SUMMARY OF THE 15TH INTERNATIONAL CONFERENCE ON PLASMA SCIENCES, SEATTLE, WASHINGTON, JUNE 6-8, 1988

INTRODUCTION

The 15th International Conference on Plasma Sciences (ICOPS) was held at the Sheraton Hotel and Towers in Seattle, Washington, June 6–8, 1988. The scientific program consisted of oral and poster presentations of research papers, given in parallel sessions, and several review lectures in plenary sessions. The printed proceedings contained 328 abstracts of these presentations. Among the 369 registrants at the conference were 30 from nine foreign countries. The technical topics covered a broad range: basic plasma phenomena, space plasmas, magnetic fusion plasmas, and various plasma applications (e.g., fast-opening switches, high-power microwaves, electromagnetic launchers, intense electron and ion beams). One evening, conference participants were treated to a Northwest Indian-style salmon bake on nearby Blake Island.

The plenary review sessions, held at the beginning of each morning, focused on supernovas, fast-opening switches, and dense *Z*-pinches. R. McCray (Joint Institute for Laboratory Astrophysics) reviewed the plasma aspects of Supernova 1987a, which has been touted as the astrophysical event of the century. G. Cooperstein [Naval Research Laboratory (NRL)] reviewed recent research on fast-opening switches for high-power inductive energy storage, which generally feature plasmas in the key role of switching medium. M. Haines (Imperial College) reviewed recent progress on the high-density *Z*-pinch, which has reemerged as an interesting possibility for compact magnetic fusion, as well as other applications.

Early afternoon plenary sessions were used for the first time for two special purposes. The first Plasma Science and Applications Committee award was presented to C. K. Birdsall (University of California, Berkeley) for his outstanding contributions to plasma science over many years, particularly for his work in computer simulations of plasmas. Birdsall presented an interesting discourse on the role of serendipitous discovery in plasma research. The other new feature in the plenary sessions was the review of plasma science history topics. The motivation for this was the feeling that too little attention has been paid to past developments and that much could be learned by viewing today's research problems in the light of historical perspectives. The first topic was the "History of Pulsed Power" by A. Kolb (Maxwell Laboratories). He summarized the development of pulsed power in terms of its applications and stressed that it was important to look at pulsed power as essentially an application-driven technology. He also prophesied future developments into the next century. The second session was devoted to the "History of the *Z*-Pinch" by R. Lovberg (University of California, San Diego), who was one of the original workers in the field. He emphasized that many of the phenomena now being investigated in the *Z*-pinches actually occurred long ago, but were not understood. He emphasized the need for open-ended research to investigate higher risk approaches.

The reviews of the technical sessions, which follow, were prepared by the session organizers: J. Alcock, P. M. Bellan, J. Benford, R. N. Carlile, J. N. Chapman, N. J. Dionne, A. T. Drobot, A. K. Ganguly, A. Hirose, C. Joshi, M. Krishnan, J. Maenchen, M. K. Matzen, J. E. Osher, P. J. Ottinger, A. L. Peratt, A. L. Pregenzer, D. J. Rej, M.-J. Rhee, J. R. Roth, K. H. Schoenbach, K. F. Schoenberg, R. W. Schumacher, J. L. Shohet, and C. D. Striffler.

The presentations at the conference are documented in the conference record—*Abstracts of the 1988 IEEE International Conference on Plasma Sciences*, published by the Institute of Electric and Electronics Engineers.

BASIC PLASMA SCIENCE

Basic Plasma Phenomena

The basic plasma phenomena papers covered a wide range of subjects. However, there was a common theme: They discussed novel, somewhat counterintuitive, anomalous phenomena that require a distinctly subtler understanding of plasma than would have been typical in the past. The main results consisted of (a) peculiar effects coming from plasma nonneutrality (i.e., sheaths, double layers, ambipolar effects) and (b) wave-induced phenomena (transport enhancement and heating).

Nonneutral Phenomena

The invited paper (Hairapetian and Stenzel) described an experiment where a freely expanding plasma with a two-temperature Maxwellian developed a traveling double layer (caused by fast electrons moving out faster than slow electrons and ions). This layer would then accelerate ions, and, because the double layer was moving (nonstatic potential), it would accelerate ions to energies higher than the thermal energy of the hot electron component! Related to the issue of expanding plasmas is the transport of ions into the wake of a flowing plasma (Sheehan and McWilliams); here, anomalously large ion accelerations through an ambipolar sheath were also observed using the technique of laser-induced fluorescence. Another unexpected phenomena related to sheaths and nonneutrality was the focusing of an ion beam flowing along a longitudinal magnetic field (Merlino, Johnson, and D'Angelo); here, preferential background ion transport across the dc magnetic field (because ion Larmor orbits are larger than electron Larmor orbits) would cause the plasma to develop a radial potential well, which would radially focus the ion beam. If the dc magnetic field was turned off, then electron rather than ion radial transport would dominate and the focusing would disappear.

Wave Phenomena

Two papers showed that waves could enhance transport: Electron cyclotron waves can enhance the effective electron collision frequency (Spence, Stafford, and Roth), which would then affect drift wave instability, and ion acoustic waves enhance the electron cross-field thermal conductivity (Needelman and Stenzel). Finally, it was shown that electron cyclotron waves could produce a spatially localized temperature spike in a magnetized plasma (Lam, Mett, and Scharer).

