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SUMMARY OF U.S. - JAPAN WORKSHOP ON THE THEORY OF NON-AXISYMMETRIC CONFINEMENT SYSTEMS

Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712

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SUMMARY OF U.S. - JAPAN WORKSHOP ON THE THEORY OF NON-AXISYMMETRIC CONFINEMENT SYSTEMS

December 8-12, 1980

Institute for Fusion Studies
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Austin, Texas

Contents of U.S. - Japan Workshop Summary

Program of U.S.-Japan Workshop on

"The Theory of Non-Axisymmetric Confinement Systems"
December 8-12, 1980, Austin, Texas

Monday, 2:00 PM	OPENING ADDRESS: Prof. J.A. Wheeler
2:30-5:30 PM	EQUILIBRIUM, STABILITY AND TRANSPORT Chairman: W. Horton
1. M. Wakatani	"Interchange Ballooning Mode in Stellarators"
2. H. Strauss	"Limiting β of Stellarators with No Net Current"
3. H. Grad	"3-D Transport and Code Development"
4. T. Watanabe	"Numerical Scheme for Stability Analysis Using Integral Equation in Wave Number Space"
Tuesday, 9:00AM-12:00 PM	TANDEM MIRRORS Chairman: D. Ross
1. T. Kamimura	"Monte Carlo Simulation of Radial Transport in Nonaxisymmetric Tandem Mirrors"
2. T. Kaiser	"Analytic Equilibria for Tandem Mirrors"
3. R. Cohen	"Tandem Mirror Resonant Transport"
4. T. Katanuma	"Simulation on Thermal Barrier in Tandem Mirror"
2:00-5:00 PM	WORKING SESSIONS
	Stellarators and Heliotrons Study Group Co-Chairmen: H. Grad, M. Wakatani and S. Yoshikawa
	Tandem Mirror Study Group Chairman: D. Pearlstein
	Bumpy Torus Study Group Co-Chairmen: D. Spong and H. Berk
Wednesday 9:00 AM-12:00 PM	BUMPY TORUS Chairman: J. Van Dam
1. D. Spong	"Low and High Frequency Stability in EBT"

Wednesday (Cont.)

9:00 AM-12:00 PM

2.	J. Todoroki	"Transport Theory of Non-Symmetric Torus"
3.	H. Sanuki	"Numerical Analysis for Stability in Bumpy Tori"
4.	H. Berk	"EBT Stability Theory"

2:00-5:00 PM — WORKING SESSIONS

Stellarators and Heliotrons Study Group
Co-Chairmen: H. Grad, M. Wakatani and S. Yoshikawa

Bumpy Torus Study Group
Co-Chairmen: L. Hedrick and H. Berk

"Monte Carlo Simulation of Nagoya Bumpy Torus"
Comment: T. Kamimura

Tandem Mirror Study Group
Co-Chairmen: T. Kaiser and T. Katanuma

Thursday

9:00 AM-12:00 PM — TRANSPORT AND GENERAL THEORY
Chairman: T. Kamimura

1.	S. Yoshikawa	"Stellarator Theory and Experiments"
2.	A. Boozer	"Transport in Asymmetric Devices"
3.	R. Hazeltine	"On Omnigenity"
4.	J. Derr	"Ripple Trapping in Modular Stellarators"

2:00-5:00 PM — HELIOTRON, STELLARATORS AND HELICAL PINCH
Chairman: T. Watanabe

1.	M. Wakatani	"Monte Carlo Simulation of NBI Heating in Heliotron-E"
2.	C. Chu	"Helical Pinch Equilibria with Pitch Reversal (OHTE)"
3.	M. Schmidt	"FLR Stabilization of Diffuse Profile in High Beta Stellarators"
4.	D. Barnes	"Nonlinear Stability Calculation for a Compact Torus"

Friday
9:00 AM-12:00 PM — DISCUSSION, SUMMARY, AND FUTURE PLANNING
Co-Chairmen: T. Kamimura and M.N. Rosenbluth

Stellarator and Heliotron Working Session Report
H. Grad, M. Wakatani and S. Yoshikawa

Tandem Mirror Working Session Report
T. Kaiser, T. Katanuma, W. Horton

Bumpy Torus Working Session Report
L. Hedrick, J. Todoroki, H. Berk

CLOSING REMARKS - T. Kamimura and M.N. Rosenbluth

Additional Workshop Activities

Wednesday
3:30-5:00 PM — Introduction of the Japanese Delegation to the Chairman of the Physics Department, Professor T.A. Griffy and to the Physics Department at the colloquium.

