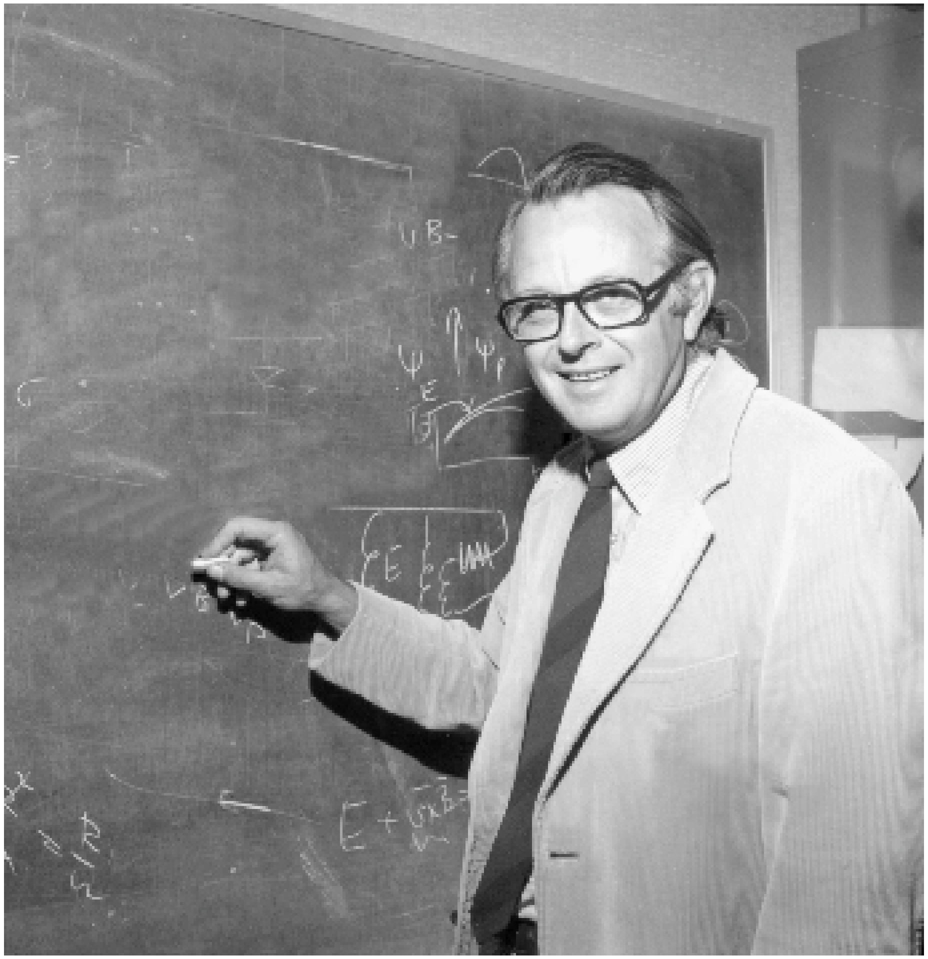


Contributions of Torkil Jensen to MHD & Stability

Andrea M. Garofalo

9TH WORKSHOP ON MHD STABILITY CONTROL
"CONTROL OF MHD STABILITY: BACK TO THE BASICS"
NOVEMBER 21-23, 2004
PRINCETON PLASMA PHYSICS LABORATORY

Columbia University

A great privilege: Torkil was to me both a mentor and a friend

- **“Together with Tihiro Ohkawa, he has shaped and formed understanding of the realistic confinement concepts to quite a number of the more mature physicists at General Atomics”** - Ming Chu
- **“Besides his scientific abilities he had the gift of honesty and fairness”** - Bruno Coppi
- **“Torkil was a gifted scientist with deep theoretical insight rooted in a very sound empirical and experimental background. He was a no-nonsense researcher with a classy style and sound wisdom”** - George Morales
- **“One particular pleasure in working with Torkil was his extremely contagious enthusiasm and his ability to make the simplest assumption to get at the essential physics”** - Ming Chu

Torkil Hesselberg Jensen becomes a Fusion Scientist in 1958

- Torkil's very productive and uniquely innovative scientific career started in Denmark and spanned almost 50 years.
- In 1958 American, British and Soviet scientists began to share previously classified fusion research, as their countries declassified controlled fusion work as part of the "Atoms for Peace" conference in Geneva (an amazing development considering the Cold War political climate of the time)
- He was part of the General Atomics fusion Group since 1960 (with a one-year gap in 1963)
- Wrote ~50 main-author articles in peer-reviewed publications including:
  - The Astrophysical Journal
  - Fusion Engineering and Design
  - J. Applied Physics
  - J. Plasma Physics
  - Nuclear Fusion
  - Nuclear Instruments and Methods
  - Physical Review A
  - Physical Review Letters
  - Physics Letters
  - Physics of Fluids
  - Phys. Fluids B - Phys. Plasmas
  - Plasma Physics
  - Plasma Physics and Controlled Fusion
  - Plasma Physics and Controlled Nuclear Fusion Research
  - Revista de la Real Academia de Ciencias Exactas, Fisicas y Naturales

Torkil contributed to many areas of plasma physics, in particular to MHD stability

