MEETING REPORTS

SUMMARY OF THE TENTH U.S.-JAPAN WORKSHOP ON COMPACT TOROIDS, GOHRA, HAKONE, JAPAN, NOVEMBER 14-16, 1988

BACKGROUND

The purpose of the workshop was to discuss extensively the formation, stability, and confinement of compact toroid plasmas [spheromak and field-reversed configuration (FRC)], and to pursue the feasibility of a D-^{3}He/FRC reactor. This workshop was mainly supported by the Japan-U.S. Scientific Collaboration Program P114 (1988), under which 12 U.S. scientists came to Japan and held discussions with 29 Japanese scientists. Twenty-six papers were presented.

The key figures of the workshop were K. Watanabe (Osaka University) and W. F. Dove (U.S. Department of Energy). The technical leaders were Y. Nogi (Nihon University) and L. C. Steinhauer (Spectra Technology).

REVIEW OF PRESENTED PAPERS

Y. Kato (Osaka University) reported that the CTCC-II spheromak was confined in a spheroidal flux conserver for ~1.2 ms at close shots and 1.5 ms at good shots. Detailed measurements of magnetic fields in the spheromak made clear the existence of a flux hole having no toroidal field. A stainless steel plate covering the choking field coil acts as a current limiter for the flux hole. It enhanced the magnetic shear near the plasma surface and improved the stability of the plasma.

N. Satomi (Osaka University) described the efforts to measure the electron temperature of the CTCC-II spheromak. Two vacuum ultraviolet spectrometers, a triple Langmuir probe, and a Thomson scattering system were prepared. The intensity ratio of OVI lines (1032 Å, 150 Å) showed 30 to 50 eV for the core plasma. The temperature of the peripheral plasma was 10 to 20 eV, which was estimated by using two OV lines (630 Å, 193 Å) and the Langmuir probe. These results were not conclusive because the cross check between the above values and the Thomson scattering temperature have not been made.

M. Nagata (Himeji Institute of Technology) presented the initial results of the Flux Amplification Compact Torus (FACT) spheromak experiment. A feature of the FACT device is that it has a flux amplification region between a coaxial plasma gun and a flux conserver. The plasma ejected from the gun can catch fluxes both in the gun and in the flux amplification regions. A threefold increase of the poloidal flux was observed in the flux conserver as a result of flux amplification.

T. Uyama (Himeji Institute of Technology) concluded that the stepwise phenomena in the CTCC-II plasma were caused by a current-driven instability. Mode analysis of magnetic field fluctuations showed that an $n = 2$ toroidal mode started to grow ~100 μs prior to the stepwise drop of the poloidal field (PF). The simulation code developed by A. Sgro et al. explained well the experimental behavior except that the transition of q value took much longer compared with the relaxation time in the experiment.

M. Yamada (Princeton Plasma Physics Laboratory) summarized the S-1 spheromak experiment. The most significant finding was that the peak electron pressure $n_{e0}T_{e0}$ scales with the square of the peak toroidal field B_{t0}^2. On the typical operation regime, the energy and the particle confinement times of the core plasma were estimated to be $30 < \tau_E < 100$ μs and $100 < \tau_p < 700$ μs, respectively. In the last phase of the S-1 operation, a compression experiment was carried out. During the compression of $C = R_0/R_c = 1.6$ (where R_0 is the initial minor radius and R_c is the final minor radius), T_{e0} rose substantially from 40 eV to 80 to 130 eV. The ion temperature was observed to rise as high as 0.5 keV. In addition, the sawtooth-type relaxation cycle observed in the earlier operation of the S-1 was analyzed in detail.

E. C. Morse (University of California-Berkeley) reported preliminary results and future plans of the Berkeley Compact Toroid Experiment (BCTX). Spheromak plasmas were formed in a 70-cm-diam flux conserver. Magnetic configuration lifetimes on the order of several hundred microseconds have been observed. A primary goal of the BCTX is to study the performance of the plasma during a transient radio-frequency (rf) heating pulse. For this purpose, a high-power rf drive system consisting of a 450-MHz, 60-MW pulsed source is now being assembled.

