PLASMA DYNAMICS

XVI. PLASMA DYNAMICS

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A. Basic Plasma Research

1. NONLINEAR WAVE INTERACTIONS

National Science Foundation (Grant ENG75-06242-A01)

Abraham Bers, George L. Johnston, Abhijit Sen, Frank W. Chambers, Allan H. Reiman, Nathaniel J. Fisch, Charles F. F. Karney, John L. Kulp, Jr., Stavros M. Macrakis, Vladimir B. Krapchev

This theoretical research is aimed at understanding the evolution of large-amplitude coherent waves and strong turbulence in a plasma. We are particularly interested in third-order perturbation theory for coherent waves in a magnetic field, nonlinear evolution of wave coupling and nonlinear propagation of waves in inhomogeneous plasmas, and resonance broadening and strong wave turbulence, based on soliton states.

Our work during the past year included:

(i) A new formulation for the nonlinear coupling of kinetic waves in a plasma.[1] This allows for a pump with finite wavevectors, and waves of arbitrary orientation to the magnetic field.

(ii) A complete analytic solution for the linearly unstable eigenmodes in an inhomogeneous plasma of finite extent.[2] This shows that the unstable eigenmodes persisting when the interaction length is increased are tied to the abrupt boundaries and may have no physical significance relative to the saturated gain convective instability.

(iii) An analysis that shows the interrelationship of oscillating two-stream (OTS) instabilities and modulational instabilities for finite pump wavevectors.[3]

(iv) A complete solution of time-space nonlinear evolution of three-coupled wave packets.[4, 5] We have recently extended this solution to describe the two-dimensional nonlinear interaction in an inhomogeneous medium.[5]

(v) A new derivation of our proposed resonance-broadening corrections to weak turbulence theory.[7] A particularly interesting aspect of this work is that we can begin to relate strong turbulence and stochasticity associated with large-amplitude coherent waves.

(vi) A summary presentation and publication of our work on symbolic computation (MACSYMA) in nonlinear wave interactions.[8]

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2. STUDIES OF NONLINEAR WAVE-PARTICLE INTERACTIONS

National Science Foundation (Grant ENG75-06242-A01)

Peter A. Politzer, Ady Hershcovitch, Gillis R. Otten

In order to study spatial and velocity diffusion processes in a controlled experiment, we are using a counterstreaming electron-beam facility to observe the time history of the particle velocity distribution function and the electric-field spectrum. We can apply a known spectrum of electric-field fluctuations to this system and observe the consequent diffusion. Measurements of the velocity-space diffusion coefficients as a function of the amplitude and width of the applied turbulence spectrum have been made. Using the formalism of strong turbulence theory, we have calculated the expected diffusion coefficients for this system, and these predictions agree well with observations. We are also concerned with the effects of externally applied turbulence on unstable plasmas, and have found theoretically that application of a controlled spectrum of high-frequency turbulence can disrupt particle orbits sufficiently to interfere with the growth of low-frequency instabilities, and even to suppress them entirely. We have applied this calculation to trapped-particle modes in toroidal devices and find that the power required, though large, is not unreasonable and that the cross-field transport can be considerably reduced. We have also applied this model to the half-cyclotron instability in the counterstreaming electron-beam system and have undertaken an experiment to check the predictions of power required to suppress this mode. Thus far, the results are in agreement with our predictions.

3. TRAPPED-PARTICLE EXPERIMENTS

National Science Foundation (Grant ENG75-06242-A01)

Lawrence M. Lidsky, Peter A. Politzer

The trapped electron scattering mode in periodic cylindrical geometry is a high mode number, drift-type mode propagating in the electron diamagnetic drift direction and standing in the direction parallel to B. Our earlier work showed that this mode saturated at relatively small amplitudes, which implied that this particular mode might not have especially serious consequences for particle containment or energy loss. The curve of fluctuation amplitude vs system pressure, however, did not quite level out at the lowest pressures attainable previously and it was not clear that the wave was truly nonlinearly saturated. We have recently modified the apparatus to allow operation at

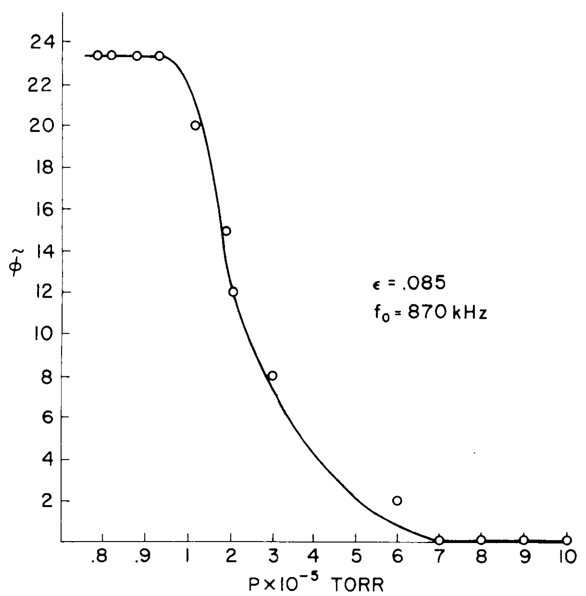

Fig. XVI-1.
Relative potential fluctuation amplitude as a function of normal gas pressure.

appreciably lower pressures and we have repeated our earlier measurements. The essential results of this study are shown in Fig. XVI-1. The collision frequency at the onset of the instability (6×10^{-5} Torr) is comparable to the electron axial bounce frequency in our apparatus. The saturation below 1.0×10^{-5} Torr is adequately demonstrated and we conclude that results that we reported earlier[1] are correct.

