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3D effects on fast (and slow) ion confinement and wall loads in tokamaks

T. Kurki-Suonio, Aalto University

for the ASCOT team

O. Asunta, E. Hirvijoki, T. Koskela,
J. Miettunen, S. Sipilä, A. Snicker,
and S. Äkäslompolo

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.

In the dream world of theorists:
The Perfect Axisymmetry

- Passing particles and banana-trapped ones
- Trapping due to $B_T \propto 1/R$ dependence in toroidal geometry

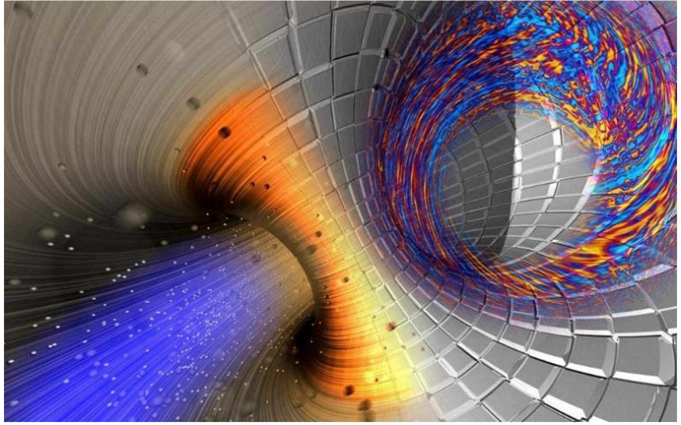
➔ NC transport w/ the step size of banana orbit width $\Delta_b \propto v/\Omega_p = mv/qB_p$.

increases w/ particle energy

reduces with I_p

➔ need high I_p to confine fusion alphas

Tokamak reality



- ★ Inside the plasma, a multitude of *MHD modes* can exist, pushing it around, twisting it and even breaking it into islands
- ★ Near the periphery, the plasma sees the *engineering* reality:
  - the field-producing coils are not infinitesimally close to each other
  - some components get magnetized, sucking in part of the magnetic flux
  - external coils shape and perturb (at least) the edge magnetic field

EXTERNAL 3D EFFECTS

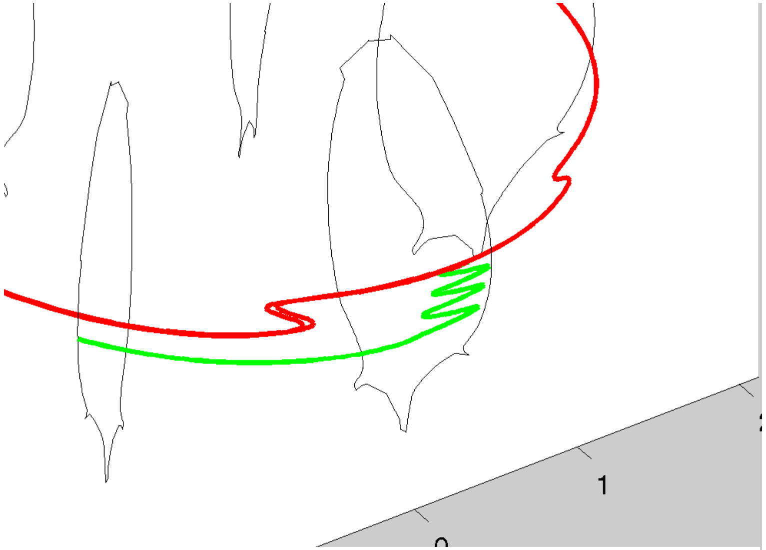
Basic tokamak reality

★ Only finite # of TF coils

➔ B-field becomes a "toroidal sausage" = Toroidal Field Ripple

➔ ions w/ small enough $v_{||}$ can get trapped even *toroidally*, between adjacent field coils

➔ direct ripple losses = practically vertical



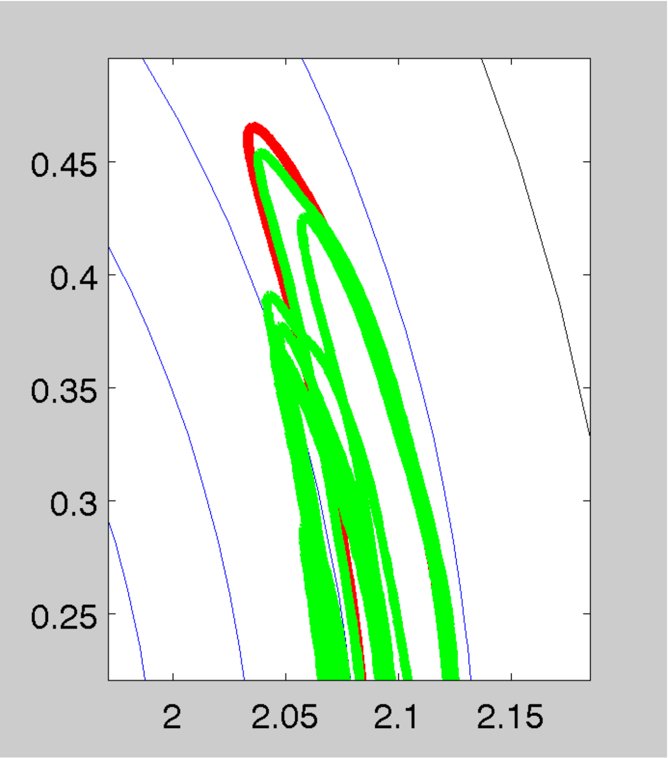
A 100keV deuteron v||/v = 0.07 followed for 100μs in AUG:

- axisymmetric B-field
- with TF ripple

Basic tokamak reality cont’d

★ Even ions w/ higher $v_{||}$ get affected: the banana tips start to wander due to the toroidal variation of the ‘TF sausage’

- ➔ ripple-enhanced collisional diffusion, or
- ➔ stochastic ripple diffusion



A 100keV deuteron $v_{||}/v = 0.2$ followed for 100μs in AUG:

- ➢ axisymmetric B field
- ➢ with TF ripple

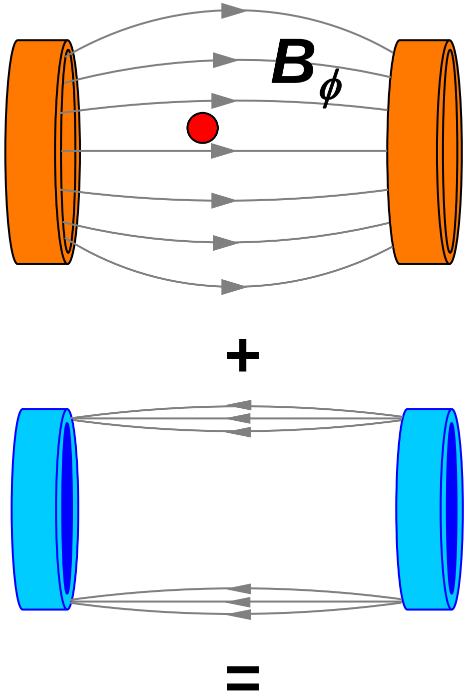
ITER reality:

There is more to life than the TF ripple...

Even the harmonic ripple structure is destroyed by things like

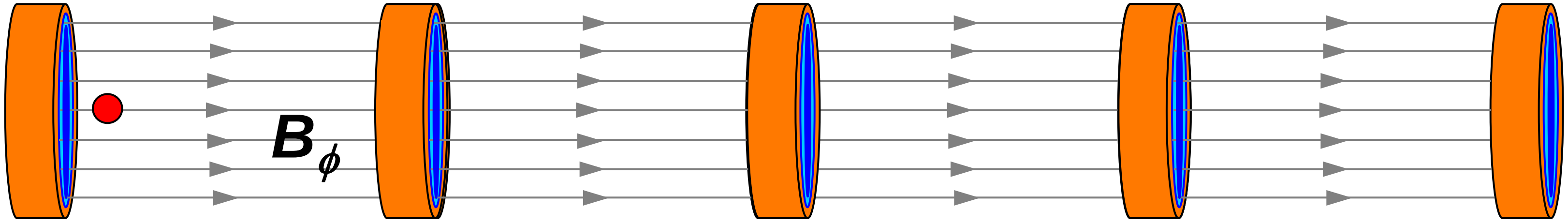
- ★ Presence of ferritic material in the walls
  - * Ferritic inserts (FI) reduce the TF ripple
  - * Ferritic structures can introduce strong *local* perturbations. Prime example: TBMs in ITER
  - * Also by lack of FIs (around NBI ports)
- ★ External coils can generate their own 'ripples' at their will.
  - * Prime example: ELM mitigation coils in ITER (and, today, at AUG, DIII-D, JET)

