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# Tearing stable stationary ITER baseline operation in DIII-D

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## Abstract

We present a tearing stable, stationary and reproducible operating solution for DIII-D plasmas characterized by the ITER baseline scenario normalized parameter set and shape. In these plasmas low differential rotation ( $\Delta f_{1,2}$ ) between the core and edge is identified as the single root cause of the onset of the primary limiting instability, the 2,1 Neoclassical Tearing Mode (NTM), while a group of other examined parameters have a much weaker impact on the stability. Explanation is offered by drift kinetic simulations, which show a six-fold reduction in the NTM onset threshold due to diminished stabilizing ion polarization currents when the seed island drift frequency ceases in the local plasma frame. Based on the experimental observation and the explanation provided by the theory, a new discharge program is developed to sustain  $\Delta f_{1,2}$  by modifying the edge neoclassical potential through neutral gas fueling. This method enables stationary ITER baseline operation free of disruptive 2,1 tearing modes.

Keywords: tearing, tokamak, stability, magnetic island

(Some figures may appear in colour only in the online journal)

## 1. Introduction

In magnetically confined fusion-grade tokamak plasmas with a toroidally shaped and helical directed magnetic field structure and significant normalized plasma pressure, magnetic reconnection can occur near low-order rational magnetic flux surfaces, driven by the Neoclassical Tearing Mode [1] (NTM).

This instability forms radially localized magnetic islands [2–4], which can lead to a rapid and violent termination of the plasma current, damaging the reactor vessel. The  $m, n = 2, 1$  NTM is the primary instability limiting the attainable pulse length in plasmas matching the ITER baseline normalized parameter set and shape [5] ( $m$  and  $n$  are the poloidal and toroidal mode numbers).

In the broad spectrum of high-confinement mode plasmas, NTMs can be destabilized by a number of magneto-hydrodynamic (MHD) transients when a seed island is produced whose width ( $w_s$ ) is greater than the NTM threshold ( $w_c$ ) [6–9].  $w_c$  depends on the competition between current perturbations induced by the seed island itself, such as the stabilizing bootstrap current perturbation [1, 10] ( $\Delta j_{BS}$ ) and the usually destabilizing polarization current [11–13] ( $j_{pol}$ ).

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In most plasmas a sequence of MHD transients precedes NTM triggering without changing typical trigger characteristics [14]. Thus, the 2,1 NTM onset at a particular seed may be caused by reduction of  $w_c$  below  $w_s$ . Identifying the parameter transition responsible for reducing  $w_c$  is important, as it can explain the root cause of disruptive NTM onsets, and can enable control paths to tearing stable plasma operation essential for ITER and beyond.

We report a database study of nearly 300 DIII-D plasmas characterized by the ITER baseline scenario (IBS) parameter set and shape. This study identifies the loss of differential plasma rotation ( $\Delta f_{1,2}$ ) between the  $q = 1$  and  $q = 2$  surfaces to be the root cause of 2,1 NTM onsets ( $q$  is the safety factor). In these plasmas, the dominant seeding mechanism is provided by three-wave coupling of sawtooth oscillations to the  $m, n = 1, 0$  Shafranov-shift and/or to 3,2 islands [5], while the loss of  $\Delta f_{1,2}$  selects the particular sawtooth at which the 2,1 seed island turns into a robustly growing NTM. These plasmas remain stable as long as  $\Delta f_{1,2} \gtrsim 0.8$  kHz, while 2,1 NTMs are triggered when  $\Delta f_{1,2}$  falls below 0.8 kHz. Other plasma parameters, such as those characterizing the current profile, do not exhibit statistically significant differences between the stable and unstable states, making a causal relationship with the 2,1 NTM onset highly unlikely.

Explanation of the role of  $\Delta f_{1,2}$  is provided by decreasing stabilization from  $j_{pol}$  when the sawtooth induced seed island co-rotates with the plasma at  $q = 2$ , which occurs as  $\Delta f_{1,2} \rightarrow 0$  kHz. Reduced drift-kinetic (RDK) simulations of these plasmas, presented here, clarify that  $j_{pol}$  flips sign (from stabilizing to destabilizing) at 0.5 kHz as the seed island drift frequency ( $\Delta f_d$ ) with respect to the plasma rotation approaches zero. This reduces  $w_c$  by a remarkable factor of 6 in the experimental range of  $\Delta f_{1,2}$ . Thus, the simulations show that these plasmas become much more susceptible to sawtooth triggering of NTMs as  $\Delta f_{1,2}$  decreases.

On the merit of the experimentally observed role of  $\Delta f_{1,2}$  and the explanation provided by RDK simulations, a new control method was developed at DIII-D to avoid disruptive NTMs via actuators that are practicable on the reactor-scale. A control loop composed of gas puffing in the edge and density pump out via electron cyclotron heating in the  $q \simeq 1.5 - 2.0$  range reduces the  $q = 2$  rotation and thereby sustains  $\Delta f_{1,2} \gtrsim 0.8$  kHz via modifying the edge neoclassical potential, leading to a robustly reproducible stationary tearing stable operating solution for the IBS even at near zero neutral beam torque.

## 2. The root cause of disruptive NTMs in DIII-D IBS plasmas

The IBS is an operational regime specifically designed for ITER to meet its mission objectives, including achieving high fusion gain ( $Q \geq 10$ ) in a steady-state or quasi-steady-state operation [18]. In DIII-D, and other tokamaks, IBS plasmas are routinely performed by matching the IBS normalized

