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Fundamental plasma studies at IPR

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Introduction

A plasma is a classical many body system with a large number of degrees of freedom. Its behaviour is dominated by collective phenomena arising due to long range Coulomb force which urges groups of particles to move cooperatively. Furthermore, a plasma is typically born when violence is done to matter in some form, and is therefore characterized by large deviations from thermodynamic equilibrium. It may thus have enormous reservoirs of free energy in the form of pressure gradients ('confined' plasmas), magnetic field gradients (plasma currents), distribution function anisotropies, etc. The plasma often gets rid of excess free energy by driving up collective oscillations and waves to high amplitudes. These waves then typically drive the plasma into a highly nonlinear state—sometimes a very coherent one with nonlinear structures like solitons, vortices, double layers, periodic waves, etc. and sometimes (more often) a stochastic one with seething turbulence and chaos. Most fundamental studies in plasma physics are therefore devoted to an exploration of nonlinear collective phenomena. The research programmes at IPR are thus also primarily directed to these studies. We classify all the activities under four heads, viz. (A) Studies of chaos and turbulence, (B) Coherent nonlinear phenomena, (C) Studies of some exotic plasma systems, and (D) Modelling of fusion phenomena. A number of new experimental facilities have been set up to explore the above phenomena. We shall now present an overview of the research activities in the above areas—highlighting both the experimental facilities and the physics results that have already been obtained over the past few years.

Studies on chaos and turbulence

We first describe the BETA device which has been set up to conduct experiments on a variety of fundamental plasma problems, especially those connected with physics of chaos and turbulence.

BETA is an acronym for Basic Experiments in Toroidal Assembly and is shown in Figure 1. This device has a number of special features in comparison to conventional basic plasma research machines[1]. It is a toroidal system, hence it is endless along the direction of the magnetic field. The effect of end plates present in the linear devices with magnetic fields is thus excluded. It has only a toroidal magnetic field and hence is simple compared to tokamaks. The vertical electric field arising due to the gradient and curvature drifts is partly short circuited with the help of the annular conducting aperture, thus providing a partial equilibrium to the

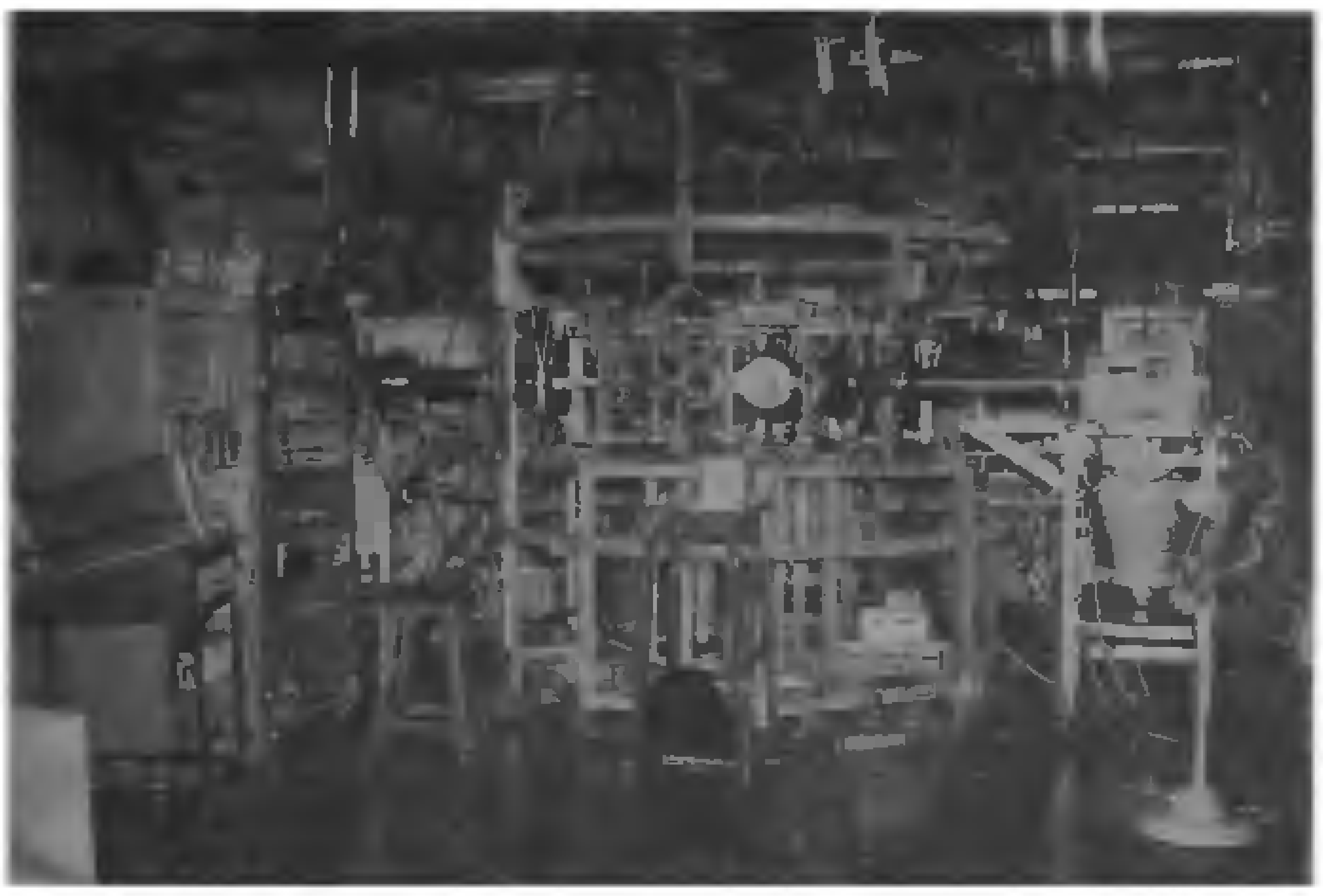

Figure 1. A view of the BETA device.

toroidal plasma. The plasma is generally produced by striking a discharge with a hot cathode at pressures in the range 10^{-4}–10^{-5} torr. However, other methods of plasma filling such as by using plasma guns and RF ionization of neutral gases have also been explored. The major radius of the torus is 45 cm and the minor radius is 15 cm. The material used is SS 304 L. The working gas is argon or hydrogen and the rotary backed diffusion pumps give a background pressure of 10^{-6} torr. Twenty picture frame coils, each having 4 turns, produce the toroidal magnetic field of 4 kGauss. The power system is a capacitor bank by which the field can be crowbarred at its peak value with a decay time of ~120 msecs. Steady magnetic fields up to a kilogauss can be obtained with a standard power supply. Conventional electrostatic Langmuir probes have been used to measure the plasma parameters and the properties of various collective fluctuations. A 22-GHz-microwave interferometer has been used to measure chord average plasma densities and with hot cathode discharge one routinely gets $n_e \sim 10^{11}\ \mathrm{cm}^{-3}$ and $T_e \sim$ 10 eV. A number of experiments related to turbulence and chaos in plasmas have been carried out on this device. We now summarize the various research activities in this area.

BETA plasma is characterized by finite pressure gradients and curved (toroidal) magnetic fields. It is therefore expected that natural electric field fluctuations in BETA will be dominated by electrostatic low-frequency waves driven by pressure gradients and 'effective gravity'. The situation is very similar to the F-region of ionosphere where excitation of density irregularities has been observed with rockets, satellites and ground-based instrumentation. We have carried out extensive exploration of the turbulence in BETA[2–6] using modern statistical methods. The turbulent power spectra of density and potential have been measured in various regimes of collisionality. Conditional averaging techniques have been used and coherent two-dimensional structures observed[6]. There seems to be definite evidence for non-gaussianity of this turbulence; we are now considering possible interpretations of this non-gaussianity. In another series of experiments[7], the nature of turbulence generated by beam plasma instabilities in the neighbourhood of the filament has been explored. It is speculated that electron plasma waves are excited which then lead to caviton formation and give chaos in low-frequency turbulence. Some measurements of emissions around the plasma frequency have been made to support this model. Detailed study of the dimensionality of low-frequency fluctuation under various conditions have also been made. In yet another experiment on BETA we have studied the period doubling route to chaos[8]. This is one of the first plasma experiments of this kind. An RF field near lower hybrid frequency was used to generate nonlinear electrostatic ion cyclotron waves in the BETA plasma. As the RF power was increased various subharmonics appeared. The Feigenbaum number of period doubling bifurcations was calculated and found to be 4.138 as against the universal asymptotic value[9] of 4.66. A fourth experiment on generation of chaos[10], which was carried out in collaboration with UCLA, used a beam plasma discharge to produce a plasma with strongly magnetized electrons and weakly magnetized ions. In this configuration, the radial confining electric field generates an azimuthal current which leads to instabilities. At large amplitudes, these waves trap ions and assist in a period doubling bifurcation towards chaos. In this way a specific route for period doubling bifurcations was identified for a plasma problem.

