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Clearing the road for high-fidelity fast ion simulations in full 3D

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[4] *CCFE, Culham, U.K.*
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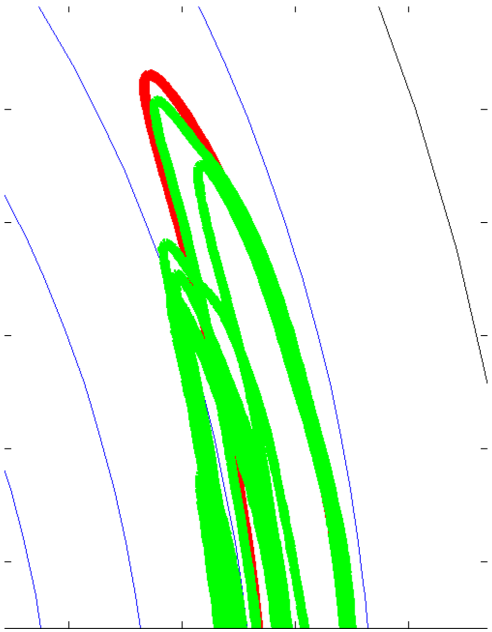
Motivation:
What happens when axisymmetry is relaxed ?

Many banana orbits in axisymmetry

Banana orbits in strong TF ripple



« Energetic ions have very low collisionality

è Faithful to magnetic configuration

è particularly vulnerable to 3D perturbations:

« ITER will have a significant fast ion population: fast ion pressure about 1/3 of the plasma pressure

â fast ions have to be well confined

Situation with ITER and beyond?

The axisymmetry of ITER magnetic field is broken by

- Finite number & finite extent of the TF coils â 18-fold TF ripple
  - Efficiently remedied by ferritic inserts (FI)
- 6 tritium-breeding modules (TBM) made of ferritic material
- ELM control coils (ECC)

The effect of complex perturbations can only be assessed with numerical simulations, keeping in mind that

The ITER wall tiles can take ***2 – 5MW/m²****, depending on location*[(*)]

[(*)]R.A. Pitts et al., J. Nucl. Mater. 415 (2011) S957–64

Contents

- Vacuum high-fidelity magnetic field w/ *external* perturbations
  - FIs, TBMs, ECCs
- Including plasma response:
  - still some open issues
  - JOREK vs MARS-F
- Including *internal* 3D perturbations
  - NTMs, TAEs & turbulence
- Particle following:
  - GC vs GO
- Results: ITER & DEMO & W7-X + JT-60SA
  - Important observations on 'what matters'

’High-fidelity’ magnetic fields

Vacuum approximation

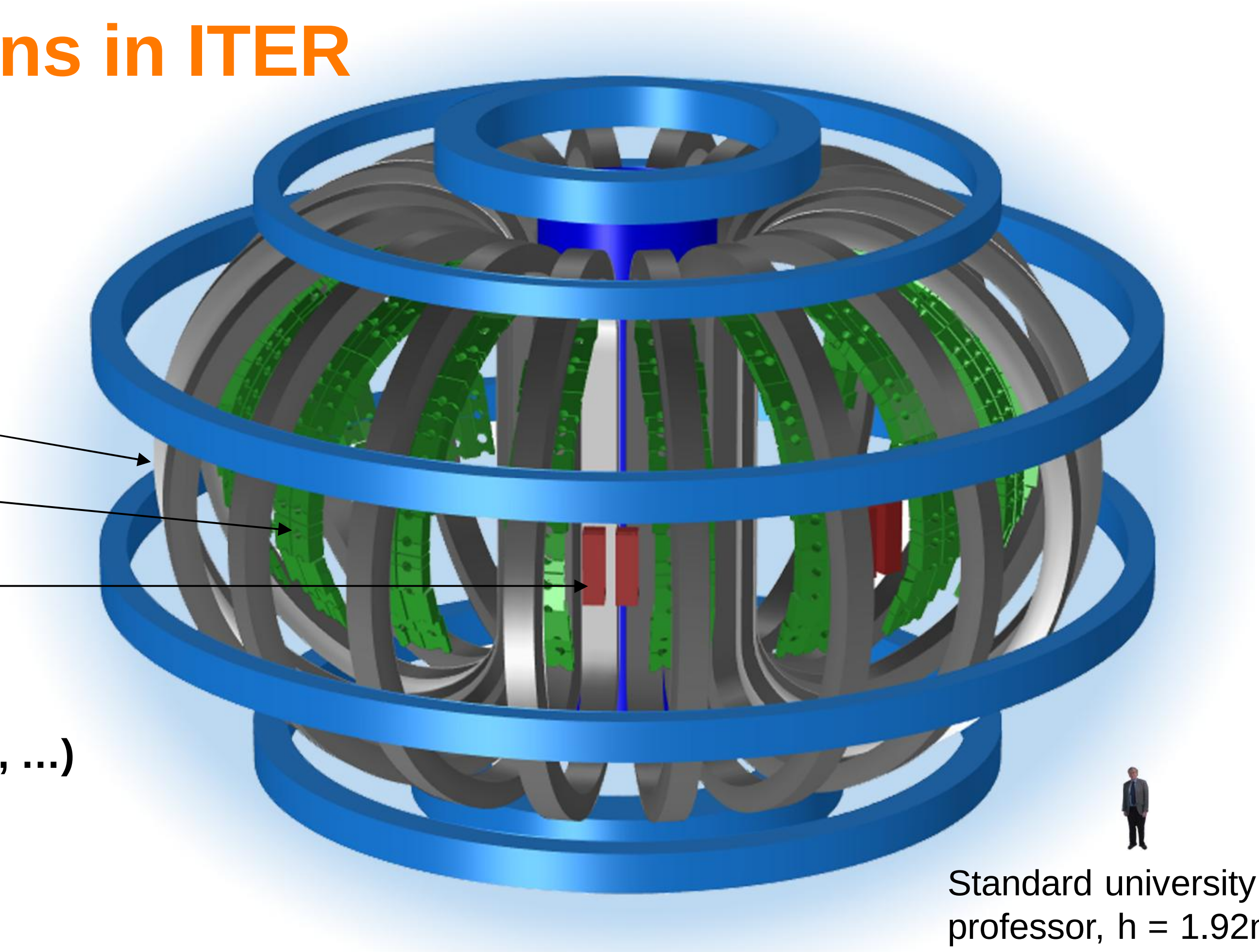
External perturbations in ITER

Toroidal field coils

FIs (Ferritic Inserts)

TBMs (Test Blanket Modules)

+ external coils (EFCC, RMP, ECC, …)



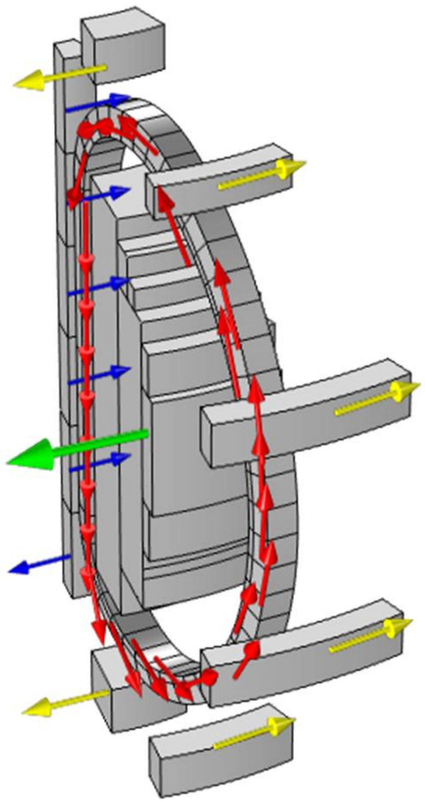
Standard university professor, h = 1.92m

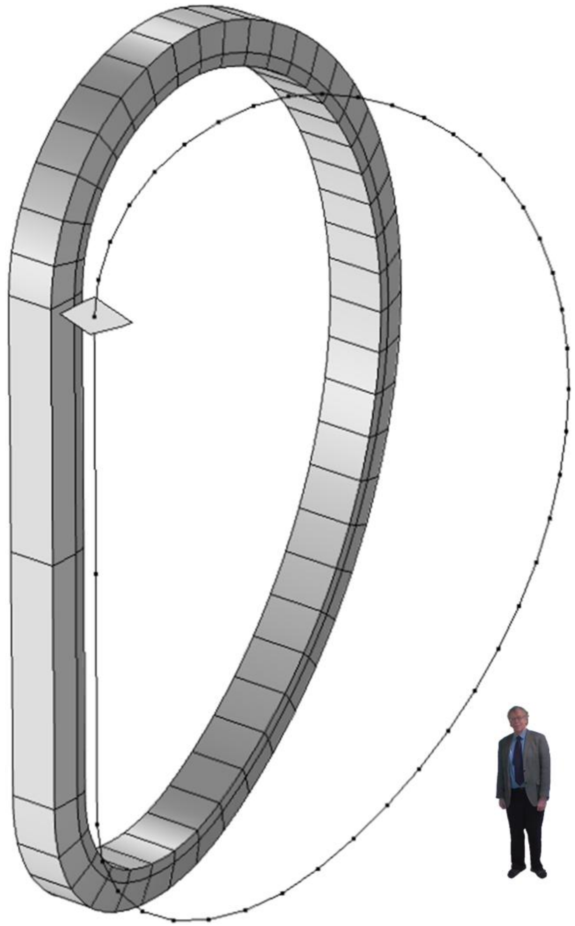
3-step procedure to high(er) fidelity

- Earlier: 3D magnetic field calculated by pure FEM
  è numerical drift of the magnetic field lines
- Now: a cost-efficient way of obtaining high-resolution, high-quality fields [1]
  - a FEM-solver (here: commercial COMSOL package) calculates the magnetizing field from the geometry and currents in the coils and plasma
  - the magnetized components (ferritic inserts, TBMs, …) modelled as permanent magnets
    è COMSOL calculates the resulting perturbation field
  - add the perturbation field to global high-resolution vacuum field calculated w/ a Biot-Savart solver

[1] S. Äkäslompolo *et al.*, Fusion Eng. and Design, **98-99** (2015) 1039

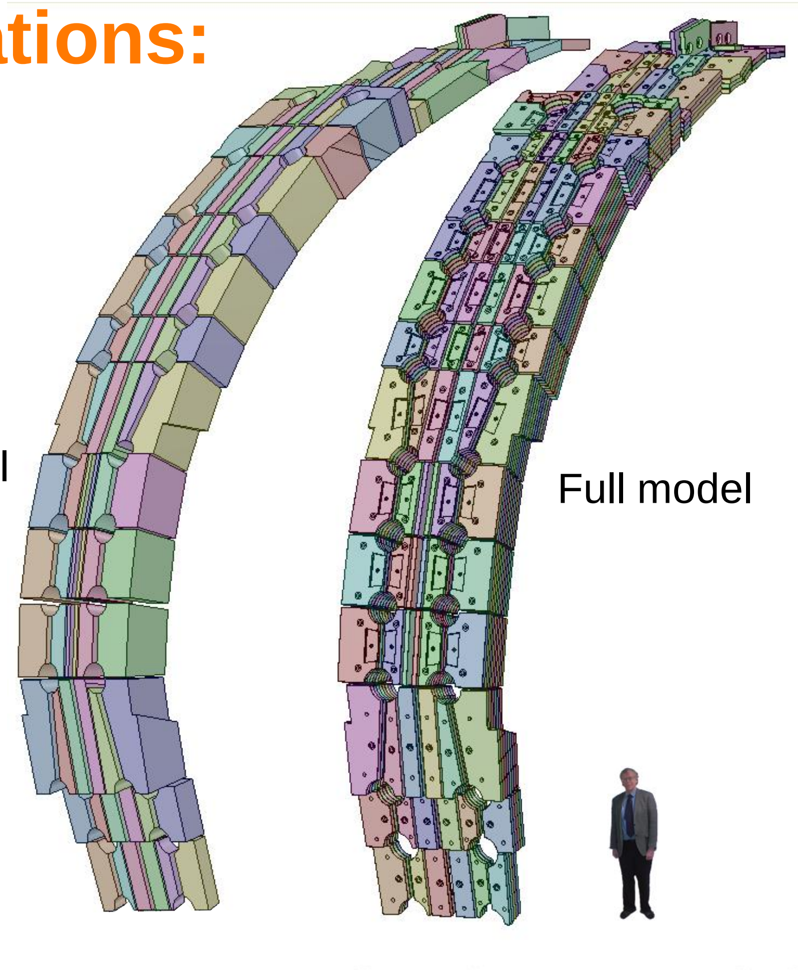
External perturbations: TF coils





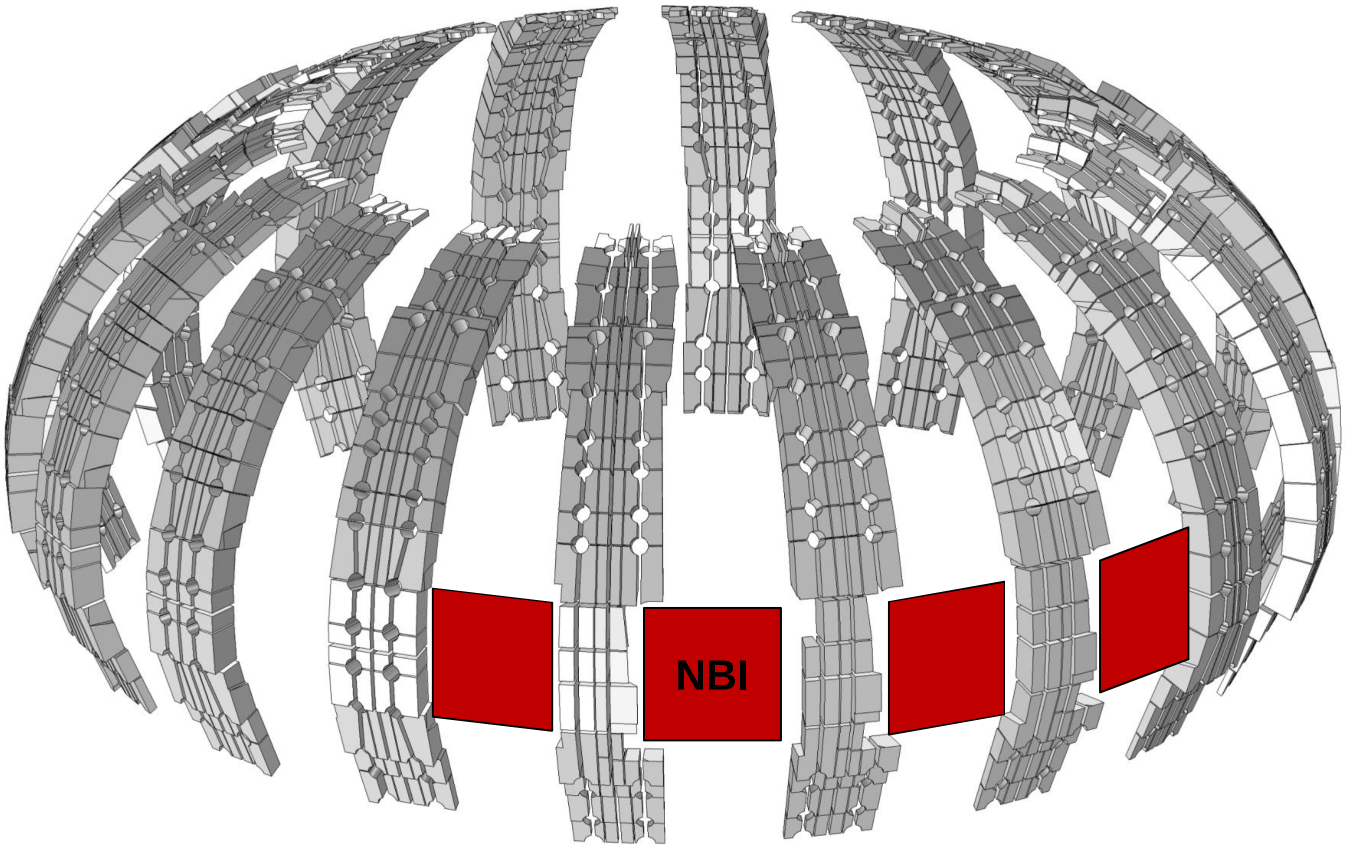
Standard university professor, h = 1.92m

