PPPL-3249 - Preprint: May 1997, UC-420,421,422,426,427

WORKSHOP ON FEEDBACK STABILIZATION OF MHD INSTABILITIES

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ABSTRACT

The feedback stabilization of MHD instabilities is an area of research that is critical for improving the performance and economic attractiveness of magnetic confinement devices. A Workshop dedicated to feedback stabilization of MHD instabilities was held from December 11-13, 1996 at the Princeton Plasma Physics Laboratory, Princeton NJ, USA. The resulting presentations, conclusions, and recommendations are summarized.

1. INTRODUCTION

A workshop on feedback stabilization of MHD instabilities was held from December 11-13, 1996 at the Princeton Plasma Physics Laboratory, Princeton, NJ, USA. The feedback stabilization of MHD instabilities is an area of research that is critical for improving the performance and economic attractiveness of magnetic confinement devices. The scope of the workshop included active and passive control of MHD modes, such as kinks and tearing modes or tilting modes, and the feedback control of plasma profiles in order to prevent the onset of instabilities.

Feedback control has a long history within the fusion program. In some respects, it has been very successful—active feedback control of the vertical position (an unstable n=0 MHD mode) is routinely employed on major tokamaks throughout the world. In other respects, this effort has been less successful—promising results in the feedback control of $n \neq 0$ MHD modes in several early experiments has not resulted in a substantial program for controlling MHD instabilities, or enhancing β-limits on today's large experimental facilities. The participants in the Workshop, representing a broad spectrum of interests from 19 US and 6 international institutions, were eager to revisit this research area, and to establish an active program of feedback control as a means of improving the performance of fusion-relevant confinement devices.

In evaluating the need for an expanded effort in feedback control of plasma instabilities, it should be asked "is the absence of feedback control an important limiting factor in today's experiments?" In the best studied magnetic confinement devices, tokamaks, it is well established that β-limits and disruptions are caused by low-n MHD modes, and high-n ballooning modes coupled to low n modes. Feedback control of these modes might provide a means of avoiding disruptions, a major limitation in today's large tokamaks, a serious concern in the design of the next-generation tokamaks aimed at achieving ignition, and a potential show-stopper in a reactor. Feedback control of low-n MHD modes might also allow an increase in the plasma pressure that can be achieved routinely, and increase the time interval over which high pressures can be maintained in today's experiments. Any increase in tokamak β-limits would both increase our confidence in achieving ignition in the next generation of tokamak experiments and improve the projected performance of a fusion power reactor. Hence, disruptions and β-limits are two key areas in which today's tokamak experimental program might benefit from a feedback control initiative. Other magnetic confinement schemes might also benefit from a feedback control initiative. The performance of Reversed Field Pinches (RFPs), for example, might be improved through the control of tearing modes—thereby both reducing the consumption of poloidal flux and possibly improving the energy confinement. In Spheromak experiments, active control of the shift mode would allow operation beyond the L/R time of the flux conserver, and in Stellerators, active control might provide a useful and interesting tool for challenging stability limits.

Given the merits of pursuing feedback stabilization research, it is useful to define the objectives for a feedback stabilization initiative. We suggest that an appropriate goal would be to demonstrate, on the present generation of experiments, that feedback control of $n \neq 0$ modes can substantially improve their performance, and develop the tools required to design reliable feedback control systems that might be employed on next-generation devices.

The achievement of these goals requires an understanding of the instabilities which limit the performance of present day experiments, the development of effective means for identifying and characterizing such instabilities in real time on experiments, development of practical means of acting on these instabilities with external systems, and development of control algorithms which actuate these external systems to control important instabilities. These issues were addressed at the Workshop on Feedback Stabilization of MHD Instabilities in 39 talks and panel discussions, the highlights of which are reviewed below.