We now describe important theoretical investigations, among which mention should be made of modelling of chaotic time series[11], studies on interesting Hamiltonian systems[12,13] and modelling of intermittency in tokamak edge turbulence[14].

The origin of chaos in Hamiltonian systems is a problem of considerable interest and complexity. Many nonlinear systems have Hamiltonians with hidden symmetries which lead to unexpected invariants of motion and integrable trajectories. If enough invariants do not exist, the motion is chaotic. We have investigated the Hamiltonian describing relativistically intense nonlinear stationary coupled em-plasma waves in a plasma[12]. Unlike usual Hamiltonians, which are polynomial in nature, this one has a square root potential. Its numerical exploration indicated a nearly integrable system although additional invariants could not be written down. This Hamiltonian attracted considerable attention because of its unusual form and was finally proved to be non-integrable by mathematicians[15]. We have also carried out similar investigations for the coupled plasma wave-ion wave problem and explored regions of chaos in parameter space[14]. Physically, the chaotic solutions correspond to a situation where the coupled waves become turbulent in nature. We have separately examined the chaos in certain Yang–Mills–Higgs systems by carrying out a Painlave analysis and numerically plotting the Poincare surface of sections[16]. The chaotic behaviour is confirmed by calculation of the Lyapunov exponents.

Another major concern of the theoretical effort is an understanding of properties of edge turbulence in ADITYA. In particular, one needs to attempt a model of the observed intermittency in this turbulence. An exploration of the existing model equations such as the Hasegawa–Mima equation[17] by the newly discovered mapping closure technique of Kraichnan and his collaborators[18] has revealed that this equation cannot explain the observed intermittency in density potential fluctuations. This is also consistent with detailed numerical study of these equations by several workers[19]. We have recently discovered[20] that introduction of parallel ion dynamics in these equations leads to several new features. Firstly, it permits the excitation of secondary instabilities which give a non-local interaction in k-space[21]. Secondly, the compressibility of parallel motions and the viscous relaxation due to parallel ion viscosity (and/or Landau type interactions) lead to model mapping equations which give possibility of non-gaussianity in plasma turbulence. Many features of our model are similar to those of Navier–Stokes fluids[18].

Modelling of a chaotic system with differential equations is a topic of great interest both from the point of view of use in short time predictability and also for possible feedback control methods. Often we experimentally obtain time series which demonstrate chaos which is low-dimensional. This physically corresponds to a situation where the true independent nonlinear dynamic variables responsible for the observations are only few in number. Since one does not have enough intuition to know what these variables might be, it is useful, to find a mathematical method for finding the best variables to describe a chaotic system. We have evolved such a method[11] and applied it to some well-known problems of dissipative chaos.

Coherent nonlinear phenomena

Double layers, sheaths, etc.

It is well known that if an external electric field is set up in a plasma, the plasma shields it by 'polarizing' the electron and ion fluids in such a manner that the internal fields oppose the external field. However, if the plasma is far from thermodynamic equilibrium (such as with a large relative drift between electrons and ions) intense electric fields can be set-up self-consistently in localized regions called as *double layers*. Physically, if potential drop in a layer $e\Delta\phi/T \gtrsim 1$, the trajectories of the shielding particles are very strongly modified by the potential; the result is that because of insufficient thermal energy many particles are unable to go to certain high potential regions (because they get reflected or 'trapped') to carry out the shielding process. Thus self-consistently, the plasma can sustain layers with large electric fields. Such double layers have been extensively observed in magnetospheric plasmas, laboratory devices and computer simulations and are believed to play an important role in the observed phenomenon of d.c. anomalous resistivity.

An exploration of double layer phenomena has been carried out in the Double Plasma Device (Figure 2). This device consists of source and target regions as shown. The source chamber is a cylindrical vessel (30 cm long and 30 cm diameter). Plasma is produced in the source region by electron impact ionization of neutrals by energetic electrons emitted thermionically from tungsten filaments. The anode mesh is left floating for electrostatic confinement of primary electrons. The assembly is put inside the main vacuum chamber (125 cm long, 50 cm diameter). The plasma in the target chamber is produced by ionization from energetic electrons flowing from source region into target region. The target region is separated from the source region by two grids suitably biased with respect to the two plasma regions. In order to generate a double layer, a potential is applied to the source with respect to the target which is grounded. An end grid is also provided in target region to provide a population of reflected electrons. Measurements of temperature, density and distribution function were made using Langmuir probes. A hot electron emissive probe is used to measure plasma potentials at various positions. A multigrid analyser is used to obtain the ion energy distribution function. Depending upon the biasing conditions, neutrals gas pressure and current flow from the source to target regions, various kinds of double layers have been observed in this device[22–25].

Figure 2. A view of the Double-Plasma device.

The most novel observations have been those on the so-called ion acoustic double layers. Computer simulations[26] of the double layers in the presence of drifting electrons have found weak multiple double layers with potential dips preceeding the double layer transition. These structures were seen to evolve from subsonic to ion-acoustic pulses which propagate in the direction of the electron drift and have become known as ion acoustic double layers. These layers have been observed for the first time anywhere in the double plasma device in IPR[24]. A constant relative bias is maintained between the source and the target region with the bias value kept below that required for the formation of the strong double layers. This bias results in a steady electron beam with drift velocity below thermal velocity to enter the target region from the source region. A step potential is superimposed on the applied bias resulting in the modulation of the electron beam density/velocity. As a result of this modulation an ion acoustic pulse, growing in amplitude as it moves away from separating grid, is observed. Close to grid, the potential exhibits a solitary negative pulse. As the pulse moves from the grid, ion acoustic fluctuations growing in amplitude and cascading down in frequency are seen on trailing edge of the negative pulse. The leading pulse still maintains negative potential, undergoes steepening and its trailing edge develops into a shock-like structure. Following the shock formation the ion acoustic fluctuations on high potential side are seen to damp out leaving an asymmetric potential structure with negative dip on low potential side (Figure 3). The observations

