ELMs control
by
Resonant Magnetic Perturbations (RMPs)

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Outline

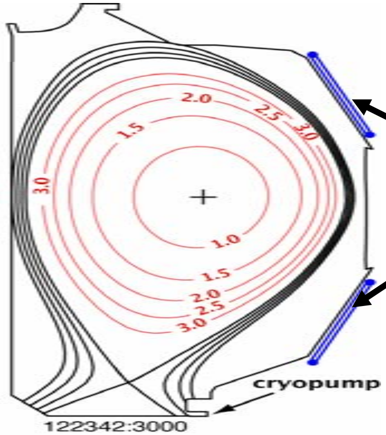
- DIII-D experimental results and interpretation

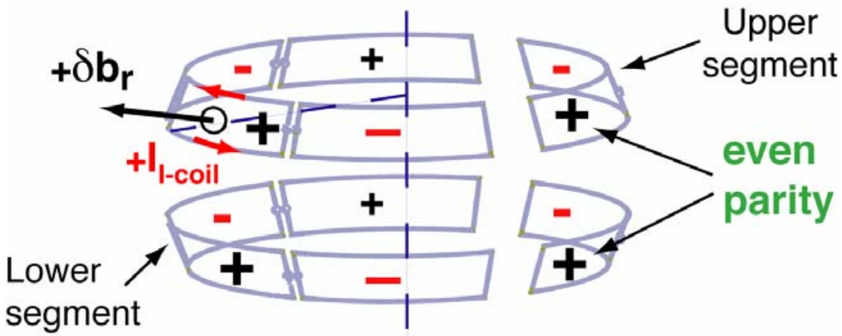
- A model for ELMs control by RMPs using the Vacuum Field (VF) hypothesis

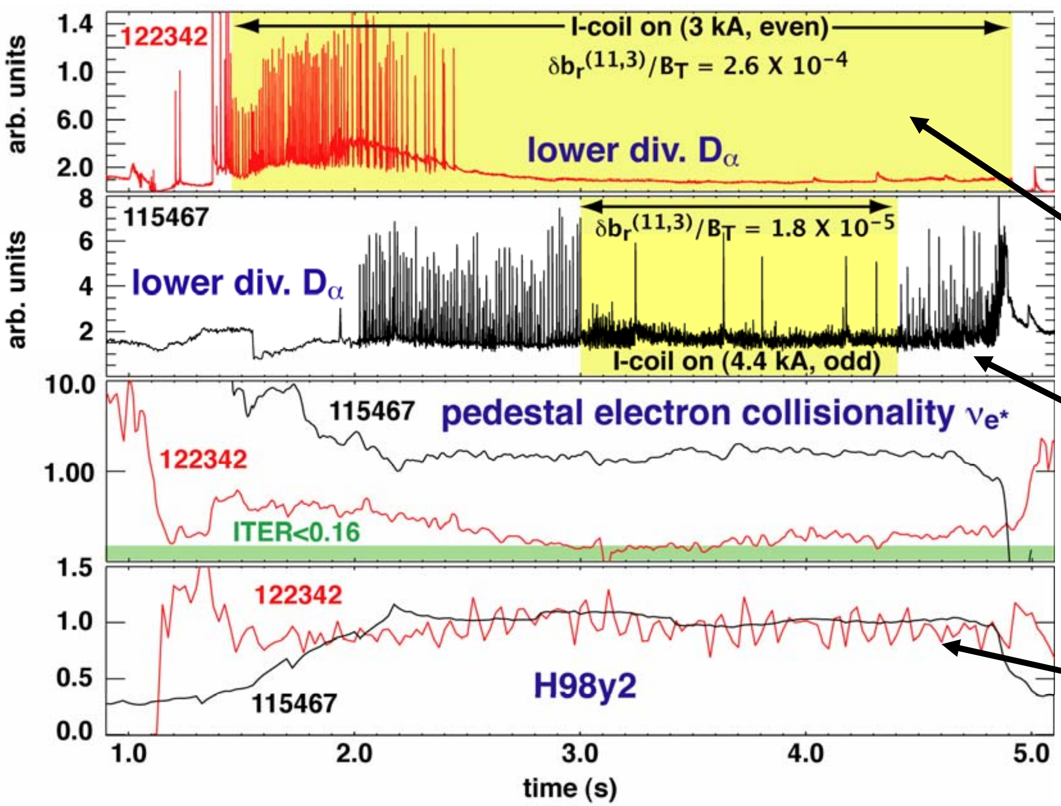
- Design of the coils for JET and ITER using the VF hypothesis

- The plasma MHD reaction to the RMPs, or is the VF hypothesis right?

DIII-D experimental results and interpretation (1/2)





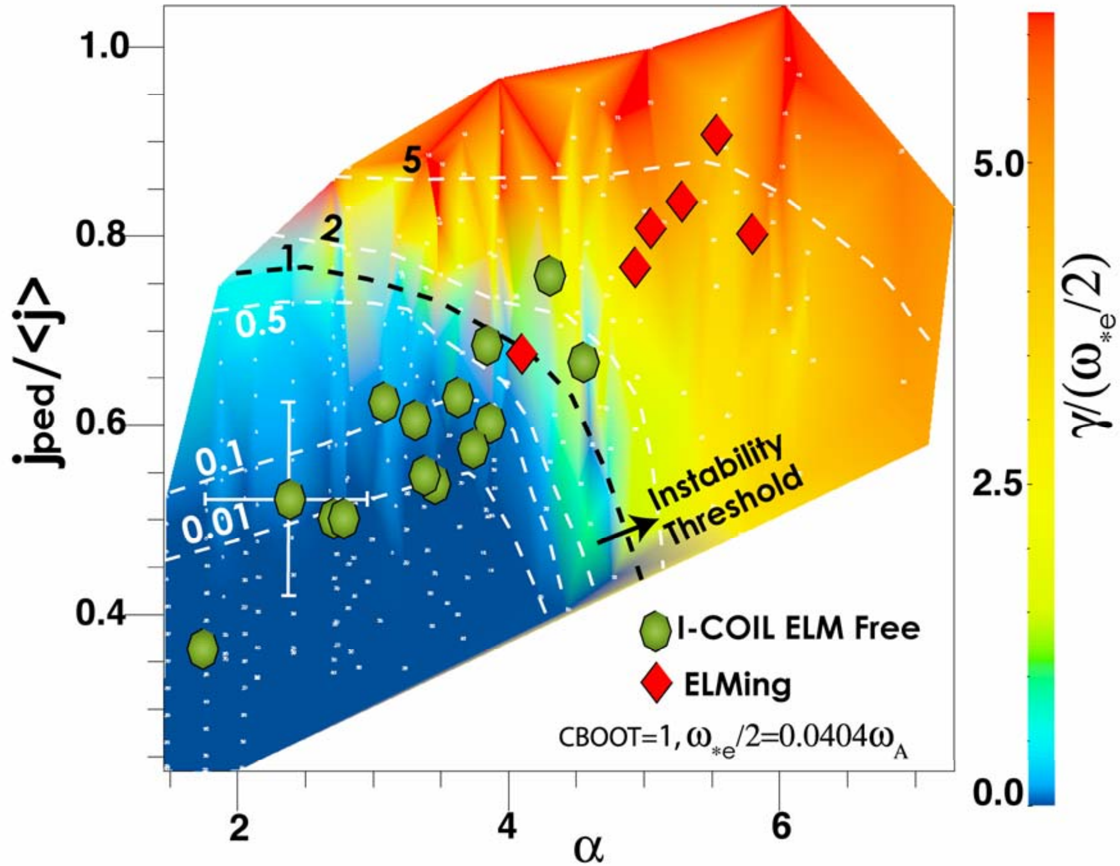


ELMs suppression established…

at low collisionality,

at high collisionality,

…and with no degradation of confinement!

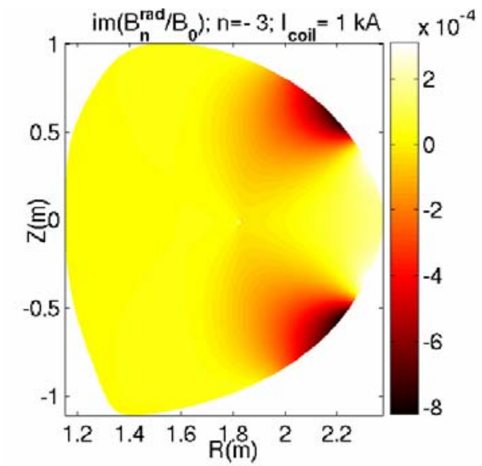


T. Osborne, EPS 2005

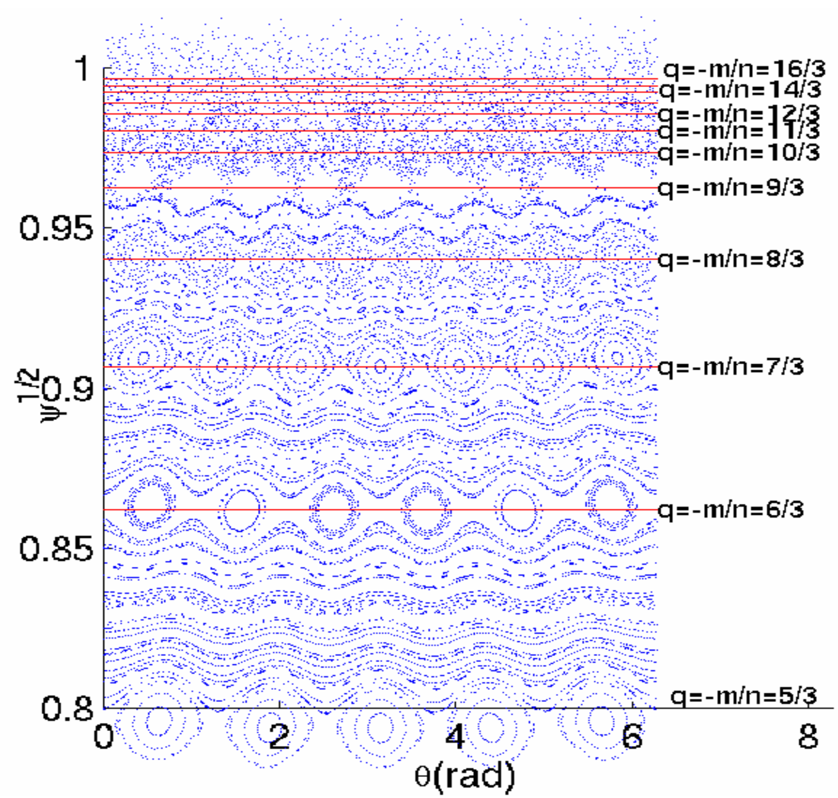
ELMs suppression seems due to a decrease in $\left|\partial_r P\right|_{ped}$ and $\left|j\right|_{ped}$

A model for ELMs control by RMPs, using the Vacuum Field (VF) hypothesis (1/2)

<u>VF hypothesis</u> = one considers the magnetic field in the plasma is the same as it would be in vacuum
= one neglects any magnetic response of the plasma