2. THEORY OF GLOBAL INSTABILITIES

The role of external kinks on β-limits and the implications for their stabilization was reviewed by J. Manickam [1]. It was noted that the dependence of the ideal kink on the strength of poloidal mode coupling is determined by the details of the pressure and q-profiles. Improvements in the β-limits can occur from wall stabilization, particularly for reversed shear experiments. However, if the profiles are not chosen properly, higher-n modes and the infernal kink modes can work to reduce β-limits. The role of the resistive mode in setting β-limits was discussed, and ideal stability limits for ITER advanced mode operation were given. A review of the available work suggests positive opportunities for feedback stabilization albeit with some limitations.

The feedback stabilization of the resistive shell mode was discussed by R. Fitzpatrick [2]. It was suggested that feedback stabilization of the resistive shell mode in tokamaks can be achieved at modest power levels using a relatively small number of feedback coils and power amplifiers. However, the feedback stabilization of the resistive shell mode is likely to be more difficult to achieve in RFP's, and possibly spheromaks, because in these devices, the critical radius r_c of the external shell typically lies relatively close to the edge of the plasma, and there is generally more than one unstable mode.

Feedback stabilization issues in the Reversed Field Pinch (RFP) were reviewed by D. Schnack [3]. A comparison of RFP and tokamak q-profiles and linear stability issues was given. The nonlinear dynamics of the RFP dynamo and the implications for control were outlined, and the effects of resistive wall modes on dynamo behavior, external modes, increased loop voltage, and termination were discussed. It was proposed that passive feedback in the presence of a resistive wall may improve performance to near conducting wall levels, and active feedback may yield a performance improvement beyond that of conducting walls.

M. Rosenbluth [4] discussed work by F. Perkins [5] and R. Harvey [6] (ray tracing) on neoclassical tearing modes in ITER and the possibilities for stabilization using Electron Cyclotron Current Drive (ECCD). In ITER, the dominant expected instability is a tearing mode driven by neoclassical effects resulting in slowly growing islands (20 sec). A directed ECCD wave with a deposition width of about 15 cm could be used to drive co-current within 10 cm of an island O-point to provide mode stabilization. Results were presented for "G", the relative effectiveness of current drive in the vicinity of the O-point relative to depositing all the current at an island O-point. A value of G=0.37 was obtained indicating a reasonable response with the available localization. Modulation and an optimized launcher design could improve coupling efficiency and reduce power requirements.

Work on the correlation between observations of resistive wall modes in PBX-M and the predictions of the NOVA-W code was presented by N. Pomphrey [7]. The NOVA-W code accurately models the geometry and conductivity of the poloidally segmented passive plates in PBX-M. Plasma rotation is treated as rigid body rotation and simulated by rotating the conducting shell. The plasma rotation velocity is treated as a variable input parameter. A comparison was made between NOVA-W growth rates and real frequencies, and the experimental results obtained from eddy current measurements taken during two major disruption events. It was concluded that resistive wall mode theory predicts a rich dependence on equilibrium profile variation (p, q, Ω) in the transition regions $r_W \approx r_\Omega$ and $r_W \approx r_{crit}$, and that PBX-M observations of eddy current disruption precursors for strongly coupled bean configurations are consistent with the theory of resistive wall mode suppression by plasma rotation.

S. Jardin [8] and J. Schmidt [9] proposed feedback stabilization of n=0 modes using driven halo currents. Noting that currents in the plasma halo have been observed to provide stabilization of the vertical n=0 mode during VDE disruptions where the halo slows the plasma motion, they added feedback-driven voltages to drive halo currents in a TSC study of the effectiveness of this technique. The results indicated a very weak dependence on halo width and vacuum region resistivity (in the range from 0.1 eV to 5 eV). Larger gain parameters and hotter and wider halo regions were always more effective. When the halo region is small, hotter vacuum regions perform more effectively than colder ones.

