Newsletter

JOINT INSTITUTE FOR FUSION THEORY

June 1988 **No. 11**

The Institute for Fusion Studies (IFS) at The University of Texas at Austin and the International Center for Fusion Theory (ICFT) in Nagoya work together to form the Joint Institute for Fusion Theory (JIFT). The primary purpose of JIFT is to foster the progress of scientific research by providing a planned set of exchange visits, workshops, and computational projects that involve United States and Japanese theoretical plasma physicists working on problems associated with the development of fusion systems.

The JIFT Steering Committee members are:

Dr. David E. Baldwin - Director of IFS, The University of Texas at Austin
Prof. John M. Dawson - University of California at Los Angeles
Prof. Yoshi H. Ichikawa - Director of ICFT, Nagoya University
Prof. Kyoji Nishikawa - Hiroshima University
Dr. Walter Sadowski - Chief, Fusion Theory and Computer Service, U.S. Dept. of Energy

JIFT activities are coordinated in the US and Japan by two committees. The Japanese Management Committee consists of T. Kamimura (IPP)—Chairman, T. Sato (HIFT), T. Takeda (JAERI), and M. Wakatani (Kyoto). The US Management Committee consists of W. Horton—Chairman, A. Aydemir, J-N. Leboeuf (ORNL), T. Tajima, P. Terry and J. Van Dam.

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EXCHANGE SCIENTISTS for 1988 to 1989

From US to Japan

1. *Plasma Modeling and Particle Simulations* — **IL 24**
   C.K. Birdsall, UC, Berkeley, Visiting Professor to IPP Nagoya
   August 1988

2. *Alfvén Wave Heating and Anomalous Transport* — **IL 25**
   S. Mahajan, IFS, Visiting Scientist to IPP Nagoya and Hiroshima
   March 1989

3. *ECRH Heating* — **IL 26**
   Y. Matsuda, LLNL, Visiting Scientist to Nagoya and Hiroshima
   April 1988

From Japan to US

4. *Theoretical Study of Toroidal Helical Plasmas* — **JL 19**
   M. Wakatani, Kyoto, Visiting Professor to IFS, ORNL, and PPPL

5. *Theoretical Study on Sustainment Mechanism of RFP Configuration* — **JL 20**
   K. Kusano, HIFT, Visiting Scientist to IFS and GA

6. *3D MHD Simulation in Torus Geometry* — **JL 21**
   N. Nakajima, IPP Nagoya, Visiting Scientist to IFS and LANL

WORKSHOPS for 1988 to 1989

To be held in Japan

1. *Structures in Confined Plasmas* — **I 23**
   Y. Ichikawa and W. Horton
   March 1989 (in Nagoya)

2. *Edge Plasma Physics* — **I 24**
   T. Sato and F. Hinton
   November 1988 (in Hiroshima)

To be held in US

3. *Kinetic Modification of MHD Modes, Second Stability, and Alpha Particle Dynamics in Toroidal Systems* — **J 20**
   M. Wakatani (Kyoto) and R. White (PPPL)
   December 1988 (in Princeton)

4. *Numerical Simulation for Reversed Field Pinches* — **J 21**
   T. Sato (HIFT), Y. Ichikawa (Nagoya), D. Schnack and B. Grossman (SAIC)
   January 1989

5. *Steering Committee Meeting* — **J 22**
   November 1988 (in US)

JOINT COMPUTATIONAL PROJECTS for 1988 to 1989

1. *MHD Stability and Control of a High Beta Tokamak* — **JC 1**
   T. Takeda, T. Tsunematsu, and S. Tokuda (JAERI),
   J. Manickam (PPPL)

2. *Gyrokinetic Transport Simulation* — **JC 2**
   T. Kamimura, H. Naitou, and Y. Abe (Nagoya),
   J. Dawson, V. Decyk, and R. Sydora (UCLA), and W. Lee (PPPL)

3. *Implicit Methods for Particle Simulation Codes* — **JC 3**
   T. Kamimura and Y. Abe (Nagoya)
   J.N. Leboeuf (ORNL), T. Tajima, and A. Aydemir (IFS), and D.C. Barnes (SAIC)

