CONSORZIO RFX
Ricerca Formazione Innovazione

Progress in controlling tearing modes in RFX-mod

L. Marrelli

A.Alfier,T.Bolzonella, F.Bonomo, L.Frassinetti, M.Gobbin, S.C.Guo, P.Franz, A.Luchetta, G.Manduchi, G.Marchiori, P.Martin, S.Martini, P.Piovesan, R.Paccagnella, R. Pasqualotto, A.Soppelsa, G.Spizzo, D.Terranova, P.Zanca and the RFX-mod team

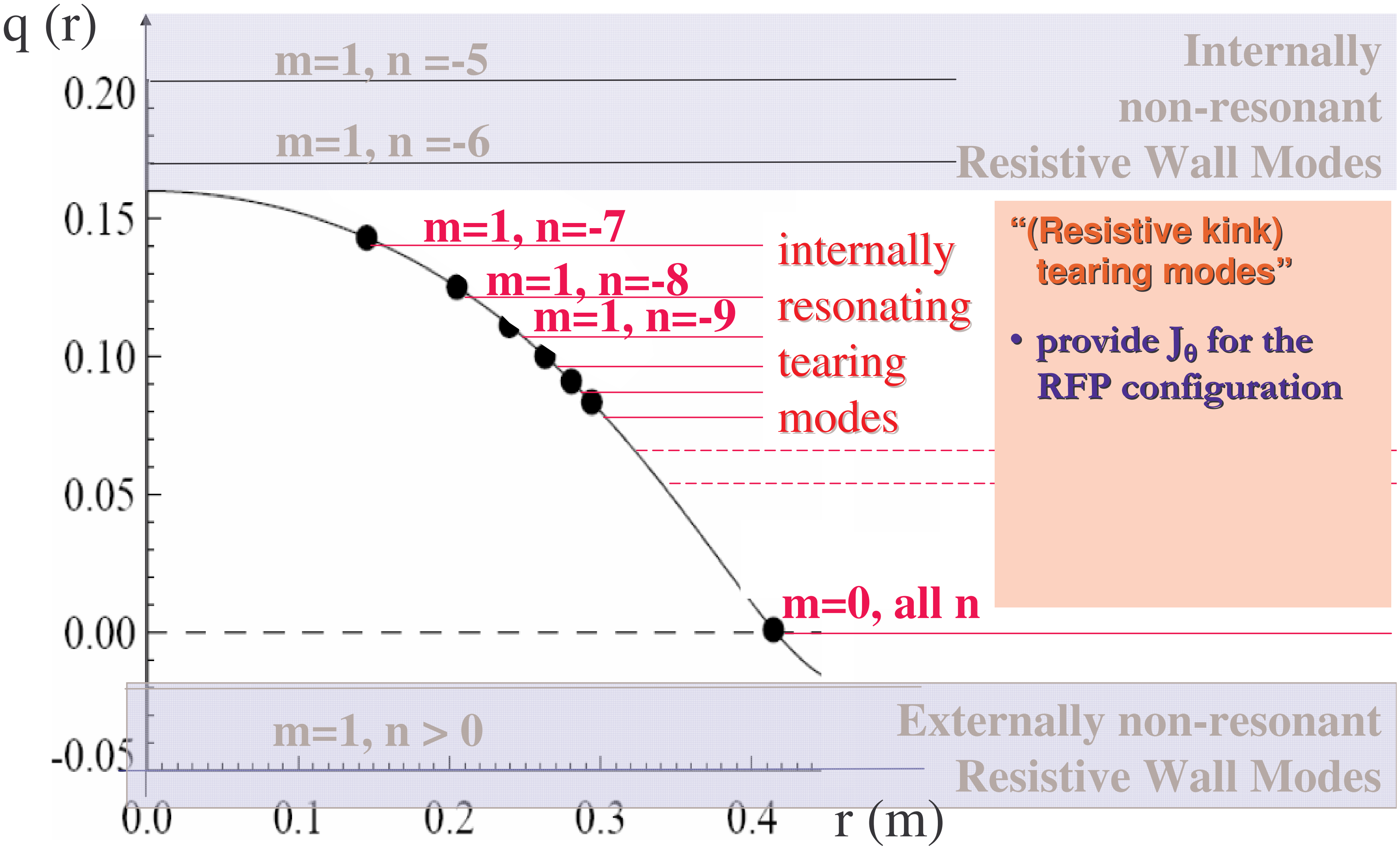
Consorzio RFX-Associazione EURATOM ENEA sulla Fusione

11th Active Control of MHD Stability Workshop, Princeton, NJ, 6th Nov-8th Nov 2006

Outline

- Tearing modes in RFX-mod
- Standard Virtual Shell experiments
- Closer Virtual Shell
- Active control experiments (m=1)
  - QSH induction (single mode)
  - LM mitigation (multiple modes)
- Open issues / Controller optimizations

Reversed Field Pinch Mode Classification



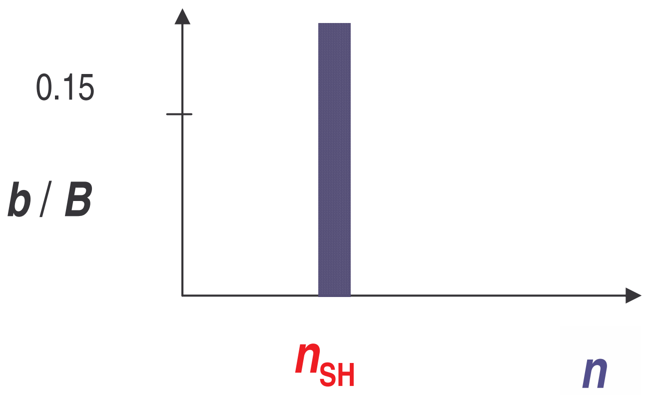
"(Resistive kink) tearing modes"

- provide J_θ for the RFP configuration

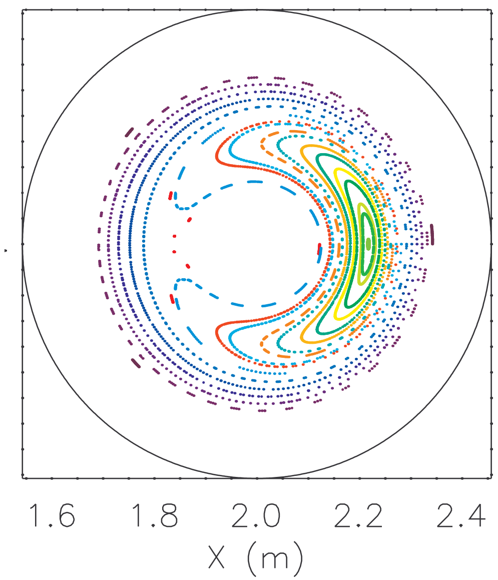
Single (SH) vs Multiple (MH) Helicity

- 3D viscoresistive MHD simulations (SpeCyl code with ideal wall boundary) have shown that the dynamo can be

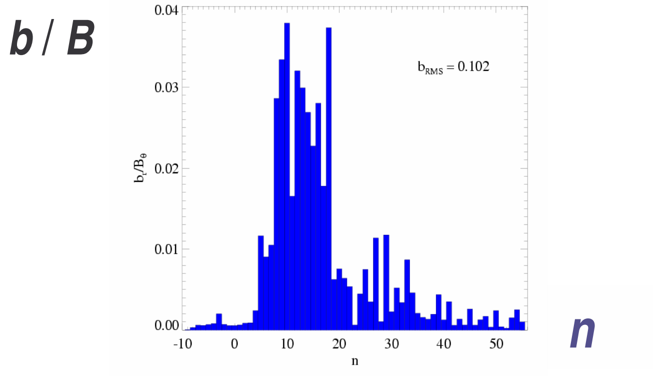
Laminar (**Single Helicity**)



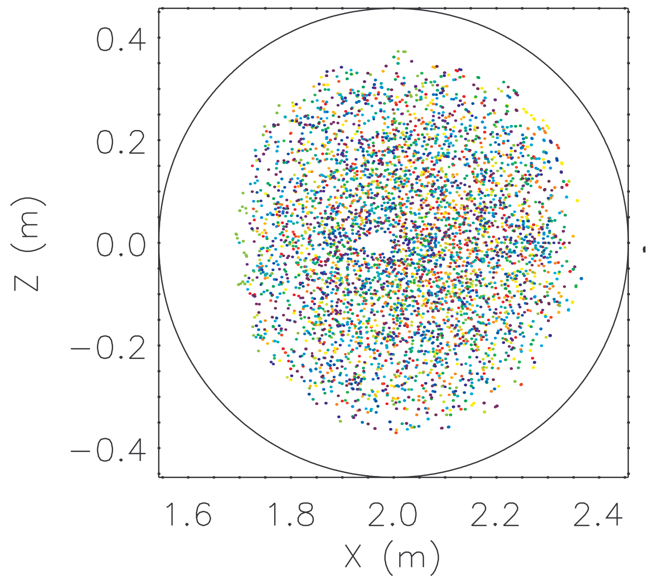
Good magnetic flux surfaces



Turbulent (**Multiple Helicity**)

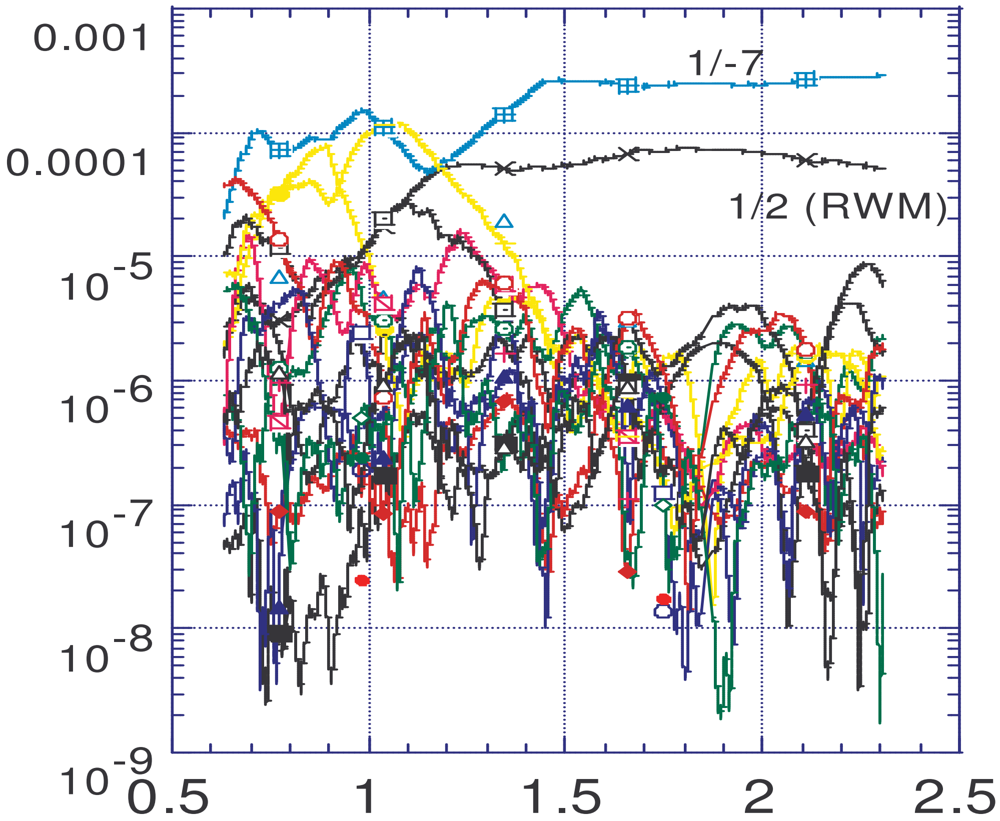


Stochasticity by island overlap



Active induction of SH

- MHD simulations (DEBS) including active control of boundary radial field indicate that it is possible to stimulate the onset of a Single Helicity



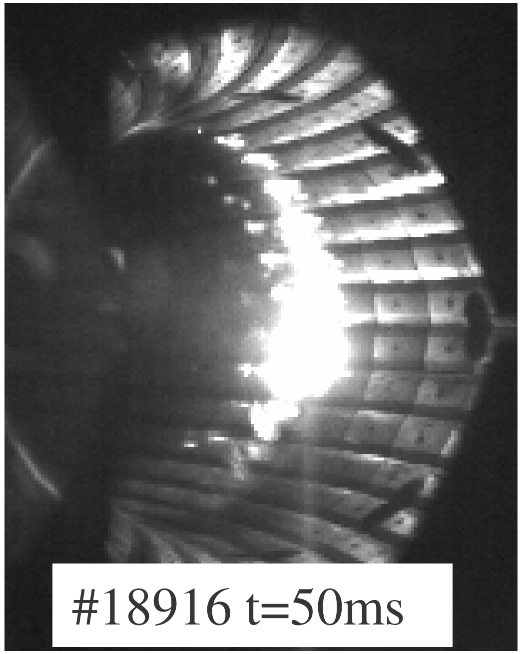
mode energy spectrum computed by DEBS in a run with complex gains

