CONSORZIO RFX
Ricerca Formazione Innovazione

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

M.E. Puiatti for the RFX-mod team

Consorzio RFX, Padova, Italy

The RFX-mod team and collaborators: S. Dal Bello1), L. Marrelli 1), P. Martin 1), P. Agostinetti 1), M. Agostini 1), V. Antoni 1), F. Auriemma 1), M. Barbisan 1), T. Barbui 1), M. Baruzzo 1), M. Battistella 1), F. Belli 2), P. Bettini 1), M. Bigi 1), R. Bilel 1), M. Boldrin 1), T. Bolzonella 1), D. Bonfiglio 1), M. Brombin 1), A. Buffa 1), A. Canton 1), S. Cappello 1), L. Carraro 1), R. Cavazzana 1), D. Cester 3), L. Chacon 4), B. Chapman 5), G. Chitarin 1), G. Ciaccio 1) , W. A. Cooper 6), M. Dalla Palma 1), S. Deambrosis 7), R. Delogu 1), A. De Lorenzi 1), G. De Masi 1), J. Q. Dong 8), D. F. Escande 9), B. Esposito 2), A. Fassina 1), F. Fellin 1), A. Ferro 1), C. Finotti 1), P. Franz 1), L. Frassinetti 10), M. Furno Palumbo 1), E. Gaio 1), F. Ghezzi 11), L. Giudicotti 1), F. Gnesotto 1), M. Gobbin 1), W.A. Gonzales 1), L. Grando 1), S. C. Guo 1), J.D. Hanson 12), S. P. Hirshman 4), P. Innocente 1), J. L. Jackson 13), S. Kiyama 14), M. Komm 15), L. Laguardia 11), S. F. Liu 16), Y. Q. Liu 17), R. Lorenzini 1), T. C. Luce 13), A. Luchetta 1), A. Maistrello 1), G. Manduchi 1), D. K. Mansfield 18), G. Marchiori 1), N. Marconato 1), D. Marocco 2), D. Marcuzzi 1), S. Martini 1), G. Matsunaga 19), E. Martines 1), G. Mazzitelli 2), E. Miorin 5), B. Momo 1), M. Moresco 1), M. Okabayashi 18), E. Olofsson 10), R. Paccagnella 1), N. Patel 1), M. Pavei 1), S. Peruzzo 1), N. Pilan 1), L. Pigatto 1), R. Piovan 1), P. Piovesan 1), C. Piron1), L. Piron 1), I. Predebon 1), C. Rea 1) 3), M. Recchia 1), V. Rigato 1), A. Rizzolo 1), A.L. Roquemore 18), G. Rostagni 1), C Ruset 20), A. Ruzzon 1), L. Sajò-Bohus 21), H. Sakakita 14), R. Sanchez 4) 22), J. S. Sarff 5), E. Sartori 1),F. Sattin 1), A. Scaggion 1), P. Scarin 1), O. Schmitz 23), P. Sonato 1), E. Spada 1), S. Spagnolo 1), M. Spolaore 1), D. A. Spong 4), G. Spizzo 1), L. Stevanato 2), M. Takechi 19), C. Taliercio 1), D. Terranova 1), G.L. Trevisan 1), G. Urso 24), M. Valente 1), M. Valisa 1), M. Veranda 1), N. Vianello 1), G. Viesti 3), F. Villone 25), P. Vincenzi 1), N. Visona' 1), Z.R. Wang 18), R. B. White 18), P. Xanthopoulos 26) , X. Y. Xu 1), V. Yanovskiy 1), A. Zamengo 1), P. Zanca 1), B. Zaniol 1), L. Zanotto 1), E. Zilli 1), M. Zuin 1)

RFX-mod is a flexible device

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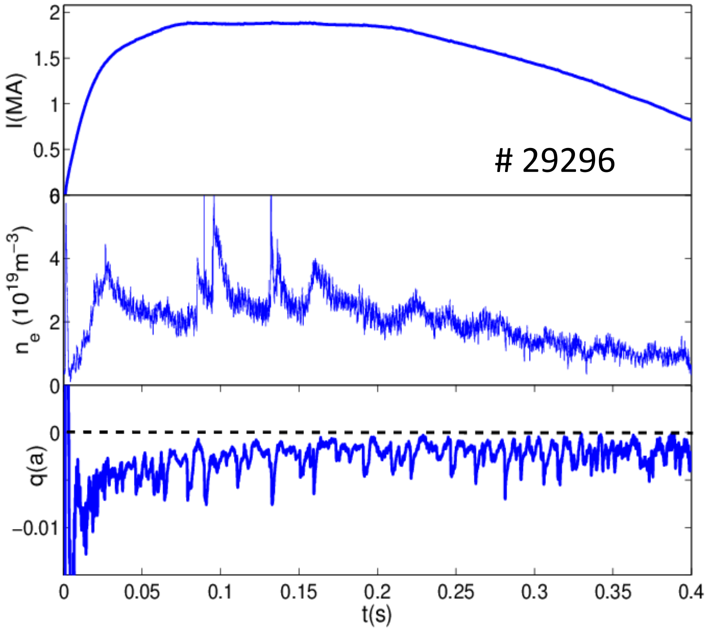
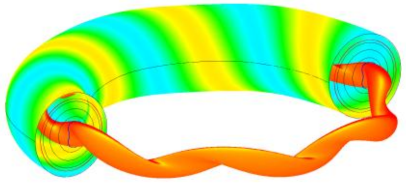
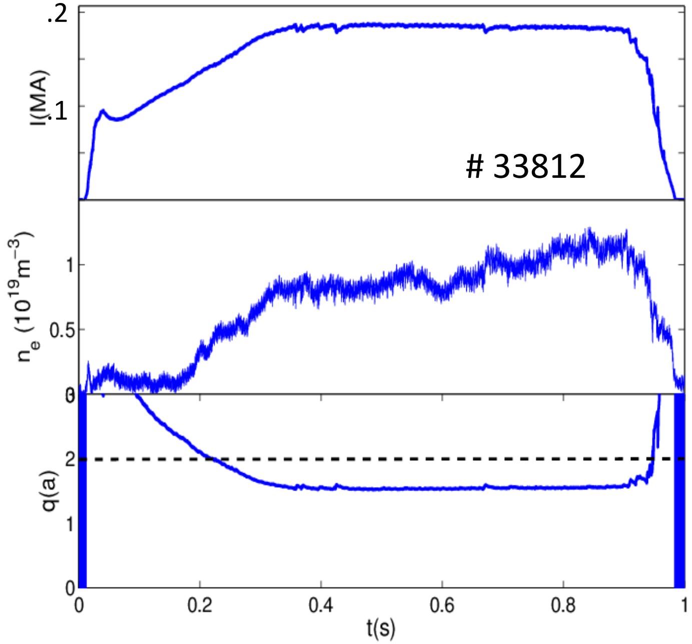
High current Reversed Field Pinch



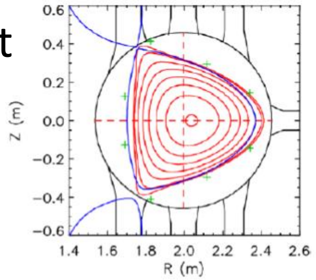


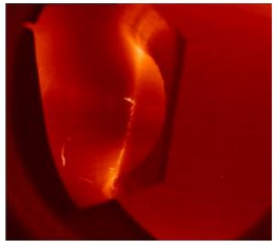
Quasi-single helicity states

Low current Tokamak



Ohmic circular, but first double-null equilibria recently produced





A cross-configuration view of open issues

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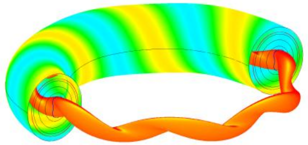
RFX-mod RFP:



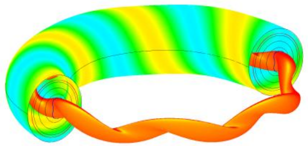
high current RFP physics

…not only for RFP confinement but also for general fusion topics

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

A cross-configuration view of open issues

RFX-mod RFP:



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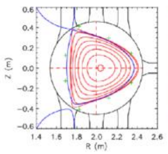
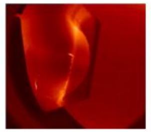
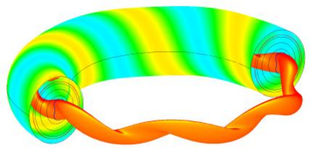
RFX-mod Tokamak:



