HELICAL STATES AND FEEDBACK CONTROL: THE REVERSED FIELD PINCH IN THE ITER ERA

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Oak Ridge National Laboratory, September 10th, 2009

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12) Oak Ridge National Laboratory, USA

1. The RFX-mod device
2. A structural change for the RFP
3. High current operation & helical states: a change of paradigm
4. Summary and conclusions

The RFX-mod device

1

RFX-mod

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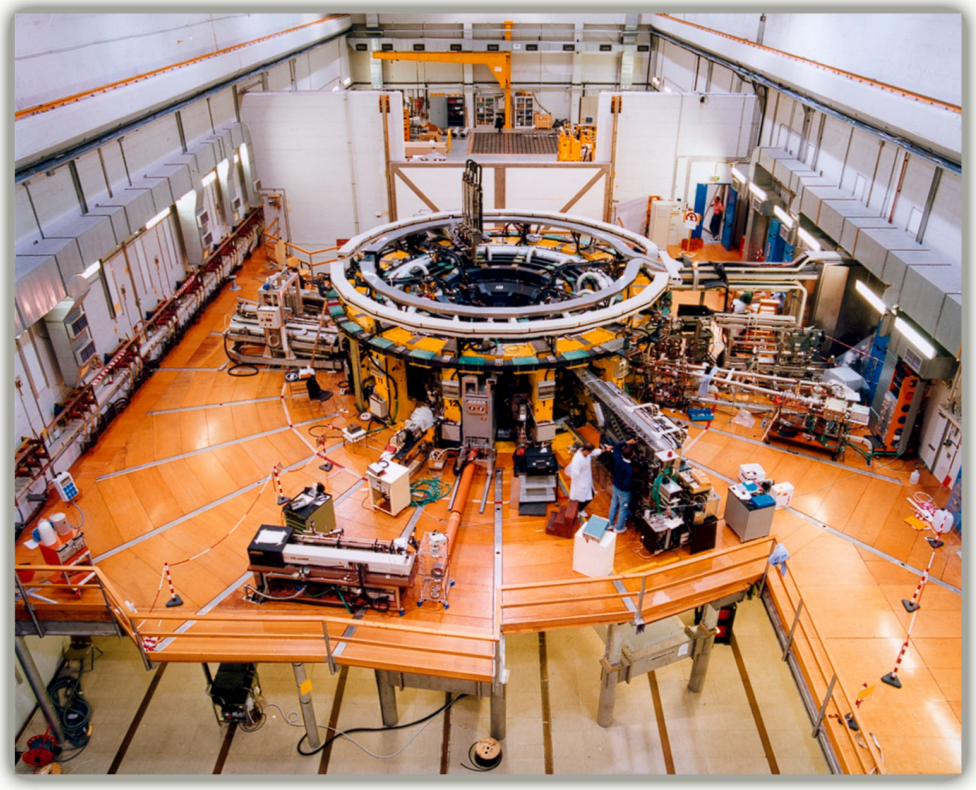
The largest RFP in the world, located in Padova, Italy

A fusion facility for MHD mode control



a=0.459 m, *R*=2 m, *plasma current* up to 2 MA

A dynamic and well-integrated community

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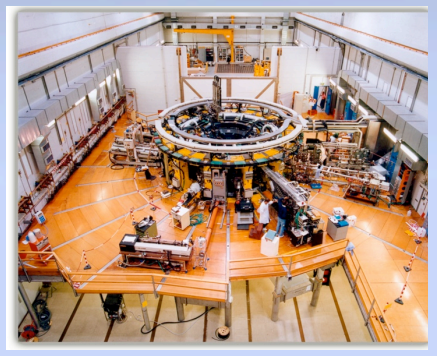
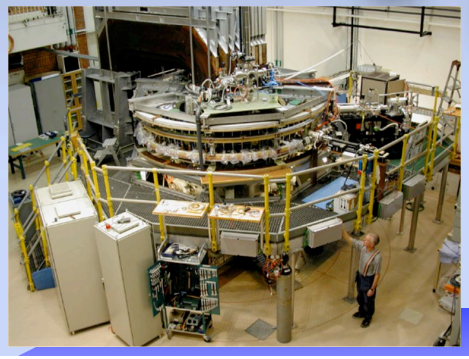
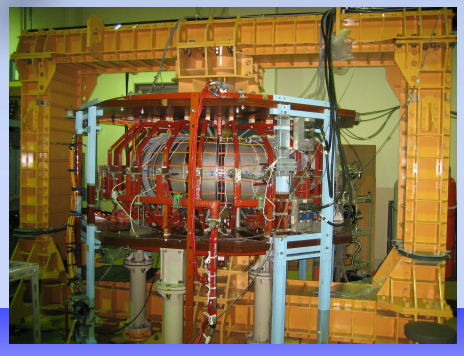
RFX-mod



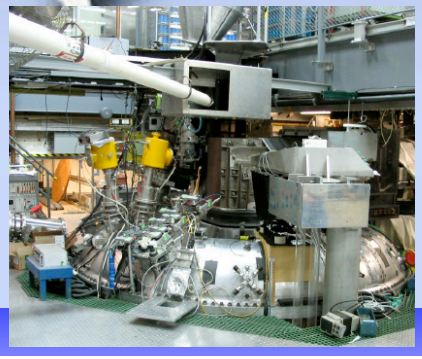
EXTRAP T2R



RELAX



MST



The RFP: a tight link with University

(all experiments in University environment)

and a nursery for the fusion community

At the leading edge of active stability control

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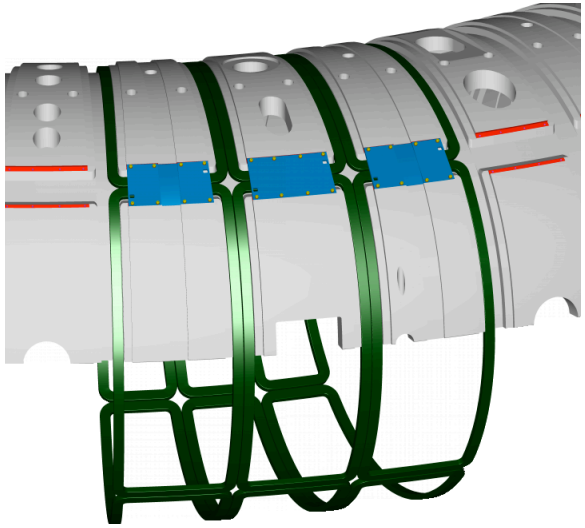
RFX-mod has the best feedback system for real time control of MHD stability ever realized for a fusion device

Full stabilization of multiple RWMs and

control of individual tearing modes achieved in RFX-mod and EXTRAP T2-R

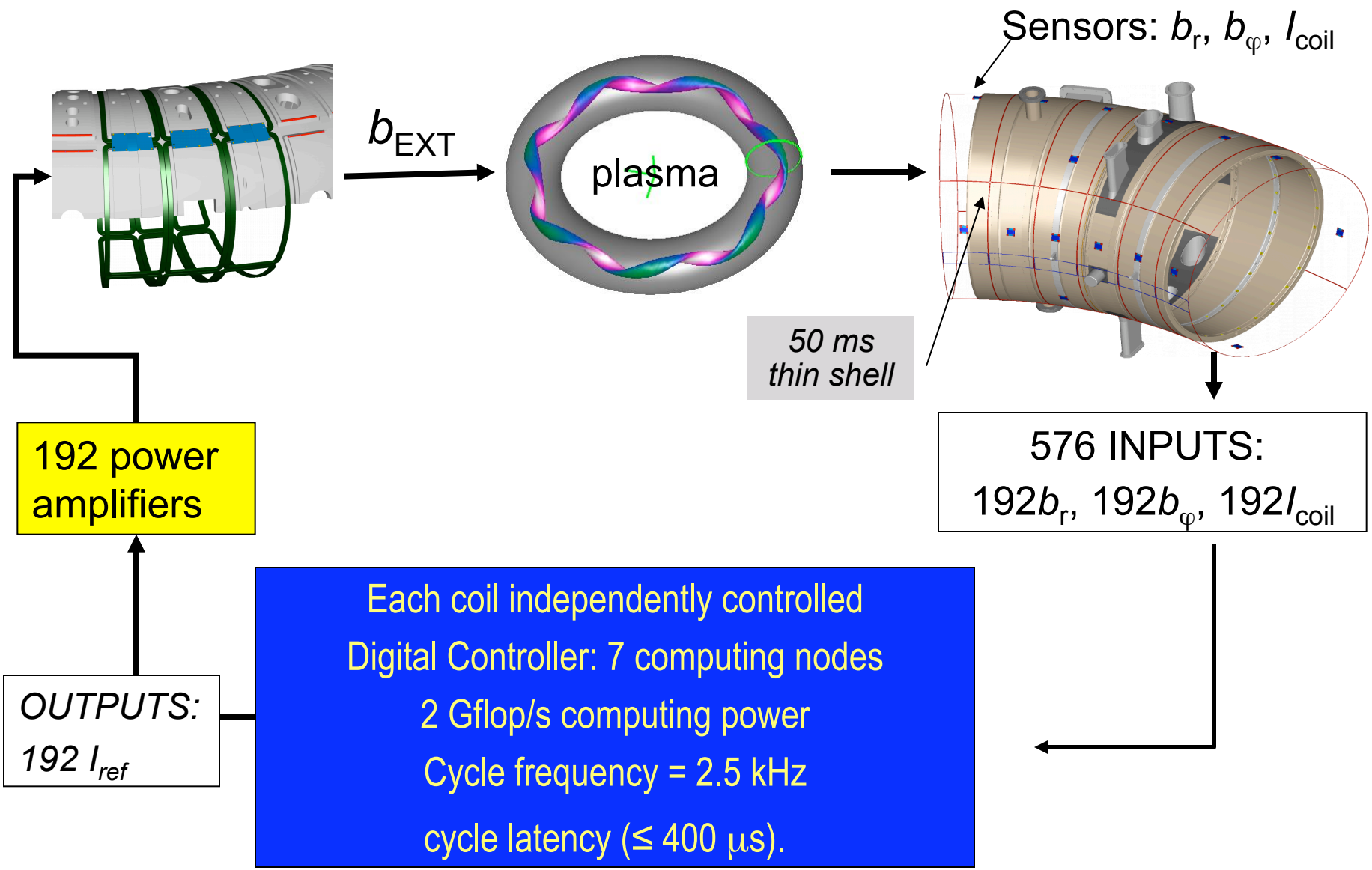
Demonstrates that a thick stabilizing shell is NOT needed

- 192 coils arranged in 48 toroidal positions cover the whole plasma surface
- Each is independently driven (60 turns, 650 V x 400 A)
- Digital controller elaborates real-time 576 inputs



Strong integration between physics and control engineering key for success

Feedback Control System Architecture



MHD stability feedback control

- Full stabilization of multiple resistive wall modes in presence of a thin shell (and RWM physics/code benchmarking)
- Control and tailoring of core resonant tearing modes – mitigation of mode-locking
- Test of new algorithms and models for feedback control
- Design of mode controllers

EXPERIMENTAL PROPOSALS FOR 2009 FROM

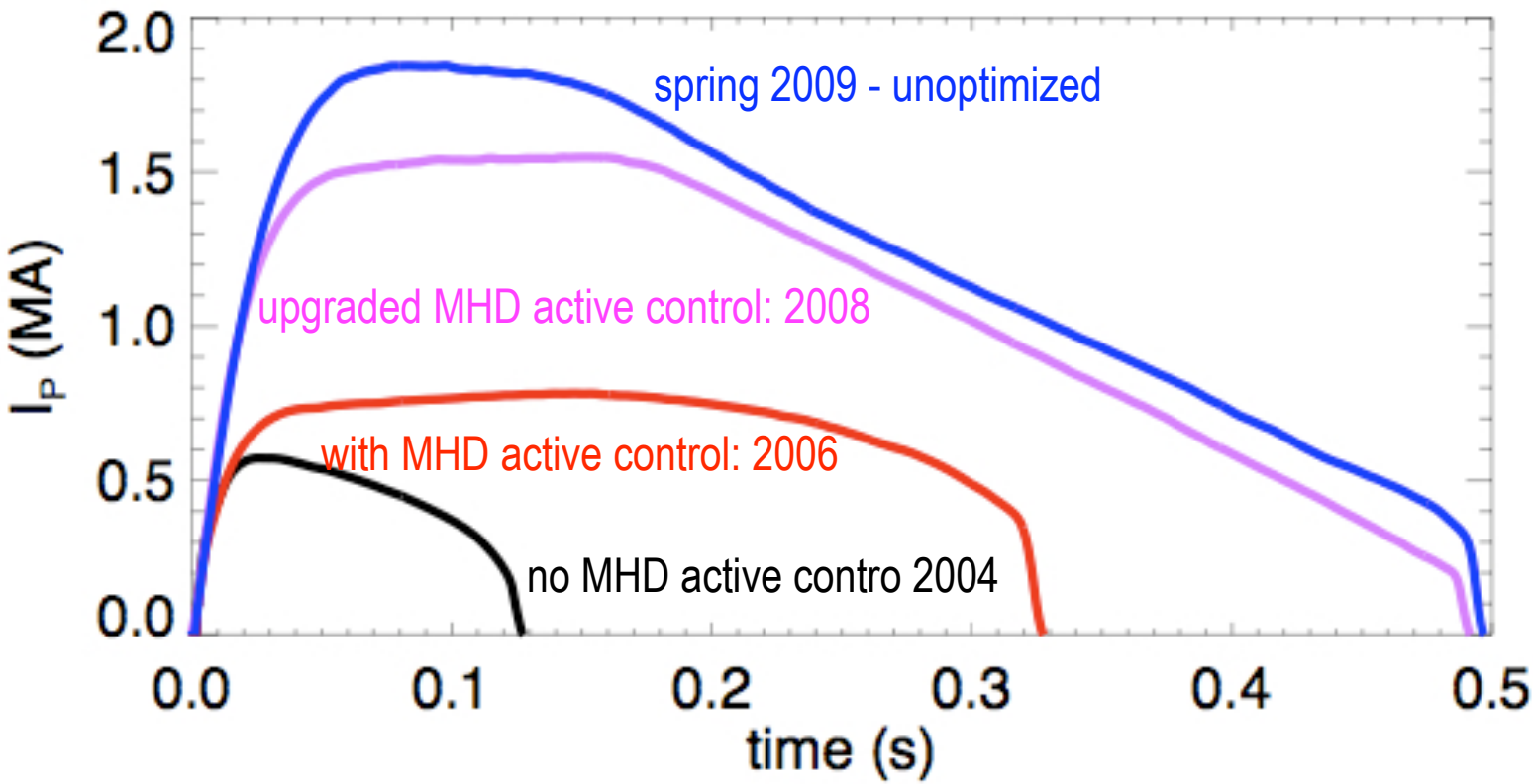
IPP (AUG), DIII-D, JT60-SA

RFX PERFORMANCE IMPROVEMENT

CONTRIBUTION TO THE GENERAL ISSUE OF MHD STABILITY ACTIVE CONTROL

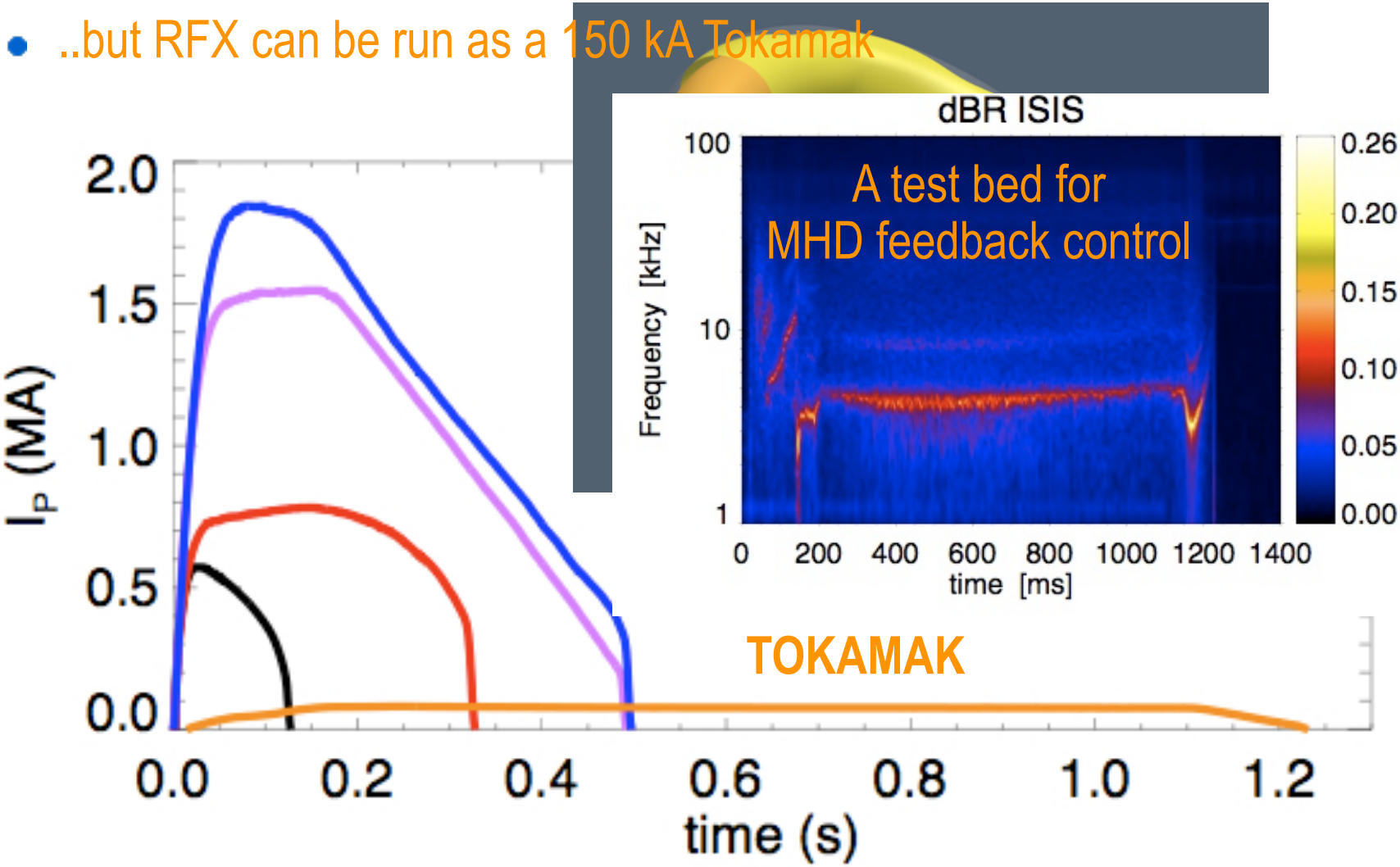
Steady progress in performance in a reliable device

- Fully reliable MHD stability control system



The value of flexibility: high perfomance RFP,… but not only RFP

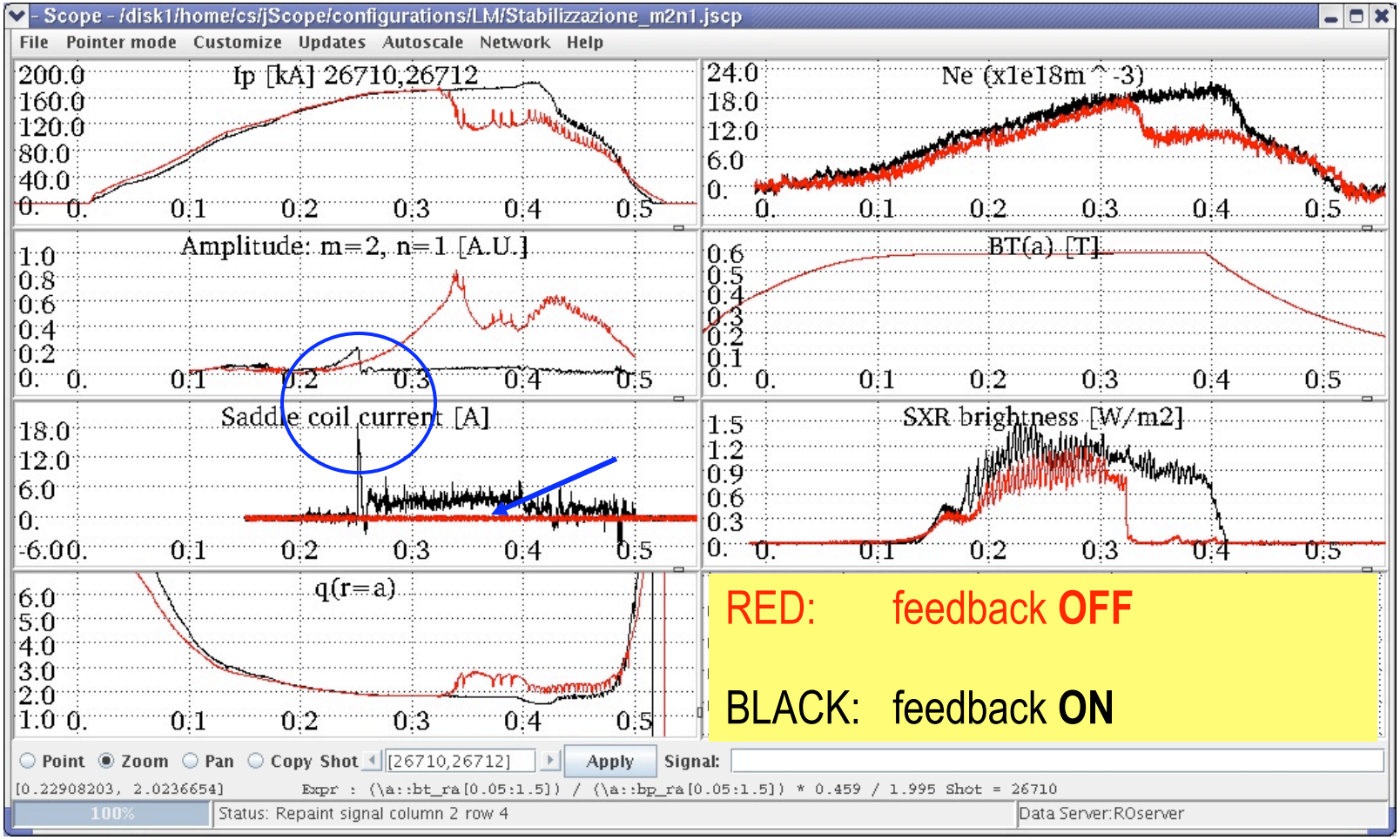
- Exploration of high current RFP allows for the discovery of new physics, with structural changes
- ..but RFX can be run as a 150 kA Tokamak