Computer Applications

The submissions on computer applications consisted of 14 oral and poster papers. The central theme was multiple time scale particle-in-cell (PIC) simulations and the state of implicit PIC codes (papers by Friedman and Ray, Richard and Haines, Hewett and Langdon, and Mason). A panel discussion led by Hewett [Lawrence Livermore National Laboratory (LLNL)] resulted in a lively session that held a high attendance level and added almost an extra hour to the scheduled time.

The applications of direct and moment implicit methods to the simulation of plasmas on the ion time scale was examined and the successes as well as pitfalls described. The use of time-step control to improve the speed and accuracy of multiple time scale PIC simulations was reviewed.

Other notable papers covered parallel processing using finite element methods for modeling plasma turbulence (Succi et al., given as a poster paper) and the use of improved geometric representation in PIC simulations (Eastwood in a postdeadline paper, Fritts and Drobot, and Westermann). The remaining papers stressed applications of simulation methods for specific physics problems or numerical techniques (paper on turbulence below the plasma frequency by Suh et al., on reflex triodes by Ambrosimo and Geary, on helicity injection by Nelson et al., on supersonic plasma flow by Bilboa, and on charge conservation in electromagnetic PIC codes by Nielsen and Drobot).

Plasma Diagnostics

The papers on plasma diagnostics continued a tradition of broad scope and high quality at the ICOPS meeting. Especially welcome this year were several papers directly related to the diagnosis of industrially relevant plasmas, a carryover from last year's workshop on this subject.

Several papers described the latest results from Rensselaer Polytechnic Institute on ion beam probing of plasmas of fusion interest. The conceptual design of a fusion gamma-ray experiment for the Tokamak Fusion Test Reactor (TFTR) was proposed, using the 16.7-MeV gamma ray produced by a rarely occurring branch of the deuterium-tritium (D-T) fusion reaction to provide diagnostic information from burning D-T plasmas. A single-shot microwave spectral diagnostic technique based on the use of a textronic 7250 transient digitizing oscilloscope to capture signals up to 6 GHz in frequency was described. The digitized data from the time series can then be Fourier analyzed and a complete frequency spectrum obtained. Other papers were concerned with laser-induced fluorescence measurements of ion distribution functions in a multipole discharge and the effect of hot electrons on line ratio temperature measurements in laser plasmas. The issue in the latter paper was inaccuracies in electron temperature measurements that have been observed in certain plasmas. The inaccuracies could be accounted for by the presence of a nonthermal population of hot electrons. One paper described the use of atomic emission spectroscopy to determine the temperature in the plume of a nontransferred argon plasma torch. Finally, the effects of refraction on temperature measurements of thermal plasmas by holographic interferometry were discussed. In this paper, two different diagnostic methods were used to measure the temperature of a free-burning argon arc. Temperatures above 8000°C were measured spectroscopically, while off-axis, double-exposure holographic interferometry was used in the lower temperature region of the arc.

In addition to these papers, other diagnostic papers appeared in sessions on other specialty topics.

Waves and Instabilities

Waves and instabilities are phenomena common to most plasma science areas. Topics presented at this conference were diversified, from low-density cold plasmas to high-density hot plasmas relevant to fusion studies.

The oral session was highlighted by an invited paper by Stenzel [University of California, Los Angeles (UCLA)] in which experimental studies of high-frequency ($\omega \leq \omega_{pe}$) electromagnetic instability due to sheath-plasma resonance was described in detail. The sheath instability occurs only when an electrode (probe) is positively biased with a sharp threshold in the bias voltage. In the same device, measurements of high-frequency ($\omega \simeq \omega_{pe}$) thermal fluctuations were also made.

Experiments of Alfvén (both compressional and torsional) and ion cyclotron resonance frequency (ICRF) waves in the Phaedrus-β tandem mirror were reported by the University of Wisconsin group. For Alfvén waves, it was pointed out that at the end of the central cell, $k_{\parallel} L_B \leq 1$, where L_B is the magnetic gradient scale length. This complicates physics through coupling between fast and slow Alfvén waves. Parametric instabilities associated ICRF, ion Bernstein waves, and whistler waves have been theoretically investigated by the Indian Institute of Technology group.

Kuehl and coworker (University of Southern California) have reported the results of theoretical investigation of the generalized nonlinear Schrodinger equation, which is relevant to a wide variety of nonlinear physics (plasma waves, nonlinear optics, etc.). Experimental studies on tunneling of ion acoustic solitons through sheaths were reported by Nishida (Utsunomiya University).

Ishihara (Texas Tech University) and coworkers have shown, through numerical experiments, that particles diffuse in a prescribed random electric field even when the condition for resonance overlapping (Chirikov condition) is not satisfied.

Finally, Hirose (University of Saskatchewan) and coworker have reported that in the tokamak magnetic geometry, resistive modes (rippling, electrostatic interchange, electromagnetic resistive ballooning) are unlikely to exist because of the required strong radial localization about a magnetic rational surface, which makes the magnetic drift frequency $[\omega_D(\eta)]$ secular in the ballooning space.

SPACE PLASMAS

Because of *in situ* measurements of plasmas in the solar system and observations from high-altitude rockets, satellites, and radio telescopes, space plasma continues to represent a growing field of research in plasma science. It is now known that Birkeland currents, double layers, and field-aligned electric fields play an important role in the evolution of plasma in space, including the acceleration of charged particles to high energies. Because the properties of plasmas in space are found to differ little from those in the laboratory, empirical knowledge gained from earthbound experiments has found application in situations orders of magnitude greater in dimension. Kirchoff's laws for currents in circuits appear equally valid regardless of whether the plasma is measured in centimetres, kilometres, parsecs, kiloparsecs, or megaparsecs.

