4th international workshop on Stochasticity in Fusion Plasmas

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Edge Localised Modes control by Resonant Magnetic Perturbations

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Many thanks to F. Waelbroeck, F. Militello, J. Connor,
C. Gimblett, J. Hastie for their interest and advice

Outline

- Background

- Experimental results on MAST with the EFCCs and the new ELM control coils

- Attempting at full ELM suppression with the EFCCs on JET

- Non-linear MHD modelling of plasma response to Resonant Magnetic Perturbations

- Summary and outlook

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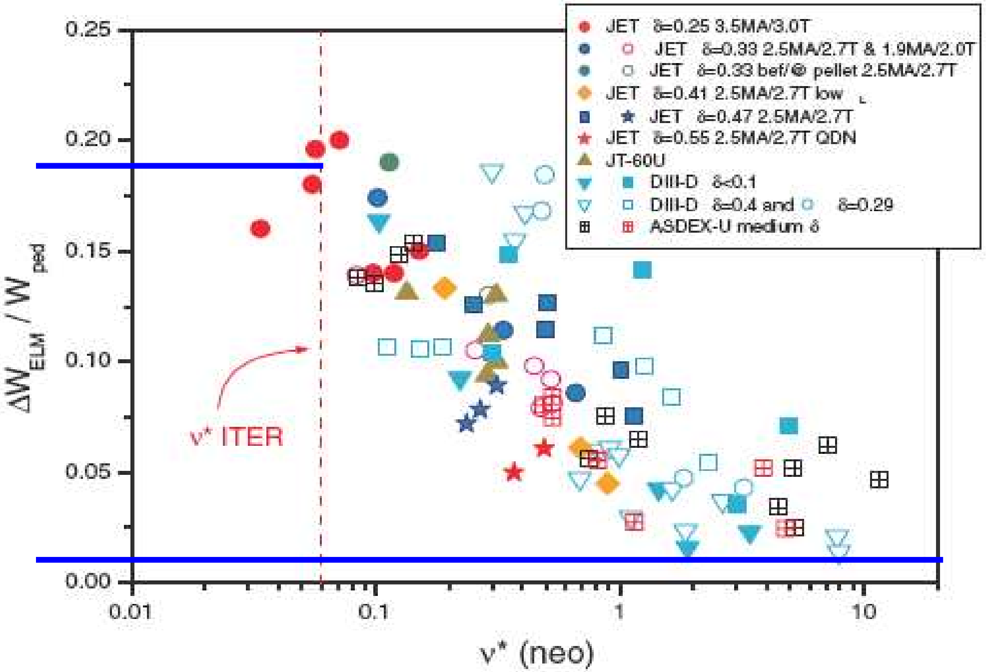
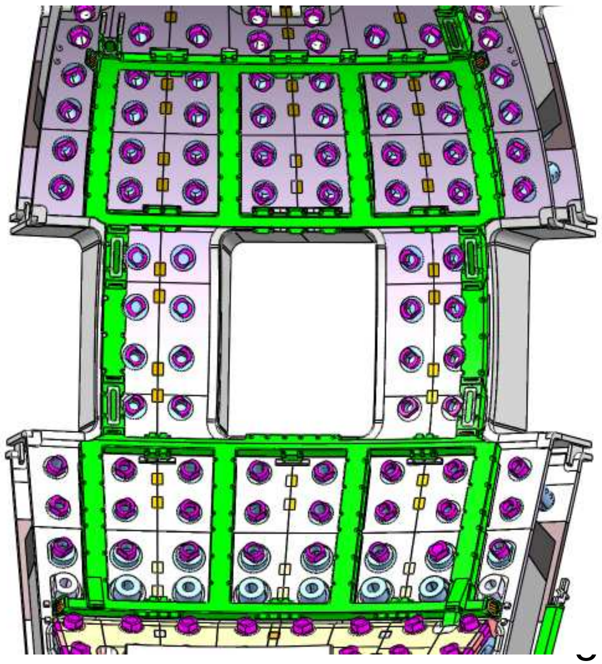
ELM control is necessary for ITER

Predicted
ELM size

Tolerable
ELM size



ITER ELM control coils casings

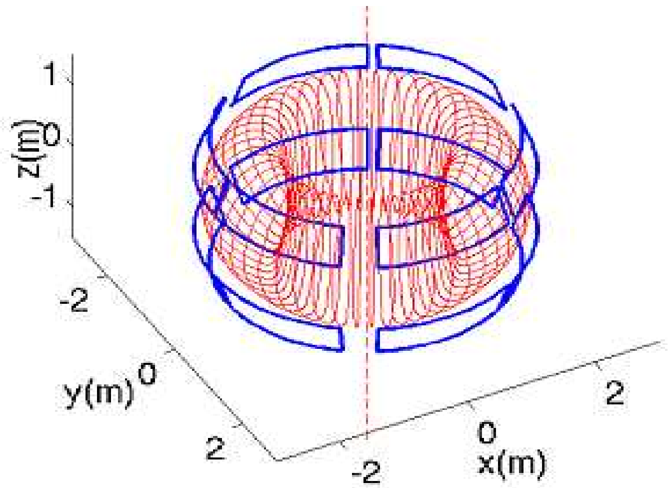


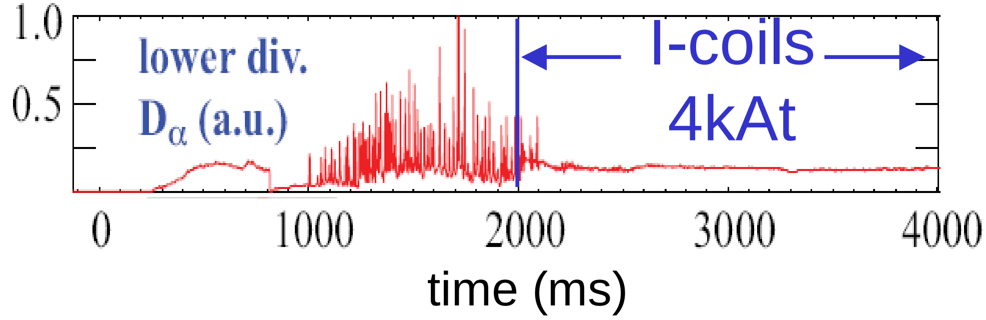
- Type-I ELMs in ITER have to be reduced from 20MJ to below 1MJ

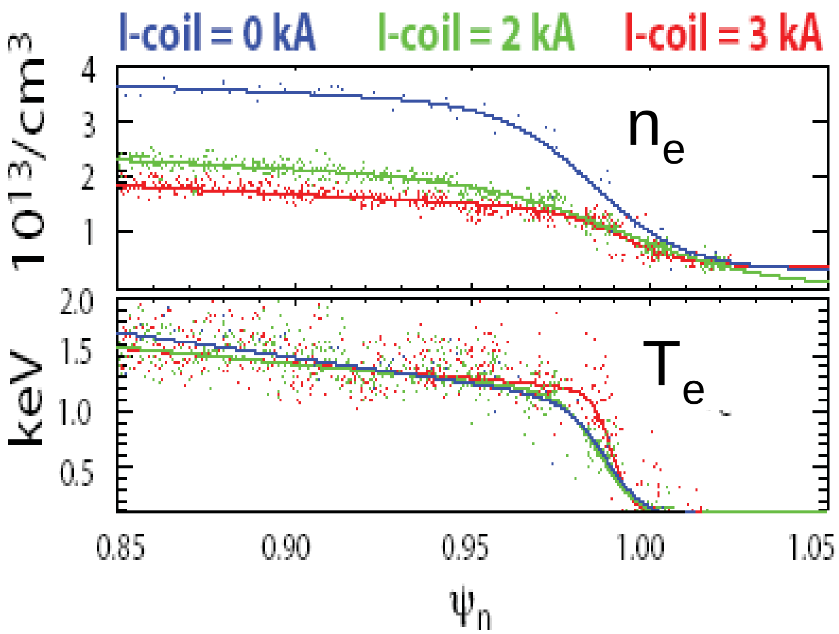
- ELM control coils are under study for ITER

ELM suppression demonstrated on DIII-D

I-coils: 6+6 coils, n=3, ~4kAt



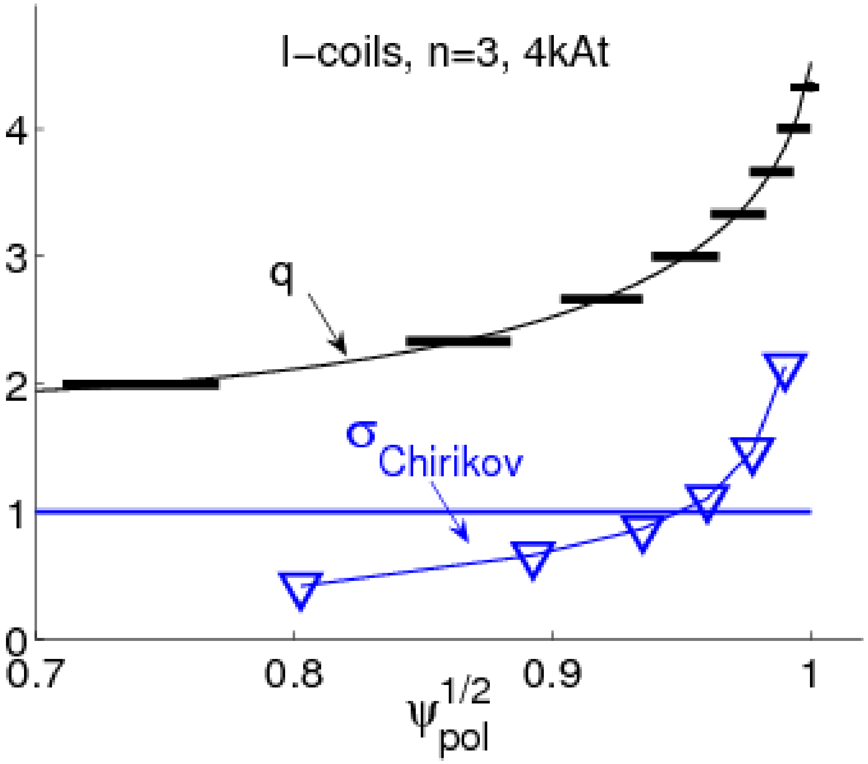


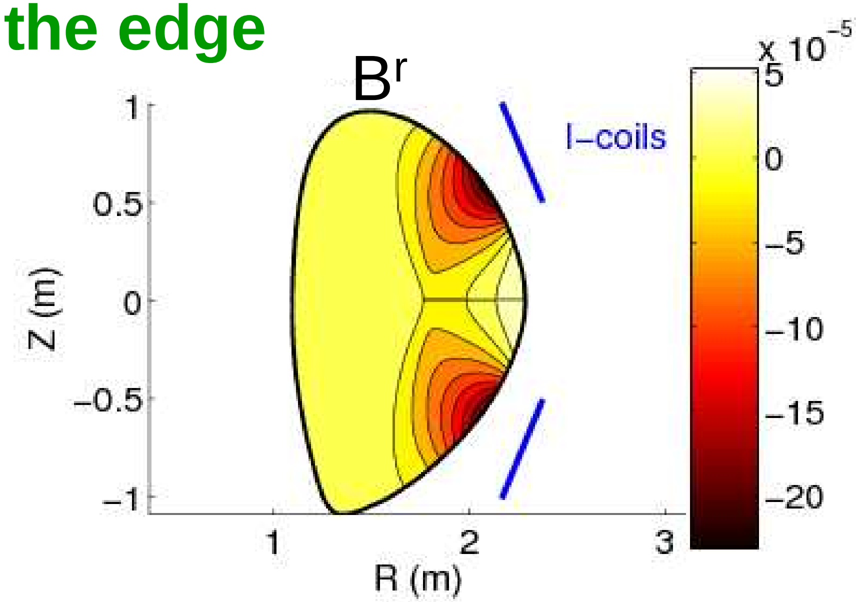


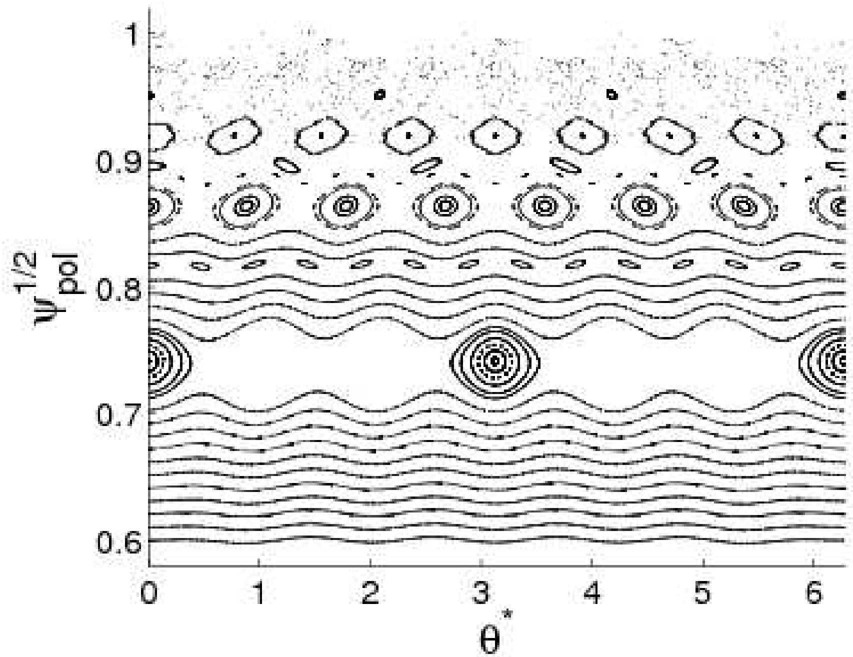
- ELM suppressed for tens of τ_E
- $H_{98(y,2)}$ not affected
- Works only in a narrow resonant q_{95} window
- Drop in density: « pump-out »
- $dT_e/dr|_{ETB}$ increases rather than drops!