Thursday
7:00-10:00 PM — Workshop Banquet hosted by the Institute for Fusion Studies and sponsored by TRACOR, Inc.

FORMAT OF U.S.-JAPAN WORKSHOP ON NON-AXISYMMETRIC SYSTEMS, DEC. 8-12, AUSTIN, TEXAS

Monday Dec. 8	Tuesday Dec. 9	Wednesday Dec. 10	Thursday Dec. 11	Friday Dec. 12
	9:00 Opening TANDEM MIRRORS 12:00 Closing	9:00 Opening BUMPY TORUS 12:00 Closing	9:00 Opening TRANSPORT AND GENERAL THEORY 12:00 Closing	9:00 Opening DISCUSSION, SUMMARY AND FUTURE PLANNING 12:00 Closing
1:30 Opening Address-Prof. J.A. Wheeler EQUILIBRIUM, STABILITY AND TRANSPORT 5:00 Closing	1:30 Opening WORKING GROUPS	1:30 Opening WORKING GROUPS 4:00 Physics Colloq. Don Dubois, LASL Plasma Turbulence Theory	1:30 Opening HELIOTRON, STELLARATORS AND HELICAL PINCH 7:00 Workshop Dinner	1:30 Opening WORKING GROUPS

U.S.-Japan Workshop on

"Theory of Non-Axisymmetric Confinement Systems"

The University of Texas at Austin

December 8-12, 1980

Organizing Committee

W. Horton, Scientific Secretary, IFS, University of Texas
D. W. Ross, Assistant Director, IFS, University of Texas

Participants

JAPAN

A. Fukuyama	Okayama University and IFS, University of Texas
T. Kamimura	Institute of Plasma Physics, Nagoya University
I. Katanuma	Plasma Research Center, Tsukuba University
H. Sanuki	Institute of Plasma Physics, Nagoya University
J. Todoroki	Institute of Plasma Physics, Nagoya University
M. Wakatani	Plasma Physics Lab, Kyoto University
T. Watanabe	Institute for Fusion Theory, Hiroshima Univ.

UNITED STATES

D. Barnes	IFS, University of Texas
A. Bayliss	Courant Institute, New York University
H. Berk	IFS, University of Texas
A. Boozer	Princeton Plasma Physics Laboratory
C. Chu	General Atomic Co.
R. Cohen	Lawrence Livermore National Laboratory
J. Derr	University of Wisconsin
H. Grad	Courant Institute, New York University
A. Hasegawa	Bell Telephone Laboratories
R. Hazeltine	IFS, University of Texas
L. Hedrick	Oak Ridge National Laboratory
T. Kaiser	Lawrence Livermore National Laboratory
G. Miller	Los Alamos Scientific Laboratory
D. Pearlstein	Lawrence Livermore National Laboratory
T. Cayton	Los Alamos Scientific Laboratory
M. N. Rosenbluth	Director, IFS, University of Texas
M. Schmidt	Science Applications, Inc.
K-C Shaing	University of Wisconsin
D. Spong	Oak Ridge National Laboratory
H. Strauss	Courant Institute, New York University
J. Van Dam	IFS, University of Texas
S. Yoshikawa	Princeton Plasma Physics Laboratory