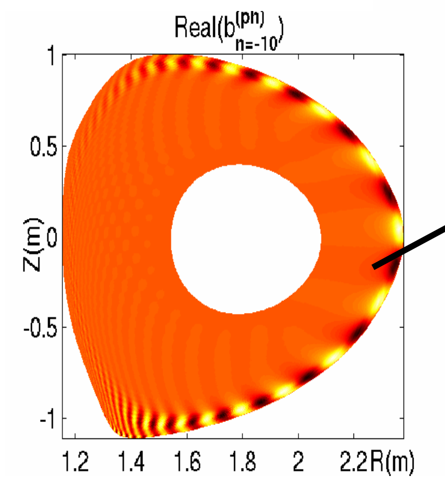
DIII-D I-coil radial perturbation: δB_r

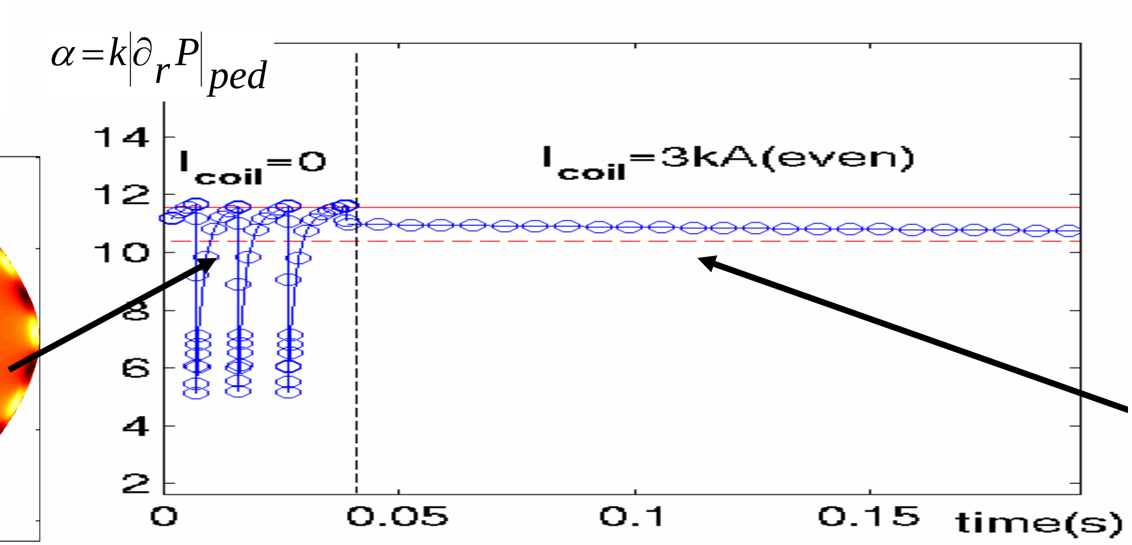


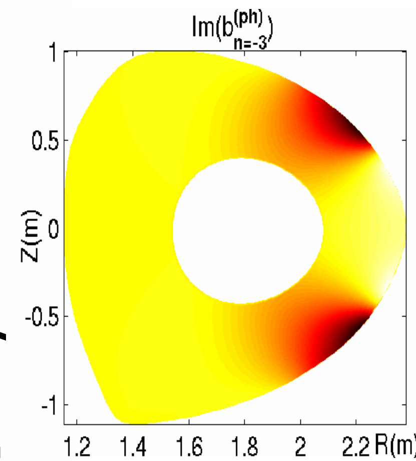
The Poincaré plot shows edge ergodization
<u>Model</u> = edge ergodization => enhancement of radial heat transport => reduction of $\left|\partial_r P\right|_{ped}$ => ELMs suppression

A model for ELMs control by RMPs, using the VF hypothesis (2/2)

<u>Heat transport simulation with TELM</u>



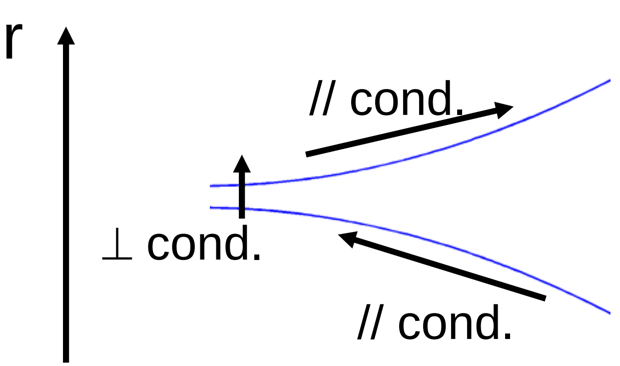




I-coil perturbation

n=10 ballooning mode (MISHKA)

Mechanism of radial heat transport enhancement:



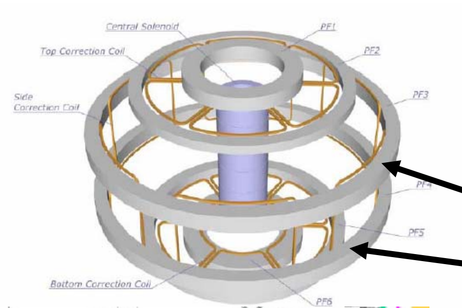
Difficulty in the model: one needs a flux limit for the parrallel conduction

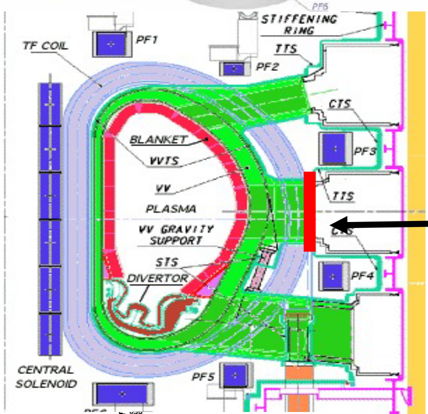
Design of the coils for JET and ITER, using the VF hypothesis (1/6)

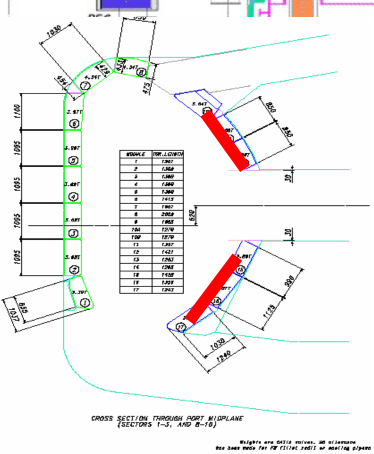
- Goal: to reach a level of edge RMPs comparable to DIII-D's (Chirikov parameter~1 in the pedestal)

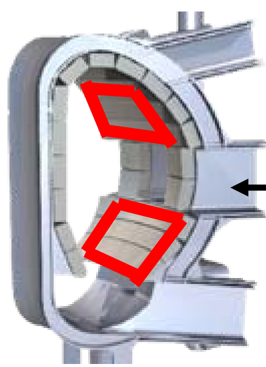
- Constraints:
  - Technical feasibility (location of the coils, required current…)
  - Core perturbations

We will now detail only the case of ITER (the work for JET is similar). This work is done under an EFDA contract: « ERGITER ».









Step 1: Look for reasonable places

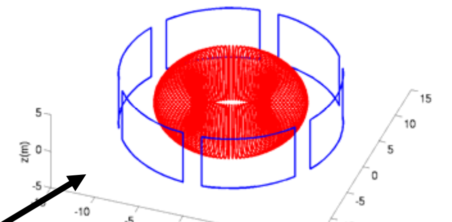
2 main options…

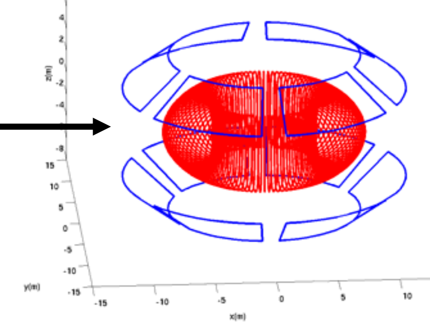
- Coils fixed on the Poloidal Field (PF) coils

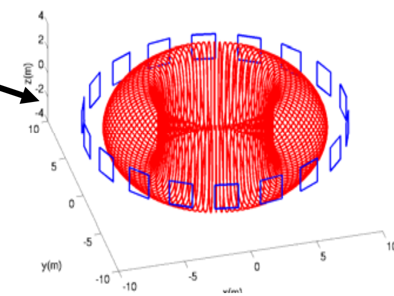
- Coils rolled around the port plug walls

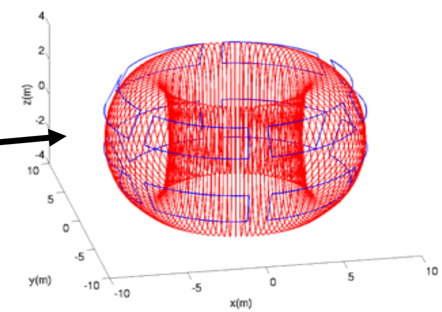
You may also want
to consider « unreasonable » places…