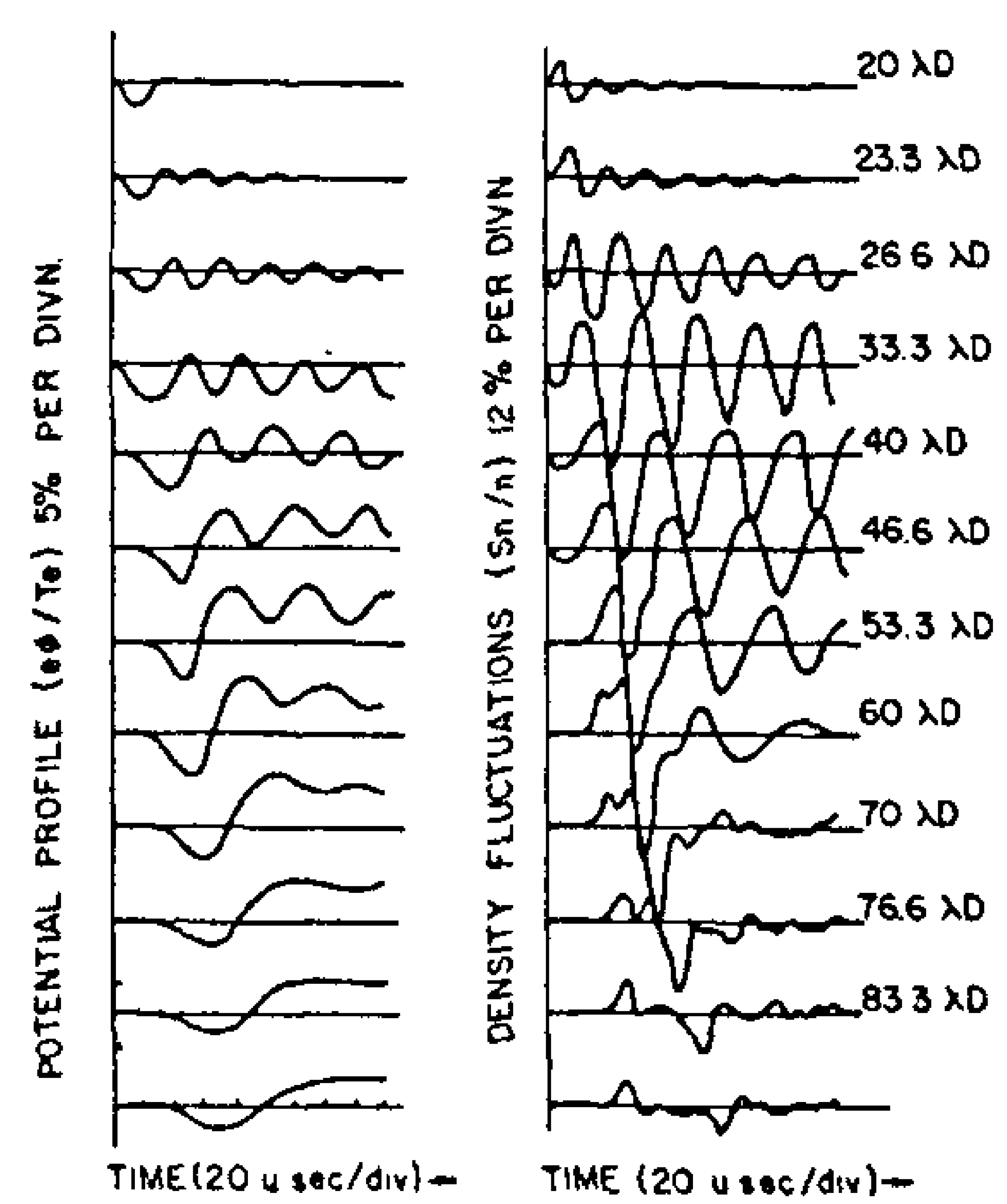

Figure 3. Evolution of Ion Acoustic Double Layer from a negative pulse launched in a Plasma. Potential and density fluctuations at various spatial positions are shown.

are very similar to the scenario envisaged in numerical simulations[26] and analytical treatments[27], which predict the growth of an ion hole triggered by current-driven ion acoustic fluctuations, leading to a nonlinear coherent state.

Other interesting observations on double layers relate to strong double layers with $e\Delta\phi/T_e \gtrsim 25$ which are formed when the biasing arrangement is so modified that larger amounts of currents may be extracted from the source to target region. In some experiments, extended potential structures and moving double layers on an expanding plasma have also been observed. In other experiments, the phenomena of trapping of particles in a large amplitude ion acoustic pulse which has been postulated as a possible mechanism for the formation of weak (ion acoustic) double layers has been observed. A specially designed three-grid analyser has been used to measure ion distribution. As expected, in the presence of rarefaction ion–acoustic waves, a modification of ion energy distribution has been observed. Very recently, the double plasma device has been modified to study the properties of strongly driven ion sheaths[29]. It has been observed that when large negative potentials are applied to a grid, the conventional picture of flux conserving flow into the sheath is modified because of charge exchange collisions.

Nonlinear magnetic structures

A second variety of nonlinear equilibria of interest in plasma physics are those which arise because of interaction of current filaments in external magnetic fields. A simple example of this type is the nonlinear state of $m=1$ and $m=2$ tearing instabilities in a tokamak which arise because of the natural tendency of tokamak current filament to break up into several helically symmetric filaments. Nonlinear theories of $m=1$ instabilities in $q \lesssim 1$ regions of these plasmas have been worked out for the first time[30,31].

An interesting experiment[32–35] generating cylindrical sheet currents which reverse the externally imposed axial fields has been carried out using the relativistic electron beam facility (REB). Short duration electron beams (~100 nsec) are produced by a vacuum field emission diode powered by a Marx generator—coaxial water line pulse generator. For production of long duration electron beams (~500 nsec), the Marx generator is directly connected to field emission diode through an oil filled coaxial transmission line. Typical parameters of the REB on most of these experiments are energy ~ 250 keV, currents up to 15 kA and diameters of circular beams up to a few cm. The earliest experiments on reversed field configurations[32,35] were done in a vacuum chamber of 30 cm diameter, 2.3 m length and a base pressure of 10^{-5} torr (Figure 4). The

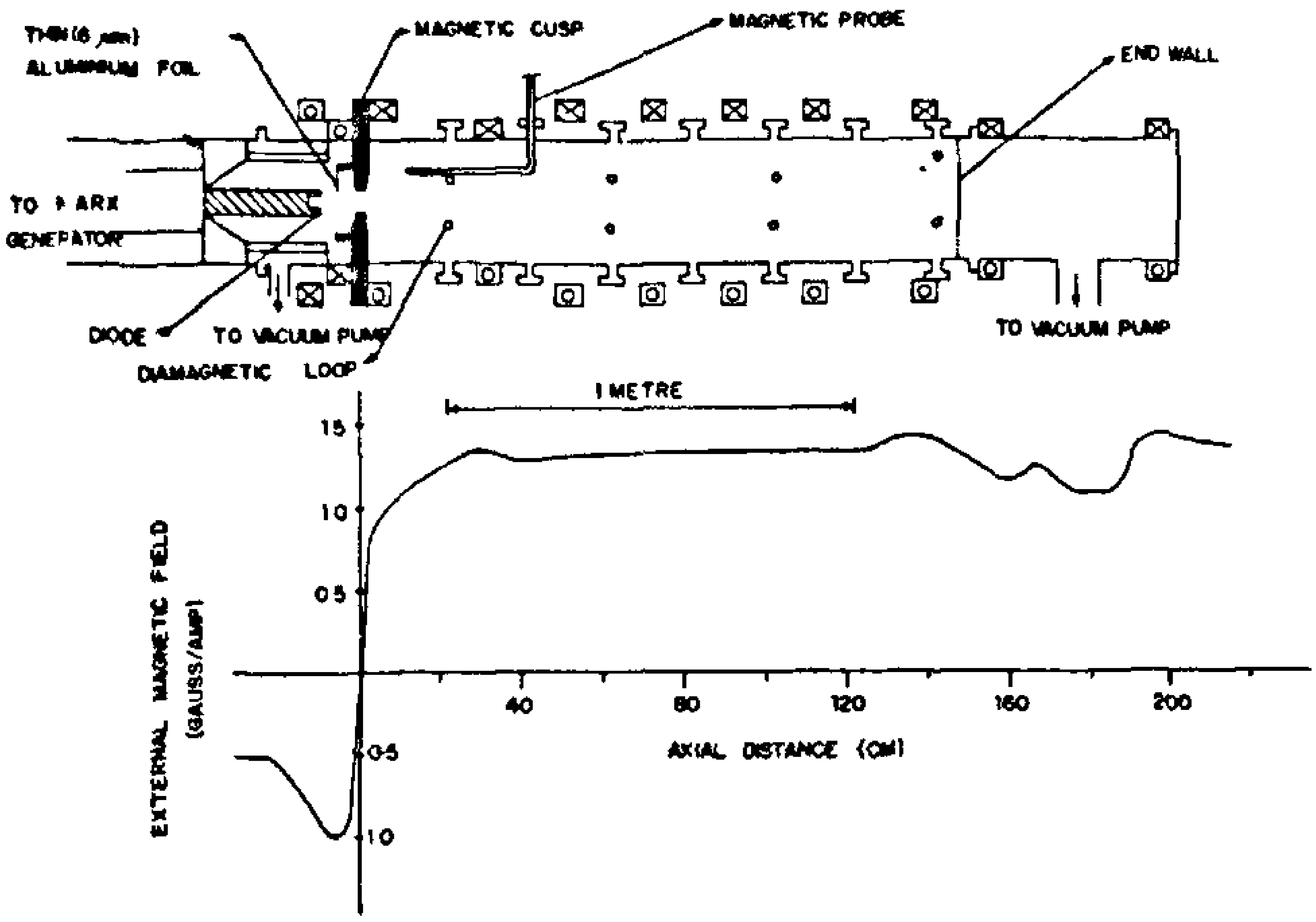

Figure 4. A schematic of the relativistic electron beam device.

