Holistic approach against performance-limiting instabilities in steady state plasmas

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Issues:

Ever since the tokamak concept was introduced in late 1960s, significant progress has been made in nuclear fusion research for the last 50 years. Assuming that the ITER-construction is right on the schedule for the next 8 years, we will meet a new era of fusion research whose goal is to lay out the details about a commercially viable fusion reactor. Then, all the fusion research themes will be inevitably challenged to meet the electric power industry standards, which would require us not only to demonstrate the feasibility of fusion reactor concept but also to ensure the safety of the fusion reactor operation for burning steady state plasmas.

Arguably, one of the most stringent requirements in steady state plasmas will be how to eliminate or mitigate any performance-limiting instabilities in reactor-grade fusion devices. Although various MHD stabilization studies, such as neo-classical tearing mode (NTM) and resistive-wall-mode (RWM) stabilizations, became mature enough to earn many of the knowledgeable plasma physicists' confidence [1], they are still required to demonstrate the compatibility of these schemes with long pulse steady-state plasmas.

It is to be noted that all the past instability studies were performed to destabilize any relevant instability being studied first, which often required us to tailor pressure and current density profiles with more instability-prone conditions than otherwise. However, as for the future research of burning steady state plasmas, such research approach needs to be reversely prioritized to address **how to tailor the plasma profiles that are more resilient to performance-limiting instabilities first.** Then, should an eventful instability occur, various MHD control tools, active and passive means, need to be mobilized **not only to eliminate the performance-limiting instabilities, but also should be integrated to help the reactor system recover the desired profiles with minimal repercussions to the reactor-grade operation.**

In a sense, it aims on 'reactor-oriented' research, while the existing research devices would remain focused on to 'science-oriented' research.

Research Requirements:

To achieve high performance steady state plasmas in reactor-grade machine, like DEMO, the research requirements are

1) to establish robust plasma profiles in reactor-relevant high performance steady state plasmas
2) to integrate various means of the MHD control tools aiming to restore the reactor-grade performance as soon as possible, as well as to eliminate or mitigate the MHD activity.

First, a research focus is to establish robust plasma profiles at various operational scenarios in terms of pressure and current density profiles. Specifically, the future operation scenarios, like ITER-baseline, hybrid, and advanced tokamaks (ATs) scenarios, should be determined by **theoretically sound, experimentally confirmed and operationally demonstrated physics results.**

Thus, this physics requirement is to fill any lack of physics understanding among theory, experiment and operation. For each scenario to be identified, the successful research will enable us to specify a set of metrics, such as

q_{95}, q_0, q_{min}, li, pressure peaking factor, elongation, triangularity, squareness, dRsep, pedestal width/height etc.

Here, each operation scenario with the specified parameters should be not only easily reproducible but also readily comprehensible to any operators with minimal knowledge of plasma physics. Meanwhile, we cannot overemphasize the importance not only to explore various steady state operation candidates (e.g. Quiescent H-modes (QH) and enhanced D-alpha (EDA) H-modes) in one machine extensively but also to produce the same quality operation results in other devices, which will assure us of the universality of the physics results.

Second, another research focus is to integrate various MHD control tools aiming not only **to eliminate or mitigate the performance-limiting instabilities but also to restore the reactor-grade performance as soon as possible**, should there be an eventful MHD.
Although the number of occurrence of performance-limiting instabilities could be dramatically reduced by establishing plasma profiles resilient to MHD activity, it is very unlikely that an eventful but deleterious MHD will be completely eradicated. In particular, it is a legitimate concern when we admit the fact that there are important areas in burning steady state plasmas which we are not able to explore using the existing research devices; *for example, alpha particle-driven instabilities, linearly stable but nonlinearly unstable modes, various mode-mode couplings, fast particle population impacts on equilibrium and stability etc.*

Thus, it is vital to equip a future steady state device with a set of tools to control or mitigate any eventful MHD, should it occur. Table 1 lists a few samples of performance-limiting macroscopic instabilities for the purpose of a short discussion.

