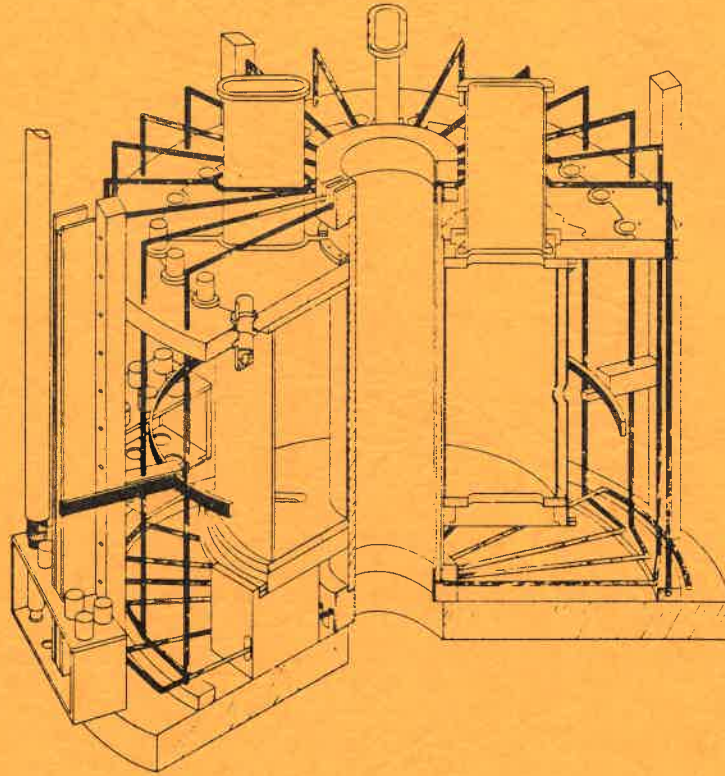


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RESEARCH PROGRAMS



UNIVERSITY OF MARYLAND

LABORATORY FOR PLASMA AND FUSION ENERGY STUDIES

COLLEGE PARK, MARYLAND

20742

PROGRAMS

	Page
I. <u>PLASMA THEORY</u>	1
II. <u>PLASMA EXPERIMENTS</u>	2
1. Toroidal Magnetic Confinement Experiment Terp.....	3
2. Spheromak.....	4
3. Electron Cyclotron Emission from Mirror Plasmas.....	6
4. Waves and Instabilities in Mirror Confined Plasmas.....	7
5. Diagnostics Support Laboratory (For Infrared and Millimeter Wave Plasma Diagnostics).....	8
6. Neutral Hydrogen Density Measurements in Fusion Plasmas...	10
7. Highly Charged Ions in High Temperature Plasmas.....	11
8. Magnetic Field Diagnostics.....	12
9. Fluctuations of a High Density Plasma.....	13
10. Electric Field Fluctuations in a Turbulent Plasma.....	13
III. <u>CHARGED PARTICLE BEAM RESEARCH</u>	15
1. Collective Ion Acceleration.....	16
2. Intense Microwave Generation.....	17
3. Pulse Powered Plasma Focus.....	18
4. Transport of Intense Charged Particle Beam.....	19

1. Plasma Theory

(Ott, Liu, Antonsen, Blaha, Bondeson, Chen, Drake, Grebogi, Guillory, Guzdar, Hassam, Kleva, Lee, Levush, Menyuk, Papadopoulos, Montgomery, Rowland, Tripathi, Winske, Wu)

One aim of this program is to understand relaxation processes of unstable plasmas. Theoretical research in this area includes studies of the stability behavior of current-carrying plasma, the quasilinear and nonlinear development of instabilities, the kinetics of nonlinear wave-wave interactions, magnetic field line reconnection, microinstabilities in nonuniform plasma, and studies of the Vlasov equilibrium and stability properties of high- β plasmas. Such a theoretical program therefore relates both to the general problem of controlled thermonuclear reactions and to our toroidal experiments (which require relaxation of unstable plasma). Computer studies are used as a major tool both in checking the theory and in directing theoretical attention toward other interesting problems. These numerical investigations include studies of spheromak formation and modeling as well as general stability studies.

Other areas of active research include stability, confinement and heating of low but finite β plasmas, such as Tokamaks; anomalous transport processes, either by particles or by waves, in magnetically confined plasmas; parametric instabilities of intense radiation in plasmas as in the case of a laser-driven fusion experiment or wave heating of toroidal systems; solitons, strange attractors, ergodicity, spectral cascades, and other fundamental problems in plasma turbulence;

instabilities driven by the runaway electrons and the associated enhanced synchrotron radiation in tokamaks; tearing modes; collisionless trapped particle instabilities; stability of toroidal configurations; rf plasma heating and current drive; drift waves; cyclotron emission from hot plasmas; the theory of intense charged particle beams; laser plasma interactions; space plasmas, including solar, interplanetary and magnetospheric studies; etc.

