Chapter 1

Introduction

This chapter initially reviews history of helicon wave research and its applications in brief. Later, it reviews research on helicon physics relevant to the present thesis work. This will be followed by the motivation and objectives of the thesis work. Finally, the content and important findings of this thesis work will be summarized.

1.1 History of Helicon Sources

Plasma is a complex medium which supports many mechanical and electromagnetic waves. Plasma waves are often classified as electrostatic or electromagnetic waves. Moreover, the direction of propagation and polarization with respect to the magnetic field is often used for detailed classification. Magnetic fields introduce anisotropy in the plasma medium for which magnetized plasmas support a number of waves both in parallel and perpendicular directions. Right circularly polarized electromagnetic waves propagating along the magnetic field are typically referred to as whistler [1]. The name is derived from the whistling audio tones with constant amplitude and declining frequency received in radio receivers during World War I [2] which were mistaken as flying grenades. Barkhausen [3] explained this phenomenon as the highly dispersive broadening of a sharp pulse, initiated by lightning that propagates in the ionosphere. Storey [4] performed measurement on whistling atmospherics and described them as right handed circularly polarized waves that propagate in free space where ion effects and collisions were neglected. Helicon waves are whistler waves in a bounded plasma so that the wavelength is of the order of the plasma dimensions. They are quasi-electromagnetic waves and
are different from classical whistler waves which are purely electromagnetic in nature. Helicons can have both right and left handed polarizations compared to whistlers which have only right hand polarization.

In 1960, Aigrain [5] suggested the possibilities of observing whistler waves in solid state plasmas. Aigrain called the wave a helicon wave because the electric field traces out a helix when the wave propagates along the magnetic field. In an accidental observation, Bowers et al [6] reported experimental finding of helicon wave while measuring the hall resistivity of a pure sodium metal using a static magnetic field parallel to the applied oscillating magnetic fields. They observed a damped oscillation whose frequency was proportional to the applied DC magnetic field instead of an expected decaying signal in the output of the receiver coil. They identified the waves as those proposed by Aigrain. Detailed theory for the propagation and damping of helicon waves was given by Legendy [7] for solid state plasmas and Klosenberg, McNamara and Thonemann (KMT theory) [8] for gaseous plasmas. Following these theories, Harding and Thonemann [9] carried experiment in indium and showed good agreement with the theoretical prediction. Much of the early work on helicon wave was in solid state plasmas because of an immediate use as a diagnostics for measuring Hall coefficients in pure metals. Lehane and Thonemann [10] first observed helicon waves in gaseous plasma and found a very good agreement with wave axial damping rates given by KMT theory. Gallet et al [11] used helicon waves in gaseous plasma in toroidal ZETA fusion device as a diagnostics for measurement of plasma density and static magnetic field by measuring the damping of the helicon waves using magnetic probes.

First use of helicon waves as an efficient source for plasma production was demonstrated by Boswell [12] who using a double loop antenna at 8 MHz produced plasma of $4 \times 10^{18}$/m$^3$ density with a magnetic field of 1.5 kilo Gauss and RF power of 600 W. This density was higher by an order from the conventional RF discharges with equal RF input power and magnetic field. This high efficiency plasma production led to increased interest in helicon plasma physics as well as its various potential applications. Today they are considered for many applications like material processing, [13], negative ion production [14], Preionization [15-17] and current drive [18-19] in fusion plasmas and for space propulsion [20-22].
The mechanism responsible for efficient coupling of RF power into helicon source plasmas is still under investigation. Many collisional and collisionless processes are proposed in the last two decades. The prominent models are Landau damping [23-27], parametric turbulence [28-29], helicon to TG mode conversion [30-32], radially localized helicon modes [33-34] and nonlinear trapping of electrons in helicon wave fields [35-36].

1.2 Review of Relevant Previous Work

Diverging magnetic fields in nature are found in our magnetosphere and solar coronal funnels. Diverging magnetic fields are seldom used in helicon sources. Recent observation of efficient helicon plasma production at low diverging magnetic fields [37] invites attention. Diverging magnetic fields are used in low pressure helicon discharges to produce ion beams for space propulsion and surface functionalization of semiconductor materials. Ion beams in helicon discharges are produced when ions get accelerated in an electric field produced self consistently in the bulk of the plasma. In a diverging magnetic field, design of efficient low magnetic field (<100 G) helicon sources and creation of potential structures at high magnetic fields (>100 G) are the topics of study in this thesis.