Reducing toroidal ripple: ferritic inserts

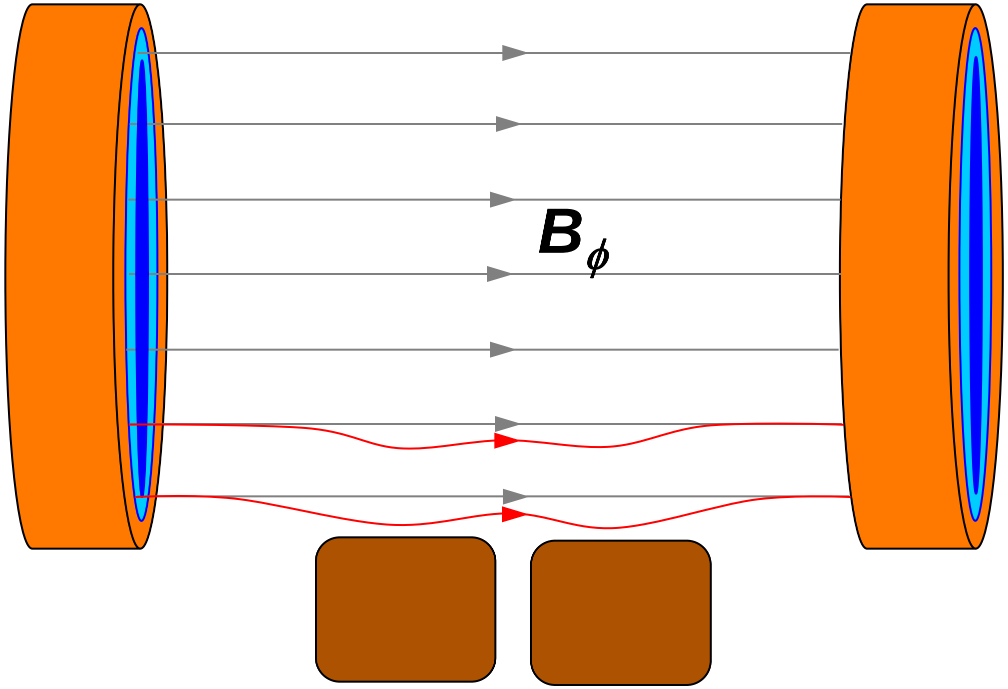


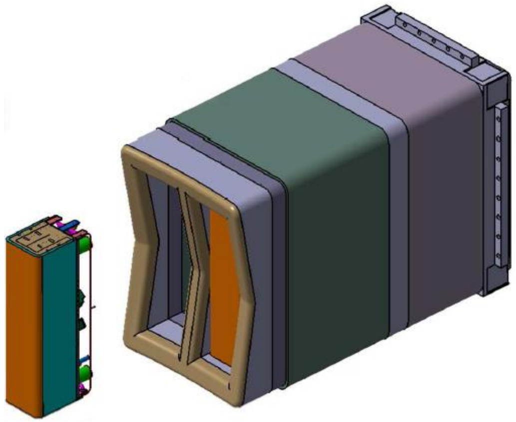
A finite number of TF coils
→ non-axisymmetric field.
The local magnetic “bottle” between two TF coils can trap charged particles, which quickly drift out of the plasma.

With ferromagnetic steel inserts placed at the coils, the ripple can be minimized.



Test Blanket Modules (TBM)





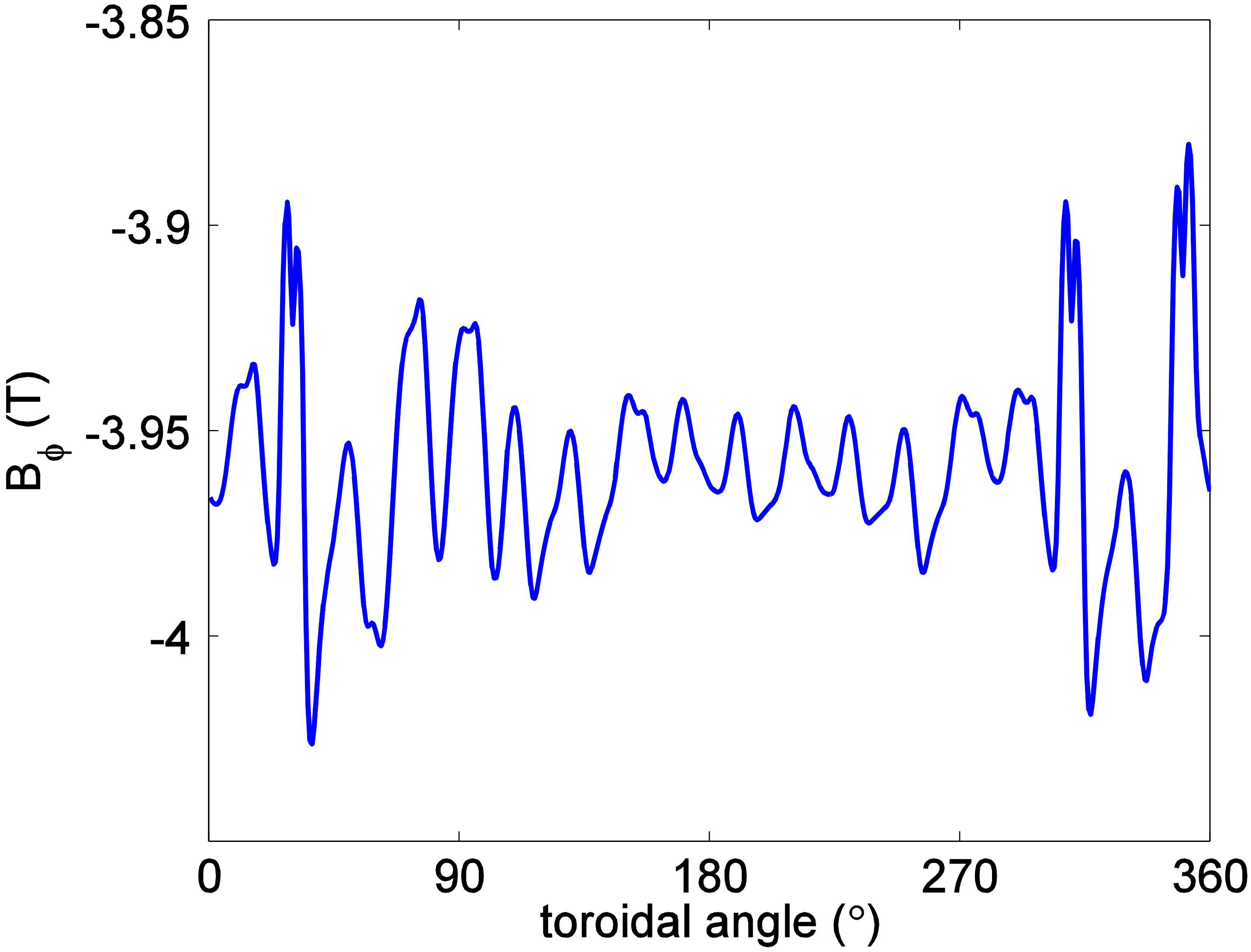
TBM's containing ferritic steel very close to the plasma are placed at three toroidal locations between TF coils

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%



Theoretical understanding

★ The effect of the periodic ripple is well understood (Goldston & al., PRL **47** (1981) 647)

★ The effect of *non-periodic* perturbations is NOT under command (the ripple theory cannot be applied to a *local* perturbation)

→ the only way to address the effect of non-periodic field perturbations is by 3D computer simulations

Simulating ions in strongly inhomogeneous magnetic fields

- ★ Field description: no analytic expression possible
  - ➔ discrete field values given on a mesh

- ★ Particle description:
  - GC orbits: e.g. 4th order Runge Kutta w/ 5th order error estimate. Fast but limited to 'boring' backgrounds
  - Gyro orbits: e.g., Leap-Frog. CPU-expensive

- ★ 3D fast ion codes available worldwide:
  - OFMC-3D (Japan)
  - DRIFT (Russia)
  - SPIRAL (USA)
  - ASCOT (Finland)
  - ...

ASCOT

Racetrack for tokamak particles

Fully 3D

- 3D magnetic field
- 3D Wall

Ab initio particle loading

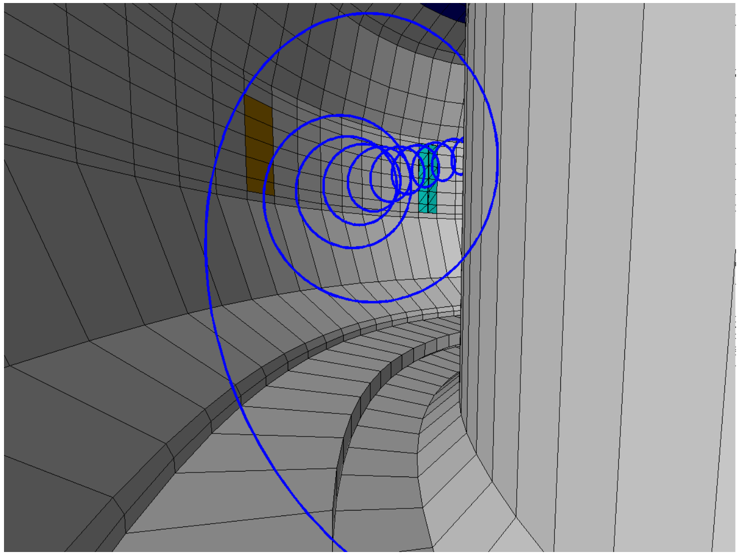
- Fusion alphas (thermonuclear, beam-target, beam-beam)
- NBI-generated ions

Realistic orbit tracing

- Guiding center (fast)
- gyro orbit (accurate)

Comprehensive interactions

- Coulomb collisions
- Turbulent transport
- Models for relevant MHD:
  - NTM-type magnetic islands
  - Alfven Eigenmodes



Some examples:
3D effects on tokamak ions à l’ASCOT

- The 3D nature of the 1st wall:
  - The effect of 1st wall structure on fusion-a wall load in ITER
  - The mystery of missing C-13 in ASDEX Upgrade

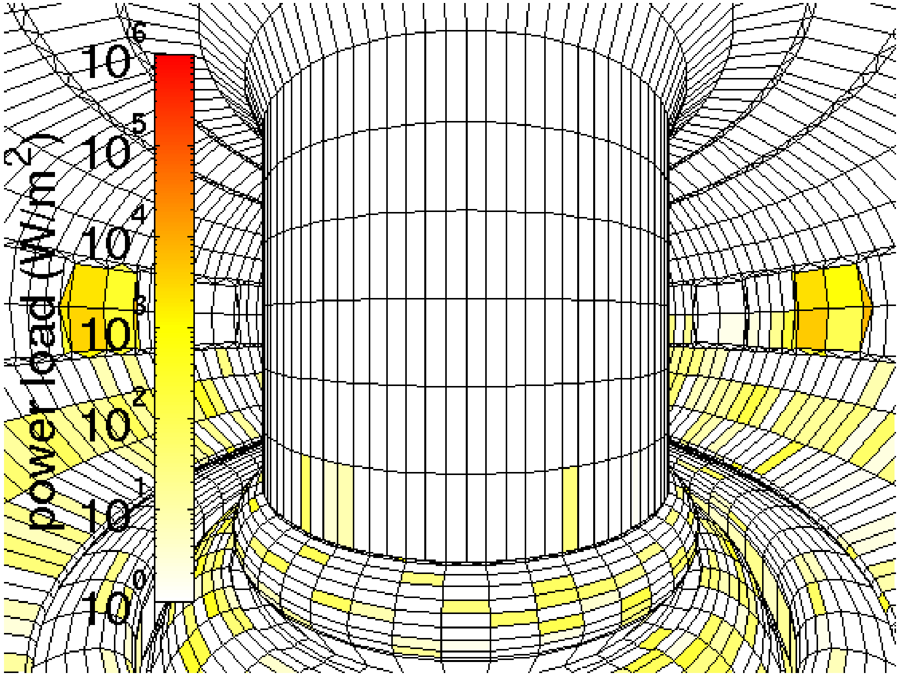
- The effect of ferritic structures: TBM mock-up experiments at DIII-D
  - Effect on NBI ions
  - Effect on neutrons from DD -> DT fusion reactions