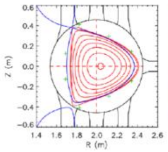


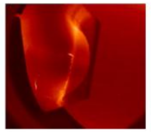
unexplored parameter regions

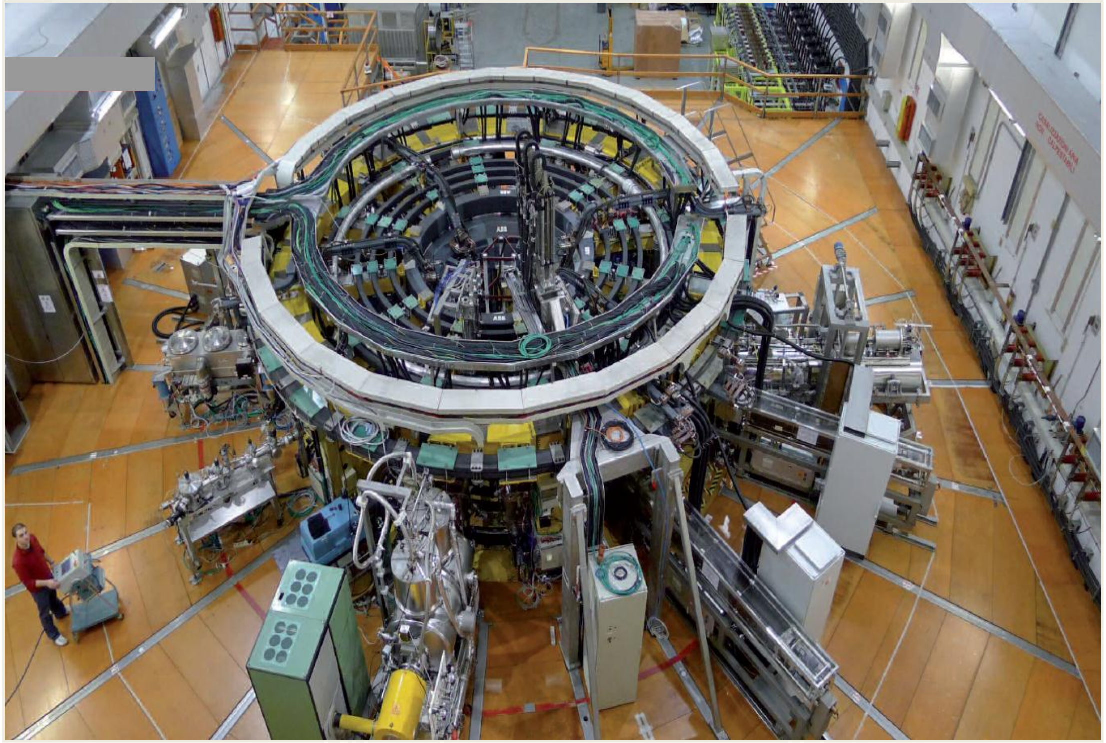
- robust q(a) < 2 operation
- advanced MHD instability control alghoritms
- disruption control
- effect of MP on turbulence
- sawtooth and runaway electrons control via MP



The RFX-mod device







a=0.459 m , R=2 m

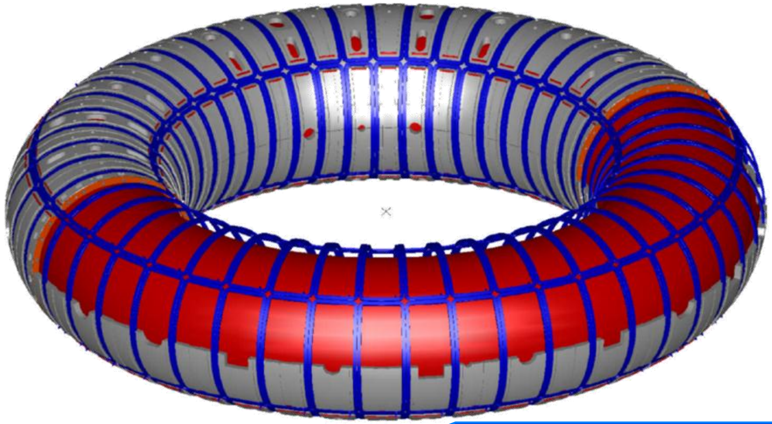
Ip ≤ 2 MA RFP, 0.2 MA Tokamak

B_t=0.7 T

Te, Ti ≤1.5keV

ne ≤10^{20} m^{-3}

ohmic, no divertor



Advanced MHD stability control system

→ 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
- Magnetic Perturbatiion to control sawteeth and fast electrons
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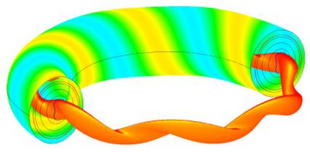
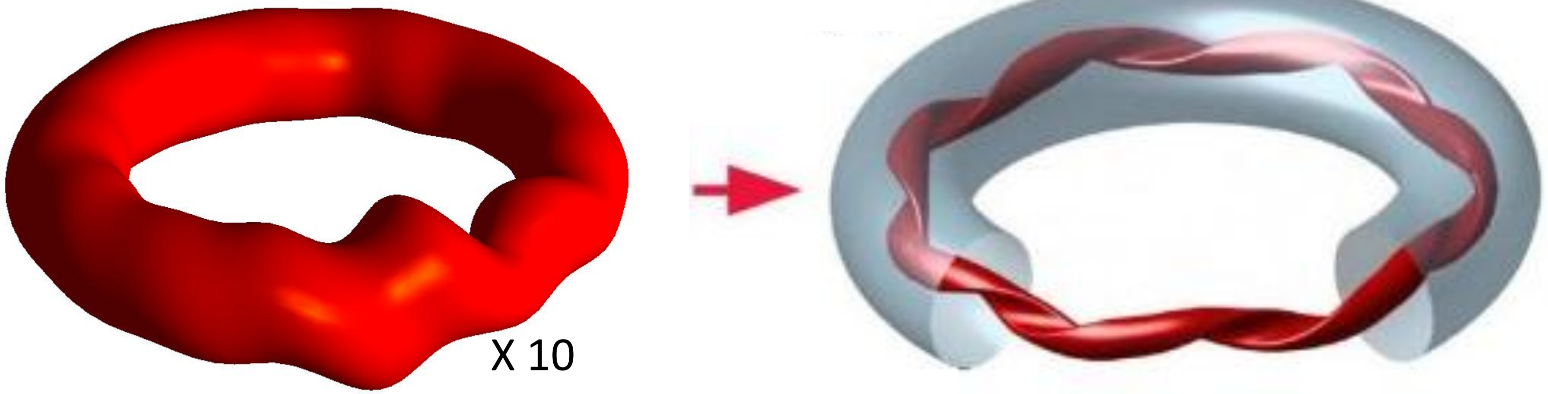
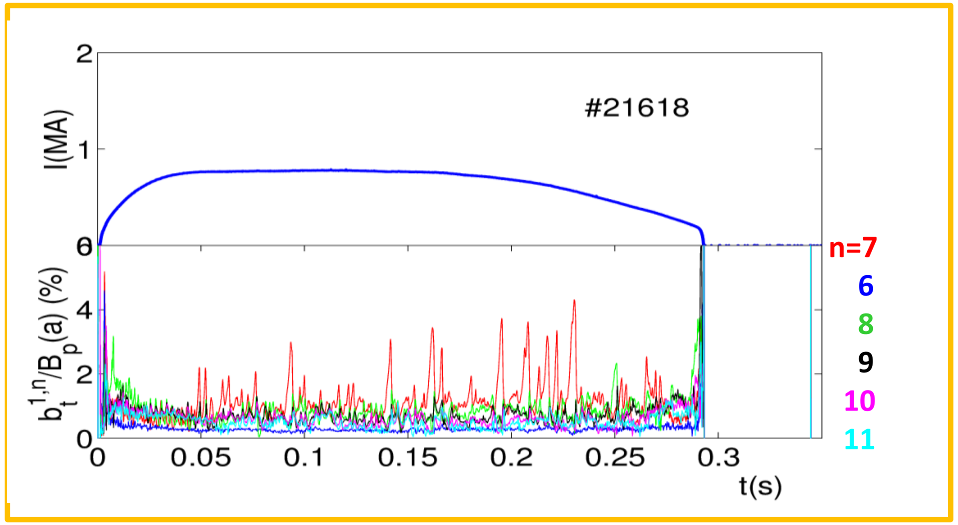


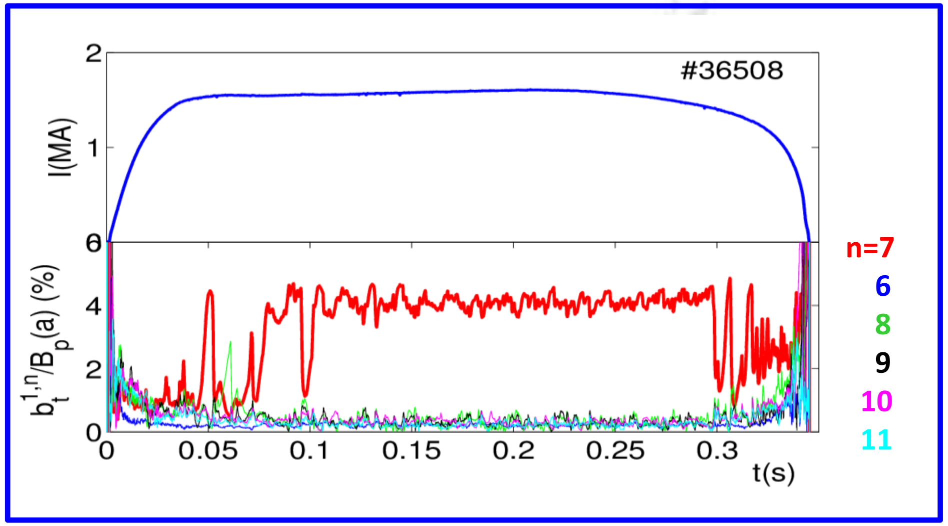
In RFP, helical states are the result of a self-organization process

Low CURRENT

High CURRENT

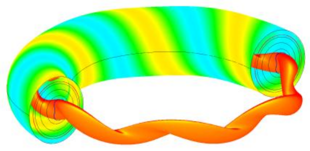






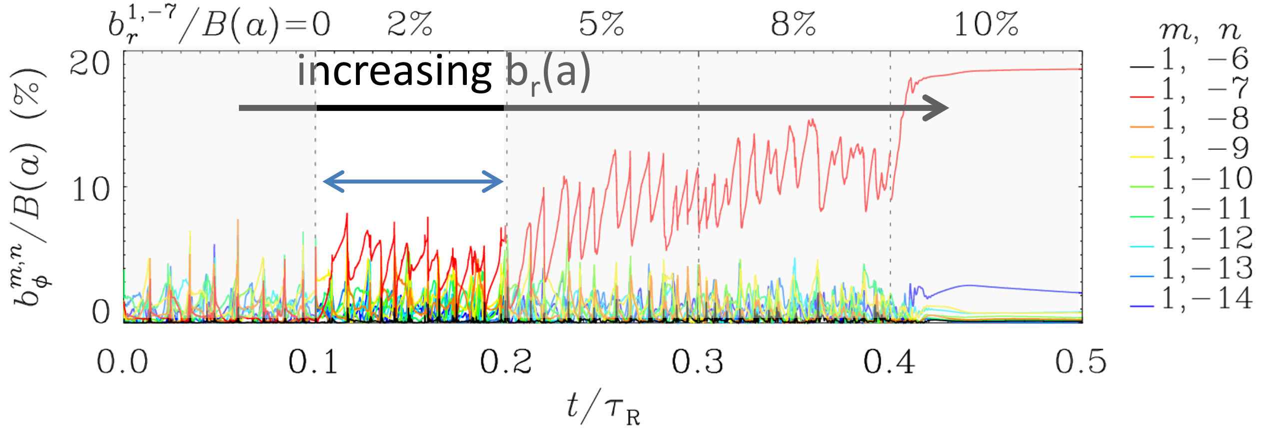
Bifurcation of RFP equilibria predicted by 3D MHD modeling before the experimental observation

