

## Understanding and controlling the ITER baseline plasma response

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### Introduction

Measurements of the magnetic plasma response to applied low-frequency,  $n = 1$  perturbations made in low-torque DIII-D ITER baseline scenario (IBS) demonstration discharges (Fig. 1) are related to the observed and predicted stability and used as a realtime control variable. Although the frequency of the applied perturbations, 20 Hz, is considerably lower than the typical kHz-range rotation frequencies of tearing modes that precede disruptions in these discharges, a central hypothesis is that the measurements can aid in uncovering MHD stability trends that influence the observed instabilities.

A key step in preparing for burning plasma operation in the ITER device is to create discharges in existing devices with some normalized plasma parameters matching the those of ITER's plasma operating scenarios. Efforts to replicate parameters of the inductive, fusion gain  $Q = 10$  IBS [1], have been undertaken on several devices, including DIII-D [2–5]. In the DIII-D experiments, the ITER values of normalized plasma current,  $I_N \equiv I_p/(aB) = 1.44$ , and normalized pressure,  $\beta \equiv 2\mu_0\langle p\rangle/B^2 = 2.55\%$ , have been achieved in ELMing, H-mode discharges with a cross-sectional plasma shape and aspect ratio  $R/a$  closely matching ITER's [3]. Here,  $I_p$  is the plasma current in MA,  $a$  is the plasma minor radius in m,  $B$  is the toroidal field strength in T,  $\langle p \rangle$  is the volume-averaged plasma pressure, and  $R$  is the plasma major radius in m. The  $\beta$  value is consistent with the 500 MW IBS fusion power target, and is normalized to give  $\beta_N \equiv \beta/I_N = 1.8$ .

MHD stability is a concern for the IBS due to its high current; the shape and  $I_N$  targets correspond with a low safety factor at the 95% flux surface,  $q_{95} \approx 3$ . Although stable operation was achieved in the initial DIII-D experiments, disruptivity increased when an additional parameter, the neutral beam injected (NBI) torque  $T_{NBI}$ , was reduced to the ITER-equivalent level [4,5].

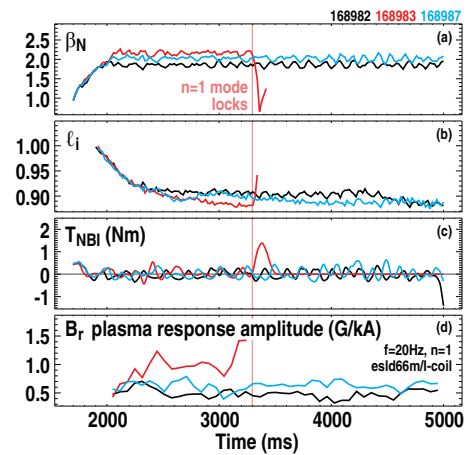


Fig. 1: Timeseries from example DIII-D IBS discharges showing (a) normalized pressure  $\beta_N$ , (b) normalized internal inductance  $\ell_i$ , (c) neutral beam torque  $T_{NBI}$  and (d) measurements of the  $B_r$  plasma response amplitude.

The dominant cause of the disruptions was the onset of rotating tearing instabilities that eventually slowed and locked to the lab frame. Although some progress was made in avoiding the tearing instabilities by empirically tuning the initial  $I_p$  ramp rate and timing of the H-mode transition, understanding the IBS instability boundaries remains an open area of research.

### Plasma response dataset

Measurements of the stable plasma response to  $n = 1$ , 20 Hz toroidally rotating perturbations from the DIII-D internal coil array (I-coil) were made during IBS demonstration discharges. We report on synchronous,  $n = 1$  response data from ex-vessel radial field  $B_r$  and in-vessel poloidal field  $B_p$  sensor arrays on the low-field side (LFS) midplane. The synchronous response shown in Figs. 1–4 is identified by Fourier analyzing the magnetic measurements in 2-period (100 ms) windows, compensating for the direct (vacuum) coupling to the I-coil, and fitting the toroidal dependence of the result to a rotating  $n = 1$  mode. The amplitude and toroidal phase of the response are normalized to those of the perturbing I-coil current. Similar measurements have been used to validate MHD stability models including non-ideal contributions [6].

