Plasma Dynamics

18. Plasma Dynamics

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18.1 Relativistic Electron Beams and Generation of Coherent Electromagnetic Radiation

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This group concerns itself with experimental and theoretical studies of generating intense, coherent electromagnetic radiation in the microwave and submillimeter wavelength range, by energy conversion of relativistic beam electrons. Three major types of systems are under investigation: relativistic magnetrons, gyrotrons (cyclotron masers), and free electron lasers. Three pulsed, high-

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voltage accelerators capable of delivering up to 1000 kA of current at 0.5 to 1.5 MV are used in the experiments. Their characteristics are summarized below:

Pulserad 110 A

Voltage	1.5 MV
Current	20 kA
Pulse Length	30 ns

Pulserad 615 MR

Voltage	0.5 MV
Current	4 kA
Pulse Length	1μs

Nereus

Voltage	0.6 MV
Current	100 kA
Pulse Length	30 ns

Intense, coherent sources of electromagnetic radiation are needed in many diverse fields of research and technology including the heating and diagnostics of thermonuclear fusion plasmas, photochemistry, solid state physics, and biophysics. The advantage of free electron interactions (as opposed to bound electron interactions, as is the case in conventional lasers) is tunability of the radiation frequency, large intensities, and good efficiencies. Studies of various "free-electron" sources of potential interest are pursued at numerous research centers in the U.S.A. and abroad with the view of improving the emission characteristics. Indeed, much work at the fundamental physics level and at the technological level remains before the expected goals are likely to be achieved.

Radiation sources using free electrons exploit certain types of high-frequency instabilities caused when an electron beam is subjected to external forces. The three main types of instabilities studied by us are the following:

(i) The crossed-field instability (of which the magnetron is a typical example) in which the electrons are subjected simultaneously to an E x B force created by an external magnetic field oriented perpendicular to an external electric field;

(ii) the cyclotron maser (gyrotron) instability characterized by azimuthal electron bunching, and emission frequencies associated with the electron gyrofrequency or one of its harmonics; and

(iii) the free electron laser instability characterized by axial electron bunching, and emission frequencies associated with the Doppler upshifted period of an imposed, transverse, periodic (wiggler) magnetic field. Below we give a brief summary of our work in these areas of research.

a. Relativistic Magnetrons

Very large rf powers (~1GW) have been achieved in relativistic magnetrons operating at voltages from several hundred kilovolts to 1 MV, and drawing kiloamperes of current from field emission cathodes. This novel radiation source has been discovered[1] and studied extensively[2] under the aegis of an earlier NSF Grant. These impressive results have reawakened an interest to better understand the interaction of the electromagnetic field and the dense space charge cloud in magnetron-type devices. Numerous attempts have been made over a span of forty years to calculate self-consistently the rf fields under the large signal conditions prevalent in the magnetron, and from these to predict the current, voltage, microwave power and efficiency. Since these studies are based on certain assumed steady state configurations, they give but a qualitative understanding of the phenomena. At best, they yield magnetron scaling laws useful to microwave tube designers. To better understand our experimental results, a self-consistent numerical simulation which addresses itself to those questions that have eluded analytic techniques has been developed. The simulation is a two-dimensional, electromagnetic, fully relativistic particle-in-cell code. It includes the complete geometry of the vane resonators embedded in the anode block, rf loading of the resonators, space-charged limited emission from the cathode, and the external voltage source of finite impedance. The simulation is also applicable to smooth-bore magnetrons and to the study of magnetically insulated high-voltage transmission systems. The simulation is, in its comprehensiveness, a first of its kind, and was carried out in cooperation with Adam Drobot at Science Applications Inc. and the Naval Research Laboratory.

Our simulation has been applied to a 54-vane inverted relativistic magnetron operating at a voltage of ~300 kV and a magnetic field of ~0.17 T. Because of the large radius of curvature of the anode block, it was possible to approximate the cylindrical device by a planar analog. In the simulation, the two-vane structure was represented on a 32 x 32 mesh, and the fields and particle positions were integrated forward in time with successive time steps of 2×10^{-12} s. Each of the simulation particles contained 2×10^{10} electrons. At time $t = 0$, a voltage ramp was applied to the cathode-anode gap with a rise time of 3×10^{-9} s (~15 cyclotron period) reaching a maximum value of 600 kV.

The simulation described above has been recently extended to include curvature (i.e. r-θ geometry) and has been applied to the six-vane A-6 magnetron described in Ref. 2. The first encouraging result is that the peak power occurs at a magnetic field of ~7.5 kG in agreement with experiments. Also the code predicts an efficiency of 10% which is in good agreement with the experimental efficiency of 12%.

The relativistic magnetron operating in 400 kV range is capable of producing microwave bursts on the order of 0.5 GW at 12% efficiency. [2] Scaling to higher voltage (1.0 MV) results in increased power (0.8 GW); however, the overall efficiency is reduced due to the presence of a large axial, noninteracting current. This problem is difficult to overcome at high field strengths in a conventional magnetron design with the cathode placed coaxially inside the anode. A solution to this problem is to operate in an inverted geometry with the cathode located outside the anode. In this configuration, an electron emitted from the cathode that flows axially returns to the cathode with no loss of current. This property of the inverted magnetron has been investigated experimentally.