External perturbations: Ferritic inserts

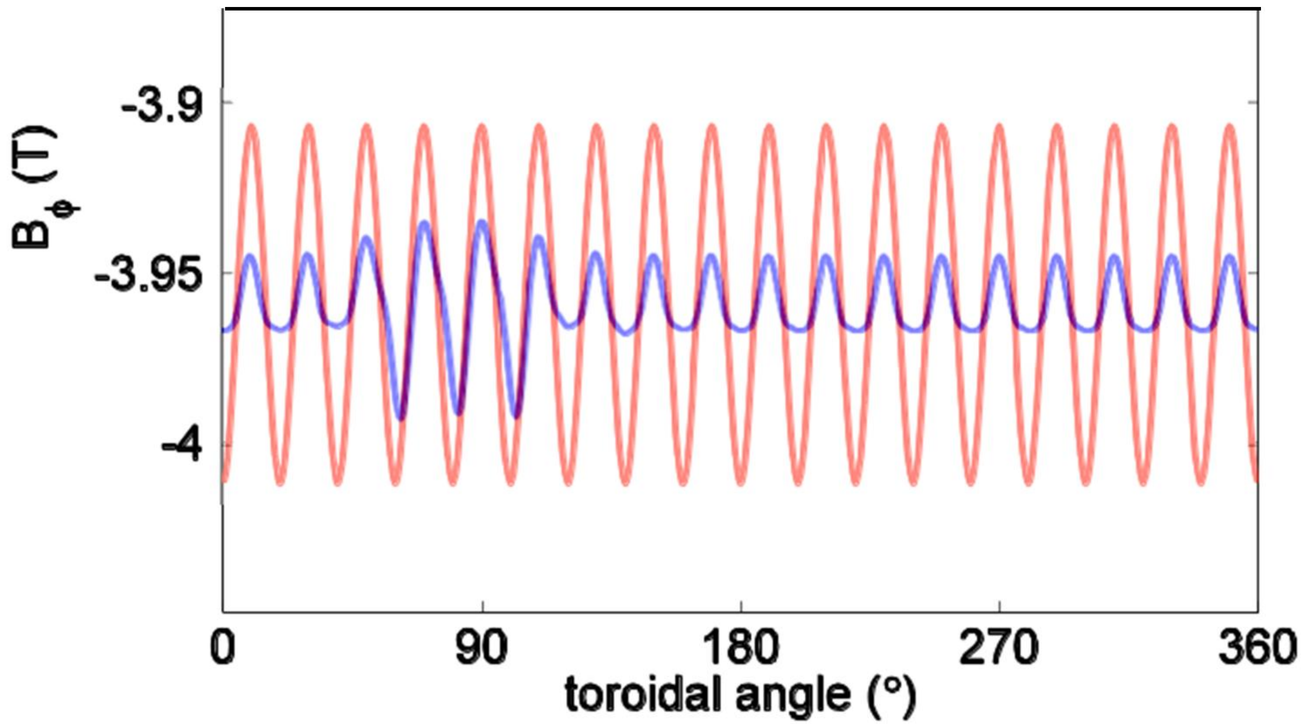


Ferritic inserts of ITER

- Ferritic shields are placed at each TF coil
- efficient reduction of TF ripple
- less efficient at NBI (Neutral Beam Injection) ports



Toroidal field strength near separatrix at OMP

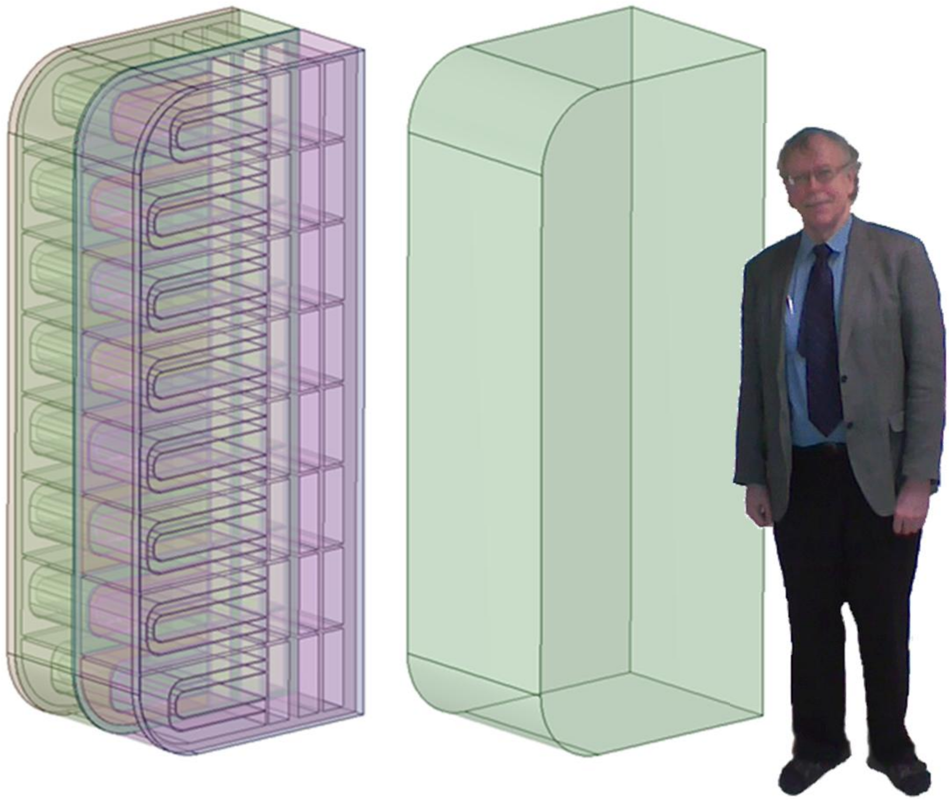


External perturbations: Test Blanket Modules

In the past, the effect of ferritic components on fast ion confinement were only carried out using solid block models. (*)

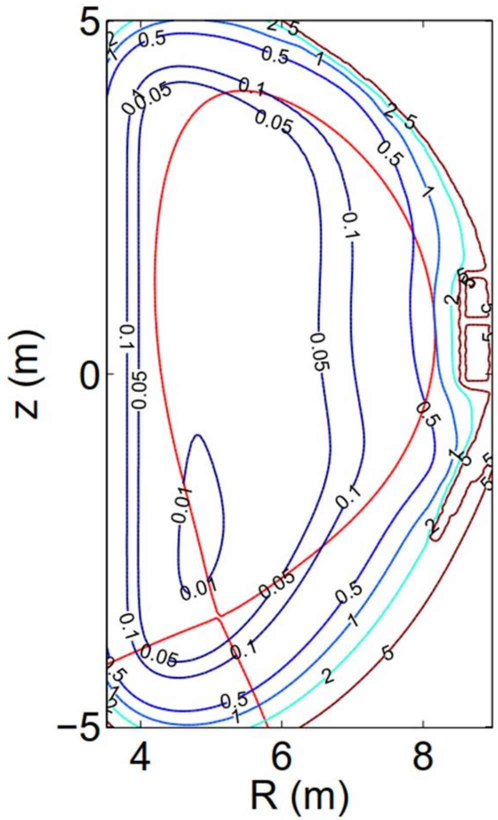
Configuration model from F4E

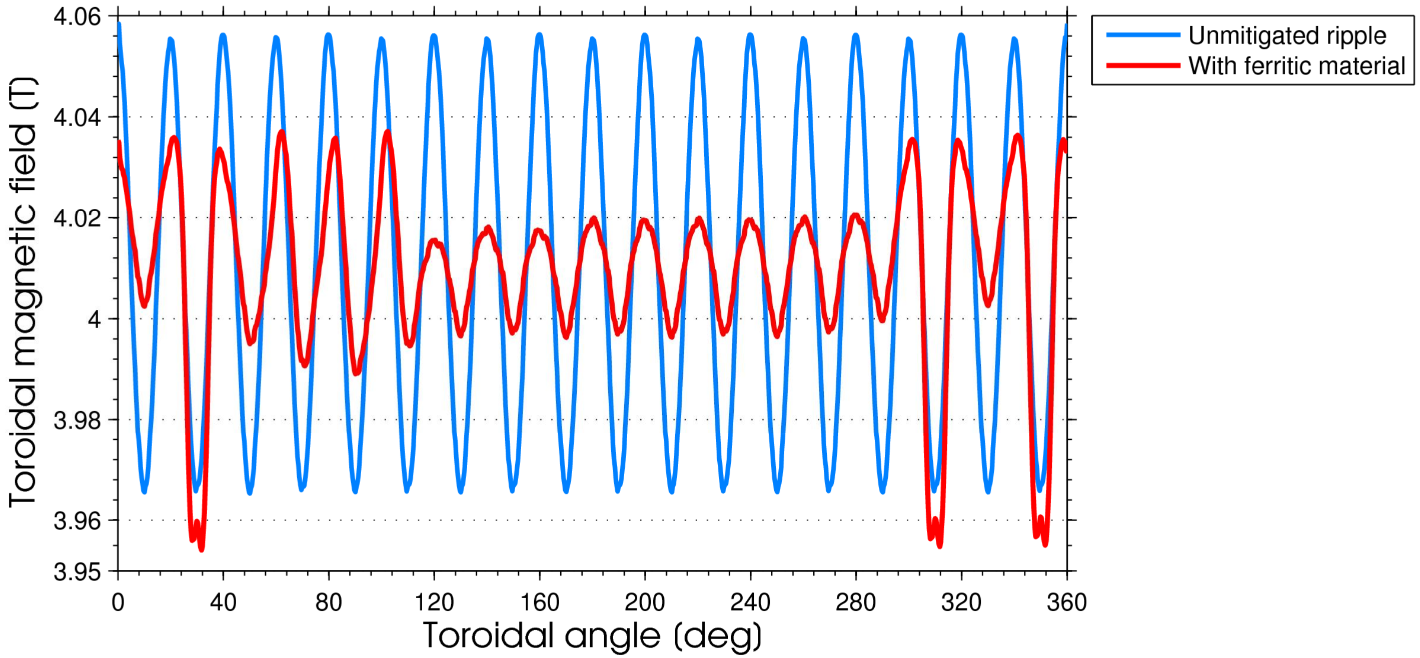
Solid block model used in earlier studies



(*)K.Shinohara, NF **51** (2011) 063028
T. Kurki-Suonio et al, NF **51** (2011) 063028
S.D. Pinches et al., PoP **22** (2015) 021807

TBM perturbation size ~ TF ripple! … but *local* …

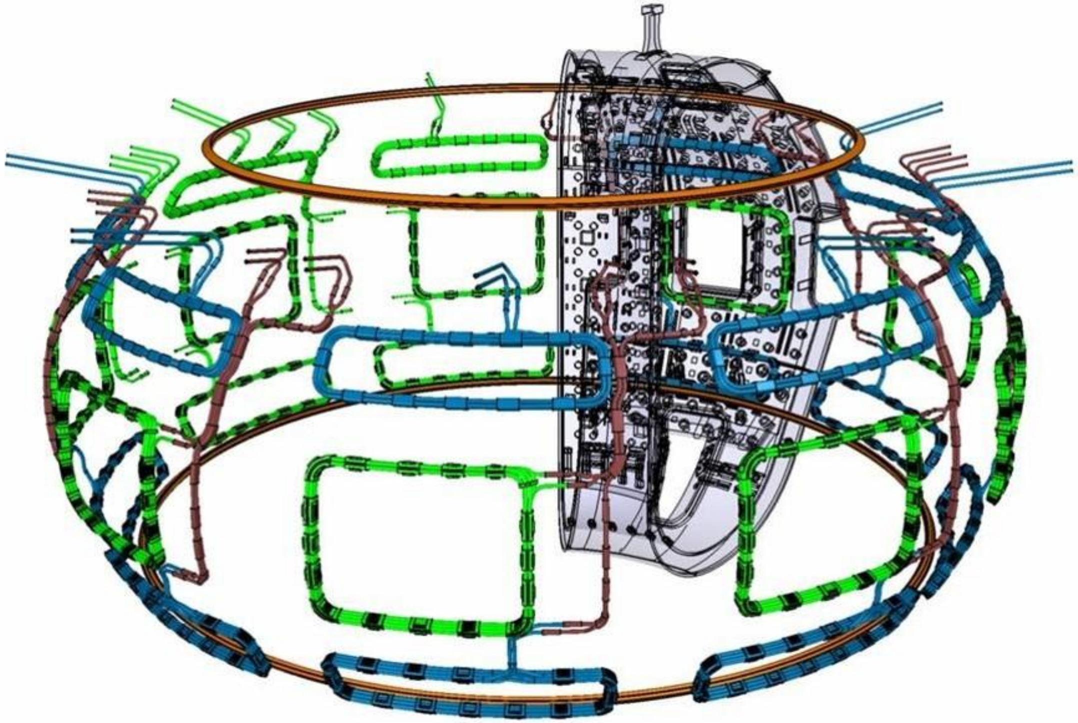




External perturbations: ELM control coils

- ECCs needed to suppress/mitigate ELMs
- What is their effect on fast ion confinement ?
- For ITER, we use configurations from