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



QSH dynamical behavior in 3D nonlinear MHD modeling

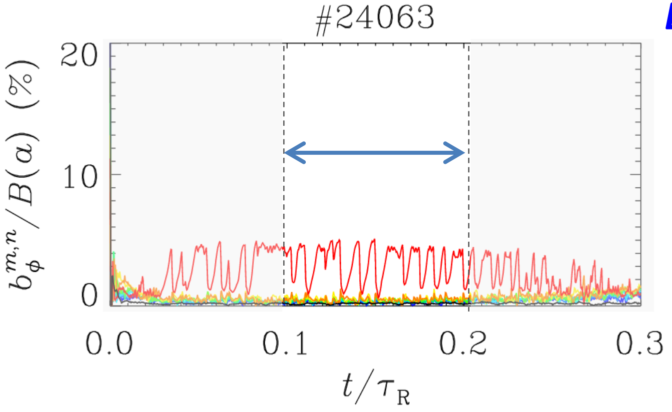
Helical boundary conditions a key feature to favor steady helical states



SPECYL-PIXIE3D benchmarked codes PoP 2010

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

Experiment (RFX-mod)



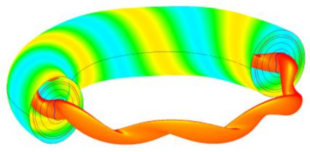
Transition to QSH ruled also by resistivity and/or viscosity (Hartman dimensionless number)

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)



