# FIVE YEAR RETROSPECTIVE ON MODE CONTROL: 1997 MHD MODE CONTROL WORKSHOP

Gerald A. Navratil
*Columbia University*

Workshop on Active Control of MHD Instability:
Extension of Performance
Columbia University, New York
18-20 November 2002

# Workshop on Control of MHD Modes in Tokamaks with Non-axisymmetric Coils

23–25 November 1997
Columbia University
New York

Sponsored by: Columbia University
General Atomics
Princeton Plasma Physics Laboratory

# Major Issues Discussed at 1997 Workshop

## Theme: Use of Non-axisymmetric Coils for Mode Control

- RWM on DIII-D: Do we really see it?
  - **Ideal Mode Structure & Slowing Down of Rotation**
- How to formulate active control model of the RWM?
  - **Analogy to n=0 control problem**
  - **Lumped Parameter Circuit Approach**
  - **Bishop “Intelligent” Shell**
- Plans for Implementation/Installation of Control Coils
  - **HBT-EP & DIII-D: How to “optimize”?**
- Tearing Mode Control Experiments
  - **JIPP T-IIU, JET, HBT-EP, plans for FSX and DIII-D**
- Neoclassical Tearing Modes
  - **Observations & Plans for Control (with coils)**

# Workshop on Control of MHD Modes in Tokamaks with Non-axisymmetric Coils

23–25 November 1997
Columbia University

**Sunday, Nov 23 2:00pm-6:00pm Background/General**

Session Chairman: Navratil

| | | |
|---|---|---|
| 2:00-2:10 | Welcome & Introduction to Workshop | Navratil |
| 2:10-2:40 | JET Feedback Program | de Benedetti |
| 2:40-2:50 | Discussion | |
| 2:50-3:20 | The Axisymmetric Control Strategy on DIII-D and Implication for Control of External Kinks | Lazarus |
| 3:20-3:30 | Discussion | |
| 3:30-3:50 | break | |
| 3:50-4:20 | Disruption Control Using Helical Coils and Experimental Planning for LHD | Yamazaki |
| 4:20-4:30 | Discussion | |
| 4:30-5:00 | TEXTOR Dynamic Ergodic Divertor | Finken |
| 5:00-5:10 | Discussion | |
| 5:10-6:00 | General Discussion | |

## Monday, Nov 24 9:00am-12:30pm Tearing Mode Control

Session Chairman: Taylor

| | | |
|---|---|---|
| 9:00-9:30 | Neoclassical Islands | Gates |
| 9:30-9:40 | Discussion | |
| 9:40-10:00 | Tearing Mode Stabilization | Fredrickson |
| 10:00-10:10 | Discussion | |
| 10:10-10:25 | Active Stabilization of Tearing Modes in HBT-EP | Nadle |
| 10:25-10:30 | Discussion | |
| 10:30-10:50 | break | |
| 10:50-11:10 | Use of External Perturbations to Investigate Neoclassical Tearing Modes | Hegna |
| 11:10-11:15 | Discussion | |
| 11:15-11:30 | A Conceptual Inside Vessel Coil for DIII-D | LaHaye |
| 11:30-11:35 | Discussion | |
| 11:35-11:50 | Numerical Optimization of Coil Geometry for Tearing Mode Feedback Stabilization | Woolley |
| 11:50-11:55 | Discussion | |
| 11:55-12:30 | General Discussion | |

| | |
|---|---|
| 12:30-2:00 | Lunch at Monsoon Restaurant (Broadway between 110th - 111th St) |

## Monday, Nov 24 2:00pm-6:00pm RWM Mode Control

Session Chairman: LaHaye

| | | |
|---|---|---|
| 2:00-2:30 | Elaboration on Bishop's Intelligent Shell | Jensen |
| 2:30-2:40 | Discussion | |
| 2:40-3:00 | Lumped-parameter Circuit Approach for RWM Feedback Control Analysis | Okabayashi/Pomphrey |
| 3:00-3:10 | Discussion | |
| 3:10-3:30 | Synthesized Vacuum Calculation in Toroidal Geometry | Chance |
| 3:30-3:40 | Discussion | |
| 3:40-4:00 | break | |
| 4:00-4:15 | RWM Studies on DIII-D | Garofalo |
| 4:15-4:20 | Discussion | |
| 4:20-4:40 | RWM Plans and Prototype Experiments on HBT-EP | Mauel |
| 4:40-4:50 | Discussion | |
| 4:50-5:05 | RWM Stability Issues on DIII-D | Okabayashi |
| 5:05-5:15 | Discussion | |
| 5:15-5:30 | Plans for C-Coil RWM Control on DIII-D | Scoville |
| 5:30-5:35 | Discussion | |
| 5:35-6:00 | General Discussion | |

| | | |
|---|---|---|
| 6:00-6:30 | Tour of HBT-EP Facility (Room 102A Mudd) | Mauel/Navratil |

| | |
|---|---|
| 7:00-9:30 | Workshop Dinner (Columbia University Faculty House) |

**Tuesday, Nov 25 9:00am-12:30pm RWM/Feedback/Ergodization**

Session Chairman: Okabayashi

| | | |
|---|---|---|
| 9:00-9:20 | RWM Control by Toroidal Rotation | Chu |
| 9:20-9:30 | Discussion | |
| 9:30-9:45 | Rotation Control Experiments on HBT-EP | Mauer |
| 9:45-9:50 | Discussion | |
| 9:50-10:05 | RWM Active Control Modeling | Bialek |
| 10:05-10:10 | Discussion | |
| 10:10-10:25 | Plasma Response for RWM Control Modeling | Boozer |
| 10:25-10:30 | Discussion | |
| 10:30-10:50 | break | |
| 10:50-11:10 | External Kink Mode Theory in Toroidal Geometry | Betti |
| 10:10-11:15 | Discussion | |
| 10:15-11:35 | Feedback Control of Plasma Systems | Sen/Chiu |
| 11:35-11:40 | Discussion | |
| 11:40-11:55 | Plasma Helical Coil Approach for Feedback Stabilization | Kugel |
| 11:55-Noon | Discussion | |
| Noon-12:15 | Ergodization Coils for Control of Edge T and $\nabla p$ in DIII-D | Evans/LaHaye |
| 12:15-12:20 | Discussion | |
| 12:20-12:30 | General Discussion | |
| 12:30-2:00 | Lunch at Café St. John (SW corner Amsterdam and 110th St.) | |

**Tuesday, Nov 25 2:00pm-3:00pm Concluding Discussion**

| | |
|---|---|
| 2:00-3:00 | Formulation of Principal Conclusions & Recommendations |

# MAJOR ISSUES DISCUSSED AT 1997 WORKSHOP

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  - **IDEAL MODE STRUCTURE & SLOWING DOWN OF ROTATION**
- HOW TO FORMULATE ACTIVE CONTROL MODEL OF THE RWM?
  - **ANALOGY TO n=0 CONTROL PROBLEM**
  - **LUMPED PARAMETER CIRCUIT APPROACH**
  - **BISHOP “INTELLIGENT” SHELL**
- PLANS FOR IMPLEMENTATION/INSTALLATION OF CONTROL COILS
  - **HBT-EP & DIII-D: HOW TO “OPTIMIZE”?**
- TEARING MODE CONTROL EXPERIMENTS
  - **JIPP T-IIU, JET, HBT-EP, PLANS FOR FSX AND DIII-D**
- NEOCLASSICAL TEARING MODES
  - **OBSERVATIONS & PLANS FOR CONTROL (WITH COILS)**