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4. RENORMALIZATION METHODS IN PLASMA TURBULENCE THEORY

National Science Foundation (Grant ENG75-06242-A01)

Thomas H. Dupree, David J. Tetreault

An improved version of strong turbulence theory has been developed to deal with predominantly two-dimensional turbulence involving $E \times B$ drifts and quasi-neutral fluctuations. This development leads to a renormalized quasi-linear theory that conserves energy and momentum, which earlier theories failed to do. This theory preserves the essential perpendicularity between the random drifts and the random electric fields. The nonlinear damping also vanishes, as it must, when the electron response is exactly adiabatic. We are now applying the theory to a variety of drift wavelike instabilities.

5. INTENSE RELATIVISTIC ELECTRON BEAMS

National Science Foundation (Grant ENG75-06242-A01)
U. S. Energy Research and Development Administration (Contract E(11-1)-2766)
U. S. Air Force – Office of Scientific Research (Grant AFOSR-77-3143)

George Bekefi

During the past year we have studied the microwave emission from relativistic electron diodes. In particular, we have constructed a relativistic electron beam magnetron that generates microwave powers in the gigawatt range.

In the coming year we shall concentrate on the following areas of study.

(i) We shall optimize the magnetron design in order to obtain higher powers with higher efficiencies. We shall measure the spectral output of the device. To investigate the scaling laws for these magnetrons, we shall go to higher voltages in the 1-MV range. This work will be carried out on higher voltage facilities such as those available at the Naval Research Laboratory and at Sandia Laboratories, Albuquerque, New Mexico.

(ii) This magnetron will be used as the microwave source in the study of nonlinear wave-plasma interaction. Specifically, by luminating an unmagnetized plasma, we are interested in determining the nonlinear absorption and reflection coefficients of the plasma medium.

(iii) By bouncing the microwave emission off another relativistic electron beam, the scattered radiation is shifted to higher frequency. As a result, intense millimeter and submillimeter radiation may be achieved. This work will be carried on in conjunction with the Naval Research Laboratory.

(iv) Because of instabilities, a self-pinched electron beam is expected to emit microwaves, and we shall study it.

B. Plasma Research Related to Fusion

Confinement Systems

1. PHYSICS OF HIGH-TEMPERATURE PLASMAS

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Bruno Coppi

An understanding of the physics of high-temperature plasmas is of primary importance in the solution of the problem of controlled thermonuclear fusion. One of our goals is the magnetic confinement and heating of plasmas with densities larger than 10^{14} particles/cm^3 and thermal energies in the few kiloelectronvolt range. The macroscopic transport properties (e.g., particle diffusion and thermal conductivity) of plasmas in these regimes are weakly affected by two-body collisions between particles. The relevant transport coefficients, in fact, are influenced significantly by the type of collective mode that can be excited, such as density and temperature fluctuations caused by micro-instabilities.

Relevant theoretical and experimental contributions have been presented at national and international conferences[1] or published in professional journals. The primary focus has been on the experimental effort involving the Alcator A machine. Our purpose has been to realize plasmas that can sustain very high current densities without becoming macroscopically unstable, in order to achieve the highest possible rate of resistive heating of the plasma.

Alcator's unique properties -- lack of impurities ($Z \approx 1$), high current density, and large toroidal field, have led to its emergence as the preeminent toroidal confinement device. Specifically, we can point to the following achievements:

(i) Peak plasma densities up to $\sim 7.5 \times 10^{14}$/cm^{-3}, with energy confinement times of ~20 ms have been attained. This yields $n\tau$ values above 10^{13} sec/cm^3 which exceed by a considerable factor those of any existing confinement system.

(ii) Since the particle density can be varied over two orders of magnitude, while the temperature can be independently controlled by the plasma current, and macroscopically stable plasmas can be obtained, we have been able to study a sequence of plasma regimes with a varying degree of collisionality and to derive valuable information about the nature of various transport coefficients such as electrical resistivity and energy replacement time.

(iii) Complete control over the plasma density level can be maintained during a given discharge by further exploitation of the gas injection technique, which was developed in previous years, and by using a new infrared laser interferometer for accurate density measurements. Consequently, a direct derivation of the scaling laws for the particle confinement time has become possible. Direct measurements of the ion temperature in high-density regimes have also been made which have confirmed our expectations that it would be close to the electron temperature.

(iv) A numerical transport code has been developed which can simulate the high-density plasma regimes in Alcator. In fact, elaborate codes developed previously in other laboratories have been inadequate for reproducing these regimes.