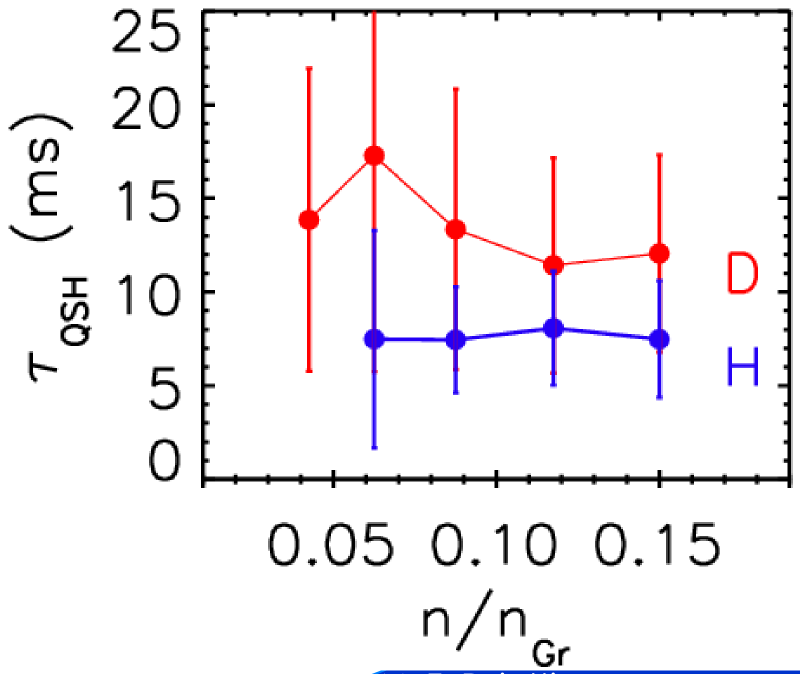
The isotope effect

Deuterium as filling gas improves plasma performance

Deuterium plasmas more resilient to reconnection events

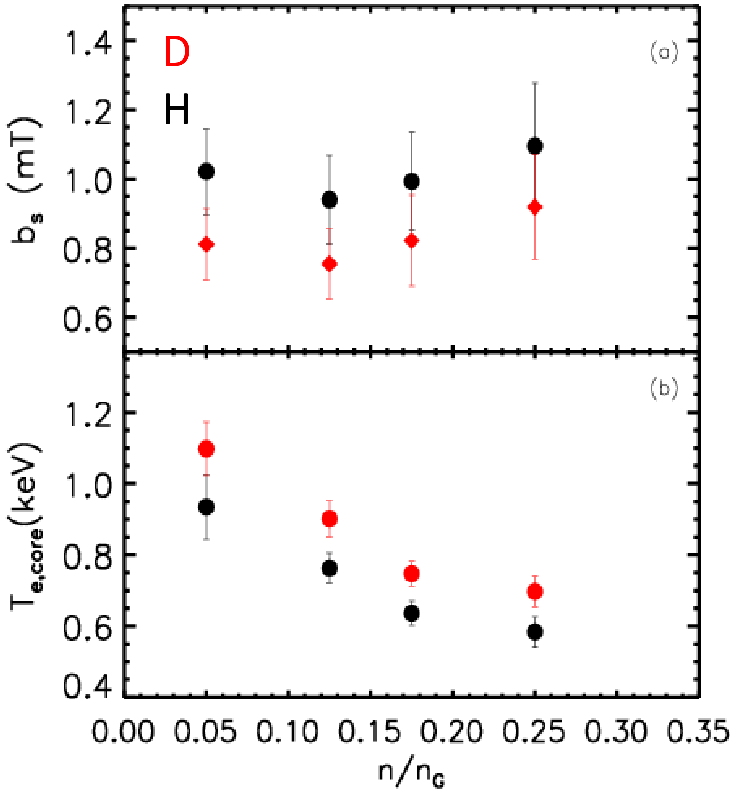
- QSH crashes less frequent

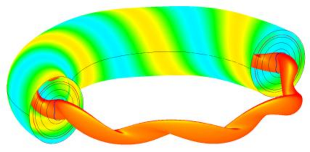
Average QSH duration



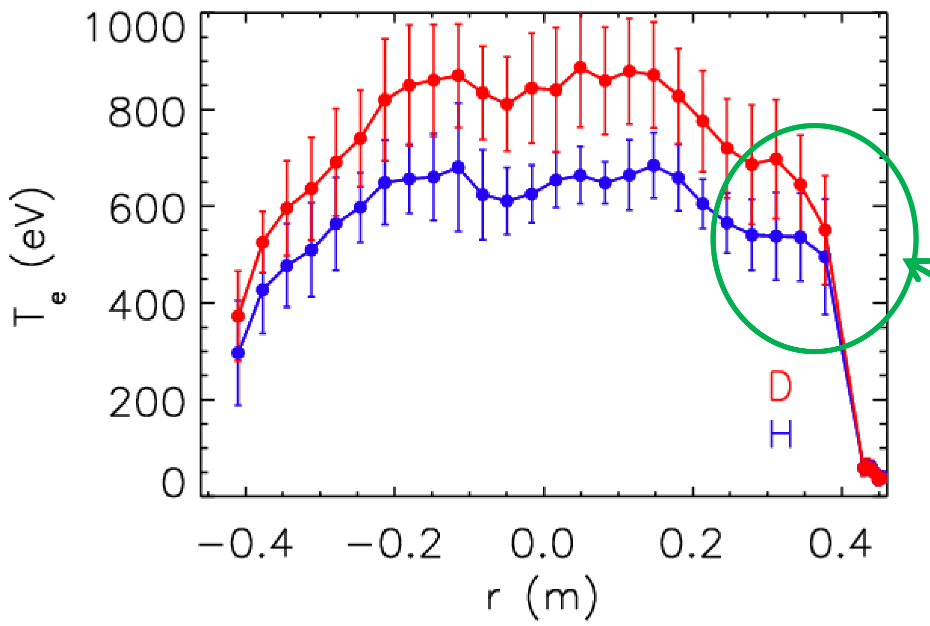
Impact of majority ion mass on MHD

- lower secondary modes
- higher Te

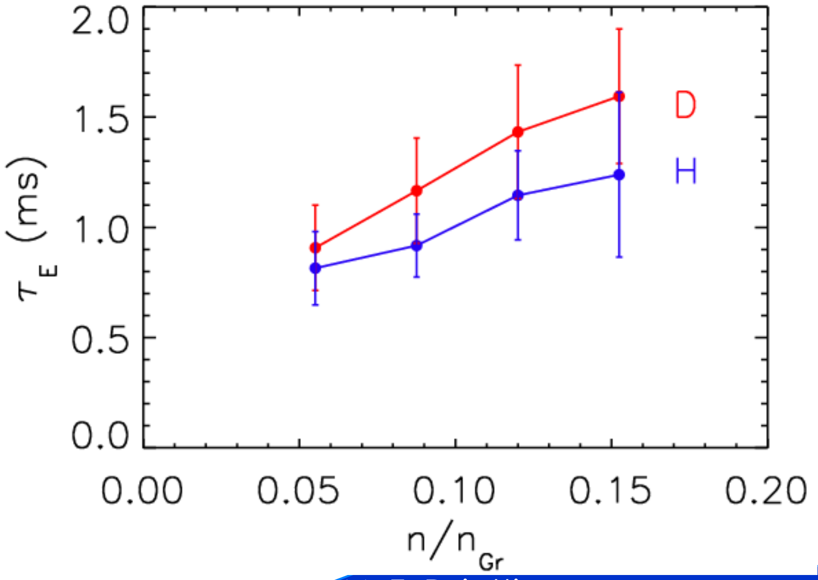




Confinement improvement in D



Higher temperature pedestal : isotope effect on edge transport



$\tau_E \approx M_i^{0.3}$

Lorenzini, paper EX/P1-41

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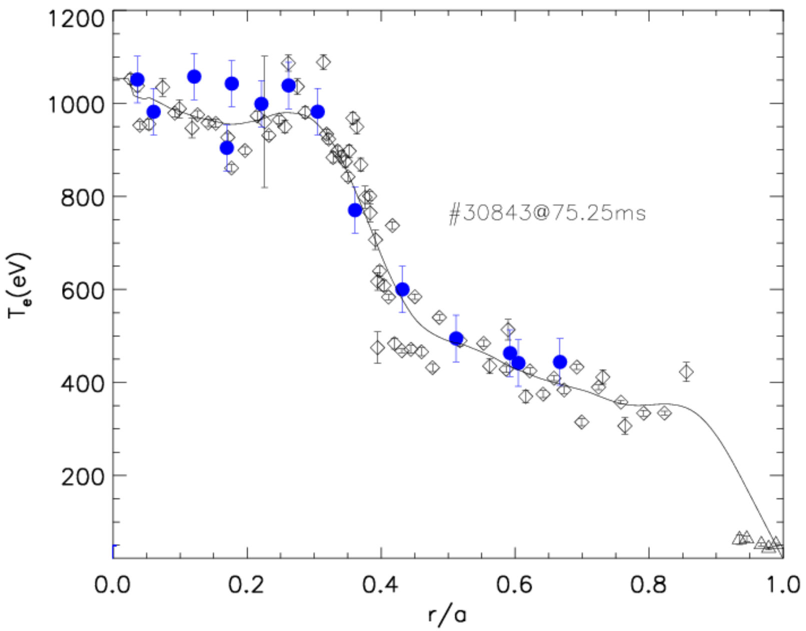
QSH states with the island axis collapsed on the magnetic axis

Temperature profile



- strong Te gradients

QSH states with the island axis collapsed on the magnetic axis

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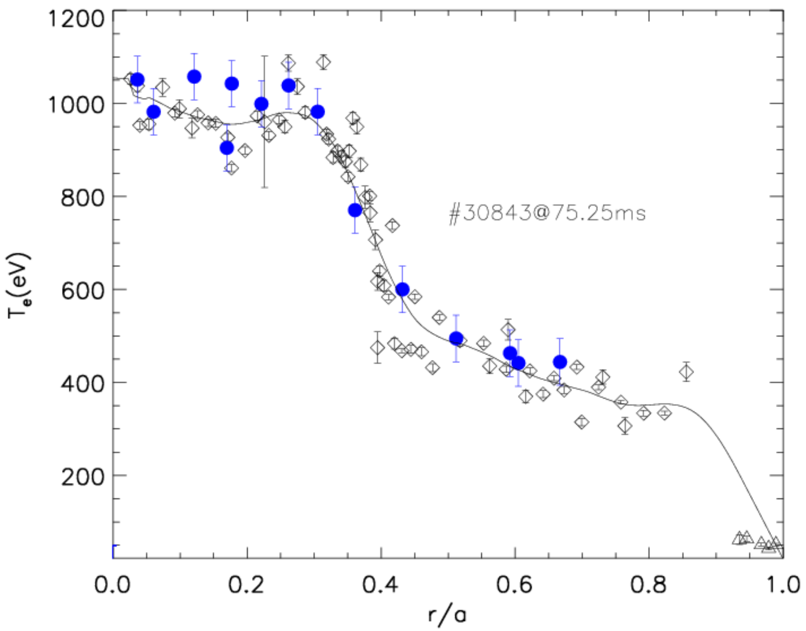

- strong Te gradients
- reduced thermal and particle transport:

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

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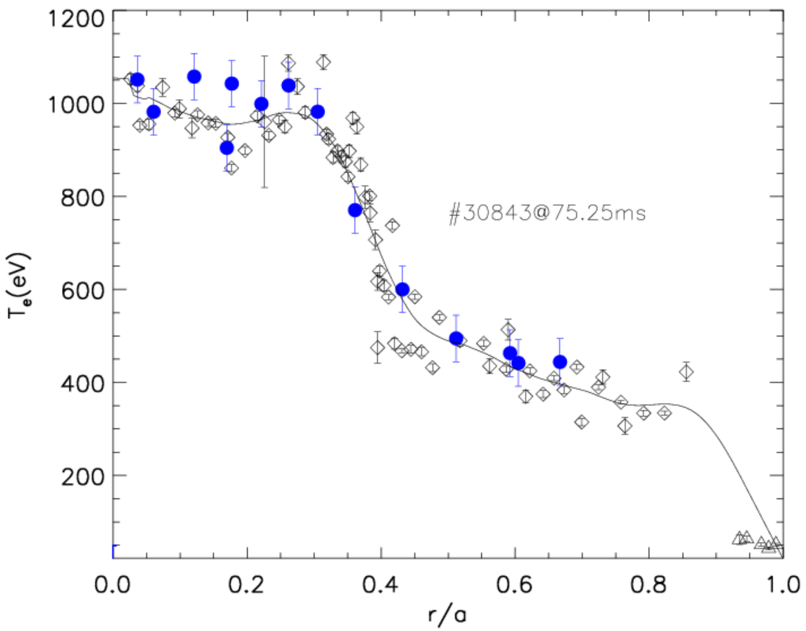
Temperature profile



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

- impurities not penetrating the barrier

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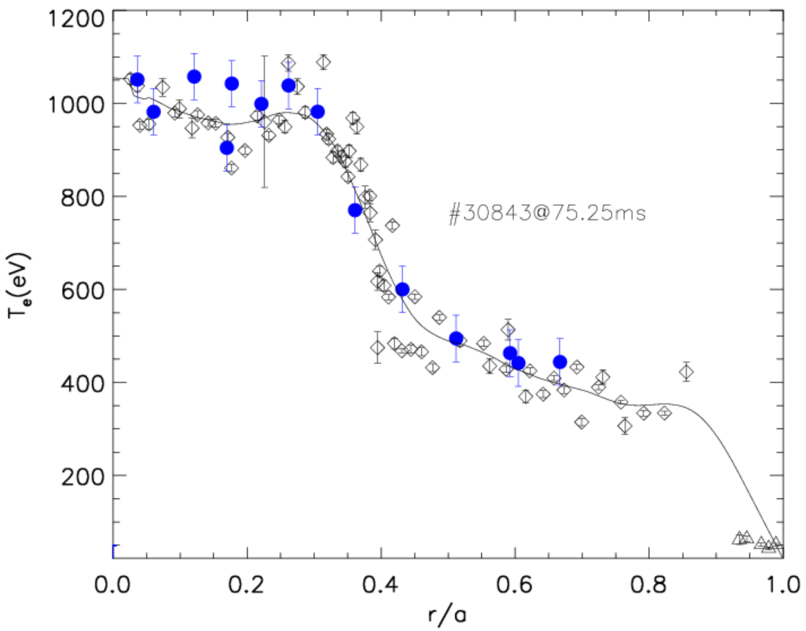

- strong Te gradients
- reduced thermal and particle transport:

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

- impurities not penetrating the barrier
- residual stochasticity and microtearing and g-driven modes main contributors to transport at the barrier

M. Gobbin et al., PPCF 55 105010 (2013), Auriemma et al., submitted to NF
I.Predebon, F.Sattin PoP 20, 040701 (2013) , M. Zuin et al., PRL 110, 055002 (2013)

- Self-organized helical states in RFP and the isotope effect
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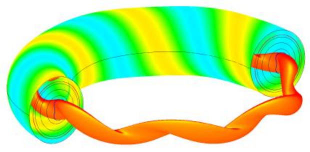
Blobs drive edge transport

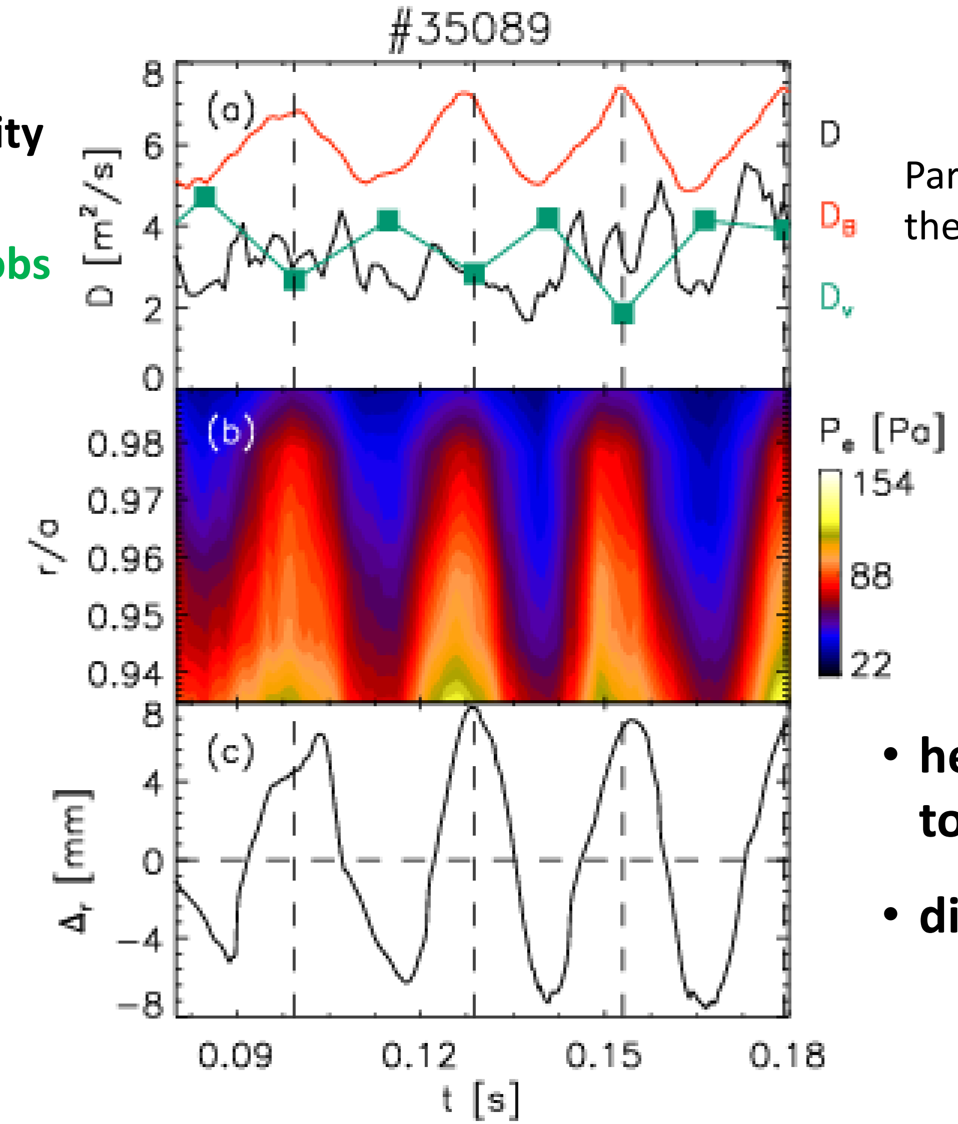


Total diffusivity

Diffusivity related to blobs

Bohm

Pressure (THB)