*Evans et al., NF **53** (2013) 093029*



$B_T(\varphi)$ at outer midplane separatrix, ITER 9MA scenario

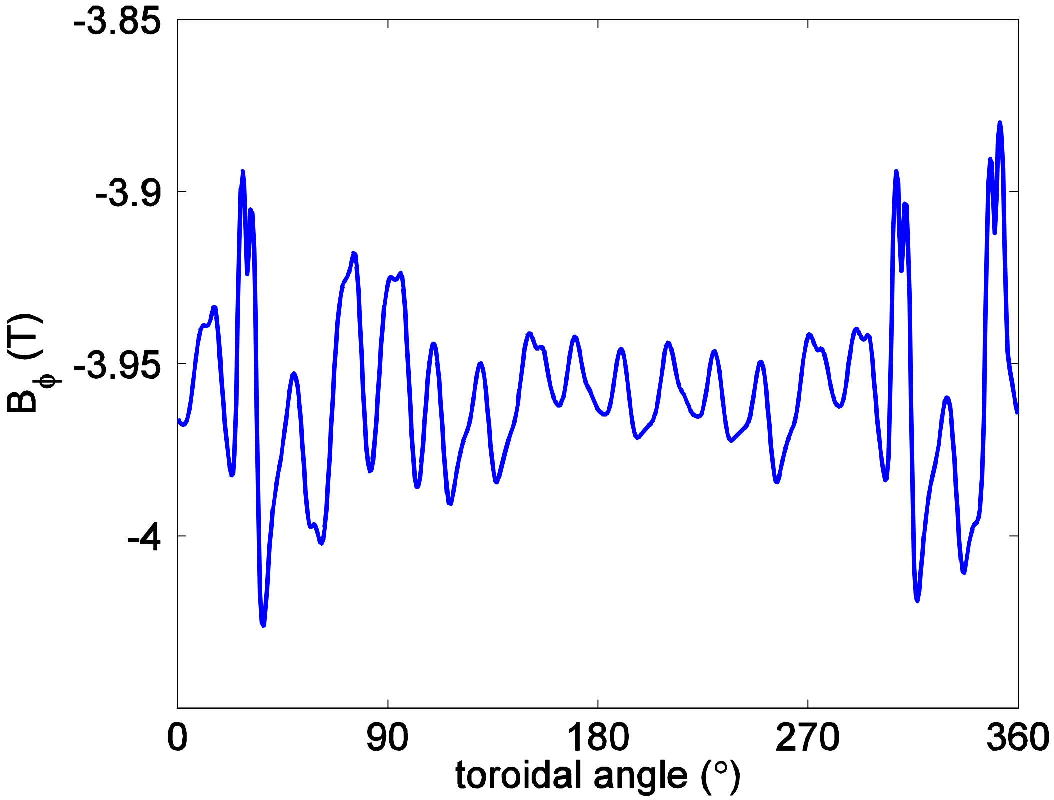
Axisymmetric field

Toroidal ripple 1.1%

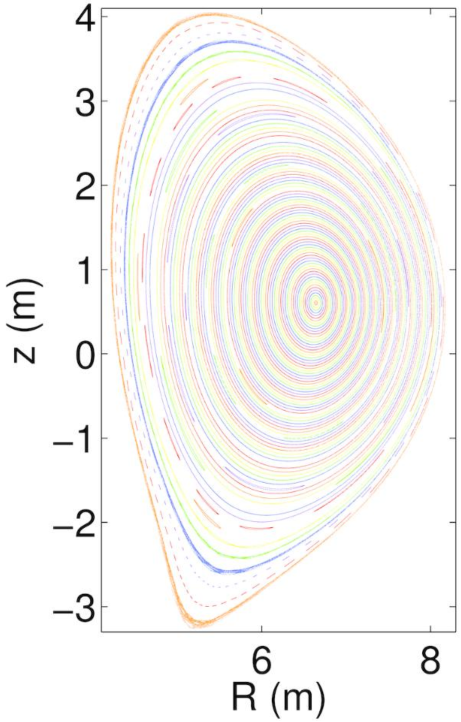
Ferritic inserts added, field bump due to NBI ports 0.57%

Field bump due to TBMs 1.1%

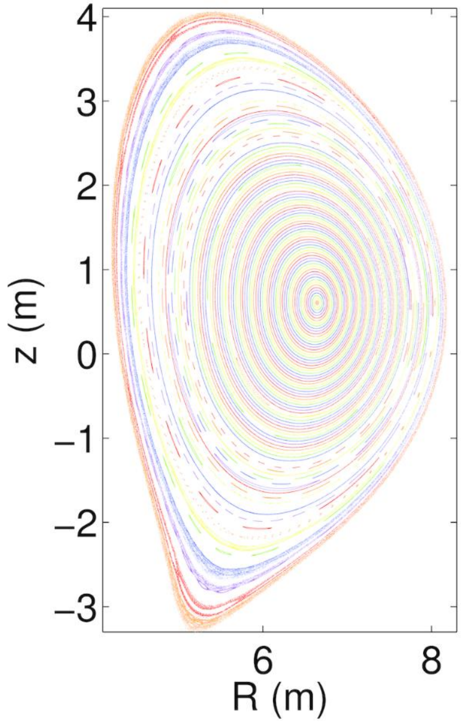
+ ELM control coils…



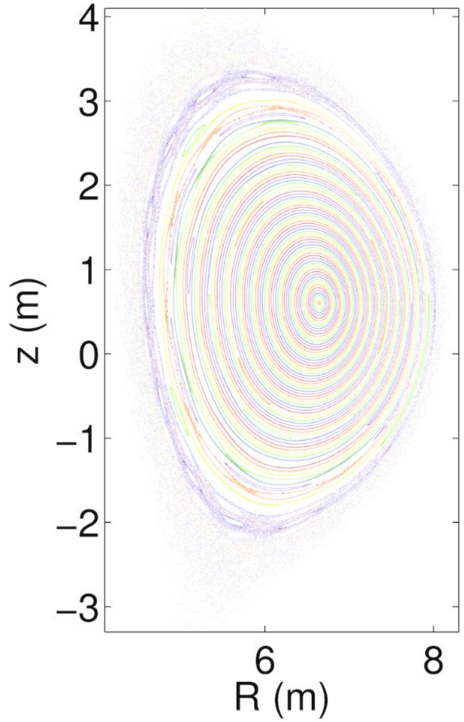
15MA baseline scenario: Poincaré plots reveal significant erosion of confinement volume by ECCs



TF ripple mitigated by FI's



Include the effect of 3 pairs of TBMs



ECC: n = 3, 45 kAt, 86°-0°-34°

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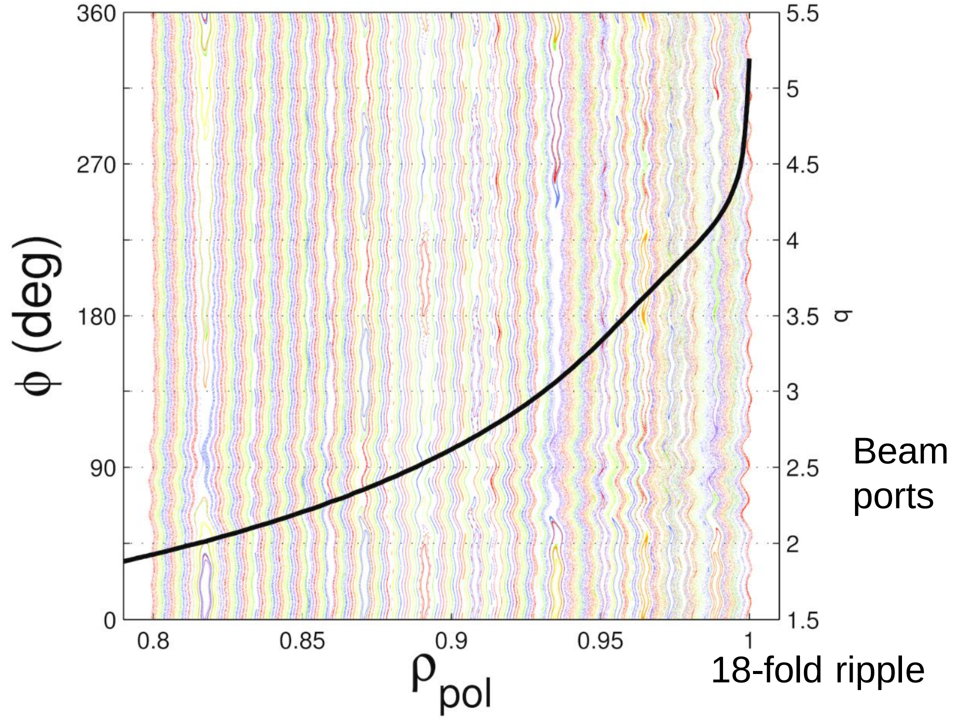
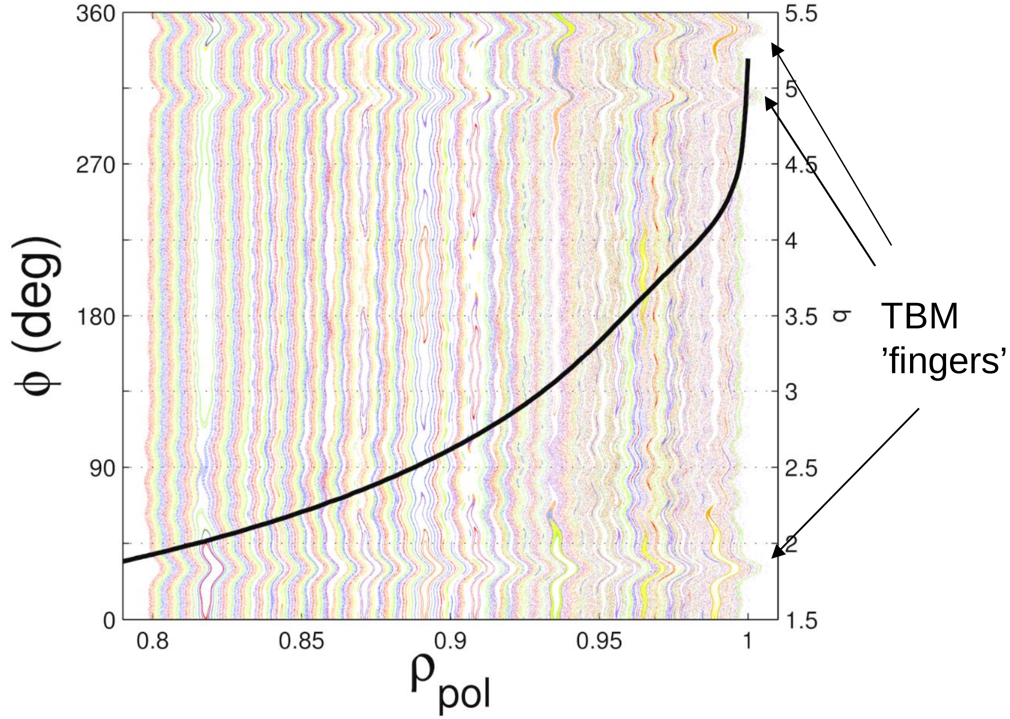
12.5MA hybrid scenario: edge Poincaré plots show the mitigated 18-fold TF ripple and TBM 'fingers'

TF ripple mitigated w/ FI's



Include the effect of 3 pairs of TBMs



Internal perturbations: NTMs & TAEs

- MHD modes *in equations of motion*
- Parameterized islands as in [1,2]

but

- Use non-canonical Hamiltonian formalism & write equations of motion in vector form [3] è
  - applicable in the presence of non-axisymmetric field!
  - time-dependency for the modes included

$$\alpha = \sum_{nm} \alpha_{nm}(\psi_p) \sin(n\zeta - m\theta - \omega_{nm}t) \qquad \delta\mathbf{A} = \alpha\mathbf{B}$$

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

$$\dot{\rho}_{\parallel} = \frac{\boldsymbol{E}^{\star} \cdot \boldsymbol{B}^{\star}}{\boldsymbol{B}^{\star} \cdot \boldsymbol{B}} - \dot{\alpha} \quad ; \; \rho_{\parallel} = p_{\parallel}/eB$$

$$\dot{\boldsymbol{R}} = \frac{eB^2\rho_{\parallel}}{\gamma m} \frac{\boldsymbol{B}^{\star}}{\boldsymbol{B}^{\star} \cdot \boldsymbol{B}} + \frac{\boldsymbol{E}^{\star} \times \boldsymbol{B}}{\boldsymbol{B}^{\star} \cdot \boldsymbol{B}}$$

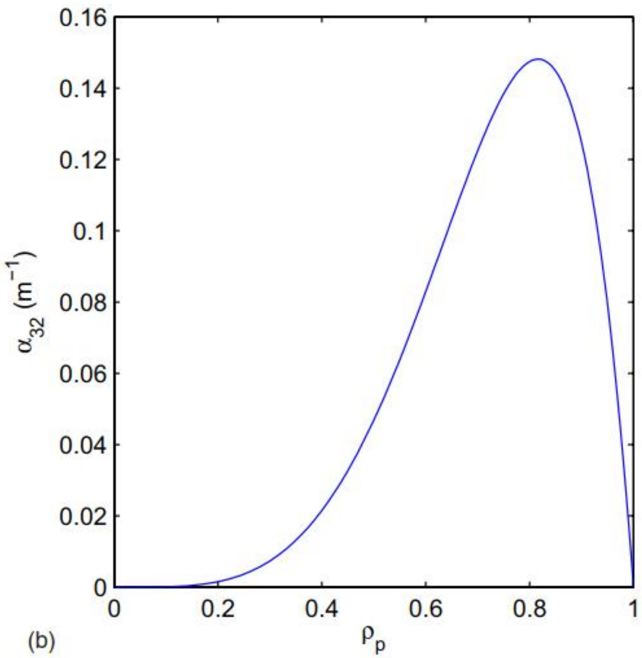
$$\boldsymbol{B}^{\star} = \boldsymbol{B} + (\rho_{\parallel} + \alpha)\nabla \times \boldsymbol{B}$$

$$\boldsymbol{E}^{\star} = \boldsymbol{E} - \frac{1}{e\gamma}\left(\mu + \frac{e^2 B \rho_{\parallel}^2}{m}\right)\nabla B - \nabla\tilde{\Phi} + \frac{eB^2\rho_{\parallel}}{\gamma m}\nabla\alpha$$

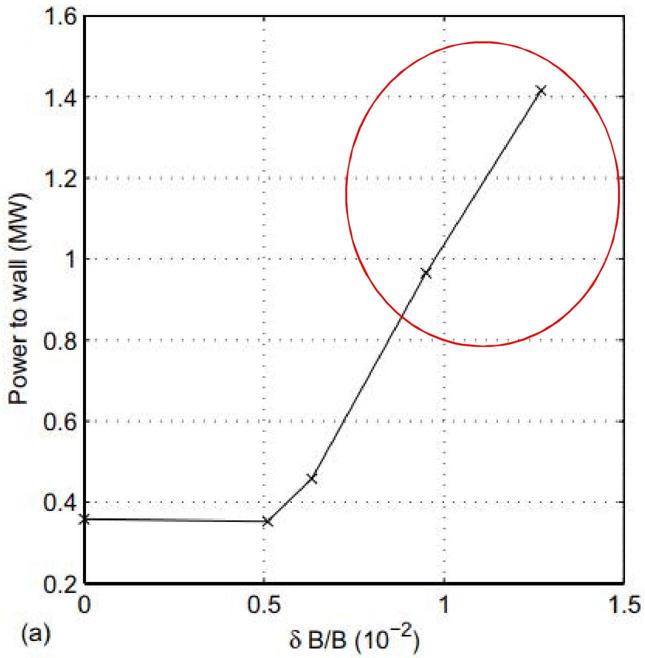
[1] R. B. White and M. S. Chance, PF, **27** (1984) 10
[2] E. Strumberger *et al.,* New J. Phys. **10** (2008) 023017
[3] E. Hirvijoki et al., CPC **183** (2012) 2589

