Progresses in disruptions theory and some new experiments in disruption control

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OUTLINE

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3 different topics:

- Some linear results on the role of surface currents
- A simple cylindrical model to study mode rotation and mode locking in ITER
- New experimental results from RFX-mod of feedback controlled disruptions

HALO vs HIRO

- DOES HALO EXIST?

IT DOES..in PRINCETON at least

Surface currents calculations

- The skin current $\mathbf{i}_{pl}$ is determined by

$$\mu_0 \mathbf{i}_{pl} = \mathbf{n} \times < \mathbf{B} >$$

where $\mathbf{n}$ is the unit normal and $< \mathbf{B} >$ means the jump of the magnetic field across the perturbed plasma surface

- To calculate $\mathbf{i}_{pl}$ we consider the following model: the ideal and incompressible plasma cylinder of radius a surrounded by coaxial magnetically-thin resistive wall with radius b and the time constant τ_w, the plasma-wall gap and space behind the wall are treated as vacuum. Large aspect ratio, long-wave modes $nr / mR << 1$

- Neglecting the term with the pressure gradient, for locked modes with $m > 1$ the radial displacement $\xi(r)$ in the plasma region is described by

$$\left\{ r^3 \left[(m/q - n)^2 + (\gamma \tau_A)^2 \right] \xi' \right\}' - \left\{ (m^2 - 1) \left[(m/q - n)^2 + (\gamma \tau_A)^2 \right] - (\gamma \tau_A)^2 (r\rho' / \rho) \right\} r \xi = 0$$

- Integrating of the last equation across the plasma boundary and matching with solutions in vacuum and wall regions yields

Surface currents calculations

$$i_{pl} = \mathbf{i}_{pl} \cdot \mathbf{e}_z = -\bar{j}\xi_a \frac{(q_a\tau_A\gamma)^2}{(q_a\tau_A\gamma)^2 + (m-nq_a)^2}\left\{1-(m-nq_a)\left[\frac{1}{2}+\frac{(a/b)^{2m}}{1+2m/(\gamma\tau_w)-(a/b)^{2m}}\right]\right\}$$

- where $\bar{j} = I_p/(\pi a^2)$ is the mean plasma current density and $\tau_A \equiv R\sqrt{\mu_0\rho}/B_z$
- Hence, far from the points $nq_a = m$ for slow RWMs with $\gamma \approx 1/\tau_w$

$$i_{pl} \propto -\bar{j}\xi_a(\tau_A/\tau_w)^2$$

- Let us illustrate it for the flat current distribution, in this case we have

dispersion relation

$$(q_a\tau_A\gamma)^2 = 2(m-nq_a)\left(1-\frac{(m-nq_a)(1+2m/\tau_w\gamma)}{1-(a/b)^{2m}+2m/\tau_w\gamma}\right)$$

plasma surface current

$$i_{pl} = -\bar{j}\xi_a\left\{1-\frac{(m-nq_a)[1+2m/(\tau_w\gamma)]}{1-(a/b)^{2m}+2m/(\tau_w\gamma)}\right\} = -\frac{\bar{j}\xi_a(q_a\tau_A\gamma)^2}{2(m-nq_a)}$$

eddy currents in the wall

$$i_{wall} = -\bar{j}\xi_a\frac{(m-nq_a)(a/b)^{m+1}}{1-(a/b)^{2m}+2m/(\tau_w\gamma)}$$

Skin and eddy currents for the flat current profile

- Surface current

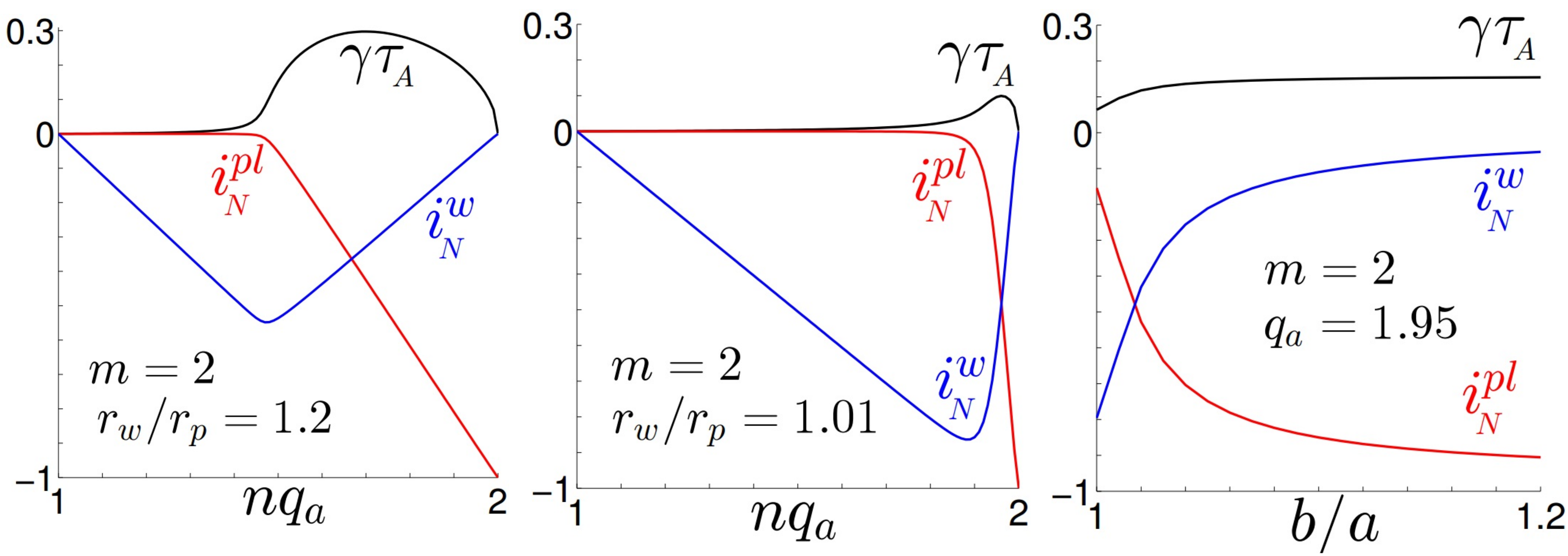
$$i_N^{pl} \equiv \frac{i_{pl}}{\bar{j}\xi_a} = -\frac{(q_a \tau_A \gamma)^2}{2(m - nq_a)}$$

