MEETING REPORTS

SUMMARY OF THE U.S.-JAPAN WORKSHOP ON FIELD-REVERSED CONFIGURATIONS WITH STEADY-STATE HIGH-TEMPERATURE FUSION PLASMAS AND THE 11th U.S.-JAPAN WORKSHOP ON COMPACT TOROIDS, LOS ALAMOS, NEW MEXICO, NOVEMBER 7-9, 1989

INTRODUCTION

Two U.S.-Japan workshops on the physics and technology of compact toroid (CT) plasmas were hosted by Los Alamos National Laboratory (LANL) November 7-9, 1989. Compact toroids are configurations confined principally by magnetic fields generated by internal plasma currents. The toroidal currents are unencumbered by material objects such as magnet coils or a vacuum vessel. Compact toroids are usually classified into two categories, the field-reversed configuration (FRC), a very high-beta prolate plasma, and the spheromak, often a more oblate configuration.

The first workshop, the U.S.-Japan Workshop on Field-Reversed Configurations with Steady-State High-Temperature Fusion Plasmas, dealt exclusively with the theoretical aspects of the FRC. Both experimental and theoretical papers on FRCs and spheromaks were presented at the second workshop, the 11th U.S.-Japan Workshop on Compact Toroids, which immediately followed.

Altogether, there were 61 registered participants from 23 different institutions. Ten participants were from Japan, two from Europe, and the remainder were from the United States. There were 48 presentations, evenly divided into oral and poster sessions. Companion four-page papers were submitted for the combined workshop proceedings, which was published recently by LANL.

U.S.-JAPAN WORKSHOP ON FRCs WITH STEADY-STATE HIGH-TEMPERATURE FUSION PLASMAS

Fifteen papers from nine different institutions were presented. These contributions were related to the possible achievement of a steady-state high-temperature FRC plasma in a reactor-relevant regime. Areas emphasized were reactor studies, stability, and transport.

In the area of reactor studies, the main issues facing the FRC are to increase confinement by several orders of magnitude to a few seconds in a reactor-relevant regime and to address issues specific to the FRC geometry, including the optimum ion temperature for a deuterium-tritium (D-T) reactor, the possibility of nonignited systems, operation in an intermediate-*s* regime (similar to the field-reversed mirror regime), and the attractive possibility of using advanced fuel cycles, such as D-^{3}He.

Progress on FRC reactor studies includes optimized start-up scenarios using neutral beam injection to increase flux and current by the Ohkawa current and a novel design for direct conversion of 15-MeV protons using an "inverse Linac" approach. In addition, several presentations consistently identified the design points for D-T and D-^{3}He systems. For D-T, $r_s \sim 1.2$ to 1.5 m, $s \sim 20$, and $\tau_E \sim 2$ s are required, while for D-^{3}He, r_s is comparable, s is raised to ~ 40 and τ_E to ~ 5 s.

The directions for near-term FRC reactor research were identified. Considerable work is planned by the Nagoya Fusion Institute group in identifying a start-up scenario to avoid the need for a D-T burn phase. Reactor designs continue to evolve as more complete models of equilibrium and stability become available. In addition, the unique features of the FRC may lead to reactor embodiments differing considerably from the *in situ* designs of current interest, such as formation at low density using fast reconnection, translation, compression heating, etc.

Considerable progress on stability issues, primarily concerned with the internal tilt mode, was reported. The main issues continue to be possible avenues to tilt stability at increasing *s* and improved fluid models to corroborate and extend Vlasov calculations. Progress was reported in extending the linearized fluid work begun at Niigata University and Spectra Technology, Inc. (STI) by the inclusion of gyroviscosity. A new Migma-like system called Exyder was described and shown to derive stability from the properties of the applied magnetic field. Finally, two LANL papers described tilt stability results for non-Maxwellian ion distributions, in the two extreme cases of a two-temperature ion distribution and of a relatively cold rotating ion beam component. In the latter case, stability with energetic beam components of a few 10^{-3} inventory fraction was demonstrated by simulation of a magnetohydrodynamic (MHD)/beam system.