II. Plasma Experiments

(Griem, Billard, Boyd, Chin-Fatt, Datla, DeSilva, Ellis, Fischer, Goldenbaum, Hess, Mahon, McIlrath, Majeski, Stauffer, Tsakiris)

The various experiments described in the following cover a wide range of physical conditions, namely plasma densities from 10^{12} cm^{-3} to 10^{22} cm^{-3} and temperatures from 10^4 K to 10^8 K. They are motivated by problems in basic plasma physics, confinement of fusion plasmas, and the measurement (diagnostics) of high temperature plasmas. The laboratory is well equipped with apparatus to produce plasma by various techniques as well as to measure its properties, for example, from its electromagnetic radiation in all ranges of the spectrum (x-rays to mm radiation).

1. Toroidal Magnetic Confinement Experiment Terp

(Professor G. C. Goldenbaum)

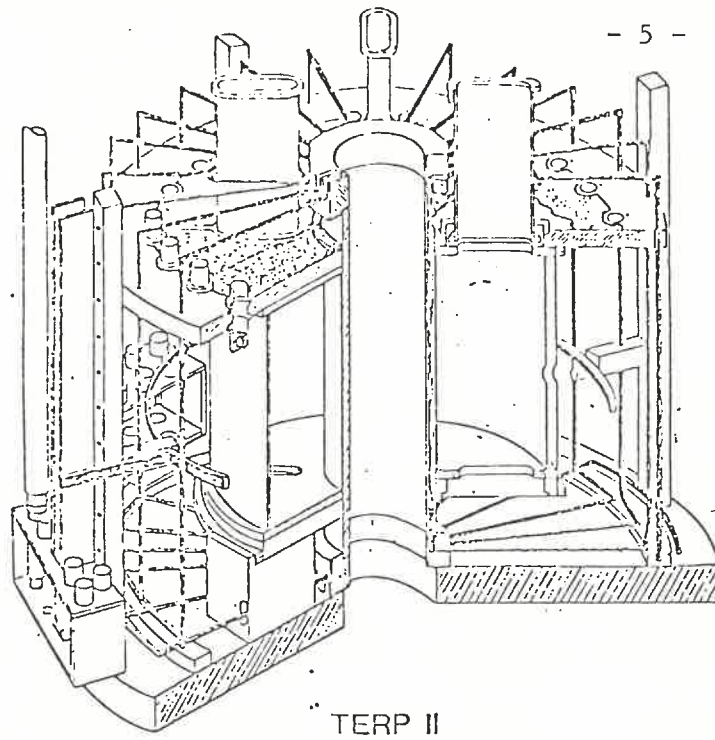
We study physics problems associated with approaches to magnetic confinement of plasmas in two experiments. One experiment, called Terp (Toroidal Experimental Research Plasma) is a high beta tokamak. The problems investigated in Terp have to do with the fact that in magnetic confinement experiments one wishes to confine the most plasma thermal energy W_p with the smallest amount of magnetic energy W_m . The ratio of these quantities is called beta ($\beta \equiv W_p / W_m$). The potential energy of the plasma is the sum of these quantities, $W_p + W_m$. It is believed that there are limitations on the value of β obtainable due to collective motions of the plasma, called instabilities, which convert some of the potential energy to kinetic energy causing this plasma to leave the confinement volume. For example, as β increases the thermal energy of the plasma can become a source for driving instabilities called ballooning modes and interchange instabilities. In Terp, the plasma and magnetic fields are produced by a series of capacitor bank discharges into solenoid coils which surround this plasma. Typical plasma currents are 20kA and magnetic fields are 3.5 kG. The plasma is diagnosed by using small coils to measure the magnetic field, by the scattering of ruby laser radiation to measure the plasma electron temperature and by the phase shift of He-Ne laser radiation to measure the density of electrons. Radiation emitted from the plasma is also used to measure the temperature. Results are then compared with the predictions of analytic theory and computer simulation.