OTHER

E. Maschke	Fontenay-aux-Roses, FRANCE

SUMMARY OF STELLARATOR AND HELIOTRON SESSIONS

M. Wakatani, H. Grad, and S. Yoshikawa

Recent important developments in MHD codes point to where accurate values of the critical plasma pressure β_c will soon be available. Present preliminary estimates were reported to range from 0.5% to 5% for a range of unoptimized profiles and system parameters. Two codes, by Wakatani and by Strauss, are based on the same theoretical approximations of low β and large aspect ratio (stellarator expansion) with a linear initial value solution of the reduced equations; but the codes are sufficiently different in the numerical algorithms to provide an accurate check on each code, if they are both run for the same equilibrium. This check will be made soon by Strauss. The third code by Betancourt-Garabedian is sufficiently different, including finite geometry without a parameter expansion and based on the method of steepest descent instead of initial value solution, to provide a more sophisticated check on the general reproducibility of the MHD stability of the different models. Without having the codes run for identical profiles, the present "discrepancy" of a factor of two between codes is held to be irrelevant, as noted by Grad.

Since toroidal stellarator MHD stability requires three-dimensional code calculations, the physical meaning of the differences in the codes cannot be easily interpreted. Thus an understanding of the critical β for straight stellarators may be necessary for the prediction of stellarator equilibrium and stability, as noted by S. Yoshikawa. The straight stellarator suffers from bad curvature ($V'' > 0$), but has shear. Also, the ballooning mode is not dangerous as the distance between good and bad curvature regions is of the order of the pitch length, which Yoshikawa notes is not long enough to have significant ballooning.

Neutral beam heating experiments with 2.5 MW that begin next year will give some information about β limits in the Heliotron-E device.

Recent Monte Carlo simulations of neoclassical transport by M. Wakatani suggest that helical ripple effects are not as large as expected from analytic theory. More intensive studies of transport will be required before the details of the radial loss rates are understood.

Numerical computation of stellarator equilibria with finite parameters is in a well-developed state using the Garabedian-Betancourt code. A modification of this code to include classical Braginsky transport (and incidentally speed up the code) will soon be available (Bayliss, Betancourt, Grad).

SUMMARY OF TANDEM MIRROR EQUILIBRIUM, STABILITY, AND TRANSPORT

T. Kaiser, T. Katanuma, and W. Horton

The current status of MHD equilibrium and stability studies at Livermore was summarized by L.D. Pearlstein and T. Kaiser. It is now possible to calculate three-dimensional anisotropic equilibria for straight-axis large-aspect-ratio configurations to the first order in β. These equilibria are essentially analytic in that the only numerical calculations required are quadratures of known vacuum field quantities. The ballooning stability of these equilibria is determined by Pearlstein and Kaiser using a computer code which solves on each field line the eigenmode equation derived from the guiding center energy principle. Localization to a field line is the result of using an eikonal representation of the waves perpendicular to the magnetic field. In more recent calculations, finite-Larmor-radius effects have been included according to the kinetic theory of Tang and Catto and found to be strongly stabilizing in the zero-perpendicular-wavelength limit.

The most serious deficiencies of the MHD calculations to date are acknowledged to be the limitation of the equilibrium calculation to first order in β, and of the stability calculation to infinite $k_\perp$. Several approaches to overcoming these difficulties have been suggested and are under active consideration by the Livermore group.

Regarding the equilibrium calculations, the general equations (that is, to all orders in β) have been derived by Pearlstein, Kaiser and Newcomb; but the solution of the reduced equation remains elusive. One promising approach is an iterative one in which an equilibrium calculated by present techniques for a particular value of β would be linearly perturbed to obtain another equilibrium of incrementally higher β. This procedure could be repeated, thereby generating a succession of equilibria of increasing β. Another interesting approach is to minimize the magnetic field and plasma energy in the large-aspect-ratio limit with appropriate constraints, à la the Betancourt and Garabedian calculation for toroidal equilibria.

The real importance of FLR stabilization cannot be assessed until the stability of modes with $k_\perp r_p \sim 1$ can be investigated. The most promising approach for going beyond the infinite-$k_\perp$ limit appears to be a two-dimensional WKB treatment in which Einstein-Brillouin-Keller quantization techniques would be employed; this line is currently being pursued at Livermore. Other possiblities include construction of a PEST-like code for tandem mirrors, and solution of the nonlinear MHD equations in the large-aspect-ratio limit as an initial value problem.