The Alcator C device that we proposed in 1975 for funding by ERDA has now been approved and its construction is under way. A new power supply to exploit the design parameters of this device will be acquired and installed at the Francis Bitter National Magnet Laboratory. The major aim of this experiment is to increase the value of $n\tau$ to approximately 10^{14} sec/cm^3 with particle temperatures in the range 2 ÷ 3 keV. The main parameters are: minor plasma radius $a \approx 17$ cm, major radius $R \approx 64$ cm, magnetic field up to 140 kG, and plasma currents up to 1 MA. This device will also complement the results that are expected from the FT machine of Frascati that features $a \approx 21$ cm, $R \approx 83$ cm, magnetic fields up to 100 kG, and plasma currents up to 1.2 MA.

Direct measurements of temperature and density profiles have been performed on the Rector experimental device with the plasma cross section elongated vertically (noncircular) by an appropriate mesh of Thomson-scattering measurements. Thus, for the first time, direct identification of the relevant magnetic surfaces has become possible. This technique will permit a detailed investigation of the confinement properties of a toroidal system with noncircular cross section.

We have continued to benefit from collaboration with visiting scientists from other national and foreign institutions.

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Research – Theoretical

2. RF HEATING AND HF MICROTURBULENCE

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Abraham Bers, Frank W. Chambers, George L. Johnston, Gérard P. Leclert, Abhijit Sen, Charles F. F. Karney, Miloslav S. Tekula, Nathaniel J. Fisch, John L. Kulp, Kim S. Theilhaber, Stavros M. Macrakis

We have continued our theoretical studies on problems associated with the need for supplementary heating of Tokamak plasmas. Several aspects related to RF heating with external power near the lower hybrid frequency have been analyzed in detail:

(a) A three-dimensional WKB formulation of group velocity ray tracing for a Tokamak plasma has been completed and prepared for computation.[1,2] This formulation includes the effects of toroidal geometry, and of plasma and magnetic field inhomogeneity.

(b) Nonlinear phenomena associated with the propagation of high powers from localized sources at the wall have been studied. These include self-modulation and parametric excitations.[3,4]

(c) The following heating mechanisms have been treated in some detail.

(i) Electron heating by the lower hybrid fields propagating in resonance cone structures in the plasma.[5,6]

(ii) Stochastic ion heating induced either by the large-amplitude and short-wavelength lower hybrid fields or by their parametrically excited fields.[7]

(iii) Heating by parametric decay waves coupling to electrons and/or ions, which we have emphasized in the past.

Several reviews of our work have been presented during the past year.[8-10] Many aspects of this work are still incomplete and continue to receive our attention. Our work has included feasibility studies for RF heating experiments on Alcator A which we are now proposing.

We have also continued our studies of high-frequency microturbulence associated with the runaway tail in Tokamak plasmas. Three interrelated aspects are included: (i) anomalous radiation associated with instabilities driven by the electron velocity distribution function tail; (ii) evolution of the electron velocity distribution function in the presence of the applied E-field and the turbulence generated by the instabilities; and (iii) anomalous ion heating which has also been observed. During the past year we have begun to tie these together. A study on the generation of unstable plasma waves by a model electron distribution function has been completed.[11] A quasi-linear analysis of the tail evolution has been initiated and is nearly finished.[12] An important result of this work is that the power radiated by these instabilities can be an appreciable energy loss mechanism in moderate density Tokamaks. It also is important for supplementary heating schemes in which the tail of the electron velocity distribution function may be modified significantly.

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3. NONLINEAR THEORY OF TRAPPED-PARTICLE INSTABILITIES

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Thomas H. Dupree, David A. Ehst

Strong-turbulence theory is being applied to trapped-electron and trapped-ion modes. We have computed the rate of wave energy cascade in wave-number space, as well as the rate of wave energy absorption by the ions caused by stochastic ion motion at high turbulence levels. This permits calculation of many important transport properties of the steady turbulent state including mass and heat transport.

An important aspect of the theory is the prediction of the spectral density of the fluctuations, a quantity that can be compared in detail with experiments.

4. NODAL EXPANSION IN 2 + ϵ DIMENSIONS

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Claude Deutsch

A one-component plasma (OCP) model with neutralizing background has been extended to real dimensionality $\nu = 2 + \epsilon$ with $-2 \leqslant \epsilon \leqslant 2$. The equilibrium properties (pair correlation and thermodynamic functions) investigated within the Debye approximation, up to the second-order in the plasma parameter $e^2/k_BT\lambda_D^\epsilon$, with the aid of the Wilson quadratures, interpolate between two- and three-dimensional results for $0 < \epsilon < 1$, and extend the $\nu = 3$ behavior to all $\nu \leqslant 2$. In this work, the dimensionality $\nu = 2$ has been shown to play a special role.[1] Quantum diffraction corrections are included in the high-temperature limit through a temperature-dependent effective Coulomb interaction. As a by-product, the particle diffusion coefficient (Bohm) of the strongly magnetized two-component plasma taken in the fluid limit may be given a finite volume-independent expression in the thermodynamic limit when $\nu = 2$, provided due attention is paid to the Tauberian properties of the Coulomb potential for $-2 \leqslant \epsilon \leqslant 0$.