Helicon wave frequency lies in the frequency range $\omega_{ci} \ll \omega \ll \omega_{ce} \ll \omega_{pe}$ where $\omega_{ci}$, $\omega$, $\omega_{ce}$ and $\omega_{pe}$ are the ion cyclotron, RF source, electron cyclotron, and plasma frequencies respectively. Most of the helicon source including the one presented in this thesis use 13.56 MHz RF source. This correspond electron cyclotron frequency for axial magnetic field of 5 G. Helicon sources normally operate with magnetic fields in the range of 200 G to 1000 G. This makes electron cyclotron frequency is at least 15 times than applied RF frequency. This we will call as normal magnetic field operation. However, when the magnetic goes down near to the value where cyclotron frequency is few times the applied RF frequency we will call it low magnetic field (“low-B”) operation.

Appearance of helicon mode is generally identified by mode transitions which involves a transition from a capacitive to inductive to wave sustained discharge. The step like transitions can be observed in measured plasma density and antenna-plasma resistance, obtained by either
increasing power at fixed magnetic field (B) of few hundred Gauss or vice versa. At high magnetic fields, it is observed that the density increases with applied magnetic field when the discharge is in helicon mode as per the dispersion relation. However, previous studies have shown that at low magnetic fields of less than 100 Gauss, plasma density peaks at some specific magnetic fields, generally between 20 Gauss to 50 Gauss in different experiments using 13.56 MHz RF system [37-44]. Unlike usual helicon discharge mode transitions at high magnetic fields (few hundred Gauss), the observation of density peaks at low magnetic fields seems to be a resonance phenomenon.

Chen [39] first reported this low magnetic peak in 2 cm diameter helicon discharge using 1600 W RF power where the density peak was observed at ~ 50 G with peak density of $6 \times 10^{18}$ m$^{-3}$ an increase of nearly 40% from the no field case. Degeling et al [38] have observed density peak around 50G for RF powers in 500-2000 W in a 18 cm diameter source using single loop antenna at 13.56 MHz. Wang et al [41] have shown that the a higher magnetic field is required for the density peak to occur for a plasma formed using higher ion mass or a higher source frequency. Recently Lafleur et al [37] have done extensive experiments in a diverging magnetic field helicon experiment and have shown that the density can increase by an order from the no field case.

Few explanations are available for the observed density peak at low magnetic fields. Some of them are TG-helicon coupling [45, 47] at low magnetic fields, non-linear wave particle trapping [37-38] and wall reflection [46].

More recently, helicon waves have been considered for space plasma propulsion. They have been considered either as an ionizing source with a secondary stage for acceleration or as a stand-alone propulsion device. Concept such as VASIMIR [20] utilizes helicon as an ionizing source and worry about magnetic field detachment separately. Similarly, annular geometry helicon plasma is being investigated as a primary stage for space propulsion [21] and will have to address detachment and/or acceleration mechanism following the source. Another proposed method to circumvent the problem of detachment is utilizing double layer formation in helicon plasma [22]. The claim for this acceleration mechanism is that a sharp potential drop occurs downstream at lower pressure (<1 mTorr) in helicon plasma which can accelerate ions to supersonic speeds.
Double layer is a localized structure of layers of positive and negative space charges giving rise to a localized electric field much higher than the electric field outside double layer and is formed in the bulk of the plasma away from the boundaries unlike the sheaths which form near the boundary. In general, various groups of trapped electron/ion and passing electron/ion are postulated to maintain DL structure. All groups combinedly decide the net current across DL. A non zero net current corresponds to current driven DL (CDDL) whereas zero net current corresponds to CFDL. A large number of experiments on DL have been carried out in different devices such as, discharge tube, double and triple plasma devices, Q-machines and expanding plasma devices. [48-50]. Following Perkins and Sun’s prediction of CFDL in 1981 [51] experimental observations were reported on CFDL by Chan 1981 [52] and Hatakeyama 1983 [53] in a triple plasma device. Subsequently, two new classes of CFDL were reported; one by Hairapetian and Stenzel [54] and the other by Charles and Boswell [55] in expanding plasmas produced by helicon antenna. Hairapetian and Stenzel have explained the existence of CFDL based on two electron population. However, for expanding plasma in helicon devices four prominent models [56-59] have been proposed. These models while not complete have described experimental observation to some extent. All of these models include a thermal ion population in the upstream and a flowing ion population downstream as well as a thermal electron population upstream. They differ in their treatment of an additional electron population on the upstream side of the double layer. Model by Takahashi et al [59] proposes an electron distribution in the downstream as a depleted energetic electron tail to overcome the potential drop of the DL and neutralize the ion beam.

