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Strategy to cope with 3-D field effects on DEMO

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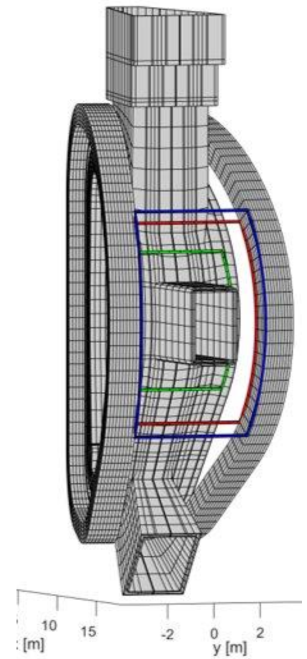
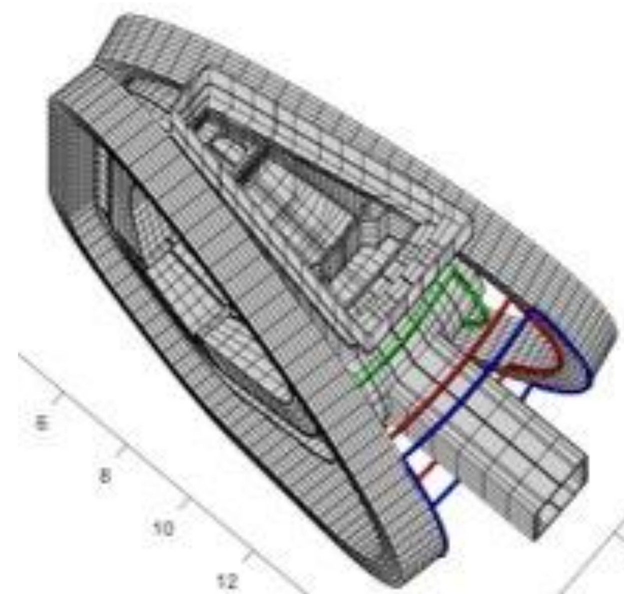
Outline

We discuss (ex-vessel) 3-D ('RMP') coils for:

- **Error field correction**
- **3-D ELM suppression**
- **Manipulation of locked tearing modes**
- **Tailoring of edge profiles**





We also discuss as a boundary condition

- **Impact of 3-D fields on exhaust / first wall loads (both helical and TF ripple)**

These topics were discussed in the FTD-FSD meeting and I just give short summaries (assuming you know what I am talking about, if not, just interrupt me)

Strategy for 3-D coils on DEMO

The present baseline does not foresee any 3-D coils

Introducing these coils will relax some severe constraints

- active correction of unavoidable error fields (probably a must)
- application for ELM suppression or mitigation
- manipulation of the relative phase of locked tearing modes for NTM control by ECCD
- additional knob for tailoring of edge profiles (e.g. rotation shear for no-ELM regimes)

Contrary to ITER, we can design these coils with all applications in mind from the start

- present DEMO scenario has sufficient no-wall beta-limit: we do not foresee active RWM control, so coils could be ex-vessel (and superconducting?)
- can one set of coils do the full job?

N.B.: we are discussing in-vessel coils as well, but only axisymmetric ones for vertical stability control and strike point sweeping…

Summary of discussion on error field correction

Plasma response method by now quite established and is recommended by the experts

- Experimental results from COMPASS, MAST-U and KSTAR support its applicability
- No direct 1:1 comparison experiment versus the 3-mode criterion yet (some of it in Paz-Soldan, Nucl. Fusion 2014)
- Will be done under RT01 (MAST-U, AUG)

A variety of numerical tools to calculate plasma response exists

- IPEC (GPEC), VMEC and MARS-F have not been benchmarked rigorously
- GPEC is probably easiest to use, VMEC has the full toroidal mode coupling
- Will be a subject of further discussion in the TSVV 3-D effects meeting

Think about methods different from ‘compass-scan’ to determine error fields

- W7-X and MAST-U measured coil positions during assembly to correct ‘on the fly’
- DIII-D did a vacuum measurement of their intrinsic error field

Summary of discussion on ELM suppression by RMPs

Design based on optimising edge kink response is a pragmatic start

- tools well developed, heuristic criterion, was largely done for DEMO ex-vessel coils by (Liu, Zhou)

Full understanding of RMP ELM suppression (density threshold) missing – hampers extrapolability

- Assuming an island forms that increases pedestal transport, there should be a penetration criterion. Hu criterion (density = f(rotation)) agrees with DIII-D, but not with AUG.
- RMPs do enhance (toroidally localised) fluctuations in the pedestal (AUG), and correlate well with occurrence of density pump-out. May stabilise ELMs by reducing pressure gradient.
- Pedestal stability itself will be altered by RMP fields.
- Quantitative assessment needed if RMP induced transport sufficient to stay below that limit.

