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Ricerca Formazione Innovazione

Advantage and disadvantage of 3D effects in magnetically controlled fusion plasmas

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Presented at the 531st Wilhelm and Else Heraeus Seminar "3D vs. 2D in Hot Plasmas"

Physikzentrum Bad Hoennef, April 30th, May 2nd 2013

1. Dealing with 3D issues
2. Advantages and disadvantages of 3D effects
3. 3D equilibria
4. Tailoring a 3D edge for ELM control
5. 3D plasma-wall interaction and divertors
6. MHD stability and its control with 3D effects
7. 3D effects and fast particles
8. What next ?

3D disruptions NTM **fast ions** MHD stellarator ***divertor*** **disadvantage** sawtooth equilibrium stability control **feedback** coil tokamak **MODELING** RFP experiment **helical** edge core **transport** **turbulence** **RMP** ***ELM*** ITER **effects** ***advantage*** Marfe *density limits*

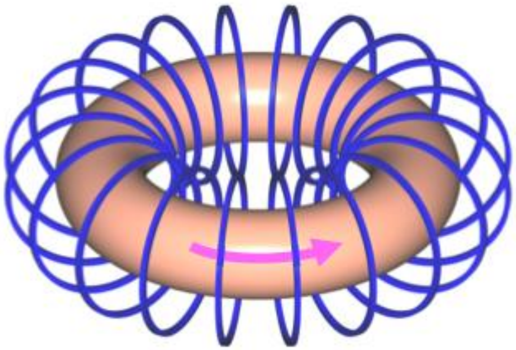
Many precious inputs, many options to combine them to tell a story…

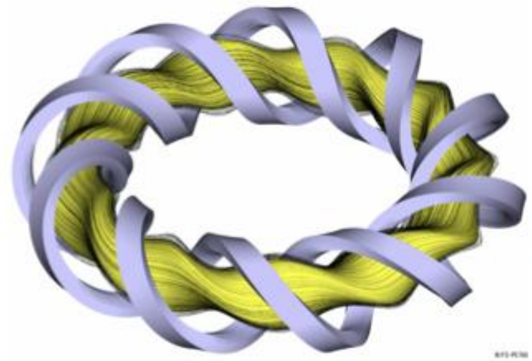
…. Today I have put together one out of many….

Thanks to all the participants to the workshop!

There are two 3 D effects

Shape ? with/without Toroidal symmetry



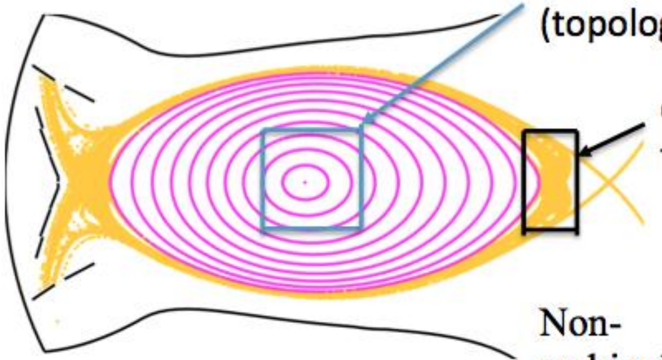


Lack of symmetry

Magnetic field ripple

Toroidal (parallel) viscosity

Topology ? closed/open Magnetic flux surface

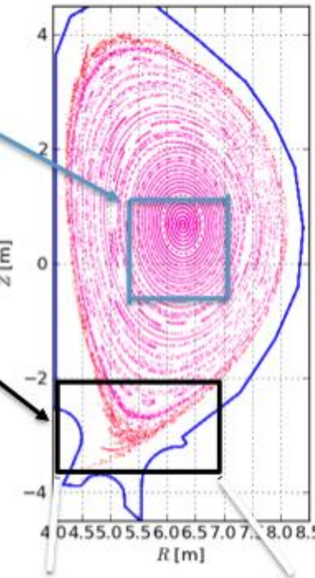


Closed magnetic flux surface (topologically 2 dimensional

open magnetic flux surface

Non-ambipolar loss

Parallel transport



Ida

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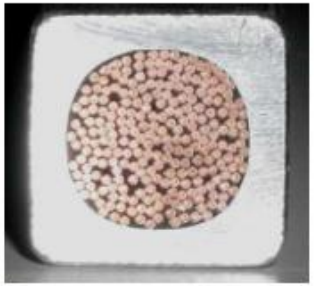
1

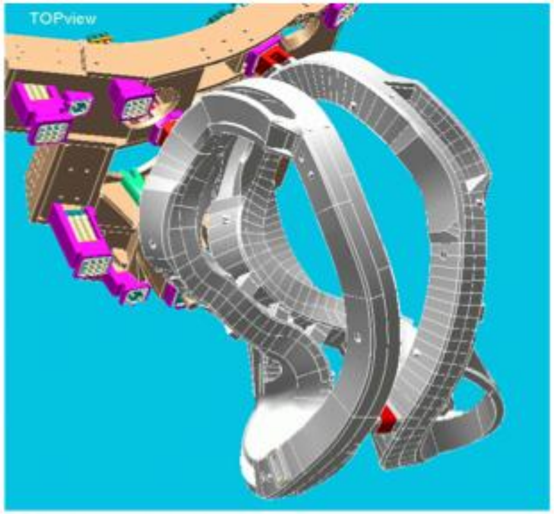
DEALING WITH 3 D ISSUES:
…NOT A PIECE OF CAKE

Some technical issues of (modular) coils

- Space between coils (also valid for the high filed side in a tokamak)
- In some areas strong bends required
  - influences choice of superconducting cable conduit
- Coils casings must be strong enough
  - support only in some positions
  - or more or less closed coil housing (NCSX)



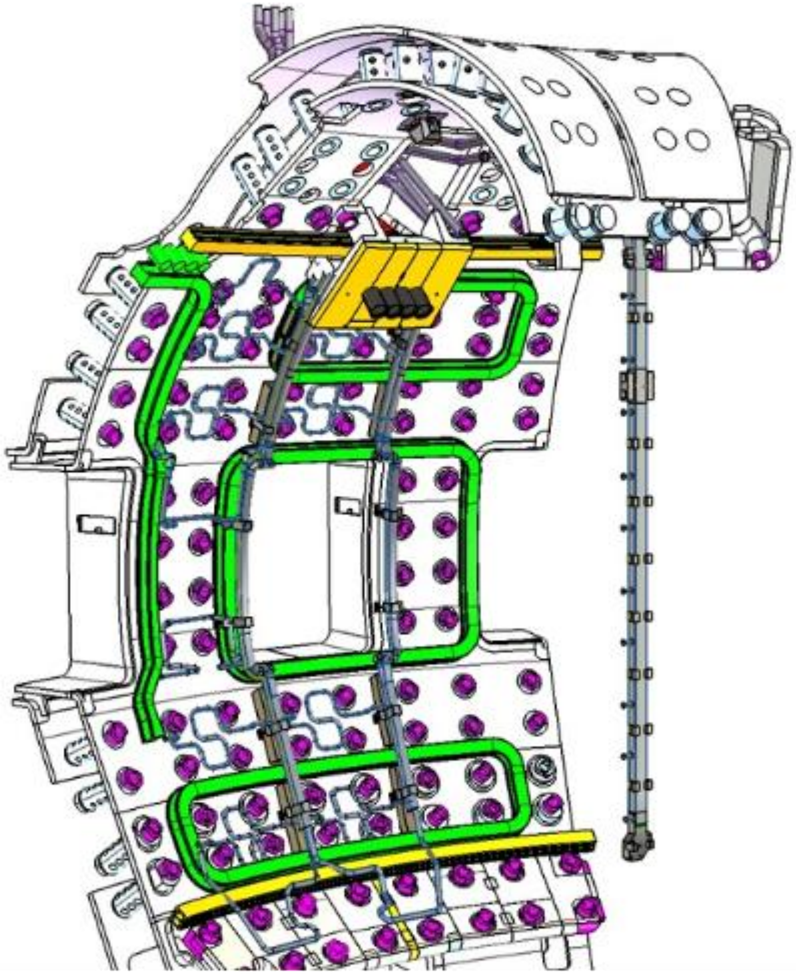
Cable-in conduit conductor NbTi



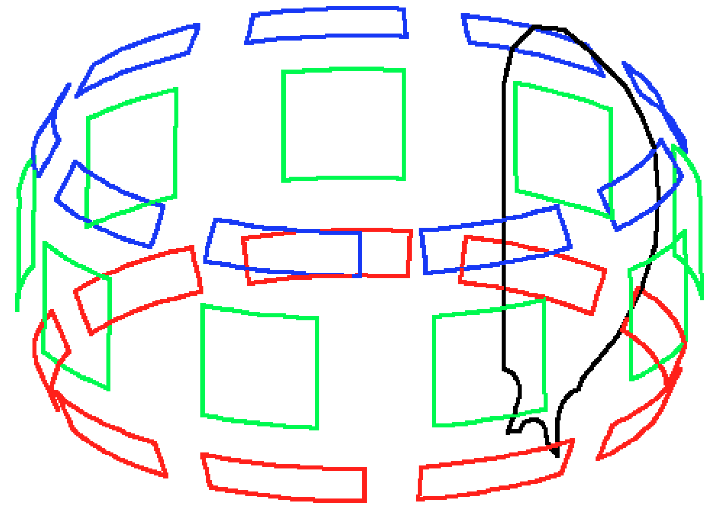
W7-X coil support

NCSX coil with support

ELM control coil setup at ITER



In vessel coil set for ITER



- In vessel coils mounted behind blanket
- 9x3 coils with single power supplies

Coil set with wide spectral flexibility

Toroidal mode number n=3 and n=4 fields seem to be advantageous at the moment

Schmitz

3D effects of RMP-coils in ASDEX Upgrade: results

- The corrugation patterns of the flux surfaces reflect the kink structure of the nearest rational q-surfaces and the periodicity of the perturbation field.
- Odd and even RMP-coil currents modulate strength and phase of the corrugation.
- Here, both, stabilizing and destabilizing effects of the RMP-field have been found.
- In order to get an accurate eigenvalue many poloidal harmonics (here: ~30 poloidal harmonics per n) and several n have to be taken into account. The two toroidal harmonics, which have been considered here, are very probably not enough.

→ a tremendous numerical effort is necessary

Strumberger

2

ADVANTAGE AND DISADVANTAGES OF 3D EFFECTS.

BUT…, DO WE HAVE A REAL CHOICE?

The fusion idea about a "straight" magnetic field line.

i.e.:

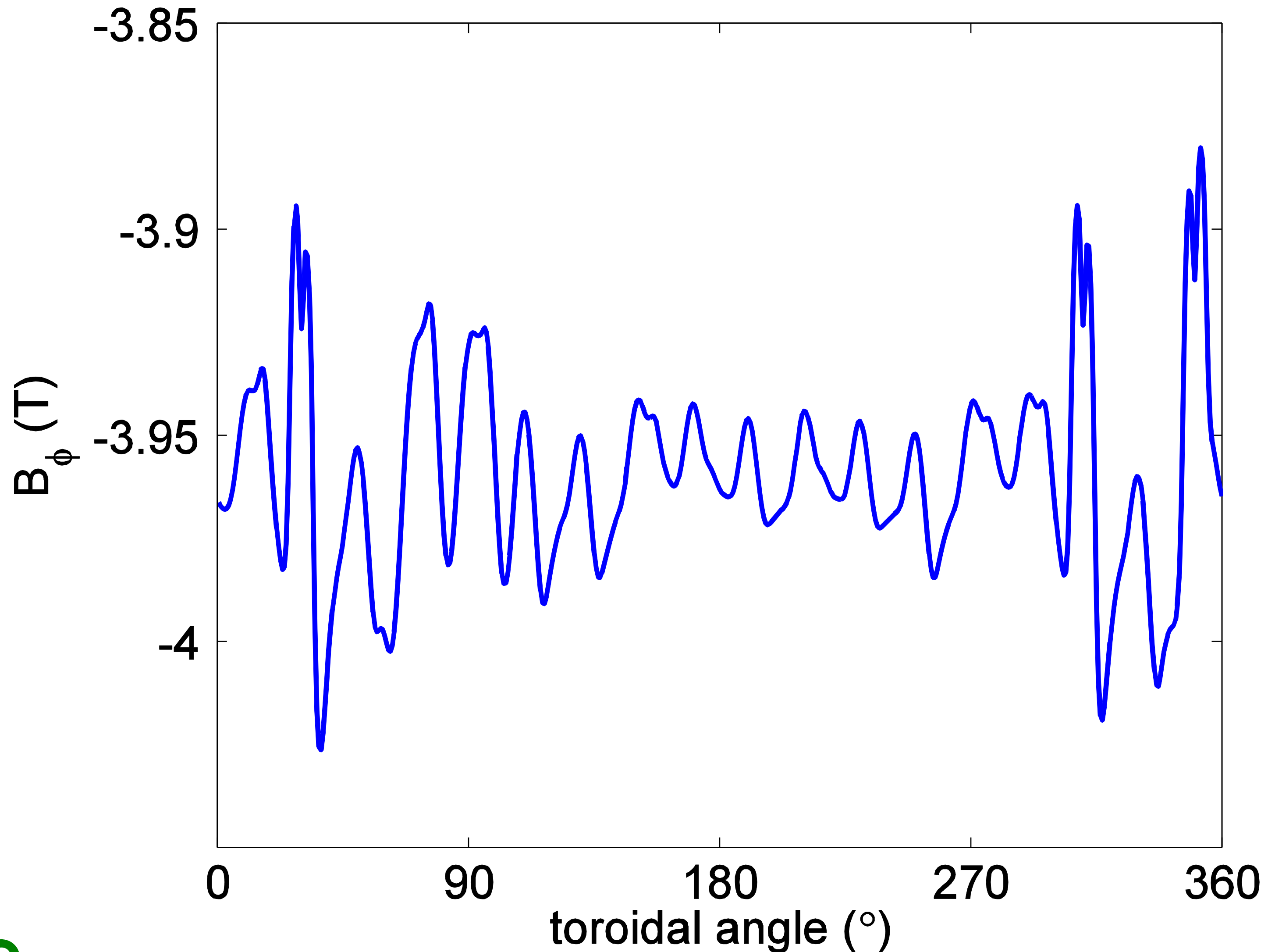
"The engineering world is coming alarmingly close to the world of physicists"

B_T (φ) at the OMP separatrix in ITER 9MA Scenario

Toroidal ripple 1.1%,

Field bump due to NBI ports 0.57%

Field bump due to TBMs 1,1%



Kurki-Suonio

3D effects in tokamaks

- **Toroidal field coils: mostly high-n perturbations, e.g. n=16 in AUG**
- **Test blanket moduls: low-n perturbation (n=1) in ITER**
- **RMP coils: low-n perturbations, e.g. n=1, 2 or 4 in AUG**
- **resistive wall: e.g. medium-n perturbation (n=9) in ITER**
- **equilibrium with helical core: low-n perturbation, observed in MAST, TCV, RFX, ….**
- **error fields: small undesignedly or unavoidable non-axisymmetric magnetic fields $(\Delta B/B) \sim 10^{-4}$**

n= leading toroidal harmonic of the magn. field perturbation

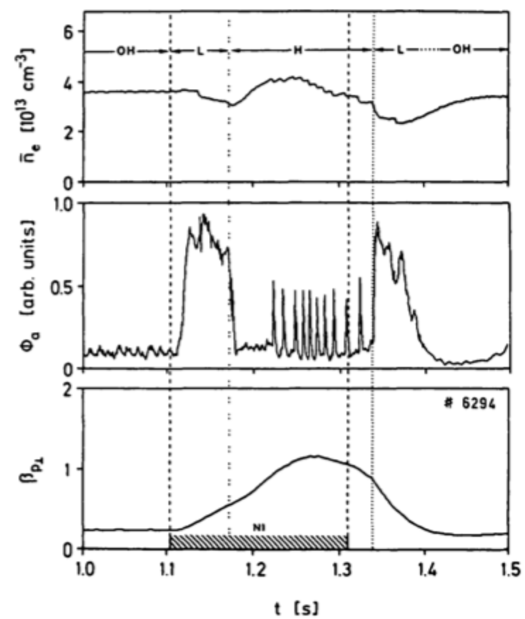
Edge Localized Modes

Large and repetitive MHD instabilities

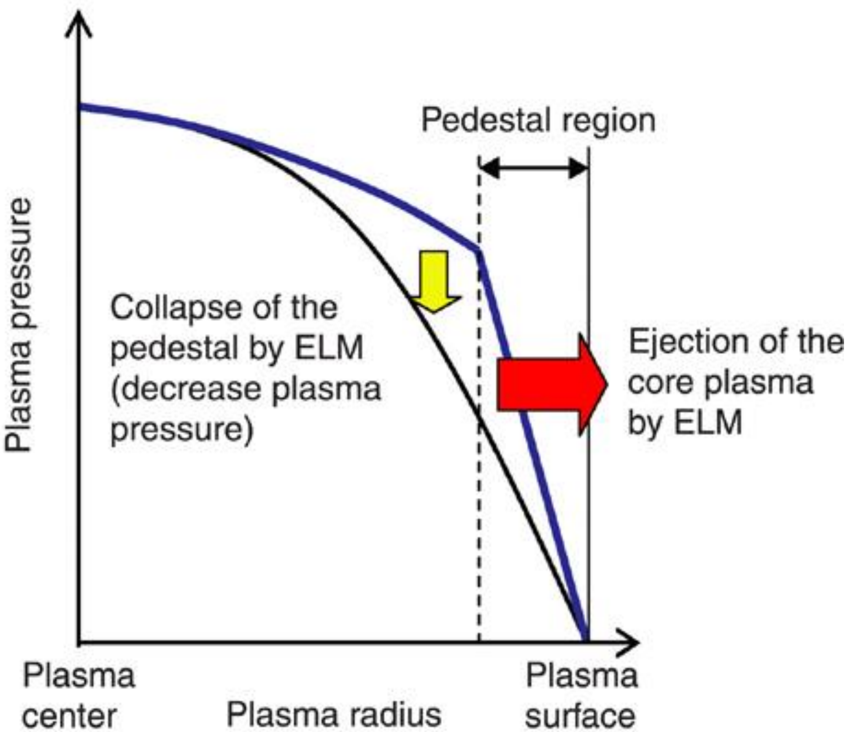
Caused by **steep edge pressure gradient** present in H-mode

Release a significant amount of the stored energy.