The papers presented in the three sessions devoted to space plasmas represent an update of the knowledge gathered about our plasma universe. A wide range of phenomena in space physics was represented, from a review talk on Supernova 1987a, the first visible-eye supernova in 383 yr, to a detailed proposal to establish a radio telescope array of leaky-wave antennas on the far side of the moon.

There were several papers on double layers in space and laboratory plasmas. These covered measurements of dynamic potential drops from laboratory and space probes to computer simulations of electromagnetic radiation from double-layer emitted beams.

Charged-particle beams in space were highlighted by an invited talk by Storey (National Aeronautics and Space Administration Space Physics Division), who described peculiar phenomena in the parallel propagation of high-beta plasma beams. Other closely related topics included instabilities in solar and magnetospheric plasmas, critical velocity ionization processes, and the red shift of plasma spectral lines in the sun's chromosphere. The spectral profile of the cosmic microwave background radiation and its deviation from blackbody at submillimetre wavelengths was described in terms of emission and absorption in filamentary cosmic plasmas.

MAGNETIC FUSION APPLICATIONS

Compact Toroid

A compact toroid (CT) is a generic plasma configuration that is confined with magnetic fields generated by internal plasma currents. There are no material objects (e.g., vacuum chambers, magnets, transformers) linking the toroid. Nineteen papers on CT subjects were presented at the conference by researchers from ten different U.S. institutions. Sessions were organized around two specific CT configurations, the spheromak and the field-reversed configuration (FRC).

The spheromak is a low aspect ratio CT with about equal toroidal and poloidal B-field maxima. Relaxation toward a minimum-energy, helicity-conserving "Taylor" state is universally observed. The spheromak session was highlighted by new experimental results. On the Los Alamos National Laboratory (LANL) CTX device, a reduction in field error and the addition of titanium gettering significantly improved confinement ($\tau_E \leq 180$ μs); consequently, β was increased to a value limited by pressure-driven magnetohydrodynamic (MHD) modes. Magnetic compression experiments were performed on the Princeton S-1 device. Higher temperatures were observed, presumably due to increased ohmic heating associated with a larger current density. On the LLNL Ring Accelerator Compression Experiment facility, spheromak plasmas were successfully accelerated and reflected in a coaxial railgun arrangement. Directed energies up to 20 kJ were reported.

An FRC is a prolate CT confined only by poloidal B fields. Eleven FRC papers were presented including results from the Triggered Reconnection Experiment (TRX) at Spectra Technology and the LANL FRX-C/LSM experiments. Visible continuum emission was used to determine FRC equilibrium profiles on TRX. Particle transport was found to dominate the energy confinement on FRX-C/LSM. Alternatives to theta-pinch formation were discussed by two groups. On the University of Washington Coaxial Slow Source device, plasmas were produced over 90-μs time scales, and radial pressure balance was confirmed with Thomson scattering. Rotating-magnetic-field current drive was demonstrated at UCLA. A timely review of FRC stability theory was given in an invited talk by Barnes (Science Applications International Corporation). While stable in the laboratory, MHD theory predicts that an internal tilt mode will rapidly destroy the FRC. Kinetic, two-fluid, and rotation effects have been considered to resolve this paradox. Stability might be improved through the injection of high-energy particles. At Cornell University, axis-encircling ions were translated through a magnetized plasma. Neutral beam injection into an FRC is of particular interest in Japan. A relevant injection experiment, with existing neutral beam and FRC technologies, was defined. Updates were given on two new FRC facilities under construction. At STI, the Large-S Experiment device (operational in 1990) will address the formation, stability, and confinement of larger, less kinetic FRCs. The LANL FRX-C device will be modified soon to enable 1-GW auxiliary heating studies with magnetic compression.

Mirrors

The basic mirror device offers a simple magnetic configuration for plasma confinement studies. Mirror research in the United States is primarily centered at the University of Wisconsin Phaedrus-B facility. Reported research from Phaedrus-B focused on basic radial and axial transport studies under several different operating conditions. Experiments with grounded and floating end rings demonstrated that floating end rings modified the central cell density. The density modification is believed to result from changes in both radial and axial transport.

Other Phaedrus-B studies demonstrated that it is possible to achieve axial plugging and a decrease in ambipolar radial transport by means of ion cyclotron resonance heating end cell injection. The plugging of the ion endloss results from the creation of ICRF-enhanced potentials in the end cells and agrees with theory. Increases in central cell density are believed to result primarily from a reduction in ambipolar radial transport.

Reversed-Field Pinch

The reversed-field pinch (RFP) is an axisymmetric toroidal containment device in which plasma is primarily confined by a self-generated, high-shear magnetic field. In contrast to the tokamak, the RFP is characterized by a toroidal field that is reversed on the plasma exterior with respect to its direction on the magnetic axis. This reversed-field, high-shear magnetic configuration enables the confinement of relatively high beta plasma and offers the promise of ohmic plasma heating to ignition.