- Coils rolled around the blanket modules



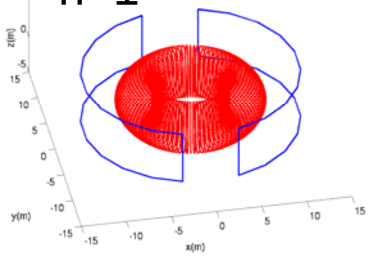




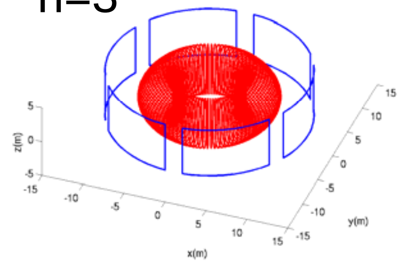


Step 2: Determine the best toroidal symmetry of the coils configuration

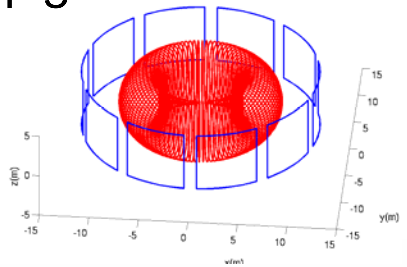
n=1

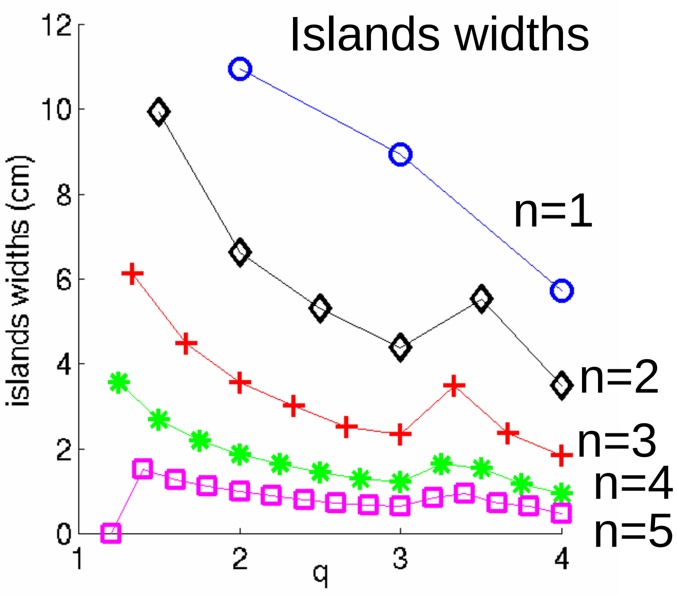


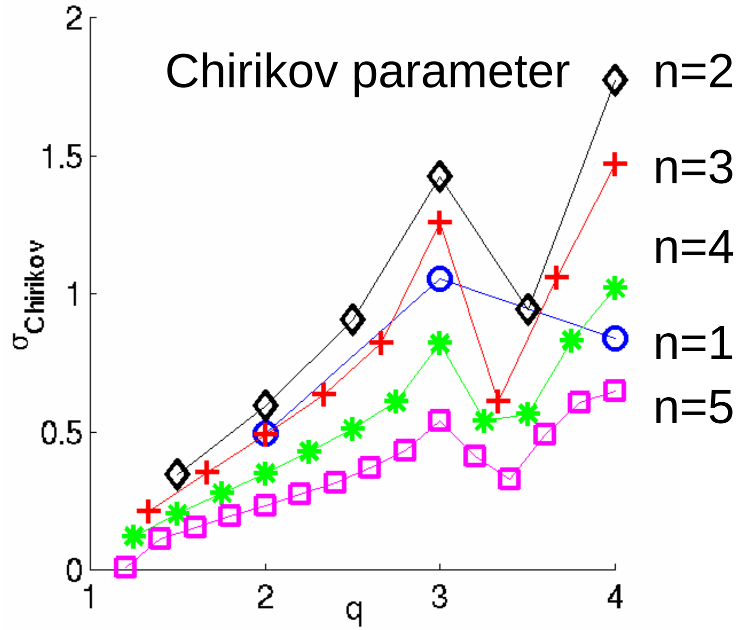
n=3



n=5





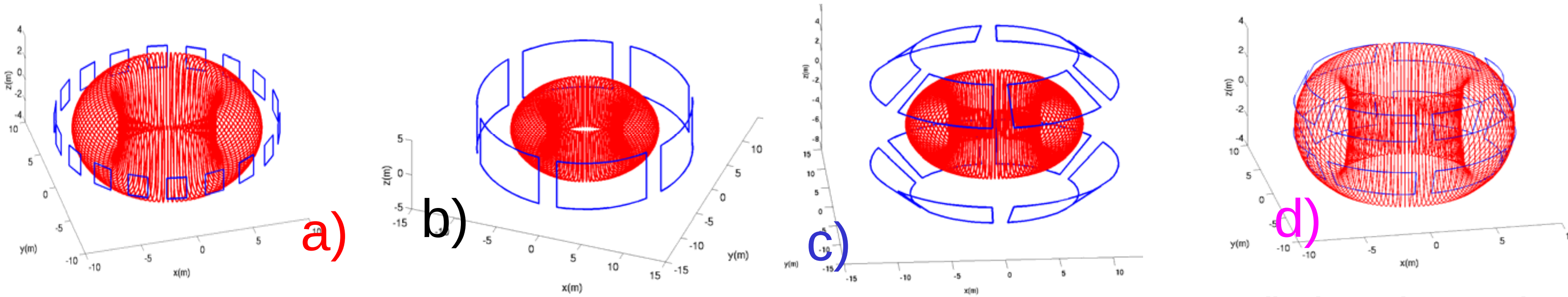


Question of compromise…

strong edge RMPs / low core RMPs / low current

=> n=3 seems to be the best

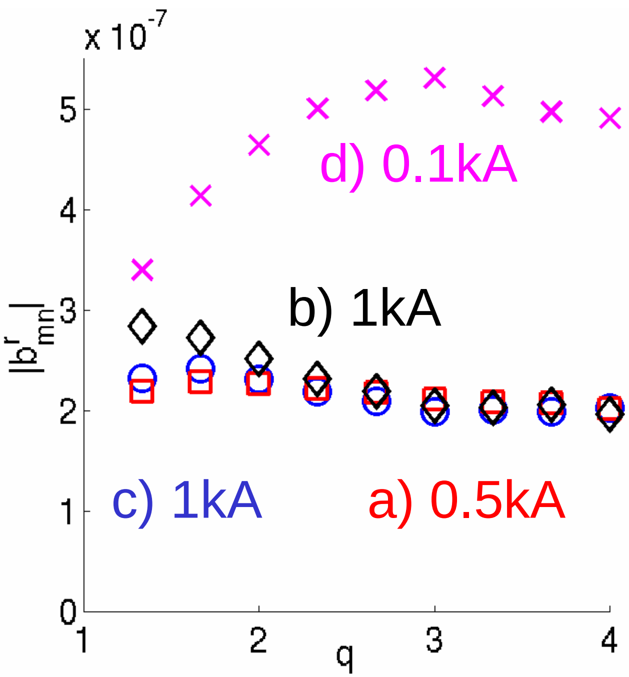
Step 3: Choose among n=3 configurations



a): port plugs coils

b) and c): PF coils coils

d): blanket coils



- H mode from ASTRA provided by EFDA

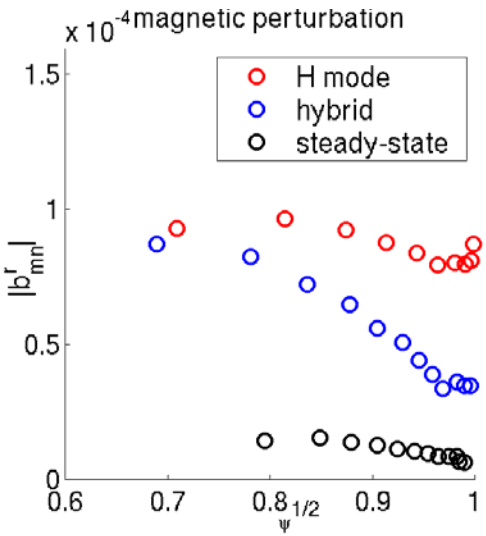
- RMPs profiles look alike for a), b) and c)

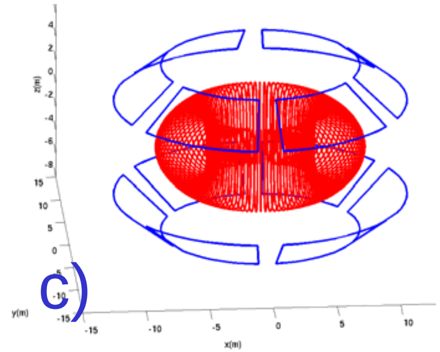
- a) requires two times less current than b) or c), while d) requires ~25 times less current…

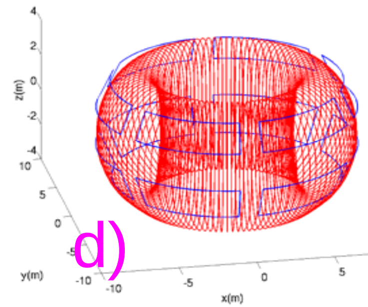
- Current required to get a DIII-D-order edge perturbation: ~400kA for b) and c), 200kA for a), 16kA for d)

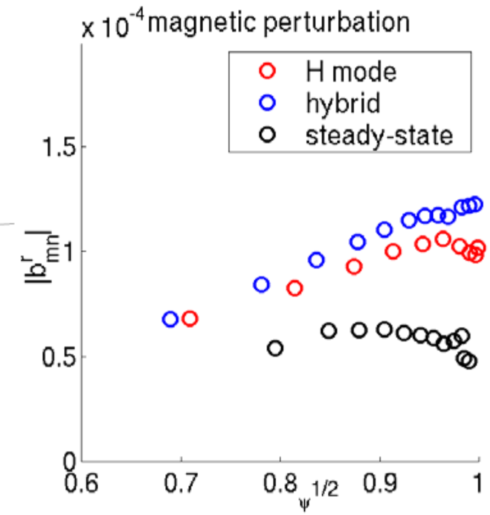
- The 4/3 island is about 6cm wide for a), b) and c), 1.5cm for d)

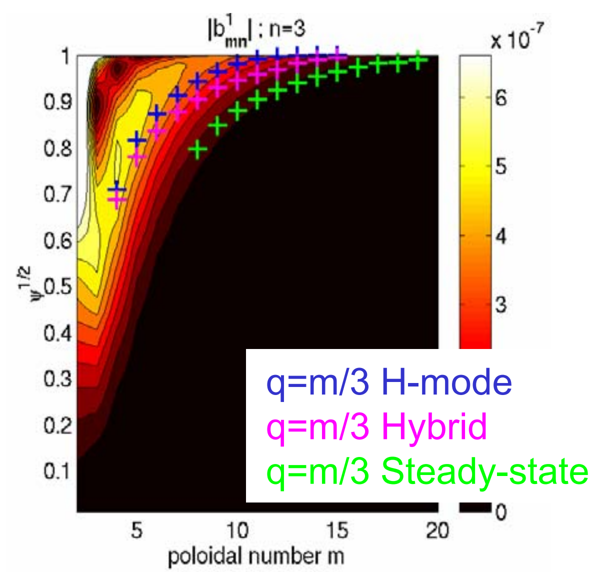
Design performances can vary with the equilibrium…

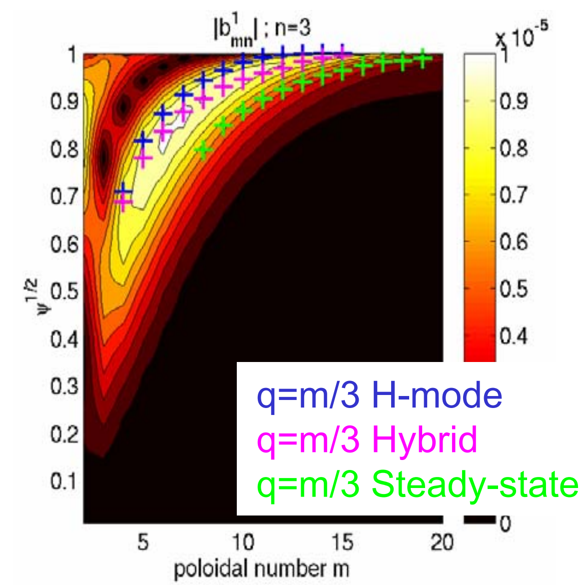




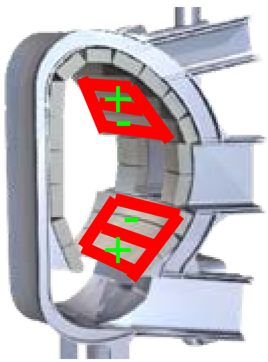


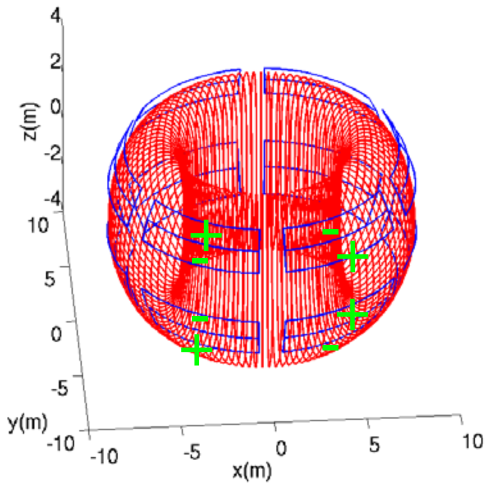




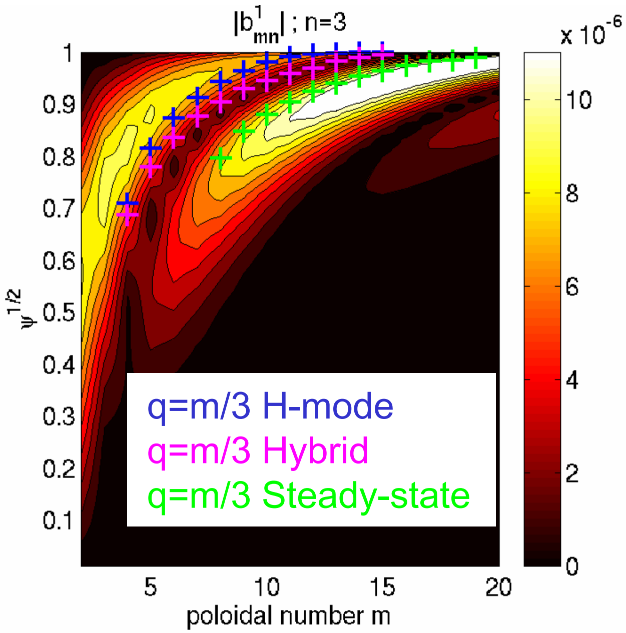


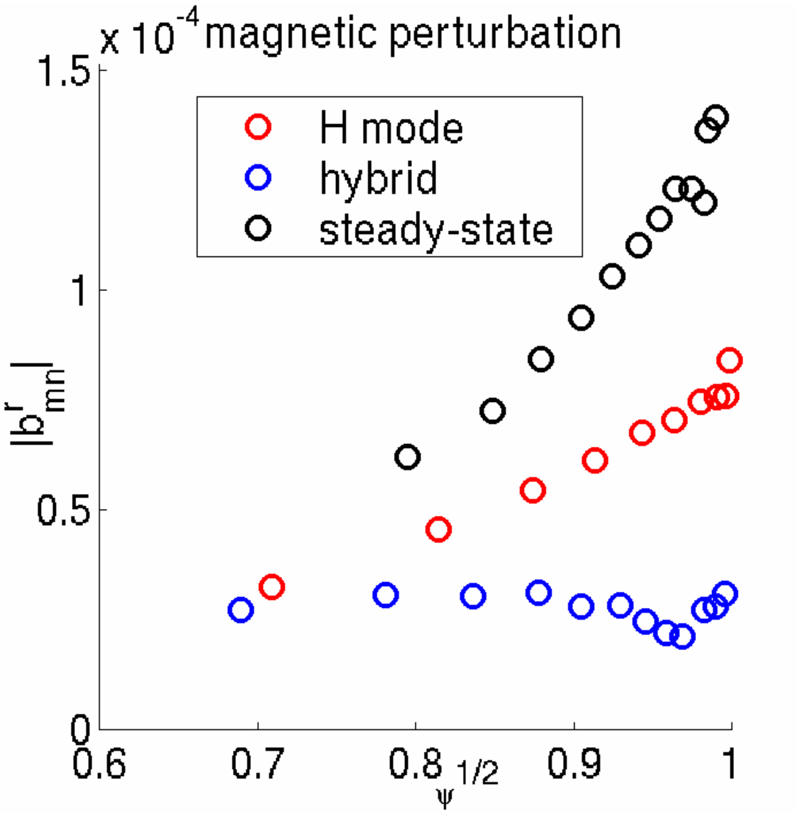
…Blanket coils can adapt if one uses different polarities!