Experimental data on Lower Hybrid Current Drive (LHCD) localization through synergistic interaction with Ion Bernstein Waves (IBW), and the results of theoretical modeling this effect, were reviewed by F. Paoletti [10]. The theoretical investigations included the use of a toroidal 3-D ray-tracing with a 2-D Fokker-Planck numerical code. The results indicate that due to the IBW $n_{//}(x)$ oscillatory behavior, the IBW power is deposited in limited regions of space. When the IBW power is damped on a pre-existing electron tail (generated through LHCD), it generates localized current channels. In the case presented, the location of the first IBW $n_{//}(x)$ maximum is consistent with the radial position of the region where the highest distortion is observed with the PBX-M Hard X-Ray (HXR) camera.

The physics of neoclassical MHD tearing modes and possible stabilization techniques were reviewed by C. Hegna [11]. Neoclassical MHD tearing modes are observed in a number of tokamak experiments, in particular, at low collisionality, long pulse, and high β_p. A number of issues remain, for example, the nature and scaling of the threshold, and "seed" island physics. Neoclassical predictions for parallel Ohm's law seem to describe accurately both equilibrium current profiles and the evolution properties of resistive instabilities. It was proposed that feedback using modest amounts of localized current drive could completely stabilize MHD tearing modes, since even small amounts of localized currents can raise the nonlinear threshold width of the mode.

The feedback issues in Spheromaks were discussed by E. B. Hooper [12] Feedback control of MHD modes may be essential for sustained Spheromak physics experiments. The feedback stabilization of the tilt/shift modes is likely to be necessary, and n> 1 resistive wall mode stabilization may also be needed. Current profile control may be possible using feedback control to limit transport and improve β-limits. Although experiments on a tokamak cannot be applied directly to the Spheromak, the analysis and modeling methods, experience and hardware developed on a tokamak facility dedicated to the investigation of multimode feedback stabilization could provide a basis for Spheromak (and RFP) applications [12].

The history of pondermotive feedback stabilization of external kinks and resistive wall modes in tokamaks was reviewed by D. D'Ippolito [13]. Initial experimental and theoretical results are encouraging. The critical issues for large, high-magnetic field tokamaks is the strength of coupling to various edge modes. In particular, they concern the required overlap between the mode and the antenna, the effect of the scrape-off layer (SOL) resisitivity on coupling efficiency, and whether or not sufficient force for mode suppression can be applied without unacceptable edge perturbations. Varying the antenna modulation frequency across the MHD range and detecting MHD mode resonances ("MHD Spectroscopy") would give valuable information on the coupling strength. An experimental test of pondermotive feedback stabilization in a PBX-M sized machine is needed to motivate and guide further theoretical work, and the existence of an IBW system on that device would enable this to be done rapidly and economically.

The stabilization of external kink modes by driving scrape-off layer (SOL) currents was discussed by J. Kesner [14]. Experimental and theoretical evidence for the stabilizing effects of negative edge currents was noted. Large negative currents can be made to flow in the SOL in diverted tokamaks from electron emitting end plates. The I-V characteristic could be used to control the current without additional biasing.

A. Boozer [15] discussed the implications of inductance, wall modes, and singular surfaces for tokamak toroidal geometries. Torque is a quadratic function of κ given by the anti-Hermitian part of the inductance. If torque causes a wall mode to rotate relative to the wall faster than the mode growth rate, the wall mode is stabilized. If the plasma were ideal, the inductance would be Hermitian. Hermitian inductance operators can be calculated using 3-D equilibrium codes. In addition, Faraday's Law implies that Hermitian resistance operators can be calculated which are positive and definite. These inductance and resistance Hermitian operators can be used in a feedback equation to choose the optimum geometry for wall stabilization. In conclusion, it was noted that robustly ideal modes (*i.e.*, no surface current on singular surfaces) are far more dangerous than ordinary ideal modes (*i.e.*, surface current on singular surfaces), and can be studied using 3-D equilibrium codes.

