MEETING REPORT

SUMMARY OF THE U.S.-JAPAN WORKSHOP ON D-^{3}He FIELD-REVERSED CONFIGURATIONS, BERKELEY, CALIFORNIA, NOVEMBER 20–21, 1989

INTRODUCTION

The fifth in a series of workshops on D-^{3}He field-reversed configuration (FRC) fusion reactors was held at the University of California at Berkeley.[1] Cochaired by G. H. Miley (University of Illinois) and H. Momota [National Institute for Fusion Science (NIFS)], it included 11 formal presentations and was attended by 8 representatives from the United States, 6 from Japan, and 1 from Austria. The purpose of these workshops encompasses both long- and short-term perspectives. The long-range goal is to identify both the attractive features of D-^{3}He fuels in an FRC commercial fusion reactor and the critical issues that must be resolved in the development of such a reactor. The short-range goal is to initiate an experiment dedicated to resolving these issues.

Various emphases have emerged in each of the workshops, ranging from basic physics understanding in earlier meetings to the details of a reactor plasma scenario more recently. In a previous workshop, held in Nagoya in March 1989, the elements of a comprehensive reactor design were presented for the first time. In the present workshop, the main theme was the critical examination of physics and engineering issues raised in this design. The Japanese were commended for assembling a multi-institutional team that has developed a remarkably comprehensive reactor concept in a relatively short time. The team has divided the reactor problem into six areas:

1. formation of the FRC and its translation into the burner chamber (S. Ohi, Osaka University)
2. control and heating to ignition (Y. Tomita, NIFS)
3. burning plasma physics (M. Ohnishi, Kyoto University)
4. direct conversion (K. Sato, Himeji University)
5. stability (A. Ishida, Niigata University)
6. comprehensive reactor design (H. Momota, NIFS).

Unlike previous workshops, little attention was devoted to the question of stability. Along this line, it was observed that FRC research has tended to focus strongly on the issue of gross stability. However, in the task of developing a reactor concept, it is important to avoid the pitfall of "single-issue" research. Difficulties that loom as fatal flaws at an early stage may turn out to have simple and quite satisfactory solutions later on. Pursuit of an FRC reactor concept is motivated by the manifest attractiveness of the system: intrinsically high beta (efficient utilization of magnetic energy, low synchrotron losses), simplicity of the magnetic system (only one field component), simplicity of the geometry (singly connected plasma, straight cylindrical geometry), and the presence of a natural divertor. These attributes are sufficiently appealing to offer strong motivation for solving what may presently be perceived as severe problems.

The basic elements in the reactor design are as follows. Formation is accomplished in a field-reversed theta pinch (as in present experiments). The FRC is then translated along a guide field from the theta pinch into the burn chamber, where it remains thereafter in a stationary position. Heating to ignition takes place in the burn chamber; this phase includes heating and flux addition by energetic neutral beams and refueling by pellet injection. Burn then proceeds in a steady-state mode. Current drive is provided by prompt fusion product losses and possibly a modest injected neutral beam.

This summary is organized as follows. First, each presentation is reviewed and the major issues raised in the discussion periods are noted. Next, a concise list of these issues is given, expressed in the form of "needs" for D-^{3}He FRC reactor development. Finally, recommended emphases of future studies are presented as discussed in the final summary sessions of the workshop.

PRESENTATIONS

Comprehensive Reactor Design

An overall view of the evolving D-^{3}He FRC reactor design was given by Momota. In its present form, the design assumes a 100-keV plasma and targets a gross electric power of 1 GW and a total fusion power output of 1.4 GW. This is broken down into 0.9 GW of energetic particles (0.7 GW of 100-keV thermal energy and 0.25 GW of 15-MeV protons), 0.06 GW of neutron power ($\sim$4% of the total), and the remainder ($\sim$0.35 GW) in the form of bremsstrahlung and synchrotron radiation. The charged-particle energy is converted directly to electricity in two-part convertors located at each end of the system. During the burn phase, the magnetic field is 6.4 T. The FRC radius and length are 1.25 and 17 m, respectively, corresponding to a volume of $\sim$80 m^3.