Effect of NTMs in the 15MA ITER baseline scenario

A. Snicker et al., NF **53** (2013) 093028



Radial profile used to generate the perturbation for the (3,2) NTM

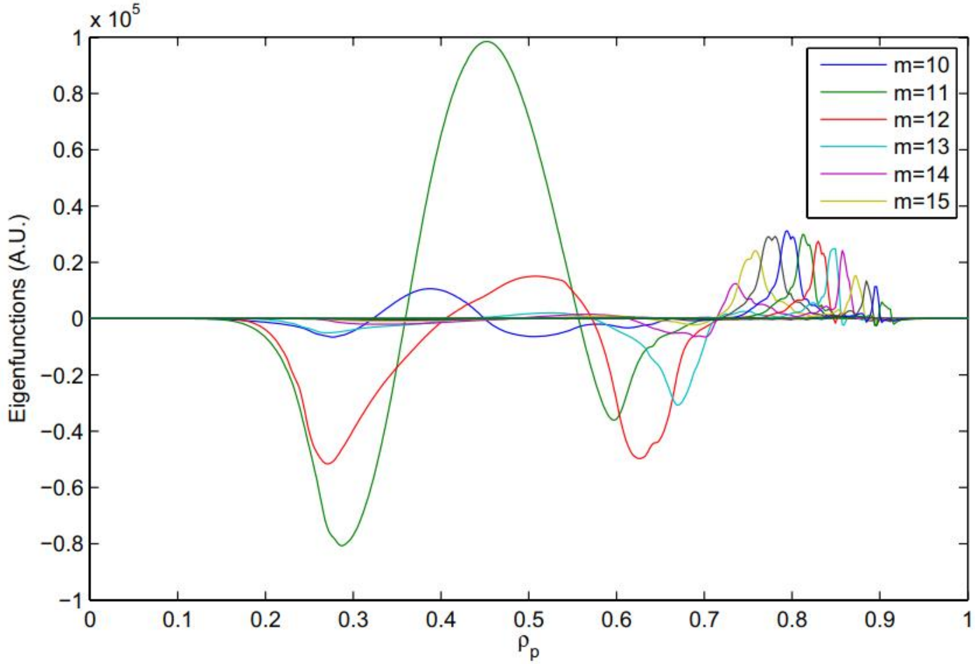


Unacceptably large islands for ITER operation – cannot be mitigated by ECCD

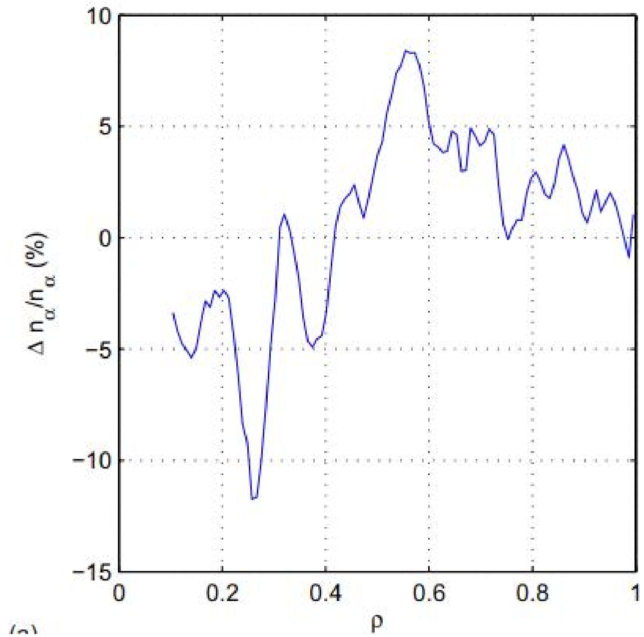
Total alpha particle wall power load versus perturbation amplitude

Effect of TAEs in the 9MA ITER advanced scenario

A. Snicker et al., NF **53** (2013) 093028



Eigenfunctions for the most unstable TAE n = 5 as calculated by LIGKA. Poloidal harmonics with m = 10–25 used in the simulations



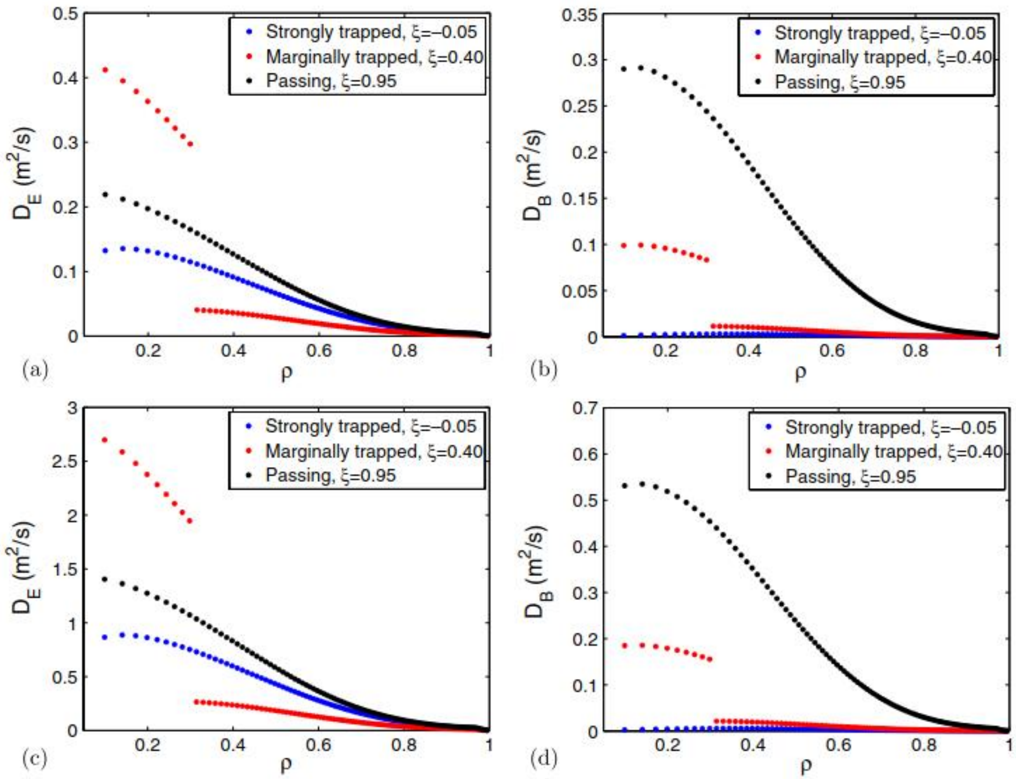
Relative change in the alpha density, brought about by the n = 5 TAEs

Internal perturbations: turbulence

*Hauff&Jenko PRL **102** (2009) 075004:*

- *Fast ion diffusion coefficients due to electrostatic (D_E) and magnetic (D_M) turbulence*
- *Coefficients depend on*
  - *background plasma*
  - *fast ion energy*
  - *fast ion pitch*

3.5 MeV alpha



1 MeV deuteron

Some coefficients in old ITER scenario-2 plasma
*T. Kurki-Suonio et al., **51** (2011) 083041*

Effect of turbulence in old ITER scenario 2

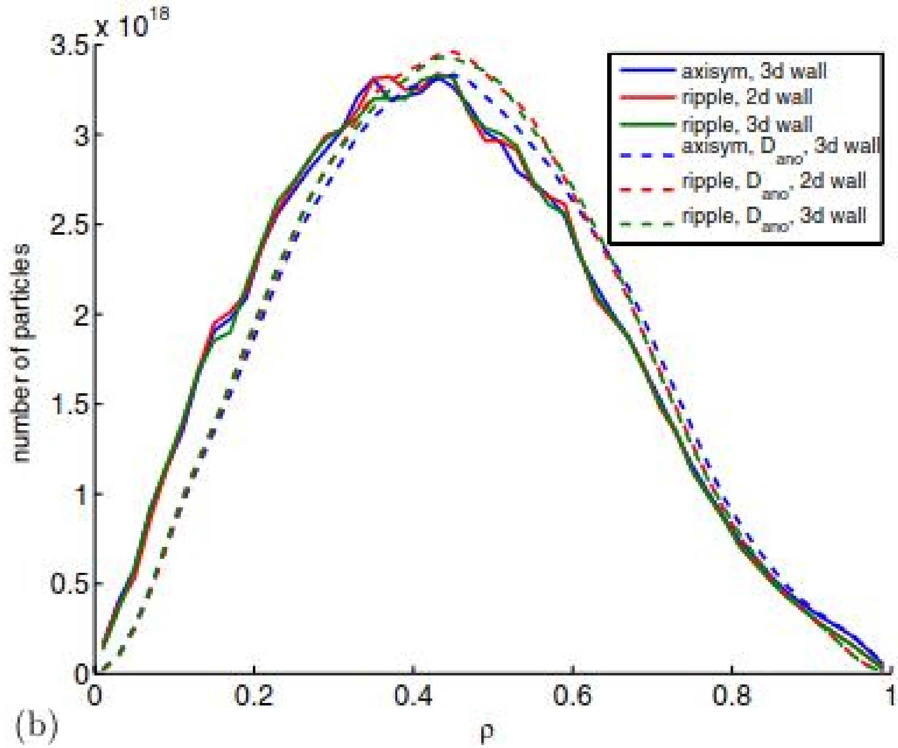
T.Kurki-Suonio et al., Nucl. Fusion 51 (2011) 083041

The radial profile of the slowing-down distribution of fusion alphas comparing

- The effect turbulent vs NC transport
- The effect of wall shape
- The effect of TF ripple

« Turbulence shifts the profile outward

« w/ turbulence, the TF ripple has a bigger effect



Calculating the plasma response

MARS-F vs JOREK

Developed by Y.Q. Liu *et al*. @Chalmers

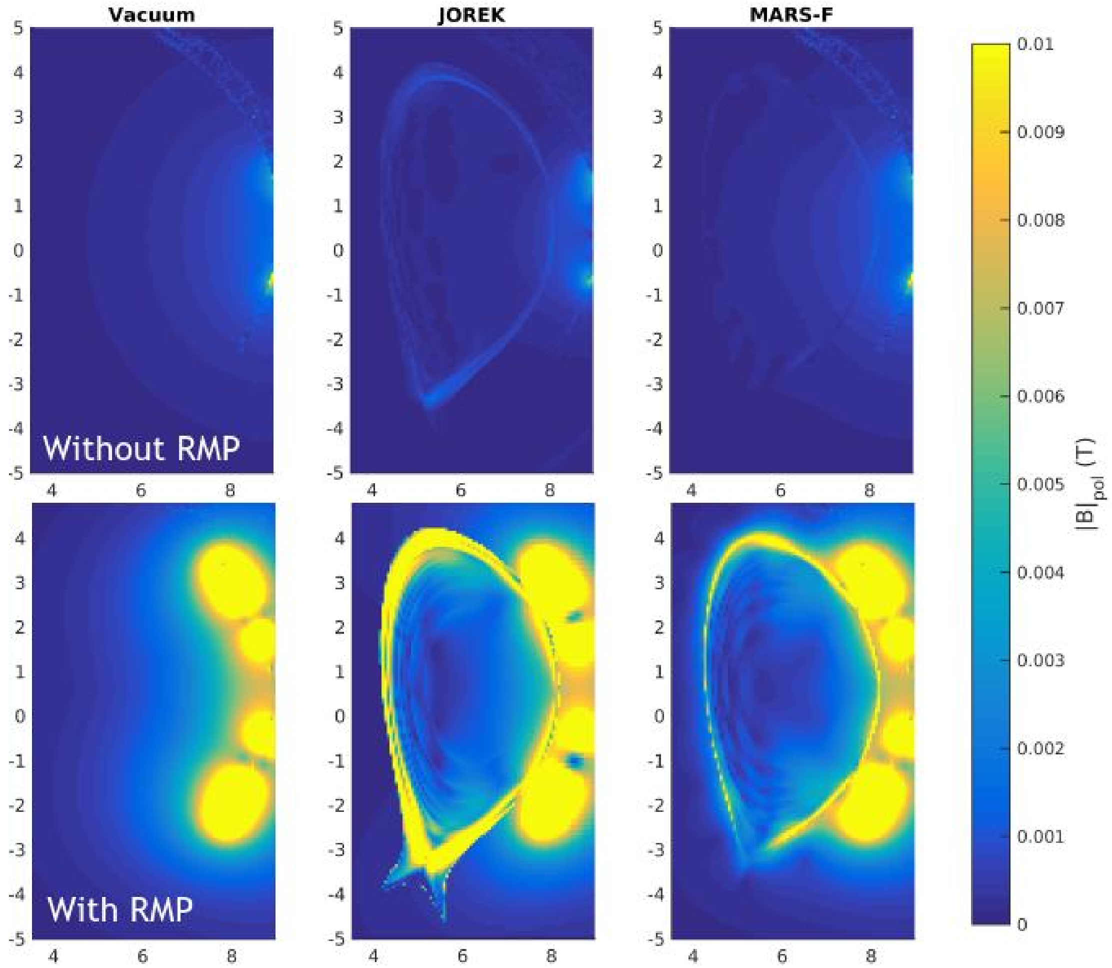
- Linear code
- Full MHD
- Limited physical region
- No X-point
- Very fast

Developed at IPP and CEA

- Non-linear code
- Reduced MHD
- Extends over separatrix
- Includes X-point
- S-l-o-w

There are differences in the plasma response

- Here: *n = 3 component only*
- Poloidal structure depends on grid resolution
- work ongoing
- not yet obvious which features are physical/numerical



Following particle trajectories

Considerations

« In a device of ITER size, following guiding centers (GC) of fusion alphas for the full slowing-down takes about 500 – 1000s/pcle.
  – If interested not only in zero-dimensional numbers (e.g., total power load), N = 10^5 OK,
  – If want distributions (MW/m^2) è 10^6's of markers needed

« Acceleration of interaction (collision) time scales of limited use due to 3D irregularities in the magnetic field

« Hybrid formalism:
  – GC in the plasma bulk
  – Approach PFC è revert to 'co-GO'-following
  – No wall hit è drop GO, continue w/ GC

There are issues …

« It is generally assumed that adopting GC approach does not alter the general validity of the results

However …

« RIPLOS-2: repeat a couple of simulations with full gyro orbit (GO) following

è the alpha wall loads were found to reduced by a factor of 25 – 50% !