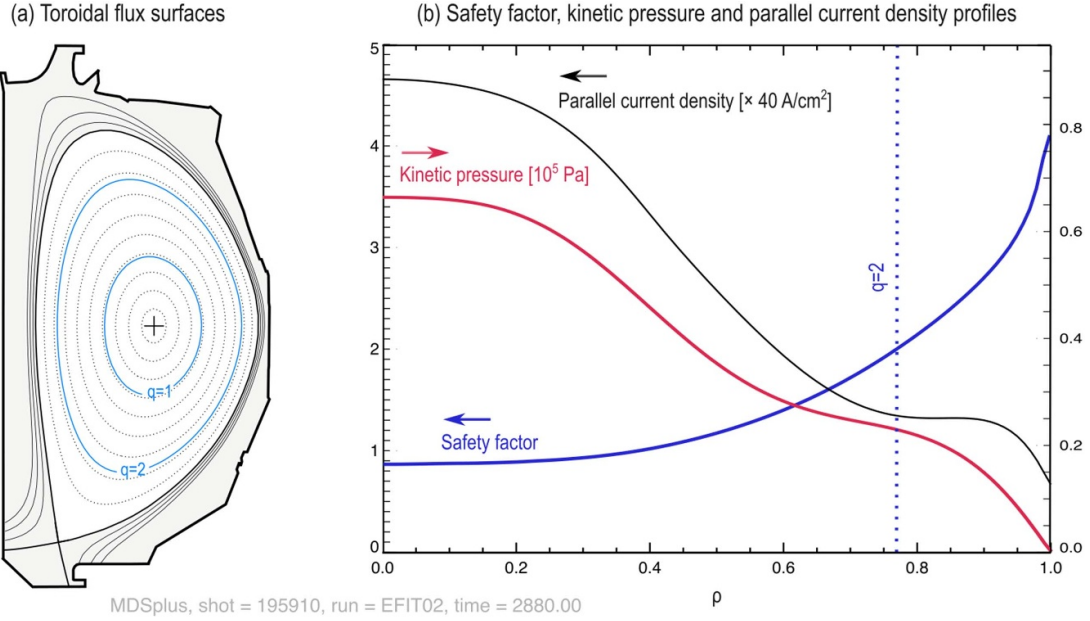
plasma parameters such as the safety factor ( $q_{95}$ ), normalized beta ( $\beta_N$ ), and shaping parameters, as well as near torque-free conditions representative of intrinsic rotation expected in ITER.

In this study we analyzed 160 (134) IBS discharges that were unstable (stable) to the 2,1 NTM. Relevant plasma parameters include: major radius 1.73 m, minor radius 0.56 m, neutral beam (NBI) power 5 MW, NBI torque less than  $T_{NBI} \simeq 1$  Nm, toroidal magnetic field 1.74 T in the opposite direction of the plasma current, plasma current  $I_p \simeq 1.37$  MA, normalized plasma beta  $\beta_N \simeq 1.8 - 2.2$  and edge safety factor  $q_{95} \simeq 3$ . The 2,1 islands grow at the  $q = 2$  rational surface, located at  $\rho \simeq 0.78$  ( $\rho$  is the toroidal flux coordinate). The plasma shape, typical safety factor, kinetic pressure and parallel current density profiles are depicted in figure 1. To explore the dominant driving mechanisms of NTMs predicted by the modified Rutherford equation [1], a group of relevant local and global plasma parameters are considered. These include parameters of the current profile (affecting classical stability), thermodynamic quantities (affecting  $j_{BS}$ ) and rotation profile parameters (affecting  $j_{pol}$ ) as shown in figure 2 ( $\nabla j_{in}$  ( $\nabla j_{out}$ ) is the normalized parallel current density gradient inside (outside) of the current density minimum (well) located near  $q = 2$  as defined in [19].)

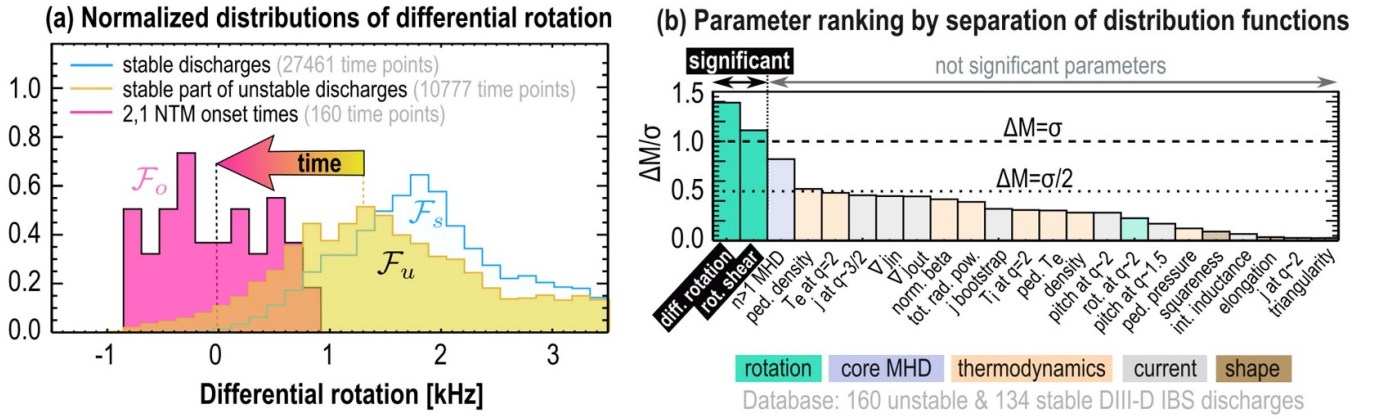
The analysis method compares the distribution functions ( $\mathcal{F}$ ) of each parameter: (i) in stable discharges ( $\mathcal{F}_s$ , 27 461 time slices), (ii) in the stable part of unstable discharges ( $\mathcal{F}_u$ , 10 777 time slices) and (iii) preceding the 2,1 NTM onset in the unstable discharges ( $\mathcal{F}_o$ , 160 time slices). These data sets are constructed by dividing the high-confinement-mode part of each discharge into 20 ms time-slices and calculating the time average of each parameter within each time-slice (by doing so we average over transient MHD instabilities such as edge localized modes and sawteeth). Here, the length of the time intervals are chosen to avoid averaging over rapidly changing kinetic profiles. Both rotating and non-rotating modes are included.

As an example, the functions  $\mathcal{F}_s$ ,  $\mathcal{F}_u$  and  $\mathcal{F}_o$  of  $\Delta f_{1,2}$  in figure 2(a) show that the instability onset points cluster around  $\Delta f_{1,2} \simeq 0$ , while the plasmas remain stable as long as  $\Delta f_{1,2} \gtrsim 0.8$  kHz. The mean of  $\mathcal{F}_u$  and  $\mathcal{F}_s$  peak near  $\Delta f_{1,2} \simeq 1.37$  kHz and  $\Delta f_{1,2} \simeq 1.61$  kHz, respectively, and their standard deviations are  $\sigma \simeq 0.68$  kHz and  $\sigma \simeq 0.56$  kHz, respectively. Thus, the mean of  $\mathcal{F}_o$  is separated from the mean of  $\mathcal{F}_u$  by about  $1.4\sigma$ . Therefore, the change of  $\Delta f_{1,2}$  preceding the instability onset is statistically significant in this database. Some overlap exists between  $\mathcal{F}_o(\Delta f_{1,2})$  and the other two distributions which is attributed mostly to broadening caused by measurement noise.