The operation of an oscillating magnetron in the inverted geometry requires a nonconventional method for extracting the rf power since there intervenes a dense space charge cloud between the external world and the rf resonators. One technique is to build a large radius tube with many vanes ($N > 20$). Here the power is extracted from the backs of the resonators, is stored in a center cavity, and then coupled out the front. Alternatively, it may be possible to extract the rf fields with magnetic coupling through an iris in the outer cathode surface. This allows for a compact design with a small number of anode vanes. We have chosen the latter extraction technique. We have successfully operated the inverted magnetron, and its characteristics are: magnetic field = 6.86 kG; voltage = 1.73 MV; current = 8.4 kA; frequency = 3.68 GHz; microwave power = 400 MW.

b. Cyclotron Masers (Gyrotrons)

Knowledge of the spectral characteristics is essential to an understanding of the emission physics and also in unraveling the various radiation mechanisms that may occur simultaneously. Our studies were concentrated on millimeter-wave radiation from the relativistic electron beam propagating both in a uniform longitudinal magnetic field and also in combined longitudinal and spatially periodic transverse magnetic fields. In these experiments, a 1 to 1.5 MV, 1-10 kA electron beam produced in a field-emission diode propagates down a 1m long drift tube immersed in the guiding longitudinal magnetic field, B_z, of a pulsed solenoid. Values of B_z between 4 and 15 kG are utilized. A radial, spatially modulated magnetic field of variable amplitude ($B_r = 0 - 1$ kG) and 4 or 6 cm periodicity produced by a magnetic diffusion wiggler (see below) is superposed on the axial field in the drift tube region.

Power and spectral characteristics of the emitted radiation were studied in four frequency bands; 8-12 GHz (X-band), 26-40 GHz(Ka-band) and 75-140 GHz (R and N bands), using calibrated microwave crystal detectors in conjunction with waveguide dispersive lines and a grating spectrometer. We find that, in the absence of the wiggler field, the radiated power levels are typically 25 kW in X-band, 500 kW in Ka-band and 50 kW in the R and N-bands. The emission is strongly peaked as a function of longitudinal magnetic field B_z, and one or more narrow band $\Delta\omega/\omega \simeq 0.1$ features are detected in each frequency range.

The radiation observed in the absence of the wiggler field is interpreted within the framework of a fast wave cyclotron maser instability in the beam. The observed emission frequencies are consistent with the theoretical emission frequencies for the cyclotron maser modes of the system calculated from the experimental parameters at peak power generation. Having identified the cyclotron maser modes, we also calculate the ratio of transverse to axial electron energy $\gamma_\perp/\gamma_\parallel$. For the beams produced in our foilless electron guns, we find that $\gamma_\perp/\gamma_\parallel$ = 0.5. This large ratio of $\gamma_\perp/\gamma_\parallel$ is significant in that the transverse energy of the beam electrons supplies the free energy for the instability.

When the wiggler field is turned on, the radiated power increases by one to two orders of magnitude as the radial field amplitude is increased from zero to ~500 G. At the same time the spectral characteristics of the radiation are preserved. This increase in radiated power is therefore attributed to the increased growth rate of the cyclotron maser instability due to the additional transverse electron velocity induced by the wiggler field. Spectral features indicative of a Raman-type free electron laser interaction are not detected.

Our observations are similar to those of other experimenters who, not having studied the low level emission at zero wiggler field, interpret their results as Raman, free electron laser phenomena. Careful spectral observations with and without the wiggler field allow us to identify the mechanism in our experiments. We conclude that the electron-cyclotron maser instability dominates over the free electron laser instability because of the large transverse electron velocity produced at the electron gun.

c. Free Electron Lasers

A free electron laser requires for its operation a quasi-static, spatially periodic magnetic field (wiggler) which induces stimulated synchrotron emission in the beam electrons. To achieve large instability growth rates at the shortest possible wavelength requires a large amplitude pump field at the shortest possible periodicity ℓ.

Previously, magnetic wigglers have been produced by passing current through helical windings or metal rings around the beam drift tube, or by using iron rings to modulate the field of a solenoid.

In our novel system the relativistic electron beam propagates down a drift tube surrounded by a solenoid containing a periodic assembly of copper rings, separated by Plexiglas rings. The solenoid is powered by a capacitor bank which supplies a current pulse in the shape of half a sine wave. Since the copper rings are good electrical conductors, the magnetic field diffuses gradually through them. On the other hand, the Plexiglas rings are insulators, and the magnetic field penetrates almost instantaneously. Thus the magnetic field is stronger in a Plexiglas ring and weaker in a copper ring.

When the solenoid is empty, it produces a uniform, purely axial field B_z. Putting in the rings introduces a modulation in B_z, but in order to keep $\nabla \cdot B = 0$, a radial magnetic field B_r is also generated. It is this radial field which is used in the FEL interaction. Note, however, that the field in the drift tube is primarily axial and therefore the same solenoid also provides the field which guides the electrons.

Experiments indicate that the electron beams produced in conventional foilless field emission guns are not suitable for free electron laser applications. The problem arises from the large transverse component of electron velocity produced at the gun which renders the beam susceptible to the electron-cyclotron maser instability. We plan to utilize a new electron gun design[1] to produce an electron beam having laminar axial flow. The gun design consists of an electrostatically focused, six-electrode Pierce-type gun with shaped anodes which will replace the present vacuum diode of the Pulserad 110A electron beam generator. The electron gun will be situated in a region of zero magnetic field so that all beam focusing in the accelerating region will be purely electrostatic. We point out that this electron gun design has been used successfully by Fink *et al* at the Max Planck Institute (Garching) on a 2 MV electron beam generator. The modifications necessary to adapt their design to our system has been made with the help of an electrostatic Herrmannsfeldt code in order to insure that the beam characteristics are preserved.

d. Two-Stream Free Electron Lasers

The generation of coherent electromagnetic radiation in magnetically pumped free electron lasers (FEL) is connected intimately with axial bunching of the electrons in their passage through a transverse, periodic (wiggler) magnetic field. Calculations and experiments suggest that injection of a *prebunched* electron beam greatly enhances the radiation intensity of the parametrically excited back-scattered wave. Moreover, the threshold beam current required to initiate wave generation is much lower with prebunching than in the case of the conventional FEL configuration, where prebunching is not used.

