HBT-EP MHD mode control research program

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Abstract. The High Beta Tokamak-Extended Pulse (HBT-EP) magnetohydrodynamic (MHD) mode control research program is studying ITER relevant internal modular feedback control coil configurations and their impact on kink mode rigidity, advanced digital control algorithms, and the effects of plasma rotation and three dimensional magnetic fields on MHD mode stability. A new segmented adjustable conducting wall has been installed on HBT-EP made up of 20 independent, movable, wall shell segments instrumented with 3 distinct sets of 40 saddle coils totaling 120 in-vessel modular feedback control coils. Each internal coil set has been designed with varying toroidal angular coil coverage of 5°, 10°, and 15°, spanning the toroidal angle range of an ITER port plug based internal coil to test Resistive Wall Mode (RWM) interaction and multimode MHD plasma response to such highly localized control fields. In addition, we have implemented 336 new poloidal and radial magnetic sensors to quantify the applied three dimensional fields of our control coils along with the observed plasma response. This paper describes the design and implementation of the new control shell incorporating these control and sensor coils on HBT-EP, and the research program plan on the upgraded HBT-EP to understand how best to optimize the use of modular feedback coils to control instability growth near the ideal wall stabilization limit, answer critical questions about the role of plasma rotation in active control of the RWM and the Ferritic Resistive Wall Mode (FRWM), and to improve the performance of MHD control systems used in fusion experiments and future burning plasma systems.

PACS numbers: 52.35.Py, 52.55.Fa, 52.55.Tn, 52.30.Cv, 07.05.Dz

Submitted to: *Plasma Phys. Control. Fusion*

1. Introduction

While the development and effectiveness of active MHD RWM control techniques has progressed significantly [1, 2, 3, 4, 5, 6], important questions regarding the coupling and driving of marginally stable modes by the feedback system as the ideal wall limit is approached still need to be experimentally addressed. Non-rigid, multimode behavior has been theoretically predicted [7] in tokamaks, and initial experimental evidence on NSTX [5] and HBT-EP [8] has been reported, as well as previous detailed study of these issues for RFP devices [9, 10] . Plasma response effects will be crucial

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to understanding these multimode MHD physics issues. One of the most important plasma response effects is to quantify the extent to which one can perform feedback on one unstable mode without destabilizing other stable MHD modes leading to a non-rigid, multimode plasma response of these MHD modes as they approach marginal stability while the plasma current or pressure is increased. This effect becomes particularly important when the feedback control coil coverage is decreased due to the large sideband field harmonics inherent in using small, modular control coils. Also, additional low n modes becoming unstable as the plasma pressure is further increased can lead to a multimode feedback situation. At high plasma pressure, multimode VALEN calculations for ITER predict it is unstable to both $n = 1$ and $n = 2$ RWMs, but in addition has three $n = 1$ and two $n = 2$ stable modes close to marginal stability that are expected to contribute to the plasma response. The new HBT-EP control shell has been built to study these important non-rigid kink mode effects. This paper is organized as follows: section 2 describes our newly installed passive wall, control, and sensor coil systems, section 3 then discusses future research plans for the investigation of the effects of shaping, stochastic edge fields, and ferrtic wall effects on kink multimode control physics, and finally section 4 gives a brief summary of this review of our new control wall and future physics plans on HBT-EP.

2. New fully-instrumented control shell

A new 20 segment passive stabilizing wall instrumented with 120 new control coils of varying toroidal angular extent has been constructed to study non-rigid, multimode MHD control physics issues. This system, depicted in Fig. 1, is now installed in vacuum vessel on HBT-EP. The new control wall system has three sets of 40 overlapping control coil arrays that have varying toroidal angular extents of 5°, 10°, and 15° to enable systematic study of the effect of varying control coil modularity and its effect on sideband interaction with other marginally stable or unstable MHD modes that might contribute to plasma response while attempting $n = 1$ mode control feedback.

