MEETING REPORT

SUMMARY OF THE U.S.-JAPAN WORKSHOP ON THE PHYSICS OF D-^{3}He FUSION, NAGOYA, JAPAN, DECEMBER 5–7, 1994

INTRODUCTION

The purpose of this U.S.-Japan workshop, the latest in a series of related exchanges, was to discuss various advanced-fuel and alternate-fusion concepts. In particular, the workshop focused on

1. physics and technology unique to D-^{3}He fusion
2. D-^{3}He fusion reactor design
3. review of current and near-term research programs relevant to D-^{3}He fusion
4. D-^{3}He field-reversed configuration (FRC) physics and engineering
5. innovative advanced-fuel concepts.

This workshop was well attended, with 25 Japanese and 5 U.S. representatives. Five Russians and one Austrian also presented papers as observers. A total of 23 papers were given, most of which reported FRC research, although papers on the spheromak, spherical torus, tandem mirror, and inertial-electrostatic confinement (IEC) approaches were also presented. The workshop was jointly chaired by Hiromu Momota [National Institute for Fusion Science (NIFS)] and John F. Santarius (University of Wisconsin, Madison).

FUSION HISTORY AND FUTURE

I. N. Golovin [Kurchatov Institute of Atomic Energy (KIAE)] gave a brief overview of fusion history based on his involvement with fusion since the birth of the Russian program in the early 1950s. He expressed his view that the "child has grown up" and fusion is entering a new era of understanding reactor physics and engineering properties, where consideration of the electricity customers' needs is necessary. Key points included the engineering benefits of linear geometry, maintaining symmetry, and having an end plate that serves as the "divertor" at the end of a linear device. Several advanced concepts are well suited to take advantage of these benefits, such as the FRC and tandem mirror.

FRC EXPERIMENTS

A. L. Hoffman (University of Washington) reviewed experimental results of the Triggered Reconnection Experiment (TRX) and Large s Experiment (LSX) devices. The TRX device was run in the first half of the 1980s, and efficient new methods for forming FRCs were developed, e.g., "programmed" reconnection and axial compression. These methods demonstrated the trade-offs between high flux retention for early compression and increased heating for late compression. Preliminary indications were also obtained that FRCs with $s > 2$ ($s \equiv$ number of ion gyroradii in the minor radius) were stable to tilt modes, although symmetric quiescent equilibria with good lifetime scaling were not produced for such high flux, high filling pressure conditions. Based on these results, a larger experimental device, LSX, was constructed to study stability and confinement of FRCs in higher s magnetohydrodynamic (MHD) regimes. Field-reversed configurations up to $s = 4$ were formed with good confinement ($D_\perp \sim 5$ to $10\ m^2/s$) and particle lifetimes up to 1 ms. High ion and electron temperatures (1 and 0.4 keV, respectively) were also measured, demonstrating low electron conduction losses. Studies to obtain a large amount of flux retention and an improvement of confinement are needed to develop a commercial fusion reactor.

S. Okada (Osaka University) described recent research in the FRC Injection Experiment (FIX). The FIX device forms its initial plasma in a theta-pinch chamber with a magnetic field of $B \simeq 0.7$ T, giving plasma parameters of $n \simeq 6 \times 10^{20}\ m^{-3}$, $T \simeq 400$ eV, and separatrix radius $r_s \simeq 30$ mm. The plasma is then translated into a chamber with $B \simeq 0.05$ T, $n \simeq 5 \times 10^{19}\ m^{-3}$, $T \simeq 140$ eV, and $r_s \simeq 150$ mm. The particle lifetime of 150 μs appears to contradict lower-hybrid drift transport theory, as it is about six times the theoretical value. The magnetic fluxes in the scrape-off layer and end-jet regions are approximately equal, indicating that the plasma is flowing smoothly and the x point is not having a significant effect on flow in the edge layer.

T. Takahashi (Nihon University) discussed recent NUCTE-3 FRC experimental results on formation, shape control, and fueling, plus a colliding FRC study. The results indicate that high-flux FRC plasmas can be formed and that bias-field control is more effective than fill-pressure control in the complicated formation process. In fusion reactor startup, it is desirable to form FRCs at as low a density and as high a temperature as possible. By these control techniques, formation densities as low as 1.1×10^{21} m^{-3} and temperatures as high as 700 eV have been achieved, and the flux confinement time has been improved. These densities are a factor of 2 or more lower than achievable by more conventional techniques. The colliding-FRC study indicates that both volume and total particle inventory can be increased by this method. The poloidal flux, however, is not increased, which appears to be related to the plasma elongation.