4. *Plasma Rotation and Anomalous Transport* — **JC 4**
   A. Aydemir, W. Horton, J. Meiss, and T. Tajima (IFS)
   K. Nozaki and T. Taniuti (Nagoya) and N. Bekki (Nihon)

EXCHANGE SCIENTISTS
Reports from 1987 - 1988

Masao Okamoto
Visiting Scientist

Location: IFS, Austin
Date: November 16, 1987 - March 15, 1988

Dr. Masao Okamoto, of the Institute of Plasma Physics, Nagoya University, visited the IFS for four months. There he developed a theory on steady state current drive in the field reversed configuration (FRC) in collaboration with Professor H.L. Berk.

Drs. Okamoto and Berk considered the rotation of a beam driven steady state FRC. The steady state occurs when an input beam produces a seed current (or equivalently an effective voltage) through either the Ohkawa effect (when $Z_{eff} > Z_{beam}$), or magnetic pumping (if the FRC is imbedded in a multipole field).

It was found that without multipole fields the back current is inhibited by the Ohkawa effect. However, the resulting rotation of the plasma often leads to instability. For systems with a large bootstrap effect the rotation can be moderate, but it is then difficult to contain fusion products. In the presence of quadrupole fields they found that the back current is inhibited due to magnetic pumping. In this case, a steady state configuration with moderate input power can be maintained in both reactors and present day experiments. The resulting rotation seems slow enough to fulfill stability conditions.

Dr. J.H. Hammer from LLNL also joined the collaboration. Their combined results of calculations were presented at the workshop on *Steady State Compact Toroids for Fusion Systems* held at LLNL, March 2-3, 1988 and at the Sherwood Theory Meeting in Gatlinburg, Tennessee, April 16-18, 1988.

During his visit to the United States, Dr. Okamoto also travelled to Princeton Plasma Physics Laboratory where he stayed for three weeks. There he collaborated with Dr. M. Ono from PPPL on numerical simulation of ion Bernstein wave heating with application to the JIPP T-IIU tokamak of IPP, Nagoya. Using the BALDUR transport code they obtained reasonable agreement with the experimental results.

John L. Johnson
Visiting Professor

Location: IPP Nagoya
Date: August 17, 1987 - December 19, 1987

Dr. John Johnson, from Princeton University Plasma Physics Laboratory, visited Japan for four months, spending the first and last months at Nagoya University IPP and the other two months at Kyoto University Plasma Physics Laboratory. While in Nagoya he collaborated most closely with J. Todoroki on three different subjects: (1) comparisons of the STEP and H-APPOLO numerical codes for determination of stellarator equilibrium, with emphasis on the differences in formulation; (2) equilibrium and stability calculations for the LHS stellarator; and (3) application of averaged codes like STEP and H-APPOLO to the investigation of the effect of plasma currents on the magnitude of the toroidal field ripple in tokamaks with discrete coils. He worked with M. Wakatani and his colleagues at Kyoto on making improvements and extensions to the STEP code and on MHD studies for LHS. This work led to a technique for using two-dimensional codes to investigate the MHD stability of three-dimensional configurations, an idea that is being developed. He had many discussions with members of the staff of both universities concerning the LHS device, including questions of its purpose, the need for flexibility in the design, the desirability of large or small rotational transform, and the arguments that can be made for and against the use of superconducting coils. While at Nagoya he prepared and presented a series of lectures on *Magnetohydrodynamic Techniques for Toroidal Confinement Studies* which was published as an IPP report entitled *Adventures in Magnetohydrodynamics*, Report No. IPPJ-862 (March 1988). At both institutions he also gave seminars on the effect of plasma current on the toroidal field ripple in tokamaks. The current status of stellarator research was detailed in seminars presented at Hiroshima University, Nihon University, JAERI, and Chubu University. While in Kyoto he gave an invited paper on *Net Currentless Confinement in Stellarator/Heliotron* at the Japanese Society of Plasma Science and Nuclear Fusion Research.