2. Spheromak

(Professors G. C. Goldenbaum and A. W. DeSilva)

In tokamaks the toroidal component of magnetic field, which is necessary for suppressing instabilities, is produced by currents in metallic coils which pass through a hole in the middle of the plasma—the plasma has the shape of a doughnut. Having the coils close to the plasma will be undesirable in a reactor. We are therefore investigating the physics of another type of confinement configuration, called the spheromak, which does not have these coils. In the spheromak, the toroidal field is produced by plasma currents and consequently there is no need for these coils. While the fusion reactor motivations for studying this configuration are principally technological, there are interesting physics issues associated with the lack of metallic boundary conditions at the center of the plasma. Originally these issues were studied theoretically for application to astrophysical problems. For example, these configurations minimize the amount of magnetic energy available to drive instabilities and can be thought of as "ground state" plasmas in analogy with atomic structure, and thus may be more immune to instabilities. The methods for studying these plasmas are the same as with the tokamak, i.e. probes, laser diagnostics, emission spectroscopy, etc.

Schematics of our two toroidal confinement experiments are shown in Figs. 1 and 2.



TERP II

FIG. 1. Terp Experiment

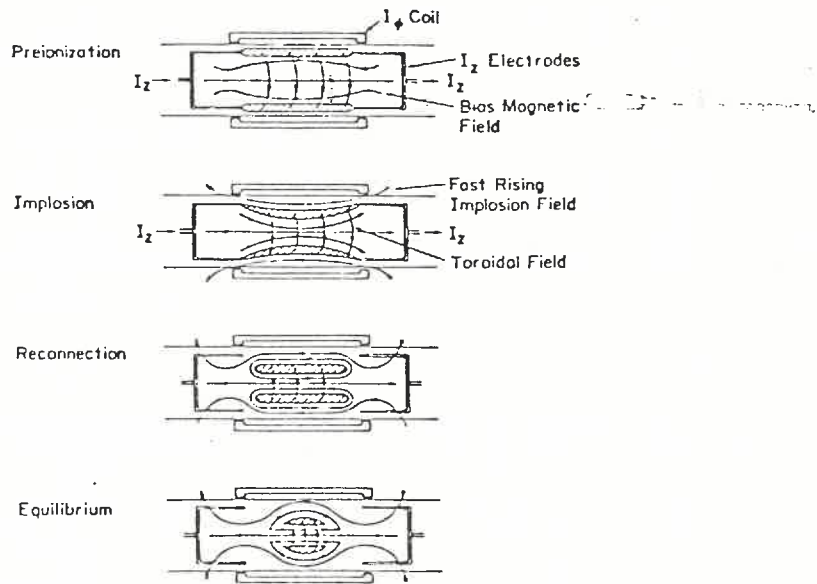


FIG. 2. Formation of a Spheromak Plasma Configuration

3. Electron Cyclotron Emission from Mirror Plasmas

(Professors Ellis, Tsakiris and Boyd)

In a magnetic field B , electrons spiraling about field lines emit radiation at the electron cyclotron frequency $\omega_{ce} = eB/m_e$ and its harmonics. This radiation has proven to be an excellent diagnostic on tokamak devices for measuring the electron temperature and its radial variation. At Maryland we have undertaken a program to study electron cyclotron radiation from mirror confined plasmas and to develop an electron temperature diagnostic based upon this emission. Our efforts have focused on studying the emission parallel to the magnetic field in the so called whistler mode of propagation. Because a mirror machine is an open ended device viewing along B is possible. Moreover, the condition $\omega = n\omega_{ce}$ and the fact that B varies axially, means that one can obtain information about the axial variation of electron temperature. We have recently completed a study of this emission on the Maryland Mirror Machine and confirmed the basic theory of the process for the first time. In the next few years we will shift our emphasis to Lawrence Livermore National Laboratory, where we are presently setting up to do measurements on the Tandem-Mirror Experiment Upgrade (TMX-U). The plasma on this machine is expected to be quite complex and we anticipate some interesting results, with the eventual development of a useful diagnostic. Work at Maryland will also continue, both in developing microwave techniques and conducting experiments on the Maryland Mirror Machine.

4. Waves and Instabilities in Mirror Confined Plasmas

(Professor Ellis)

Mirror machines have historically been plagued by plasma instabilities which reduce drastically the plasma confinement time. At present the most important instability is one which occurs near the ion cyclotron frequency $\omega_{ci} = eB/M_i$. We have recently completed construction of a new state of the art small mirror machine MIXI which has been designed to investigate both the small and large amplitude behavior of this instability. Over the next few years we plan to study this mode in great detail, using a broad spectrum of diagnostics, and emphasizing careful comparisons with theory. In addition, next year we will also begin a series of experiments on the absorption of high power electromagnetic waves in a mirror plasma and the resulting effects on the electron energy distribution. In general, we expect that in the future MIXI will be an excellent experimental device for studying waves and instabilities in mirror confined plasmas.