Configuration « +--+ » is adapted to the steady-state scenario





The plasma MHD reaction to the RMPs, or is the VF hypothesis right? (1/4)

- All the computations done up to now use the vacuum field…
Is it correct to do that?

- Possible effects:
    - Enhancement/screening by « plasma effects »
    - Screening by toroidal rotation

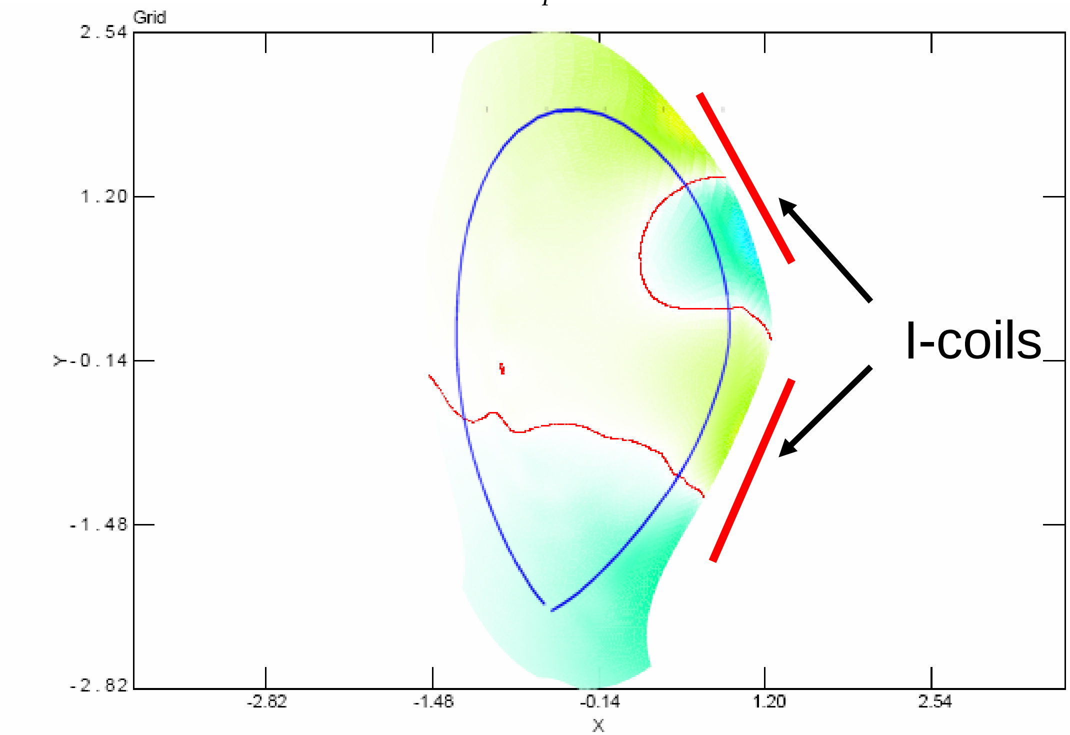
- The new JOREK code (G. Huysmans): reduced non-linear MHD in 3D, toroidal geometry, with X-point

- ~ realistic DIII-D equilibrium

- 2 toroidal harmonics: n=0 (equilibrium) and n=3 (I-coils perturbation symmetry)

The plasma MHD reaction to the RMPs, or is the VF hypothesis right? (2/4)

$\psi_{pol}^{n=3}$



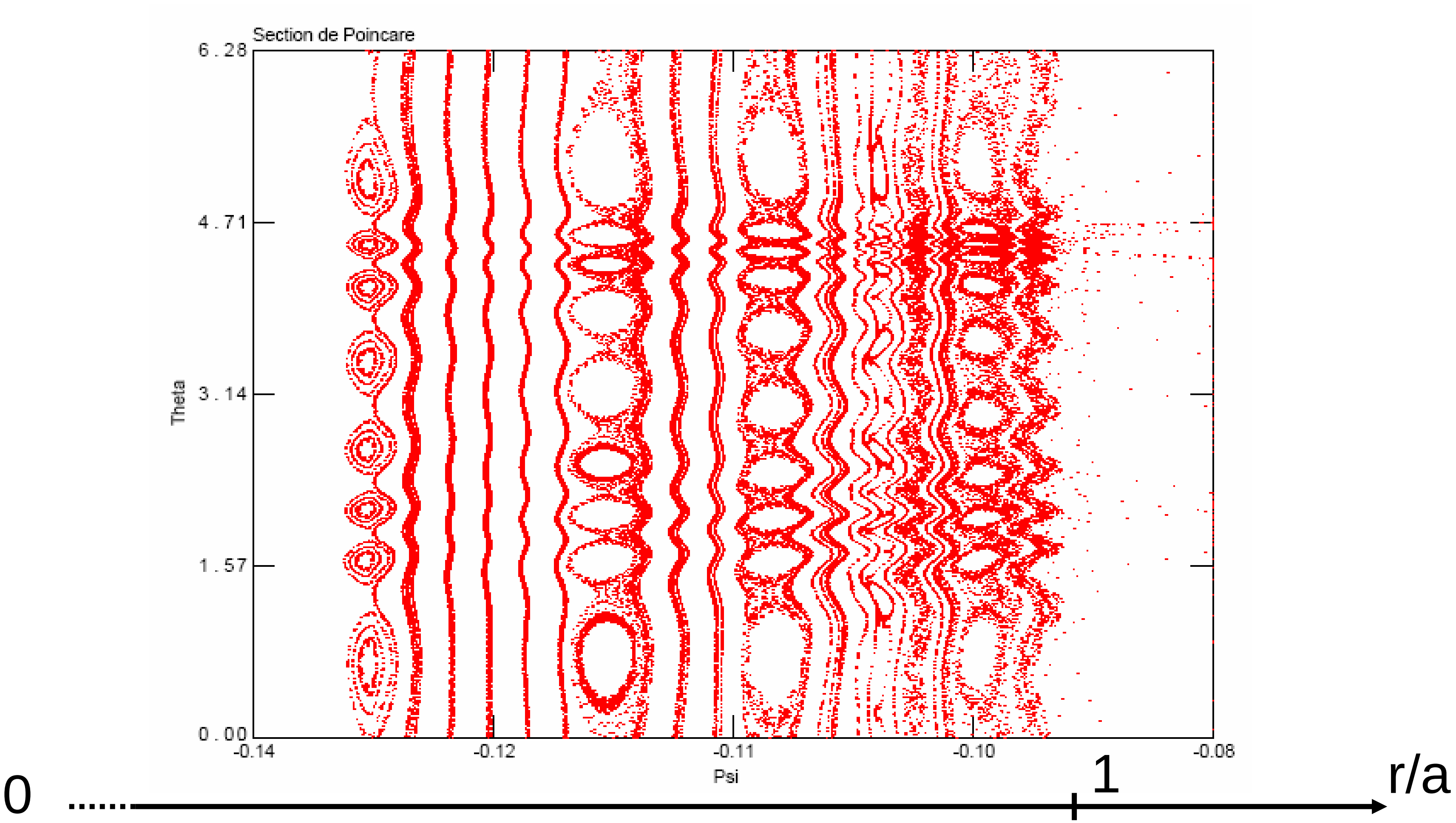
Vacuum magnetic perturbations imposed only as boundary conditions
The current in the coils is proportional to $1-\exp\left(-t/\tau\right)$, where $\tau=500\,\tau_A$

Comparison between 2 cases:

- Static perturbation
- Toroidally rotating perturbation at frequency $f=\left(0.01/\tau_A\right)\approx 10kHz$

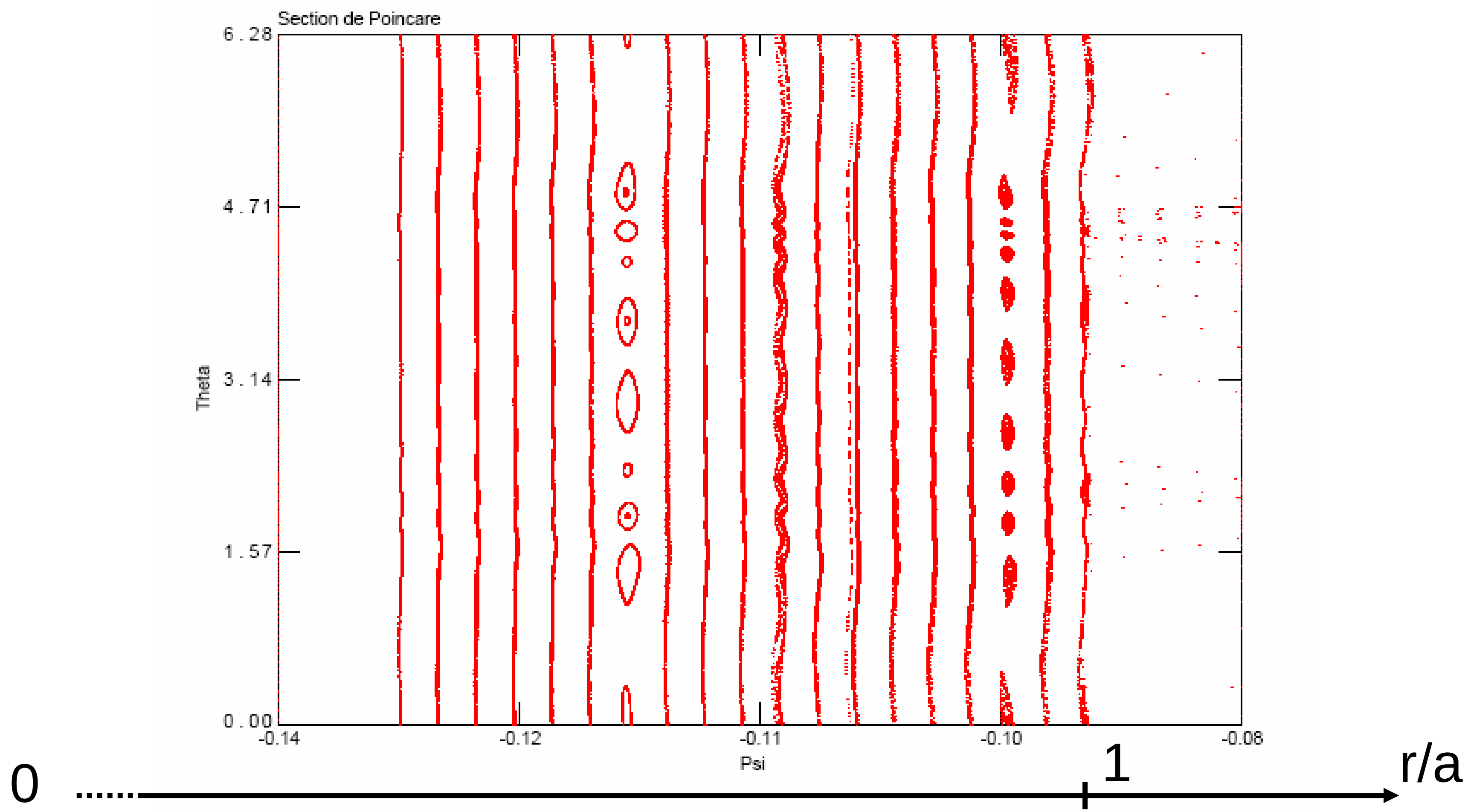
The plasma MHD reaction to the RMPs, or is the VF hypothesis right? (3/4)

Static perturbation, after 1500 Alfvén times



The plasma MHD reaction to the RMPs, or is the VF hypothesis right? (4/4)

Rotating perturbation, after 1500 Alfvén times => <u>Screening!</u>



Conclusions and perspectives

- DIII-D experiments have shown that RMPs are a potential solution to the problem of ELMs in ITER