- The ELM-mitigation coils and wall loads:
  - NBI ions in ASDEX Upgrade
  - Fusion alphas and NBI ions in ITER

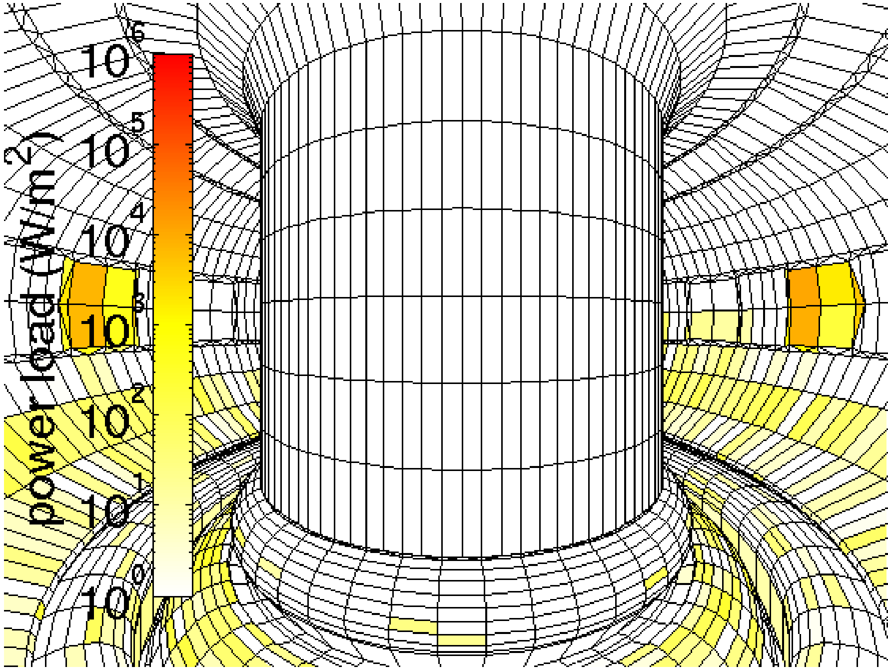
The effect of wall configuration

Case study:
Different walls in ITER

Axisymmetry vs ripple vs FI
Fusion alphas in 15MA scenario



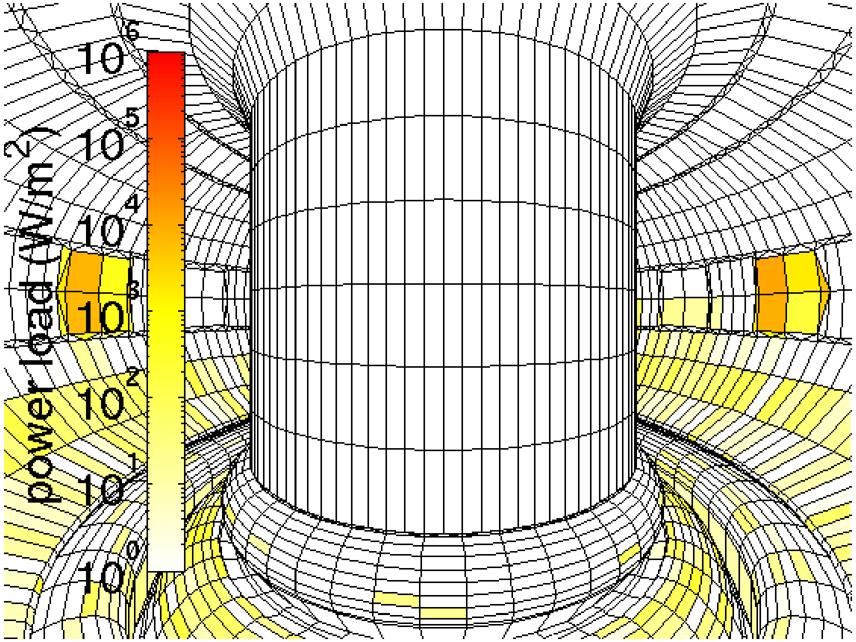
Axisymmetric B field



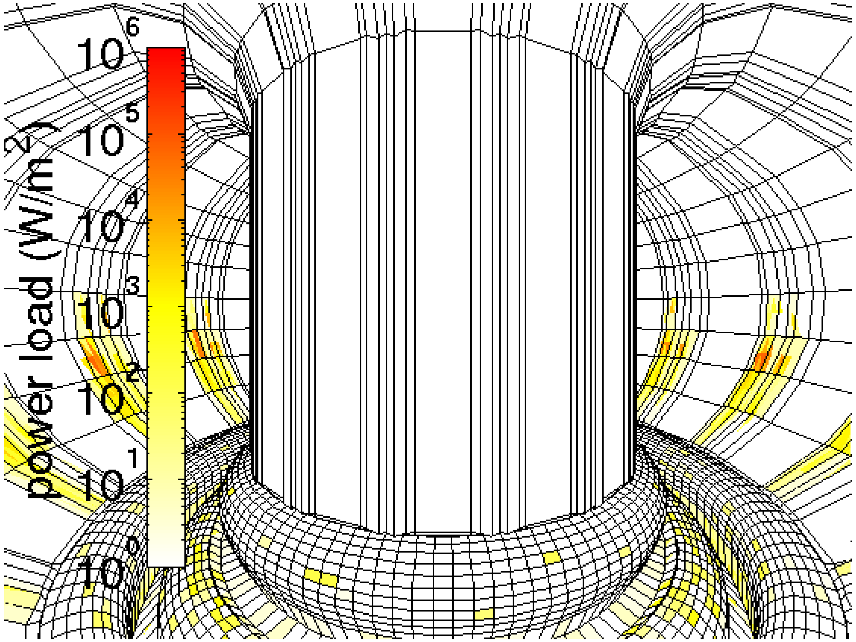
Ripple w/ FI's

With bare ripple

Also wall shape matters…



Original wall w/ 2 limiters



Present wall design w/
poloidally extended
'continuous' limiters

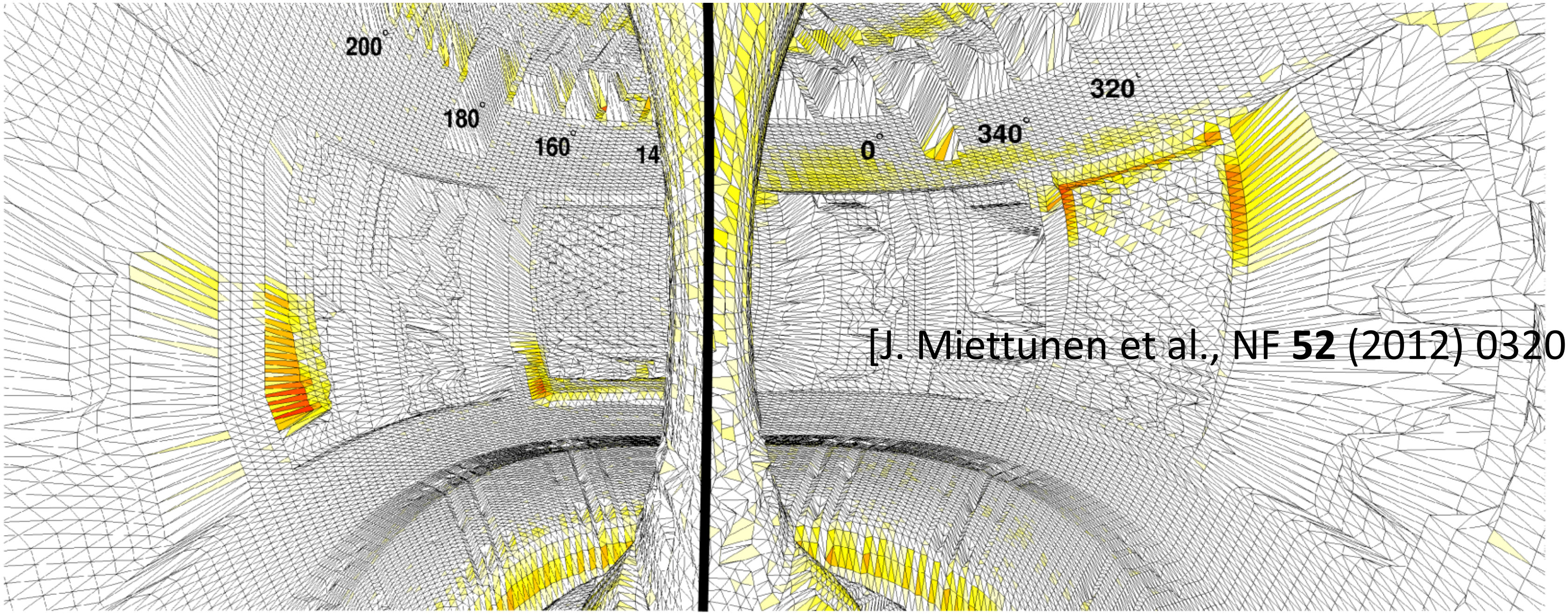
The effect of wall configuration

Case study:
Impurity injection experiments in AUG

The case of missing ^{13}C in AUG

Besides fast ions, tritium retention is a hot issue for ITER ➔

- ★Global impurity migration studies in AUG by injecting $^{13}CH_4$
- ★ post mortem analysis of samples from selected wall tiles -> 90% missing??
- ★ Common assumption: axisymmetric ^{13}C deposition
- ★ ASCOT simulation w/ a 3D wall and magnetic field: notable non-axisymmetry in ^{13}C deposition (limiters, ICRH antennas, …)