Several new RFP experiments have recently obtained operational status. The Madison Symmetric Torus (MST) is a moderately large RFP experiment (R/a = 1.5/0.52 m) designed for the dual purpose of exploring the basic physics of RFP boundary conditions and supporting the next generation of RFP experiments presently under construction (RFX at Padua and ZTH at LANL). The MST is expected to achieve plasma currents in the 0.4- to 1-MA range with discharge durations of 10 to 40 ms.

The Reversatron II RFP at the University of Colorado, Boulder, is a new upgrade of the Reversatron I experiment incorporating minimum error field coils, a new vacuum vessel, and removable shell. Initial operation with no shell has produced 23-kA RFP discharges lasting 0.4 ms with magnetic fluctuations similar to those seen in shell-less Reversatron I operation. Experiments are planned to study the effect of vertical field indexing on discharge stability.

Presently operating RFP experiments are continuing work on physics issues critical to RFP concept development. The Culham Laboratory HBTX-1C experiment (R/a = 0.8/0.26 m), operating with a conducting shell of short time constant (<1 ms), is investigating the stability and confinement properties of RFP plasmas whose duration exceed the shell time constant. Initial results indicate the growth of ideal MHD nonresonant modes consistent with theoretical expectations. Work is continuing to more fully investigate the unstable mode spectrum and its parameter dependence.

Experiments in ZT-40M (R/a = 1.14/0.2 m) have investigated ion and electron dynamics in the RFP under a variety of conditions. For normal operation, the ratio of ion to electron temperature is usually near unity. However, in deeply reversed ramping discharges, the peak ion temperature can reach 1 keV with $T_i/T_e \simeq 4$. The anomalous ion heating is strongly correlated with plasma fluctuational activity, indicating the presence of a fluctuation-driven ion heating mechanism. Investigations are continuing on the coupling between MHD and kinetic processes in the RFP and their associated effects on confinement, transport, and sustainment.

In the future, the ZTH experiment (R/a = 2.5/0.4 m) will be the first device tested in the Confinement Physics Research Facility (CPRF) presently under design and construction at LANL. The ZTH is being designed to study RFP confinement dynamics under long-pulse (0.5-s), high-current (2-MA), high-temperature ($T_e \simeq T_i \simeq$ 2 keV) plasma conditions. Operation is presently scheduled to commence in late 1992.

Tokamaks and Stellarators

This session consisted of presentations related to the general subject of toroidal confinement. Wong and Cheng of Princeton Plasma Physics Laboratory discussed the effects on transport of impurities in TFTR considering the effects of plasma rotation and offered a theoretical explanation of the higher impurity concentrations present when the plasma rotates in the presence of counter beams. Murray presented a discussion on disruptions and the edge current in tokamaks based on his view that disruptions were caused entirely by cross currents in the edge plasma and walls as a coupled circuit. Thullin (LANL) discussed the CPRF and ZTH experimental design and predicted completion of these experiments by the last quarter of 1992.

Thomassen (LLNL) discussed the program for heating physics and demonstration of free-electron technology in the Microwave-Tokamak Experiment, which will have 8 to 10 GW at 250 GHz coupled to a tokamak plasma. Helton (GA Technologies) described the MHD computations made for tokamak design reliability that determine which computer simulations were liable to occur in practice and which were not. In particular, this method was applied to poloidal field (PF) shaping coils. A related paper by Paulson and Todd (Grumman Aerospace Corporation) described their PF coil design code that utilizes a Green's function that determines the coil locations and currents that are optimum for any given plasma configuration. Finally, a postdeadline paper by Janos described the compression experiments on the S-1 spheromak device.

PLASMA APPLICATIONS

Advanced Thermionics Concepts

A new session called advanced thermionic concepts was added to this year's technical program. It was designed to feature papers concerned with electron-beam-based microwave devices, novel in kind or in application. Two papers considered interesting lightweight coherent radio-frequency (rf) source alternatives to conventional klystrons (employing systems such as Linacs) because of their higher efficiency capabilities. Simulation results for the lasertron device were compared with klystrons by Tallerico (LANL). Preliminary experimental results using a cathode-driven cross-field amplifier, acting as its own isolator, were reported by a Raytheon group (which also considered the problem of the coaxial TWT as a potential high-power, wideband, millimetre-wave amplifier). Another paper presented by a University of Utah group described the impact of space-charge fields upon the anticipated high efficiency associated with the harmonic autoresonant peniotron device. In an invited paper, True (Litton) reviewed the basic approach for designing and quantifying high-quality O-type electron beams including both their launching and focusing systems.

Electromagnetic Launchers

This session considered accelerators or guns designed to use plasma-related electromagnetic means to accelerate or launch either solid projectiles or tightly grouped clumps of material or plasma to hypervelocities for target impact damage or appropriate target material equation-of-state studies.

Highlights for this session included an invited paper by Gilligan (North Carolina State University) on "Fundamental Studies (of railgun-type plasma/wall interactions) to Reduce High-Heat Flux Erosion of Surfaces" and an invited paper by Shvetsov (USSR Academy of Science Siberian Division) on "Structure and Dynamic of Plasma Armature of Railgun Macroparticle Accelerators." International participation at this session was good, also including a contributed paper by Lebedev et al. (Institute for High Temperature, USSR) on "Disintegration of a Current (armature) Due to Electrical Strength Limit on Electromagnetic Launcher (EML) Bore."