Figure 1 is a schematic of the reactor elements in the present design.

Formation

The formation technique employed in the reactor design is a field-reversed theta pinch as has been used in essentially all experiments. Ohi described a zero-dimensional time-dependent model of formation in a theta pinch, followed by translation along a guide field into the burn chamber. This model was baselined to existing devices and then used to extrapolate to the larger sizes needed in a reactor. The model represents an advance over previous formation models, which were not truly time dependent. In the reactor design, a single turn voltage of 400 kV (33 MJ) is assumed in the 4-m-diam, 10-m-long theta pinch. After translation into the burn chamber, the plasma has a temperature of 1 keV in an external magnetic field of 0.3 T and has roughly the same dimensions as in the eventual ignited state. In discussions following the presentation, it was pointed out that the present model assumes an instantaneous axial contraction phase, while a more realistic time-dependent axial contraction could easily be included.

Heating

Studies of the heating phase, which links the formation and burn phases, were presented by Tomita. During this phase, heating and current drive (to add internal magnetic flux to the FRC) are accomplished by neutral beam injection (NBI), and refueling is done by pellet injection. The study also examined control issues such as controlling the length of the FRC during the heatup to prevent it from getting too short. The required neutral beam power in the current design is sizable: 200 MW. The 1-MeV beam energy (set by neutral beam penetration requirements) assumes an extrapolation of the 500-keV negative ion beam technology presently in use on the Japan Atomic Energy Research Institute device. In discussions following the presentation, it was noted that the assumption of one-third classical energy confinement at the beginning of heatup (1 keV) is probably optimistic; poorer confinement would exacerbate the neutral beam power requirements. It was suggested that an alternative heatup recipe be considered in which the plasma size increases during the heatup; this might reduce the power requirement.

Stability

Ishida gave the only presentation on stability: a gyroviscous fluid theory of stability and its application to the internal tilt mode. Both present and reactor-relevant FRCs are in an intermediate regime where both kinetic and fluidlike effects are important. Expressed in terms of the s parameter (minor radius/average internal ion gyroradius), FRCs of interest have neither $s \ll 1$ (dominantly kinetic) nor $s \rightarrow \infty$ (magnetohydrodynamic-like). Analysis of this intermediate regime benefits from a two-pronged approach using both kinetic and fluid-based methods. The gyroviscous theory is a fluid-based treatment of perpendicular ion kinetics (i.e., finite Larmor radius). A variational principle has been developed as a practical way to solve the equation of motion. In applying the results to the internal tilt mode, it was found that the eigenvectors are quite close to ideal magnetohydrodynamic predictions, but the stability is very different. A gyroviscous plasma has a stable region resembling that produced by the Hall effect; stability is predicted for S_* (separatrix radius/collisionless skin depth) less than ~1.5 times the elongation of the separatrix. Gyroviscous stability is not strong enough by itself to account for the gross stability of current experiments.

Confinement

Confinement discussions focused on possible transport mechanisms including low-frequency drift (LFD) transport and velocity-space particle loss (VSPL). L.C. Steinhauer (Spectra Technology) presented work applying a recently developed global transport model to predict the particle confinement time in a reactor-grade FRC plasma assuming LFD transport. The LFD mechanism has three collisionality regimes: collisional, plateau, and weakly collisional. Most present experiments are in the plateau, but reactor plasmas will be weakly collisional. In reactorlike conditions, the predicted particle confinement time is lower than classical by roughly a factor of S (radius of O-point/ion gyroradius in the external field). Reactor conditions (comparable to the reactor design under discussions) have $n\tau_N \sim 5$ to $20 \times 10^{15}\ \mathrm{s \cdot cm^{-3}}$. If the energy confinement time is a sizable fraction of the particle confinement time, this is more than adequate for ignition of a D-^{3}He fuel. However, because of the strong favorable scaling with temperature, the confinement during the heatup phase (lower temperatures) is poorer and exacerbates the problem of large heating power.