The frequency of the prebunching space-charge wave must be equal to the desired radiation frequency of the FEL. In a system designed to operate at low (microwave) frequencies, prebunching is readily achieved, as for example by passing the electron stream through the modulating gap of a resonant cavity, or by allowing the beam to interact with a neighboring slow-wave structure. Prebunching in the submillimeter wavelength range, where many FEL's are designed to operate, is difficult. We propose here a prebunching technique which exploits the well-known fact that two parallel electron streams with different velocities support unstable, exponentially growing space-charge waves over a wide frequency range. In contrast to other prebunching methods, the present one has the virtue that no physical medium or other wave-supporting structures are required. It is comprised of a prebunching section and a wiggler field section. Two relativistic electron streams with velocities v_1 and v_2 travel along the axis of the system. A space-charge wave grows exponentially out of noise with a frequency determined by the electron number densities of the two streams, and their velocity difference $|v_1 - v_2|$. The prebunched streams then traverse the wiggler magnetic field where the electromagnetic wave is generated.

A detailed analytical study of the proposed device has been made. We intend to carry out an experiment on our PULSERAD 110A accelerator (V~1.5MV). The two-stream electron gun will be almost identical with that described above. The anode structure will remain unchanged. However, the cathode will be split and a ~150Ω copper sulfate resistor will be placed between the two cathode halves. In this way a voltage difference between the two streams of 50 kV will be established.

e. The LOWBITRON

The LOWBITRON, a longitudinal wiggler, beam interaction device is a novel source of submillimeter wave radiation. It comprises a relativistic electron beam gyrating in a longitudinal rippled, periodic magnetic field of the form $\vec{B} = \hat{z}[B_o + B_1\sin(k_oz)]$, where $k_o = 2\pi/\ell$ and ℓ is the period. Axial and transverse electron density bunching gives rise to a convectively unstable wave that propagates along the guiding magnetic field $\hat{z}B_o$. Its growth rate has been computed for the case of a cold beam.

The Lowbitron is a hybrid system between a gyrotron and a free electron laser. A relativistic electron beam in the form of a thin pencil propagates *on axis* of an evacuated drift tube, which also acts as the waveguide for the electromagnetic radiation. The beam electrons gyrate in the combined, uniform magnetic field of a solenoid, and a *longitudinally* rippled (wiggler) field, such that the total imposed field on the axis has the form

$$\vec{B} = \hat{z}[B_0 + B_1 \sin(k_0z)], \qquad (1)$$

where $k_0 = 2\pi/\ell$ is the wavenumber and ℓ is the periodicity of the wiggler. Such a field can be generated in one of several ways, as, for example, by driving current azimuthally in alternate directions through a periodic assembly of copper rings; or by making the rings from samarium cobalt or other magnetic material and magnetizing the rings in the axial direction as is done in systems employing periodic focusing; or in pulsed systems by using the technique of magnetic diffusion discussed above. In all of these methods, the magnetic field at a distance r from the axis is approximately

$$B \simeq \hat{z}[B_0 + B_1I_0(k_0r)\sin(k_0z)] - \hat{r}B_1I_1(k_0r)\cos(k_0z), \qquad (2)$$

where I_0 and I_1 are modified Bessel functions. Near the axis, such that $k_0r < 1$, Eq. 2 reduces to Eq. 1. We point out that in the Lowbitron the periodic field modulation is longitudinal rather than transverse, as in the case of free electron lasers. This is advantageous because longitudinal modulations can be more easily produced and at larger amplitudes. For example, calculations show that the longitudinal magnetic field modulation in a ring system is nearly twice as large as the transverse magnetic field modulation in a FEL using a bifilar helix of the same periodicity and carrying the same current. Also, the periodicity of a ring system is easily changed and an adiabatic field shaper at the electron gun end is readily incorporated.

Hitherto, all of our studies, made in cooperation with W.A. McMullin, are of an analytical nature. We have begun to set up an experiment on our Physics International PULSERAD accelerator.

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18.2 Nonlinear Wave Interactions - RF Heating and Current Generation in Plasmas

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In a broad sense, this project concerns itself with the *electrodynamics of waves and their interactions in magnetized plasmas.* Such studies encompass the linear and nonlinear excitation and propagation of waves, and the nonlinear interactions involved in energy and momentum transfer among waves and between waves and the plasma particles. The theoretical work of this project has as its primary objective the modeling and understanding of the above described phenomena as they relate to *plasma heating and current generation* by externally applied electromagnetic power sources for achieving *energy generation by fusion*. Important experiments in this area are being carried out in the U.S. and abroad, and our work is strongly coupled to these. At M.I.T., there are currently two major RF heating experiments in operation; these are on the toroidally confined plasmas of VERSATOR II and ALCATOR C. RF heating is also being planned for the mirror confined plasma of TARA which is under construction. Our studies are not focused on specific means of heating or specific fusion experiments, but rather they emphasize the *basic phenomena* that enter into any scheme of plasma heating, and that in fact may transcend current application and enhance our basic understanding of plasma dynamics for a variety of other applications. Thus, some of the basic phenomena encountered in studies on the electrodynamics of plasma heating also have application to current attempts of *generating very short-wavelength, high-power sources* using relativistic electron beams - e.g. gyrotrons and free electron lasers. In addition, the phenomena we study in the electrodynamic heating of plasmas can have an impact on studies of *high-power propagation in the ionosphere*, and the understanding *of space plasma phenomena* in general.

In order to put in perspective our accomplishments over the past year, consider in some detail the problem of plasma heating. Figure 1 is a schematic representation of what is involved, and can

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provide a good guide toward understanding what unifies the large variety of problems we have studied. The confined plasma is shown in cross section, and is permeated by a time-invariant magnetic field $\overline{B}_0$. The object in plasma heating and current generation is to irreversibly deliver energy and momentum to the plasma particles in the core of the plasma (region III). The energy for this heating and current generation comes originally from electromagnetic power sources external to the plasma, located in essentially free-space. Hence, in order for the desired heating and/or current generation to occur the following must be made to happen:

I) The electromagnetic power from free space must be coupled to waves in the plasma.

II) The power in the excited plasma waves must propagate to the core of the plasma.