G. C. Goldenbaum (University of Maryland) presented recent results on the MS spheromak experiment. The spheromak decayed over a period of 100 to 200 μs, depending on the stabilization coil configuration. A solid metal core installed on the symmetric axis of the MS spheromak extended the plasma lifetime to ~300 μs, but the decay rate of the configuration indicated temperatures below 10 eV. Many spectral lines of chromium and nickel were observed. Though tantalum-coated aluminum electrodes and glow discharge cleaning were used to lower the impurity level, there was no perceptible improvement in the lifetime. To obtain spheromaks with a much longer life, the experiment will be modified by inserting a cylindrical metallic wall inside the reversal coils in the near future.

N. Amemiya (The University of Tokyo) described recent results of the TS-3 spheromak experiment. Some modifications of the device created a flux-core (or flux-hole) region in the spheromak. The configuration lifetime ($\sim 100\ \mu s$) was estimated from the time evolution of the B_z field on the symmetric axis. Successful sustainment was obtained in the "linked mode" operation, which had flux linkage between the PF coils and the spheromak plasma. In the "nonlinked mode," the lifetime was much shorter than the pulse width of the current.

S. Shimamura (Nihon University) presented the effect of external field applied to a spheromak. The plasma was sustained for 300 μs in a small flux conserver (10 cm long and 20-cm diam) by the oscillating gun current with a dc component. A magnetic field on the geometrical axis of the flux conserver suggested the existence of a flux-core region. The flux passing through the core region became small with increase of the external field, but the confinement of the spheromak was improved.

S. Kaneko and H. Tsutsui (The University of Tokyo) reported two results from their magnetohydrodynamic (MHD) stability investigations for spheromak plasmas. The first was the effect of a flux hole that was produced by the intersection of some magnetic surfaces with the resistive cover of a choking coil in the CTCC-II experiment. The stabilities of this configuration were studied by using the Mercier criterion. They confirmed the strong stabilizing effect of the flux hole. The second result was the resistive instability of the spheromak with a peak current near the minor axis. The most dangerous resistive mode in the cylindrical spheromak was an $m/n = 1/2$ mode (where m is the poloidal mode number and n is the toroidal mode number). The growth rate of the mode increased to the same order of magnitude as that of the ideal mode in the plasma with a strongly peaked current profile.

S. Okada (Osaka University) estimated the resistivity η of PIACE-II FRC plasma. He used the following plasma parameters: x_s (separatrix radius r_s/coil radius r_c), particle and flux decay times, τ_N and τ_ϕ, and $\int n_e\, dl$. Experiments were done on high- and low-compression modes. The high-compression mode could produce a smaller x_s plasma (0.426) than that (0.635) of the low-compression mode. His analyses showed that the η profile was flatter for smaller x_s. However, the discrepancy between the values of his estimation and the lower hybrid drift (LHD) theory near the separatrix remained to be solved.

S. Sugimoto (Osaka University) presented the first result of a spectroscopic tomography measurement of the PIACE-II plasma. The unique feature of the system was that an emission intensity profile could be imaged without any assumption about the internal structure of the FRC. The system was composed of 5 fan-array photocollectors, 5 visible monochrometers, and 50 photomultipliers. The bremsstrahlung intensity of $\lambda = 497.6$ nm was analyzed. He succeeded in observing the hollow region of the FRC near the geometrical axis and the elliptical deformation and the rotation of the FRC plasma with $\sim$10-mm spatial resolution.

E. A. Crawford (Spectra Technology) explained the diagnostics with good spatial resolution for FRC structure studies in LSX. End viewing diagnostics, which include a visible and soft X-ray camera, are expected to perform real-time image acquisition and analysis on LSX using video frame storage and image processing techniques. Side viewing diagnostics include multichord interferometers, continuum emission tomography, and axially deployed magnetic probes (B_z, B_θ, B_r) arrays. To clearly understand the connection between the data from these various diagnostics and the behavior of the FRC, a general three-dimensional dynamic MHD code has been developed.

R. D. Brooks (University of Washington) presented the results of the coaxial slow source (CSS) experiment. The CSS was developed to produce "annular FRCs" on a small time scale and at low voltages relative to conventional FRC generators. It has been upgraded to supply flux for 67 μs (previously 32 μs) while maintaining a loop voltage of <2 kV. The configuration continued to exceed the flux supply time, whose duration was much longer than Alfvén transit times. Spectroscopic measurements, Thomson scattering, and simulations indicated that the oxygen radiation barrier might be limiting plasma temperature ($\sim$25 eV). Even at these temperatures, however, $\sim$10 to 20 times classical resistivity was needed to explain the experimentally observed flux decay time.