- Landau damping
- Doublet II, Doublet IIA Experiments
- Axisymmetic equilibrium and stability of doublets
- Heating of a doublet
- Doublet III tokamak plasmas (single axis)
- Helicity injection
- Tearing mode
- Dynamo
- Resistive wall mode
- Transport, other

Torkil touched the lives of many, many people

- **This can be clearly seen from the list of his co-authors**
- **Note that quite a number of them were his junior partners in the collaborations**
- **Principal co-authors include:**

BONDESON, A.
BRENNAN, D.
BROOKS, N.H.
CALLEN, J.D.
CHU, M.S.
deGRASSIE, J.S.
DOBROTT, D.
DY, B.
FISHER, R.K.
FITZPATRICK, R.
FREEMAN, R.L.
GAROFALO, A.M.
GRAD, H.
GREENE, J.M.
HASSAM, A.B.
de HOFFMANN, F.
HSIEH, C.L.
HSU, J.Y.
HURRICANE, O.A.
HYATT, A.W.
IKEZI, H.
JOHNSON, R.W.
LA HAYE, R.J.
LAO, L.L.
LEE, J.K.
LEE, P.S.C.
LEONARD, A.W.
LIN-LIU, Y.R.
MAHDAVI, M.A.
MALMBERG, J.H.
MATSUDA, K.
McCLAIN, F.W.
MILLER, R.L.
MOELLER, C.P.
MOORE, R.W.
O'NEIL, T.M.
OHKAWA, T.
OHYABU, N.
POLITZER, P.A.
REN, C.
ROBERTS, P.H.
SCOTT, F.R.
SKINNER, D.G.
STRAIT, E.J.
TAMANO, T.
THOMPSON, W.B.
VANEK, V.
VOORHIES, H.G.
WANG, T.S.
YOKOMIZO, H.

Landau damping

- Preliminary experimental observations of Landau damping came in 1964 (J. H. Malmberg and C. B. Wharton)
- At the time Torkil delves into this topic, the issue was still whether Landau damping was “real” or just on paper
- Torkil contributed with several sets of clever, clear-cut Landau-damping experiments on plasma electron waves
  - Measurement of velocity space diffusion using the plasma wave echo

    T.H. JENSEN, J.H. MALMBERG, T.M. O’NEIL

    The Physics of Fluids, 1969
  - Theory and measurement of the perturbation in the electron velocity distribution caused by a landau damped wave

    J.H. MALMBERG, T.H. JENSEN, T.M. O’NEIL

    IAEA, 1969

In 1970 Torkil started working on Doublet II and on MHD

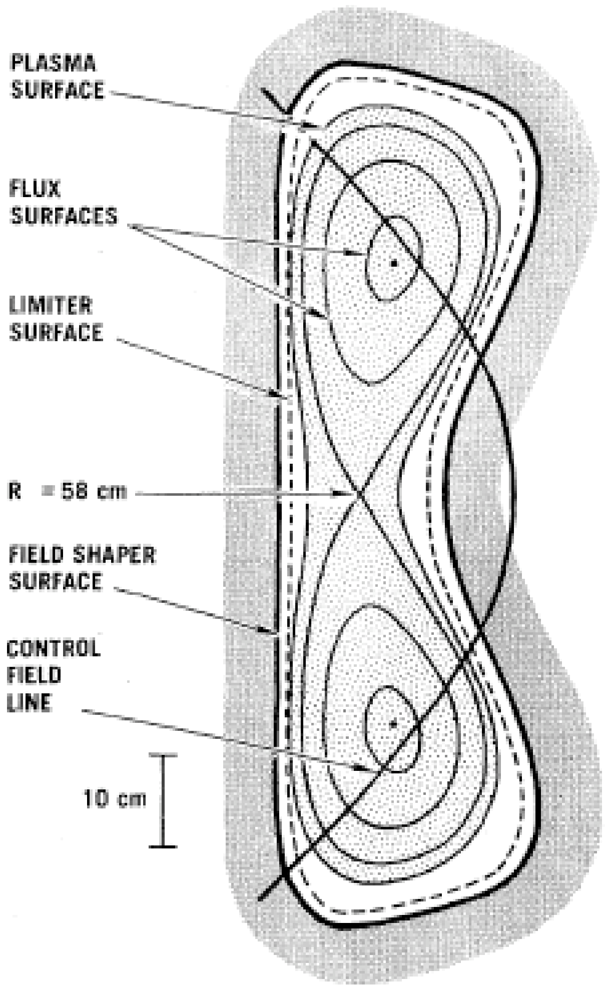


FIG. 2. Computed plasma equilibrium with external control field.

- During the Doublet II period, Torkil was responsible for creating and maintaining the doublet configuration
  - Parameter studies for tokamaks and doublets
    T. OHKAWA and T.H. JENSEN
    Plasma Physics, 1970
- The importance of this paper comes from the impact it has on the direction of research at General Atomics. This paper is the main reason that GA started the work on non-circular tokamaks

"Torkil's lament"
To the rain and snow I say shove it
I'll go study a machine called Doublet
And to give it a stab
I'll assume it a slab
And then I'll take beta and doubl'it

Confinement of Plasma in the Doublet-II Device

T.H. JENSEN, R.K. FISHER, C..L. HSIEH, M.A. MAHDAVI, V. VANEK, and T. OHKAWA

***Phys. Rev. Lett.*, 1975**

A study[3] comparing tokamaks and doublets suggests that the toroidal magnetic field required for stable confinement of a plasma is about 3 times larger in tokamaks than in doublets, or, for the same value of toroidal magnetic field, that the plasma pressure can be nearly an order of magnitude larger in doublets than in tokamaks.