The session generally centered around experimental, theoretical, and computational work directed toward the use of a plasma armature for driving the sabot and projectile down the bore of a railgun to velocities higher than the presently attained ~8 km/s. The one paper outside of this subject area described the characteristics of the exploding foil plasma used to power an electric gun and the measured characteristics of the thin plastic flyers produced at velocities up to 20 km/s. The topic presented and discussed in most detail involved the observed dynamic plasma/wall and armature environment in a railgun. Specific measurements of both electrode and insulator ablation and erosion show this topic to be a well-defined problem for most types of EMLs. Probe measurements and streak photographs of the railgun channel show the presence of both arc filament precursors ahead of the armature and restrike arcs behind the armature, generally at different times, limiting predicted performance. Predictions using models including limited thermal conduction, electrode channel or insulator surface breakdown, and the role of copious secondary electrons from the intense radiation were described or discussed during question periods. A new approach using a gas gun as the first stage to inject the projectile at high velocity into a railgun second stage to reduce electrode local heating and erosion, as well as to allow pressurization of the region behind the armature to increase the threshold voltage for breech breakdown and reduce restrike arcing was described. Preliminary tests at Sandia National Laboratories (SNL) were at the stage of work to form a suitable railgun armature in synchronization with the gas gun injected projectile.

Fast-Opening Switches

The sessions on fast-opening switches included contributions on the plasma erosion opening switch (PEOS), the plasma flow switch, the *B*-field toggled opening switch, the reflex switch, the plasma-filled diode, and fuses. Results showed significant progress in all these switching concepts, but particular note should be made of extending the operation of the PEOS from the 100-ns conduction time regime to the microsecond conduction time regime. In an invited talk given by Kim (High Current Electronics Institute, USSR), exciting new high-power, long-conduction time results were reported. The GIT-4 generator current rose in 1.1 μs to 1.1 MA before the PEOS opened to ~2.2 MV. Lower power, long-conduction time results were also reported by the NRL and by PIC. Results were presented in the 100-ns conduction time regime from experiments on the Blackjack 5 generator at Maxwell Laboratories. In these experiments, the front end hardware from Particle Beam Fusion Accelerator (PBFA) II was used in order to optimize switching in this geometry at the 2- to 3-MA level.

Progress in understanding PEOS physics was also reported by a number of contributors. New PEOS diagnostics were reported, including measurement of ion current collected at the PEOS cathode, microwave interferometric measurements of the plasma density in a PEOS, and a promising resonant holographic interferometry technique for measuring the ion density distribution. Simulation of the PEOS using PIC codes and the implicit fluid codes were also presented. The PIC code results using the actually conical PBFA II geometry were presented for the first time and fluid code work stressed the importance of treating the boundary condition properly and of including Hall effects and anomalous collisions. Experiments on the Lion accelerator at Cornell University studied coupling of a PEOS to an applied-*B* diode and experiments at PIC investigated coupling between a PEOS and a plasma-filled diode.

Exciting new results from PFS experiments on the Shiva Star capacitor bank at the Air Force Weapons Laboratory were reported in an invited talk by Turchi (RDA). Low-density, very high speed plasma flow in the switch supported voltages >0.5 MV at the end of the coaxial gun muzzle. *B*-field toggled opening switch experiments on the Supermite generator at SNL demonstrated very high voltage switching as well, with >5 MV being measured at the switch location. The report on the latest reflex switch results demonstrated operation on long conduction time driven by simple and Marxed capacitor banks.

Finally, new fuse designs were discussed. A flux-efficient fuse configuration was reported whereby energy efficiency was significantly improved and faster current transfer was achieved. In addition, high-performance fuse designs for magnetic flux compression generators were presented. Up to 800 kA were interrupted in <1 μs, generating voltages >0.1 MV. Theoretical work provided good agreement with experimental results and implications of using fuses in 10-MJ systems were discussed.

Fast Wave Devices

The papers in this area covered a wide variety of interaction mechanisms, e.g., gyrotron, cyclotron auto-resonance maser, Cusptron, free-electron laser (FEL), and Orbitron. The emphasis is to achieve high frequency, high power, and high efficiency.

High-frequency gyrotron oscillators with output power >1 MW are being developed at Massachusetts Institute of Technology (MIT) for electron cyclotron resonance heating of tokamaks. High power has been generated in the 123- to 247-GHz frequency range by using an overmoded cavity. The highest power achieved was 760 kW with 100 kV and a 37-Å beam in the $TE_{16,2,1}$ mode. A peak efficiency of 30% has been achieved with this mode at a lower beam current of 15 A. Mode competition is a problem in overmoded cavities. The phase-locked gyroklystron has been suggested as one method of mode control. Phase-locked multicavity gyroklystrons are being developed at NRL for operation at 35 and 85 GHz. Theoretical and experimental results on the higher harmonic operation of gyrotron with an axisymmetric beam in slotted cavities (Cusptron) were reported.

Experiments at MIT measured millimetre and submillimetre wave emission (240 to 470 GHz) from a free-electron laser. The output frequency is tuned by a variation of the beam energy. Peak output power of ~18 MW is observed at a frequency of 470 GHz with a 2-MV, 1-kA electron beam. In another experiment, the effects of electron prebunching in a Raman FEL were studied at 10 GHz. Theoretical modeling shows the feasibility of higher harmonic operation of

FEL and Ubitron. Harmonic operation provides a method to reduce the beam voltage required for operation at a given frequency. Experiments were also proposed for short period wigglers with sheet beam for operation at low beam voltage.

