Error Field and its Correction Strategy in Tokamaks

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While error field correction (EFC) is to minimize the unwanted kink-resonant non-axisymmetric components, resonant magnetic perturbation (RMP) application is to maximize the benefits of pitch-resonant non-axisymmetric components. As the plasma response against non-axisymmetric field increases with beta increase, feedback-controlled EFC is a more promising EFC strategy in reactor-relevant high-beta regimes. Nonetheless, various physical aspects and uncertainties associated with EFC should be taken into account and clarified in the terms of multiple low-*n* EFC and multiple MHD modes, in addition to the compatibility issue with RMP application. Such a multi-faceted view of EFC strategy is briefly discussed.

1. Introduction

The presence of the non-axisymmetric fields in tokamaks is so critical to determine whether steady-state, high-performance fusion plasmas can be achieved and sustained in reactor-relevant regimes [1]. While it has been recognized for more than two decades that the unwanted non-axisymmetric field [called 'error field (EF)'] should be minimized, such a conventional paradigm needs to be reconsidered to reflect the benefits of intentionally applied non-axisymmetric field [often described as 'resonant magnetic perturbation (RMP)')]. In general, the $n=1$ EF and $n > 1$ RMP may be configured not to pose a conflict to differentiate two functions in fusion plasmas. Here, n refers to a toroidal mode number. However, when both EF and RMP use the same toroidal mode number, it might not be straightforward to differentiate two separate roles without addressing the relevant physical mechanisms. In particular, the recent successful operation of $n=1$ RMP-driven ELM-suppression in KSTAR [2] shows a good evidence that the $n=1$ non-axisymmetric field itself should not be regarded solely as 'error field', in that it can be also tailored to maximize the beneficial effects of RMP application. Thus, it would be desirable to re-examine the prevailing error field correction (EFC) strategy, while taking into account a variety of non-axisymmetric field aspects. At the same time, the uncertainties and limitation in the present understanding of the EF and its EFC strategy should be also factored in establishing the non-axisymmetric field control.

Thus, this paper delineates a strategic view of physical aspects associated with error field and its correction in tokamaks, which is not limited to certain conditions, but could be directly applicable to enhance the performance of advanced tokamak regimes where the presence of EF could be significantly influential.

In Section 2, a brief description of feedback-controlled error field correction is presented as a promising candidate of EFC strategy, followed by the discussion to incorporate multiple low-n EFC and MHD stabilization needs. In Section 3, the compatibility issues with the RMP application and other uncertainties are discussed. A short summary is given in Section 4.

2. Feedback-controlled Error Field Correction

Feedback-controlled error field correction [also known as dynamic error field correction (DEFC)] is one of the promising EFC strategies that can be practically used for steady-state, high-performance fusion plasmas. Typically, an intrinsic non-axisymmetry (i.e. error field) is investigated in each toroidal device, and then its correction waveform is empirically constructed, which is usually determined in low-beta plasmas [3]. However, as beta increases, the plasma response against the presence of non-axisymmetric (NA) field increases. Thus, an empirically determined pre-programmed EFC waveform based on low-beta plasmas becomes inherently uncertain in high-beta plasmas. On the other hand, taking advantage of the increased plasma response against non-axisymmetric field in real-time detection system, the feedback-controlled error field correction is configured to nullify the measured non-axisymmetry as minimal as possible using the non-axisymmetric EFC coils [4]. Hence, this DEFC keeps reducing the ever-present uncorrected error field continuously. Considering that high-beta plasmas are accompanied by stronger plasma response against non-axisymmetric fields than low-beta plasmas, ***the DEFC is expected to be much more effective in advanced tokamak regimes***. For example, in DIII-D, the n=1 DEFC has been developed and tested in high-beta plasmas, showing affirmative results [5]. Thus, even if there are multiple low-n EF (e.g. as measured in DIII-D and NSTX), the expansion of the DEFC for multiple low-n EFC is not expected to be technically difficult to deploy the necessary multiple low-n compatible DEFC strategy.

But, caution should be exercised in several areas as follows;

First, the impact of $n > 1$ fields in high beta plasmas differs quite substantially from that of $n = 1$ field. Fundamentally, all the existing EFC strategy has been laid out based on the assumption of a single dominant mode, where the spatial distribution of predominant least-stable mode remains the same even if the mode amplitude may change (i.e. single-mode rigidity). However, the accumulative effects of multiple low-n modes may not be understood in the frame of such a single mode assumption. Specifically, there is a vastly different dependence of plasma rotation influenced by n = 1 field, in comparison with n > 1 field. For example, the reducing rotation coming from an increased n=1 NA field often results in a mode-locking, while an increased n > 1 NA field is accompanied by globally reducing rotation without mode-locking. The former is thought to be primarily due to the resonant components at integer rational surfaces, while the latter is predominantly due to the non-resonant components associated with neoclassical toroidal viscosity (NTV). In practice, there are very few (if not none) models that could be consistent with the resonant torque experimental results, though the NTV-related associated non-resonant torque calculations appear in good agreement with experimental observations [6].

Second,, the DEFC should be also compatible with the RMP application as a pre-requisite. Considering that the main purpose of EFC is to minimize the non-axisymmetric field, this requirement appears to conflict with the RMP application that is designed to maximize the benefits of the NA field for ELM-suppression. However, these two non-axisymmetric field control methods are differentiable, in that the DEFC should emphasize the reduction of the kink-resonant components, while the RMP requires sufficient strengths of the pitch-resonant components. Thus, for example, when the n=1 DEFC is used to avoid the kink-resonant response in high beta plasmas, the accompanying n > 1 RMP is expected to be safely configured to maximize the pitch-resonant components necessary for ELM suppression (e.g. [7]).