Confinement of Plasma in the Doublet-II Device

T.H. JENSEN, R.K. FISHER, C..L. HSIEH, M.A. MAHDAVI, V. VANEK, and T. OHKAWA

Phys. Rev. Lett., 1975

A study[3] com-
paring tokamaks and doublets suggests that the
toroidal magnetic field required for stable con-
finement of a
tokamaks tha
ue of toroida
pressure ca
larger in dou

The Doublet-II device[4] was built to test this assumption experimentally. Therefore, the design parameters were chosen such that the dimensions, the plasma current density, and the safety factor would be similar to those of tokamaks, but the toroidal magnetic field strength would be low compared to tokamaks, namely below 10 kG.

Confinement of Plasma in the Doublet-II Device

T.H. JENSEN, R.K. FISHER, C..L. HSIEH, M.A. MAHDAVI, V. VANEK, and T. OHKAWA

Phys. Rev. Lett., 1975

A study[3] com-
paring tokamaks and doublets suggests that the
toroidal magnetic field required for stable con-
finement of a
tokamaks tha
ue of toroida
pressure car
larger in dou

The Doublet-II device[4] was built to test this as-
sumption experimentally. Therefore, the design
parameters were chosen such that the dimen-
sions, the plasma current density, and the safety
fa
th
co

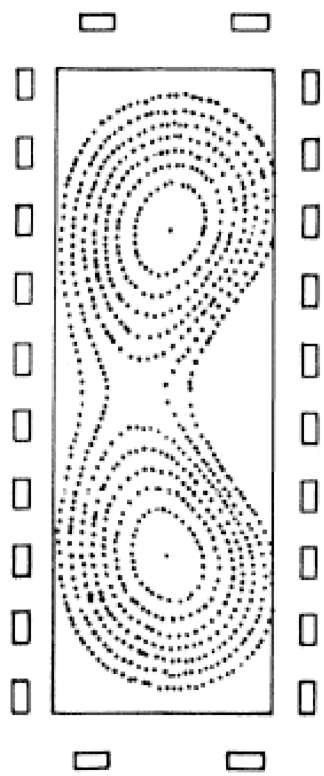
In summary, experimental results show that the doublet plasma characteristics are similar to those of comparable tokamaks, with the important exception that the magnetic field is much smaller.

Studies of Doublet Plasmas in Doublet IIA

R. K. Fisher, S. J. Adcock, J. F. Baur, N. H. Brooks, J. C. DeBoo, R. L. Freeman, W. C. Guss, F. J. Helton, C. L. Hsieh, T. H. Jensen, A. F. Lietzke, J. M. Lohr, M. A. Mahdavi, K. Matsuda, C. P. Moeller, T. Ohkawa, N. Ohyabu, S. C. Prager, J. M. Rawls, T. Tamano, V. Vanek,[a] and T. S. Wang
General Atomic Company, San Diego, California 92138
(Received 3 January 1977)

Doublet plasmas have been produced in Doublet IIA using an active field-shaping coil system. Significant increases in the electron density and energy confinement time have been observed for the doublet configuration relative to elliptic and circular plasmas in Doublet IIA.

- **1974: Doublet IIA pioneers the use of external coils to shape a wide range of noncircular plasmas**



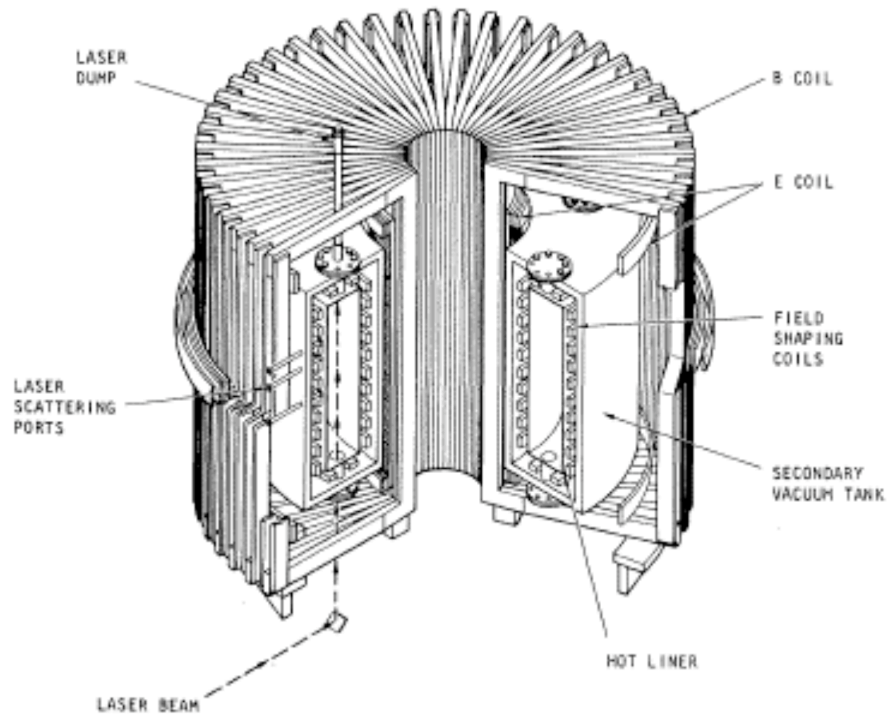


FIG. 1. Schematic view of Doublet IIA.