Vacuum modelling suggests stochasticity could be present at the edge

<ins>ERGOS modelling for DIII-D I-coils</ins>

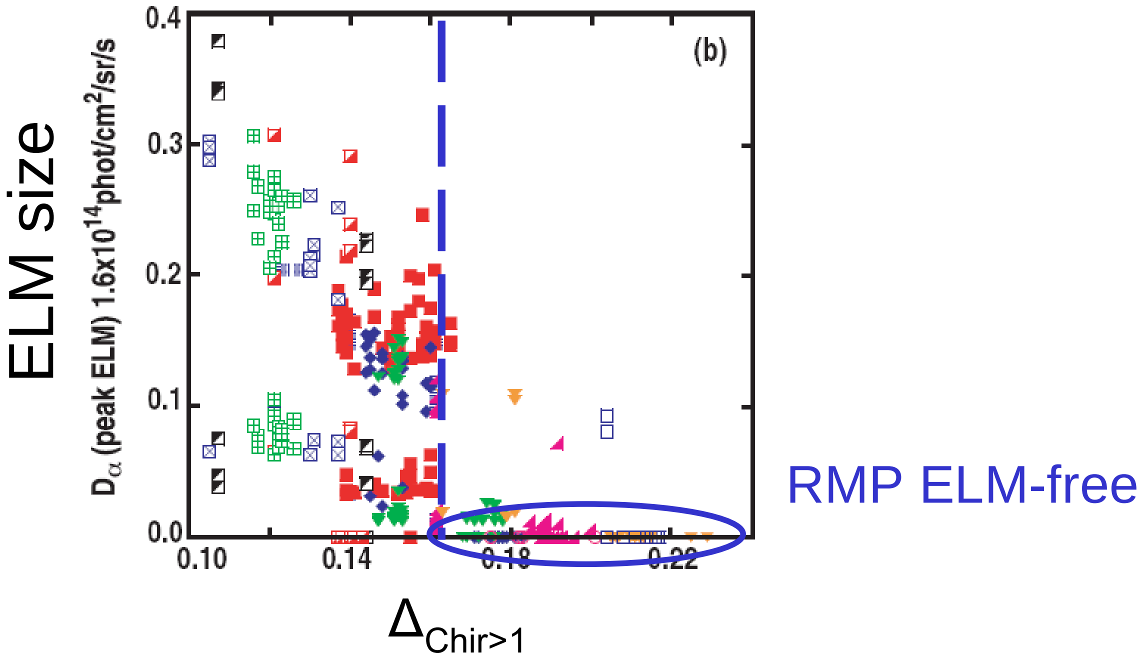






ELM suppression in DIII-D is correlated with stochastisation in vacuum modelling

- Fenstermacher '08:
  Width of stochastic layer ($\Delta_{Chir>1}$) = good ordering parameter for ELM size
  - Critical width for ELM suppression = ~3 pedestal widths



⇒ ITER coils have been designed following the requirement $\Delta_{Chir>1}$= 8%

But the physics is still not fully understood and DIII-D is the only machine to have obtained ELM suppression so far

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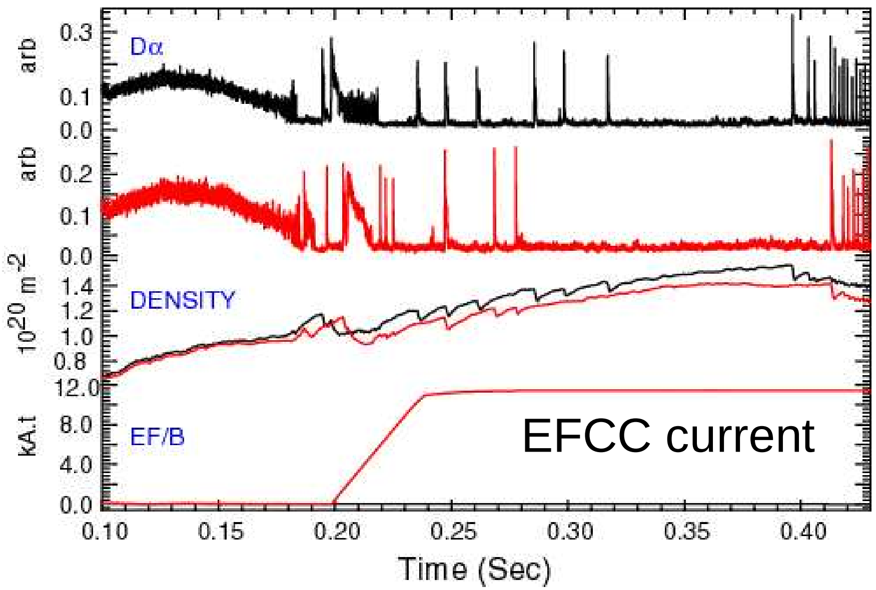
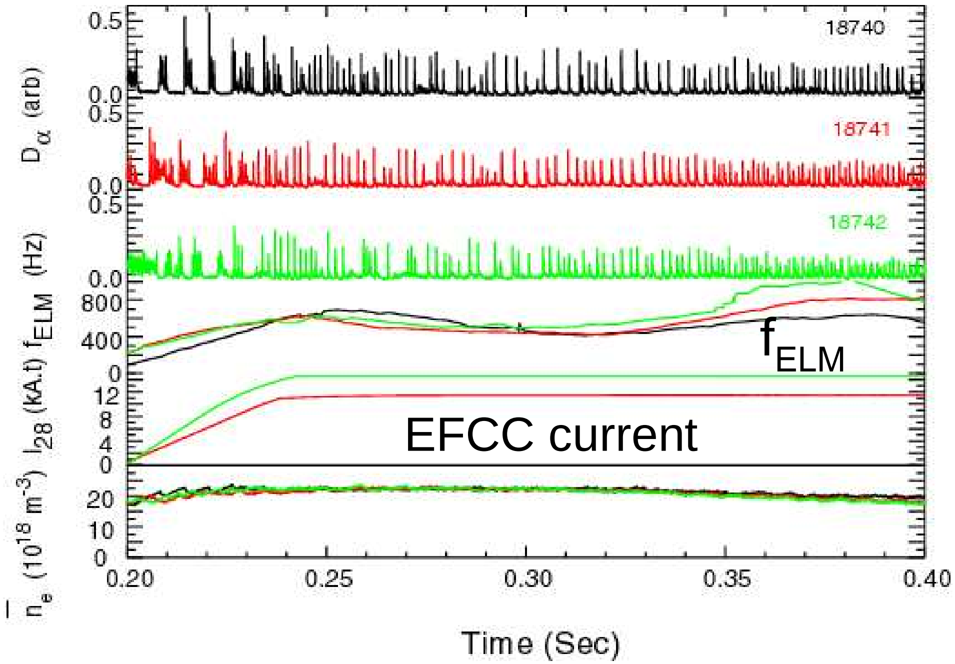
2007 MAST experiments using the Error Field Correction Coils

- 4 ex-vessel EFCCs which can produce n=1 or n=2
- n=1 delayed L-H transition / caused H-L back-transition
- n=2 worked better and had some effect on ELMs
  - – Type-I ELMy ref. discharge is not ideal
  - ⇒ Possible effect but hard to tell for sure
  - – Caused increase in Type-IV ELM frequency

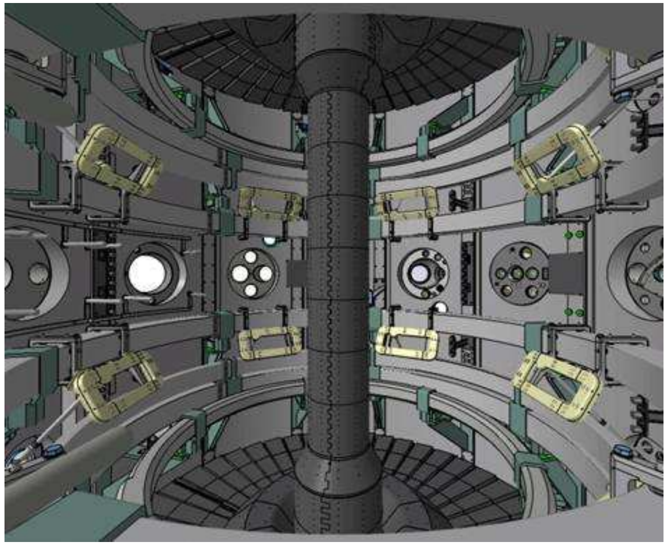
MAST EFCCs

n=2 experiments

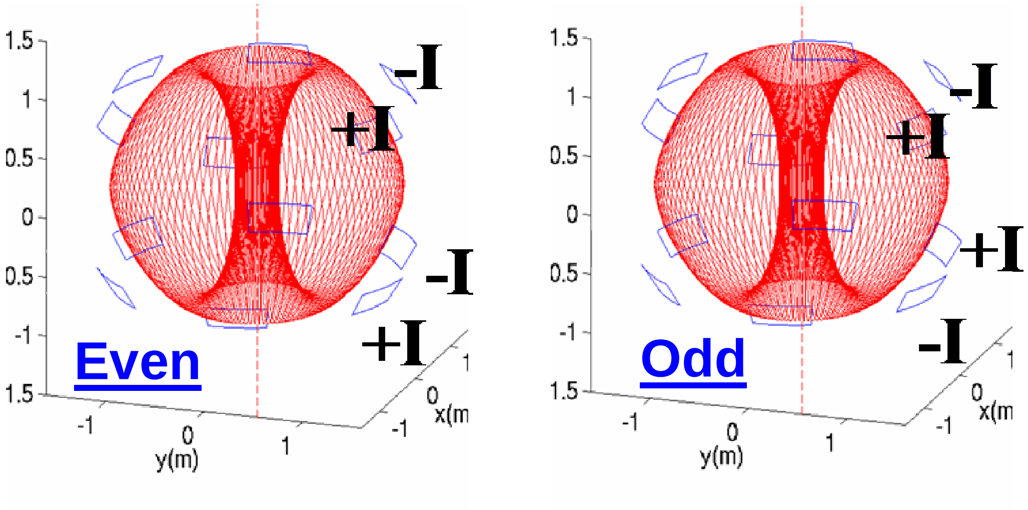


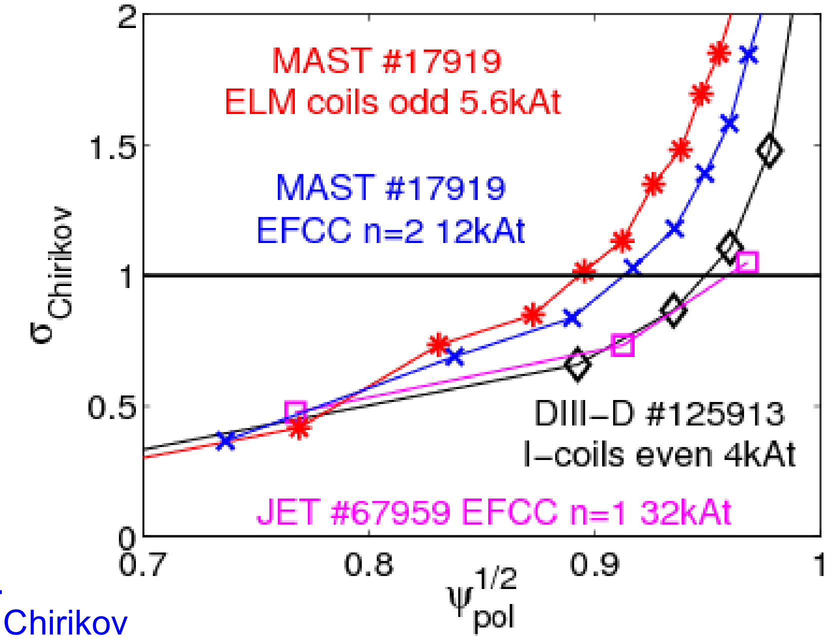


2008 MAST experiments using new internal dedicated ELM control coils



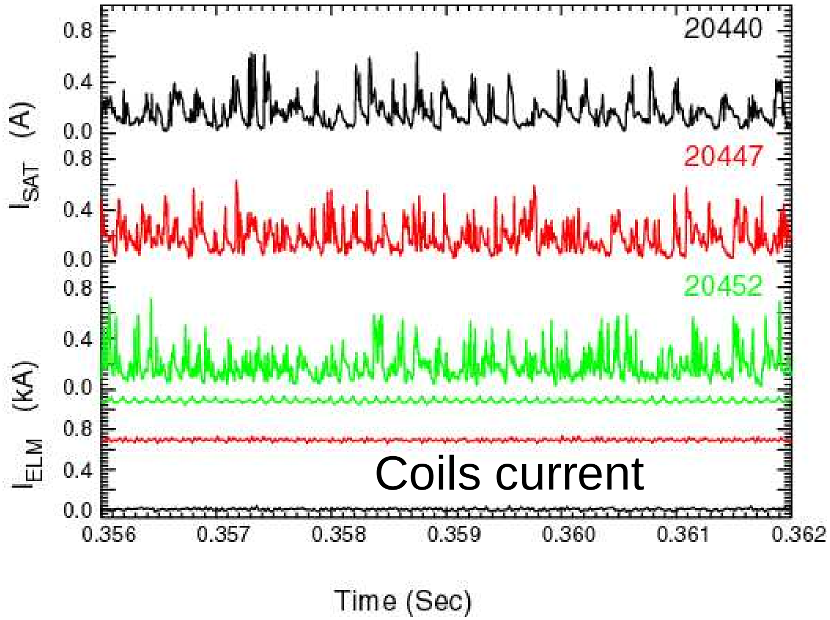
- 6+6 coils producing n=3 perturbations
- Even and odd configurations are possible
  - Which one is most resonant depends on q_{95}
  - When even is on resonance, odd is off-resonance and vice versa