- Eddy current

$$i_N^{w} = \frac{i_w}{\bar{j}\xi_a} = -\frac{(m - nq_a)(a/b)^{m+1}}{1-(a/b)^{2m} + 2m/(\tau_w \gamma)}$$

- At $nq_a \to m$ $\quad i_N^{pl} = -1$, $\quad i_N^{w} = 0$

- For slow RWMs $\quad i_N^{pl} \approx -\frac{(q_a \tau_A / \tau_w)^2}{2(m - nq_a)}$



Parabolic current profile/ What does WTKM mean?

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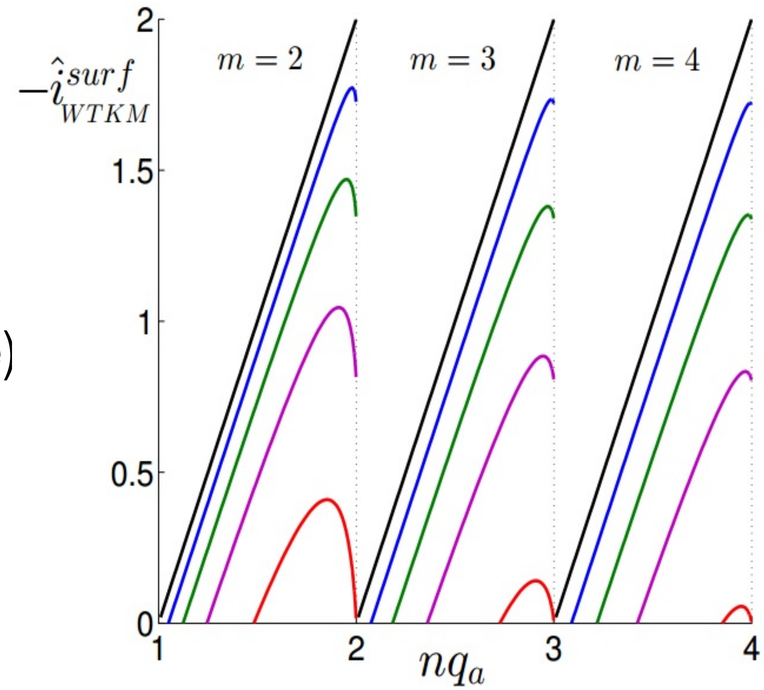
- For the parabolic current profile of the form $j = j_0\left(1-\alpha\frac{r^2}{a^2}\right)$ $\quad 0 \le \alpha \le 1$
- And marginally stable modes $\gamma = 0$
- The solution for the plasma has analytical form and expresses in terms of hypergeometrical functions

$$\xi \propto z^{(m-1)/2}(1-z)^{-1}F((m-\sqrt{m^2+8})/2,(m+\sqrt{m^2+8})/2;m+1;z)$$