- The physics underneath is not completely understood, but radial heat transport enhancement due to ergodisation of the edge field lines might be involved (and we have numerical tools to model that)

- Design work for RMPs coils systems for JET and ITER has been undertaken, and things seem neither obvious nor impossible

- All of the work up to now has been done in the VF hypothesis, but one should probably take into account plasma reaction, in particular the screening by toroidal rotation

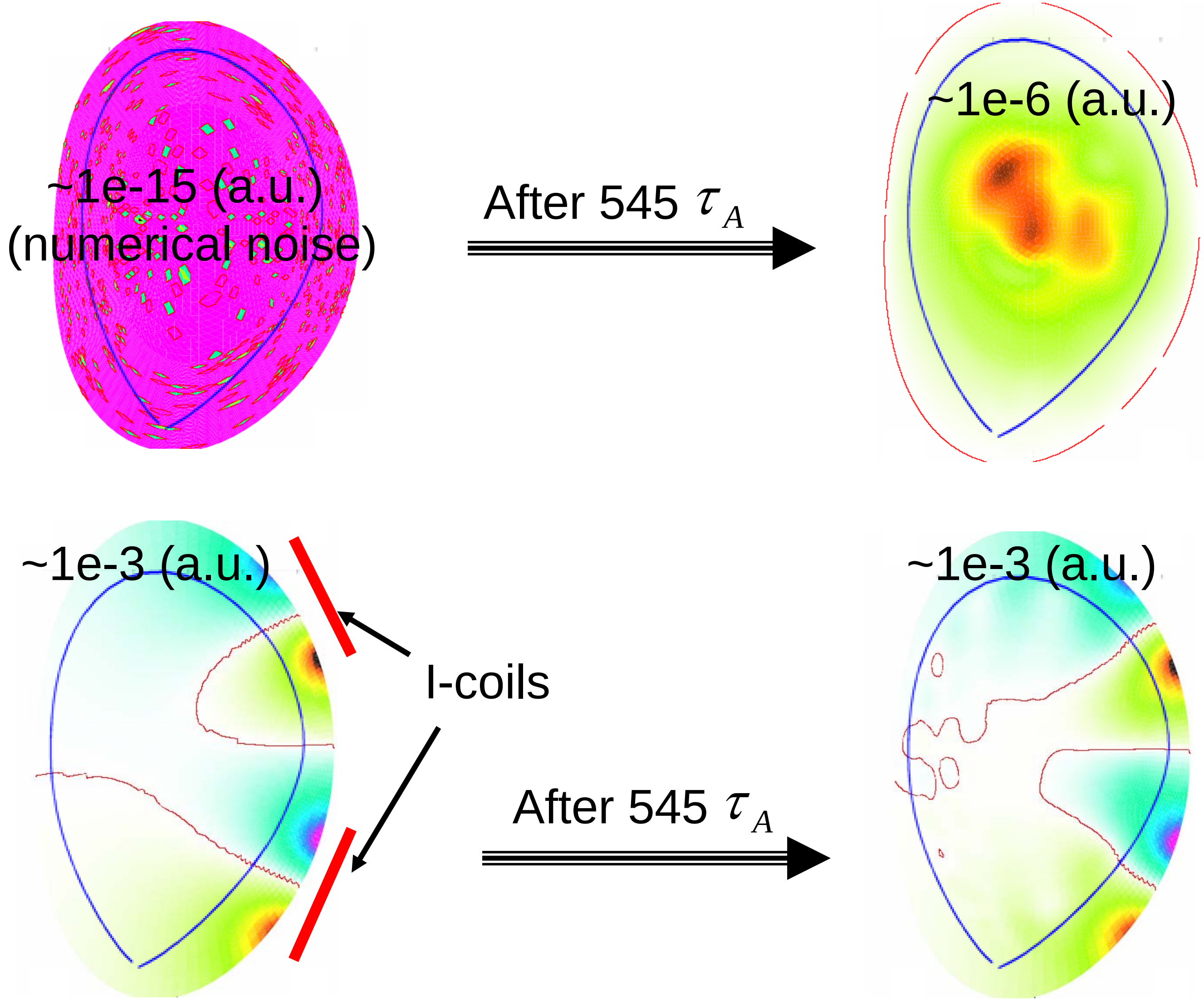
The plasma MHD reaction to the RMPs (2/6)

- Beginning of the simulations: vacuum poloidal magnetic flux $\psi_{pol}^{n=3}$ everywhere
- $\psi_{pol}^{n=3}$ fixed at the boundary while things evolve inside

Poloidal flux n=3 : $\psi_{pol}^{n=3}$

I-coils off: 0kA

I-coils on: 1kA



Electric potential n=3 : $\phi_{n=3}$

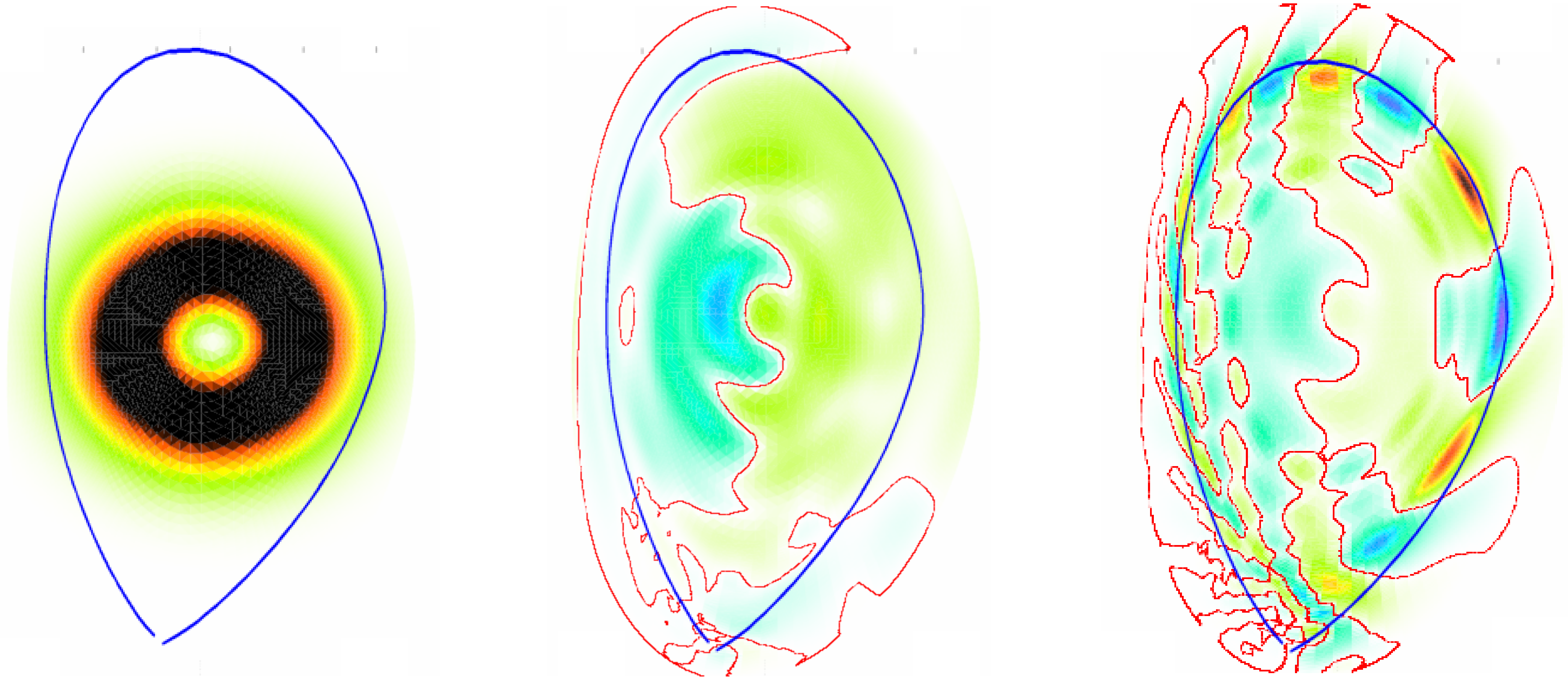
At t=0

~1e-5 (a.u.)

After 545 τ_A

0kA
~3e-6 (a.u.)

1kA
~2e-5 (a.u.)

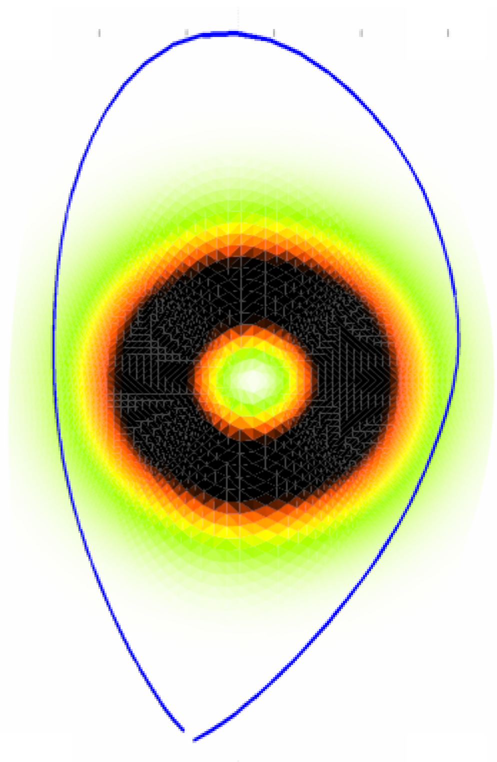


The plasma MHD reaction to the RMPs (4/6)

Density n=3 : $n_e^{n=3}$

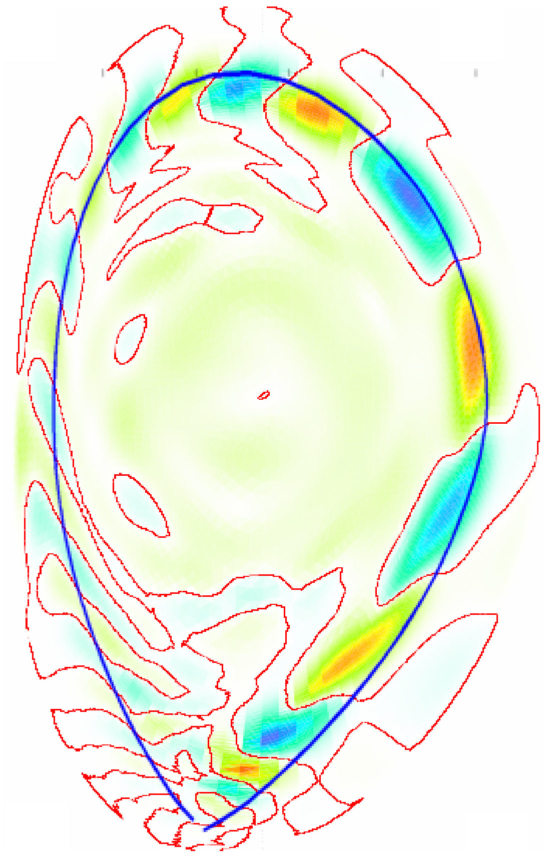
At t=0

~1e-5 (a.u.)

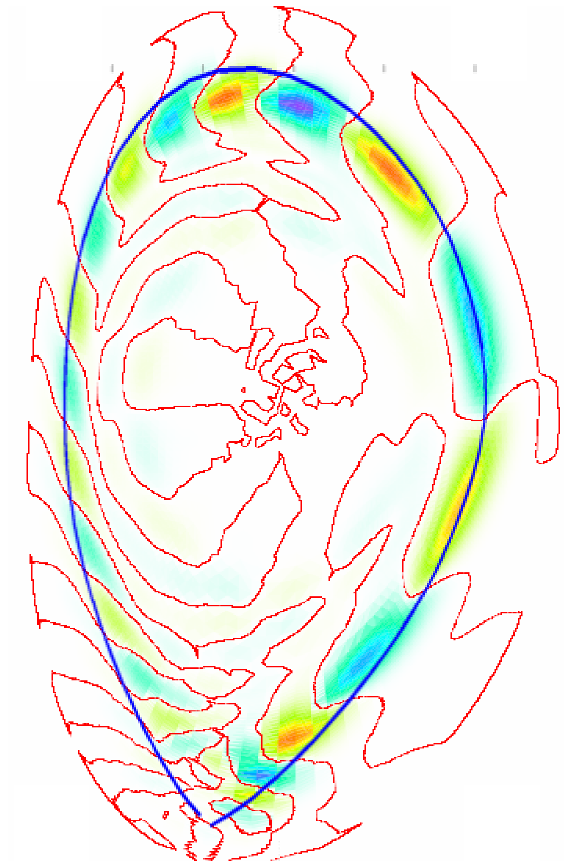


After 545 τ_A

0kA
~2e-4 (norm.)