Next, the normalized separation ( $\Delta M/\sigma$ ) of  $\mathcal{F}_u$  and  $\mathcal{F}_o$  is used as a metric to rank all examined parameters by their importance in the NTM onset. Here  $\Delta M$  is the difference of the medians of  $\mathcal{F}_u$  and  $\mathcal{F}_o$  and  $\sigma$  is the algebraic mean of the standard deviations of  $\mathcal{F}_u$  and  $\mathcal{F}_o$ . Figure 2(b) shows that only two parameters,  $\Delta f_{1,2}$  and the rotation shear are significantly different in the stable and unstable datasets.



**Figure 1.** (a) Toroidal flux surfaces, (b) safety factor, kinetic pressure and parallel current density profiles of a typical ITER baseline scenario plasma in DIII-D. These profiles are calculated by the EFIT magnetic equilibrium reconstruction code [15] constrained by magnetic data [16] and motional Stark-effect data [17].



**Figure 2.** (a) Distribution functions of  $\Delta f_{1,2}$ . (b) Separation of  $\mathcal{F}_o$  and  $\mathcal{F}_u$  for a group of relevant parameters.

The strong correlation and chronological order between the rotation profile flattening and the 2,1 island onset supports that  $\Delta f_{1,2} \rightarrow 0$  kHz may lower the NTM threshold thereby enabling the next sawtooth to destabilize the NTM (i.e. reduces  $w_c$  below  $w_s$ ). This result aligns with prior research emphasizing the importance of rotation in tearing stability [20–25]. Interestingly, the amplitude of  $n > 1$  tearing modes ( $A_{n>1}$ ) is a relatively common predictor of the 2,1 NTM onset, i.e. these plasmas usually develop a chain of non-disruptive core NTMs along with the reduction of  $\Delta f_{1,2}$  prior to the 2,1 NTM onset. This is in agreement with previous work reporting seeding of disruptive NTMs in this scenario by three-wave coupling of core islands and the sawtooth precursor [5]. The rest of the analyzed parameters have little or no predictive value of the instability onset. Specifically, typical variations of kinetic profile parameters, current profile

parameters and magnetic equilibrium shape parameters within the scenario do not affect the NTM stability significantly (i.e.  $\Delta M/\sigma < 1$  in figure 2(b)) thus, they cannot explain the majority of 2,1 NTM onsets in this database. For clarity, we note that the reported data of the current density gradients in figure 2(b) is in agreement with previous work, i.e.  $\Delta M/\sigma \simeq 0.5$  (figure 5. in [19]). Although [19] concluded that the current profile governs the stability of the scenario, it is shown here (figure 2(b)) that  $\Delta f_{1,2}$  has much better predictive capability. Importantly, there are no known measured current profile parameters that can predict the 2,1 NTM onset time. Recent simulations show a qualitative trend of the linear tearing stability worsening when the current gradient hollows in this scenario [26, 27] as expected, while analytic theory quantitatively predicts that  $\Delta'$  is an order of magnitude too small to destabilize 2,1 islands in these plasmas [28].

Thus, these observations strongly support that sustaining  $\Delta f_{1,2}$  is key to avoid  $m, n = 2, 1$  NTM onset, in agreement with a recent analyses of current and rotation profiles [29, 30]. We emphasize, that the stable plasmas and the stable part of the unstable plasmas are both in the same (stable)  $\Delta f_{1,2} \gtrsim 0.8$  kHz parameter space. The stable plasmas remain in this stable space, while the tearing instabilities occur when the plasmas enter the  $\Delta f_{1,2} \lesssim 0.8$  kHz unstable space.

### 3. Small island stability in reduced drift-kinetic simulations

Direct experimental measurements of the seed island magnetic amplitude are unavailable due to challenges in isolating the  $m = 1$  and  $m = 2$  components of the  $n = 1$  signal at small amplitudes due to phase mixing and uncertainties introduced by diagnostic noise and model limitations in mapping the diagnostic data to the mode rational surface. Instead, to model the NTM onset threshold dependence on the seed island drift frequency ( $\Delta f_d$ , measured relative to the plasma), we employ the reduced drift-kinetic—NTM (RDK-NTM) model, based on the drift island theory of [31–33], supported by recent experiments [34]. The RDK-NTM model retains finite orbit width effects of ions trapped in tokamak plasmas relevant to the NTM onset threshold. The plasma response to the 2,1 NTM magnetic island is obtained as a solution of the orbit-averaged, generalized, drift kinetic equation (e.g. equation (28)/(30) of [32]) for each plasma species coupled via collisional processes and plasma quasi-neutrality. The latter is important to accurately quantify polarization effects associated with the perturbed electrostatic potential driven by the 2,1 island. In particular, RDK-NTM solves for a 4D perturbed particle distribution function, namely  $g_0 = g_0(p_\phi, \xi, \lambda, V; \sigma)$ , to quantify how plasma responds to a prescribed magnetic island perturbation of a given shape. Here  $p_\phi = p_\phi(\psi, \theta, \lambda, V; \sigma)$  is the toroidal component of the canonical angular momentum employed as a radial variable. It depends on the poloidal flux function,  $\psi$ , poloidal angle,  $\theta$ , pitch angle,  $\lambda$ , as well as the particle speed,  $V$ , with the note that  $\sigma = \pm 1$  is the sign of the parallel component of velocity.  $\xi$  is the helical angle defined as  $\xi = \phi - (m/n)\theta$  with  $\phi$  being the toroidal angle. RDK-NTM is a hybrid code, i.e. while the radial variation is retained in perturbations associated with the island, all equilibrium quantities are Taylor expanded around the rational surface of interest (i.e. the 2,1 rational surface in the present paper). Hence, RDK-NTM depends on plasma equilibria, including plasma geometry, rotation, equilibrium density and temperature ( $n_j$  and  $T_j$ , where  $j$  denotes the species type), their gradients [via  $(\psi_s/n_j) dn_j/d\psi$  and  $(\psi_s/T_j) dT_j/d\psi$ , where  $\psi_s$  is associated with the 2,1 rational surface] and curvature [via  $(\psi_s^2/n_j) d^2 n_j/d\psi^2$  and  $(\psi_s^2/T_j) d^2 T_j/d\psi^2$ ]. Based on these input parameters, RDK-NTM then calculates the associated  $g_0$  for each particle species.

According to the drift island theory [31], the distribution function of passing particles is found to be a ‘drift surface’ quantity, where the drift surfaces have the same topology as the flux surfaces of the magnetic island but are shifted

radially by an amount proportional to the poloidal Larmor radius ( $\rho_\theta$ ). This then supports a contribution to the ion density gradient across the magnetic island O-point near  $w_c$ , while the electron density gradient at the O-point is restored by the perturbed potential to satisfy quasi-neutrality. This ultimately restores the bootstrap current density within the magnetic island, providing the NTM threshold mechanism.