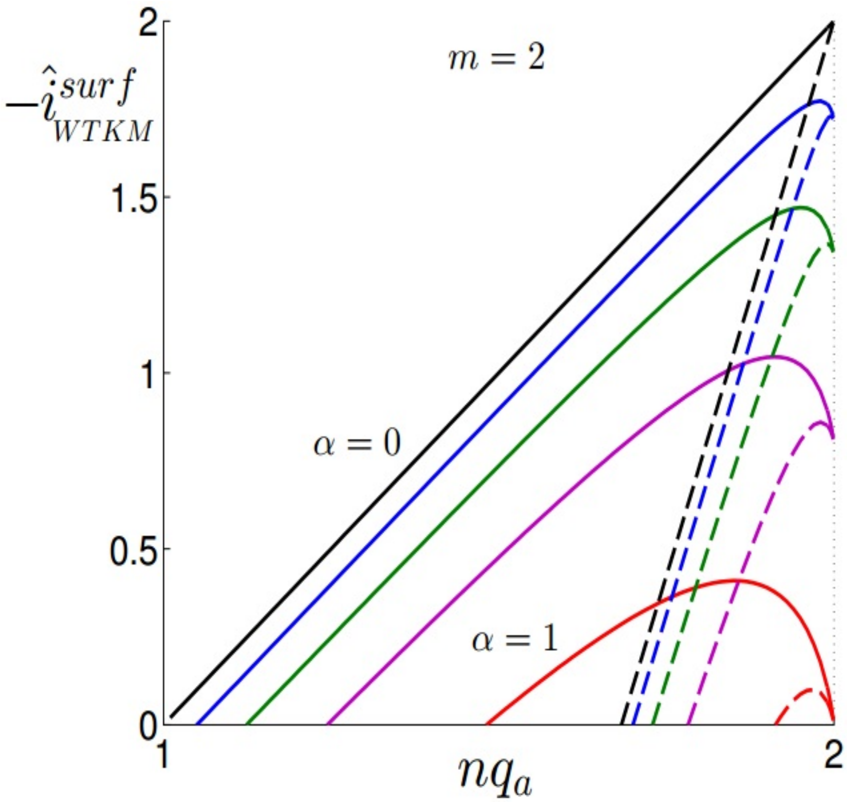
$$z = \frac{\alpha r^2}{2a^2(1-nq_0/m)}$$

- This allows us to reproduce analytically the numerical results from [1] for the so called WTKM. (the fig.2b is plotted for the no-wall case)
- The assumption $\gamma = 0$ is adequate only in the ranges of nq_a , where $i_{pl} = 0$ or near the points $nq_a = m$



[1] L E Zakharov Physics of Plasmas 18, 062503 (2011) (cf. fig. 2b)

Parabolic current profile : Wall effect



Continous No-wall case

Dashed Ideal-wall at $b/a = 1.1$

Summary on surface currents:

- The sign of eddy and surface currents is the same (they are both stabilizing)

- For the flat current model the surface currents should be accounted for:

  - If the q in the plasma is rational
  - for perturbations growing on the Alfven time scale (in this case they are comparable with eddy currents)

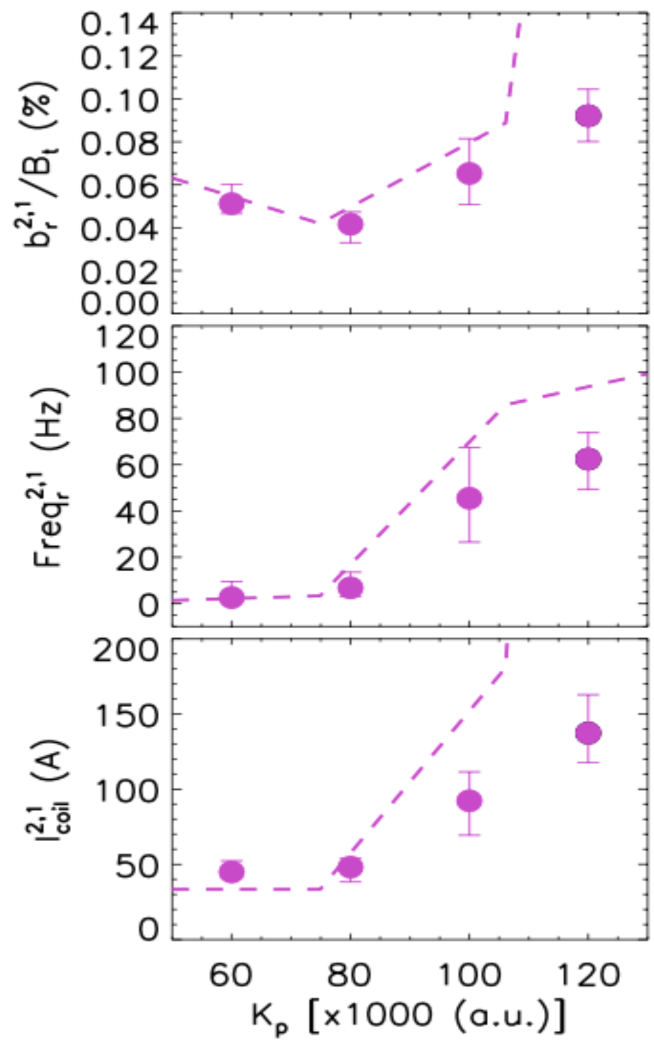
  * Instead for perturbations growing on a time scale much less then Alfvènic (and with q not rational) the surface currents are negligibly small in comparison with the eddy currents.