A. P. Kreshchuk (TRINITI) described experimental studies in the Besstolknovitelnij Nagrev device on internal processes in high-β plasmas by controlling spontaneous evolution of antiparallel magnetic structure. By controlling the start time of an additional trigger coil, various relaxation modes of FRC plasmas were realized, i.e., soft (start time delayed from main coil $\Delta t \sim 0.6$ to 1.0 μs), hard ($\Delta t \sim 0.5$ μs), and spontaneous ($\Delta t = 0$) modes. In hard mode, the plasma length sharply decreased, which is connected with degradation of the shock process and increase of irregular dynamic activities and plasma losses. The inner measurements confirmed that the soft mode has the strongest axial shock heating, minimal losses, and fast transition to equilibrium. These give 70% overall heating, x_s (ratio of separatrix radius to coil radius) up to 0.7 with $(T_e + T_i) \sim 1$ keV, and relaxation time to a Maxwellian distribution of 1 μs.

Y. Ono (University of Tokyo) presented results on the slow formation of FRCs by merging spheromaks with opposite toroidal magnetic fluxes in the TS-3 device. Advantages of this formation method are that it is slower and transforms most of the toroidal magnetic energy into ion kinetic energy. The ion temperature rises by over a factor of 10, to ~180 eV. The merging spheromaks relax to a spheromak if the helicity is above a critical value and to an FRC if the helicity is below that value. This raises an important question: whether the FRC is a minimum energy state if looked at from the correct perspective. Preliminary results also indicate that ohmic current drive can prolong the flux lifetime of an FRC to 200 μs, compared with 120 μs without ohmic current drive.

FRC THEORY

M. Yamada (Princeton Plasma Physics Laboratory) provided some comments on Ono's FRC formation experiments. He pointed out that such schemes are the most efficient mechanism for transferring magnetic energy into plasma kinetic energy. He indicated that the very high s numbers for the merging-FRC experiments in TS-3 and the observations of the $n = 1$ tilt instability allow a very useful connection between theory and experiment.

L. C. Steinhauer (University of Washington) showed that FRCs could be ideally MHD stable to the internal tilt mode if they had very racetrack-like separatrix shapes and hollow current profiles. This result is reasonable considering the basic internal tilt stability of oblate compact toroids and the fact that such FRCs have straight field line central regions and oblate end regions. However, the previous calculations have been criticized as incomplete because of the use of a finite set of perturbation trial functions. The present calculations involve using a finite element method to identify the true eigenmodes, but the analysis is not yet complete.

A. Ishida (Niigata University) used a variational form of the energy principle and a Rayleigh-Ritz minimization method to examine modes of the form $\xi(r,z)\exp[i(l\phi - \omega t)]$ for $l \gg 1$ (i.e., local modes). In contrast to the results for global modes, hollow-current, racetrack-like profiles were found to be most unstable to local modes. The observed appearance of such profiles in stable experiments suggests that finite orbit effects in the unfavorable curvature regions near the FRC ends must be important. Such effects will be examined in the future.

Y. Nakao (Kyushu University) presented Fokker-Planck calculations showing that at high plasma temperatures where Coulomb collision cross sections are small, nuclear elastic scattering with high-energy reaction products could produce a high-energy tail on the fuel ion distribution function. The effect on basic reactivity depends on the reaction product density but is generally small. For deuterium-tritium, it reduces the reactivity 5 to 10%; for deuterium-deuterium, it increases the reactivity 5 to 15%; but for D-^{3}He, it has no appreciable effect.

M. Ohnishi (Kyoto University) presented a numerical simulation with a rest-ion model of the time-dependent penetration of a rotating magnetic field (RMF) into a low-temperature ($T_e \sim 50$ eV) FRC for current drive. The RMF current drive, originally demonstrated theoretically and experimentally by Blevin and co-workers, extends discharge lifetimes beyond the 1-ms pulse length characteristic of field-reversed theta pinches. Ohnishi showed that the applied RMF can quickly penetrate, and it may be possible to maintain the initial configuration if the RMF amplitude B_ω exceeds a critical value that is much less than the initial axial field of the FRC.

A. L. Hoffman presented the requirements for RMF current drive in LSX/mod and a D-^{3}He FRC reactor. If the resistivity is classical, the requirement is not severe, but if the resistivity is determined by the particle diffusivity obtained in present FRCs, the requirement is difficult to satisfy. Hoffman suggested the possibility that the collisionality related to the particle loss in the radial direction may be different from the collisionality related to the RMF current drive in the azimuthal direction. This issue will be one of the most important in the future LSX/mod experiment. The coupling of an RMF antenna with a plasma, however, cannot be as effective under the condition of full penetration.