R. Paccagnella et al.,IAEA 2006 paper THP3-19

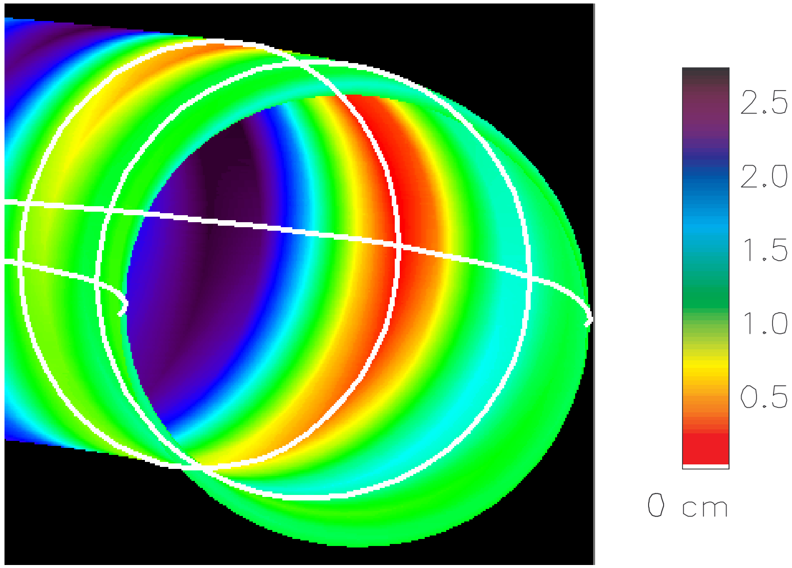
Tearing Modes: Locking

- Last Closed Magnetic Surface is distorted by the tearing modes
- Modes tend to be phase locked and, in RFX-mod, are always wall locked
  - toroidally localized plasma wall-interaction

CCD image of C I(908nm): C influx



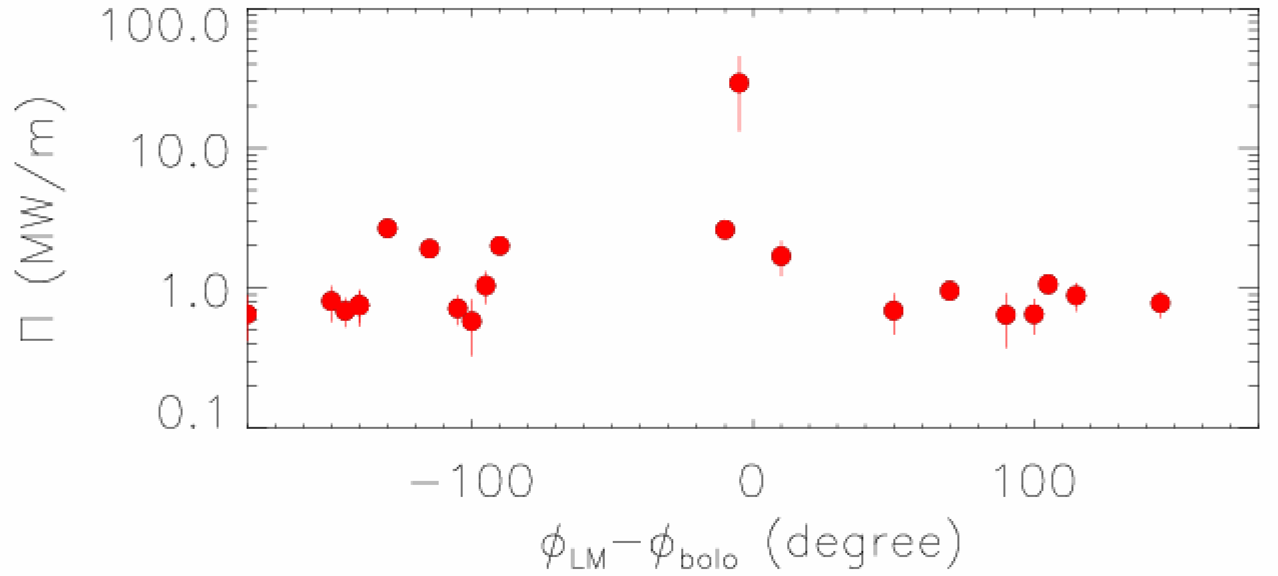
LCMF Distance from the wall



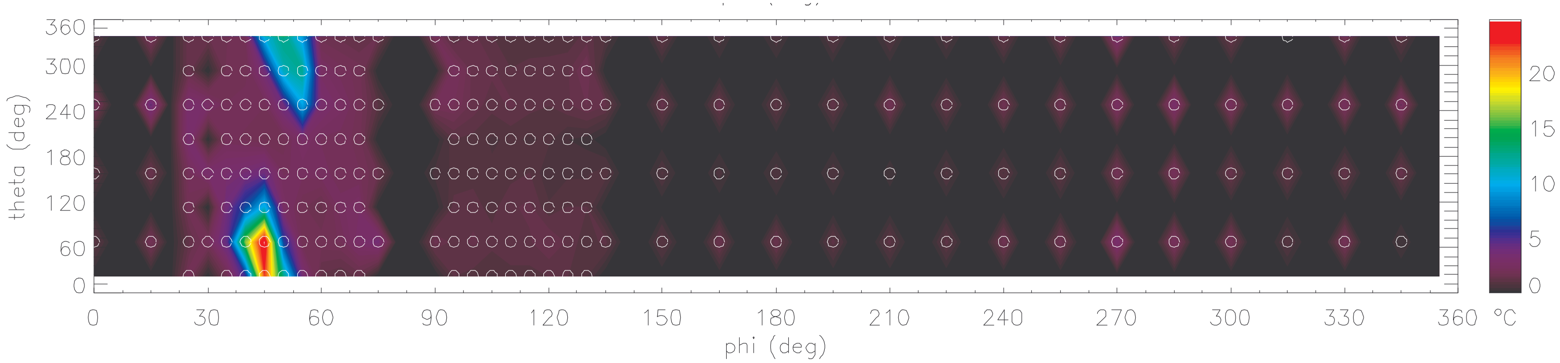
P.Zanca, et al, 17th Conference on Plasma Surface Interaction, Hefei (2006)

If no LM mitigation technique is applied, the enhanced interaction induces

- increased radiated power



- enhanced non axisymmetric post shot vessel temperature increases, with m=1 pattern



CONSORZIO RFX
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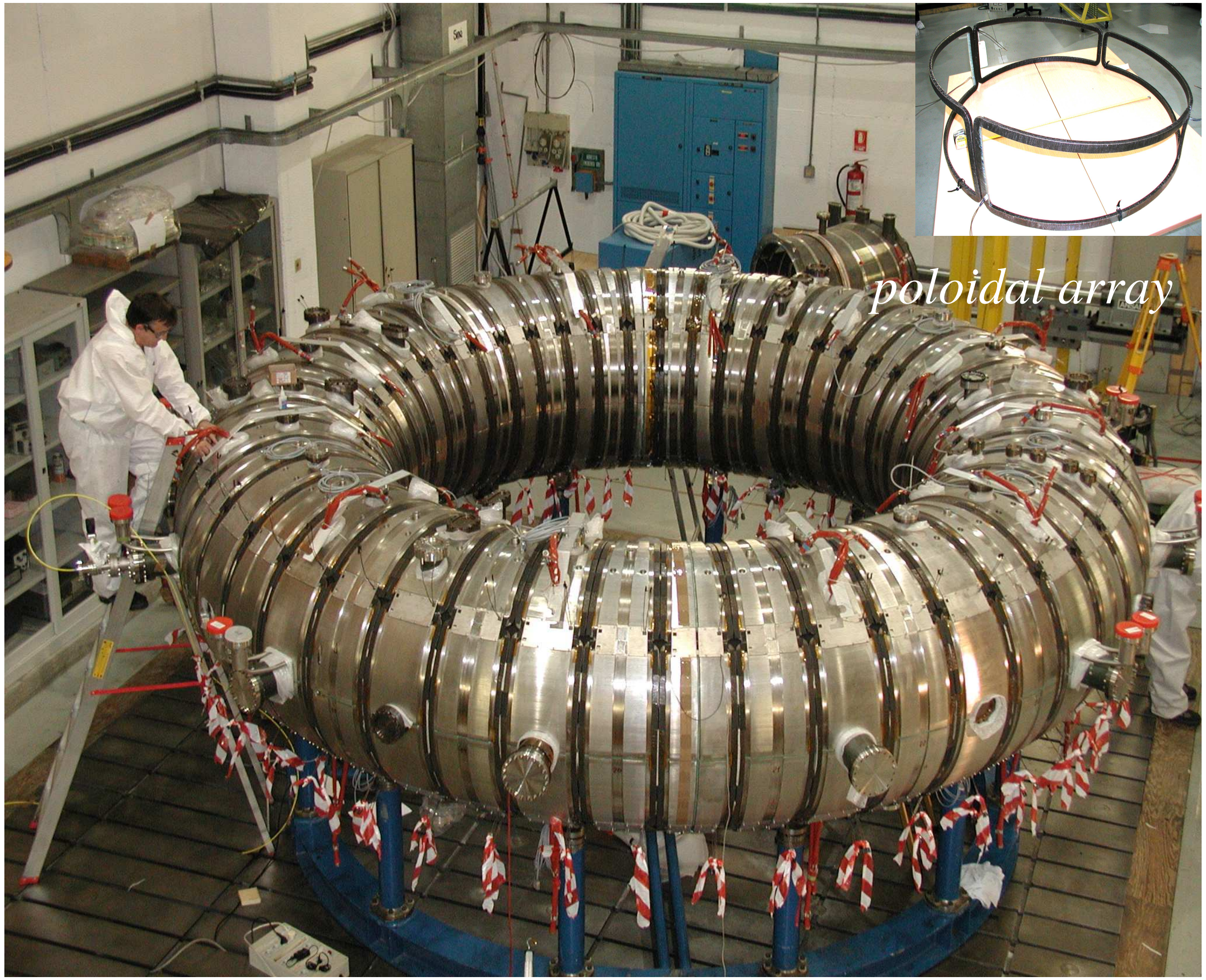
RFX-mod control system overview

- The edge radial magnetic field is controlled by saddle coils



assembly of saddle coils on vacuum vessel

•full coverage of vessel

•4(pol) x 48(tor) = 192 saddle coils independently fed

•can generate modes
m=1 n=-24 to +23
m=0 n=1 to 24
m=2 |n| =0 to 24

Radial field at 24 kAt	*** (mT)***
DC	**50**
@10Hz	**35**
@50Hz	**12**
@100Hz (I=16 kAt)	**3.5**

radial field at plasma edge

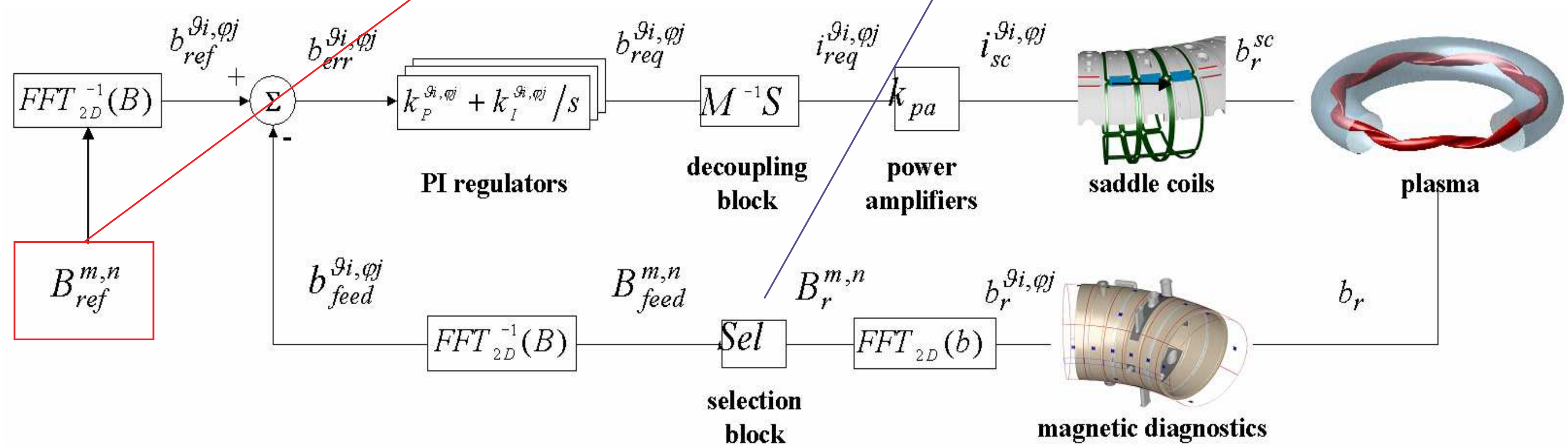
A. Luchetta, et al: Symposium on Fusion Technology, Warsaw, Poland, 2006: submitted to FED

Selective virtual shell

- ***Virtual Shell (VS)*** : active cancellation of radial magnetic field, at radius of 192 field sensors: analogy with passive cancellation by ideal superconducting shell [§]