# Resistive Wall Mode Studies on DIII-D

A. M. Garofalo

Workshop on Control of MHD Modes in Tokamaks with Non-axisymmetric Coils

Columbia University

November 24, 1997

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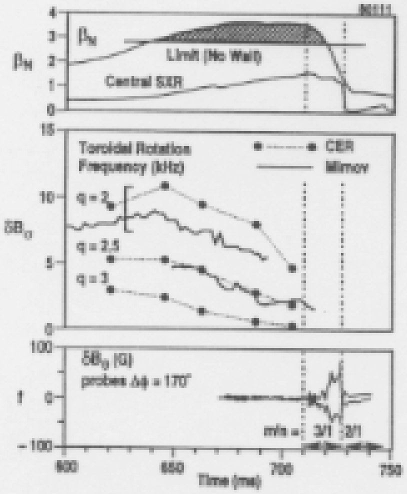
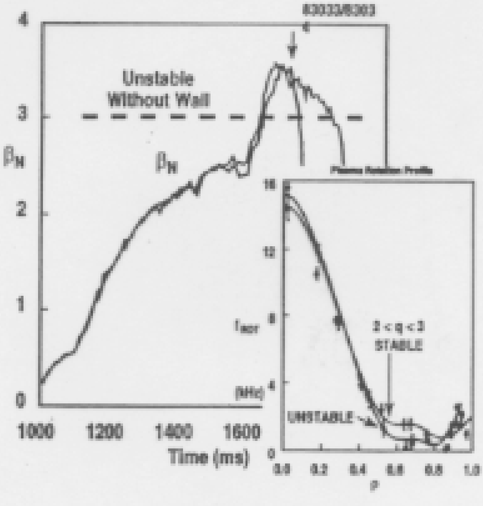
# WALL STABILIZATION OF LOW–n MODES AT HIGH $\beta_N$ IS PRESENTLY LIMITED BY SLOWING OF PLASMA ROTATION

- Wall stabilization maintained in low $\ell_i$ plasmas for ~10 wall times but is lost when rotation is lost

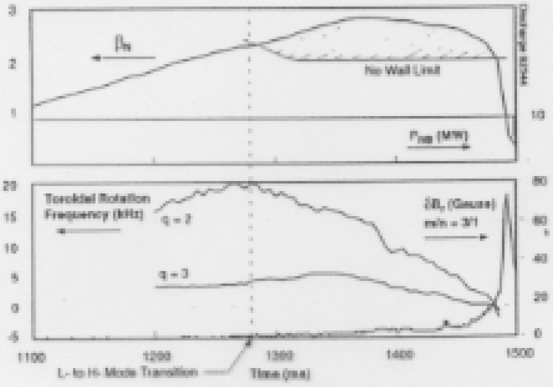


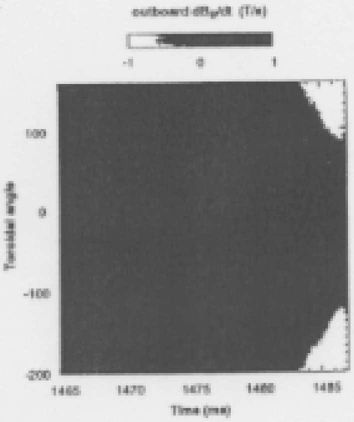
- Braking experiments predict rotation required is modest



# PLASMA STABILIZED BY ROTATION AND RESISTIVE WALL ABOVE NO-WALL $\beta_N$-LIMIT FOR ~ 200 ms

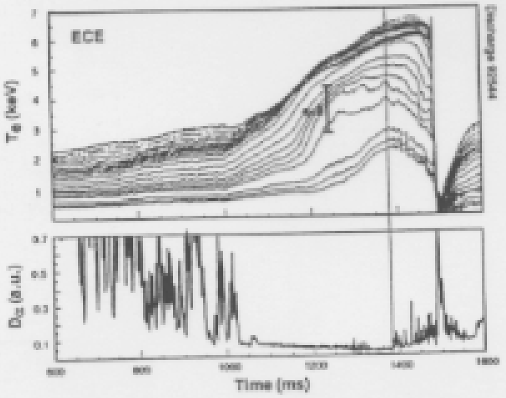
- Slowly rotating $m/n = 3/1$ mode starts to grow after toroidal rotation of $q = 3$ surface has decreased below ~ 1 kHz
- Growth time decreases to 3 ms when mode becomes nearly stationary with respect to the wall
- What causes the plasma rotation to slow down?

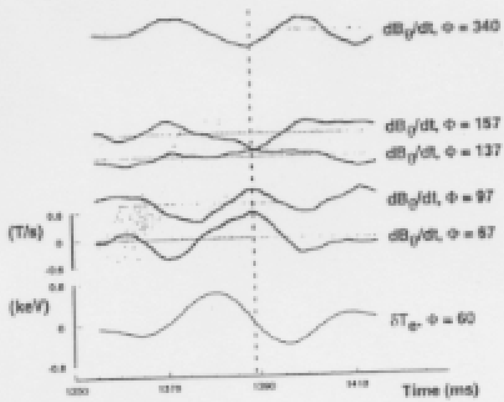




# A LOW FREQUENCY PERTURBATION NEAR $q = 2$ SURFACE COINCIDES WITH CONTRACTION OF CORE TRANSPORT BARRIER AND START OF ELMING PHASE

- No evidence of $\pi$ shift in $T_e$ fluctuation phase between nearby ECE channels
- Toroidal mode number $n = 2$ and real frequency ~ 20 Hz in direction counter to beam injection determined from magnetic data





# MAJOR ISSUES DISCUSSED AT 1997 WORKSHOP

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  - OBSERVATIONS & PLANS FOR CONTROL (WITH COILS)

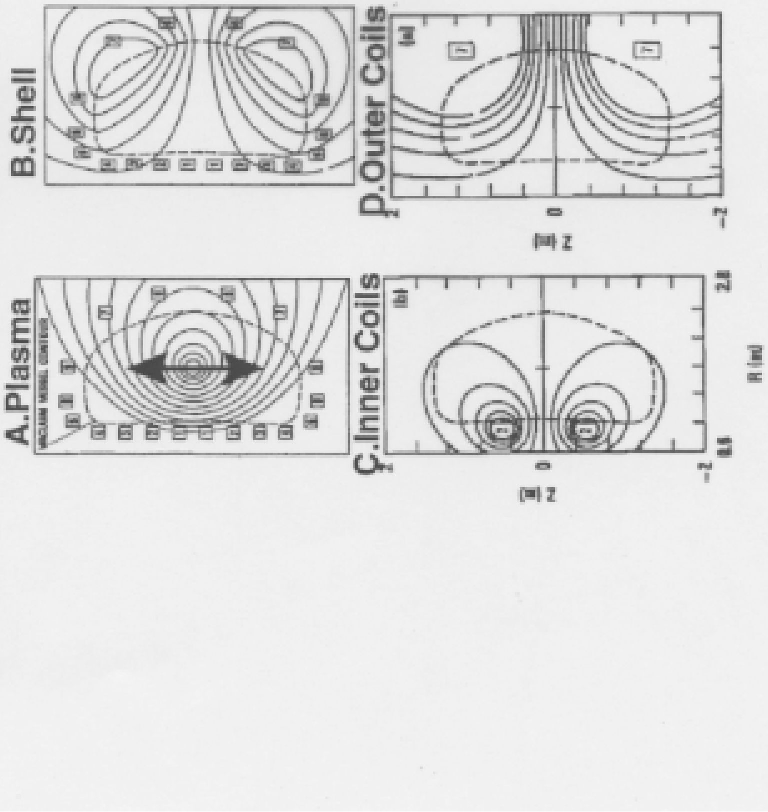
# The Axisymmetric Control Strategy on DIII-D and Its Implication for Control of External Kinks

Edward A. Lazarus
Oak Ridge National Laboratory
presented at
Workshop on Control of MHD Modes in Tokamaks with Non-axisymmetric Coils
23-25 November 1997
Columbia University

- DIII-D routinely operates at plasma elongation near the ideal limit for the axisymmetric instability. The control was developed from a simple analytic model.
- The key to control is an understanding of the interaction of the three elements of the system: the plasma, the shell and the control coil. In particular the interaction of the shell and the active coil, which dictates the appropriate choice of coil.
- The n=1 dispersion relation in its simplest form is quite similar to the simplest n=0 dispersion relation.