The VSPL mechanism was described by M.-Y. Hsiao (Pennsylvania State University). Modeling of this mechanism has recently been enhanced to include the self-consistent electric field (determined by the criterion of quasi-neutrality) and a more realistic description of the loss rate of unconfined particles. It was noted that the VSPL model using two limiting case representations of the unconfined particle loss exhibits

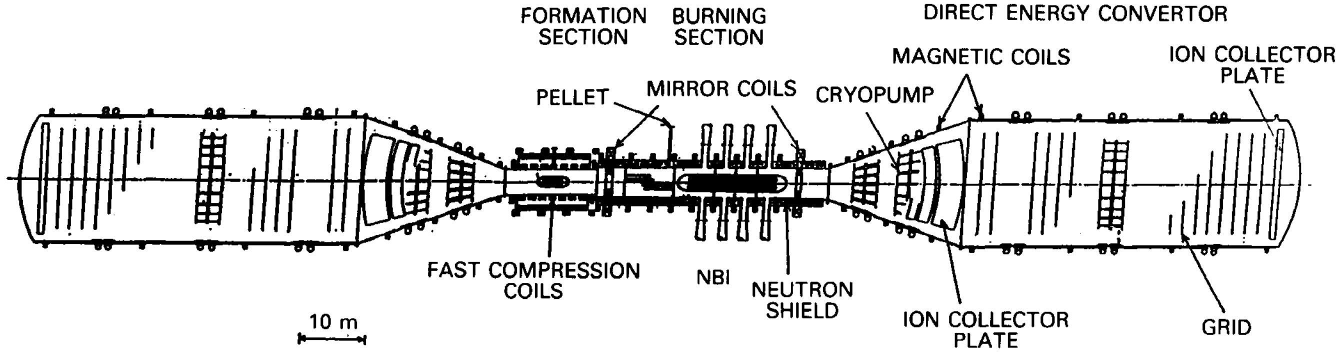

Fig. 1. Schematic of a 1-GW D-^{3}He FRC reactor.

a parametric confinement scaling with some resemblance to the empirical scaling. The combination of classical transport plus the VSPL mechanism is the absolute upper bound on confinement time; indeed, if the VSPL effect can be expressed in a simple way, "classical plus VSPL" is a suitable yardstick for evaluating particle confinement.

In discussions following the presentation, considerable attention was given to the nature of the self-consistent electric field, which in the present model points outward near the separatrix. It was observed that the present model does not properly treat the flow in the edge layer. Interest was shown in a precise treatment of the loss region employing a Fokker-Planck calculation.

The question of the transport mechanism was addressed in the final summary session of the workshop. It was noted that, as yet, no facility has been dedicated primarily to the transport question. The existing transport data base (quite limited in parameter space) has been gleaned entirely as a by-product of experiments focused on other issues such as formation, stability, and translation. It was suggested that the determination of the transport physics, especially in a weakly collisional regime, be an objective of a future experiment. It was noted that the Large-S Experiment (LSX) should considerably add to the transport data base, albeit not in the weakly collisional regime. The LSX, at Spectra Technology, is scheduled for start of operations in mid-1990.

Burn

The conditions for ignition with D-^{3}He fuel were examined by W. Kernbichler (Graz University). The analysis employed a Fokker-Planck treatment of thermal fusion products. The criterion for fusion product confinement was taken to be that only particles that do not penetrate the separatrix are confined.[2] It was observed that the question of ignition can be examined "to zero order" without reference to global steady-state issues such as current drive. The boundaries of the ignition domain were identified in terms of the temperature, confinement $n\tau_E$, the s parameter, and the ratio of energy to particle confinement time (which has a strong effect on the buildup of ash). Power densities and neutron production rates associated with the plasma size and the external magnetic field were described. For reference, the ignition domain was compared with that for deuterium-tritium fuel. In discussions following the presentation, it was noted that the adopted criterion[2] for fusion product confinement is pessimistic, perhaps excessively so, particularly when self-consistent electric fields are taken into account.

