High Resolution Study of 3D Magnetic Fields on Tokamak Plasmas

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The primary research objectives of the High Beta Tokamak (HBT-EP) research program are (i) to understand the full plasma response to external magnetic control coils and wall eddy currents and magnetization fields and (ii) to test and optimize techniques to actively control long-wavelength instabilities near the ideal wall stabilization limit. We report high-resolution detection of the 3D plasma magnetic response of wall-stabilized tokamak plasmas in the upgraded High Beta Tokamak-Extended Pulse (HBT-EP). A new, segmented adjustable conducting wall has been installed on HBT-EP made up of 20 elements with 40 sets of internal modular feedback control coils [1]. Each internal coil set can be independently driven and is capable of varying the toroidal angular control coil coverage width of 5˚, 10˚, and 15˚, to generate a wide variety of external magnetic perturbations. Measurements of non-axisymmetric radial and poloidal plasma response magnetic fields are made using a high-resolution array of 216 sensors positioned near the plasma surface [2] as shown in Fig. 1.

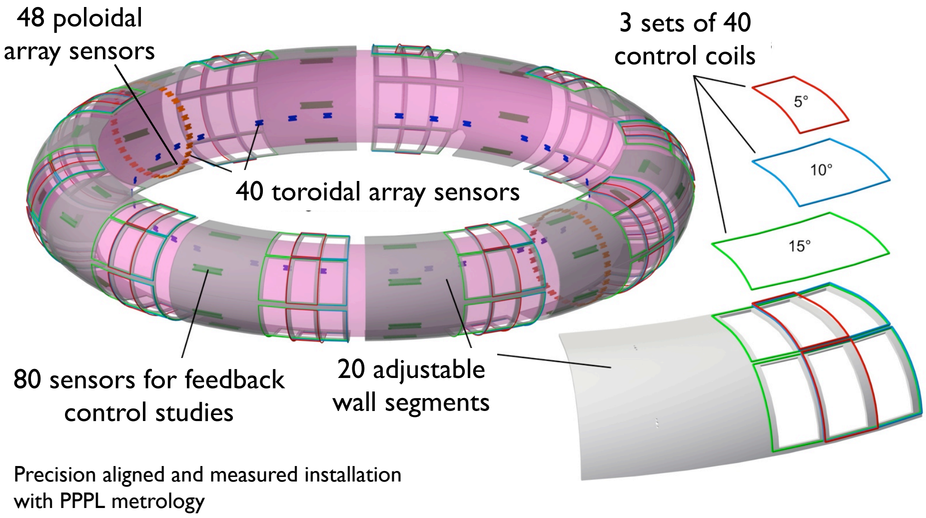

Figure 1. The HBT-EP modular instrumented control wall with 216 precisely located magnetic sensors and 120 modular feedback coils that allow selection of 5˚, 10˚, or 15˚ toroidal angle width.

Biorthogonal Decomposition Analysis of Multi-Mode MHD: In HBT-EP, external kink-mode structures are strongly linked to resonances with the edge safety factor. Transitions between dominant poloidal mode numbers as the edge-q changes are expected since the $q = m/n$ resonant surface changes position as time evolves. These m-number transitions can be observed using two high-resolution 32-channel magnetic sensor arrays with full poloidal coverage. An example of a persistent $n = 1$ mode making a transition from $m = 4$ to 3, then from $m = 3$ to 2 is shown in Fig. 2. Biorthogonal decomposition (BD) of all poloidal field sensors and radial field feedback sensors provides the poloidal mode structures shown in Fig. 2(c-f) with mode amplitudes and phases shown in Fig. 2(g-n) [3]. The first two quadrature-mode pairs show the m/n = 3/1 mode growing as the 4/1 decays, in agreement with the contour plots. Rather than growth and decay of two separate modes, this can be considered the gradual change of the poloidal mode number spectrum for the n = 1 mode.