This analysis is being extended to two-component plasmas, including this real matter at high temperature. The nodal expansion has been extended to the latter case.

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Research – Experimental

5. TOKAMAK RESEARCH

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

George Bekefi, Lawrence M. Lidsky, Louis D. Smullin

During the past year we concentrated our efforts on three areas of Tokamak research:

a. A study of the impurity influx into the Tokamak discharge using ultraviolet spectroscopy of impurity ions. Spatial and temporal measurements of absolute line intensity were made at wavelengths in the 1000-2600 Å range.

b. A direct determination of the energy confinement time. The energy confinement time in Versator I was determined using a novel technique in which a short heating pulse was applied to the discharge and the subsequent decay of electron temperature was determined. The measured energy decay was 1.1 ms.

c. We have almost completed construction of the Versator II facility, which will become operational during the spring of 1977, and we shall carry out our ultraviolet studies and measurements of energy decay time in Versator II. We shall also perform the following investigations:

(i) Thomson scattering from the electrons with the goal of determining both the parallel and perpendicular electron temperatures of the Tokamak discharge. This work will be undertaken with the use of a 10 J ruby laser.

(ii) Ion fluctuations will be determined from the microwave scattering of 4-mm radiation. For this purpose we have designed a scattering system that contains a microwave source capable of generating 150 W of 4-mm waves.

(iii) Cyclotron radiation in both presence and absence of runaways will be investigated in Versator II in the 15-70 GHz frequency range.

(iv) Certain aspects of microwave heating at the lower hybrid frequency will be studied in Versator II. In particular, we shall attempt to determine the location of the heating signal by using microwave scattering as the diagnostic. We are also setting up the necessary microwave plumbing to study microwave breakdown at the input to the Tokamak. Particular attention will be paid to such questions as microwave breakdown caused by multipacting.

6. COHERENT SCATTERING EXPERIMENT – MEASUREMENT OF ION TEMPERATURE AND LOW-FREQUENCY TURBULENCE

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Puthenveetil K. John, Lawrence M. Lidsky

An experiment is in progress to measure the low-frequency "ion component" of 10.6 μm radiation scattered from a hollow-cathode discharge plasma. This experiment is based on modifications and improvements of apparatus already used successfully to measure the "electron component" of the same spectrum. Our goal is to develop a diagnostic suitable for measuring the relatively low-frequency turbulence that plays the most important role in ion transport and heat transfer.

We use apparatus developed previously and used successfully to detect and resolve high-frequency (electron wing) scattering from thermal level density fluctuations in a plasma with density of order $5 \times 10^{19}/m^3$ and electron temperature of order 5 eV. The radiation source was a 100 W steady-state, stabilized, single-frequency CO_2 laser, and the radiation was detected by a liquid-helium-cooled H_g:G_e photodetector after spectral resolution had been accomplished by means of a liquid-nitrogen-cooled Fabry-Perot spectrometer. The scattering at high frequency indicates that the collective density fluctuation level with wave number in the range 10^5 m^{-1} to 2.5×10^5 m^{-1} was very close to the thermal level. Furthermore, the shape of the scattered spectrum agrees very well with that predicted by theory (see Fig. XVI-2). Our attempts to resolve the ionic component have not been successful. In trying to understand this we have extended

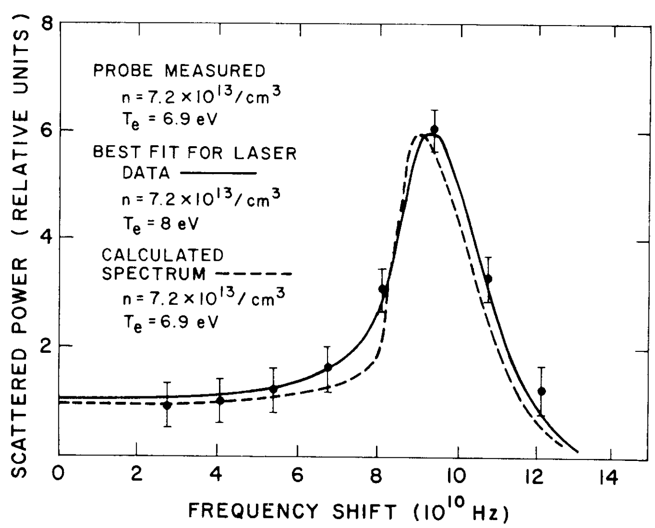

Fig. XVI-2. Comparison of laser and probe-measured plasma parameters.