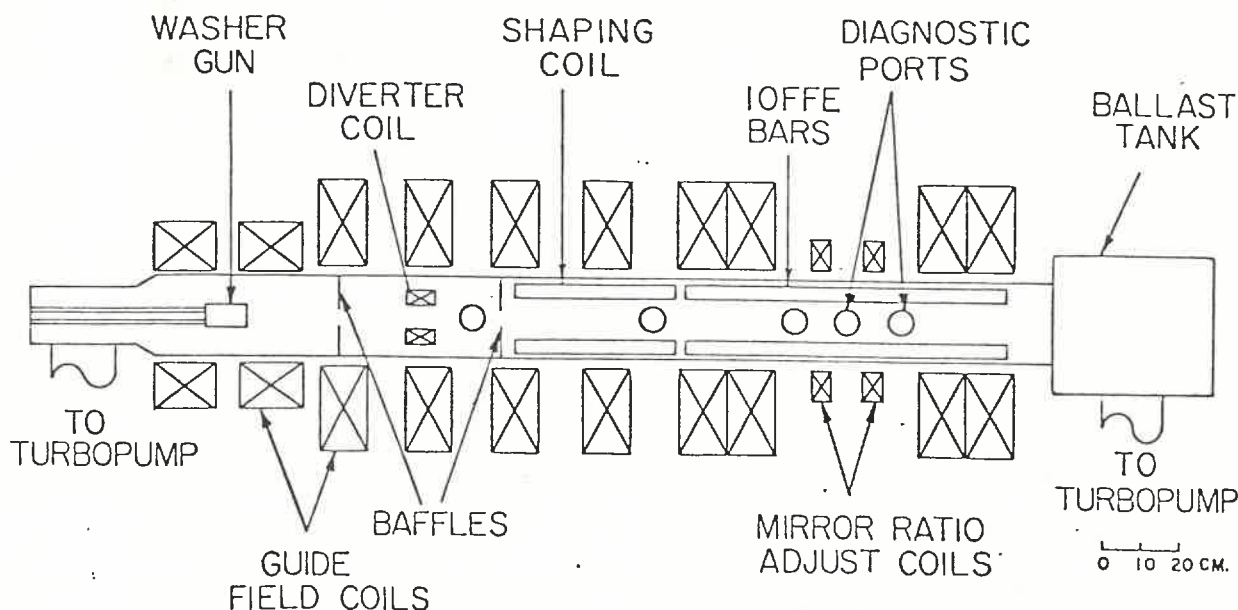


FIG. 3. Magnetic Mirror Experiment MIXI

5. Diagnostics Support Laboratory

(For Infrared and Millimeter Wave Plasma Diagnostics)

(Professor Tsakiris, Dr. Fischer, and Professor Boyd)

This laboratory is concerned with the development of infrared and millimeter wave optical systems for use in plasma diagnostic experiments on the PLT and TFTR tokamaks at the Princeton Plasma Physics Laboratory and on the EBT machine at Oak Ridge National Laboratory.

As part of the joint University of Maryland-Princeton Plasma Physics Laboratory research program for studying electron cyclotron radiation from tokamaks, we are developing infrared and millimeter wave ($\lambda \sim 0.2 - 5\text{mm}$) spectrometers with high temporal and spectral resolution. For example, under construction are a fast-scanning Fabry-Perot interferometer and a grating polychromator. These spectrometers will be able to measure the electron temperature distribution as well as temperature fluctuations in the Princeton Large Torus (PLT) and the Tokamak Fusion Test Reactor (TFTR). Also, a polarimeter has been fabricated and used to measure the polarization parameters of the cyclotron radiation and their time dependence.

The spectral polarimeter will also be used for reflection and polarization measurements on model cylindrical and toroidal vacuum chambers in order to understand the role that reflections of the cyclotron radiation by the vacuum chamber wall will play in the energy balance of future reactors.

In addition, a polarizing Michelson interferometer, fabricated at the University of Maryland, is being used to measure the spectral properties of optical systems in the infrared and millimeter spectral

range. It is being used (1) to measure the reflection and absorption properties of candidate materials for a blackbody source to be placed within the vacuum vessel for the calibration of cyclotron diagnostics, (2) to study the spectral properties of waveguides and trains of lenses that are used for radiation transport, and (3) to evaluate the performance of near millimeter spectrometers and filter systems that are presently under development.

Another part of this laboratory is dedicated to the study and development of radiometers and quasi-optical techniques in the wavelength range of $2 < \lambda < 3$ mm. These instruments are intended for use on the Elmo Bumpy Torus (EBT) machine at Oak Ridge National Laboratory. The University of Maryland has a joint research program with Oak Ridge to measure the synchrotron radiation spectrum emitted by the stabilizing electron rings that exist in each sector of the EBT machine. The Maryland group has undertaken the effort of developing two fixed frequency superheterodyne receivers ($f_1 = 80 \text{ GHz}$ and $f_2 = 138 \text{ GHz}$) and the quasi-optical systems which will gather primary radiation by discriminating against multiple reflections from the metal walls of the vacuum chamber.