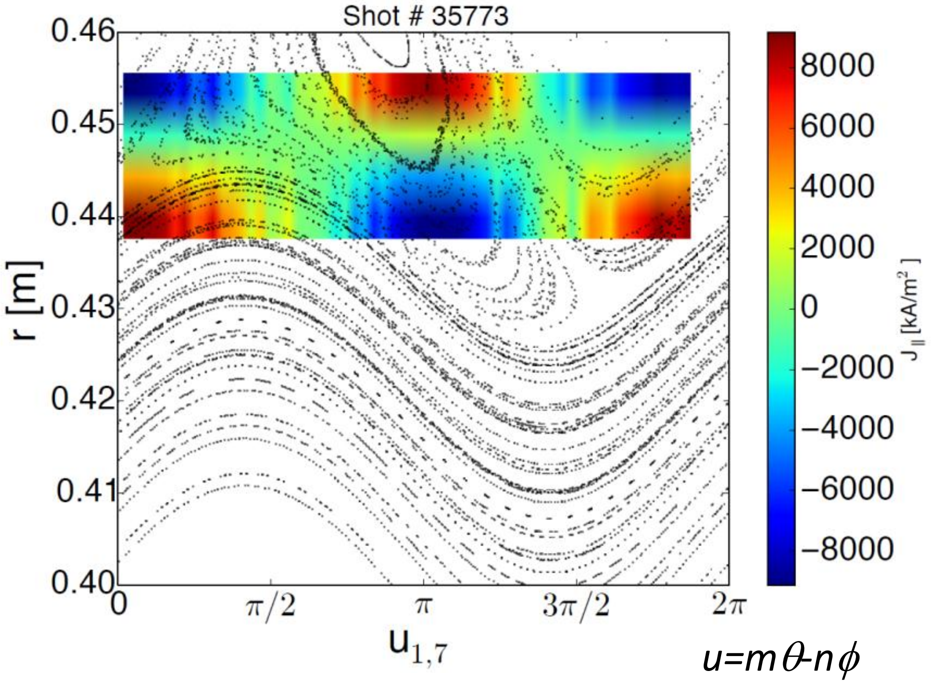
Particle influx (assuming Γin=Γout) + thermal helium beam & GPI diagnostics

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

Magnetic Perturbation applied in RFP and tokamak configuration

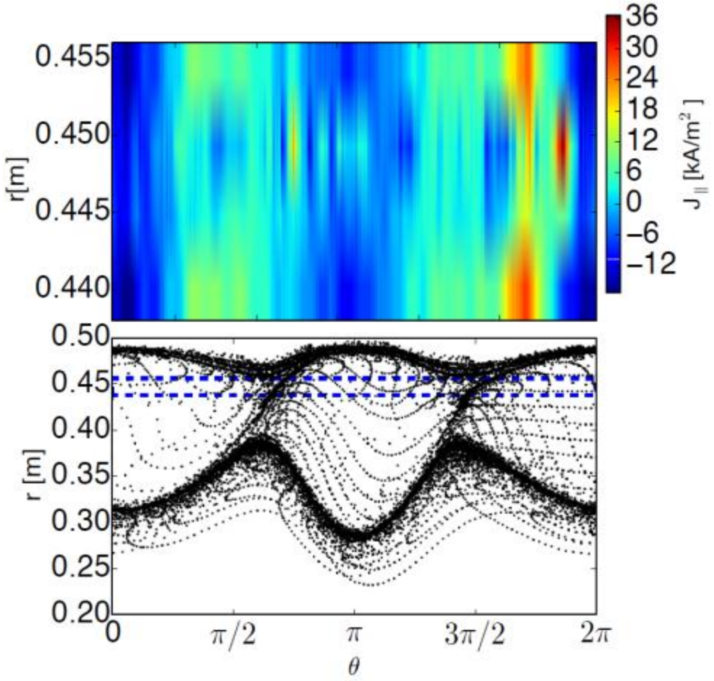
$J_{||}$ and flow modulated according to external perturbation

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



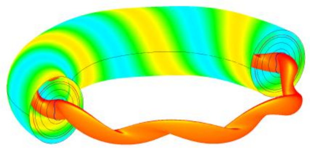
$u=m\theta-n\phi$

Tokamak: *RMP (2,1)*

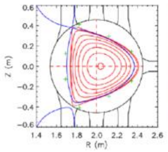


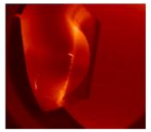
- number of blobs and particle & thermal fluxes also modulated by MP
- tight relation between blobs and transport
- **MP as a means to control filaments and related transport**

Spolaore, paper EX/P1-40



High density limit is related to edge MHD

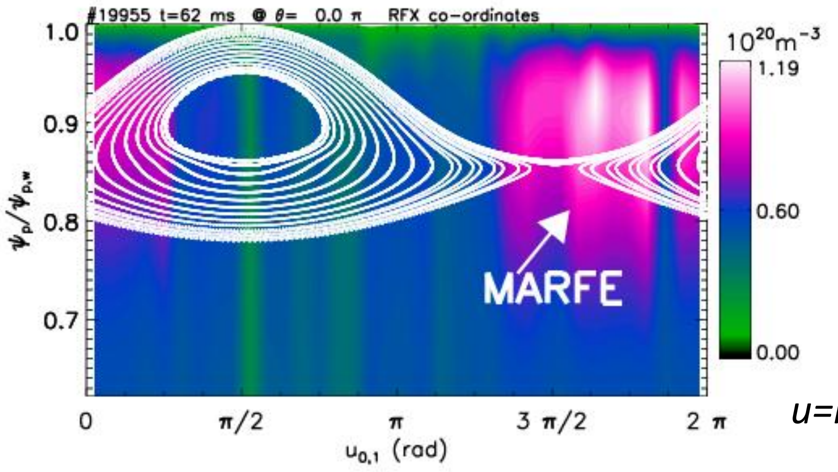




High density limit follows **Greenwald scaling of the edge density** $n_e \approx 0.35\ n_G$.

Same scaling found in FTU tokamak.

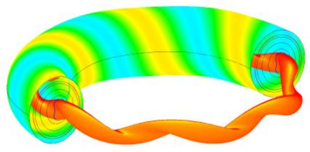
Above such density a poloidal MARFE-like structure develops



$u = m\theta - n\phi$

RFP:

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



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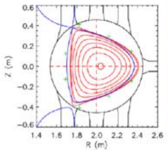

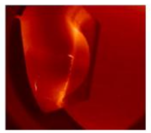

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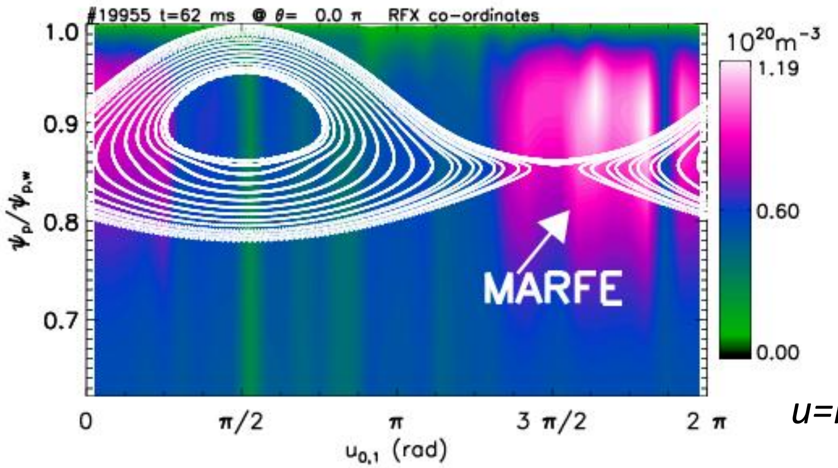
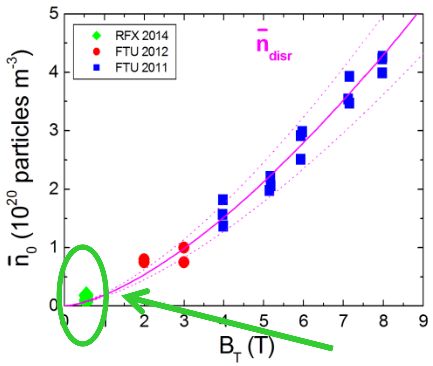