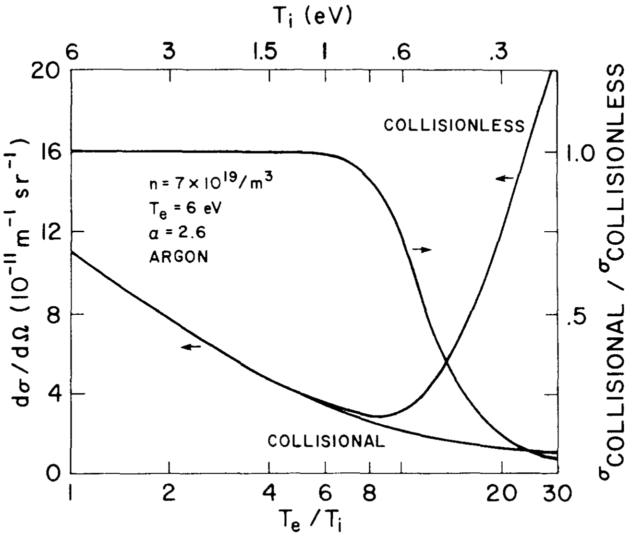

Fig. XVI-3. Total power scattered into the ionic component calculated with collisionless and collisional theories.

the theory of collective Thomson scattering to include the collisional effects in regimes where T_e/T_i is much greater than 1. In these regimes the collisionless Landau damping of the ion acoustic mode is very small and inclusion in the theory of collisional effects has been shown to lead to substantially reduced scattering. The results of calculations for plasmas in the regime of interest are shown in Fig. XVI-3. The scattering in the presence of collisions for the case of interest was reduced by nearly a factor of 10. We are now engaged in modifying the apparatus to improve resolution and signal-to-noise behavior and we hope this will enable us to observe a reduced scattering level.

7. LYMAN-α DOPPLER SPECTROMETER

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Peter A. Politzer, Louis S. Scaturro, Lawrence M. Lidsky

There is an acknowledged need for new diagnostic techniques for measuring plasma parameters in large confinement devices. In particular, we need accurate measurement of the ion temperature with good spatial and temporal resolution. We are designing an instrument to enable measurement of the ion energy distribution with approximately 10 ms time resolution and 2 cm spatial resolution, based on observation of the Doppler-broadened profile of the Lyman-α (1216 Å) emission line of atomic hydrogen. The source volume is defined by the intersection of the viewing light cone and a low-current neutral beam injected across the plasma. The beam energy is chosen to give good probability of charge exchange with plasma ions directly into the n = 2 state. The lifetime of the neutralized ions in this state is very short, and hence they radiate before leaving the source volume and before collisional de-excitation is possible. The line profile is analyzed by using an echelle grating in 46^{th} order in a Czerny-Turner configuration, and a multichannel plate is used as detector. The dispersion of this instrument is 0.2 Å/mm, which enables us to measure the Doppler profile accurately. This instrument will provide a direct and unambiguous measurement of the ion energy distribution within the plasma. It alleviates some of the problems associated with alternative techniques such as neutral-particle energy analysis because the Lyman-α photons escape from the plasma without reabsorption.

8. BOLOMETRY

U.S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Louis S. Scaturro, Lawrence M. Lidsky, Neil S. Novich

A fast-rise bolometric probe has been constructed and mounted flush with the vacuum vessel wall on the Alcator confinement system. The bolometer is a BeO substrate 0.0254 cm thick, flash-coated with molybdenum, backed with thermistor material. Radiative or particulate energy impinging on the surface heats the bolometer and is measured as a voltage change across the changing thermistor resistance. The bolometer was calibrated with a chopped CO_2 laser and found to have a total response of 2.7 volts/joule with a rise time of approximately 1 ms and a fall time of 0.1 s. Preliminary measurements during low-density operation in Alcator indicate a constant energy loss rate to the wall amounting to approximately 5-10% of the ohmic heating power input. For high-density operation ($n_e \gtrsim 1 \times 10^{14}$ cm^{-3}) the power output seems to scale like n_e during the pulsed-gas feed stage, but decreases when the electron density reaches a maximum constant value. These data may shed light on the processes leading to charged-particle density buildup in the central plasma regions when pulsed-gas feed is employed. If so, various theoretical models can be tested.

9. EXPERIMENTAL MIRROR STUDIES

U. S. Energy Research and Development Administration
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Louis D. Smullin, James E. McCune, Robert E. Klinkowstein,
Joseph L. Jones, Kurt D. Cogswell

The purpose of this program is to study instabilities driven by loss-cone-generated velocity distributions.

The apparatus is a chamber 174 cm long and 27 cm in diameter within a mirror field with ratio ~2 and peak field ~4 kG. An array of ceramic bar magnets 64 cm long surrounds the plasma to produce a cusp field of various periodicities up to 12, and peak field at the faces ~1.5 kG. The plasma is injected from a Ti washer gun. Base pressures of (few) $\times 10^{-8}$ will be maintained by a combination of oil diffusion pump and Ti getters in the ends of the main chamber.

The system should be operative in January 1977. The recent success of the 2X11 minimum-B mirror system in achieving nearly classical loss rates has revived interest in mirror confinement systems. This success, in large part, was due to the empirical suppression of loss-cone instabilities by injection of cold plasma. The details of the suppression mechanism are not well understood and our studies are aimed at explaining this process.

The system will be pulsed with plasma injected from a Ti washer gun at one end. At the end of the gun pulse (in the afterglow), we shall measure n(r, t), $f(v_{i\perp})$ (using a charge-exchange analyzer), and plasma potential, as well as fluctuation phenomena. A similar system at the Kurchatov Institute in Moscow has been in operation for some time, and our first efforts will be to correlate our results and plasma parameters with theirs. The Ti washer gun can be fired over a voltage range (on the delay-line capacitors) of 700-3000 volts. The pulse duration is 2 ms. After the installation of a crowbar ignition, pulse width will be adjustable to "arbitrarily" small widths below the maximum.