M. Chance [16] presented a two-dimensional feedback calculation using the PEST-VACUUM code. The objective was to understand the mode coupling effects in a feedback system on realistic tokamak plasma configurations. Initial results from this work in progress were reported for the case of an ideally conducting shell around a weakly unstable plasma, such as, for example, a plasma evolving across the stability threshold on the equilibrium time scale. It was found that mode coupling due to shaping and other factors could complicate an efficient feedback system by driving extraneous modes. 2-D analysis is complicated and care must be taken to ensure that the self-adjointness of the PEST-VACUUM formalism is not compromised. A resistive shell version will be developed to include a second shell with a feedback system.

3. EXPERIMENTAL DATABASE

A cross-device experimental database of the underlaying physics, behavior, issues, implications, and technology of active multimode stabilization in various confinement geometries has been developing. Experiments have been performed on a wide variety of instabilities: resistive wall modes arising from finite conductivity shells in RFPs and in tokamaks, n=0 vertical instabilities in shaped tokamaks which come from operating at or beyond the critical field index, internal tearing modes including q=1 sawteeth and q > 1 rotating tearing modes, and dynamo modes in the RFP which maintain the current profile but induce transport loss. The experiments can be grouped into two classes, those that use closed loop feedback for suppression or control of the instability and those that are open loop in which a proactive action is taken.

A. CLOSED LOOP FEEDBACK EXPERIMENTS

A great success in tokamaks is the feedback control of n=0, vertical instability in elongated plasmas. This is now well understood and routinely used for PBX-M [17] and DIII-D [19]. While resistive wall modes appear in both the RFP and the tokamak and intelligent shells have been proposed and discussed for many years, the only successful attempt was the active stabilization of the external m/n=1/2 mode on the HBTX-1C device [20]. While that single mode was suppressed, other internal modes continued to grow, indicating the need for separate windings for each mode or a true smart shell. Successful experiments on active feedback stabilization of rotating 2/1 tearing modes by applied ac fields with phase control are progressing on JET [31] and

HBT-EP [21,22]. Thus there has already been some success on feedback control of instabilities involving shape, resistive walls, and tearing.

B. OPEN LOOP EXPERIMENTS

A number of devices have shown that adding passive conducting stabilizers suppresses instability, or slows it down, allowing active control to be possible. The addition of a distant "overcoat" shell in HBTX-1C [20] slowed both external and internal mode growth rates; conducting shell/stabilizing plates in PBX-M turned external kinks into resistive wall modes [17,18], and HBT-EP showed how moving the shell closer to the plasma surface stabilizes or at least obviates external kinks and resistive shell modes [21,22]. Current profile modification with lower hybrid current drive (LHCD) on PBX-M [23] was used to suppress sawteeth by keeping q(o) > 1, and for TORE SUPRA it was reported that LHCD is effective for current profile control/modification [24]. The application of a voltage to an edge electrode in the CCT tokamak [25] produced a poloidal torque whose resulting poloidal rotation suppressed 2/1 tearing modes at low edge q just above 2. The RFX has obtained extensive data on locked modes, field errors, and the effects of edge conditions [26,27]. Locked mode correlations with toroidal field distortion, spatial distribution, time evolution, stationary average spectrum, and induced field errors have been studied, as has locked mode sensitivity to edge conditions, matched and asymmetric reversals of the toroidal field, and short-circuiting of a poloidal and a equatorial gap. Finally, the application of a ramped toroidal field in the MST RFP induced a poloidal electric field, and the resulting current transiently kept the plasma closer to the minimum energy Taylor state, thus reducing the dynamo turbulence and greatly improving confinement [28,29]. Hence the open loop techniques cover a wide and diverse set of tools, including passive stabilizers, current profile modification, and rotation drive by electrodes.

4. EXTERNAL CONTROL SYSTEMS

Of the 39 talks and panel discussions presented at this Workshop, about 20 talks discussed specific external control systems for MHD stabilization. About half of the control talks described active magnetic coil systems; the other half described control systems using RF power deposition, neutral beam momentum injection, edge current control, and inductive poloidal current drive. The external control systems discussed were either actual functioning systems used in the reported work, or were systems proposed as part of promising techniques for future work. These external control systems, both actual and proposed, for either open- or closed- loop experiments, involved one or more of the following methods: Active Magnetic Coil Systems, Passive Coil Active Control, Lower Hybrid Current Drive (LHCD), Electron Cyclotron Current Drive (ECCD), Mode-Conversion Current Drive (MCCD), directly-launched Ion Bernstein Wave (IBW) Ponderomotive Force, Neutral Beam Modulation, Edge Current Modulation, Inductive Poloidal Current Drive, and various synergetic combinations of these techniques.