The dataset has 194 shots with 74 cases where rotating  $n = 1$  tearing modes slow and lock, bringing about an eventual disruption. The mean time between the locking event and disruption is 189 ms, close to the mean H-mode energy confinement time for the dataset,  $\tau_E = 156$  ms. In shots where locking occurs, the plasma response is analyzed up until the locking event is imminent, defined here as the moment when the frequency of the slowing mode drops below 200 Hz. Bounding the dataset in this way minimizes the influence of quasi-stable or unstable islands on the synchronous analysis used to identify the stable plasma equilibrium response to the I-coil perturbation.

### Link between plasma response and stability

Consistent with previous analysis [4,5], the stability of low-torque DIII-D IBS demonstration discharges appears to be sensitive to aspects of the current profile, such as the normalized internal inductance  $\ell_i$ . Fig. 1 shows the evolutions of three similar low-torque discharges with

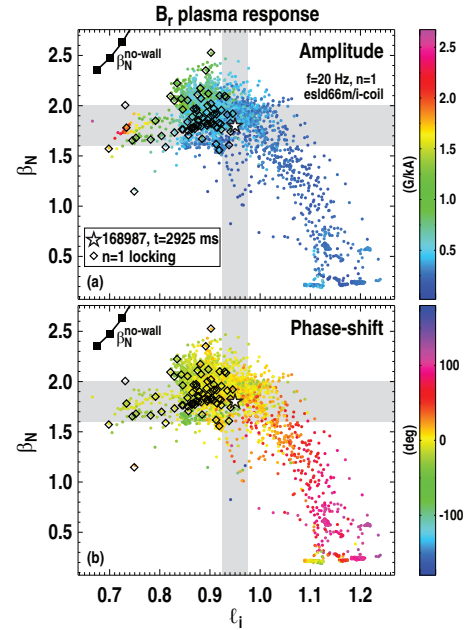


Fig. 2: Dependence of the  $B_r$  plasma response (a) amplitude and (b) phase-shift (colored circles) on  $\beta_N$  and  $\ell_i$ , with  $n = 1$  tearing mode locking events (black diamonds), parameters of example discharge 168987 (white stars) and ideal MHD no-wall limit (black squares).

differences in  $\beta_N$  and  $\ell_i$ . The discharge that evolves to the lowest  $\ell_i$  value exhibits an elevated plasma response amplitude and, eventually, a plasma disruption preceded by a locking  $n = 1$  tearing mode. An analysis of the entire dataset shows that the response amplitude is correlated with  $n = 1$  mode locking, increasing with time as locking approaches, to a final mean level 50% higher (roughly one standard deviation) than the mean over the whole dataset including discharges with and without locking events.

The dependence of the plasma response from the entire dataset on  $\beta_N$  and  $\ell_i$  is shown in Fig. 2. The response amplitude and phase-shift exhibit clear sensitivities to both plasma parameters, with the amplitude increasing with  $\beta_N$  and decreasing with  $\ell_i$ . The highest amplitude response values occur at intermediate  $\beta_N$  and the lowest values of  $\ell_i$ , that is, the broadest current density profiles. The dependence of the ideal MHD no-wall stability limit was evaluated using the DCON code [7] by varying the pressure and current density profiles of an example equilibrium and is overlaid in Fig. 2. Although the dataset is typically well below the no-wall  $\beta_N$ -limit, the limit decreases as  $\ell_i$  decreases, becoming closer to the experimentally realized  $\beta_N$  values at low  $\ell_i$ .

A more detailed comparison with ideal MHD is performed by calculating the resistive wall mode (RWM) growth rate  $\gamma$  normalized to the wall eddy current decay timescale using a linearized dispersion relation [8]. This growth rate can be compared with that calculated from the response measurements using a single mode model and assuming fixed values for the model's coupling parameter and  $\tau_w$  [6]. Fig. 3 shows a comparison between the ideal MHD and experimental  $\gamma\tau_w$  calcu-

lations, where an effort has been made to isolate the experimental dependencies on  $\beta_N$  and  $\ell_i$  by limiting the data to the shaded bands shown in Fig. 2, and  $1.34 < I_N < 1.45$ . The trends in the experimental data are compatible with those of the ideal MHD calculation, although many of the data points are closer to marginal stability,  $\text{Re } \gamma = 0$ , than the predictions.