[J. Miettunen et al., NF **52** (2012) 032001]

The effect of ferritic structures

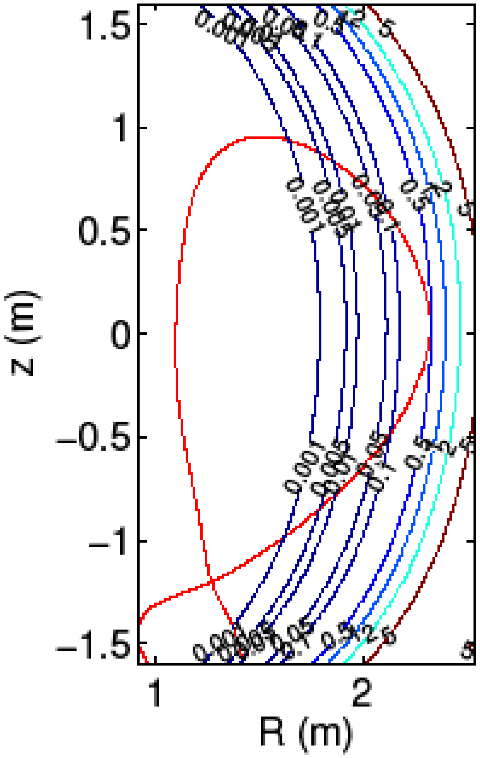
Case Study:

TBM mock-up experiments @ DIII-D

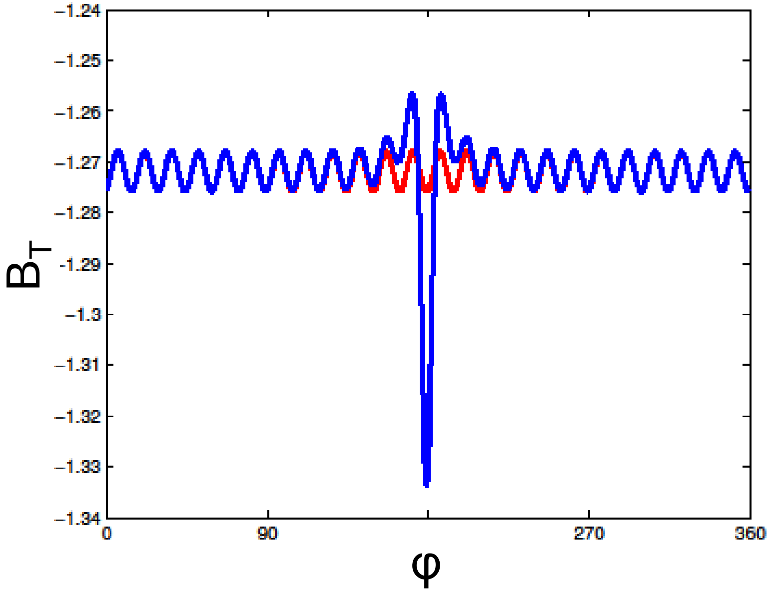
Ripple map w/ and w/o TBM field bump

Max field perturbation along separatrix close to 5% with TBM

TF ripple



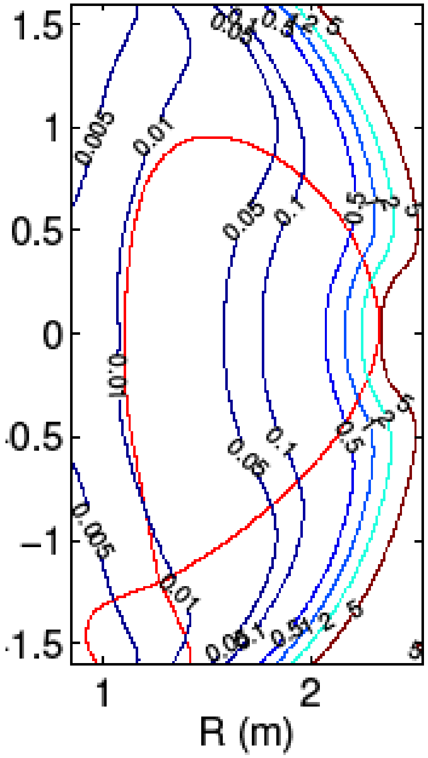
$$\delta(R,z)=\frac{B_{\max}(\phi)-B_{\min}(\phi)}{B_{\max}(\phi)+B_{\min}(\phi)}$$