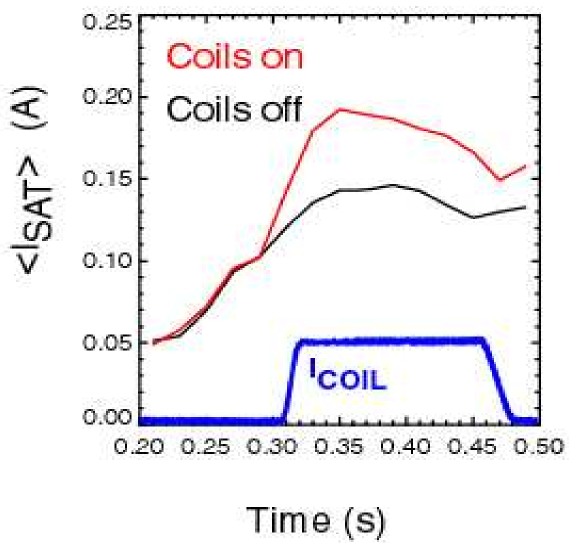


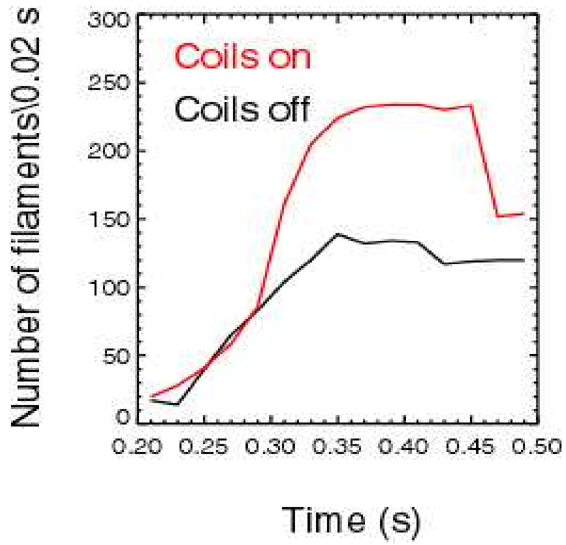


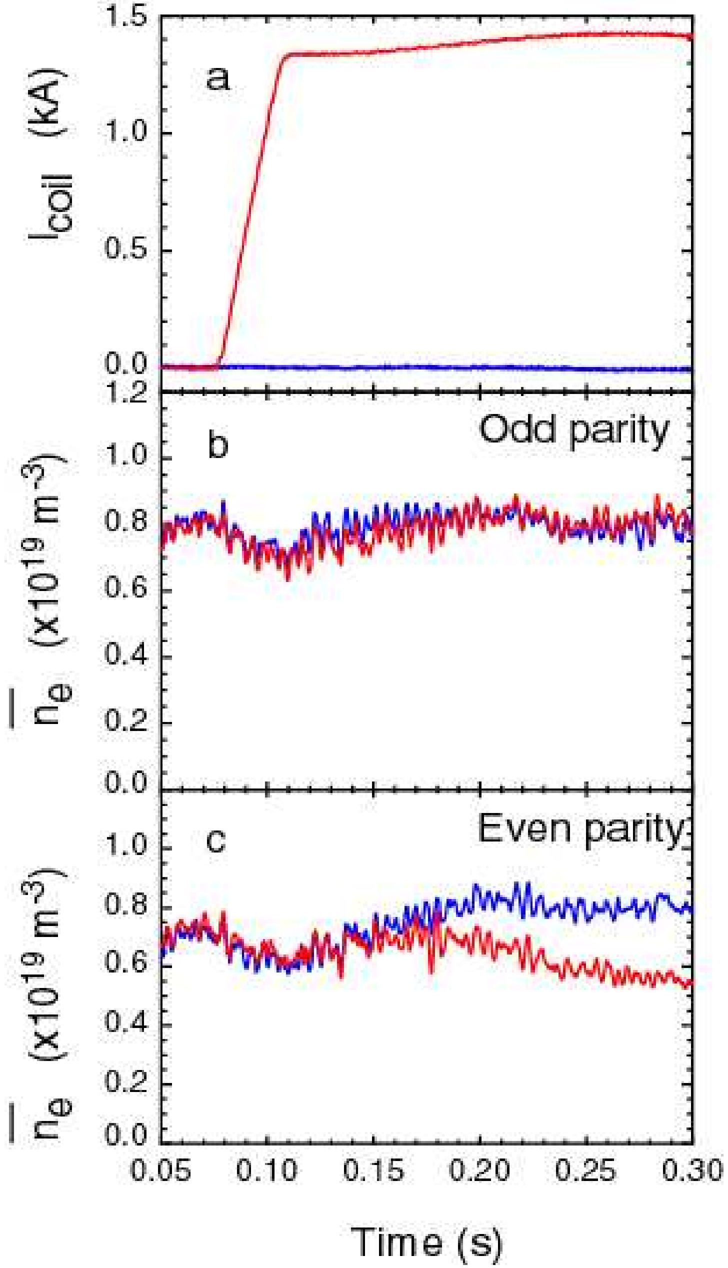
- ERGOS vacuum modelling predicts large $\sigma_{Chirikov}$
  - Larger than for ELM suppression with the I-coils on DIII-D
  - This is also the case for the MAST EFCCs

- In L-mode, a density pump-out is observed
  - – Only with the resonant configuration of the coils (here even)
  - – Associated with a clear effect on I_{SAT} signal from the reciprocating probe





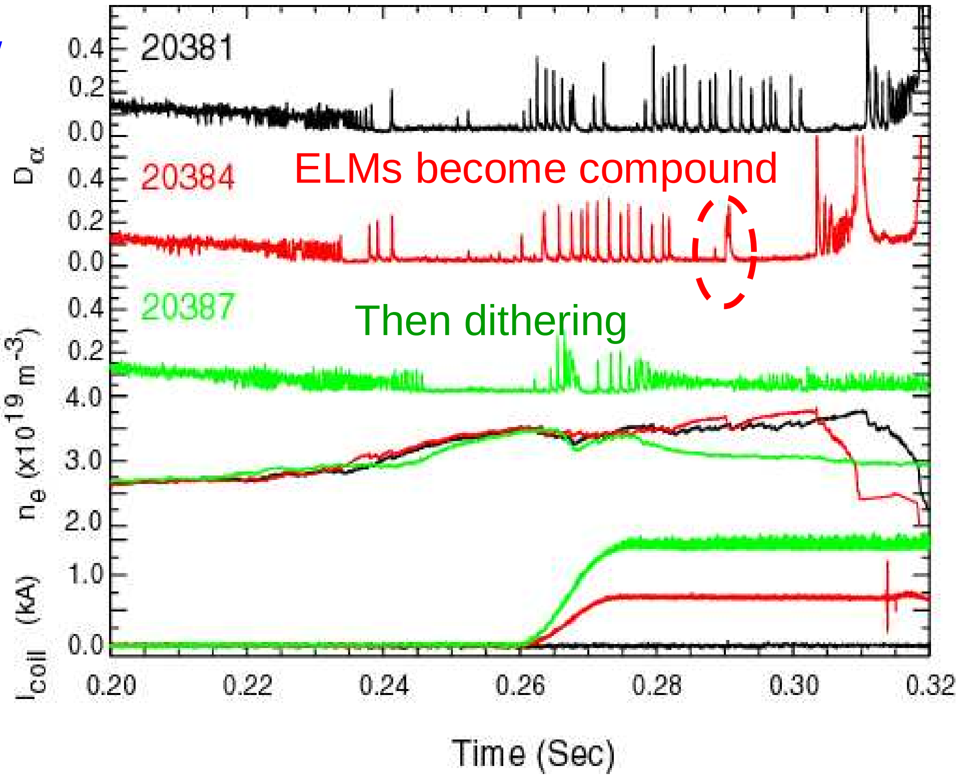


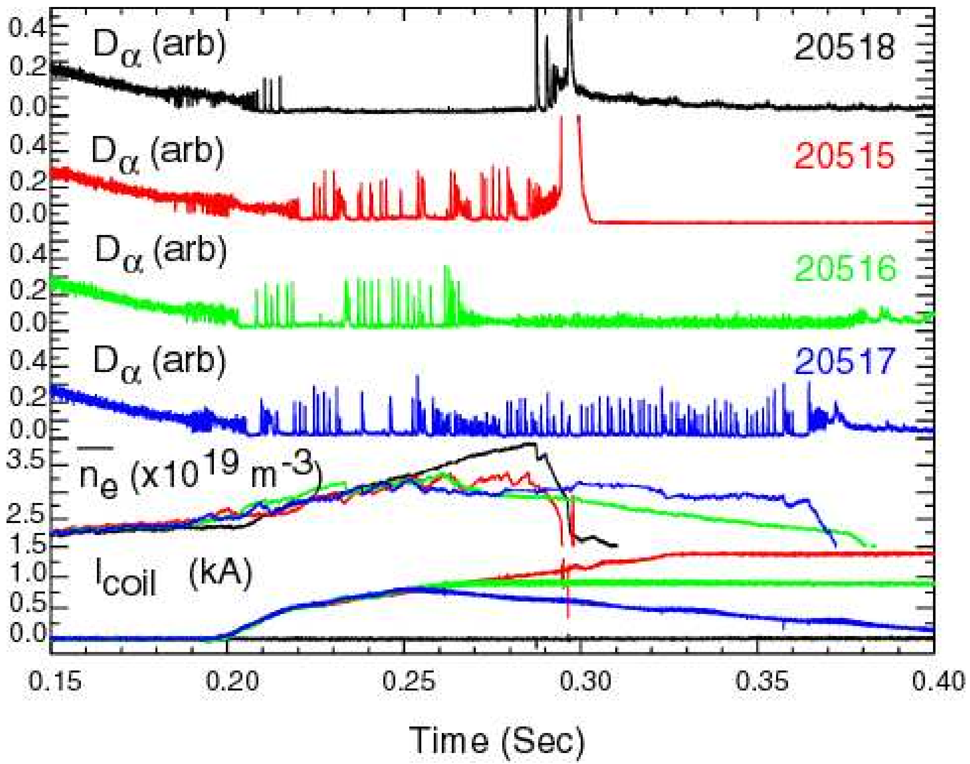


• Preliminary H-mode experiments show clear effect on the ELMs

– When increasing I_{coil}, the ELMs become compound, then dithering

– An ELM-free plasma can be turned into a regular ELMing one by applying the coils (~NSTX, COMPASS, JFT-2M)





– Again, the effect is much stronger with the resonant coils configuration

– Further tests are required when a repeatable ELMing discharge is fully established (second NBI available after Christmas)

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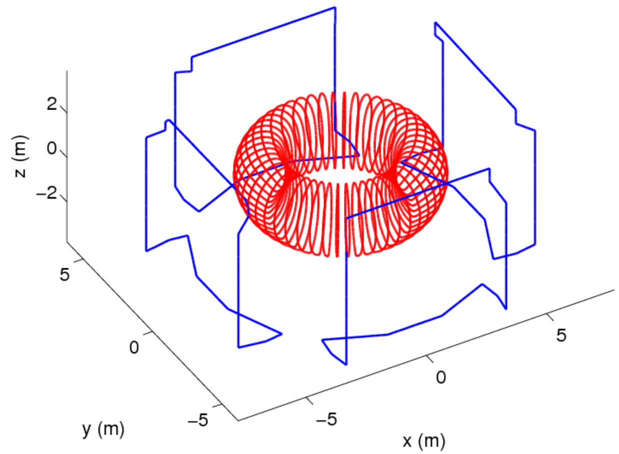
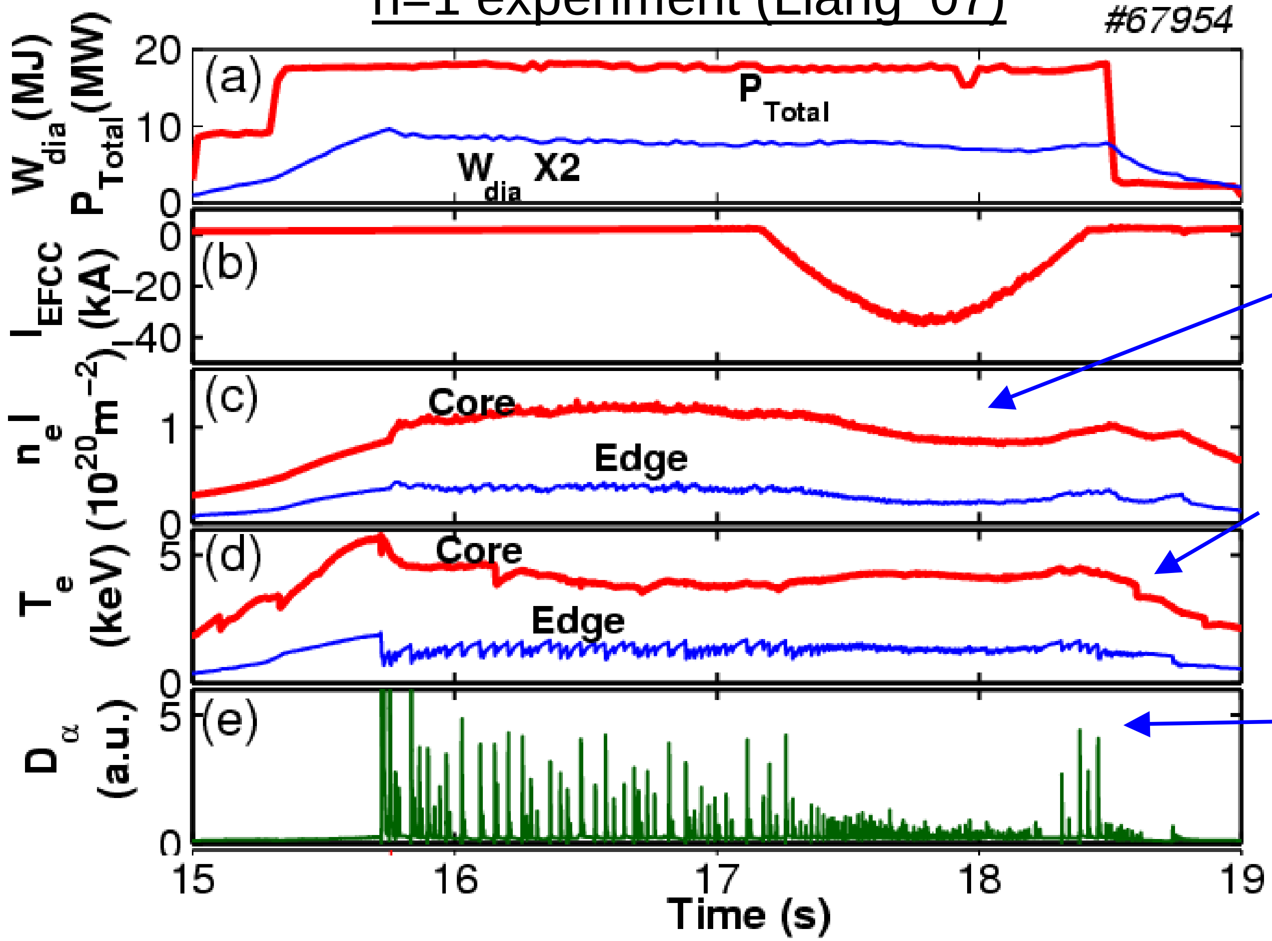
EFCCs: n = 1 or 2, <36.8kAt