Torkil was "the person" who understood doublets

- Doublets were found subject to a free-boundary MHD instability, called the droplet-ellipse mode
- It is a very special instability, related to the resistivity of both of the plasma and the external wall. Leads to two sudden, mostly axisymmetric, deformations:
  - the plasma split into two separate plasmas, each with one elliptic axis
  - the three magnetic axes tended first to merge at the midplane and secondly the plasma became unstable toward motion toward either up or down
- Torkil is "the person" in the world who understood the importance of the basic underlying plasma dynamics involved
- As one can see from the sequence of his papers on the subject, Torkil started from the most basic equilibrium considerations, and evolved to linear and non-linear droplet- ellipse mode, the importance of the location of the wall and the resistivity of both the wall and the plasma, and finally its feedback stabilization

Heating of a doublet

Low-frequency heating of doublets

T.H. JENSEN, F.W. MCCLAIN and H. GRAD

J. Plasma Physics, 1981

- "Under circumstances where the plasma is stable, partial reconnection may be driven in an oscillatory fashion by the external circuits. Since reconnections are accompanied by resistive dissipation, such forced reconnections may be used for heating the plasma"
  - Low technology required for low-frequency power sources
  - Field-shaping coils may also be used as the antennae
  - The power can be transmitted through resistive walls
  - Insensitivity to plasma temperature and density
  - Simple physical model

With Doublet III, GA abandoned doublets and went on to D-shaped plasmas

- Dee-shaped plasmas proved easiest to form and immediately became a big success in the high beta work, projected to reach beta values adequate for viable power plants
- Experiments with a wide range of plasma configurations demonstrated the importance of elongation and shape control
  - Much of Torkil work here is in understanding the axisymmetric (n=0) resistive wall mode, and in modeling the Vertical Displacement Episodes
  - The ground work that Torkil invested his time into with doublets led to his tremendous insight in this area
- The rapid successes pushed into a re-construction of the Doublet III tokamak into a large dee-shaped cross section: DIII-D (1986)

Helicity injection

Ming Chu:

"Torkil was very fond of the idea of plasma relaxation through tearing modes to achieve the Taylor state. Therefore, there are a series of papers dealing with this subject, such as:

- **The Bumpy z-pinch**

  T.H. JENSEN and M.S. CHU

  J. Plasma Physics ,1981
- **Current drive and helicity injection**

  T.H. JENSEN and M.S. CHU

  Physics of Fluids, 1984
- **Multipinch – a reversed field pinch with a magnetic well**

  R.J. LA HAYE, T.H. JENSEN, P.S.C. LEE, R.W. MOORE, T. OHKAWA

  Nuclear Fusion, 1986

This is a very good paper which shows that the basic governing dynamics in strongly driven plasma system is the achievement of the Taylor state."

Rob la Haye:

"Torkil played a key role in the understanding for this paper"

Tearing mode

- **Torkil worked on the tearing mode as an extention of his work on the droplet-ellipse mode, also a mode that caused configuration change and magnetic reconnection.**

Ming Chu:

"Torkil had a special way of understanding the tearing mode, starting just from the response of the plasma to the singular currents"

"Once Torkil got on to an idea, he would always examine it back and forth until it was crystal clear"

- **Torkil was very interested in the problem of the interaction of a plasma with islands and of islands with external perturbations**

Torkil Jensen:

"One motivation for studying this problem is the possibility of using deliberately imposed surfaces of moving islands as a means of velocity profile control

- **Velocity profile control may allow for confinement improvement, since turbulent transport may be impeded by shear of the plasma rotation**
- **The subject studied may also be relevant to the phenomenon of "locked modes" associated with field errors**
- **The subject may also be of importance for stability against ideal and resistive MHD modes: it may be that plasma rotation mitigates the instability of modes"**

"Tradition should not be a fetter"

Torkil Jensen

- **An early precursor to Bondeson's RWM stabilization by plasma rotation: the plasma flow stabilizes the tearing mode by dragging it into rotation with respect to the wall**
  - **A linear model for the tearing mode of a tokamak plasma with flow and a resistive wall boundary condition**

    T.H. JENSEN and M.S. CHU

    J. Plasma Physics 30, 57-63 (1983)
- **The following paper introduced the "almost ideal MHD" constraint: assuming large electrical conductivity**
  - **Effect of plasma flow on error field islands**

    T.H. JENSEN, A.W. LEONARD, R.J. LA HAYE, and M.S. CHU

    Phys. of Fluids, 1991
  - **Nonlinear tearing mode study using the "almost ideal magnetohydrodynamics (MHD)" constraint**