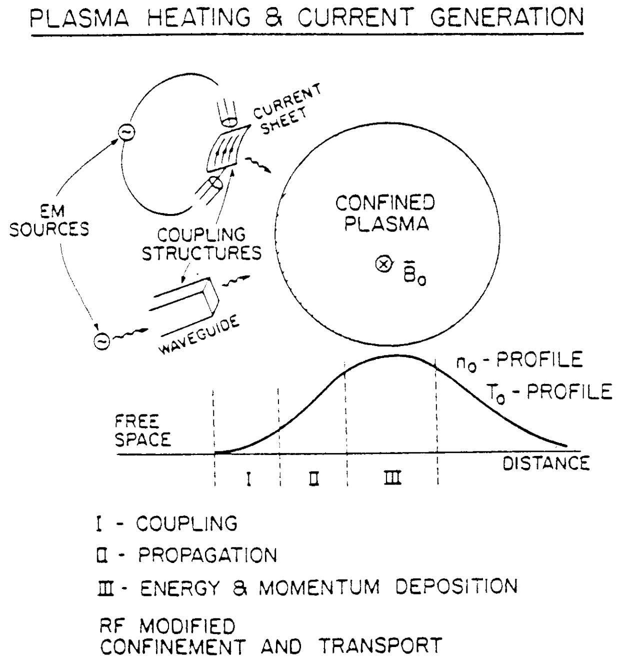
III) The waves that arrive at the core of the plasma must be such that they will deliver their energy and momentum irreversibly to the plasma charged particles.

These objectives allow one to define specific problems that require theoretical modeling analysis, and understanding. Although in the overall objective all three types of problems are, of course, coupled, nevertheless the distinct plasma parameter regimes of density, n_0, and temperature, T_0, in which these problems occur allow one to look at each problem independently and in depth.

The following are some highlights of our accomplishments of the past year together with our publications (cited as references at the end). Parts 1, 2, and 3 relate to coupling, linear (1 and 2) and nonlinear (3); part 4 relates to propagation; parts 5 and 6 describe work on momentum deposition ("current drive"); and part 7 relates to transport phenomena in plasma heating toward a thermally stable regime of reactor operation.

a.Three-Dimensional Theory of Coupling of Electromagnetic Power from Waveguide Arrays to a Plasma

We have recently formulated a general linear theory to describe the coupling of EM power from waveguides to a plasma in a magnetic field. The coupling region is taken as the inhomogeneous plasma extending from the free-space waveguide openings in the plasma wall to where the desired plasma modes are excited. The excited plasma modes are assumed to be dissipated beyond the coupling region, further into the plasma core. The plasma is taken to be of sufficiently large (reactor) size so that the limited extent of the coupling region can be modeled in slab geometry. For definiteness, the plasma in the coupling region is described by the cold plasma model with inhomogeneous density and magnetic field in one direction, into the plasma. Far from the plasma wall the waveguides are assumed to propagate only their dominant mode. Given the amplitudes and phases of the incident fields in each of the waveguides and the unperturbed characteristics of the plasma in the coupling region, we have shown how to determine the reflection coefficient in each of the waveguides and the excited fields and power flow into the plasma modes in and beyond the coupling region.



Previous analyses of the waveguide-plasma coupling problem have concentrated on the LHRF (lower-hybrid range of frequencies). All of these analyses were carried out in detail in only two dimensions: the waveguides were assumed to be perfectly conducting parallel-plates of infinite extent, and the excited plasma modes were thus forced to have no variation in the direction of the plates. In our recent analysis this restriction is removed, and full account is taken of the excitation in all directions of the higher-order waveguide modes in the vicinity of the waveguide opening in the plasma wall. In addition, we do not restrict ourselves to any particular frequency regime. Instead, the differential equations describing the fields in the inhomogeneous plasma, in the coupling region, are derived to apply to any of the frequency regimes (ICRF, LHRF, and ECRF, respectively, ion-cyclotron, lower-hybrid and electron-cyclotron). In general, the equations are four coupled first-order differential equations with nonconstant coefficients, and without further approximations their solutions must be arrived at by numerical techniques. This together with the mode expansion for the fields in the waveguides is shown to lead to a complete solution of the linear coupling problem.[1]

b. Antenna-Plasma Coupling Theory for ICRF Heating of Large Tokamaks

In recent experiments, the most successful of the various RF heating schemes has been the one using the fast magnetosonic wave in the ion-cyclotron range of frequencies (ICRF). Bulk ion temperature increases of around 2eV/kW and substantial electron heating has been observed in plasmas with densities up to $10^{14}/cm^3$. One of the important steps towards achieving this heating is the coupling characteristics of the external antenna structure (which launches the fast wave) to the tokamak plasma. In present-day experiments the antenna is a current carrying conducting loop which goes around half-way along the minor circumference (poloidal direction) of the tokamak. Since the free-space wavelength is long compared to the plasma radius, the poloidal variation of the antenna current can be ignored. However, for reactors this will not be the case and the fast wave will have to be launched by conductors having smaller dimensions compared to the minor radius. The antenna has to be of finite extent in both the toroidal and the poloidal directions. We have been investigating the coupling characteristics of waves launched by such conducting sheets into the plasma. The initial results indicate that the finite extent of the antenna in the poloidal direction is very important.[2] We find that a set of appropriately phased antennas that launch a wave spectrum which is shifted towards negative poloidal wavenumbers will lead to a very effective coupling.[3]

c. Nonlinear Coupling to Waves in a Plasma

We have studied how nonlinear effects modify the coupling from a waveguide array which excited lower hybrid waves in a plasma. The nonlinearity considered is that of the "ponderomotive force" exerted by the RF fields. This force creates density depressions in the plasma. Because of the low edge temperatures in the plasma (a few electron volts) the ponderomotive force is sizable even for moderate power densities, say 1 kW/cm^2.