A. ACTIVE COILS

The Culham HBTX1C RFP used active feedback coils to suppress the m=1, n=2 mode external mode. Little effect was seen on the m=1 internal modes. Sine and cosine m=1, n=2 coils were used with GTO gated thyristor technology, providing ±200V, ±500A which was triggered either "On" or "Off" by magnetic sensor thresholds [20].

A many-coil autonomous system for resistive wall feedback stabilization was proposed by T. Jensen [30]. Sensors would detect induced changes in the perpendicular field, and appropriate coils would be driven to oppose the sensed perpendicular field. Increasing the number of coils could significantly reduce the power supply requirements.

The JET feedback stabilization experiments utilized input signals from four magnetic pickup coils and two Rogowski coils, which are processed by a digital computer, and used to drive two fast high power amplifiers, each connected to a pair of saddle coils placed in the bottom of the vessel [31]. The digital computer subtracts the feedthrough compensation from the detected signals and generates two reference signals with specified amplitude and phase in respect to perturbations. Experiments demonstrated strong dependency of the feedthrough on the plasma parameters. Strategy and technology of the feedback experiments in a large tokamak were tested, but more extensive experiments are required on a dedicated facility.

Active feedback experiments in HBT-EP demonstrated mode rotation control with several configurations of modular saddle coils [21,22]. A 9-turn saddle coil pair is mounted outside the chamber at 5 locations. Each coil set is highly localized, spanning about a 6^0 toroidal angle. The winding configuration is m=2, n=1. Single phase (series) and two-phase (quadrature) windings are configured. The coils are driven by LANL power supplies capable of $\pm$600 A at $\geq$30 KHz.

A feedback system which mimics the effect of a close fitting ideal wall for stabilization of resistive wall modes was proposed by R. Fitzpatrick [2]. This would be accomplished with a fake rotating shell consisting of a fine network of low resistance coils. Each network cell has an associated sensor loop which detects the local rate at which magnetic flux leaks through the network. The signals from the sensor loops are processed and used to control power amplifiers. The feedback causes the resistive shell mode to rotate in the direction of apparent rotation of the fake shell, and also modifies the growth rate of the mode. The large number of coils reduces the gain, bandwidth, current, and total power requirements of the system.

A rotating magnetic perturbation was used in the MST RFP for investigating the control of mode and plasma rotation [29]. Rotating n=6 and n=1 radial magnetic field perturbations have been applied through the toroidal gap in the conductive shell of MST. Initial low power experiments provide a perturbation of a few gauss at the plasma edge at fixed frequencies of 11 and 23 KHz, and indicate that a slight acceleration or deceleration can be applied to the natural 10 to 15 KHz rotation of the n=6, m=1 global tearing mode. The addition of variable frequency control, additional perturbations (n=7,8), and higher powers are planned for experiments to increase the size of the perturbation, and cause the tearing mode to rotate at a fixed frequency and resist locking.

A perturbation coil was used in TEXT to generate a mixed mode perturbation for studies of external field interactions with rotating MHD and feedback issues [32]. A maximum perturbation of 0.01% in the m=2, n=1 mode at the q=2 surface was obtained.

B. PASSIVE COIL ACTIVE CONTROL

The sensing of eddy current flows through the PBX-M Passive Plate structure was used to detect and successfully control an active coil to suppress the n=0 vertical position instability. This experiment, using the passive shell current, is an n=0 mode version of an n=1 "smart shell" resistive wall mode stabilization. This experiment served as a "proof of principle experiment" for the next step. The results were presented by M. Okabayashi [17].