The polarization current density,  $j_{\text{pol}}$ , and the associated polarization contribution to the island evolution ( $\Delta_{\text{pol}}$ ), in turn, is defined as the part of the parallel current density that varies on the magnetic island flux surfaces (and averages to zero over a flux surface):

$$\Delta_{\text{pol}} = -\frac{\mu_0 R}{2\tilde{\psi}} \int_{\mathbb{R}} d\psi \int_{-\pi}^{\pi} \left( \bar{j}_{\parallel} - \langle \bar{j}_{\parallel} \rangle_{\xi}^{\Omega} \right) \cos(n\xi) d\xi,$$

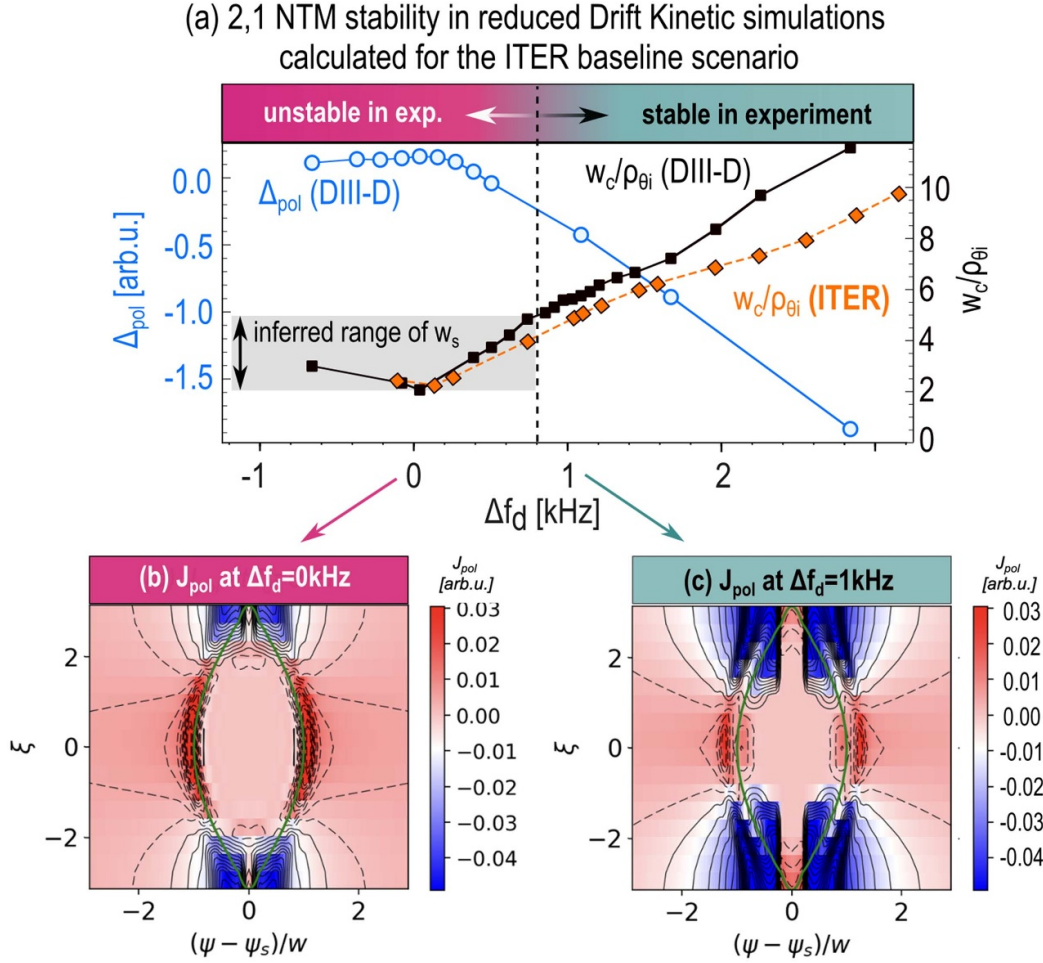
where  $\bar{j}_{\parallel}$  is the  $\theta$ -average of the parallel current density perturbation,  $j_{\parallel}$ , reconstructed from the ion and electron  $g_0 = g_0(\psi, \theta, \xi, \lambda, V; \sigma)$ .  $\langle \dots \rangle_{\xi}^{\Omega}$  denotes the magnetic island flux surface average.  $\mu_0$  is the magnetic permeability of free space,  $R$  is the major radius and  $\tilde{\psi}$  is the perturbation amplitude.  $j_{\text{pol}}$  is predominantly associated with the perturbed potential due to the difference in the ion and electron responses to the magnetic island. Depending on  $\Delta f_d$ , it can further amplify or suppress the stabilizing effect of drift islands as shown in figure 3(a).

In figures 3(b) and (c), we show  $j_{\text{pol}}$  in the  $(\psi, \xi)$  plane at  $\Delta f_d = 0$  kHz and  $\Delta f_d = 1.0$  kHz, respectively. The solid green curve indicates the position of the magnetic island separatrix, and  $w$  is the magnetic island half-width (in units of  $\psi$ ).

As we decrease  $\Delta f_d$  towards and then under  $\Delta f_d = 0$  kHz, the negative (stabilizing) flows that spread into the island region in the vicinity of the island X-points ( $\xi = \pm\pi$ ) become smaller (as can be seen from comparing figure 3(b) to figure 3(c)), while positive (destabilizing) flows right outside of the island separatrix grow larger and become more elongated in the helical direction. This then results in the  $j_{\text{pol}}$  contribution ( $\Delta_{\text{pol}}$ ), changing its sign with  $\Delta f_d$ , and becoming destabilizing as  $\Delta f_d$  approaches zero (figure 3(a)), which then reduces  $w_c$ . Note that as  $\Delta f_d \rightarrow 0$  kHz, the radial shift of the ion drift islands decreases [31–33], resulting in a minimum in the NTM onset threshold at  $\Delta f_d \simeq 0$ , making such a plasma more prone to tearing instabilities. The simulation results are shown both for the DIII-D IBS plasmas, as well as for steady-state ITER plasmas (case #131041 in the ITER database).

It is interesting to note that  $w_c$  in RDK changes by a remarkable factor of 6 within the experimental range of  $\Delta f_{1,2}$  ( $\Delta f_{1,2} \simeq \Delta f_d$  is assumed as the islands are sawtooth seeded). This change strongly supports that triggers with quasi-stationary seed island widths ( $w_s$ ) are more likely to destabilize NTMs as the rotation profile flattens.