The use of mirrors and lenses in a frequency range where the diameter of quasi-optical components are a few times the wavelength, is justified only when the effects of diffraction have been taken into consideration. In designing the quasi-optical system for use with the EBT machine, we used the Gaussian optics theory. The system was tested on a mock-up arrangement with excellent results. The design principles are applicable to any other situation where similar requirements arise.

6. Neutral Hydrogen Density Measurements in Fusion Plasmas

(Dr. Mahon)

The measurement of low ($\sim 10^7 \text{ cm}^{-3}$) density of neutral hydrogen atoms in the center of Tokamak type fusion plasmas, in the presence of much higher ($\sim 10^{10} \text{ cm}^{-3}$) densities near the walls, poses a difficult problem. This program's aim is to carry out such density determinations, with both time and spatial resolution, by detecting the resonance fluorescence radiation emitted when the plasma volume under study is irradiated by a collimated source of light at hydrogen Lyman- α (1216 Å). Since no laser operates directly at this vacuum ultraviolet wavelength, much of the research has centered on the non-linear optics involved in the frequency up-conversion processes utilised in converting longer wavelength tuneable lasers into high power (>1kW) sources in the 1200 Å spectral region. For instance, the nonlinear atomic (and diatomic!) physics of the rare gases: argon, krypton and xenon, as well as the metal vapors: mercury, cadmium, zinc and beryllium, have been investigated to assess their individual capabilities and limitations as non-linear media in the VUV.

Plasma diagnostic experiments will initially be conducted at the Oak Ridge National Laboratory on the EBT r.f. heated torus and subsequently on the ISX-B tokamak. The injected neutral hydrogen beams, used for heating magnetically confined plasmas such as ISX-B, present a whole range of interesting experiments which are particularly suited to this diagnostic technique.

7. Highly Charged Ions in High Temperature Plasmas.

(Professor Griem)

Because of the high electron temperatures and densities in reasonably well confined plasmas, impurity atoms are rather highly stripped. However, as long as any bound electrons remain, they are also giving off copious line radiation which is undesirable in the central region of a fusion plasma but beneficial in the outer region. The radiation cooling of the latter region helps to reduce wall bombardment by energetic particles which are especially effective in sputtering, etc., of the first material wall adjacent to the magnetized plasma. Using quantitative soft x-ray spectroscopy and Thomson scattering diagnostics, we investigate the atomic physics of highly charged iron ions to provide basic electron-ion collision data for fusion research and astrophysics.

These measurements are done on a plasma generated in a theta pinch capable of reaching electron temperatures of 250eV at an electron density of $3 \times 10^{15} \text{ cm}^{-3}$. To extend the measurements to higher temperatures and therefore ionization stages ($Z > 10$) we are now preparing measurements on the TEXT tokamak at the University of Texas.

Another experiment utilizes laser-produced plasmas which reach much higher densities than magnetically confined plasmas. We study high density effects on spectral line profiles e.g., of CVI, in order to develop methods for the analysis of extremely dense high temperature plasmas as encountered in stellar interiors or in inertial fusion research. To extend the densities characteristic of 1μ laser matter interactions ($\approx 10^{21} \text{ cm}^{-3}$) we plan to perform measurements using

frequency-tripled radiation at the University of Rochester National Laser Users Facility ($\approx 9 \times 10^{21} \text{ cm}^{-3}$).

8. Magnetic Field Diagnostics

(Professor DeSilva)

Knowledge of the magnetic field structure in a magnetically confined plasma is necessary to understanding the confined state, and to diagnosing observed loss of confinement. In high energy density plasmas the use of internal flux probes is prohibited, as the probe would be destroyed by the heat input from the plasma. Internal probes also would destroy the confinement, acting as heat sinks.

We are attempting to develop a system for measuring the magnetic field in confined plasmas by observing the deflection of energetic ion beams that have passed through. The observed coordinates of exit points of several beams that were introduced on well defined initial trajectories are used to generate a model of the internal magnetic field, using a high speed computer. The parameters of the internal field are adjusted systematically, using a matrix inversion technique, until the pattern of exit coordinates matches the observed pattern. Close fits to assumed model fields have been obtained in slab geometry. Present efforts are directed to use of a more realistic three-dimensional model field, and to determining the limits to the accuracy and uniqueness of the technique.