CFDL in a helicon plasma device is forced to be current free due to insulating source tube allowing no net current. Since the reporting of low pressure helicon CFDL in 2003 [55] a lot of work [60-69] has been focused on parametric study like effect of magnetic field, pressure, gas mass, geometry of experimental set up and antenna frequency. Ion beams created by acceleration due to the potential structure are a potential option for space propulsion. The rapid potential change near the expanding magnetic field with an associated acceleration of ions by the DL electric field is now being employed in the development of plasma thrusters. Meige et al [70] have done 1D simulation and found that finite wall charging is necessary for the CFDL formation and it may be noted that this can be a reason that no CFDL formation is reported so far without use of dielectric source tubes. So, it is important to understand the dependence of DL
strength on various plasma parameters as well as magnetic field geometry along with the role of wall charging on CFDL formation.

Charles and Boswell [71] studied the role of magnetic field on CFDL formation. By increasing the magnetic field they have observed ion beam formation in downstream plasma for a critical magnetic field of 50 G in the source. The source potential and density increased simultaneously at 50 G but in the downstream plasma the effect was little. Ion magnetization at 50 G is attributed to this transition from an expanding plasma to a plasma containing a CFDL. When the ion is magnetized the ion loss to the radial wall decreases and amounted to the density rise. Similar results were obtained by Takahashi et al [69] in EMPI source have shown that for two different dielectric source tubes of radii of 3.25 cm and 2.3 cm, the CFDL is formed for 125 G and 195 G respectively the values of these magnetic fields also are the magnetic fields where the ions got magnetized.

Though the observations of the CFDL were reported by many authors, the location and strength of the CFDL dependency on magnetic field gradient and magnetic field topology is not clear. The role of magnetic field gradient and its location was studied by Sutherland et al [67], Byhring et al [63] and Schroder et al [64]. Sutherland et al. [67] showed that the CFDL strength could be scaled by a factor of at least 2 in a bigger system and that the double layer presumably forms in the vicinity of maximal gradient of the magnetic field. Byhring et al [63] changed the magnetic field gradient by using an extra coil in which the current is passed in the same direction as the other coils. So by increasing the current in their last coil they could decrease the magnetic field gradient which location was much inside the source plasma. They have found that CFDL vanished for higher last coil currents which were confirmed by RFEA measurements. A study on independent effects of geometric expansion, magnetic field and field gradient along with its location are studied by Schroder et al [64] in VINETA device. For magnetic field gradient location coinciding with the geometric expansion they have found the CFDL strength is highest.

1.3 Motivation and objective

The primary objective of the work described here in the thesis is to develop a helicon plasma source in geometrically and magnetically diverging configuration. Design, fabricate and operation of each subsystems have been carried out during the thesis work. This thesis aims to
study characterizing discharge modes, investigating the mechanism responsible for low magnetic field density peak, studying double layer and its relation with the wall charging.