- ***Selective:*** control system can act on modes selectively

- ***Mode control in SVS***: non zero reference value; complex gains



[§] *C.M. Bishop, Plasma Phys. Controlled Fusion, 31, 1179 (1989)*

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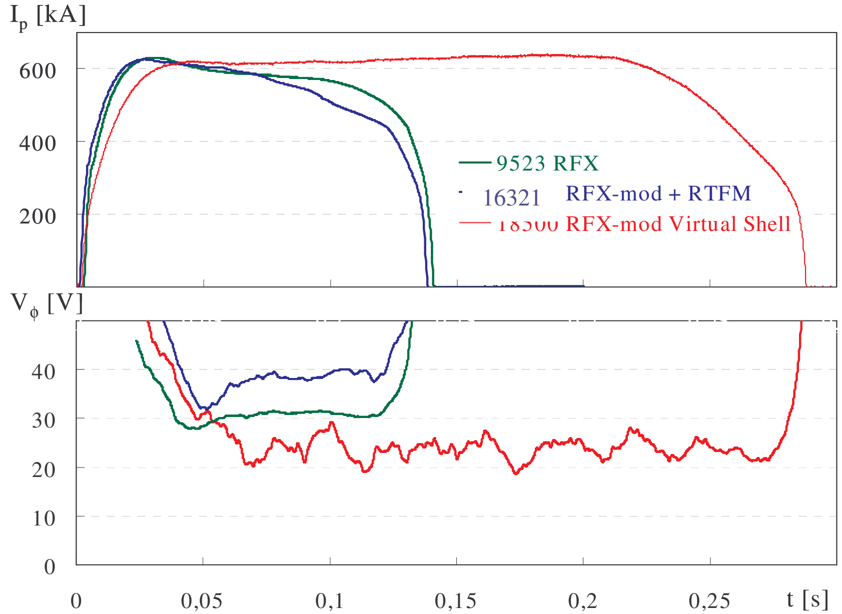
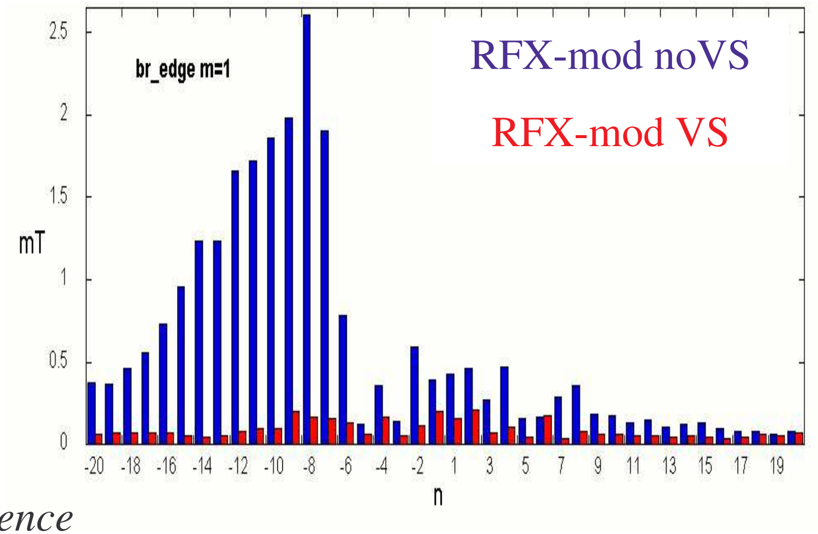
Standard Virtual Shell

- Reproducible increase of pulse length, compared to non-VS operations has been obtained
  - Limited by sustainment power
  - Reduced loop voltage



  - Measured radial field at the edge is significantly reduced compared to non-VS
  - A substantial reduction is observed on the **tearing**-branch of the edge radial field spectrum

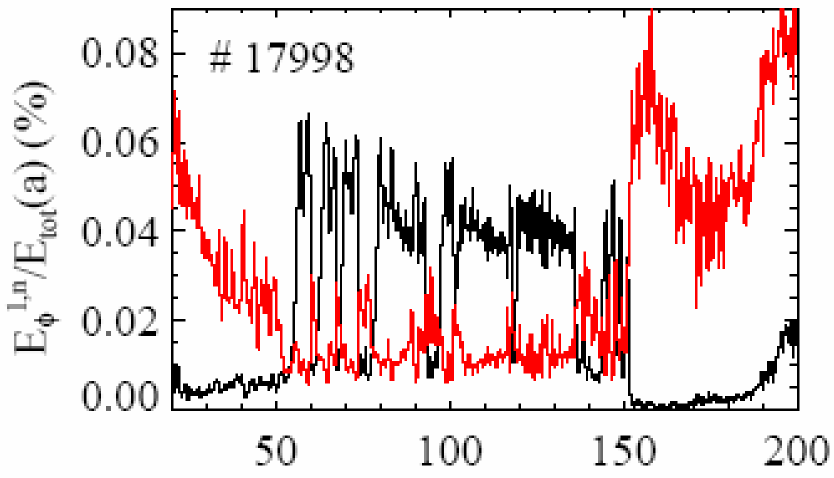


S. Martini, et al., 21st IAEA Fusion Energy Conference

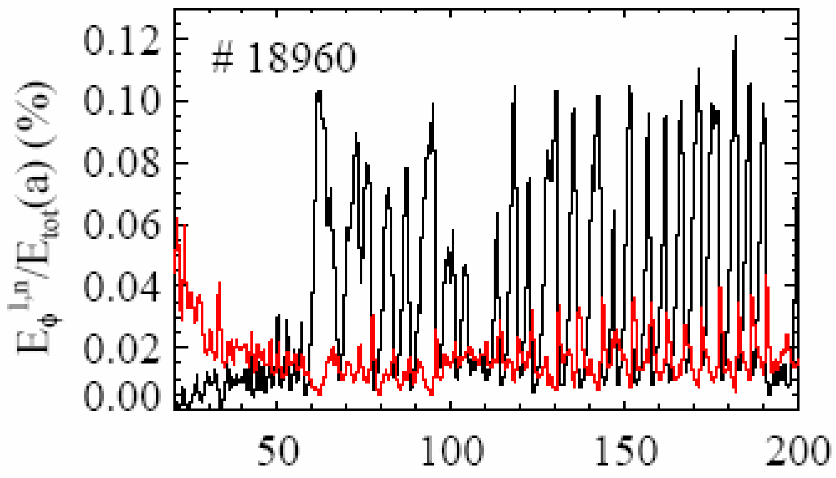
Virtual Shell: Spontaneous QSH

- In Standard Virtual Shell, especially at high current levels (0.8-0.9MA), Tearing Modes spectrum tends to n=-7 QSH more often.

Quasi-stationary QSH



Intermittent QSH

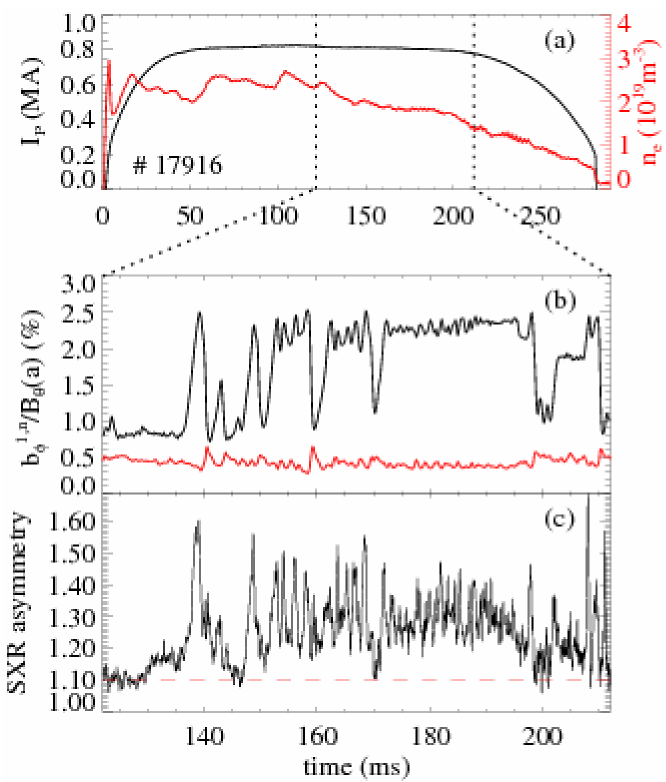


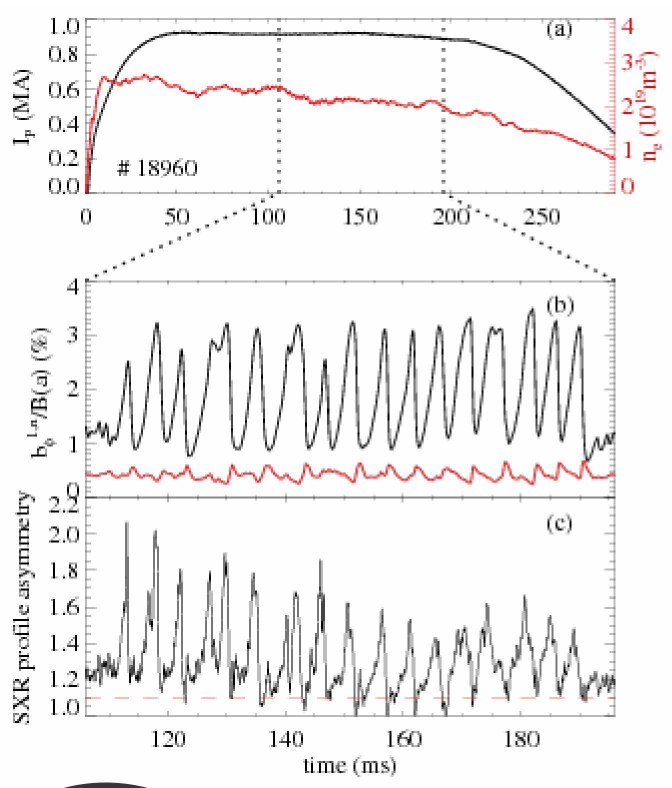
- Normalized magnetic energy in the dominant mode
- Normalized average magnetic energy in secondary modes

P. Martin , ICPP 2006 – Kiev 22-26/05/2006. submitted to PPCF

Virtual Shell: Spontaneous QSH

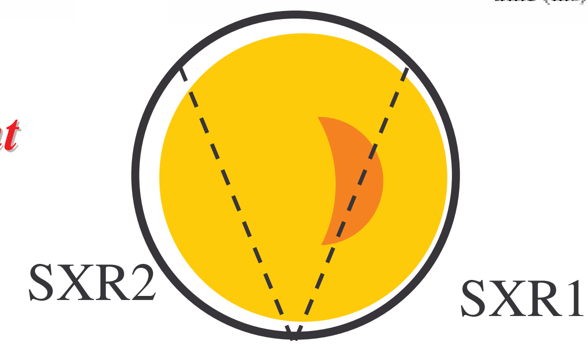
- Electron temperature and SXR emissivity increase in the plasma core





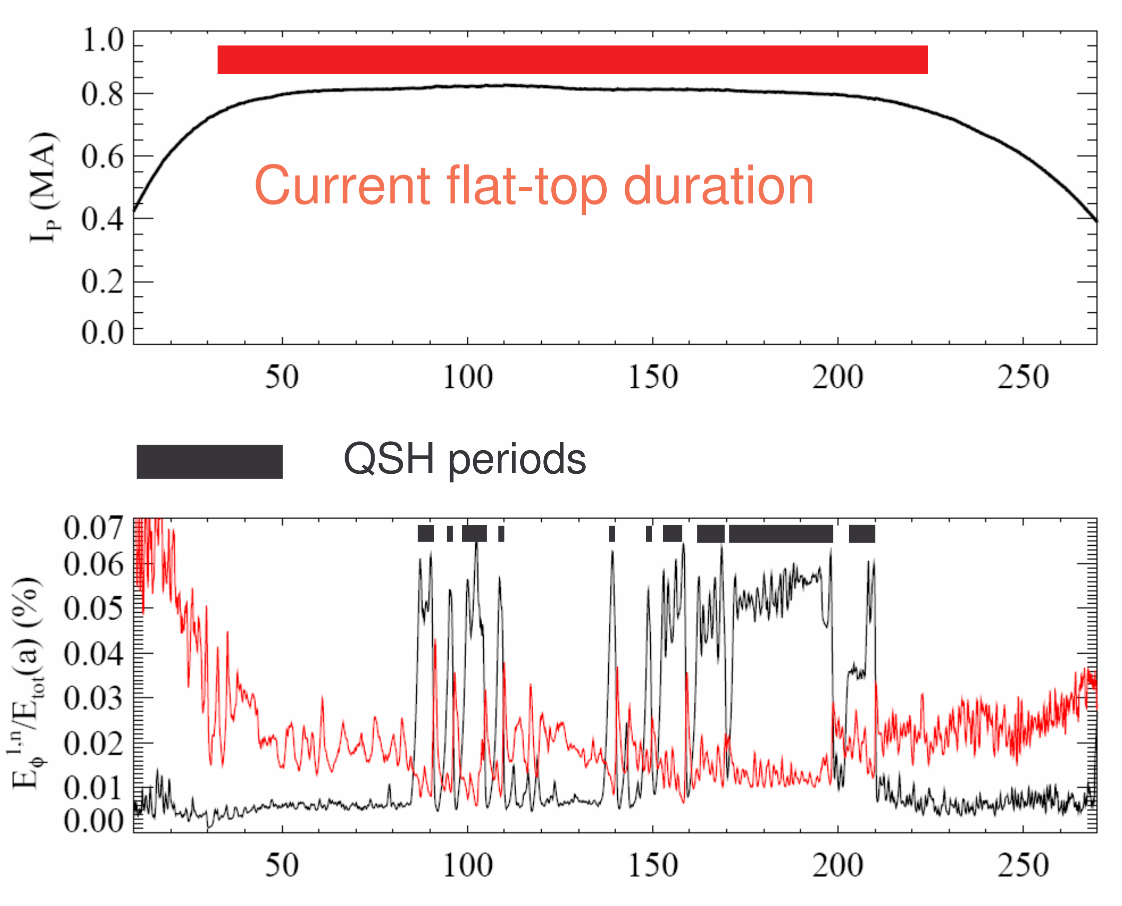
Shafranov shift

a hot helical core is present for time periods > τ_E



Virtual Shell: Spontaneous QSH

- This behavior is observed in standard V.S. discharges, *without LM mitigation*.
  - Statistical indicators for QSH: "probability" and "duration" measurements