Full control of a (2,1) mode in a ramped tokamak

Follows an idea realized in **DIII-D** on a proposal by **In, Okabayashi, et al** (with RFX participation)

Okabayashi et al., paper EX/P9-5 2008 IAEA FEC, Geneva



(Cavazzana, Marrelli, et al. 2009)

The fusion-oriented RFX mission

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1. understanding the RFP physics and optimizing confinement to assess the configuration reactor's potentials

2. Providing state-of-the-art facilities for developing active control of MHD stability in fusion devices and in ITER in particular

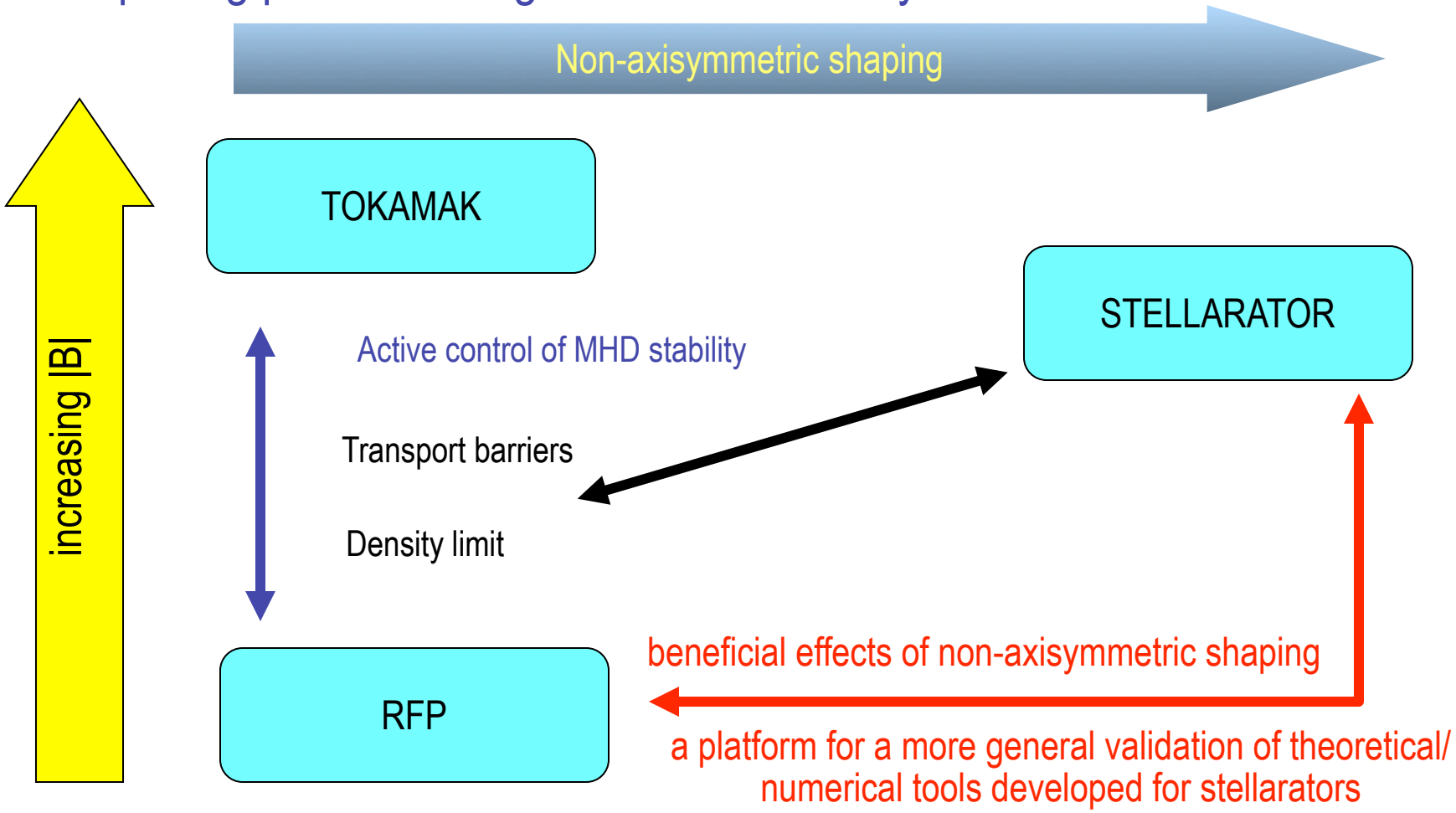
3. contributing to the understanding and advancement of fusion and plasma science, in particular:

   – exploring *fusion parameters ranges otherwise inaccessible* to tokamak and stellarator, enhancing therefore the fusion *predictive capabilities*
   – to test *tokamak physics* at the extreme of *low field*
   – to study analogies and synergies with the *stellarator*
   – To provide test beds for experiment and theory on *basic plasma issues*

All this done being also a fertile environment for training and education of young generation of scientists

Fostering integration

- RFX may contribute to address physic issue relevant to all configuration exploring parameter regions not covered by Tokamak and Stellarator



A modern task-oriented approach within the IA

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The RFX experience:

- Supported by the success of the first 2008 attempt, also for 2009 the experimental work-programme has been defined on the basis of a **public call for proposals**.

- This was open to to international laboratories and universities, with the aim of ***opening even more the RFX-mod facility to the community use, within the framework of the EFDA programme***.

- More than ***130 proposals*** received, from EU, USA and Japan (also from tokamak labs: GA, IPP, JT-SA, PPPL)

2009 RFX task force structure for a focused effort

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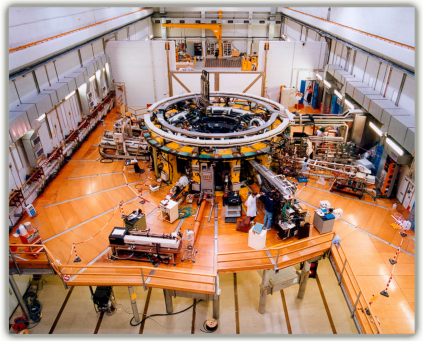
RFP performance: high current operation and advanced scenarios

Particle, momentum and energy transport



MHD and active control of stability

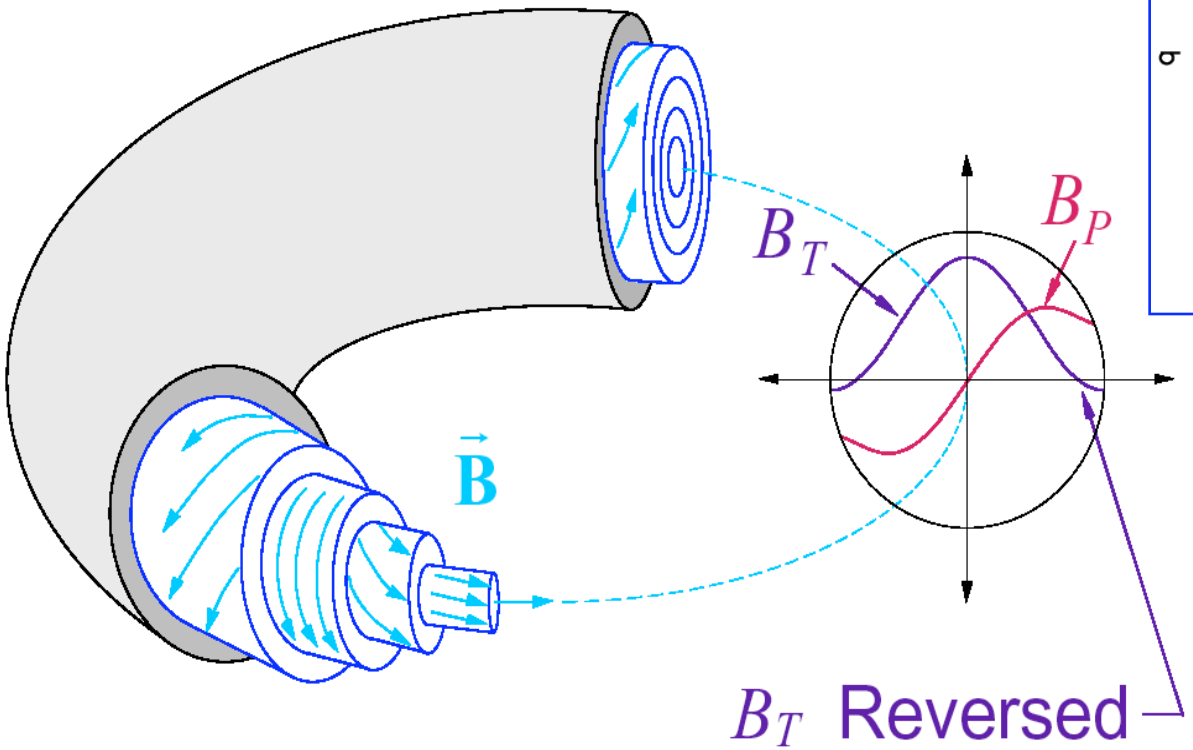
Magnetic and fuelling optimization

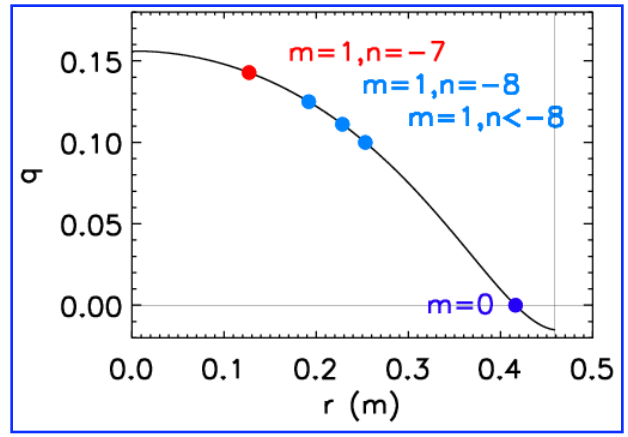
PROGRAM IMPLEMENTATION SUPPORT TEAM

A structural change for the RFP

2

RFP: exploiting the low external field approach to fusion

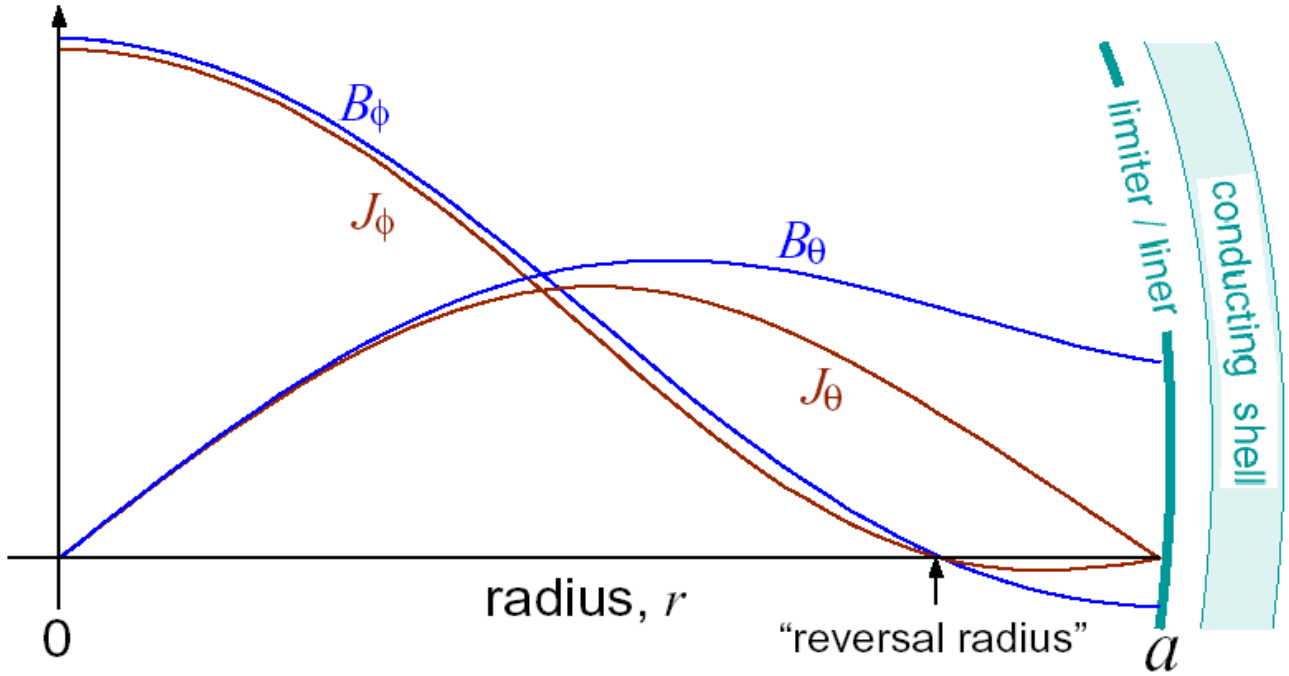




oidal electrical current in a
effect.

- ... but the applied toroidal field is at least 10 times weaker !
  Most of the RFP magnetic field is generated by current flowing in the plasma (driven also by a self-organized mechanism)
  No need for large magnetic coils.

The reversed field pinch magnetic equilibrium



The old story

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For a long time it was considered that….

- ….a $q < 1$ configuration like the RFP would have been intrinsically unstable,
- with a broad spectrum of MHD resistive instabilities,
- causing magnetic chaos and driving anomalous transport.

This was viewed as an interesting scientific case but a show-stopper for the RFP reactor ambitions

An emerging view for the RFP

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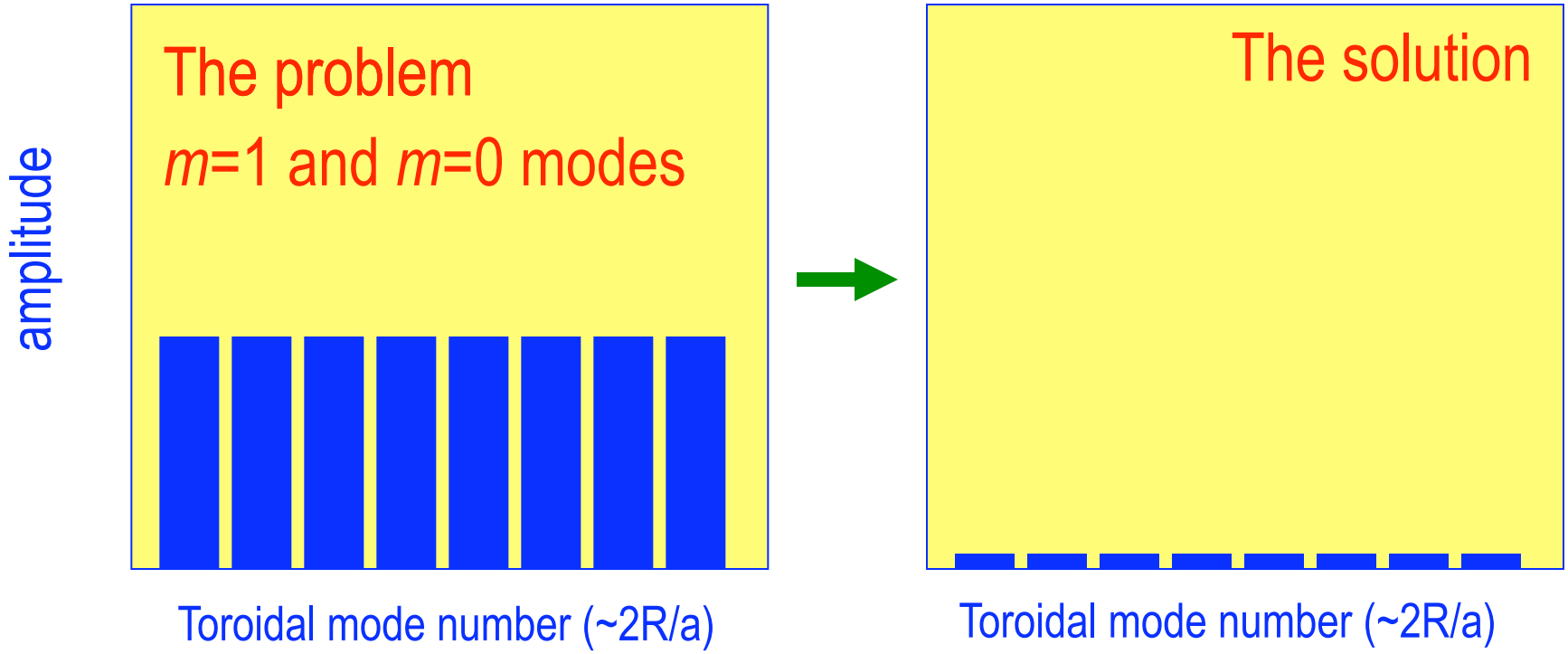
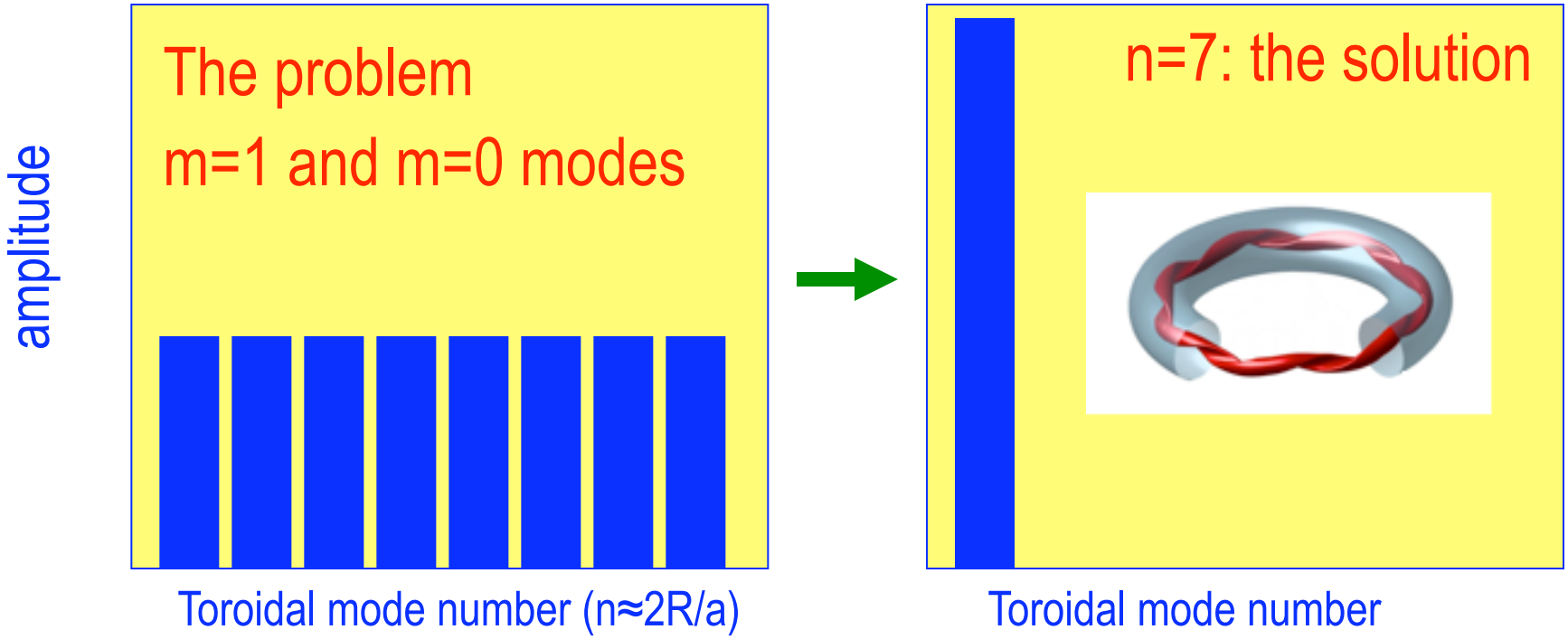
THE STORY IS CHANGED

Two strategies for chaos-free RFP: 1



- **Control of the current profile** to stabilize tearing modes
- **Proof of principle experiment in MST** to test RFP confinement and beta limits at the limit of negligible magnetic fluctuation (**record values τ_E and β**)
  (most recent results in Chapman et al, IAE FEC paper EX/7-1Ra, to appear in NF 2009)