9. Fluctuations of a High Density Plasma

(Professor DeSilva)

Much of plasma theory is done under the assumption that close collisions among the various charged particles are rare enough that their effects may be largely neglected. However, under conditions of relatively low temperature and high density found in several areas of plasma research interest - arcs used as spectroscopic sources, stellar interiors and laser fusion plasmas- collisions may strongly affect emission spectra and various transport phenomena. Theory that includes collisions is difficult, and the various theories are not in agreement on their effects.

In this experiment we are trying to determine the role of collisions in the kinetic modeling of plasmas. Using a plasma in thermal equilibrium, we measure the density fluctuation spectrum by laser scattering techniques. The fluctuation spectra are sensitive to collisional effects, and so such a measurement provides the necessary information to test the various kinetic theories in question.

10. Electric Field Fluctuations in a Turbulent Plasma

(Professor Griem)

Turbulent plasmas contain a much higher level of electric field fluctuations than would be expected from thermodynamic considerations. These fluctuations have a direct effect on energy and particle transport and also on the emission of radiation. To relate effective transport

coefficients with microinstability theory, we are making direct measurements of the fluctuation level using laser spectroscopy.

The plasma is produced by a high voltage, electrode-less discharge. It is diagnosed by a variety of methods, but the principal method involves the Raman-like scattering of tunable laser light on excited helium atoms that are "dressed" by the presence of large amplitude collective excitations in the plasma.

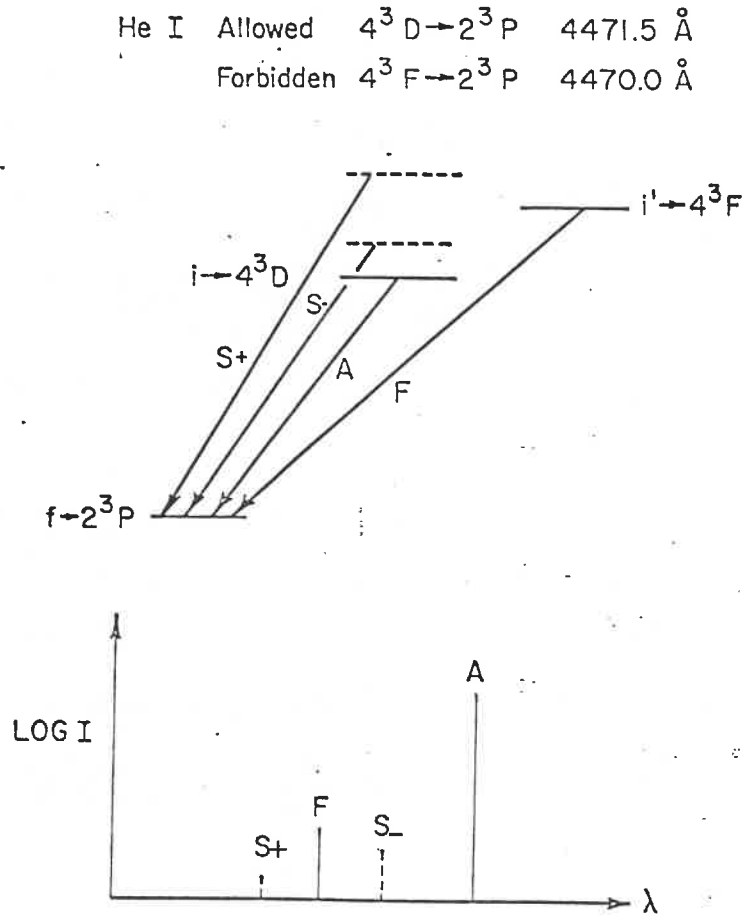


FIG. 4. Energy levels of helium with "virtual" levels involved in the scattering experiment.

III. Charged Particle Beam Research

(Reiser, Destler, Namkung, Rhee, Striffler)

The Charged Particle Beam Research Group is conducting experimental and theoretical studies with intense charged particle beams. These studies have possible applications in the field of particle accelerators, microwave devices, and fusion. The largest facility available for experiments in the laboratory is a high-voltage 1-3 MV, 30-50 kA, 30 ns electron beam generator. Fig. 5 shows the front end (diode) of this generator with diagnostic apparatus. A second, more powerful intense electron beam generator, called DRAGON, producing 1 MV, 150 kA, 100 ns pulses, is being built and should be in operation by summer 1982. Other equipment includes a 15-Joule, 15 ns ruby laser with electrostatic analyzer to measure ion charge and energy distributions, a low-energy (1-10 kV) electron beam transport facility with a high-perveance electron gun and solenoid magnets, and a variety of diagnostic instruments and devices.

The main research projects are concerned with collective ion acceleration, intense microwave generation, pulse powered plasma focus, and transport of intense beams. These projects are discussed separately.