    C. REN, T.H. JENSEN and J.D.CALLEN

    Physics of Plasmas, 1998
- **"We have demonstrated in this paper that the ''almost ideal MHD'' constraint can be used to determine linear stability of an equilibrium of slab geometry against the tearing mode. We have also demonstrated that the constraint can be used to determine the saturation amplitude for the linearly unstable case.**
- **The saturation amplitude found differs somewhat from that predicted by the theory of White, *et al.*. We do not know the origin of this discrepancy"**

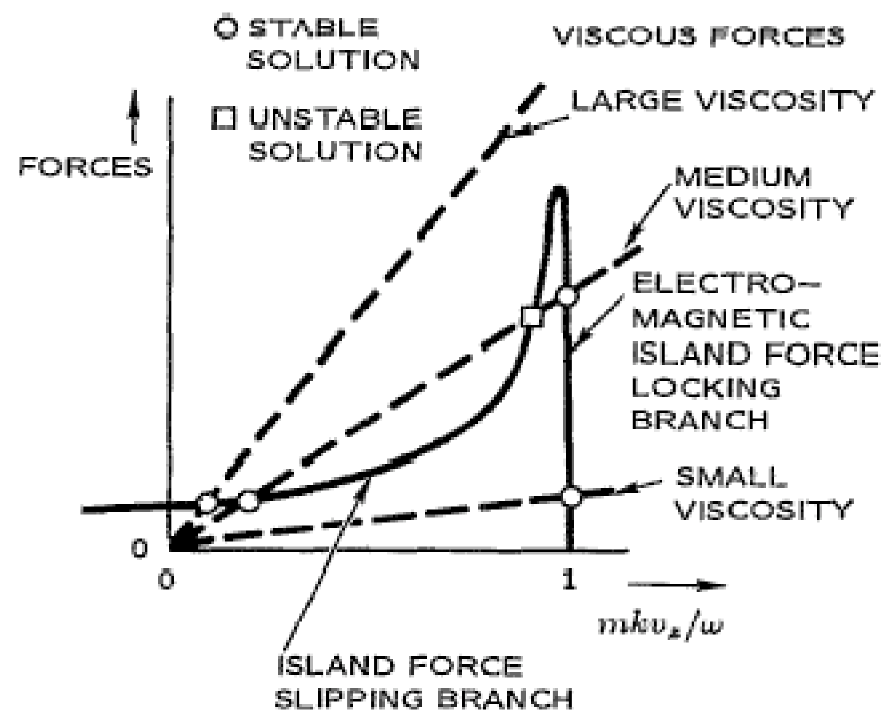
The induction motor model

– A simple model for driven islands in tokamaks

T.H. JENSEN. A.W. LEONARD, and A.W. HYATT

Physics of Fluids, 1993

- The model described is similar to that of an asynchronous motor stirring a viscous fluid
- It can account both for "locking" circumstances, under which plasma inside islands is almost at rest in the island frame, and "slipping" circumstances under which plasma slips rapidly in and out of islands
- It can also account for discontinuous transitions between "locking" and "slipping" circumstances



Viscous and electromagnetic island forces vs. normalized flow velocity. An intersection represents a solution of force balance.

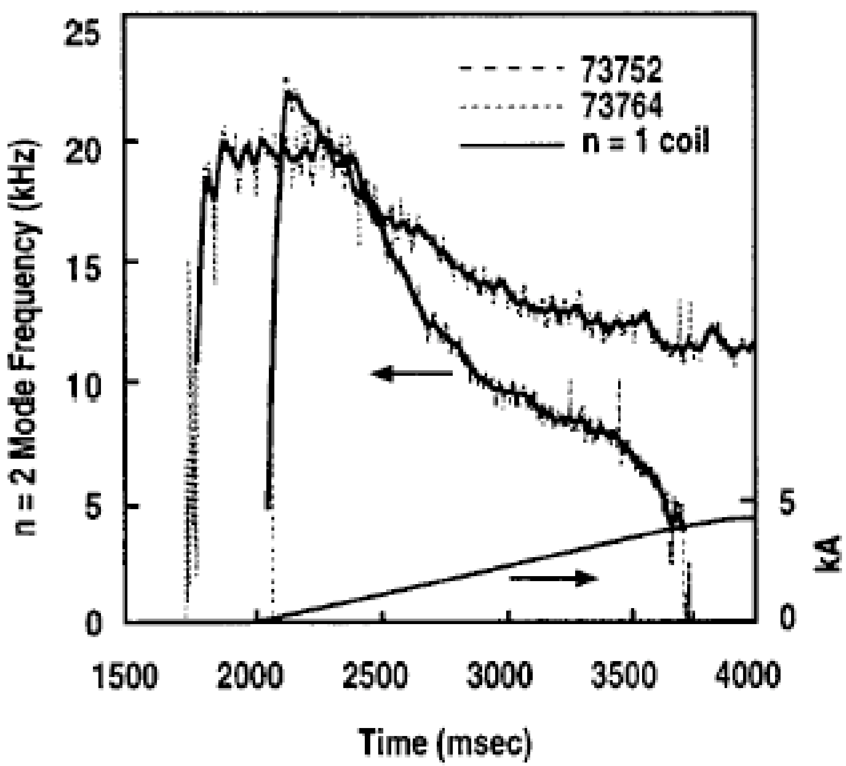
The induction motor model, expanded

– A nonlinear model for the singular surface response

T.H. JENSEN, R.J. LA HAYE, and A.W. HYATT

Physics of Plasmas, 1996

- Previously proposed models failed to account for results from magnetic braking experiments in DIII-D.
- The new model can account for the essential features of the magnetic braking experiment, namely the character of the braking and a “discontinuous” locking of the plasma during the braking process, as well as the amplitude of the perturbation needed for braking
- The key idea is that fluctuations exist in the region of the singular layer, driven by dissipation during magnetic braking
- These fluctuations tend to diminish the current induced at the singular layer
- Since in the parameter region of interest the dissipation increases with a decreasing singular layer current the ingredients for a positive feedback exist



DIII-D discharge #73752 has an applied n=1 field ramp, discharge #73764 has no applied n=1 field.

