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A rather simple approach to the numerical study of instabilities, associated with coupled plasma and wall-related transport processes, is suggested. It allows coupling of different plasma and wall-related transport models without performing additional simulations. *Published by AIP Publishing.*
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It is usually assumed that anomalous scrape off layer (SOL) plasma transport is driven by the instabilities attributed solely to plasma dynamics. However, these instabilities cause a spatiotemporal variation of plasma particles and heat fluxes to plasma facing components, resulting in some feedback from the wall processes (e.g., hydrogen outgassing and impurity influx into plasma). Such feedback could alter plasma dynamics and might be the reason for some specific coupled plasma-wall instabilities. For example, they could affect global SOL plasma stability by triggering Multifaceted Asymmetric Radiation From the Edge (MARFE) or, possibly, anomalous plasma transport. As a matter of fact, fast MARFE formation caused by uncontrollable hydrogen release from divertor targets overheated by plasma was already observed in JT-60 tokamak experiments.[1,2] In Refs. 3 and 4, it was demonstrated that specific thermal instability related to coupled plasma-wall interactions could be the reason for the MARFE onset seen in JT-60. In addition, an implementation of a rather simple neutral model into the 2D plasma turbulence code has shown significant impacts of plasma-neutral interactions on intermittent SOL plasma transport.[6] These examples suggest that more attention should be paid to the interplay of plasma dynamics and wall-related processes, in particular to the synergistic effects, which could result in new types of instabilities.

Obviously that to address the issue of an impact of the wall processes on plasma stability, we should implement some "dynamic" wall models accounting for the wall feedback to varying plasma parameters. However, in most current analytic and numerical studies of edge plasma processes, the wall feedback (if any) is described by the constant recycling coefficient, which is often chosen to fit experimental data (e.g., in 2D simulation of edge plasma transport[5]) Unlike 2D edge plasma transport codes, 3D edge plasma turbulence codes lack impurity transport and radiation effects (playing one of the crucial roles in divertor plasma detachment[5]) and implement (if any) simplified neutral and atomic physics models (see, e.g., Ref. 6). On the other hand, dynamic wall models considered in Refs. 3 and 4 are rather rudimentary, whereas more sophisticated dynamic wall models are largely still under development. Nonetheless, improved 3D plasma turbulence and dynamic wall codes are developing. However, at any case, analytical treatment of coupled plasma-wall instabilities becomes virtually impossible for the case of complex plasma and wall models and strongly inhomogeneous plasma and wall-related parameters. As a result, we should rely, largely, on the numerical study of coupled plasma-wall stability issues.

However, it is plausible that there will be different versions of improved plasma and wall codes, which will be based on somewhat different approximations and physical models, suitable for the study of coupled plasma-wall stability. Taking into account that the coupling of complex plasma and wall codes is a difficult task, one of the issues is how to make the study of coupled plasma-wall stability more flexible and avoid tedious coupling of different plasma and wall codes.

In this paper, we present an approximate method to study coupled plasma-wall instabilities numerically without direct coupling of plasma and wall codes.

We assume that there are stationary self-consistent plasma and wall settings, whereas plasma and wall related processes affect each other through plasma particles and heat flux to the wall and neutral hydrogen outflux from the wall surface into plasma volume. To consider the linear stability of the coupled plasma-wall system, let us introduce the functionals $\hat{F}_w^p\{\ldots\}$ and $\hat{F}_p^w\{\ldots\}$, which account for linear responses of plasma flux to the wall, $\delta j_p(t)$, on neutral flux from the wall, $\delta j_w(t)$, and vice versa, respectively. Since radiation loss from plasma could heat the wall and promote wall outgassing, we also introduce the functional $\hat{\Phi}_w^R\{\ldots\}$, which accounts for the effect of the variation of radiation loss from plasma causing wall outgassing in response to $\delta j_w(t)$. As a result, we have

$$\hat{F}_w^p\{\delta j_w(t)\} = \delta j_p(t), \tag{1}$$

$$\hat{F}_p^w\{\delta j_p(t)\} + \hat{\Phi}_w^R\{\delta j_w(t)\} = \delta j_w(t). \tag{2}$$