Further, the  $w_c(\Delta f_d)$  relation in figure 3(a) and the experimentally obtained  $\Delta f_d \simeq 0.8$  kHz critical differential rotation in figure 2(a) together produce the estimate that  $2 \leq w_s/\rho_{\theta,i} \leq 5$  in these DIII-D IBS plasmas ( $\rho_{\theta,i}$  is the ion poloidal Larmor radius). In addition, the  $w_c(\Delta f_d)$  relationship provides a quantitative scaling of the critical  $\Delta f_{1,2}$  with respect to the triggering MHD amplitude at the  $q = 2$  surface. For



**Figure 3.** (a)  $\Delta_{\text{pol}}$  and the NTM onset threshold ( $w_c$ ) v.s.  $\Delta f_d \cdot j_{\text{pol}}(\psi, \xi)$  at (b)  $\Delta f_d = 0.0$  kHz and at (c)  $\Delta f_d = 1.0$  kHz.

example, if  $w_s$  drops by a factor of 2, then the critical differential rotation drops by a factor of 5, to about 0.12 kHz. Such a low  $\Delta f_{1,2}$  target is much more practicable in large and dense reactor plasmas where neutral beams cannot deliver substantial torque into the core. Thus, reducing the sawtooth amplitude may provide substantial benefits for NTM stabilization by  $\Delta f_{1,2}$ , in synergy with a previous proposition [35].

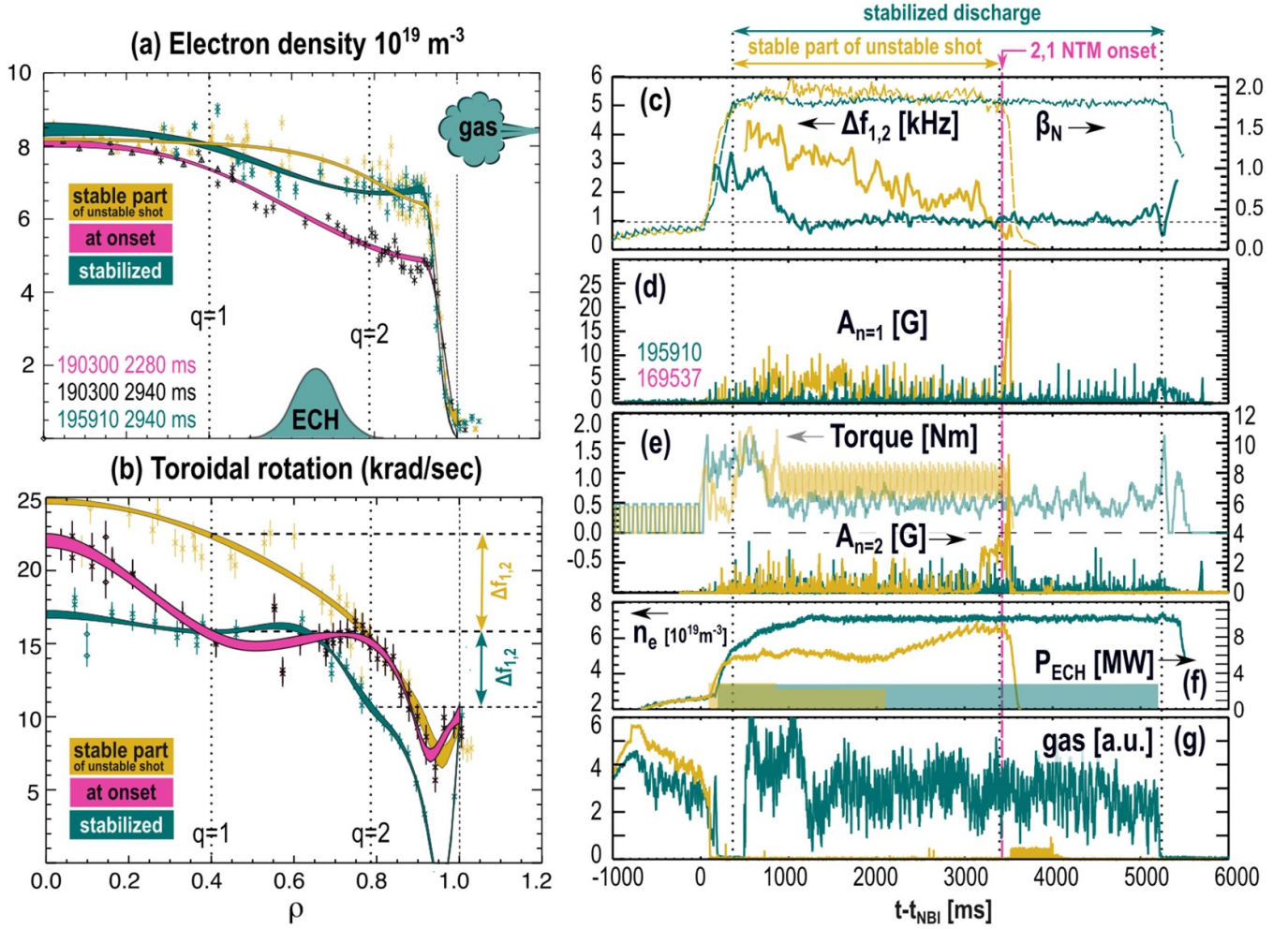
#### 4. Stationary tearing-free ITER baseline operation

Motivated by the observed correlation between  $\Delta f_{1,2}$  and the 2,1 NTM onset, and the physical explanation provided by RDK simulations showing strong stabilization by differential rotation, a new discharge program was developed to avoid 2,1 NTMs by ensuring  $\Delta f_{1,2} \gtrsim 0.8$  kHz (figure 4).

Starting from the setup of a typical unstable reference discharge, we utilize neutral gas fueling which modifies the edge neoclassical potential and thereby sustains a sharp rotation gradient across the  $q = 2$  rational surface. The plasma control system is programmed to feedback the gas puff (figure 4(g)) to maintain a fixed line-averaged core density ( $n_e$ ) (figure 4(f)). The target  $n_e$  is chosen to maintain  $\Delta f_{1,2} > 1$  kHz. To prevent overshooting of  $n_e$ , the control loop uses electron cyclotron

heating (ECH) for density pump-out [36], without current drive. This results in well controlled  $n_e \simeq 6.7 \times 10^{19} \text{ m}^{-3}$  at the top of the pedestal (figure 4(a)), wider and deeper edge toroidal rotation shear layer and the  $q = 2$  surface rotation decreases to about 1 kHz below the  $q = 1$  surface rotation (figure 4(b)). Despite the ECH also decreasing the core rotation by increasing the angular momentum transport, the target  $\Delta f_{1,2} \simeq 1$  kHz is sustained (figure 4(c)) and the 2,1 NTM is avoided throughout the full programmed duration of the discharge (figure 4(d)). The stabilized discharge has a sawtooth-free core, but 2,1 NTMs are absent (figure 4(d)). Along with the 2,1 NTM stabilization, the 3,2 NTM is also absent in nearly all discharges (figure 4(e)). As the  $n > 1$  NTMs flatten the toroidal rotation by radially redistributing the fast ions [37], they are closely correlated with the 2,1 NTM onset (figure 2(b)). Thus, the absence of the  $n > 1$  modes in the stabilized discharges is likely a significant contributing factor to the sustained  $\Delta f_{1,2}$  and the concomitant stability of the scenario.