WORKSHOPS
Reports from 1987 - 1988

MHD Relaxation Processes
Organizers: T. Sato and T. Hayashi (University of Hiroshima)
D. Schnack (SAIC) and W. Horton (IFS)
Location: Hiroshima University
Date: March 16-20, 1987

This workshop was attended by ten Japanese scientists and seven U.S. scientsts. The U.S. delegation included D. Schnack (SAIC), D. Monticello (PPPL), A. Bhattacharjee (Columbia University), A. Aydemir (IFS), C.Z. Cheng (PPPL), W. Horton (IFS), and W. Sadowski (DoE). This work focused on theoretical and computational studies of resistive MHD relaxation processes in current carrying plasmas. Both the intrinsic dynamo current drive mechanisms of the turbulent reversed field pinch (RFP) and the possibility of current drive by helicity injection with externally applied oscillating magnetic fields were reported and described at the workshop. It was pointed out that anomalous heat transport is apparently intrinsically related to the self-sustaining dynamo effect in the RFP. The turbulent dynamo and anomalous transport scaling laws were considered both theoretically and from simulations. Theoretical results for the turbulent transport of magnetic flux and thermal energy based on renormalized turbulence were discussed. Both resistive MHD code and kinetic theory code results for the m = 1 dynamics in tokamaks were reported with new results being given for the growth and nonlinear evalution of the internal reconnection ($q \leq 1$) and sawteeth activity. The classical calculation of compressible, driven reconnection was repeated with

improved, higher order algorithms that show in more detail the current sheet structure and the slow shock-like structures occurring in the classical problem of reconnection physics. Onset conditions for anomalous resistivity from the current-sheet driven micro-turbulence were reported and discussed with respect to the subgrid scale modeling.

Plasma Modeling with MHD and Particle Simulation
Organizers: C. Birdsall (UC Berkeley) and T. Kamimura (IPP Nagoya)
Location: Napa Valley, California
Date: September 25 -26, 1987

Seventeen US scientists and seven Japanese scientists participated in this workshop. The Japanese delegation consisted of H. Abe (Kyoto University), T. Kamimura (IPP, Nagoya), H. Naitou (IPP, Nagoya), K. Nishihara (Osaka University), T. Sato (Hiroshima), T. Takeda (JAERI), and M. Tanaka (Hiroshima). This workshop was the third in a recent series of simulation workshops on new modeling techniques. The papers which were presented described simulations with scales ranging from microscopic (Debye length in simulation of the plasma-wall interaction) to scales on the order of the size of fusion devices (ICRF antenna coupling to the tokamak cavity) to multiscales in time and space. All of the techniques were applied to fusion problems. The simulation techniques included implicit particle simulation, high accuracy particle-particle particle-mesh codes, macroscale implicit particle simulation, multi-scale particle simulations, gyrokinetic particle simulations, fluid-particle hybrid simulation, a CFL condition free semi-implicit scheme, and the use of multigrid, multiblock architecture. The fusion problems addressed by these simultions included hot electron stabilization, potential formation in a mirror system, laser produced dense plasmas, plasmas bounded by conducting walls, relativistic electron beam injection into a magnetized plasma, intense ECH and beat-wave current drive, 3-D modeling of ICRH, relativistic electron beam propagation through a diffuse plasma, and MHD modes and plasma instabilities.

The conclusions, prepared by the workshop's organizers, noted the challenges faced in doing fusion computation and cited 2-D electromagnetic simulations with widely disparate space scales, multiple time scale simulations, and whole-machine global simulations as examples. The need to use a variety of methods in any one problem was stated. It was also noted, however, that improvements in computer speed, memory, and parallel processing are making the task of software writing easier. Because these workshops provide the principal researchers in the US and Japan with a clearinghouse for exploring and verifying new methods and broadening applications, it was strongly recommended that this series of workshops continue.

Large Gyroradius Equilibrium and Stability Theory
Organizers: H. Momota (IPP Nagoya) and H. Berk (IFS)
Location: Niigata University
Date: September 28 - October 2, 1987

Fifteen scientists met in Niigata, Japan for the workshop on large gyroradius equilibrium and stability. The US delegation consisted of H. Berk (IFS), G. Miley (Illinois), E. Morse (UC Berkeley), L. Steinhauer (Spectra Technology), and M. Tuszewski (LANL). The emphasis of the workshop was to discuss finite Larmor theory as it applies to fusion experiments, particularly the Field Reversed Configuration (FRC). Several talks were given on the status of FRC experiments, and most of the theoretical papers detailed attempts to better describe the equilibrium and stability of an FRC. Related stability problems such as the properties of a beam injected tokamak and the stability of mirror-like configurations with hot particles were discussed as well.