The wall segments shown in Fig. 1 are made of spun 4.7 millimeter 316 stainless steel (SS). Spun shell sections were then annealed to 1010 °C to remove any residual stresses embedded into the annular shells sections that might lead to wall segment deformation when they were machined into separate segments. The machined individual wall segments were then electro-polished to minimize out-gassing when they are installed in the HBT-EP vacuum vessel. The continuous portions of the wall segments have been plated with thin ≈ 0.063 millimeter layers of copper on the front and back of the shell to adjust the wall time for an $n = 1$ RWM mode to be ≈ 400 microseconds as calculated by the VALEN code. VALEN is a three dimensional RWM feedback analysis code based on a finite element circuit formulation of the RWM feedback problem [11]. This choice of wall time was designed to adjust the growth time of the RWM so that it is easily detectable during typical experimental discharge times on HBT-EP. The continuous wall sections along with their windowpane structure has increased the plasma wall coupling and hence the ideal wall limit of the device by a factor of two relative to the previous passive stabilizer employed on HBT-EP. This combination of new wall time and plasma wall coupling yields a larger parameter range over which we can observe the RWM on our device. The entire shell segments were finally flash coated with 0.00762 millimeter of chrome to act as a plasma-facing surface to minimize the possibility of excessive copper sputtering due to scrape off layer plasma interaction. The individual shell segments may be moved using radial actuators

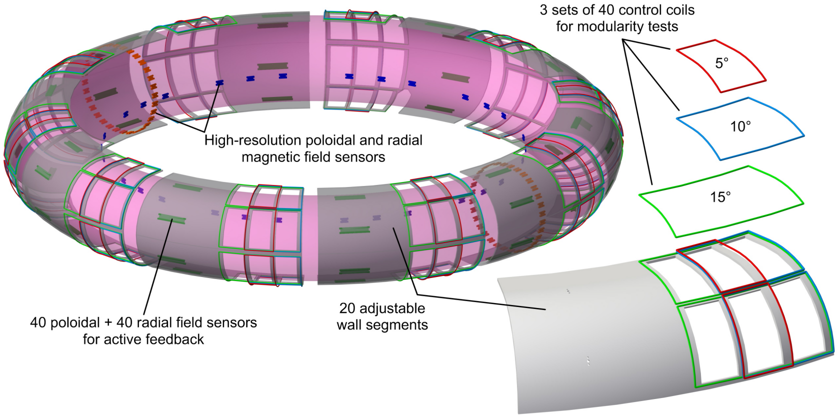


Figure 1. Illustration of the new HBT-EP modular instrumented control shell now installed at Columbia University. HBT-EPs control wall has over 216 precisely located magnetic sensors, 120 modular feedback coils, for investigating MHD interactions between tokamak plasmas and surrounding structures. The adjustable conducting wall has been designed to optimize observations of the RWM and assembled to provide accurate detection of the plasmas full multiple-mode MHD activity and response to resonant magnetic perturbations (RMPs).

relative to the plasma surface by ~ 2.5 centimeters. This increment corresponds to a change in normalized wall radius relative to the plasma surface of 1.07 to 1.23. This adjustability allows us to systematically vary the plasma-wall and plasma-control coil coupling in experiments.

The new shell segments have been instrumented with sets of control coil arrays and magnetic diagnostic capability in preparation for upcoming non-rigid, multimode MHD control experiments. These new magnetic sensors are either mounted directly on the plasma facing side of the new wall segments or on standoffs mounted on the high field side (HFS) of the vacuum chamber. The new control coils are comprised of three distinct sets of 40 overlapping coils each as shown in Fig. 1. The control coils can be configured into 40 separate coil sets of 5°, 10°, and 15° toroidal extent. In addition, different angular extent coils can be chosen independently for each shell segment for added configuration flexibility. Typical HBT-EP current ramp discharges have a dominant (m,n)=(3,1) RWM helicity. By configuring the 5°, 10°, and 15° 40 coil arrays for a (3,1) applied field the typical sideband harmonics vary from being of the same magnitude as the applied (3,1) component for the 5° case, to being of approximately 3 times lower than the (3,1) field for the 15° array. The new magnetic diagnostic set is comprised of 216 poloidal and radial magnetic field sensor coils. The new diagnostic arrays will allow toroidal and poloidal mode numbers up to $n \sim 14$ and $m \sim 15$ to be resolved in the absence of noise. In addition, the control coils are wired up to be used as additional saddle coil sensors when they are not energized for experiments. These additional control coil sensors provide another new 120 diagnostic measurements for equilibrium and MHD mode diagnosis. Initial experiments will be conducted using our current 40 channel field programable gate array processor digital controller [12]. The control coil sets will be driven by new 2.5 kW Crown XLS5000 power amplifiers capable of driving a peak current of 40A. The new arrays of sensors will be amplified by Texas Instruments THS4131 differential input/output amplifiers, and 288 new 16 bit D-TacQ 500kSPS digitizers have been configured to sample the