## * The key to reaching the ideal limit is in the shell's flux linkages. *

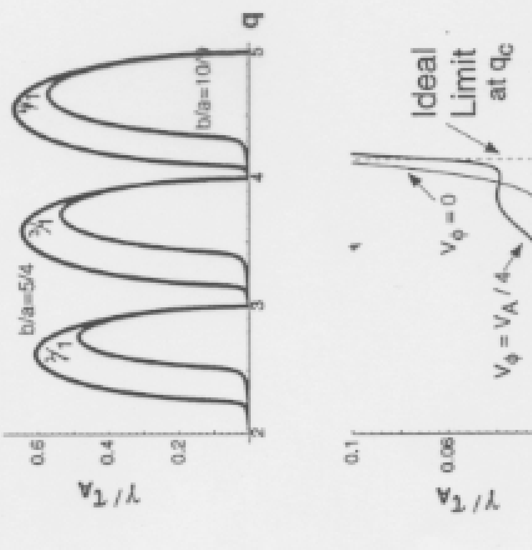
- A Toroidicity leads to eddy currents peaked outboard
- B Eddy Current strongly couples to outboard coils
- C Coils poorly linked to vessel are best for stabilising
- D Coils well linked to shell are destabilising (Lenz's Law)



- These flux couplings are the reason I do not find the use of passive plates with low R and hence large L/R times to be reasonable. If the active coil remains well-coupled to the passive structure, then no gain has been achieved.
  - If the increased L/R time is from structure poorly-coupled to the active coil, then it may be useful. To the extent that the passive plates concentrate the eddy currents nearer the active coil, they will worsen the prospects for stabilisation. Apparent slowing of the growth rate may indicate less likeleyhood of actually achieving a negative growth rate(stabilisation).
  - The way to reduce the growth rate is to design an active coil which reduces $\gamma_{OL}$. I should note that outboard, near the midplane, as the F6 coils on DIII-D is not hopeless. While stabilisation of high growth rates is desireable, it merely indicates the bandwidth of the power supply.
  - There is a decay index, similar to $n_C$, but calculated for the active coil rather than the shell, below which stabilisation can be achieved without derivative gain. This corresponds to $\kappa<2$ in DIII-D.
- I expect these same features to be present in the kink control problem.

## Plasma - Shell n=1 Dispersion relation

The gap width depends on helicity as well as the closeness of the wall.



The electromagnetic branch structure of $\gamma$ is similar to that for n=0

The relevant growth rates are » than $1/\tau_S$

Since the eddy currents are assymetric, so what part of the shell is important in defining the ratio "b/a"?

# Developing a Control Strategy for the External Kink

- Hopefully I have convinced you of the following:
  - (1) The external kink can be controlled, i.e., the dispersion relation is essentially separable into inertial and electromagnetic branches as is true for n=0.
  - (2) Toroidicity will be a key feature in developing the strategy. Calculations by Chance, et.al., of the eddy currents for kink-ballooning modes show a strong in-out asymmetry. Accounting for first order toroidal effects (Neilson & Harris) in calculating fields from helices show the essential structure.
  - (3) It is unlikely that outboard coils will be appropriate for stabilisation. It is therefore likely the inductance calculations will have to be extended to partial helices.
- Some tasks that need work in order to develop a model are:
  - (1) Some of the essential calculations needed are the mutual and self inductance of toroidal helices, or more correctly, fixed systems of 2m helices which describe the instability.
  - (2) A simple torque balance for the effect of the external fields on the mode is needed.
  - (3) A vessel expansion similar to the axisymmetric eigenmode expansion is needed. Probably a simple representation of the vessel as a set of helices like the plasma but out of phase will be adequate to get started

Boozer
PoP 1998

- Note that I have not appealed to the "resistive wall mode" to provide stabilisation. It is possible that this blessed plasma state exists and our attempts to find it will be favored by readily available stable paths to this blessed final state.

$\gamma \sim 1/\tau_w$

But, just in case ...

The problem of stabilising the kink to its ideal limit seems to me worthy of considerable effort. If successful, it may change our ideas about tokamak design and make large aspect ratio more attractive. The first step is the development of a model problem.

$\gamma \gg 1/\tau_w$

# Lumped-parameter Circuit Approach for RWM Feedback Control Analysis

**M. Okabayashi, N. Pomphrey, R. E. Hatcher**

*Princeton Plasma Physics Laboratory*
*P.O. Box 451, Princeton, NJ 08543*

Workshop on Control of MHD Modes in Tokamaks with Non-axisymmetric Coils
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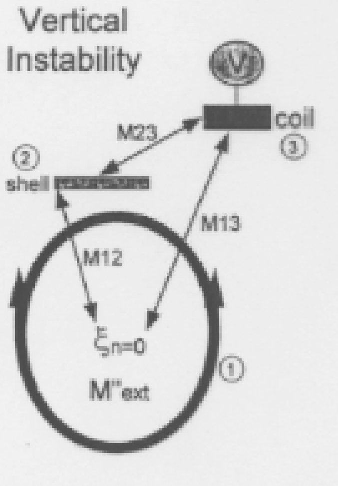
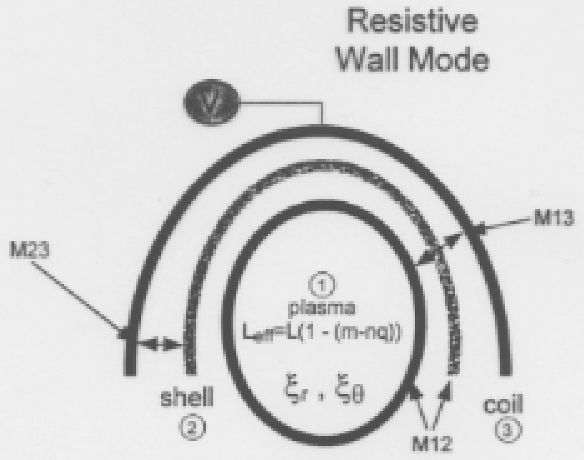
## Resistive Wall Mode control is analagous to n = 0 vertical control



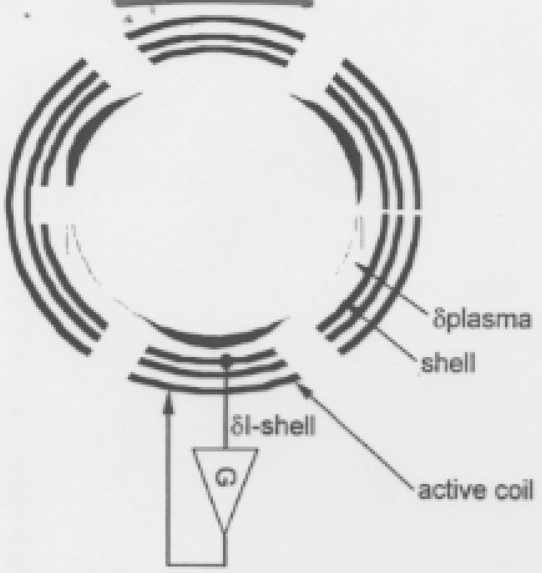


$$\gamma\tau_w = \frac{1}{1 - (M'_{12})^2 / M''_{ext} L_2}$$

$$\gamma\tau_w = \frac{1}{1 - (M_{12})^2 / (L_2 L_{eff})} = \frac{1}{1 - \frac{(a/b)^{(2m)}}{(1-f)}}$$