ASDEX



ASDEX Team NF **29** (1989)



- **ELM size scaling to ITER is a serious concern** (though physics not fully assessed, yet)
- **The associated energy losses are unacceptable.**
  - Energy fluxes during ELM ($\Delta W_{ELM} \approx 20$ MJ) in ITER ≤15MJm^{-2}, i.e. x30 **larger than material damage treshold** (W & CFC)

Edge Localized Modes

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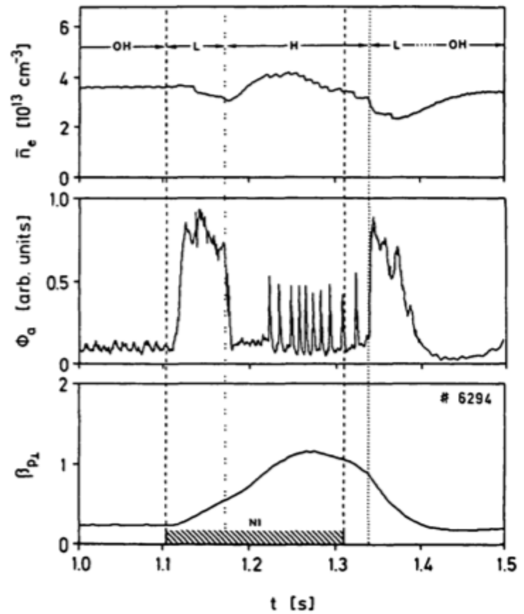

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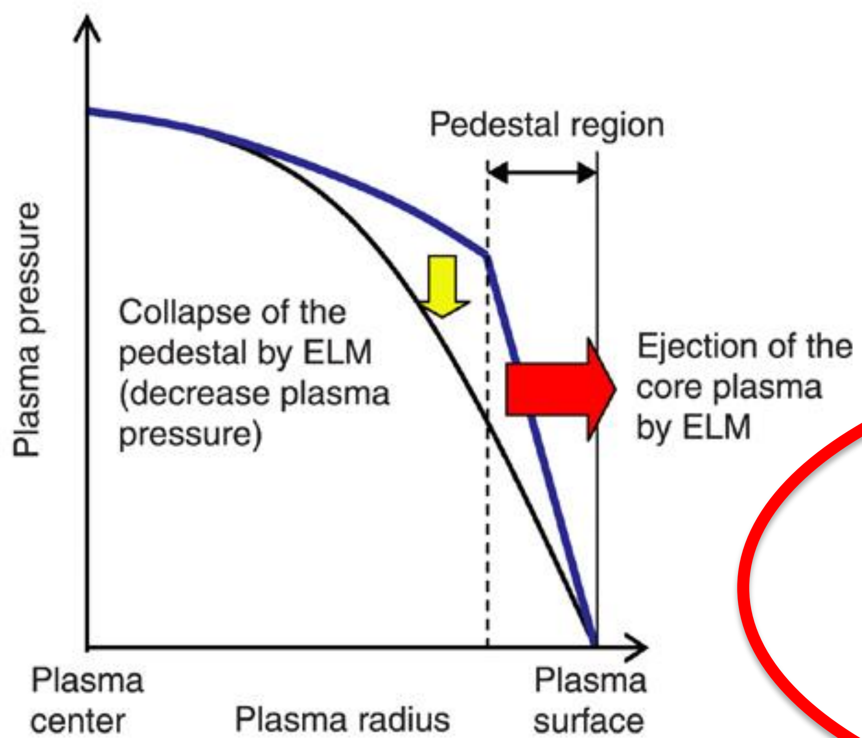

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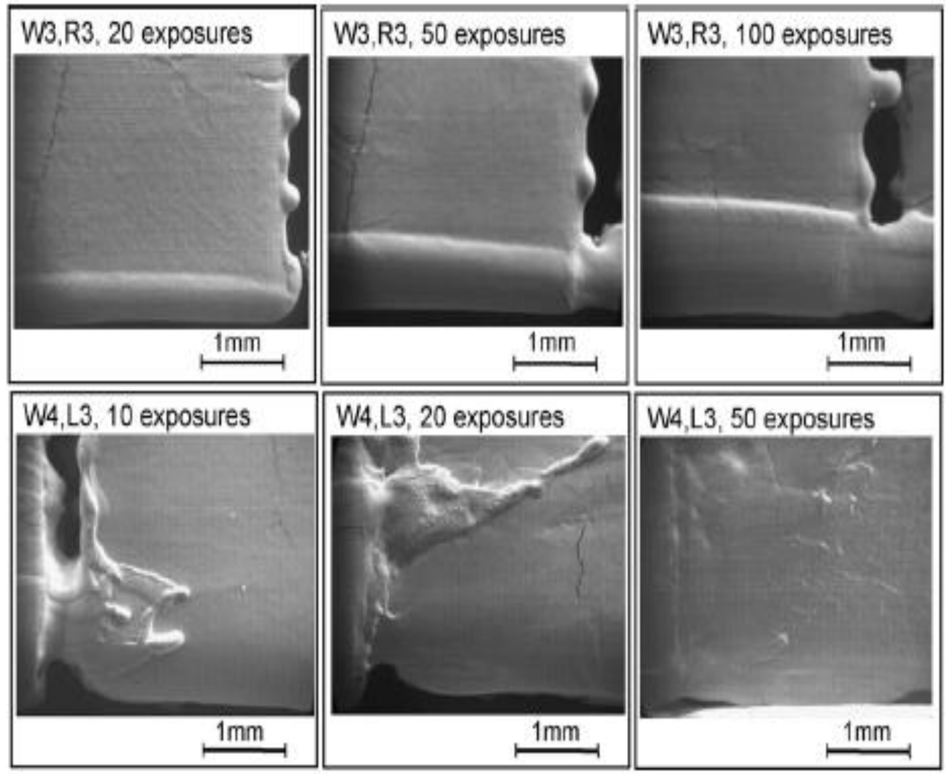
ITER need ELM control

Liang

Q = 1.0 MJ/m²

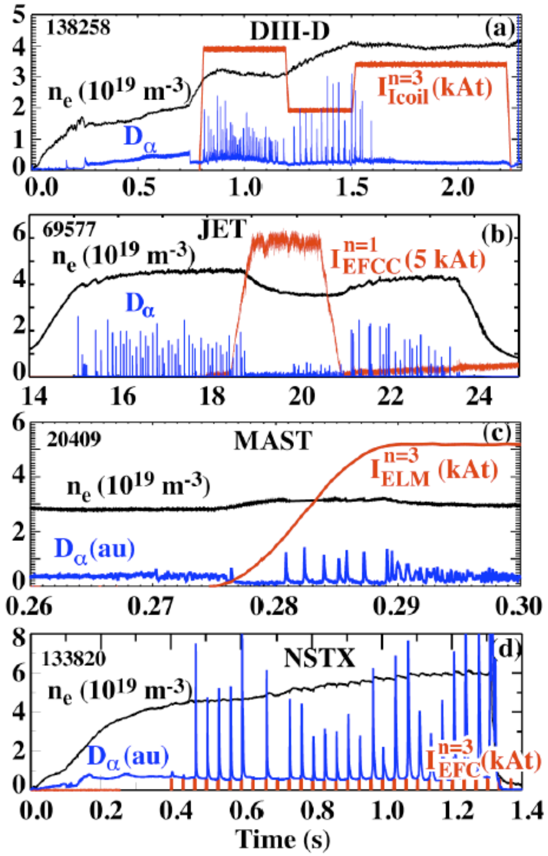
Q = 1.6 MJ/m²



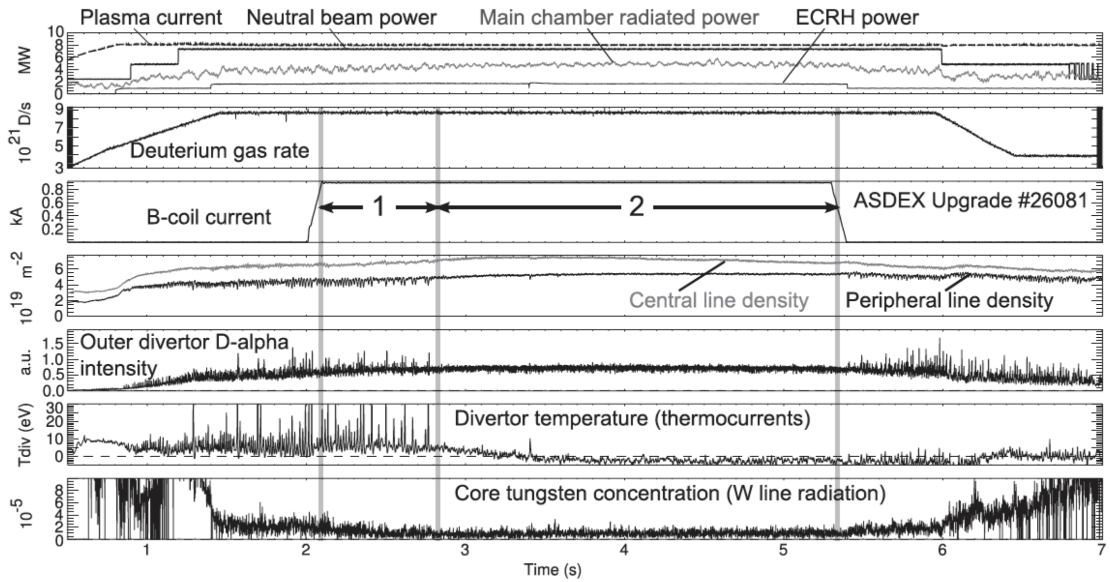
Zhitlukhin JNM 2007

- **0.4-1.0 MJ/m² (JET<1.0 MJ/m²) → Edge melting and surface cracking**
- **1.0-1.6 MJ/m² → Surface melting, bridge formation and droplet ejection**
- **High frequency ELMs may be required to avoid W accumulation**

Motivation: ELM suppression by edge resonant magnetic perturbations is a worldwide effort



[M. Fenstermacher et al., IAEA FEC 2010, Daejon, Korea]



[W. Suttrop et al., Phys. Rev. Letters 106 (2011)225004]

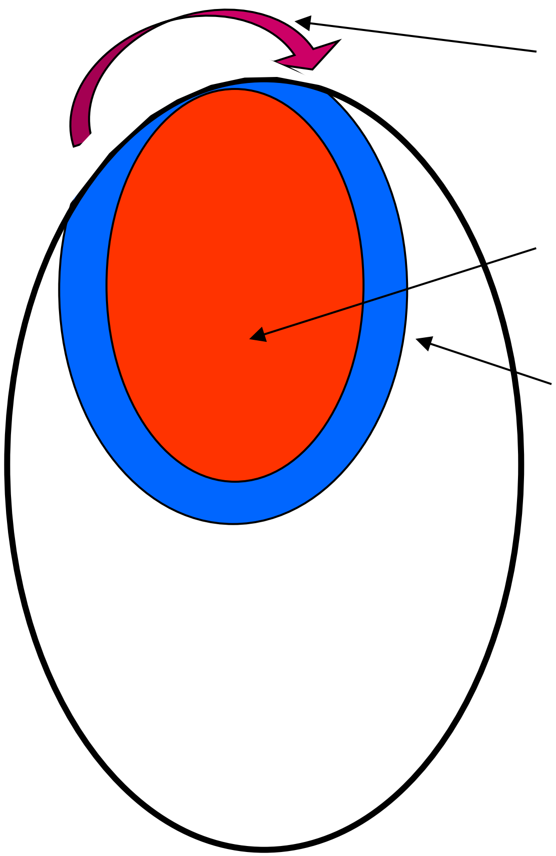
Control of ELMs by RMP is envisaged as key functionality for protection of the wall integrity at ITER

Schmitz

Disruptions are three-dimensional events

Forces

- Forces from halo and eddy currents are the main design constraint on the vessel and in-vessel components in ITER
  - Symmetric loads on the vessel reach ~10,800 tonnes
  - Asymmetric sideways loads ~5,000 tonnes

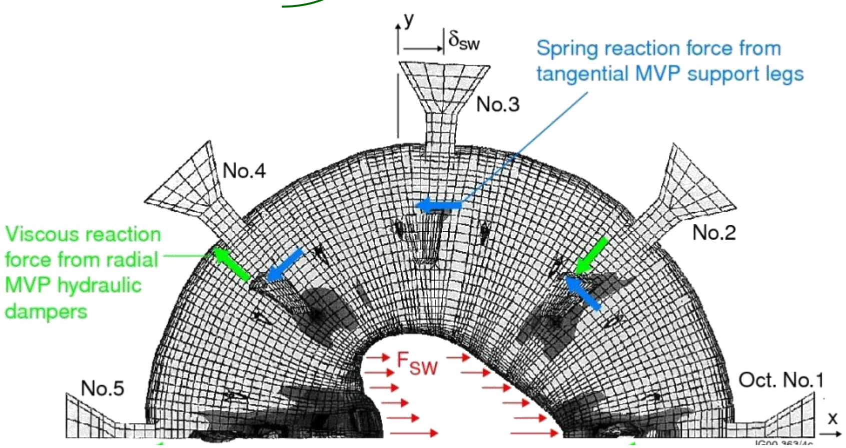


Halo current flowing in vessel etc, (normally dominantly *poloidal flow* for symmetric currents)

Core plasma:- shrinking and I_p decreasing

Halo region

Toroidal halo current flows in I_p direction and poloidal current in direction to increase B_t



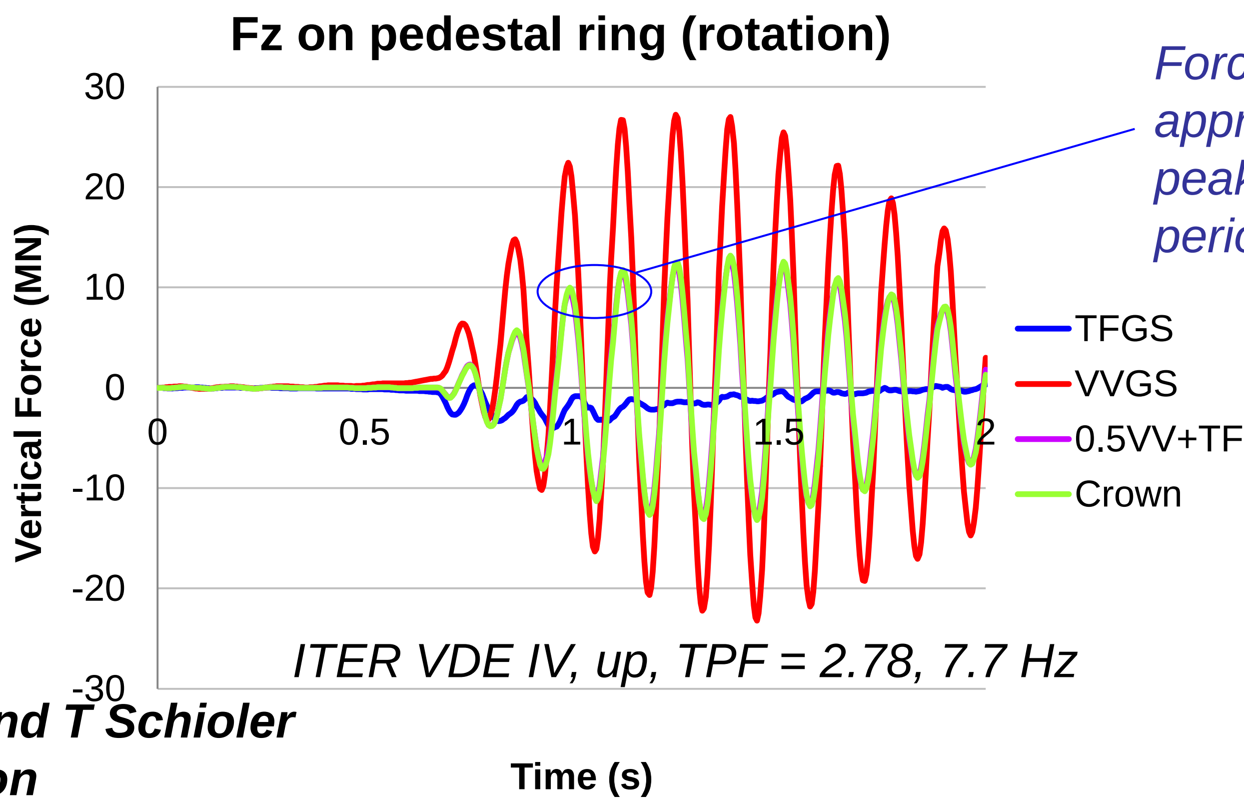
- For JET peak sideways force ~400Tonnes

Halo current rotation important

- **Vacuum vessel and coil systems have low frequency resonances**
- **Possibility of dynamic amplification**

Mode	F (Hz)	Mass fraction
U – xy	2.77	0.95
U – z	8.61	0.77
Rot - xy	8.41	0.80
Rot - z	4.50	0.88

Natural frequencies of the 360° VV



Forces approach peak in 2 to 3 periods

G. Sannazzaro and T Schioler
ITER Organisation

Hender

Halo current rotation important

- **Vacuum vessel and coil systems have low frequency resonances**
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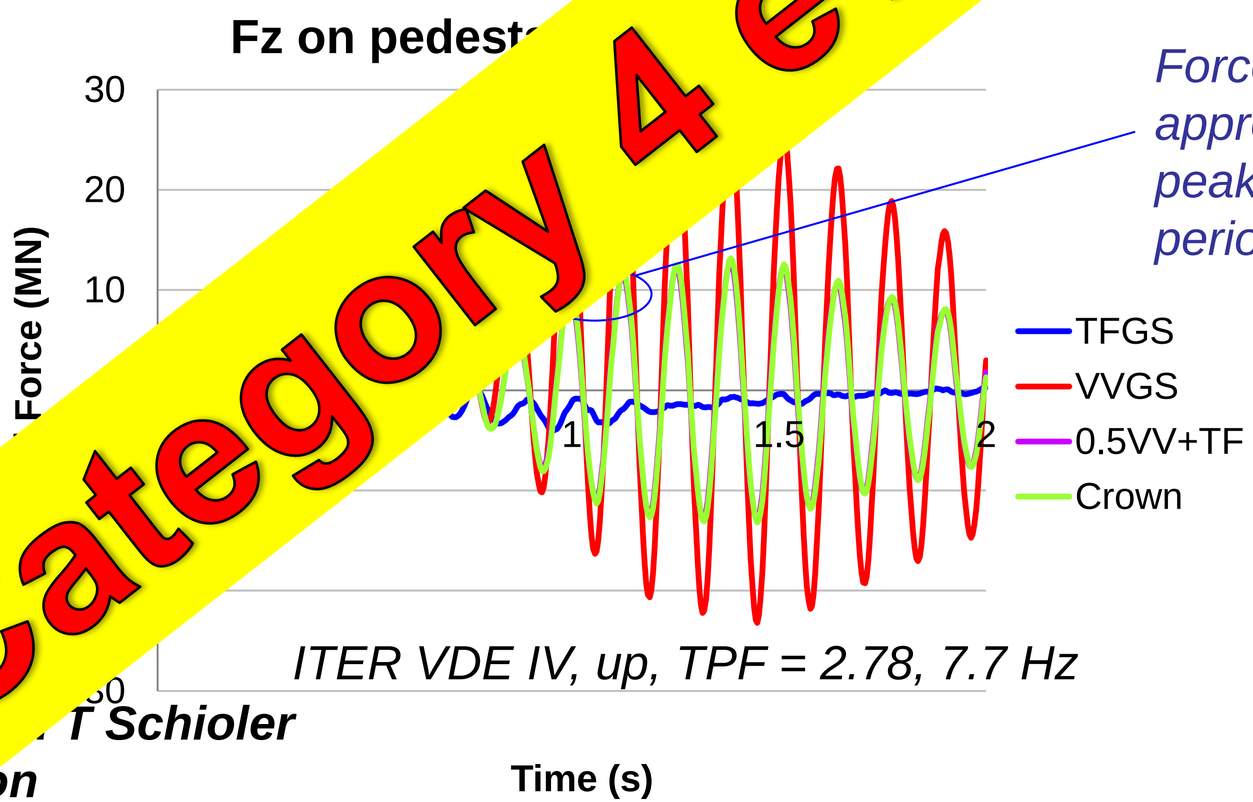
Mode		Mass fraction
U		0.95
		0.77
		0.80
	.50	0.88

...quencies of the 360° VV

Category 4 events



Forces approach peak in 2 to 3 periods

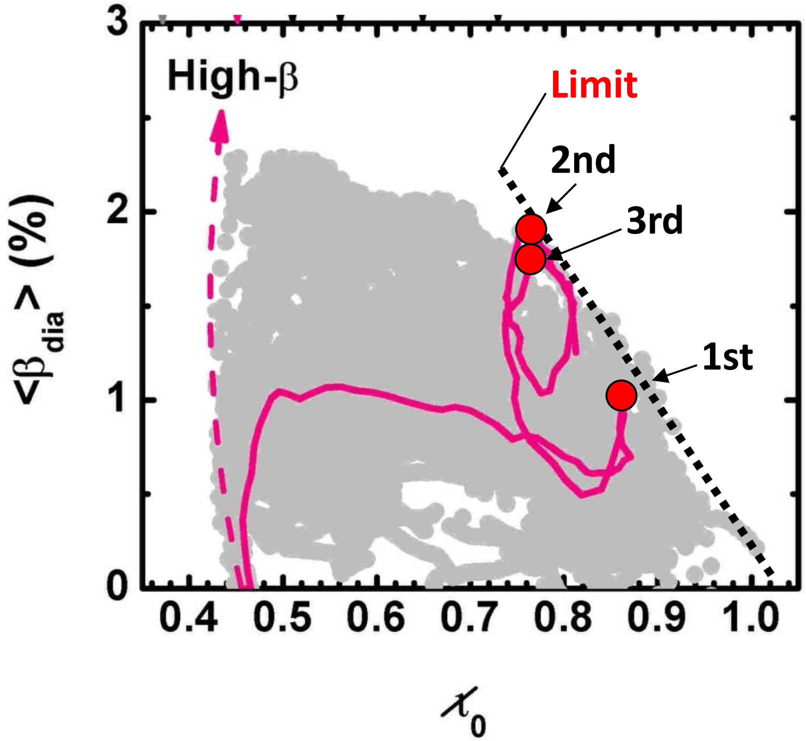
G. Sannazza... T Schioler
ITER Organisa...on

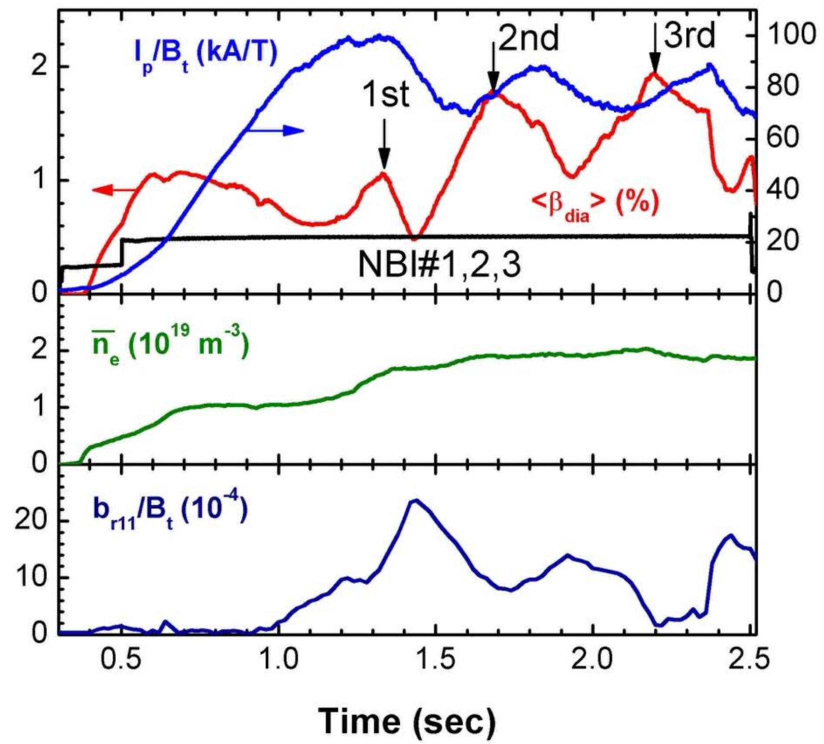
- China is facing to the serious shortage and pollution of energy from now and will more serious in near future;
- China must develop renewable energy and nuclear energy as fast as possible;
- Both development of fission power plant and fusion research in China are getting strong support now.