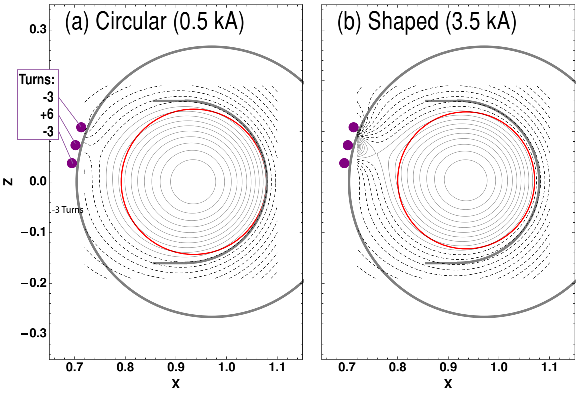


Figure 2. Example HBT-EP equilibria produced with (a) low current (0.5 kA) and (b) high current (3.5 kA) in the zero-net-turns shaping coils in a 15 kA discharges at 0.35 T. The red circle defines the position of a circular closed flux surface defined by the HBT-EP limiter system. The shaping coils will link the TF coils and be mounted in the gap between the coil casings and the vacuum chamber. The 12 turn, counter wound coil has a total inductance of 65 μH and requires a relatively low energy 500 J capacitive storage bank to energize case (b). Dimensions in MKS

raw sensor data.

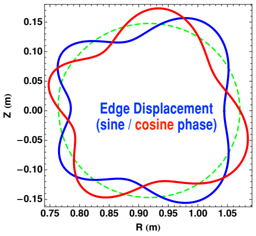
3. Future research plans

We plan to use this new, fully-instrumented control shell to conduct investigations of multi-mode control by measuring the dominant non-axisymmteric magnetic structure of the plasma torus under a variety of natural and driven conditions including the investigation of the FRWM. These measurements will be compared with VALEN calculations and develop the basic scientific understanding in four areas: (i) control coil geometry and mode rigidity during feedback, (ii) advanced feedback digital control algorithms, (iii) multi-mode plasma response and control in a wide range of configurations that include rapidly rotating and shaped discharges, and (iv) multi-mode feedback control in a variety of wall conditions. The results from this research will not only advance our basic understanding of the three-dimensional boundary of toroidal plasmas but it will also aid the design and experimental plans for control coil operation and feedback experiments currently being discussed for implementation on ITER and needed for the design of future fusion experiments. We next briefly describe the effects of plasma shaping and applied 3D magnetic fields on MHD mode stability as well as options for incorporating ferritic wall elements on HBT-EP to excite and study the FRWM.

