Summary/discussion

8th IAEA DEMO WS Topic 1:

Transient operational phases and transient loading environments for fusion DEMO power plants

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Plasma transient challenges and resulting requirements for the machine design of a DEMO tokamak reactor by F. Maviglia

- Difference in heat load requirements between ITER and DEMO: irradiation resistant FW materials have lower thermal conductivity, tritium breeding requirement (thin FW), and energy conversion efficiency (high coolant temperature).
- **Transient (heat) loads on FW will be come from normal (ramp-up/down), and off normal events (up/down-VDE, loss of confinement, mitigated/unmitigated disruptions).**
- All of them except mitigated disruption will be resolved with limiters in EU-DEMO.
- In-vessel coils (IVCs) will be necessary to robustly control vertical stability/displacements in plasmas with large elongation.
- Fast radial control (with IVCs) will help to make operation much safer.
- **(Heat) loads by disruption must be reduced with mitigation technique relaxing toroidal/poloidal peaking of heat loads.**
- 3D heat flux (HF)on limiters and first wall is evaluated, and thermal calculations of PFC designs are also carried out.
- Vapor shielding modeling results foresee a factor heat flux 10 reduction for major disruption.
- Limiter design of EU-DEMO are updated with the latest considered perturbations.
- Transient heat load on divertor will be come from 1) reattachment and 2) ELMs. (ramp-up will be shown in discussion session)
- **Detached plasma conditions on divertor plate is necessary to protect the divertor. Since ramp-down rate in DEMO must be slow (density limit, density required for detatchment are also key, safe way for ramp-down, SCRAM?), attached condition will be kept for a long time enough to burn-out the divertor (don’t know how long,).**
- Strike point (on divertor plate) sweeping is a candidate mitigating loss of detatchment. This technique will require IVC, but the integration is challenging. In addition, a technique for diagnostics is also necessary.
- **Naturally ELM-free regime will be on priority for EU-DEMO, because one ELM can melt the divertor and a few tens of ELMs can erode one-half of W width.**

Development of the Fenix flight simulator for DEMO transient scenarios by E. Fable

- Fenix is a simulator for checking pulse schedule, developing/improving plasma control schemes for operation scenario/against transients etc..
- Many transients/perturbations in ramp-up/flat-top/ramp-down phases are listed.
- **Transients/perturbations mainly discussed in this talk are 1) failure of aux. heating, 2) tungsten (W) drop into plasma, 3) unexpected H-L transition in EU DEMO. Simulation results investigating their impacts are presented.**
- Impact of W drop into plasma should be relaxed with (localized) ECW heating (near edge) to avoid radiation collapse.
- Role of impurity for divertor protection during ramp-up is critical at L-H transition.
- **Exit from burn (flat-top) phase and interplay with impurities is also critical during ramp-down.**
- **Ramp-down rate is restricted to keep plasma equilibrium under control, Hence, fast shutdown is not easy.**
- **Reactor SCRAM scenario design is necessary.**
- Small perturbations to plasma can have large impact on operation; ex. failures of fueling/heating.
- **Application to transient scenarios are becoming increasingly complex and realistic, towards the full definition of a self-consistent DEMO scenario.**
- To evaluate torelence to transients with Fenix, further physics models should be included (in ASTRA).
- Power exhaust during ramp-up/down will be one of main topics.

Strategies for gradual increase of flat-top plasma performance towards the operational point according to the ITER operational plan by W. Treutterer

- Summarizing ITER goals/research plan, including milestones in each phase (FP/PFPO/FPO).
- In ITER, disruption mitigation system (DMS) will be demonstrated in PFPO-1 to avoid/dissipate run away electron. Also, disruption avoidance strategies will be validated.
- ELM control (with RMP/kicks/pellet pacing) will be demonstrated in PFPO-2.
- **In FPO, plasma will be operated stable to MHD, but if it became unstable, DMS will play a key role to reduce heat load to PFC.**
- Quantitative prediction of all the effects from energetic (alpha) ions is difficult, because ITER FPO is the first case that plasma heating will be maintained by itself (burning).
- **Areas of concern from the viewpoint of thermal loads in ITER (up to $q_{\perp} \sim 4.5 MW/m^2$) are 1) limiter for ramp-up/down, 2) secondary (upper) X-point region, 3) divertor region (during ramp-down).**
- Burn control with fueling is important to access to high Q conditions.
- **Exit from high Q conditions is more difficult, because to avoid fast H-L transition is needed. Adjustment of aux heating and impurity seeding are important in this control.**
- IMAS was created to develop 1) integrated scenario, 2) experimental analysis workflow. This has been applied to develop (PFPO/FPO) scenarios. Physics-based simulation will be able to perform in IMAS framework.