Several experiments were reviewed. Formation techniques which combine theta pinch formation and forced field line tearing to produce reliable, clean, and hot FRC's were described. The plasma equilibrium seems properly described by relatively simple analytic expressions based on MHD theory. FRC stability, however, is not understood theoretically. No clear indication of a tilt mode has been obtained. The m = 2 rotational mode, which has caused configurational

termination in the past, is under control, either from the use of quadrapole or helical stabilization fields, or by various methods to delay the unstable onset to beyond a confinement time. FRC experiments at Spectra Technology have succeeded in producing configurations lasting many growth times (typically the plasma lifetime is ≥ 100 MHD tilt growth times, or equivalently ≥ 20 kinetic tilt growth times). Magnetic perturbations during formation may indicate a transient tilt; however, the interpretation is not unambiguous. Experimental development of FRC's with larger $\overline{s}$ (ratio of minor radius to mean Larmor radius) was described. These plasmas are characterized by low energy and short magnetic flux confinement. Consequently more progress is needed to produce hot plasmas with larger $\overline{s}$. Successful FRC translation experiments at the University of Osaka were detailed. In these experiments, it has been demonstrated that the integrity of an FRC is maintained even with mirror reflections. The temperature of the translated plasma is found to be 0.8 of its temperature at formation. Of considerable interest is the observation that the particle lifetime is of order 150 μs, which is 4-5 times larger than the particle lifetime of the untranslated plasma. The particle lifetime τ_n is found to scale as $\tau_n \propto \overline{s}$.

The theoretical presentations focused on FRC equilibria, stability, novel concepts for stabilization, and the inclusion of more realistic physics for the description of FRC's. Equilibrium studies included a model relating the variation of $\overline{s}$ and β with a given amount of seed current and specified particle and energy transport rates, and a model providing for a steady state field reversed system on the basis of cross field electron viscosity. Results of a one-dimensional Vlasov equilibrium code were presented which showed that for the class of distributions considered, an electrostatic potential is required for finite electron temperature. Equilibrium and stability from a Vlasov code permiting solution even with stochastic orbit behavior was discussed. The results suggested a minimum in the growth rate of tilt/precessional instability for $\overline{s} \approx 2$.

The results of a hybrid particle code showing FRC stability to the rotational mode were presented. With as few as 1% of the particles orbiting near the field null but with directed particle kinetic energy comparable to the stored energy of the background plasma, stability was achieved in the simulations. Stability theory for plasmas with hot particles which has been applied to mirror and EBT plasmas was reviewed and its application to FRC's discussed. The stabilization of the $n = 2$ rotational instability by a multipole field was detailed in the context of ideal MHD theory. By modifying the theory to account for the finite length of the plasma column, agreement with experimental thresholds of multipole field for stabilization has been obtained to within a factor of two. A presentation of a two-fluid MHD model of an FRC plasma including non-standard MHD effects such as the Hall current, finite electron pressure, rotation of ions, and equilibrium electric field was given. A variational analysis including these effects obtained stability of a Hill's vortex-like solution for sufficiently large elongation (Hall current stabilization) and for a ratio of rotational to thermal velocities at the null in excess of 1.33 (ion rotation stabilization).

The issue of hot particles was further explored in the context of SPAC, a tokamak-like device with a large component of relativistic electrons supplying the toroidal current. Theoretical calculations applicable to this device were described which indicated that the safety factor can be less than unity on axis as long as the safety factor is greater than unity at the edge. Injection of an energetic beam into a toroidal plasma, particularly for an advanced fuel, in order to provide stabilization against tilt and kink modes was also discussed. Stabilization of FRC plasmas by the ponderomotive force was proposed. Studies to determine antennae design and methods appropriate for high beta are needed. The need to include additional physics in FRC theory was also underscored in several presentations. These presentations emphasized the need to explore edge physics in order to explain the plasma observed outside the separatrix and, in particular, the structure of the electrostatic potential; the role of loss cones in determining the FRC lifetime; and the role of charged fusion products in the FRC equilibrium.