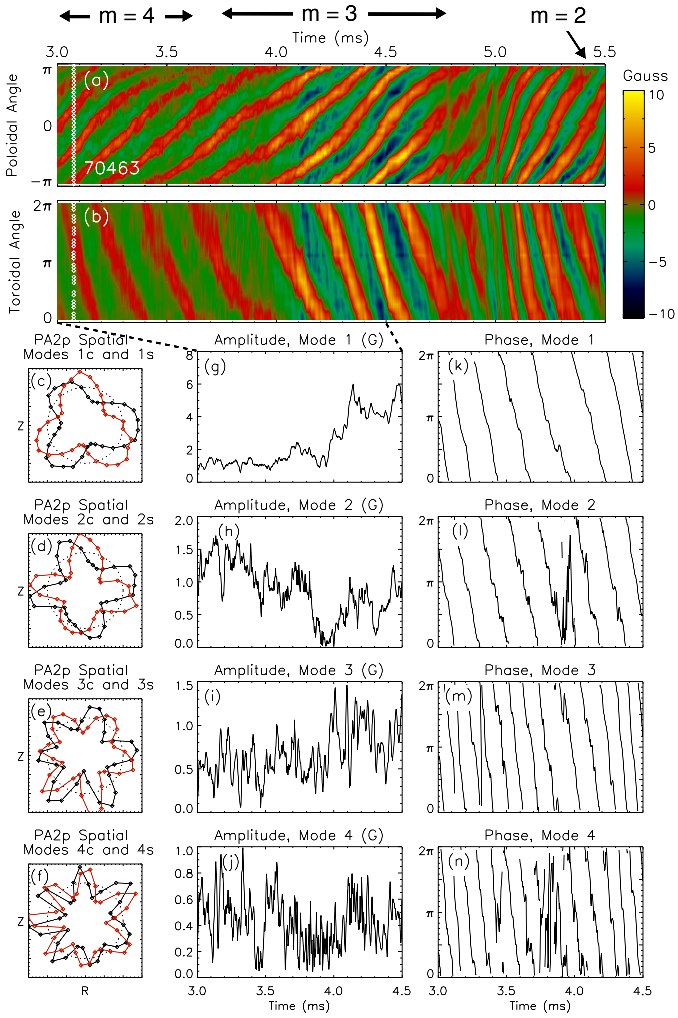

Figure 2. Contour plots of δB_θ versus poloidal angle (a) and toroidal angle (b), primarily showing rotating n = 1 activity which transitions between dominant poloidal mode numbers. White diamonds in (a) and (b) near 3.1 ms denote sensor locations. Biorthogonal decomposition of the sensor data during 3– 4.5 ms gives the poloidal spatial modes in (c-f). Toroidal mode numbers are n = 1 for the first two modes, and n = 2 for the third and fourth modes. Amplitude and toroidal phase of each mode are shown in (g-n). The plasma disrupts due to the m=2 mode at 5.6ms.

This mode number evolution occurs due a decreasing edge safety factor over time as q^* decreases below 3 at 3.5 ms. While the dominant n = 1 mode is changing shape, an n = 2 mode is also making a transition from 7/2 to 6/2, as shown in the bottom two rows of Fig. 2. The 7/2 mode is weak but coherent throughout the 3 to 4.5 ms time range, and the 6/2 mode becomes stronger while the 3/1 mode is growing. DCON stability analysis of representative equilibria predicts the 4/1 → 3/1 and 7/2 → 6/2 evolution in the least-stable modes. These observations illustrate the need for a multimode description of kink mode dynamics when designing a robust active feedback control system for wall-stabilized kink modes.

GPU Digital MIMO Low Latency Controller: In HBT-EP, strong saturated kink modes are excited having kHz growth rates and rotation frequencies that evolve on a millisecond timescale. To control these instabilities, the HBT-EP internal control coils shown in Fig. 1, are energized with high-power solid-state amplifiers that are controlled by a massively-parallel Graphical Processing Unit (GPU), high-throughput low-latency multiple-input/output (MIMO) digital signal processing (DSP) system. This GPU-DSP control system achieves cycle times of 5 μs and I/O latencies below 10 μs for up to 96 inputs and 64 outputs. To handle the resulting computational complexity under the given time constraints, the control algorithms are designed for massively-parallel processing. An NVIDIA GeForce GTX580 GPU, offering a total of 512 computing cores running at 0.85 GHz each, provides the necessary hardware resources. New control architecture allows control input from magnetic diagnostics to be pushed directly into GPU memory by a D-TACQ ACQ196 digitizer, and control output to be pulled directly from GPU memory by two D-TACQ AO32 analog output modules. By using peer-to-peer PCI express connections, this technique completely eliminates the use of host RAM and central processing unit (CPU) from the control cycle, permitting single-digit microsecond latencies on a standard Linux host system without any real-time extensions [4].