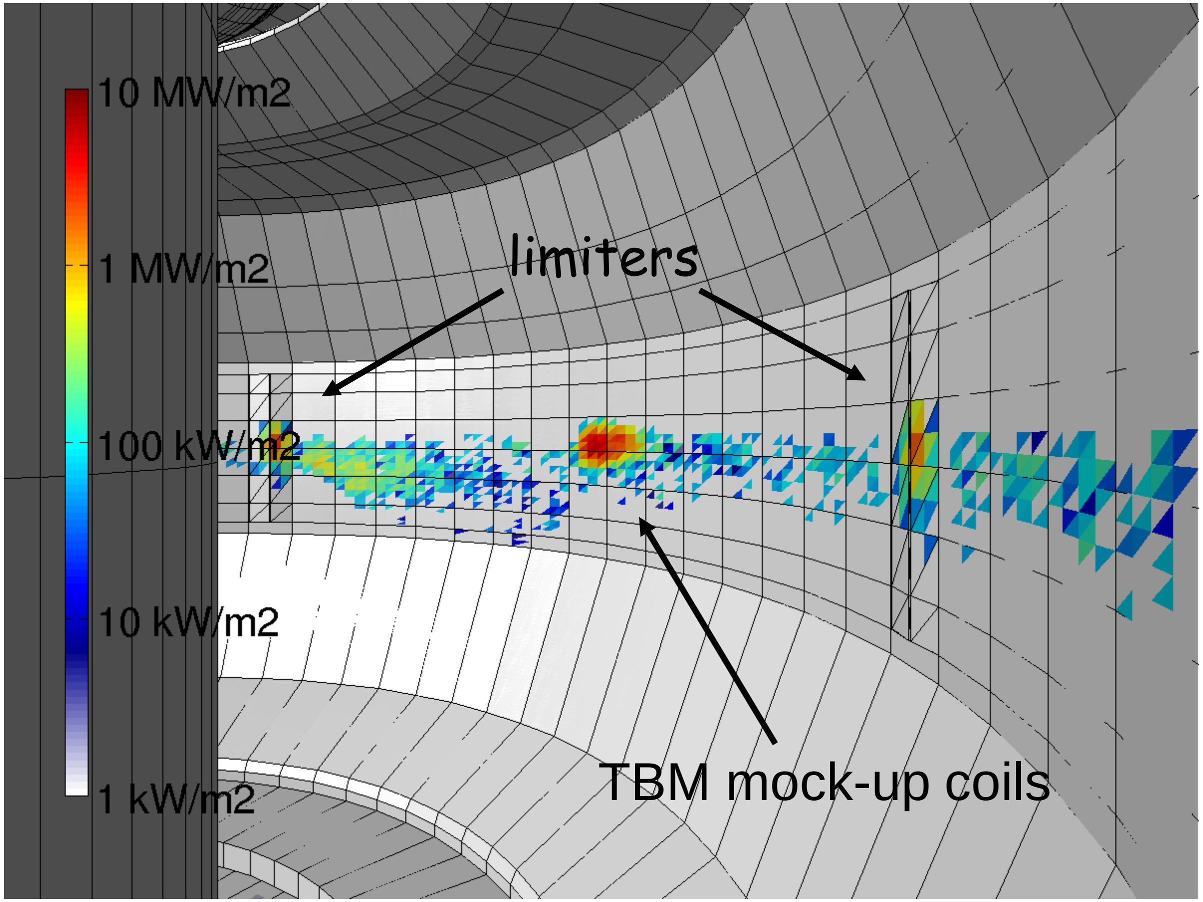
Variation of the toroidal field

- with the TBM coils
- in the absence of TBM coils

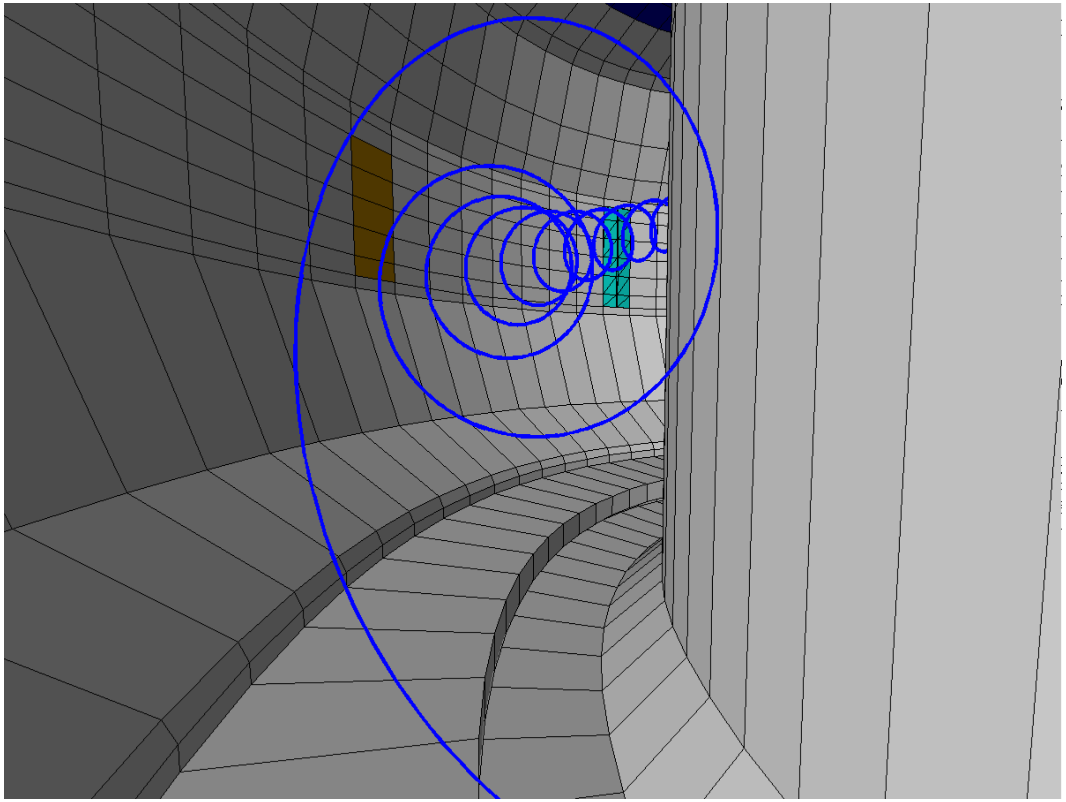
TBM field bump



NBI-generated deuterons in DIII-D discharges w/ TBM mock-up



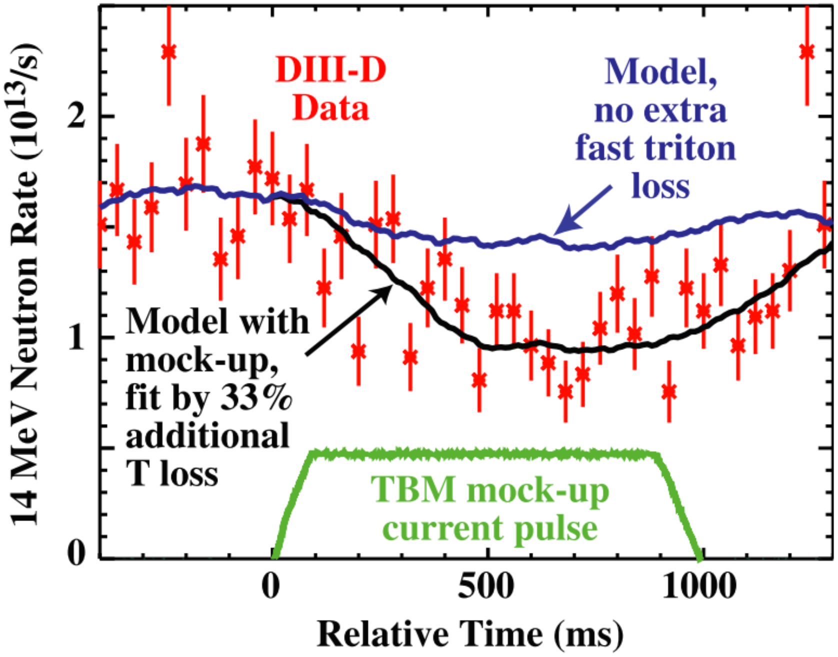
Beam-target DD reaction ➔T(1 MeV)

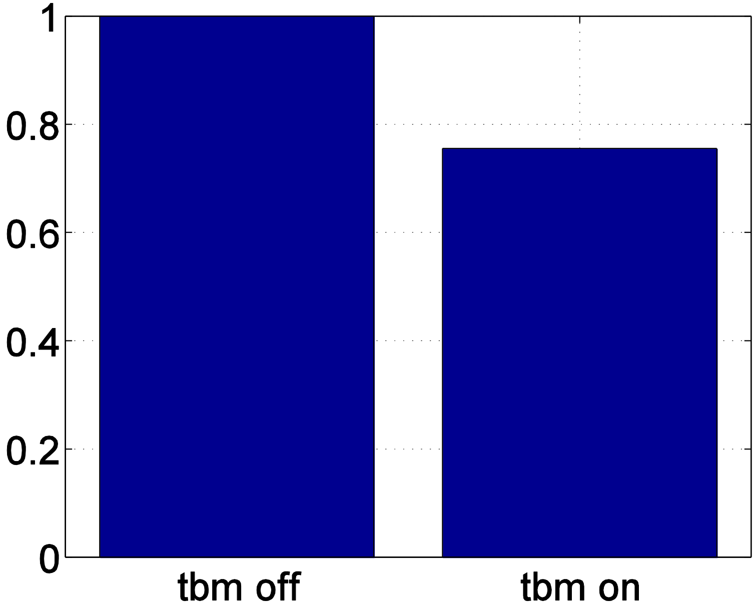


Guiding-center following clearly not applicable
➔ follow full gyro motion (FO integration)

DD → DT → n (14 MeV)

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





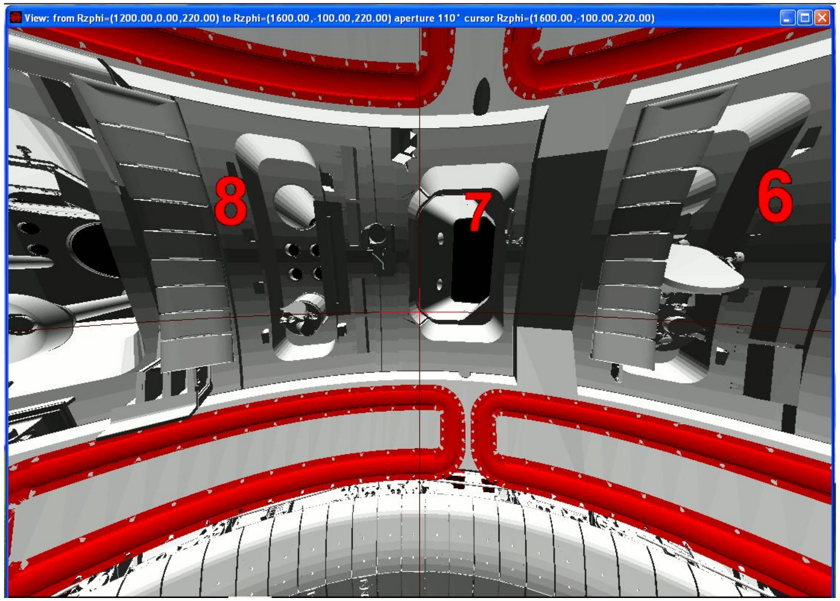
Experimental neutron flux in the TBM mock-up experiment

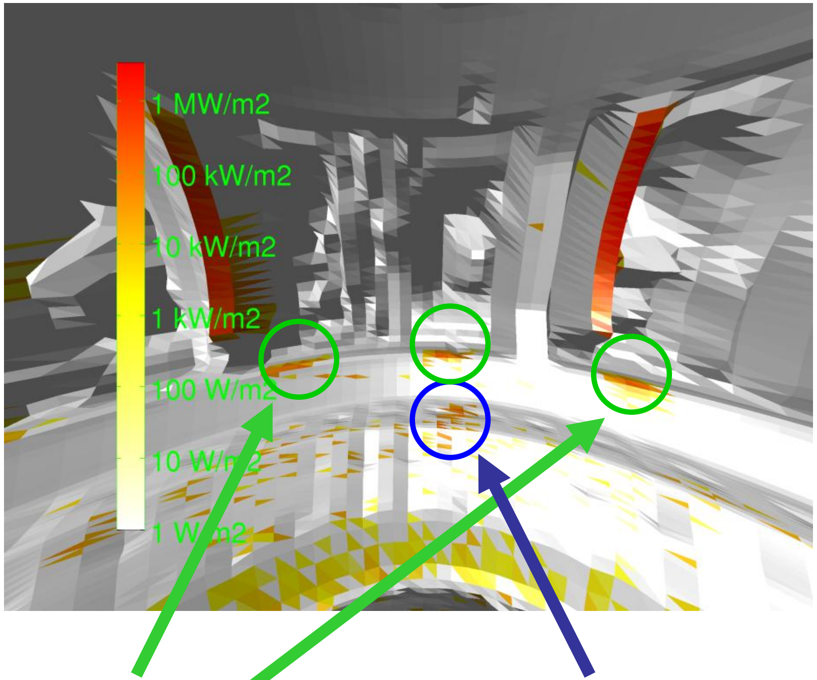
Fraction of *confined* tritium in the plasma as calculated by ASCOT