### Controlling the response

Preliminary experiments were performed to determine whether controlling the plasma response using feedback could help optimize the low-torque IBS stability. In the control scheme, previously developed in high-torque discharges, the NBI power is feedback modulated in proportion the error between the plasma response amplitude and a pre-defined target [9]. Following

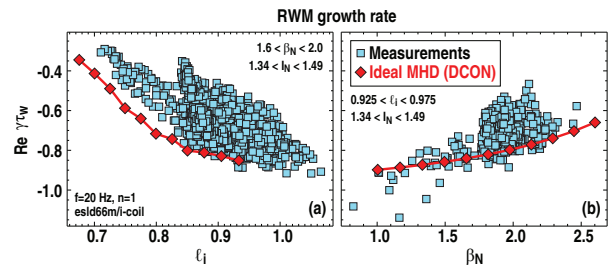


Fig. 3: Comparisons of the (a)  $\ell_i$  and (b)  $\beta_N$  dependencies of the normalized RWM growth rate  $\text{Re } \gamma\tau_w$  inferred from plasma response measurements (blue squares) with predictions of the linearized, ideal MHD, resistive wall dispersion relation (red diamonds).

empirical optimization of the feedback gains, an example discharge was obtained in which the control enables a lower plasma response amplitude, compared with a reference discharge that used the more standard technique of controlling  $\beta_N$  with NBI power feedback (Fig. 4). The normalized fusion gain,  $G = \beta_N H_{89} / q_{95}^2$ , remains close to the required ITER value of 0.42 owing to slightly lower  $q_{95}$  and higher normalized confinement  $H_{89}$ .

## Conclusions

The magnetic plasma response to applied 20 Hz,  $n = 1$  perturbations is an indicator of the stability of DIII-D IBS demonstration discharges. The response amplitude is maximized at the lowest  $\ell_i$  values in the dataset and is also correlated with  $\beta_N$ . Both of these trends are consistent with ideal MHD predictions. However, the real growth rate from the ideal MHD dispersion relation is more stable in many cases than that inferred from the response measurements, leaving open the possibility of non-ideal influences, such as resistivity and kinetic effects, on the response. Instances of  $n = 1$  tearing mode locking are correlated with higher amplitude plasma response and  $\ell_i < 0.95$ , suggesting that the plasma current density profile plays an important role in the stability of these discharges. Finally, the  $\beta_N$ -dependence of the response was exploited to demonstrate closed-loop control via feedback modulation of the NBI power. Using heating power to directly control a plasma stability-related parameter, such as the response, may help facilitate the optimization of fusion output while simultaneously avoiding stability limits.

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[https://fusion.gat.com/global/D3D\\_DMP](https://fusion.gat.com/global/D3D_DMP).

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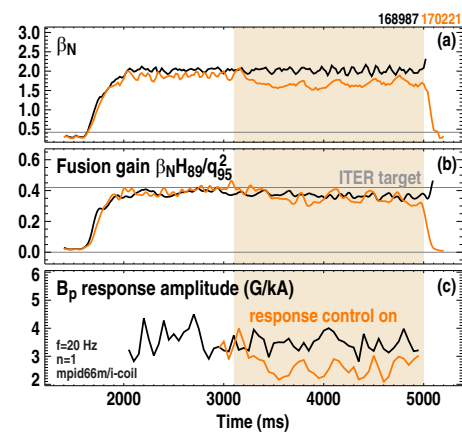


Fig. 4: Timeseries of (a)  $\beta_N$ , (b) normalized fusion gain, and (c)  $B_p$  plasma response amplitude from discharges with standard  $\beta_N$  control (black) and with the plasma response amplitude control enabled during the shaded window (orange).