Solutions for the transients and heat load variations of the CFETR operation scenarios by G. Zhuang

- Transients discussed in this talk are 1) ELMs, 2) VDEs/disruption.
- Also, relaxing steady-state heat exhaust (to divertor)is discussed.
- Coupled core-pedestal modeling is applied to simulate flattop phase with self-consistent H&CD.
- Baseline hybrid/steady-state scenarios will have grassy ELM whose energy loss is <0.4% of pedestal stored energy. Ideal MHD is robustly stable in both scenarios, so, disruptions by this reason will be avoided.
- **Grassy ELM has many advantages; 1) small ELM energy loss, 2) impurity cleaning, 3) high plasma performance.** (cracking (of divertor plate) limit is much less than melting one, CFETR team is trying to fix it. EU-side has tried to strength divertor material.)
- Large grassy ELM frequency is necessary to avoid tungsten erosion.
- **Long-leg divertor with Ar seeding can help to satisfy physics requirements easily (partial detachment). The lifetime requirements will be also satisfied.**
- In-vessel coils (IVCs) and disruption mitigation system are necessary to avoid VDE/disruption control.
- Dependence of VDE growth rate on IVCs locations is investigated. IVCs closer to plasma has advantage.
- Comparison of disruption impacts between ITER and CFETR is performed.

Current status of helical fusion reactor design and study on operation control scenario by T. Goto

- Helical reactor has large advantage due to no plasma current. => no disruptive event.
- Transients discussed in this talk are 1) density limit, 2) beta limit.
- Sudo(-like) density limit scaling may determine 'edge' density limit.
- Core/edge MHD can restrict operation regime (not cause major collapse) in helical reactors.
  => MHD can be avoided by choosing operation regime, but in some case, the regime has poor confinement.
- **Density limit (due to radiation collapse) can be increased with large heating power.**
- Beta limit can be increased by controlling vertical field/rotational transform and optimizing coil configuration. => to realize both good stability and good confinement.
- **Density limit control can be achieved with feedback control of pellet fueling/aux. heating power**.
  => Feble-san's will present the reliability of pellet inject is ~90%, which may have impact on controllability.
- Data-driven approach used for controlling heating power is helpful to avoid collapse in LHD.
- **Detachment condition for divertor plasma is necessary in helical/stellarator DEMO, as in tokamak DEMO.**
- Achievable fusion gain of LHD-type DEMO will be limited to Q~10, and the size of DEMO should be large.
  => Experimental data in LHD predict this limit for Q. Optimization of coil shape will help to improve it. Confinement performance in LHD is different from that in W7-X; LHD has much larger neoclassical heat flux but smaller turbulent heat flux than W7-X. No stellarator reactor design use improved confinement mode (H-mode). Turbulent transport is sometimes dominant even in stellarator.
- New concept "FFHR-b3" with twice the size of LHD is designed by optimizing coil shape/current design.

Pieces of material for discussion (1)

We focus on two kinds of transients

1) transient operation phases

2) transient loading environments.

- Transient operation phases
  - Tokamak

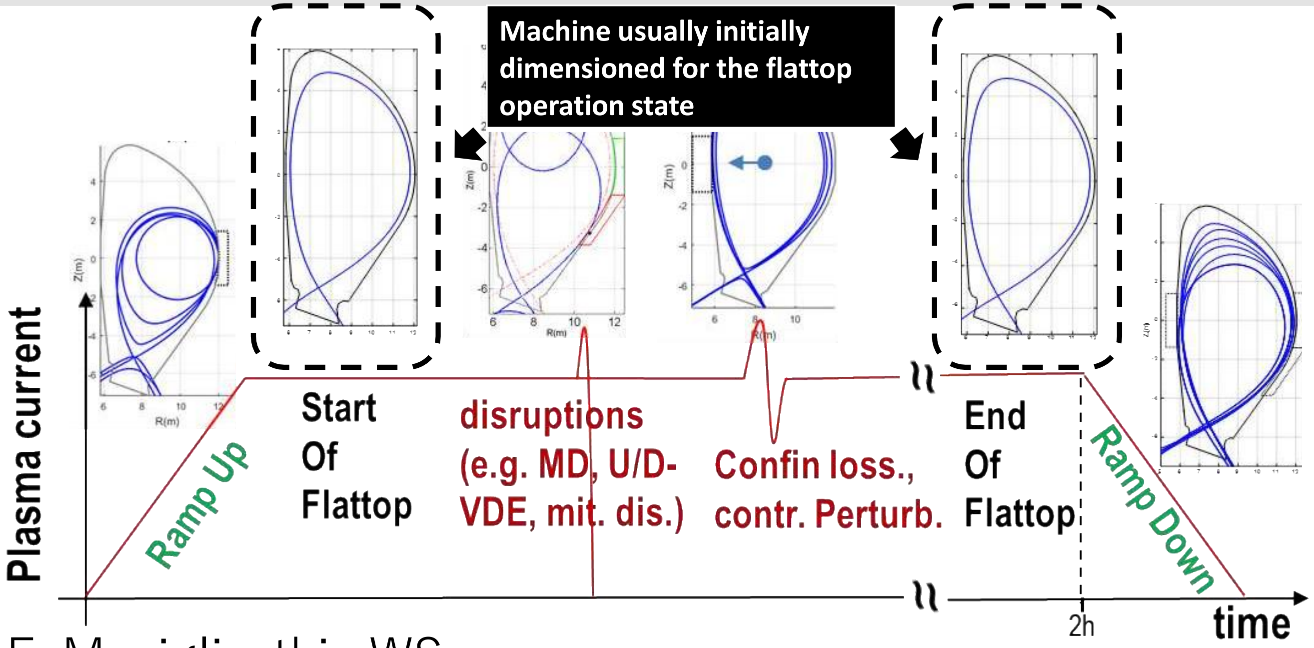
    Ramp-up, L-H transition, Burn control, Ramp-down, H-L transition
  - Helical/stellarator