The effect of ELM mitigation coils

Case study:
B coils in ASDEX Upgrade

Losses of 60 keV NBI deuterons



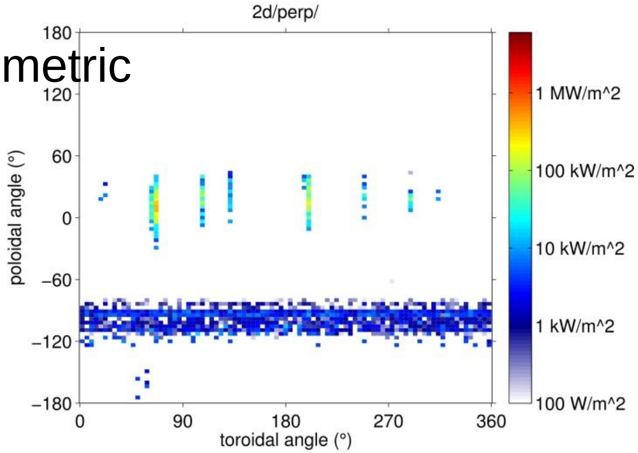


Direct ripple well losses

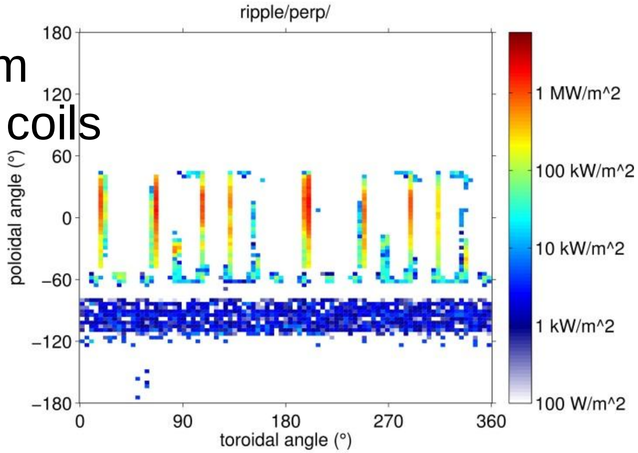
Additional spot next to the coil

NBI wall power loads: comparing effects of ripple and/or coils

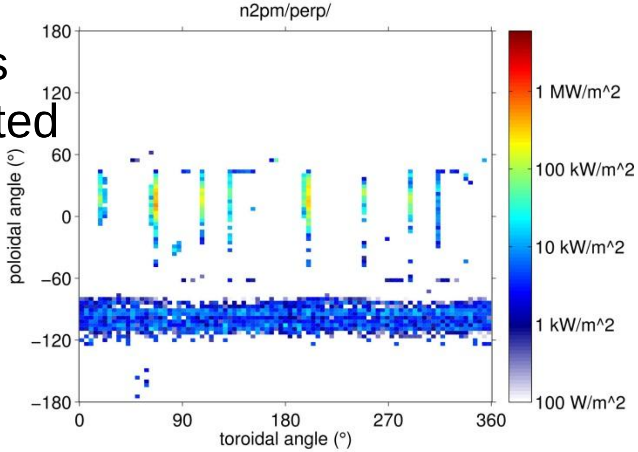
axisymmetric
B field



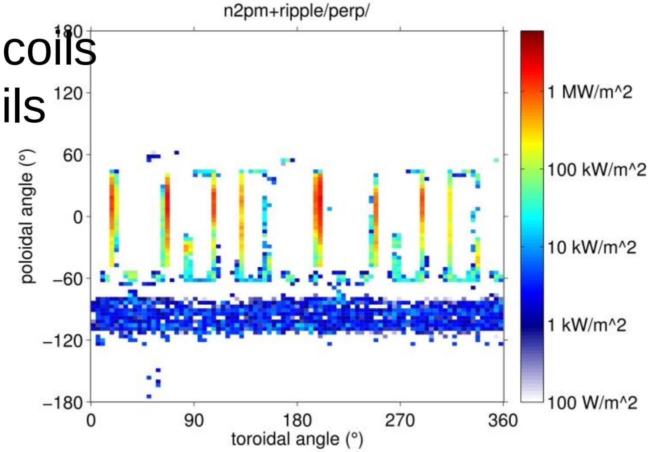
B_T from
16 TF coils



B coils
activated



16 TF coils
+ B coils



Ps. Note the n=2 nature of divertor loads...

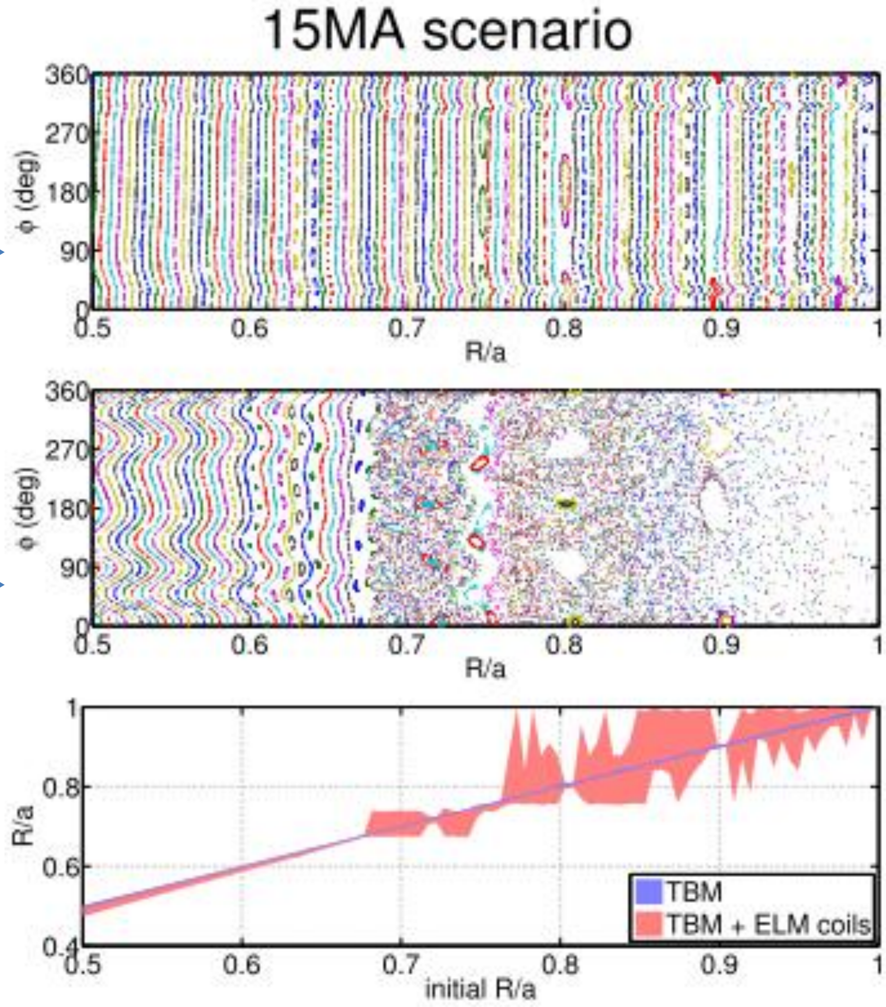
The effect of ELM mitigation coils

Case study:
ELM mitigation coils in ITER

Effect of ELM mitigation coils w/ full 90kAt

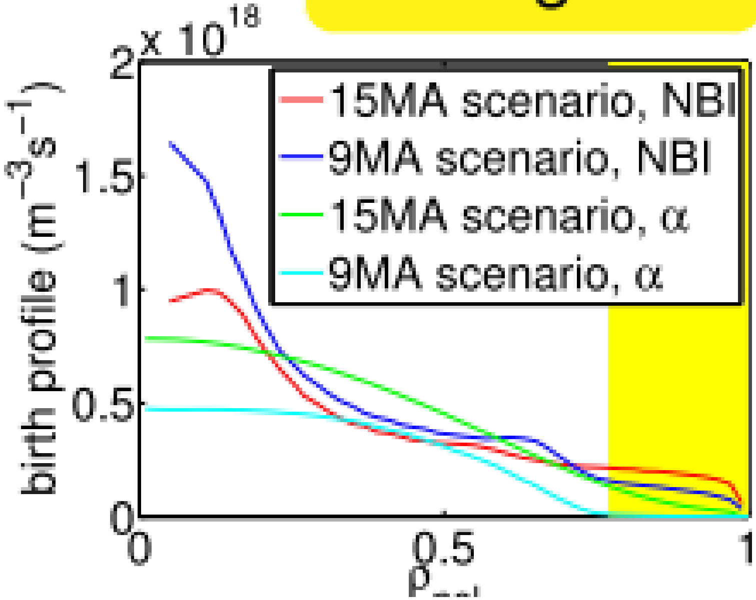
ITER 15MA scenario

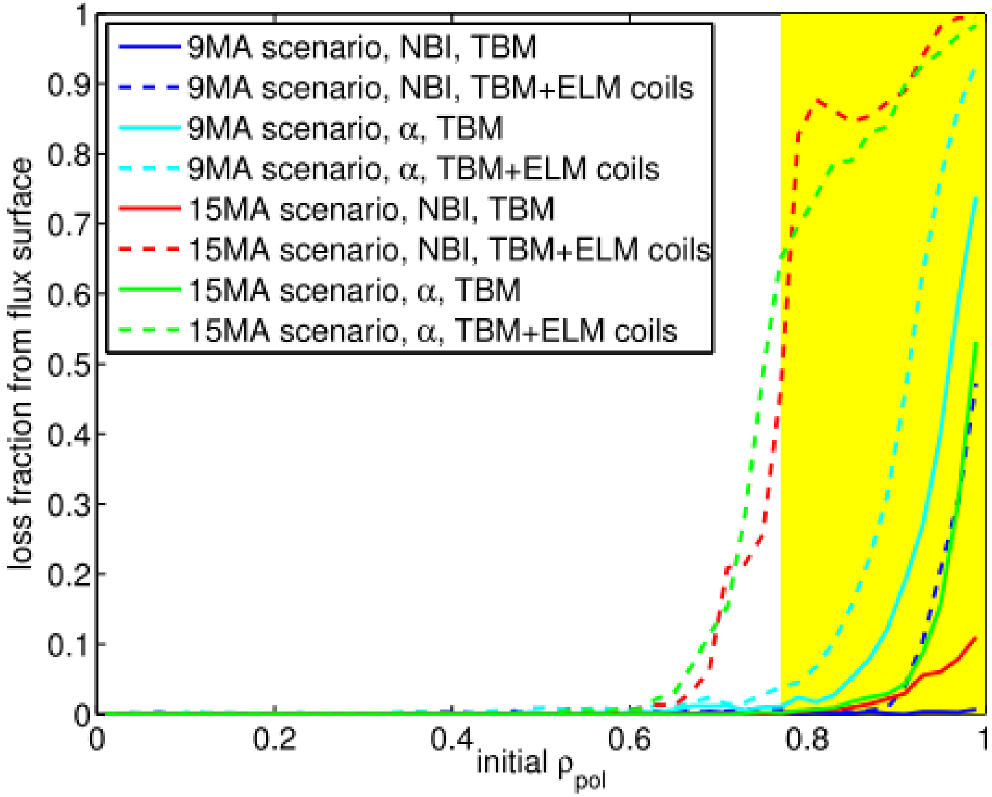
- ★ TBMs alone do not compromise the fast ion confinement
- ★ In the vacuum approximation, ELM coils may create wide ergodic regions inside the separatrix
- ★ Majority of fast (and thermal) ions born on ergodic field lines is lost