The resulting real-time control system achieved good results surpassing previous MHD mode control results reported on HBT-EP using a Kalman filter based control system implemented with an FPGA based DSP [5]. The massively-parallel computing capacity of the GPU allows implementation of a non-linear observer that tracks on a microsecond timescale both non-axisymmetric magnetic perturbations and the dynamical stability coefficients. The amplitude and toroidal phase of multiple rotating quadrature mode pairs are extracted from 80 radial and poloidal field sensors. The time-evolution of each mode is continuously fit to a slowly evolving stability coefficient which is used to filter out noise and dynamically compensate for feedback latency, amplifier response, and wall eddy currents before generating control signals for 40 independent control coils. The system model allows accurate tracking of the dominant kink mode even while its poloidal spectrum is changing due to the varying edge safety factor. Using only poloidal field sensors as input to the feedback system, the overall MHD kink-mode amplitude can be increased to the point of plasma disruption, but kink-mode suppression has so-far been limited to about 60% due to changes in the plasma toroidal rotation during application of feedback and by the excitation of a slowly-rotating “control surface mode” having the same helical structure as the uncontrolled kink [6]. Shown in Fig. 3 are the observed MHD mode spectra for both moderate and high closed feedback loop gains. We observe that high-gain control only marginally improve suppression, and excites an additional "control mode" which slowly rotates and increases in amplitude. The helical structures of both the natural rotating kink and the excited slowly rotating mode have the same spatial structures. The slow-mode excitation is the likely reason for the lack of further improvement in suppression of the dominant mode because it invalidates the control algorithm's assumption of rigid rotation at constant frequency.

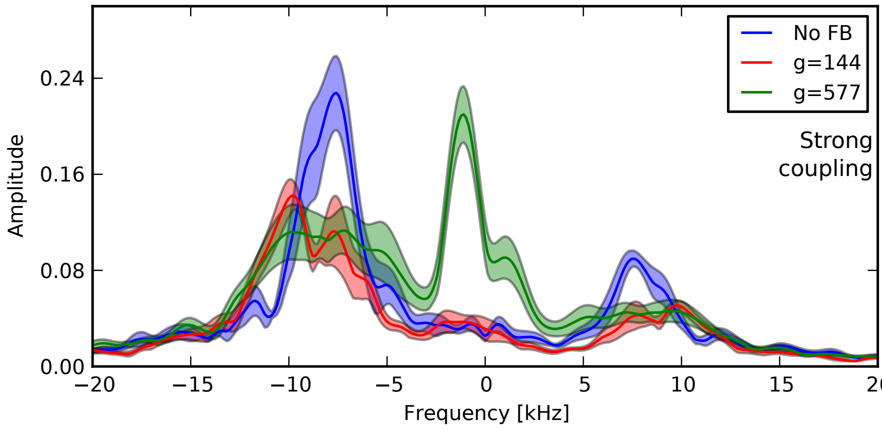

Figure 3. Mode spectrum for moderate (g = 144) and high (g = 577) feedback gains programmed for active suppression of the wall-stabilized rotating kink mode. Reducing the gain from 544 to 144 does not change suppression, but prevents excitation of the slow 1.4 kHz mode. Further reductions in gain reduce suppression as expected.

In HBT-EP, single-helicity kink-mode dynamics during active feedback control is modelled with a formulism that combines Boozer's general prescription for the coupling of currents in external conductors [7] and VALEN-based models [8] of the plasma coupling in the presence of non-ideal dissipation. We have previously shown the use of single-helicity dynamics [9] with relatively high levels of plasma dissipation well describes the plasma's time-response to the application of "phase-flip" resonant magnetic perturbations (RMPs) [10]. The ability to discriminate the RWM from other types of MHD activity will be an important component of any feedback system that operates reliably at the ideal wall limit of performance. Next steps on HBT-EP will further develop our MHD mode state estimators or observers capable of discriminating between the external kink and other quasi-coherent or impulsive MHD “noise” sources as well as the adaptive, nonlinear tracking algorithms used to maintain control as the plasma’s equilibrium position and rotation rate change using adaptive filtering and advanced digital signal processing techniques that extend our successful implementations of both simple Kalman filtering and adaptive rotation tracking.

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