The main directions for FRC stability studies are to incorporate additional large-orbit and two-fluid effects into fluid stability studies to sharpen the predictions of stability boundaries, to continue to examine MHD/beam systems to optimize the required beam fraction, and to refine detailed comparisons of theoretical stability predictions with experimental observations.

Progress on FRC transport issues was also reported. Transport issues are anomalous transport associated with low-level turbulence, geometric and profile effects on global confinement, and narrowing of various candidate models that make vastly different predictions for confinement when extrapolated to the reactor regime. Progress included (angular) momentum constraints associated with anomalous transport, a new "1.4-dimensional" transport model incorporating dominant geometric effects in a fast algorithm, and further understanding of the nonlinear stage of high-frequency flutelike electrostatic modes. In addition, possible enhancement of the FRC flux loss rate by turbulent and stochastic ion orbit effects was considered. Velocity space particle loss was also discussed and shown to be an important effect in the current FRC regime.

Current directions include a more detailed comparison of competing models with the expanding experimental data base and the extension of plasma simulation methods to longer time scales.

Two main points emerged in the workshop. First, recent improvements in the calculation of the equilibrium and stability of MHD/beam FRC systems suggest that an early experimental investigation of the formation and stability properties of a beam-stabilized FRC is an appropriate element of the present large-s experimental thrust of the international program. Second, understanding the physics of anomalous transport will likely require a more detailed measurement of the fluctuation spectra and a simultaneous improvement in the theoretical predictions.

11th U.S.-JAPAN WORKSHOP ON CTs

Field-Reversed Configurations

Fourteen papers by researchers from six different institutions related to the FRC were presented. Results from experiments dominated the presentations. Principal topics included FRC formation, equilibrium, stability, heating and confinement, and high-energy ion production and injection.

The STI group optimized FRC formation at large reversed-bias magnetic fields on the TRX device. Rapid losses caused by violent axial contractions were eliminated through the application of duodecopole barrier fields during the preionization phase. Survival of the contractions was attributed to an increased symmetry in the preionization plasma caused by the barrier field. Advanced formation techniques developed on the TRX devices have been incorporated into the design of the new LSX facility, under construction at STI. The scientific goals, engineering details, schedule, and status of LSX were the subject of another paper presented at the workshop.

Tomographic inversions of visible continuum light were successfully implemented for the first time on an FRC. The 50-chord system, developed at Osaka University, was used to reconstruct the radial and azimuthal equilibrium profile of the emission intensity of FRCs in the FIX device. Axially integrated two-dimensional intensity profiles were also inferred with a new soft X-ray imaging diagnostic under development by a LANL group.

The magnitude of the $n = 2$ rotational instability was suppressed by oscillating toroidal fields on the NUCTE device at Nihon University. The B_θ fields, generated by oscillating axial currents applied to an equilibrium FRC, however, did drive a disruptive kink mode. Control of the $n = 2$ mode without kinking should be achievable, provided the B_θ stability threshold is sufficiently small with a shear factor $q < 1$. A theory developed at Osaka University predicts such a threshold at higher B_θ frequencies.

Odd $n = 1$ magnetic asymmetries, consistent with MHD predictions of the internal tilt mode, were detected with external magnetic probes on FRCs in the theta-pinch source of the FRX-C/LSM device at LANL. Large-magnitude asymmetry was found to be correlated with short confinement times.

High-power auxiliary heating was also demonstrated on FRX-C/LSM. Translated FRCs were compressed by a magnetic field and substantial heating was observed. Ion temperatures >1 keV were confirmed by pressure balance, neutron emission, and impurity Doppler broadening. Significant electron heating was also measured.

While FRCs were translated and compressed at LANL, they were translated and expanded on the FIX device at Osaka University. Large separatrix volumes (up to 0.4 m^3) resulted, and remarkably long configuration lifetimes of up to 0.5 ms were observed, without any evidence of the $n = 2$ mode. Another important first, realized on FIX, was the injection of high-energy neutral particle beams into FRCs. Preliminary observations with hydrogen and helium beams, used as ion and electron temperature diagnostics, were reported.

A new parallel-powered coil configuration was brought into operation on the CSS device at the University of Washington. Annular FRCs were formed at relatively low loop voltages (≤100 V), and the poloidal flux confinement times were longer than in previous experiments. A power balance model for CSS was also presented. A concentrated current density profile results in more localized ohmic heating; consequently, impurity radiation losses, believed to dominate earlier shorter lived experiments, may be better tolerated during formation.