The meeting summary, prepared by its organizers, mentioned the following points as indicative of the overall status of the discipline discussed in the meeting:

(1) Stable FRC plasmas have been produced with $\overline{s} \leq 2$. It remains to be established in the next phase of experiments whether long lived, hot, FRC plasmas can be made with larger values of $\overline{s}$.
(2) A kinetic stability theory is beginning to emerge. It is highly computational in character and it involves sophisticated numerical techniques. Nonetheless an analytic theory is still needed to better understand computer results. There is still concern that the kinetic theory may lack some important physics aspects of the experiment associated with plasma loss mechanisms.
(3) More reliable and accurate transport theories are needed to describe present experimental data and to study systems that would be useful in reactors. Turbulent transport will almost certainly have to be developed in order to explain FRC phenomena.

Stability and Current Drive in Toroidal Systems
Organizers: P. Rutherford (PPPL) and K. Itoh (Kyoto)
Location: Kyoto University
Date: November 16-19, 1987

At this workshop, held at Kyoto University, seven U.S. scientists and some twenty Japanese scientists gathered to discuss current drive and stability in toroidal systems. The U.S. delegation consisted of B. Carreras (ORNL), V. Chan (GA Technologies), R. Kleva (Maryland), M. Kotschenreuther (IFS), W. Park (PPPL), D. Pearlstein (LLNL), and P. Rutherford (PPPL). Topics covered at the workshop included the physical processes of current drive (especially the role of suprathermal particles), novel types of current drive (especially those involving electron-cyclotron waves), bootstrap current effects, experimental results on lower-hybrid current drive (LHCD) from JT-60 and ASDEX, and the effects of current drive on stability (especially m = 1 modes and sawteeth).

The stability of the resistive m = 1 mode and the prospects for sawtooth suppression by rf current drive were the topics of several presentations. The results of numerical studies of m = 1 resistive stability for low shear at the q = 1 surface were presented. TEXTOR-like profiles for sufficiently low aspect ratio were shown to be stable, whereas flat q(r) profiles with an off-axis dip to a $q_{min} \lesssim 1$ were unstable to m = 1 "double" tearing modes. A scenario was also presented in which strong line radiation produces steepened j(r) profiles outside the sawtooth region and results in a succession of sawtooth crashes due to m = 1 "double" tearing modes. Eventually q(0) pushes well above unity and a strong m = 2 mode leads to a "density limit" disruption.

The suppression of sawteeth and m = 1 modes by current drive and current drive feedback (current profile control) was discussed in several presentations. Electron cyclotron current drive (ECCD) with a resonant surface outside the q = 1 radius was demonstrated to produce profiles stable to the m = 1 mode. The electron cyclotron power required to shape the current profile directly by ECCD was found to be much less than for indirect current profile shaping by electron cyclotron heating. The control of m = 1 modes by rf current-drive feedback for TEXTOR-like profiles was shown to require manageable feedback power. Inclusion of hot electrons inside the magnetic island and their radial diffusion in the theory of rf current-drive feedback led to the conclusion that a high degree of localization of the rf power is desirable. Large pressure peaking within magnetic islands was also shown to lead to stabilization of the m = 1 mode.

Experimental results on the suppression of MHD-like modes by lower hybrid current drive (LHCD) were presented for the tokamaks WT-3, ASDEX, and JT-60. In the small tokamak WT-3, an increase of LHCD power initially results in sawtooth suppression, leaving an m = 1 mode that disappears at higher power. At the highest power, it is possible to excite very large sawteeth with fast crash times. On ASDEX, sawtooth suppression occurs only for LHCD [suppression is not observed with lower hybrid heating (LHH)] and only at low density, implying that suppression results from a change in the current profile and requires a substantial rf-driven current. When

LHCD is added to a neutral-beam-heated-discharge, suppression occurs with decreased lower hybrid power. An m = 2 mode is observed after suppression but only in discharges with low q(a) (< 2). With both LHCD and LHH, the sawtooth period increases. This is explained in terms of enhanced conductivity from a suprathermal electron population which is created in all but the highest density discharges. In JT-60, m = 1 modes and sawteeth are generally suppressed with LHCD, although an m = 2 mode is sometimes observed during the NBI phase. When the neutral beam is injected into a plasma that has been prepared with LHCD, an improvement in the incremental confinement time is observed. This is attributed to the fact that the current profile is broadened with LHCD. At high NB power (> 18 MW) and moderate densities, an H-mode-like transition is seen when about 5 MW of LHH power is added. Improvement in stored energy is transient because the LH power tends to be reflected by the higher edge density associated with the H-mode.