To summarize the results,[4-8] it is found that the plasma admittance presented to the waveguides can be substantially modified at large powers. The effects are more pronounced if the density gradient is weak or if the excitation spectrum is wide in k_z space. We also found that the power spectrum can be changed appreciably because the fields self-focus and filament in real space, and this results in a broadening of the spectrum.

d. Propagation and Mode Conversion in an Inhomogeneous Vlasov Plasma

Linear wave propagation in an inhomogeneous plasma described by *hydrodynamic* fluid equations is by now a "classical problem" that has received much attention since the early days of intensive research in ionospheric radio wave propagation. In the simplest situations, where the WKB technique is applicable, wave propagation is described by a local dispersion relation, e.g in one dimension, $D(k,\omega,x) = 0$, where for a fixed frequency of excitation ω, the local dispersion relation gives the change of the wave number k with position x. This description breaks down near "singular points" where the nature of the wave changes abruptly, e.g., near cutoffs ($k \to o$) and resonances ($k \to \infty$) or more appropriately where the latter is avoided by inclusion of finite thermal effects, near mode-conversion. In the vicinity of such points, the local description breaks down and one must revert to a differential equation description of these regions. In the case of mode-conversion, which is frequently characterized by the coupling of a fast wave to a slow wave, the problem is to formulate an appropriate second-order differential equation valid in the vicinity of the mode-conversion point. For the hydrodynamic, fluid description of plasma, which in general involves a finite-order differential equation, i.e., a finite number of waves and a local dispersion relation which is just a polynomial, it is relatively easy to find a unique second-order differential equation which describes such mode-conversions. On the other hand, for a high temperature plasma in a magnetic field where the particle dynamics must be described by the Vlasov equation, the system of Vlasov-Maxwell equations is an integro-differential one, containing in general an infinite number of waves, described by a transcendental dispersion relation. For such a case, the usual techniques of analyzing mode-conversion become inapplicable. It is, however, precisely under these conditions that mode-conversion has the most important application in plasma heating, since the Vlasov description directly incorporates the non-collisional damping mechanisms (Landau damping and cyclotron harmonic damping) which can lead to heating in the vicinity of mode-conversion. We have developed the detailed mathematical and practical "machinery" as well as the physical insight, for analyzing mode-conversion in a Vlasov plasma when such conversion occurs through pair-wise coupling of modes.[9-11]

e. Nonlinear Theory of Current Generation by a Large Amplitude Coherent Wave

To provide particle confinement in the steady-state operation of a tokamak reactor, a poloidal magnetic field generated by a toroidal current is necessary. One of the techniques proposed in 1977-1978 is to launch a uni-directional lower-hybrid (LH) wave by a wave-guide array. To show the feasibility of this, the Fokker-Planck equation with the quasi-linear diffusion coefficient was solved for the space-averaged electron distribution function. This theory is limited to $\tau_{TR} \gg \tau_{AC}$ where $\tau_{TR} = \sqrt{m/ek_zE_z}$ and $\tau_{AC} = k_z/\omega\Delta k_z$ are the trapping and auto-correlation time-scales, with $k_z(E_z)$ being the wave vector (electric field) along the toroidal magnetic field and Δk_z being the spread in the k_z-spectrum. For typical reactor type parameters the electric field may be large enough to violate this condition. In the opposite limit, $\tau_{AC} \gg \tau_{TR}$, the single wave theory becomes applicable for times shorter than the collisional time scale. To determine the feasibility of the current drive scheme in this last case collisional damping has to be included, via the Fokker-Planck equation together with the nonlinear dynamics of a single wave. Our preliminary results, on analyzing such a model, indicate that in this nonlinear limit the current drive efficiency is reduced.[12]

f. Steady State Current Generation by LH Waves

To achieve a steady state tokamak operation one has explored many RF and beam injection schemes. Among those the best studied and experimentally documented is the current drive near the lower hybrid (LH) frequency. For this, a quasilinear theory coupled to a one dimensional Fokker-Planck equation in the absence of a DC electric field was developed. It was shown that a unidirectional wave transfers momentum to the resonant electrons in the tail and drives toroidal current necessary for plasma confinement. Recent experiments show that the predicted efficiency is nearly achieved but only at low densities. For most tokamaks no LH steady state current is observed above $n = 10^{13}$ cm^{-3}. Alcator C is the only exception where current was observed up to $n = 5 \times 10^{13}$ cm^{-3}. It is apparent that a serious disagreement between theory and experiment exists and the major problem is to find a way to drive a LH current at higher densities.

We believe that the discrepancy may stem from the fact that tokamaks have a DC electric field, which was neglected in the original theory. The presence of a DC electric field changes the Maxwellian character of the distribution function. This change is particularly significant near the runaway critical velocity (V_c). In low density experiments the spectrum of the wave is positioned close to V_c and only then significant currents are observed. We have initiated a study of the two-dimensional Fokker-Planck equation with a DC electric field and include the RF diffusion term. A simple model indicates that the electron dynamics near V_c are strongly modified by the presence of RF fields having phase velocities near V_c.

g. Thermal Stability in Heating to Ignition

We have demonstrated the existence of thermally stable sub-ignited equilibria of a tokamak reactor, sustained in operation by a feedback-controlled supplementary heating source.[13] The establishment of stability depends on a number of radially nonuniform processes whose effect we have attempted to analyze using the WKB method, the Gelfand method, and a one-dimensional radial transport code.[14]

With transport coefficients based on empirical scaling laws and existing theories the peaked thermal conductivities tend to stabilize non-equilibria and destabilize equilibria. Using a narrow supplementary heating profile ("core heating") results in more rapid heating with less total power than does a broad heating profile ("bulk heating") but core heating can lead to a contraction instability of the temperature profile in the presence of high-Z impurities. Reactor parameters have been found that can yield about 2000 MW thermal power with $Q \approx 50$ when run at $n_o \approx 3 \times 10^{20}/m^3$ and $T \approx 15$ keV (parabolic profiles).