- A non flat (decreasing to the edge) equilibrium current profile mitigate them

- A shell near to the plasma further narrows (near to rational values) the region of qa for which surface currents could play a role

All these results are strictly valid in the linear phase and for external modes

RFXlocking code: mode/walls/feedback interaction



Good comparison between experiment (dots) and RFXlocking (traces) for m=2, n=1 control in 2<q(a)<2.5 RFX-mod tokamak shots

We want to apply this relatively simple model to get a feeling of the 2/1 locking threshold in ITER and to estimate the mode rotation frequencies below threshold
(any result to show for now)

Eventually more physics can be added (see next slides) to the model

RFXlocking code: mode/walls/feedback interaction

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TM dynamic in the presence of magnetic feedback is simulated by a cylindrical, spectral code (RFXlocking) solving:

- **Single-fluid motion equations** with perpedicular viscosity μ, phenomenological sources $S_{\theta,\varphi}$, em. torque δT_{EM} localized at the resonant radius $r_{m,n}$

$$\rho \frac{\partial \Omega_\phi}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\mu r \frac{\partial}{\partial r}\Omega_\phi\right) + S_\phi + \frac{\delta T^{m,n}_{EM,\phi}}{4\pi^2 r R_0^3}\delta\left(r - r_{m,n}\right)$$

$$\rho \frac{\partial \Omega_\theta}{\partial t} = \frac{1}{r^3}\frac{\partial}{\partial r}\left(\mu r^3 \frac{\partial}{\partial r}\Omega_\theta\right) - \frac{\rho}{\tau_D}\Omega_\theta + S_\theta + \frac{\delta T^{m,n}_{EM,\theta}}{4\pi^2 r^3 R_0}\delta\left(r - r_{m,n}\right)$$

- Em. Torque, due to interaction with the passive and active external structures, is modelled exploiting **Newcomb's equation**

- **Rutherford equation** for mode island width, where Δ'(W) incorporates the saturation term [N. Arcis, D. F. Escande, M. Ottaviani, *Phys. of Plasmas* **14** (2007) 032308-1] and the effect of passive conductive walls and active coils

RFXlocking code: mode/walls/feedback interaction

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- Island phase determined by n**o-slip** condition including the diamagnetic drifts

$$\frac{d\varphi^{m,n}}{dt} = n\ \Omega_\phi\left(r_{m,n},t\right) - m\ \Omega_\theta\left(r_{m,n},t\right) + \frac{n B_\theta}{e R_0 B^2}\left(1 + \frac{m^2 R_0^2}{n^2 r^2}\right)\frac{d\left(T_e + T_i\right)}{dr}\Bigg|_{r_{m,n}}$$

- **Diffusion equations** for radial field penetration across the passive structures

$$\mu_0\,\sigma\frac{\partial b_r^{m,n}}{\partial t} = \frac{\partial^2 b_r^{m,n}}{\partial r^2}$$

- **RL coils equation**

$$\tau_c^{m,n}\frac{dI_c^{m,n}}{dt} + I_c^{m,n} \approx V_c^{m,n}$$

- **Discrete-time feedback equation**

$$V_c^{m,n}\left(t_j \le t \le t_{j+1}\right) \propto K_p^{m,n} b_{feed}^{m,n}\left(t_j\right) + K_d^{m,n}\frac{d}{dt} b_{feed}^{m,n}\left(t_j\right)$$

Observations:

- 2/1 modes are well controlled in q(a) <= 2 tokamak plasmas using active feedback (RFX-mod and DIIID)
- 2/1 modes are not well controlled by feedback at medium/high density and/or with q(a) > 2.5
- 2/1 modes are often the main cause of disruptions

Strategy:

If a sudden decrease of q(a), triggered by a 2/1 mode detection, starting from a normal q(a) (> 3) can be achieved, the plasma could be actively controlled in a low q(a) state **avoiding the current quench**