Dynamo

  - Homogeneous dynamos: Theory and practice
    P.H. ROBERTS and T.H. JENSEN
    Physics of Plasmas B, 1993
- Torkil tried very hard to start a liquid sodium experiment at General Atomics, unsuccessfully
- A few years later Cary Forest left GA and started a liquid sodium experiment in Madison, Wisconsin
  - Pressure driven tokamaks
    T.H. JENSEN, R.L. MILLER, and Y.R. LINLIU
    Physics of Plasmas, 1996
- Torkil was excited about current-hole plasmas long before they were observed in experiments
- In this paper the current drive is produced by Ohm’s law and the plasma flowing radially across magnetic surfaces

Dynamo

  - Homogeneous dynamos: Theory and practice
    P.H. ROBERTS and T.H. JENSEN
    Physics of Plasmas B, 1993
- Torkil tried very hard to start a liquid sodium experiment at General Atomics, unsuccessfully
- A few years later Cary Forest left GA and started a liquid sodium experiment in Madison, Wisconsin
  - Pressure driven tokamaks
    T.H. JENSEN, R.L. MILLER, and Y.R. LINLIU
    Physics of Plasmas, 1996
- Torkil was excited about current-hole plasmas long before they were observed in experiments
- In this paper the current drive is not bootstrap current drive (there is no need of a "seed current")
- The current drive is produced by Ohm's law and the plasma flowing radially across magnetic surfaces

"Beta-Poloidal Equals One Always"
There once was a Dane named Jensen
Who urged us to all pay attention
That beta poloidal is one
And current holes are fun
There really ought be no d'ssension

Resistive wall mode

- Torkil was fond of the idea of using the resistive wall to slow down the growth of the external kink mode and stabilize it
- He is interested not only in the plasma behavior, but he also understood very early that the behavior of the external circuit is very important
  - Effect of toroidal plasma flow and flow shear on global magnetohydrodynamic MHD modes

    M.S. CHU, J.M. GREEN, T.H. JENSEN, R.L. MILLER, A. BONDESON, R.W. JOHNSON, and M.E. MAUEL

    Physics of Plasmas, 1995
  - Stabilization of the resistive wall mode using a fake rotating shell

    R. FITZPATRICK and T.H. JENSEN

    Physics of Plasmas, 1996

One of Torkil's dreams: using lots of RadioShack amplifiers for RWM feedback

- Effects of finite feedback loop gain and bandwidth on stabilization of magnetohydrodynamic instabilities by an "intelligent shell"

  T.H. JENSEN and A.M. GAROFALO

  Physics of Plasmas, 1999

- Semiquantitative analysis of feedback systems for resistive wall modes

  A.M. GAROFALO, T.H. JENSEN, and E.J. STRAIT

  Physics of Plasmas, 2002

- One of Torkil's idea was to fit measurements of the open-loop transfer function in DIII-D to a simple analytic form, to include them in a simple but realistic model