electron beam was made to pass through a non-adiabatic cusp and a mirror field produced by a set of spatially dispersed pancake-type coils[33]. During the field reversal experiments, some coils of the magnetic field assembly were shorted so that after the cusp, the magnetic field is homogeneous. Most measurements on the magnetic structures and their time development were made with specially designed magnetic probes. The experiments demonstrated the formation of a compact torus configuration by reconnection of field lines at the edges (Figure 5). The compact torus (CT) is an axisymmetric field configuration in which poloidal field lines are closed and encircle the plasma while the toroidal field is trapped within the plasma. The CT formation works as follows:

A high current electron beam, spiralling around the axis is injected into a metal chamber kept in an external, axial magnetic field. The chamber contains neutral gas (hydrogen) at the required pressure. The spiralling beam is like a current carrying coil and generates a magnetic field of its own, in a direction opposite to the external field. Two things simultaneously happen when the spiralling beam passes through gas. First, the magnetic field at the axis is reversed due to the self-field of the beam, and the neutral gas is converted into a plasma by the absorption of the beam energy. Secondly, when the pulsed beam leaves the electrically conducting plasma after embedding the reversed field, an almost equal current is induced in the plasma, with the result that the reversed field configuration is sustained now by the plasma currents. To increase life time of reversed field configuration, Marx generator was directly connected to the field emission diode and thus, a long duration electron beam was injected into the neutral gas. Due to increase in the duration of the electron beam, we observed formation of a long lived reversed field configuration. Detailed temporal evolution of magnetic field topology in our experiment was obtained by a two-dimensional mapping of the magnetic flux surface with the help of an array of magnetic probes. Reconnection of the beam produced field and the external magnetic field has been observed which results in the formation of a prolate spheroid.

Other studies with this device included the effect of self-fields on propagation of REB[36] and numerical simulation of the formation and dynamics of rotating relativistic electron beams.

In another series of experiments, the REB facility was used to inject an electron ring into a toroidal magnetic field in the BETA device[37]. The basic idea was to see if one can load a ring current so that one may be able to form tokamak-like configuration with relativistic electron beams replacing thermal current carriers. For this purpose, an REB generator based on Tesla Transformer (Figure 6) principles was fabricated[38]. Plasma was injected into the torus with the help of a gas injected, washer stack plasma gun. Using plasma as anode, the electron beam was injected into the torus. The beam injection was studied in two different plasma densities —low (5×10^{12} cm^{-3}) and high ($\sim 10^{13}$ cm^{-3}) decided by the operation of the plasma gun with two different pulse forming networks. When beam was injected into low-density plasma, the beam was lost by hitting the

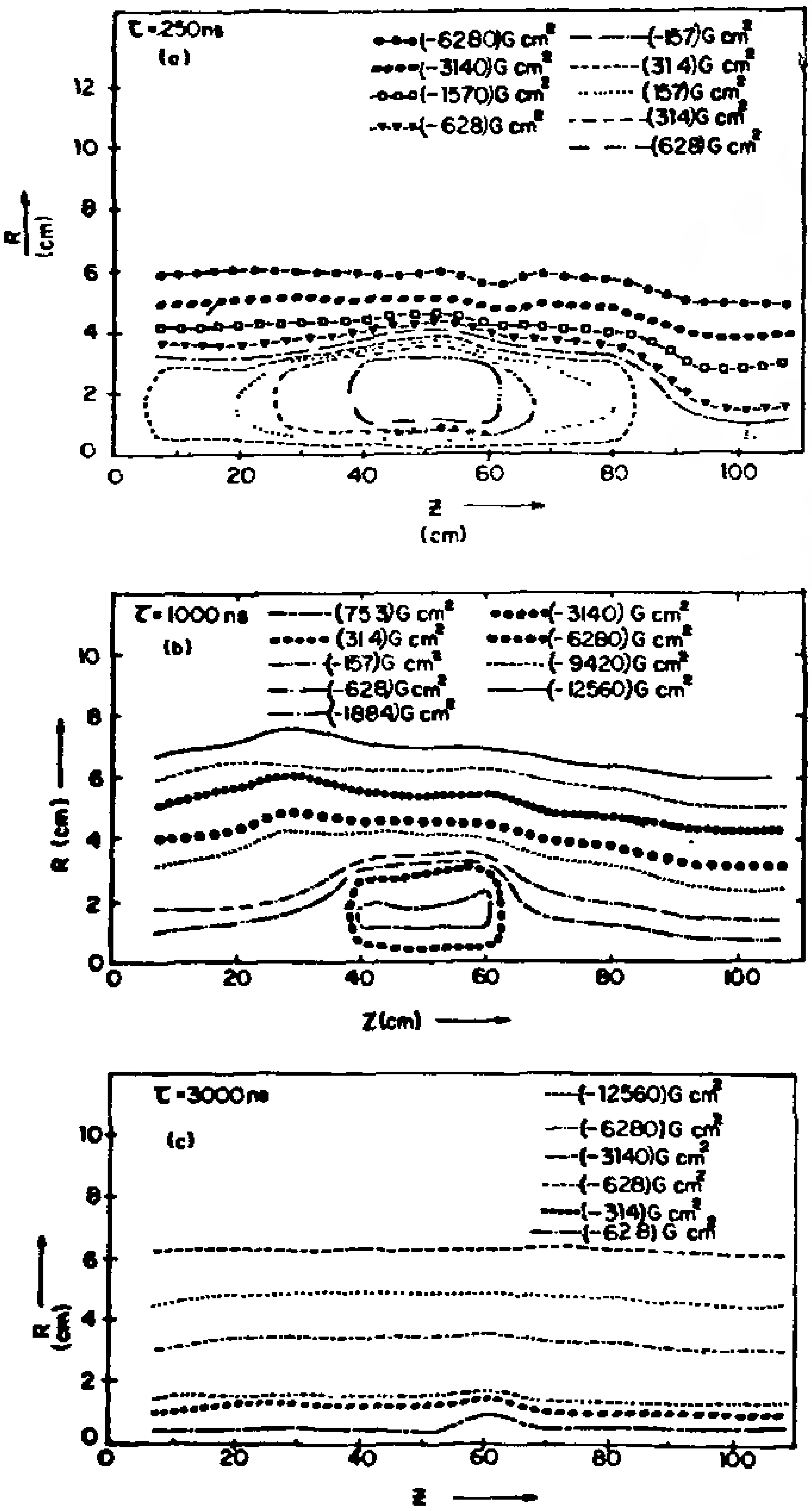

Figure 5. The formation and evolution of field reversed configuration when a rotating REB is injected in a plasma. Plots are magnetic field lines monitored by magnetic probes.

injector from the back after one toroidal transit. No net toroidal current was observed. In the case of injection into a high-density plasma, the beam drifted inward, cleared the injector and was trapped. A net toroidal current of about 5 kA was generated in this case. Temporally and spatially resolved measurements with miniature Faraday cups and small Rogowski coils showed that beam trapping was due to a fast return current decay. The return current decay time calculated from ion-acoustic turbulence was found to be consistent with the observed net current rise time. Localized measurements of the poloidal field indicated a net current channel moving radially inward with no