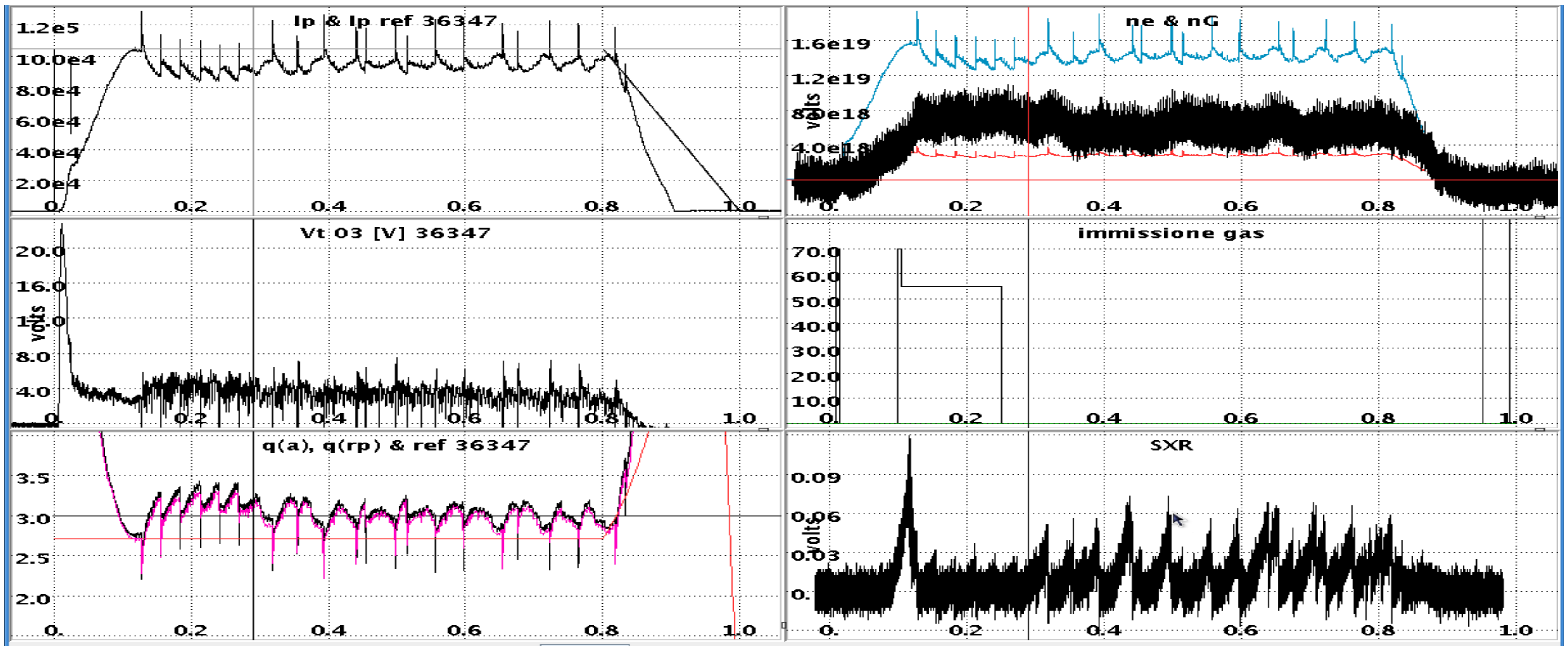
Employed Method:

In RFX-mod the q(a) is controlled by controlling the plasma current through fast power supplies (PCAT)

- The trigger is a Bp (2,1) mode (around 0.3G)
- A step-like waveform is pre-programmend on PCAT's for the current rise
- The control can be active only after a chosen time

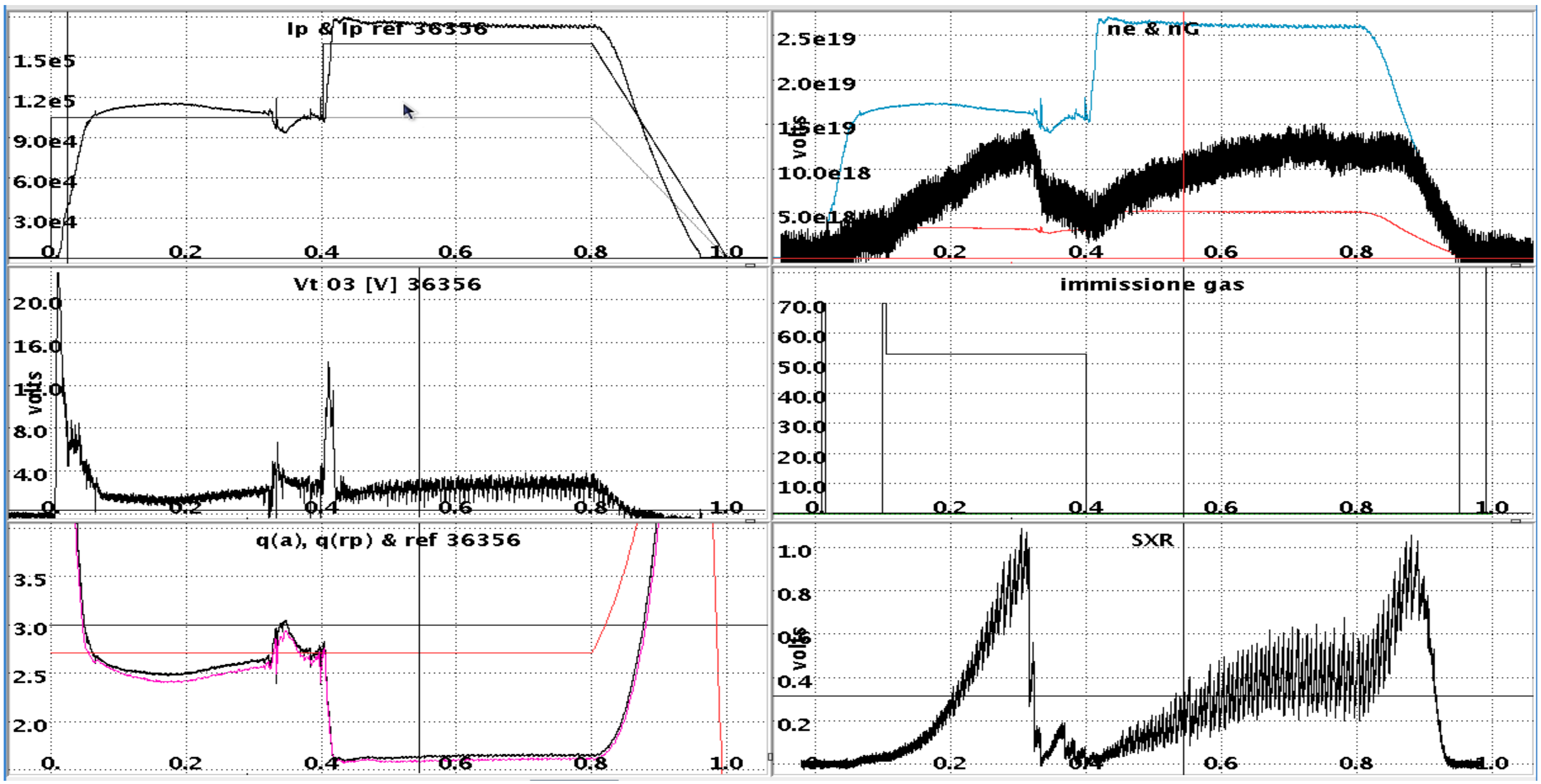
Feedback control of q(a) in tokamak configuration in RFX-mod for disruptions avoidance