C. LOWER HYBRID CURRENT DRIVE

Lower Hybrid Current Drive (LHCD) for MHD feedback stabilization was discussed by S. Bernabei [23]. The LHCD stabilization of m=1 modes and suppression of sawteeth, achieved in various experiments by current profile broadening and q_o >1, were reviewed. Extending these techniques to the suppression of the m=2 mode, by driving current at the O-point to replace the inductive current, was proposed for investigation on a possible dedicated Feedback Stabilization Experiment (FSX). The physics issues involve determining and achieving the appropriate radial localization, and controlling the optimum amount of additional current drive to provide suppression without shifting the q=2 surface outward. This requires an optimized coupler design that differs from one designed for pure current drive. A similar application on ITER would be facilitated by the larger size and higher electron temperature.

Experimental results from PBX-M on the control of LHCD localization through synergistic interaction with IBW indicate a strong confirmation of the synergy between LHCD and IBW [10]. Theoretical investigations indicate that the oscillatory behavior of the IBW electric field results in power deposition in limited regions of space, and when IBW power is damped on a pre-existing electron tail generated by LHCD, it generates controllable localized current channels.

D. ELECTRON CYCLOTRON CURRENT DRIVE

Fast Wave Current Drive (FWCD) and Electron Cyclotron Current Dive (ECCD) were discussed by R. Pinsker [19] in the context of the tools and techniques for avoiding MHD instabilities in DIII-D. With the near-term commissioning of a 3 MW ECH system on DIII-D, a series of j-profile control experiments to avoid MHD instabilities are planned in which 3 MW of FWCD is to be used to control the central current, and ECCD used to drive off-axis currents. Of particular interest is the use of these systems to stabilize neoclassical tearing modes, and upgrading to higher powers for experiments in high performance regimes.

E. Lazzaro [31] proposed using ECCD for RF power deposition within an island to provide stabilizing action through restoring the inner power balance by replacing radiation losses, and driving sufficient local current of suitable sign to compensate for the mode induced plasma current perturbation.

M. Rosenbluth [14] discussed neoclassical tearing mode stabilization in ITER with ECCD. In ITER about 8 MW is needed if phase modulated and aimed over a 10 cm wide deposition region, or 20 MW if applied asymmetrically. Improvements of about a factor of 2 may be achievable by optimizing the launcher.

E. MODE CONVERSION CURRENT DRIVE

The use of external control systems, based on Mode-Converted IBW alone or in combination with LHCD, was discussed by R. Majeski [33] as a powerful tool to induce localized current profile modification and flow-shear generation for MHD stabilization. MHD stabilization based on Mode-Conversion techniques demonstrated on TFTR, C-MOD, and ASDEX were reviewed. As a specific example of the stabilization possibilities for Mode-Conversion control systems, the use of a large area, high field side combline antenna was proposed for a possible dedicated Feedback Stabilization Experiment (FSX). This hardware would allow unique Mode-Conversion electron heating experiments to localize LHCD deposition, Mode-Conversion plus LHCD with modulation to feedback stabilize internal MHD, Mode-Conversion with or without MHD to drive co- or counter-edge currents inside the lasty closed flux surface (LCFS) as opposed to currents outside the LCFS (refer to edge current modulation below), and controlled internal sheared poloidal flows that can be located near rational surfaces.

F. ION BERNSTEIN WAVE PONDERMOTIVE

D. D'Ippolito [13] proposed directl-launched IBW feedback stabilization of external kink and resistive wall modes in tokamaks. The application of the pondermotive force as a nonlinear force exerted on a charged particle or fluid element by a spatially decaying RF electric field was reviewed. RF system requirements for pondermotive feedback stabilization were given, and as an example, specific RF requirements for application on a possible dedicated Feedback Stabilization Experiment (FSX) were presented. Several experimental tests were proposed to explore the critical physics issues (*eg.,* radial overlap, SOL resistivity, edge perturbations) involving the coupling strength of the pondermotive force to various edge modes.