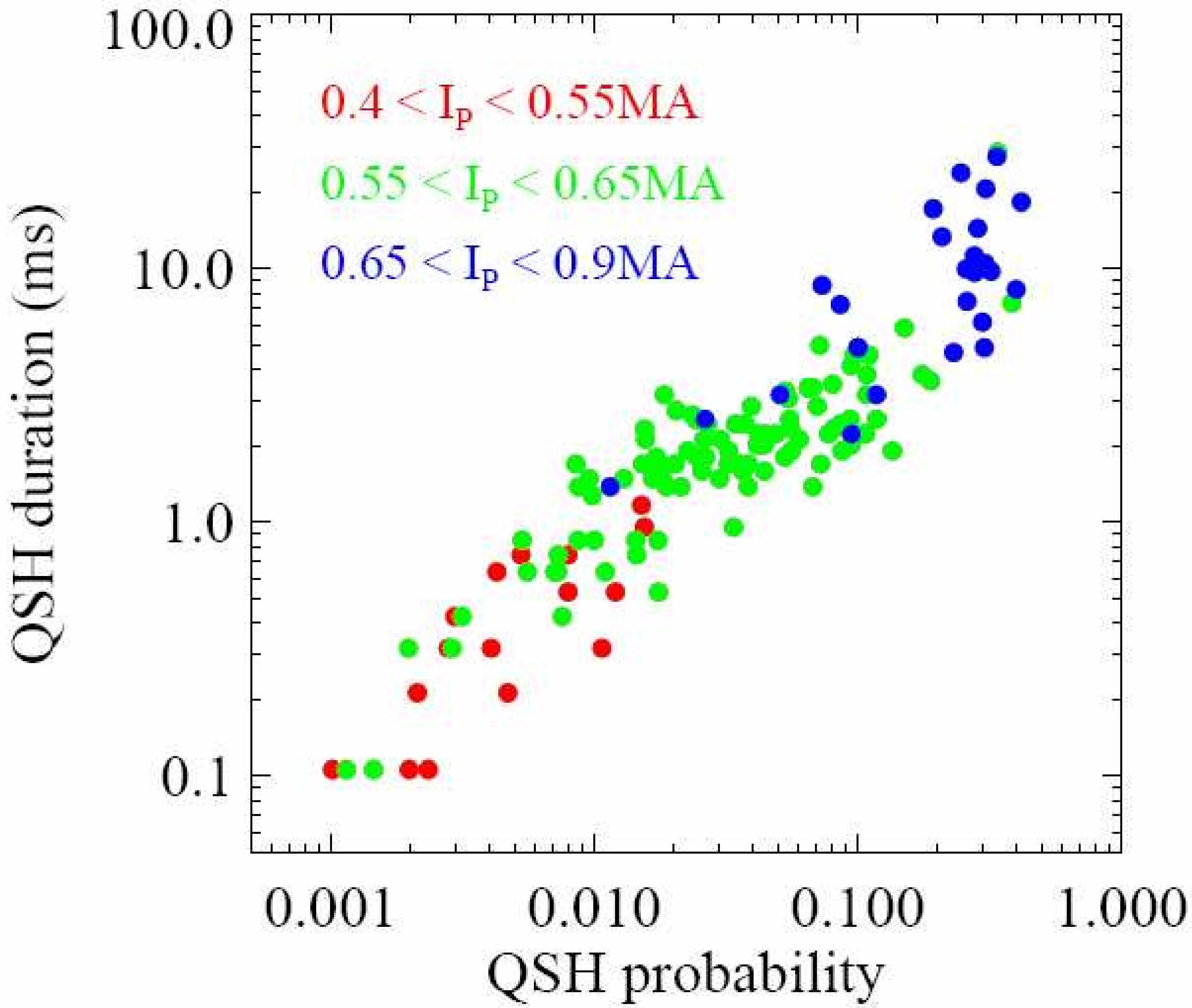


DURATION: longest QSH

PROBABILITY: sum(QSH periods)/current flat-top

Virtual Shell: Spontaneous QSH

- Both probability and duration increase with the level of plasma current



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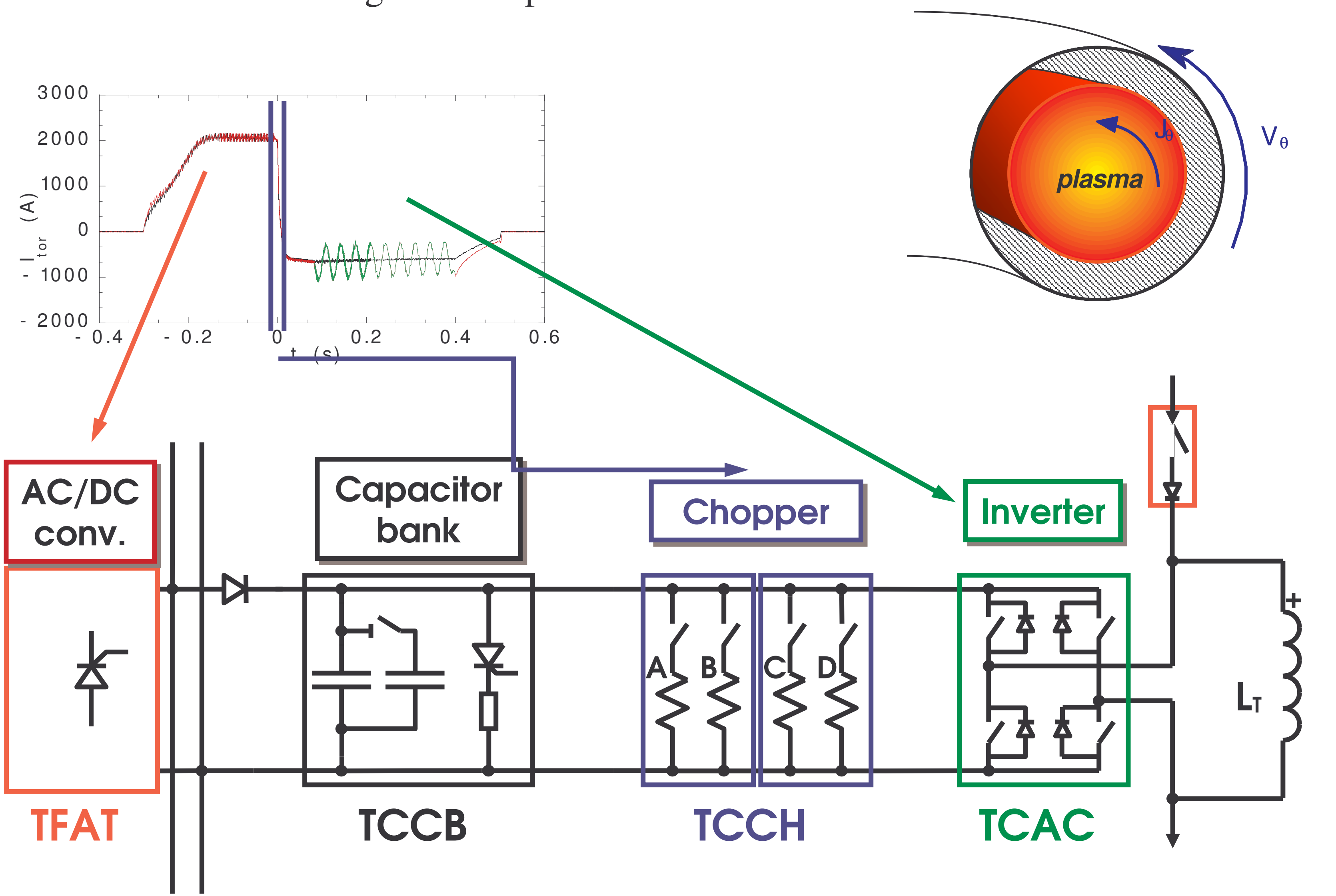
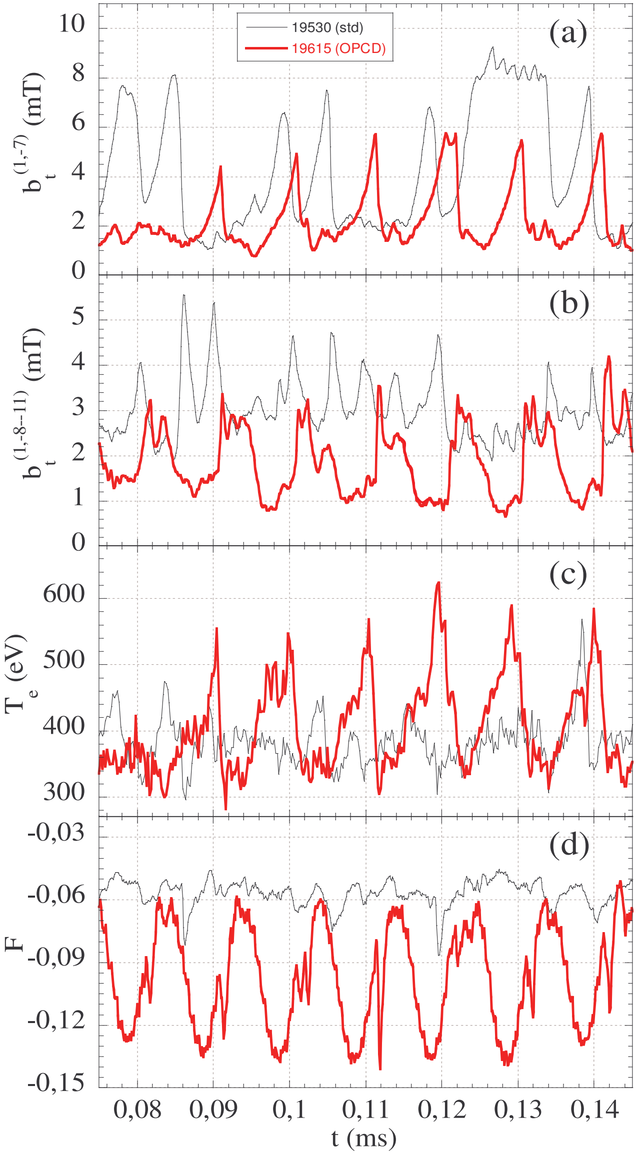
Virtual Shell+OPCD

- Tearing mode spectrum is significantly affected when during OPCD operations



D. Terranova, et al 48th Annual Meeting of the Division of Plasma Physics, Philadelphia Oct 2006

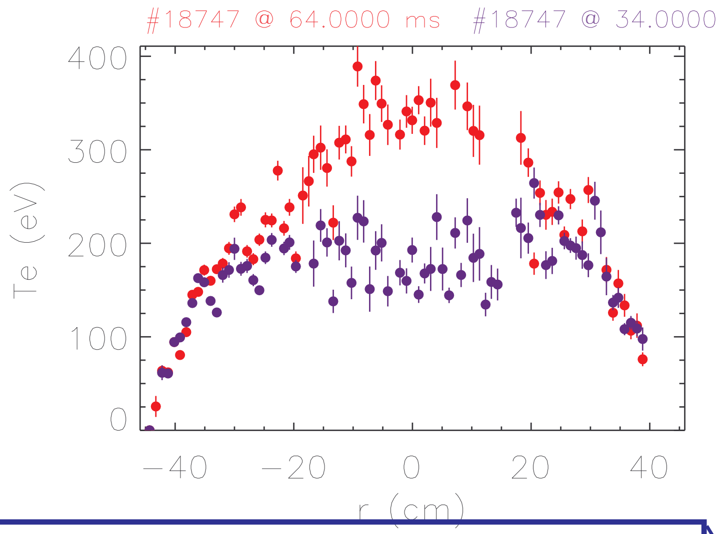
Virtual Shell + OPCD

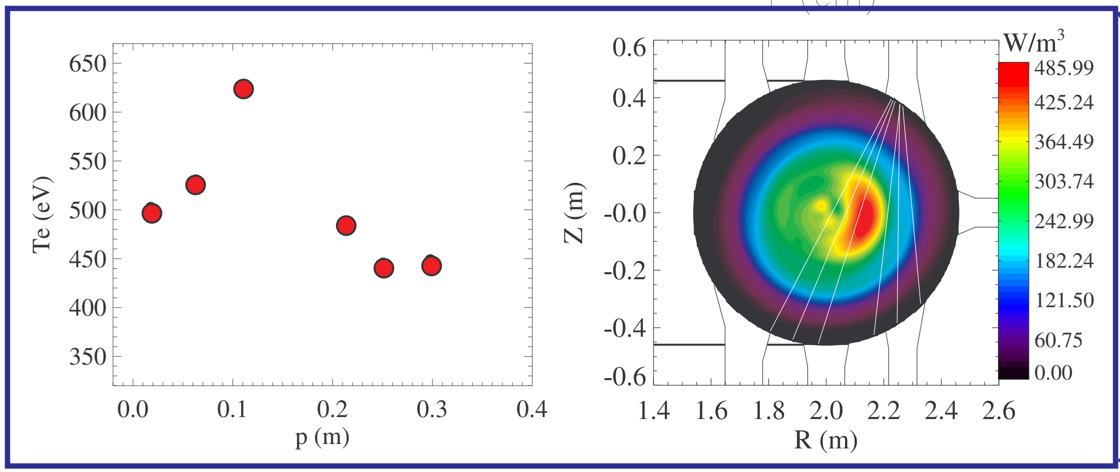


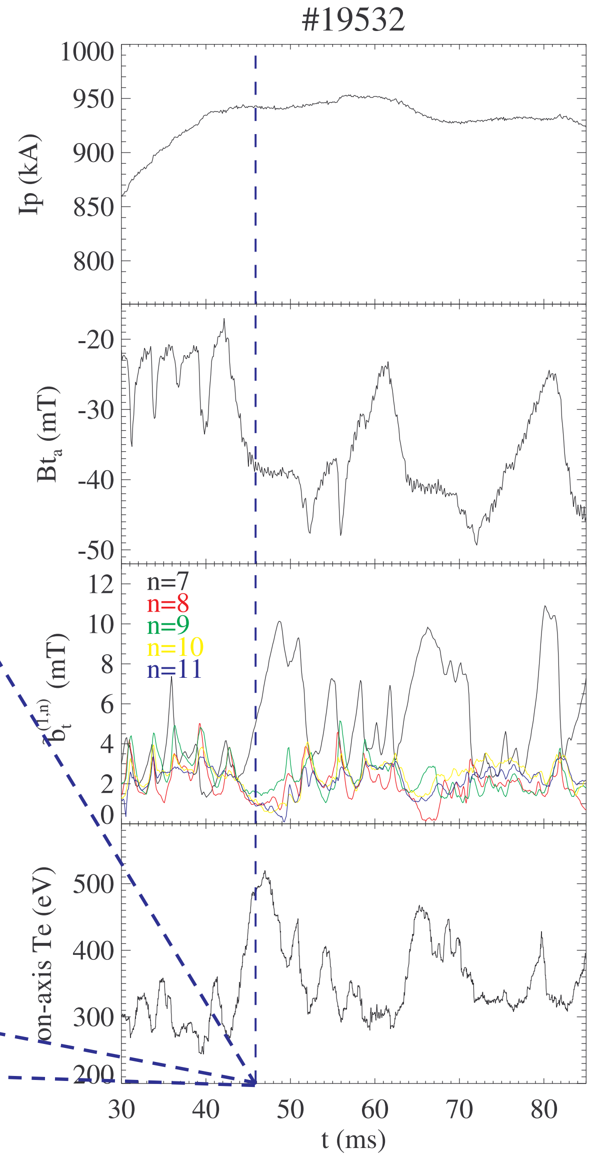
- **OPCD** is an efficient way for inducing a Quasi Single Helicity state in the plasma
- The transient QSH state is characterized by an *increased electron temperature* and *reduced chaos* thanks to the *reduction of secondary modes*.
- OPCD induced QSH states generally have smaller secondary modes with respect to spontaneous QSH States.