KINK
MODE
DRIVE

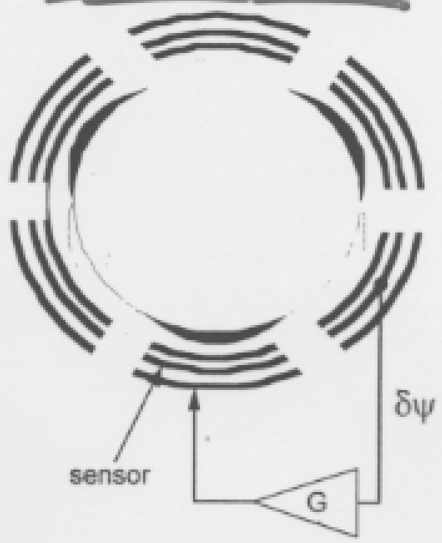
**Smart Shell**



- δI_shell --> zero

" ideal conductor "

**Fake Rotating Shell**



- δψ at a different location provides phased signal

"shell rotating"

## SMART SHELL FEEDBACK SYSTEM

$$V_3\tau_3 = G_s L_2 I_2. \tag{19}$$

$$\gamma\tau_2 = \frac{1}{\dfrac{1}{D} - G_s\left[\hat{M}_{23} - \hat{M}_{21}\hat{M}_{31}\left(\dfrac{\gamma_\infty^2\tau_A^2 + \frac{2f^2}{\beta^0}}{\gamma_\infty^2\tau_A^2}\right)\right]}, \tag{20}$$

$D$ : the growth rate of the RWM in the absence of the active feedback circuit. Since $D > 0$, a necessary condition for decreasing the growth rate

$$G_s\left[\hat{M}_{23} - \hat{M}_{21}\hat{M}_{31}\left(\frac{\gamma_\infty^2\tau_A^2 + \frac{2f^2}{\beta^0}}{\gamma_\infty^2\tau_A^2}\right)\right] < 0. \tag{21}$$

The sign of $G_s$ should be chosen positive to have the system stable without mode excitation.

## INDUCTANCE OPERATOR AND FEEDBACK STABILIZATION OF WALL MODES

Allen H. Boozer
Department of Applied Physics, Columbia University, New York, NY 10027 and
Max-Planck-Institut für Plasmaphysik EURATOM-Association, D-85748 Garching, Germany

The plasma response to currents, $\kappa(\theta,\varphi)$, in a thin shell surrounding a plasma can be represented by an inductance operator $\overset{\leftrightarrow}{\mathcal{L}}$, which relates $\kappa$ and the normal component of the magnetic field, b, on the shell. The current density in the shell is written as $\mathbf{j} = \left(\nabla\kappa(\theta,\varphi,t) \times \nabla r\right)/\Delta$ with the radial coordinate $r$ defined so the shell is at constant $r$, $r = r_s$. The thickness of the shell is $\Delta$. The normal component of the perturbed magnetic field is chosen so that it has units of magnetic flux, $b = \mathcal{J}\,\mathbf{b}\cdot\nabla r$ with $\mathcal{J}$ the Jacobian of $(r,\theta,\varphi)$ coordinates. In perturbation theory, the current in the shell $\kappa(\theta,\varphi,t)$ and $b(\theta,\varphi,t)$ are linearly related,

$$b = \int_{-\pi}^{\pi} d\theta' \int_{-\pi}^{\pi} d\varphi' \int_{-\infty}^{t=0} dt'\, \mathcal{L}(\theta,\theta',\varphi-\varphi',t-t')\kappa(\theta',\varphi',t') = \overset{\leftrightarrow}{\mathcal{L}}[\kappa].$$

If feedback currents $\kappa_f$ are driven in coils behind the shell, $r = r_f$, then the normal field on the shell is the sum of two terms, an inductance and a mutual inductance, $b = \overset{\leftrightarrow}{\mathcal{L}}\left[\kappa\right] + \overset{\leftrightarrow}{\mathcal{M}}\left[\kappa_f\right]$. A feedback system drives a current $\kappa_f$ in response to a measured normal magnetic field on the shell, or $\kappa_f = -\overset{\leftrightarrow}{\mathcal{G}}[b]$. Combining operators $b = \overset{\leftrightarrow}{\mathcal{L}}_{eff}[\kappa]$. The combination of Faraday's law and Ohm's law imply $\partial b/\partial t = -\overset{\leftrightarrow}{\mathcal{R}}[\kappa]$. The resistance operator $\overset{\leftrightarrow}{\mathcal{R}}$ is positive definite and Hermitian,

$$\overset{\leftrightarrow}{\mathcal{R}} = -\mathcal{J}\,\nabla\cdot\left(\frac{\eta}{\Delta}\,\nabla r\cdot(\nabla\kappa \times \nabla r)\right)$$

Wall modes are stable with feedback if the equation

$$\overset{\leftrightarrow}{\mathcal{L}}_{eff}\left[\frac{\partial\kappa}{\partial t'}\right] = -\overset{\leftrightarrow}{\mathcal{R}}\left[\kappa\right]$$

yields no growing solutions. In a cylinder, the eigenvalues of $\overset{\leftrightarrow}{\mathcal{M}}$ are $(r_f/r_s)^m$ times those of $\overset{\leftrightarrow}{\mathcal{L}}$. Each eigenvalue of $\overset{\leftrightarrow}{\mathcal{L}}_{eff}$ can be written as $L_{eff} = L/(1+\alpha L)$ with $\alpha$ proportional to the feedback. A wall mode arises if L is negative but is stabilized if $L_{eff}$ is positive.

Supported by U.S. DoE grant DE-FG02-95ER54333.

# INDUCTANCE OPERATOR
# and
# FEEDBACK STABILIZATION
# of
# WALL MODES

Allen H. Boozer
Columbia University
April 1997

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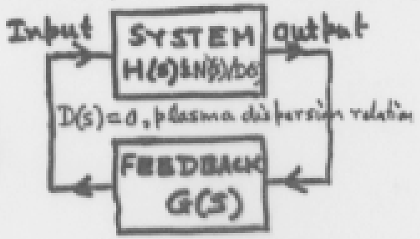
Inductance operator:

1. Given by perturbed plasma equilibria.
2. Defines stability of wall modes including effects of rotation [PoP, 2, 4521 (1995) and PoP 3, 4620 (1996)].
3. With mutual inductance determines feedback requirements.

PROVIDES FORM OF $L_{eff}$ FOR MODEL CALCULATIONS

# A.K. SEN

## A SIMPLE NON-RIGOROUS DEMONSTRATION



$$\frac{\mathcal{L}[\text{Output}]}{\mathcal{L}[\text{Input}]} = \frac{H(s)}{1-G(s)H(s)}$$

$$= \frac{N(s)/D(s)}{1-G(s)N(s)/D(s)}$$

$$= \frac{N(\text{const.})}{D(s)-G(s)N} \rightsquigarrow =0$$

is the feedback modified dispersion relation

GOAL OF F.B.: Determine $G(s)$ such that all these poles are stable!

Let $D(s) = s^n + a_{n-1}s^{n-1} + \cdots + a_0 = 0$

With const. f.b. $G_0$: $D(s) - G_0 N = s^n + a_{n-1}s^{n-1} + \cdots + \boxed{(a_0 - G_0 N)} = 0$

can modify only one root

For complete stability: $G(s) = G_{n-1}s^{n-1} + \cdots + G_0$

$\therefore D(s) - G(s)N = s^n + (a_{n-1} - NG_{n-1}) + \cdots + (a_0 - NG_0) = 0$

(can modify all roots!