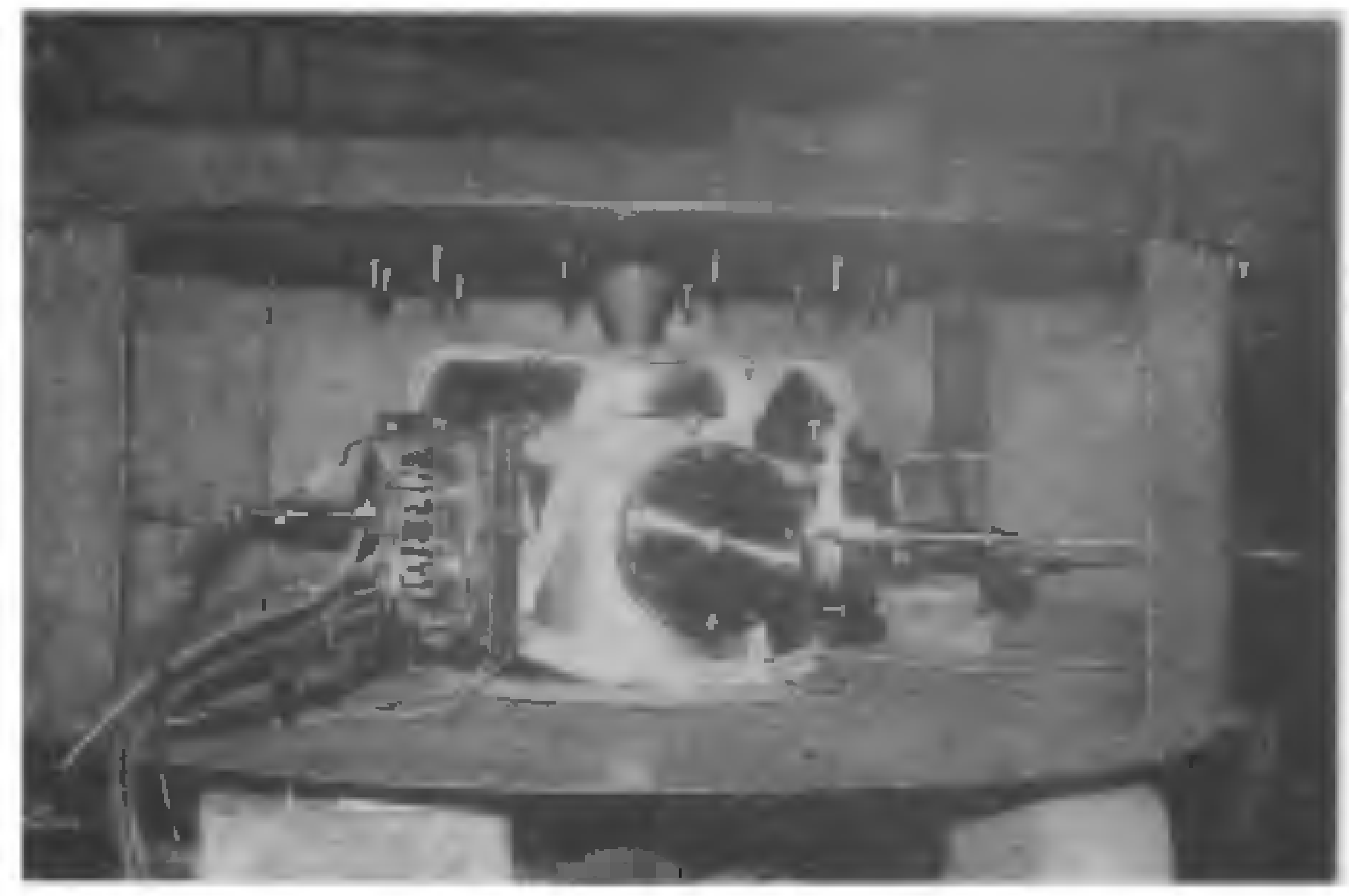

Figure 6. Photograph of the device for non-neutral plasma studies.

observable vertical motion. This is attributed to the drift injection-energy loss mechanism proposed for beam trapping. From these measurements it was also found that about 50% of the beam energy appears as plasma perpendicular energy and the heating was mainly due to return current dissipation. The q profiles obtained from the magnetic field measurements indicated that the system goes into a low q state as time progresses. The beam energies calculated from the observed net currents and shift of the current channel were found to be consistent with the beam energy transfer observed from diamagnetic measurements[39].

Nonlinear variational principles and plasma relaxation

The usual description of an observed nonlinear plasma state is quite complex. One starts with an expected initial state with free energy sources, studies its stability to perturbations and then follows the perturbations to large amplitudes by complicated nonlinear theories. Sometimes, one can recover the final state by simple application of a minimization principle subject to certain important constraints[40]. Both, the choice of what to minimize, and what to keep constant is guided by physical intuition. The best known example of such a variational principle in plasma physics is that developed by Taylor to explain the observed properties of reversed field pinch discharge. We have generalized Taylor's variational principle to the case with mechanical flows[41]. This had led to the concept of constraints related to total helicity $\mathbf{p}\cdot\nabla\times\mathbf{p}$ where $\mathbf{p}=\mathbf{P}-e\mathbf{A}/c$ is the canonical momentum and retains effects due to fluid vorticity and the field vorticity separately. This variational principle has then been applied to a number of interesting relaxed states[42]. We have also considered a possible generalization of Taylor's ideas to a tokamak where we do a multi-region minimization and observe the formation of tokamak like q-profiles[43]. Such multi-region relaxation phenomena are close to the recently analysed relaxation studies for discharges which demonstrate profile consistency. In another calculation we have used a variational principle to construct equilibria with minimum potential energy subject to a global invariant which is preserved exactly by ideal motions of the plasma and approximately by a tearing mode of the $m=1$, $n=1$ type[44]. A general variational approach to study stationary solutions of two-fluid MHD equations has also been constructed and solutions are used to model z-pinch, Bennet pinch and θ-pinch like configurations[45].

Multidimensional structures in magnetized plasmas

Plasma at the edge of a tokamak displays an interesting interplay between the atomic physics and collective plasma phenomena. An important example of this type is the so-called MARFE and detached plasma structure observed at the tokamak edge when its density approaches the density limit. These are asymmetric cold dense spots which are formed because the plasma electrons excite impurity atoms which radiate copiously. Similar phenomena are observed in solar prominences. The observed nonlinear structures can be understood in terms of the solutions of a two-dimensional thermal equilibrium model in which heat conduction by electrons parallel and perpendicular to the magnetic field lines balances the radiated power output from the cold spot. We have recently carried out a model nonlinear calculation[46] which explains many features of the observed MARFE—detached plasma transition in tokamaks. After making some simplifying approximations, the problem has been reduced to a well-known nonlinear two-dimensional equilibrium equation, for which exact solutions are known. It is well known that the confinement properties of an inhomogeneous magnetized plasma are strongly influenced by low-frequency drift like instabilities. Typically, these instabilities generate a strongly turbulent spectrum of waves. However, there are many situations when the plasma supports coherent two or three dimensional vortex structures, which are also solutions of the exact equations. There are also situations where such coherent structures exist simultaneously with the turbulent drift waves either as short lived entities which are constantly being created and destroyed in various locations and with various scale sizes or which coexist in a time independent manner. Such structures lead to interesting phenomena like intermittency in magnetized plasma turbulence[47]. We have investigated multidimensional monopole vortex solutions of the magnetized plasma equations taking account of nonlinear ion parallel motions[48]. More recently, we have extended these solutions to incorporate effects due to magnetic curvature, velocity shear, magnetic shear, viscous dissipation, etc. We have also considered the possibility of strained vortex solutions in the plasma context and discussed it as a possible source of intermittency. We have also investigated nonlinear coherent solutions of the vortex type for kinetic drift waves[49]. The maximum entropy method is used to determine the most probable distribution of electrons in the presence of their space and perpendicular trapping nonlinearities. The resultant potential structures in one and two dimensions have been studied numerically.

In a recent investigation[21] the study of the stability of vortex structures in magnetized plasmas has been systematically carried out. It has been found that secondary instabilities of alfven waves and acoustic waves may be generated when the amplitude of the vortex potential exceeds a critical value. This provides a mechanism for nonlocal transfer of energy in k-space and prevents accumulation of energy at the long wavelength end.

One-dimensional solitary wave studies

Solitons or solitary waves are stationary nonlinear structures in a plasma which arise, when the spreading effects due to wave dispersion are counterbalanced by steepening effects due to nonlinearity. Such waves are of considerable interest since they propagate undistorted as 'nonlinear normal modes' of the medium. Recently, we have studied the propagation of relativistically intense laser pulses in a cold plasma and have demonstrated the existence of soliton-like solutions when the light wave is coupled to plasma waves[50]. We have also shown that the group velocity of the light pulse is reduced because of the drag of plasma waves. These studies are of direct interest to experimenters attempting particle acceleration using novel plasma-based concepts[51] and currently many attempts are being made to extend such solutions to two-dimensional problems[52].