An analysis of conditions in a steady-state D-^{3}He FRC reactor plasma was presented by Ohnishi. A steady-state magnetic configuration was assumed to be maintained by current drive from a combination of prompt 15-MeV proton loss, NBI, and Ohkawa currents. For simplicity, the present model assumes a rigid rotor profile and thus does not attempt to determine the self-consistent profiles. It is nevertheless useful for determining global requirements such as the required sources (neutral beam energy, pellet refueling rate). The model incorporates the pessimistic fusion product confinement criterion mentioned earlier.[2] The required neutral beam power to sustain steady state was calculated to be 5 MW. Ohnishi also gave a presentation on an issue of importance in the burn phase, the rotation driven by the loss of 15-MeV protons (which have a preferential angular momentum). The associated rotation depends sensitively on the anomaly factor (compared to classical) of the particle transport rate; larger anomalies correspond to lower rotation rate. Following the presentation, there was considerable discussion on current cancellation by electrons. A particularly lucid description of the Ohkawa current (which is not cancelled) was presented by Momota, who showed that anomalous resistivity probably strengthens the Ohkawa effect. It was also noted that the calculation of required neutral beam power is specific to the assumed rigid rotor profile; a self-consistent profile calculation would likely lead to a flattening of the profile near the zero point, which would reduce the neutral beam power requirement.

Direct Conversion

A traveling wave direct convertor concept for the 15-MeV protons has been developed and was presented by Sato. This effort was undertaken in response to the call at the October 1988 workshop for a specific concept for direct conversion of the fusion product energy. The convertor is designed for the 250 MW of 15-MeV protons, i.e., the unconfined fusion protons that suffer prompt loss. The end flow of thermal plasma, 700 MW at 100 keV, is converted using a more "conventional" Venetian blind system located upstream from the 15-MeV convertor. A modulator converts the 15-MeV particle stream into a modulated beam from which energy is extracted by a series of properly spaced antennas. The most promising modulator concept appears to be an L-C (inductive-capacitive) resonant circuit. Estimated conversion efficiencies of 70% were calculated assuming negligible power is required to produce the modulation. The 15-MeV beam convertors are quite large; each unit is 80 m long compared to a 15- to 20-m FRC length. In the discussion after the presentation, the question was raised on the economy of devoting such a large and proportionately expensive system to convert only one-fifth of the fusion power; it may be more practical to simply collect the 15-MeV proton power and convert it using a thermal cycle.

New Concepts: Spheromak Imbedded in an FRC

Evidence from the LSM/T experiment was presented by M. Tuszewski [Los Alamos National Laboratory (LANL)] suggesting that a force-free spheromak core may be present inside a translating FRC (Ref. 3). This inference was drawn from internal magnetic probe data. The reduced data with some smoothing are consistent with a force-free equilibrium (Bessel function model). The observations are consistent with related measurements on FRX-C/T (LANL) in 1985 and recently on FIX (Osaka University). In the other experiments, the toroidal field might be attributed to FRC formation in a conical theta pinch; in LSM/T, an attempt was made to eliminate this formation-related phenomenon by forming the FRC in a more or less symmetric way and then ejecting the fully formed FRC from the theta pinch. It was noted that net toroidal fields are not observed in nontranslating FRCs. Tuszewski commented on the mechanism for the helicity generation. The Hall effect seems an unlikely cause since Hall effect computations predict a toroidal field that is too low and in the wrong direction. It was speculated that the helicity may come from torsional Alfvén "end-shorting" waves on the open field lines, which (by a mechanism not yet understood) is absorbed into the FRC. In discussions after the presentation, it was observed that even in LSM/T, symmetric conditions are not achieved since asymmetric magnetic forces are needed to get the FRC moving. It was also noted that Taylor's relaxation theory is not restricted to a "force-free" plasma but a "pressure-gradient-free" plasma. The interior of the observed objects (i.e., inside the current sheaths in the edge layer) appears to have uniform pressure and thus might be subject to Taylor relaxation.