Without control in RFX-mod at q(a) > 3 we can reach densities where several disruptions appear. The current is sustained only with an high Vloop.



Feedback control of q(a) in tokamak configuration in RFX-mod for disruptions avoidance

With control (after t=0.4 s) we can reach q(a) < 2 and no disruptive events afterwards



Feedback control of q(a) in tokamak configuration in RFX-mod for disruptions avoidance

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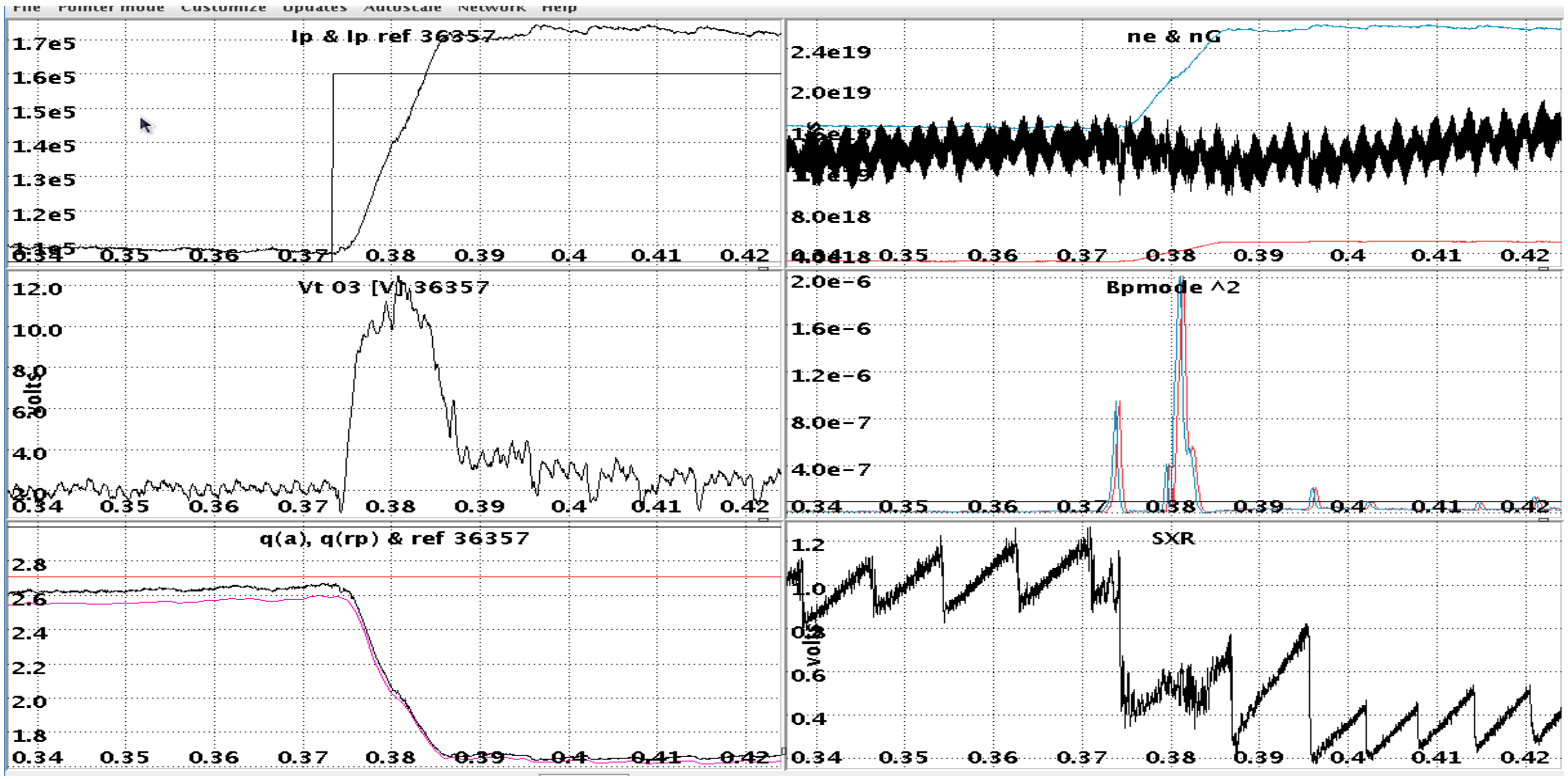
Although one thermal quench can't be avoided, we recover reasonable plasma conditions in the q(a) <2 phase and full control of the 2/1 mode