In another investigation we have shown[53] that nonlinear saturated states of a free electron laser pulse in which hydrodynamic nonlinearities are dominating can also give rise to solitons. This is the first such solution which has appeared in the literature and would be experimentally quite interesting. A kinetic analysis of the nonlinear evolution of the free electron laser instability has also been carried out[54,55]. The governing equations are the coupled Vlasov–Maxwell equations which are investigated for a system consisting of a relativistic electron beam propagating through a helical wiggler magnetic field. A general nonlinear solution is obtained and the saturation properties of the FEL are discussed by numerical and analytical methods. We are also carrying out experimental investigations of a free electron laser in which a sheet electron beam emitted by a special diode (with particle energy

~ 0.5 MeV, plasma current ~ 10 kA) is passed over electromagnetic wigglers to generate radiation pulses with a wavelength of order few mms (ref. 56). Such radiation pulses are of considerable interest from the point of view of plasma heating and plasma diagnostics in fusion systems.

Studies on exotic plasma systems

An exploration of the collective nonlinear properties of non-neutral electron clouds, quark–gluon plasmas and dusty plasmas has also been initiated at IPR.

Non-neutral electron clouds

Non-neutral toroidal clouds of electrons or ions are interesting from several points of view. In the early days of controlled thermonuclear fusion research, it was shown by Budker[57] that pure ion clouds could be trapped in a toroidal field with the self-consistent space charge field producing a rotation in the poloidal direction and thereby preventing the charge separation effects. However, these devices were not considered suitable for fusion systems because it had been shown that the density limit due to space charge does not permit significant plasma pressures to be trapped in realistic magnetic fields. However, recent theoretical work[58] has shown that by appropriate shaping of the equipotential contours, one may be able to improve on the density limits and thus go into interesting parameter regimes. Over the years, one has also learnt from experiments with electron clouds[59] that confinement of singly charged species in cylinders is excellent because like-particle collisions do not lead to any net transport of the electron fluid across field lines. Thus it appears useful to reinvestigate the potential of toroidal traps as interesting pure ion fusion systems. Similarly, there is interest in toroidal electron clouds from the point of view of betatron accelerators and trapping of ions in potential wells created by electrons. Finally, as a fundamental system pure electron or ion systems are interesting because of severe constraints they impose on overall particle motions and transport etc.

We have built two toroidal electron traps in which experiments on pure electron clouds are being carried out[60]. The first device (Figure 6) essentially consists of a central conductor carrying an incoming current of 50 kA from the capacitor bank to a cylindrical shell (current chamber) made of copper before returning to the bank. The vacuum vessel is a fat torus with rectangular cross-section. It sits inside current chamber, very close to the central conductor. The aspect ratio is 1:2. The central conductor produces a toroidal magnetic field inside the current chamber with very small error field (~0.3%). The capacitor bank is a lumped transmission line with 10 sections of capacitors and inductors. Each capacitor has a capacitance of 700 microfarads and each inductance is 3.4 microhenries. This gives a constant toroidal magnetic field of 1 ms duration and a rise time of 75 μsecs. For switching, we have used an externally triggered spark gap. Electrons are extracted from a hot tungsten cathode and either injected by the inductive charging technique or in the steady state just using the toroidal drifts. Electron densities up to 10^7 cm^{-3} have been trapped inside the cloud. In the first experiment[61] we have used the inductive charging method to produce a low aspect ratio toroidal electron cloud in a given external magnetic field. Many properties of the equipotential contours (Figure 7) have been noted and compared with theoretical toroidal equilibria[61]. In more recent experiments we have investigated steady state injection of electrons in a *static* toroidal magnetic field using the toroidal drift and the bias on an inner electrode to facilitate the cloud formation[62]. This scheme is of greater interest for steady fusion systems. This bias is also found to be effective in purging the system of ions which are formed by ionization of the background neutral gas. In the second experiment[63] we are exploring the trapping of electrons in a novel trap in which a poloidal magnetic field is produced by an internal conductor inside a toroidal vacuum chamber. This kind of a trap has additional invariants because of the conservation of toroidal canonical angular momentum and it will be interesting to see how these additional symmetries and constraints modify the confining properties of this trap[64]. A number of theoretical investigations of equilibrium and stability in toroidal electron clouds with and without external electric fields

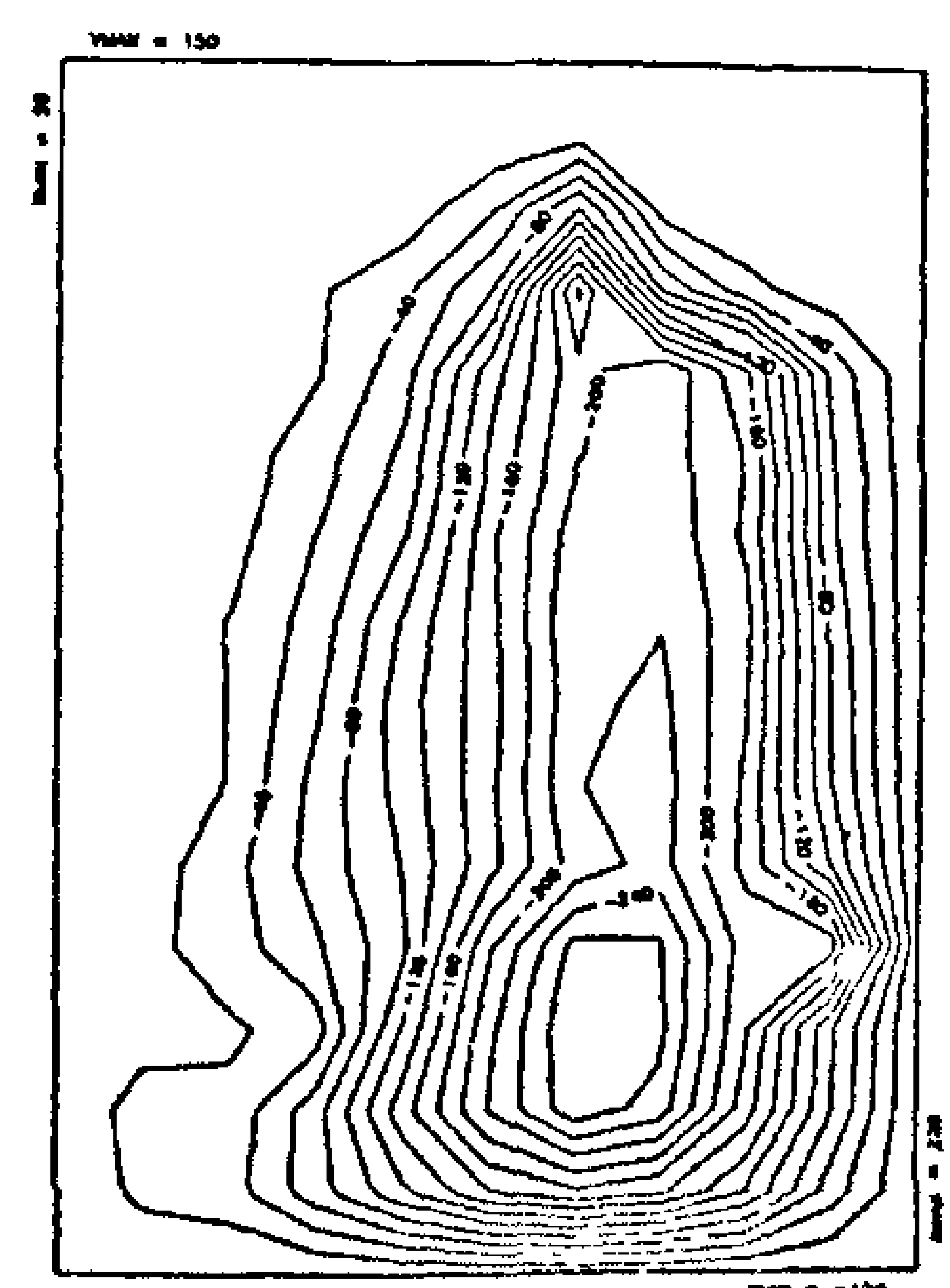

Figure 7. Contours of equipotentials (values in volts) of the electron plasma cloud obtained in non-neutral plasma device at 800 microseconds after injection. The xmin and xmax correspond to the inner and outer radii of vacuum vessel in mm. The toroidal field was 150 Gauss.

have been carried out[65–70]. Equilibrium considerations have shown that fluid drift surfaces with finite pressure and finite mass are displaced inwards with respect to equipotential surfaces[66]. With toroidal current it is found that in a large aspect ratio conducting torus the equilibrium is governed by a competition between forces produced by image charges and image currents. From stability investigations it has been found[68,69] that for toroidal systems, the quantity n/B^2 which is the density of electrons per flux tube plays the same role as n in cylindrical systems. Thus the stability criteria, growth rate, etc. are directly related to gradients of (n/B^2). We have also investigated the stability of elliptic vortex cores of electron clouds to hf plasma perturbations and found that shear of the electron flow can excite instabilities[70]. These instabilities may be instrumental in modifying the transport of electrons in a toroidal cloud compared to a cylindrical cloud.