An Orbitron maser experiment verified the theoretical prediction that an external magnetic field suppresses rf output.

Intense Electron and Ion Beams

Forty papers were delivered relating to intense electron and ion beams, which were divided into subcategories of electron beams (10), ion beams (10), ion beam diagnostics (6), and plasma sources and diodes (14). These papers represent a significant increase in the quality of research in the coupling of plasma sources with beam-generating diodes and in the development of diode and beam measurement techniques. Diode spectroscopy is rapidly maturing, providing critical information for the advancement of the intense beam sources. Theoretical tools, both analytic and numerical, have become better matched to both insight and experimental data bases. Intense beam measurement techniques, intrinsically a different area, are advancing with corroborative diagnostic sets and entering new parameter spaces.

Intense Microwave Sources

In this category, where space-charge effects of an electron beam are of prime importance in the system configuration for the generation of microwaves, there were eight oral presentations (one invited) and eight poster presentations. The three main sources in this area are (a) vicators, devices relying on the formation of a virtual cathode; (b) magnetrons; and (c) magnetically insulated transmission line oscillators (MILOs). In addition, one poster presented experimental results on a plasma-filled backward-wave oscillator.

The research on vicators is concentrating on improvements in their operation via mode control and phase locking, besides increasing power and efficiency and longer pulse operation. These improvements are achieved by making use of modulated electron beams, cavities, and preinjected microwave power. The invited talk presented initial results on a device called the "Reditron," which is designed to produce radiation via only the virtual cathode oscillations. They reported 2 to 3 GW of microwave power, at 7 to 10% efficiency, near 2 GHz. Significantly higher powers are predicted from simulations incorporating modulated beams and cavities.

Research on magnetrons using higher voltages for high-power operation and the extension of magnetron designs for longer pulse operation also received attention at this conference. The MILO device, which requires no applied magnetic field for operation, relies on the interaction of magnetically insulated electron flow with a magnetronlike vane structure. The key features of this device for increased efficiency and power have been delineated and are in the early stages of experimental confirmation.

Ion Sources, Plasma Sources, and Diodes

Work on many diverse light ion sources was presented. Ion sources produced by many mechanisms were discussed, including electrohydrodynamically driven, surface flashover, cryogenic, field-desorption, vaporization-ionization, and bulk dielectric breakdown ion sources. Most of this research is done in the context of producing an ion source for light-ion beams. Very important work was presented describing spectroscopic investigation of the plasma behavior in high-power diodes. Spectroscopic techniques can provide accurate information about the electric and magnetic field distributions in the diode region, temporal evolution of the plasma, and charged and neutral species distribution. Such information is extremely useful to researchers in this field.

Recent work on the analytic theory and numerical simulation of magnetically insulated ion beam diodes was also presented. The success of the analytic theory at predicting operating parameters of several large experiments was emphasized.

Laser/Plasma Applications

The papers in this area covered a number of distinctly different topics. In one case, two-dimensional modeling of laser ablation and fragmentation of calcified biological materials (e.g., kidney stones and gallstones, etc.), which has been carried out with the radiation hydrodynamics code LASNEX, was reported by both Gitomer and Jones (LANL). Good quantitative fits between simulation and experiments were obtained for electron density, plasma pressure, mass loss, and cavitation bubble growth. A very different interaction regime was described in a paper on high-power, picosecond KrF laser irradiation of solid targets. In this work, reported by Smith et al. (Rutherford-Appleton Laboratory), 1-J, 3.5-ps pulses were focused on aluminum and titanium targets to give irradiances of up to 10^{17} W/cm^2. Prepulse energy was found to have a significant effect on the resulting plasma parameters and at prepulse levels $<10^{-3}$ of the main pulse energy, 400-eV plasmas at close to solid density were produced. The effect of hot electrons on line ratio temperature measurements in laser-produced plasmas was discussed in a paper by Olsen (SNL). The excitation and ionization model described in this paper indicated that hot electron populations of a few percent can result in excited state population ratios significantly different from those existing in fully Maxwellian plasmas. The application of laser triggering to a high-voltage vacuum switch was discussed by Brannon and Riley (SNL). These authors reported that reliable triggering of a vacuum switch, incorporating a target pellet that contained either KCl or KI, had been achieved with laser energies as low as 20 μJ and that jitter times of <15 ns had been observed.

A number of other papers described experiments in which laser/plasma interactions played a major role. In particular, plasma and pulsed ion sources, described by Tisone et al. (SNL) and Kasuya et al. (Tokyo Institute of Technology), involved irradiation of lithium targets with various types of pulsed laser sources.

MHD Generation

The MHD session featured papers on space-based MHD power, MHD generator phenomena, materials for MHD generators, and a study of the applicability of various coals for MHD central power application.

Space-based power was highlighted by two papers covering different technologies for achieving the desired 100-MW burst power for 500 s to meet the Strategic Defense Initiative weapon requirement. Holman (Westinghouse Advanced Energy Systems Division) discussed the Westinghouse-MIT concept for using a gas-cooled nuclear reactor to heat stored, onboard hydrogen and using it in an open-cycle MHD generator in the disk configuration to generate the desired power.

Solbes (TRW, Inc.) covered the TRW concept in which a chemical fuel with alkali seed is combusted to provide a highly conducting gas that is used in twin-disk MHD generators configured in an opposing physical configuration to generate the required power.

