MEETING REPORT

SUMMARY OF THE U.S.-JAPAN WORKSHOP ON D-^{3}He/FIELD-REVERSED CONFIGURATIONS, NAGOYA, JAPAN, MARCH 20–23, 1989

The objectives of this workshop are to continue the discussion of crucial issues for a D-^{3}He field-reversed configuration (FRC) design study as well as its role in an overall experimental and theoretical development strategy and to elaborate in more detail the joint reactor study plan.

Japanese participants in this workshop included A. Hatayama (Toshiba Corporation), H. Ikegami (Nagoya University), A. Ishida (Niigata University), M. Iwamoto (Mitsubishi Electric Corporation), Y. Kohzaki (Institute for Future Technology), H. Momota (Nagoya University), Y. Nogi (Nihon University), S. Ohi (Osaka University), M. Ohnishi (Kyoto University), S. Okada (Osaka University), M. Okamoto (Nagoya University), K. Sato (Himeji Institute of Technology), Y. Tomita (Nagoya University), and K. Yoshikawa (Kyoto University).

United States participants in this workshop were M.-Y. Hsiao (Pennsylvania State University), G. H. Miley (University of Illinois), and J. T. Slough (Spectral Technologies, Inc.).

Momota and Miley served as coordinators of this workshop.

Momota explained the advantages and disadvantages of D-^{3}He fuel in comparison with deuterium-tritium (D-T), catalyzed deuterium, and D-D-^{3}He fuel cycles. For a D-^{3}He fusion reactor, the 14-MeV neutrons produced carry only ~1% of the total fusion power, although a D-^{3}He plasma requires a higher beta, a higher temperature, and a larger $n\tau$ value. Since an FRC meets the requirements for a D-^{3}He fusion, i.e., attainment of high beta and possession of divertor configuration for a direct energy convertor (DEC), it was pointed out that the combination of an FRC and a D-^{3}He fuel opens up the possibility of realizing an ideal fusion reactor in engineering and environmental aspects.

Miley presented a brief summary of discussions and conclusions from three past U.S.-Japan workshops:

1. Advanced Fuels in a Field-Reversed Configuration, Nagoya, Japan, June 1986
2. Large Gyroradius Equilibrium and Stability Theory, Niigata, Japan, September 1987
3. D-^{3}He Field-Reversed Configurations, University of Illinois, Urbana-Champaign, Illinois, October 1988.

He also presented the results of a parametric study on D-^{3}He FRC reactors by the University of Illinois group. A set of basic parameters for an ignited D-^{3}He FRC reactor was chosen; sensitivities of various reactor parameters were displayed. In particular, particle confinement times based on various theoretical and emperical scalings were presented and compared with the values required for ignition. It was shown that values needed for ignition are within the widespread range between Bohm (lower end) and classical (upper end) scalings—well below those predicted by the velocity space particle loss (VSPL) scaling, but well above predictions resulting from instability-based scalings. The validity of extrapolating the instability-based scalings to reactor regime, however, was questioned and discussed by other participants. Other ignition requirements were also discussed.

In addition, Miley presented a scoping study on the application of the D-^{3}He FRC to space propulsion. Compared with other competing magnetic confinement systems, the FRC scheme offers many potential advantages in terms of power density, power-to-weight ratio, propellant thermalization, etc. Several critical issues and possible solutions were identified, and the need for a design study was pointed out.

A series of design data bases for a scenario to realize a D-^{3}He ignited plasma in an FRC was presented by Ohi, Tomita, and Ohnishi. Ohi evaluated the initial plasma parameters produced by the fast rising theta pinch (FRTP): $r_c = 2$ m, $x_s = 0.4$, $l_s = 10$ m, $B_w = 0.86$ T, $T_i + T_e = 2$ keV, and $\langle n \rangle = 8.4 \times 10^{20}$ m^{-3}. His analysis includes three stages of the FRTP: (a) "snow plow model" implosion, (b) expansion, and (c) adiabatic compression, and it gives the results consistent with the FRX-C/LSM experiment. It was emphasized that the discharge bank needed for the plasma formation is as large as 2 MV and has a capacity of 100 MJ, provided that the volume and density of the initial plasma are large.

The FRC plasma ($T \sim 1$ keV) is translated to a burning section and evolved to D-T ignited plasma ($T \sim 15$ keV) by compression and neutral beam injection (NBI) heating. Tomita estimated the heating power and flux enhancement needed during the process, assuming that the classical energy confinement scaling with an anomaly factor ξ^* of 100, the heating power P_{in} of 1 GW, and the flux increase rate $d\phi_i/dt$ of 20 V are required at the initial stage, if the initial plasma density and plasma volume are large. For the case of $\xi^* = 10$, the requirements are reduced to $P_{in} \sim 100$ MW and $d\phi_i/dt \sim 2$V. He also evaluated the power necessary to realize a direct D-^{3}He ignition without the intermediate state of D-T burning.