A series of 7 repeat discharges each with a 5 s pressure flat-top utilizing this new method demonstrate reproducible stable operation free of disruptive 2,1 NTMs with  $\Delta f_{1,2} \gtrsim 1.0$  kHz (figures 5 and 6). Scanning the ECH location confirms that the local ECH heating effect is not the cause of the stability. Adjusting the mirrors to drive electron cyclotron current



**Figure 4.** Radial profiles of (a)  $n_e$  and (b) toroidal rotation. (c)  $\beta_N$  and  $\Delta f_{1,2}$ , (d)  $n = 1$  magnetic amplitude ( $A_{n=1}$ ), (e) neutral beam torque and  $n = 2$  magnetic amplitude ( $A_{n=2}$ ), (f) line averaged core  $n_e$  and (g) gas flow ( $t_{\text{NBI}}$  is when the neutral beams are activated).

in the direction of the plasma current in repeat shots preserves the stability as well. Scanning the ECH power between 0.7 and 3.1 MW shows robust density and edge rotation control and stability above 1.3 MW of ECH power. At lower ECH power the density overshoots, followed by the loss of differential rotation and concomitant disruption. This stabilization method remains robust when the average external neutral beam torque drops down to 0.0 Nm (figure 6). The reproducibility of the method is demonstrated through a group of examples in figure 5.

## 5. Higher order gyrokinetic simulations of the edge rotation

To understand how edge fueling influences the rotation profile and the associated rotation shear in the stabilized plasma (when magnetic islands are not present), we employ a coupled, electromagnetic *neoclassical-gyrokinetic theory* [38–40] written in the limit of a large aspect ratio tokamak, relevant to DIII-D plasmas. Amongst other effects, the model [39, 40] retains deviations from a Maxwellian equilibrium, including corrections associated with the neoclassical physics, such

as the bootstrap current and neoclassical polarization current. Capturing those is crucial as edge fueling predominantly impacts the density gradient (figure 4(a)), consequently amplifying a spike in the bootstrap current density at  $\rho \approx 0.9$  (not shown here) and enhancing the role of the neoclassical electrostatic potential.

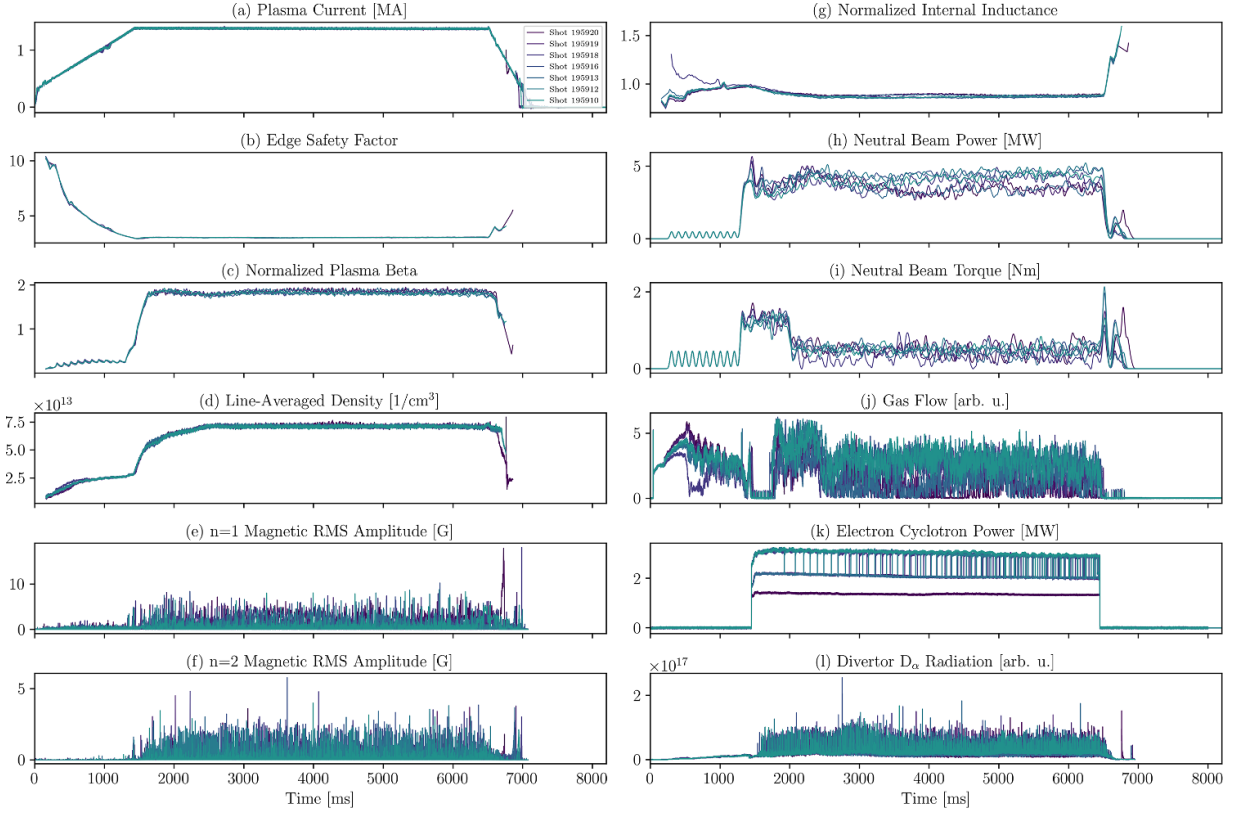
Higher order gyrokinetic simulations are performed using NEO GS2 [40]—an extension of the local, gyrokinetic turbulence code GS2 [41] to second order in the  $\rho_j/L$  expansion ( $\rho_j$  is the particle Larmor radius of species  $j$  and  $L$  is the system size) with the ratio of poloidal to total equilibrium magnetic field being small.