Winkleman (University of Tennessee Space Institute) reported on work done with data taken in a high-interaction MHD generator test in China to infer physical phenomena in the MHD generator from high-frequency fluctuations.

Aoki (Hokkaido University) presented two papers covering results recently achieved in the Japanese MHD program. In the first, he reported on the results of measuring the seed material number density and plasma temperature in the boundary layer of an MHD generator. The measurements were made with a light polarization line reversal system. The results indicated that the seed partial pressure is ~1% of the total pressure in the particular plasma used, which was seeded to ~1% by mass. In the other paper, he reported on development of silicon carbide bonded to metals as wall elements for MHD generators. Experimental results from a simulation test facility indicated that the material easily met the conditions anticipated in an MHD generator.

Sawhney (Indian Institute of Technology) reported on a study done on the principal coals indigenous to India for application to MHD central power plants. He found that the lignites and lower ranking coals are not good candidates for the conditions desired, but that their bituminous coals would be excellent candidates.

Microwave/Plasma Interactions

Microwave/plasma interaction is a rapidly growing plasma science topic that encompasses several significant applications of plasma physics. These include microwave/millimetre-wave generation, phase-conjugate reflection of electromagnetic radiation, and the absorption and specular reflection of radiation from plasmas that are artificially created in the atmosphere. Seventeen papers were presented on these topics in two sessions at the ICOPS meeting.

Papers on microwave generation reported on the conversion of electron-beam-driven plasma waves to radiation fields in several different configurations. One conversion technique employed the nonlinear coupling of two counterstreaming-beam-driven waves to radiation in the frequency range of 7 to 60 GHz with a conversion efficiency >1%. Another technique used a single high-power, relativistic beam to drive strongly turbulent electric fields (≥10 kV/cm) that decay into broadband microwave to millimetre-wave radiation. A third technique proposed the use of a relativistic beam in a magnetized, plasma-filled waveguide to directly drive a Gould-Trivelpiece TM mode. Also proposed was a plasma-electron microwave source concept where energy stored in an electron-cyclotron-heated, hot electron ring is suddenly converted to radiation at half the electron-cyclotron frequency.

Many papers on the reflection and absorption of electromagnetic radiation from laboratory and atmospheric plasmas were also presented. A particularly interesting paper was given on the prospects for demonstrating phase-conjugate reflection from a high-density laboratory plasma using degenerate four-wave mixing. A rather large number of papers focused on the production of artificial atmospheric plasmas for use as reflective elements in communication and radar systems. Laboratory simulation experiments were presented that demonstrated the generation of suitable plasmas using crossed microwave beams in a chamber filled with low-pressure (0.01- to 3-Torr) gas.

Plasma-Based Accelerators

The 1988 ICOPS had, for the first time, a poster session devoted to an emerging field in plasma technology: plasma-based accelerators. The importance of plasmas is beginning to be evident in accelerator technology. For instance, the colliding electron-positron or proton-antiprotron bunches at the interaction point colliders act as a plasma. Analytical and computational tools used in plasma physics can be used to predict the self-pinching (disruption) behavior of such bunches as they pass through one another. More recently, plasmas have been proposed for focusing high-energy particles because they are capable of providing focusing strengths far greater than conventional lenses using magnets. There is considerable interest in developing collective accelerators using a plasma, to support the accelerating structure that is basically a space-charge wave propagating at the speed of light.

The papers contributed to the poster session on plasma-based accelerators reflected the direct or indirect role that plasmas will play in future accelerators. For instance, a paper by Sherman et al. investigated the efficiency and durability of photoelectric emission from metal photocathodes that can be used in place of conventional thermionic cathodes in future Linacs. Use of metal photocathodes eliminates the problem of longish (1- to 2-ps) intrinsic emission times of semiconductor photocathodes and, in principle, allows the production of subpicosecond electron pulses. The quantum efficiency of such metallic photocathodes (typically 10^{-6}), however, is quite small, which means that more laser energy is required to produce the bunch. On the other hand, the vacuum requirements are not as stringent.

There were two papers on the plasma wake field accelerator (PWFA) scheme. The first, by Krall et al., simulated the excitation of a plasma wake by tailored electron bunches using a fully relativistic, electromagnetic code FRIEZR. The second, by Ting et al., analyzed the effects of a guide magnetic field on the PWFA. Such a field may be necessary to confine and guide the driving electron beam through the plasma and for reducing the various transverse beam-plasma instabilities.

A paper by Nishida and Luhmann reported the effects of rf risetime on the accelerated electrons due to the $v_{ph} \times B$ mechanism in a microwave/plasma interaction experiment. These studies applicable to the so-called SURFATRON acceleration scheme in which the accelerating particles are accelerated parallel to the wavefront of the wave while being phase-locked longitudinally.

There were two papers on the plasma beat wave accelerator (PBWA). The first, by Joshi et al., summarized the progress at UCLA on the PBWA concept. They have achieved accelerating gradients of ~250 MV/m over a length of ~1.5 cm. The trapping threshold for accelerating the injected 1.5-MeV electrons is ~800 MV/m in the UCLA experiment and efforts are under way to increase the accelerating gradient. The issue of relativistic focusing of the intense laser light was addressed by Esarey et al. and Joshi et al. Esarey et al. suggested that the relativistic self-focusing could be used for continuous phase-velocity control in the PBWA, which, in addition to keeping the laser beams focused over a length greater than the Rayleigh length, reduces the problem of phase slippage.