Ohnishi showed that D-^{3}He ignited plasma is achieved through a transition from D-T burning plasma without large additional input power. For the case of poor energy confinement ($\xi^* \sim 500$), the engineering problems caused by the large amount of 14-MeV neutrons should be resolved. For the case of better confinement ($\xi^* \sim 100$), an additional external heating scheme is also feasible and may be preferable to a utilization of D-T burning, because tritium inventory and radioactive issues of 14-MeV neutrons can be avoided.

Slough reported for L. C. Steinhauer (Spectral Technologies, Inc.) and G. C. Vlases (University of Washington) on the results of a plasma power balance study. A zero-dimensional power balance model for D-^{3}He FRC reactors, including bremsstrahlung loss, synchrotron loss, and conductive loss, was used for a preliminary study. Two designs, high field and low field, were modeled and compared with the Apollo tokamak reactor design. Attractive advantages of D-^{3}He-based FRC reactors were clearly identified. Again, stability and transport properties of a low-collisionality FRC with large-orbit ions are considered to be the key physics issues. Further improvements to the model were also pointed out, including a more accurate description of profile effects, alternative D-^{3}He fuel mixes, a survey of confinement prospects in fusion regime, and specialized calculation of neutron productions.

Hsiao discussed the electric field effects due to VSPL in FRCs. It was shown that as a result of the VSPL, an electric field would be developed. This electric field was suggested to explain the origin of the rotation and the unusually broad edge layer. Including the electric field and using a finite-loss-time model, the VSPL mechanism can explain these anomalies to a certain extent. Self-consistent, one-dimensional density, electric current, magnetic field, and electric field profiles were also presented. The effect of the VSPL electric field on particle confinement was also discussed. The previous VSPL scaling for particle confinement time, which assumed fast loss of unconfined particles and no electric field, was generalized to include the effects of the electric field and the finite loss time of unconfined particles. Preliminary results were presented, which showed qualitative agreement with experimental observations.

The steady-state maintenance of FRC plasma was presented by Okamoto. The neutral beam injected near-field null makes an Ohkawa current, which serves as a seed driving a bootstrap current to maintain a steady state. He also evaluated the rotation speed induced by the scheme and concluded that a fueling of a large amount of ions, i.e., large radial diffusion loss, drives a large bootstrap current and reduces the NBI current needed for the seed as well as the induced rotation.

Momota described an innovative direct energy conversion for 14-MeV protons. His technique involves the expansion of the protons leaking from the x point of an FRC to change the perpendicular kinetic energy to the parallel energy, the velocity modulation by a radio-frequency wave to bunch the proton beam and energy recovery due to the interaction with the bunched beam, and an applied traveling wave with resonant frequency of approximately megahertz. Sato showed that the traveling wave, instead of the stationary wave, can improve the velocity modulation. He also discussed the effects of secondary electrons emitted from thin wire grids at the energy recovery section. The importance of suppressing the secondary electrons to keep a high efficiency was pointed out.

Ishida discussed the effects of gyroviscosity on the internal tilt mode. The variational form, including a gyroviscosity term, was reformulated. The numerical calculations showed a wider stability region than his previous studies, but still not consistent with the experimental data. He asserted that the model refinement, as well as the other effects such as kinetic effects, should be included in the stability analysis in order to explain the present experimental results.

Two recent experimental results of FRCs were presented by Okada and Nogi. Okada explained the experimental results of the FRC Injection Experiment (FIX), an FRC translation and confinement machine. The plasma that possessed the parameters such as $B_w = 0.4$ kG, $x_s = 0.5$, $R_s = 20$ cm, $\langle n \rangle = 5 \times 10^{19}$ m^{-3}, $l_s = 3$ m, and $T_i + T_e = 100$ eV was produced after translation to a confinement chamber in FIX. The particle confinement time was better than the value expected by lower hybrid drift instability scaling. The experiment of an NBI ($E_b \sim 10$ keV) to the FRC will be started in the near future.

Nogi reported the results of the Nihon University Compact Torus Experiment III with long mirror field. Stabilization of the rotational mode was attempted by applying an alternating axial current after FRC plasma formation. The theory gave the threshold value of an axial current for rotational stability. However, the currents applied in the experiment were only able to reduce the growth rate but were not sufficient to stabilize the instability.