Third, the DEFC is desirable to have the capability of stabilizing multiple MHD modes. Such a stringent requirement about the non-axisymmetric field control system could be much more easily resolved than might have been imagined. Specifically, while the needs of EFC and RMP application would remain in a low frequency range, various MHD modes (e.g. resistive wall modes (RWM)) that usually grow in fast time scales would require the magnetic feedback in a high frequency range. Thus, a system equipped with broadband power supply should be able to provide a hardware solution for both low and high frequencies of non-axisymmetric field control [8]. But, the remaining concern lies in the difficulty of how to with cope with *noise issues*. Although several special schemes (e.g. Kalman filtering [9]) and model-based controller design studies (e.g. [10]) are promising, further studies should be made to verify and validate various relevant physics-models, as well as to demonstrate the benefits of model-based controllers in experiments.

Last but not least, such experimental observations and expectations are not necessarily consistent with mathematical/theoretical perspectives, in which the use of the non-axisymmetric control coils would increase, rather than decrease, the resonant components in experimentally optimized fusion plasmas [11]. That is one of the important reasons why further studies of EFC should be made to clarify several unresolved discrepancies between experiment and theory.

3. Compatibility issues of EFC with RMP application

Ever since the n=3 RMP-driven ELM-suppression was reported from DIII-D [12], the relevant physics mechanism has been vigorously investigated in various devices. While a majority of the tokamaks were able to achieve ELM-mitigations with non-axisymmetric fields (such as JET, AUG, and MAST), KSTAR is the only device that additionally achieved full ELM-suppression with RMP application [2]. In particular, the n=1 RMP-driven ELM-suppression in KSTAR is very unique, in that no other machine has ever succeeded with n=1 RMP ELM-suppression so far. (To be fair, both DIII-D and KSTAR recently accomplished the n=2 RMP ELM-suppression, as well.). Although no definitive answer about the physical mechanism has been found, a leading theory [e.g. [13]] and experimental results suggest that RMP-driven stochastic fields form island overlaps on top of edge pedestal, enhancing the particle transport (observed with density pump-out) and avoiding the destabilizing conditions of ELMs.

As mentioned earlier, ***as long as the kink-resonant components of EFC do not conflict with the pitch-resonant components of RMP application, the compatibility issue between them could be minimal.*** In this regard, the extremely low intrinsic n=1 error field in KSTAR [14] is thought to be one of the key contributing factors that helps us explain the n=1 RMP-driven ELM suppression. Since no or little intrinsic n=1 EF in KSTAR implies that the kink-resonant components would be also negligible, the KSTAR would be much more resilient against n=1 mode-locking, until the pitch-resonant components of n=1 RMP exceeds the threshold necessary for ELM-suppression. Considering that similar attempts in DIII-D with the n=1 RMP application were not successful due to strong n=1 mode-lockings [15], the minimization of the kink-resonant components seems to be quite critical, while securing the sufficient strengths of pitch-resonant components necessary for ELM-suppression. In fact, the pitch-resonant phasing (i.e. +90 degree) of n=1 RMP application between RMP coil arrays in KSTAR was very effective in ELM-suppression, while the kink-resonant phasing (i.e. +180 degree) was plagued by mode-lockings [16]. As a result, it is foreseen that the dominantly pitch-resonant n=1 RMP application might work for ELM-suppression even in other tokamaks, as long as the intrinsic kink-resonant components can be controlled (or corrected) to be low enough to avoid early mode-lockings.

Nonetheless, before making definitive conclusions, we should be able to differentiate the roles of kink-resonant and pitch-resonant components in experiments more rigorously in the near future. In particular, it is worthwhile to note that recent experiments in DIII-D suggested the n=2 RMP-driven ELM suppression appeared rather keen on the kink-resonant components, though they did not rule out the possibility that such kink-components were potentially used to enhance the total pitch-resonant components necessary for ELM-suppression [17].

4. Summary

The prevailing EF and its correction strategy needs to be re-examined, as the understanding of the non-axisymmetric field is being enhanced. While static pre-programmed EFC waveforms are empirically developed to minimize the intrinsic EF typically measured in low-beta plasmas, feedback-controlled EFC appears more adequate in high-beta plasmas, where the plasma response gets strong with beta increase. Although the DEFC can be easily expanded to deal with multiple low-n EFC needs, a few outstanding differences between $n=1$ and $n>1$ non-axisymmetric fields in terms of their influences (e.g. plasma rotation) should be taken into account. Also, when the EFC strategy can be easily re-configured to address the needs of multiple MHD modes using a broadband power supply, the inevitably accompanying noise issues and physics model-based controllers should be further studied. Additionally, as long as the EFC strategy is established to minimize the kink-resonant components without interfering with the RMP application that should provide the sufficient strengths of pitch-resonant components, the compatibility issue of the EFC with the RMP application is expected to be none or minimal. ***Nonetheless, further studies are still needed to resolve the discrepancies between experiment and theory, as well as to demonstrate that the aforementioned EFC strategy would be feasible with steady-state, high-performance fusion plasmas in reactor-relevant regimes.***

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