Two strategies for chaos-free RFP: 2



- **Self-organized helical state:** at high current the plasma **spontaneously chooses** a helical equilibrium where only one saturated mode is present, and **sustains the configuration**
- This is **potentially chaos-free** and allows to retain the good features of self-organization without the past degradation of confinement.
- For Ip > 1 MA this is the **preferred state in RFX-mod**, with **strong electron transport barriers and improved confinement**

Dramatic improvements in the helical state

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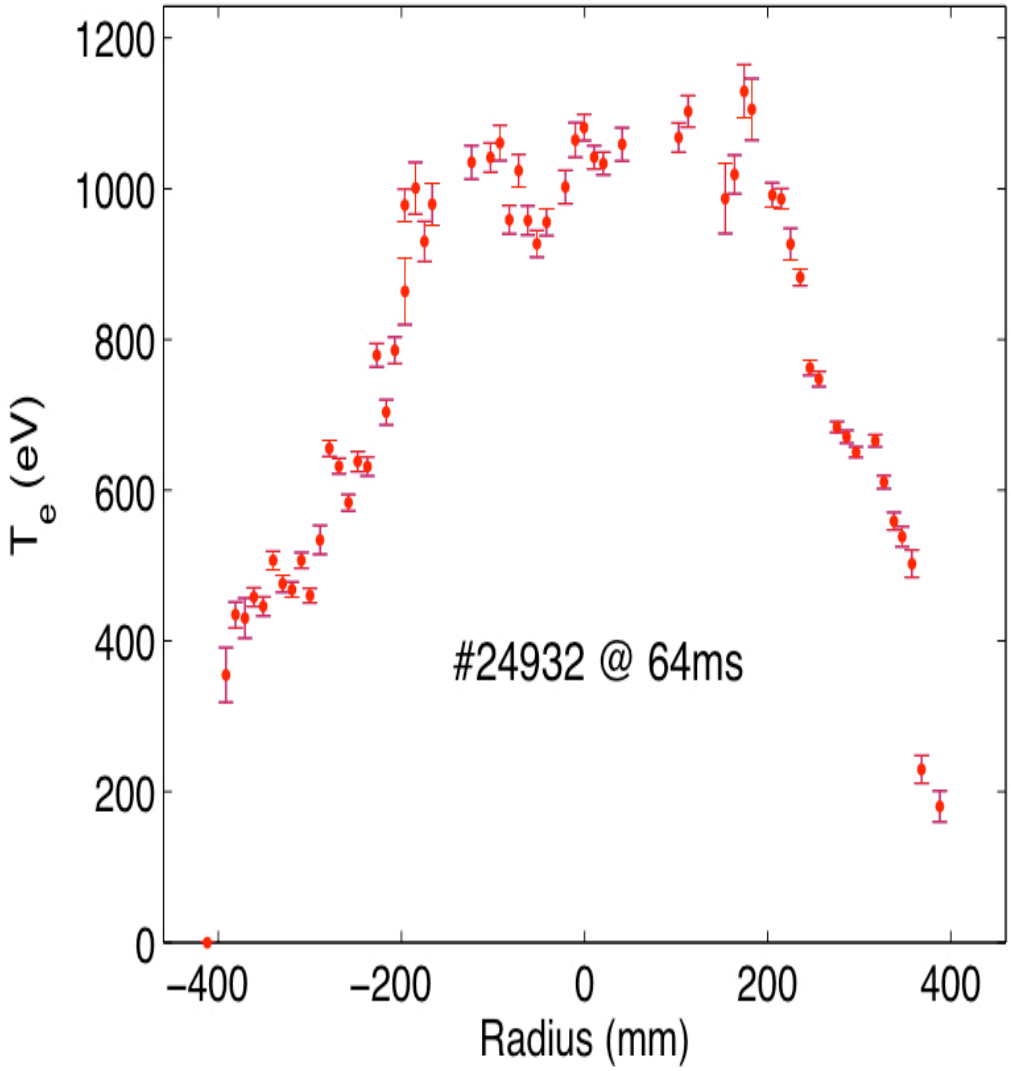
Strong electron transport barriers



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nature physics

LETTERS

PUBLISHED ONLINE: 14 JUNE 2009 | DOI: 10.1038/NPHYS1308

Self-organized helical equilibria as a new paradigm for ohmically heated fusion plasmas

R. Lorenzini[1]*, E. Martines[1], P. Piovesan[1], D. Terranova[1], P. Zanca[1], M. Zuin[1], A. Alfier[1], D. Bonfiglio[1], F. Bonomo[1], A. Canton[1], S. Cappello[1], L. Carraro[1], R. Cavazzana[1], D. F. Escande[2], A. Fassina[1,3], P. Franz[1], M. Gobbin[1], P. Innocente[1], L. Marrelli[1], R. Pasqualotto[1], M. E. Puiatti[1], M. Spolaore[1], M. Valisa[1], N. Vianello[1], P. Martin[1,3] and RFX-mod team and collaborators[4]

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Current issue

August 2009 - Vol 5 No 8

Reversed-field pinch gets self-organized

Efimov states: Two trimers to scale

Supersolid helium: The plot stiffens

Two-way ratchets: Living cells sorted

- Current issue table of contents
- Advance online publication (AOP)
- Impact factor 16.821

High current operation and helical states: a change of paradigm

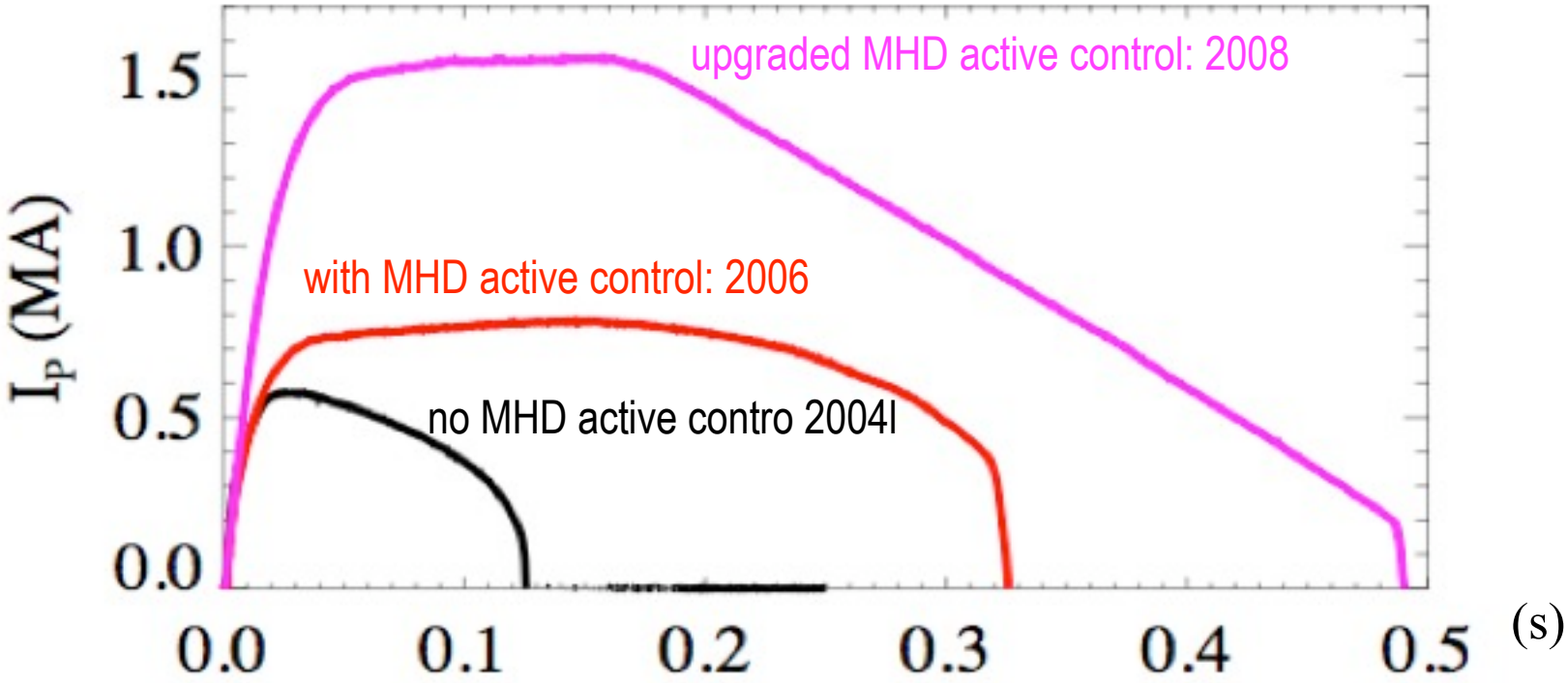
3

High current operation and helical states: a change of paradigm

3

3.1 the route to helical

RFX-mod: new physics at 1.5 MA

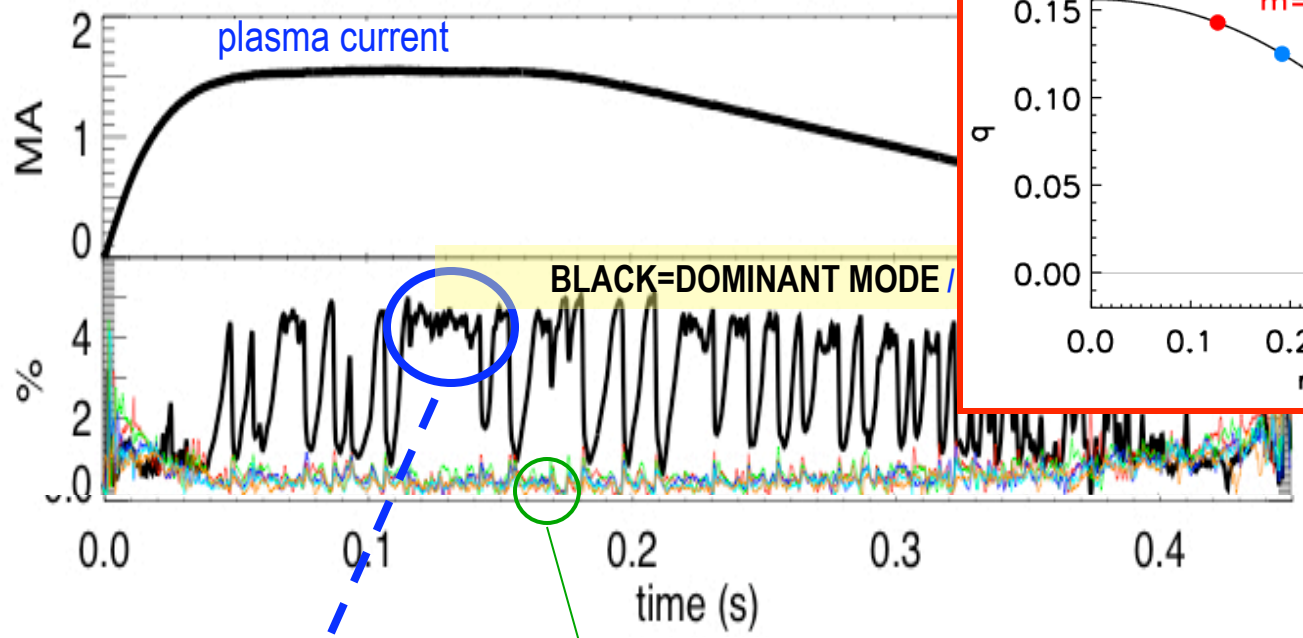


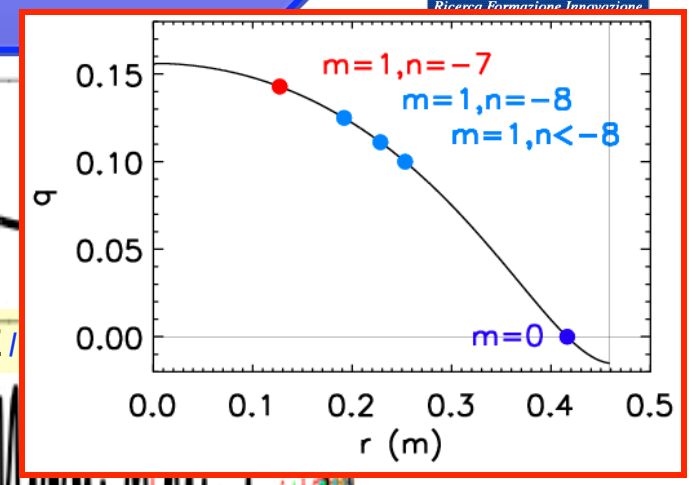
A new regime is discovered,

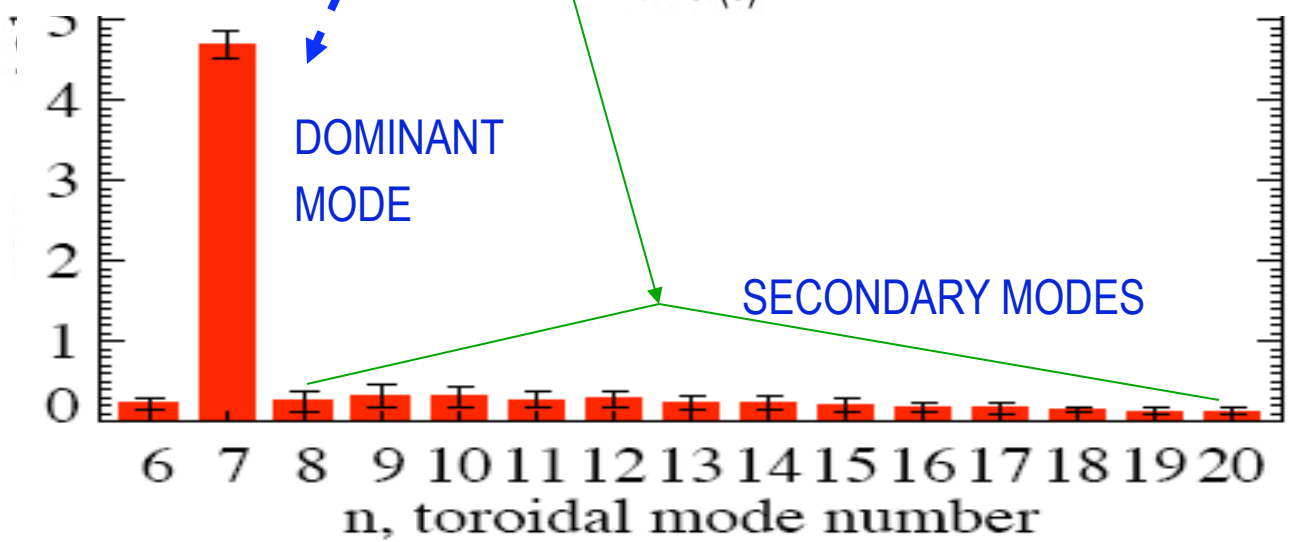
where the plasma spontaneously self-organizes in a single-axis helical state,

with strongly improved core confinement.

Long periods with one large saturated *m* =1 mode

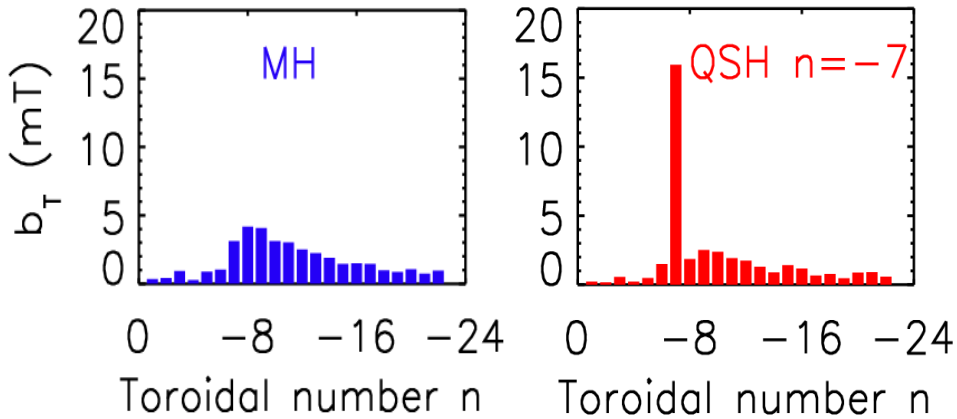




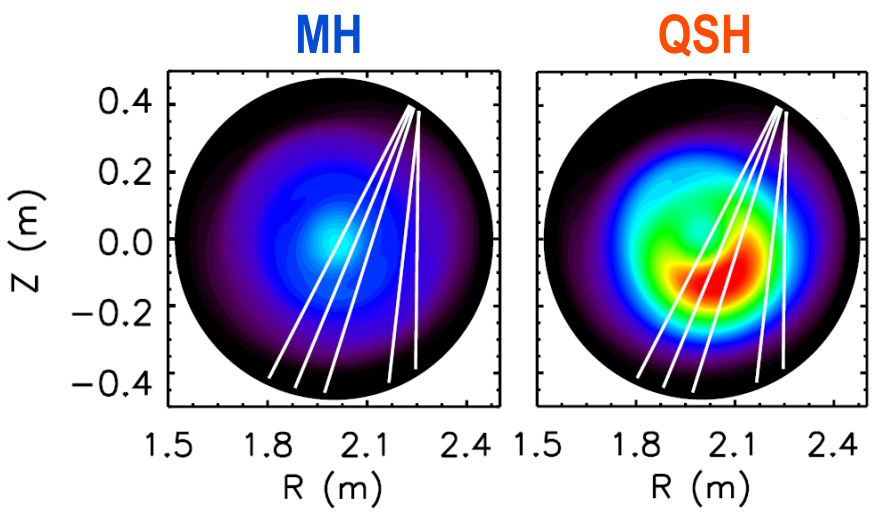


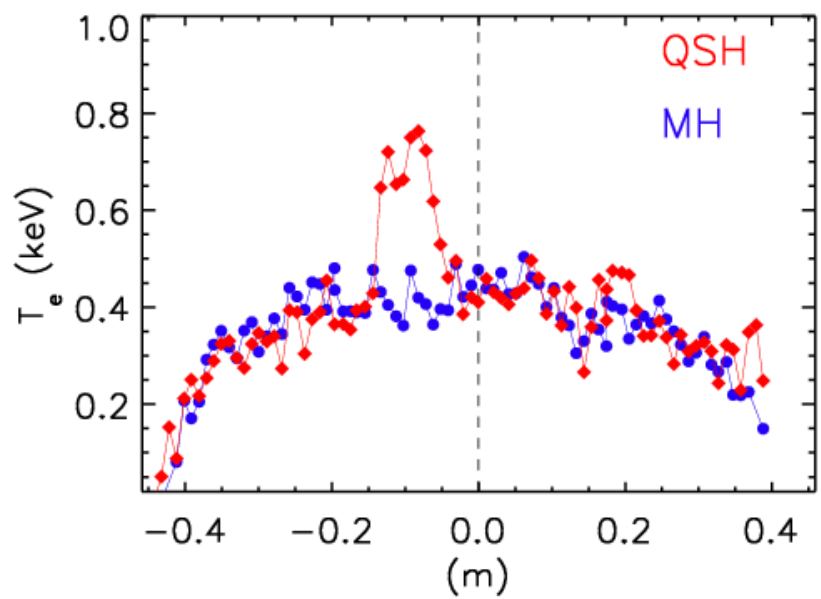
The 1st bifurcation: from MH to QSH

- **Quasi Single Helicity (QSH)** states, where the mode n = -7 dominates, and the secondary mode amplitudes are reduced, are observed at medium current (0.5 MA < I_p < 1 MA)
  Escande et al, PRL 2000
  Cappello et al., PPCF 46 B313 (2004)