The success rate is 100%



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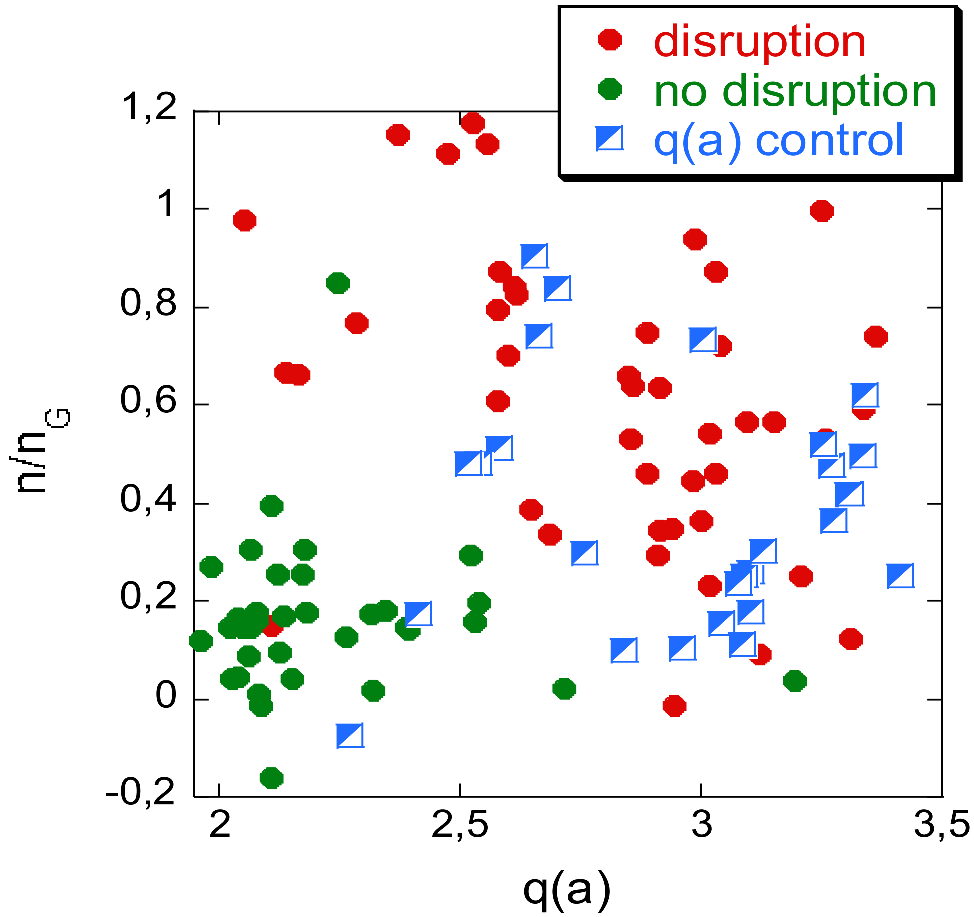
Experimental cases with and without feedback in the q(a) and density operating space (measured before the application of the voltage pulse for the feedback cases)



What about q(a) control in large tokamaks ?