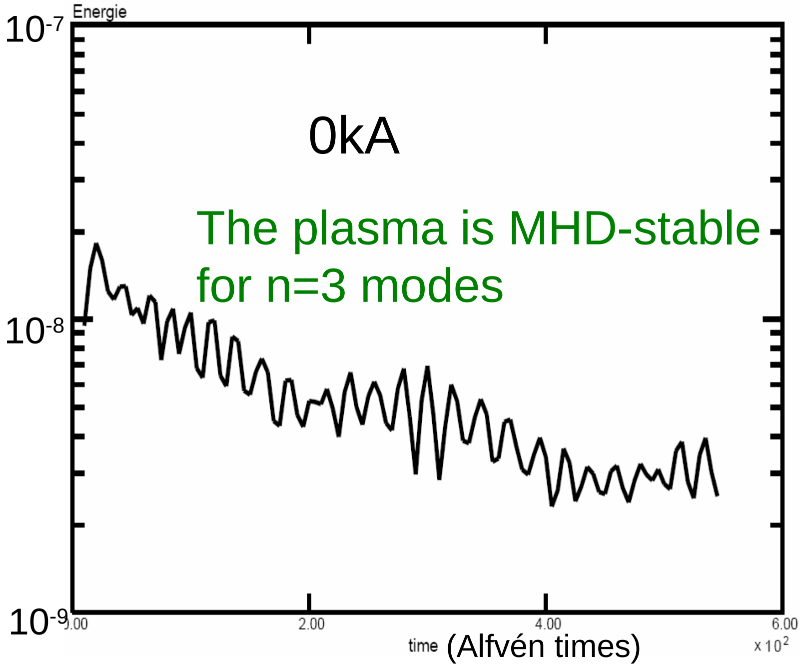
1kA
~1e-1 (norm.)

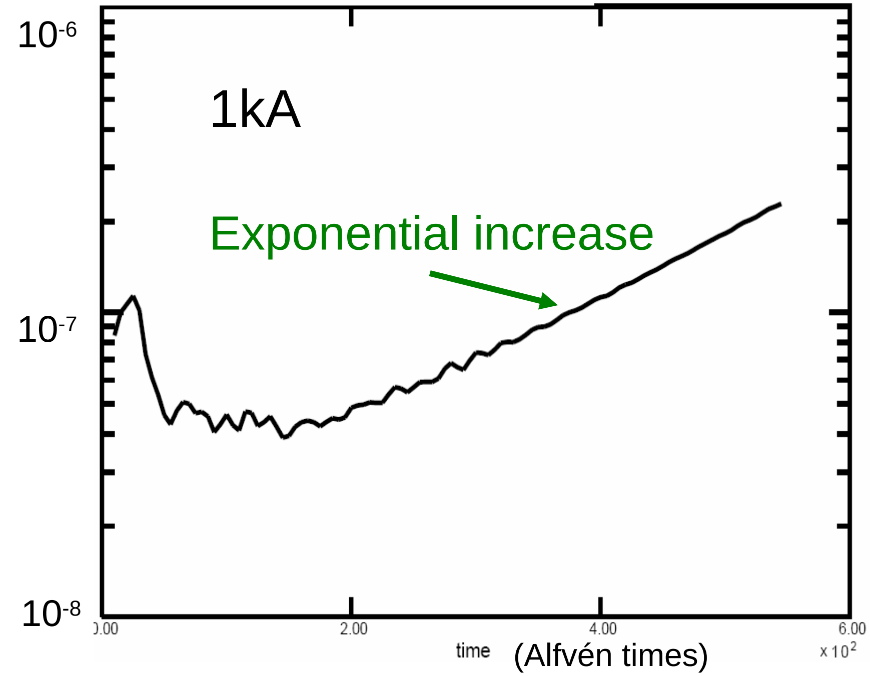


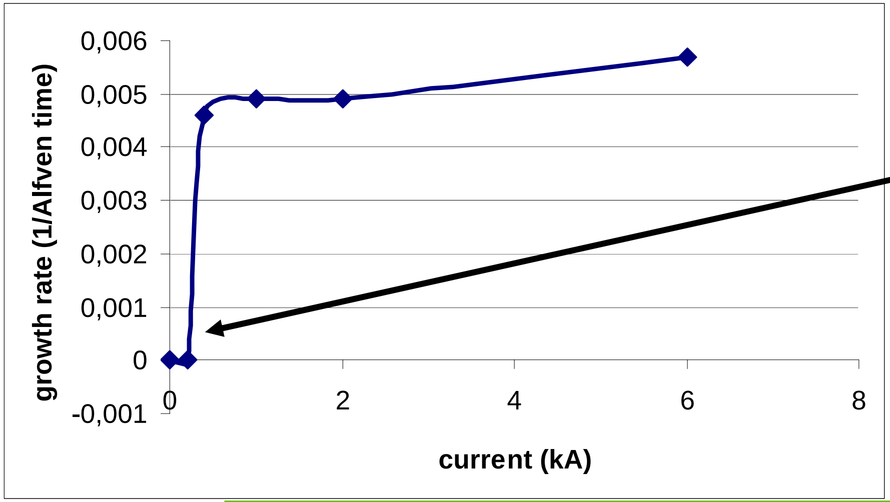
=> Possibly significant density transport

The plasma MHD reaction to the RMPs (5/6)

Magnetic energy in the n=3 harmonic: $W_{MHD}^{n=3} \equiv \iiint_{plasma} \left\| \vec{\nabla} \psi_{pol}^{n=3} \right\|^2 dV$

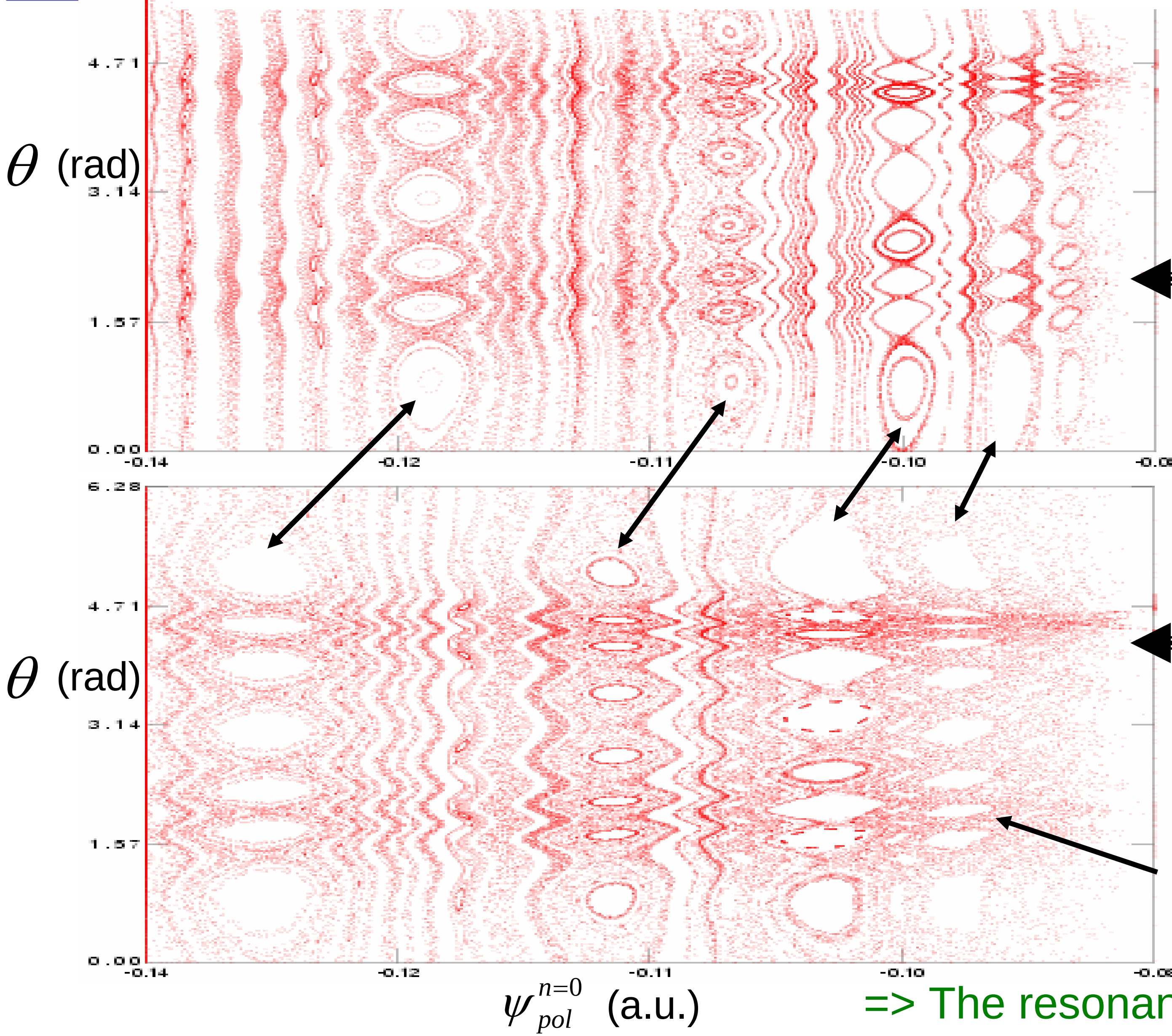






Growth rate as a function of current: There is a threshold current for amplification (~0.3kA)

The plasma MHD reaction to the RMPs (6/6)



<u>1kA</u>

At t=0
(vacuum field)

After 545 τ_A

The islands have grown

The edge seems
ergodized

=> The resonant components of $\psi_{pol}^{n=3}$ have been amplified

Conclusions

A model for ELMs control by RMPs:
edge ergodization => transport enhancement => $\left|\partial_r P\right|_{ped} \searrow$
=> plasma MHD-stable => no more ELMs

Design of the coils for JET and ITER underway,
computations done with the vacuum field

Vacuum field hypothesis being checked…
The first case shows an amplification of the perturbation
Work to come = to include in the simulations…

- toroidal rotation
- bootstrap current
- pressure

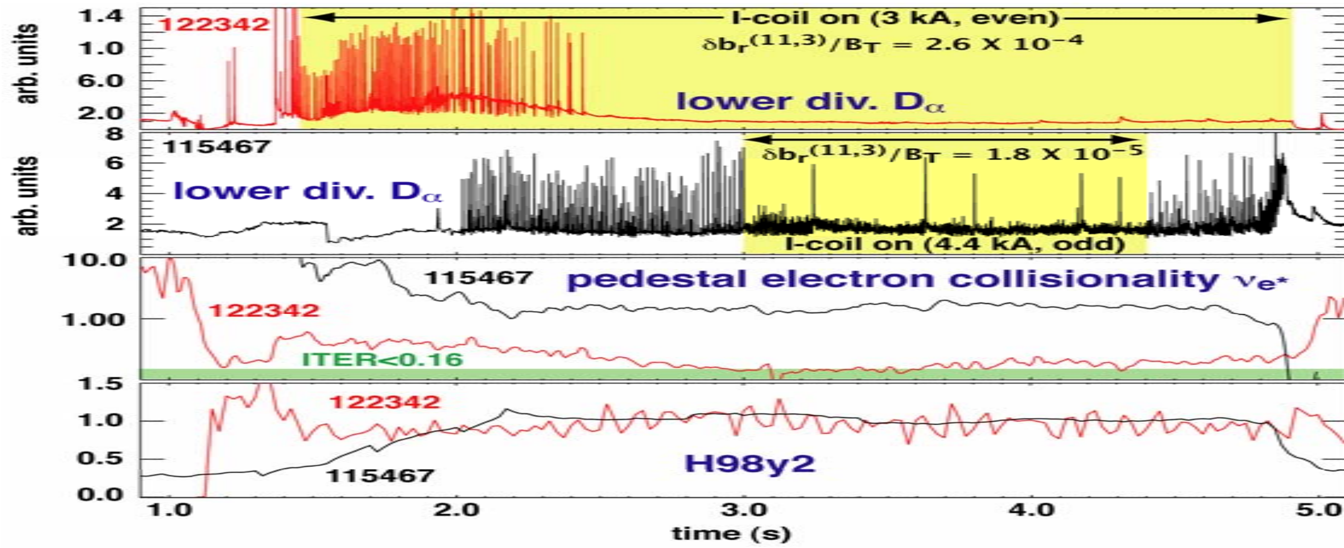
2 main types of experiments:

2004: High collisionality

2005: Low collisionality

Some common results…

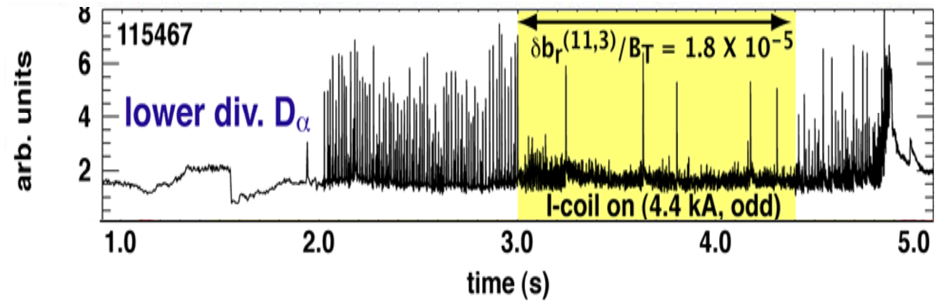
- ELMs suppression with no degradation of confinement
- Resonant window in q95



Evans, EPS 2005

…but many differences as well

2004: High collisionality (e.g. Evans et al., PRL **92**)



Best suppression obtained with the odd configuration

The ELMs are suppressed immediately after the I-coils are turned on

Some ELMs however remain during the I-coil phase

Small bursty 130Hz oscillations are observed (Dalpha, Mirnov coils signals)

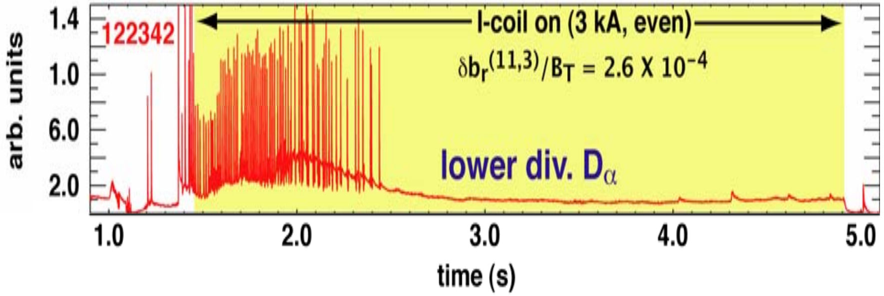
No degradation of confinement

The density remains constant

The effect on the pressure / temperature profiles is not clear

Drop in the edge toroidal speed

2005: Low collisionality (e.g. Evans, EPS 2005)



Best suppression obtained with the even configuration

There is a delay before the ELMs disappear

After this delay, the ELMs suppression is complete (no remaining ELM)

The bursty oscillations seen at high collisionality are not observed anymore

No degradation in confinement

Large drop in density

Rise of the edge temperature gradients but the edge pressure gradient drops because of the drop in density

Rise of the edge toroidal speed

Theory of plasmas in an ergodic magnetic field (2/3)

- Transport (1/2)

2 cases:

Collisional: $\lambda << L_K$ / collisionless: $\lambda >> L_K$ (λ = mean free path)

- Collisionless case: The parallel ballistic transport at speed v gives a radial diffusion:

$$D_r^{erg} \sim D_{FL} v$$

$$\Rightarrow \chi_r^{erg}(electron\ heat) \sim D_{FL} v_{th}^{e} >> D_r^{erg}(matter) \sim D_{FL} v_{th}^{i}$$

- Collisional case:

  - Heat transport: strong local $\nabla_\perp T$ appear due to « random motion » of the field lines

  => Diffusive transport (weaker than collisionless):

$$\chi_r^{erg} \sim \frac{D_{FL}\chi_{//}}{L_c} \text{ , where } L_c \equiv L_K \ln\left[\left(\frac{r}{mL_K}\right)\left(\frac{\chi_{//}}{\chi_\perp}\right)^{1/2}\right]$$

Theory of plasmas in an ergodic magnetic field (3/3)

- Transport (2/2)

Matter transport:

- Parallel ballistic transport: much weaker than heat transport
- Other mechanisms?

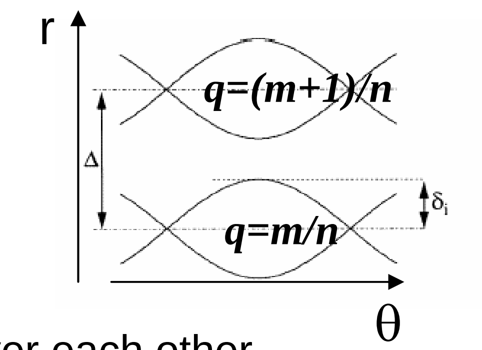
Effect of the electric drift:

Negligible in cold edge plasmas (T<100eV) (Samain et al., PoF B **5**, 1993)

In hot plasmas (H mode edge for instance)?

Complicated problem…

Theory of plasmas in an ergodic magnetic field (1/3)



- « Geometry »

- Ergodicity happens when neighbouring magnetic islands recover each other

Characterized by the Chirikov parameter: $\sigma_{chir} \equiv \dfrac{\delta_m + \delta_{m+1}}{\Delta_{m,m+1}}$

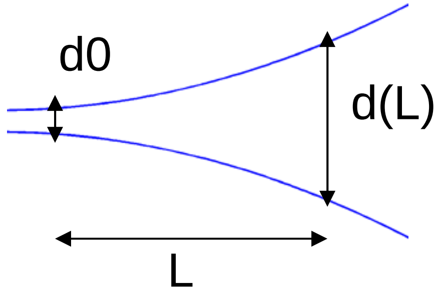
Ergodicity $\Leftrightarrow \sigma_{chir} > 1$

- Two characteristic features in the behaviour of the field lines:

- Exponential divergence:

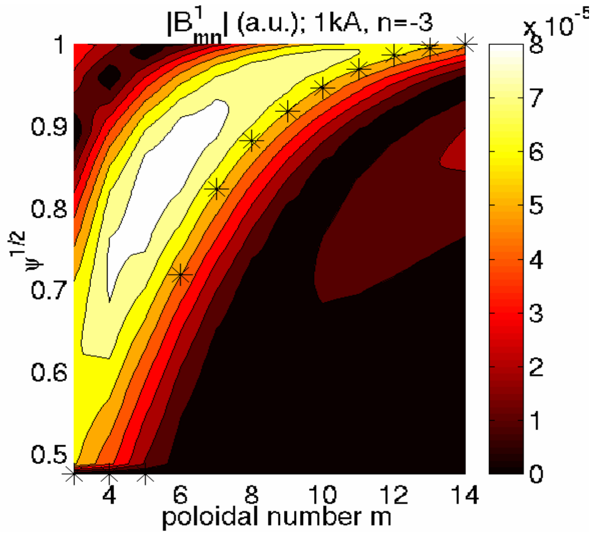
L_K : Kolmogorov length

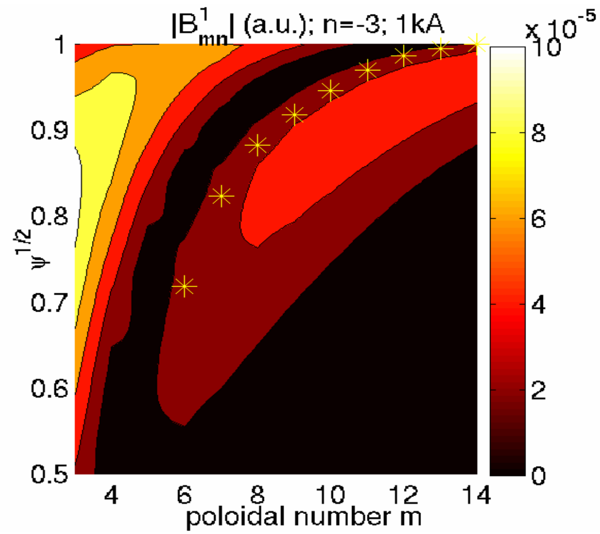
For $L \sim L_K$, $d(L) = d_0 \exp\left(\dfrac{L}{L_K}\right)$

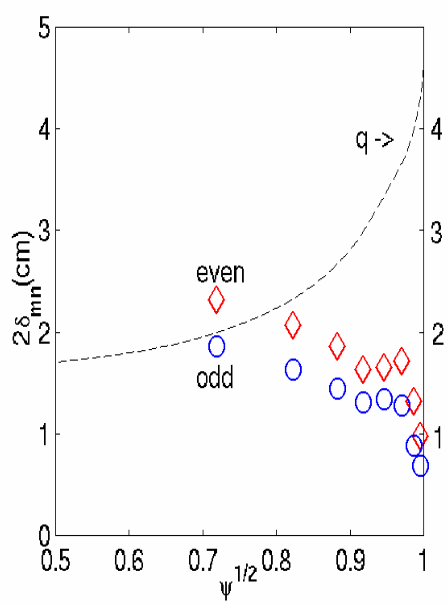


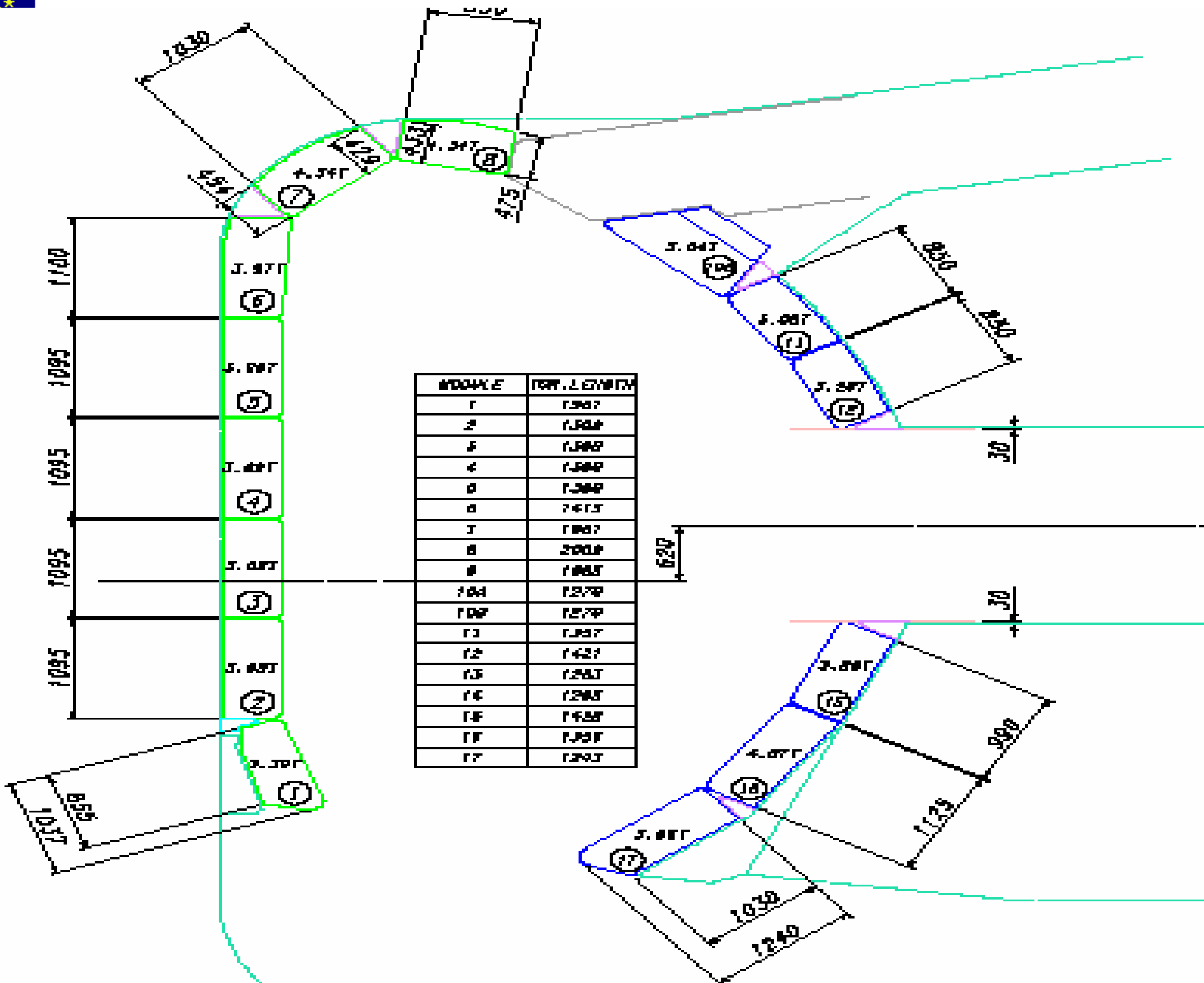
- Radial diffusion:

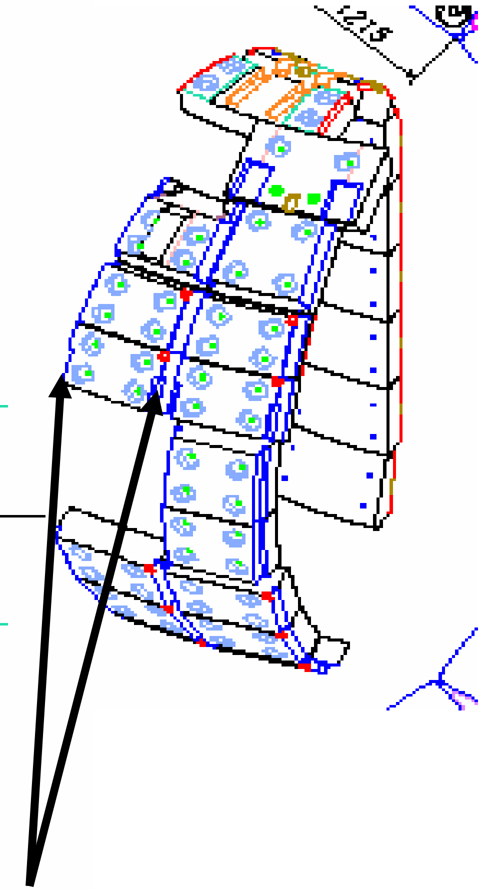
For $L >> L_K$, $\left\langle (\Delta r)^2 \right\rangle = 2LD_{FL}$


|B1mn| (a.u.); 1kA, n=-3
x 10-5
ψ1/2
poloidal number m

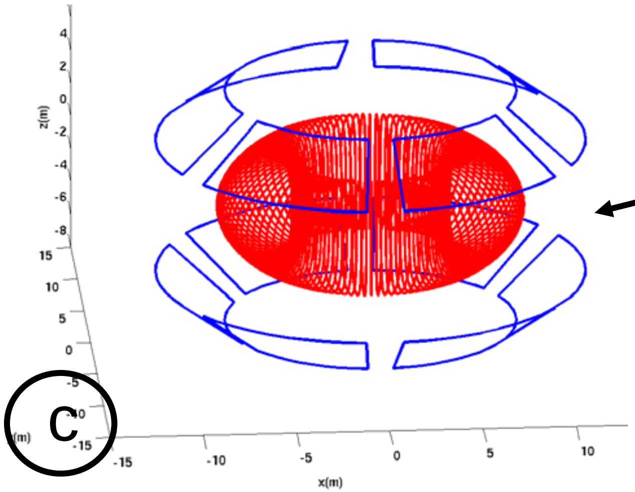

|B1mn| (a.u.); n=-3; 1kA
x 10-5
ψ1/2
poloidal number m


q ->
even
odd
2δmn(cm)
ψ1/2



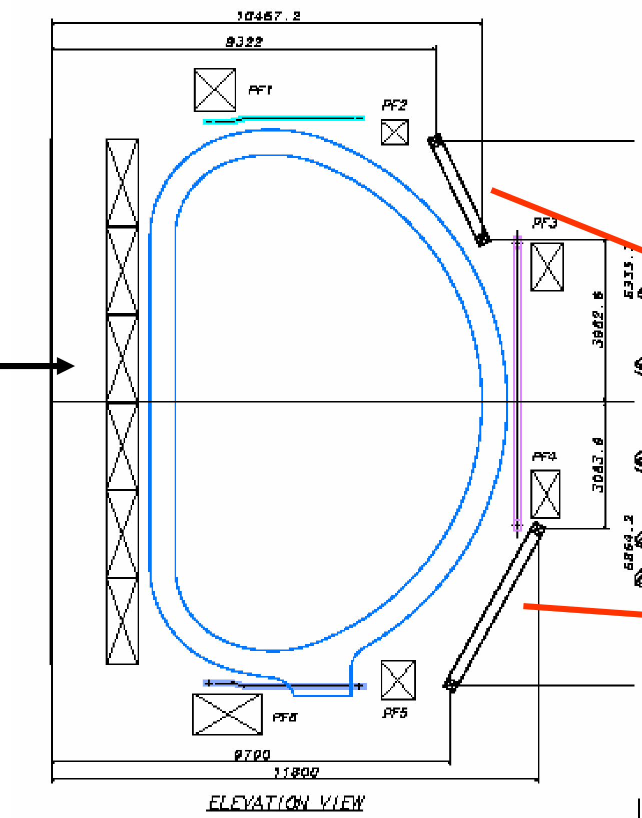


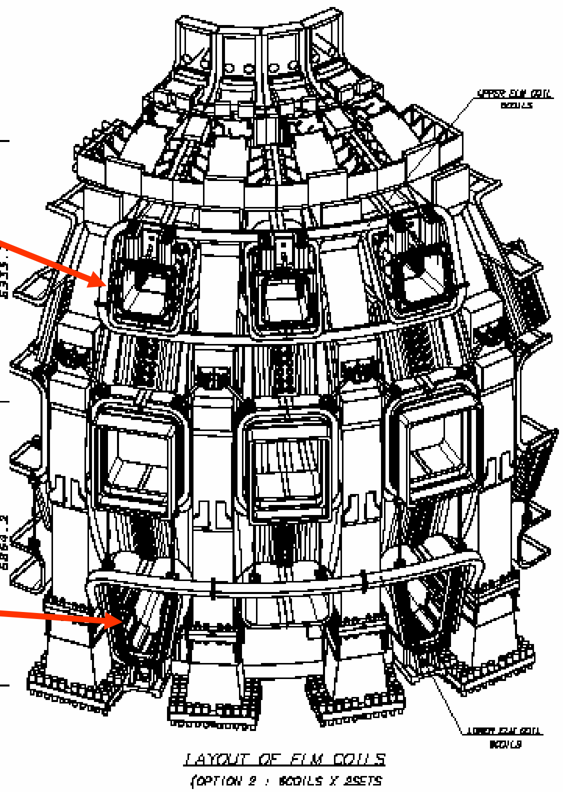
CROSS SECTION THROUGH PORT MIDPLANE
(SECTORS 1–5, AND 8–18)



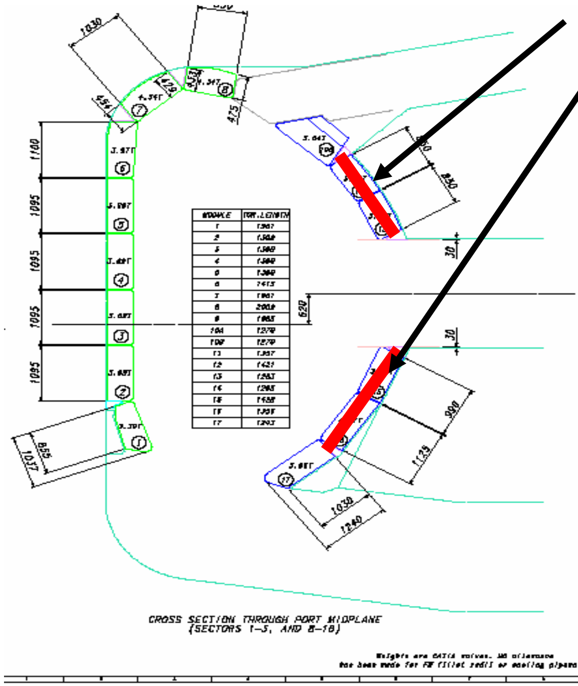
From concept…

…to reality
(Y. Gribov's drawings)

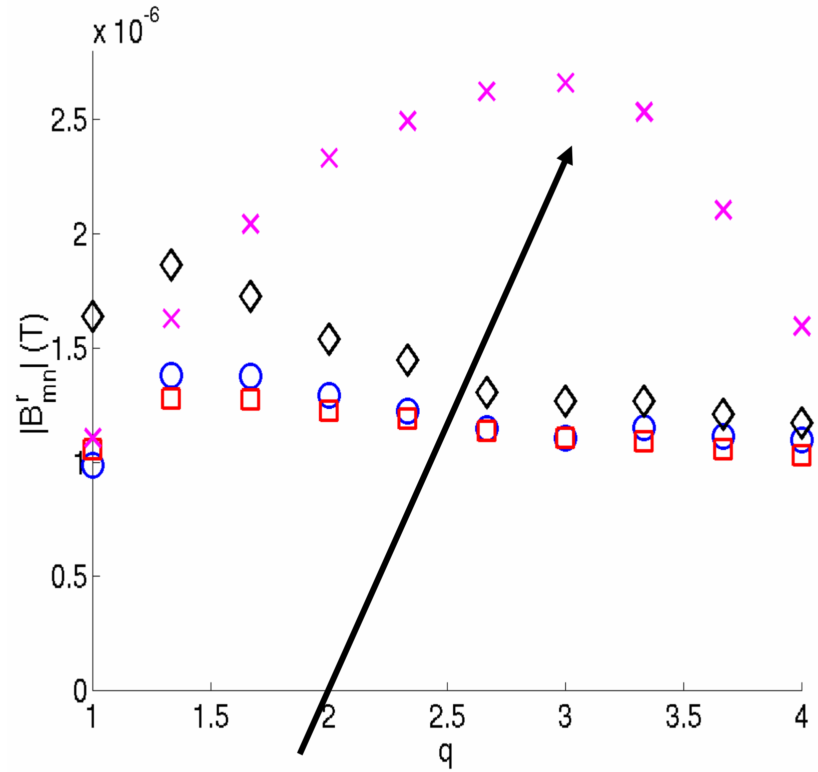


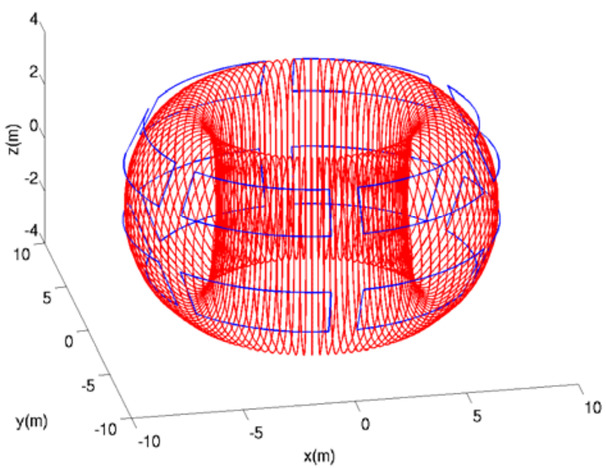


Just to see… Coils inside the vacuum vessel



Possibility to roll coils around the blanket modules





« Blanket coils », 0.1kA
=> Factor 10 better in terms of required current

Design of the coils for JET and ITER, using the VF hypothesis

The DIII-D case

Design

$\delta B_r(r,\theta,\varphi)$ (vacuum field)

$\delta B_r^{m,n}(r)$

Chirikov parameter

I-coils