« Following GO's instead of GC's requires 10 – 100 shorter timestep

è we embarked on scrutinizing the source of the difference

Does our GC transformation contain some inconsistency?

A closer look at the Lie transformation

Thanks to Alain Brizard

- *Consistent* GC description requires both the equations of motion and ***the collision operator*** to be transformed from particle frame to GC frame
- ASCOT now has a genuine GC collision operator [1,2]
- These transformations were carried out to the first order in the formal expansion parameter (not the same as the common ρ_L/L_B)
- The fast ion birth *location* to the GC location transformed to the same order
- However, *magnetic moment & parallel momentum* still at their 0^{th} order (particle) value

[1] A. Brizard et al., PoP **11** (2004) 442

[2] E. Hirvijoki et al., PoP **20** (2013) 092505

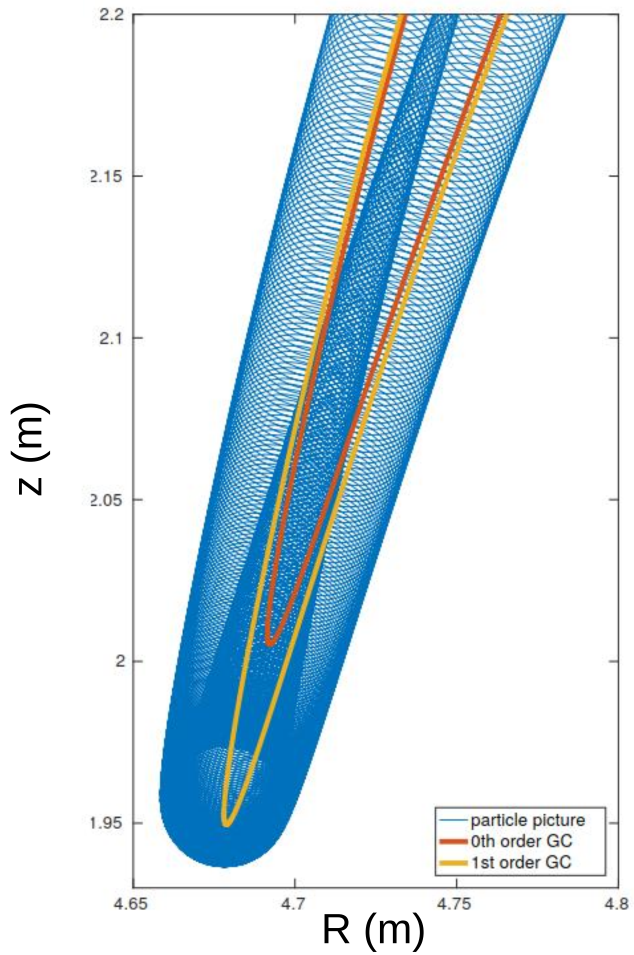
Consistent GC transformation of initial phase space coordinates

$$
\begin{aligned}
\mathbf{X} &= \mathbf{x} - \rho \\
p_{||}^{GC} &= p_{||} + p_{||}^{1} \\
\mu^{GC} &= \mu + \mu^{1},
\end{aligned}
$$

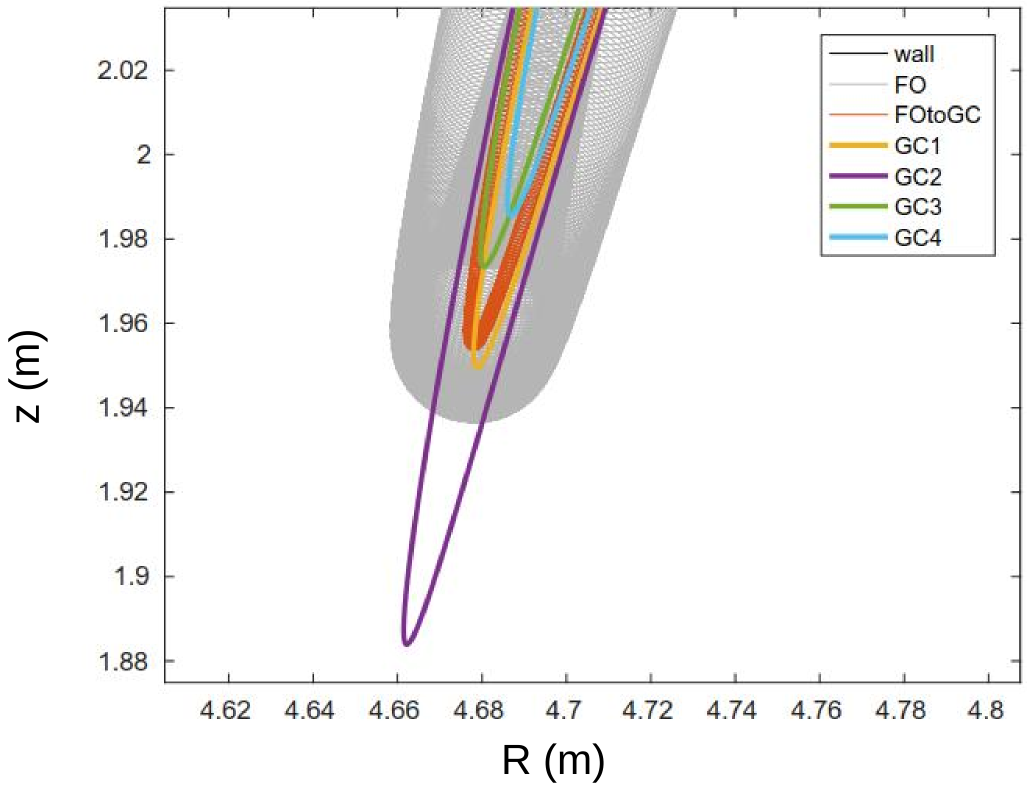
$$
p_{||}^{1} = -p_{||}\rho_{\mathbf{0}} \cdot \kappa + \frac{m\mu}{q}(\tau_B + \mathbf{a}_1 : \nabla\hat{\mathbf{b}}),
$$

$$
\mu^{1} = \rho_0 \cdot (\mu\nabla \ln B + \frac{p_{||}^2}{mB}\kappa) - \frac{\mu p_{||}}{qB}(\tau_B + \mathbf{a}_1 : \nabla\hat{\mathbf{b}}).
$$

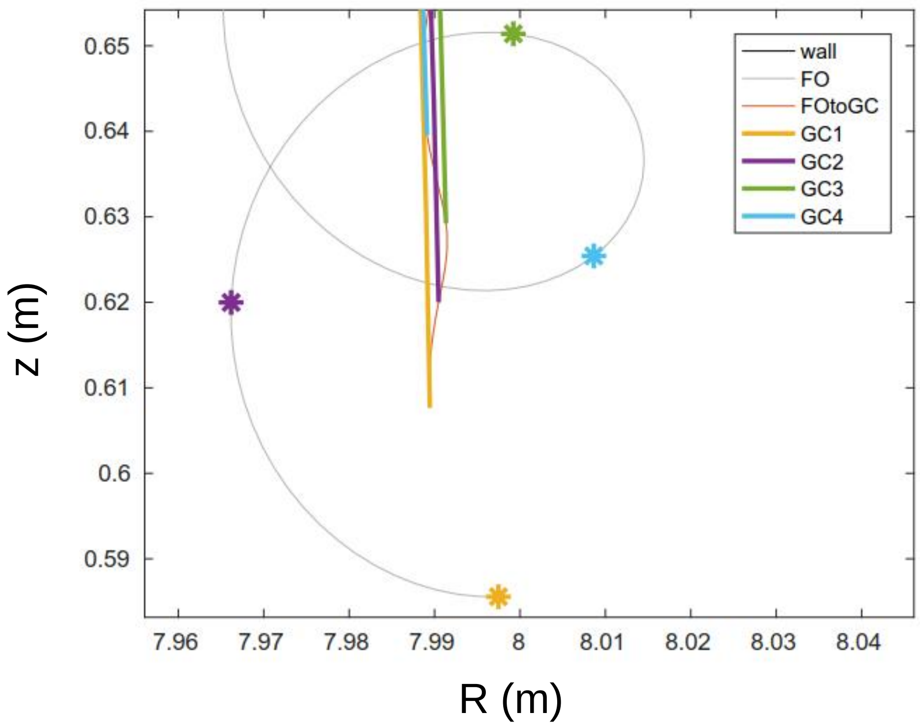
Brilliant improvement …



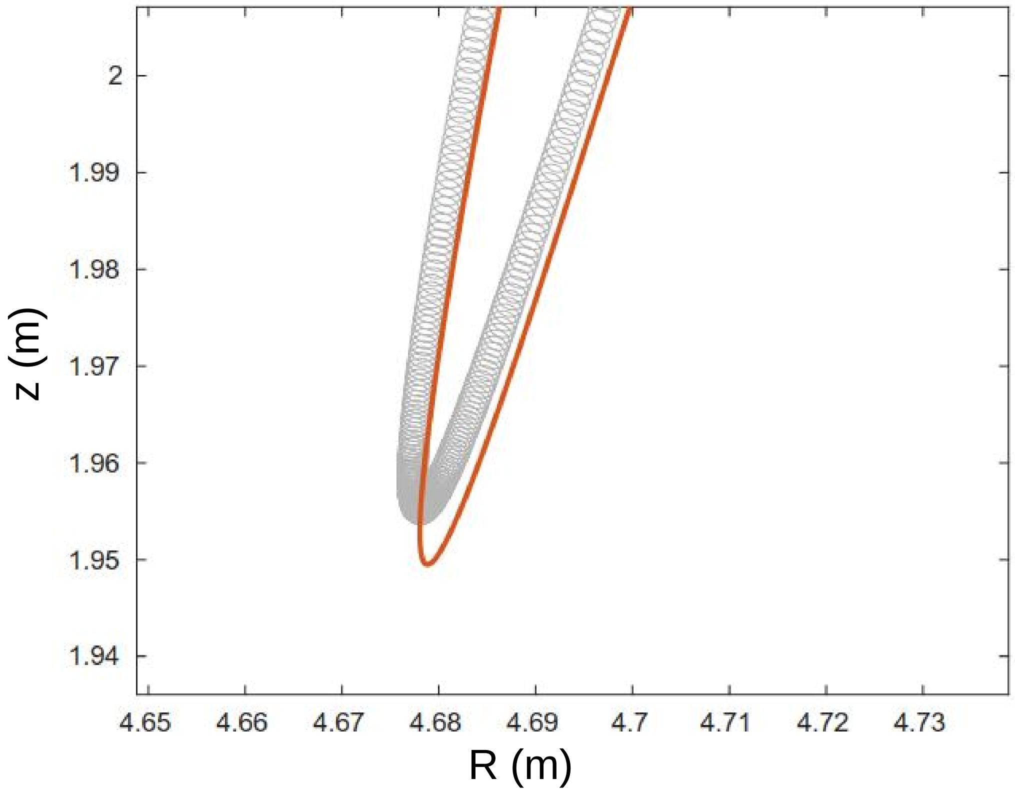
… but not so fast …



Gyro phase does matter



GC vs GO w/ *instantaneous* GC transformation



So does this jeopardize the reliability of results?

Probably not:

- Having now simulated more cases with pure GO-following made 'deterministic' wall load reduction disappear
- For fusion alphas, the gyro phase is random to begin with
- However, for *counter-injected* beam ions this might make a (small) difference in *only* the wall loads:
  - At the time of switching from GC to GO, the gyro phase is randomly given

Is GC approach really superior?

- Rob Akers, IAEA-FEC 2016:
  - The length of a time step is not all that matters …
  - GC following:
    - Time step $\Delta t \sim 0.01\mu s$, but
    - 4th-order Runge-Kutta w/ 5th-order error correction requires 6 look-ups for the magnetic field
  - Boris method for GO:
    - Time step $\Delta t < 1ns$, but
    - Only 1 look-up for the magnetic field

Careful studies are being carried out together with Rob and his LOCUST code

ASCOT simulations

ITER

Summary of wall power loads in different scenarios

	Scenario	α wall load (kW)	α divertor load (kW)	NBI wall load (kW)	NBI divertor load (kW)
Non-activation phase	7.5 MA	-/-	-/-	12/13	0/3
	+TBM	-/-	-/-	19/19	0/3
	9 MA	160/160	130/150	6/5	2/4
	+TBM	250/270	130/180	15/14	2/9
	12.5 MA	510/530	190/190	3/3	1/1
	+TBM	580/640	190/210	7/8	1/3
	15 MA	20/19	120/120	2/-	1/-
	+TBM	39/42	110/130	7/-	1/-
	+ECC	70/160	1900/1300	9/10	1150/1300

Without / with plasma response

Fusion alpha loads highest for the hybrid scenario

	Scenario	α wall load (kW)	α divertor load (kW)	NBI wall load (kW)	NBI divertor load (kW)
Non-activation phase	7.5 MA	-/-	-/-	12/13	0/3
	+TBM	-/-	-/-	19/19	0/3
	9 MA	160/160	130/150	6/5	2/4
	+TBM	250/270	130/180	15/14	2/9
	12.5 MA	510/530	190/190	3/3	1/1
	+TBM	580/640	190/210	7/8	1/3
	15 MA	20/19	120/120	2/-	1/-
	+TBM	39/42	110/130	7/-	1/-
	+ECC	70/160	1900/1300	9/10	1150/1300

Without / with plasma response

Why? Not obvious:

- Not lowest current
- Pedestal quantities not different enough

ELM control coils *appear* to ruin confinement !

	Scenario	α wall load (kW)	α divertor load (kW)	NBI wall load (kW)	NBI divertor load (kW)
Non-activation phase	7.5 MA	-/-	-/-	12/13	0/3
	+TBM	-/-	-/-	19/19	0/3
	9 MA	160/160	130/150	6/5	2/4
	+TBM	250/270	130/180	15/14	2/9
	12.5 MA	510/530	190/190	3/3	1/1
	+TBM	580/640	190/210	7/8	1/3
	15 MA	20/19	120/120	2/-	1/-
	+TBM	39/42	110/130	7/-	1/-
	+ECC	70/160	1900/1300	9/10	1150/1300

Without / with plasma response

- Both alpha and NBI confinement affected
- The dramatic increase concerns only losses to the divertor

For beam ions, plasma response *increases* loads?!!

