Summary/discussion

8th IAEA DEMO WS Topic 1:

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

N. Aiba (QST), F. Maviglia (EUROFusion),
W. Biel (Forschungszentrum Jülich)

Plasma transient challenges and resulting requirements for the machine design of a DEMO tokamak reactor by Francesco 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).** Disruption free (due to phys. reasons) scenarios should be developed in present machines and ITER to learn to operate DEMO.
- In-vessel coils are necessary to robustly control vertical stability in plasmas with large elongation, and can improve radial control. Complication of using IVC (e.g. integration, nuclear radiation), should be carefully trade-off with control performance improvements, control power requirements, etc.
- **(Heat) loads by disruption must be reduced with mitigation technique relaxing toroidal/poloidal peaking loads.**
- Initial limiter design activity started, from evaluated 3D heat flux during plasma transient phases.
- R&D ongoing (e.g. PFC vapor shielding and advanced materials modeling/experiments, disruption mitigation).
- **Detached plasma conditions on divertor plate is necessary to protect the divertor.** Consistent normal Ramp up/down transients being tackled with aid of flight simulators (more physics needed - next slides).
- Strike point (on divertor plate) sweeping is a candidate mitigating loss of detatchment (SCRAM not yet available). 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 type 1 ELM can melt the divertor.** Small ELMs/ELMs free regimes should be carefully assessed in present devices, and possibly ITER, including diagnostic of possible fall back to ELMy mode (depending on the scenario)
- **Transients strongly impact key systems: PFC (e.g. limiters, divertor, FW), and Control systems, (diagnostics and actuators)**
- The plasma **operating scenario** must be **chosen to reduce** the **severity** and the **probability** of the **transient** loads

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

- Fenix is a simulator for checking pulse schedule, developing/improving plasma control schemes for operation scenario/against transients etc. Trade of between high fidelity physics, and reliable/fast models. At present (at EU-IPP) RT control of all models at each time step is not a priority (most likely we need to forecast few variables we believe are important).
- Many transients/perturbations in ramp-up/flat-top/ramp-down phases are listed.
- **Ramp-down rate is restricted (≤0.2MA/s) by plasma equilibrium control: 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.
- Power exhaust during ramp-up/down will be one of main topics. Ramp up/down relatively straightforward until L-H transition (e.g. difficult detached L to H transition, and interplay with impurities) – slower ramps may help (check flux consumption)
- **Application to transient scenarios are becoming increasingly complex and realistic, towards the full definition of a self-consistent DEMO scenario.** Flight simulator to integrate more **physics models** on the long term (e.g. edge physics: radiation instability, detachment, SOL, exhaust, fueling) – difficult task. Integration of **power plant systems** important for a flight simulator (e.g. balance of plant, turbines, power supplies etc.)
- Machine learning can help to speed up high fidelity simulations for present machines (e.g. for the core transport and pedestal, grad shafranow the use of neural network being investigated). But you need exp. data/models. Big data for use in detecting onset of disruptions is also an active field of research - Extrapolability to be demonstrated

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

- Summarizing ITER goals/research plan, including milestones in each phase (FP/PFPO/FPO). Staged, iterative approach driven by: Component availability/upgrade (e.g. heating, diagnostic, license), risk mitigation (e.g. stored energy, alternative paths), ongoing research (Advancement of scenarios, R&D)
- 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 loads.
- 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 $\boldsymbol{q_{\perp} \sim 4.5 MW/m^2}$) 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. Modelling synergies with DEMO.
- 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.
- We should use ITER experience to learn and study how to operate DEMO as unwanted transient (related to physics)free events. But If we want to do things in a reasonable timescale we have to do things in parallel (e.g. proposed EU strategy). Many startups may answer to specific aspects, or completely different concepts.

Solutions for the transients and heat load variations of the CFETR operation scenarios by Ge 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.**
- Grassy ELM high frequency is necessary to avoid tungsten erosion. Study should be made about the possibility to diagnose the fall back in larger ELMs regime. Also studies on the tungsten behavior above the recrystallization temperature should be checked.
- 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. As for DEMO, also for CFETR neutron irradiation and integration studies should be performed on these actuators.
- Comparison of disruption impacts between ITER and CFETR is performed.

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

- **Helical/stellarator reactor has large advantage due to no plasma current.**
- Two major 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. In case this happen the energy release to the PFC needs to be accounted for.
- 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 due to radiation collapse and beta limit due to MHD stability (transients) restricts the achievable Q.**
- 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. New concept "FFHR-b3" with twice the size of LHD is designed by optimizing coil shape/current design (e.g. to increase blanket space).