ELM control has been demonstrated on JET with the EFCCs

n=1 experiment (Liang '07)



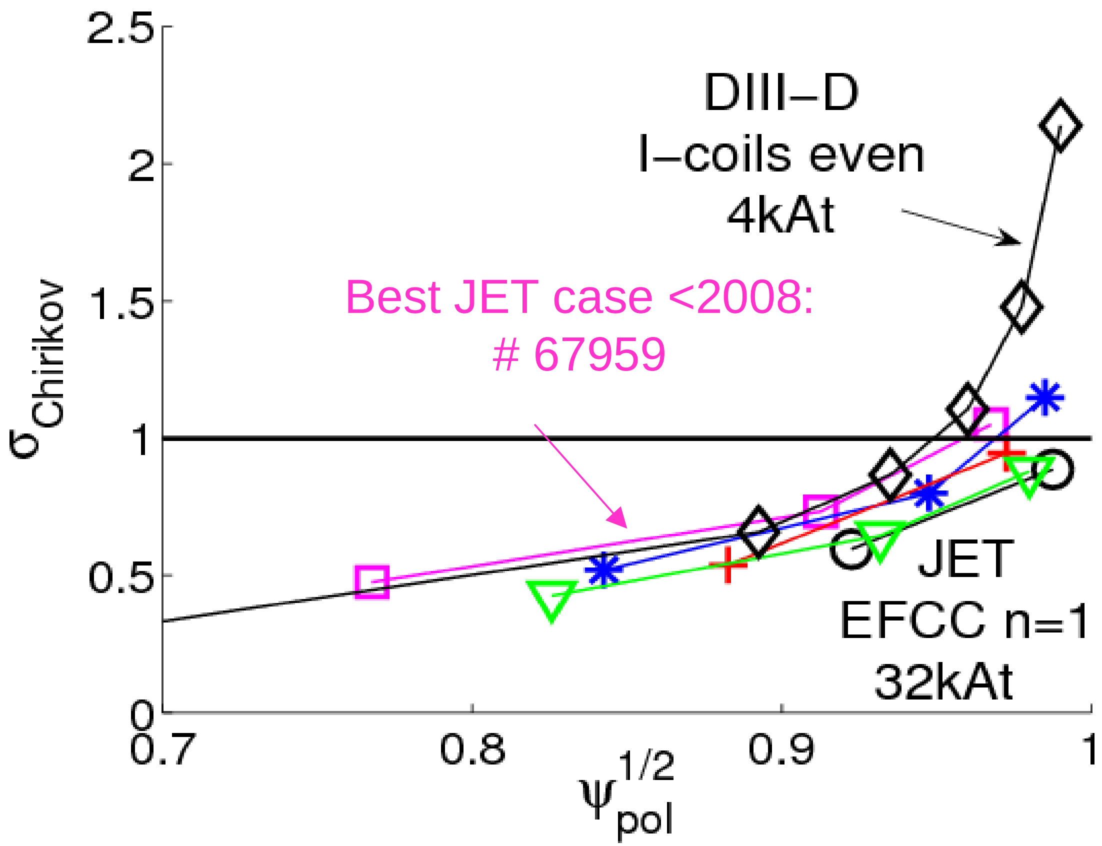
Pump-out (~DIII-D)

No drop in $dT_e/dr|_{ETB}$ (~DIII-D)

$f_{ELM}\uparrow$, $\Delta W_{ELM}\downarrow$

…But ELM suppression was not obtained so far

- ERGOS modelling suggested that the perturbation from the EFCCs was possibly not strong enough up to now
  - The DIII-D criterion $\Delta_{Chir>1}$ > ~8% was not fulfilled

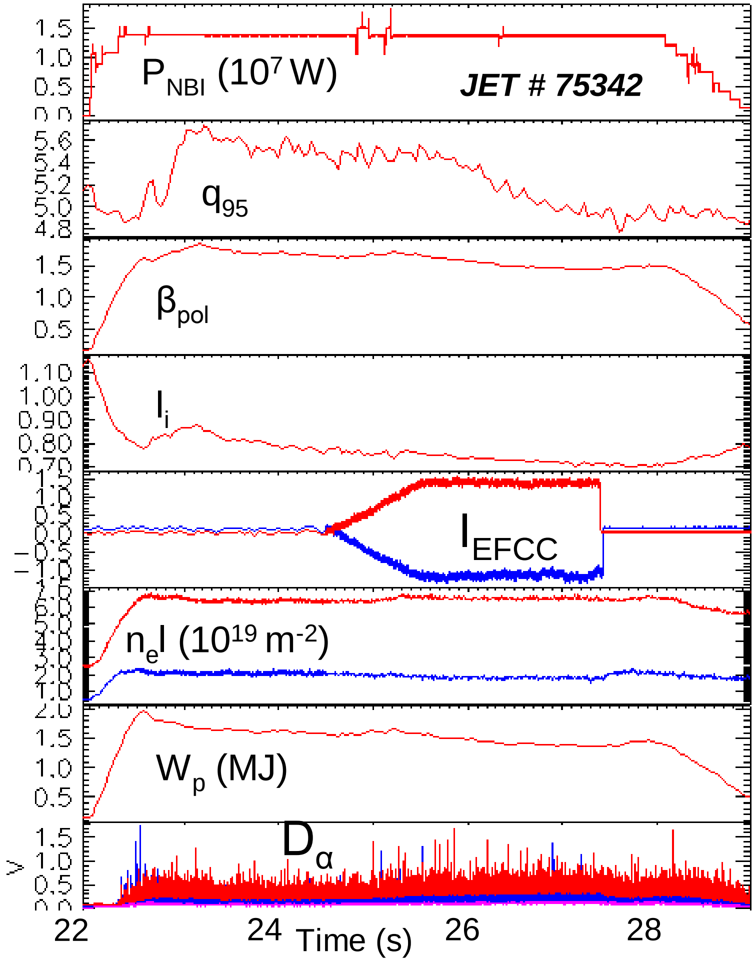


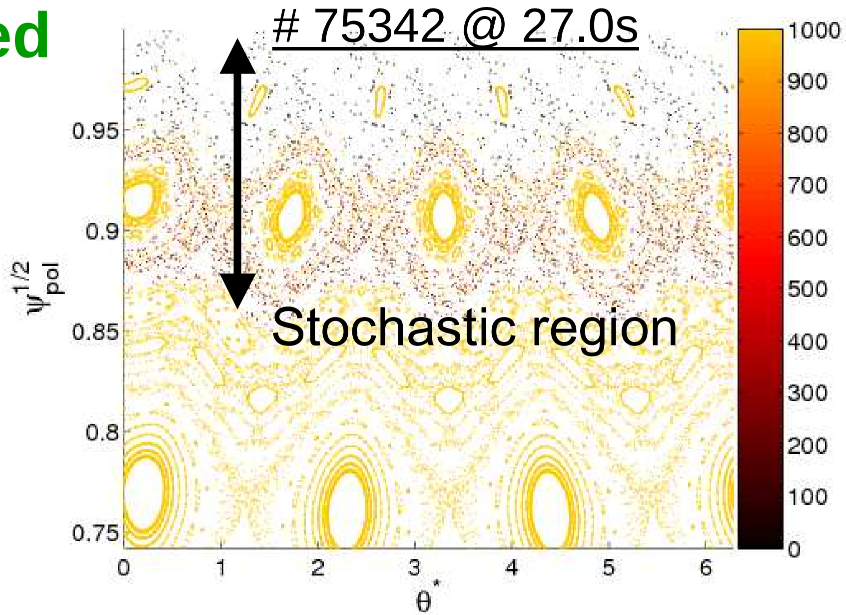
In recent experiments, we optimised the scenario to maximise $\Delta_{Chir>1}$

- Optimisation based on ERGOS vacuum modelling

$\Rightarrow$ Work at low I_p & B_t, high β_p, EFCCs n=1

I_p= 0.84 MA; B_t= 1.26-1.16T





- The criterion $\Delta_{Chir>1}$ > ~8% was fulfilled but **no success on ELM suppression**
  - Other "ingredients" may be required
    - Remark: DIII-D has never claimed that the criterion $\Delta_{Chir>1}$ > ~8% is sufficient for ELM suppression
  - Midplane coils not suited for ELM suppression?
    - In line with DIII-D results using midplane C-coils
  - Relevance of vacuum approximation?

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Is the B field really stochastic over the outer 8% of the radius?

➢ This is suggested by the vacuum modelling, but

- Difficult to believe considering that $dT_e/dr|_{ETB}$ increases rather than drops
- What about rotational screening?

➢ Here, we present a basic non-linear MHD modelling in cylindrical geometry for DIII-D-like parameters

➢ Islands penetration into the pedestal is slightly different from islands penetration into the core

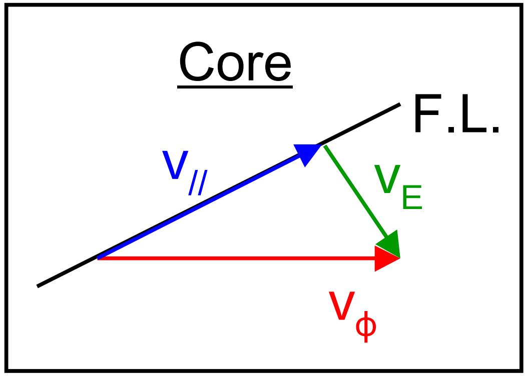
- Indeed, what matters for the screening is

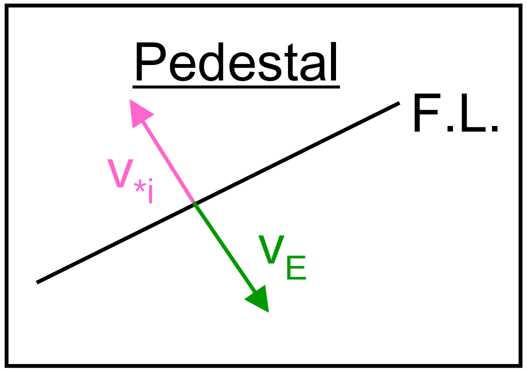
$$v_{e,perp} = v_E + v_{*e}$$

with $v_E = (E_r x B)/B^2$

and $E_r = v_{\phi i}B_\theta - v_{\theta i}B_\phi + v_{*i}B$

- Core and pedestal are different because:
  - While in the core $E_r \sim v_{\phi i}B_\theta$, in the pedestal $E_r \sim v_{*i}B$
  - And while in the core $v_{*e} << v_E$, in the pedestal $v_{*e} \sim v_E$



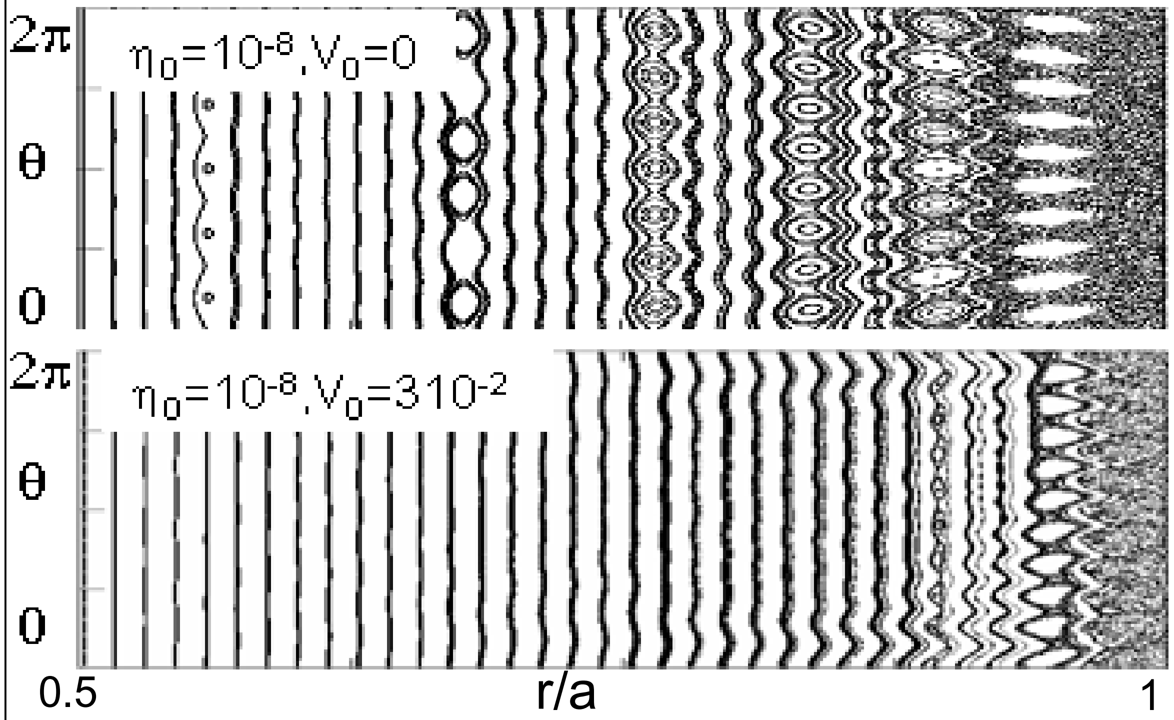


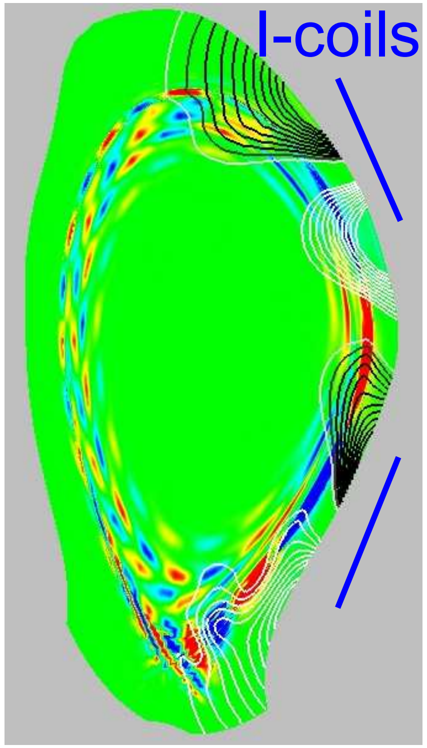
⇒ Diagmagnetic effects are of order 0 in the pedestal