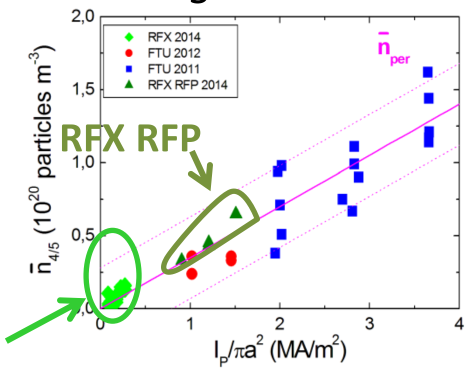
u=mθ-nϕ

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

core



edge



RFX Tokamak

Tokamak:
RFX scalings compared with FTU

Spizzo & Pucella, paper EX/P1-42

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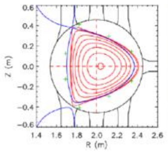
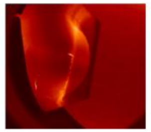
RFX tokamak : *(2,1)* mode control in disruptive conditions

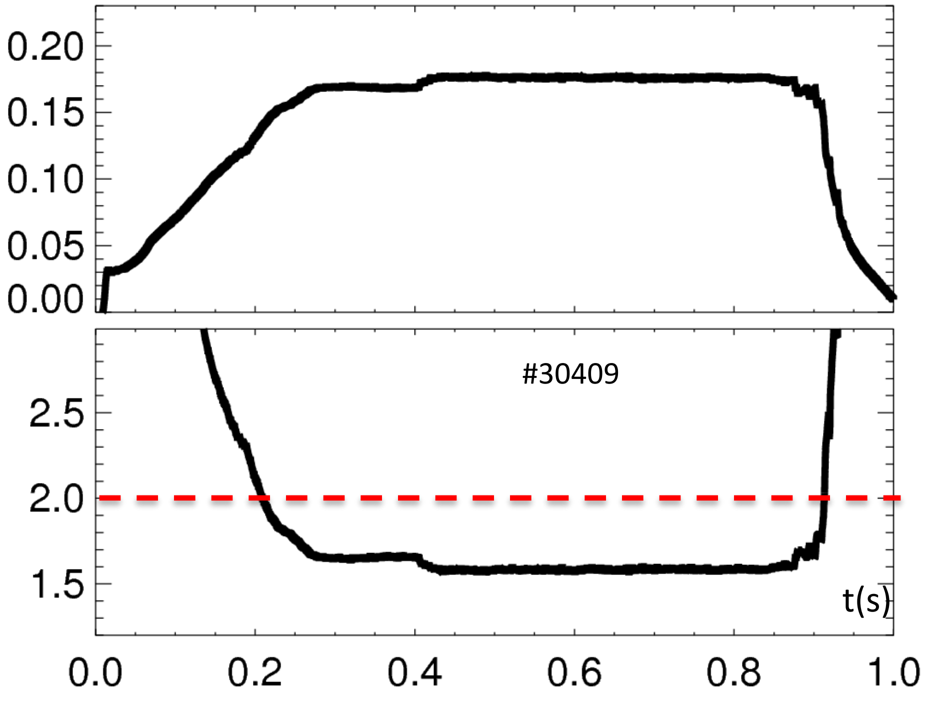




Feedback control avoids disruptions at q(a) < 2.5 below the Greenwald density

***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

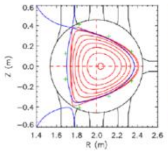
***q*(a)>2.5:** disruption occurs even if the mode is not locked

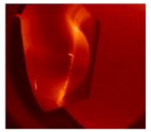
Collaboration with DIII-D wall locking avoidance experiments and q_{95}<2

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

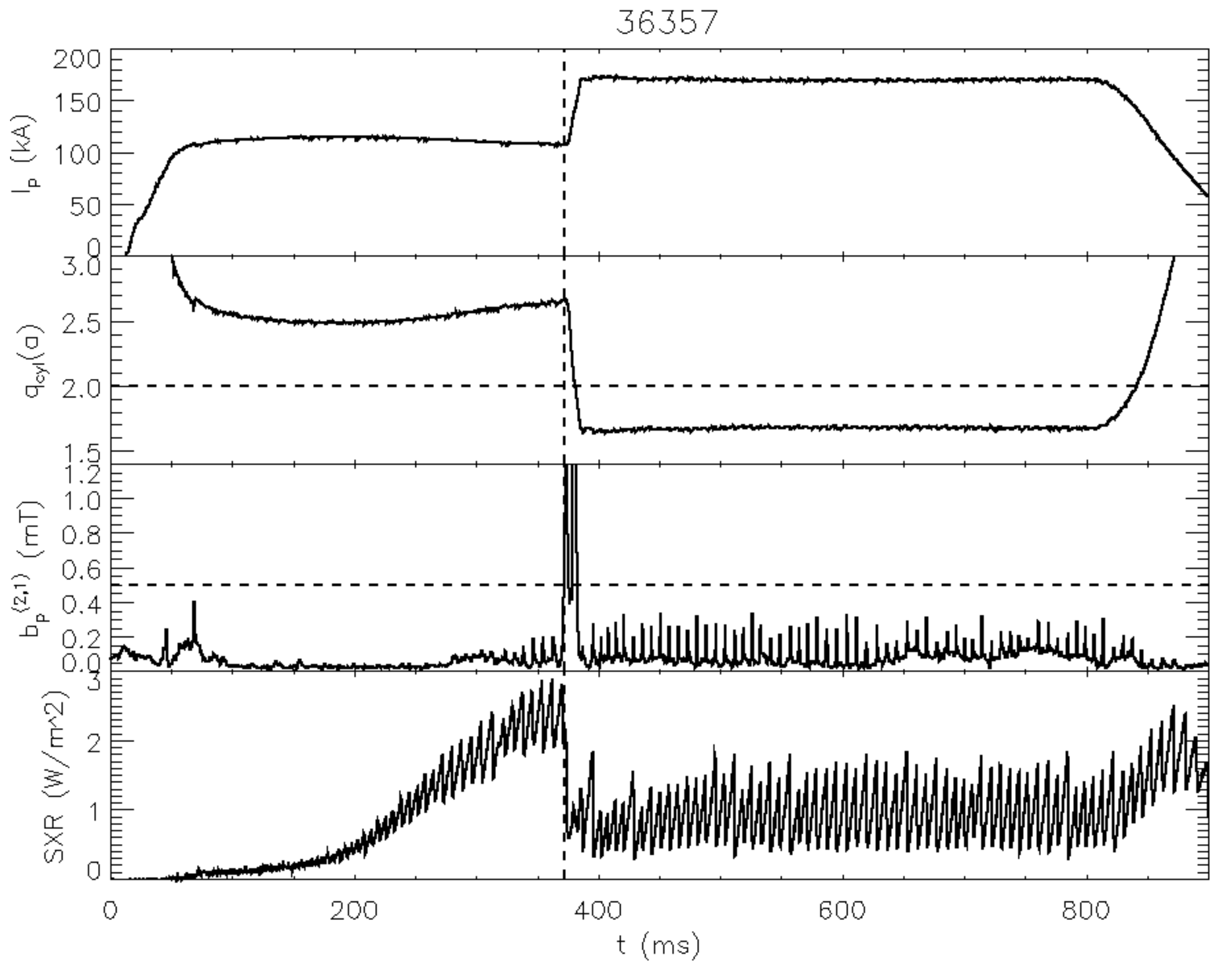
Okabayashi, paper EX/P2-42

Disruption control by q(a) control





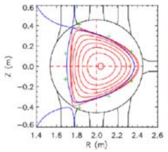
controlled decrease of q(a)→ to dynamically converting the *(2,1) TM* to a RWM, which is controlled

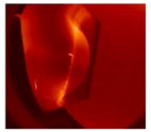


Successful experiment with 100% rate

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

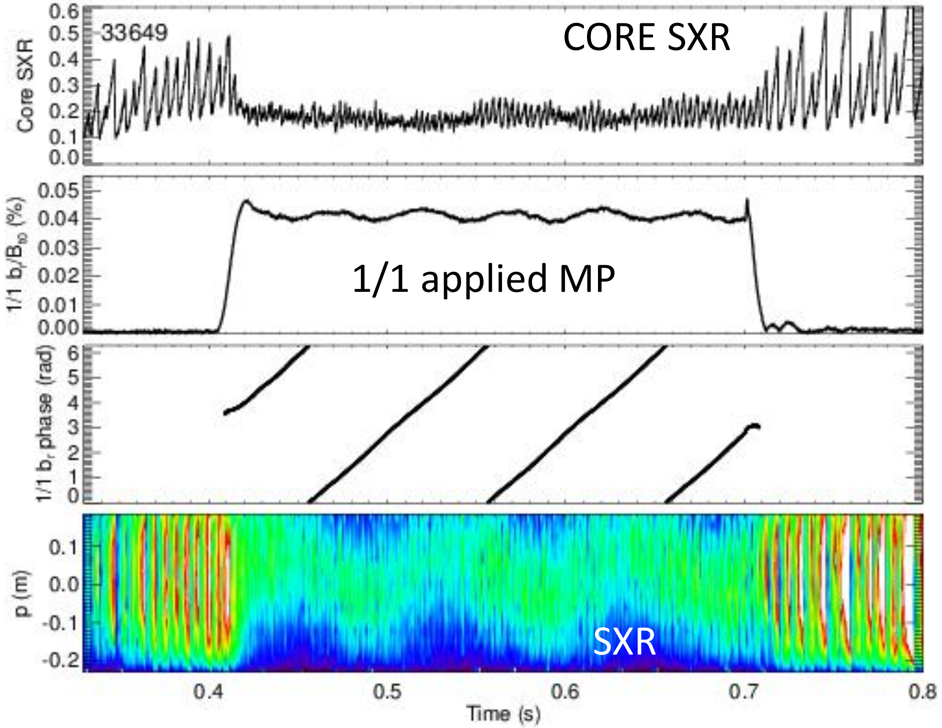
- Self-organized helical states in RFP and the isotope effect
- Edge properties in RFP and Tokamak
- Low-*q* operational scenarios in Tokamak
- **Magnetic Perturbation to control sawteeth and fast electrons**
- Summary and perspectives