Virtual shell + OPCD

- Thermal structures appear in the core of the plasma.







Double Filter temperature profile diagnostic

F. Bonomo et al, **Rev. Sci. Instr. 77**, 10F313 (2006)

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Closer Virtual Shell /1

- The Virtual Shell cancels the radial field at the sensor radius
- The Closer Virtual Shell approach perform feedback on “virtual” b_r sensors closer (or farther away) to the plasma
  - Simultaneous measurement of radial AND toroidal component INSIDE the shell allows for “moving” the Virtual Shell closer to the plasma boundary:
  - A cylindrical vacuum model is assumed

$$b_r^{m,n}(r) = a^{m,n} I'_m\left(\frac{|n|r}{R_0}\right) + b^{m,n} K'_m\left(\frac{|n|r}{R_0}\right)$$

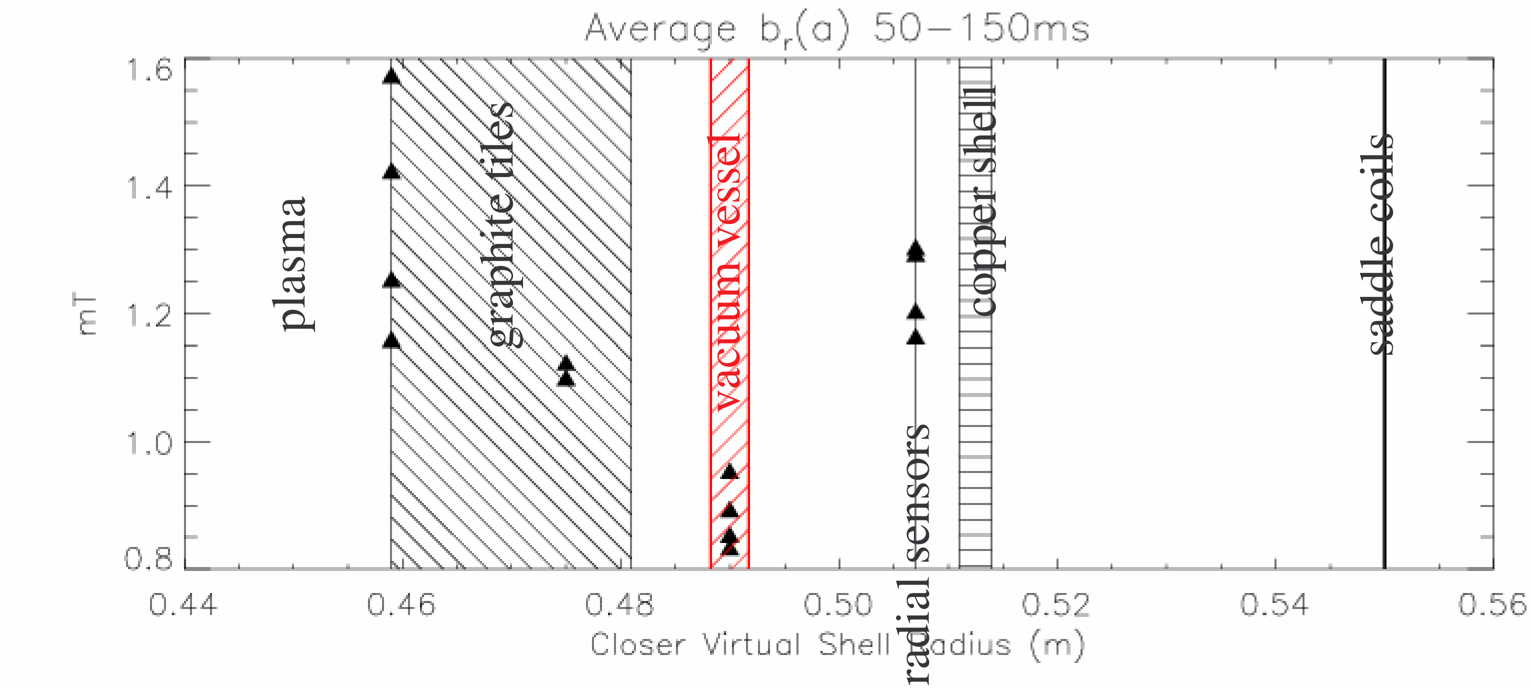
$$-i\,\mathrm{sgn}(n)\, b_\varphi^{m,n}(r) = a^{m,n} I_m\left(\frac{|n|r}{R_0}\right) + b^{m,n} K_m\left(\frac{|n|r}{R_0}\right)$$

coefficients $a^{m,n}$ b^{mn} are computed at measurement positions...

... and used to extrapolate b_r at desired radius

Closer Virtual Shell

- Preliminary experiments have been performed @ 600kA+800kA
- A decrease of radial field @plasma surface is observed,



... but <u>it is not monotonous</u> with the effective plasma-closer shell distance

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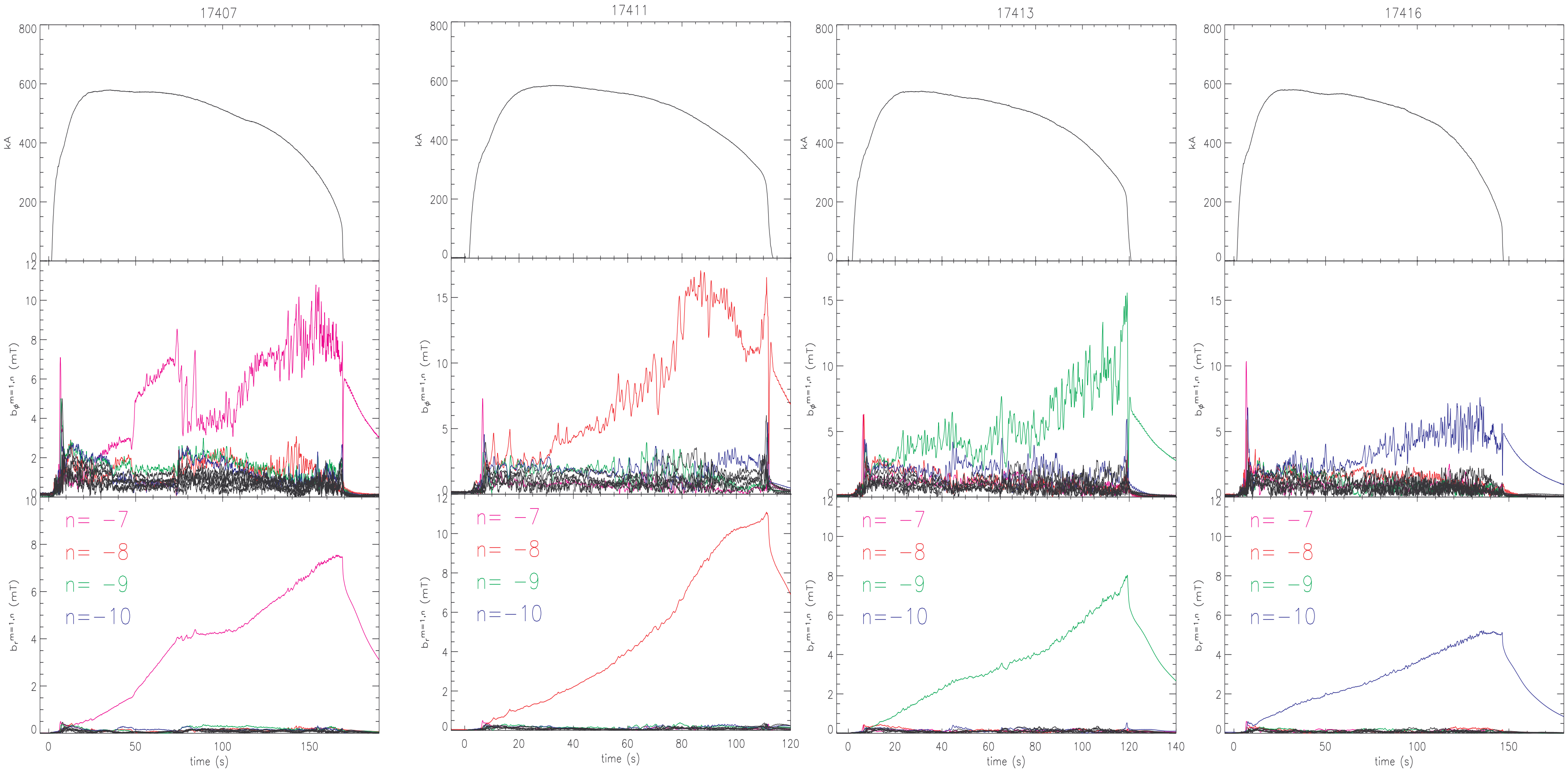
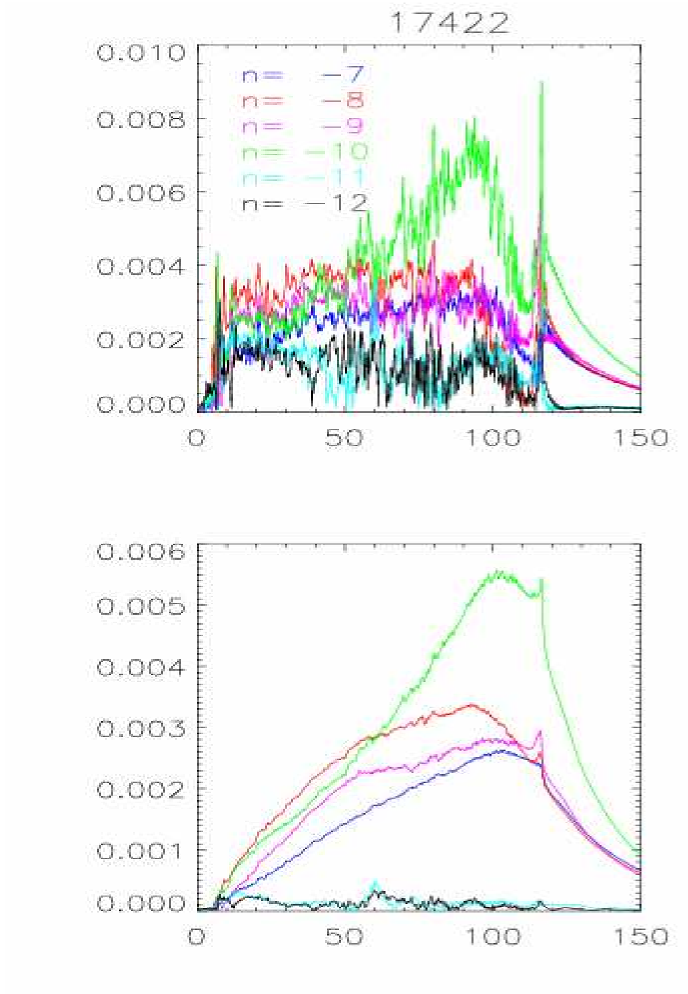
natural evolution

- If the control of a tearing mode is switched off
  - discharge duration is significantly shortened for n=-7 .. -10
  - This does not apply for n=-13



natural evolution: Multiple modes

- When several tearing modes are not controlled, the higher n mode tends to dominate the spectrum