Need for a diverse, multi-configuration and ambitious strategy on magnetic fusion

Stellarator is not disruptive

Collapsed events are observed but not disruptive!



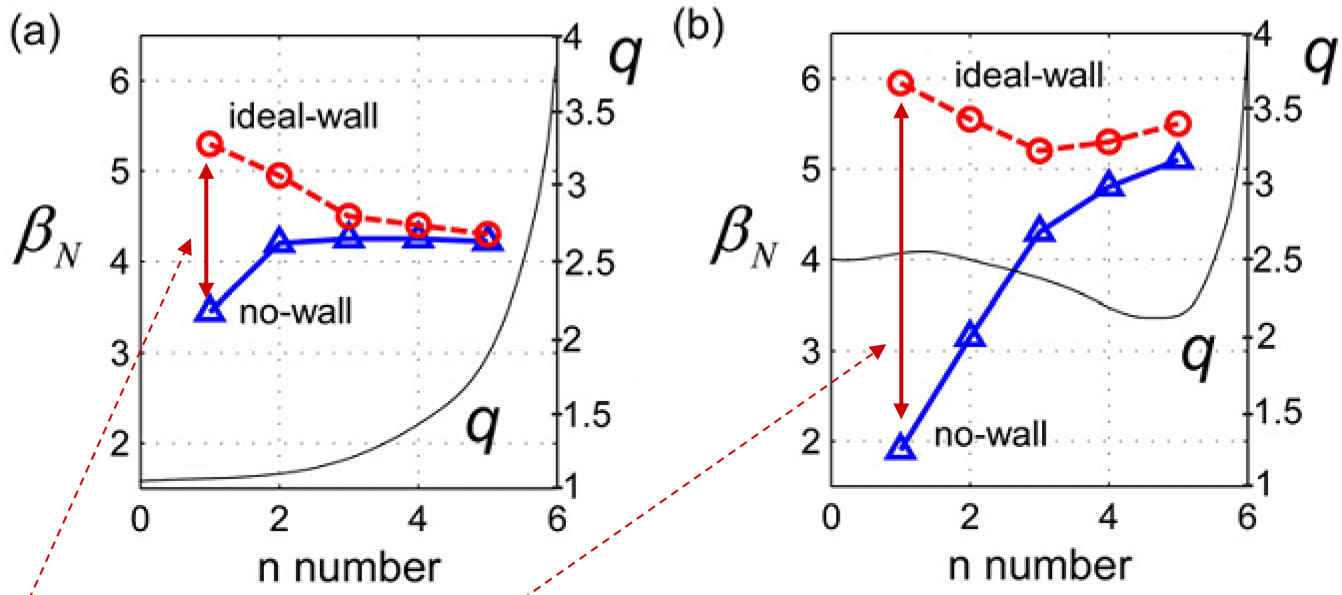


The total energy is minimum at the vacuum.

When the RWM stabilization is important?

Conventional scenario
(moderate improvements)

Advanced scenario
(crucial improvements)



V. Igochine Nucl. Fusion **52** (2012) 074010
Manickam J. *et al* 1994 *Phys. Plasmas*

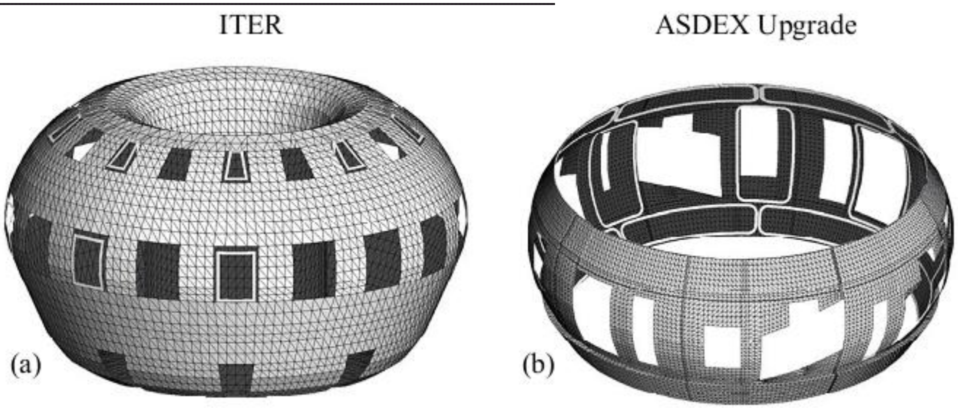
RWM stabilization allows to gain this region.

Stabilization is really important only in the advanced scenario for low n.

Growth rate of the RWM is strongly different in 2D and 3D cases if holes in the wall are big (the low field side holes are especially important)

TABLE I. Unstable normalized eigenvalues $\gamma\mu_0\sigma d$ (1/m).

n	ITER 2D	ITER 3D	AUG 2D	AUG 3D
1	0.79	1.65	1.79	10.32
1	0.79	1.64	1.79	9.91
2	1.65	4.40	1.69	6.24
2	1.65	4.38	1.69	5.86



Effects of the 3D wall structure on the growth rate in RFX

Growth rates are close to the measured values if one takes into account 3D effects (RFX-mod)

Table 2. Comparison of growth rates for two RFX-mod equilibria (all results in s^{-1}). Only unstable RWMs are considered.

	Equil A					Equil B				
Code	ETAW	MARS-F	CarMa2D	CarMa	Exp	ETAW	MARS-F	CarMa2D	CarMa	Exp
$n = 1$	0.909	<0	<0	<0	<0	<0	<0	<0	<0	<0
$n = 2$	1.56	0.78	0.74	0.87 0.93	N.A.	<0	0.43	0.37	0.45 0.46	N.A.
	1.82	1.29	1.48	1.67 1.81		2.45	1.81	1.94	2.33 2.36	
$n = 3$	0.73	1.10	1.17	1.37 1.40	N.A.	1.82	2.08	1.91	2.61 2.64	N.A.
	3.09	2.71	3.05	3.69 3.78		1.90	2.16	2.49	3.13 3.26	
$n = 4$	5.27	5.07	5.86	7.30 7.48	≈ 6	4.09	4.04	4.27	5.63 5.78	≈ 6
$n = 5$	8.63	8.55	10.13	12.8 13.1	≈ 12	6.81	6.89	7.45	9.91 10.2	≈ 8
$n = 6$	14.5	14.4	17.56	22.6 23.4	≈ 22	11.8	11.7	12.90 18.2	17.6	≈ 17

2D 3D Exp

M. Baruzzo *et al*
Nucl. Fusion **51** (2011) 083037

3

3-D EQUILIBRIA

The stellarator concept: advantages

- **Intrinsically steady state magnetic field (no current drive)**
  - current drive requirements limited to small adjustments of the rotational transform
    (one to two orders of magnitude smaller than in tokamaks)
  - intrinsically lower re-circulating power (could operate ignited)
  - quiescent steady state (at high β)
- **No current driven instabilities**
  - no need to control profiles (?)
  - no need for feedback or rotation to control instabilities, or nearby conducting structure
- **No disruptions**
  - eases design of plasma facing components (breeding blanket)
  - disruption avoidance or mitigation schemes not required
- **Very high density limit (no Greenwald limit)**
  - easier plasma solutions for divertor
  - reduced fast-ion instability drive

Wolf

Results from HINT well describes deformation of magnetic surfaces

3-D equilibrium consistent with experimental observation, i.e., Shafranov shift, pressure profile, etc.

Significant pressure (T_e) gradient exists in the edge stochastic area

Hypothesis

1) Plasma heals flux surfaces
2) Profile is consistent with characteristics of stochastic field
3) Somewhere between 1) & 2)

$L_{C\text{-}TB}$: connection length between the torus-top and - bottom

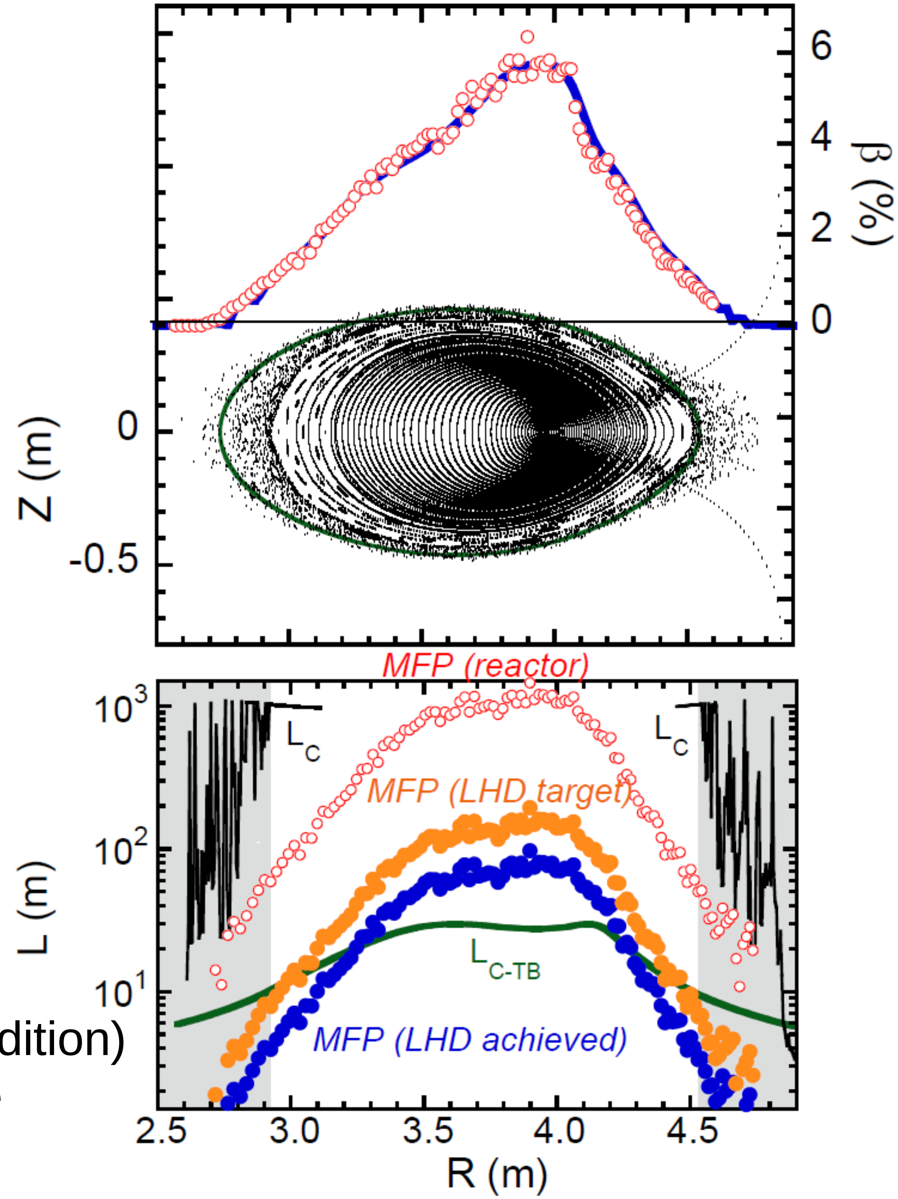
✓ L_C >> $L_{C\text{-}TB}$

➔ Pfirsch-Schlüter current is effective

➔ Secure MHD equilibrium

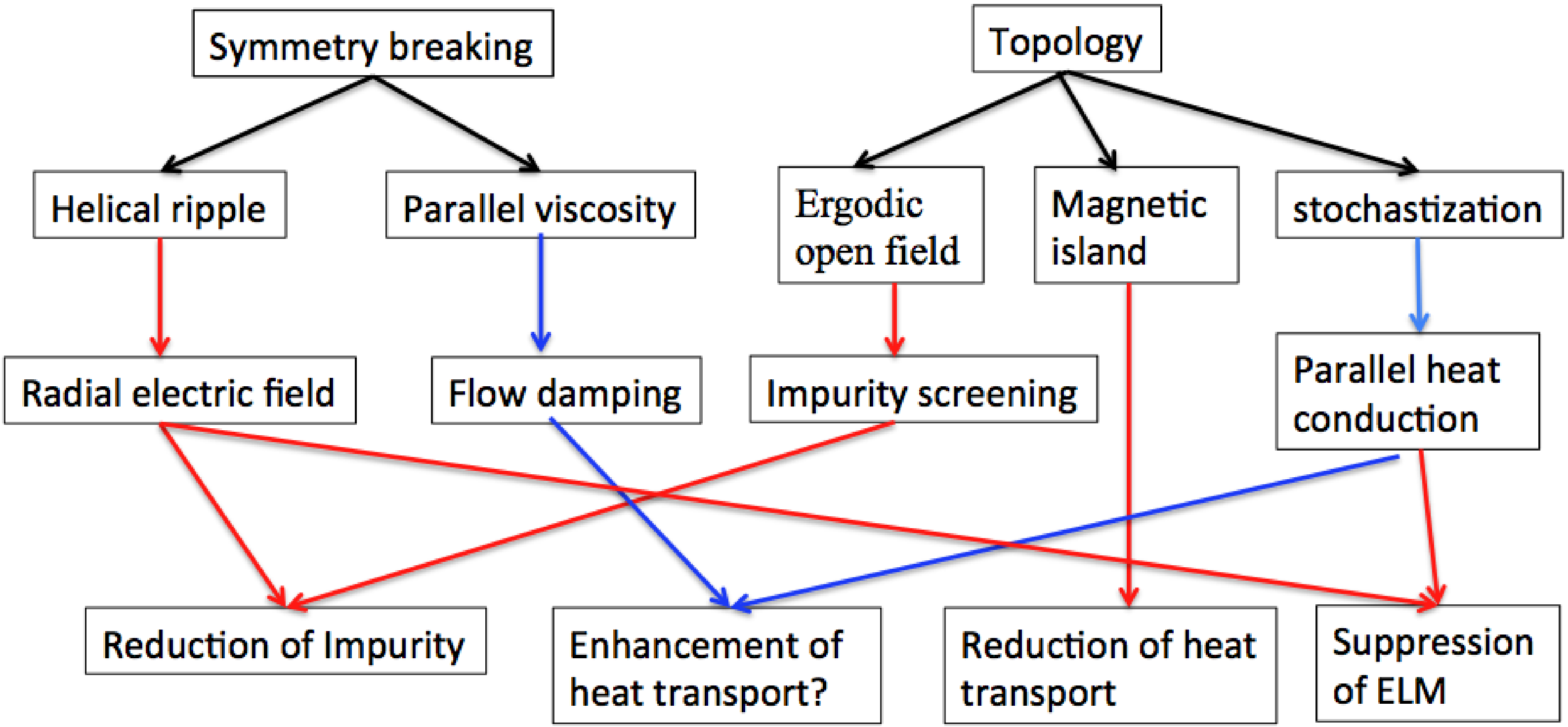
✓ L_C >> MFP (even under a reactor condition)

➔ Plasma is collisional enough to secure isotropic pressure



Summary

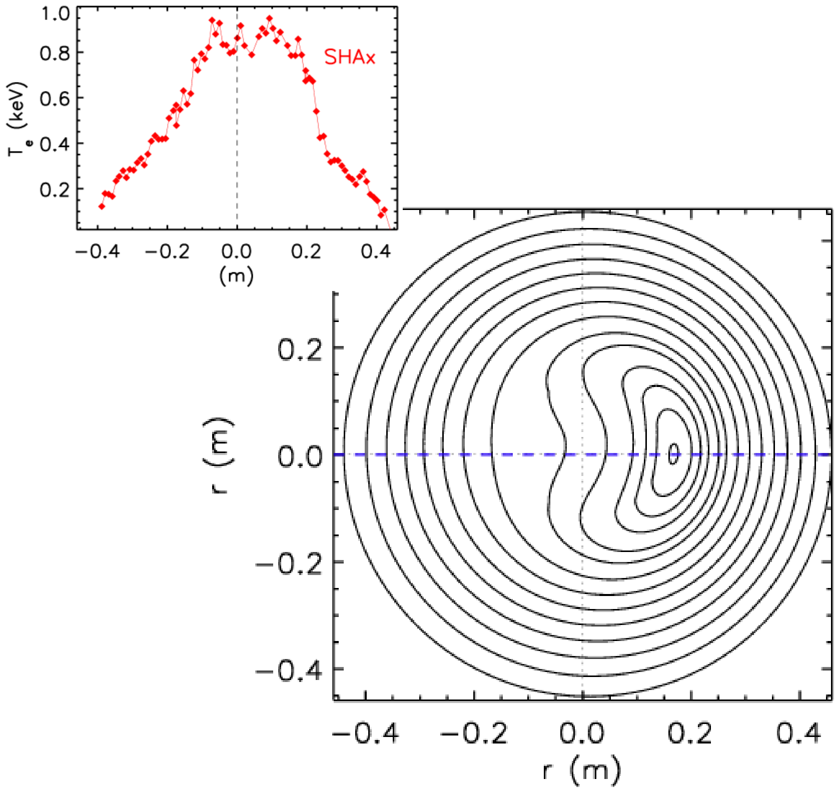
There are two 3D effects
1 Symmetry : tokamak⇔ helical → ripple and viscosity
2 Topology: 2D closed flux surface ⇔3D magnetic field strucutre

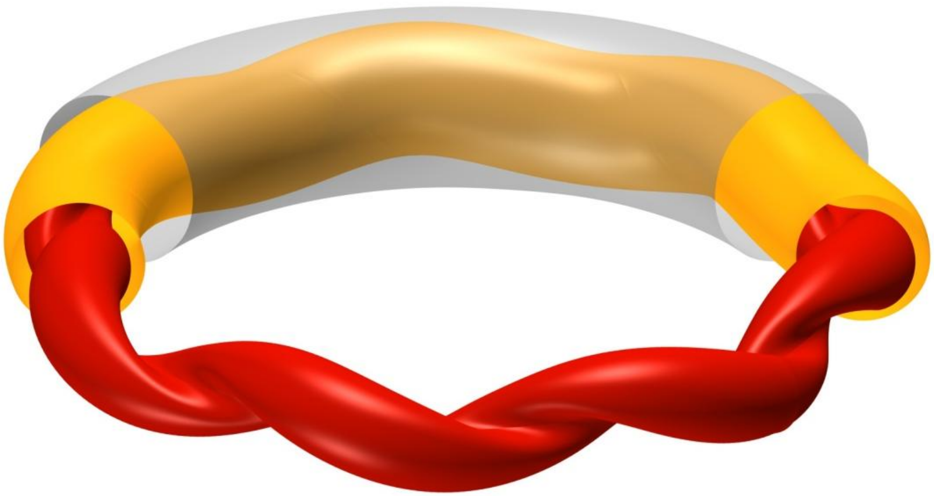


3D effects contribute reduction of impurity but not reduction of heat transport because of flow damping and also suppression of ELM trough change in transport and Er (flow)

Ida

Helical equilibrium





Constant helical flux surfaces define the topology of plasma equilibrium: all measured quantities can be correctly interpreted in terms of the dominant helicity.

R. Lorenzini *et al.*, Nature Physics **5** (2009) 570-574

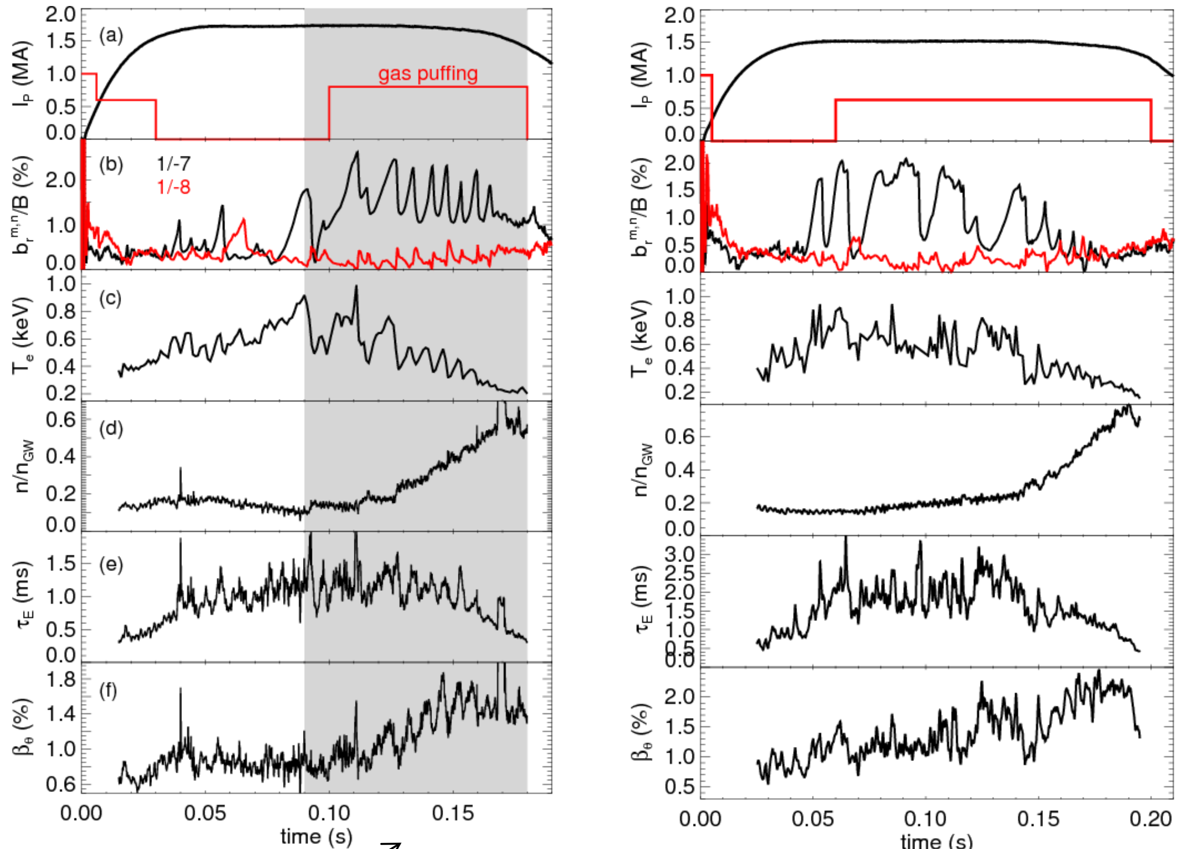
High density helical regimes

Helical shaping allows **extending** the **density range** where helical states exist.