10. NEUTRAL BEAM STUDIES

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

National Science Foundation (Grant ENG75-06242-A01)

Louis D. Smullin, Leslie Bromberg, Peter Kenyon, Yo Misaki

a. Theory

Louis D. Smullin, Leslie Bromberg

We have developed models that predict the operating characteristics of multifilament, low-pressure plasma sources as functions of geometry, gas filling, and applied voltage. The agreement with experiment is very good for the unmagnetized discharge (Berkeley multifilament arc). In the case of the magnetic cusp protected discharge (University of California at Los Angeles) there is some disagreement between experiment and theory, and we are trying to resolve this by discussions with the authors of the experimental results.

The theory of space-charge effects in cesium charge-exchange cells has been examined to determine whether ion beam blowup should be expected. This seems not to be the case, since a plasma builds up with densities approximately 100 times that of the drifting ion beam, and the resulting space potentials are quite low. The large cold electron density, however, poses a problem for extraction and acceleration of negative ions (D^-). The electrons will have to be separated from the negative ions by a decelerating grid of approximately −500 volts. It is not yet clear what other problems may be caused by this large plasma density and we plan to study this further.

This theoretical research will be submitted as the doctoral thesis of Leslie Bromberg.

b. Plasma Sources

Louis D. Smullin, Peter Kenyon

The work on the magnetron-cathode, θ-cusp plasma source will constitute the Master's thesis research of Peter Kenyon. It will include measurements of terminal characteristics, plasma density at the extraction plane, fluctuation characteristics, and some of the detailed measurements of plasma velocity distributions. With the completion of the detailed studies of the 4" diameter system, we shall now resume the study of a scaled-up 7" diameter system, whose construction was completed some time ago.

c. Charge Exchange between H^+ and Optically Excited Sodium

Louis D. Smullin, Yo Misaki

This study is concerned with measuring the change in the yield of the double charge-exchange process $I_{H^+} \rightarrow I'_{H^\circ} + I'_{H^-} + I'_{H^+}$ when a proton beam (H^+) is incident on an alkali metal vapor (Na), and the vapor has been excited by optical pumping. The system has a variable energy H^+ ion beam (1 – 4 keV) incident on a Na vapor region, with an optical source to excite the sodium to its first level (2.1 eV).

At present, we are studying illumination sources. Since the H^+ beam must pass through a Na vapor target of $\sim 10^{13}$-$10^{14}/cm^2$ (line density), we shall need an extended illumination source. Thus, lasers with their ability to focus to very small spot sizes have no particular advantages, and we are investigating the problem of adapting commercial low-pressure Na vapor lamps to our purpose. We plan to design and build a Na vapor channel integrated with an illumination source.

Fusion Technology Studies

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

The fusion technology program is an interdepartmental effort supported by the Development and Technology branch of ERDA DMFE. The program's goal is to investigate various engineering problems of controlled fusion reactors with particular emphasis on radiation damage, reactor fueling, reactor blanket analysis, safety and environmental studies, and "new concepts development." The fusion technology group is involved in studies of radiation damage, intense neutron source evaluation, fission-fusion symbiosis, EBT reactor design, fusion reactor blanket analysis, pellet fueling of fusion reactors, and reactor safety and environmental studies. The program is centered in the Department of Nuclear Engineering, M. I. T., but a substantial portion of the work is carried out under the auspices of the Research Laboratory of Electronics.

11. HIGH-INTENSITY NEUTRON SOURCE

Lawrence M. Lidsky, Alan R. Forbes

The gas target source is a prime candidate for the intense 14 MeV facility that must be developed for testing fusion reactor materials. We are planning to perform experimental measurements of the detailed behavior of a beam-heated jet in a quarter-scale, intermittently pulsed model of such a device. Our goal is to generate experimental data to compare with theoretical predictions and the extensive numerical computations that have been done at M. I. T. and elsewhere.

This experiment utilizes a pulse circulating gas loop in counterflow with a 150 kV ion beam directed into the nozzle from a duoplasmatron. The gas loop and ion beam transport tubes have been designed, constructed, and tested. Parts needed to complete the duoplasmatron have been machined and the ion source test stand has been constructed. A feedback-stabilized, highly regulated pulsed power supply for the duoplasmatron has been designed and tested and the requisite step-up transformer is under construction. The E-beam gas density probe has been made and tested.