Progress in both theory and experiments is needed

- Need testable theoretical predictions for penetration / turbulent transport: kinetic effects on penetration, nonlinear MHD mode coupling, 3-D turbulent transport? to be discussed further in the TSVV - 3-D meeting
- Experiments will be done in WPTE, focus on model testing (rather than ITER ‘demonstration’)?
- open points: penetration, transport, stability models to be (de)validated for extrapolation

Summary of discussion on locked mode manipulation

Experiments in DIII-D validated the technique to rotate NTMs in front of ECCD launchers

- clear proof of principle, but not feedback controlled yet
- once we have a clear strategy, this could be a topic for WPTE

Modelling is at present done on a simple analytical basis

- coupled momentum balance and Rutherford equation should capture the principal dependencies
- at some point, we may want to validate this in a nonlinear MHD code (but needs realistic wall, momentum balance and RMPs)

Summary on tailoring of edge profiles (n(r), T(r), v(r))

When applying RMPs, edge profile change ⇒ possibility to tailor edge conditions in DEMO?

- has been used in DIII-D to sustain QH-mode (Garofalo, NF 2013), access 'wide pedestal' QH-mode (Burrell, NF 2020), 'control' confinement (Hawryluk, NF 2015)
- need to understand if this could be applied in DEMO
- quantify achievable range of edge rotation and related effects on kinetic profiles

Priority of the NTV experiments in FSD (JET)?

Need to sort out the modelling tools (3-D meeting…)

- we have secured resources for MARS-K and started discussions with TU Graz (NEO-2…)

Summary on heat loads by *resonant* 3-D fields

For RMP applications, it will be crucial to understand the lobe structure in the divertor

- experiments on reattachment of secondary lobes in AUG showed no concern, but unclear if DIII-D results are contradicting this – need to use experiments as code validation and not as ‘demonstration’ in a regime that is not equal to ITER/DEMO
- there was consensus that lobes that reach out of the divertor and hit main chamber structures have to be avoided – this has already been adapted as a requirement for the 3-D coils in DEMO

Modelling should draw on existing experience in stellarators

- codes developed for stellarators are full 3-D (e.g. EMC3-EIRENE)
- validation of loads due to particle losses is an important topic for W7-X

Summary of discussions on TF ripple - status

Split ripple requirements in two areas: first wall loads and impact on plasma performance

First wall loads seem to be well understood

- use of orbit following (coupled to Fokker-Planck for distribution function if needed) gives a good description of the measured localised heat loads
- impact on divertor loads detected in attached state when ripple variation is of order of grazing angle on target (could be important for XD configuration)

Effects on plasma performance are not fully understood

- change in rotation probably consistent with additional torque from ion losses, but the closure of the ASCOT calculations is not consistent
- change in edge rotation may explain some impact (ELM change, LH threshold)
- strong density pump out not straightforward to understand - analogy to RMPs, does the non-resonant component (e.g. NTV) play the dominant role and how about turbulence?
- decreased confinement with additional gas puff looks similar to axisymmetric case (?)

Summary of discussions on TF ripple – open issues

Can we reduce the impact on plasma performance to axisymmetric

- change of H-mode pedestal (ELMs, LH threshold) due to changed rotation?
- change of energy confinement due to need for increased gas puff?

This would leave us with understanding the change of rotation and particle confinement

- change in rotation roughly consistent with additional torque from ion losses calculated by ASCOT, but including the electric field in a self-consistent way would be preferable ('NTV including ripple and fast particles') – this will be tackled with NTV codes

Strong density pump out not straightforward to understand

- analogy to RMPs hints at non-resonant component playing a strong role
    - experimentally: comparison experiments resonant RMPs, non-resonant RMPs, ripple, but not possible in a single device – **JET the only device with 'ripple control'**
- need to sort out neoclassical losses versus change in turbulence
    - neoclassical part should be possible using 'generalised NTV tools'
    - turbulent part mainly experimental characterisation at this stage…