The first work on radial transport in the tandem mirror reported at this workshop was by Kamimura using Monte Carlo simulations of the nonaxisymmetric system. The objective of these simulations was to investigate resonant particle diffusion, which will be a large loss mechanism as long as nonaxisymmetric plug coils are used. In the simulation model, the potential profile was assumed to be such that the particles' azimuthal drift $\Delta\psi$ is independent of the radial distance from the axis. The results of the Monte Carlo simulations show that the observed diffusion is in agreement with the theoretical resonant diffusion formula. However, the confinement time in the TMX experiment is longer than that of the simulation when the ambipolar potential Φ_0 of the experiment is used. The simulation results described by Kamimura show that the radial diffusion coefficient becomes large with large Φ_0. Hence, the next subject to investigate is the potential profile dependence of the radial diffusion, which will be carried out soon at Nagoya.

Work on the simulation on the physics of the thermal barrier in tandem mirrors was reported by Katanuma. The object of this work is to investigate the barrier physics using self-consistent one-dimensional particle simulation codes. To include mirror effects partly in the one dimensional simulation, a force term is added to the electron and ion equations of motion. The system thus includes the acceleration and deceleration regions due to the mirror forces. The results of the simulation as reported by Katanuma, show that in a steady state, a large potential dip is observed in the mirror region along with an expected dip of the plasma density, although a sheath-like profile of the potential at the edge of the mirror was also observed.

The next step will be to undertake a more quantitative investigation of this result by using 2D or 3D particle simulation codes that will include more realistic effects.

Analytic theory of radial transport in the tandem mirror system was reported by Cohen. For given axial magnetic and potential profiles, the guiding center equations of motion can be integrated approximately over one axial bounce period to determine the successive radial and azimuthal positions. In this manner Cohen derived mapping equations with an extrinsic stochasticity parameter σ for collisions and a nonlinear resonance overlap parameter K. In the asymptotic limits of small and large σ and K, analytic formulas were obtained for the guiding center diffusion. In the transition regions where σ and K, which are functions of energy and magnetic moment, are of order unity, the analytic formulas are joined by interpolation. To facilitate comparison of the simulation transport and the analytic transport, it was suggested that the accuracy of the mapping representation of the continuous dynamics should be tested for samples of particles which contribute strongly to the loss rates.

Complete radial transport equations for the ion and electron densities and temperatures are obtained form the test particle diffusion by integrating over the Maxwellian distributions. Solutions of the transport equations were discussed by Cohen, who pointed out the occurence of a bifurcation in the rotational states obtained by radial charge balance. The multiple rotational states lead to difficulties similar to those already encountered in bumpy torus transport studies. The tandem mirror group and the bumpy torus group compared their experiences in this area.

SUMMARY OF BUMPY TORUS SESSIONS

L. Hedrick, D. Spong, J. Todoroki, and H.L. Berk

The bumpy torus working sessions began with a summary of the various areas in which theoretical work is underway and of the people involved in each area in the U.S. and Japan. During the workshop, talks concerning calculations in the areas of equilibrium, stability, and transport were presented.

Hedrick described a number of important results that have been obtained at Oak Ridge. Data from recent toroidal experiments on EBT and NBT, as well as from the linear STM experiment and several simple mirror experiments at Oak Ridge and Nagoya, in both the fundamental and standard resonance modes, were noticed to all fit the empirical relationship $\rho/L \cong$ constant (to within 20%), with ρ the ring electron gyroradius and L a typical equilibrium scale length. It was suggested that this may be related to a recent finding from numerical computations, which is that at high energies approximately equal to the experimentally observed hot electron ring temperature ($\simeq$ 500 keV), the magnetic moment μ is no longer an invariant but begins to fluctuate in a way that tends to prevent a hot electron from reaching the resonant zone.

Particle motion studies in time varying electromagnetic fields have also found that the lower energy electrons exhibit large periodic charges in energy. A hybrid treatment using Monte Carlo techniques for low energy electrons and quasilinear theory for high energy electrons thus appears to be a more adequate approach than existing quasilinear heating theories for treating the formation of the hot electron rings from the much cooler toroidal core plasma.