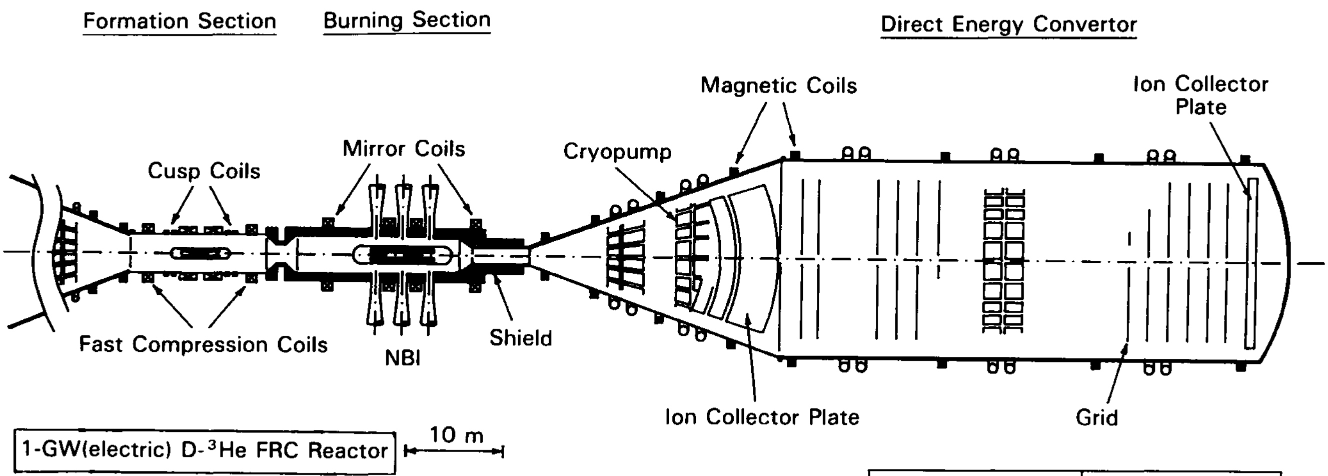
In planning the activities for joint U.S.-Japan near-term D-^{3}He FRC reactor studies, attention of the discussion was focused mainly on stability and transport issues, since most uncertainties were considered to be in these areas. Key issues and proposed approaches for continuing joint studies are summarized as follows.

In stability, both tilting and rotational instabilities were discussed. Current theories predict the stabilizing effect of kinetic ions; however, no stability threshold value $\bar{S}$ has been determined. In a reactor, in addition to kinetic background ions, charged fusion products and ions from NBI also have a stabilizing effect. Therefore, for the current reactor studies, all these stabilizing components should be taken into account; a new parameter that may be a certain combination of the $\bar{S}$'s for various components was suggested to accomplish this purpose and to be used in reactor design.

The stabilizing effect of gyroviscosity on internal tilt was presented. It was suggested that the stability criterion based on the current gyroviscosity treatment, together with a multiplicative factor to allow for the stabilizing effect from other ion species, may be used for current design studies.

Regarding rotational instability, several methods were discussed and their advantages and disadvantages were compared. Counterinjection of helium beams appeared most attractive and was chosen to be the first candidate for stabilizing the rotational instability. The methods of using quadrupole field and axial current were alternatives.

The importance of the 14-MeV protons in the open field region was particularly noted due to their large contribution to current. If this current was included in a design, a reactor would become more attractive. Therefore, the analysis of



Formation Section	Burning Section
$T \sim 1$ keV $n \sim 10^{21}$ m^{-3} $B \sim 2$ T $r_s \sim 1$ m	⟨D-T Ignition⟩ $T \sim 15$ keV $B \sim 2$ T ⟨D-^{3}He Ignition⟩ $T \sim 100$ keV $B \sim 8$ T

Fig. 1. Schematic of a reactor design presented by the Japanese team.

fusion products in the edge plasma was an important task. It was also noted that the velocity distribution of an FRC plasma was spatially dependent. In the separatrix region, fusion products were more kinetic, thus having a more significant stabilizing effect.

In transport, the uncertainty of transport mechanisms is a major concern. Identifying reliable scaling laws is again the most important task. Among the experimental scalings, based on Miley's reactor study reported in the workshop, the triggered reconnection experiment (TRX) scaling was the most favorable one and would produce an ignited D-^{3}He FRC reactor. In addition, Slough reported that the revised TRX scaling was even more favorable than the previous one. On the theoretical side, assuming that instabilities could be stabilized or suppressed, the VSPL scaling was suggested to be used for the current joint reactor studies, with the improvements including fusion products, electric field, and finite loss time. Ash control was also discussed. It was shown that as long as the particle confinement time for ashes is comparable to that for background plasma, ash control was not a problem for an ignited D-^{3}He reactor.

Also discussed was FRC source production by various techniques. For the current reactor study, the FRTP method was chosen, since the technique was well established and readily available. To minimize the power or energy requirement, optimization based on a given scaling law with respect to various reactor parameters needs to be studied.

Because of the high power density of an FRC reactor, development of advanced concepts for the first wall for high heat flux carried by bremsstrahlung radiation is needed. Here, "advanced concepts" refer to the development of materials and structures to handle high heat flux with low radioactivity.

In the area of energy conversion, the feasibility of a DEC was studied and reported; the traveling wave DEC was chosen for the present reactor studies, and its efficiency needs to be optimized.

To tie all of these various questions together, the Japanese team has carried out a preliminary study of a reactor design. A schematic of their concept is shown in Fig. 1. Momota discussed this design in some detail, stressing that the objective was to obtain a reference data base that would help coordinate the various teams working on different subsystems. A full set of reference parameters is being prepared for distribution to all staff involved in the project.

A preliminary schedule and task assignments were completed at the workshop. The first-phase design was expected to be completed and reported at the workshop scheduled for May 1989. The first reactor design is tentatively scheduled to be completed by October 1989.

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