1.4 Description of chapters and main findings

The work described in this thesis has two main elements; (1) Development of experimental system and (2) Physics studies in the system. This thesis consists of seven chapters. The first chapter is an introduction to helicon research and also includes the motivation and objective of the thesis. The second chapter describes theory of helicon wave dispersion, wave mode structure, physics of discharge mode transitions and power coupling to plasma. In the third chapter experimental set up and its sub-systems along with various diagnostics used are discussed. After describing the previous studies, experimental set up and diagnostics in chapter 1, 2 and 3, the initial characterization of the RF plasma produced in the linear plasma device is described in Chapter four. Once the system is evacuated to $1 \times 10^{-6}$ mbar, Argon gas is fed into the system at $5 \times 10^{-3}$ mbar pressure through the end flange connected to the source chamber. After that RF power is slowly delivered to the antenna through the matching network. Gas breakdown is observed at few W ($< 10$ W) of RF power with almost no reflected power without magnetic field. We have obtained various plasma discharges in the pressure range of $1 \times 10^{-4}$ mbar to $1 \times 10^{-2}$ mbar by applying suitable magnetic field in the span of 0 to 280 Gauss and RF power in the range of few Watts to 1.5 kW. Thus the neutral pressure, magnetic field and RF power are the controlling parameters of our experiment. Mode transitions are studied by measuring density and load capacitance values (a measure of antenna-plasma coupling) for different pressures by varying the RF power. By increasing the pressure, Helicon operation regime is achieved for 112 Gauss magnetic field. The values of RF power at which the transitions occurred are lower for higher neutral pressures. Helicon m=+1 modes are characterized by measuring the radial and axial wave profile. The axial wavelength of the helicon waves are measured by measuring the axial phase variation using a single loop B-dot probe with respect to another reference B-dot probe phase fixed at a constant radial and axial location. Axial plasma potential is measured with a floating emissive probe at low pressure, 600 W RF power and 288 Gauss magnetic field. Plasma potential drops of ~$8T_e$ are observed over ~$1000 \lambda_D$ distance. These above mentioned preliminary results along with the details of the experimental set up and its capabilities are published in *Rev. Sci. Instrum. 83*, 063501 (2012).
Low field helicon experiments in a diverging magnetic field configuration are discussed in chapter five. Experiments are carried out using argon gas with $m = +1$ right helical antenna operating at 13.56 MHz by varying the magnetic field from 0 Gauss to 100 Gauss (G). The plasma density 18 cm away from antenna centre varies with varying the magnetic field at constant input power and gas pressure and reaches to its peak value at a magnetic field value of ~25 G. Another peak of smaller magnitude in density has been observed near 50 G. Measurement of amplitude and phase of the axial component of the wave using magnetic probes for two magnetic field values corresponding to the observed density peaks indicated the existence of radial modes. Measured parallel wave number together with the estimated perpendicular wave number suggests oblique mode propagation of helicon waves along the resonance cone boundary for these magnetic field values. Further, the observations of larger floating potential fluctuations measured with Langmuir probes at those magnetic fields values, indicate that near resonance cone boundary, these electrostatic fluctuations are proposed to take energy from helicon wave and dump power to the plasma causing density peaks. The results are published in *Physics of Plasmas* 20, 042119 (2013). Asymmetry in density peaks on either side of an $m = +1$ half helical antenna is observed both in terms of peak position and its magnitude with respect to magnetic field variation. However, the density peaks occurred at different critical magnetic fields on both sides of antenna. Depending upon the direction of the magnetic field, in the $m = +1$ propagation side, the main density peak has been observed around 27 Gauss (G) of magnetic field. On this side the density peaks around 5 G, corresponding to electron cyclotron resonance (ECR) is not very pronounced whereas on the $m = -1$ propagation side, very pronounced ECR peak has been observed around 5 G. Another prominent density peak around 13 G has also been observed on $m = -1$ side. However, no peak has been observed around 27 G on the $m = -1$ side. The density peak data is also supported by the light intensity measurements on both sides of the antenna. Reversing the magnetic field direction symmetrically reverses all the density peak observations. Observation of ECR peak around 5 G on $m = -1$ side is explained on the basis of the polarization reversal effect of circularly polarized waves in a bounded plasma while the other peaks on either side are explained with the help of cyclotron resonance for obliquely propagating helicon waves. The measured antenna-plasma resistance, a measure of power coupled to the plasma by the antenna, can only be explained if density variations on both sides of the antenna are taken into account. The results are published in *Physics of Plasmas* 20, 012123 (2013). Experiments were
further performed by changing the divergence of the magnetic field near the helicon antenna. By increasing the divergence it is observed that the antenna plasma coupling increases. A helicon antenna generally has a k-spectrum but when the antenna is in a uniform magnetic field, the resonance cone propagation is achieved only for a single mode at a certain magnetic field. With a diverging magnetic field, many modes can have resonance cone propagation at a single magnetic field value at the antenna centre. The efficient coupling is explained on the basis of multiple mode absorption near antenna through resonance cone absorption for different magnetic fields available near the antenna. This conjecture is further strengthened by the observed higher values of density maintained for more values of magnetic field of 20 – 60 Gauss i.e. widening of the density peak as the divergence is increased. The manuscript based on these results is ready for submission. The resonance cone absorption is further studied at the downstream of the plasma where the magnetic field reduces to ~10 Gauss from ~100 Gauss at the source. Phase measurements show that helicon waves are stationary near the antenna and propagate only in the diffusion chamber. Density peaks are observed in the downstream where the resonance cone propagation angles are near the wave propagation angles. These results are reproduced for different power and pressure values. Normal ECR absorption at location where magnetic field ~5 Gauss, is observed in the downstream by varying the magnetic field configuration using an extra coil and supplying negative current to it w. r. t to other coils. The manuscript based on these results is ready to be submitted for publication.

Chapter six discusses the study of current free double layer near the geometrical expansion region of the plasma and the relation of this potential structure to charging of the dielectric wall and magnetic field gradient. Experiments are carried out to study the role of magnetic field gradient near the geometrical expansion location. The experiments are done at 100 W RF power and 2×10^{-4} mbar with different magnetic field gradients near the geometrical expansion of the chamber. It is observed that the increasing the magnetic field gradient, the CFDL structure evolved from a single weak CFDL to a multiple structure which consists of a strong CFDL and a weak CFDL. The plasma potential in the source dielectric chamber is with respect to the floating glass wall. The wall charges to a higher negative potential and lifts the plasma potential in the source chamber to higher positive values at low pressures. So the parametric dependence of dielectric wall charging caused by RF potential fluctuation induced into the plasma through the capacitance of the glass tube is studied near the antenna for different
RF power, neutral pressure, magnetic field and gas mass. Conclusions and future scopes are presented in the last chapter.
References