The energy confinement does not change with helical shaping, as long as $b_r^{1,-7}(a)/B<2\%$.

Some confinement degradation occurs at the highest density reached ($n/n_{GW}\approx0.5$).

DENSITY INCREASES MAINLY DUE TO GAS PUFFING



Shaded area **helical boundary ON**

Theme

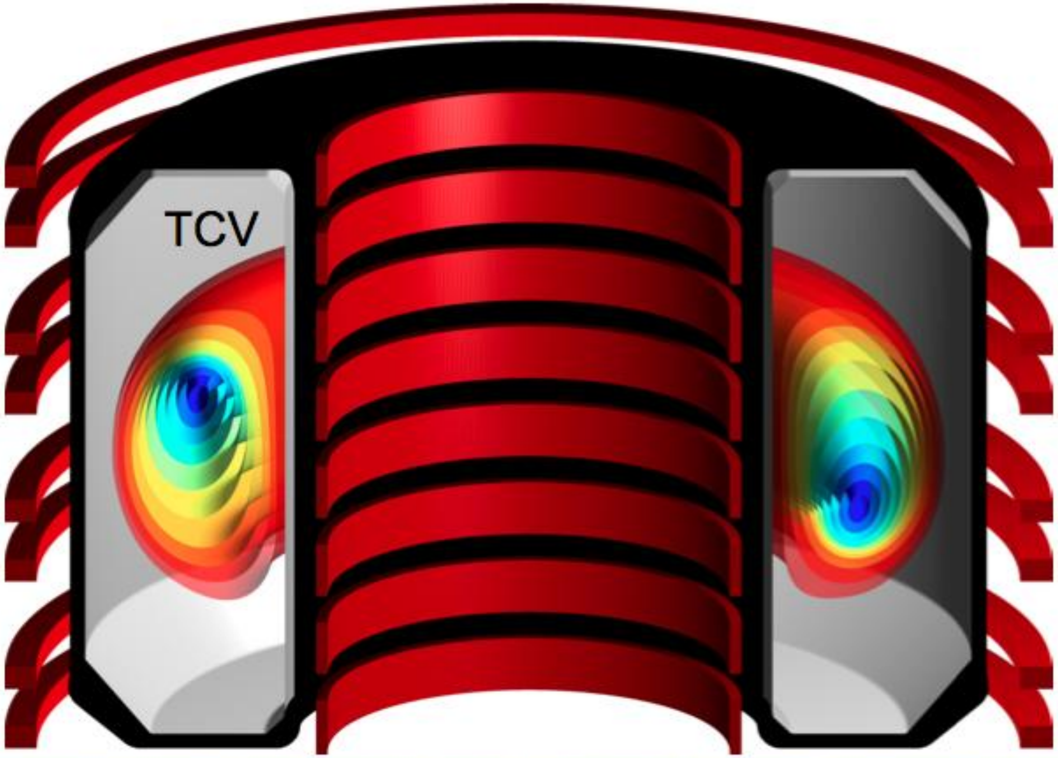
(1) We can assume an exactly axisymmetric plasma boundary

(2) We solve for internal flux surfaces in equilibrium: $\rho \frac{dV}{dt} \xrightarrow{} 0 = \underline{J} \times \underline{B} - \underline{\nabla} P$

- Relax axisymmetry constraint **inside** plasma

- Two solutions possible:
  - One axisymmetric,
  - the other is helical

- Hybrid scenario susceptible to helical core deformations [Cooper et al, PRL 2010]



Graves

RFP-Stellarator synergistic collaboration

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RFP ***needs "3D glasses"***

stellarator tools to investigate plasma physics in the helical configuration

STELLARATORS ***may explore a new range of parameters***

application and validation of existing codes

a ***common language*** for

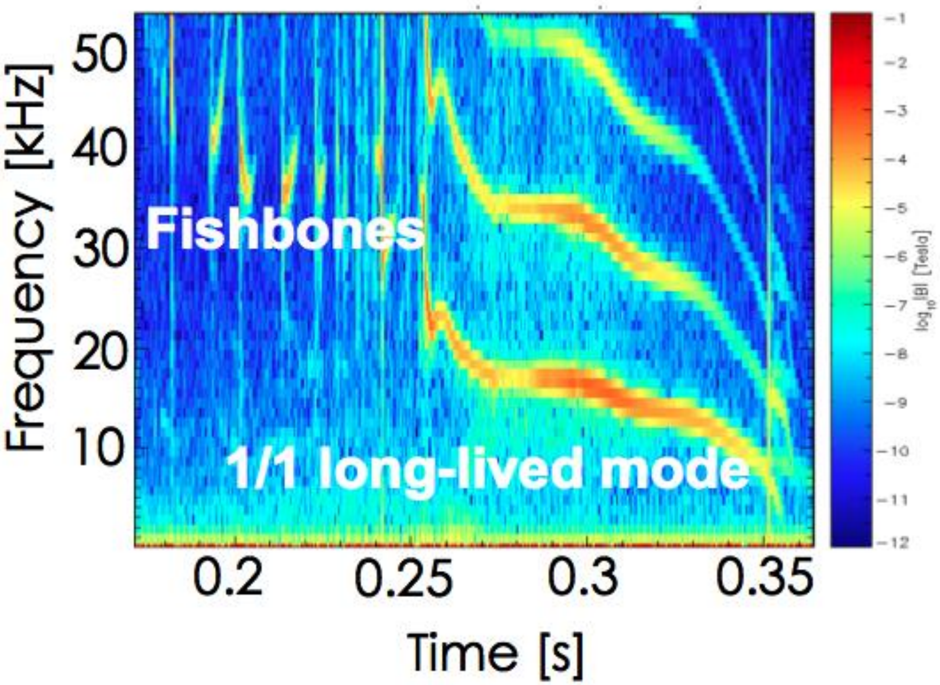
TRANSPORT

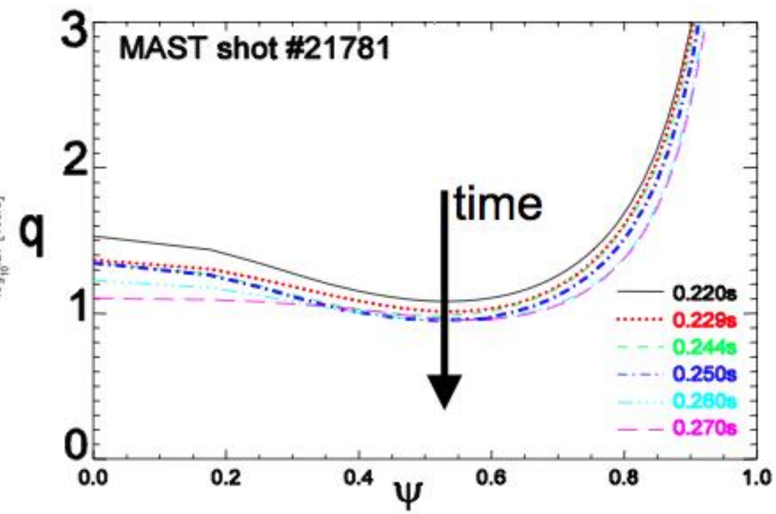
- ✓ **ORBIT** adapted to helical RFPs
- ✓ **ASTRA** for power balance studies
- ✓ **DKES/PENTA** for neoclassical transport
- ✓ **gyrokinetic codes** for turbulence

M. Gobbin

Long-Lived Mode (LLM) in MAST

- LLM reported to be [Chapman NF 2010] is a saturated ideal n=1 mode observed when q-profile is reversed shear or ~flat
- Causes rotation braking and fast ion redistribution



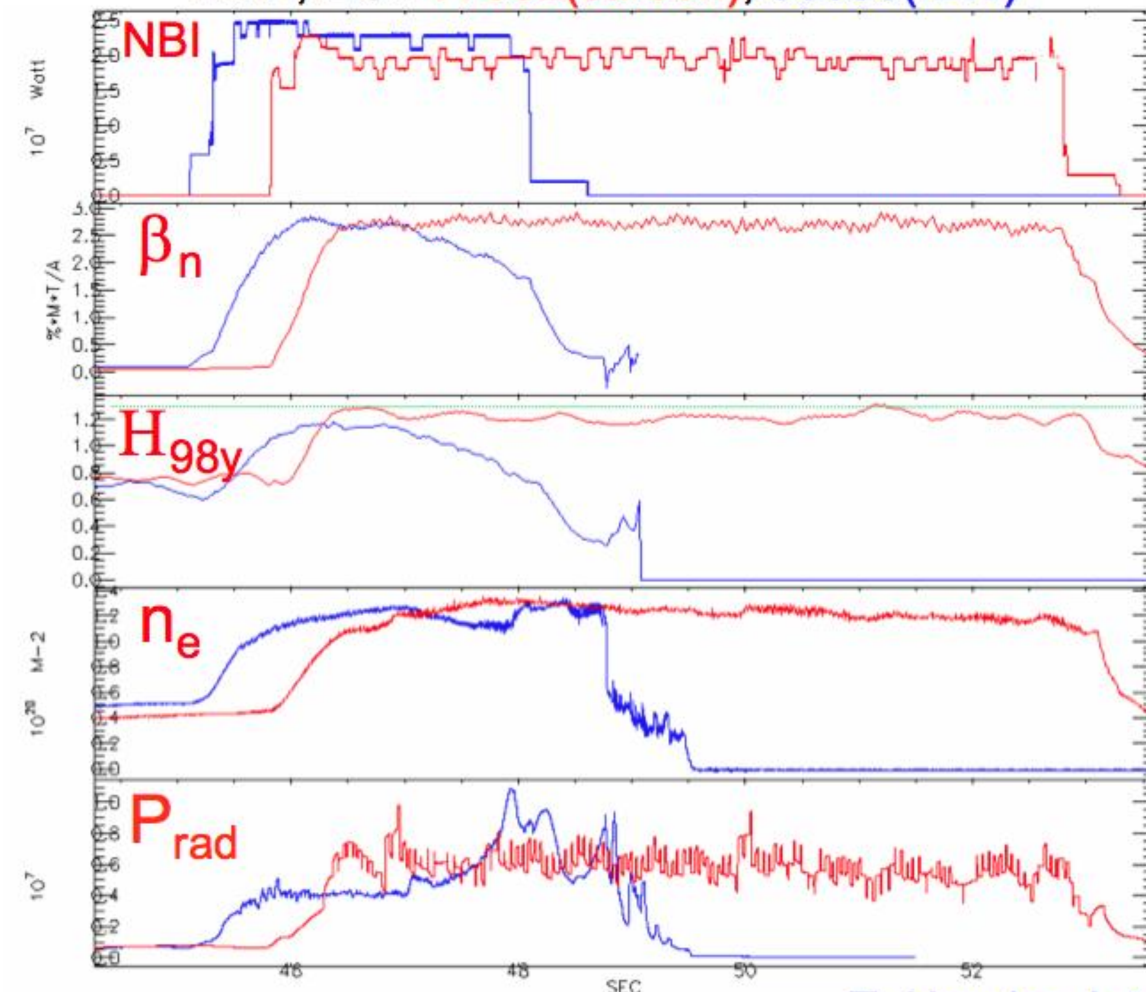


IT Chapman et al, Nucl Fusion, 2010

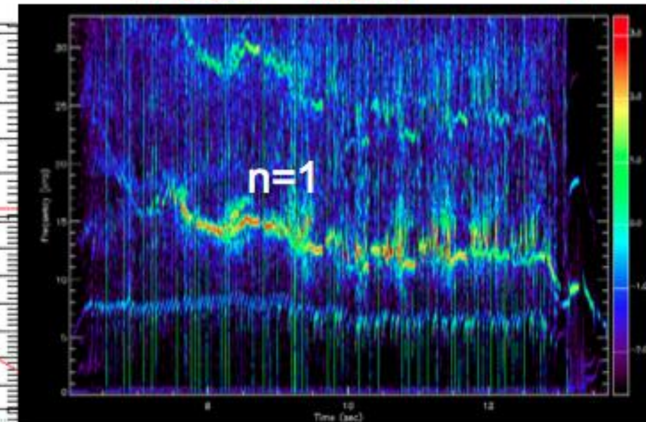
Graves

Hybrid Scenarios in JET

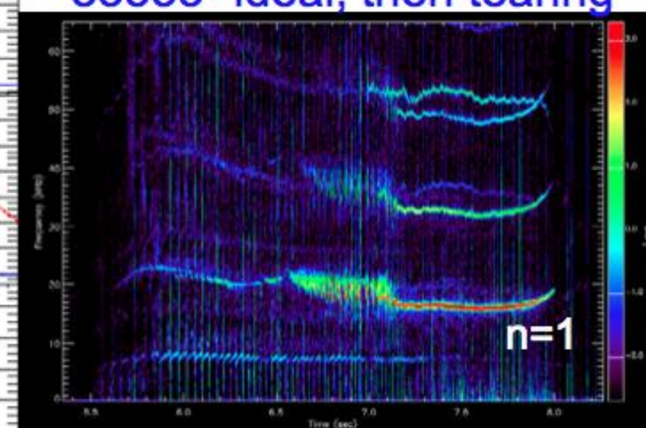
2MA, 2.3T 77932(carbon), 83533(ILW)



77932 – ideal



83533- ideal, then tearing



T. Hender: Interplay of MHD and W peaking

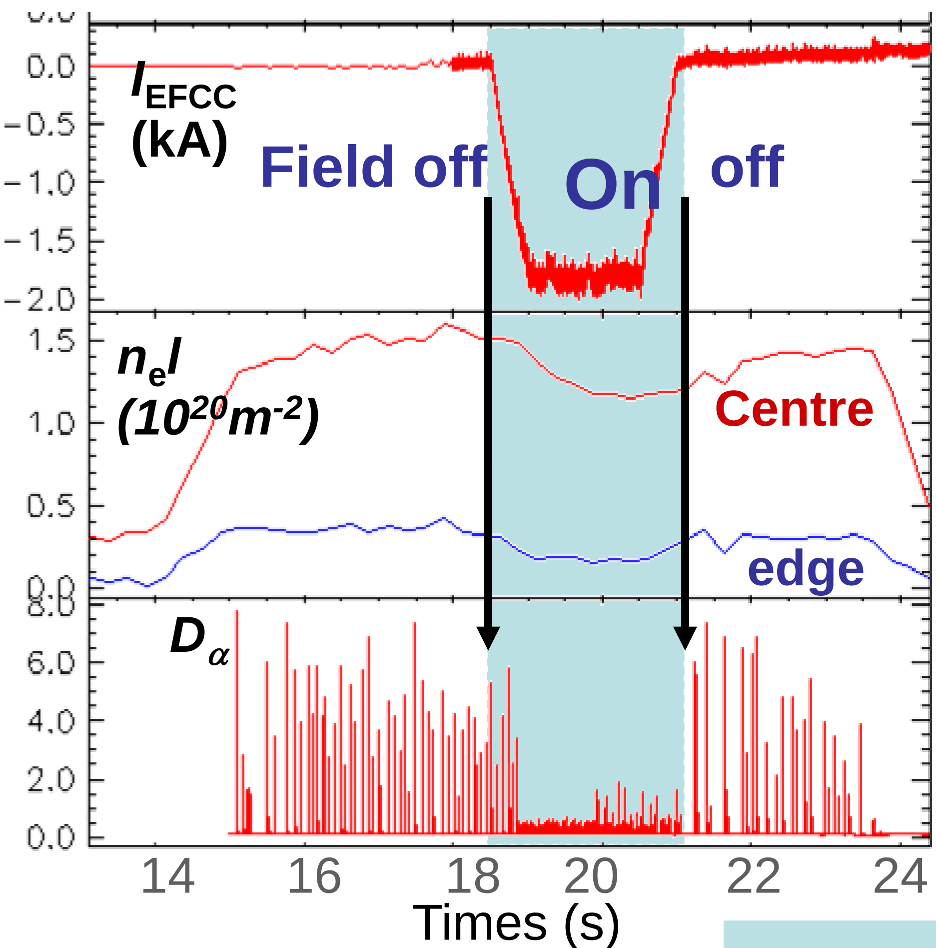
Graves

4

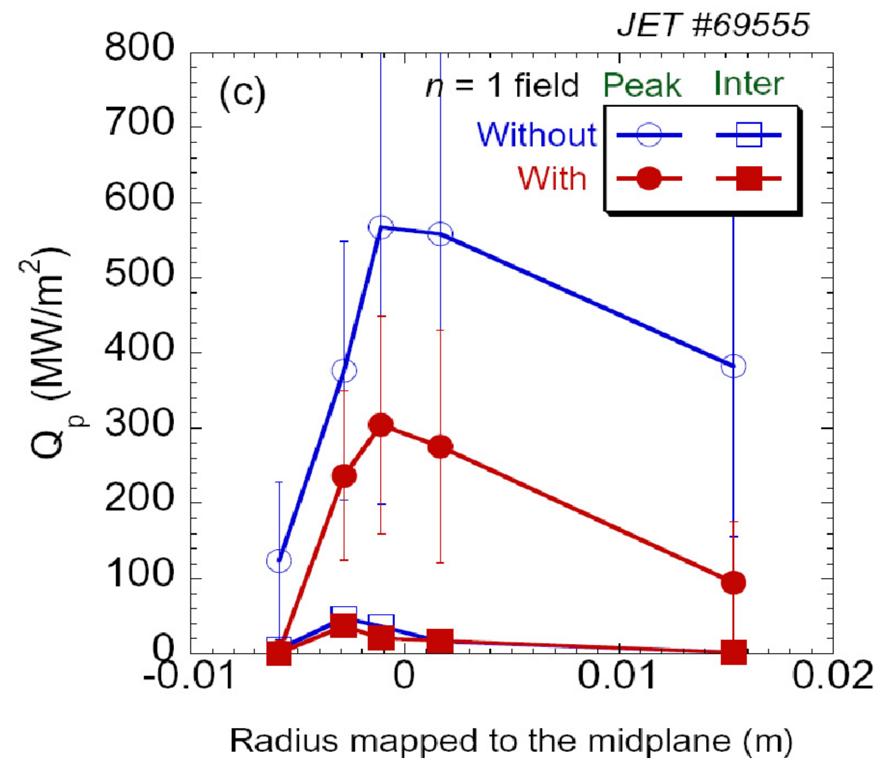
TAILORING A 3D EDGE FOR ELM CONTROL

Active ELM Control with Low *n* Magnetic Perturbation fields on JET

I_p = 1.8 MA; B_t = 2.1 T; q_{95} ~ 4.0; δ_U ~ 0.45



Heat flux onto the outer divertor



Y Liang, et al, PRL, 98, 265004 (2007)

Y Liang, et al, PPCF , 49, B581 (2007)

Y Liang et al, JNM, 390–391, 733–739 (2009)

Active ELM control (frequency/size) observed in a wide q_{95} window, but no ELM suppression

- **Many** physical mechanisms can affect toroidal rotation:
  - In an axisymmetric tokamak, turbulent transport provides a few candidates (especially for residual stress)
  - Break the toroidal symmetry and NTV will give you even more of them
- Rough estimates indicate that turbulent transport and NTV will often have a comparable effect on the stationary rotation profile
- This is not the full story:
  - the boundary condition (friction on neutrals, CX losses, orbit losses...) is at least as important.
  - difference between impurity (measured) and bulk rotation is likely non negligible
- Toroidal rotation physics is definitely complex...
  Makes our life a bit difficult but also provides more knobs to control the resulting profile (and to explain the wealth of puzzling

Camenen

RMP Conclusions

- Resonant Pfirsch-Schlüter currents

  - Modulate the local magnetic shear near rational surfaces

  - Effect sensitive to q95, RMP phase, pressure gradient

  - MHD ballooning: stabilizes some field lines, destabilizes others

  - No conclusions yet for ITG turbulence: sometimes stabilizing, sometimes destabilizing.

- Big 3D deformations, as observed in experiment (cm-sized)

  - Modulate significantly most of the relevant quantities for turbulence

  - Enhances ITG turbulence when br/B0~10^-3

  - Decrease in long range poloidal correlation – primarily a NL effect

  - Evidence of enhanced GAM damping

- Future work

  - Closer modeling of experiments

  - Modeling the pedestal: KBMs

Bird

Summary

- With RMP, edge equilibrium profiles (n_e,T_e, V_f, E_r) are modified.
- With RMP, edge fluctuation amplitudes and transport are affected.
- With RMP, both S(f) and S(k) are modified.
- With RMP, turbulence correlation lengths are changed.
- With RMP, turbulence poloidal propagation changes sign, consistent with E_rXB flow change.
- With RMP, blob transport is reduced in the SOL.
- With RMP, GAM zonal flows are suppressed.