Performance-limiting MHD	**CONTROL MEANS**	**Impact to Profiles**
Neo-classical Tearing Mode (NTM)	ECCD	Local pressure and current density profiles
Resistive-wall-mode (RWM)	Torque/ Active Feedback control coils (compatible with RMP coils[1])	Mid-radius to edge profiles
Locked mode	Suppressible by ECCD/RMP [2]	Global profiles
Disruption	Possible mitigation/elimination[3]	'Soft landing'/Quick recovery

[1]under investigation [2] under speculation [3] must be developed

Table 1. Performance-limiting instabilities, control means and their impact on plasma profiles

While all the established control means, such as ECCD, torque, and active feedback coils, could be integrated to suppress various relevant instabilities simultaneously, it is highly desirable to find a way to restore the original plasma performance with minimal repercussions to the operation. The third column of Table 1 shows the area of the plasma profiles that could be most influenced by each MHD and control means. Considering that there are many other possible control tools we haven't explored yet, we need to make significant efforts to develop or utilize a new control means. For example, unlike conventional heating of ICRF wave, recent study showed that mode converted ion-cyclotron-frequency wave could drive the plasma flow rapidly [2], which had not been tested to control plasma rotation related to NTM or RWM studies. Also, using n=3 resonant magnetic perturbations (RMP) that had been regarded as 'non-resonant' magnetic braking tool, the plasma rotation increased under such conditions as ITER-like low-rotation plasmas, rather than decreased [3]. Also, the MHD studies under the lower hybrid current-drive (LHCD) and heating experience are pretty limited, though LHCD is considered for

future devices [4].
Thus, the future physics research should be as open to new innovative ideas as possible, whose preliminary study should be executed on the existing devices as 'science-oriented' research. Once the promising aspects for possible control means are identified and confirmed, the 'reactor-oriented' research should be performed to provide the necessary metrics for future machines.

Diagnostic requirements: It is highly desirable to diagnose the plasma responses using MHD spectroscopy as a routine tool [5]. While the magnitude of the probing field is much smaller than any other relevant MHD, the time evolution of the plasma response to a known probing field will be the best indicator for the control system to be ready for any eventful MHD. Also, fast particle diagnostics, including alpha particles, should be significantly reinforced to fully diagnose the interactions of particles with MHD.

Research Thrusts:
Assuming that the existing devices remain focused on the 'science-oriented' research, there is a need to have a new fusion device that could perform 'reactor-oriented' research. **The new device should have at least all the reactor-grade power components, including *Ion-cyclotron-resonance frequency (ICRF), lower-hybrid current-drive (LHCD), electron-cyclotron-resonance (ECR) frequency and neutral beam injector (NBI*).** It is envisioned that the NBI is NOT main heating source, BUT is used for fueling, rotation control, and edge profile control.

In this regard, **Fusion Development Facility (FDF) under consideration by the fusion community is close to an ideal device which should be also equipped with the capability of the ICRF heating scheme.**

Here are some specific tasks that should be included but are not limited to
- Stable/Stabilizable operation maps for each operation scenario to be adopted
  (e.g. q_{95}, q_0, q_{min}, *li, pressure peaking factor, elongation, triangularity, squareness etc)*
- Macroscopic instabilities at q_{95}~3 (including NTM, RWM) near no-wall limits
- Feasibility study for RF-based instability control
- Recovery scenarios (soft landing/quick recovery)

Remarks:
This thrust will help to satisfy the industry-specifications, which should be operable by personnel with minimal knowledge of plasma physics. Thus, the focus would be to find a set of plasma conditions where the chances to meet any macroscopic instabilities would be minimal (safety first) and then maintain it in the maximum affordable pulse length. Nonetheless, if any eventful MHD activity occurs and needs to be controlled, all the possible means will be mobilized with the focus to recover the original MHD-resilient plasma profiles.

References

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