1. Collective Ion Acceleration

(Professors Destler, Reiser, Striffler)

In these experiments, the electron beam from the high-voltage generator is injected through a localized gas cloud or a laser-produced plasma into a vacuum drift tube. The electron beam current is above the space-charge limit and does, therefore, not propagate in vacuum. A virtual cathode forms downstream from the plasma, and positive ions are accelerated to high energies by the large electric fields (200-600 MV/m) of the electron beam. Accelerated protons, light and heavy ions of various atomic species from helium to xenon, have been observed with energies of several MeV per nucleon. The maximum energy of xenon ions near 1 GeV is the highest achieved yet in a collective acceleration experiment anywhere in the world. The use of a slow-wave structure is being investigated to control the acceleration process and increase the ion energy. So far, a factor two increase of the kinetic energy has been obtained for protons by this method. Most of the experimental and theoretical work is aimed at obtaining an understanding of the physical mechanisms responsible for the collective acceleration process. Theoretical work entails investigation of various models and numerical simulation studies of virtual cathode formation, ionization, and acceleration. Of particular interest is the existence of a high energy tail in the ion distribution for which so far no satisfactory explanation has found.

2. Intense Microwave Generation

(Professors Destler, Namkung, Striffler)

In this study, a hollow, rotating annular electron beam is generated that produces high-power microwave radiation after passing through a cusped magnetic field (see Fig. 6). The nominal beam properties transmitted through the iron plate into the downstream beam interaction chamber are 2 MeV, 2 kA, and a 5 ns pulse width. The structure of the downstream chambers that have been examined to date are a smooth hollow cylindrical wall and a magnetron-type wall chamber with small rectangular structures. The most notable difference between these two chambers is the broadband nature of the spectrum for a smooth guide and the single mode spectrum for the magnetron type guide.

The radiation phenomena discussed above has been quantitatively examined and the following explanation has evolved. The annular beam azimuthally bunches due to the negative-mass effect. The azimuthally modulated beam in turn produces the coherent synchrotron radiation, and this radiation is transmitted out of the cylindrical chamber for those azimuthally modulated modes that can couple to a waveguide mode. These studies have indicated that this system holds promise as an efficient broadband radiation source down to millimeter wavelengths and also as a single mode source.

3. Pulse Powered Plasma Focus

(Professor Rhee)

High quality ion beams of various elements produced by a new type of plasma focus device are being investigated. In this device, the Marx-Blumlein pulse power system of the electron beam generator is used with a positive output polarity to power a plasma gun (diode). This plasma diode consists of a metallic rod anode and a planar cathode with a localized gas density maintained near the A-K gap. Typical pulse parameters are 300 kV, 10 kA, and 50 ns. The ions and electrons are accelerated in the positive and negative axial directions, respectively, as in the conventional plasma focus device. Ion beams of gaseous elements (He, N, Ar) and solid elements (Fe, Cu, Mo, W) of anode material are produced and found to have very small divergence. Diagnostic techniques employed in the experiment are time-of-flight, range-energy method, nuclear track detector, magnetic spectrometer, $E \parallel B$ Thomson spectrometer, PIN diode, Faraday cup, and x-ray spectrometer. Typical results obtained in the experiments so far are 10^{10} ions/shot, peak ion energies of ~ 0.6 MeV per charge, fully stripped charge state, and normalized emittance $\epsilon_n < 0.05$ cm-mrad. Fig. 7 shows a typical Thomson parabola spectrum of Argon ions. The upper trace corresponds to A^{18+} ions with a peak energy of 9.9 MeV. Attempts to understand the acceleration mechanism by modeling the system with a simple transmission line and plasma diode have produced good agreement with the experimental data.

4. Transport of Intense Charged Particle Beams

(Professors Namkung, Reiser)

In recent years considerable interest has developed in high-current accelerators for applications such as intense neutron sources, neutral beam injectors for tokamaks, heavy ion fusion, etc. Theoretical studies predict that the beam intensity in such accelerators and associated beam transport systems is limited by instabilities resulting from the interaction between space-charge beam modes and the periodic external forces. A low-energy electron beam experiment was started (in collaboration with J. D. Lawson of the Rutherford Laboratory) to study these instabilities and current limits. The high-perveance electron gun operates at voltages of 1-10 kV, and is pulsed (1-5 μ s, 60 Hz) to avoid space-charge neutralization. The beam is being transported through a long periodic focusing channel with solenoid magnets. In addition to space-charge induced instabilities, various other effects that lead to beam deterioration, such as aberrations and parametric resonances, are being studied both experimentally and theoretically. A special feature of the experiment is the fact that the parameters determining the beam physics (plasma frequency, transverse temperature, etc.) can be varied over a wide range. The results can be scaled to many accelerators and beam transport systems involving higher energies and other particle species.