Several previous works miss the important diamagnetic effects

- Nardon '07: JOREK simulations (non-linear MHD in realistic geometry)
  – No diamagnetic effects (screening only from v_ϕ)
  – Also, η several 100 times larger than experimental
- Bécoulet '08: cylindrical non-linear MHD simulations and formulas from Fitzpatrick '98
  – No diamagnetic effects (screening only from v_ϕ)

Bécoulet IAEA '08 (DIII-D simulation)





JOREK
DIII-D simulation
Colorplot of $j_\phi^{n=3}$
+ isocontour lines
of $\psi_{pol}^{n=3}$

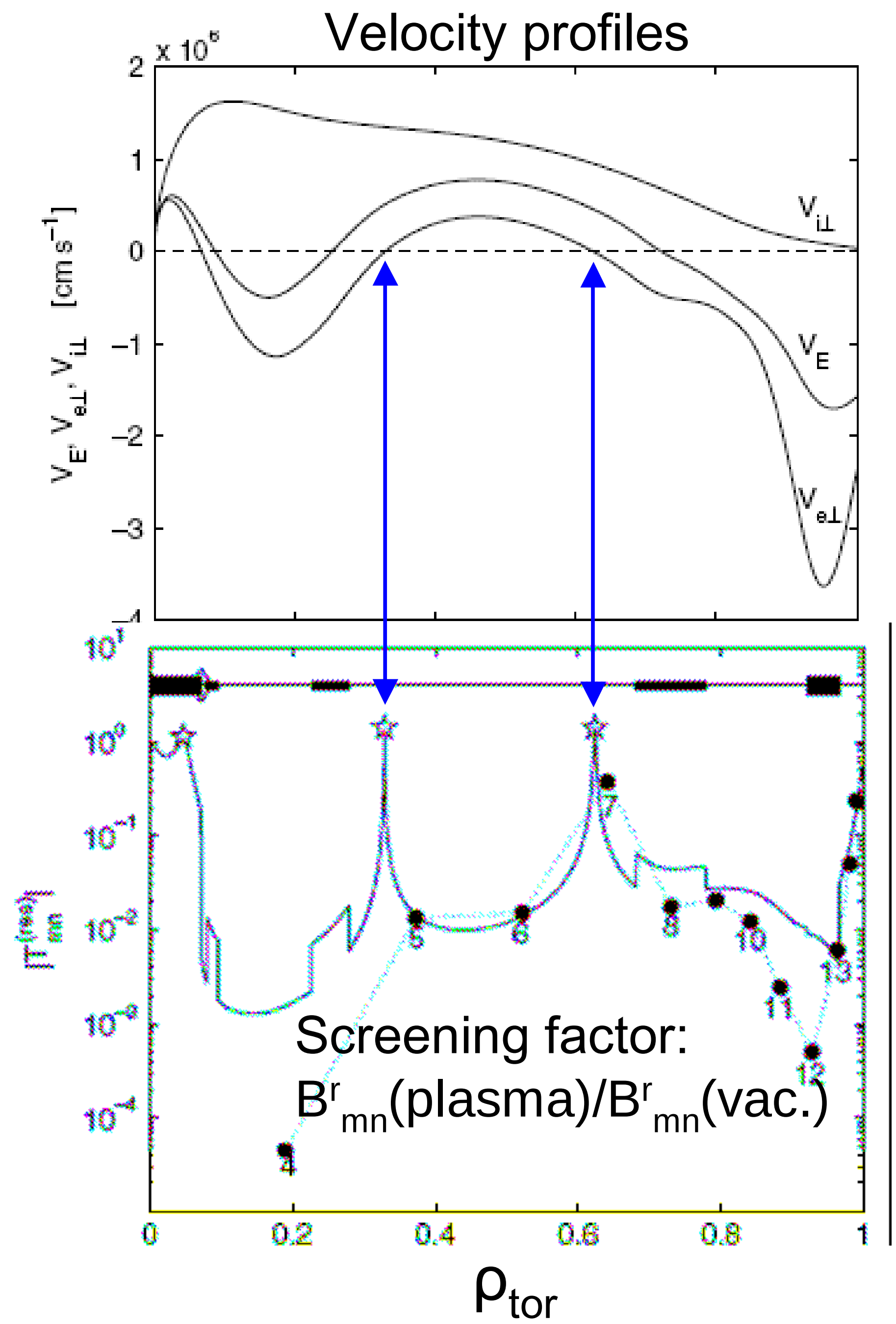
Heyn '08 includes the diamagnetic effects

➢ Cylindrical, kinetic simulations and formulas from Cole '06

➢ E_r is calculated from $v_{\phi i}$ and v_{*i} experimental profiles, assuming $v_{\theta i}=0$

⇒ Strong screening (factor ~100) everywhere except
- at the very edge (large η)
- at locations where $v_{e,perp}=0$

➢ Our work resembles M. Heyn's but it is based on a fluid model and we directly use the experimental E_r profile



M.F. Heyn et al., Nucl. Fusion 48 (2008) 024005

The model: cylindrical non-linear reduced MHD with cold ions and β=0

Induction equation: $$\partial_t \psi + \boxed{\nabla_{//}(\phi - \delta p)} = \eta (J - J_0)$$

Origin of screening currents:

$$\boxed{(\overline{v}_E + \overline{v}_{*e}) \cdot \widetilde{B}_r}$$

Source term through which we impose the E_r profile

Vorticity equation: $$\partial_t W + [\phi, W] + \nabla_{//} J = \boxed{\nu_\perp} \Delta_\perp (W - \boxed{W_0})$$

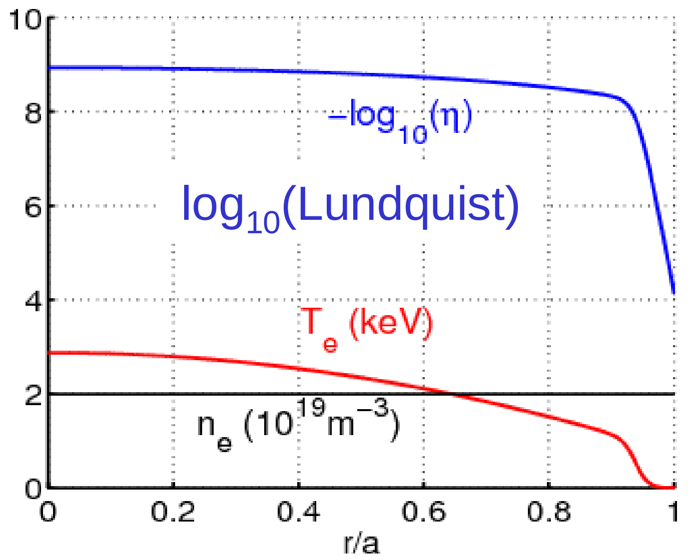
Limitation of the model: complex mechanisms (damping of poloidal rotation, physics of rotation in H-mode pedestal) are treated as viscosity

Pressure equation: $$\partial_t p + [\phi, p] = \kappa_\perp \Delta_\perp (p - \boxed{p_0})$$

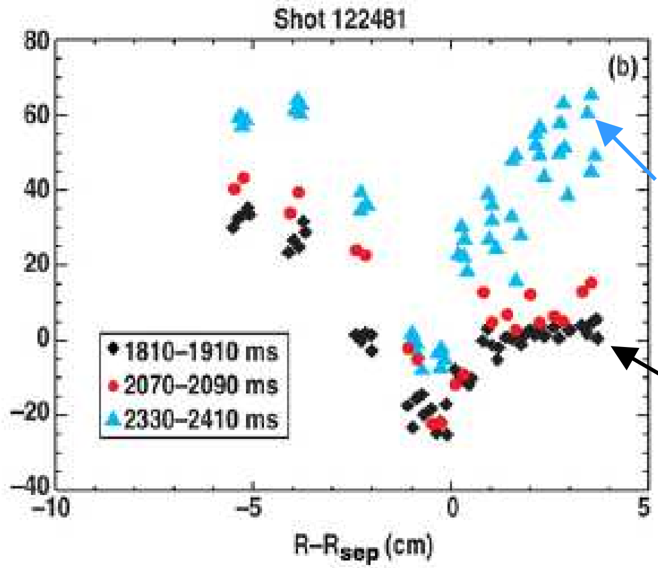
Source term through which we impose the H-mode pressure profile

Input parameters

- DIII-D-like parameters: $R=1.69m$, $a=0.6m$, $B_t=1.89T$
- Flat density: $n_e=2.10^{19}m^{-3}$
- 1keV T_e pedestal
- Realistic resistivity
  - This was a problematic limitation in JOREK simulations

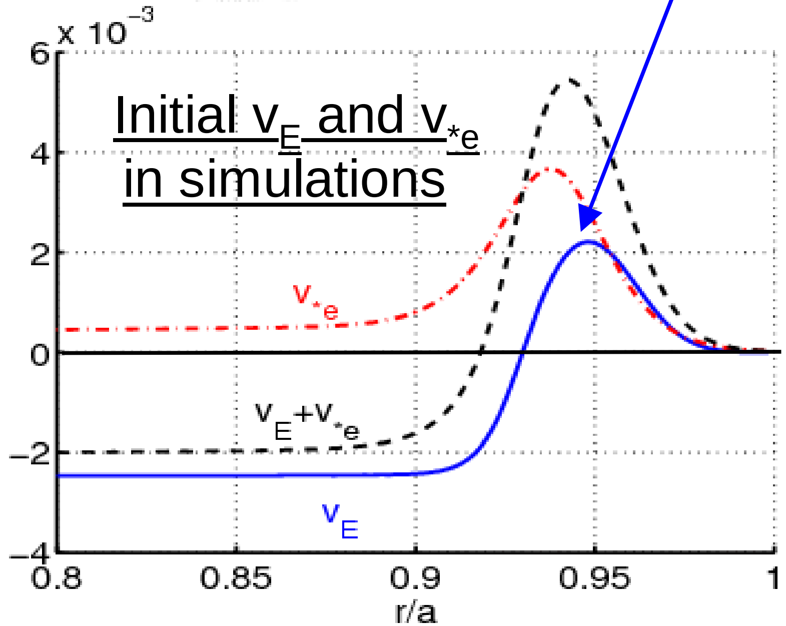


- Experimental E_r (kV/m) (Burrell, PPCF 47 (2005) B37)



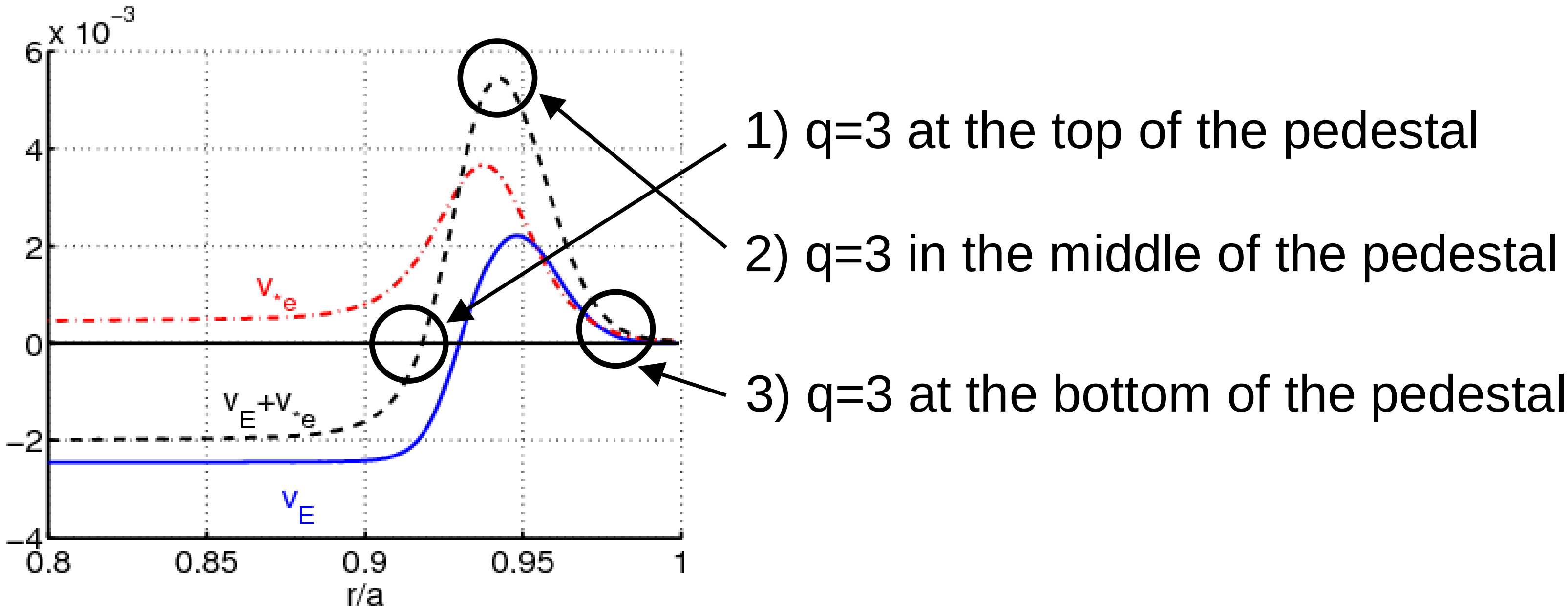
During I-coils (ELMs suppressed)