The important new theoretical results on energetic particle ring stabilization of the FRC internal tilt mode were complemented by the experimental work performed by two groups at Cornell University. Initial results from ion injection and ring formation in the MICE device were presented, along with a review of the physics, parameters, and projections for a ring FRC merging experiment. Two principal issues include the number of particles that can be extracted from an intense particle beam accelerator and the trapping mechanism in an FRC. Experiments with a plasma anode, similar to the one that enhanced ion production on the Longshot experiment, were about to start on the higher energy Neptune accelerator.

Spheromaks

Nineteen papers were related to the spheromak, which shows that, in addition to the traditional spheromak research motivated by fusion energy applications, there are now at least comparable resources devoted to spheromak research motivated by defense-related applications (radiation production, hypervelocity projectiles, etc.). Happily, regardless of the motivation behind the research, the results from all groups are generally useful, either because of their complementary or comparative natures. Although the majority of the contributions are experimental in nature, there are significant contributions of a more theoretical, modeling, or systems analysis nature.

The TS-3 group from the University of Tokyo presented results from their recently modified device, which allowed flexible magnetic helicity injection (and spheromak production) with an axial discharge between the outer electrodes of two opposed coaxial guns and/or with a Z-θ discharge. An external bias field could also be used. They presented data about the production of stable flux-core spheromaks (FCS) (also known as "bumpy Z pinches"). In the FCS, a current hole (flux trapped in the spheromak geometric axis along which no current flows) could modify the spheromak q profile to increase magnetic shear and increase the beta limit. The q profile could be modified to the extent that it can resemble that of the ultralow-q and tokamak configurations.

The CTCC-II device at Osaka University features helicity injection by a magnetized plasma gun into an ellipsoidal aluminum flux conserver. The combination of a "choking coil" and a stainless steel entrance region allowed current limiting on the outer flux surfaces to produce a FCS. The CTCC-II discharges are known to have 7 to 12% beta at the magnetic axis, as determined from Thomson scattering. The Osaka paper illustrated how an MHD equilibrium model, incorporating separate parallel and perpendicular pressures, produces a significantly better fit to the experimentally measured magnetic profiles.

Although primarily a U.S.-Japan workshop, this conference broadened its scope with the British contribution on the SPHEX device at the University of Manchester. The SPHEX features magnetic helicity injection into a flux conserver designed to minimize the magnetic flux penetrating the solid wall (field errors) and the associated helicity losses. The SPHEX group presented results that reproduce well some expected key features. These include magnetic profiles close to the minimum energy state, the presence of rotating kink modes, and a gun current/flux ratio that must be exceeded to obtain plasma and helicity injection. The surprising feature is the large current that enters the flux conserver wall opposite to the gun, probably caused by processes other than simple flux diffusion.

The Marauder experiment, under construction at the Kirtland Air Force Base Weapons Laboratory, intends to form a spheromak with a 500-kJ capacitor bank driving a coaxial gun, and accelerate the spheromak with the 9-MJ Shiva Star bank. The aim is to achieve ultrahigh directed energy and radiation. Simulations of spheromak formation were performed with the two-dimensional MHD code MACH2. The results explored the range of gun parameters that result (or do not result) in spheromak formation. A key feature identified is the need for sufficient mass density to allow a sufficiently high ratio of magnetic/kinetic energy, which in turn allows proper reconnection of the magnetic field.

In the Lawrence Livermore National Laboratory RACE experiment, a coaxial gun forms spheromaks (plasma rings) that are then accelerated along coaxial electrodes. Rings have been generated with velocities of up to 3×10^8 cm/s, with kinetic energies of 20 kJ. Stagnation of the rings against a copper plate has produced 2.7 kJ of soft X rays, with a spectrum >10 eV. Focusing of the rings to about one-third of the initial diameter has been demonstrated. Design of the Compact Torus Accelerator (CTA) within the RACE program is proceeding. The CTA has potential, when scaled to high energies (~100 MJ), for fusion applications. These include radiation production for indirect inertial confinement fusion drive and magnetically insulated, inertially confined fusion.