H. Momota (NIFS) pointed out that the RMF current-cancellation problem (the potential spinup of the nondriven species canceling the current in the driven species) is shared with other current drive methods. This effect may be insignificant in an FRC with RMF-driven electron current if the lifetime of ions is much smaller than the ion-electron collision time.

H. Matsuura (Kyushu University) studied tail effects on D-^{3}He FRC startup heating. Previous studies of startup in a D-^{3}He FRC reactor have assumed a Maxwellian distribution of ions throughout the startup process. The required neutral beam power for startup, using this assumption, is significant, calculated to be 110 MW in the "H" version of the ARTEMIS reactor study, and 280 MW in the "L" version. However, neutral beam injection produces a significant tail on the distribution and may increase the reactivity enough to significantly reduce the neutral beam power requirement. Using a quasi-steady Fokker-Planck calculation and ignoring nuclear-elastic scattering, the effect of a non-Maxwellian distribution has been calculated. The required neutral beam power is reduced to 40 MW (ARTEMIS-H) and 160 MW (ARTEMIS-L) using a suitably altered fueling recipe. The best startup trajectory in the non-Maxwellian case first increases the density while holding the temperature at ~20 keV, then raises the temperature at approximately constant density.

FRC DIRECT ENERGY CONVERSION

Y. Tomita (NIFS) presented analytical studies of a traveling wave direct energy converter (TWDEC). Previous studies of the TWDEC have been based on particle simulations. The present study represents a quasi-analytic approach to better understanding the scaling and basic behavior. A drifting Maxwellian distribution is assumed for the initially 15-MeV protons, which carry ~30% of the fusion energy. A coupled set of circuit equations is used to represent the grid voltages and currents. By this model, approximate criteria for trapping and deceleration of the proton stream can be found. The efficiency of the TWDEC is higher if a larger fraction of the protons is trapped in the decelerating potential "buckets."

Y. Yasaka (Kyoto University) discussed experimental plans to test the traveling wave direct energy converter concept. The first experiments developing a technology that is uniquely germane to D-^{3}He fusion have been initiated at Kyoto University. It is a proof-of-principle experiment for the TWDEC. A helicon wave plasma source producing 10 to 20 mA of 5- to 7-keV ions in a 20-mm-diam stream is used for the source. The modulator grid is driven by a 1-kV oscillating circuit at a frequency of 7 MHz. The grid spacing in the deceleration section is 23 mm. A getter pump in the deceleration section is used to keep the stray gas pressure (which leads to parasitic losses) as low as possible. The grid transparency is 90% for each of the six grids. In many ways, the technological demands on the proof-of-principle facility are more severe than they would be on a fusion reactor. It is anticipated that experimental operations will begin in March 1995.

FRC CONCEPTUAL REACTOR DESIGNS

V. N. Litunovsky (Efremov Scientific Research Institute of Electrophysical Apparatus) presented work done with M. V. Krivosheev on the optimization of the D-^{3}He FRC power plant based on the PULSATOR configuration. Key sensitivities found for this concept are (a) fusion power (a high value gives a good economy of scale), (b) fuel cost, (c) fuel-injector efficiency, and (d) direct-energy-converter efficiency. Weaker dependencies include magnet cost and energy confinement.

H. Nakashima (Kyushu University) carried out a design study of a D-^{3}He–fueled fusion rocket employing an FRC. Fusion rockets have potential advantages over conventional rockets in specific impulse (exhaust velocity) and specific power, making a fusion rocket a leading candidate for an interplanetary transport system. The design was evolved from a terrestrial version of the D-^{3}He reactor ARTEMIS. The difference from the ARTEMIS design is that one of a pair of direct energy converters is removed and replaced by a magnetic nozzle, and a hybrid coil is added in front of the other converter to choke the plasma flow. The results show that the FRC rocket could achieve a high specific power (i.e., the ratio of the thrust power to the total system mass) of ~4 kW/kg, or approximately ten times better than a projected nuclear-electric fission rocket. The conceptual vehicle is capable of interplanetary flight to Mars in about 50 days with a payload fraction of 0.3. Critical issues include recovery and processing of unburnt ^{3}He fuel, mixing of propellant material with the exhaust plasma, and neutralization of the plasma-propellant mixture.