Hence, in general, need nth order feedback network!

Complication in practice: $G(s) = \dfrac{\text{Polynomial in } s}{\text{Polynomial in } s}$

CONCLUSIONS:

In all probability the Intelligent Shell may be smarter than me. In any case, this is the kind of innovative concept which should be tested experimentally inspite of some conjectural reservations

Boozer 1998 PoP showed single mode RWM

$D(s) = a_3\nu^3 + a_2\nu^2 + a_1\nu + a_0$

with feedback on $\Phi$ or $\Phi'$

Stability for $a_n > 0$

# RWM Active Control Modeling

J.Bialek, M.Mauel, J.Navratil

Presented at
Workshop on Control of MHD Modes in Tokamaks
with Non-axisymmetric Coils
23 - 25 November 1997

We examine the performance of proposed control schemes in a 3-D thin shell model of the HBT-EP tokamak.

- The 3-D thin shell model of HBT ( spark - code )
- A (m,n) = (3,1) perturbation is assumed
- Proposed 'Figure of Merit' ( similar to TPX work )
- Evaluation of several configurations

  Present Aluminum passive stabilizers

  Planned Stainless Steel passive stabilizers

  Stainless Steel passive stabilizers with coils

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# The HBT-EP model

The SPARK eddy current code was used to realistically model the geometry.

## SPARK

The 'Thin Shell' approximation is used. The geometry is approximated by rectangular elements and 'element thickness' is a parameter. This means that skin-effects must be approximated via multiple layers of elements.

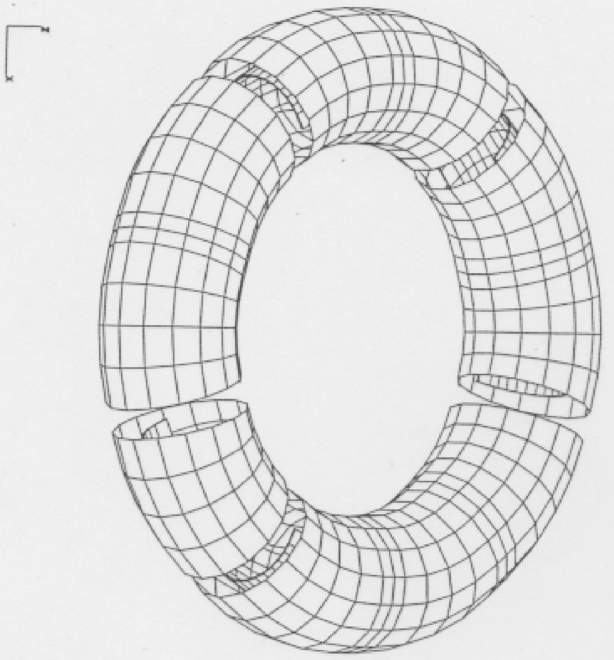
Each 'element' in the model has a circulating 'mesh-current'. These 'mesh-currents' are the variables in the model.

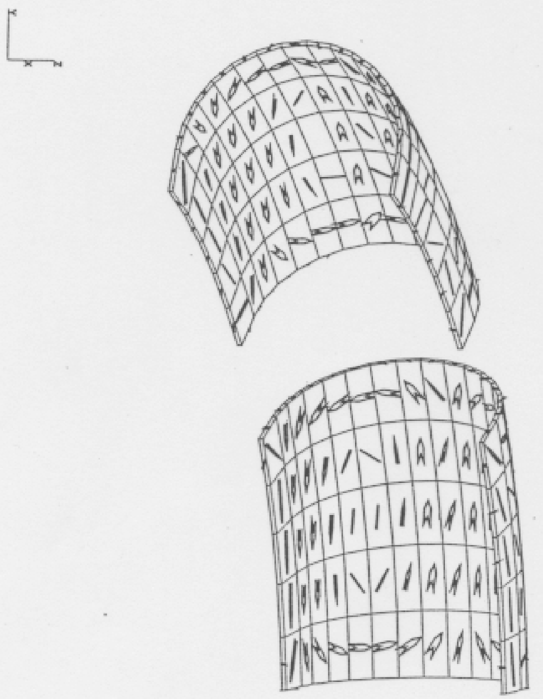
$$[\mathrm{L}]\left\{\frac{d\,\mathrm{I_m}}{dt}\right\}+[\mathrm{R}]\{\mathrm{I_m}\}=-\frac{d\Phi}{dt}$$

where

$$\{\mathrm{I_m}\}=\text{'mesh}-\text{current'}$$

The results may be used to compute fields and forces anywhere in the model. We use the eddy current fields to calculate the distributed force on the assumed source of flux change ( the r.h.s.)


Z
X


Y
X
Z

# The Plasma Perturbation and Figure of Merit

We examine a plasma perturbation that approximates a (m,n) = (3,1) mode. This perturbation has zero net poloidal & toroidal flux and is approximated by two sets of filaments.

Two sets of filaments are placed on the surface of a circular cross section torus ( (R,a) = (0.92,0.13) ) . Each set of finite length filaments approximates a helix with pitch (m,n) = (3,1). The pitch in both helices is the same, the currents in the two sets are directed in opposite directions. The current in each helix starts at zero and increases with a positive time constant of 500. micro sec.

We needed a simple ( scalar ) indicator of 'how effectively the induced eddy current fields push back on the plasma perturbation' . We have used the Figure of Merit ( FOM ) described by:

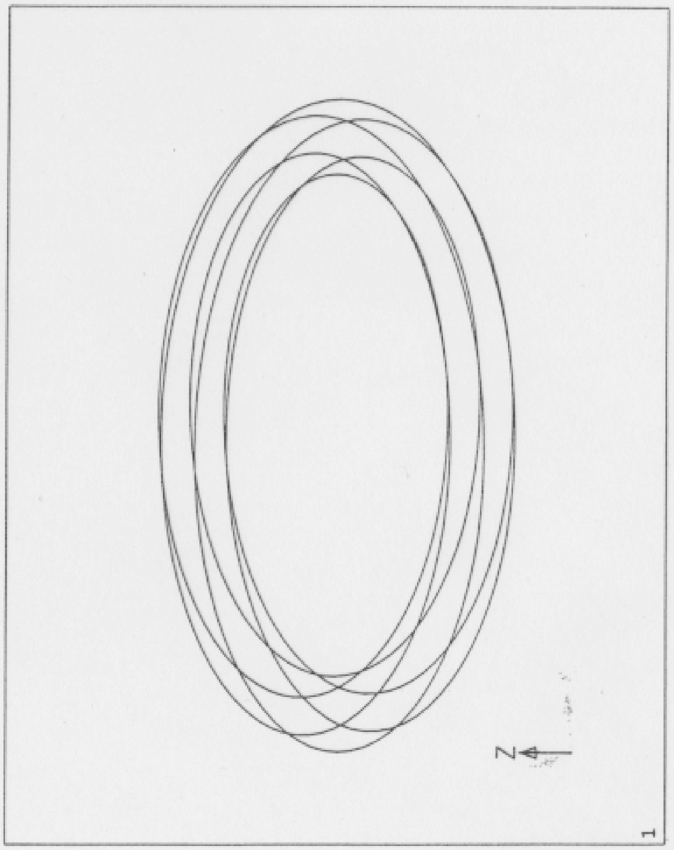
$$\mathrm{FOM} = \sum_{\mathrm{all-helices}} \oint \hat{n} \bullet \left( I_s \left( d\bar{l} \right) \times \vec{B}_e \right)$$

where:

$\hat{n}$ = unit_normal_to_plasma_surface

$I_s$ = current_in_flux_source

$\vec{B}_e$ = field_from_eddy_currents



# Workshop on Control of MHD Modes in Tokamaks with Non-Axisymmetric Coils

# RWM Control by Toroidal Rotation

Nov. 23 -- Nov. 25 1997
Columbia University

M.S.Chu, A. Bondeson[†], and D. Ward[*]
General Atomics
[†] Chalmers Univ.
[*] CRPP, Lausanne

RWM Stability Diagram for 80111

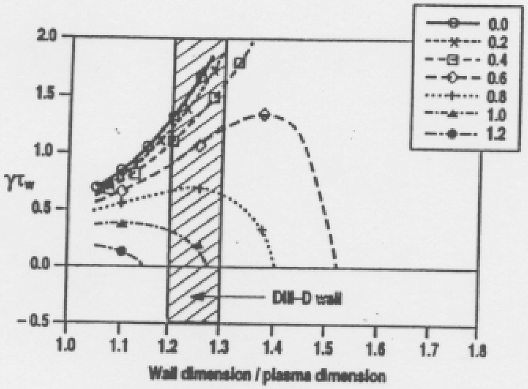
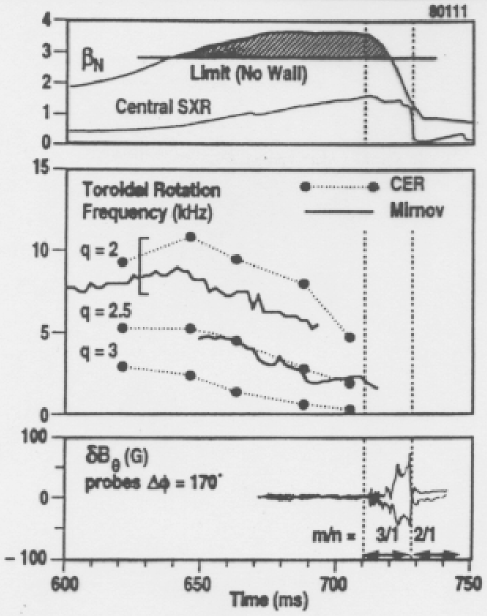


FIG. 7. Stability diagram for the same equilibrium as shown in Fig. 6 with fitted profiles to experimental rotation and density profiles. Computed are growth rates for different levels of rotation frequency and with $\kappa_{\parallel}=0.5$. It is shown that the experimentally observed threshold is well within the computed range of values.

## COLLAPSE AT HIGH $\beta_N$ SHOWS IMPORTANCE OF ROTATION



- m/n = 3/1 mode becomes unstable when q = 3 surface ceases to rotate
- 3/1 mode has predicted features of “Resistive Wall Mode”

-94.Taylor.APS/ref

GENERAL ATOMICS

# Major Issues Discussed at 1997 Workshop

## Theme: Use of Non-axisymmetric Coils for Mode Control

- RWM on DIII-D: Do we really see it?
  **Ideal Mode Structure & Slowing Down of Rotation**
- How to formulate active control model of the RWM?
  **Analogy to n=0 control problem**
  **Lumped Parameter Circuit Approach**
  **Bishop "Intelligent" Shell**
- Plans for Implementation/Installation of Control Coils
  **HBT-EP & DIII-D: How to "optimize"?**
- Tearing Mode Control Experiments
  **JIPP T-IIU, JET, HBT-EP, plans for FSX and DIII-D**
- Neoclassical Tearing Modes
  **Observations & Plans for Control (with coils)**

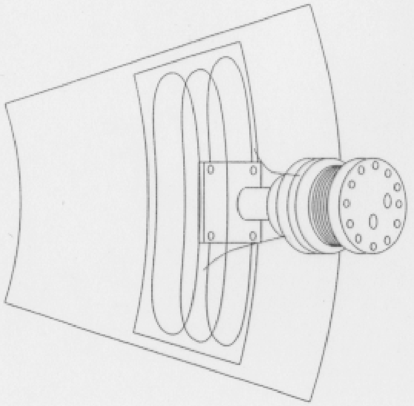
# PLANS FOR HBT-EP

## Smart Shell Options:

JUNE 12 '97

Overlapping Coils

$\Delta\theta = 40^\circ$

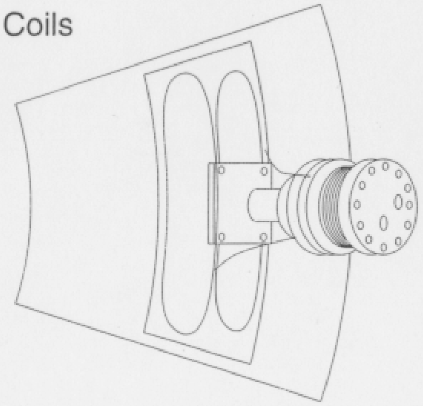


Better Stability Margin

Improved Ability to Reproduced Measured Eddy Current Patterns

Non-Overlapping Coils

$\Delta\theta = 50^\circ$



ESTIMATE OF POWER NEEDS[*]

EMPIRICAL INPUT : $\tilde{B}$

AVERAGE FEEDBACK SURFACE CURRENT DENSITY:

$$J_{EPP} \sim \tilde{B}/\mu_0$$

LOOP CURRENT $I$; $J_{EPP} \sim |\nabla I| \sim kI$

MODE GROWTH TIME : $\tau \sim \dfrac{\mu_0 \delta}{\eta k}$

LOOP VOLTAGE : $V \sim \ell^2 \tilde{B}/\tau$

$$P \equiv \frac{VI}{\ell^2} \sim \frac{\tilde{B}^2 \eta}{\mu_0^2 \delta}$$ (POWER PER UNIT AREA)

EX.: $\tilde{B} = 5\times10^{-4}\ Vs/m^2$ ; $\eta = 10^{-6}\ Vm/A$ ; $\delta = 2\times10^{-3}\ m$

$\rightarrow P \sim 75 W/m^2$

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[*] FROM JENSEN + FITZPATRICK, GA-A 22526, TO APPEAR IN PHYS. OF PLASMAS.