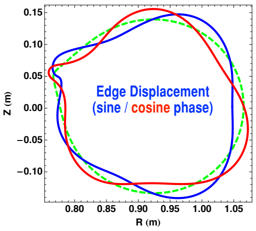
3.1. Shaped-diverted plasma effects on multimode control

The new shaping coils on HBT-EP, depicted in Fig. 2, are designed to modify only the outer boundary of HBT-EP discharges that produce significant changes to the MHD kink response, while still remaining completely compatible with existing diagnostics, wall geometry, and magnetic control systems. Additionally, by shaping only the outermost plasma edge, we are better able to make comparisons between shaped and

(a) Circular (0.5 kA Shaping Coils)



(b) Shaped (3.5 kA Shaping Coils)



(c) Variation of perturbed MHD energy as a function of β_N for constant current (15 kA) HBT-EP discharges

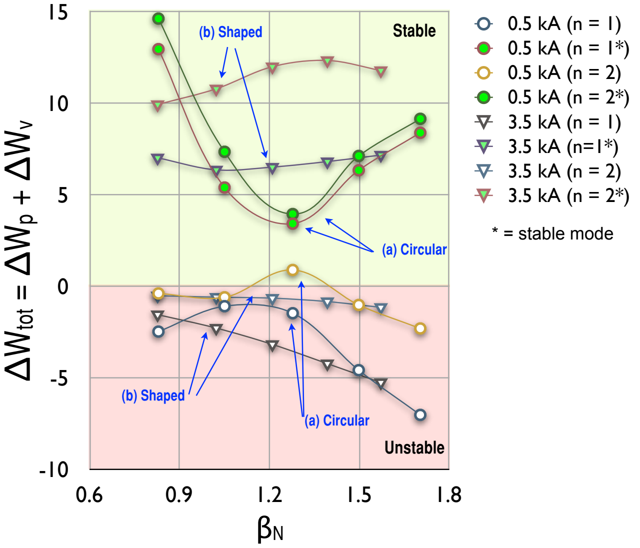


Figure 3. Ideal, no-wall kink stability of low l_i equilibria with low (0.5 kA) and high (3.5 kA) current in the HBT-EP shaping coils. These equilibria have 15 kA of plasma current with broad current profiles characteristic of the HBT-EP fast plasma current ramps. For these equilibria, the central pressure increased and DCON was used to calculate both the unstable and most marginal $n = 1$ and $n = 2$ modes. Increasing β_N, for fixed plasma current, increases the edge safety factor from 2.83 to 3.24. For circular cross-sections, the dominant mode is strongly linked to the edge safety factor as shown in (c), and this causes a strong multi-mode response to occur when $\Delta W_{tot} \approx 0$ for multiple modes and as q_a exceeds three ($\beta_N > 1.2$). The multi-mode response of shaped discharges increases with β_N without resonant helicity effects.

un-shaped discharges and to interface with existing modeling codes and theory. The coil turns will be placed in the region between the TF coils and vacuum vessel above the midplane on the HFS of the vacuum chamber. The coils have small mutual coupling with the present VF and OH coils, and the overall change in the vertical field decay index is small, maintaining radial and vertical discharge ($n = 0$) stability. Fig. 3 illustrates the multi-mode variations possible with the plasma shaping coils on HBT-EP. In these calculations, the plasma current was fixed at 15 kA, and the plasma pressure increased to see the variation of both the unstable and stable eigen-modes for $n = 1$ and $n = 2$. Multimode effects are always present in these low l_i current profiles because both the $n = 1$ and $n = 2$ modes that resonate with the edge helicity ($q_a \approx 3$) are unstable. A multimode plasma response can occur when two or more toroidal modes are simultaneously unstable, or when the magnitudes of the perturbed MHD energies become comparable. For discharges with circular cross-sections, the multimode response becomes very strong at the cross-over between two competing helicities. In figure 3, for $\beta_N < 1$, the dominant helicity is $(m, n) = (3, 1)$. When $\beta_N > 1$, the dominant helicity is $(m, n) = (4, 1)$. The cross-over region, when $\beta_N \sim 1$, becomes a strong region for multi-mode, multiple-helicity dynamics for both $n = 1$ and $n = 2$ modes. In contrast, shaped discharges having a poloidal field null, do