A California Institute of Technology group experimented with helicity and plasma injection from a coaxial gun into the ENCORE tokamak. They injected into the magnetized vacuum vessel (no plasma) and observed a resulting magnetic structure with $m = 1$ symmetry. In their experiments of injection into a tokamak discharge, they demonstrated toroidal current drive, with fast toroidal current increases of ~30%.

In BCTX at University of California, Berkeley, a coaxial magnetized gun injects magnetic helicity and plasma into a mesh-walled spheromak flux conserver. The purpose of this experiment is to eventually test a 20- to 40-MW pulsed lower hybrid heating scheme. Spheromak lifetimes of 100 μs have been achieved in the 0.7-m-radius mesh flux conserver. These spheromaks exhibit the expected $m = 1$ kink instability, rotating at a high rate. Optimization of plasma parameters is proceeding. Plasma heating experiments await the completion of the 40-MW, 450-MHz radio-frequency (rf) source. The rf drive components are now in place.

In the University of Maryland spheromak MS, formation is achieved using the Z-θ discharge method. The spheromak magnetic field structures were mapped out in detail. The plasma was asymmetric during formation, evolving into a tilt followed by rapid plasma loss. Asymmetries were attributed to the reversal field coils or feed connections to the I_z electrodes. As remedies for the tilt, a stainless steel liner and copper cones were ineffective, while figure-8 coils slowed it down. Titanium gettering and Elkonite electrodes were used to reduce impurity problems. Doppler broadening of OII, OIII, and OIV indicated anomalously high ion temperatures of ~30, 75, and 90 eV, respectively. HeII temperatures as high as 100 eV at the geometric axis were measured. Strong visible and ultraviolet radiation was observed surrounding the electrodes. Line-averaged electron density from a multichord interferometer was shown. Greater density than that provided by the fully ionized fill in some cases indicated a large impurity influx. The particle confinement time was ~95 μs. Results from a zero-dimensional energy balance code revealed that a reduction in impurity content is needed to get higher electron temperatures.

There are two spheromak devices at LANL: CTX and HESS. Currently, the CTX facility is aimed at producing clean, high-magnetic-field spheromaks by helicity and plasma injection into a flux conserver with solid walls. Suitable spheromaks will be compressed by the wall, driven by high explosives. Ultimately, the spheromak will be used as an energy transfer and switching medium for accelerating metal foils to hypervelocity. The poor energy confinement times found in the former mesh-flux conserver was attributed to high edge helicity dissipation caused by magnetic field errors at the spheromak edge. Much improved energy confinement times were subsequently observed in the solid-flux conserver (designed to minimize field errors), as high as 180 μs, and a clear pressure-driven instability under these conditions was observed. The "bow-tie" flux conserver was proposed as a simple way to achieve higher stable plasma pressures. A detailed theoretical discussion of the bow-tie high-β flux conserver was presented. A detailed comparison of the measured plasma gun impedance with an MHD model of plasma flow (assuming a nozzle is formed at the gun muzzle) yielded reasonable agreement. Thomson scattering, density interferometry, and B field data from small, high B field spheromaks were presented. The data showed T_e as high as 400 eV, n_e in the range of 3 to 8×10^{14} cm^{-3}, and maximum internal B field in the range of 2.2 to 2.6 T. The stability properties of the $n = 1$ and $n = 2$ modes during decay were discussed. Bolometry, spectroscopy, and Doppler T_i data were also presented. Radiation losses were shown not to dominate, while impurity line radiation behavior was consistent with the multihundred electron-volt electron temperatures measured with Thomson scattering. Doppler T_i values increased during strong $n = 2$ kink activity, to values as high as 1 keV. The detailed design of a new plasma gun and flux conserver suitable for the CTX programmatic goal was presented, as well as positive results from a high-explosive-driven dome inversion experiment.

The mechanical helicity injection experiment HESS was explained. In this scheme, a high-explosive driven cylindrical wall generates helicity by driving an initial solenoidal magnetic field into twisted grooves in a concentric opposing wall.