Quark gluon plasmas

It is widely known that hadronic matter at high densities and/or high temperatures can undergo a phase transition to a deconfined state in which the quarks and gluons move about freely inside a confined volume. Such a quark gluon system exhibits many collective properties due to strong quantum chromodynamic (QCD) interactions and is known as a quark–gluon plasma. It is believed that early universe had matter in this state. Currently a number of experiments are being carried out at various heavy ion accelerator facilities where conditions for formation of this state of matter are being created in ultrarelativistic collisions of heavy ions like sulphur, uranium, lead, etc. The experiments have already given indications (though not conclusive) that such a state may have been created in the laboratory.

One of the difficulties in modelling the collective properties of quark–gluon plasmas is that QCD interactions involve non-abelian Yang–Mills fields and colour dynamics of quarks and many of these are fundamentally non-perturbative in nature. Furthermore, there are no known quantum methods to describe dynamic non-abelian interactions in a non-perturbative manner. It is therefore of considerable interest to investigate non-perturbative aspects of quark–gluon plasma dynamics by classical model equations[71]. We have recently carried out a series of such investigations and discovered a number of novel phenomena[72]. We found that non-abelian plasma oscillations exhibit chaotic character, which is totally unlike what one can study using perturbative quantum chromodynamic methods[73]. This has important implications for equilibration of plasma in its early stages of formation in heavy ion collisions, effectively through collective relaxation phenomena. This effect has also been investigated in considerable detail by using particle simulation methods[74]. Similarly, the screening of moving charges in a plasma is found to be weaker because of non-abelian precession of colour vector[75]. We have also explored the collective mechanisms of stopping and transverse flow generation through the excitation of filamentation instabilities[76]. In another investigation we have re-examined the process of pair production by the so-called Schwinger mechanism[77]. We have shown that non-abelian interactions lead to an oscillating field in the conventional capacitor model and thus lead to the possibility of a multigluon pair production in contrast to the Schwinger mechanism[78]. Finite temperature modifications of these studies have also been carried out.

Another area of interest is the physics of relativistic hydrodynamic expansion of the colourless quark–gluon plasma fluid after equilibration has taken place. Here we have investigated[79] the stability of well-known models to instabilities driven by shear flow and its consequence for entropy generation. It is possible that some of these instabilities act as sources of intermittency in the particle production that is finally observed in heavy ion collision experiments. We have also discussed a two-fluid model of relativistic hydrodynamic expansion to investigate the physics of experiments which show partial stopping[80].

Dusty plasmas

In recent years, the physics of dusty plasmas in which negatively charged micron size dust particles coexist with electrons and ions, has attracted a lot of attention. It finds applications in such varied fields as planetary environments in space, fusion plasmas near edge, plasmas in arc furnaces and other plasma processing applications etc. A number of investigations of collective properties of such plasmas have been carried out[81–83]. Low frequency waves and stimulated scattering effects have been studied in detail[81–83]. In a recent paper we have explored a novel effect which arises because the charge on the dust particle itself fluctuates in response to self-consistent fields[84]. Thus a new dynamical equation is to be added to the plasma equations and the self-consistent response re-examined. It was found that a number of novel dissipative and instability phenomena can arise because of these dynamical charge fluctuations. We are also in the process of setting up an experiment to explore collective properties of dusty plasmas.

Simulation and modelling of fusion phenomena

A great deal of theoretical activity is devoted to the equilibrium and stability of fusion plasmas. Questions related to current drive and fluctuation-induced transport are being explored experimentally as well as theoretically. We now briefly summarize these activities.

Plasma equilibrium studies

Study of plasma equilibria is one of the oldest areas of research in thermonuclear physics. However, recent interest centres around difficult problems related to 3D equilibria, high β systems and systems with plasma flow.

A variational method has been developed for three-dimensional toroidal equilibria with imperfect flux surfaces[85]. An attractive feature of this work is that it deals with the problem of break-up of magnetic surface without surrendering the advantage of using 'magnetic' coordinates.

For the analysis of high β tokamak equilibria an analytic high β equilibrium in a large aspect ratio system has been investigated[86]. Two arbitrary flux functions, the pressure profile $p(\psi)$ and safety factor profile $q(\psi)$ specify the equilibrium. The solution naturally splits into two asymptotic regions: the core region where ψ is only a function of major radius and a narrow boundary layer region adjoining the conducting wall. For beta much bigger than 1, the solution contains a region (in place of magnetic axis) of zero magnetic field and constant pressure. The quantity β_I, which is essentially proportional to pressure over total current squared is largely independent of pressure.

An important theme in plasma equilibrium studies is the influence of plasma rotation (induced, for example, by neutral beam injection during auxiliary heating). The effect of sheared flows has been investigated through a detailed numerical solution of the generalized Grad–Shafranov equation. Axisymmetric rotation is found to strongly influence the form of magnetic surfaces[87]. When the flows are incompressible, considerable simplification occurs in the formulation of the equilibrium problem and analytic expressions in the large aspect ratio limit can be readily obtained[88]. A general theoretical result pertaining to the impossibility of plasma equilibrium with flows in a purely toroidal field has also been demonstrated from applications of Ohm's law[89].

Numerical codes for the study of equilibria relevant to experiments in ADITYA have also been implemented[90]. They have also been extended to consider static high β plasmas and infer the modifications of magnetic surfaces etc. for use in stability calculations[91].

Stability of fusion plasmas

It is well known that macroscopic instabilities of the plasma column determine the restricted parameter space of operation and the microscopic instabilities essentially lead to observed turbulent state and fix the magnitude of the anomalous transport of heat and particles from such confined systems. The areas of current interest in stability theory involve interaction with atomic physics at the edge leading to radiative and ionization drives for collective plasma instabilities, influence of plasma flow in poloidal or toroidal directions, effect of energetic particles giving finite larmor radius stabilization and/or 'effective rigidity', possible use of external agencies like feedback systems, radio-frequency waves, modulated neutral beams to stabilize unwanted modes and general novel effects associated with higher temperature (weakly collisional) plasmas. We now sketch some of the work in these areas.

The physics of edge instabilities is intimately tied to atomic physics phenomena like ionization and radiative excitation of impurity atoms. In recent years, the radiative condensation instability has emerged as a strong candidate to explain the phenomenon of Marfes, detached plasmas, etc. and possibly also to explain the observed fluctuation determining edge transport in the high density discharges. We have re-examined the radiative condensation instability taking account of density gradients at the plasma edge, ionization phenomena[92], non-coronal radiation effects[93], etc. and have found important modification to the growth rate. We have also examined the short scale instability and considered the effects of toroidal coupling on its excitation in various collisionality regimes[94]. Finally, we have examined the ionization effects on drift like low-frequency instabilities and found that the dependence of ionization rate on temperatures makes an important contribution to the growth rates[95]. Recently, experiments on ADITYA have indicated that low-frequency fluctuations (below 20 kHZ) are preferentially giving an inward directed transport of plasma particles[96]. We have interpreted these results in terms of the physics of ionization instabilities and have shown that this may give an interesting method to exert control over the particle confinement time at the edge of a tokamak.

The effect of flow on various plasma instabilities is also a problem of great interest. It has been found that plasma rotation may cause significant changes in the stability boundary and oscillation frequency for rigid horizontal displacements. The effect of flows on ballooning instability has also been extensively investigated[97] retaining the full effects of shift, elongation and triangularity. Similar effects for high β plasmas have also been studied[98]. We have also recently investigated the effect of a sheared poloidal flow on the various micro-instabilities believed to be important at the tokamak edge[99].