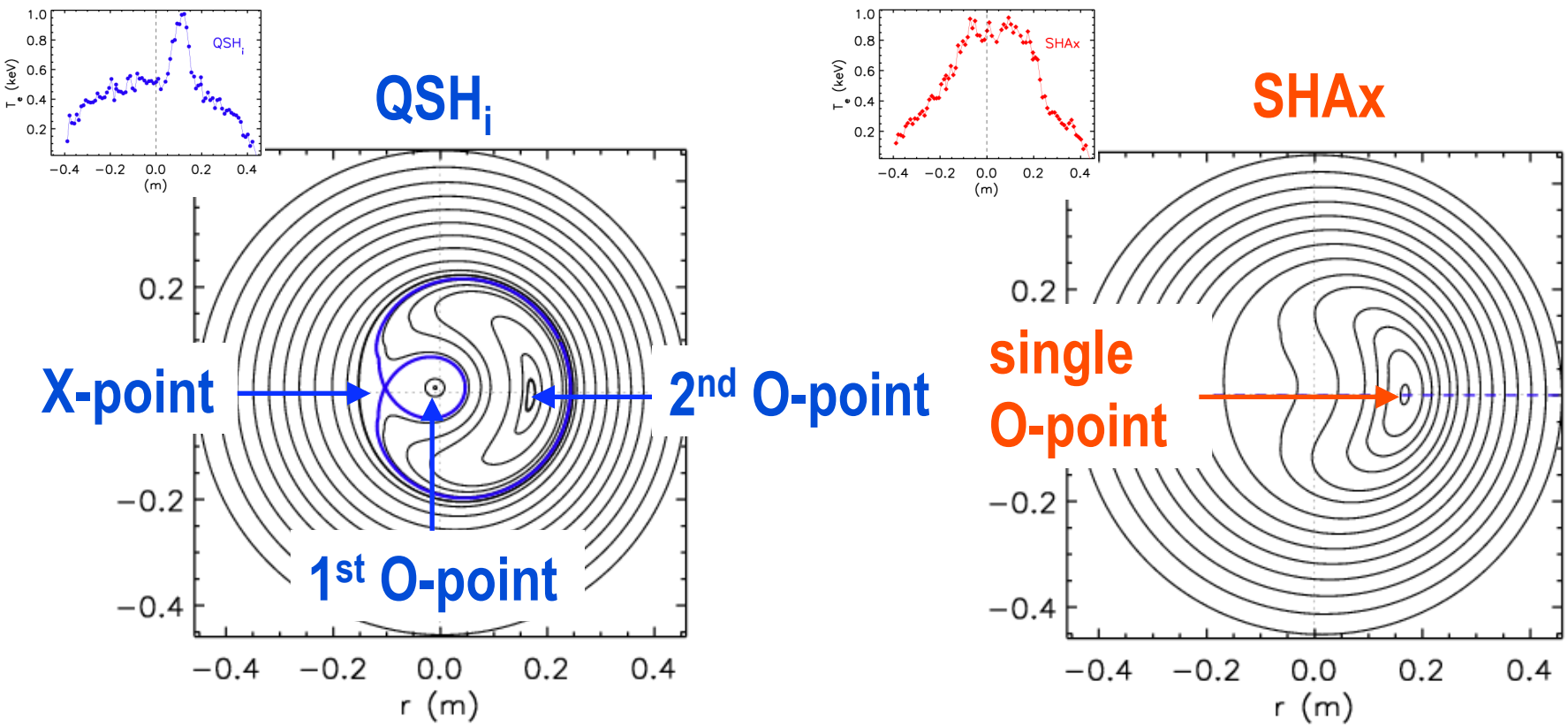
- A typical feature is the appearance of a **thin** helical, thermal structure **off-axis**





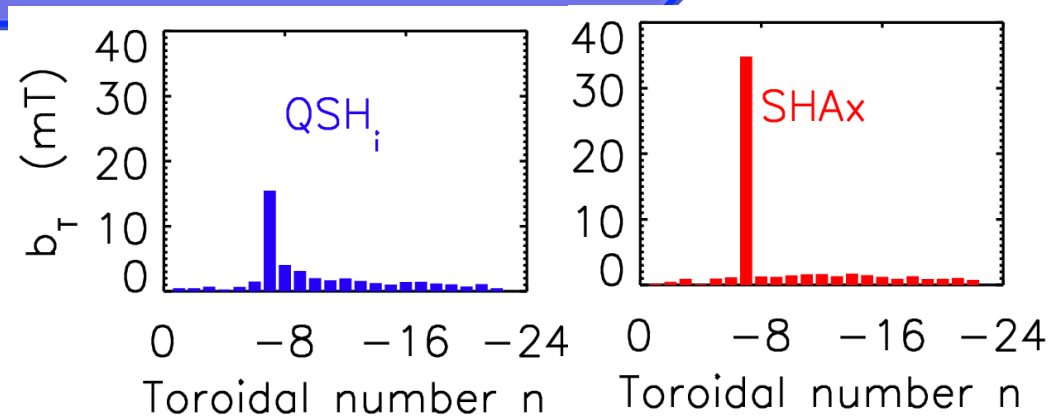
2nd bifurcation at high current: from QSH_i to SHAx

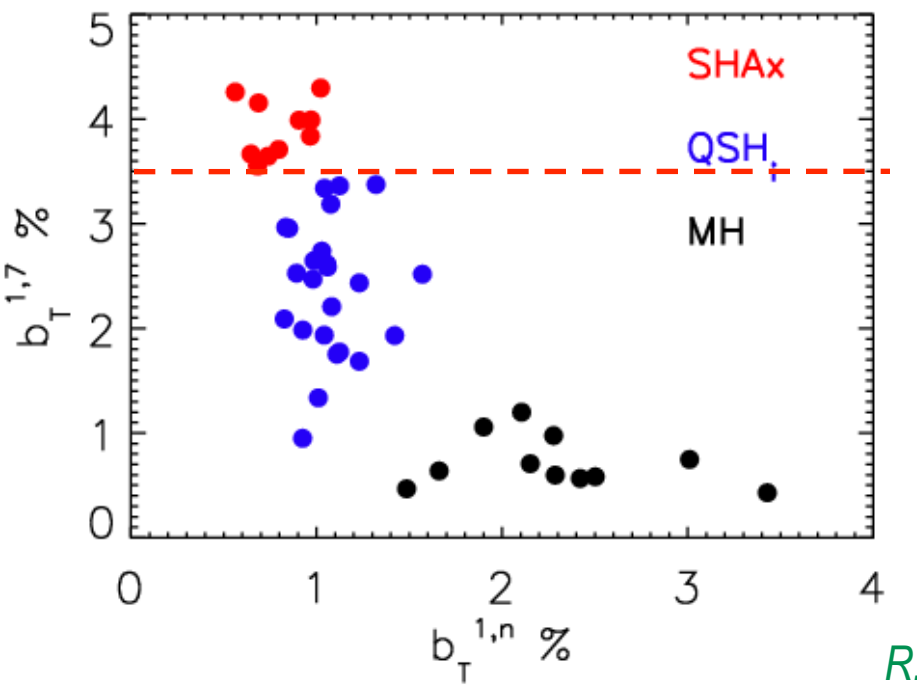
The original axisymmetric axis is replaced by a helical axis as I > 1 MA



The drive is mode amplitude: experiment & theory

SHAx states appear when the amplitude of the dominant mode exceeds a threshold





~ 4% of the total B(a)

Since the energy of secondary modes is particularly low in SHAx states, it results in a threshold on the ratio dominant/secondary

*R. Lorenzini et al., PRL **101**, 025005 (2008)*

*D. F. Escande et al., PRL. **85**, 3169 (2000)*

Synergistic dependence on Lundquist number S

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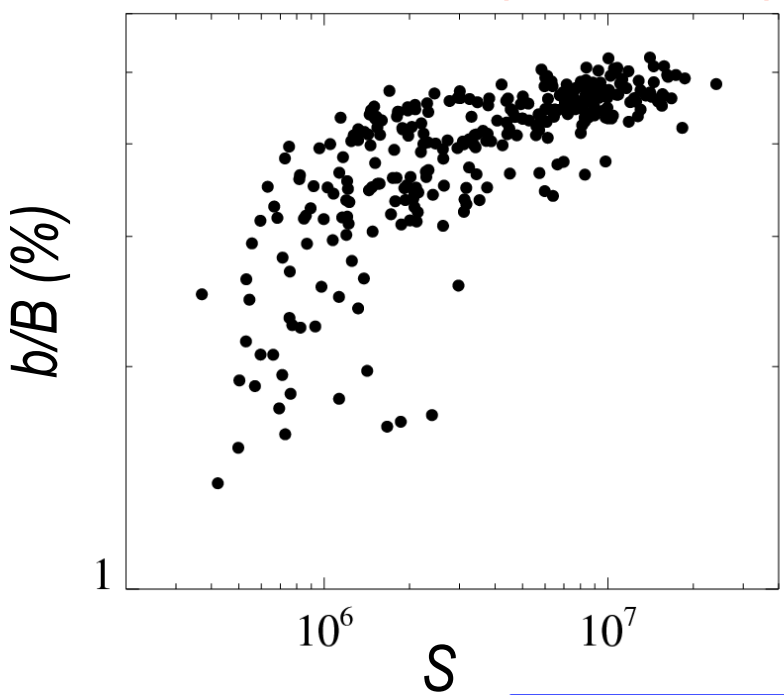
Strongly leading towards chaos-free plasmas

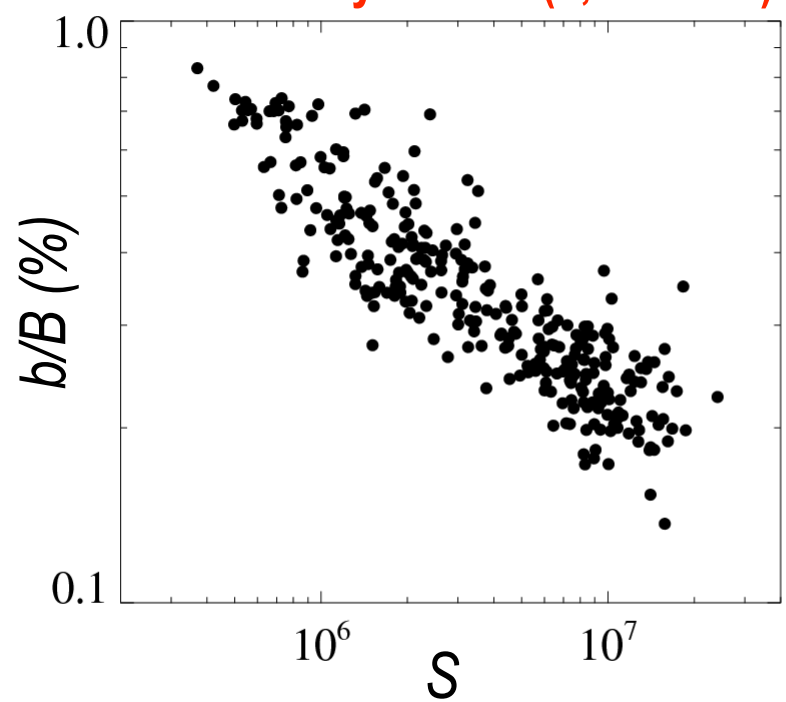
At higher current, when plasma gets hotter, the helical state is more pure

$$S = \frac{\tau_R}{\tau_A} \propto \frac{I_p T_e(0)^{3/2}}{Z_{eff} n_e^{1/2}}$$

Dominant mode (*m* = 1, *n* = -7)



Secondary modes (1,-8 to -15)



High current operation and helical states: a change of paradigm

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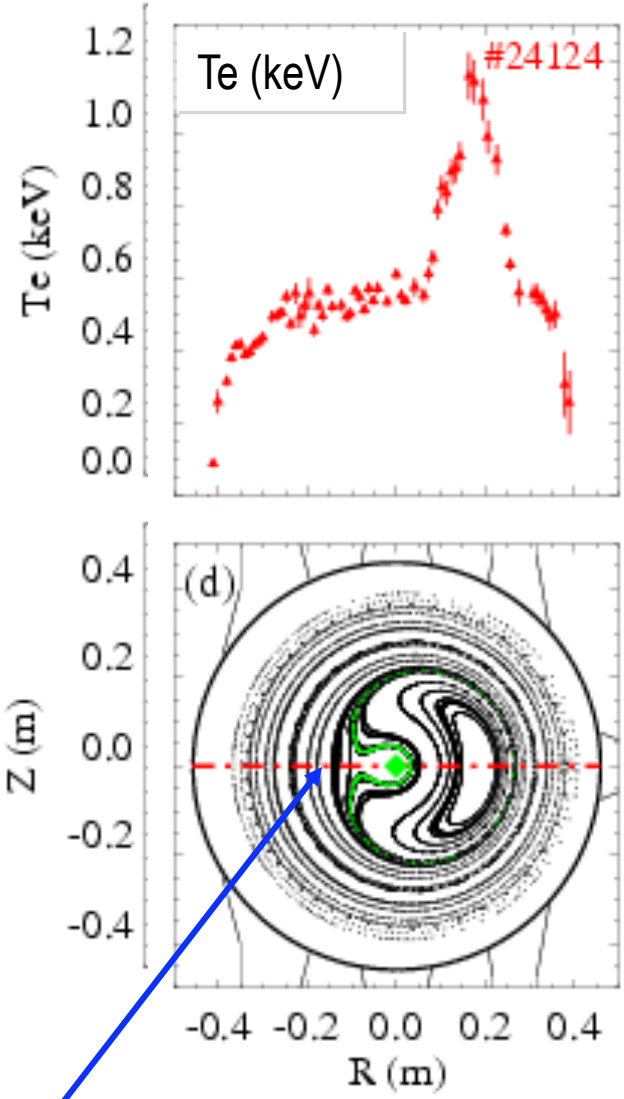
3.2 helical equilibria and transport barriers

Topology change at high current: from island to Single Helical Axis



X point and separatrix

At the time of 2006 FEC:

Quasi Single Helicity states where reported:

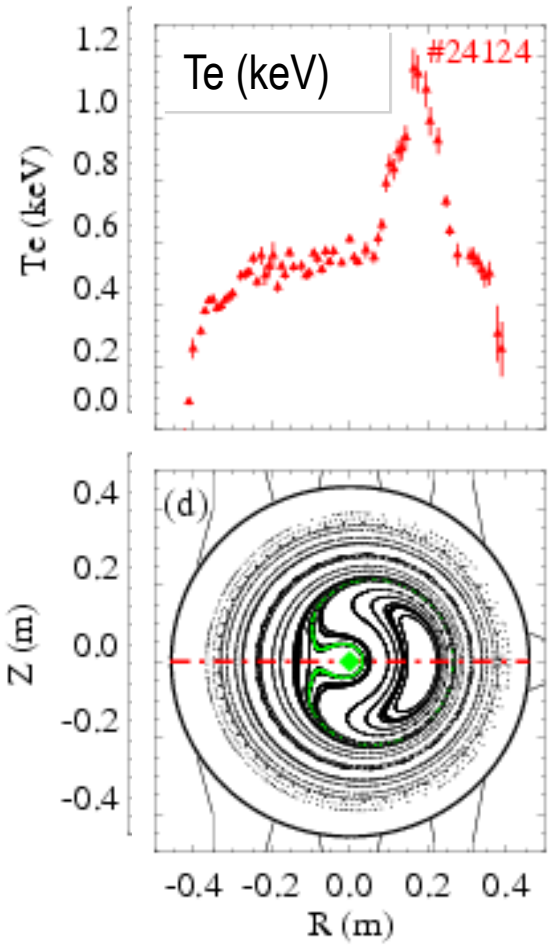
- **both the helical axis and the original axisymmetric axis were present**

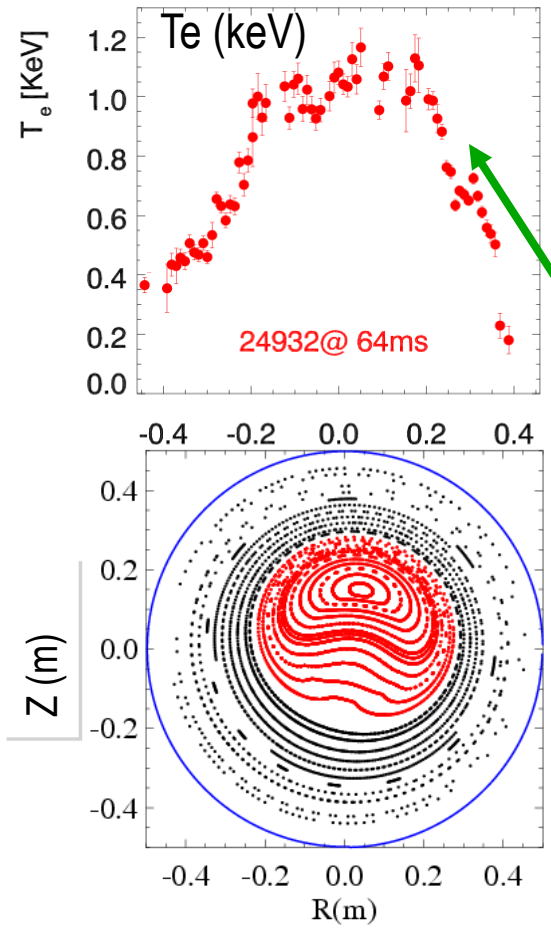
- island-like structure
- predicted physics result
- strong T gradients

…but relatively small volume of plasma involved

Single Helical Axis (SHAx) equilibrium at high current

The original axisymmetric axis is replaced by a helical magnetic axis thanks to the favourable S-scaling of the modes





Strong electron transport barriers

$1/L_{Te} \sim 20\ m^{-1}$

$\chi_e \sim 10\text{-}20\ m^2 s^{-1}$

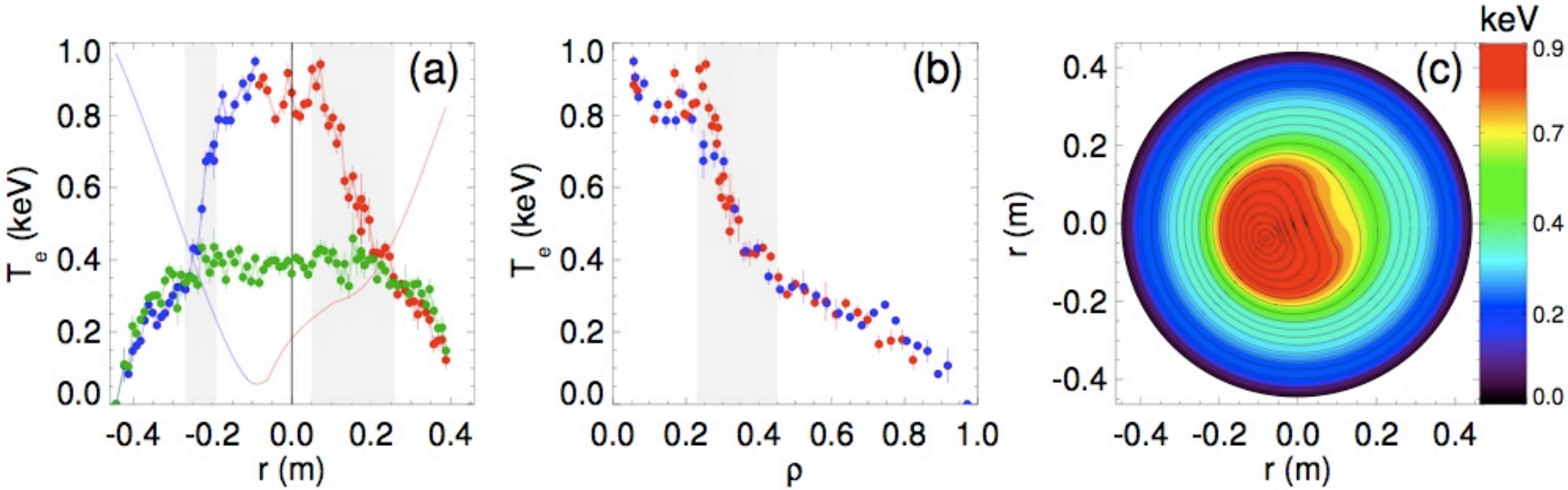
Temperature and density are constant on helical magnetic flux surfaces

Temperature and density are constant on helical magnetic flux surfaces

With appropriate reconstruction of the dominant mode eigenfunction, we can build a helical flux

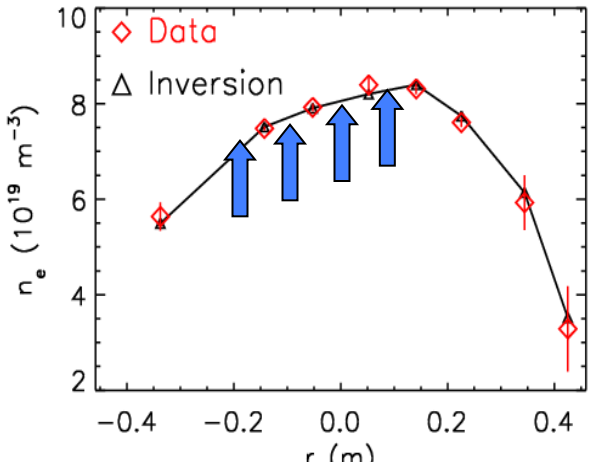
$$\chi(r,u) = m\Psi(r,u) - nF(r,u)$$

considering the axisymmetric equilibrium and the dominant mode. (r and u = $m\vartheta - n\phi$ are flux coordinates).

