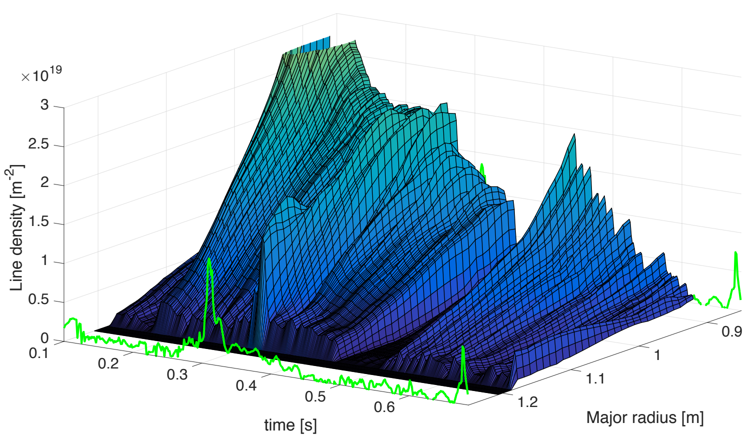
Density rises: the background plasma temperature increased, how...

back to a plasma WITH REs

Deuterium Pellets: results (3/3)



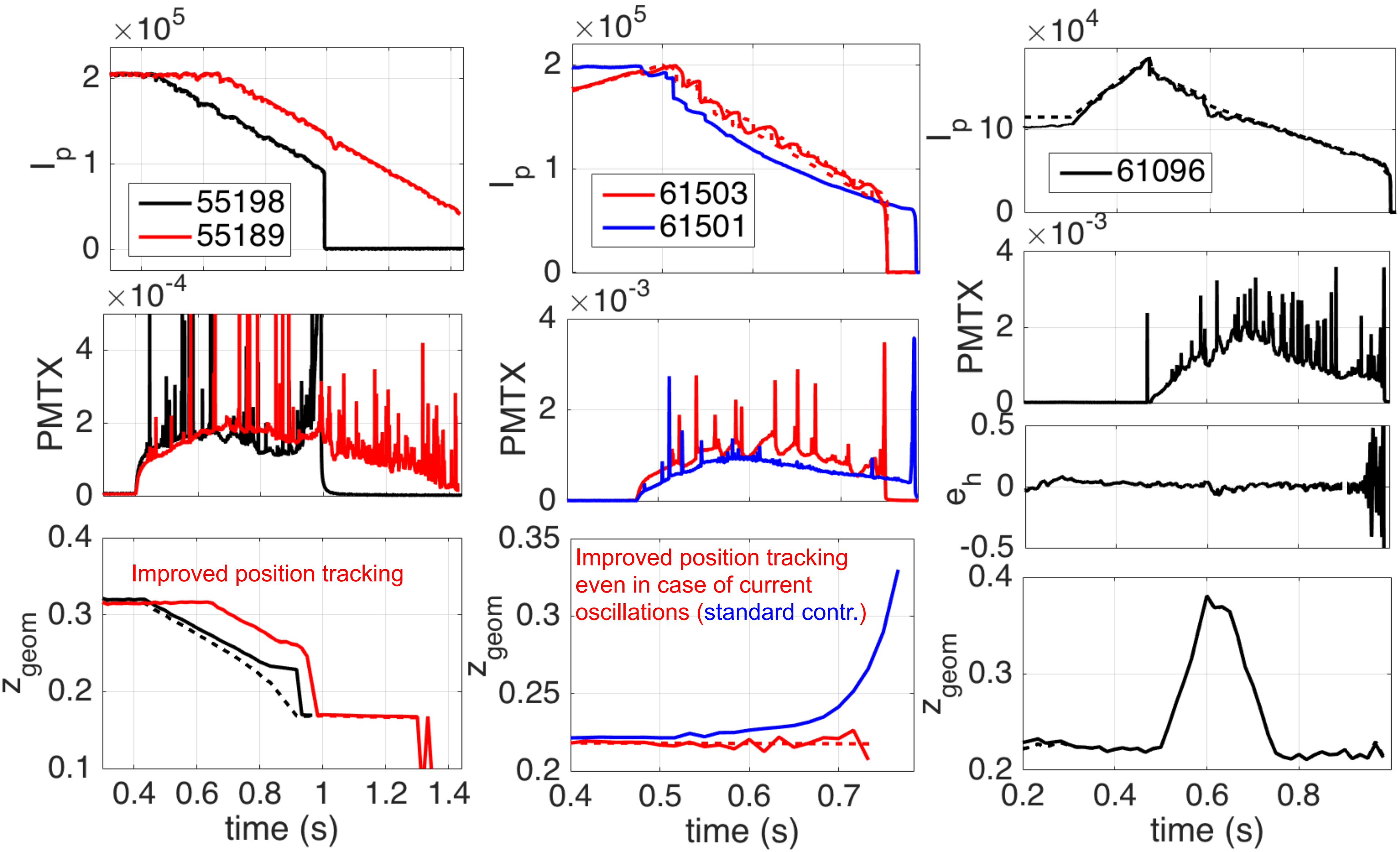




Interferometer: the large oscillations after 0.5s are larger toward the low field side and seem to be in advance with respect to high field side.
HXR, Soft-X, Cherenkov: REs leaves the core
ODIN: equi-flux surfaces does not seem to move within the ne oscillations period

Hypothesis: fluctuations density are associated to low energy electrons created from REs leaving the core and hitting the vessel and/or ionizing the surrounding gas

TCV: different type of shots



Large Vloop oscillations on flat-top plasmas with RE