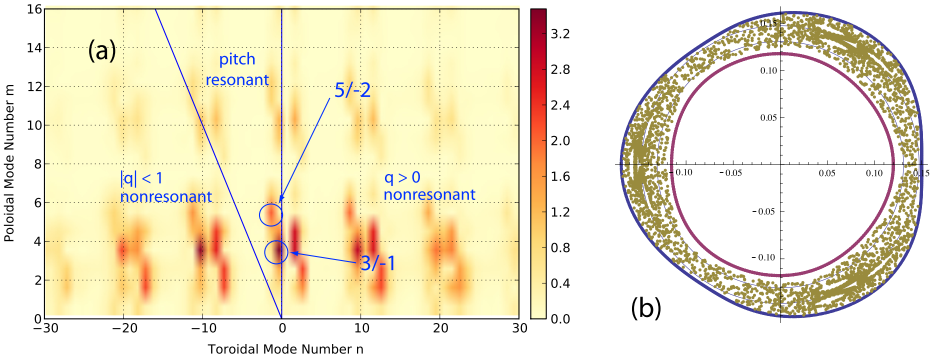


Figure 4. (a) Fourier spectrum showing the resonant and non-resonant components of the applied coil spectrum for the set of 40, 10° wide control coils with currents set to maximize the resonant $(m, n) = (3, -1)$ and $(5, -2)$ components of the magnetic field. Equilibria for this computational study have a helicity opposite to the case used in Fig. 3 (b) Poloidal cross-section of a 0.15 meter HBT-EP plasma showing a Poincare surface of section exhibiting field line chaos caused by the the interaction of these two perturbations in the plasma edge region.

not see a strong edge helicity resonance. In shaped discharges, multi-mode behavior occurs at higher $\beta_N \sim 1.5$, where the magnitudes of the stable and unstable perturbed energies become comparable.

3.2. Stochastic edge fields and their effect on multimode control

The newly installed control shell in HBT-EP, in addition to allowing the study of external kink dynamics under a variety of both active kink mode feedback control and open-loop MHD spectroscopy conditions, will also be able to apply radial fields roughly an order of magnitude larger than our previous control system. These field levels are large enough to enable the study of plasma response effects associated with tearing modes and the onset of island overlap and magnetic chaos in the edge of HBT-EP plasmas. Plasma response effects while applying fields able to create vacuum island overlap conditions are a topic of intense interest given the possibilities of their use for edge localized mode (ELM) mitigation [13, 14].

These physics issues are also closely connected to the penetration of error fields and braking of plasma rotation via resonant and non-resonant magnetic perturbations [15, 16]. The physics objective of these experiments is not to study ELM mitigation or induced stochastic field transport effects of these resonant magnetic perturbations (RMP) fields, rather, we want to study the basic MHD fluid responses of the plasma [17, 18] while applying various types of rotating and non-rotating RMPs to HBT-EP using our new flexible control coil sets. These additional control coil currents can simply be programmed into our flexible digital field programmable gate array (FPGA) controllers [Hanson RSI 2010] and will allow the study of the application of RMP fields alone or the simultaneous application of kink mode feedback control fields with additional RMPs used to create island overlap or other multimode, multiple helicity effects. Fig. 4 shows calculations of the radial magnetic field on the plasma surface along with the m and n number spectrum of the applied field. In the case shown the

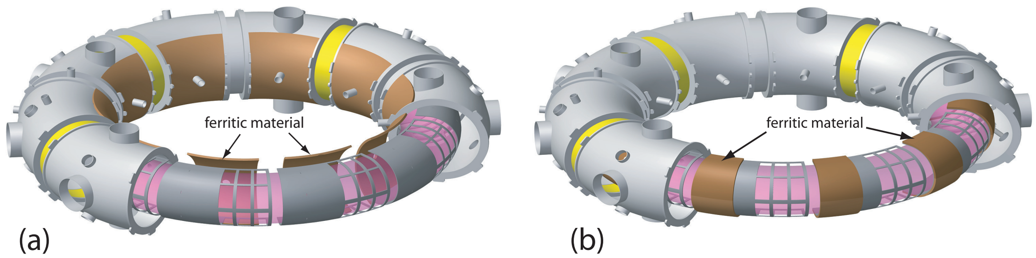


Figure 5. Two options proposed for the HBT-EP ferritic wall. The in-vessel version (b) will mount directly to the non-plasma facing low field side of the newly installed control shell. The exterior to the vacuum vessel configuration (a) would be mounted just outside of the vacuum chamber on the high field side of the machine. Placement of ferritic material is shown in brown.