G. NEUTRAL BEAM MODULATION

A novel scheme was proposed by A. Sen [34] for feedback control of major disruptions in tokamaks using a modulated neutral beam suppressor. A neutral beam is controlled in a feedback loop to inject radial momentum with appropriate amplitude and phase to the plasma to suppress MHD modes. Simple theoretical models predict modest levels of radially injected neutral beam energy, current, and power for tokamaks and other toroidal devices, and extrapolation to reactor scales appears to be practical. Specific examples were given for application on TFTR and a possible dedicated Feedback Stabilization Experiment (FSX).

H. EDGE CURRENT CONTROL

Prototypical CCT experiments demonstrating the effectiveness of edge current control for MHD stabilization were discussed [25]. In this work, a probe was used to bias the edge plasma and induce poloidal rotation at the plasma edge. Controlling the position of either the 2/1 or 3/1 surface relative to this rotating layer allowed stabilization of kink-type instabilities.

The stabilization of external kink modes in a diverted tokamaks using scrape-off layer currents was proposed by J. Kesner [14]. Large negative edge currents can be induced to flow in tokamaks from electron emitting end-plates. The I-V characteristic can be used to control the current. Feedback control of this current could be used to stabilize external kink modes. The implications of using thermionic emission as a current source were given, and simulation results were presented for ITER.

Electrostatic current injection was performed on the MST RFP using 16 miniature plasma sources to provide low impurity, high current density injection into the edge plasma [28]. Strong modification of the flow profile is observed with current injection, and work is in progress to use this as a new tool for controlling plasma rotation.

The feedback stabilization of the n=0 mode using driven halo currents was proposed S. Jardin [8] and J. Schmidt [9]. A two-dimensional MHD simulation was used to study the effectiveness of using feedback-driven voltages to drive a force-free current in the plasma halo, to create a field which acts to stabilize the plasma. The results indicate that the method appears to be feasible for a wide range of plasma parameters, and would minimize core interactions with cold structures and thereby reduce recirculating power requirements for high power reactors. A simple scaling relation showed that the maximum poloidal current in the vessel would be $1\text{x}10^4$A for PBX-M and $6\text{x}10^5$A for ITER. The results indicate that the concept appears feasible for a wide range of plasma edge parameters.

I. INDUCTIVE POLOIDAL CURRENT DRIVE

Inductive poloidal current drive (PPCD) for j(r) control was achieved in the MST RFP using a capacitor bank driven poloidal loop [28]. The lowest observed internal tearing mode amplitudes in MST were achieved during PPCD. Sawtoothing was suppressed, and in the best cases, the fluctuation amplitude fell below the between crash level. PPCD was found to increase beta and confinement.

5. CONTROL ALGORITHMS

Although issues involving mode structure identification and phase detection with available sensors, and the possible implications for control methodologies, were noted by many speakers, several papers focused explicitly on feedback stabilization control strategies, methods, and algorithms.

E. Lazzaro [31] reviewed feedback techniques for the control of low order resistive modes, using either electrodynamic compensation of the measured perturbation by means of DC and rotating resonant helical fields, or the local control of the destabilizing current profile by means of RF heating and current drive. Examples from JET were given, various control objectives and strategies were proposed, and the implications for implementation on real systems were discussed.

The DIII-D digital plasma control system, which runs control tasks on multiple parallel processors, was described in a paper by J. Ferron et al. presented by R. Pinsker [19]. Each portion of the calculation is assigned to a separate processor. Real time equilibrium reconstruction provides the basis for accurate discharge shape and profile control. First tests show stabilization by the digital vertical position control of discharges with elongation up to 2.3. Examples were given of control in real time from Motional Stark Effect (MSE) data, the use of loop voltage and β_N control to vary inductive and non-inductive currents, central current density modification by fast waves, the use of preprogrammed L-H transition to control pressure profile shape, and the use of an external coil to provide magnetic braking of plasma rotation.