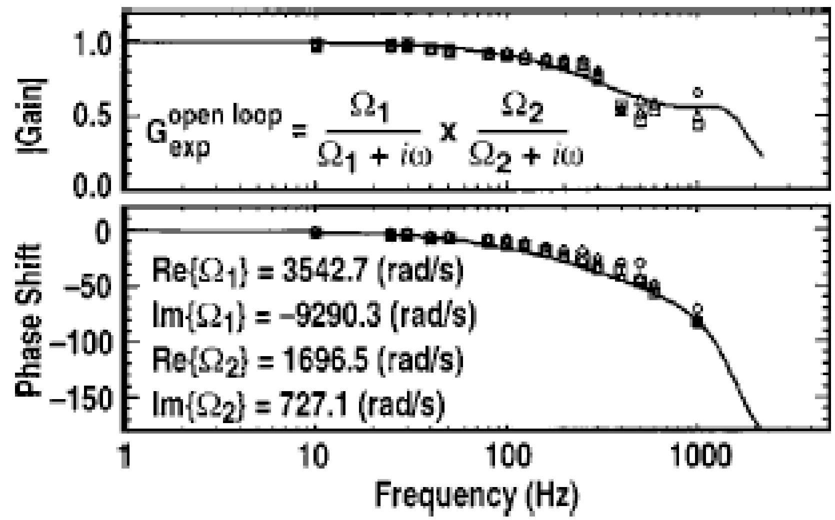
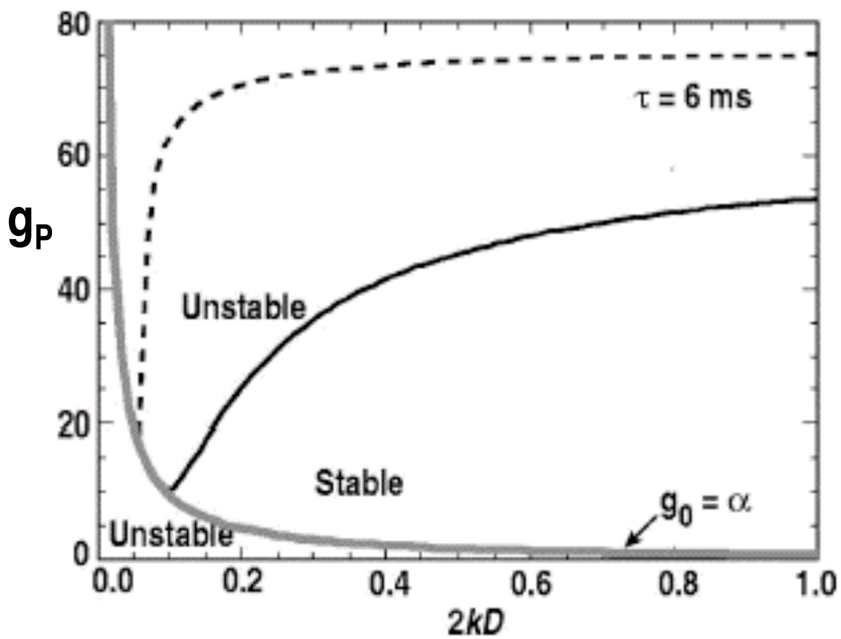


FIG. 6. Measurements of the open loop feedback system gain for the three power amplifiers in the DIII–D feedback system (open symbols) are fitted to a two-pole analytic function (—), to be inserted into the dispersion relation Eq. (20).

Finite bandwidth leads to important limitations to RWM feedback

- **Limitation on largest stabilizable growth rate:**
  - the open-loop growth rate of the instability must be at most as large as the bandwidth of the feedback system : $\gamma_0 < \Omega$ (Smart Shell algorithm)
- **Limitation on largest stable feedback gain**

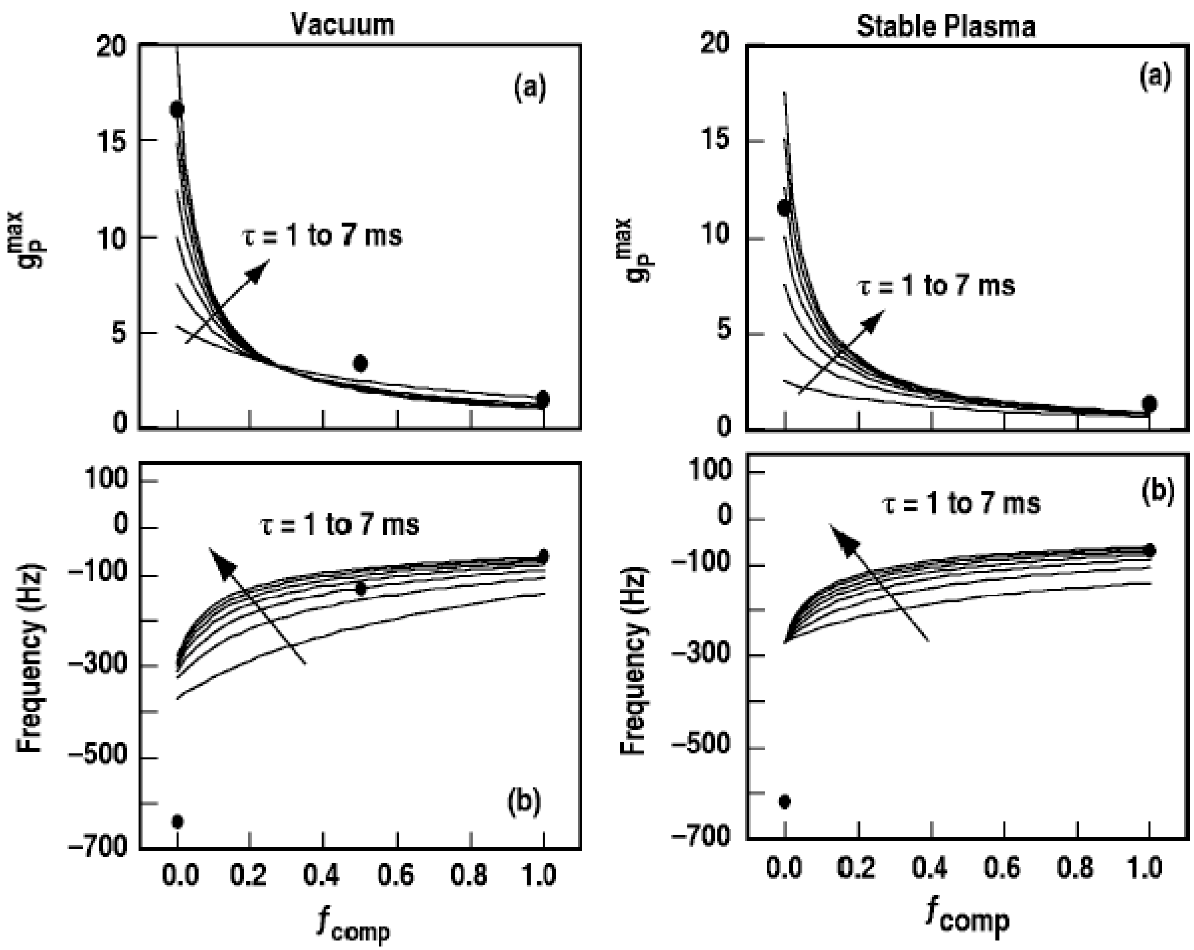


Increasing open-loop growth time
(less unstable plasma)