In addition to these papers, there were papers on numerical simulations of collective ion acceleration in a relativistic electron beam plasma interaction by Yao and Strifler and on proton ring translation in a magnetized plasma by Schamiloglu et al.

Plasma Chemistry

Several of the papers in this session were relevant to plasma processing. One paper discussed modeling of electron dynamics in a parallel plate reactor. A second paper discussed an innovative plasma source for pulse etching materials. Process engineering was the subject of a third paper in which wafer temperature was used to control the sidewall angle of a trench etch in silicon. Finally, a diagnostic technique was described in which Fourier transform mass spectroscopy was used to analyze the properties of argon ions. The remaining two papers were not plasma processing related: one concerned the microwave discharge excitation of XeO excimers and the other discussed the breakdown of organic molecules in a plasma environment.

Plasma Focus

Since the plasma focus was discovered in the early 1960s, this subtle phenomenon has been persistently studied to understand fundamental underlying physics. It has evolved into intense sources of charged particles, neutrons, and radiation. The papers in this session represent an update of the knowledge gathered about the plasma focus phenomenon. The topics include dynamics of the current sheath, high neutron yield, measurements and production of charged-particle beams, a spectroscopic investigation of plasma, and a fusion reaction study.

Ultrafast *Z*-Pinches

This poster session included ten papers, which can be divided into two groups. The first group dealt with the study of *Z*-pinches in extruded deuterium fibers. The second group dealt with the study of gas-embedded *Z*-pinches as X-ray sources. NRL and LANL discussed the dynamics of deuterium fiber *Z*-pinches driven by different current waveforms. Pease-Braginskii equilibria, radiative collapse, and the intriguing possibility of such systems for a fusion system were explored. In a related review talk, Haines (Imperial College) also described the physics of radiative collapse in *Z*-pinches.

Gas-embedded *Z*-pinches were described by groups from Cornell University, SNL, and Imperial College. The SNL papers dealt with the sensitivity of implosion dynamics to initial conditions, as well as the efficacy of gas puff-on-coaxial, thin-shelled targets for X-ray production. The Imperial College paper presented detailed insights into hot spot formation in gas puff *Z*-pinches.

X-Ray Laser

The effort to develop new X-ray lasing schemes and to push existing schemes to shorter wavelengths has continued with both optical-laser-driven and pulsed-power-driven X-ray laser experiments.

Recent X-ray laser experiments that use optical lasers as the pump source have shown progress toward soft X-ray laser wavelengths in the water window (<44 Å). LLNL personnel, in collaboration with the Centre d'Etudes de Lemeil, have studied the variation of gain as a function of pump laser wavelength (1.06, 0.53, and 0.35 μm) and intensity for both neon- and nickel-like recombination schemes. Gains near 5 cm have been measured in neon-like systems and near 1 cm in nickel-like systems. They have also begun looking at hydrogen- and lithium-like recombination schemes as alternatives to reach shorter wavelengths. Work on the lithium-like recombination scheme include experiments at the Laboratoire de Spectroscopie Atomique et Ionique in Orsay, France, where recent results indicate gains of 0.5/cm in lithium-like aluminum plasmas. Work at LLNL to model the soft X-ray optical effects in exploding foil X-ray lasers has been successful in reproducing the temporal and spatial X-ray laser beam patterns that are observed experimentally.

The pulsed-power-driver X-ray laser programs continue to work on X-ray pump source development and plasma generation. Soft X-ray laser schemes presently being emphasized include the sodium/neon line-matched, lithium-like aluminum and hydrogen-like neon recombination, and photoionization pumped neon-like recombination schemes. Although these pulsed-power accelerators have shown that they efficiently generate interesting plasmas as well as intense X-ray fluxes, no soft X-ray lasing scheme has been successfully demonstrated.

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SUMMARY OF THE U.S./JAPAN WORKSHOP ON PLASMA-BASED 14-MeV NEUTRON SOURCES, OSAKA, JAPAN, JUNE 7-10, 1988

The first U.S./Japan workshop on plasma-based 14-MeV neutron sources was held at Osaka University, Osaka, Japan, June 7-10, 1988. This workshop was organized to accelerate development of concepts for a plasma-based fusion materials irradiation facility (FMIF). Existing fission reactors and low-intensity deuterium-tritium (D-T) neutron sources are presently used in the early stages of fusion materials development. However, final selection, acquisition of engineering data, and qualification of low-activation, long-lived materials for construction of fusion reactors will require life tests in a facility that provides the appropriate D-T neutron energy spectrum at an accelerated rate. In recognition of this need, the U.S. Magnetic Fusion Program Plan specifies initial operation of materials test facilities in the mid-1990s. To provide accelerated testing, the neutron flux at the sample position should be at least an order of magnitude greater than that expected at the fusion reactor first wall. Fortunately, the volume of materials samples can be modest, possibly allowing construction of a compact facility at a small fraction of the cost of a reactor or even that of the next proposed plasma containment device.

Requirements of neutron sources were discussed in the first technical session by a panel of U.S. and Japanese materials scientists. They pointed out that an FMIF should provide sufficient neutron fluence for end-of-life (EOL) materials irradiations in ~1 yr. Here, an EOL irradiation is taken to be 100 to 200 displacements per atom, which approximately corresponds to a 10 $MW\cdot yr/m^2$ or greater 14-MeV neutron fluence. It was also pointed out that the FMIF must provide