The fast digital plasma control system and closed-loop techniques for HBT-EP magnetic feedback experiments were described [22]. A digital computer is interfaced with HBT-EP and LANL amplifiers to create a programmable, digital control loop. Initial measurements of the phase instability indicate that the current experimental configuration provides a comfortable margin for feedback control studies on low-m internal modes.

On Tore Supra, feedback has been performed on q_a by adjusting plasma position or current, and on l_i by adjusting the current ramp or Lower Hybrid (LH) power and phase [24]. Future plans include investigations of feedback on LH power and phase for controlling q(0) or q_{min}, feedback on ICRF power, and feedback on the grill-plasma distance for power coupling control.

An overview of problems to be encountered in a comprehensive control system was given by A. Sen [34], who discussed the possibilities of a marriage between control science and plasma physics. The failure of multimode feedback in the past, when the stabilization of one mode destabilized another mode, was attributed to the use of constant gain, frequency independent feedback. A possible approach was discussed in terms of characterizing instabilities as a discrete set of normal modes, and summarizing the system dynamics in terms of the temporal behavior of the amplitudes of these modes. Methods were outlined for deriving and reducing this information for use in fast feedback, mulimode, control loops.

6. SUMMARY AND CONCLUSIONS

The Workshop discussions acknowledged feedback stabilization to be a requirement to sustain high performance in a variety of magnetic configurations: in Tokamaks, external modes due to kink and resistive wall modes and internal modes due to tearing and neoclassical tearing modes, in Spherical Toruses, m=2, edge modes and IRE's (disruptions), in Reversed Field Pinches, from m=1, n=0 to 10 resisitive modes, in Spheromaks, tilt/shift modes and low-n modes, and in Stellerators, β-stability limits. The broad attendance and strong participation in the Workshop demonstrated a clear, strong interest in cross-device feedback issues. It was noted that the work on feedback stabilization, although generally of high quality and highly creative, is "scattered" and weakly connected. No dedicated experiments have been pursued, for example, on large or middle-size tokamaks, although active mode stabilization is required for their performance and safety. A proposal to form a "US National Feedback Stabilization Initiative" hosted by the Princeton Plasma Physics Laboratory was presented by K. McGuire [35] to help stimulate feedback research, enable greater visibility for this research, and provide a focus for researchers to report progress and share ideas. W. Nevins [36], M. Mauel [21], and S. Prager [37] led separate discussions summarizing the state of feedback research and planning future research for this initiative. During these discussions, considerable interest was exhibited in participating in future feedback research. In support of the feedback stabilization initiative, K. McGuire [35] indicated that PPPL was studying the feasibility of converting the PBX-M facility into a national Feedback Stabilization Experiment (FSX) that could provide copious quantities of high temperature, high pressure plasma, for long confinement times, to serve in the near-term as a dedicated user facility, for studying active mode stabilization issues relevant to a variety of confinement geometries. This facility would both contribute new ideas to be tried elsewhere, and provide a proving ground for new ideas developed elsewhere. Also in support of the feedback stabilization initiative, it was suggested that a Topical Group on feedback stabilization be formed as a Subgroup of the US National MHD Working Group. J. Manickam [1] proposed a month long Summer Institute on Feedback issues for experimentalists, theoreticians, and modelers during the summer of 1997 at PPPL. Specific topics will be determined based on the attendees, and may include resistive wall mode calculations, studying rotation, partial walls, and feedback effects, neoclassical tearing mode stabilization including detailed rf-modeling and design, real-time profile analysis and control issues, and special diagnostics for mode structure and phase detection. The Workshop participants concluded that the Workshop was successful, and proposals were put forth to plan for a successor Workshop in 1997. Further information on the work summarized here can be obtained from M. Mauel [21] and K. McGuire [35], and the indicated presenters.

ACKNOWLEDGMENTS

Supported by USDOE Contract No. DE-AC02-76CH03073. We wish to acknowledge the contributions of T. Greenberg, C. Bush, and R. Kaita in the preparation of the Workshop and this Summary.

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