dominant $(m, n) = (3, -1)$ and $(m, n) = (5, -2)$ components of the applied field are large enough to induce edge island overlap and magnetic chaos in the edge of HBT-EP. Detection of changes in MHD activity and plasma response will be performed with the high resolution toroidal and poloidal arrays which couple weakly to the control fields (see Fig. 1), and multiple tipped probes in the edge to measure plasma gradient changes.

3.3. FRWM and ferritic wall effects on multimode control

A DT fusion power plant will have a high fluence of energetic neutrons. It is important to identify suitable materials that have low activation and are resilient to radiation damage in this environment. Ferritic steel alloys are currently under consideration. Unlike the low magnetic permeability stainless steel alloys (e.g. 316L where $\mu \sim 1.003\mu_0$) routinely employed in present day toroidal fusion energy experiments, these candidate ferritic steel alloys have significant ferromagnetic properties ($\mu \sim 2\mu_0$ to $10\mu_0$) even though the strong toroidal magnetic fields ($\sim 5T$) in a fusion power plant would drive the ferritic steel structural material into magnetic saturation. In addition to the introduction of 3D magnetic field errors onto the plasma equilibrium, the residual ferromagnetism attracts magnetic flux perturbations associated with long wavelength MHD modes and provides an additional ferritic destabilization of the beta driven resistive wall kink mode, the FRWM. The destabilization of the FRWM has been modeled in tokamak geometry by Kurita [19, 20] using the AEOLUS-FT code for a basic aspect ratio $A = 3$ circular tokamak with a resistive/ferritic wall at $r = 1.2a$, where a is the plasma radius and the wall thickness $0.05a$. These indicate that for a range of modest values of μ in the $\mu \sim 1$ to 5 range showed a reduced normalized beta stability limit of 92% at $\mu = 2\mu_0$ and 80% at $\mu = 5\mu_0$.

Ferritic wall effects have been studied in the context of their effects on tearing modes [21], H-mode performance [22], and fast particle confinement [23]. Ferritic wall destabilization effects have not yet been observed experimentally in toroidal confinement geometry for the external kink mode, but were observed in a linear line-tied pinch device [24]. While this line-tied pinch experiment reported qualitative agreement with the prediction of ferromagnetic destabilization of the RWM observed in their experiment, the observed growth rate of the FRWM was much faster than theory would predict. The experiment also used Mu-metal wall with a very large

$\mu \sim 1200\mu_0$. Given the importance of developing the technology of low activation damage resistant structural materials for future DT fusion power systems (FNSF and DEMO), further study is needed to establish a quantitative understanding of these destabilizing ferritic steel effects on long wavelength MHD in a wall stabilized tokamak configuration where active feedback control is applied to stabilize the RWM. To this end we are analyzing two possible ferritic insert configurations on HBT-EP that are compatible with the geometric constraints of our vacuum chamber and new control shell. These options are depicted in Fig. 5 and will allow the first systematic study of the FRWM in a wall stabilized tokamak configuration.

4. Conclusions

The HBT-EP tokamak has been redesigned with a new segmented wall with new control and sensor coil systems to address passive and active stabilization of multimode MHD physics issues including the study of nonrigid kink mode feedback, the effects of plasma shaping on multimode MHD plasma response, the effects of 3D magnetic fields on MHD behavior, and is planning on the implementation of the ferritic inserts to study the FRWM for the first time in toroidal geometry.

Acknowledgments

The authors gratefully acknowledge the technical support of J. Andrello and N. Rivera during the course of this work. The authors also gratefully acknowledge the metrology support provided by S. Raftopoulos and the Princeton Plasma Physics Laboratory Metrology Group during the construction and installation of the new HBT-EP control shell. This work was supported by the U.S. Department of Energy Grant No. DE-FG02-86ER53222.

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