# Issues of RWM Feedback Stabilization in DIII-D

M. Okabayashi

M. Chance, J. Manickam and N. Pomphrey

Princeton Plasma Physics Laboratory

Workshop on Control of MHD Modes in Tokamaks
with Non-axisymmetric Coils

23-25 November 1997, Columbia University

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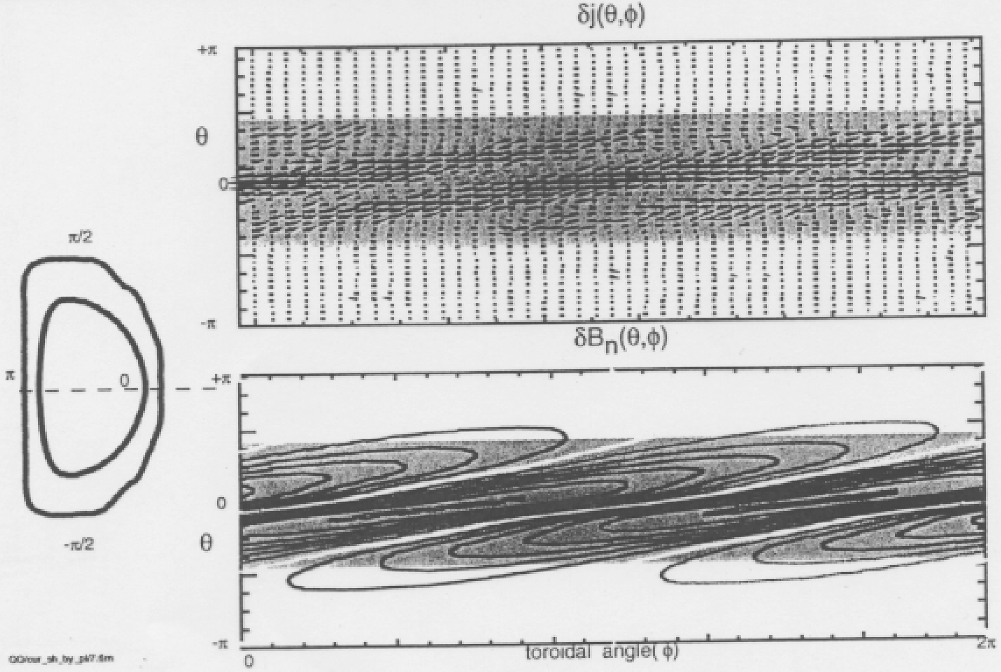
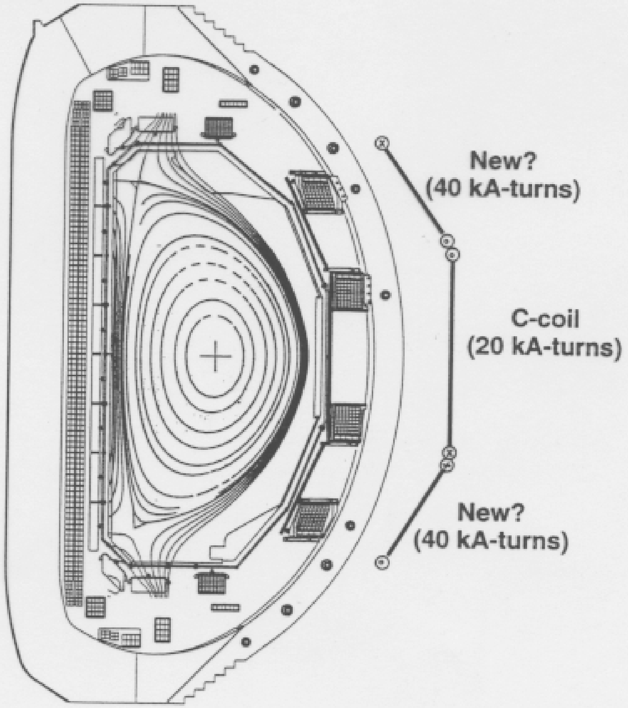
## Narrow localization of $\delta j(\theta,\phi)$, $\delta B_n(\theta,\phi)$ on the passive shell induced by $\xi_\psi$ suggests the possiblity of active RWM control



# PLANS FOR USE OF THE C-COIL ON DIII-D FOR EXTERNAL KINK STUDIES

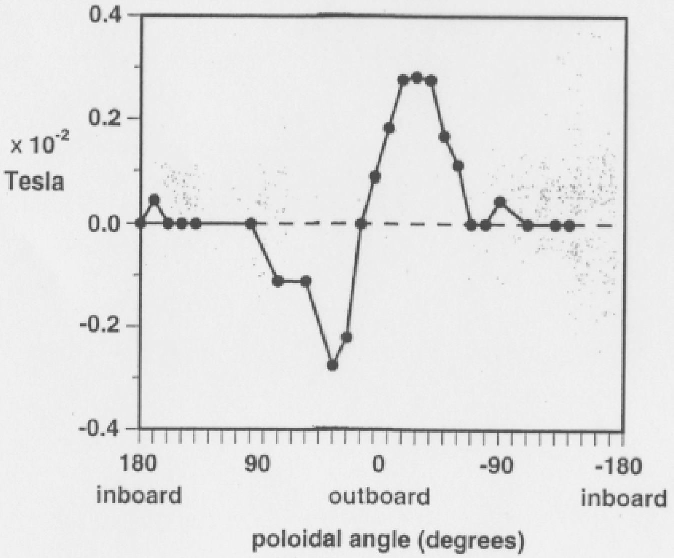
J.T. Scoville and R.J. La Haye

## ERROR FIELD COILS AND PICKUP COILS



## POLOIDAL VARIATION OF C-COIL FIELD (WITH NO PLASMA) MEASURED BY INTERNAL MAGNETIC PROBE ARRAY

- magnetic probes measure poloidal field
- maximum fields near top and bottom legs of C-coil



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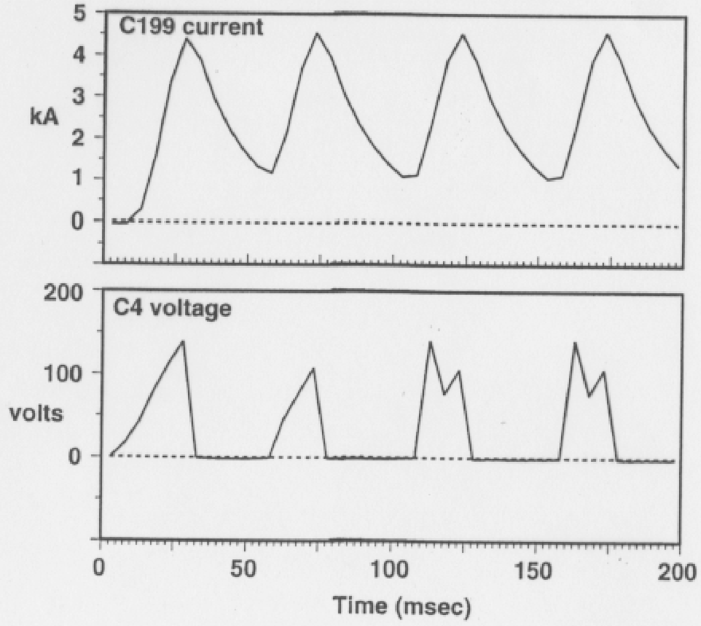
## EXISTING C-COIL POWER SUPPLIES HAVE BEEN USED TO CREATE A SLOW AC FIELD

- 3 DC unipolar supplies, 200 volt, 5000 amp
- Each drives one C-coil pair, L=130 μh, R=13 mΩ



# A CONCEPTUAL
# INSIDE VESSEL COIL FOR DIII–D

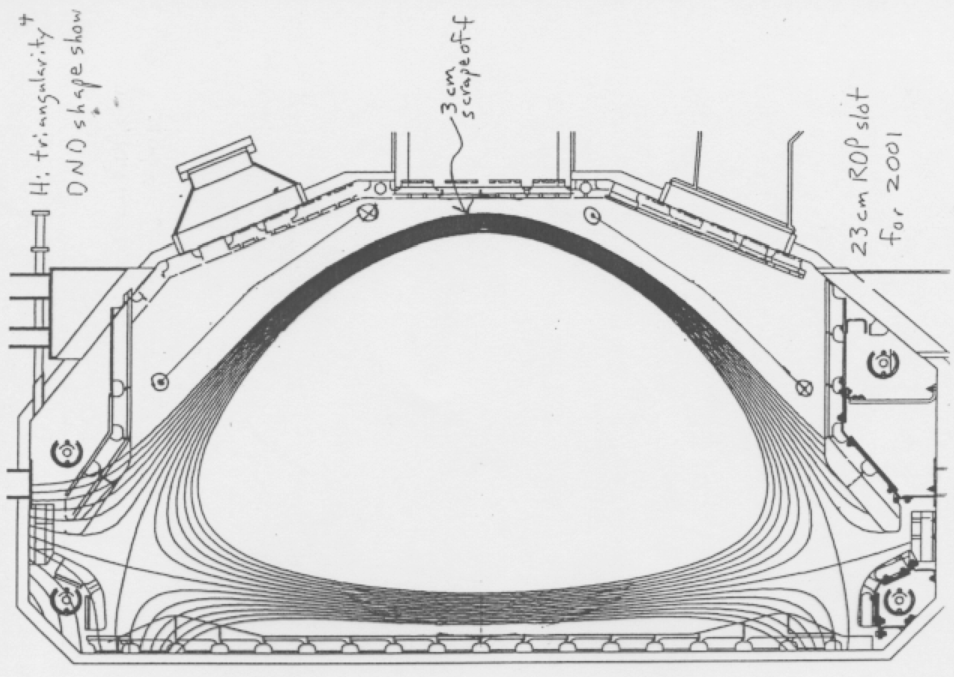
by

R.J. LA HAYE

Presented at
The Workshop on Control of MHD Modes
in Tokamaks With Non-Axisymmetric Coils
New York, New York

