Overview of the RFX-mod contribution to the International Fusion Science Program

M.E. Puiatti for the RFX-mod team

A flexible experiment

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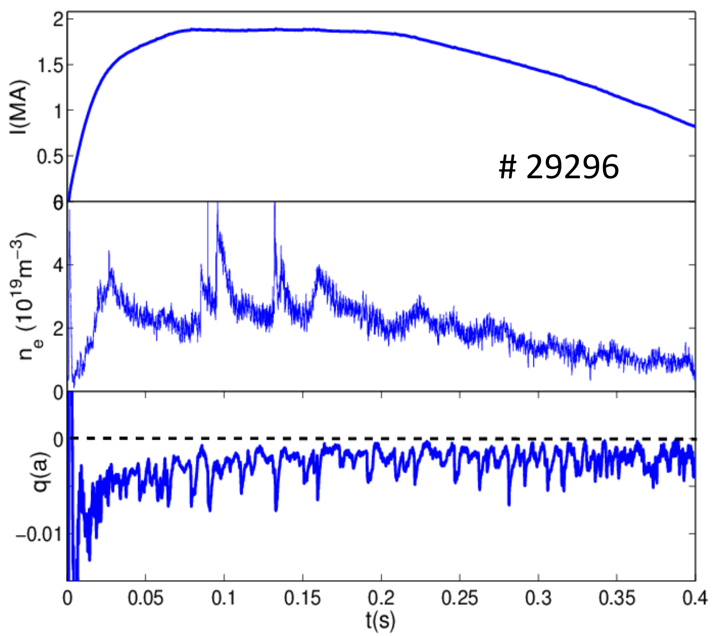
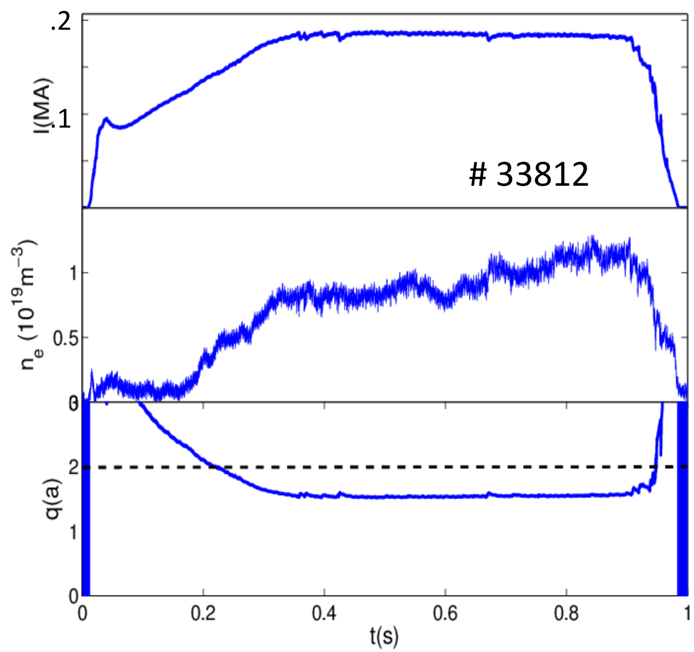
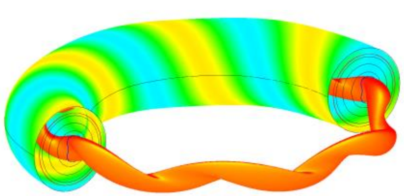
RFX-mod is a **flexible device**:

…a high current Reversed Field Pinch



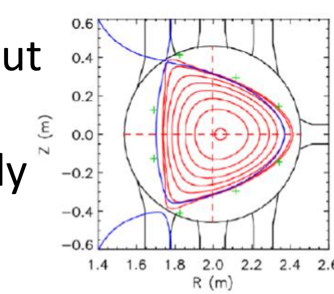
…a low current Tokamak

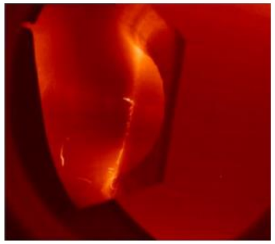




Quasi-single helicity states

Ohmic circular, but first double-null equilibria recently produced





A cross-configuration view for open issues

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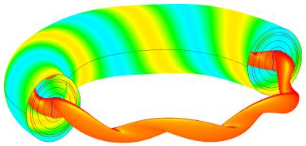
RFX-mod RFP:



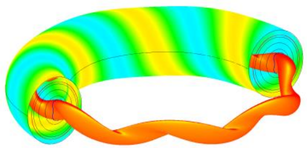
- study the high current RFP physics

…besides the confinement concept, focus on:

- helical magnetic equilibria
- MHD physics and control
- transport barriers
- edge properties and turbulence
- high density limit

A cross-configuration view for open issues

RFX-mod RFP:



- study the high current RFP physics

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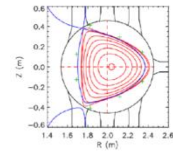
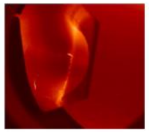
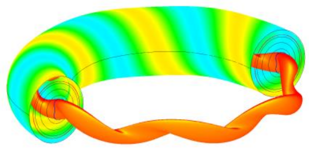
RFX-mod Tokamak:

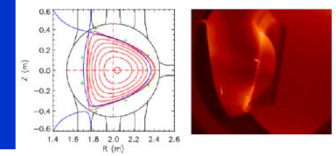


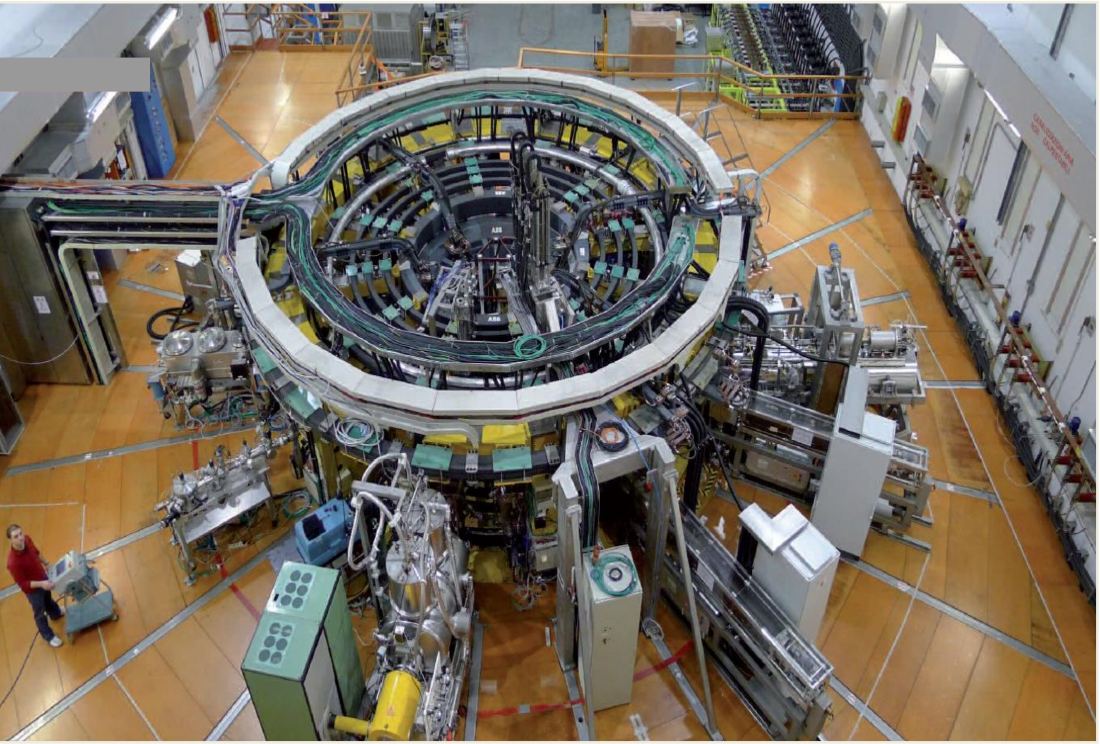


- operate in unexplored parameter regions
- robust q(a) < 2 operation
- develop advanced MHD instability control alghoritms
- disruption control studies
- effect of MP on edge properties
- sawtooth and fast electron mitigation