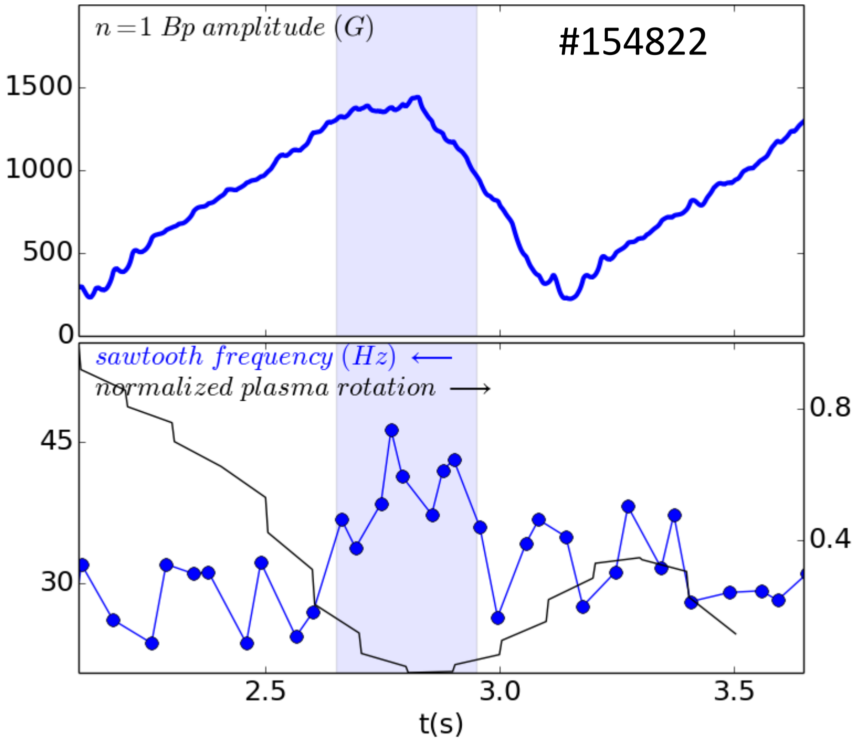


CONSORZIO RFX
Ricerca Formazione Innovazione

ST mitigation by (1,1) MP in RFX



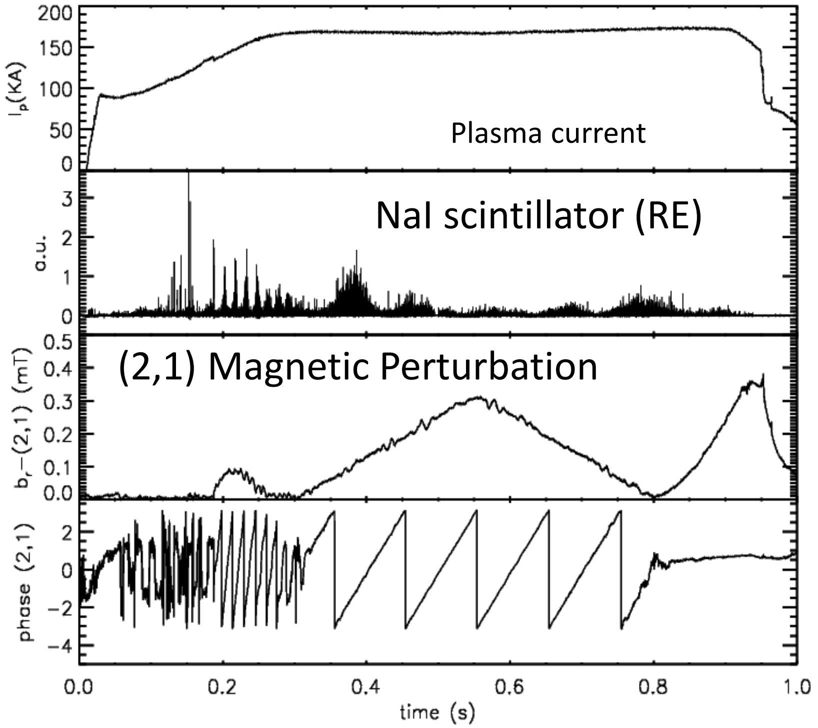
Similar experiments performed in DIII-D



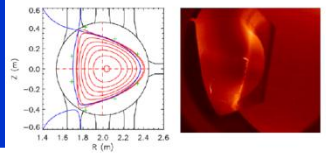
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

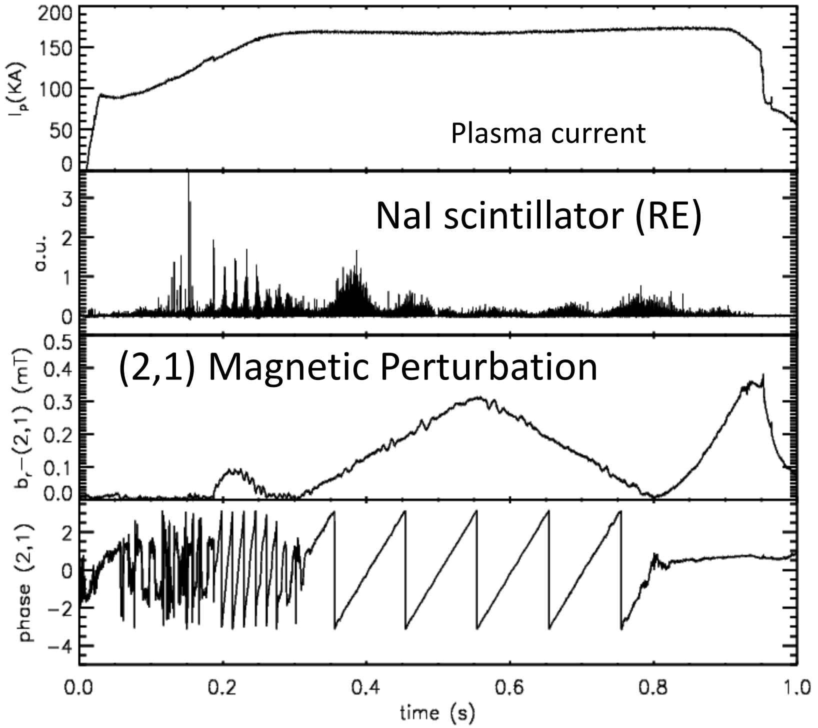
Martin, paper EX/P2-41

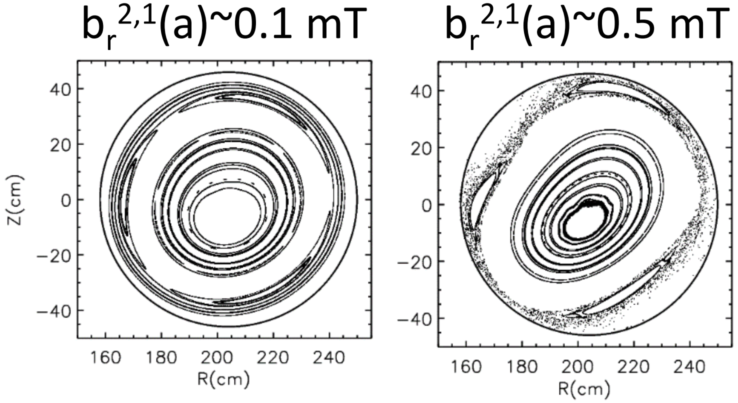
Runaway electrons mitigation by MP



Runaway electrons mitigation by MP

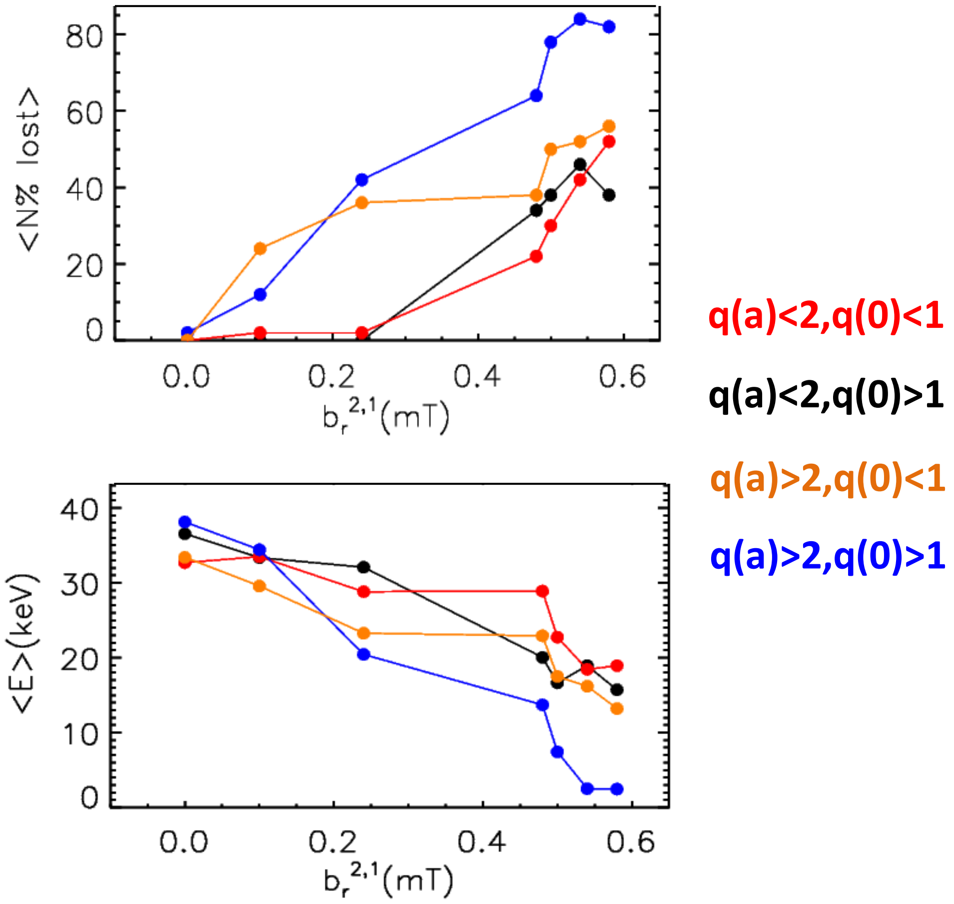






Interpretation with the ORBIT code

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



Summary: performance and cross-fertilization

Progress in RFP physics and performance

3D non linear MHD modeling (also in Tokamak and Stellarator),

helical states and ITBs, reduced thermal and particle diffusivity χ_e, $D \approx 1\text{m}^2/\text{s}$

isotope effect on MHD - τ_E increased by ≈30%

Multi-configuration studies

RFP/TOK: Density limit as an edge limit related to magnetic topology

RFP/TOK: Effect of MP on turbulence and filaments

RFP/STELL/TOK: 3D magnetic equilibria (VMEC, V3FIT,..)