All above results suggest that a stochastic magnetic boundary by RMP may have profound influence on edge turbulence and turbulent transport, and hence, for plasma-wall interaction / plasma confinement.

Xu

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5

3D PLASMA-WALL INTERACTION AND DIVERTOR

Structure of talk

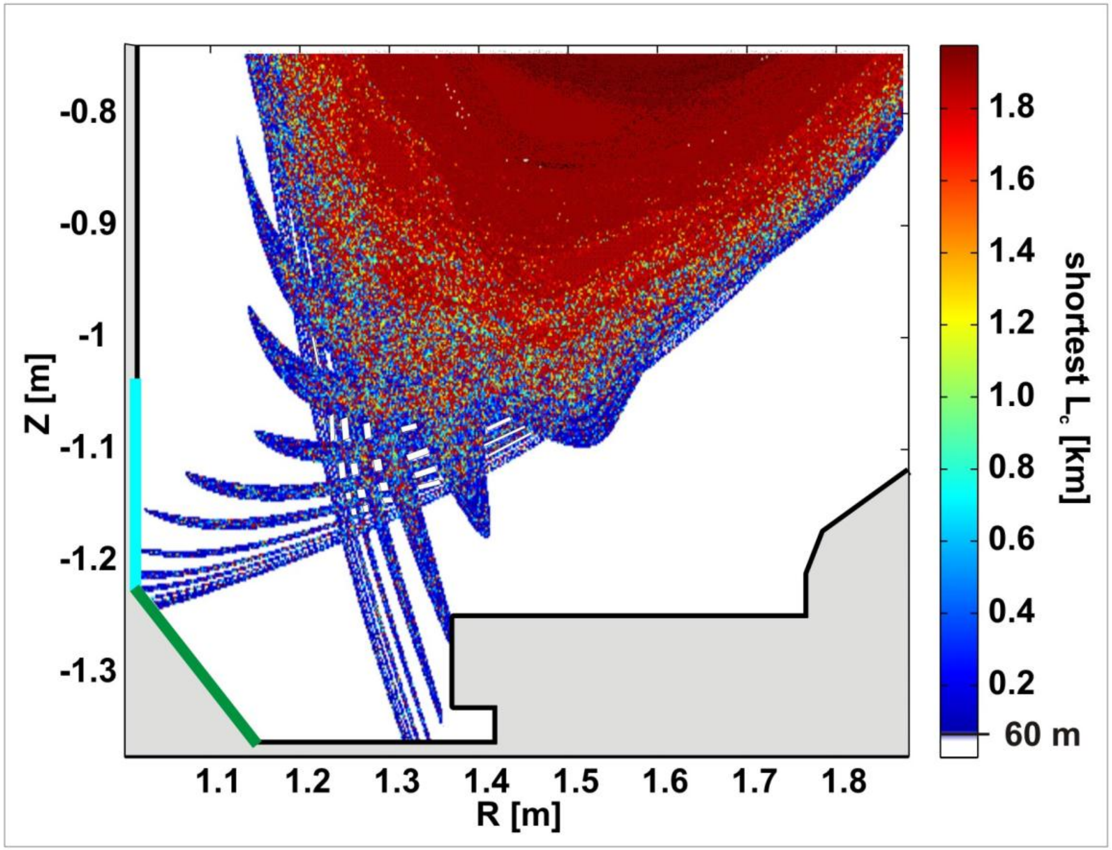
JÜLICH FORSCHUNGSZENTRUM

Motivation: why are 3D effects relevant in tokamaks?
ELM control with RMP

3D plasma boundary and plasma surface interaction
New state with new features

- RMP fields applied for ELM control break the axisymmetry of the plasma boundary

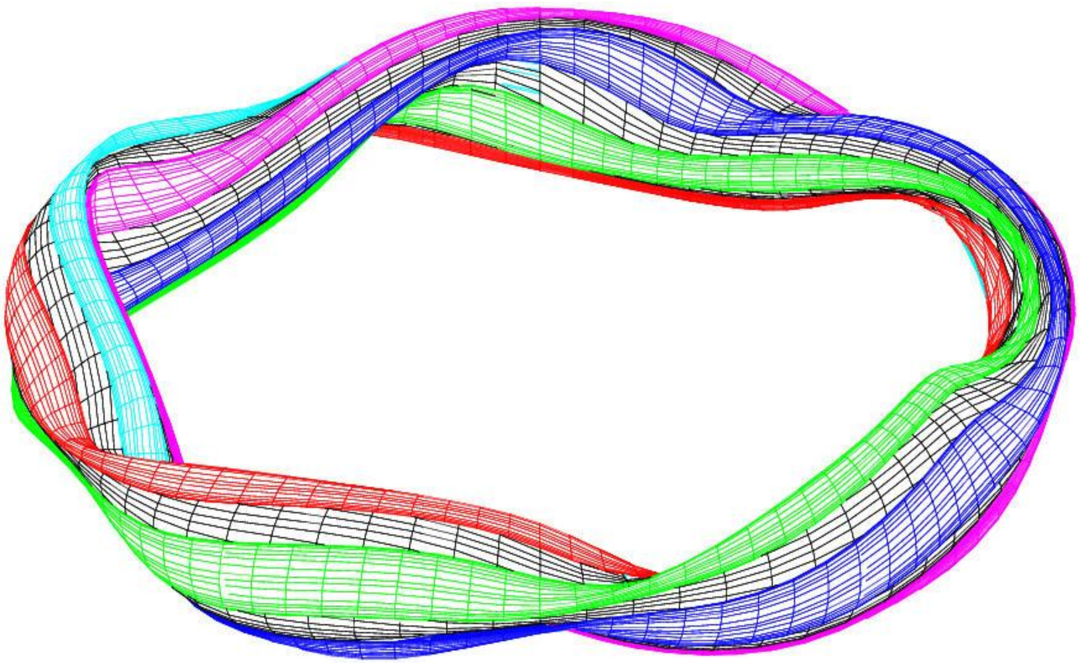
  - The separatrix is very sensitive to external and internal perturbation fields

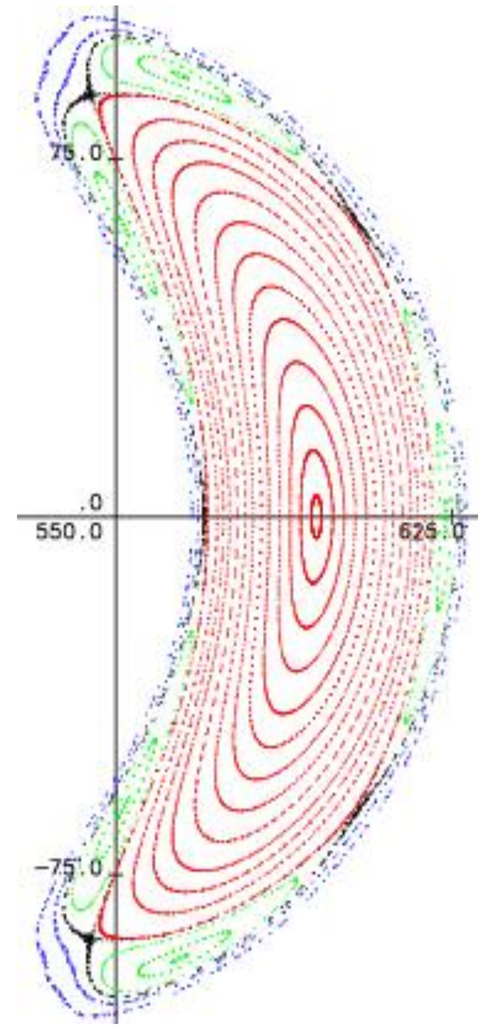


- Typical magnetic perturbation field strengths B_r applied are $B_{r,\,n=3}$= 4G, i.e. $B_r/B_T = 0.5 \times 10^{-4}$

Schmitz

The W7-X edge topology

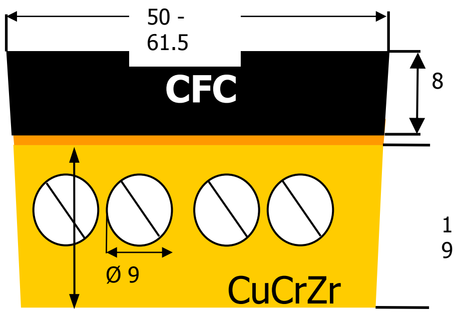


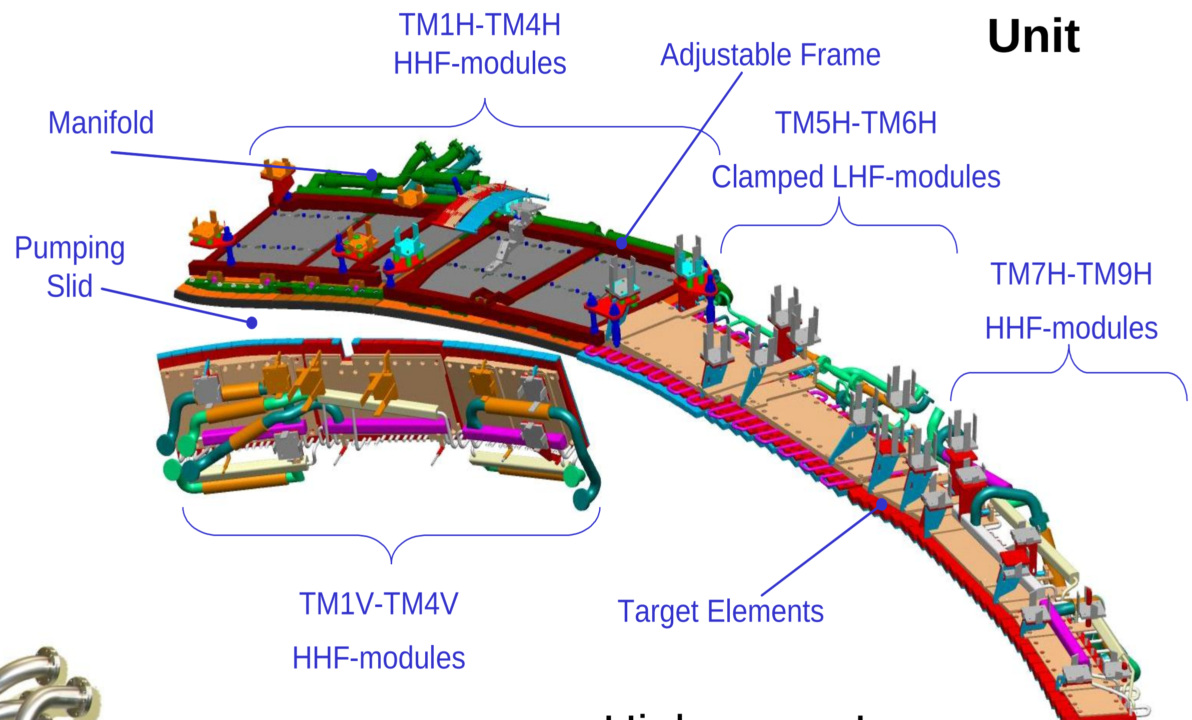


- “Standard configuration”: Edge iota=1=5/5=n/m
  - Island chain consists of five independent island bundles
- “High iota”: edge iota=5/4.
  - Island chain is one long bundle
- “Low iota”: edge iota=5/6
  - Island chain is one long bundle
- In all three cases the magnetic shear is low and the island are large and can be diverted

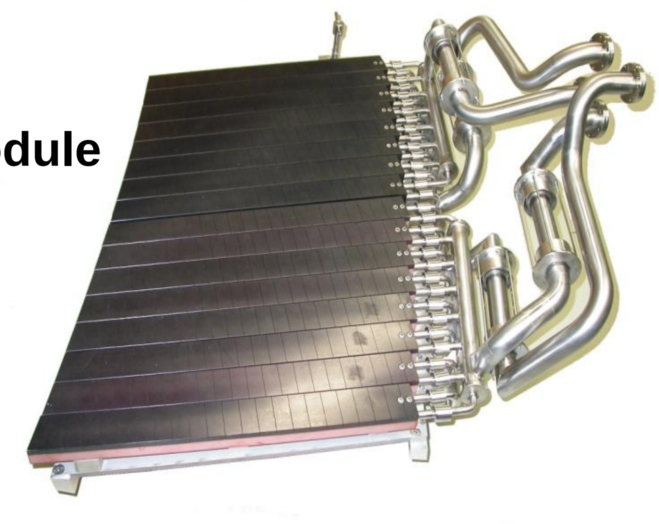
From J. Kisslinger, W7-X divertor design revie

High Heat Flux (steady state water-cooled) divertor





Module



	High power	Low power
	$10\ MW/m^2$	$1\ MW/m^2$
Total area	$19\ m^2$	$6\ m^2$
Target **units** (10)		
Target **modules**	100	20
Target **elements**	890 376	250 end of 2013
Plasma facing mat.	CFC	Graphite

6

MHD STABILITY AND ITS CONTROL WITH 3D EFFECTS

Stellarator versus 3D tokamak: results

The numerical effort for
- **transformation into magnetic coordinates, and**
- **stability studies**

is much higher for 3D tokamak equilibria than for stellarator equilibria, because of
- **the numerous rational surfaces, and**
- **the strong bending of the poloidal coordinate lines.**

3D effects of RMP-coils in ASDEX Upgrade: results

- **The corrugation patterns of the flux surfaces reflect the kink structure of the nearest rational q-surfaces and the periodicity of the perturbation field.**

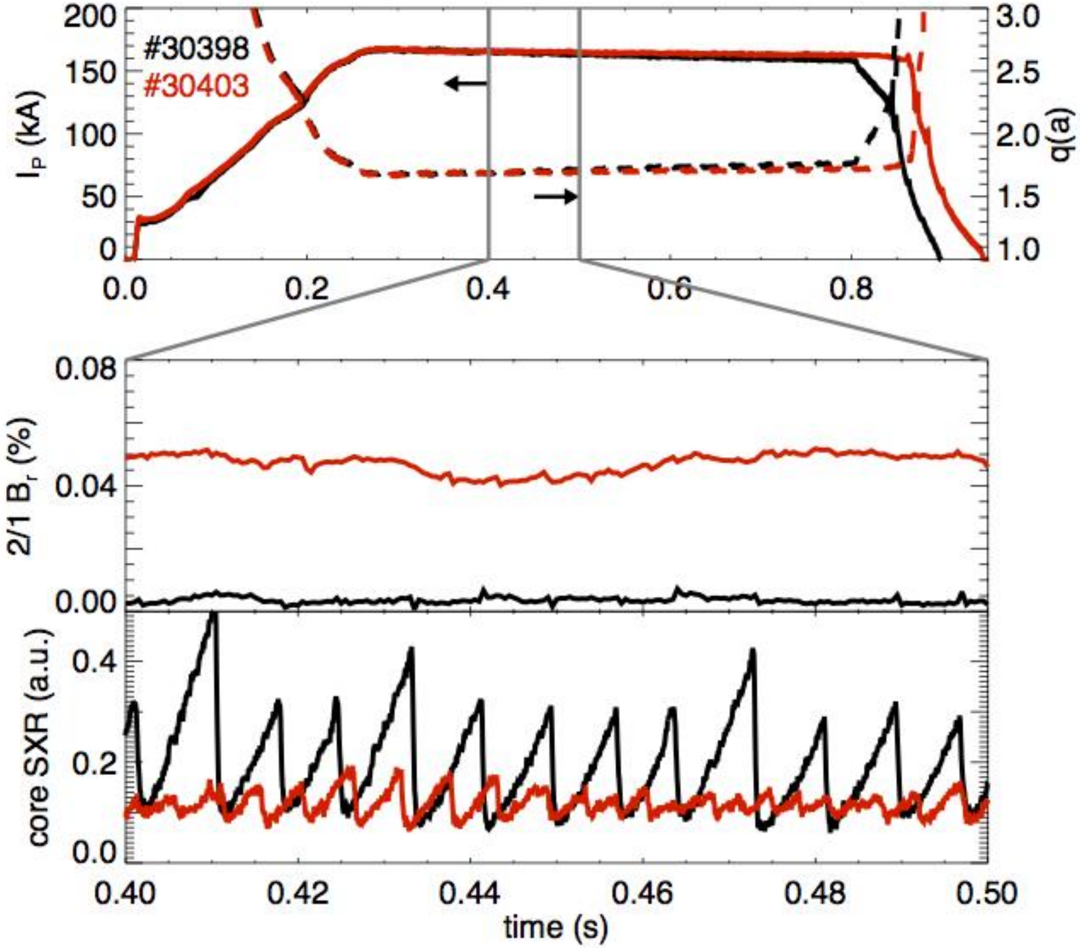
- **Odd and even RMP-coil currents modulate strength and phase of the corrugation.**

- **Here, both, stabilizing and destabilizing effects of the RMP-field have been found.**

- **In order to get an accurate eigenvalue many poloidal harmonics (here: ~ 30 poloidal harmonics per n) and several n have to be taken into account. The two toroidal harmonics, which have been considered here, are very probably not enough.**

→ **a tremendous numerical effort is necessary**

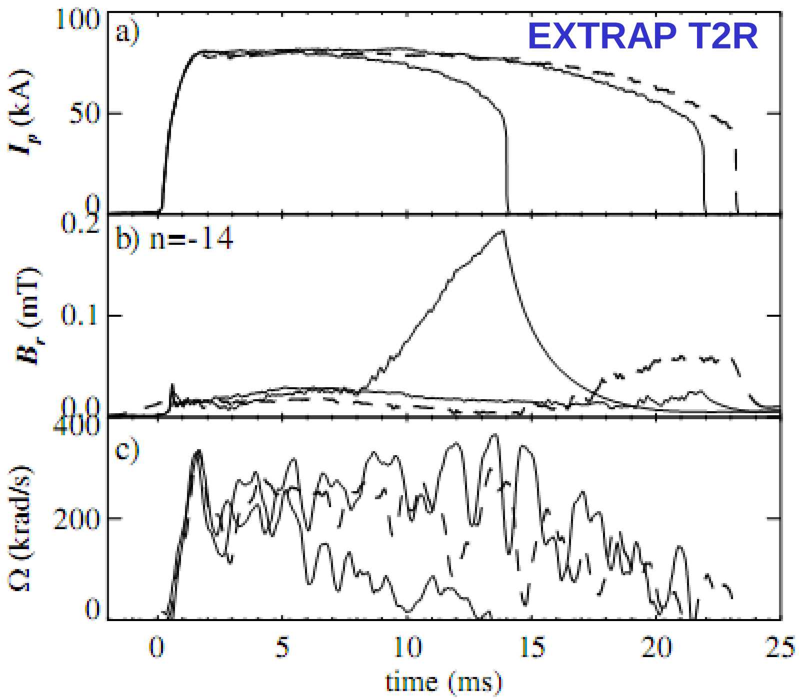
ST: smaller and more frequent



Terranova

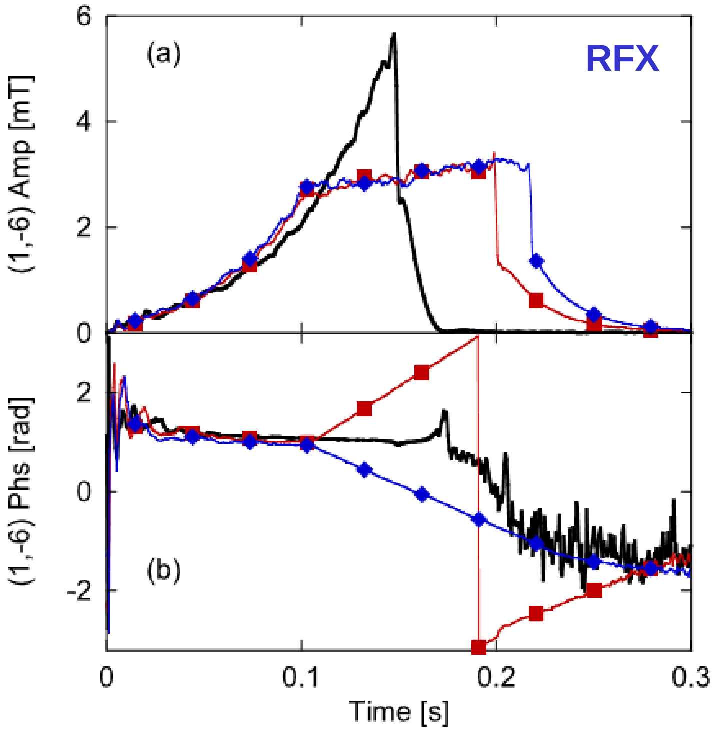
What one can achieve in RFPs with external coils ?