The RFX-mod device





a=0.459 m , R=2 m

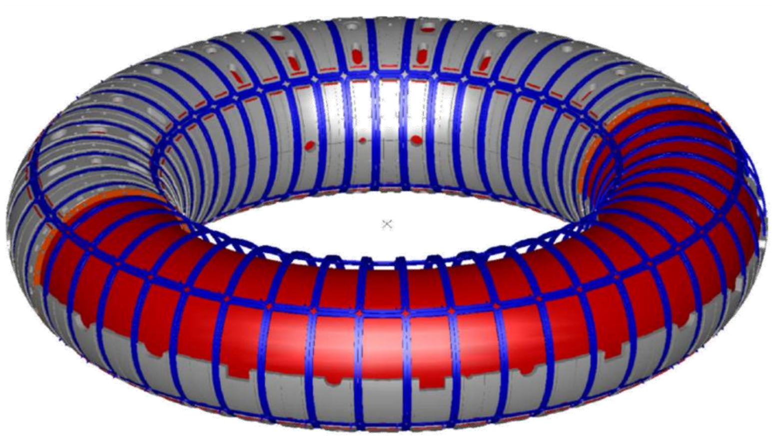
Ip ≤ 2 MA RFP, 0.2 MA Tokamak

B_t*=0.7 T*

Te, Ti ≤1.5keV

ne ≤10^{20} m^{-3}

ohmic, no divertor



Advanced MHD stability control system

based on 192 saddle coils independently driven

Exploited both in RFP and Tokamak configuration

Outline

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- Self-organized helical states in RFP and the isotope effect
- Edge properties in RFP and Tokamak
- Low-q operational scenarios in Tokamak
- Application of MP as a means to control sawteeth and fast electrons
- Summary and perspectives

- **Self-organized helical states in RFP and the isotope effect**
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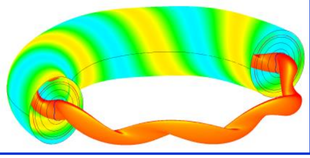
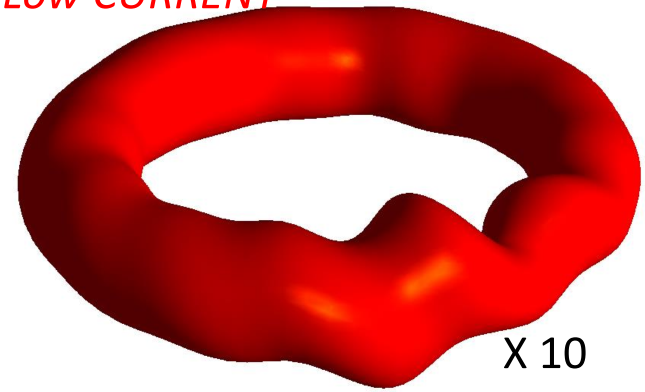
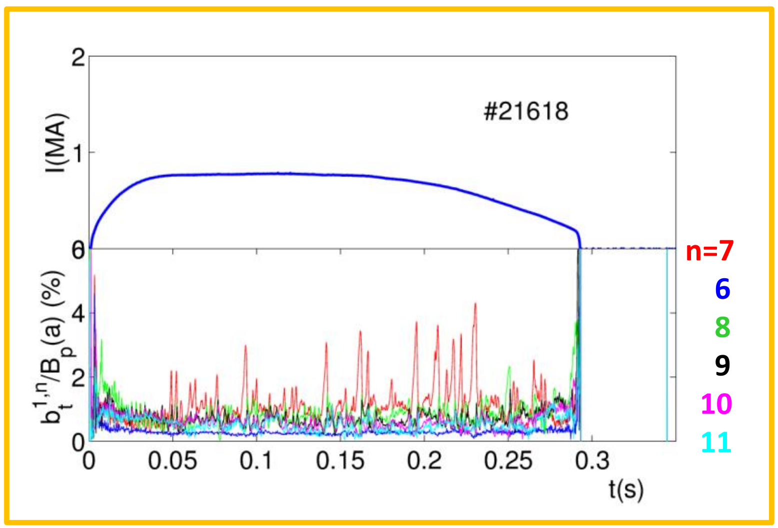


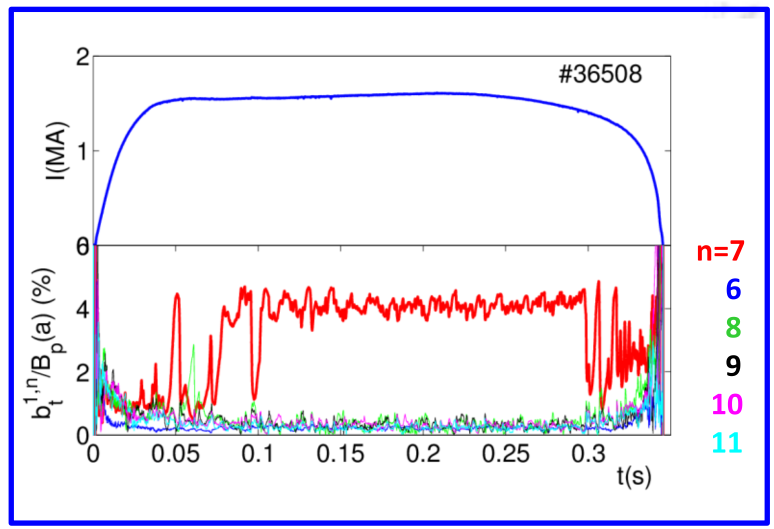
In RFP, helical states are the result of a self-organization process

Low CURRENT



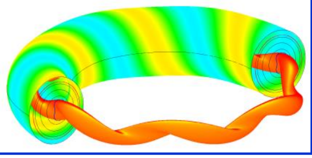
High CURRENT





Bifurcation of RFP equilibria predicted by 3D MHD modeling before the experimental observation

Escande, et al., PRL 85, 3169 (2000)
Lorenzini et al., Nature Phys. 5, 570 (2009)
Cappello et al., NF 51 103012 (2011)