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SUMMARY OF THE 21st DAMAGE SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH POWER LASERS, BOULDER, COLORADO, NOVEMBER 1-3, 1989

The symposium was held at the National Institute of Standard and Technology (NIST) at the foot of the Rocky Mountains in Boulder, Colorado. The conference was attended by 188 scientists, 32 from foreign countries. Some Chinese and Russian scientists were expected, but did not come due to the political situation in their countries. A strong participation from the defense and aerospace industries was observed.

Thirty-three oral papers and 28 posters were presented. The oral presentations were divided into four broad categories:

1. materials and measurements
2. surfaces and mirrors
3. thin films
4. fundamental mechanisms.

The study of radiation damage in optical materials is a very broad field in which investigations can be performed in various ways. Contrary to other fields of physics, no comprehensive physical theory has yet emerged to explain and predict the damage in optical materials due to high-intensity radiation. Systematic methods to harden materials have not appeared. Only "recipes" that work in one case but not in another are known to harden the films or materials against the effects of radiation.

A few welcoming words by M. J. Soileau (University of Central Florida) reminded the participants of the wide scope of the conference, which was to be reflected in the diversity of the presentations. This is due to the wide applicability of lasers (industry, medicine, computers, information, optoelectronics). As Soileau noted, future topics in optical materials research are at least as wide in scope and include thin films, new lasers and nonlinear optics, X-ray optics for lasers and for X-ray lithography, etc.

A long review of the 20-yr-old Boulder Damage Symposium was presented by L. L. Chase [Lawrence Livermore National Laboratory (LLNL)]. Chase outlined 20 yr of achievement, whether in the improved optical properties of materials in the visible and infrared ranges or in improved manufacturing techniques. He also analyzed the various ways to study damage in materials (identification of damage and experimental setups for damage testing). As the following speaker, J. Arenberg (TRW), mentioned, there is effectively a great need for standards in commerce, engineering, and science, and this need is particularly strong in optical damage analysis.

The first category of oral presentations started with various talks on measurement methods for linear and nonlinear indexes of refraction and for assessing damage in optics, as well as the investigation of laser damage on silicon arrays. A very important talk on dielectric breakdown in SiO_2 was presented by P. Braunlich (Washington State University), who stated that laser-induced breakdown was not attributable to impact ionization avalanche, as had been thought for many years. In that case, he concluded, experimental data accumulated over a period of many years have to be thrown away.

The second part of the conference was devoted to surfaces and mirrors. Only four talks were presented, one of which examined in particular the polishability of reaction-bonded silicon carbide. That material was shown to be a viable laser mirror material that can be polished to <10 Å root-mean-square (rms) and <5 Å rms when a silicon coating is applied.

The third part, devoted to thin films, was the most important of the conference by the number of papers. Review sessions of the early years of thin film research (1969 to 1979) by A. Guenther and of the later years (1980 to 1988) by B. Newnam, both from the Los Alamos National Laboratory, were presented and gave the audience a summary of the progress made during those years. They were followed by various talks on laser damage in thin films and on various methods of thin film deposition and optical damage analysis.

Preconditioning of thin films was shown in the past to increase the damage threshold and is considered an essential method of achieving that goal. One can, for example, use laser irradiation at subthreshold fluences [C. R. Wolf et al. (LLNL)], which can increase the threshold by a factor of 2 to 3 over that of the preconditioned film. This enhancement was shown to be permanent. A study on the heat resistant coating of the NOVA laser system showed small conditioning effects of these films. Experiments on small samples showed a laser damage threshold of ~30 to 45 J/cm^2. Various talks followed, especially on plasma chemical vapor deposition (CVD) of thin films. Considering, for example, the cost of NOVA's mirrors ($50 000 each), this study is an important one. Plasma CVD coatings have the highest threshold of any optical coatings, comparable to that of superpolished Corning fused silica (50 to 60 J/cm^2).

The fourth part of the conference was devoted to the study of fundamental mechanisms. Damage in silicon was found to be caused, in the ultraviolet (UV) range, by photoionization and electron avalanche. On the contrary, damage in the infrared is due to thermal effects and to the creation of defects. A similar investigation on quartz showed the cause, in the UV, to be photoionization, and, in the infrared, thermal effects.

Three poster sessions were held during the breaks. They all revolved around various experimental setups used in laser damage studies, damage threshold determination and prediction,