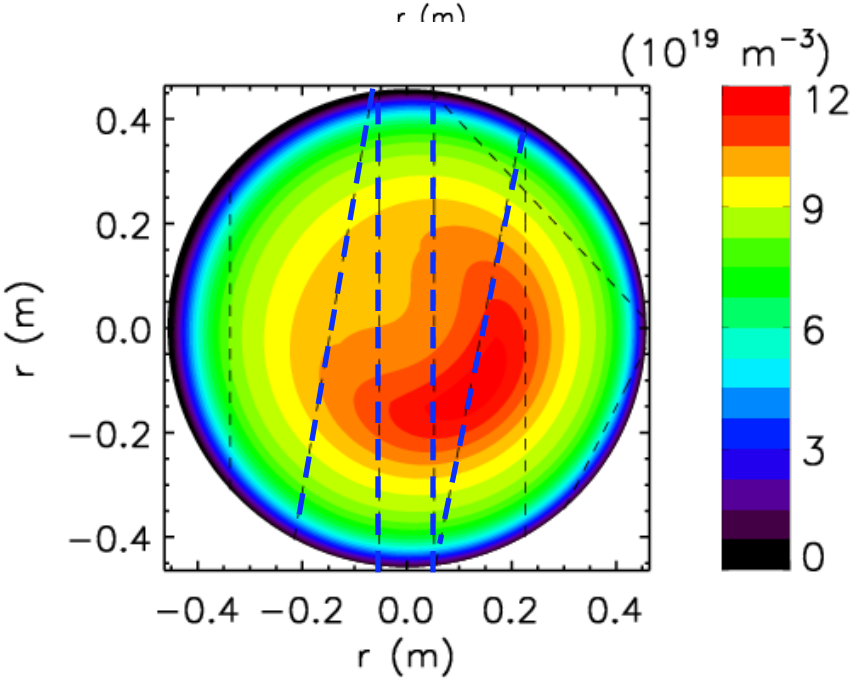


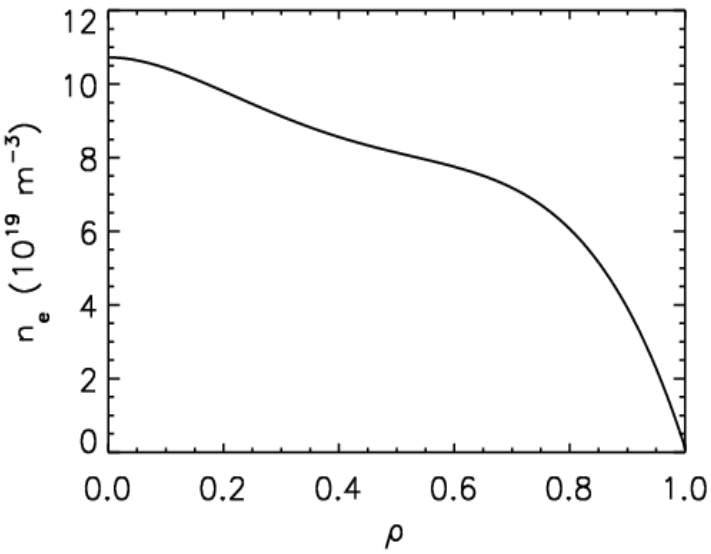
The assumption of good isobaric helical flux surfaces allows mapping of temperature profiles

Mapping electron density n_e on helical flux

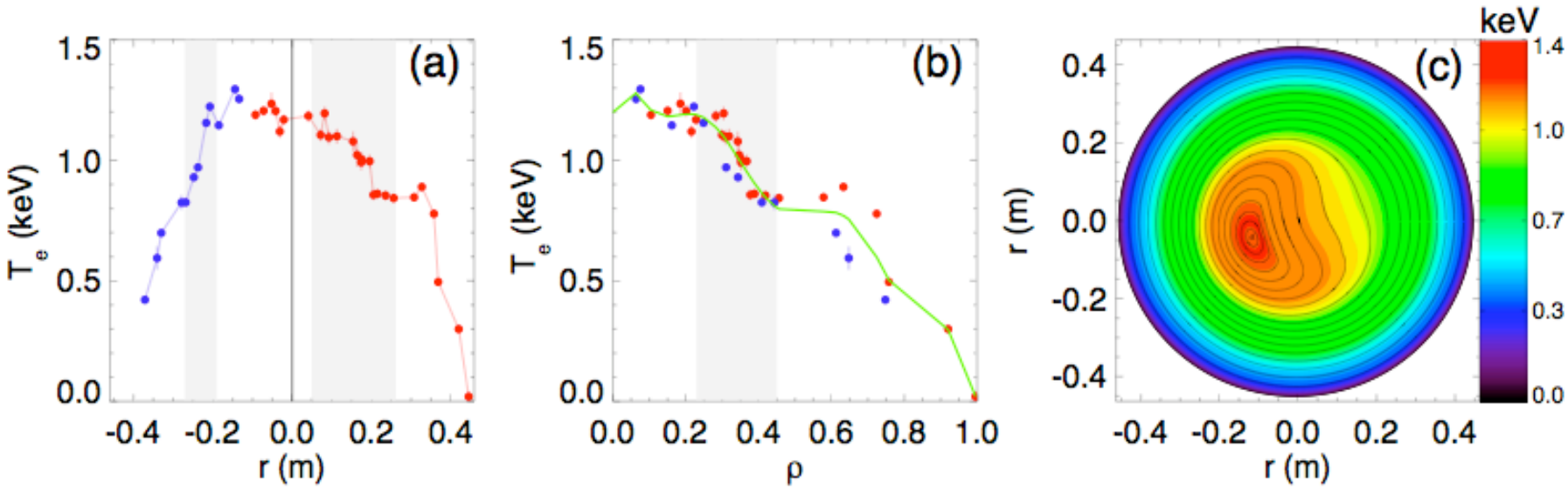


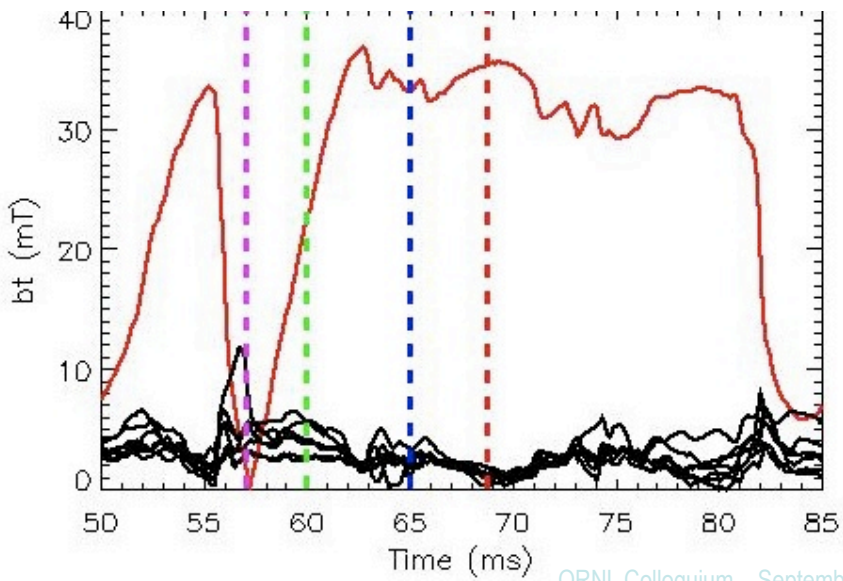
- The helical core is fuelled by injecting solid Hydrogen pellets
- Homologous interferometer chords show asymmetries that are well matched assuming n_e to be a helical function of **ρ**, as for temperature

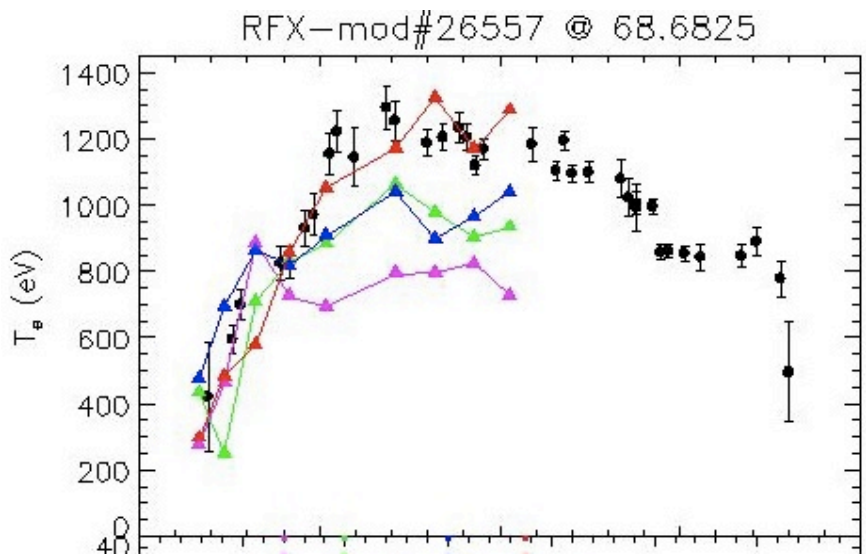




1.4 keV achieved in the helical core







Ongoing work to use VMEC for RFP helical states
collaboration with ORNL (S. Hirschmann) and PPPL (Boozer & Pomphreys)

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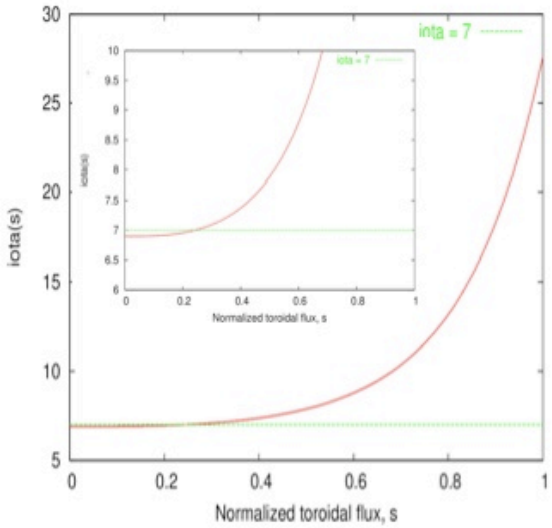
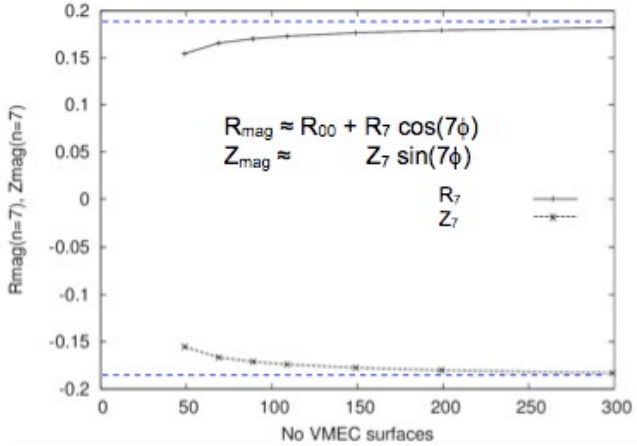
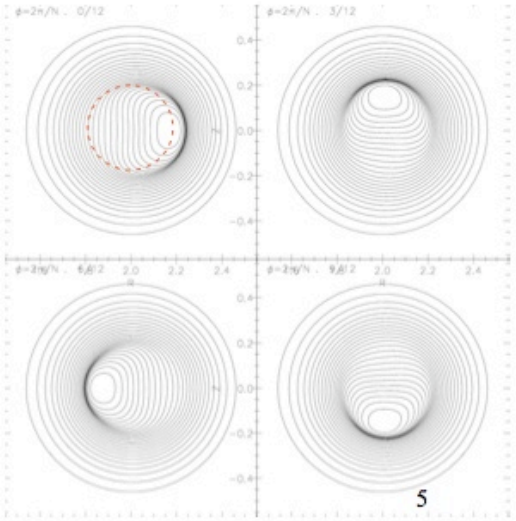
VMEC input ι and convergence of mag axis







For given profiles, and β = 2%, convergence to helical axis with shift ~18cm

Final state robust to numerics

Axis shift depends on β and ι'

Ongoing work to use VMEC for RFP helical states
collaboration with ORNL (S. Hirschmann) and PPPL (Boozer & Pomphreys)

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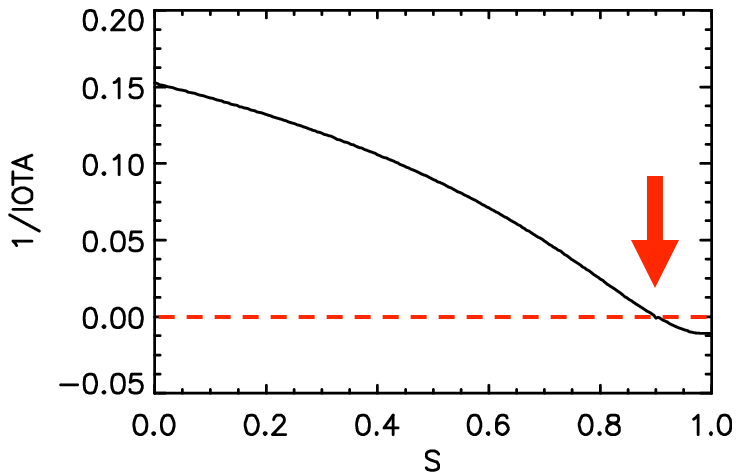
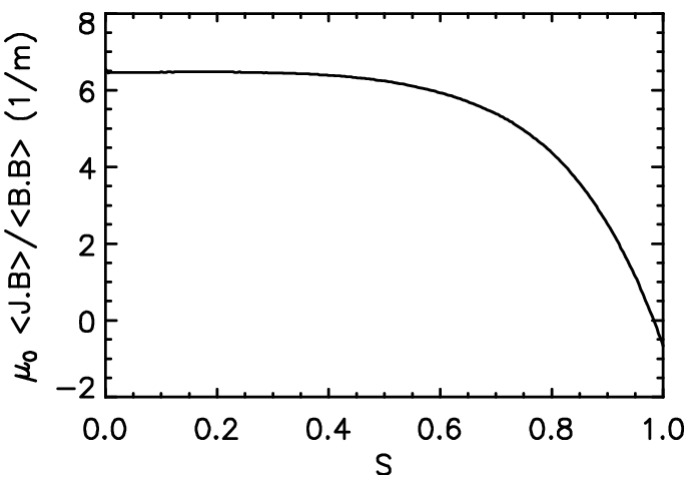
RFP axi-symmetric equilibrium



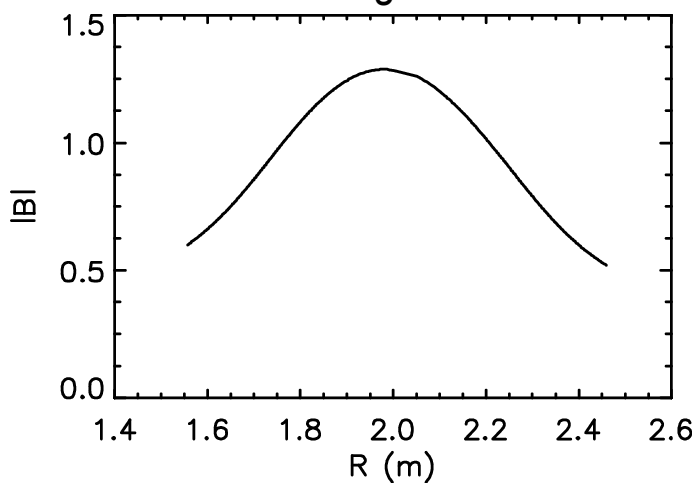
VMEC *adapted for RFP equilibria* requires the use of the POLOIDAL FLUX to deal correctly with B_ϕ reversal.

INPUT PARAMETERS:
$1/\iota(s)$
$\beta = 0$
circular LCFS (fixed boundary)

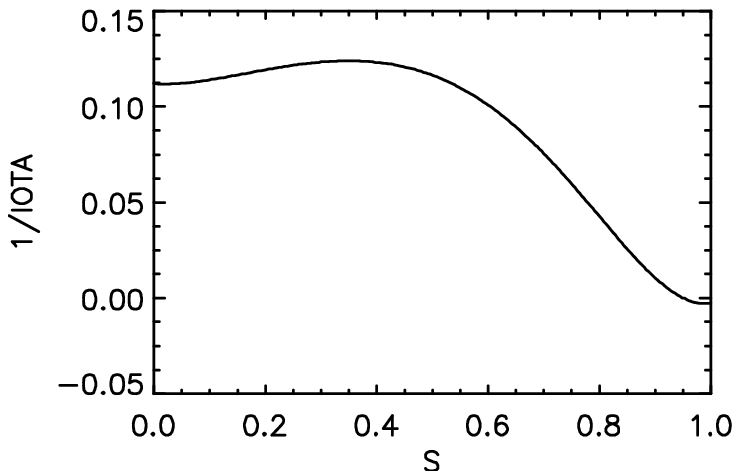
Parallel current



Total magnetic field

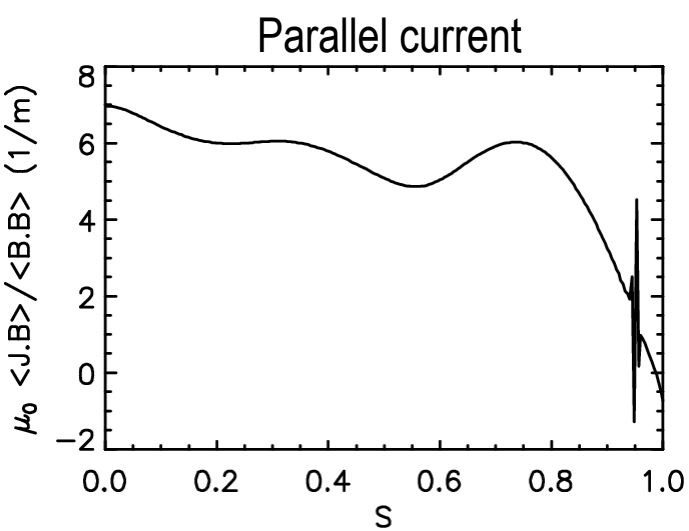


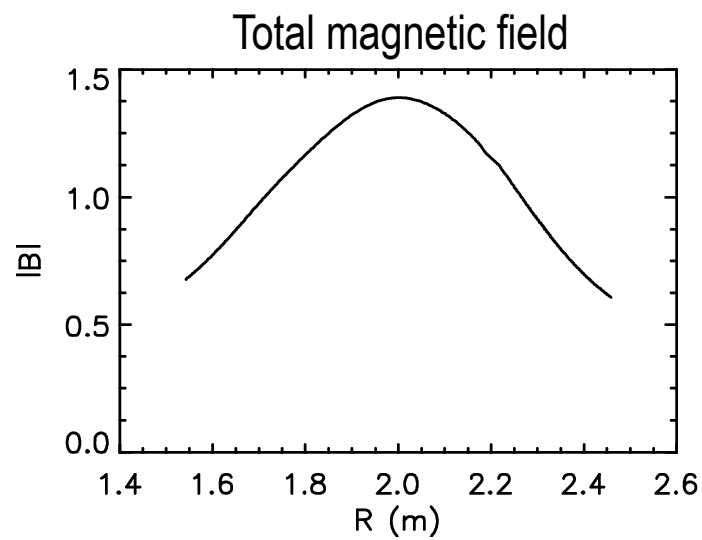
RFP Helical equilibrium



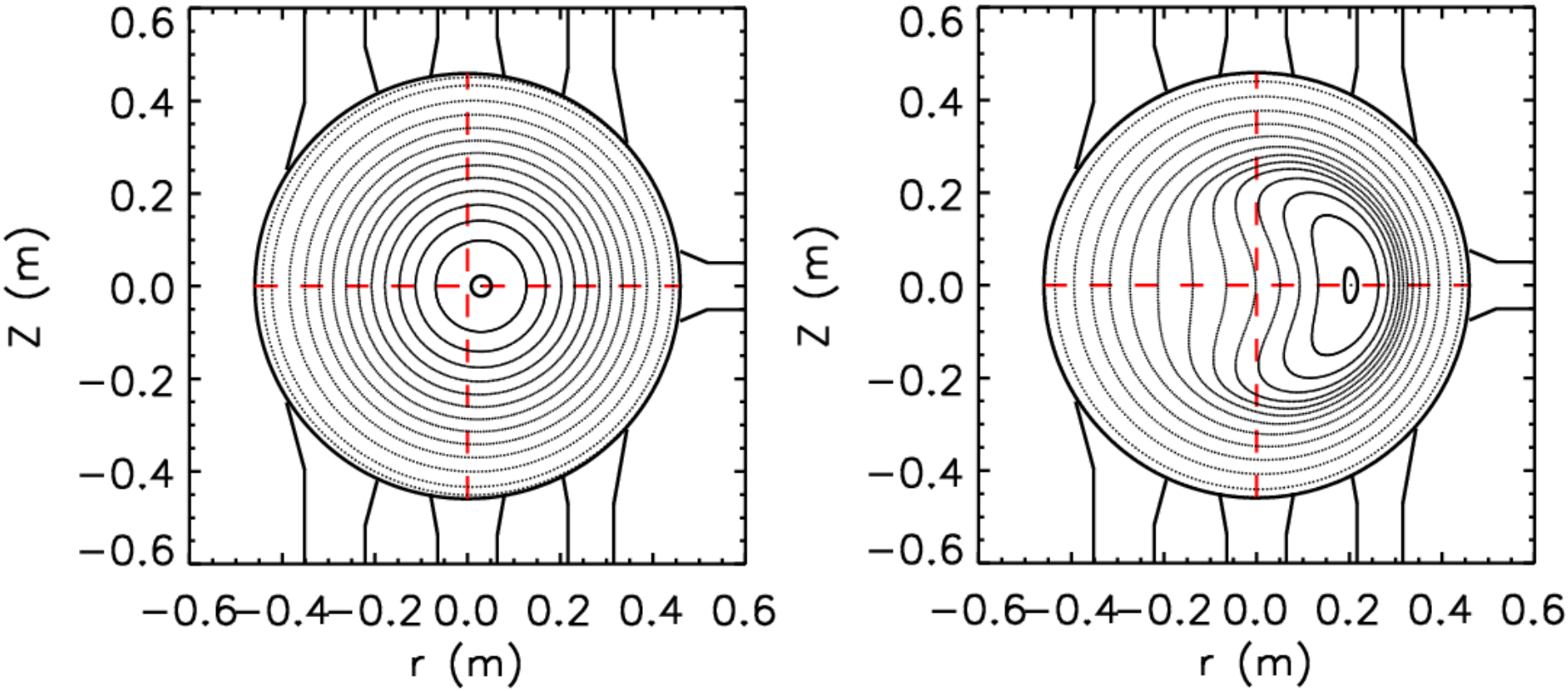
Input 1/ι profile is obtained by means of the field line tracing code ORBIT.