MHD modeling of QSH dynamics

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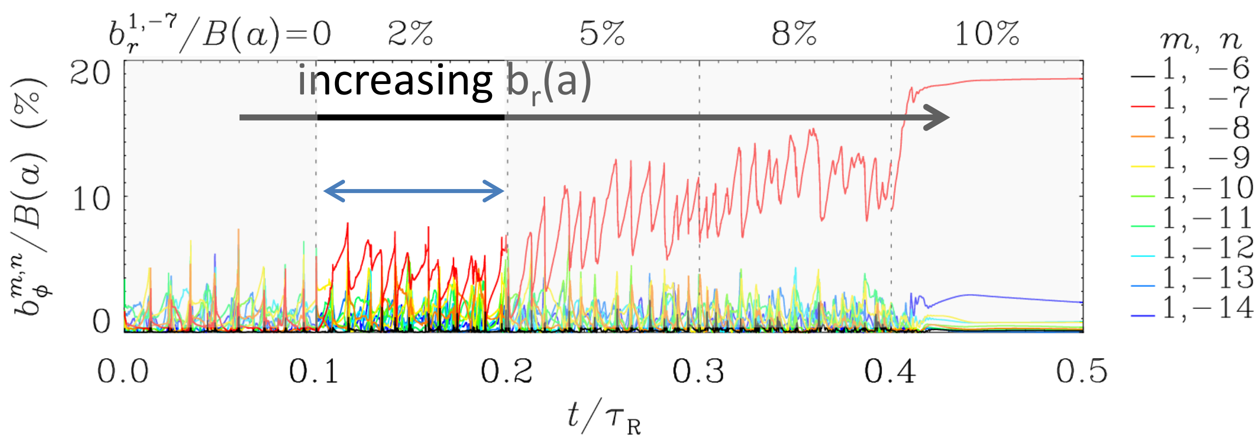
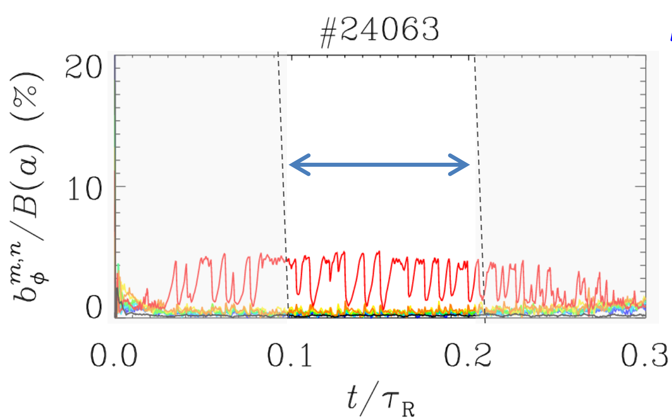
QSH dynamical behavior in 3D nonlinear MHD modeling - helical boundary conditions a key feature to favor steady helical QSH



SPECYL-PIXIE3D benchmarked codes PoP 2010

Simulations (SpeCyl), Lundquist number $S=\tau_R/\tau_A = 10^7$

Experiment (RFX-mod)

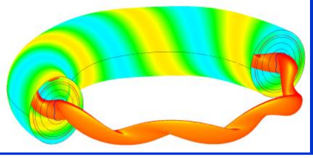


Transition to QSH ruled also by resistivity and/or viscosity (Hartman dimensionless number)

Gyroviscous effects recently discussed
King, Sovinec, Mirnov PoP 19 055905 (2012)

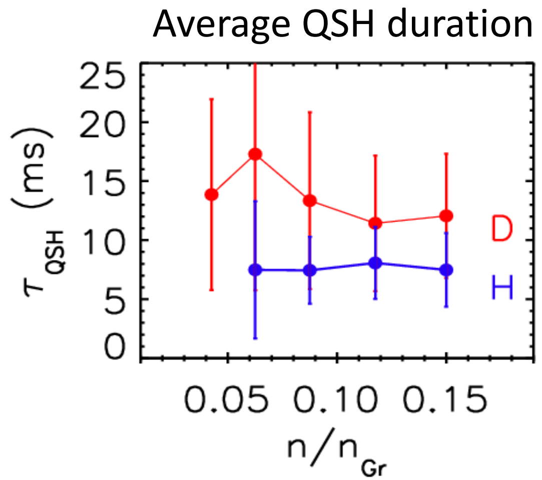
D. Bonfiglio et al, PRL 111 085002 (2013)

Guo, paper TH/P5-10 (also on kinetic effects on MHD)



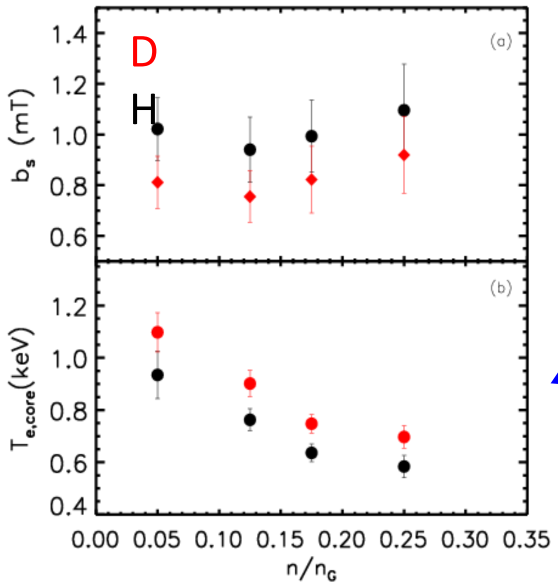
The isotope effect

Deuterium as filling gas improves plasma performance



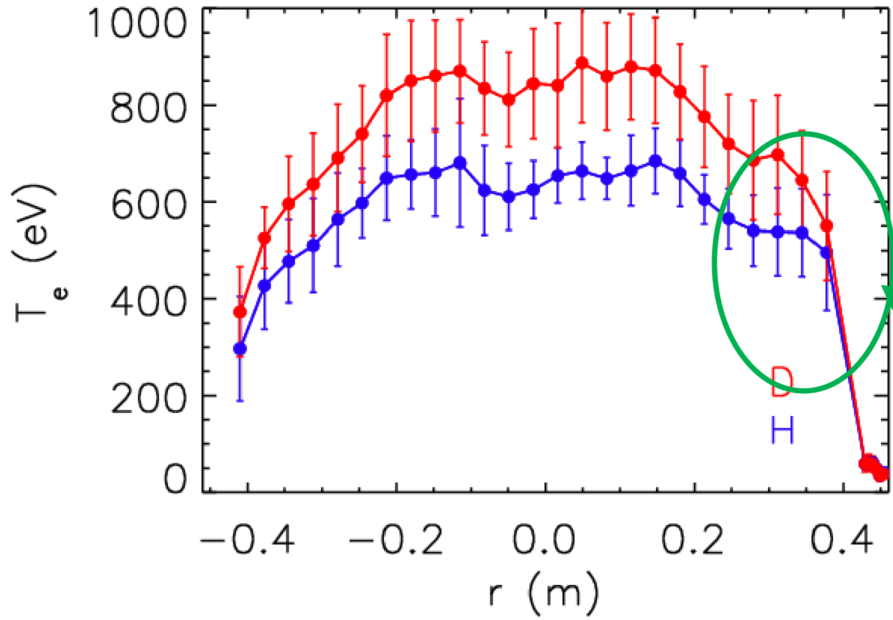
Deuterium plasmas more resilient to reconnection events