	Scenario	α wall load (kW)	α divertor load (kW)	NBI wall load (kW)	NBI divertor load (kW)
Non-activation phase	7.5 MA	-/-	-/-	12/13	0/3
	+TBM	-/-	-/-	19/19	0/3
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	12.5 MA	510/530	190/190	3/3	1/1
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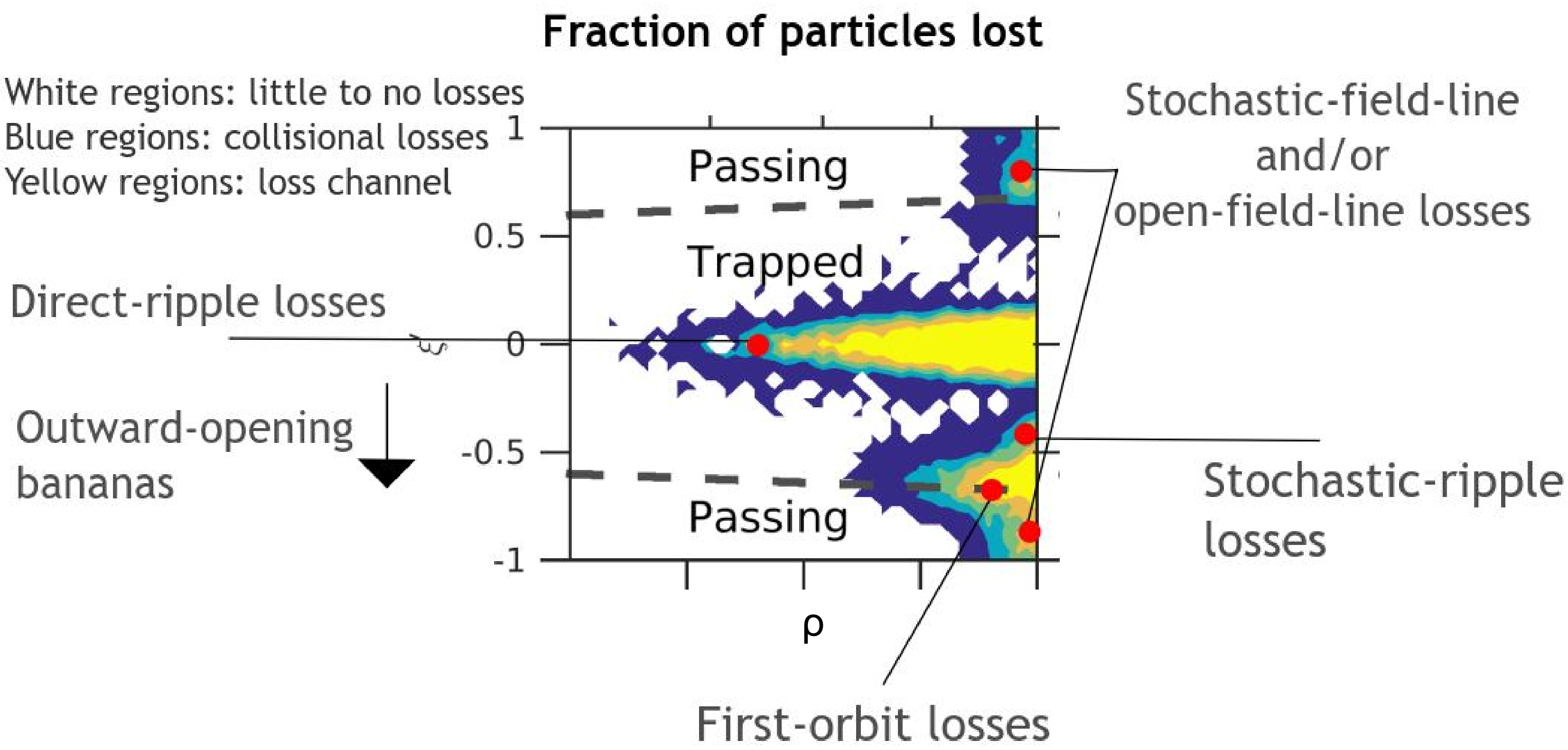
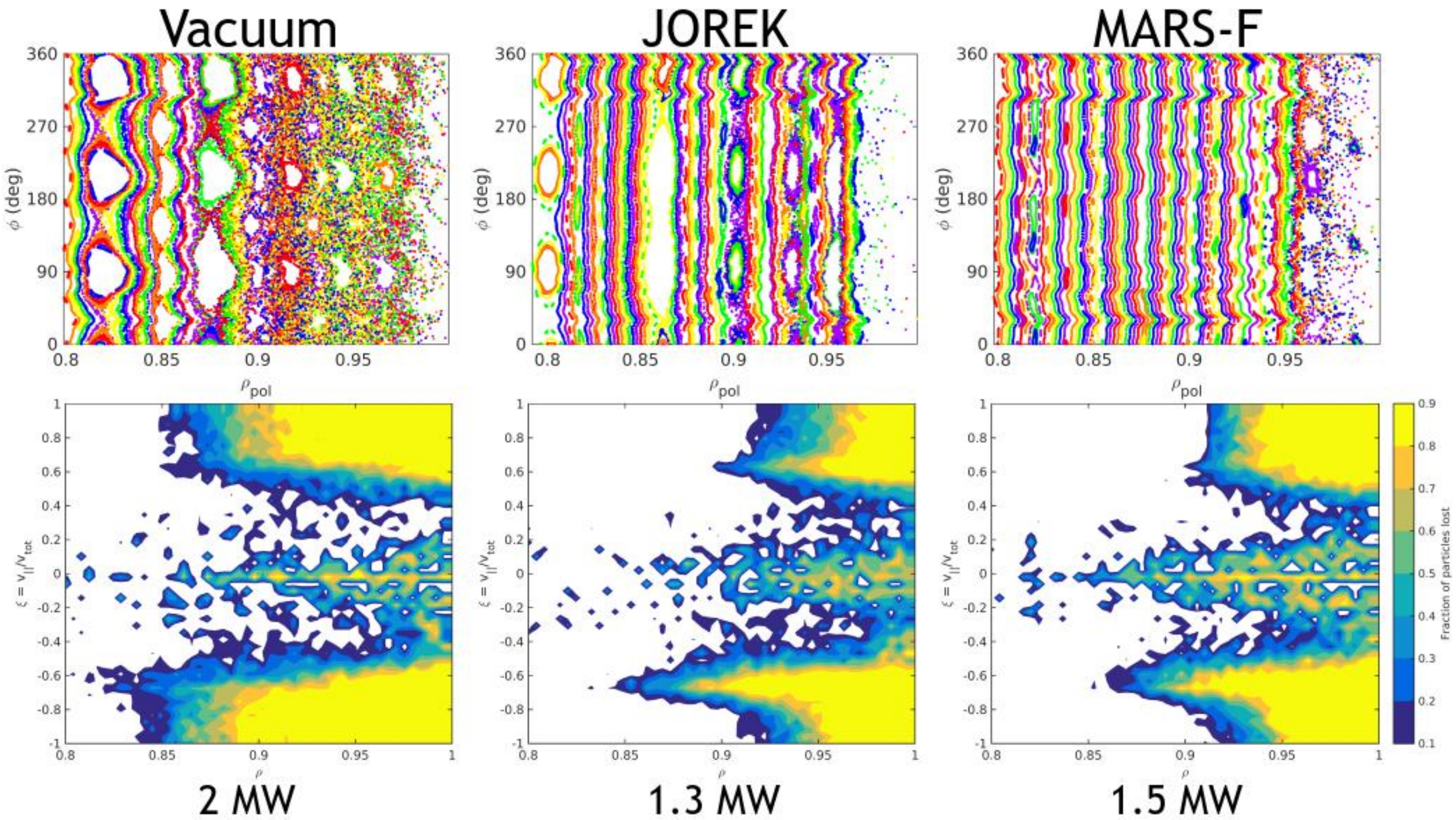
	15 MA	20/19	120/120	2/-	1/-
	+TBM	39/42	110/130	7/-	1/-
	+ECC	70/160	1900/1300	9/10	1150/1300

Without / with plasma response

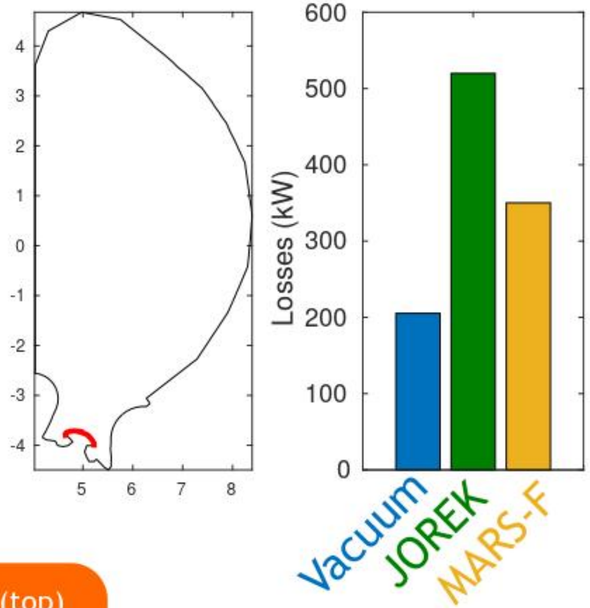
Anatomy of the fast ion losses

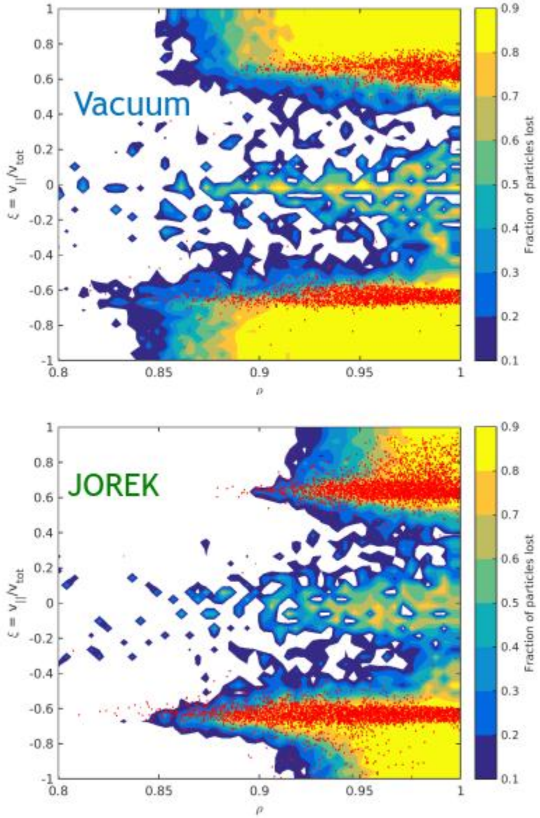


Plasma screening reduces total losses



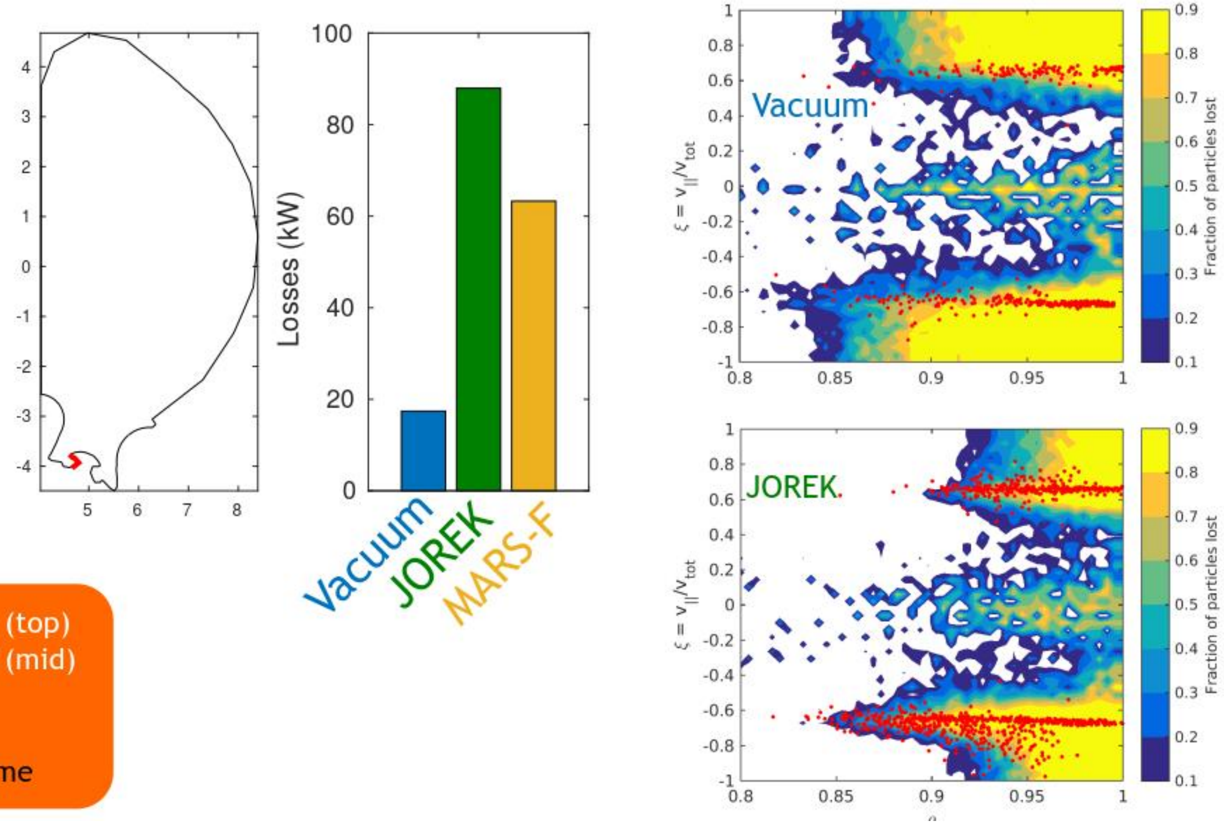
But *locally* the loads can be increased!