Specifically, NEO GS2 solves

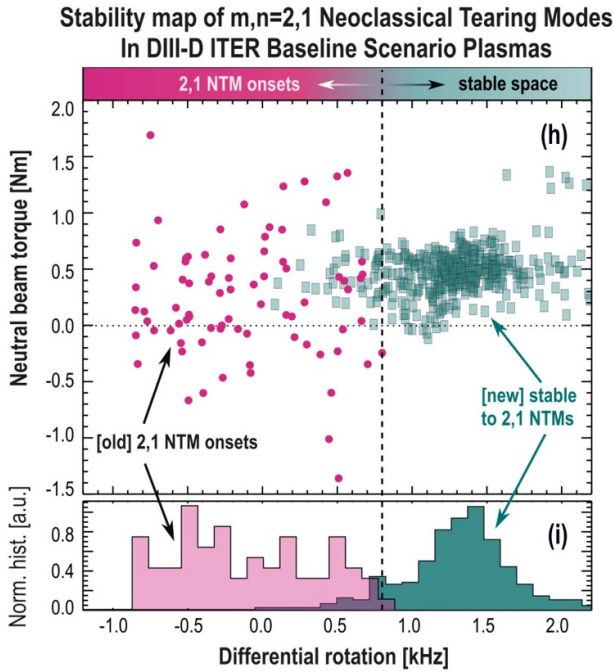
$$\begin{aligned} \frac{\partial h_j}{\partial t} + u(\mathbf{b} \cdot \nabla_{\mathbf{x}}) H_j + i(\mathbf{k}_{\perp} \cdot \mathbf{V}_D) H_j \\ = \sum_{j'} C_{jj'}^{\text{GK}}(H_j, H_{j'}) + \frac{i}{B_0} [\mathbf{k}_{\perp} \times \mathbf{b}] \cdot \nabla_{\mathbf{x}} F_j \langle \Psi_j \rangle_{\alpha}^{\mathbf{x}} \end{aligned} \quad (1)$$

for the non-adiabatic piece of the fluctuating distribution function,  $h_j$ , where

$$h_j = H_j + \frac{ez_j}{m_j} \langle \Psi_j \rangle_{\alpha}^{\mathbf{x}} \frac{\partial F_j}{\partial U} \Big|_{\mu},$$



**Figure 5.** 2,1 NTM free operation at target ITER parameters in a series of 7 discharges: time traces of a group of relevant quantities.



**Figure 6.** (a) Stability map of 2,1 NTMs in the parameter space of  $\Delta f_{1,2}$  and  $T_{NBI}$ . (b) Normalized histograms of  $\Delta f_{1,2}$  in the old database at the time of NTM onsets (magenta) and in the new, stabilized plasmas (green).

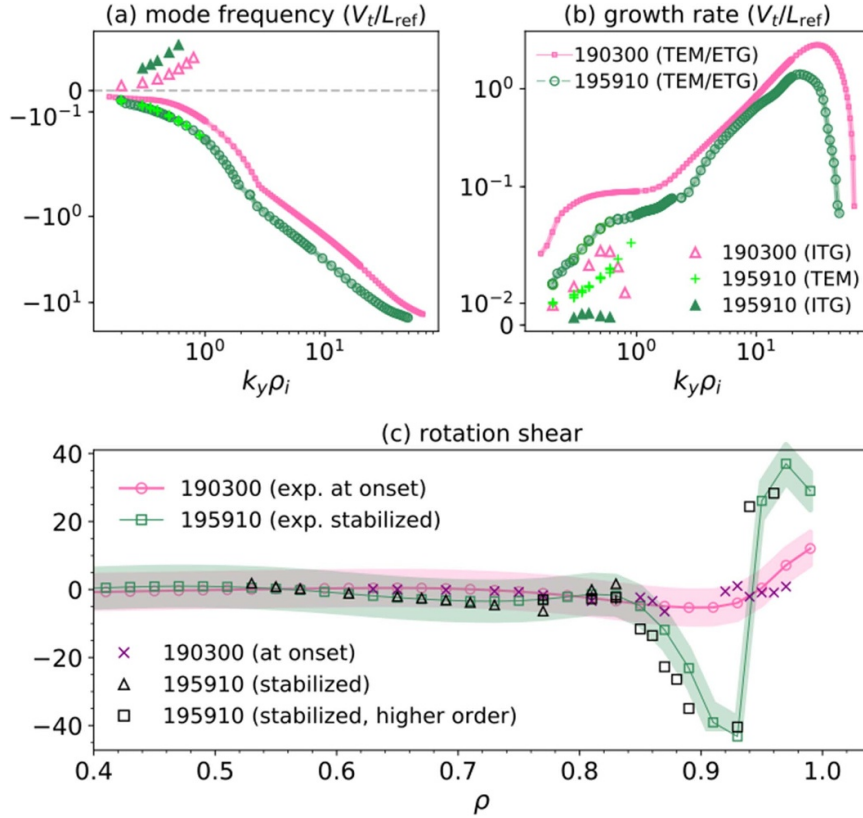
and  $H_j$  is related to the total fluctuating distribution function,  $\delta f_j$ , via

$$\delta f_j = \frac{ez_j}{m_j} \Phi' \frac{\partial F_j}{\partial U} \Big|_{\mathbf{x},u} - \frac{ez_j}{m_j} \left( uA_{\parallel}' + \langle \Psi_j \rangle_{\alpha}^{\mathbf{x}} \right) \frac{\partial F_j}{B_0 \partial \mu} \Big|_{\mathbf{x},u} + H_j.$$

Here  $ez_j$  and  $m_j$  are the particle charge and mass of species  $j$ ,  $B_0$  is the equilibrium magnetic field,  $U$  is the total particle energy per unit mass and  $\mu$  is the magnetic moment per unit mass [39].  $C^{\text{GK}}$  denotes the gyrokinetic collision operator. The gyrophase averaged generalized potential is

$$\begin{aligned} \langle \Psi_j \rangle_{\alpha}^{\mathbf{x}} &\equiv \langle \Phi' - \mathbf{V} \cdot \mathbf{A}' \rangle_{\alpha}^{\mathbf{x}} \\ &= \left( \hat{\Phi}' - u \hat{A}_{\parallel}' \right) J_0(k_{\perp} \rho_j) + \frac{s \hat{B}_{\parallel}'}{k_{\perp}} J_1(k_{\perp} \rho_j), \end{aligned} \quad (2)$$

given the eikonal approximation of fluctuating quantities [40] (electrostatic  $\Phi'$  and vector  $\mathbf{A}'$  potentials).  $J_k$  is the Bessel function of the first kind, of order  $k$ . Note that hats on the right hand side of equation (2) denote amplitudes of the associated fluctuating quantities in ballooning space. In particular,  $\hat{\Phi}'$ ,  $\hat{A}_{\parallel}'$  and  $\hat{B}_{\parallel}'$  are associated with the electrostatic, transverse electromagnetic and compressional electromagnetic potentials and are to be determined from the corresponding Poisson's and Ampère's laws (e.g. equation (22)–(24) of [40]).  $u$  and



**Figure 7.** Mode frequencies (a) and growth rates (b) versus mode number,  $k_y \rho_i$ , obtained by NEO GS2 eigenvalue solver in the vicinity of the  $q=2$  surface. (c) Radial profile of the rotation shear. The ‘higher order’ simulations retain effects of the second order equilibrium density and temperature derivatives.