QSH crashes less frequent

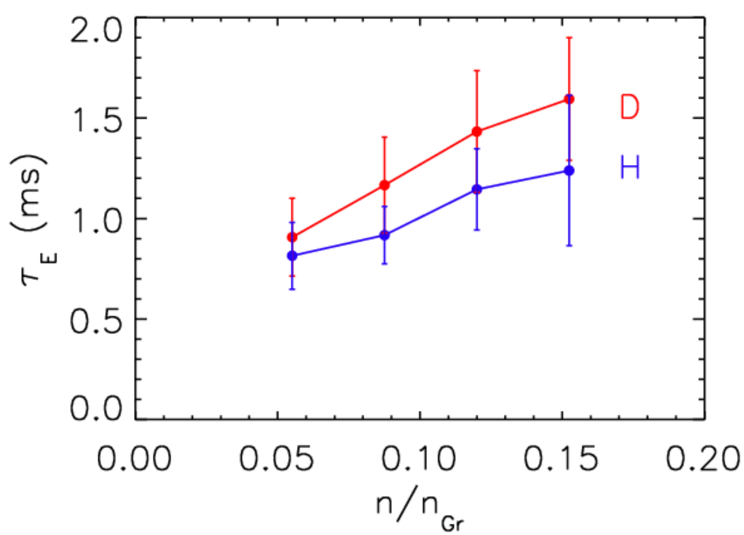


Impact of majority ion mass on MHD:
lower secondary modes
higher Te

Confinement improvement in D



Higher temperature pedestal : isotope effect on edge transport



$\tau_E \approx M_i^{0.3}$

Lorenzini, paper EX/P1-41

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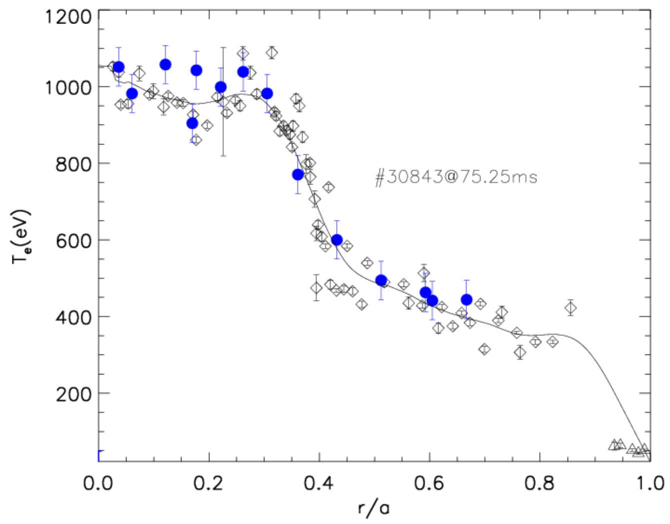
QSH states with the island axis collapsed on the magnetic axis:



- strong Te gradients

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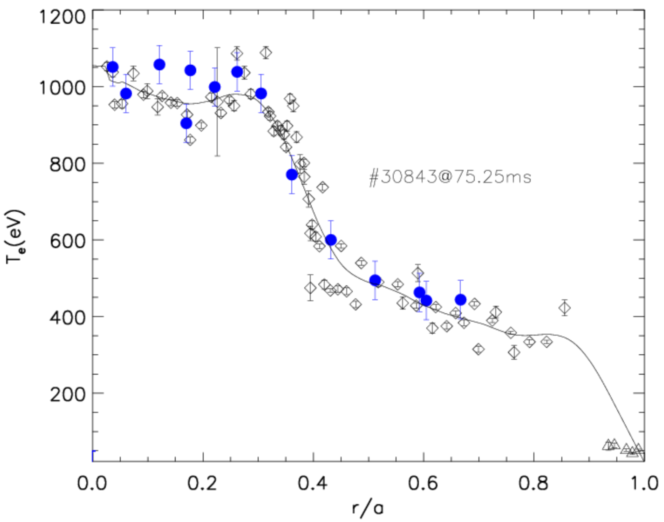
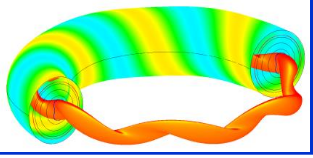


- strong Te gradients
- reduced thermal and particle transport:

$\chi_e < 5m^2/s$, $D < 1m^2/s$

M. Gobbin et al., PPCF 55 105010 (2013), Auriemma et al., submitted to NF



Transport barriers

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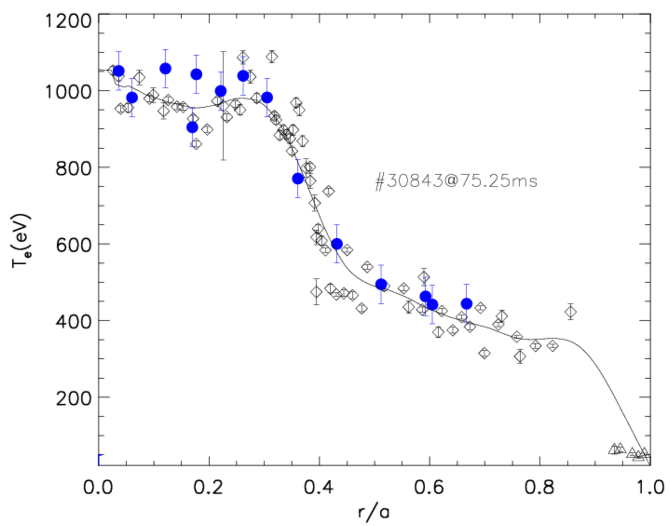

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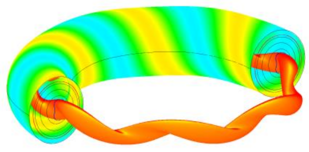
- impurities not penetrating the barrier



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Ricerca Formazione Innovazione

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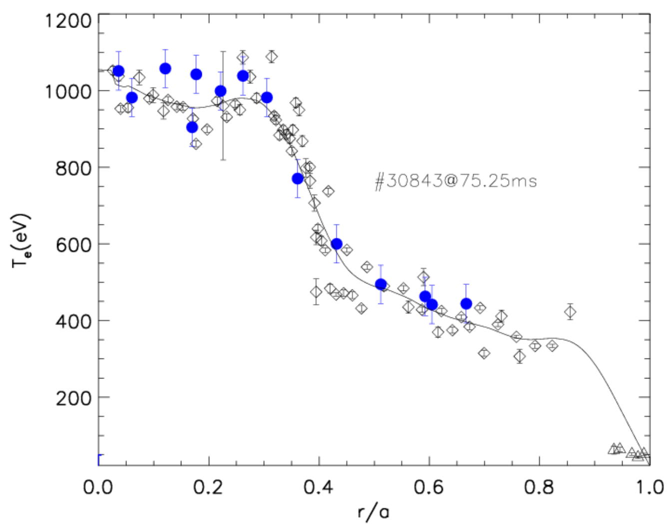

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- reduced thermal and particle transport:

  $\chi_e < 5m^2/s$, $D < 1m^2/s$

  M. Gobbin et al., PPCF 55 105010 (2013), Auriemma et al., submitted to NF
- impurities not penetrating the barrier
- residual stochasticity and microtearing/g-driven modes main contributors to transport at the barrier

I.Predebon, F.Sattin PoP 20, 040701 (2013) , M. Zuin et al., PRL 110, 055002 (2013)

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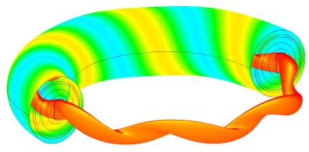

Edge transport properties in RFP

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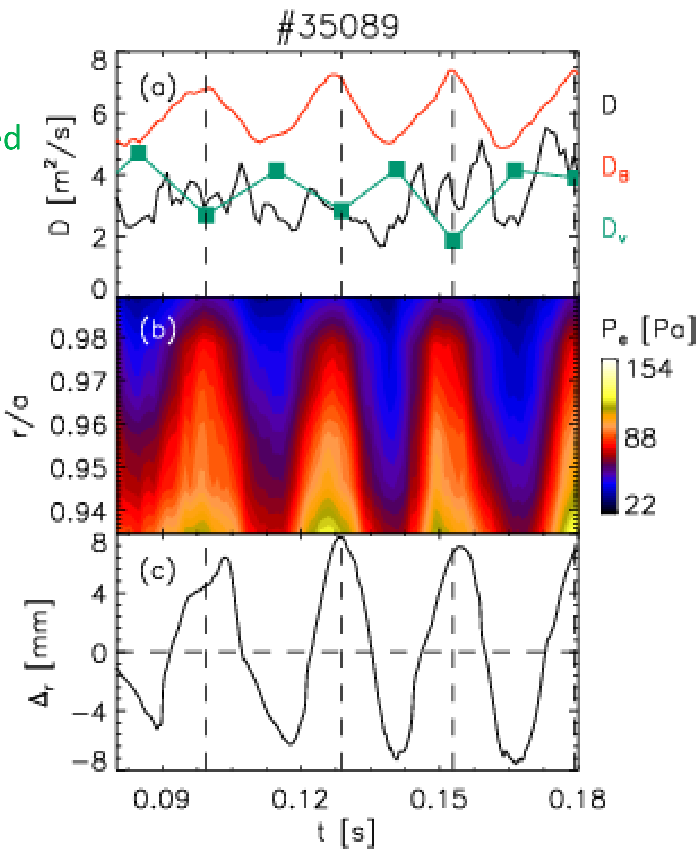
Particle influx (assuming Γin=Γout) + thermal helium beam & GPI diagnostics