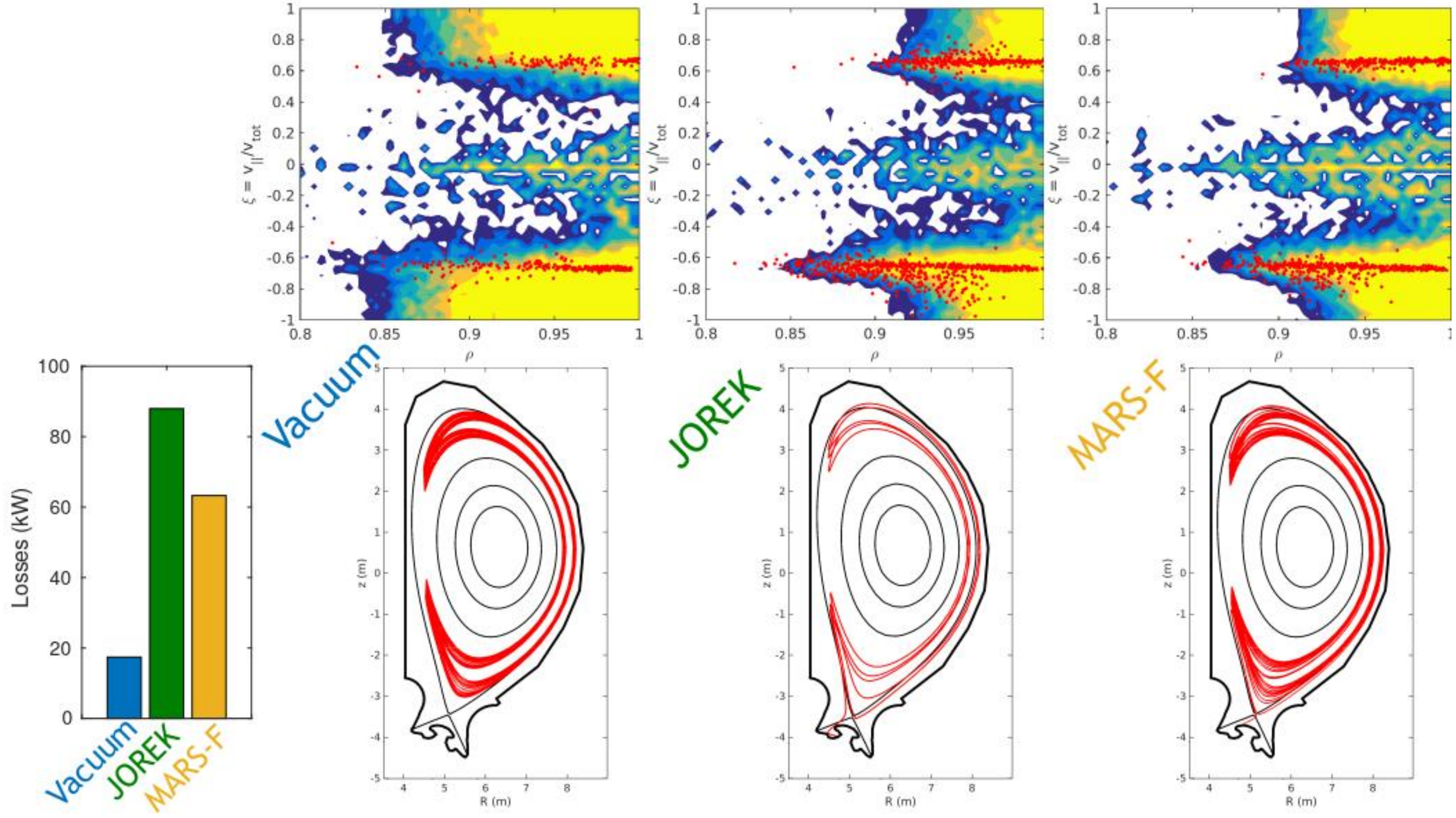
First wall LFS (top)
First wall LFS (mid)
Divertor
Dome
Under the dome

But *locally* the loads can be increased!



First wall LFS (top)
First wall LFS (mid)
Divertor
Dome
Under the dome

K. Särkimäki, P2.17: Mechanics of ELM control coil induced alpha particle transport



ASCOT simulations

DEMO

The European DEMO

- **1.8 GW fusion power, up to 50 MW NBI heating**
- Different material choices (EUROFER-97) vs ITER (CuCrZr).
- The lower thermal conductivity of EUROFER-97

è lower first wall power limits compared to ITER:

ITER: 4.7 MW/m^2, DEMO: **1 MW/m^2** [1].

*[1] R. Wenninger et al., NF **57** (2017)046002*

3D features in DEMO

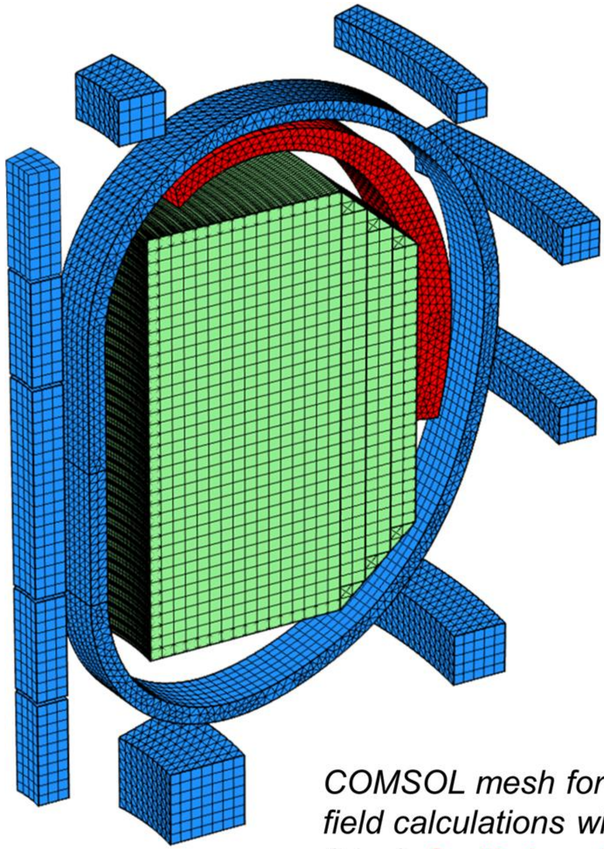
DEMO has only 18 TF coils

è On the separatrix, TF ripple of max 0.8 %

(*Note: 1.1% in ITER)*

è Introduce ferritic inserts (FI)

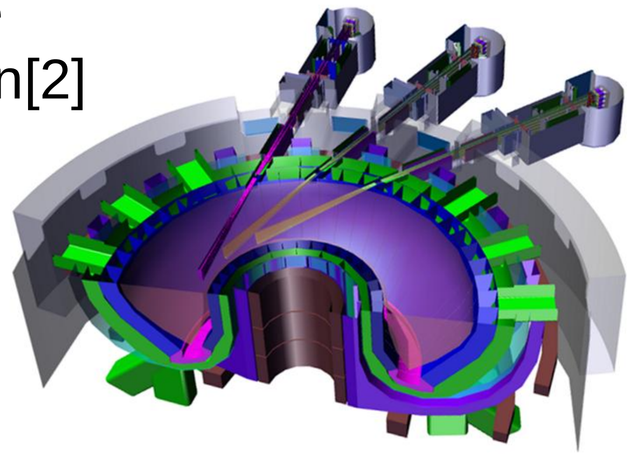
(No TBMs)



COMSOL mesh for magnetic field calculations with coils (blue), ferritic insert (red) and plasma volume (green)

Fast ion sources in DEMO

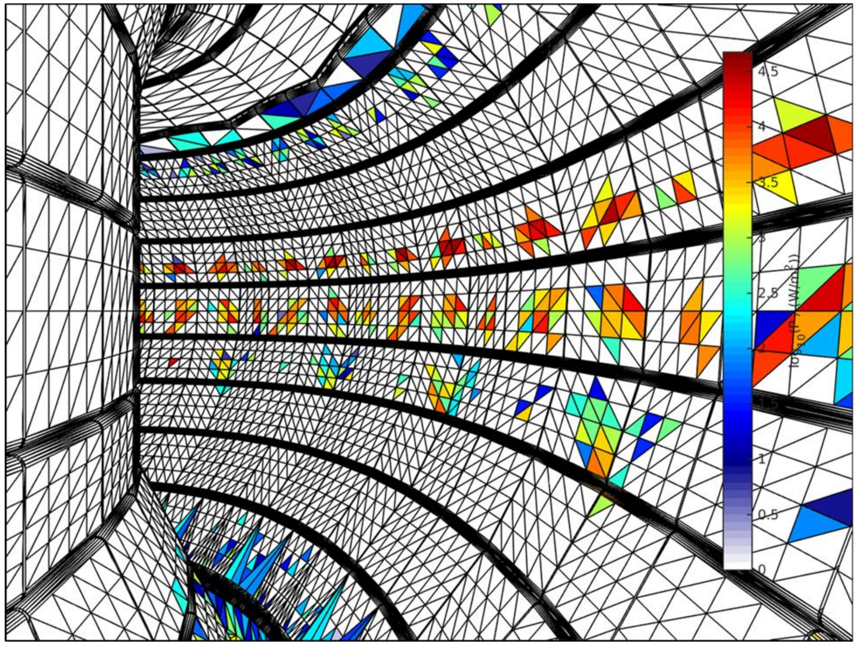
- NBI source w/ the beamlet-based NBI ionization code BBNBI[1] using the latest DEMO NBI reference design[2]
  - 16.8 MW per injector, energy 800 keV
  - 20 modules with 60 beamlets each
- Thermonuclear alpha source calculated with ASCOT fusion source integrator AFSI [3]

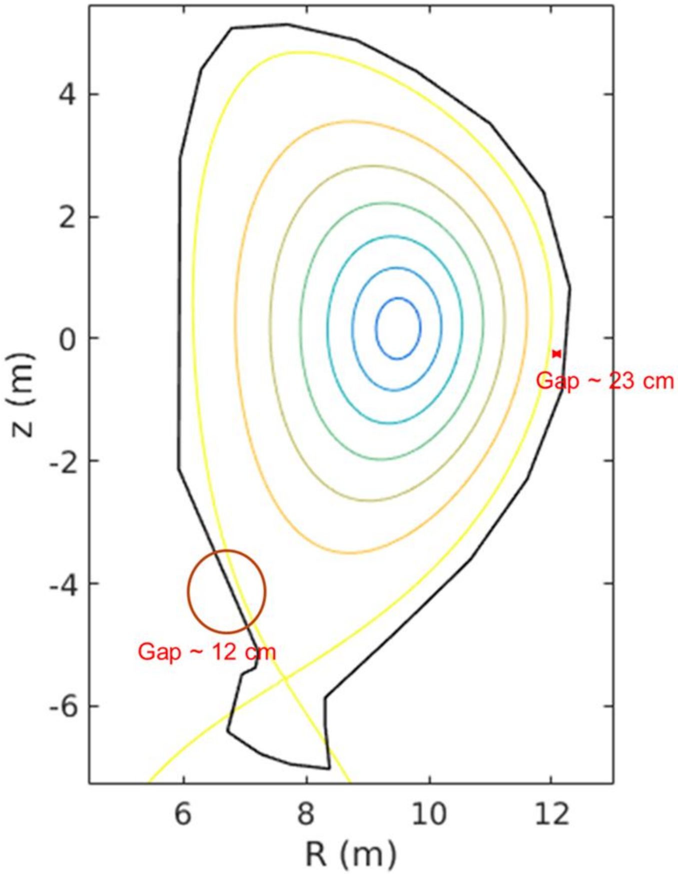


Sonato P. et al., NF 57, 2017

[1] *Asunta et al., Computer Physics Communications **188**, 33-46 (2015)*
[2] *P. Sonato et al., NF **57** (2017) 056026*
[3] *Sirén et al., 'Versatile fusion source integrator AFSI for fast ion and neutron studies in fusion devices', submitted to NF 2017*

Alpha power w/ unmitigated TF ripple





Effect of ferritic inserts on losses

Vary the strength of the 3D perturbation

	Alpha losses	
Unmitigated ripple	453 kW	0.12%
Ripple + 25% FI	177 kW	0.04%
Ripple + 50% FI	65 kW	0.02%
Ripple + 75% FI	39 kW	0.01%
Ripple + 100% FI	33 kW	0.01%

	NBI losses
2D equilibrium	< 1 kW
Unmitigated ripple	49 kW
Ripple + 100% FI	2 kW

… does DEMO even need the ferritic inserts… ?

DEMO conclusions

- due to 19.6MA & the large plasma-wall gap, less-steep pedestal, even fusion-α losses < 100kW. ***Better than ITER*** !
- FIs effective already at 50% of designed mass
- Word of warning: ELM mitigation coils and/or strong MHD activity can change the situation

Mode details:

- J. Varje et al., *Effect of 3D magnetic perturbations on fast ion confinement in the European DEMO*, P2.147, 44th EPS Conference on Plasma Physics, Belfast, Ireland, 26 - 30 June 2017
- P. Vincenzi et al., *Comparison of Neutral Beam Injection options for EU DEMO pulsed Scenario,* P2.146, 44th EPS Conference on Plasma Physics, Belfast, Ireland, 26 - 30 June 2017

ASCOT simulations

JT-60SA

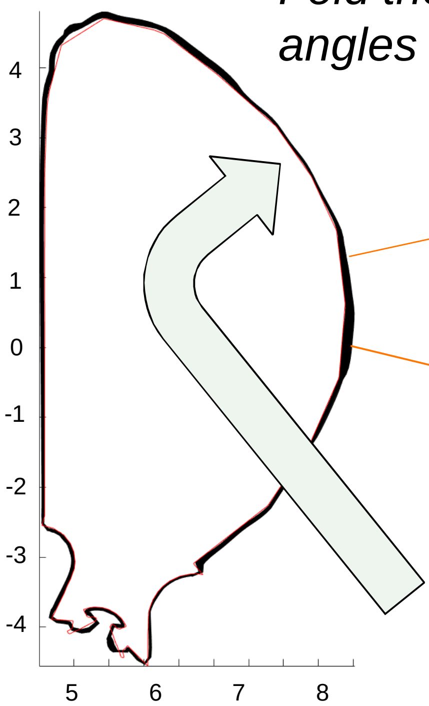
On-going ASCOT work on JT-60SA beams

- Preliminary beam simulations in axisymmetric geometry
  - EPS 2017 P1.149: *M. Vallar & al., "Neutral beam injection modelling in JT-60SA axisymmetric equilibria"*
- Currently under investigation:
  - Effect of TF ripple (JT-60SA will not have ferritic inserts) & RMP coils
  - Effect of impurities on both power deposition and beam driven current
  - Significance of CX losses

Some messages to take home from tokamak studies

- Assuming axisymmetric ***wall*** when it is not can give very misleading results on fast ion confinement and wall power loads