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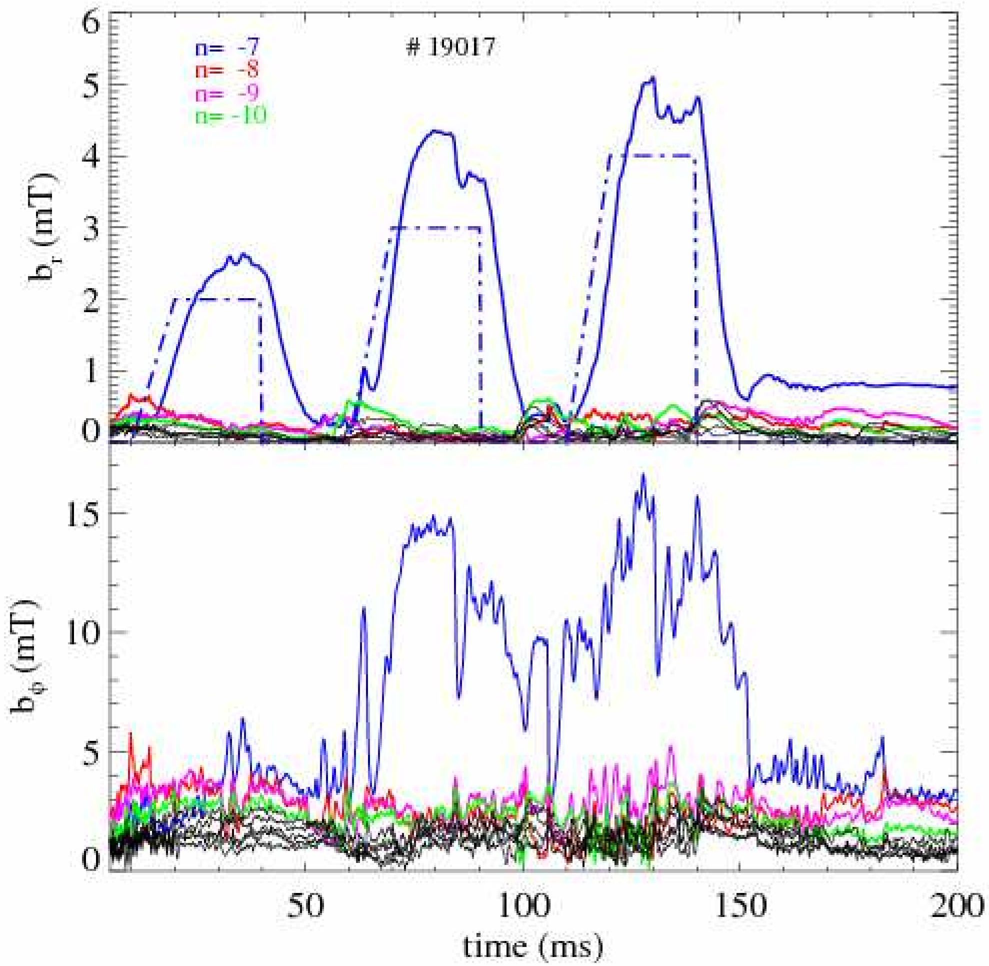
Non zero reference value

- The feedback law of the V.S. may include a non zero reference value for a mode

$$b_{mn}^{ext}(t) = k_p\left(b_{r,mn}(t) - b_{ref,mn}(t)\right) + k_I \int dt \left(b_{r,mn}(t) - b_{ref,mn}(t)\right)$$

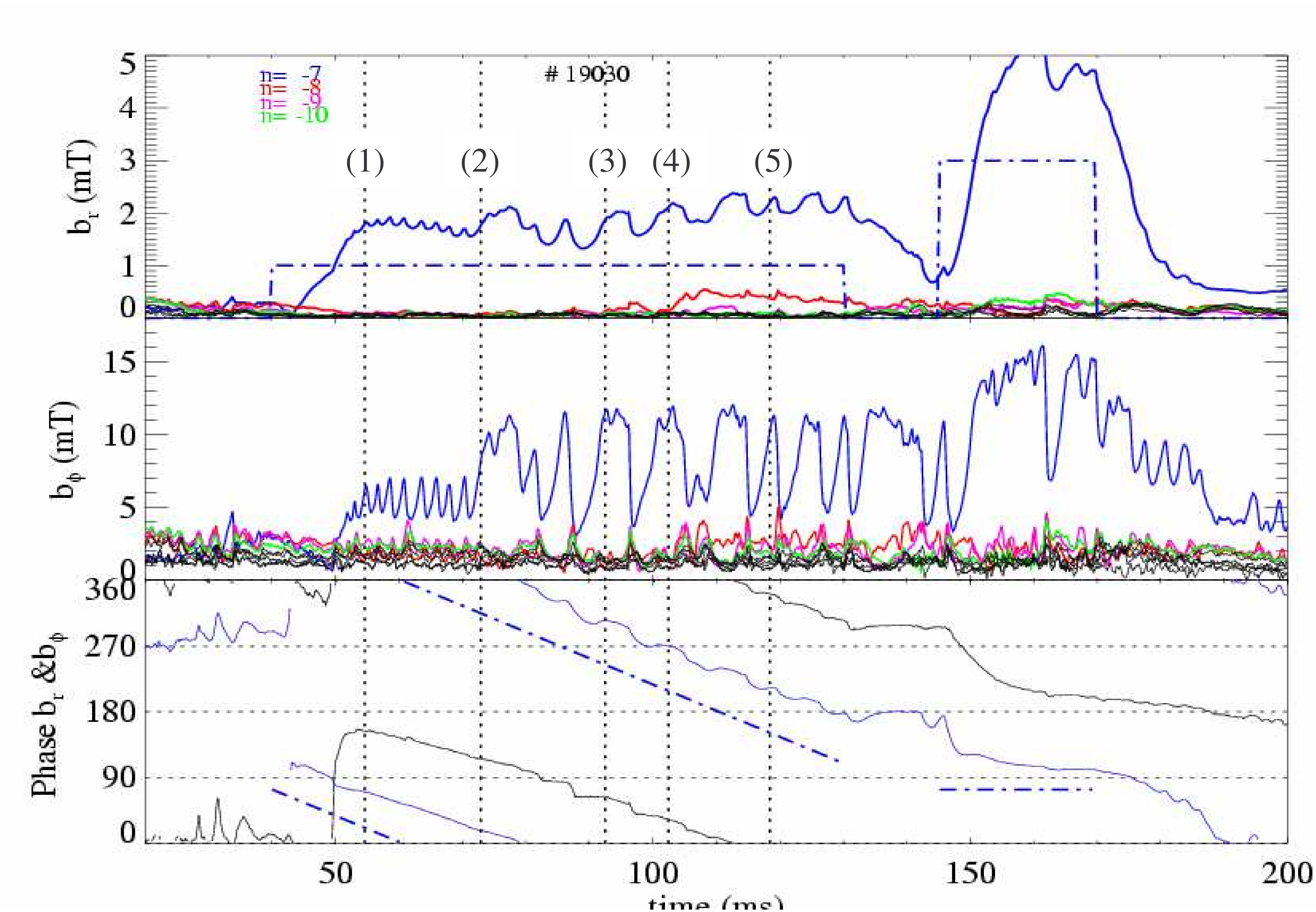
- QSH induction through a non zero reference value on n=-7 have been attempted on 800 kA discharges

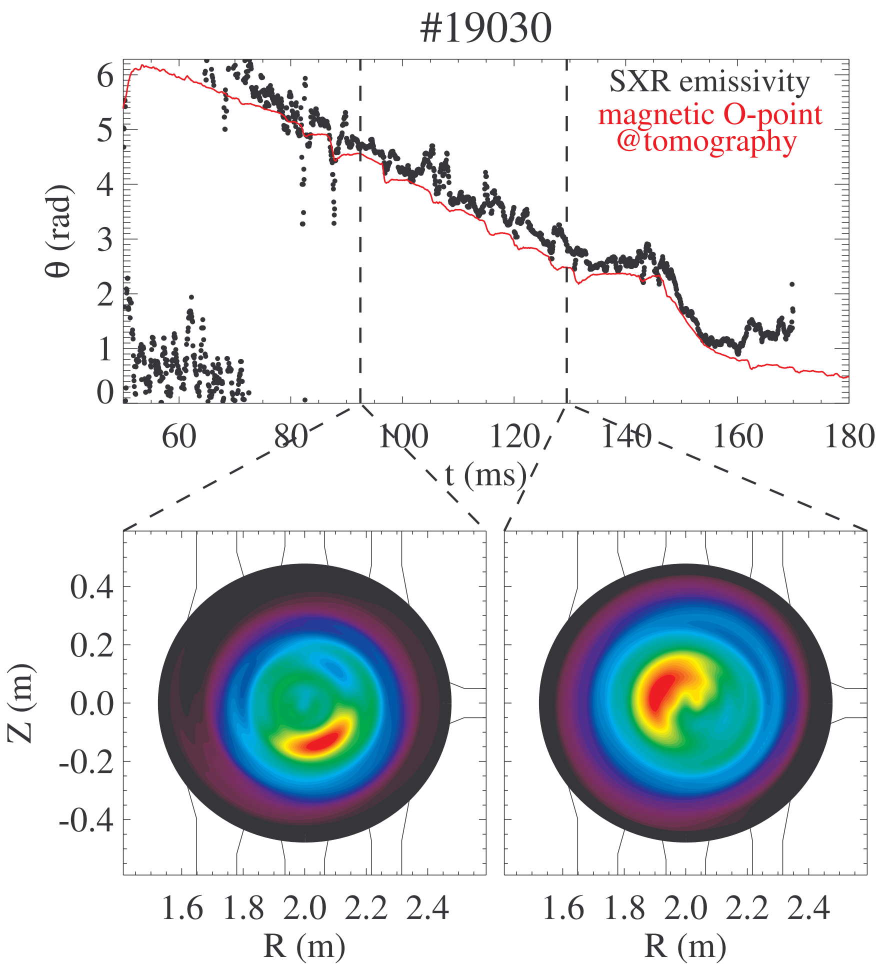
- The V.S cannot match the reference amplitude, with the present choice of gains



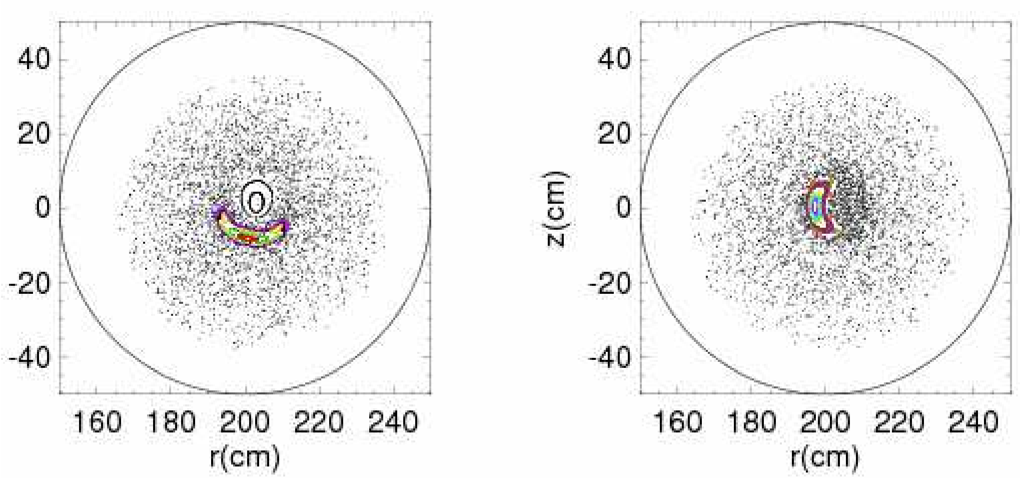
Non zero reference value

- The mode phase can be controlled and slowly (10-20Hz) varied in time





- The phase of the plasma mode locks to the reference phase
  - Intermittent islands maxima correspond to the magnetic island O-point
- Even when a thermal island is not evident, the SXR profile is still asymmetric
  - "Center of mass" of SXR emissivity follows the rotation of magnetic island O-point



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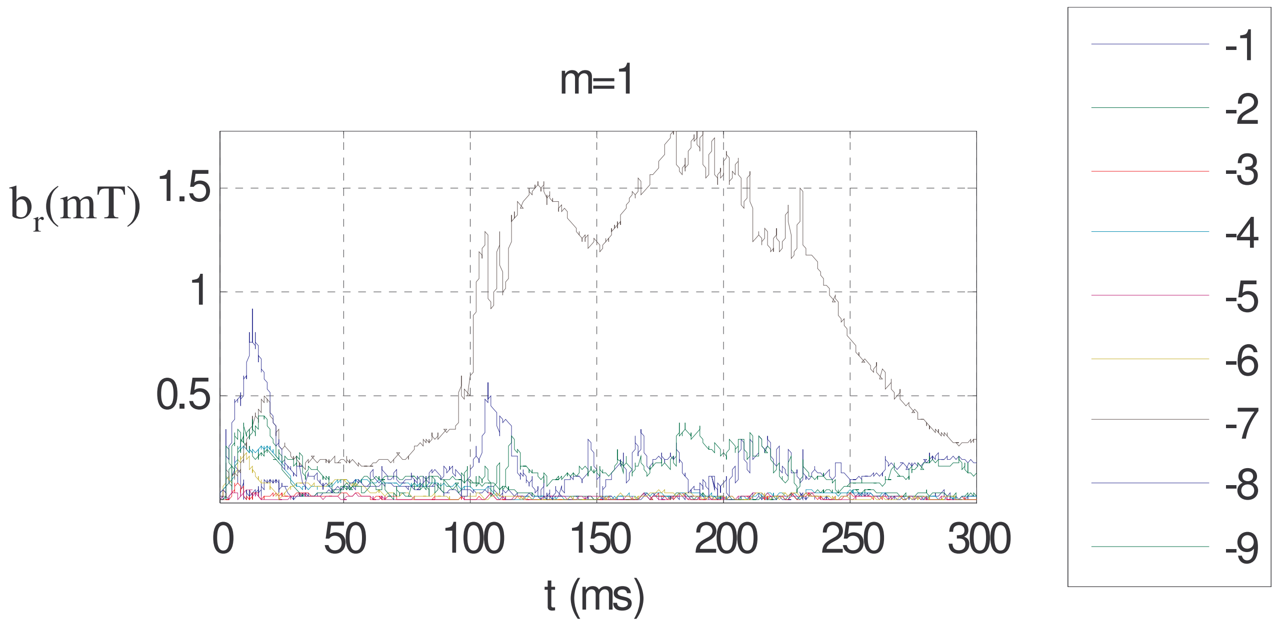
Complex gains