A problem of considerable interest is the access to second stability regimes for high β tokamak operation. For this purpose one has to devise a method of keeping the plasma in stable equilibrium while its beta is increased. We have considered the possible use of RF ponderomotive forces (Figure 8) to stabilize the ballooning instability while the second stability regime is being accessed[100]. Experimentally, this approach has not been attempted so far. We have also re-examined the physics of resistive ballooning modes in high temperature plasmas and shown that new stabilization mechanism can operate[101]. Recently, we have considered the use of phase sensitive feedback methods to stabilize the various microscopic edge instabilities in a tokamak plasma[99]. Such methods may be quite useful to excite or suppress given range of wavelength to influence the overall confinement. Other methods which have been considered for stabilization are the use of RF waves[91], energetic beam-like current carriers for tearing mode stabilization[102] and FLR effects on macroscopic MHD instabilities in pinches[103–106]. For this last problem, important new integral equation methods had to be developed to solve the eigenvalue problem. An important experiment modelling H-mode-like behaviour by limiter biasing has recently been conducted[107].

Current drive

An important concern in tokamak research is that the device is pulsed in nature because the flux stored in the Ohmic transformer at the beginning can be used to sustain the current against resistive dissipation only for a finite length of time. A number of suggestions have been made to make a steady state tokamak in which RF waves are used to sustain the plasma currents. Unfortunately, the usual schemes which rely on resonant wave-particle interaction do not have enough efficiency to be directly usable in a fusion reactor. In recent years there has been some interest in finding novel efficient methods of current drive using non-resonant forces due to RF fields. We have demonstrated from very general consideration that such AC helicity injection methods can only operate when the RF modes suffer direct dissipation; this makes these schemes also relatively inefficient[108]. We have also specifically considered the current drive by low-frequency surface Alfven type perturbations and have demonstrated that when ion inertia (through Hall term) and ion viscous effects are retained interesting current drive efficiencies may be obtained[109]. In a related investigation we have considered the effect of such terms on a bounded inhomogeneous plasma where the shear Alfven resonance condition is met locally somewhere[110].

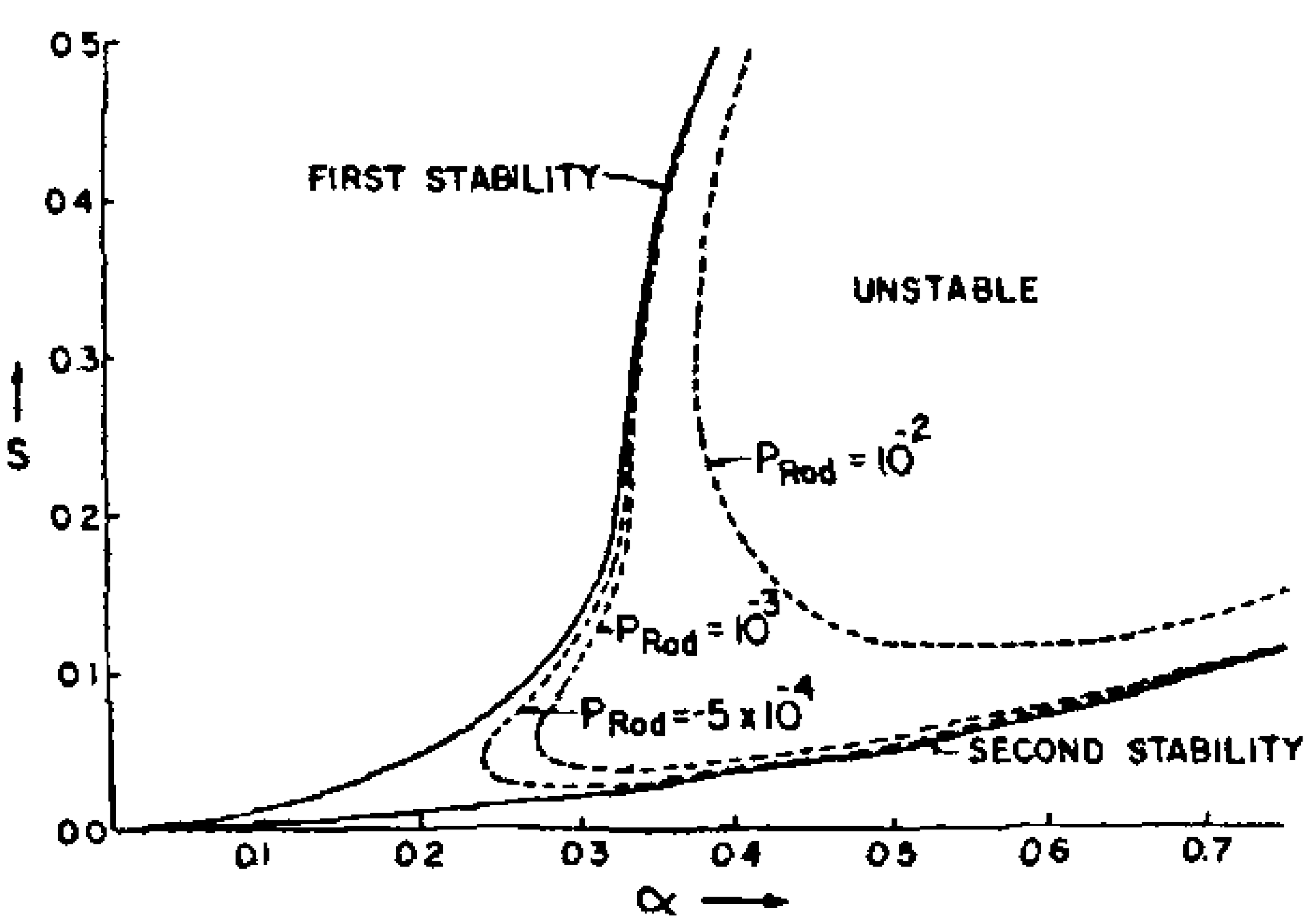

Figure 8. Marginal stability curves for ideal ballooning modes in s-α plane (s is shear parameter and α is pressure gradient parameter). The solid curves are for $P_{rod} = 0$ and the dashed curves are in the presence of RF waves.

Conclusion

From the foregoing discussion of experimental and theoretical investigations in fundamental plasma problems, one can clearly see that nonlinear phenomena are indeed ubiquitous in plasmas and that there is an incredible array of complex structures that they generate. The present state of nonlinear physics is such that one is simply generating intuition by studying a number of examples in which experiment and theory go hand in hand and looking for guiding principles. The situation is somewhat similar to that of atomic physics at the turn of the century. Furthermore, the mathematical tools available to deal with the observed complexity are rather primitive and a lot of progress is made simply by looking at special solutions with assumed symmetries or by carrying out numerical computations. It is hoped that as our intuition gets stronger and deeper we will be guided towards fundamental principles more firmly, viz. we will find out what the plasma is trying to optimize in the driven stationary state far from thermodynamic equilibrium, what the topological structure of its phase space is and how to carry out ensemble averages which are meaningful. In this way we will learn how to describe the observed statistical state of the nonlinear plasma systems. If fundamental guiding principles emerge from these studies, they are likely to be very general and will definitely impact on a broad class of phenomena in other areas of physics.

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Plasma-assisted material processing

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Introduction

THE highly visible search for controlled thermonuclear fusion in the laboratory—the plasma physicist's holy grail—has often relegated the practical applications of plasmas to the background. While the potential benefit to the society through the fusion route to energy production is enormous, plasmas have already contributed to the nucleation and growth of a new industrial technology—plasma processing—albeit without significant assistance from the plasma physicists. The purpose of this article is to discuss the science and technology of plasma processing, assess its international status and project its potential impact on the Indian industrial scene.

Materials and materials processing remain both internationally and in the Indian context a major industrial and technological concern. The various facets of this issue relate to production, transformation and conservation of materials. The thrust of this article is to highlight the promise offered by integrating the technology of plasmas to the material and manufacturing engineering technologies, assess its present status in the country and comment on the possibility of its growth into a major component of the Indian industrial scene.

Plasma state and plasma processing

Plasma is the ionized state of matter, obtained by dissociating atoms into positive ions and electrons. The electrons can be removed from the bound state by a variety of means, all of which involve imparting energy to the bound electron to enable it to become free of the attractive force of the nucleus. The minimum energy required by the electrons to do this is the ionization potential of the atom. The process of ionization can be