Tokamak operation at low *q*(a)

disruption avoidance through *q*(a) control

sawtooth, error field and runaway electron control by MPs

first **non-circular tokamak equilibria** achieved

PWI and material studies

High power loads (tens MW/m^2) driven on purpose to pre-determined locations

Next steps: innovation built on solid background

RFX has reviewed its scope/program to:

- Continue exploring RFP confinement *(tradition)*
- Help addressing some of the tokamak and stellarator challenges *(innovation)*

Upgrade of the MHD active control system to be exploited in RFP and TOKAMAK

- conductive shell closer to the plasma to optimize PWI
- More poloidal sensors and coils to stregthen the excellence in MHD feedback real time control

Additional heating for Tokamak configuration

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

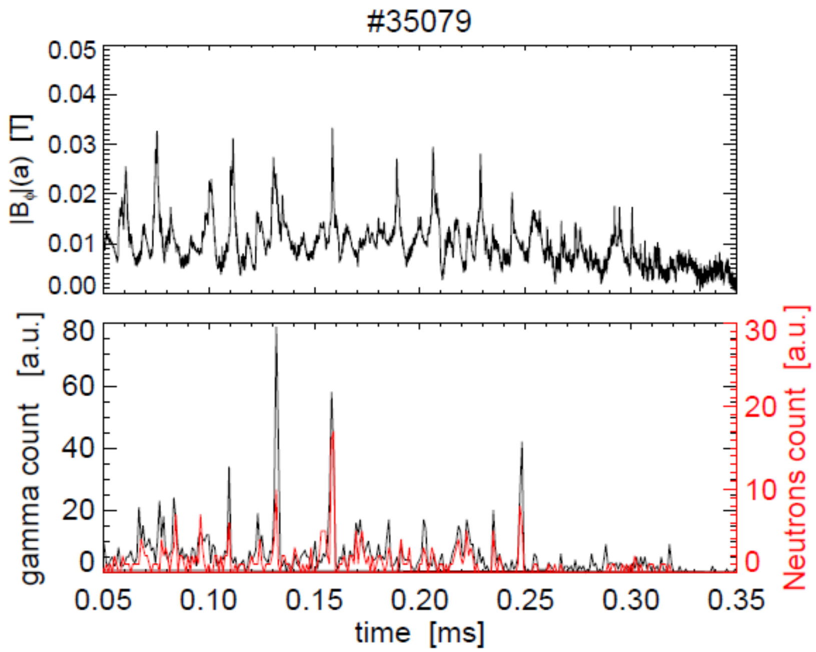
First wall upgrade

- To reduce fuel retention with wall conditioning optimization or new metallic wall
- Test of fusion materials under high power loads (transient up to 100 MW/m^2 , concentrated on pre-determined locations)

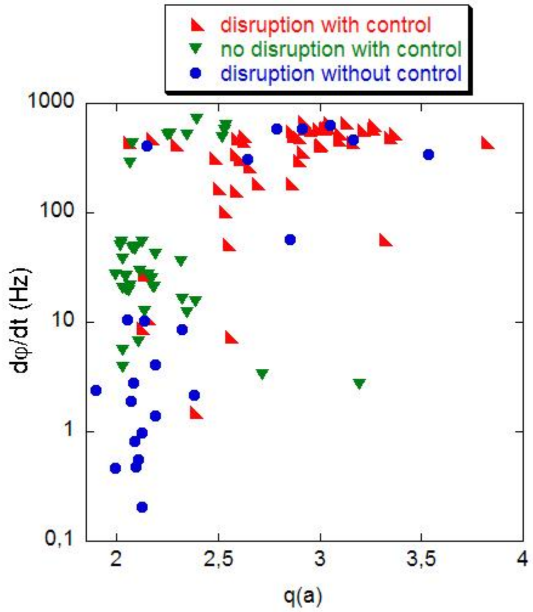
Backup slides

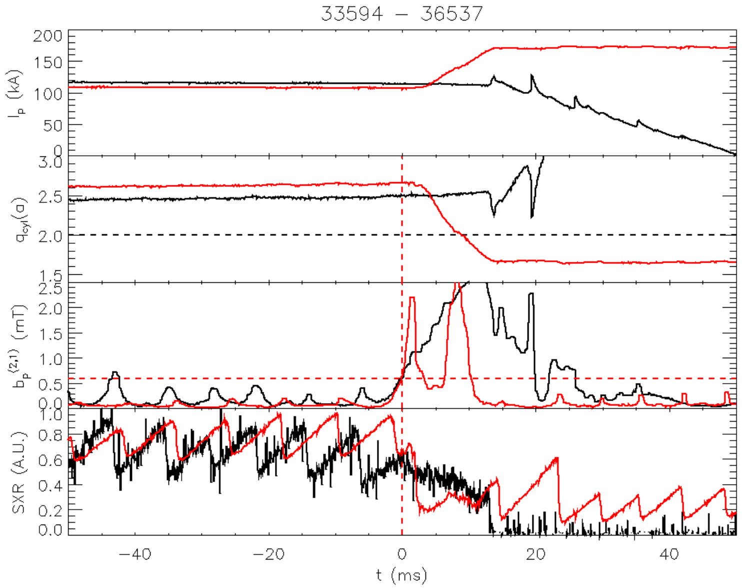
Reconnection studies

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

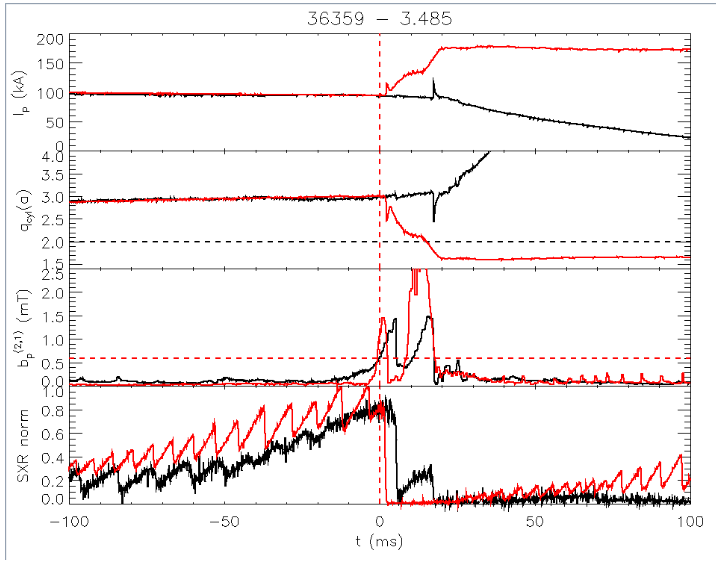


Bursty generation of DD fusion neutrons and γ rays

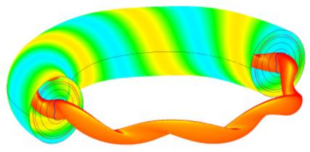

disruption with control
no disruption with control
disruption without control
1000
100
10
1
0,1
dφ/dt (Hz)
2
2,5
3
3,5
4
q(a)



avoidance



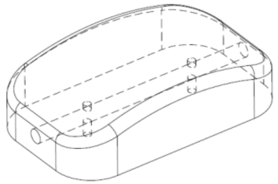
Recovery, q(a)=3



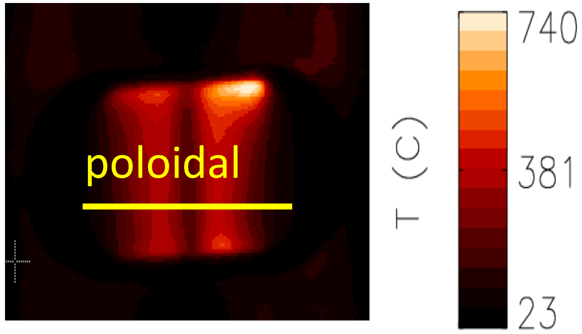
Sample exposure to high power loads

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

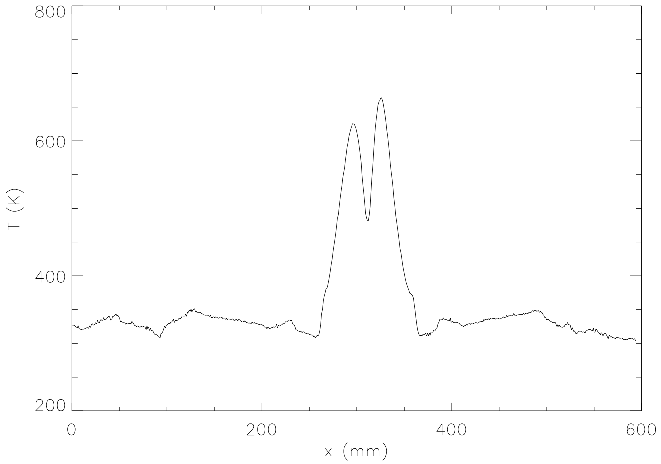
From infra-red camera
(preliminary results)



Samples exposed with 1.2 mm insertion in this example



Temperature profile



Results to be compared with the SOLEDGE-2D code