Before I-coils



- v_{*e} and v_E add up in the middle of the pedestal
- but cancel out at the top (≠ M. Heyn)

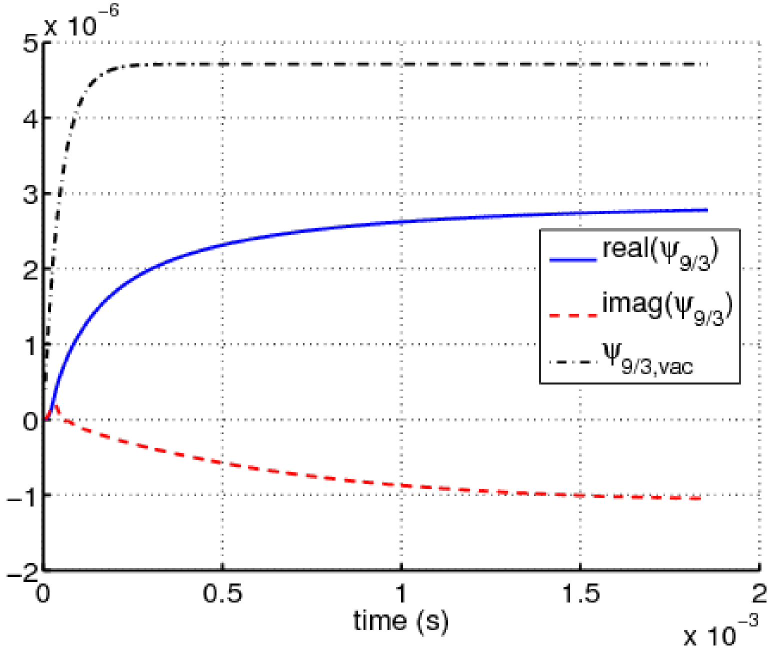
- Quadratic current profile: $J_0=J_{00}(1-(r/a)^2)^2$
- Only one harmonic of the RMPs is treated (m=9, n=3)
  - External forcing imposed through boundary conditions
  - RMPs amplitude on the order of the I-coils perturbations
- In reality there are several resonant surfaces across the pedestal
  - $\Rightarrow$ J_{00} is varied in order to move the resonant surface (q=3)



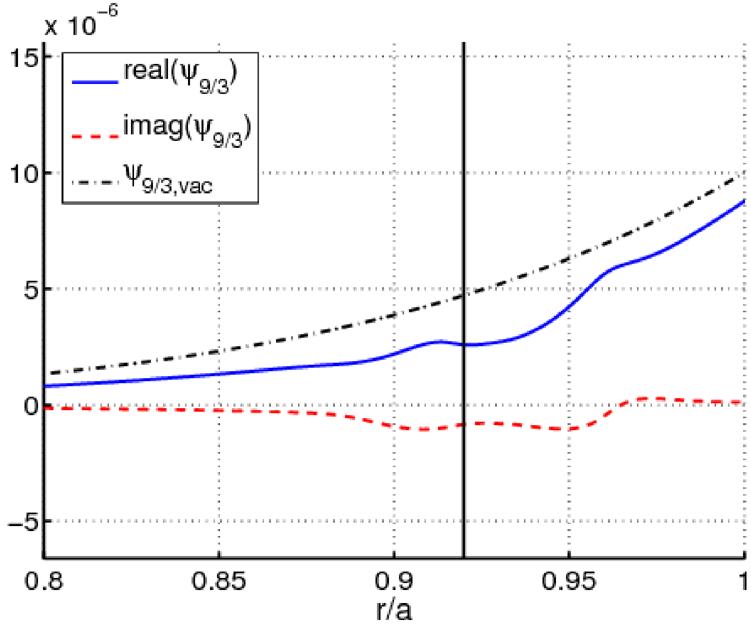
- Only the (m,n)=(0,0) and (9,3) harmonics are calculated
  - Non-linear model in the sense that (9,3) interacts with itself to modify (0,0))
- Viscosity: $Re=10^{-5} \leftrightarrow \sim 40 m^2/s$ (not clear what value to choose)

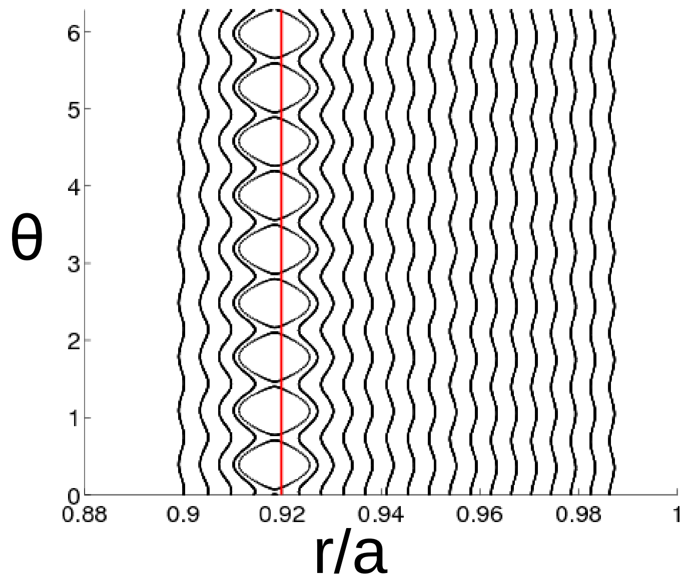
Results: 1) q=3 at the top of the pedestal

Evolution of $\Psi_{9/3}$ at q=3



Magnetic perturbations ($\Psi_{9/3}$) profile



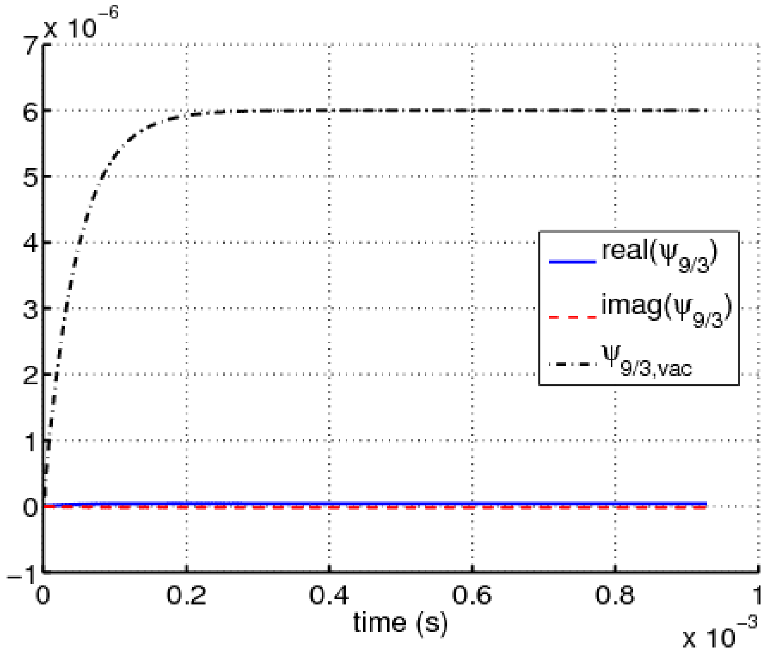


⇒ RMPs penetrate (although not fully)

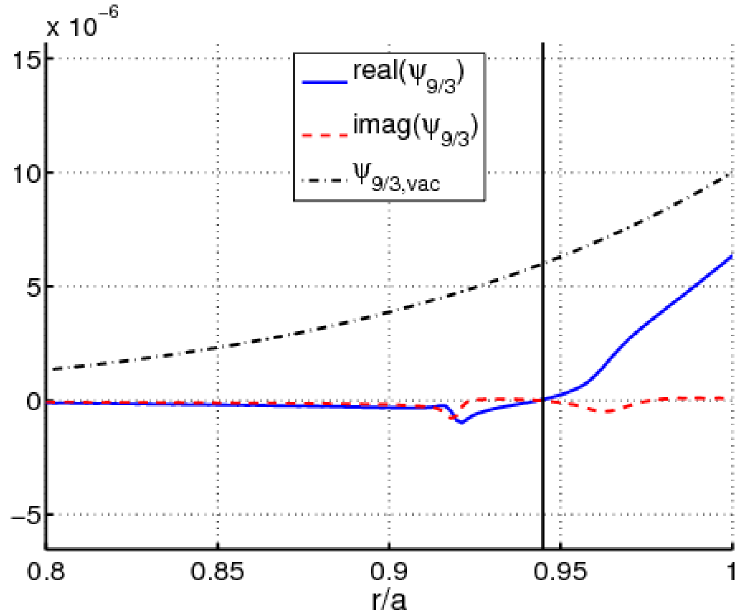
- Penetration time ~1ms

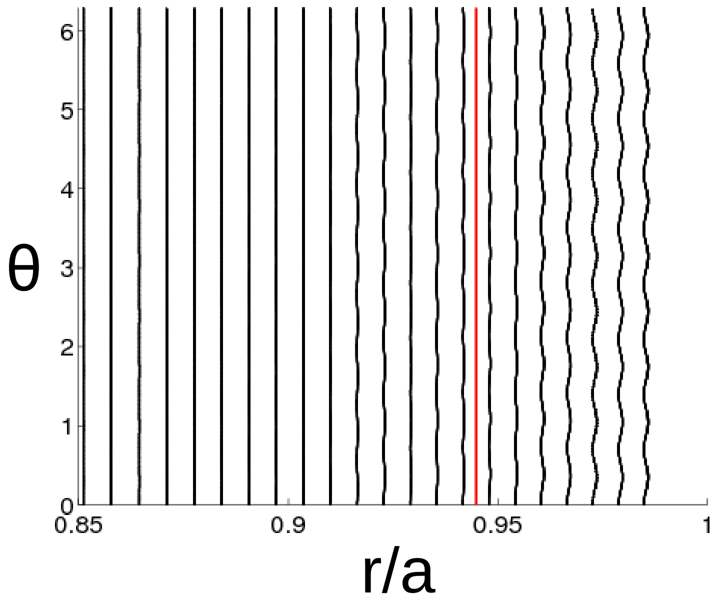
Results: 2) q=3 in the middle of the pedestal

Evolution of $\Psi_{9/3}$ at q=3



Magnetic perturbations ($\Psi_{9/3}$) profile





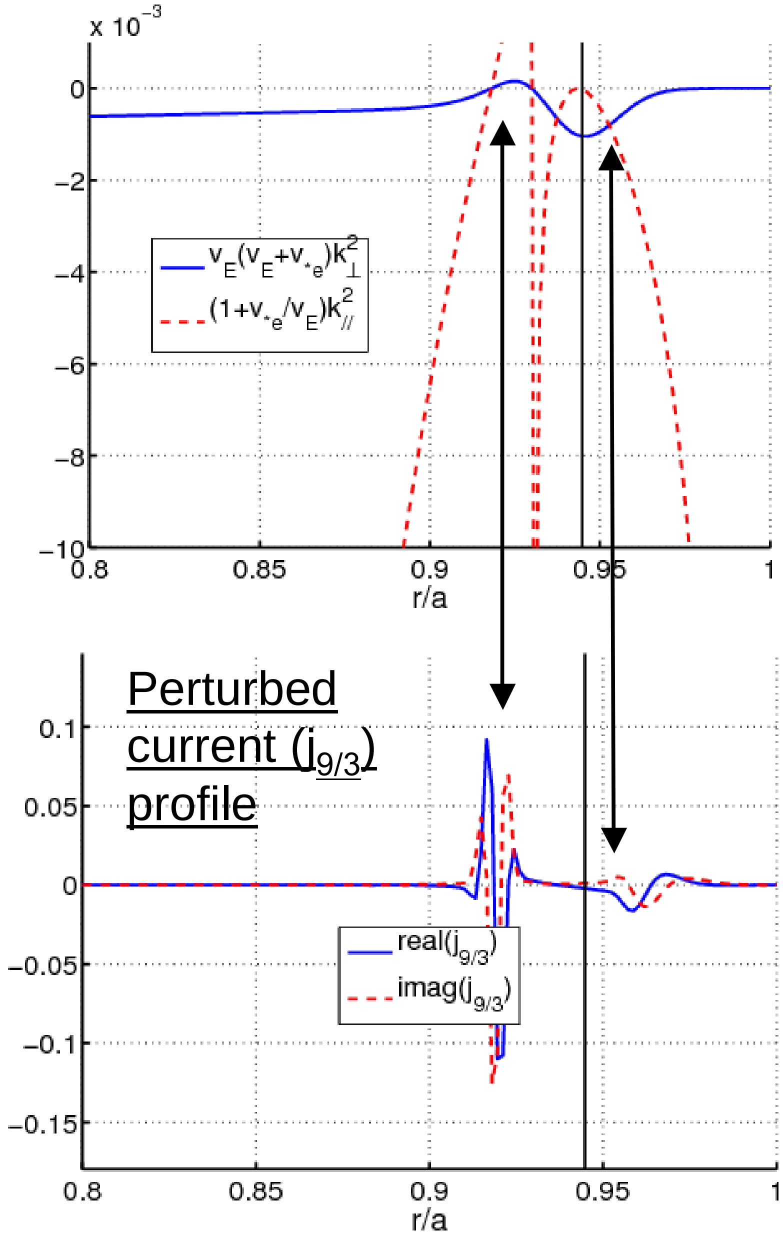
⇒ RMPs are strongly screened

- No reconnection at all: typical feature of the inertial regime *(Fitzpatrick '98)*

➢ The inertial regime is characterized by Alfvén resonances located outside the resistive layer