12. PELLET FUELING OF FUSION REACTOR

Peter A. Politzer, Mark L. McKinstry, Clarence E. Thomas

In order to operate a quasi steady-state fusion reactor, a source of deuterium and tritium fuel must be provided that is distributed throughout the reactor plasma cross section. The most promising scheme for introducing this fuel is the injection into the plasma of solid D-T pellets at high velocity. Because of the complexity of the interaction between a solid surface and a hot dense plasma, we do not know the ablation rate of a solid pellet, nor consequently the fuel deposition rate. In order to predict the required pellet velocity, we need to obtain a satisfactory model for the ablation process. We are undertaking this study in two ways. We have developed a computer model for the interaction between a very dense cold plasma cloud and a hot magnetized plasma. Unlike other ablation models, this model includes the effects of magnetic fields, and particularly magnetic shielding of the pellet surface. This code is being used in conjunction with models developed at Oak Ridge National Laboratory which describe the behavior of the ablation cloud in the region between the pellet surface and the layer in which the ablated particles become ionized. In order to have experimental verification of the model under conditions of plasma energy density corresponding to fusion reactors, we are constructing a Z-pinch discharge that will be able to sustain such conditions for short periods of time. We plan to inject plastic pellets into this plasma to get the scaling of ablation rate with plasma density and temperature. The discharge will be stabilized with a bias magnetic field and should provide a plasma with densities of $\sim 10^{16}$ cm^{-3}, temperatures of ~500 eV, for a 3-4 μs pulse length.

13. HIGH-ASPECT-RATIO TOROIDAL REACTORS – EBTRX

Lawrence M. Lidsky, James S. Herring, David L. Kaplan, Robert E. Potok

An ideal fusion reactor, from the viewpoint of a reactor designer, would be a steady-state device of moderate-β, relatively high aspect ratio, modular construction, "reasonable" surface/volume ratio, an operating wall loading of the order of several megawatts per square meter, and would allow for the relatively straightforward provision of a functional divertor. There is a relatively unexplored set of plasma configurations compatible with our understanding of plasma physics which apparently meets these requirements. One of these is the EBT concept pioneered at the Oak Ridge National Laboratory although there are others that, in fact, might be of greater ultimate interest. The Massachusetts Institute of Technology fusion group working in close collaboration with ORNL has evaluated the EBT primary concept as the basis for development of commercial fusion power. Inspired by the exciting potential of devices in this class, we are proceeding to carry out a more general study of moderate-β, high-aspect-ratio, ignited, steady-state toroids. Our initial aim will be analysis of the Heliotron-Torsatron configuration.

The multidisciplinary, self-consistent treatment of EBT reactor scaling and design developed in conjunction with Oak Ridge National Laboratory has been completed and a reference design (EBTR-48) developed. This design, based on a realistic plasma model and relatively conservative engineering parameters, is based on a steady-state ignited-mode system of high plasma power density and aspect ratio. The major design features of the 4000 MW thermal plant are illustrated in Fig. XVI-4 and Table XVI-1. The design postulates a standard module, and the design power level for a particular plant is then determined by the number of modules used. Several design variants were investigated in detail to illustrate the effect of near-term and advanced technologies and to illustrate the design freedom offered by devices with low-field, high aspect ratio. The high aspect ratio simplifies many aspects of design, most notably those associated with remote maintenance, accessibility and repair. We concluded that a commercially successful EBTR could be constructed with only slight advances in existing technology if the