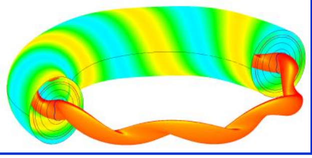
Total diffusivity
Diffusivity related to blobs
Bohm

Pressure (THB)

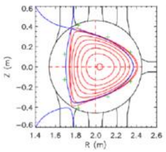


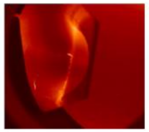
helical ripple (≈ 1%) sufficient to modulate pressure
diffusivity not clearly affected

Blobs are a main drive of edge transport



Electromagnetic filaments in presence of MP





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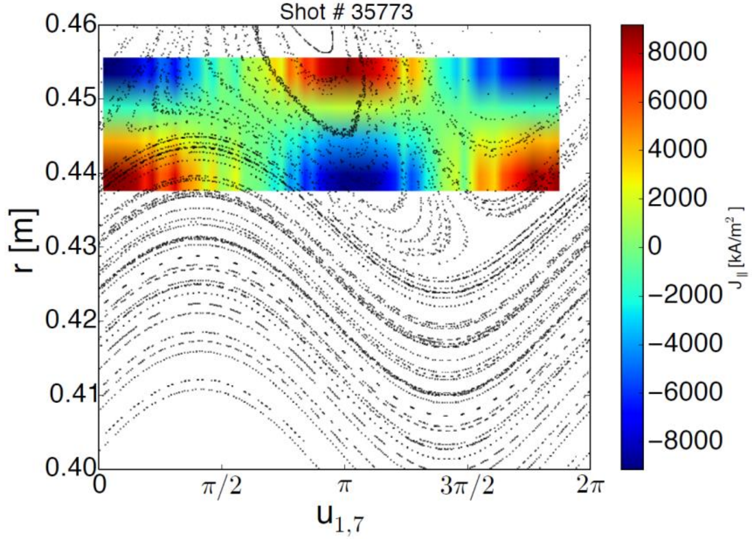
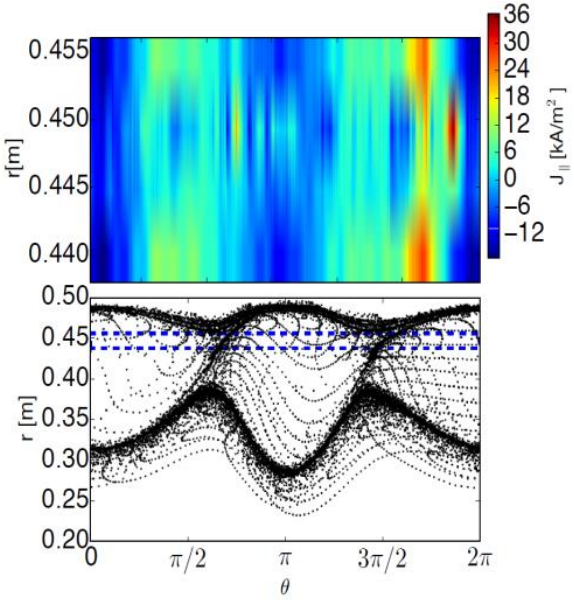
MP applied in RFP and tokamak configuration

- $J_{||}$ and flow modulated according to external perturbation

RFP: *ext pert. (1,-7)*



Tokamak: *RMP (2,1)*

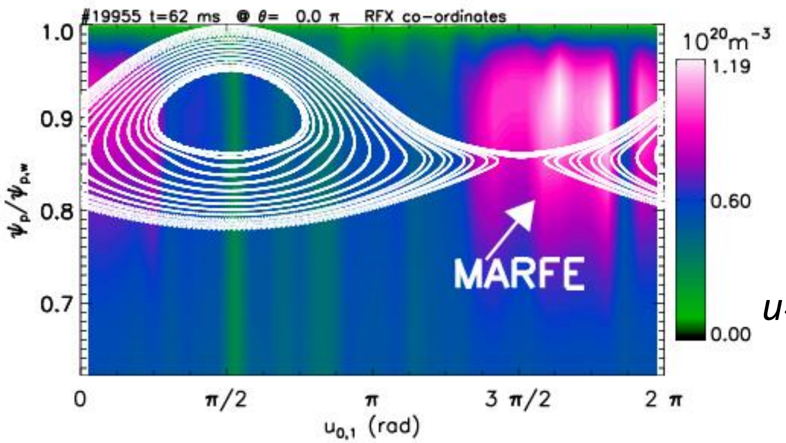


- number of blobs and particle & thermal fluxes also modulated by MP
- tight relation between blobs and transport
- **MP as a means to control filaments and related transport**

Spolaore, paper EX/P1-40

High density limit is related to edge MHD

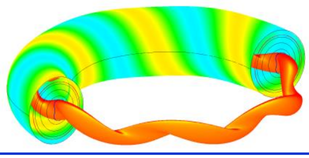
High density limit governed by a **Greenwald scaling of the edge density** $n_e \approx 0.35\ n_G$.
Same scaling found in FTU tokamak.
Above such density a poloidal MARFE-like structure develops



$u = m\theta - n\phi$

RFP:
edge magnetic topology and density accumulation above $0.35\ n_G$

Spizzo & Pucella, paper EX/P1-42



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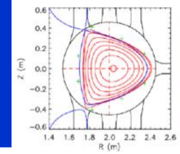

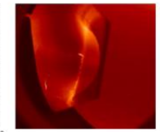

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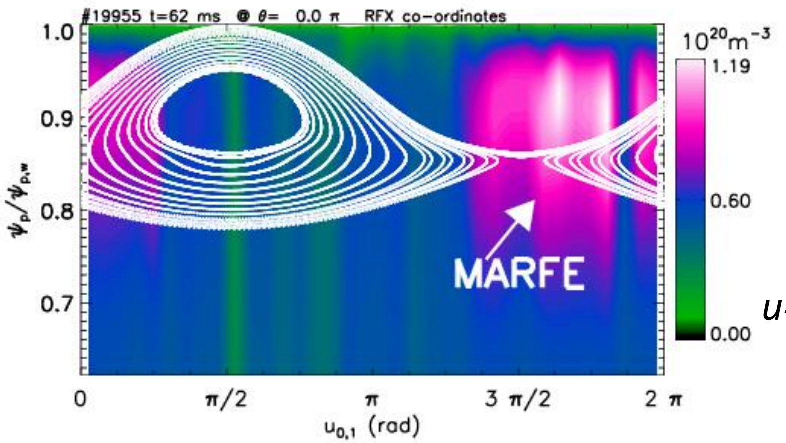


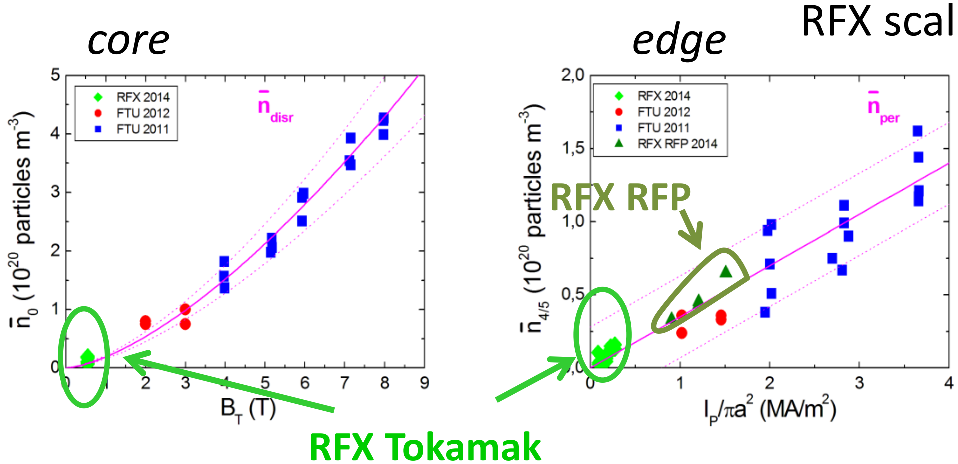
$u = m\theta - n\phi$

RFP:

edge magnetic topology and density accumulation above $0.35\, n_G$

Tokamak:

RFX scalings compared with FTU tokamak



Spizzo & Pucella, paper EX/P1-42

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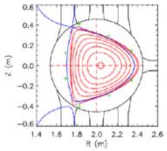
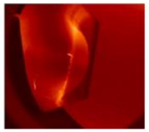
RFX tokamak : *(2,1)* mode control in disruptive conditions

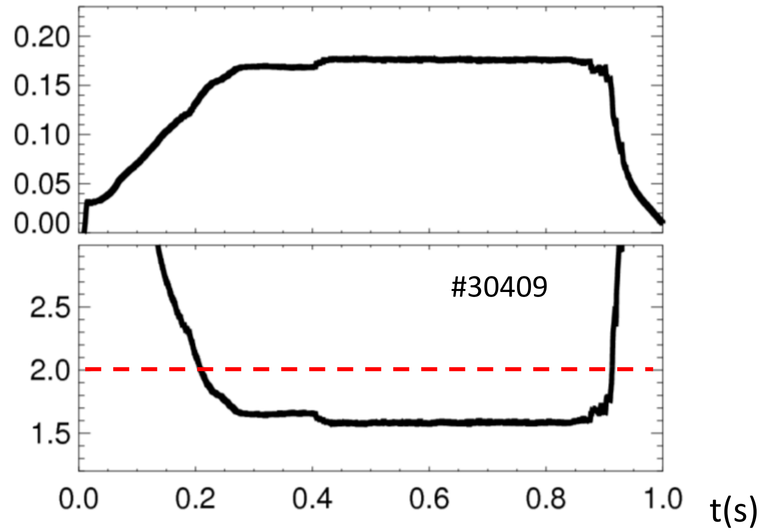



The feedback control can avoid disruptions at q(a) < 2.5 below the Greenwald density

q(a) <2 : (2,1) current driven RWM suppressed

When (2,1) TM grows up and its rotation frequency decreases :

- 2< q(a)<2.5: feedback can keep (2,1) TM in slow rotation and avoid wall locking and disruption
- q(a)>2.5: a disruption occurs even if the mode is not locked



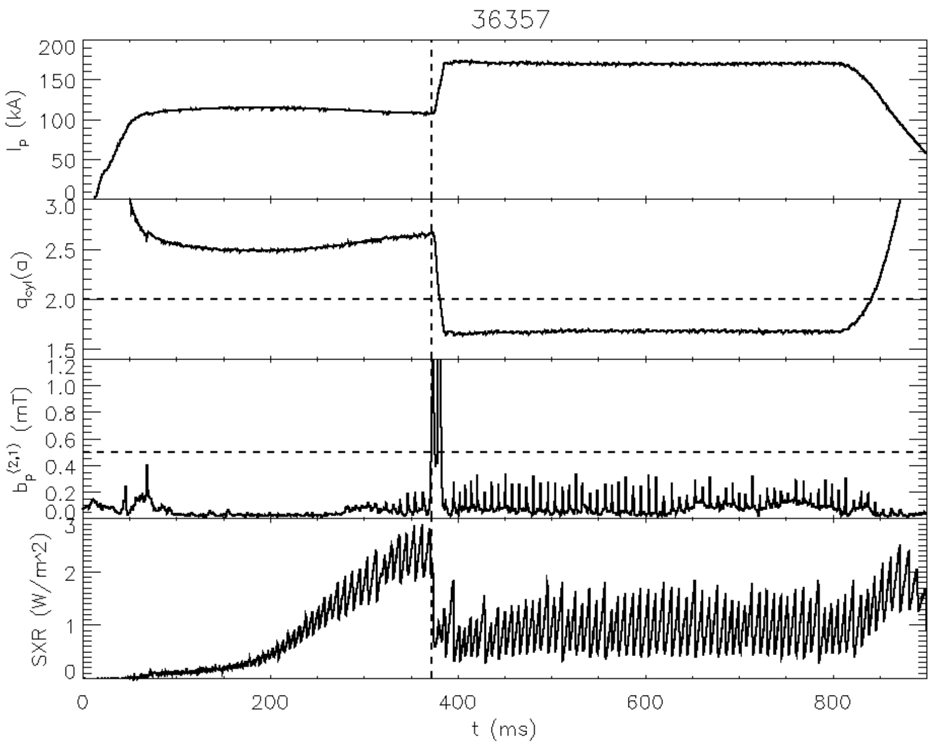
Collaboration with DIII-D wall locking avoidance experiments

Okabayashi, paper EX/P2-42

Zanca et al. *Plasma Phys. Control. Fusion* 54 124018 (2012)

Disruption control by q(a) control

controlled decrease of q(a) to dynamically converting the *(2,1) TM* to a RWM



Successful experiment with 100% rate

Next tests: decrease of q(a) through a shape control

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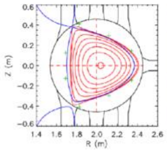
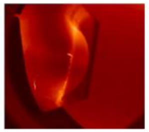
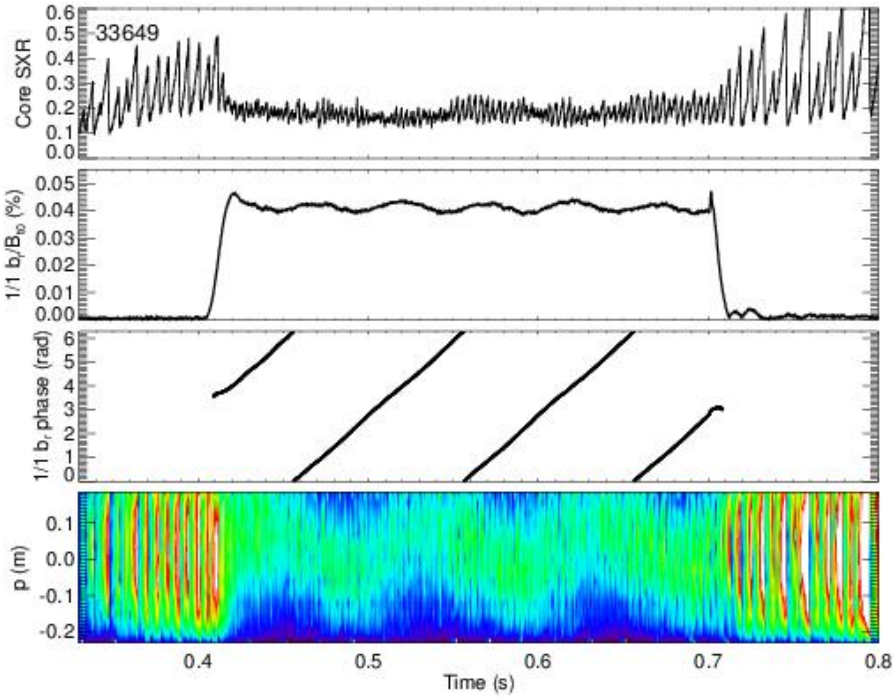
Sawtooth control by MP