INPUT PARAMETERS:
1/ι(s)
β = 0
circular LCFS (fixed boundary)





Flux surfaces



The flux surfaces obtained both in axisymmetric and helical configurations provide a good benchmark with present experimental observations and other numerical reconstructions.

High current operation and helical states: a change of paradigm

3

3.3 GHOST surfaces, REAL barriers

GHOST surfaces [Hudson & Breslau, PRL 100 (2008)]

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- **Integrable magnetic fields are an exception, more than a rule, in fusion plasmas**
- Transport is strongly anistropic ($k_\perp/k_{//} \ll 1$). This has significant consequences, depending on whether:

1) *The magnetic field line lie on nested flux surface*

$T=T(\psi)$, where ψ labels flux surfaces

2) *The field is slightly chaotic*

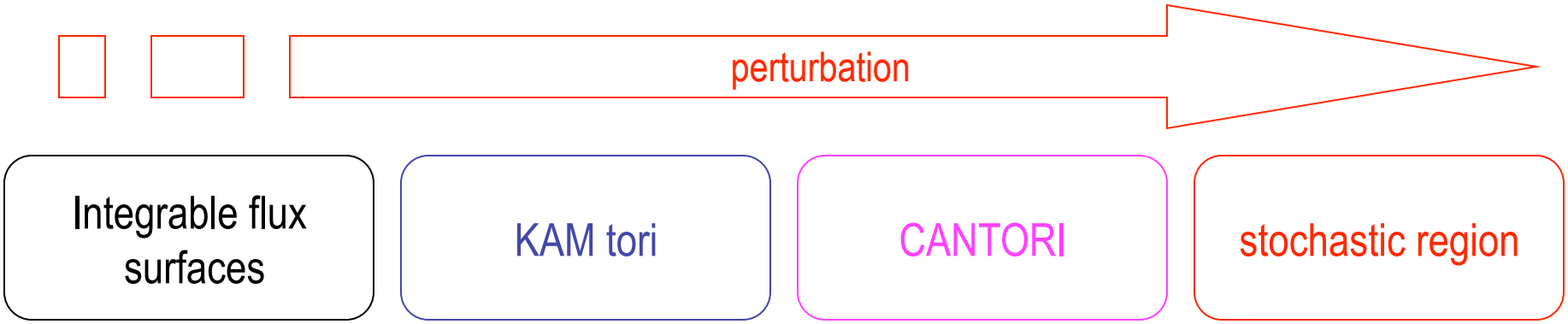
CRITICAL (NEAR TRESHOLD CHAOS): **GHOST SURFACES**

3) *The field is so chaotic that the motions of field lines is effectively random*

Extreme chaos, the field lines wander randomly over a volume

The strong parallel transport results in temperature flattening

Phase space structures

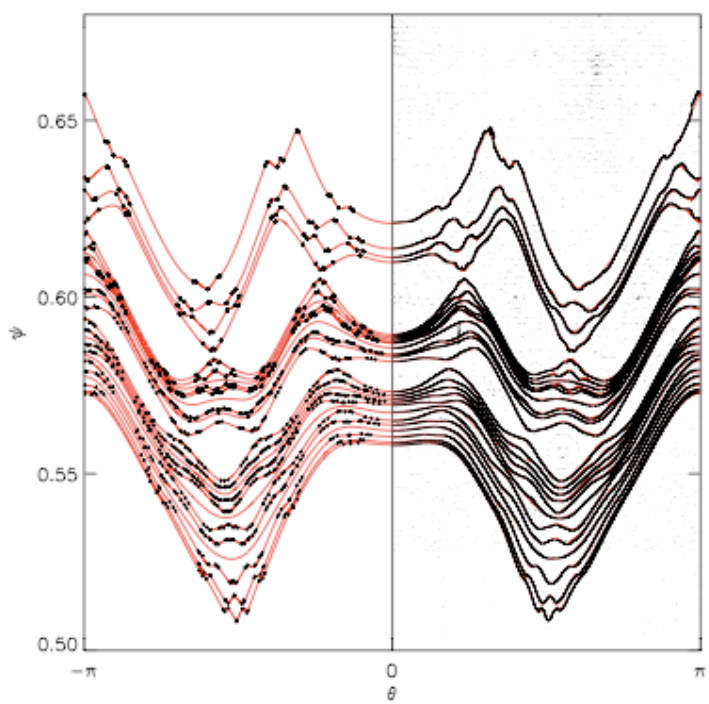


- A chaotic magnetic field is a fractal mix of:
  - **Invariant (irrational) flux surfaces (KAM tori)**
    - For a slightly perturbed system a discrete selection of KAM surfaces can be used to partition the phase space into separate regions: trajectories cannot cross KAM surfaces
  - **CANTORI (broken KAM surfaces),** in particular the near-critical cantori, which provide effective but partial barriers to field line transport
    - In contrast to KAM surfaces, CANTORI are leaky: they have gaps, and trajectories can pass through the gaps.
    - In the near-critical case, i.e. when the level of chaos just exceed that needed to break KAM surfaces, the gaps in the cantorus are small and the field line flux across the cantorus is small.
    - CANTORI can severely restrict transport
  - **The stochastic sea**

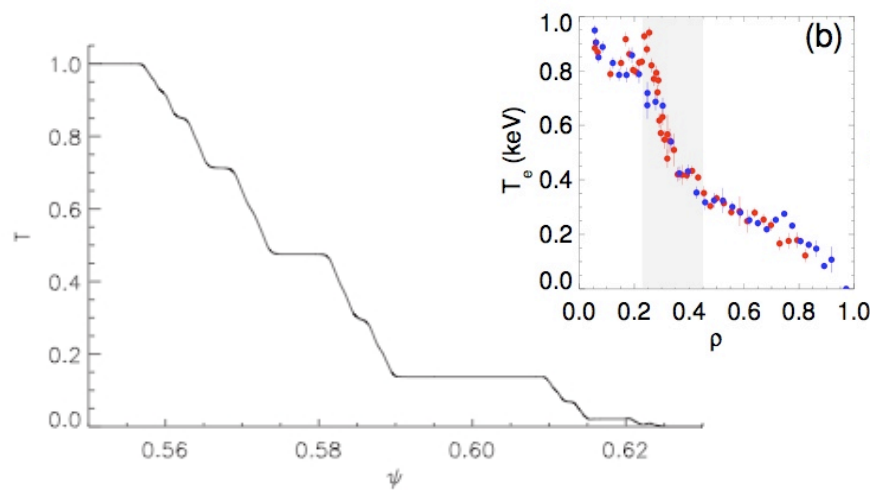
*Hudson, Phys. Rev. E **74** 2006*

Chaos is not random

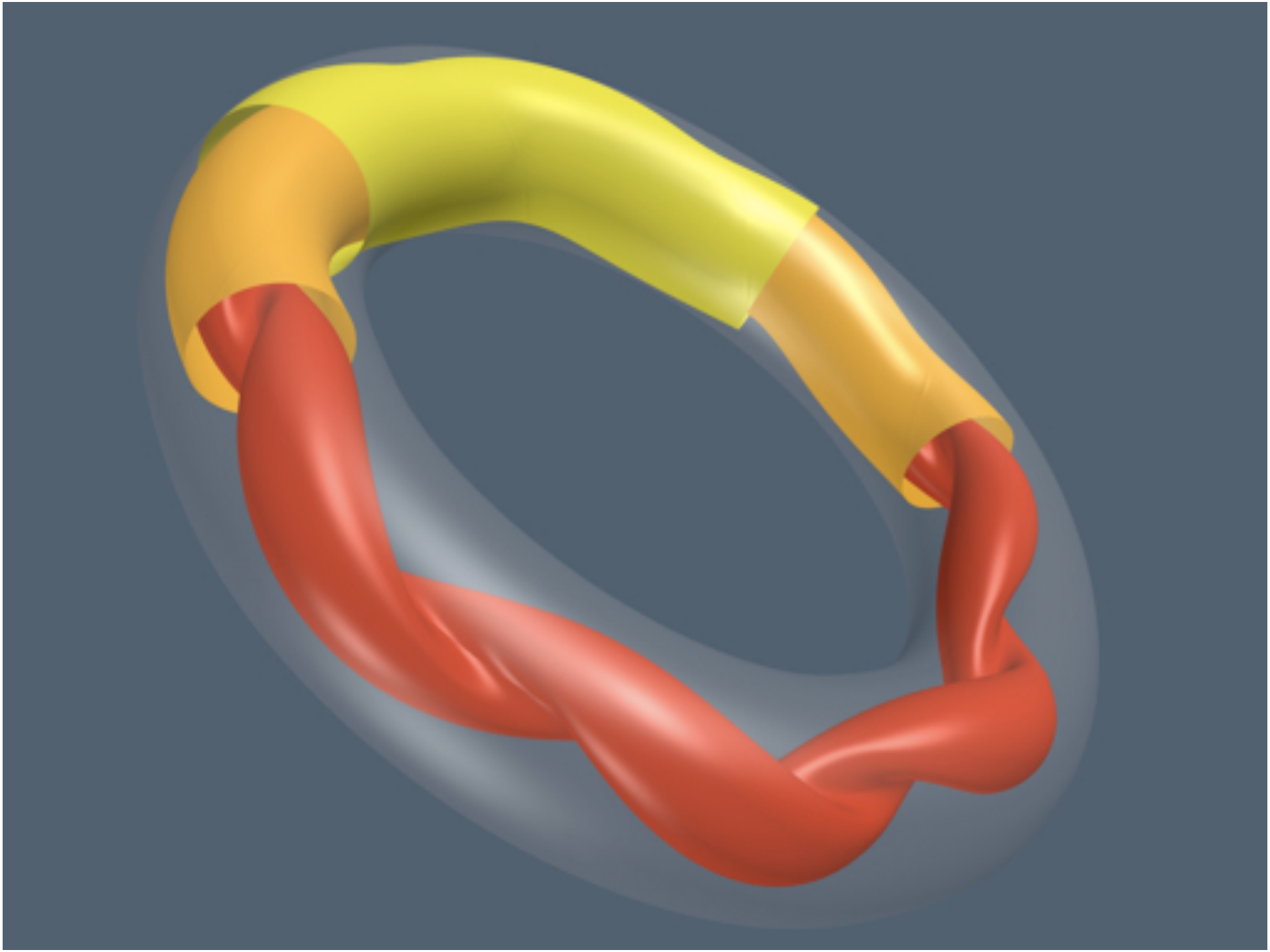
- For near-treshold chaos it is an oversimplification to say that the strong parallel transport results in flat temperature profiles.
- Coordinate surfaces are constructed that coincides with barriers: gaps on CANTORI are closed, and this is done by constructing **GHOST SURFACES**, which are "**ALMOST**" INVARIANT surfaces.



*Hudson&Breslau, PRL **100**, 2008*



Even though no KAM surfaces exist, the heat flux required to sustain the imposed temperature gradient is only enhanced by a factor of 2 compared to the integrable case



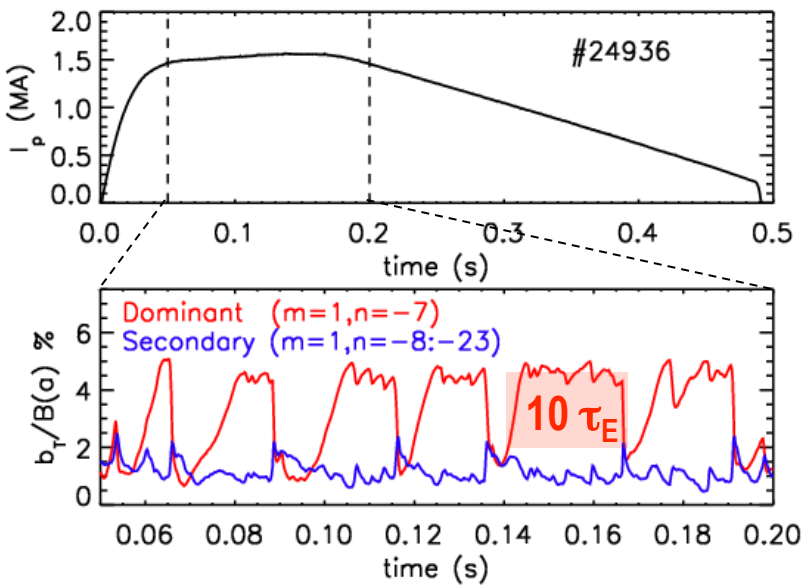
High current operation and helical states: a change of paradigm

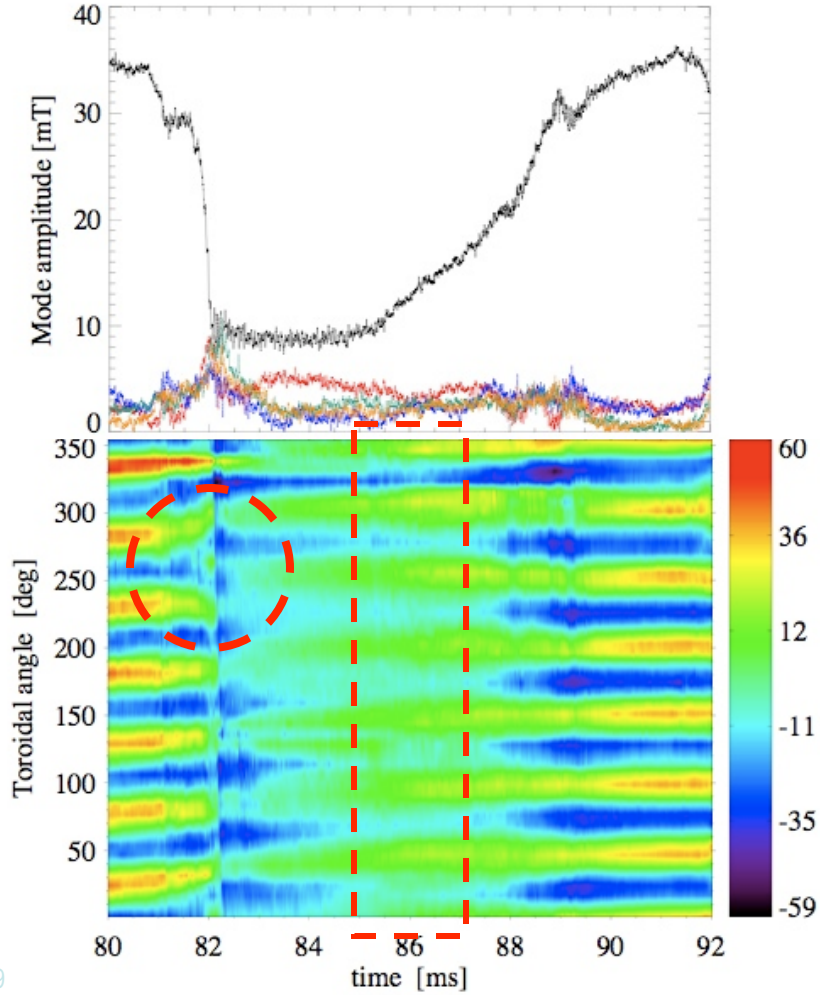
3

3.4 understanding to optimize

What is happening at back-transitions?

- Back-transitions happen when the plasma is transiently perturbed by bursts of MHD activity
- Burst is toroidally localized in real space
- Partial lost of the helical state: a helical signature remains also immediately after burst.

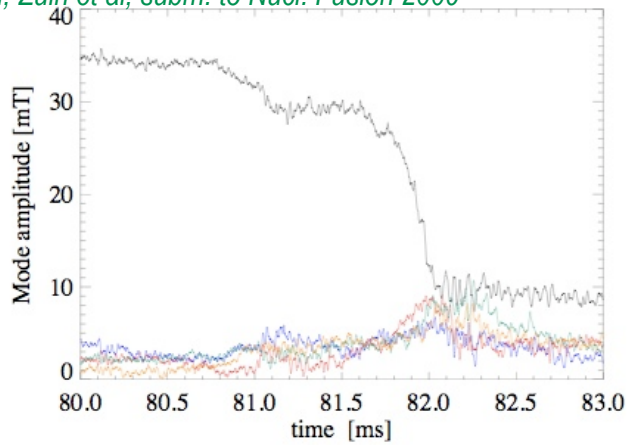


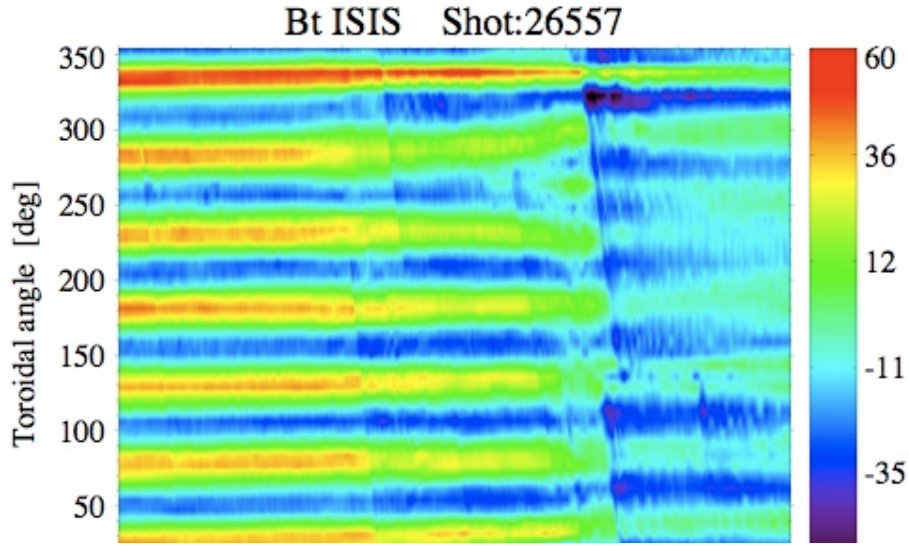


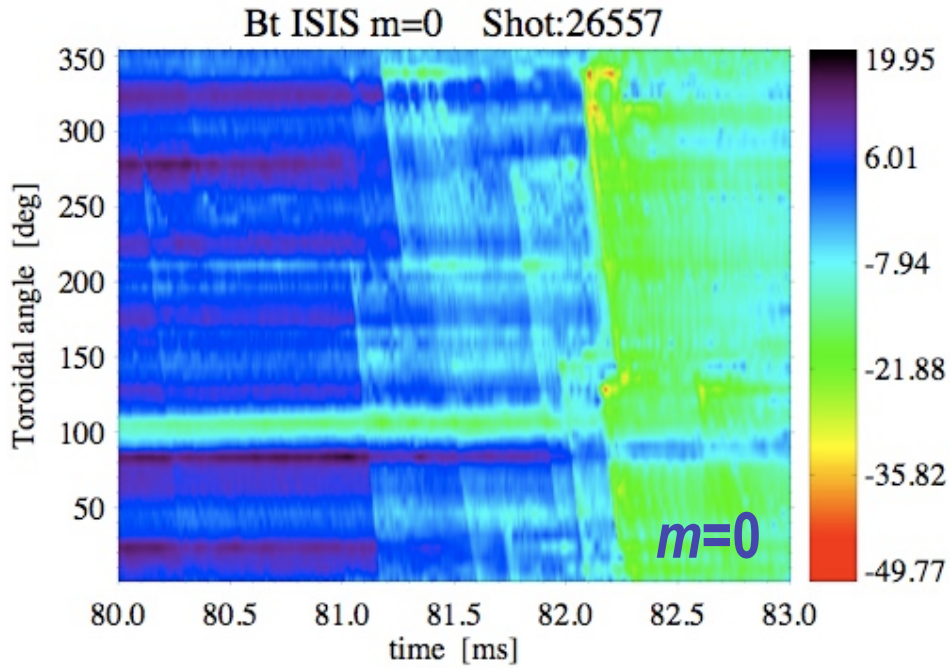
Piovesan, Zuin et al, subm. to Nucl. Fusion 2009

The perturbation has a strong *m*=0 character

Piovesan, Zuin et al, subm. to Nucl. Fusion 2009



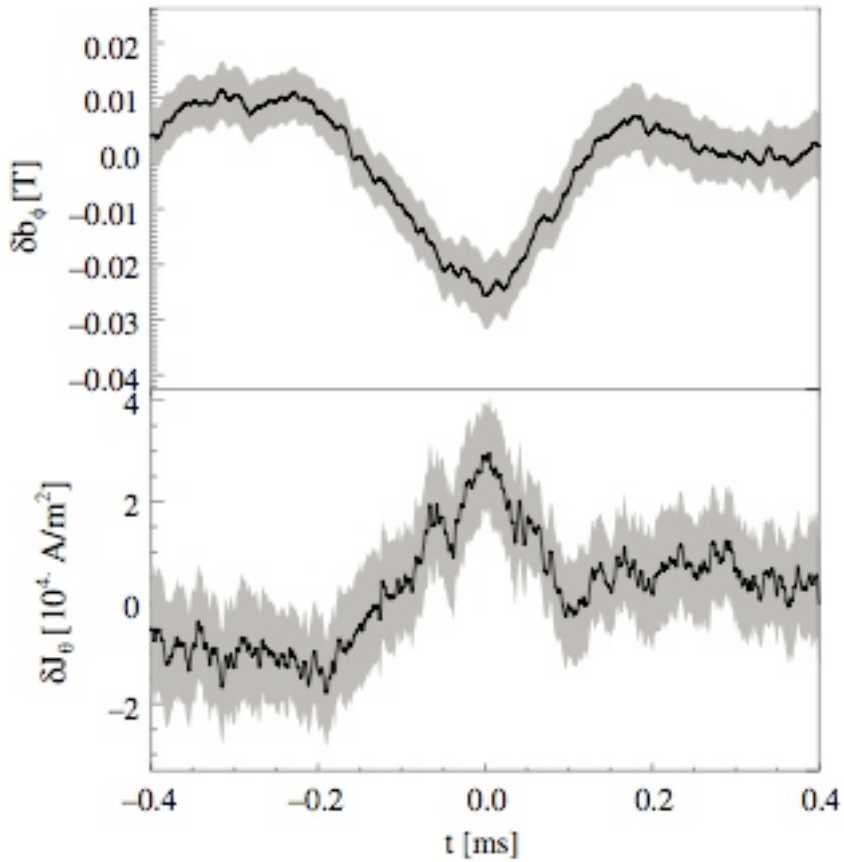




- The *m*=0 perturbation travels in the counte plasma current direction, for approx. one toroidal turn.
- In RFX and MST low current plasmas these have been identified as localized reconnection events, with field-aligned current structures
- *Crocker et al PRL 90 (2003)*
  *Choi et al., PRL **96** (2006)*
  *Zuin et al., PPCF **51** (2009)*

Poloidal current sheet

- The *m*=0 perturbation corresponds to a traveling poloidal current sheet, associated with a localized spontaneous magnetic reconnection event.