SUMMARY OF D-^{3}He FRC REACTOR DEVELOPMENT NEEDS

The following topics were identified as areas needing further research:

1. *Formation:* a better understanding of the parametric limits for formation in a theta pinch; i.e., the dominant formation pathologies and how they scale in larger devices
2. *Stability*
    a. an understanding of the stabilization effect of energetic particles. These include naturally occurring betatron particles, neutral beam injected particles, and nonthermalized fusion products
    b. allowance for the possibility of a lower *s* reactor (should confinement turn out to be favorable). Such a reactor would have an advantage from the standpoint of gross stability
3. *Confinement*
    a. a theory of VSPL including both the self-consistent electric fields and a proper treatment of the edge layer
    b. a comparison of VSPL and/or LFD transport with the confinement data base (as more comlete models become available)
    c. self-consistent radial profiles rather than the standard rigid rotor assumption used heretofore
4. *Heating:* an alternative heatup trajectory (length, radius, magnetic field, temperature, inventory versus time) requiring lower neutral beam power
5. *Burn:* application of VSPL theory to 15-MeV protons to get a more realistic criterion for their confinement
6. *Direct conversion:* evaluation of whether it is worthwhile to devote so much space and expense to direct conversion of the 15-MeV protons (only 20% of the fusion power)
7. *New ideas*
    a. verification of helicity generation using another diagnostic technique beside magnetic probes
    b. identification of the physical mechanism for helicity generation
    c. exploration of the implications of an "imbedded spheromak" in terms of equilibrium, gross stability, and transport, thus addressing the question of whether it is a desirable reactor concept.

RECOMMENDED EMPHASES IN FUTURE STUDIES

In the concluding review session of the workshop, several recommendations emerged to guide future work on the D-^{3}He FRC concept.

1. In response to comments and criticisms raised at the workshop, the present reactor design should be improved. The modifications should, however, preserve the basic configuration and reactor elements in the present "phase I" design, i.e., theta pinch source, neutral beam heating and current drive, and ignited burn. A particular effort should be devoted to reducing the heating power. In addition, preliminary examination is needed of the balance of the energy conversion system, i.e., the thermal conversion system and the direct conversion of the 100-keV thermal plasma stream.

2. About half of the next workshop should be devoted to identifying the objectives and basic configuration of a new FRC experiment at NIFS in Japan. In addition, agreement should be reached on the design-driving constraints and the physics modeling tools to be used in designing the experiment. It may be appropriate to present a "straw man" design at the workshop for initial discussion. It may also be useful to establish a bilateral committee to review the progress and directions in the experiments design.

3. More frequent contact is needed between the Japanese team and their American counterparts during the periods between workshops. This would allow critical commentary to be exchanged, help prevent unexpected oversights, and generally make the workshops themselves more efficient. In particular, linkages should be established at least in the following areas: modeling of the formation process, global confinement and transport physics (linked to reactor size), and fusion product confinement (linked to ignition requirements).

4. Certain key physics areas need continued emphasis. These include gross stability, confinement modeling, and edge-layer physics.

5. Alternate reactor configurations (e.g., other formation techniques, other current-drive techniques, etc.) should be considered for a later phase of the reactor design study.

Plans were discussed for the next two workshops. The next workshop was tentatively set for June 1990 in Kyoto, and the subsequent workshop for June 1991 in Seattle. The phase I reactor design will be finalized at the Kyoto workshop. G. Miley offered to serve as the "clearinghouse" for integration of the phase I design.

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