Feedback Stabilization of Multiple Resistive Wall Modes



[P. R. Brunsell et.al. , PRL, 2004]

Decoupling and active rotation of a particular RWM

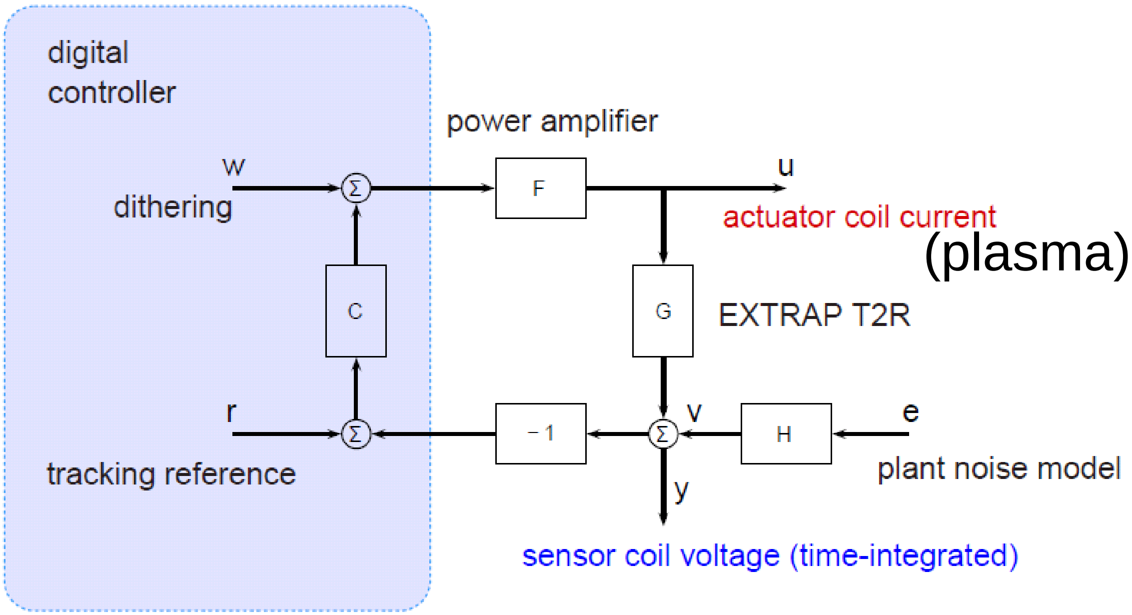


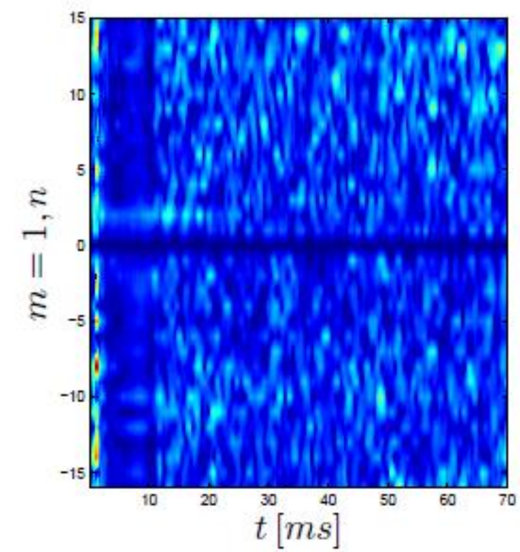
[T. Bolzonella, V. Igochine, et.al., PRL, 2008; V. Igochine, T. Bolzonella, et.al., PPCF, 2009]

Close loop system identification (reversed field pinch)

Control theory has deeply developed tools which can be applied to MHD control.

Example: Dithering technique in EXTRAP T2R

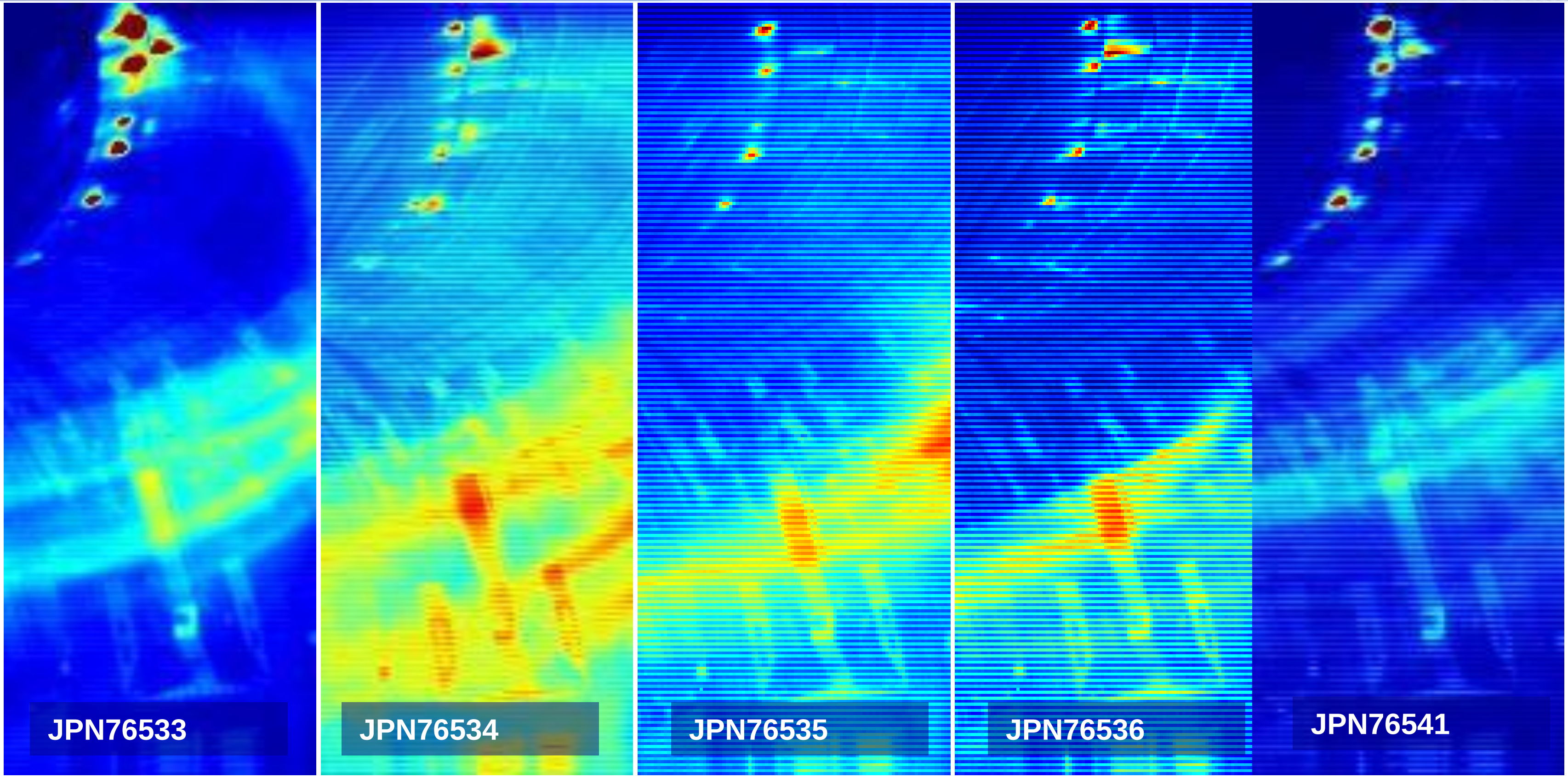




E. Olofsson et al, “Closed loop direct parametric identification of magnetohydrodynamic normal modes spectra in EXTRAP T2R reversed-field pinch,” Proceedings of the 3rd IEEE Multi-conference on Systems and Control (MSC) July 2009

E. Olofsson et al, RFX-mod programme workshop, 2011,

Runaway Electron energy is localised

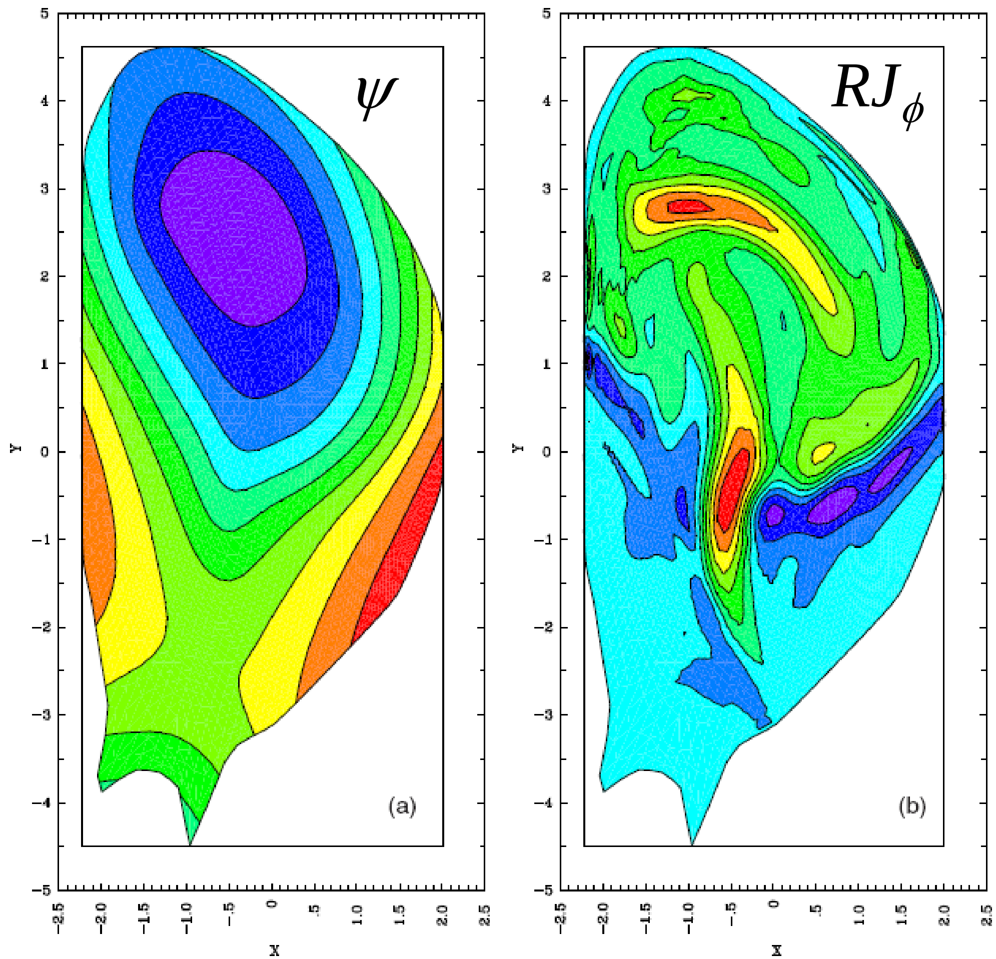


I_{RE}=502 kA | I_{RE}=425 kA | I_{RE}=285 kA | I_{RE}=360 kA | I_{RE}=502 kA

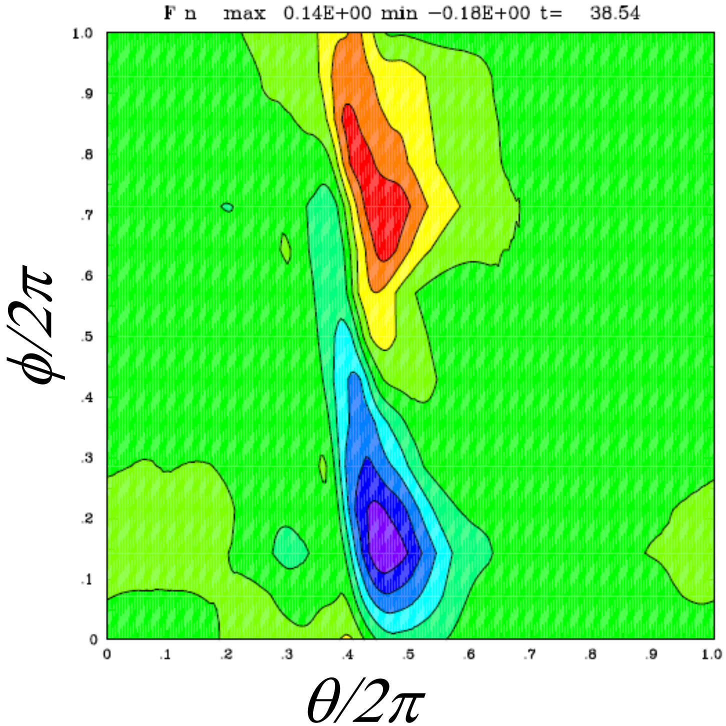
- The poloidal extent less than two tiles (area <1.3 m^2) of which only a fraction is wetted (installation inaccuracy)
- 0.5 MJ in 2 ms give $\Delta T \sim 800^oC$ ➔ wetted area is ~0.3-0.5m^2

Hender

VV Current Asymmetries – 3D MHD



Asymmetric force normal to wall

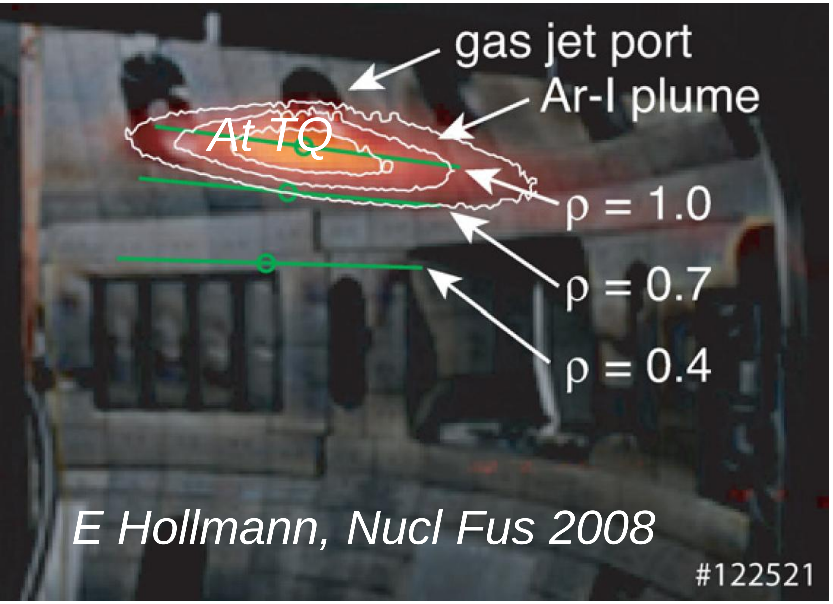


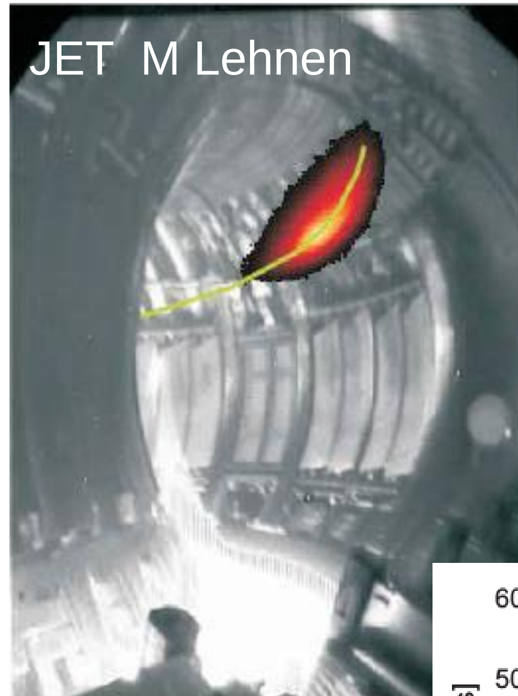
Strauss and Paccagnella, PoP 2010

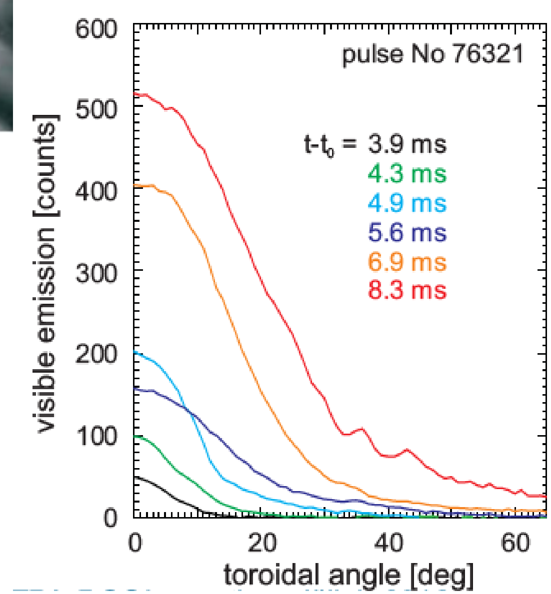
Hender

Massive Gas Injection is localised (⇒3D)

DIII-D







Hender

Summary

- Tokamak operation and performance is constraint by operational limits
- Hard (disruption) and soft (confinement deterioration) limits exist
  - Radiative collapse / MARFEs
  - Impurity accumulation
  - External kink modes (q_a)
  - (Neo-classical) tearing modes, double tearing modes
  - Locked modes / error fields
  - Resistive wall modes
  - Vertical instability (VDEs)
- Stationary performance is limited by neo-classical tearing modes
- Mode stabilisation, error field correction, and prevention/amelioration of disruptions required to optimise performance in fusion experiments

⇒ A tokamak reactor needs active control of MHD stability

7

3D EFFECTS AND FAST PARTICLES

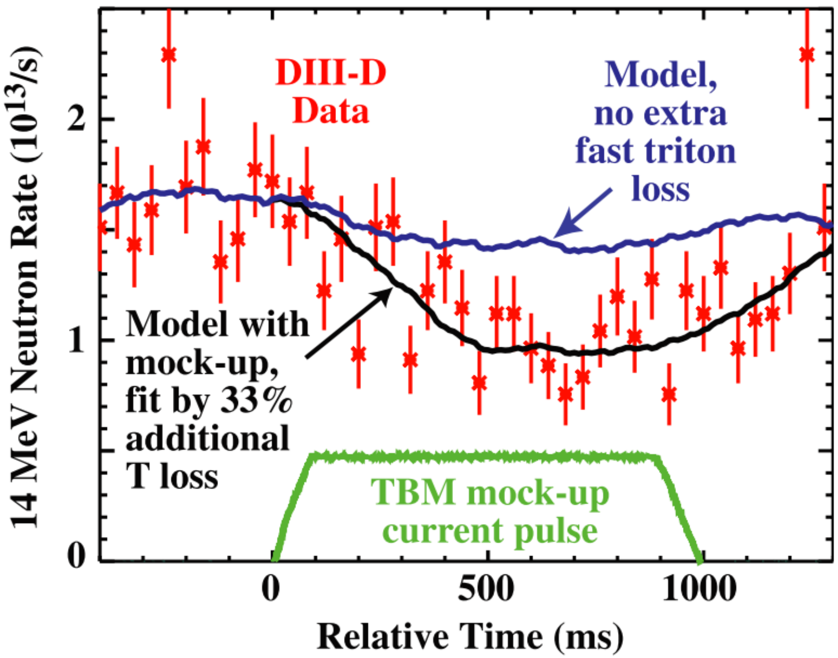
Contents

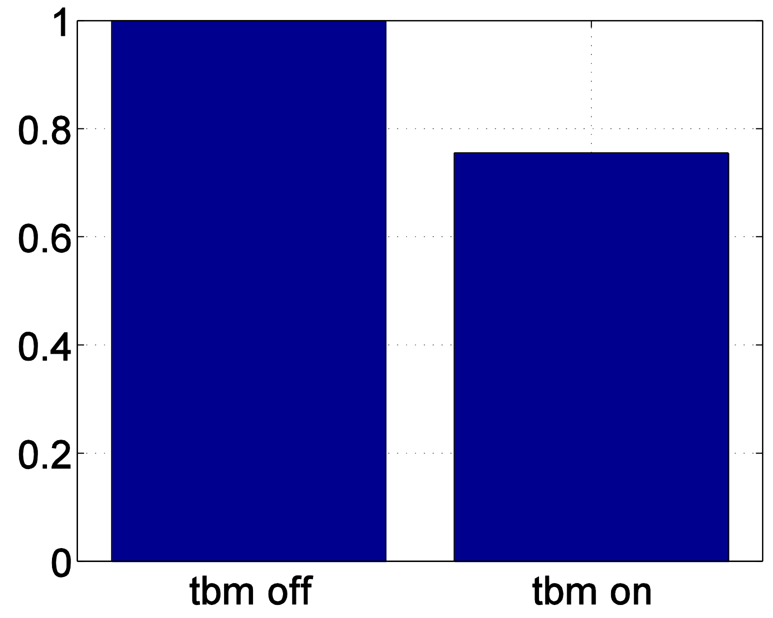
- ★ A short introduction to the tokamak world of charged particles
- ★ Away from axisymmetry, Part I: external 3D effects:
  - TF coils
  - Ferritic inserts (FI)
  - TBMs and other magnetized materials
  - ELM control coils (ECC)
- ★ Away from axisymmetry, Part II: internal 3D effects
  - Neoclassical tearing modes (NTMs)
  - Alfvén Eigenmodes (X-AEs)

These topics are seasoned with simulation examples.