Fast (and slow…) ions are lost from ergodic field lines

Ergodic field line region





T. Koskela et al., PPCF **54** (2012) 105008

INTERNAL 3D EFFECTS

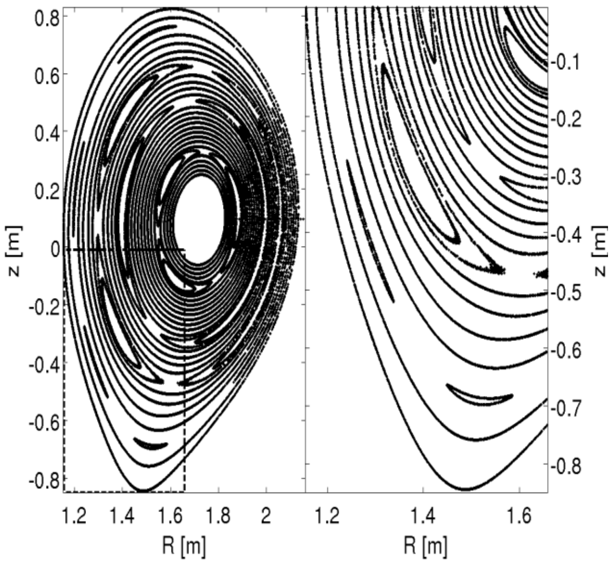
ITER plasmas = unlikely MHD quiescent

- ITER plasmas prone to **NTM-type islands** that redistribute fast ions
  - → ***what is the critical island size from fast ion confinement point of view?***

- The large population of energetic ions likely to drive a multitude of **X-AE's & other EPMs**
  - → ***Effect on fast ion confinement?***

→ **NTMs and/or X-AEs can lead to an increased fast ion population at the edge**

→ ***Is the first wall at jeopardy??***



NTMs in AUG:
modes (3,2), (2,1) ja (3,1)

Modelling MHD effects on fast ions

No existing numerical model provided all necessary features for simulating fast ion power loads ➔

Alfvén Eigenmodes and Neoclassical Tearing Modes for Orbit-Following Implementations

[E. Hirvijoki et al., *CPC* **183** (2012) 2589]

Use non-canonical Hamiltonian formalism & write equations of motion in vector form ➔

★ Applicable with **any** coordinate system, not just Boozer coordinates

★ compatible with arbitrary external field perturbations (ripple, TBMs, ELM coils)

★ Time-dependency for the modes included

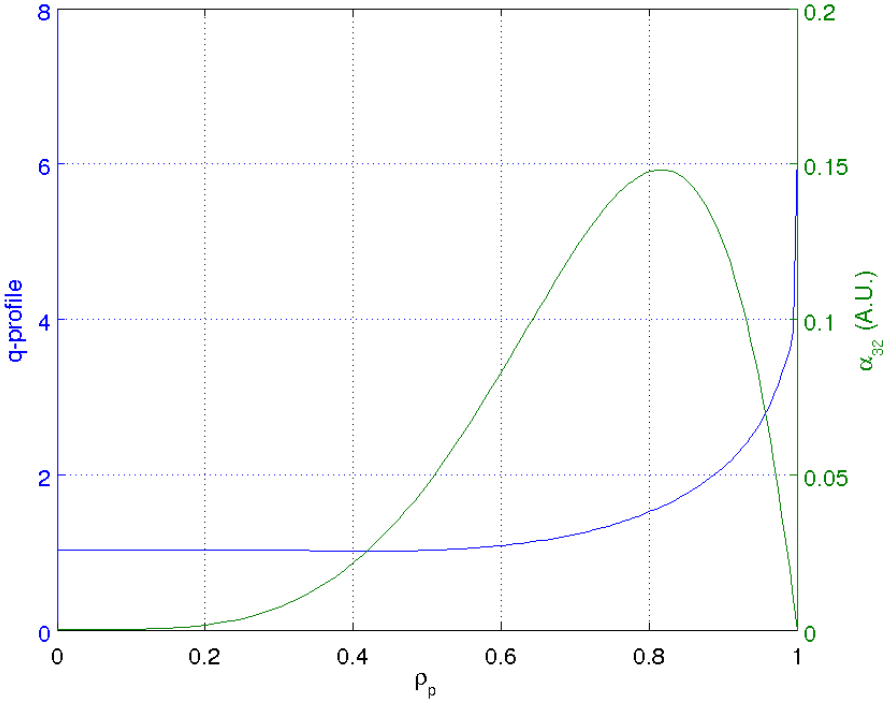
’Internal’ examples:
3D effects on fast ions à l’ASCOT

- ★ Effect of NTMs on fast ions
  - Thermonuclear alphas in ITER 15MA scenario
- ★ Effect of TAEs on fast ions
  - Thermonuclear alphas in ITER 9MA scenario w/ *n=5* TAE modes

All simulations have full 3D magnetic fields, including also TF ripple, FIs and TBMs

Fusion alphas w/ NTMs

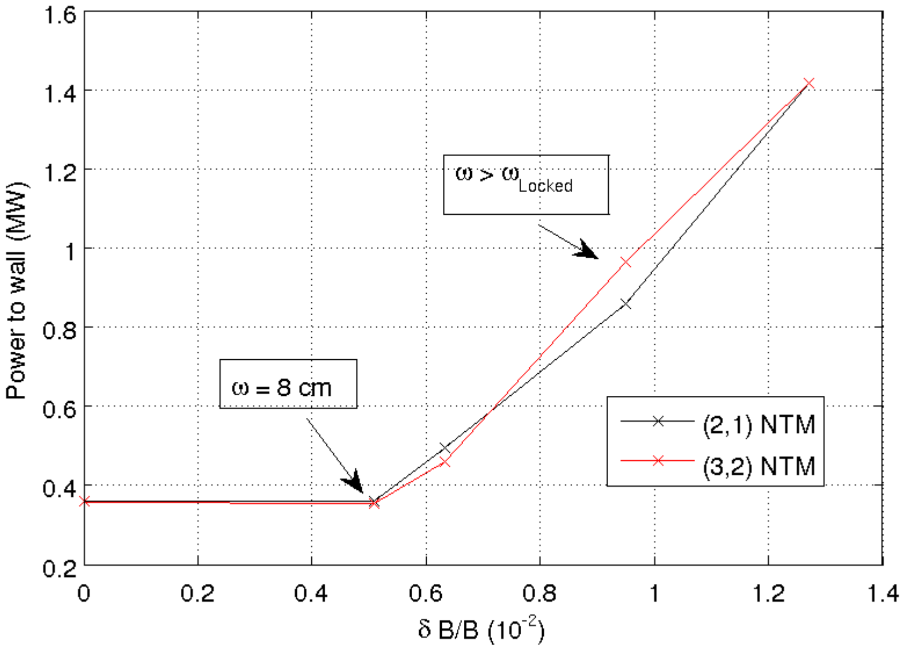
- ★ Steady-state simulation using static NTM modes
- ★ 15 MA ITER scenario using 50k alpha particles
- ★ Amplitude scans for (2,1) and (3,2) NTMs
- ★ Full slowing-down time simulation



At reasonable amplitudes wall power loads not affected

- ★ Mitigation will limit NTM widths to less than ≈ 10 cm
- ★ No additional hot spots

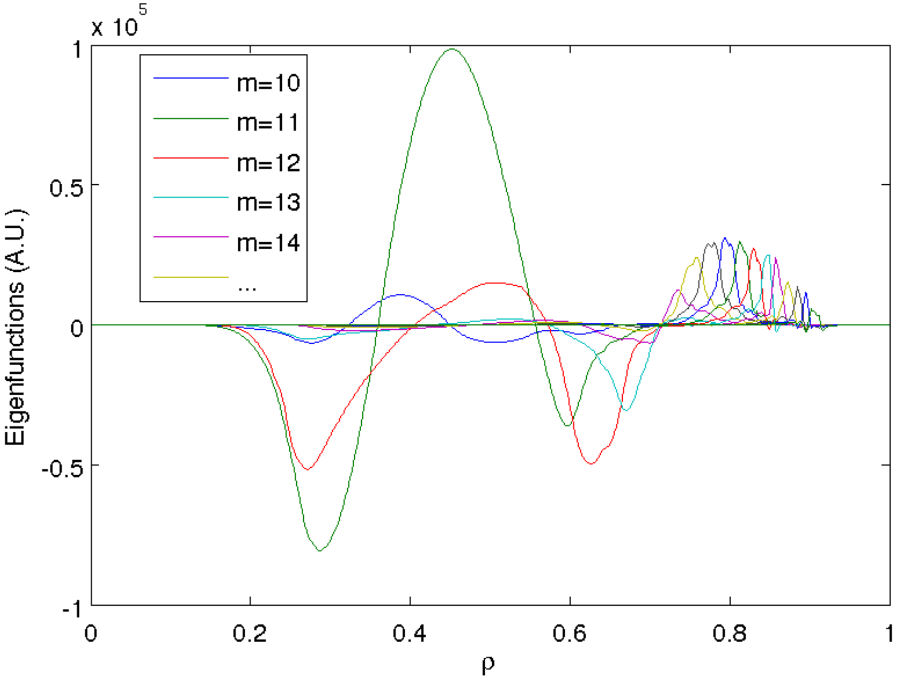
(Also NBI ions now simulated: the source and perturbation don't meet ➔ no significant effect)