The main confinement features of the toroidal core plasma are reasonably well described by neoclassical transport calculations, partly because the dominant electron transport is better understood than ion transport. Recent 1½D transport studies that include both normal and reversed gradient regions were similar in global features to earlier 1D results.

The ions observed experimentally in EBT have an enhanced population at large energies. Using <u>ad hoc</u> ion tails in the 1½D transport codes has yielded increased ambipolar potentials, closer in magnitude to those seen in the experiment. Furthermore, neoclassical Fokker-Planck calculations have indicated that very little power (e.g., 10^{-3} of that supplied to the torus by ECH) is needed to create a substantial tail by either classical or <u>ad hoc</u> non-classical mechanisms. The latter could represent ion heating by fluctuations (e.g., internal generation of ICRH or lower hybrid heating). Theoretical and experimental investigation of the significance of such non-classical mechanisms is underway at Oak Ridge.

Very recent Monte Carlo transport calculations were reported by Kamimura. These preliminary calculations in vacuum magnetic fields are for ions alone and neglect the ambipolar electric field. Subsequent work on including the effects of the finite beta hot electron rings and the ambipolar electric field is planned in Japan.

Todoroki reported progress in the general theory of transport in three dimensional systems with anisotropic pressures. The theory presented uses natural magnetic coordinates for the high beta equilibrium and yields general but complicated formulas for the transport equations.

Boozer described recent work on the high beta, three dimensional transport porblem using fluid theory and non-single-valued magnetic flux coordinates.

A numerical analysis of bumpy torus equilibrium using time dependent fluid equations with tensor pressure was presented by Sanuki. The initial position of the hot electron ring was found to shift inward to approach equilibrium when the ring pressure was increased for fixed bulk plasma pressure. However, for fixed ring pressure, the shift was inward for low bulk pressure, but outward for higher pressure, with no shift when the ratio of ring to bulk pressure was about 7 - 9.

Stability calculations being carried out at Oak Ridge and at the Institute for Fusion Studies were reported by Spong and Berk, respectively. Both groups agreed on the existence of a new instability due to coupling of the core plasma Alfven wave with the free energy of the hot electron ring. The Alfven mode leads to an upper limit on the core plasma density, whereas interchange stability of the hot electrons leads to a lower limit on the core density. Theory indicates a stability window consistent with present EBT operation. Another interchange mode limits the core plasma pressure, especially during strong heating. This background interchange mode and the Alfven mode are generally exclusive: one will be unstable where the other is stable. For present and near-term devices, theory predicts the Alfven limit to be most relevant. In reactor devices, the Alfven mode poses no difficulty, but background interchange stability may be restrictive. Also, although the Alfven mode has features similar to the T-M transition, there are discrepancies with the power and ring beta scalings.

The current calculations are based on either slab geometry approximations or expansions in the ratio of the magnetic gradient scale length to the radius of curvature. More sophisticated theories have been formulated, involving finite geometry, finite hot electron and ion gyroradius corrections, radial mode structure, relativistic effects, and bounce motion and longitudinal dependence. A result has been obtained indicating that Larmor radius effects, above a certain level, could improve the interchange stability limit. Also, a consideration of the Alfven mode radial dependence has shown that either bulk modes, where the perturbed field varies negligibly over the annulus, or body modes, whose wavelength is less than the annulus width, are possible, with the body modes being more difficult to stabilize. The ORNL and IFS groups agreed to continue work together on the radial structure problem.