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18.3 Tokamak Research: RF Heating and Current Drive

U.S. Department of energy (Contract DE-AC02-78ET-51013)

George Bekefi, Miklos Porkolab, Kuo-in Chen, Stanley C. Luckhardt

Introduction

In the worldwide effort in controlled thermonuclear fusion research, the tokamak approach has been the most successful in approaching plasma conditions closest to those needed for a fusion reactor. Further improvements in tokamak performance are needed, however. The tokamak confines a hot plasma in a toroidal configuration by means of magnetic fields produced by external coils and by a current flowing in the plasma itself. In the past the plasma current in tokamaks has been produced by transformer action, and, of course, the plasma current in such a device is sustained for a finite pulse duration limited by the maximum current of the primary transformer winding. Recently a significant improvement in tokamak operation has been proposed whereby the plasma current could be driven continuously by injection of RF (radio-frequency) power. A fusion reactor driven in the steady state with RF power has a number of attractive features distinguishing it from the commonly encountered transformer-driven pulsed devices. In particular, steady-state operation would eliminate the problems of peak loading of reactor output power equipment, and thermal cycling of the reactor walls inherent in pulsed operation.

If fusion conditions are to be achieved in a future tokamak device, efficient methods of heating the plasma must also be developed. The use of RF power to raise plasma temperatures is under study at a number of laboratories using RF sources in various frequency regimes: power is coupled into plasma waves which can propagate from the edge into the center of the tokamak plasma where they are absorbed and deposit their energy to heat the plasma electrons and/or ions. The purpose of the experimental work going on at the Versator II tokamak is to study the detailed physical processes involved in current generation and plasma heating with RF power.

The use of RF power near the lower-hybrid frequency has long been considered as a means of heating ions in tokamak discharges. More recently, it has been proposed that lower-hybrid power injected with a net toroidal angular momentum should be capable of producing, via Landau absorption, a steady-state toroidal current in a tokamak. Successful lower-hybrid current drive[2] and ion heating experiments have been carried out on Versator II using phased-array waveguide antennas to couple up to 100 kW of power at 800 MHz into tokamak discharges.

A second series of experiments is under way at Versator in which high microwave power levels at the electron-cyclotron frequency are employed. These experiments, in cooperation with the Naval Research Laboratory, use a gyrotron power source developed at NRL. The NRL gyrotron provides power of up to 150 kW at a frequency of 35 GHz. Under optimum conditions, these experiments have obtained significant increases in the electron temperature in Versator.

a. Lower-Hybrid Experiments

Current drive generation experiments have been carried out with a six-waveguide antenna with a 0.80 cm gap spacing and a 24 cm height. RF injection with pulse duration longer than the plasma L/R time has generated large increases in the net toroidal current of the tokamak discharge. Incremental increases, $\Delta I/I$, of more than 35% have been obtained. The increase in current is found to be strongly dependent on the relative phase between waveguides, $\Delta\phi$, with largest current rises occurring when $\Delta\phi = -90^{o}$ and $N_z = 7.5$. This antenna phasing launches a traveling-wave spectrum in the direction of the electron ohmic drift. Importantly, no decrease in current is observed for waves launched in the opposite direction. The central electron temperature drops from 240 eV + 45 eV to 120 eV + 20eV during the RF-driven current pulse. The decrease in temperature is due, at least in part, to a reduction in the ohmic heating input power during RF current drive. These measurements clearly eliminate bulk electron heating as a possible cause of the current increase.

For sufficiently short RF pulses and/or sufficiently low RF power levels, the RF-driven current component is found to be proportional to the RF injected power with current drive efficiency 1-2 kA/kW. For longer pulse durations, disruptive voltage transients appear to limit the amount of RF current that can be sustained. To date, efficient RF current drive can be initiated only in low-density plasmas, $n_e \simeq 6 \times 10^{12}$ cm^{-3}, which are characterized by non-thermal "slide-away" electron tails.

Further current drive experiments planned in the near future include tests of a new antenna for launching waves from the top of the torus. Such top launching is expected to improve ray penetration and possibly improve the current-generation efficiency. Experiments with the ohmic heating transformer current shut off are also planned. These experiments will test the feasibility of sustaining and/or building up the current solely with RF power. Methods of driving current in high-density plasmas are also being tested.

b. Ion Heating

Lower-hybrid ion heating studies using a four-waveguide array are being performed in the parameter range $\bar{n}_e = 1.3\text{-}3\times10^{13}$ cm^{-3} and $B_T = 1.3\text{-}1.5$T. Initial results indicate significant ion heating at $B_T = 1.3$T, $\bar{n}_e = 2.5\times10^{13}$ cm^{-3}. Ion temperature increases, $\Delta T_i \simeq 40\text{-}50$ eV ($T_{io} \sim 130\text{-}150$ eV), have been measured by the Doppler broadening of the OVII 1623 Å and NVI 1897 Å emission lines for up to 50 kW injected power. A corresponding normalized heating efficiency of 2.5 eV/(kW·10^{13} cm^{-3}) is obtained which is comparable to the efficiencies obtained in the JFT-2 lower-hybrid heating experiments.[3] In the near future, parallel charge-exchange measurements are planned, and these data will be compared to the Doppler UV results. Measurements as a function of relative waveguide phasing show that the heating efficiency at $\Delta\phi = 0^\circ$ is considerably less (if any) than at $\Delta\phi = 180^\circ$. Further studies of heating as a function of plasma density, magnetic field, and RF power (up to 100 kW) are under way.

c. RF Technology

In some of these experiments a novel waveguide coupler has been used which has no nonmetallic parts within the line-of-sight of the plasma. An auxiliary magnetic field coil pair is employed to eliminate cyclotron-resonance breakdown in the waveguide region. Such an antenna arrangement is favorable for reactor applications. Without the auxiliary vertical magnetic field, the power-handling capability of the waveguide array was limited to ~8 kW/waveguide, corresponding to 0.13 kW/cm^2 and a peak electric field of 550V/cm. At this power level an RF-produced plasma began to form in the waveguides. Upon application of an auxiliary magnetic field above the cyclotron-resonance value, 286G for $F_0 = 800$ MHz, the antenna can be operated up to the present limit of the RF source, transmitting up to 100 kW into tokamak discharges. This corresponds to a power density of at least 0.42 kW/cm^2 and peak electric field of 1 kV/cm in the waveguides. Moreover, during tokamak operation with the auxiliary field there is no evidence of plasma formation in the waveguides or any deterioration of the tokamak equilibrium. In further experiments, up to 56 kW has been transmitted through a single waveguide at a power density of 0.94 kW/cm^2 and peak electric field of 1.5 kV/cm without plasma formation or breakdown. These experiments will be continued at increased power levels in the near future.

d. Electron-Cyclotron Heating

An experiment to investigate the properties of electron-cyclotron heating (ECH) of a tokamak plasma is being carried out jointly with the gyrotron group at the Naval Research Laboratory. The gyrotron is the only efficient source of high-power mm wavelength radiation, and is under intensive development by the Department of Energy and Department of Defense. The current effort uses a 35 GHz, 150 kW, 10 msec pulse length gyrotron developed by NRL to provide energy to electrons at cyclotron resonance, corresponding to a magnetic field of 1.25T at the center of the plasma.