- **Solid curves are marginal stability curves for Smart Shell feedback with two-pole characterization of open-loop transfer function in DIII-D**
  - Dashed curve denotes marginal stability for one mode of the system, but at values of the gain for which at least another mode is unstable
- **Minimum gain increases for more unstable plasmas**

The "semiquantitative" is owed to a DIII-D gain <=> model gain conversion factor

- **This gain convention allows us to account for differences in mutual inductance values between model and experiment and to carry out the comparisons in a consistent way**



  - **f_{comp}=0 => Smart Shell algorithm**
  - **f_{comp}=1 => Simple Mode Control**
- **The variation in the measured Smart Shell g_P^{max} from vacuum to plasma cases is consistent with a vessel time constant shorter by ~2 ms when a plasma is present**

Torkil tried to find ways to use the present RWM amplifiers more efficiently

"Wall Mode control"
Tradition should not be a fetter:
Is bang-bang control may be better?
A significant role
For wall mode control?
-a paper, may be just a letter?

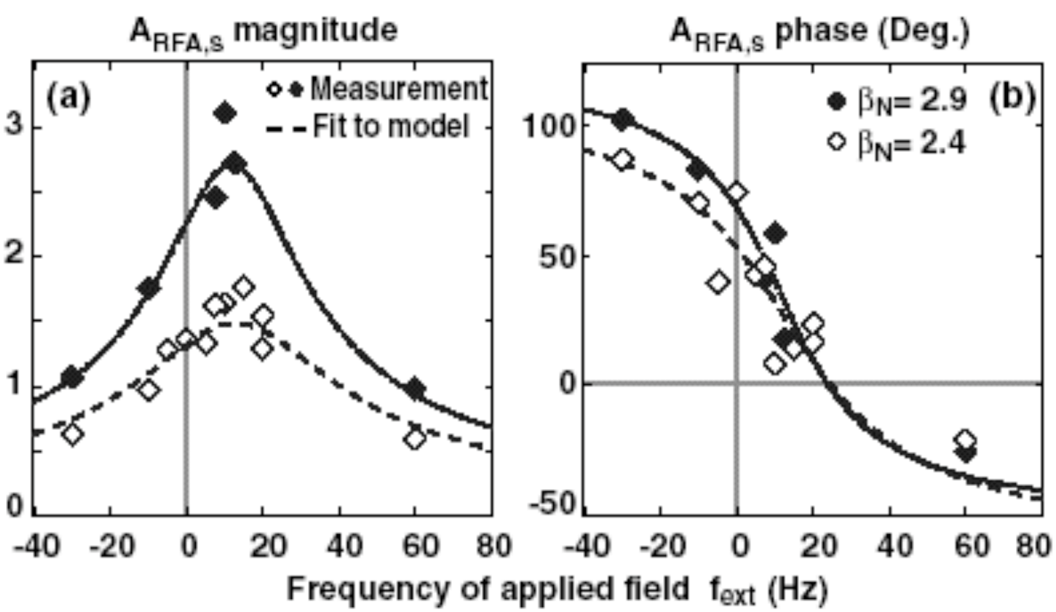
- Modeling a resistive wall mode control system of the bang-bang type
  T.H. JENSEN
  Physics of Plasmas, 2004

Active measurements of the RWM

– **Analysis of stable resistive wall modes in a rotating plasma**
  A.M. GAROFALO, T.H. JENSEN, and E.J. STRAIT
  Physics of Plasmas, 2003

- **In this paper Torkil's simple RWM model was used to interpret the first active measurements of the RWM dispersion relation, performed at DIII-D**
- **The goodness of the model is apparent when one looks at the way it describes the data from spectroscopic measurements of the RWM**

<u>Measurement of the Resistive-Wall-Mode Stability in a Rotating Plasma Using Active MHD Spectroscopy</u>
H. Reimerdes, M. S. Chu, A. M. Garofalo, G. L. Jackson, R. J. La Haye, G. A. Navratil, M. Okabayashi, J. T. Scoville, and E. J. Strait
Phys. Rev. Lett., 2004



Torkil Jensen died peacefully on May 1, 2004 after a long battle with cancer. His ashes now rest somewhere with the Pacific Ocean.
His many ideas and dreams for the field of plasma physics live on in the numerous papers he wrote and with some of us who have had the honor and pleasure of knowing him...

Torkil Jensen has gone on his way
For us, it's a very sad day
Oh, his name will be hung
On the very top rung
Of those that departed in May

Dan Baker

Many thanks to Ming Chu and Sherry Lopez for kindly providing a lot of the material used for this talk