- The V.S. feedback law can been modified, in order to apply a torque

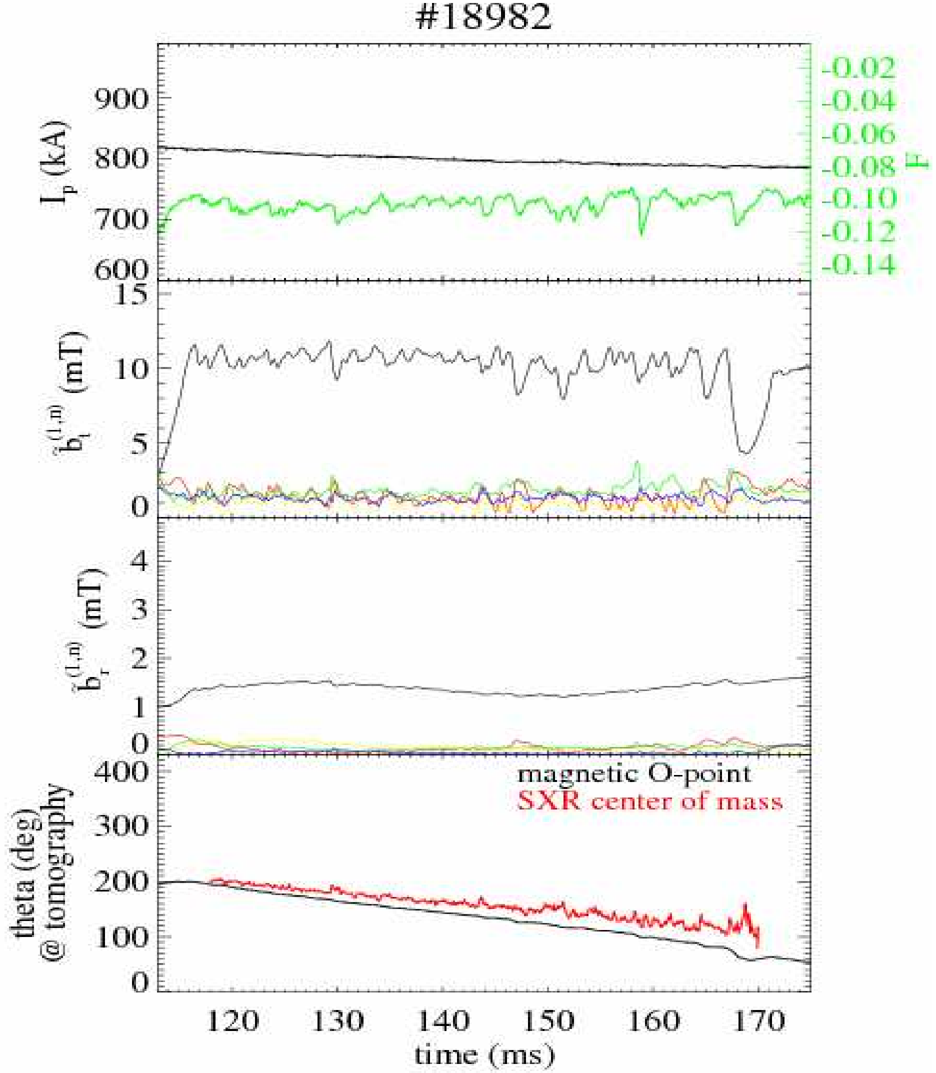
$$b_{mn}^{ext}(t) = k_p G e^{i\Phi} b_{r,mn}(t) + k_I \int dt\, G e^{i\Phi} b_{r,mn}(t)$$



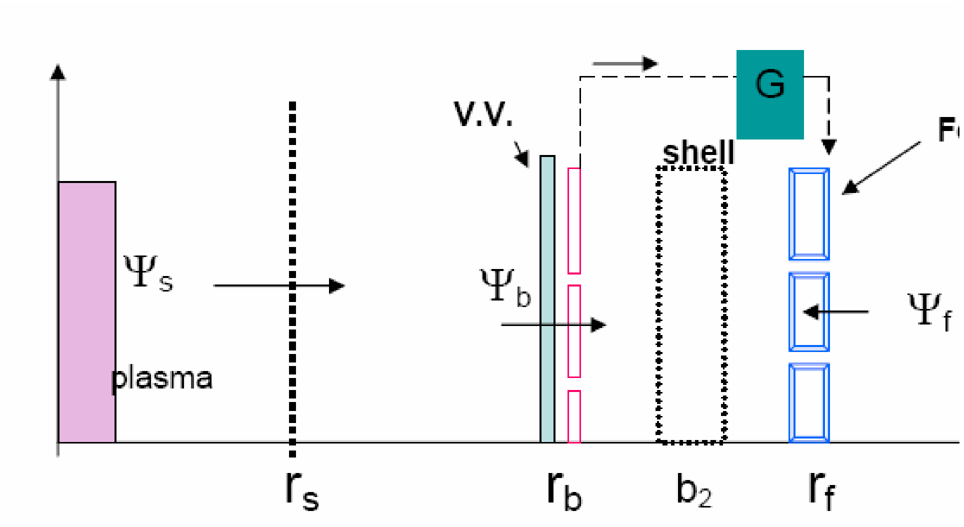
Complex gains

- For a proper choice of the gain phase
  - a long lasting QSH spectrum may arise
  - the level of the radial field at the edge remains reasonably low

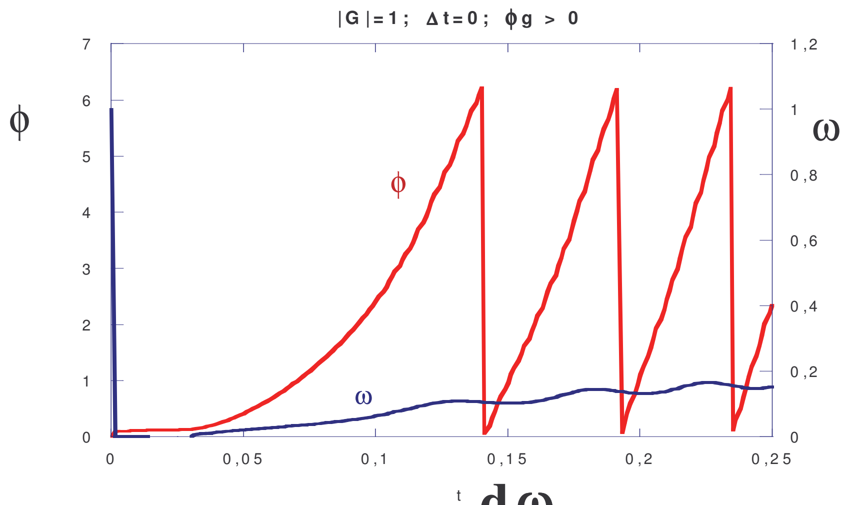
- the mode phase slowly rotates:
  - the effect is observed also on SXR profiles
  - intermittent SXR island occurs

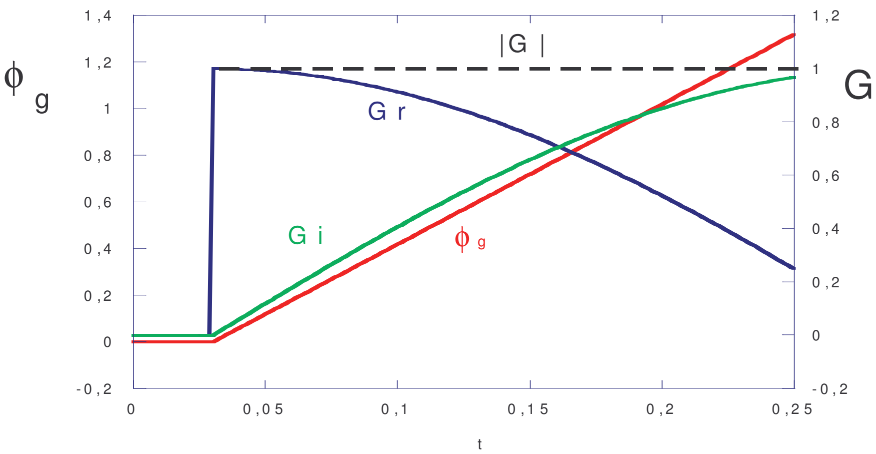


Analytical torque model for complex gain



- The imaginary part of the gain gives a net torque
- The real part cancels the field
- The sign of the imaginary part determines the rotation direction
- If |G| is constant, a tradeoff between high torque and low edge radial field need to be found





$$A\frac{d\omega}{dt} = T_w + T_G + T_{vis} + T_{error}$$

S.C. Guo, FT-NT01

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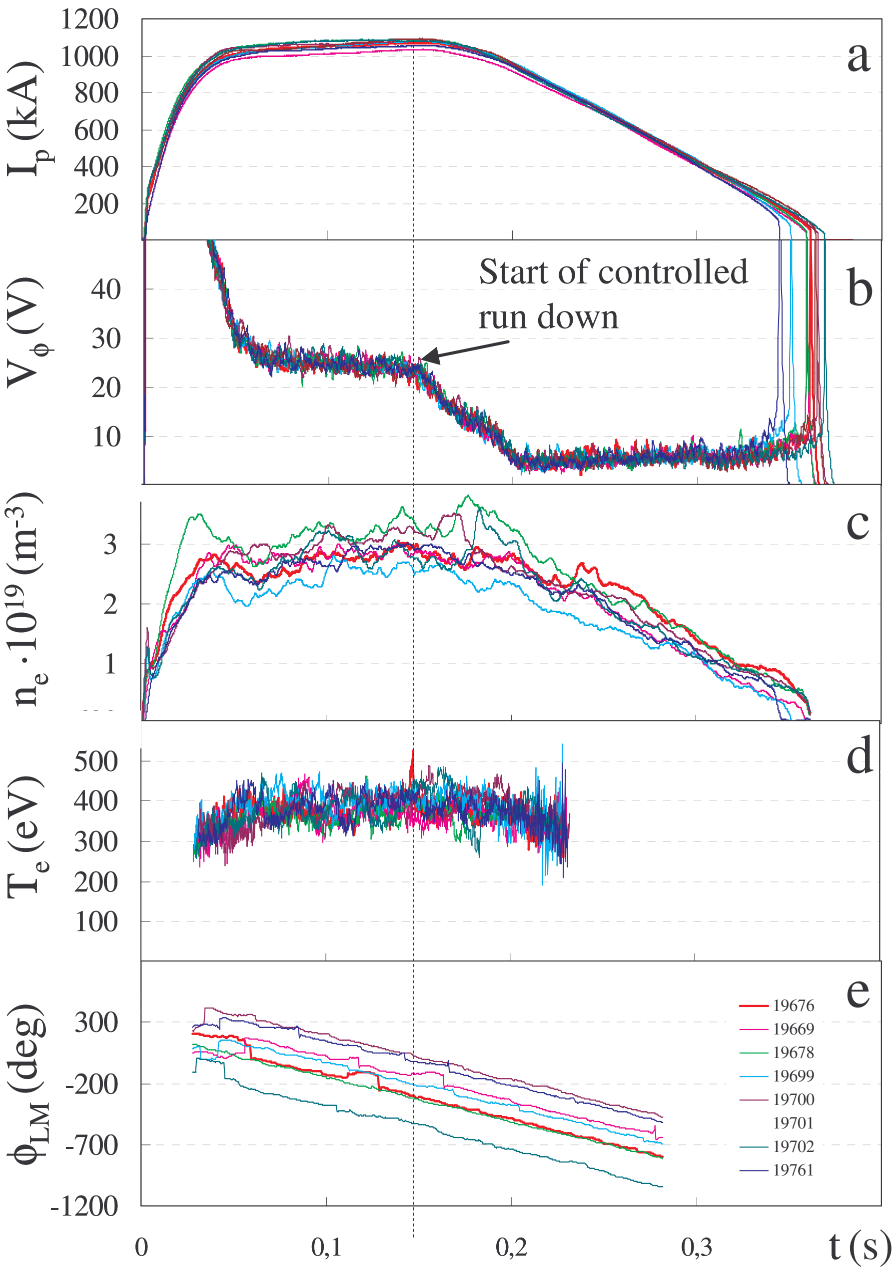
LM mitigation

- The highest current operations (1MA) up to now have been possible only with LM mitigation schemes

- Reproducible discharges are obtained with reduced interactions with the first wall...
  - no localized increase of vessel temperature
  - no localized enhancement of P_{rad}