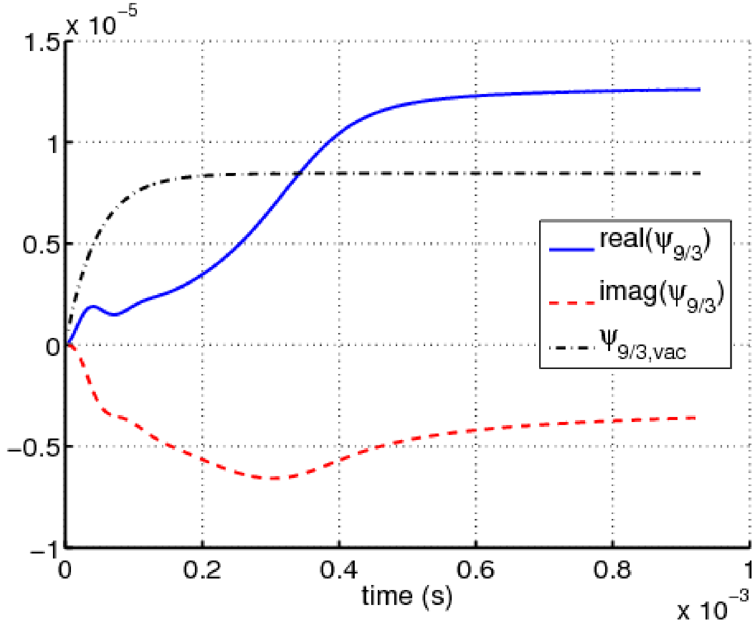
- Alfvén resonance condition:

$$v_E\left(v_E + v_{*e}\right)k_\perp^2 = \left(1 + \frac{v_{*e}}{v_E}\right)k_{//}^2$$

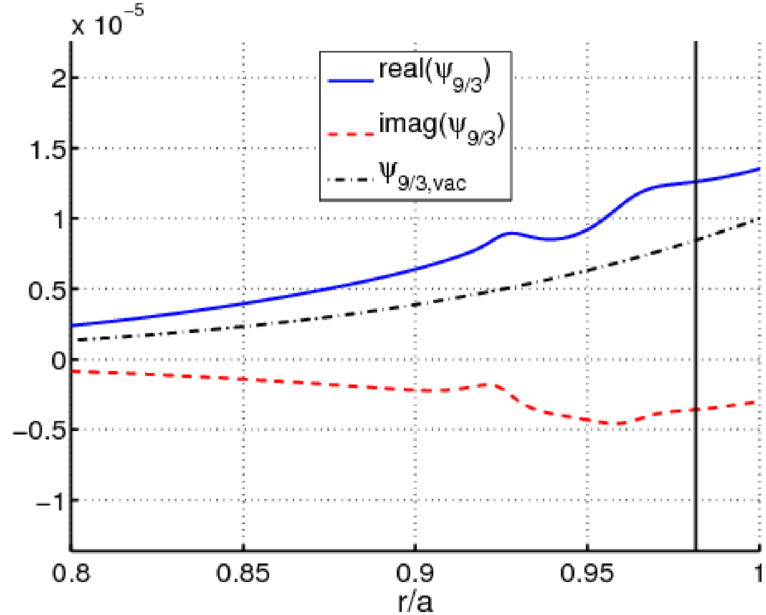


Results: 3) q=3 at the bottom of the pedestal

Evolution of $\Psi_{9/3}$ at q=3

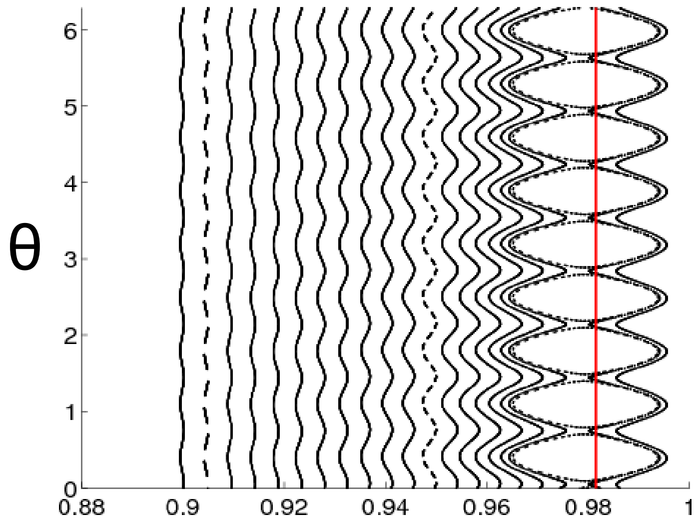


Magnetic perturbations ($\Psi_{9/3}$) profile



⇒ RMPs penetrate
(with even some amplification)

➢ Penetration time <500μs

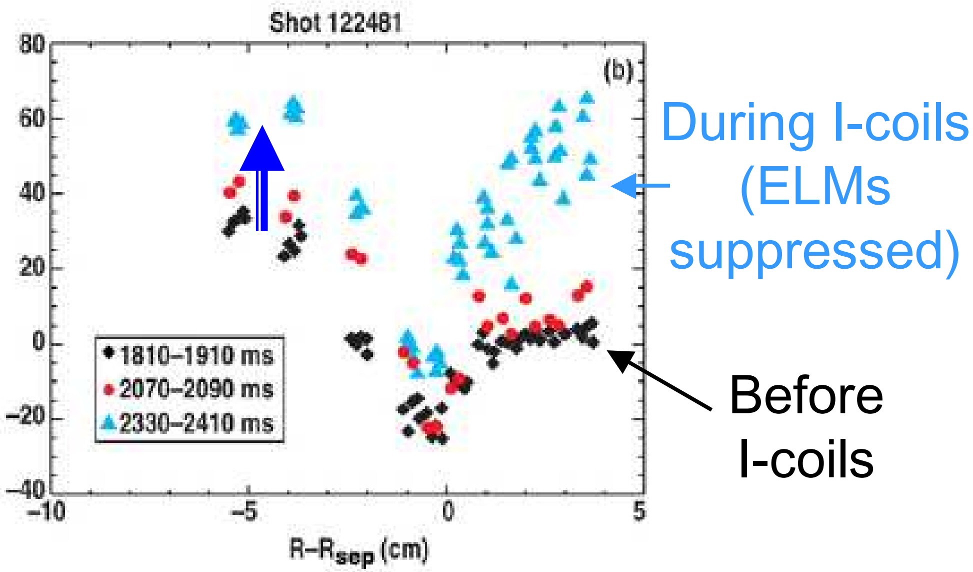


These results suggest a speculative picture of how the field may look like

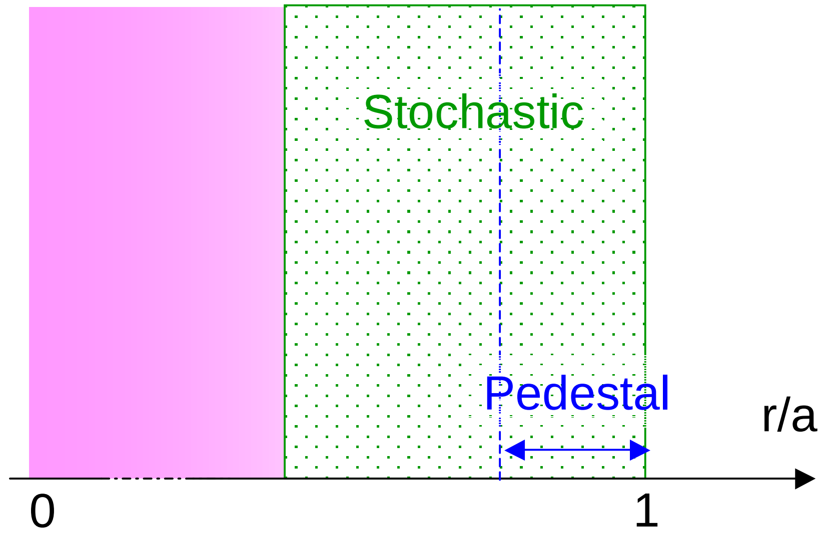
- Instead of one large stochastic layer, there could be two stochastic layers isolated by good flux surfaces

- Qualitatively consistent with both
  - the absence of drop in $dT_e/dr|_{ETB}$
  - the DIII-D criterion $\Delta_{Chir>1}$ > ~8%

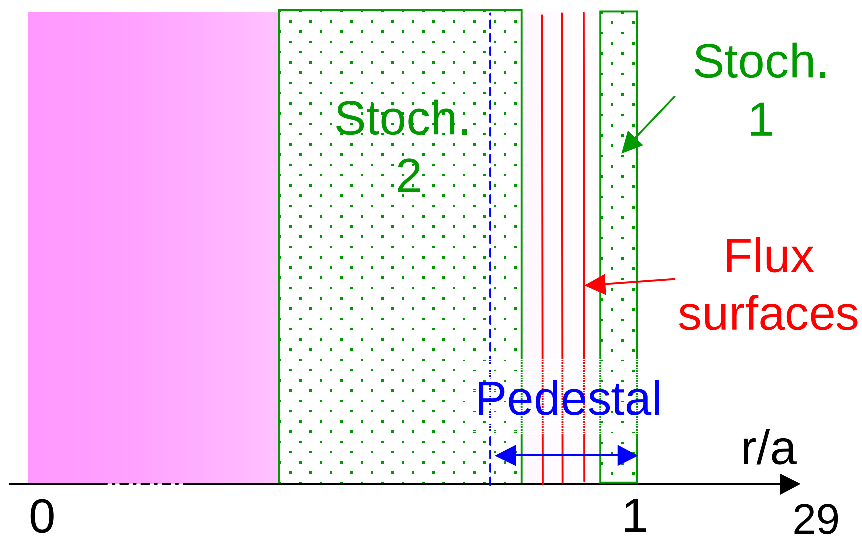
- However, at first sight it does not seem consistent with the increase in E_r inside the pedestal (because we expect penetration requires $v_E \sim v_{*e}$, and v_{*e} is small)



Vacuum field



With plasma response



Summary and outlook (1/2)

➢ ELM control by RMPs is a promising method for ITER but a better understanding is required

➢ MAST experiments show a clear effect of both EFCCs and new ELM control coils on the ELMs, but no ELM suppression in spite of large $\Delta_{Chir>1}$

- More experiments upcoming (2[nd] NBI available after Christmas)

➢ Ongoing experiments at JET aiming at maximising $\Delta_{Chir>1}$ with the EFCCs
$\Rightarrow$ No ELM suppression so far

- Next experiment will use EFCCs n=2 instead of n=1

$\Rightarrow$ ELM suppression appears more complicated to obtain than fulfilling $\Delta_{Chir>1} > 8\%$ (which is the guideline used for ITER up to now)

Summary and outlook (2/2)

- A basic non-linear MHD modelling strongly questions the vacuum approach
  - Diamagnetic effects are of order 0 in the pedestal
  - A strong screening is expected in the middle of the pedestal
  - Field penetration can take place at the very edge and towards the top of the pedestal

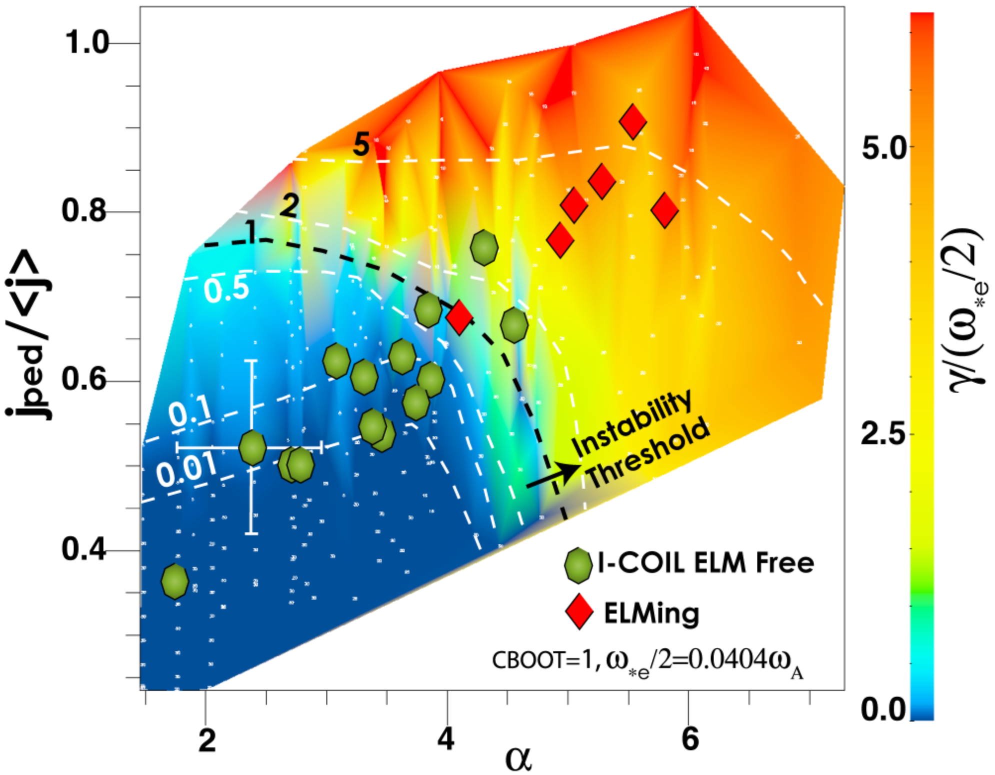
- Much progress to be done on the modelling
  - Cylindrical modelling: calculate several harmonics (e.g. 8/3+9/3+10/3), include more physics (damping of the poloidal rotation etc.)
  - Come back to realistic geometry (JOREK, BOUT++ [Univ. York]) and include diamagnetic effects