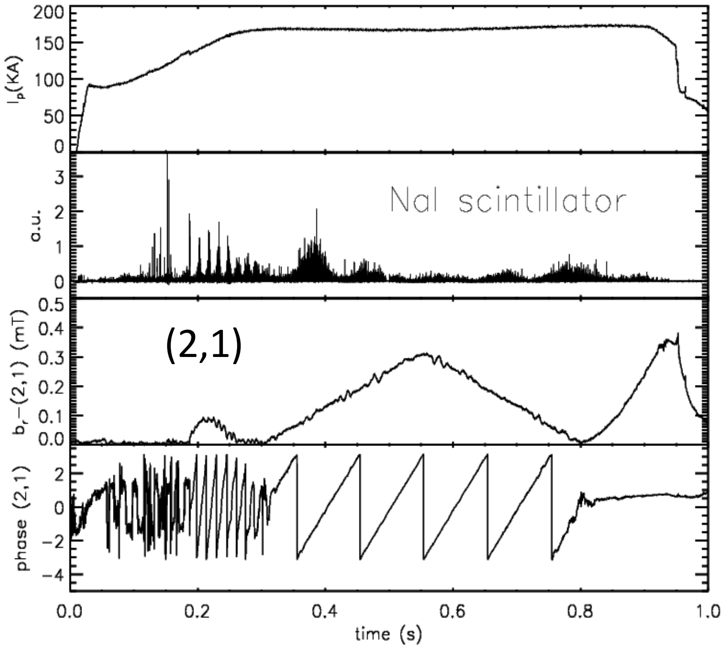
ST mitigation by (1,1) MP



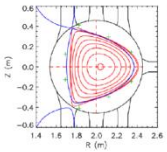
Similar experiments performed in DIII-D

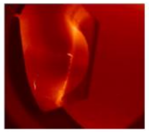
Martin, paper EX/P2-41

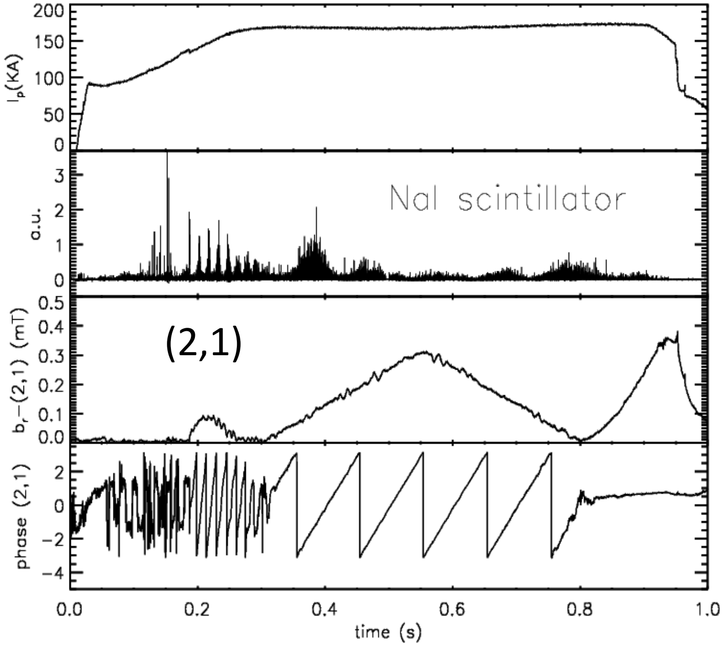
Fast electron mitigation by MP



Fast electron mitigation by MP



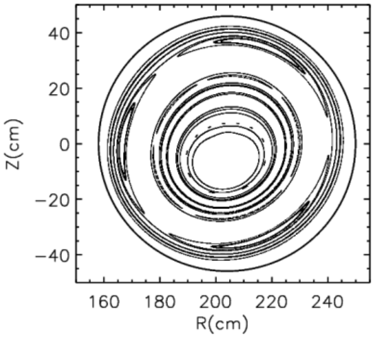




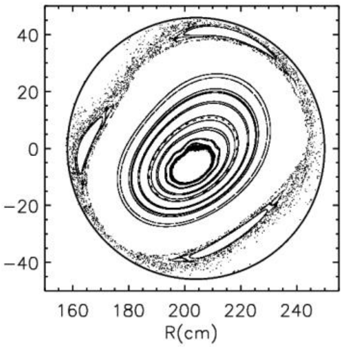
Interpretation by the ORBIT code

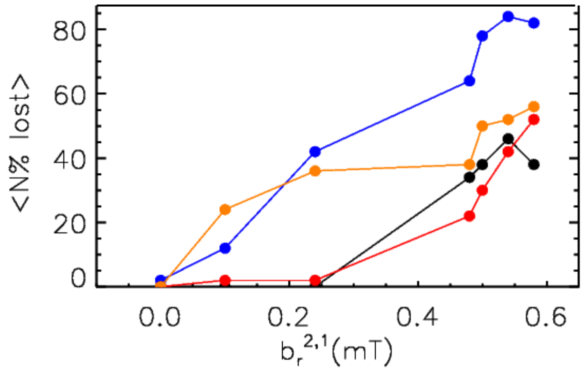
final energy & fraction of lost electrons depend on (2,1) amplitude and q profile

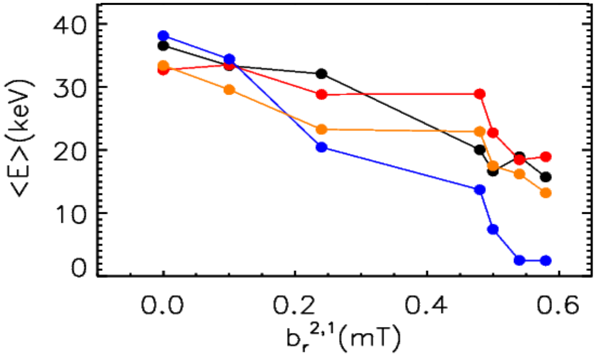
$b_r^{2,1}(a) \approx 0.1mT$



$b_r^{2,1}(a) \approx 0.5mT$







q(a)<2,q(0)<1

q(a)<2,q(0)>1

q(a)>2,q(0)<1

q(a)>2,q(0)>1

Summary

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- **Extending RFP physics studies: 3D non linear MHD modeling** (also in Tokamak and Stellarator), **helical states and ITBs**, with reduced thermal and particle diffusivity χ_e,D ≈ 1m^2/s and **isotope effect on MHD** - τ_E increased by ≈30%

- **Cross-configuration studies: density limit as an edge limit** related to magnetic topology and **effect of MP on turbulence and filaments**

- **Tokamak operation at low q(a): disruption avoidance** through q(a) control, **sawtooth, error field and fast electron control by MPs**

- First **non-circular tokamak equilibria** achieved

Next steps

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- **Improvement of the MHD active control system exploited in both configuration**
  - **conductive shell closer to the plasma**

    to reduce plasma deformation
  - **increase the number of poloidal sensors and coils**

    to enhance the MHD active control capabilities in RFP and tokamak

- **additional heating** (for Tokamak configuration):

  to favour the access to H-mode for ELM control experiments (≈ 100kW)

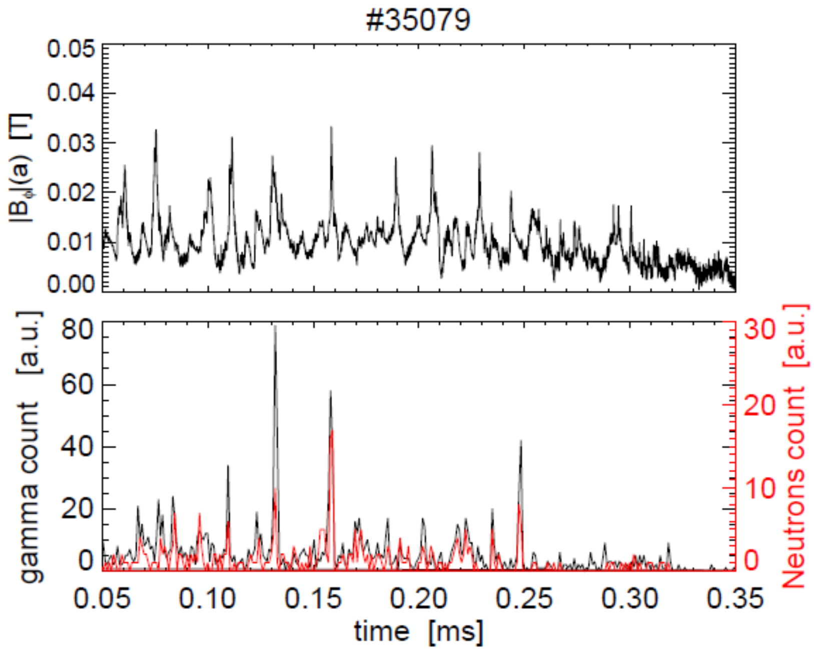
- **reduction of fuel retention** by increasing the wall conditioning techniques effectivness or by a metallic wall

  to open new scenarios with higher density helical states.