From Eqs. (1) and (2), we see that in a linear approximation, the coupled plasma-wall system splits into separate groups: plasma response to the fluxes from the wall and *vice versa*, which are determined by the functionals $\hat{F}_w^p\{\ldots\}$, $\hat{F}_p^w\{\ldots\}$, and $\hat{\Phi}_w^R\{\ldots\}$. Moreover, depending on the sophistications of plasma and wall models, these functionals and the fluxes $\delta j_p(t)$ and $\delta j_w(t)$ could have somewhat "different" meaning. For example, for the case of fluid plasma description, the distribution of plasma particles comprising plasma flux $\delta j_p(t)$ and, correspondingly, their implantation depths into the wall is described by plasma fluid parameters (e.g., density and

temperature), whereas for the case of kinetic plasma description, it will be determined by plasma distribution functions.

To find the formal dispersion equation, determining the stability of the coupled plasma-wall system, we take the expression for $\delta j_p(t)$ from Eq. (1) and substitute it in Eq. (2). As a result, we have

$$\hat{F}_p^w\left\{\hat{F}_w^p\{\delta j_w(t)\}\right\} + \hat{\Phi}_w^R\{\delta j_w(t)\} = \delta j_w(t). \tag{3}$$

Since we assume stationary equilibrium conditions, we can decompose $\delta j_w(t)$ into the time Fourier integral. For the case of the usage of improved 3D edge plasma turbulence codes, assuming the toroidal symmetry of our background plasma and wall parameters, we can decompose fluxes $\delta j_w(t)$ and $\delta j_p(t)$ into toroidal Fourier series, neglecting toroidal mode coupling due to a rather narrow SOL width. As a result, from Eq. (3), we find the dispersion equation, which could be written symbolically as

$$\hat{D}_{pw}(\omega, n) = 0, \tag{4}$$

where n is the toroidal mode number. For the case of rather dense divertor plasma, which is opaque for neutrals, we could extend Eq. (4) by applying an eikonal approximation for plasma and wall parameter variations in a radial direction.

However, in practice, this could be done only for the case of rather simple plasma and wall models. More sophisticated models, we are interested in, could only be analyzed numerically. Therefore, we suggest the following approximate approach to the linear stability problem of the coupled plasma-wall system.

From the numerical solution of the plasma transport model (fluid or kinetic), we could find the plasma response on the small harmonic time variation having some toroidal mode number n of particle flux from the wall and the wall response on the small harmonic variation of plasma flux from the wall and radiation induced effects. Since both Eqs. (1) and (2) are linear, these responses could be written as follows:

$$\begin{cases} \hat{F}_w^p\{\sin(\omega t)\} = j_{wp}^s(\omega)\sin(\omega t) + j_{wp}^c(\omega)\cos(\omega t) \\ \hat{F}_w^p\{\cos(\omega t)\} = j_{wp}^s(\omega)\cos(\omega t) - j_{wp}^c(\omega)\sin(\omega t), \end{cases} \tag{5}$$

$$\begin{cases} \hat{F}_p^w\{\sin(\omega t)\} = j_{pw}^s(\omega)\sin(\omega t) + j_{pw}^c(\omega)\cos(\omega t) \\ \hat{F}_p^w\{\cos(\omega t)\} = j_{pw}^s(\omega)\cos(\omega t) - j_{pw}^c(\omega)\sin(\omega t), \end{cases} \tag{6}$$

$$\begin{cases} \hat{\Phi}_w^R\{\sin(\omega t)\} = j_{wR}^s(\omega)\sin(\omega t) + j_{wR}^c(\omega)\cos(\omega t) \\ \hat{\Phi}_w^R\{\cos(\omega t)\} = j_{wR}^s(\omega)\cos(\omega t) - j_{wR}^c(\omega)\sin(\omega t), \end{cases} \tag{7}$$