$s$  are the parallel and perpendicular velocities with respect to the equilibrium magnetic field,  $\mathbf{b} = \mathbf{B}_0/B_0$ .  $\mathbf{k}_\perp$  is the 2D wavenumber with  $k_\perp = |\mathbf{k}_\perp|$ , and  $\mathbf{X}$  denotes the position of the guiding center. We note that  $\mathbf{V}_D$  on the left hand side of equation (1) contains equilibrium  $\mathbf{E} \times \mathbf{B}$  (namely  $\mathbf{V}_E$ ) and magnetic drifts, as well as the conventional, leading order  $\mathbf{E} \times \mathbf{B}$  nonlinearity (see [39] for more details).

It is important to note that the equilibrium distribution function,  $F_j$ , in equation (1) is provided by a combination of the leading order (Maxwellian) equilibrium and the neoclassical correction,  $F_{1j}$ , reconstructed by the multi-species drift kinetic solver NEO [42–44]. As explained in [39] and [40], the latter ensures that neoclassical effects, including the equilibrium neoclassical currents, enter the gyrokinetic formalism, impacting plasma micro-stability. Furthermore, given the difference in the first order, neoclassical electron and ion responses (i.e.  $F_{1e}$  and  $F_{1i}$ , respectively), the neoclassical electrostatic potential is generated, entering equation (1) via  $\mathbf{V}_E$  as part of the equilibrium  $\mathbf{E} \times \mathbf{B}$  velocity.

Note that equation (1) provides a finite beta, electromagnetic generalization of the electrostatic *low flow* GS2 [45] to study intrinsic rotation due to non-Maxwellian equilibrium [46, 47]. As noted above, by coupling to NEO [42–44] it allows one to retain neoclassical effects crucial when gradients are steep. For instance, NEO alone was previously successfully employed to model main-ion rotation in DIII-D plasmas in the higher density condition when the neoclassical theory can be

anticipated to be relatively accurate in capturing profile structures [48].

Simulations are finite beta, electromagnetic, performed for the  $\rho$  values varying between the  $q=2$  rational surface up to the plasma edge. In this range, both plasmas (with and without edge fueling) are unstable to ion temperature gradient modes (ITG) and trapped electron modes (TEM) at low wave numbers ( $k_y \rho_i \lesssim 1$ ); as well as to electron modes (TEM/ETG — electron temperature gradient driven modes) at higher wave numbers ( $k_y \rho_i > 1$ ). In particular, in the vicinity of the  $q=2$  surface, TEMs strongly dominate the plasma response at  $k_y \rho_i \lesssim 1$ , while ITGs are subdominant there (figures 7(a) and (b)). Furthermore, inclusion of edge fueling appears to significantly suppress the associated mode growth rates — this suppression is particularly strong at the edge, but it persists even closer to the core region (figures 7(a) and (b)). This enhanced suppression can be explained by *natural*  $\mathbf{E} \times \mathbf{B}$  flow shear [40], i.e. the  $\mathbf{E} \times \mathbf{B}$  shear component driven by the neoclassical electrostatic potential. Note that while the  $\mathbf{E} \times \mathbf{B}$  shear is generally known to have a stabilizing impact on drift wave turbulence [49, 50], the majority of the corresponding theory predictions account for the leading order,  $\mathbf{E} \times \mathbf{B}$  shear component, excluding the neoclassical corrections, important when gradients are enhanced [51].

Indeed, as found in [40], the neoclassical potential strongly responds to changes in the density gradient (less to changes in the temperature gradient). Gas puffing, in turn, impacts

the electron density gradient across all  $\rho$  values (figure 4(a)), enhancing the difference between the ion and electron neoclassical responses and therefore the role of the neoclassical potential in maintaining quasi-neutrality. The latter then influences the plasma toroidal rotation shear (figure 7(c)) and gyrokinetic stability via the  $\mathbf{E} \times \mathbf{B}$  component of the Vlasov operator, suppressing the associated turbulence. Note that the velocity profiles here are obtained by integrating the force balance equation, following [39, 40, 52]. While this analysis reconstructs the rotation shear structure in close qualitative agreement with experiment, there might be additional (residual) effects that could play a role quantitatively, including equilibrium profile shearing [53, 54] and *slow* perpendicular variations of the fluctuating quantities, not captured in NEO GS2 [55].

## 6. Summary and discussion

The loss of differential rotation is identified as the root cause of the majority of disruptive 2,1 NTMs being triggered by sawtooth instabilities in a database study of nearly 300 DIII-D IBS plasmas. The onset at low  $\Delta f_{1,2}$  is explained by reduction of stabilizing polarization currents when the seed island co-rotates with the plasma at  $q=2$ . A new solution is developed to avoid disruptive 2,1 NTMs using a feedback control loop combining gas puffing with density pump out (via ECH) to robustly sustain  $\Delta f_{1,2} \gtrsim 0.8$  kHz by modifying the edge neoclassical potential. This provides reproducibly stable, stationary ITER baseline operation at target parameters. Interestingly, at high differential rotation, the sawtooth tends to be more stable, enabling it to grow to a larger amplitude before crashing. Consequently, the seed island is expected to be larger at high differential rotation due to the increased stability of the sawtooth—somewhat counter-intuitively. However, the sheared plasma rotation at  $q=2$  could also screen the 1,1 magnetic field, potentially reducing the seed island size. While this screening effect is an intriguing consideration, it lies beyond the scope of our current study.

The intrinsic rotation of tokamak plasmas [56] along with the reported techniques provides enough differential rotation in the DIII-D IBS to avoid disruptions from the 2,1 NTM. This control method comprised of practicable actuators is promising to ensure disruption avoidance even in large fusion devices designed to operate at near zero external torque, such as ITER. For density control, pellet injection is considered as the prime core fueling system candidate in ITER [57, 58], allowing particle deposition inside the edge transport barrier. On the other hand, the density pump-out effect of ECH has been observed in many tokamaks [36, 59–61], and the ITER EC sub-system is designed to provide a potential actuator for density pump-out [62].

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