DD → DT → n (14 MeV)

M. Schaffer & al, Nucl. Fusion **51** (2011) 103028





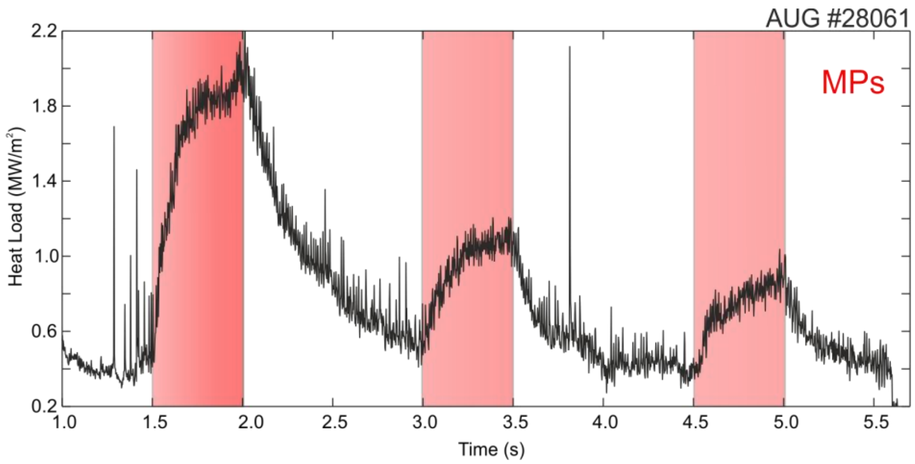
Experimental neutron flux in the TBM mock-up experiment

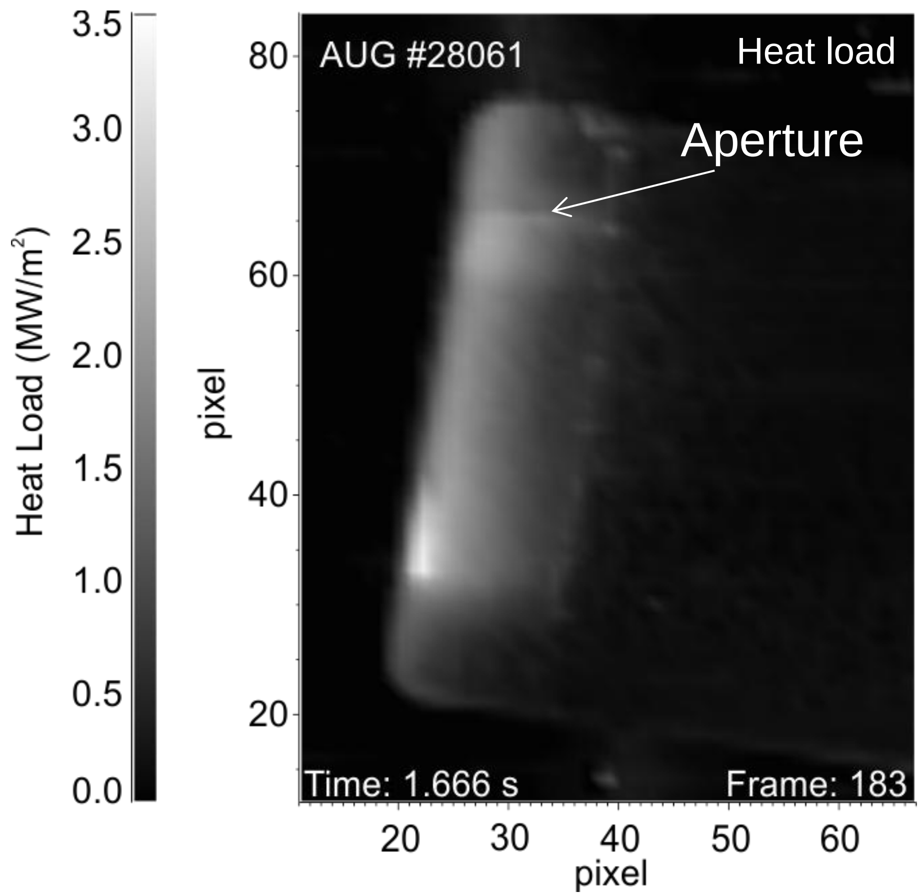
Fraction of *confined* tritium in the plasma as calculated by ASCOT

Kurki-Suonio

Infrared camera measures temporal evolution of heat load on FILD detector head, Wall & Divertor

- Heat load is up to x6 larger with RMPs than without RMPs
- Largest heat load with lowest plasma density (collisionality) and largest plasma response (density pump-out)





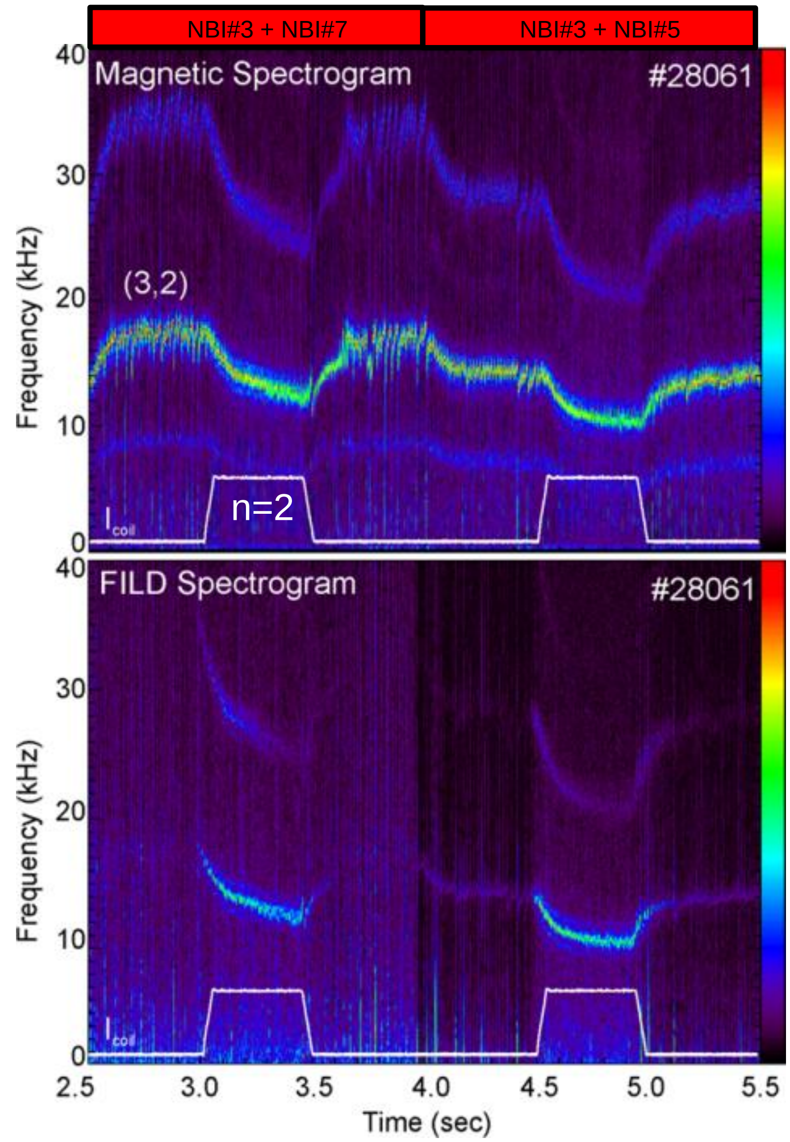
- Relaxation time (decay) much longer than response time (rise)
- Heat load measurement can be used to quantify fast-ion losses

Garcia Munoz

External RMPs may couple to internal MHD fluctuations

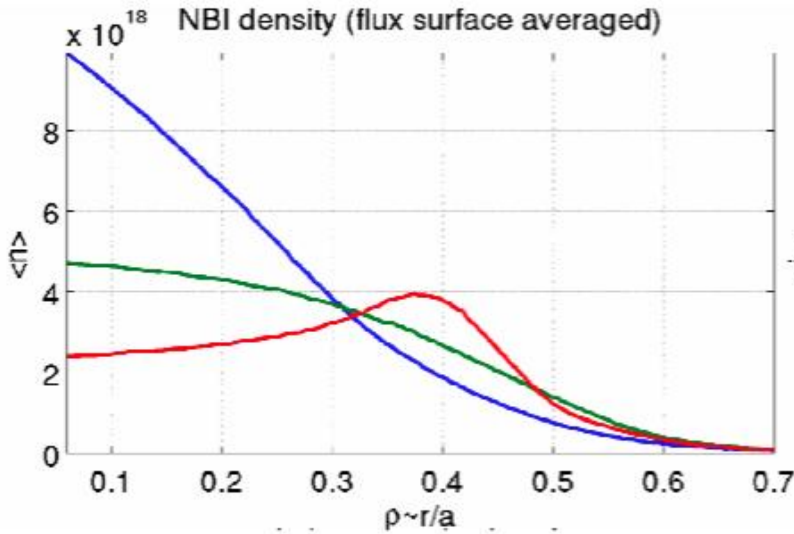
- (3,2) NTM causes measurable fast-ion losses only when RMPs are applied
- Modulation of island width and rotation with RMPs

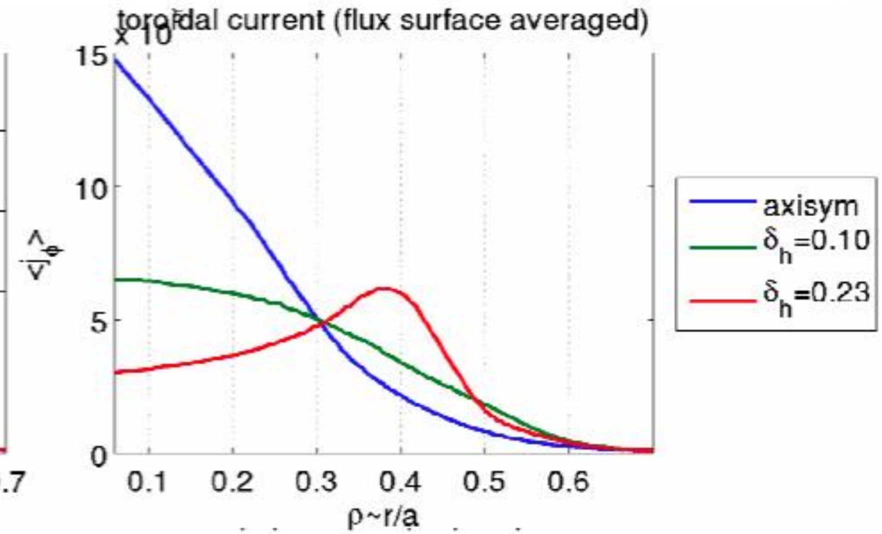
Fast-ion loss mechanisms may also couple without direct MHD coupling



Garcia Munoz

MAST NBI modelling

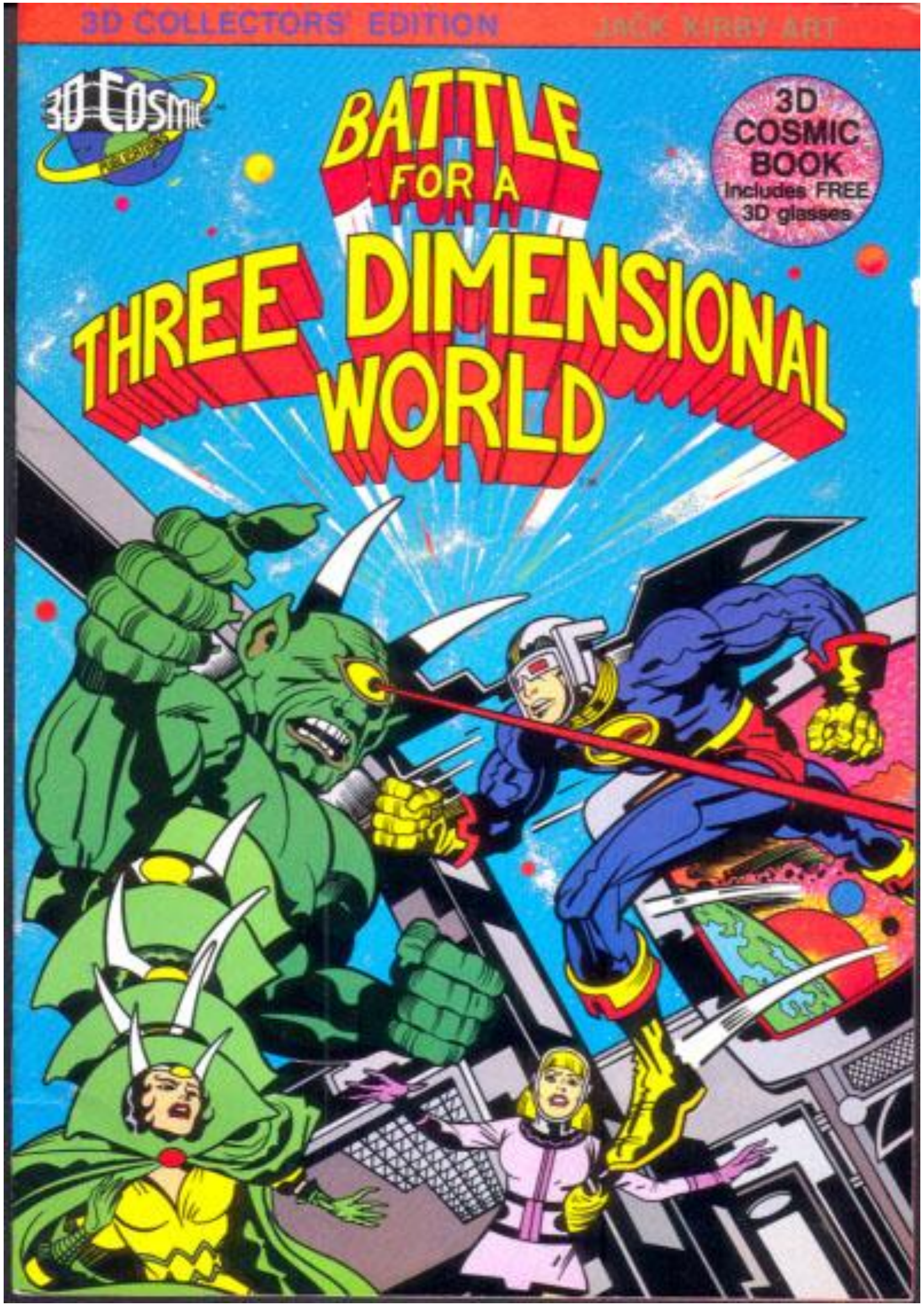




Particles deposited off axis because the LLM moves the axis relative to the NBI injection.

Total number of confined NBI ions almost the same with or without LLM. But heating and current drive off axis.

D. Pfefferlé: poster


3D COLLECTORS' EDITION
JACK KIRBY ART
3D COSMIC
BATTLE FOR A THREE DIMENSIONAL WORLD
3D COSMIC BOOK
Includes FREE 3D glasses

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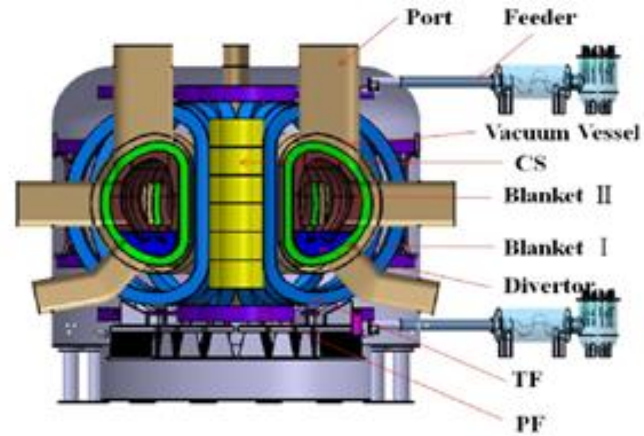
8

WHAT NEXT ?

- Experiments, experiments,….

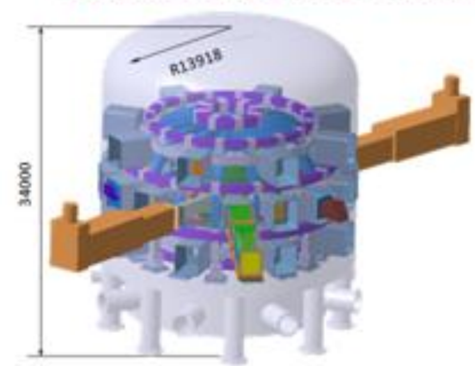
VV Conceptual Design (Superconducting)

Horizontal Big Windows



Up, Middle, Down 3 Windows

Middle Windows



ITER-like scheme

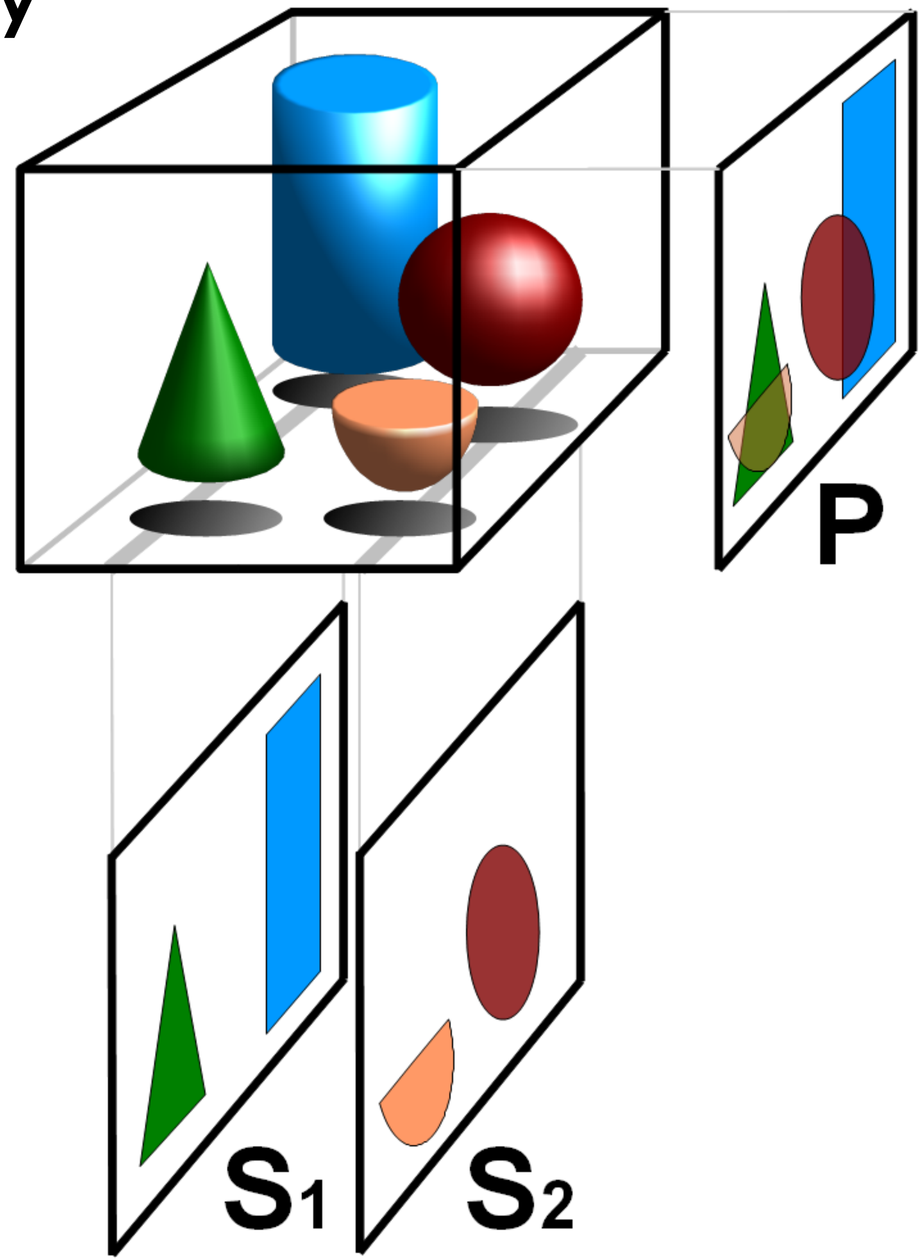
The VV design matched TF coils has been completed, which focused on the optimization of RH scheme to ensure the duty time of CFETR. Detailed design and engineering analysis will be done after the conceptual design completed.

- Use 3D views….