- ... but QSH probability is significantly reduced

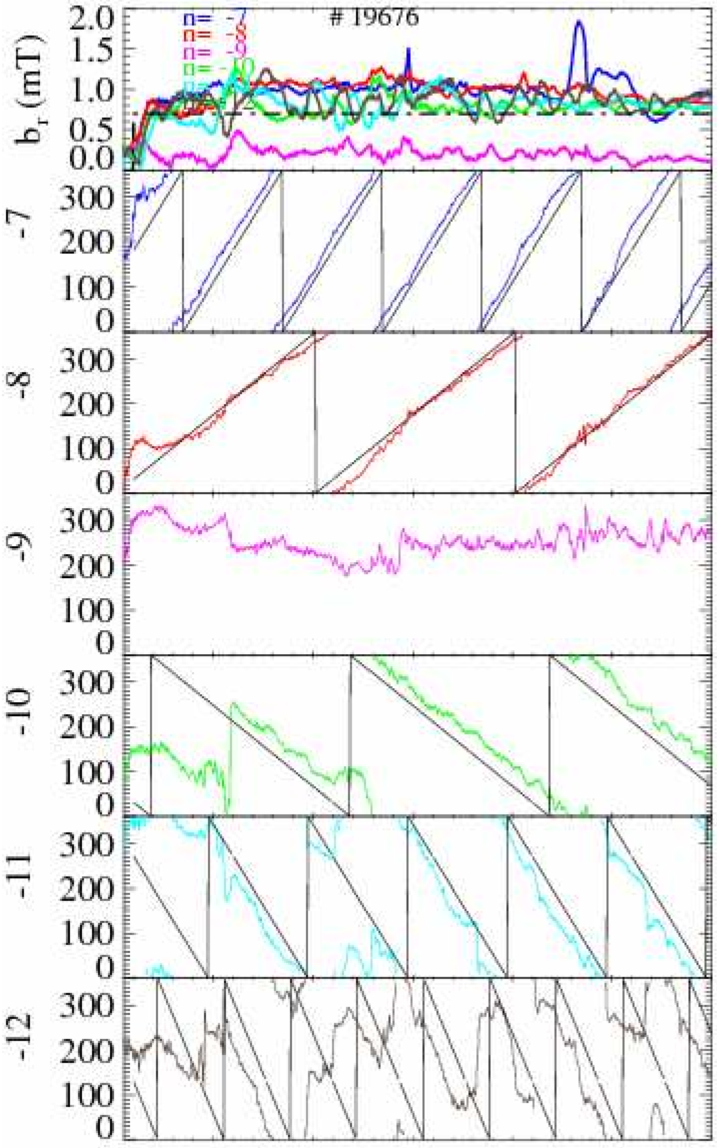


LM mitigation

- The scheme is based on non zero reference value for *m=1* edge radial field with relatively low amplitude and $\Delta f \propto \Delta n$
  - 1,-7 f= -20 Hz
  - 1,-8 f= -10 Hz
  - 1,-9 f= 0 Hz
  - 1,-10 f= 10 Hz
  - 1,-11 f= 20 Hz
  - 1,-12 f= 30 Hz

- The initial phase of the reference value is measured in real time measurements

- This scheme preserves the LM pattern and rotates it along the stationary 1,-9 mode.
- the m=0,n=1 mode rotates with the slinky: a torque is exerted on the *m= 0* modes.

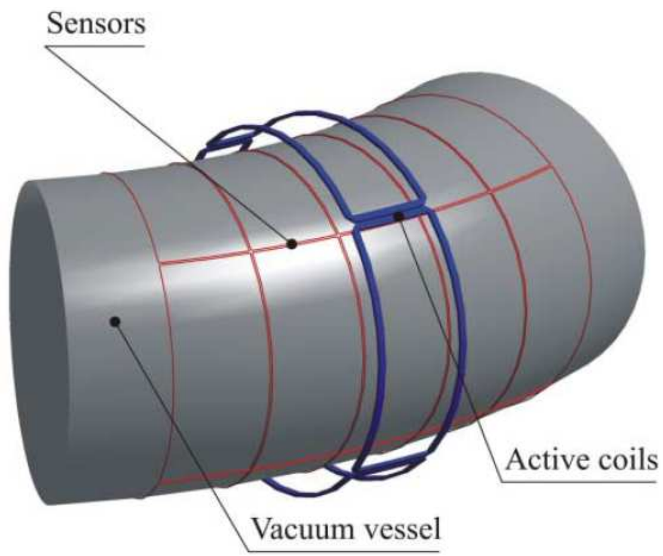


Open issues / Controller optimization

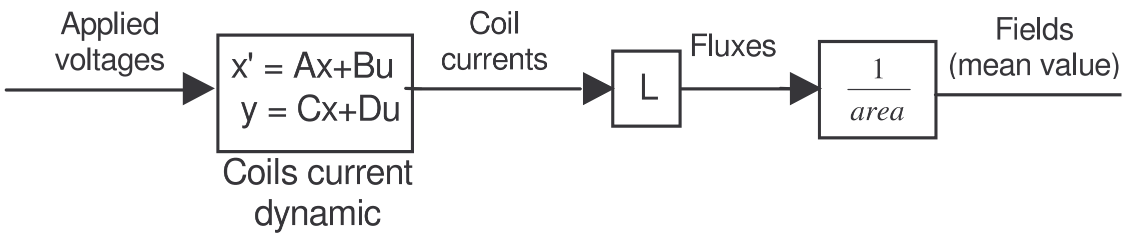
- A residual “error” (i.e. mismatch between reference and measurement) remains
  - both in standard Virtual Shell and Closer Virtual Shell
- In particular, errors are not symmetric: shell asymmetries are responsible for different dynamic behavior of the edge radial field
  - toroidal asymmetry due to the presence of the toroidal gap
  - poloidal asymmetry in the regions of gaps of the mechanical structure and the shell
- Different modes require different gains: Mode Control schemes with different gains need to be developed

Residual error / Shell Asymmetries

- These issues are being addressed by means of an electromagnetic model of the control system



- Main features of the model
  (*state space representation*)
  - ***inputs***: 48x4 voltages applied by the power supply to the saddle coils
  - ***outputs***: 48x4 magnetic fluxes measured by the sensor coils



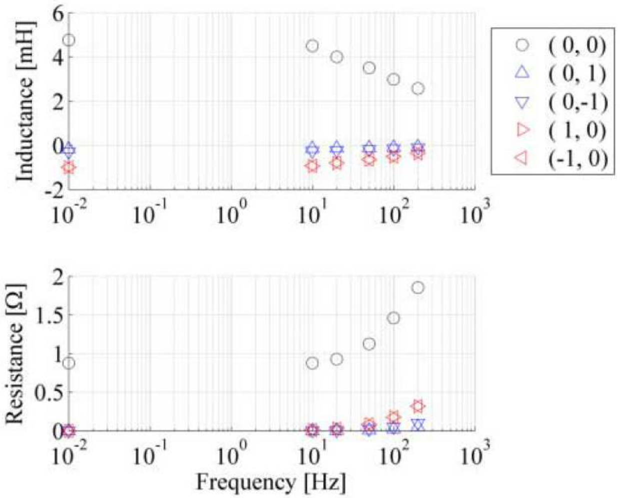
$\mathbf{A=-L^{-1}R}$ $\mathbf{B= L^{-1}}$

$\mathbf{C = 1}$ $\mathbf{D}=0$

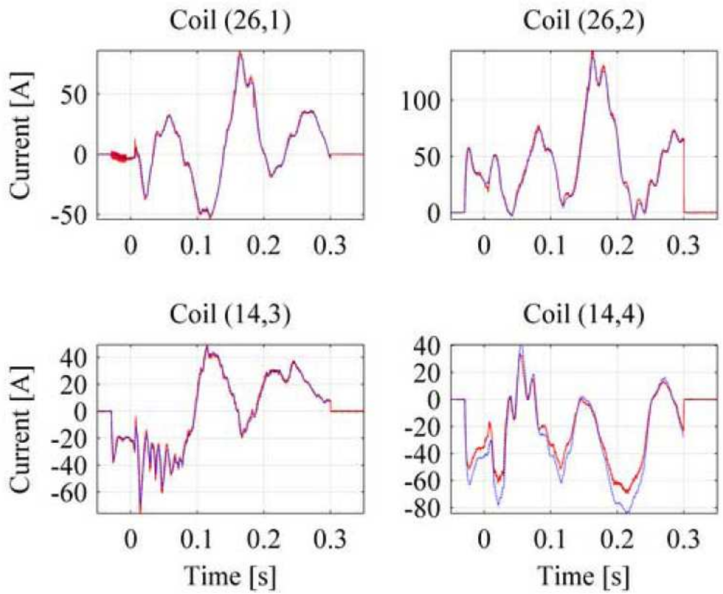
A. Soppelsa, G. Marchiori, to be published in Fusion Engineering and Design, 2006

E.M. model of active control system

1. Saddle coils inductance (**L**) and dissipation (**R**) matrices are composed by constant terms
   - four non-zero mutual inductances for each coil are considered
   - elements of L and R, corresponding to selected locations, have been <u>experimentally measured.</u>



2. No coupling with plasma
   - current flowing into saddle coils is given by externally applied voltages only
   - Model computed currents correspond in fact to experimental measurements

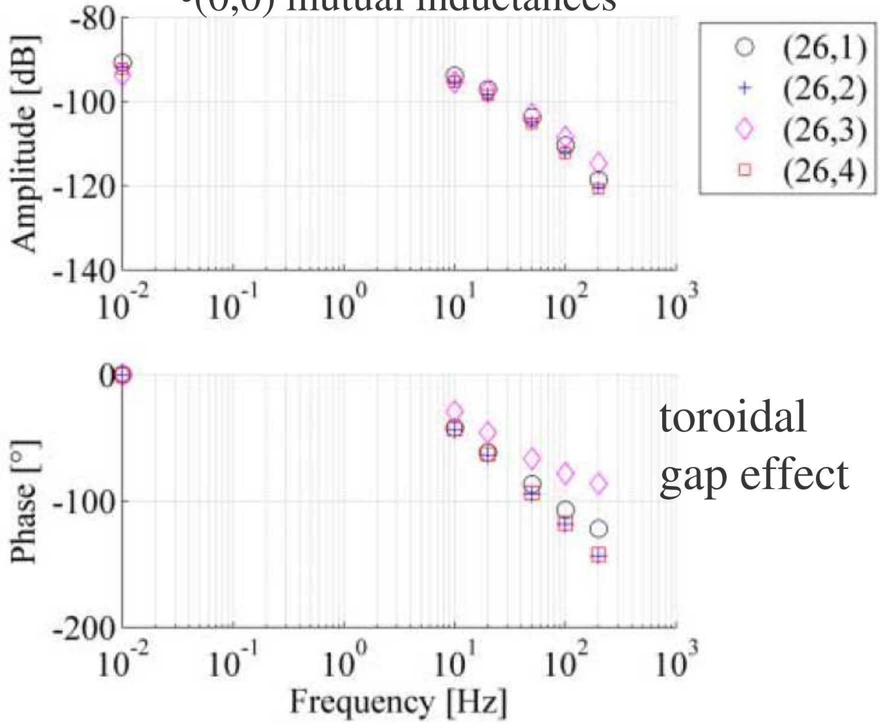


E.M. model of active control system

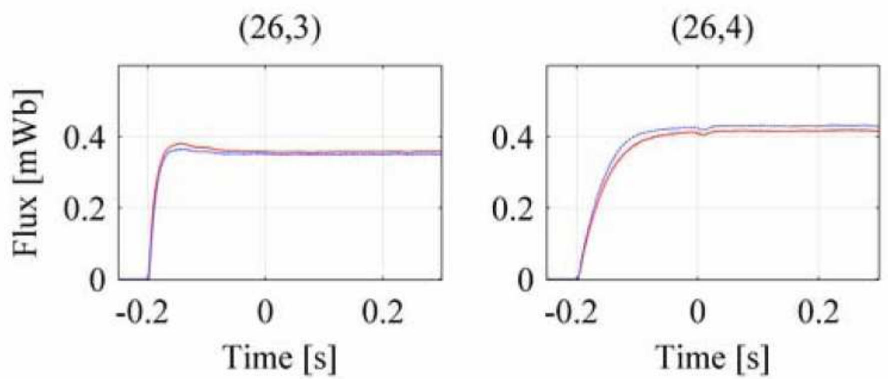
3. Accurate (i.e. non sparse) mutual inductance between coils and sensors
   - Optimal number of non zero elements identified iteratively: 1+3+2x6x4=52 for each saddle-coil are included
   - frequency response is included

- The model reproduces the dynamical behavior of the system with an accuracy of 5%
  - open loop generation of harmonic m=0,n=4
  - closed-loop PI controller: cancellation of static disturbances produced by toroidal windings
- Work in progress:
  - determination of optimal PID gains for canceling time varying fields
  - optimization of PID gains for different sections

•(0,0) mutual inductances



toroidal gap effect



Beyond Virtual Shell

- Saddle coils generates low n modes (especially m=0) with low efficiency

$$b_{rc}^{m,n}(t) = -\mu_0 K'_m\left(\frac{|n|c}{R_0}\right) I'_m\left(\frac{|n|c}{R_0}\right)\frac{n^2 c}{R_0^2}\frac{\sin\left(n\frac{\Delta\phi}{2}\right)}{n\frac{\Delta\phi}{2}}\frac{\sin\left(m\frac{\Delta\theta}{2}\right)}{m\frac{\Delta\theta}{2}} I^{m,n}(t)$$

- The saddle coils are located outside the shell
  - action on low n modes is delayed compared to high n

- To overcome these two issues: Mode control with Shell Compensation
  - the inverse of the shell transfer function for the modes is included in the gains
  - derivative gain needs to be included (a one pole filter is implemented in real-time)

$$b_{coil}^{m,n}(r,t) = \left(K_P - \frac{K_I}{A^{m,n}}\right) b_r^{m,n}(r,t) + K_I \int_{t_0}^{t} b_r^{m,n}(r,\xi)\,d\xi - \frac{K_P}{A^{m,n}}\frac{\partial b_r^{m,n}(r,t)}{\partial t} - K_P\, b_r^{m,n}(r,t_0)$$

Conclusions

- Virtual Shell scheme reduces significantly tearing mode edge radial field
  - less plasma wall interaction and lower loop voltage
- In standard V.S., spontaneus, long lasting, QSH spectra are observed at high currents.
- OPCD reproducibly increase the QSH probability
- Non zero reference values and complex gains allows to control phase of modes. Amplitude control needs to be optimized.
- Locked Mode rotation techniques are required, at present, to operate reproducibly at high current, due to non optimized controller.
  - algorithms experimented so far are not compatible with QSH
- Optimized feedback schemes are being developed