    Nothing? (long time for start up)/sensitivity of plasma performance on coil design

✓Consider good operation path and/or reactor design.

✓In particular, safe and robust ramp-down scenario in tokamaks is necessary but challenging….

Transient list: Normal v.s. Off-Normal events



Machine usually initially dimensioned for the flattop operation state

F. Maviglia, this WS

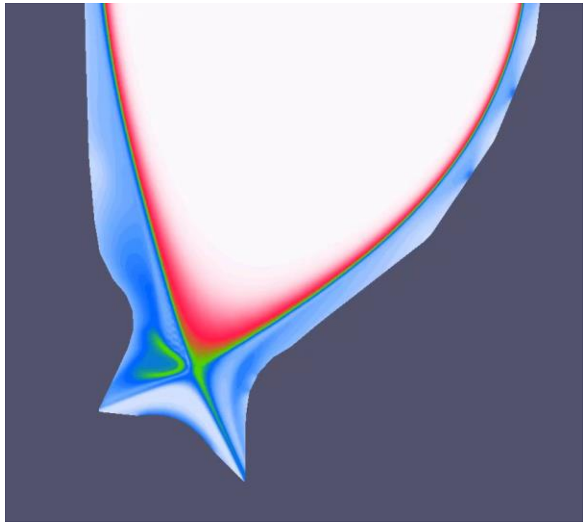
Pieces of material for discussion (2)

- Transient loading environments
  - Tokamak

    Disruption/VDE/RE, ELMs, reattachment (divertor), loss of aux. heating, W flake, unexpected H-L transition
  - Helical/stellarator

    Radiation collapse (density limit), minor collapse (beta limit), divertor detachment.

JOREK simulation by G. Huysmans
(W. Treutterer, this WS)



✓ Radiation collapse/minor collapse/detachment is the same issue in tokamak and helical/stellarator.

✓ Not only regular procedures avoiding them but also SCRAM scenario should be considered. …. Knowledge/experience in ITER will be useful (DMS, detachment, etc.).

✓ Skin effect of plasma is large because of low resistivity. Treatment of radiation loss rate during ramp-down (become 100% easily) is difficult.=> Ramp-down rate is restricted.

✓ Strategy for avoiding ELM is one of the key topic to realize steady-state operation. CFETR team chooses grassy ELM, but other DEMO concepts in the world (EU, JA etc.) may not determine it…. Main reasons are as follows.

◆Reliability of ELM-free operations/ELM control methods in DEMO.

◆Requirement from divertor material (thresholds for melting, cracking (etc.)).

Pieces of material for discussion (3)

Tools useful to consider strategies shown above.

- Physics-based simulation code (ex., CREATE, MECS, etc.)
- IMAS (ITER), flight simulator (Fenix, etc.?), integrated codes in the world etc.

Develop reliable and simple physics models for flight simulators, integrated codes.
Missing models realizing the following issues; these are proposed by E. Fable.

- Correct estimation of line radiation in pedestal-near SOL region.
- Correct prediction of plasma profiles (particularly around separatrix).
- Correct prediction of stability of MHD modes leading to TQ
- Correct detachment model at divertor
- Correct density limit model

Can we develop the models satisfying these requirements?

… Maybe, it is very very difficult to satisfy all of them, because physics are still unclear even when using physics-based (first principle-like) simulation codes. Is it possible to utilize flight simulators/integrated codes for DEMO design even if we accept reality?

=> Can machine-learning-based models/techniques be a game changer?

J. Degrave, Nature 2022