U.S. - JAPAN JOINT WORKSHOP

INSTITUTE FOR FUSION STUDIES, AUSTIN, TEXAS

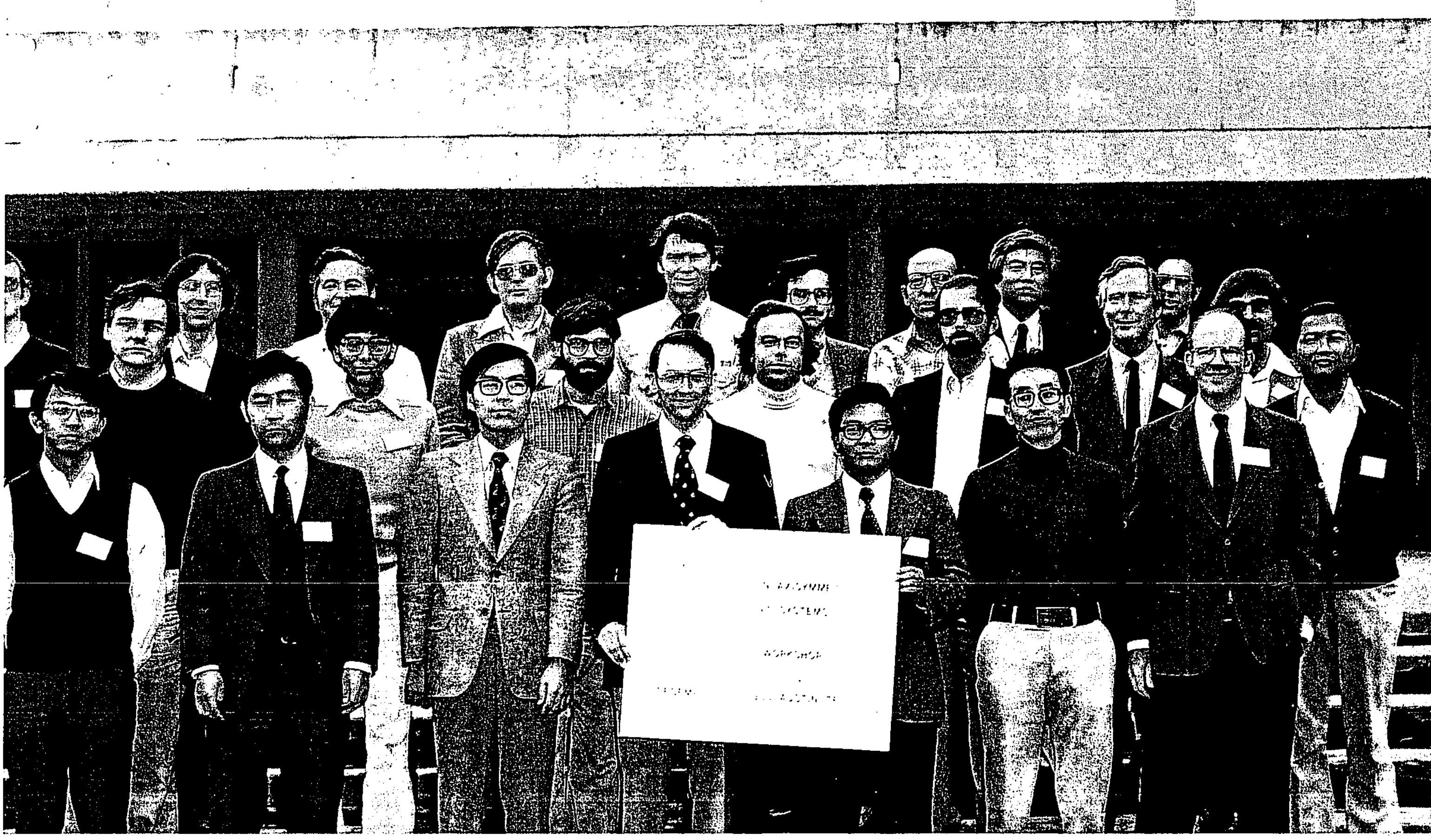
DECEMBER 8-12, 1980

GUIDE TO GROUP PHOTOGRAPH

R.Cohen, H.Berk, T.Cayton, G.Miller, A.Bayliss, D.Pearlstein, S.Yoshikawa, H.Strauss, T.Kaiser

J.Van Dam, R.Hazeltine, K-C Shaing, M.Schmidt, A.Boozer, D.Spong, E.Maschke, C.Chu

T.Watanabe, A.Fukuyama, J.Todoroki, M.Wakatani, D.Ross, T.Kamimura, H.Sanuki, W.Horton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