ELECTRON BEAM GENERATOR
(FRONT END)

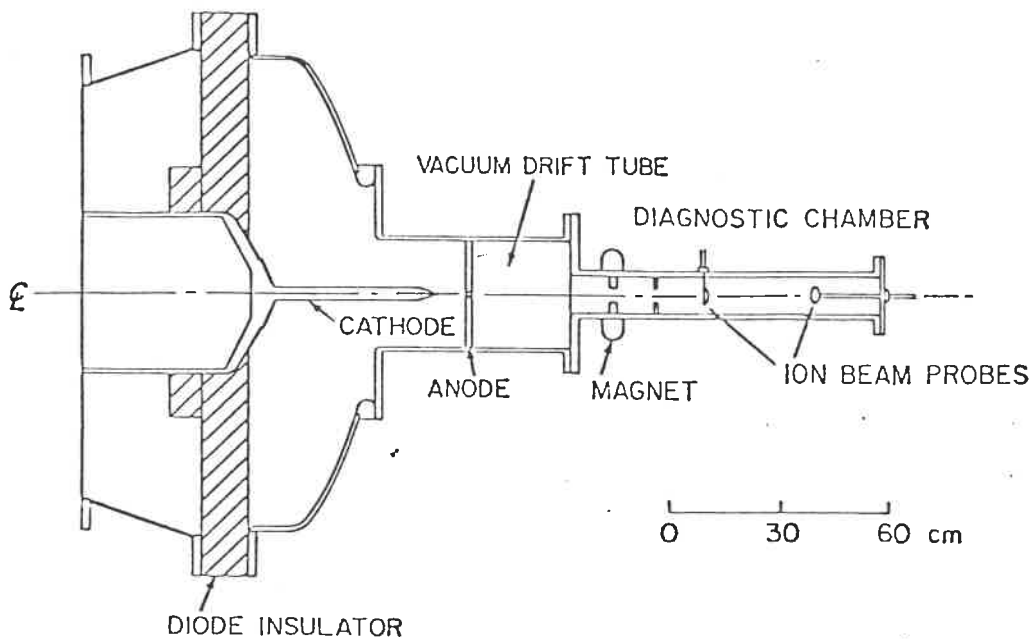


FIG. 5. Front end (diode) of high-voltage electron beam generator (1-3 MV, 30-50 kA, 30 ns) with beam probes for collective ion acceleration experiments.

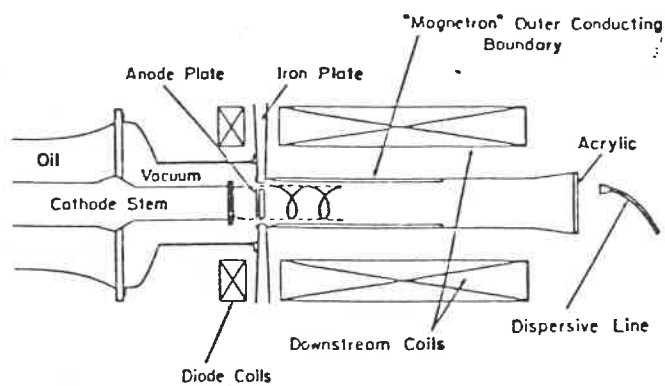


FIG. 6. General configuration of microwave experiment.

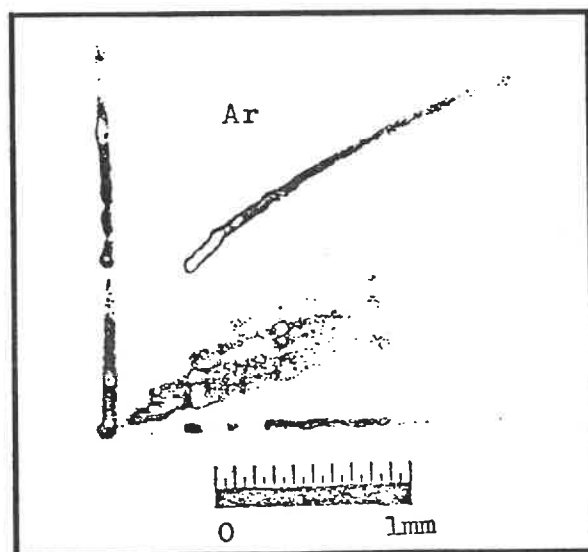


FIG. 7. Thomson parabola spectrum of Argon ions recorded on CR-39 plate in plasma focus experiment.