Allan M. Cormack

Godfrey N. Hounsfield

Tomography



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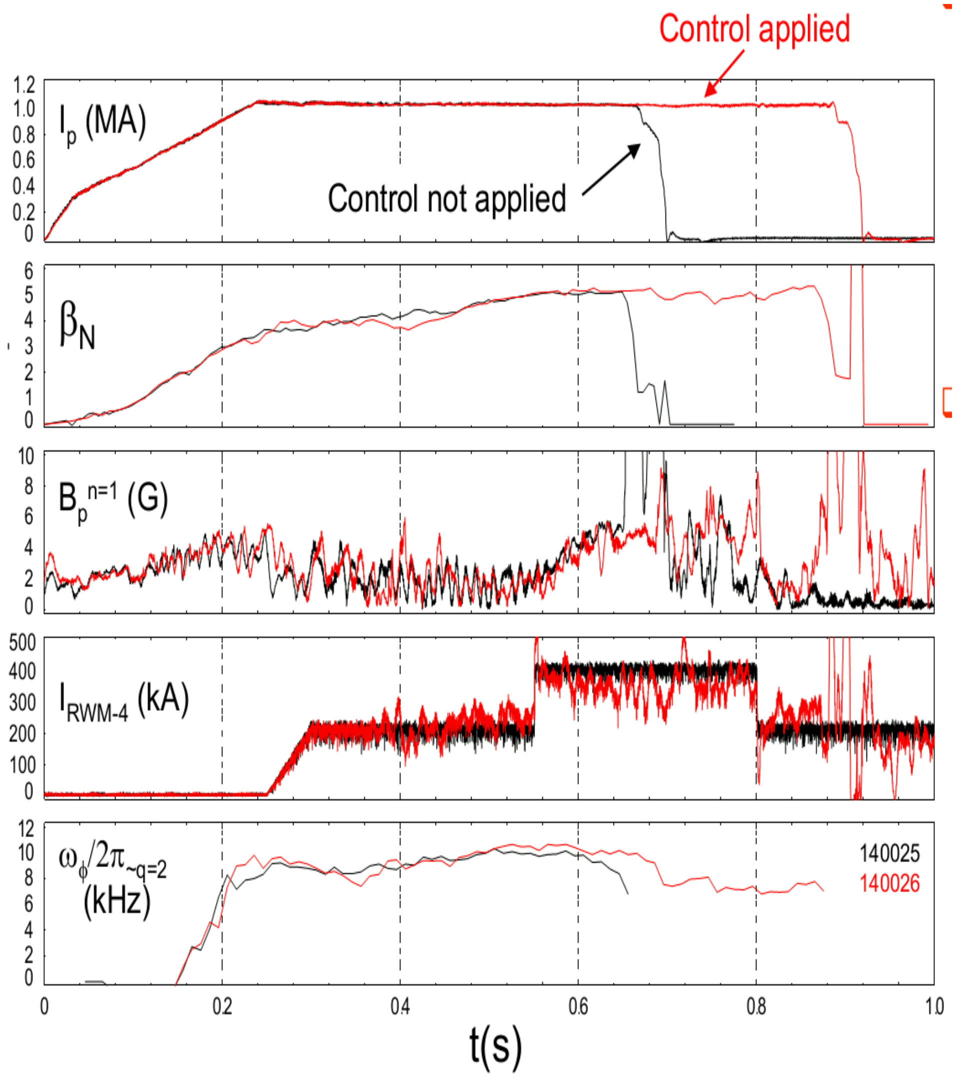
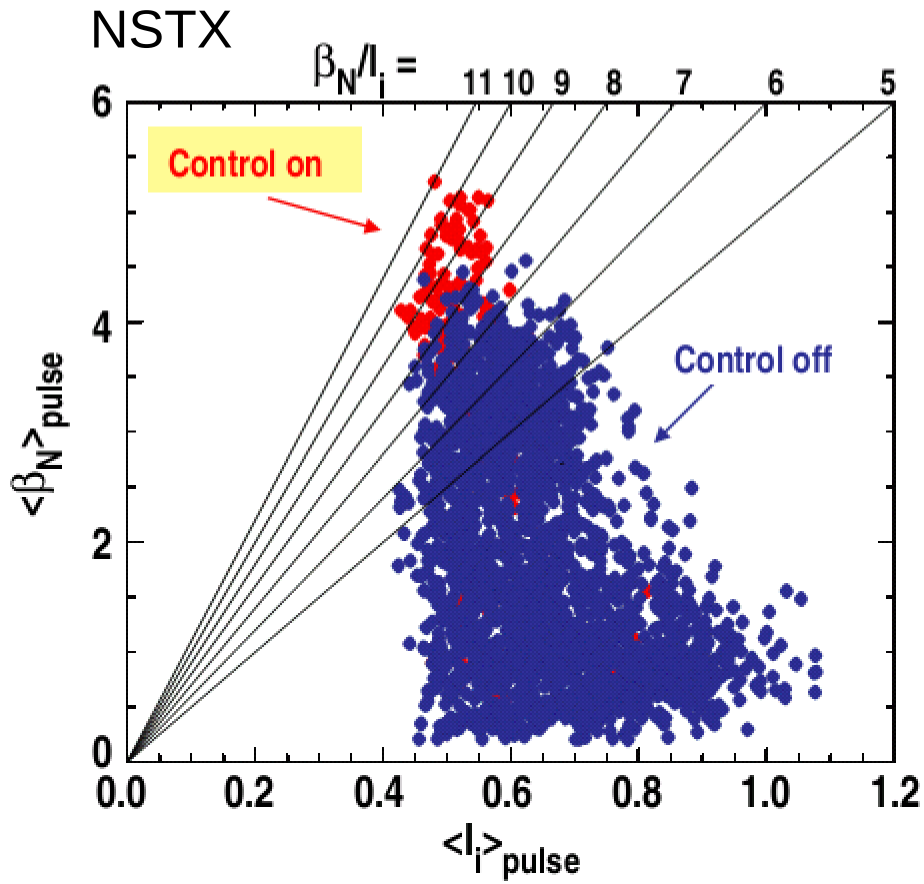
Different problems, common solutions: experiments

How important low n control close to the pressure limit?

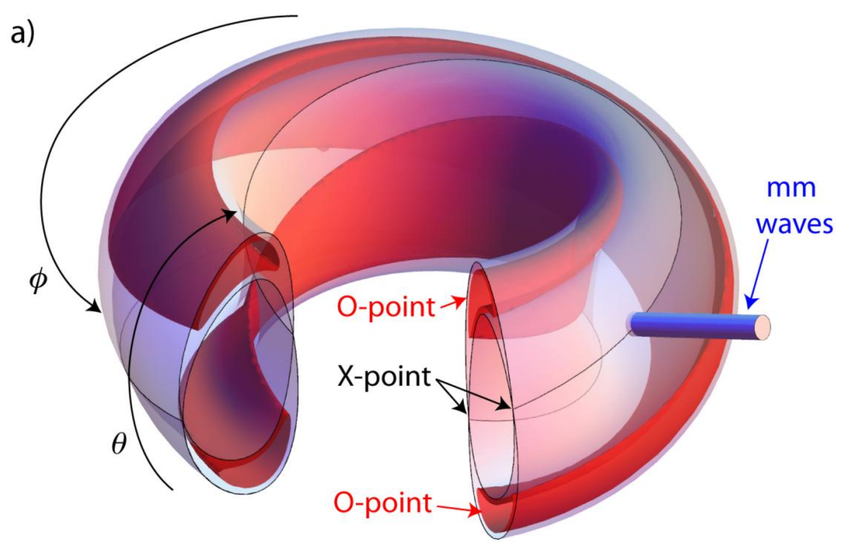


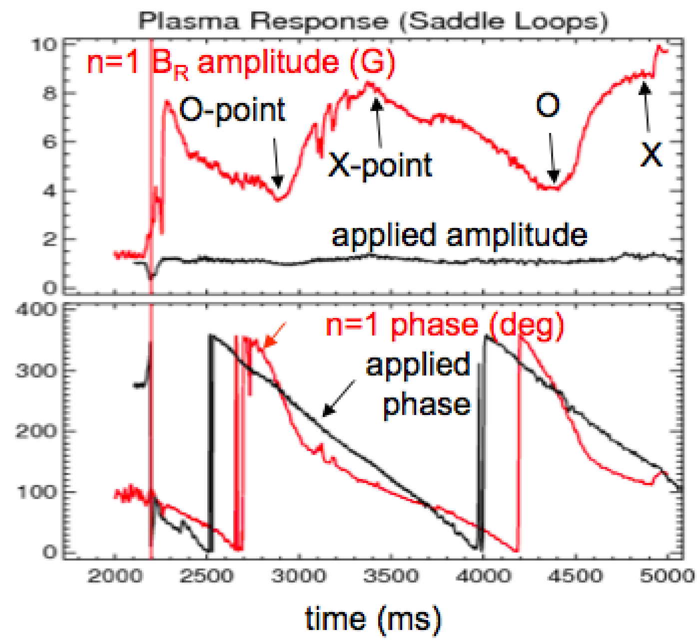


2010 *Nucl. Fusion* **50** 025020

Synergy between coils and ECCD

- Islands can lock in a **position not illuminated** by ECCD
- Bootstrap deficit in the island is like a wire carrying a counter-current.
- **Magnetic forces** can be exerted on this wire by coils **to drag the island in the optimum position for ECCD illumination**.

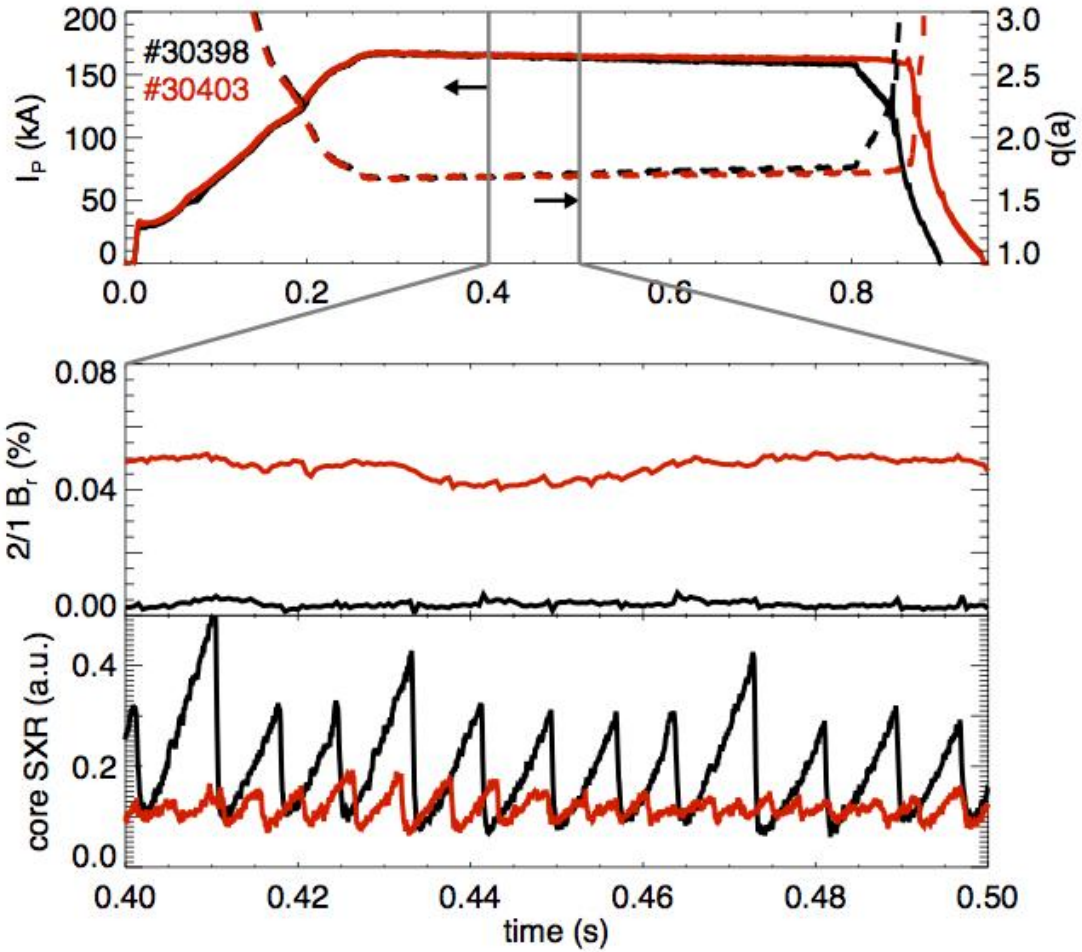




As the mode is dragged around the torus, its amplitude oscillates since ECCD is alternatively stabilizing (O-point) and destabilizing (X-point)

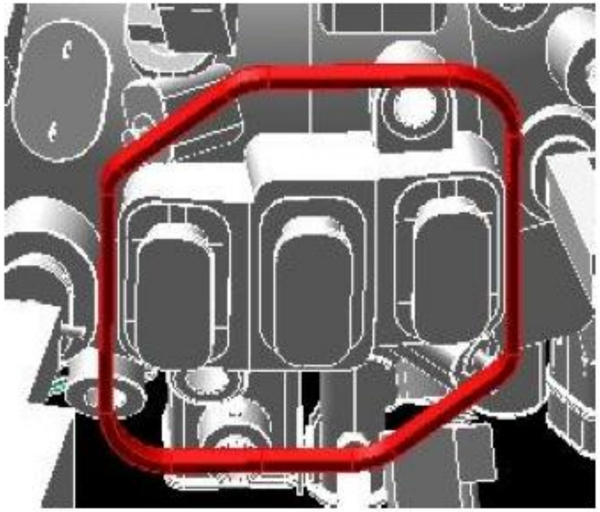
Volpe *et al* PoP **16** (2009)

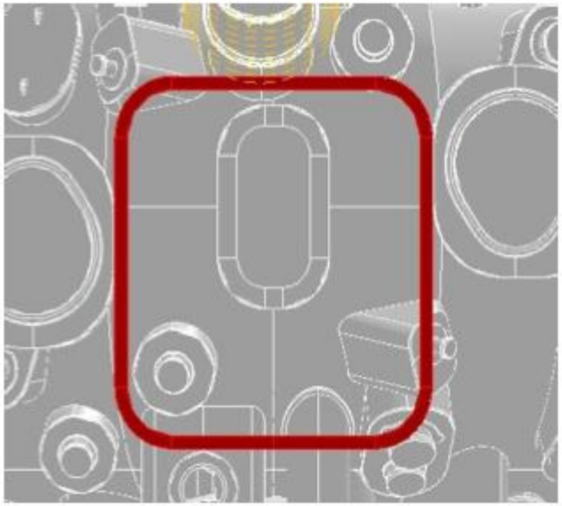
ST: smaller and more frequent



Terranova

… by 5 saddle coils (1 per magnetic field module) on the outboard side around the torus (copper coils outside cryostat)

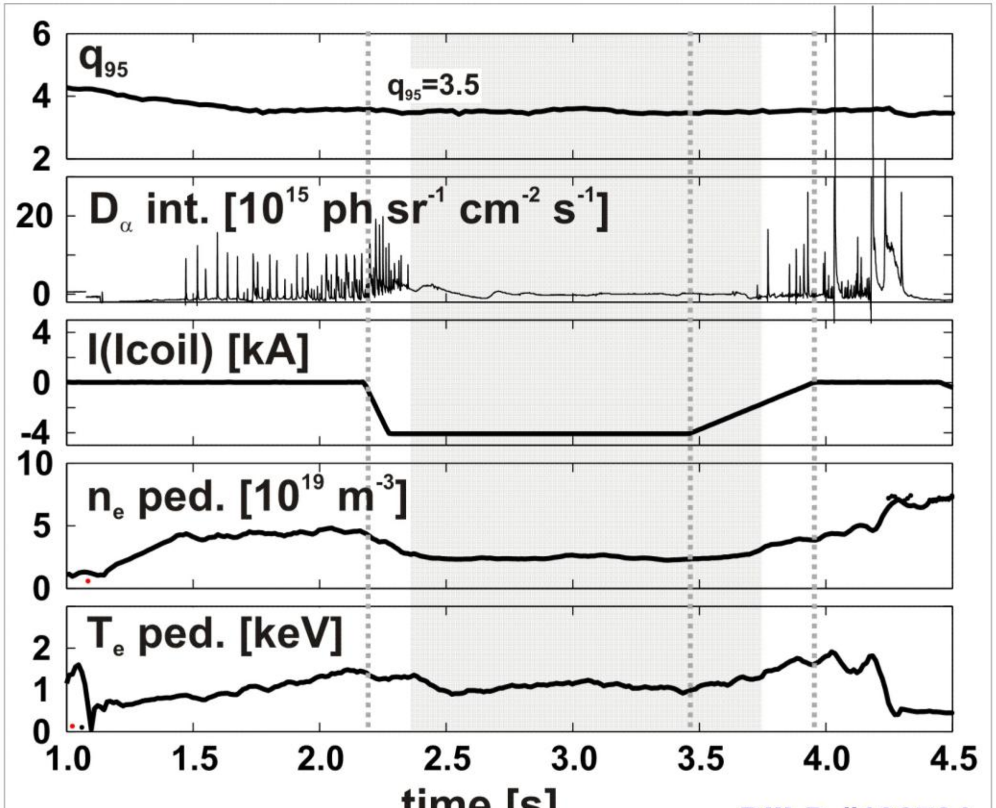




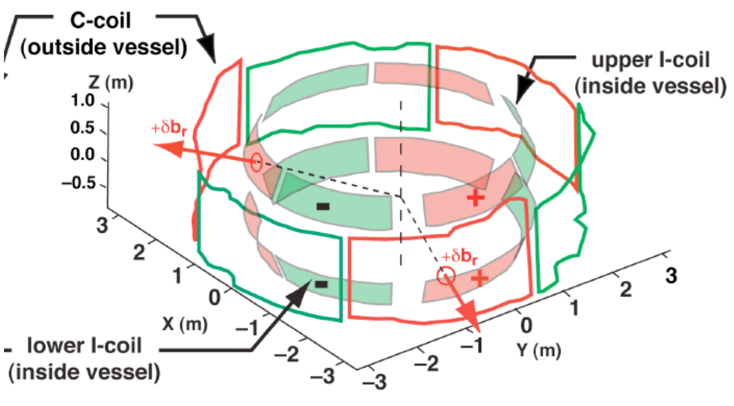
Effect of error fields:

Motivation: ELM suppression by edge resonant magnetic perturbations was demonstrated at DIIID

[T.E.Evans et al. Nature of Physics 2 (2006) 419]



[O. Schmitz et al. PPCF **50** (2008)]



Ex-vessel, mid-plane centered coils (C-coil, EFC)

In-vessel, off mid-plane coils (I-coil, RMP + EFC)

ELMs were suppressed at DIII-D for different edge collisionalities ν_e* and shapes, in particular ITER similar shape (ISS) at ITER relevant ν_e*~0.1 [T.E.Evans NF 2008]

Different problems, common solutions: codes

3D equilibrium and stability codes

3D equilibrium codes

NEMEC	upgraded version of NEMEC=NESTOR[1]+VMEC[2] code, [1]P. Merkel, [2]S. Hirshman, 3D free-bound. equilib. (assump. of nested flux surf.)
ANIMEC	W. A. Cooper, variant of the VMEC code designed to obtain 3D anisotropic pressure equilibria
PIES	A. Reiman, D. Monticello, 3D equilibrium code, handles islands and stochastic regions
HINT	T. Hayashi, 3D equilibrium code, handles islands and stochastic regions

Coordinate transformation into Boozer coordinates

COTRANS	E. Strumberger, coordinate transformation and code interface, contains parts of the JMC code of J. Nuehrenberg and R. Zille

3D linear ideal stability codes

CAS3DN	modified version (Non-equidistant radial grid) of the CAS3D code of C. Nuehrenberg
TERPSICHORE	D.V. Anderson, W.A. Cooper, uses finite elements in radial direction and Fourier decomposition in angular variables similar to CAS3D

RFP equilibria with VMEC

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VMEC solves non-linear MHD equations for an equilibrium with nested surfaces.

INPUT constraints:

1. $q(s) \propto 1/\iota(s)$
2. Pressure profile
3. Total Toroidal flux
4. Plasma boundary shape in terms of harmonic components

Fixed Boundary

INPUT guess:

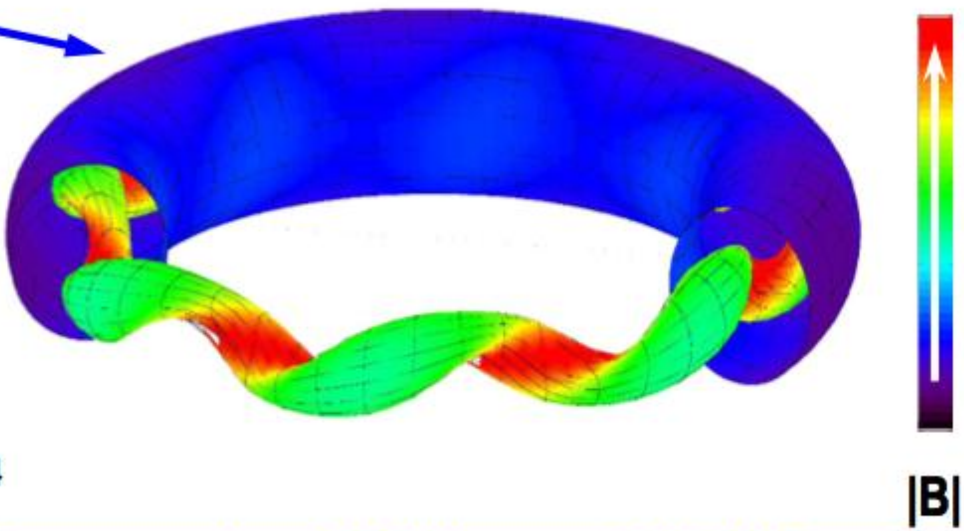
Magnetic axis structure

Configuration periodicity:

Dominant mode helicity (N_{fp}=7)

VMEC runs in <u>fixed boundary</u> mode with the constraints:

- N_{fp} = 7 (due to the plasma, not to external coils)
- NPOL=9
- NTOR=6
- LCFS shape: $\Delta_{1,0}$ $\Delta_{1,-7}$ $\Delta_{0,7}$
- Toroidal flux at the edge
- Safety factor profile q(s)
- Pressure profile



S.P. Hirshman and J.C. Whitson, Phys. Fluids **26** (1983) 3554

- **2010:** Control
- **2013:** 3D vs 2D
- **20??:**
  - Controlling 3D plasmas
  - Common 3D issues – and common solutions –
    - Pick topics, brainstorming on solutions from different worlds

Japanese proverb

“The frog in the well does not know the ocean”

Thanks to Katsumi Ida