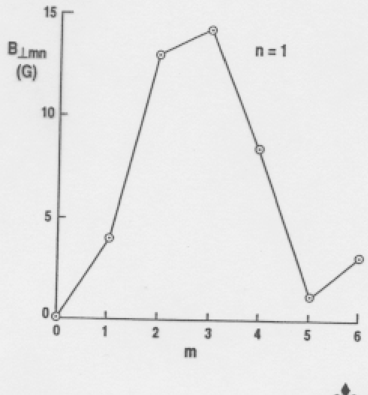
NOVEMBER 1997

**GENERAL ATOMICS**



## FOURIER ANALYSIS ON TYPICAL $q = 2$ SURFACE

- 1 turn, top-bottom, opp. quadrants subtracted
- 10 kAmps, no wall eddy included
- Left and righthand $B_{\perp mn}$ are equal
  - Spectrum peaked at $q = 3$ inside separatrix



GENERAL ATOMICS

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- Neoclassical Tearing Modes
  - **Observations & Plans for Control (with coils)**

# Active Stabilization of Tearing Modes in HBT-EP

D. Nadle, C. Cates, M.E. Mauel, D. Maurer, G.A. Navratil, W. Reass,* E. Taylor, G.A. Wurden,* and Q. Xiao
*Columbia University and *LANL*

Workshop on Control of MHD Modes in Tokamaks with Non-axisymmetric Coils

24 November 1997

Columbia University

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# Conclusions

- Control of $m/n$=2/1 mode in good agreement with model predictions (with shear stabilization term) for various values of feedback $\delta$, at medium gain.
- Disruption control and mode supression not yet demonstrated; Better phase accuracy in diagnostics and in sampling seen as key requirements.

# NUMERICAL OPTIMIZATION OF COIL GEOMETRY FOR TEARING MODE FEEDBACK STABILIZATION

ROBERT D. WOOLLEY

WORKSHOP ON CONTROL OF MHD MODES IN TOKAMAKS
WITH NON-AXISYMMETRIC COILS
23-25 NOVEMBER 1997
COLUMBIA UNIVERSITY

[redacted]

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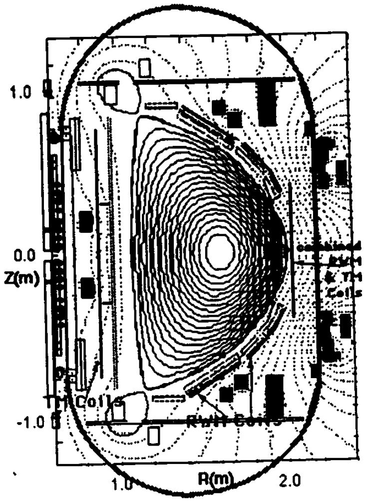
## BACKGROUND

**Early in FY97, a small group led by Dr. Kevin McGuire considered converting PPPL's existing PBX-M tokamak facility into a Feedback Stabilization Experiment (FSX) facility to explore different methods for stabilizing a plasma via active feedback, including magnetic feedback stabilization of internal tearing modes.**

**Although FSX is not now planned, some of the FSX design study considerations may apply to feedback experiments on existing multipurpose facilities.**

FSX Facility



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# Neoclassical Islands

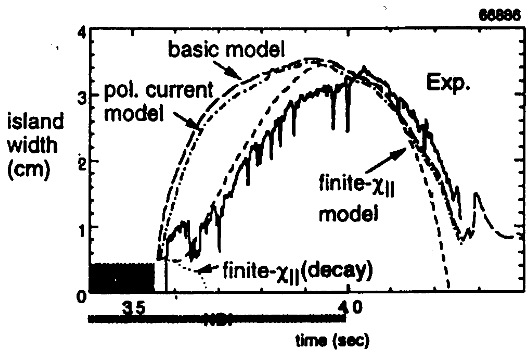
David A. Gates

With Contributions from:

COMPASS-D, UKAEA Fusion, UKAEA/EURATOM Fusion Assoc.
ASDEX-U, Max Planck Institute - IPP, Garching
TFTR, Princeton Plasma Physics Laboratory, Princeton
DIII-D, General Atomics, San Diego
JT-60U, JAERI, Naka

**UKAEA Fusion**

## Finite-$\chi_{\parallel}$ Model Fits Data Better than Pol. Model



- Basic model: $k_{nc}$=0.7, $k_d$=0, $k_p$=0.
- Finite-$\chi_{\parallel}$ model allows the existance of noise level island and slow growing rate. ($k_{nc}$=0.9, $k_d$=3.9, decay if $k_d$=4.0)
- The set of coefficients for $W_{cr}$=0.5cm automatically results in the island-decay-time consistent with experiment.
- Pol. model:
  One can force the island to disappear at any time after NBI by selecting a C (e.g., $k_{nc}$=0.7, $k_d$=0, $k_p$=0.085, C=0.22.).
  BUT, the slow growing phase is hard to be modeled by the model.

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## Summary

1. The $\beta$-limit (at low collisionality) on COMPASS-D is set by neoclassical magnetic islands

2. Threshold mechanisms identified by theory have been compared to the relevant experimental data.

3. The $\chi_{\perp}/\chi_{\parallel}$ model is found to predict a threshold island width that is inconsistent with the observed experimental threshold.

4. The polarisation current model matches both the observed density scaling for the onset of MHD and the correct magnitude for the observed threshold.

5. An expression for the q-scaling of the $\beta$-limit based on the assumption that the limit is determined by the width of neoclassical islands is shown to be in good agreement with the data.

6. Neoclassical islands are a serious issue for any future reactor designed to operate at low collisionality (e. g. ITER). There is a need to increase the predictive capability of the theory and the certainty in the experimental results.

UKAEA Fusion

# SUMMARY OF PROGRESS 1997-2002

- RWM: CLEARLY SEEN ON DIII-D, HBT-EP, JT-60U
  - **APPROACH IDEAL WALL LIMIT FOR SECONDS ON DIII-D**
- HOW TO FORMULATE ACTIVE CONTROL MODEL OF THE RWM?
  - **3D VALEN MODEL FOR SINGLE MODE, NO ROTATION**
  - **MARS WITH FEEDBACK 2D AXISYMMETRIC WITH ROTATION**
  - **VACUUM/DCON MULTI-MODE, AXISYMMETRIC**
- ~~PLANS FOR~~ IMPLEMENTATION/INSTALLATION OF CONTROL COILS
  - **DIII-D 12 INTERNAL COILS; HBT-EP 20 OPTIMIZED COILS**
  - **DESIGNS FOR NSTX, ASDEX, FIRE, ITER, KSTAR,…**
- NEOCLASSICAL TEARING MODE CONTROL EXPERIMENTS
  - **COMPLETE STABILIZATION ON ASDEX, DIII-D, JT-60U,…**
- NEOCLASSICAL TEARING MODES
  - **MATURE THEORY WITH OPEN QUESTIONS ON POLARIZATION TERMS.**