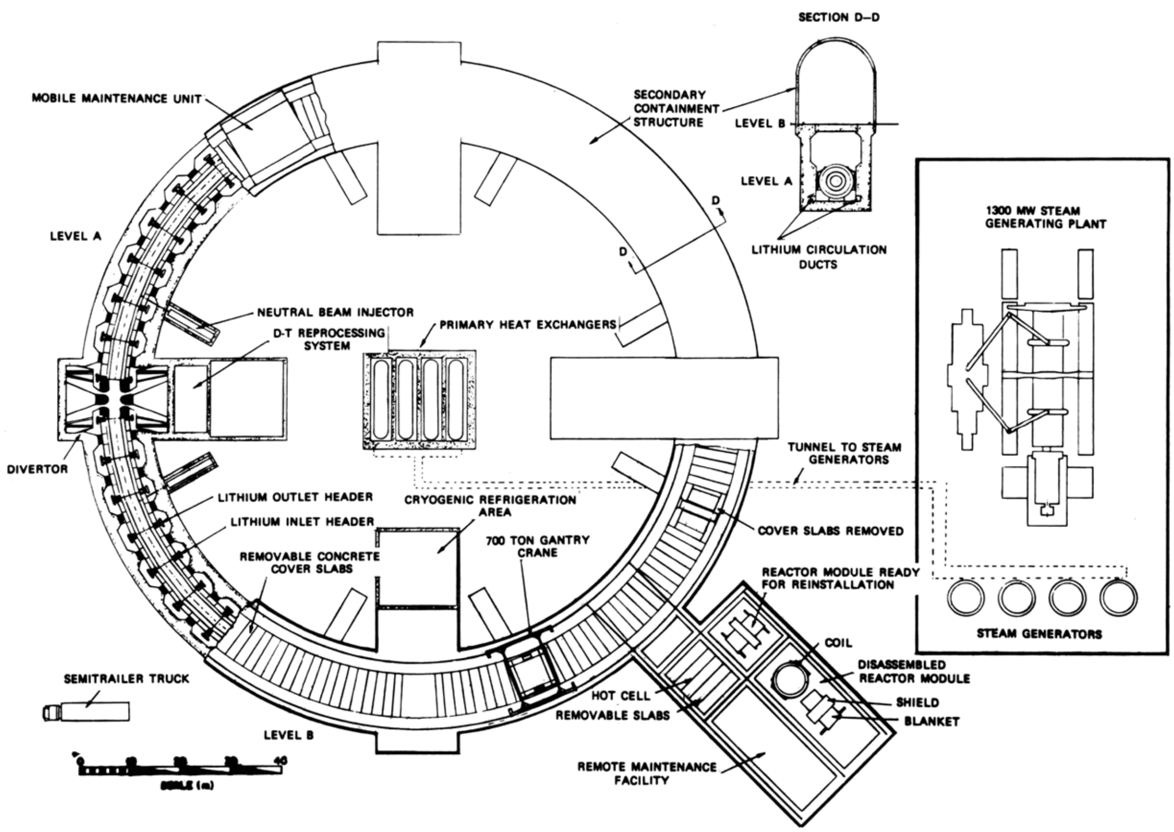

Fig. XVI-4. EBTR plan view.

Table XVI-1. EBT reactor reference parameters.

	EBTR-48
Plasma radius, a (m)	1.0
Aspect ratio, A	60
Major radius, R_o (m)	60
Mirror ratio, M	1.78
Ion temperature, keV	15
Ion density, $N_i \times 10^{-20}$	1.2
Beta, β (%)	25
Magnetic field on axis, B_T (T)	2.5-4.5
Number of coils, N	48
Power, P_{th} (MW)	4000
Power density, P_{th}/V_p (MW/m^3)	3.37
Neutron wall loading, L_w (MW/m^2)	1.13
Cold zone, δ (m)	0.2
Blanket and shield thickness, t_{sb} (m)	1.75
Coil inner radius, r_c (m)	2.95
Current density, J_c (A/cm^2)	1500
Coil radial thickness, t_c (m)	0.71
Coil half-length, L/2 (m)	1.30

plasma physics model could be extrapolated to the reactor regime. Studies are being carried out to investigate the effects of various assumptions regarding first-wall lifetime and power loading on a total operating cost of an EBT-based fusion reactor. Our tentative results indicate that wall loading of approximately 2.5 MW/m^2 neutron throughput yields the lowest total system operating cost.

We are now investigating other high-aspect-ratio moderate-β devices. A scheme has been devised in which the heliotron concept can be embodied in a design that allows individual reactor elements to be modular and self-contained. Detailed studies of magnetic field geometry and magnet design are in progress.

14. FISSION-FUSION STUDIES

Lawrence M. Lidsky, Andrew G. Cook

These studies concern aspects of fissile fuel generation in systems driven by fusion neutrons. Our previous work in this area has resulted in the development of a hierarchical structure suitable for description of a wide variety of interrelated systems and some "figures of merit" suitable for choosing among alternatives. The potential value of hybrid or symbiotic fissile fuel generators is critically dependent upon the fuel and energy values assumed to exist at the time of introduction with particular emphasis given to the cost and availability of alternative enrichment schemes. We have developed self-consistent economic models capable of determining the allowable cost of fissile-producing systems as a function of pure fusion and pure fission core costs, electricity and fuel values, and the attainable Q of the fusion device. We are engaged in the development of optimized symbiotic fuel generators and an assessment of their place, if any, in the power economy.

a. Effect of Processing and Fabrication Costs on Design Choices for Hybrid and Symbiotic Fusion Reactor Blankets

Most designs of fissile breeding blankets for fusion reactors are based on existing fission reactor technology insofar as the choices of fuel composition, fuel configuration, coolant, and operating temperatures are concerned. Fusion-based systems tend, however, to have significantly lower flux levels and fissile inventory at discharge. Conceptual systems entailing high reprocessing and fabrication costs are at a significant disadvantage; for example, it can be shown that, for any reasonable choice of fissile fuel values and reprocessing costs, most oxide-fuel, rod-based configurations are not economical.

We have analyzed U^{233} and Pu^{239} breeding systems with solid metal fast fission zones for initial neutron multiplication. The analysis includes the five major components of fuel cycle economics: ore costs, fabrication charges, shipping charges, reprocessing costs, and fissile fuel revenues. Assuming that both the dominant costs (fabrication and reprocessing) are \$110/kg of heavy metal for rod-type systems, and taking similarly conservative values for the other portions of the cycle, we find that the total fuel cycle cost of a solid metal, batch-loaded Pu^{239} breeding system is

$$C_1 = 271 + N(16.88 - 3.5\,V)\ \$/\text{kg},$$

where N is the in-core residence time in years, V is the value of the fissile product in \$/kg, and an 80% capacity factor has been assumed.

Fuel cycle costs for molten salt-based blankets are dominated by inventory costs and the prorated cost of the on-stream reprocessing system. For a U^{238} fission plate system with a thorium-based molten salt-breeding region operating at only 0.55 U^{233} atoms net breeding per incident neutron, the fuel cycle cost is

$$C_2 = 50.2 + N(2.7 - 1.19\,V)\ \$/\text{kg}$$

assuming the same capacity factor and the ratio of total to in-core inventory taken as 3:1.