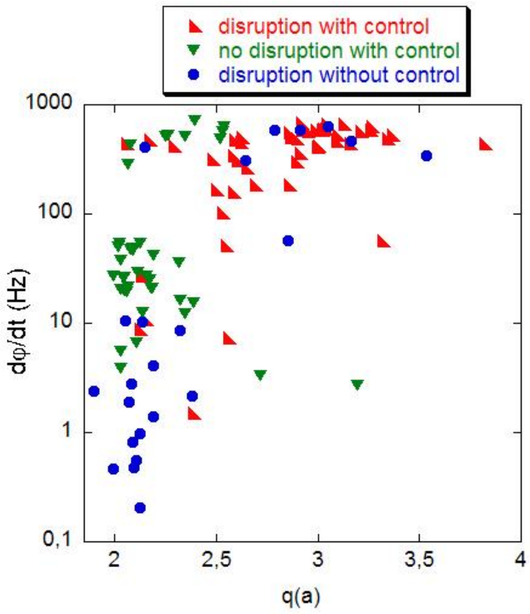
Thank you

Reconnection studies

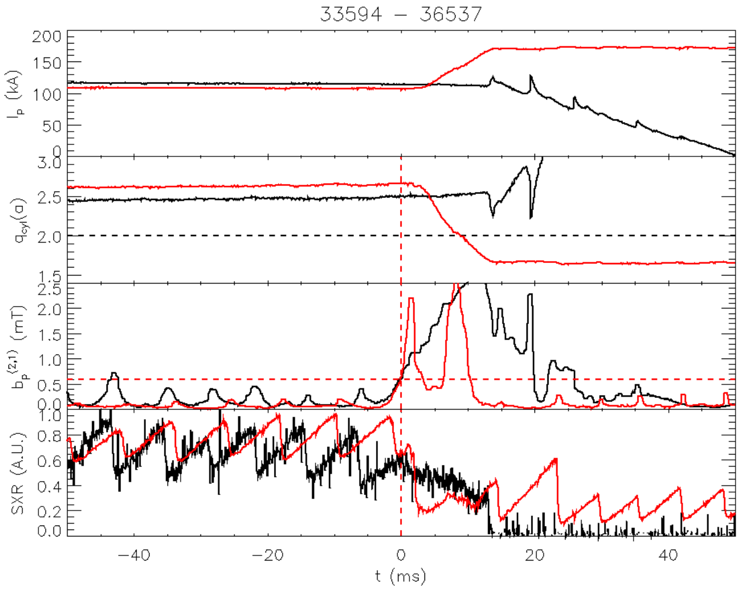
Cyclic impulsive relaxations of the magnetic field profile with generation of toroidal flux and ion heating (next talk by MST)



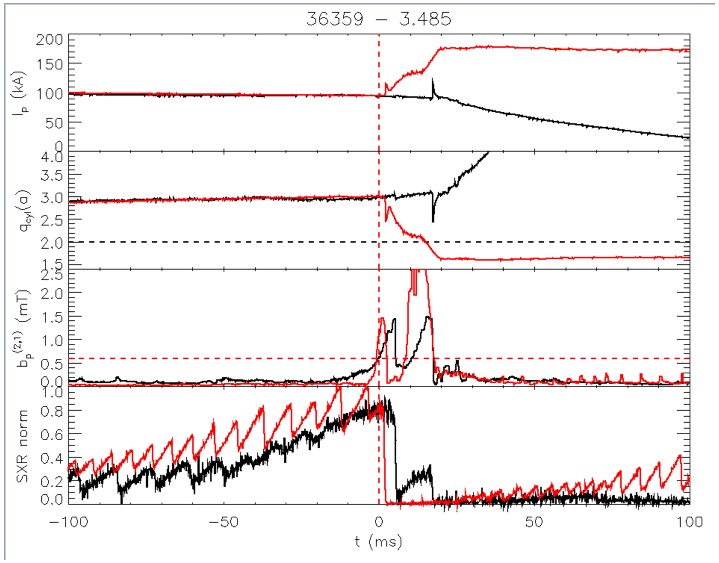
Bursty generation of DD fusion neutrons and γ rays



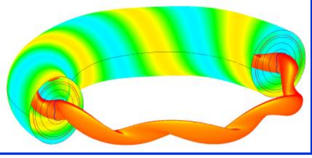
disruption with control
no disruption with control
disruption without control
1000
100
10
1
0,1
dφ/dt (Hz)
2
2,5
3
3,5
4
q(a)



avoidance



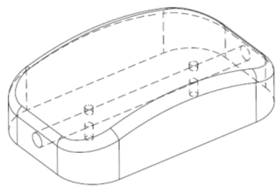
Recovery, q(a)=3



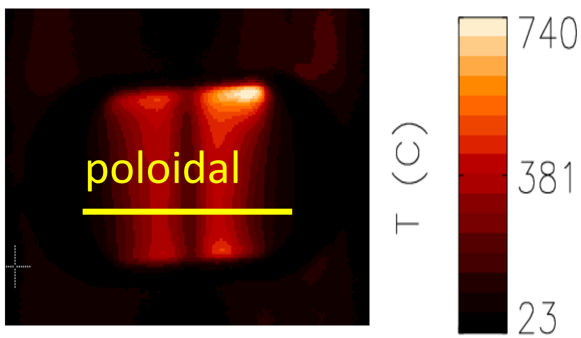
Sample exposure to high power loads

High power loads (tens MW/m²) driven on purpose to pre-determined locations

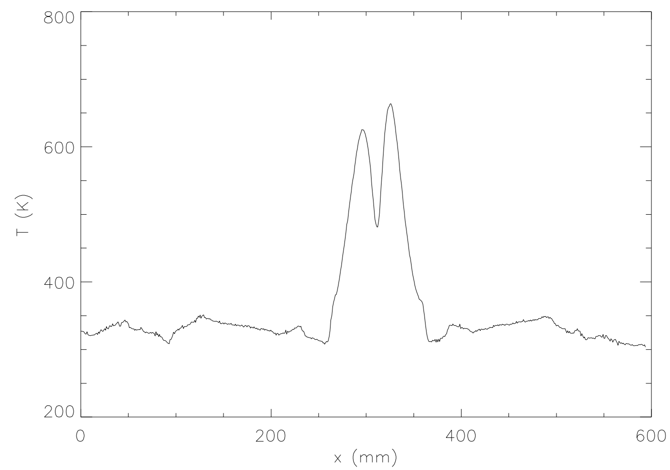
From infra-red camera
(preliminary results)



Samples exposed with 1.2 mm insertion in this example



Temperature profile



Results to be compared with the SOLEDGE-2D code