A. Snicker et al., under review in NF

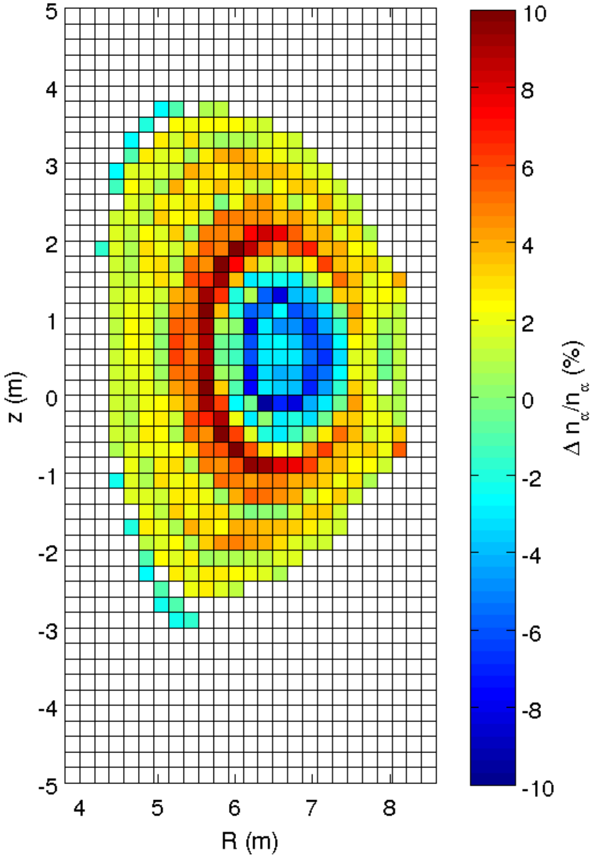
Fusion alphas w/ TAEs

- 9 MA ITER scenario w/ full 3D field
- Use only the most unstable mode: f=51.5 kHz, n=5, m=10...25 calculated by LIGKA (thanks to Dr. Lauber)
- 200 000 alpha particles sampling also the mode period ⇒ steady state solution obtained

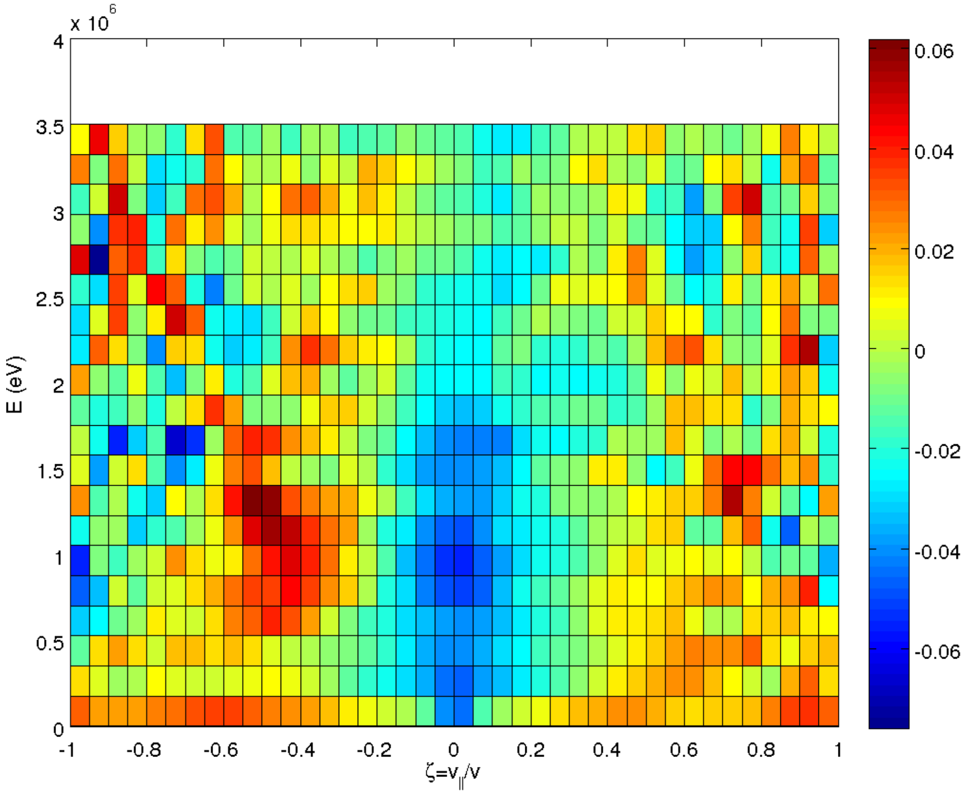


Redistribution of alphas due to TAEs

Density increased at HFS



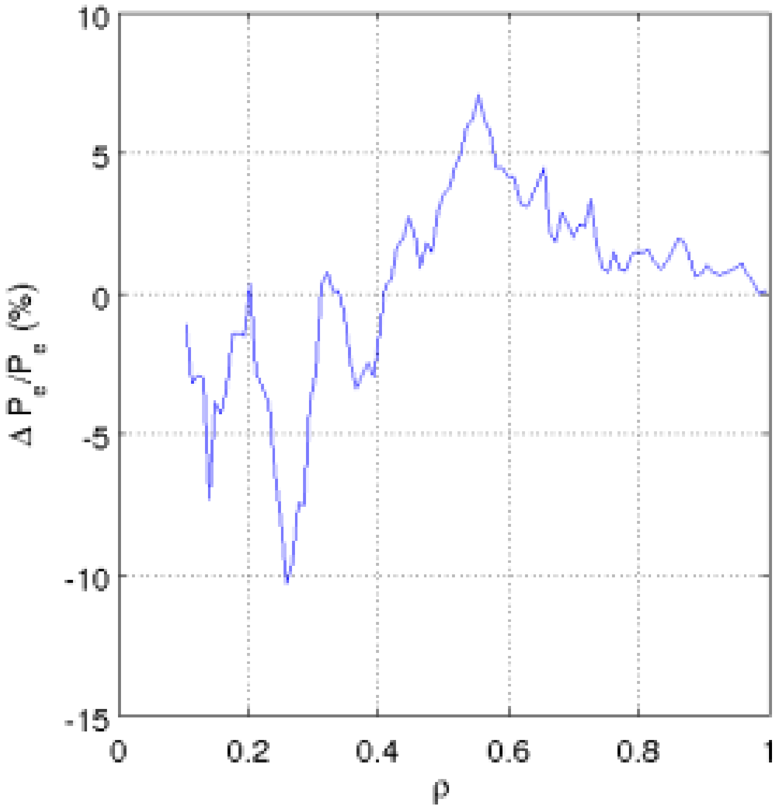
Ions moved from trapped to passing



A. Snicker et al., under review in NF

Effects due to TAE *globally*

Redistribution of fast ions likely to affect not only wall power loads but also heating and current drive profiles

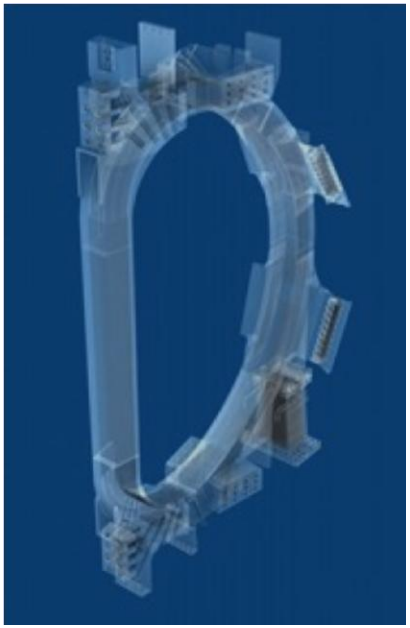


Relative change in the electron heating w/ and w/o the TAE

- A change of up to 10% in the heating profile observed
- Similar changes in current drive profile TBD
- But also good news:

Only very minor changes in the wall power loads.

Conclusions



So far, no 3D show-stopper found for ITER as far as fast ion power loads are concerned

The world of tokamak particles not fully analyzed yet – not even with ASCOT:

- ★ The engineering world is coming alarmingly close to the world of physicists
  - ➔ Refining edge calculations: GRT-379
- ★ Refining MHD modelling:
  - ➔ Multiple modes simultaneously
  - ➔ Fastest growing mode not necessarily the most hazardous
- ★ ITER problems call for 'renaissance' physicists – broader understanding needed !

Thank you for your attention!

Acknowledgements

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- ITER Organization, IPP Garching, General Atomics

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- HPC-FF and HELIOS

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Main features of the model

Perturbations in ***A*** and ***Φ*** allow time-dependent mode:

$$\tilde{\boldsymbol{A}} = \alpha(\psi_p, \theta, \zeta, t)\boldsymbol{B}$$

$$\alpha = \sum_{nm} \alpha_{nm}(\psi_p) \sin\left(n\zeta - m\theta - \omega_{nm} t\right)$$

$$\tilde{\Phi} = \sum \tilde{\Phi}_{nm}(\psi_p) \sin\left(n\zeta - m\theta - \omega_{nm} t\right)$$

$$\begin{aligned} \boldsymbol{B}^\star =& \boldsymbol{B} + (\rho_\| + \alpha)\nabla \times \boldsymbol{B}, \\ \boldsymbol{E}^\star =& \boldsymbol{E} - \frac{1}{e\gamma}\left(\mu + \frac{e^2 B \rho_\|^2}{m}\right)\nabla B \\ & - \nabla\tilde{\Phi} - (\rho_\| + \alpha)\frac{\partial \boldsymbol{B}}{\partial t} + \frac{eB^2\rho_\|}{\gamma m}\nabla\alpha \end{aligned}$$

Equations of motion

GC Lagrangian + Euler-Lagrangian equation ➔

$$
\begin{aligned}
\dot{\chi} &= \frac{eB}{\gamma m}, \\
\dot{\mu} &= 0, \\
\dot{\rho}_{\parallel} &= \frac{\boldsymbol{E}^{\star} \cdot \boldsymbol{B}^{\star}}{\boldsymbol{B}^{\star} \cdot \boldsymbol{B}} - \dot{\alpha}, \\
\dot{\boldsymbol{R}} &= \frac{eB^2 \rho_{\parallel}}{\gamma m} \frac{\boldsymbol{B}^{\star}}{\boldsymbol{B}^{\star} \cdot \boldsymbol{B}} + \frac{\boldsymbol{E}^{\star} \times \boldsymbol{B}}{\boldsymbol{B}^{\star} \cdot \boldsymbol{B}}
\end{aligned}
$$