Back-up slides

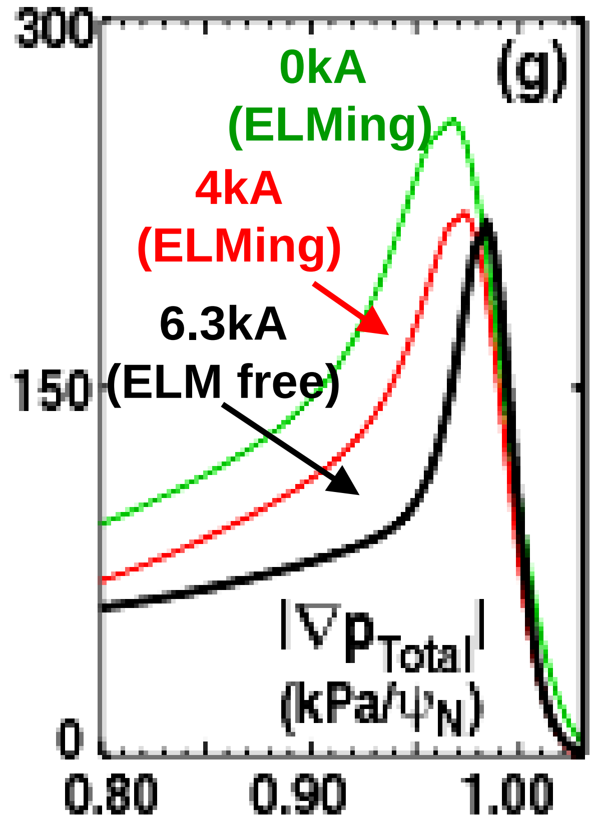
Ideal MHD stability analysis

➢ In DIII-D, RMPs maintain the profiles in the stable region for peeling-ballooning modes

- The peak value of dp/dr is not affected much
- The region most affected by the RMPs is actually inside the pedestal



Snyder '07



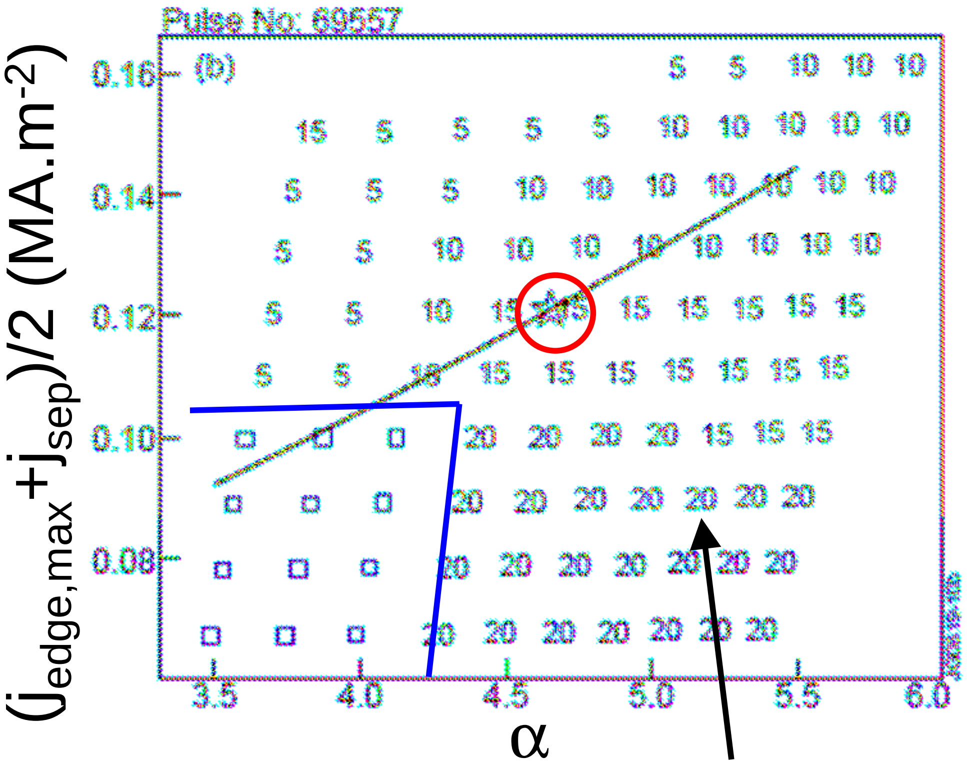
Evans '08

Ideal MHD stability analysis

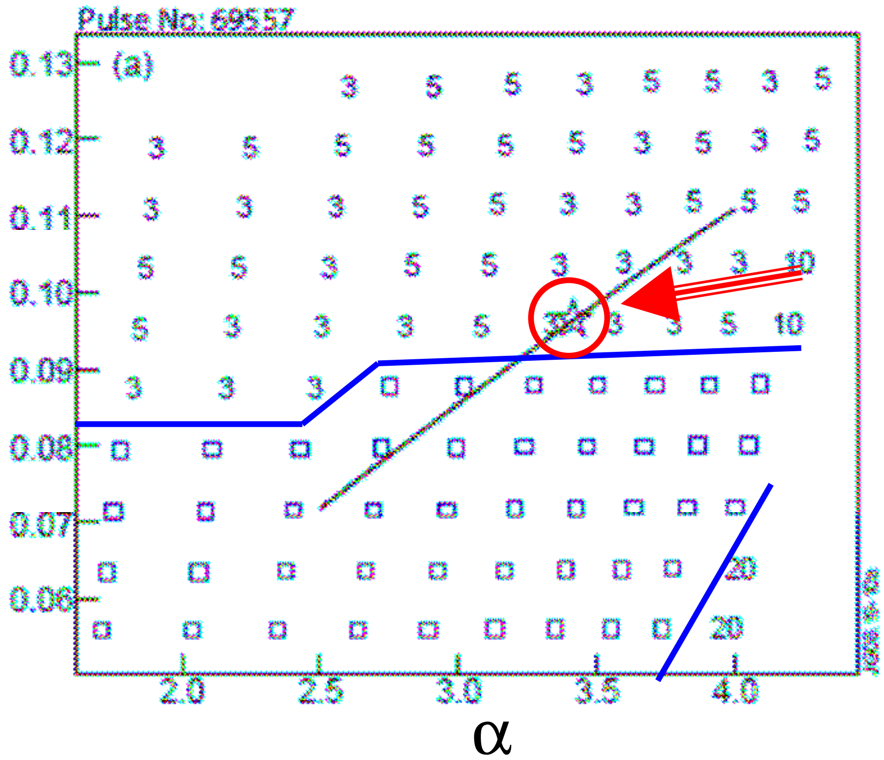
➢ In JET, the plasma remains unstable but moves towards the peeling boundary *(Saarelma '08)*

- Mode structure less extended radially, consistent with smaller ELM size

Before EFCCs pulse



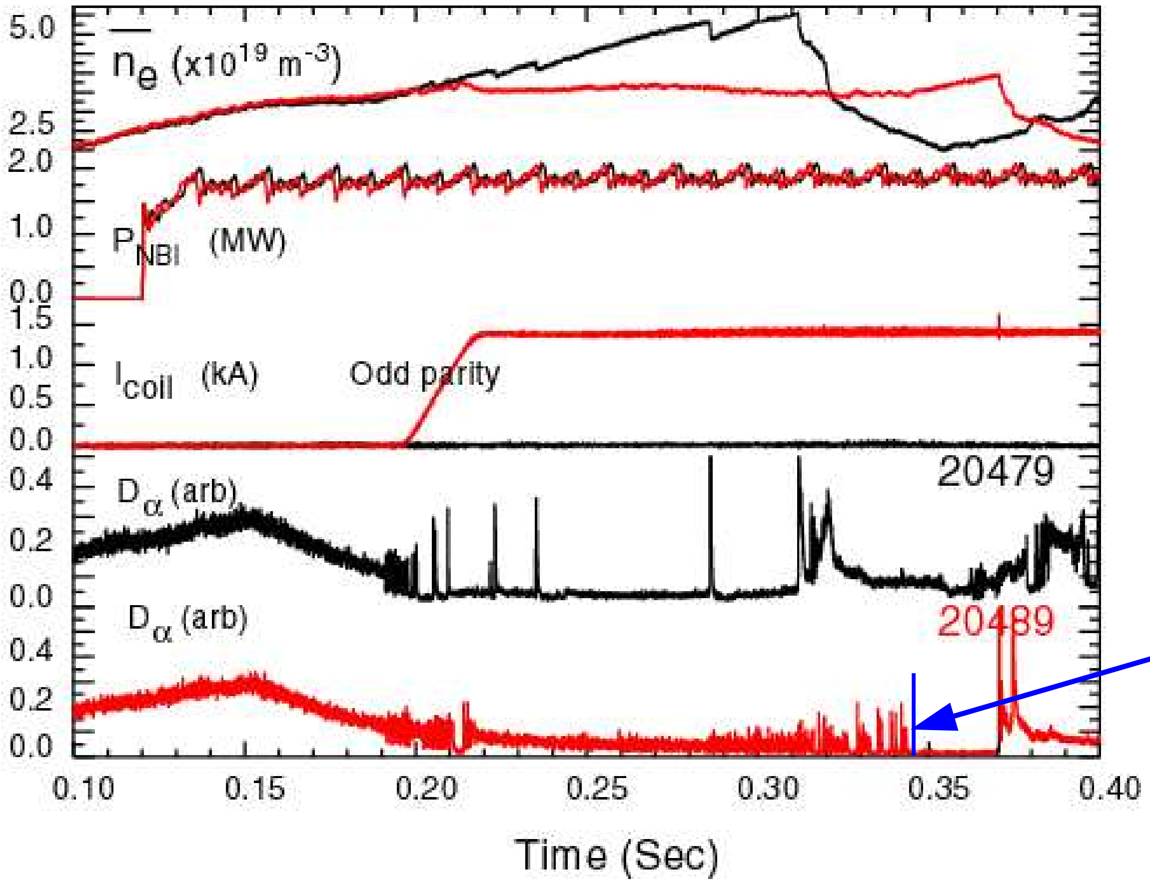
During EFCCs pulse

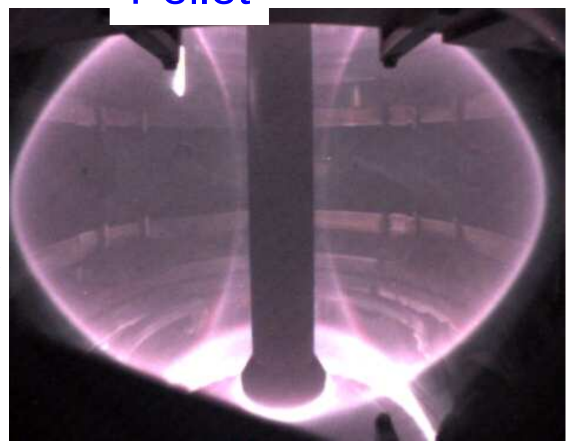


Toroidal mode number of most unstable mode

• A key question for ITER is the possibility to combine ELM mitigation and pellet fuelling

– In MAST, a pellet makes the dithering plasma become ELM-free



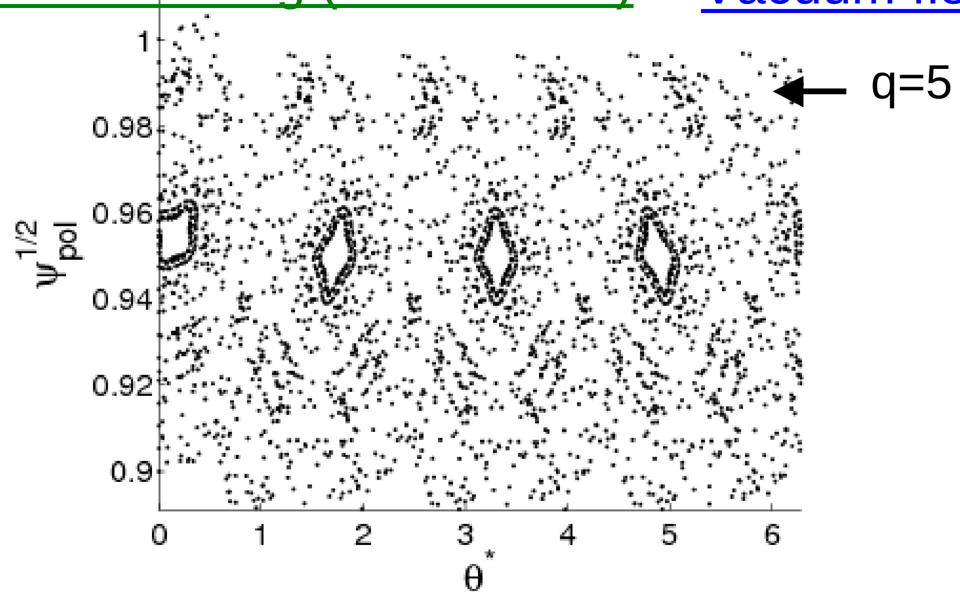


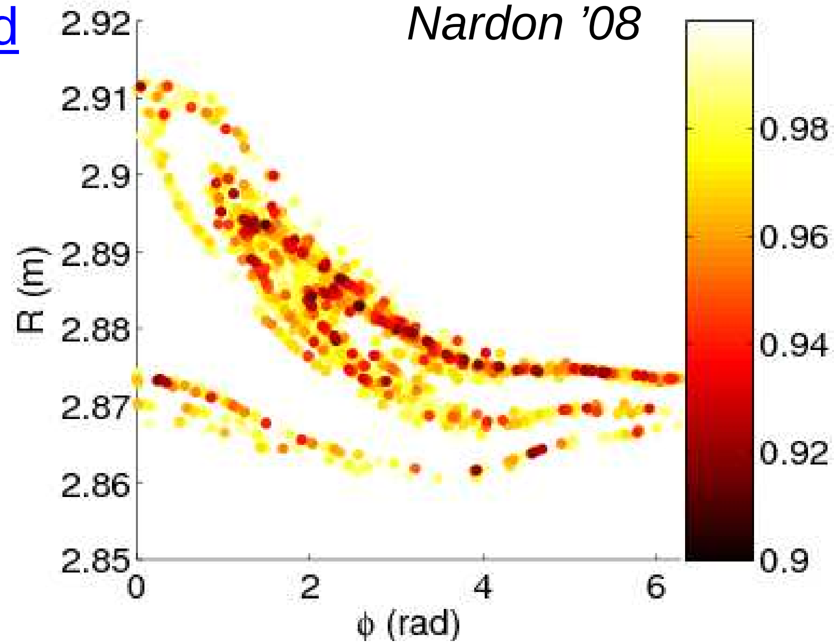
Screening currents do not change magnetic footprint envelope

JET modelling (EFCCs n=1)

Vacuum field

Nardon '08





With helical currents put by hand on q=5 to screen the local RMPs