The radiation is directed to the plasma through a series of waveguides which also linearly polarize the microwaves. Approximately 30% of the power is lost during transmission. To provide flexibility the plane of polarization may be rotated or may be left in the circularly polarized mode output by the gyrotron. The microwaves enter the vacuum vessel and bounce off a mirror toward the center of the plasma. The mirror may be rotated to vary the angle of injection with respect to the toroidal magnetic field.

Under certain plasma conditions, it has been possible to raise the electron temperature by more than 50%, with a concurrent drop in the loop voltage of 25%. Associated with the ECH is a parametric decay into a Bernstein mode and a lower-hybrid wave. In addition, there is a small increase in the plasma current of ~10%, scaling linearly with power, and apparently persisting to high plasma densities ($\omega_p/\omega_c>1$).

Many interesting phenomena have been seen during the ECH experiments, and much more work will have to be done to understand the effects which have been observed.

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18.4 Physics of Thermonuclear Plasmas

U.S. Department of Energy (Contracts DE-AC02-78ET-51013 and DE-AC02-78ET-53073.A002)

Bruno Coppi

The theme of our research program is the combined experimental and theoretical investigation of plasmas in which fusion reactions have a significant influence on their thermal energy balance and physical properties.

Our characteristic line of interest involves plasmas with relatively high densities, in the range 10^{14} to 10^{15} particle/cm^3, in view of their attractive confinement properties, and magnetic confinement configurations that are suitable to contain the high energy (in the MeV range) charge particles that are produced by fusion reactions. The line of experimental devices that we have developed for this is represented by its prototype, the Alcator A machine, and is characterized by toroidal plasma columns that can sustain both high currents and current densities. This requirement, leading to adoption of toroidal magnet configurations of compact size and relatively high fields, has made it possible to achieve and maintain the record values for the combined confinement parameters "$nT\tau$", the product of the peak particle pressure nT and the energy replacement time τ, and "$n\tau$". In addition, a sequence of plasma regimes of basic physical interest, in terms of the different characteristics of the particle distributions in velocity space that can be generated and of the collective modes that are excited, has been produced. The conditions where nearly impurity-free plasmas can be obtained have been realized at the same time.

By combining these experimental results with the theoretical analysis of the global transport properties in the plasma regimes that have been attained so far and the known physics of deuterium--tritium fusing plasmas, it has been possible to formulate a research program directed toward studying thermonuclear ignition by a series of compact devices that are called Ignitors.

The conceptual design of one of these devices has been completed in 1982 and has been successfully reviewed by an international panel convened by the C.E.C. (Euratom). This was chaired by Sr. John Adams (CERN), and the other members were R. Bickerton (JET), P. Reardon (Princeton), P. Rebut (JET), and M.N. Rosenbluth (U. Texas).

An independent program involving a compact device that has about the same philosophy and dimensions as Ignitor but gives a more enhanced role to heating by adiabatic compression is already underway in the Soviet Union. In fact the subject of compact ingnition experiments has been the theme of an official U.S.-USSR exchange held in July 1982 at Moscow and Leningrad with the participation of two of us (B. Coppi and R. Parker).

In 1980 we pointed out the feasibility of experimental fusion reactors that do not utilize tritium as a primary fuel, but are based on reactions such as D-He^3 that do not produce neutrons. These ideas have generated widespread interest and this has been enhanced in 1982 by the beginning of a serious[2,3] effort to investigate whether plasmas with spin polarized nuclei can be used as fuels in order to decrease further the already low fraction of energy produced inthe form of neutrons in D-He^3 reactors. In fact the results of our studies indicate that an experimental program for an analysis of the "burn" conditions for these so-called advanced fuels can be undertaken with present day technologies and on the basis of existing knowledge of the physics of magnetically confined plasmas.[1]

One of the necessary conditions for (the feasibility of) these experiments is to produce plasmas in which the peak plasma pressure is a finite fraction of the magnetic pressure without exciting macroscopic instabilities. In early 1978 we took a first step in this direction when we demonstrated the existence of a "second stability" region that is relevant to these experiments, regarding the onset of a set of modes, so-called "ballooning" [4,5] These had been thought previously to severely limit the value of the plasma pressure relative to that of the confining magnetic field. Following a similar line of thinking, in 1981 we reported that another important class of modes, the so-called "internal kinks" also tend to become stable[6] in a second-stability region. This region of stability overlaps the corresponding one of "ballooning" modes. Therefore now we can invision a sequence of plasma equilibria[7] that involve increasing values of the plasma temperature and remain macroscopically stable while the desired thermonuclear burn conditions are achieved.

At relatively low plasma densities, lower than 10^{13} particles/cm, where the plasma current induced by the applied d.c. electric field is carried by superthermal electrons, a regime labelled the "slide-away", was first identified[8] by a series of experiments carried out in 1974 and 1975 on the Alcator A machine. Recently, a similar regime has been observed to be induced by the appropriate injection of microwaves at the so-called lower hybrid frequency. A series of successful experiments that have produced this form of "current drive" have been carried out both on the Versator II and the Alcator C devices. In fact, current drive has been observed for record high densities with the latter experimental device while appropriate analytical and numerical models for the physical processes involved have been formulated.