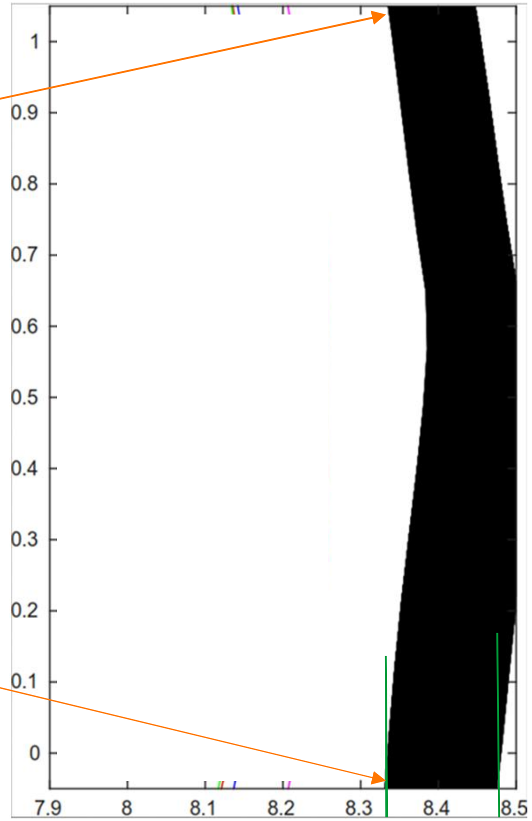
The 3D vessel wall of ITER



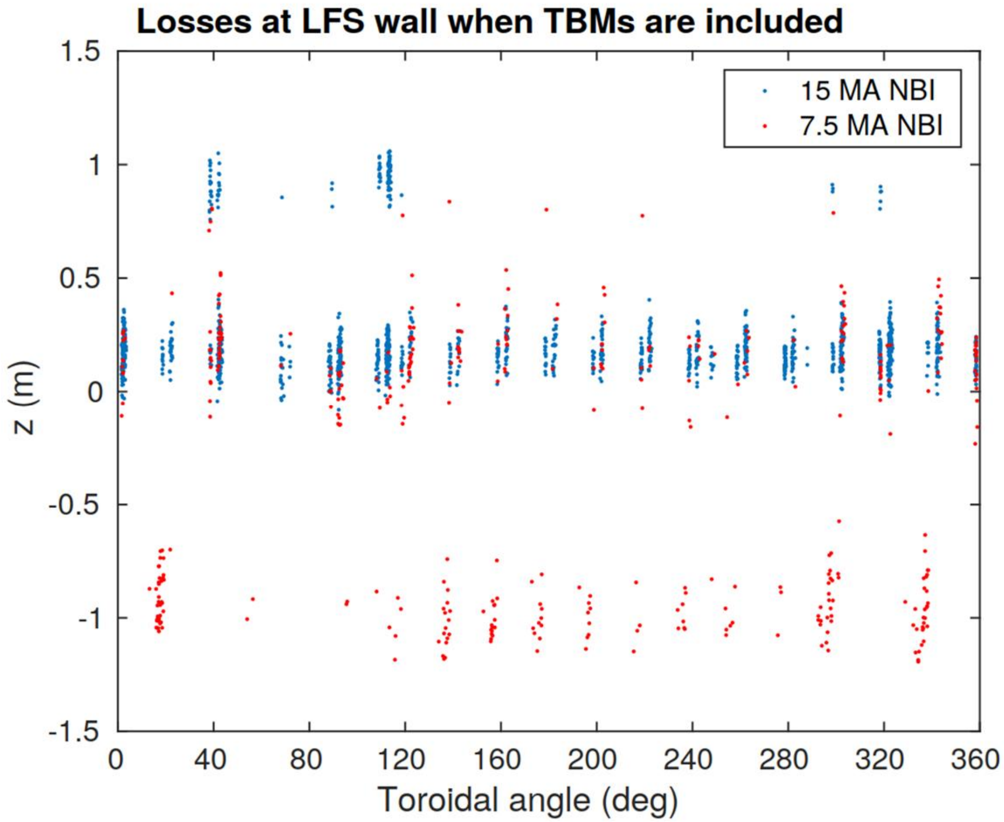
Fold the poloidal contours from 'all' toroidal angles onto the poloidal plane

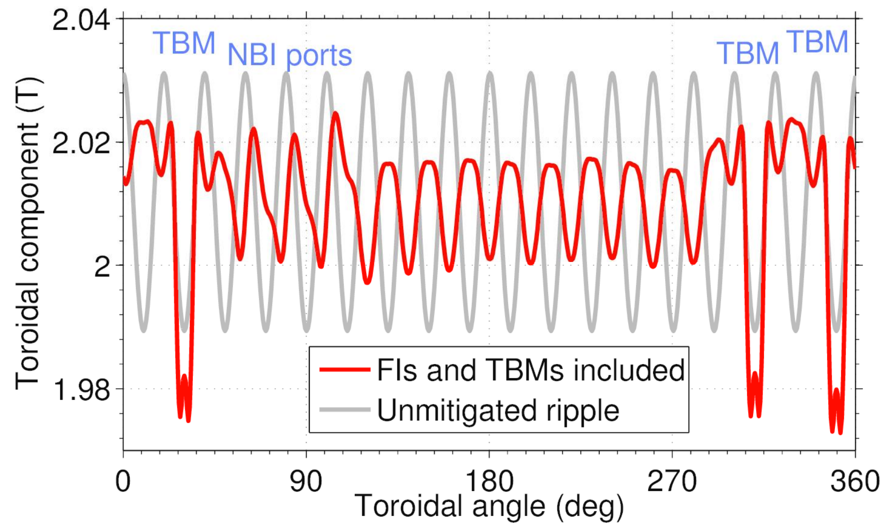
Up to 15 cm difference in the outer midplane gap between plasma and the vessel wall

The 3D wall structure explains the emergence of 'hot spots' in upper right corner



Wall shape dominates the power distribution





power arrives at the limiters even when TF ripple is 'reversed' in the *7.5MA half-field scenario* due to over-compensation by FI's

Messages to take home from tokamak studies

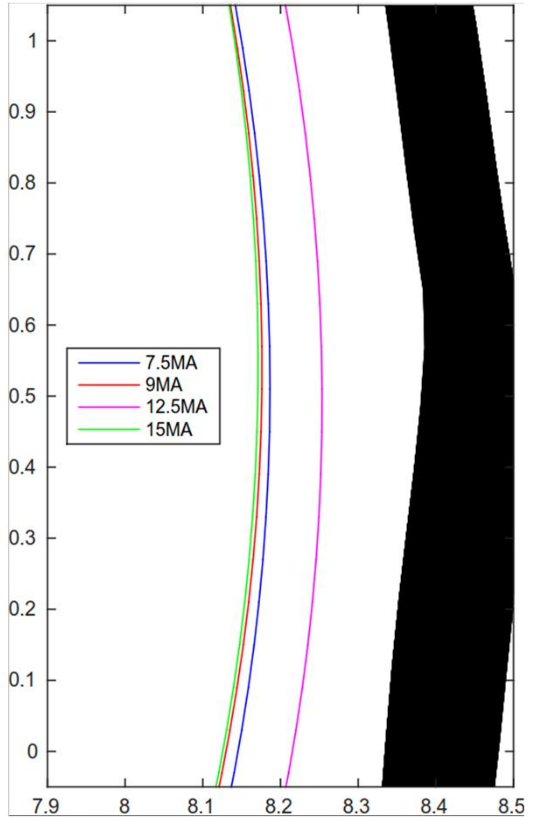
« Assuming axisymmetric ***wall*** can give misleading results on fast ion confinement and wall power loads

« The shape of the plasma matters

– the ITER 12.5MA hybrid scenario had more triangular plasma è

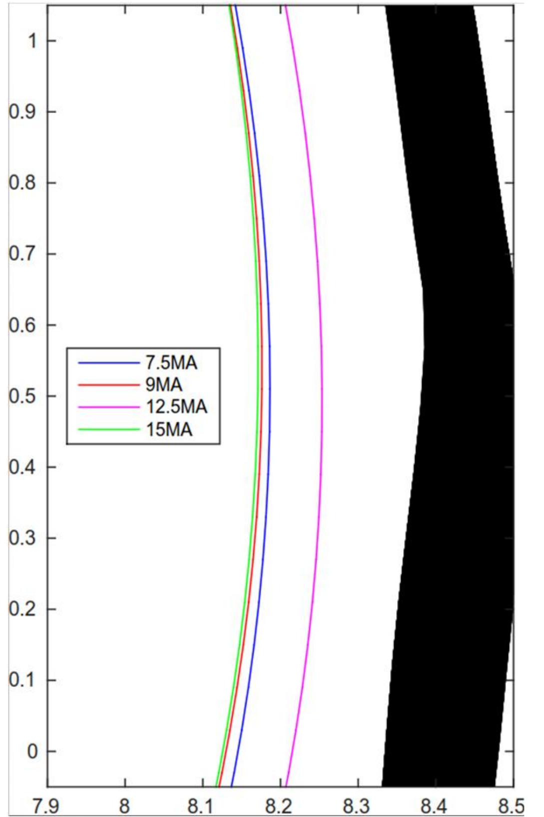
è Smaller gap at OMP

è Larger power loads



Messages to take home from tokamak studies

- Assuming axisymmetric ***wall*** can give misleading results on fast ion confinement and wall power loads
- The shape of the plasma matters
  - the ITER 12.5MA hybrid scenario had more triangular plasma è
    - è Smaller gap at OMP
    - è Larger power loads
- Vacuum approx does not necessarily lead to conservative power load estimates
- The size of the device (DEMO) matters
  - In the future, maybe the advantages of larger size vs complications introduced by ferritic inserts should be calculated also in €€€
  - Larger plasma-wall gap helps a lot



ASCOT simulations

The ultimate 3D case: Wendelstein 7-X stellarator

Exciting times for fast-ion people at W7-X

Early(?) 2018:

- 2 NBI injectors w/ 2 sources each injecting hydrogen: 55/60 keV in H/D
- Power per source up to ~1.7/2.4 MW (H/D)
- Hydrogen, Deuterium or Helium injection
- quite radial beam geometry (engineering constraints)
  è confinement a serious issue

- W7-X has 7 different types of coils, with 7 independent power sources
  è seven degrees of freedom. ECRH resonance eats one degree of freedom
  è six left to modify the magnetic cage

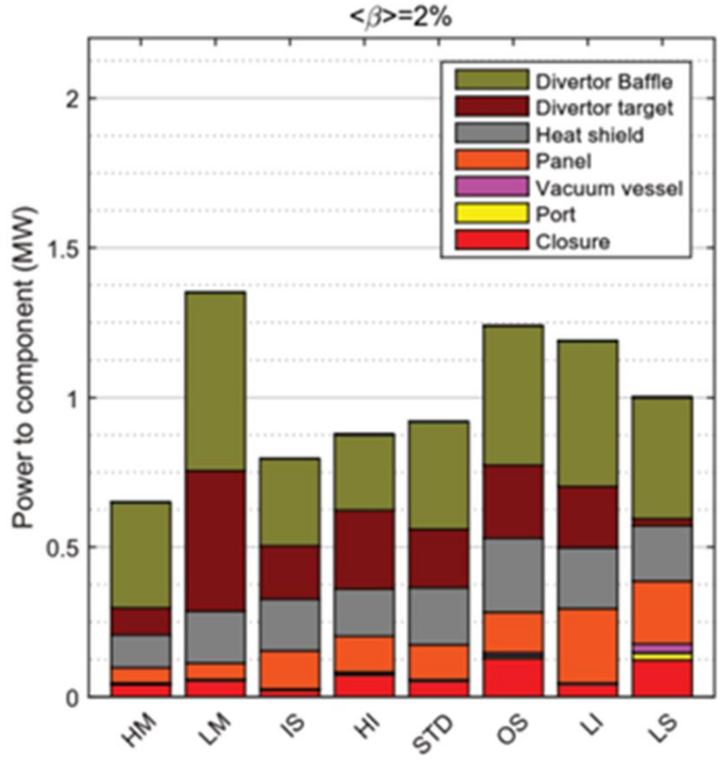
W7-X can provide a variety of configurations:

- W7-X highly optimized wrt to 3 criteria:
  - good NC confinement,
  - Small GS shift,
  - Small bootstrap current
- 9 reference scenarios represent extreme cases
- beam ions already studied with ANTS and simple wall (*Drevlak et al., NF **54** (2014) 073002*)
- Now these re-addressed with ASCOT and detailed 3D wall ($4{\cdot}10^6$ triangles)

	Name
HM	High mirror
STD	Standard case
LM	Low mirror
OS	Outward shifted
IS	Inward shifted
LS	Low shear
HI	High ι
LI	Low ι

+ a 'limiter' case (plasma very close to the divertor plates)

Power loads on different components



Sensitive wall components (made of steel): panels and poloidal closure, pumping slits, vacuum vessel, ports

Conclusions from the W7-X simulations

- Even in the optimized scenarios, beam losses are substantial, several %
  - (cmp to tokamaks where they are almost negligible – thanks to Emmy Noether)
- Configuration ***with high mirror ratio*** superior for fast ion confinement
- Most power goes to the ’right’ components: divertor parts and heat shields
- Still substantial power lands also to the vulnerable parts (red & Co)

è *Hunt for the perfect (beam) scenario still on-going !*

Thank you

-- and enjoy Simppa’s video !

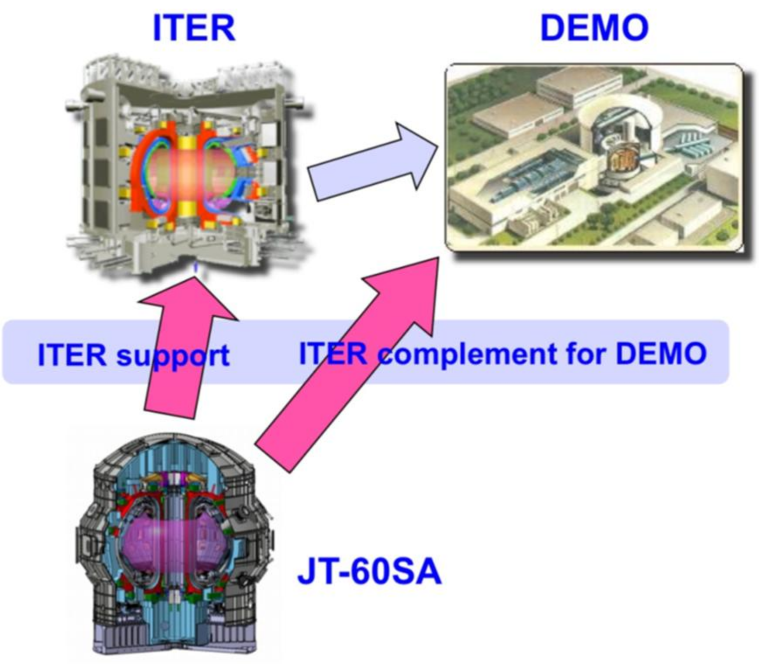
Acknowledgements

- This work was partially funded by F4E Grant 379, the Academy of Finland project No. 259675, and Tekes (the Finnish Funding Agency for Innovation under the FinnFusion Consortium).

- The simulation work was carried out in part using
  - the HELIOS supercomputer, IFERC, Aomori, Japan
  - the supercomputing resources of CSC-IT center for science, Finland.
  - computer resources within the Aalto University School of Science ‘Science-IT’ project.

JT-60SA
”the best thing since sliced bread” (read: W7-X)

- JT-60SA is part of Broader Apporach
- JT-60SA is *The Device* to
  - prepare for successful operation of ITER
  - develop diagnostics for ITER
  - test predictions for ITER
  - prepare for problem situations in ITER



â The community should take a *comprehensive* advantage of JT-60SA

– not just for ITER but for DEMO as well

EU should take a comprehensive advantage of JT-60SA

ITER's needs

- Very high plasma current, 15MA
  - Generation and control of runaways?
- High energy *negative* neutral beams: 33 MW of 1 MeV N-NB
  - Reliability? Performance?
- Long pulses (up to 1000s)
- TBMs and RMP coils

What JT-60SA can offer

- High plasma current: up to 5.5 MA
- High energy *negative* neutral beams: 10 MW of 500 keV N-NB
- super-conducting coils è long pulses (100s)
- RMP coils for ELM mitigation
- Two sizes of TBM mock-ups
  - Hopefully … J