- δJ_θ x δB_r torque
- The current sheet induces a strong perturbation of the edge plasma
- Rapid momentum transport
- Local enhancement of plasma temperature and density

*Zuin et al., PPCF **51** (2009)*

Less back-transitions at high current

CONSORZIO RFX
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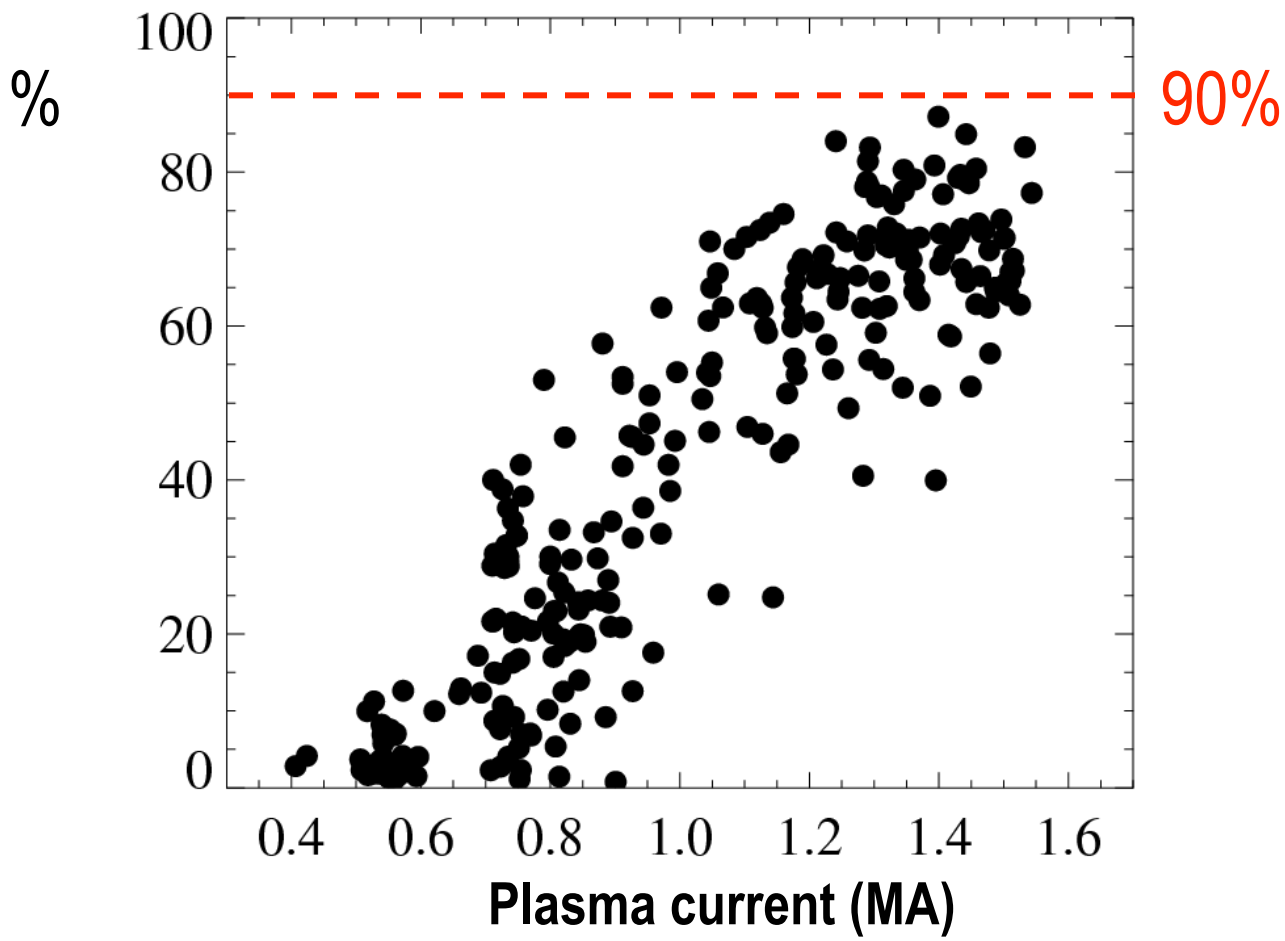
- At low current most violent reconnection events happen when the ratio between the **guiding field (poloidal)** and the **reconnecting field (toroidal)** is smaller (controlled by equilibrium at fix current).
- Once equilibrium is chosen to maximize this ratio, **further improvement is obtained at high current, since the guiding poloidal field increase**
- At high current plasma is **less resistive**

All this goes in the direction of predicting less back-transitions as plasma current is increased

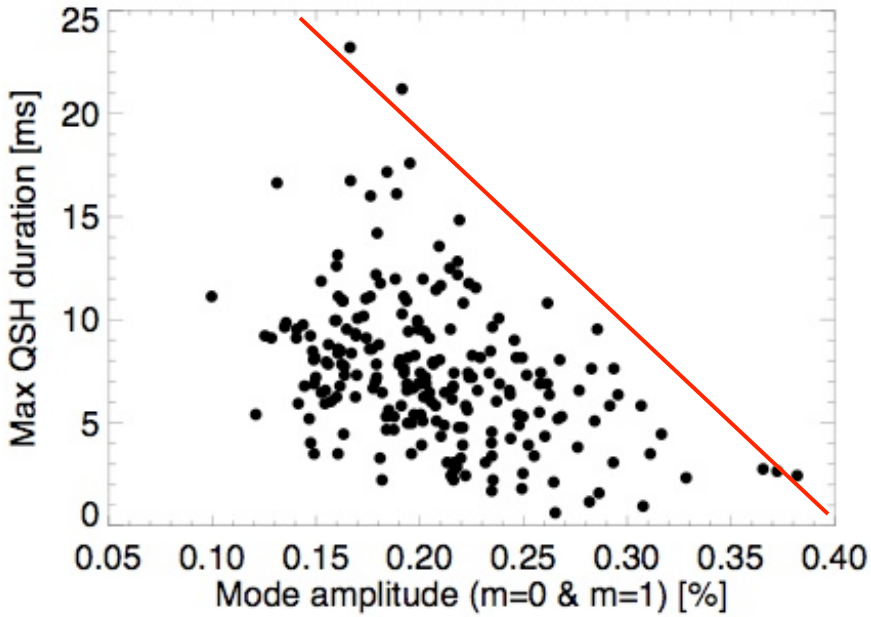
Helical state is preferred at high current

$$\text{PERSISTENCY} = \frac{\text{time spent in QSH state}}{\text{flat-top duration}}$$



Improved control of radial field

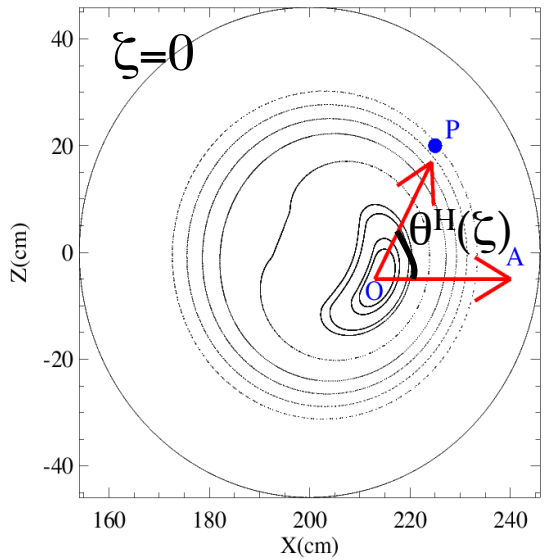
is a requirement for long helical state duration



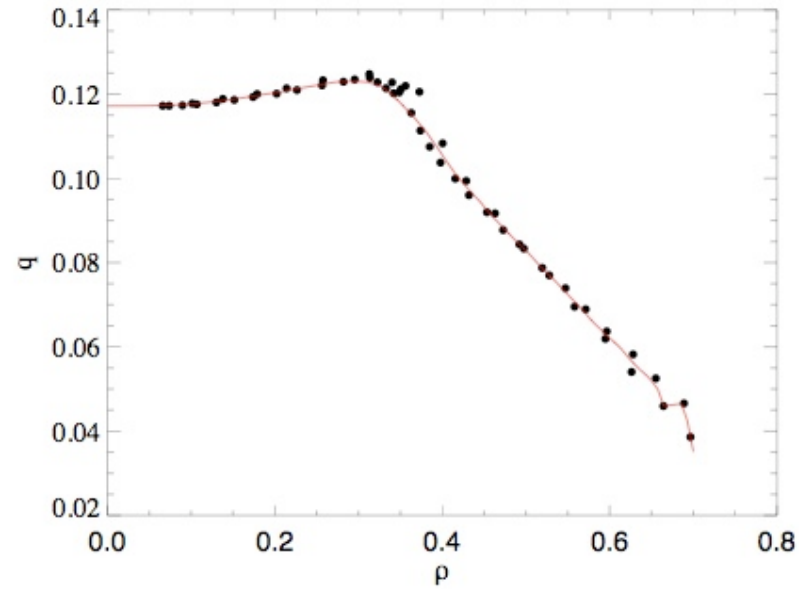
Zuin, private comm. (2009)

Transport barrier and magnetic shear

Safety factor computed in the helical state



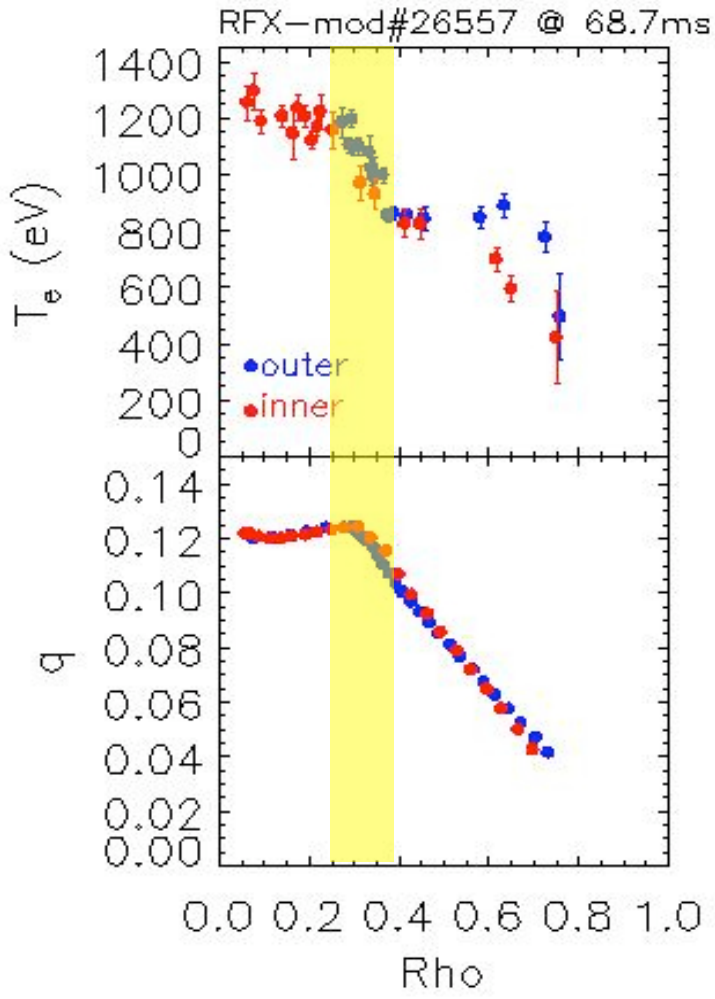
$$q^H = \frac{d\theta^H}{d\xi}$$

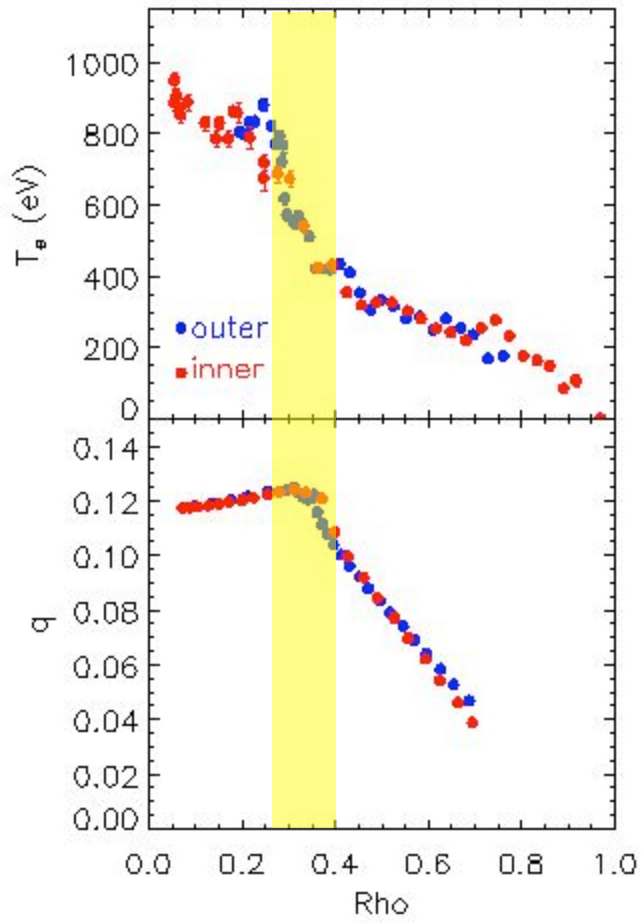


- q^H defined from field lines winding around the O-point of the mode (m=1,n=-7);
- q^H calculated: (a) **analytically**, (b) **numerically, with the ORBIT code**

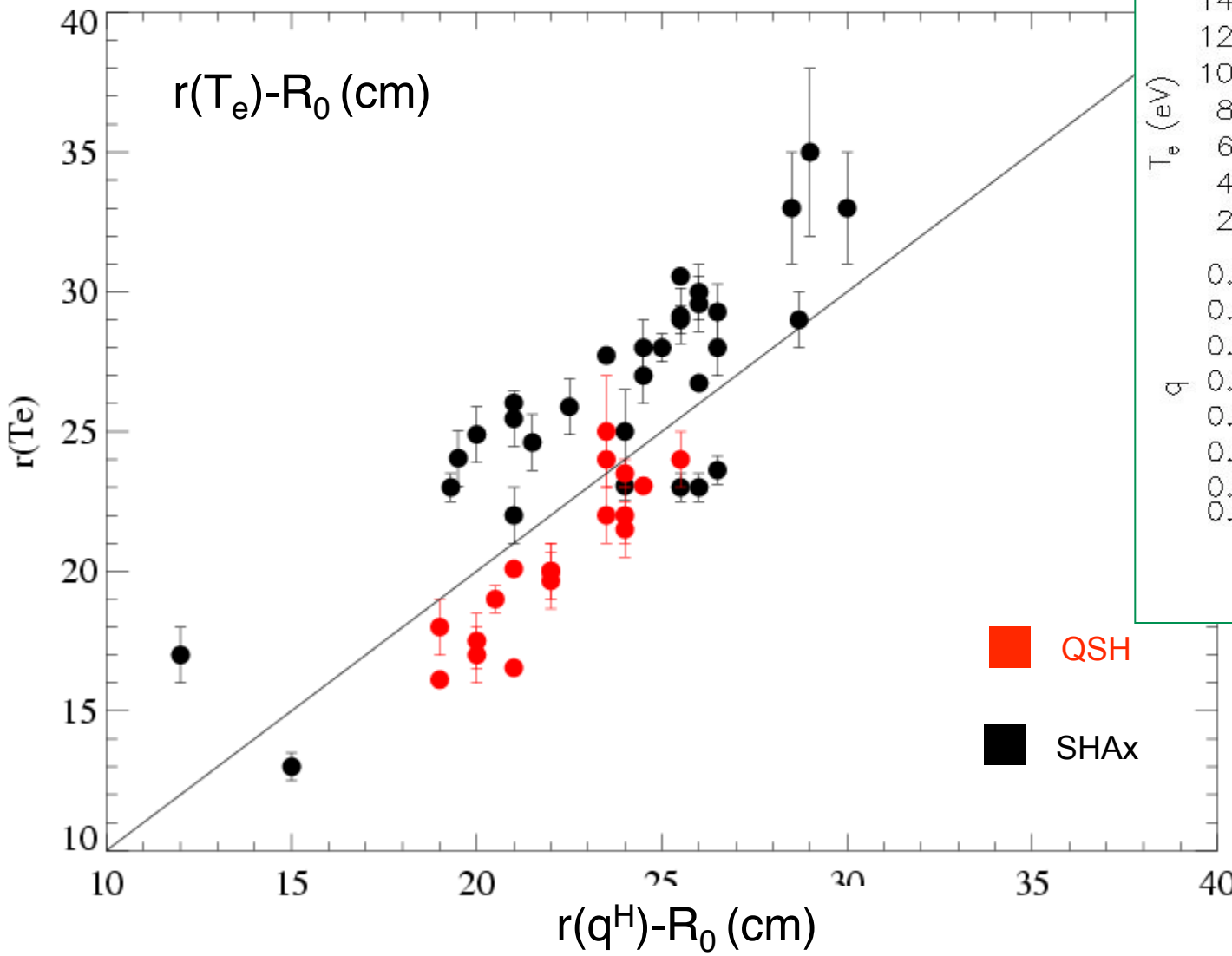
Preliminary results

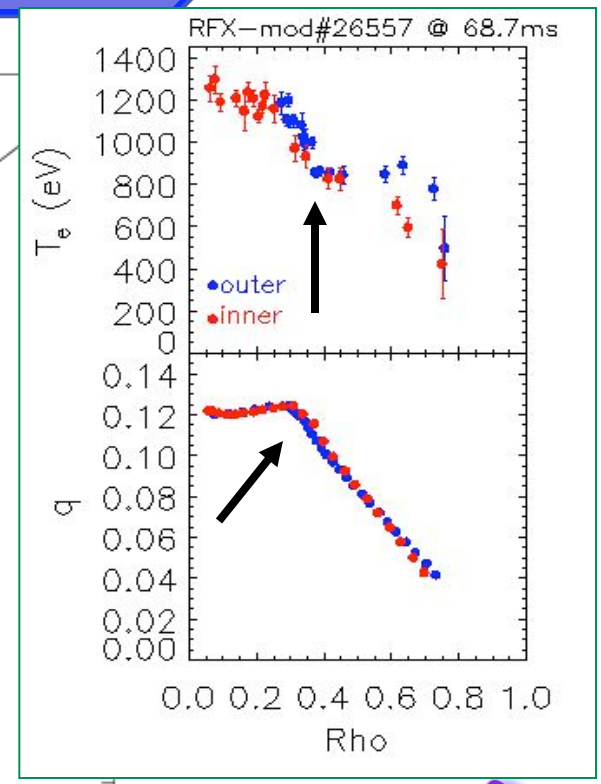
Escande, Bonfiglio, Gobbin, Marrelli, Martines, Momo, White et al


RFX−mod#26557 @ 68.7ms
T_e (eV)
1400
1200
1000
800
600
400
200
0
outer
inner
q
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0 0.2 0.4 0.6 0.8 1.0
Rho


T_e (eV)
1000
800
600
400
200
0
outer
inner
q
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0 0.2 0.4 0.6 0.8 1.0
Rho