As is traditional with our mode of operation, during 1982 we have maintained an effective system of close collaborations with national and overseas institutions for both our theoretical and experimental program. Our contributions have been presented at major national and international meetings.

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18.5 Physics of Mirror Confined Plasmas

U.S. Department of Energy (Contract DE-AC02-78-ET-51013)

Louis D. Smullin, James H. Irby, Kenneth F. Rettman, Amin K. Ezzeddine, Michael E. Mauel, Richard C. Garner, Algis Leveckis, Carey Rappaport

We are studying microinstabilities in mirror confined plasmas in a device called Constance II. There are two main streams in the effort to produce a magnetically confined, thermonuclear reactor: the closed magnetic systems (Tokamaks and Stellarators), and open systems using magnetic mirrors. The Constance II program is designed to study some of the problems that arise in the large mirror-machine programs such as TMX at Lawrence Livermore Lab and TARA at the Plasma Fusion Center at MIT. The MHD stability of these machines is reasonably well understood, but there are many so-called microinstabilities that cause excessive particle losses. Constance II is a relatively simple and flexible machine that is being used to study these phenomena.

The main parameters of our machine are as follows. The magnetic mirror has a peak field of about 6kG, with a 2/1 ratio. The peaks are 1 meter apart. Within the vacuum chamber is a linear quadrupole coil (Joffe bars). These are separately energized by a capacitor bank, and are able to produce the full min-B field configuration necessary for MHD stability. The plasma is generated by a hot-cathode plasma gun that injects a plasma stream into the mirror from one end. Plasma densities of 10^{12} to 10^{13} cm^{-3} are produced, with neutral densities of about 3 x 10^{10}. Ion temperatures are in the range 100-150 eV. Auxiliary heating of the mirror-trapped plasma is of three types:

ECRH (electron cyclotron resonance heating) provided by a 9 GHz magnetron
ICRH (ion cyclotron resonance heating) is provided by a 4-5 MHz,
pulsed 100 kW supply)
BPI (electron-beam plasma-interaction) excited by a pulsed electron
gun 5-10 keV and perveance of 10^{-5} amps/volt$^{3/2}$.

The system is instrumented, with
60 GHz interferometer
Thomson scattering
UV spectrometry
3-channel charge exchange analyzer
Diamagnetic coil
Langmuir probes
Electrostatic velocity analyzer
Secondary-emission energetic-neutrals detectors
RF and Microwave receivers
Residual gas analyzer

The signals from these instruments are brought to a control area where they are digitized and stored and processed in the MACSYMA Consortium Computer located in the Lab for Computer Science. The entire machine can be operated by one person.

During the past year the principal effort has been devoted to the perfection of the hot cathode (LaB_6) plasma gun (K. Rettman) the completion of the ruby laser Thomson scattering system with a 5 channel polychromator (J.H. Irby), and the study of ECRH. Computer codes have been written to predict (by ray tracing) the penetration of the plasma by the ECRH heating waves (R. Garner): a Fokker-Planck program has been written to study the electron cyclotron heating of the plasma (M. Mauel); a particle simulation code has been written to study the ion confinement in simple mirrors and in Min-B field configurations (J. Irby). The theory of plasma heating by electron beams modulated by signals in the range between the ion-cyclotron frequency and the lower hybrid frequency is being studied (A. Ezzeddine). An acousto-optical microwave frequency analyzer has been designed (J. Irby). This will cover a 500 MHz range with a 5 MHz resolution, and 10 μsec cycle time, and is tunable from about 50 MHz to 4 GHz.

The ECRH experiments (M. Mauel) have been concerned with the effects of the angle between the incident microwave power and the magnetic field axis. Although theory predicts important differences, experiments show little difference between the various angles of incidence. This implies that first-pass absorption of the rf is low, and the radiation is reflected from the chamber walls many times before it is finally absorbed. Absorbing material to line the chamber has been ordered so that an accurate measure of first-pass absorption can be made. Stabilization of the DCLC (drift-cyclotron loss-cone) instability by the microwave power have been observed - much as in the earlier Constance I experiment.

18.6 Preparation of Ozone

Louis D. Smullin, Michael Milbocker, and Robert Pinsker

The use of ozone (0_3) for water purification is finding increased use around the world and is replacing chlorine in many cases. It is also finding increased use in the purification of industrial waste products. For these purposes, it is manufactured *in-situ* in large installations consuming hundreds of kilowatts of electricity. The process used is the so-called "silent corona" discharge. Except for improvements in technology, the process is identical to the invention of Siemens over a hundred years ago. The patent literature is extensive, but is concerned with details of configuration and with economical ways of generating the higher frequencies (kHz) that are more efficient than 50 or 60 Hz power frequencies.

On the assumption that "there must be a better way," we have started a small scale study of the fundamental processes of 0_3 formation in electrical discharges. The analogy with the CO_2 TEA laser occurred to us (as it has to a number of other researchers here and abroad). In the TEA laser a very intense glow discharge lasting a few microseconds produces the electron population of the required energy and density to excite the gases to the states appropriate for laser action. The glow discharge is produced by providing an initial population of electrons from an external source - either a nearby corona discharge or an injected electron beam. In order to make a simple device, we have chosen to concentrate on the auxiliary discharge rather than the more complex electron-beam system.

The difference between a CO_2 laser gas (CO_2, N_2, He) and air is that oxygen strongly attenuates the ultra violet from the auxiliary discharge, and geometries must be found that put the auxiliary electrodes very close to the main discharge region. Furthermore, the lifetime of an electron in a CO_2 laser gas is very long, in air the life time is very short due to capture by oxygen to form negative ions. This imposes special requirements on the timing between the auxiliary discharge and the sustaining voltage.

During the past year, two undergraduates and I have studied the literature on the physics of 0_3 production, and on CO_2 lasers, and have made some preliminary experiments on the range of UV radiation in air and in some non-attaching gases (N_2 and A).

We are now building an apparatus to test out our ideas and to see if the electrical efficiency (kg of 0_3)/(kWhr) can be substantially increased over that of the silent corona method.

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