S. Goto (Osaka University) reported the construction of a new machine, the FRC Injection Experiment, for neutral beam injection study. The FRC plasma generated in the 0.31-m-diam, 1-m-long theta-pinch coil is translated into the 0.8-m-diam, 3.0-m-long stainless steel chamber. A neutral beam of 5 to 20 keV (50 kW) will be injected into the translated FRC of $x_s = 0.6$, $T_i = 100$ eV, $n_e = 1 \times 10^{20}\ m^{-3}$, $N = 5 \times 10^{19}$, $B_m = 0.08$ T, and $\phi_p = 3$ mWb from the side ports of the chamber. The present plasma parameters confined in the chamber are $x_s = 0.3$ to 0.35 and $n_e = 0.6$ to $1 \times 10^{19}\ m^{-3}$.

R. E. Chrien [Los Alamos National Laboratory (LANL)] summarized the experimental efforts in the large-source modification of the Field-Reversed Experiment (FRX-C/LSM). The experiments were carried out by a 50% larger bore coil compared to the previous FRX-C/LSM experiments. Equilibrium parameters of the best confined FRCs were $\langle n_e \rangle =$ 0.5 to $1.2 \times 10^{21}\ m^{-3}$, $(T_i + T_e)/2 = 170$ to 400 eV, $B = 0.35$ to 0.55 T, $r_s = 0.14$ to 0.18 m, $\phi_p = 3$ to 5 mWb, $s = 1.0$ to 2.2, $l_s = 1.8$ m, $\langle \beta \rangle = 0.9$, $\tau_N < 250\ \mu s$, $\tau_\phi < 270\ \mu s$, and $\tau_E < 100\ \mu s$. The τ_N exceeded the prediction of the LHD transport theory by a factor of 1.5 to 2 for 2- to 3-mTorr FRCs. An end viewing soft X-ray pinhole camera ($\lambda = 10$ to 20 nm) with 2-μs exposure time was developed in collaboration with E. A. Crawford. The photographs made clear the separatrix shape and the onset of fluting instability.

T. Takahashi (Nihon University) reported recent studies on NUCTE-III FRC experiments. Stabilization of the $n = 2$ rotational instability had been tried by using an alternating axial current. The current was applied to the FRC after its formation. The pressure of the azimuthal field produced by the current became large on the bulged part of the FRC deformed by the rotational instability. The magnetic pressure is expected to control the instability. The preliminary result showed that the time of the instability was delayed for 10 to 15 μs by the application of the alternating axial current. This method became effective with increase of the frequency of the current.

T. Ishimura (Osaka University) discussed the dynamic stabilization effect of alternating axial current against the rotational instability and the $n = 1$ kink instability of FRCs. He derived dispersion relations by the linearized MHD equations for $|\Omega'/\Omega| \to 0$ and $|\Omega'/\Omega| \to \infty$, where Ω is the angular velocity of an infinitely long cylindrical plasma column and Ω' is the angular frequency of the alternating axial current. The dispersion relation showed that the axial current above the critical value always stabilized the plasma on the latter condition. For $|\Omega'| \sim |\Omega|$, the dispersion relation was so complicated that the stability criterion could not be expressed by any single analytical equation. It was calculated numerically and shown graphically. The stability regions, however, were narrow in this case.

S. Ohi (Osaka University) simulated the formation of the FRC in connection with the actual discharge circuit. The simulation indicated that the response of the circuit to the plasma parameters was strong in experiments having a large bore coil. It was possible to explain the high x_s (0.5) value on the FRX-C/LSM as reported at the twelfth International Atomic Energy Agency conference.

R. B. Webster (LANL) presented the results of a recent examination of the low frequency and the large-scale stability of the FRC. He used a three-dimensional, semiimplicit resistive MHD and initial value code. He examined such effects on the tilt mode as equilibrium profile, the rotation of the plasma, the Hall term, and finite electron pressure. He also examined the ability to accurately infer internal transport quantities in FRC.

R. Horiuchi (Science Project Corporation) studied the tilt instability in FRC by using a newly developed computer code. He simulated three cases in which the plasmas were confined in a uniform field and a mirror field and were rotating. The growth rate of the internal tilt mode was shown as a function of the aspect ratio of FRC. The mode could be suppressed by driving the plasma to spin with a high velocity of Mach number $M > 2.5$.