The foot of the transport barrier coincides with the change of slope in q^H

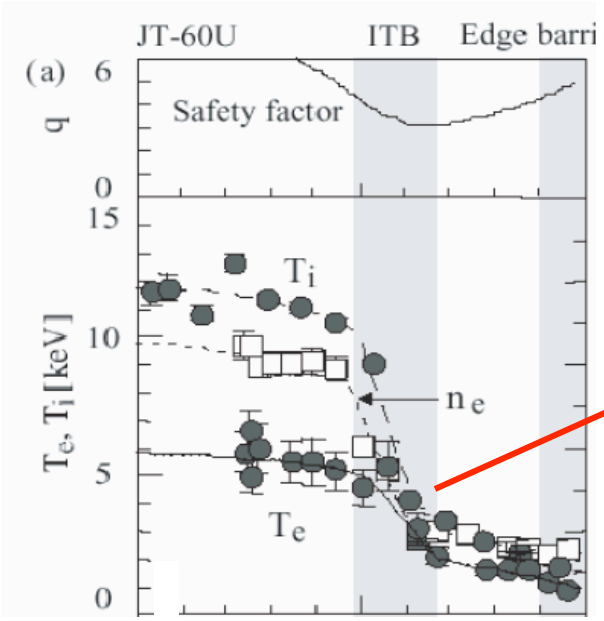


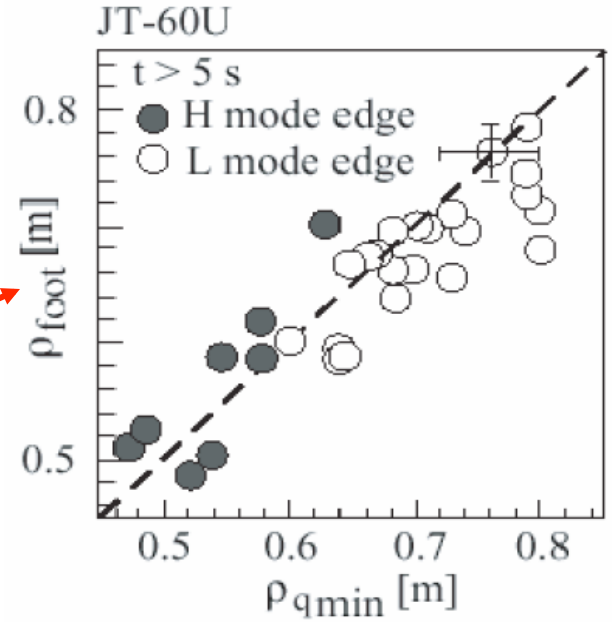


Preliminary results

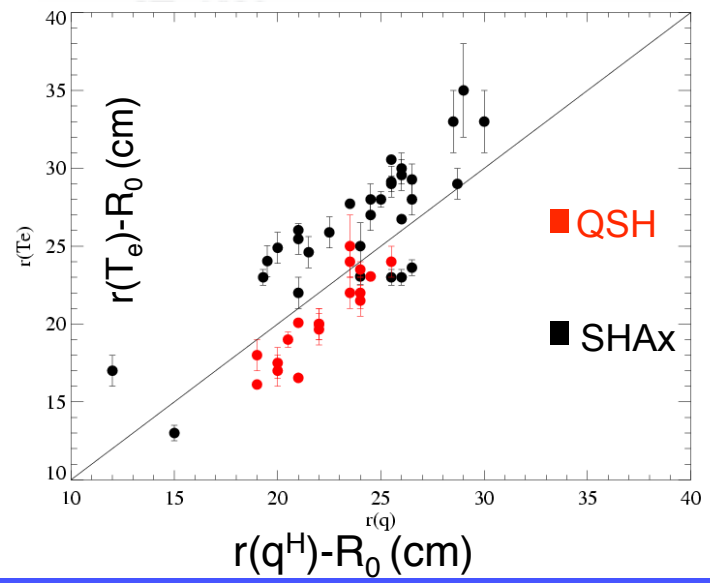
Gobbin, private comm. (2009)

Analogies with ITB in Tokamak…





- Similar relation in tokamak between the point with minimum safety factor and the foot of barrier

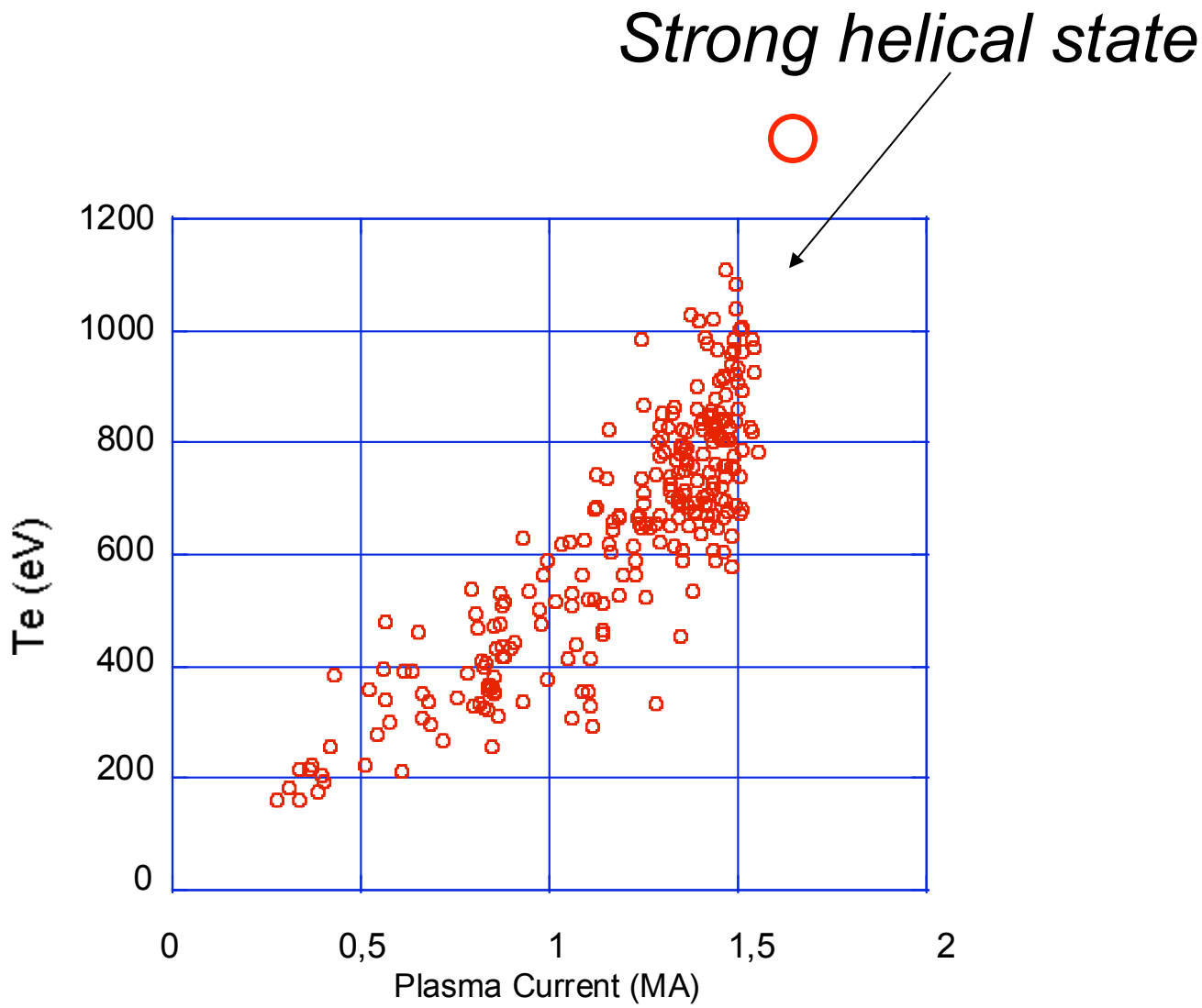


J.W. Connor, Nucl. Fusion 44 (2004)

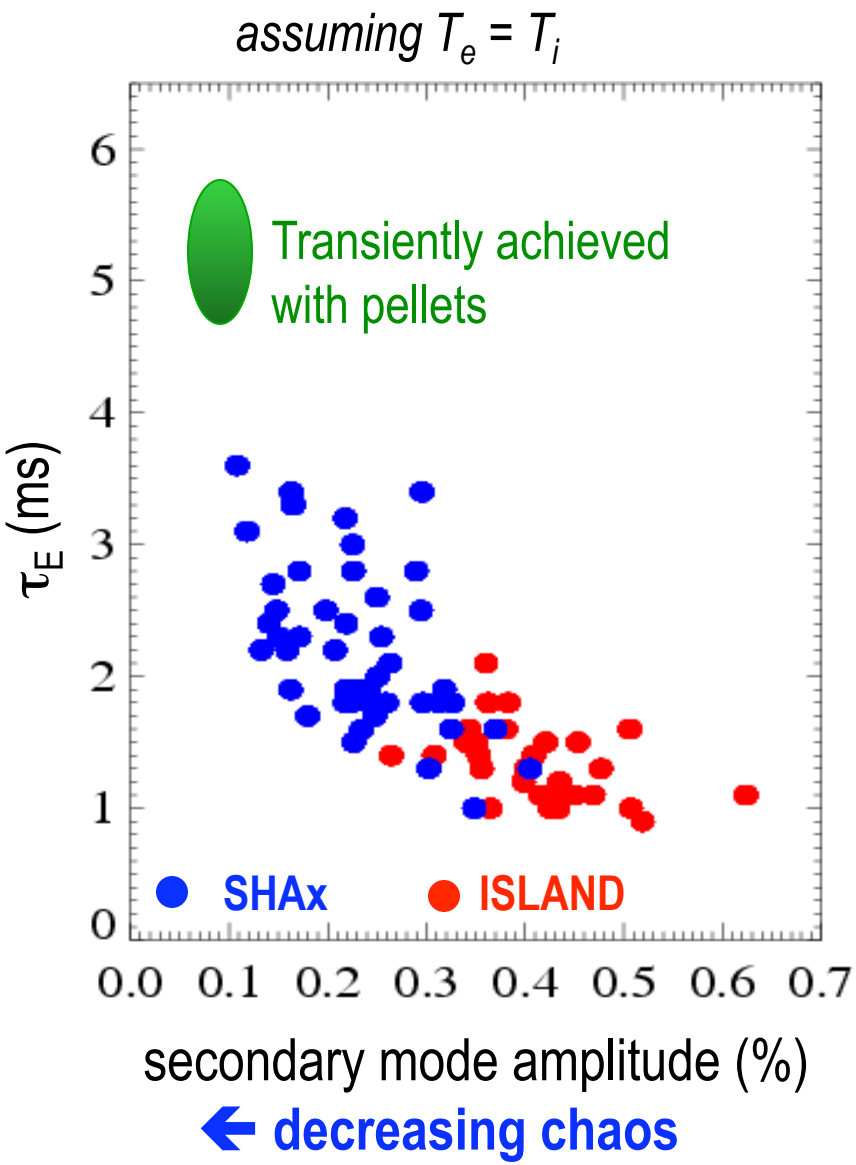
Summary and conclusions

4

T_e increases with current: no saturation



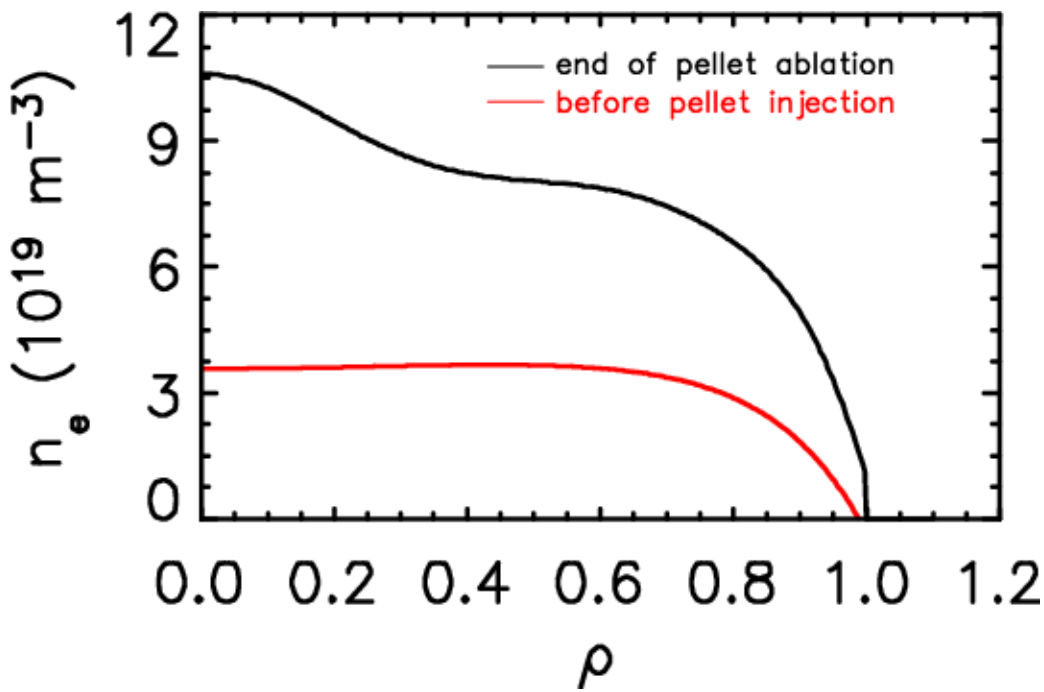
Substantial confinement improvement with SHAx

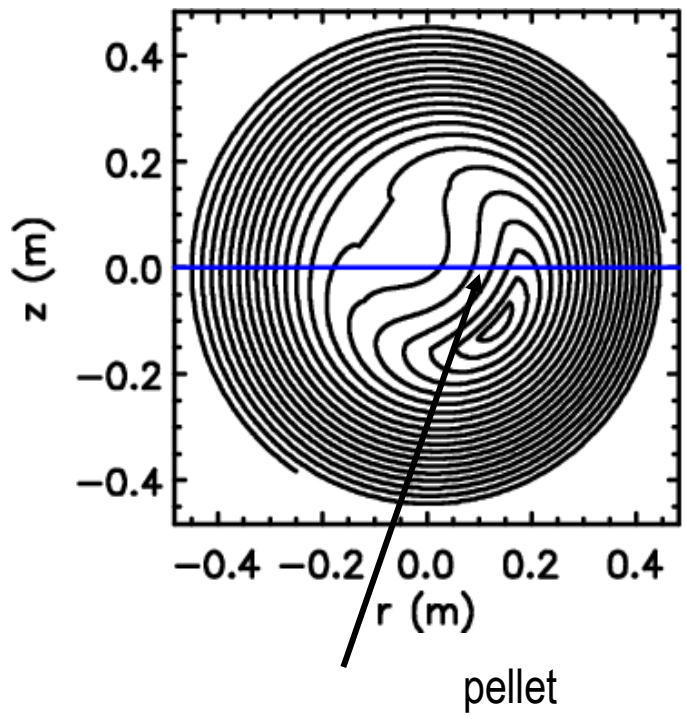


- The energy confinement time in SHAx:
  - **~ 2x wrt QSH with island**
  - **~ 4x wrt multiple helicity**
- **Particle confinement time in SHAx up to ~12.0 ms with pellet**
- **No impurity accumulation**
- **High density not reached, yet (potential issue for Ti - Ti/ Te≈0.5-1, collisional ion heating mechanism)**
- Optimization of fuelling on-going to achieve high n/n_g at high current
  - Pellets now
  - Lithization near future (Liquid Lithium Limiter)

Confinement inside the helical structure

Density profile from interferometer against the helical coordinate

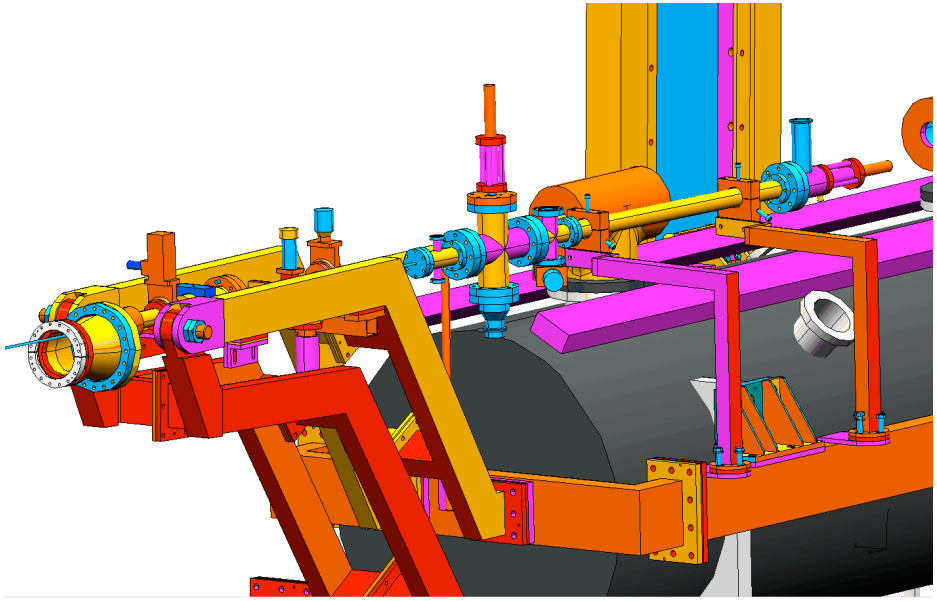




Pellet can penetrate the helical structure

Density peaks inside the helical structure

Non-cryogenic pellet injector and Capillary Porous System



- Pellet size: Ø 1.5 mm x 4 mm = 28 mm^3

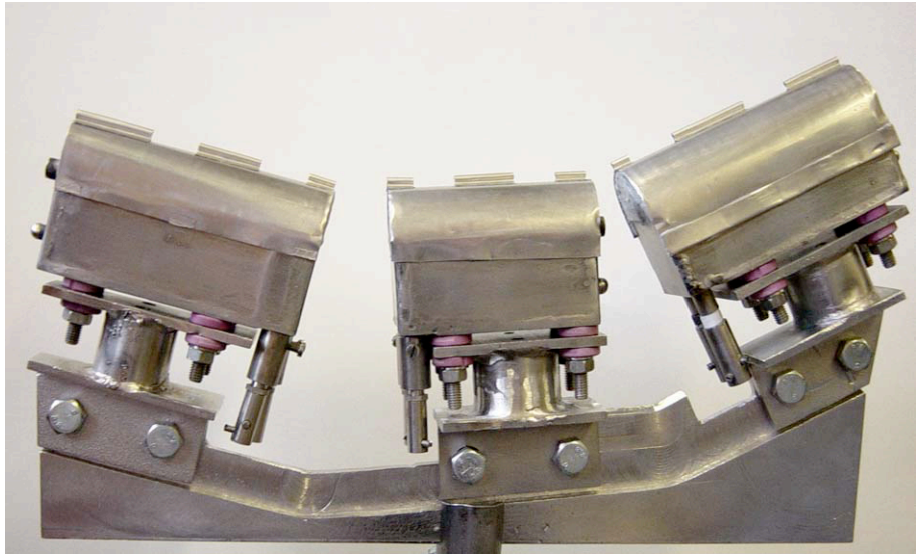
→ $N_{Li} \approx 10^{21}$ & S_{RFX}=36.3 m^2

→≈ 2.6 monolayers if uniformely distributed

(Innocente, Terranova et al.)

- CPS: on loan from FTU

(Alfier, Cavazzana, Mazzitelli, Scarin et al.)



V. Pericoli Ridolfini et al. Plas. Phys. Contr. Fusion 49 (2007) S123-S135

Change of paradigm

CONSORZIO RFX
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- The spontaneous occurrence of a new self-organized helical equilibrium with a single helical axis, reduced magnetic fluctuations and strong transport barriers provides a change of paradigm for the RFP.
- As the persistence of these improved confinement phases increases with plasma current, the likelihood of achieving steady SHAx states in multi-MA devices can be inferred.
- This opens a promising path for this configuration, since the emergence of ghost surfaces is likely to be followed, at even lower secondary mode amplitudes, by the separation of the magnetic islands. Island separation would lead to the formation of regions of conserved surfaces, giving rise to transitions to further improved confinement regimes.
- Additional improvements are also expected by optimization of magnetic boundary and fuelling, the latter supported by preliminary experiments with pellet injection.

RFX-mod: a confident approach to the future

CONSORZIO RFX
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- **A big leap with respect to only a few years ago in terms of:**
  - ***Understanding***
  - ***Performance***
  - ***Recognition / Collaborations / cross-fertilization*** from/ with the broader fusion community
  - ***Consciousness*** *of the role in the ITER era*
- **RFX-mod:**
  - **Has discovered a new regime**, where the plasma spontaneously self-organizes in a single-axis helical state, with strongly improved core confinement.
  - **provides** key contribution to **advanced MHD stability feedback control**
  - **gives** important results for broader fusion issues **(density limit, momentum transport, magnetic self-organization, …)**
  - allows a study of the beneficial effects of non-axisymmetric shaping and may provide a platform for a more general validation of theoretical tools developed for stellarators.

The new vision and the overall progress in the RFP community supports a reappraisal of the RFP as a low-external field, non-disruptive, ohmically heated approach to magnetic fusion, exploiting both self-organization and technological simplicity.

RFX : education and training

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Students from the Ph.D. schools in Physics, Energy technology, Electrical Engineering, and, since this year, from the **European Doctorate in Fusion**

Plasma and fusion taught at undergrad level in the **physics and engineering departments**

56	Ph.D. thesis	
67	Master in fusion thesis	more than 200 thesis over the last 10 years
>100	5 years diploma thesis	

- Average age of the group: **≈ 43**
- A **nursery** for EU fusion program:

  Over the last 10 years **43 professionals** have been recruited by Consorzio RFX

  ≈25 scientists educated in Padova moved to EU labs as staff members or Ph.D. students
- RFX students/post doc winners of EU awards for PhD thesis and post-doc competitions

The end

Thank you !