Several presentations dealt with neoclassical MHD effects. Bootstrap destabilization of finite-amplitude magnetic islands arising from the deficit in parallel (bootstrap) current within the magnetic island was discussed with predictions of island widths (low m) on the order of 10% of the plasma radius. Smaller islands (those initially smaller than 1-2 cm in TFTR) would be stabilized by cross-field diffusion of current-carrying electrons. Anomalous bootstrap currents were shown to arise from drift wave turbulence with an asymmetric wavenumber spectrum; and the possibility of enhancing the bootstrap current to tokamak-like levels in ATF-1 with particular magnetic configurations was also discussed.

The Japanese work on rf modeling was prominently represented at the workshop. The behavior of fast electrons in slideaway and LHCD discharges was described from a Fokker-Planck study which suggested that the energy in the fast electrons is not sufficient to account for improvements in the confinement observed experimentally, but that a decrease in fluctuations due to enhancement of the conductivity must be invoked. LHCD efficiency was addressed with reports based on both the Fokker-Planck/transport code and an analytic model. Details were given of ICRF simulations of JET discharges which included propagation and absorption of ICRF waves, suprathermal minority-ion distributions, and thermal plasma transport. Results were reported which were in good agreement with JET data with the exception that the m = 1 ideal kink was more easily destabilized and had a shorter period in the simulations than in experiment. Analyses of ICRF heating by second harmonic resonances with neutral-beam-injected energetic ions were presented, with the conclusion that the energetic tail dominates the absorption process. A model for combined NBI and LHCD in JT-60 which included ray tracing rf, quasi-linear Fokker-Planck rf-driven electrons, and radial current diffusion was discussed. It was necessary to include an ad hoc "hot" electron tail in order to fit JT-60 data on current profile, suppression of the m = 1 mode, and the onset of the m = 2 mode.

Advanced current drive techniques were discussed in two presentations. Nonlinear processes arising in high power, pulsed electron cyclotron current drive were described. Good efficiency (comparable to LHCD) and good accessibility were predicted for beat wave current drive, but accurate focusing of the two beams is crucial in order to avoid backscatter. A study of fast wave current drive was described with a favorable prognosis offered for an upcoming experiment on JFT-2M.

JIFT Steering Committee Meeting Report

Location: Nagoya University
Date: March 21-22, 1988

The JIFT Steering Committee met in Nagoya on March 22 to consider the schedule for workshops, exchange visits, and computational projects for the period April 1988 to March 1989. David Baldwin, John Dawson, and Wendell Horton represented the U. S., and Yoshi Ichikawa, Kyoji Nishikawa, and Tetsuo Kamimura represented Japan. Prior to the Steering Committee Meeting informal discussions were held in which each side described the changes in the fusion and the theory programs taking place in the two countries. Plans for the new Plasma Institute at Toki were described. The Toki site will have a new theoretical organization that will have a number of

new professorships and associated positions. Once operational in mid-1989, the new theory institute at Toki will be more comparable with the Institute for Fusion Studies in the United States.

Also participating in the Steering Committee were Prof. T. Sato, H. Momota, M. Wakatani, M. Ohkamoto, T. Takeda, T. Kamimura, R. Sugihara, T. Hatori, and N. Nakajima. After the presentation and approval of the 1988-89 JIFT exchange program given below, there was dicussion of several topics including: whether the present level of exchanges is appropriate or too intensive; new areas or exchanges, such as physics issues associated with helical systems; and what the physics issues are for plasmas producing a significant alpha particle power.

Miscellaneous...

Suggestions for topics of future JIFT workshops, exchanges, and data link projects should be transmitted to any member of either the U.S. or the Japanese Management Committee.