D-^{3}He PLASMA POWER BALANCE AND ASH PUMPING

M. Peng (Oak Ridge National Laboratory) examined ignition criteria for generic D-^{3}He reactors and applied the results to a spherical tokamak. The strong radiation losses and ash buildup raise the lower bound in the confinement parameter $n\tau_E$. For a spherical tokamak, the low aspect ratio makes high-β operation possible (for $A = 1.2$ and $\beta \sim 0.6$), which reduces the synchrotron radiation losses. The spherical tokamak concept expands the operating range compared to standard tokamaks. Synchrotron radiation transport, low aspect ratio physics, electron cyclotron current drive, fueling, and disruptions are among the important issues for which models are being improved.

V. I. Khvesyuk (Moscow State Technical University) used Fokker-Planck calculations to show that the power balance for D-^{3}He plasmas in the central cell of tandem mirrors is very sensitive to the ash fraction. He examined the effect of selective ash pumping using a magnetic perturbation coil and showed that ~10 ms or smaller ash confinement times were necessary to produce fusion power multiplications of $Q > 10$.

IEC

J. F. Santarius (University of Wisconsin) compared the features of two configurations of the IEC concept, gridded and Polywell™ devices. The experimental studies being conducted at the University of Wisconsin were also summarized. Gridded IEC devices utilize a voltage difference between grids. Ions are accelerated and converge at the origin in spherical geometry. The devices may find specialized applications at low flux levels, e.g., low-Q (fusion power/input power) producers of fusion neutrons or protons for various applications. In the Polywell™ IEC concept, a pseudospherical, cusped magnetic field is formed by currents flowing in conductors placed at the edges of a regular polyhedron. This concept appears to be more promising than gridded devices for a fusion reactor. The reactor design calculations, using a confinement model from Bussard and Krall, indicate that $Q \sim 10$ and high direct converter efficiency ≤80% can be attained for D-^{3}He reactors. The requirement on cusp magnetic field is modest (4 T). There exist, however, many physics issues to be solved; these include high convergence of ions, improvement of electron confinement, and maintenance of the configuration against collisions.

SYNCHROTON RADIATION IN D-^{3}He PLASMAS

A. B. Kukushkin (KIAE) presented an outline of his integral equation formalism (in space variables) for describing heat transport by transverse/longitudinal electromagnetic waves in magnetically confined hot plasmas. Emphasis was placed on the physical aspects of the nonreducibility of the integral equation formalism to that of a differential diffusion-type equation. The nonlinear integral equation was extended to the case of multiple reflections of the waves at the plasma boundary. The derivation of the effective kernel is based on a new generalized escape-probability method. Using this formalism, Kukushkin derived the scaling laws for power losses expressed in terms of the effective kernel of the space-integral term in the transport equation. He also analyzed the initial stage of the off-axis electron cyclotron resonance heating (ECRH) and found a mechanism for inward transport of electron energy. He showed that the transport of the electron cyclotron radiation leads to a net inward flux of electron energy from the region of ECRH resonance. The inward transport is essentially determined by transformation of the absorbed narrow-spectral-width ECRH energy into a much broader spectrum peculiar to nonlocal regimes of cyclotron radiation transport in hot plasmas.

W. Kernbichler (Technische Universität Graz) discussed the problem of passive current drive using cyclotron radiation, mainly from the viewpoint of the calculational method. The concept was originally proposed by Dawson and Kaw for a tokamak reactor. Fish-scale-like structures at the first wall help to create enough asymmetry in the plasma. Since the cyclotron radiation increases with operating temperature, this concept will be very important for a D-^{3}He tokamak reactor. Previously, the efficiency of cyclotron current drive had been intensively studied, but the calculational models adopted were not self-consistent. A self-consistent calculation demands the solution of the kinetic equation in terms of the current drive efficiency, together with the simultaneous solution for the problem of the radiation intensity distribution in the plasma. This intensity has to satisfy the boundary conditions on the specially profiled wall. Kernbichler formulated the boundary problem for the intensity in terms of a Fredholm-type integral equation. The values of the current numerically evaluated are less than those given in the previous studies by a factor of 3 or more. However, these values are still high enough to effectively provide a seed current for the bootstrap current. It was also found that the reduction of the current with increasing ^{3}He content is not dramatic, leaving this passive current drive mechanism of interest for a future D-^{3}He reactor.

SUMMARY

This very successful workshop on the physics of D-^{3}He fusion demonstrated the strong international interest in advanced fuels and alternate-fusion concepts. Perhaps even more encouraging, excellent progress is being made in these areas.

Hiromu Momota

National Institute for Fusion Science
Nagoya 464-01
Japan

John F. Santarius

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, Wisconsin 53706

March 13, 1995

ACKNOWLEDGMENTS

Substantial contributions to this summary were made by Alan L. Hoffman, Akio Ishida, Yasuyuki Nakao, and Loren C. Steinhauer.