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- a tokamak with q(a) < 2 can be feddback stabilized (RFX-mod and recent DIIID results) if a sufficient number of actuators and sensors are present
- a fast system to reduce q(a) is needed
- fast current or toroidal field control in large tokamak is not possible

What about a shape control ?

$$q_a = B\,(1+e^2)\,(\frac{2\pi a^2}{2\mu_o I\ R})$$

For typical tokamak elongations e (= 1.7-1.8 in ITER)

a factor 2 for qa can be gained

A DIIID example of shape control

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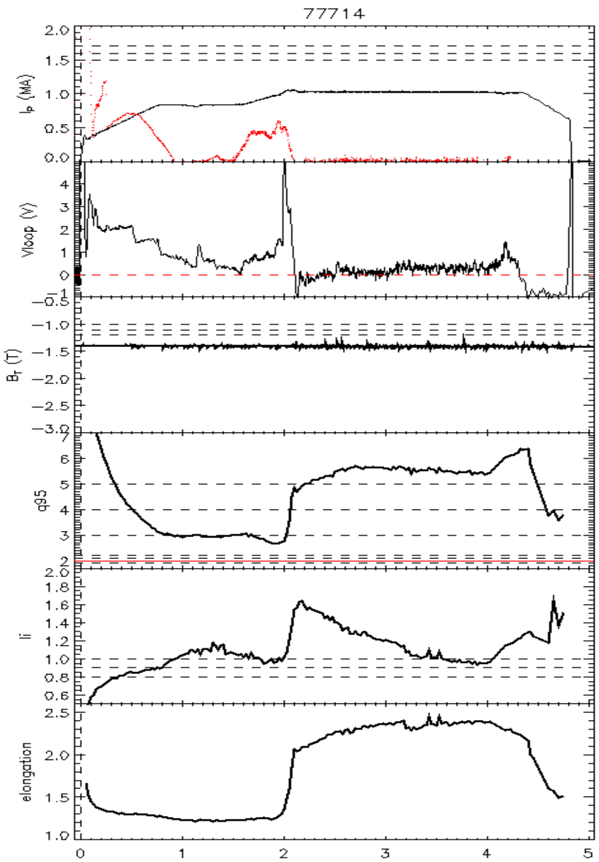

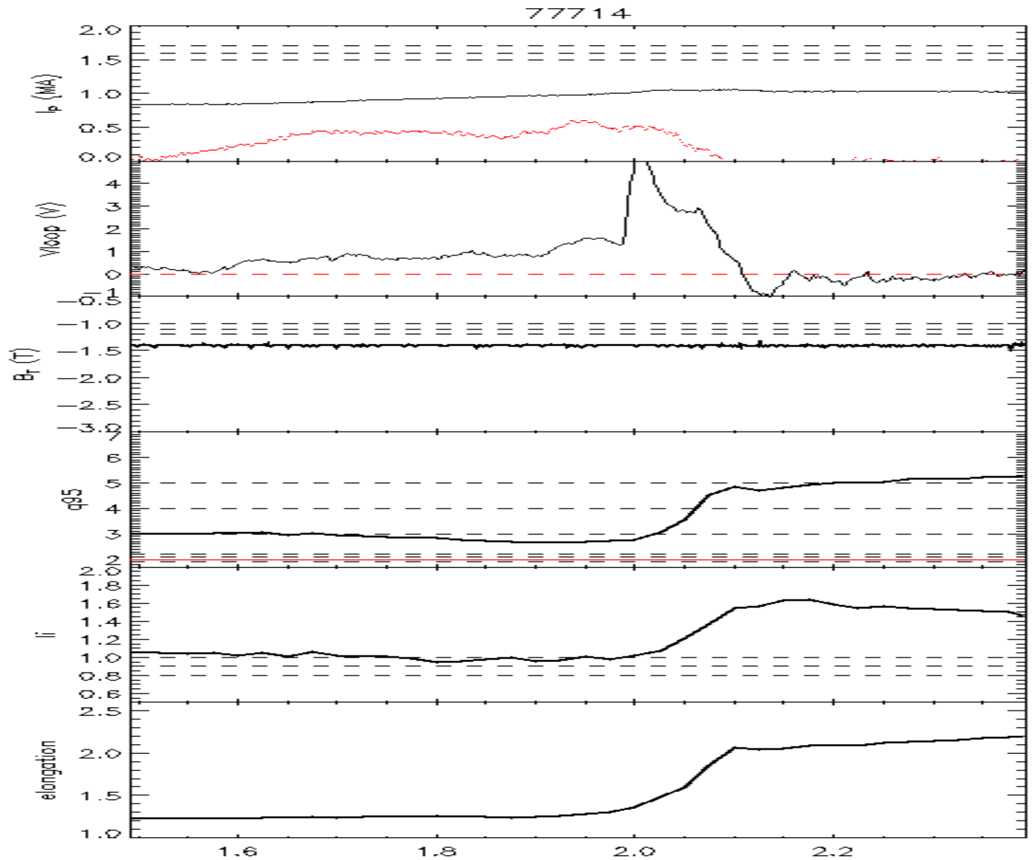

ZOOM

The time scale is around 100 ms:
is it enough ?

CONCLUSIONS

• the computational/theoretical work on disruptions should continue (several important issues are still open:
3D walls effects, role of 2/1 vs. 1/1 modes,
fast particles, rotations etc.)

Beside :
new ideas/concepts for disruption control are probably needed

• RFX-mod has shown a new possibility

• Experiments in elongated tokamaks could be done (DIIID)

• The applicability to ITER is obviously quite uncertain ..*but even if a very small chance exists it is worthwhile to explore it..*