A. Ishida (Niigata University), L. C. Steinhauer, and H. Momota (Nagoya University) developed a variational formulation of a one-fluid, gyroviscous flowing plasma in order to study the low-frequency, global-mode stability of high-temperature plasmas. The theory was applied to the internal tilt mode of FRCs. It was found that the gyroviscous stability condition was similar to that for the Hall effect with a factor of ~2 improvement. As a result, a significant fraction of the present FRC experimental data fell within the gyroviscous stable regime of the internal tilt mode.

H. Momota reviewed D-^{3}He/FRC reactor studies. He emphasized the importance of D-^{3}He fusion, of which the 14-MeV neutron fraction (the ratio of fusion power carried by neutrons to the total fusion power) was 1%. Almost all the fusion power (~83%) could be utilized by use of high-efficiency direct energy converters. Damage of structural materials of reactors, disposal of activated materials, and relatively lower plant efficiency are mitigated by the development of the D-^{3}He reactor. The ^{3}He is expected to be transported from the lunar surface to the earth. The plasma confined in FRC appears to be attractive for D-^{3}He fuels, because it is surrounded by a natural divertor magnetic field, and high beta values of stable plasmas are readily obtained in experiments.

G. H. Miley (University of Illinois) summarized the recent progress in D-^{3}He FRC reactor studies. His talk included a brief summary and comments from three past U.S.-Japan workshops: (a) Advanced Fuels in an FRC, Nagoya, Japan, June 1986; (b) D-^{3}He in FRCs, University of Illinois, October 1988; and (c) Large Gyroradius Equilibrium and Stability Theory, Niigata, Japan, September 1987. A brief review of critical issues identified in the earlier D-^{3}He reactor design SAFFIRE was also given. Critical issues from this work were problems related to steady-state operation. A recent calculation based on a steady-state, profile-averaged zero-dimensional model explained clearly several figures of merit for a burning D-^{3}He plasma.

M. Ohnishi (Kyoto University) described calculations of the rotation speed of protons that were born and confined in a D-^{3}He FRC reactor. The beam protons may rotate the fusion core plasma by transferring their momentum. The calculations showed that the rotation of the protons was reduced to the same order as the ion diamagnetic drift speed, when the anomaly factor was equal to 100, which gave roughly the confinement time needed for a D-^{3}He ignition. Hence, the proton loss did not bring about serious effects on the plasma rotation. He concluded that the use of a proton current for a seed to derive a diamagnetic current and for the current sustainment might be a promising scenario in a steady-state D-^{3}He FRC reactor.

M. Nishikawa (Osaka University) emphasized the necessity of quick replacement and maintenance technologies on compact reactors. Neutron wall loading on the compact reactors is concentrated to very high values (14 to 20 MW/m^2) in comparison with that (~3.6 MW/m^2) on the conventional low-density reactor design. The first wall under such high neutron loading had to be replaced frequently at short duration. The quick replacement technology can be accomplished by using shape-memory alloy (SMA). The use of SMA couplers and gate valves designed by Nishikawa makes it easy to replace the module of the plasma container.

SUMMARY

Spheromak experiments have recently begun at Himeji Institute of Technology and University of California-Berkeley. The compression experiment of the S-1 conducted at Princeton Plasma Physics Laboratory showed $80 < T_e < 130$ eV and $T_i = 0.5$ keV in the case of the compression ratio $C = 1.6$. Many studies at other spheromak facilities have been focused on the flux hole (or the flux core) near the symmetric axis of the spheromak to obtain much longer lived plasmas.

The best confined FRC, $n_e = 0.5$ to 1.5×10^{21} m^{-3}, $(T_i + T_e)/2 = 170$ to 400 eV, $\tau_N < 250$ μs, $\tau_E < 100$ μs, was generated by using the FRC/LSM. Efforts are continuing to detect the tilt instability of the FRC by developing new diagnostics: spectroscopic tomography, the soft X-ray pinhole camera, and three-dimensional computer simulation codes. Stabilization of the $n = 2$ rotational instability by alternating axial current was discussed experimentally and theoretically.

Recent studies of D-^{3}He FRC reactors were introduced in detail. The importance of D-^{3}He fusion was emphasized from the viewpoint of the small fraction of 14-MeV neutrons in the reactor.

The proceedings of the workshop were published and distributed to participants. About ten copies are currently available to others who are interested in compact toroid research.

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July 25, 1989