where the functions $j_{wp}^s(\omega)$, $j_{wp}^c(\omega)$, $j_{pw}^s(\omega)$, $j_{pw}^c(\omega)$, $j_{wR}^s(\omega)$, and $j_{wR}^c(\omega)$ are determined from numerical solutions of plasma and wall models and fitted with algebraic expressions as the functions of ω, allowing unique extension to the complex ω plane (however, recall that these functions also depend on toroidal mode number n). Then, taking the eigenfunction of $\delta j_w(t)$ in the form

$$\delta j_w(t) = J_s\sin(\omega t) + J_c\cos(\omega t) \tag{8}$$

substituting it in Eq. (3), and using Eq. (5–7), we arrive at the following dispersion equation:

$$\pm i\left\{j_{wp}^c(\omega)j_{pw}^s(\omega) + j_{wp}^s(\omega)j_{pw}^c(\omega) + j_{wR}^c(\omega)\right\} = 1 - j_{wp}^s(\omega)j_{pw}^s(\omega) + j_{wp}^c(\omega)j_{pw}^c(\omega) - j_{wR}^s(\omega), \tag{9}$$

where the functions $j_{wp}^s(\omega)$, $j_{wp}^c(\omega)$, $j_{pw}^s(\omega)$, $j_{pw}^c(\omega)$, $j_{wR}^s(\omega)$, and $j_{wR}^c(\omega)$ should be treated as their extensions to the complex ω plane.

Interestingly, Eq. (9) does not allow solution with real ω, which means that coupled plasma-wall modes could be either stable or unstable.

For the case where the wall response is instantaneous (i.e., $\hat{F}_w^p\{\delta j_w(t)\} \equiv \delta j_w(t)$, which corresponds to $j_{pw}^s(\omega) = 1$ and $j_{pw}^c(\omega) = 0$) from Eq. (9), we have

$$\pm i\left\{j_{wp}^c(\omega) + j_{wR}^c(\omega)\right\} = 1 - j_{wp}^s(\omega) - j_{wR}^s(\omega). \tag{10}$$

By adopting a simple transport plasma model (e.g., finite residence time approximation), Eq. (10) will describe the coupled radiation driven wall-outgassing mode, which was considered in Refs. 3 and 4 and, probably, was observed in experiments in Refs. 1 and 2. To study an impact of neutral recycling on the so-called ∇T_e instability[7] in the limit of the instantaneous wall response, one can neglect an impact of the radiation driven wall-outgassing [assuming $j_{wR}^s(\omega) = j_{wR}^c(\omega) = 0$] but keep an impact of neutral recycling on both plasma temperature and density responses and, finally, on plasma flux in the terms $j_{wp}^s(\omega)$ and $j_{wp}^c(\omega)$. We stress that this instability is sensitive to near target plasma temperature and the corresponding effective "sheath resistivity." Therefore, it is plausible that ∇T_e instability could be strongly altered by neutral recycling effects for high recycling conditions.

We note that possible limitations of the approach to the study of coupled plasma-wall instabilities based on numerical solutions of plasma and wall-related models could be related to the applicability of the extension of the functions $j_{wp}^s(\omega)$, $j_{wp}^c(\omega)$, $j_{pw}^s(\omega)$, $j_{pw}^c(\omega)$, $j_{wR}^s(\omega)$, and $j_{wR}^c(\omega)$ to the complex ω plane for the case of the large imaginary part of ω. However, in this case, it could be an indication that instability does exist although with different growth rates, which could be further studied with a direct coupling of plasma and dynamic wall codes.

In conclusion, we suggest a rather simple approach to the numerical study of coupled plasma-wall instabilities with no actual coupling of plasma and wall codes, which makes this approach rather flexible. One of the important advantages of this approach is related to splitting of plasma and wall models, which allows using in Eq. (9) the results of different plasma and wall models without performing any additional simulations. For simplicity, we considered only synergistic effects caused by hydrogen fluxes. However, our approach could be easily extended to account for impurity effects. Finally, we note that the response functions needed for dispersion equation (9) could be deduced from laboratory experimental data in a specially design experimental setup.

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