CHAPTER 2

Experimental setup and diagnostics

2.1 Introduction

The experimental works have been performed in a novel device named as the double plasma device. The double plasma device was first introduced by Taylor, Ikezi and MacKenzie in 1969 [151-153]. The device consisted of two independent plasma sources (namely driver and target chamber) separated by a conducting fine mesh grid of 80 – 90% transparency. The grid floats at some negative potential (~ − 20 V) and thus prevents the cross flow of the plasma electrons between the two chambers. This special arrangement of the device made it possible to create large cross section plane ion beam and waves, and large amplitude shock waves in a zero magnetic field by simply varying the potential of the plasma in the driver with respect to the target chamber. The original device dimension was 30 cm in diameter and 60 cm in length, where the collisionless uniform plasma was produced at a working pressure of $2 \times 10^{-4}$ Torr. At this pressure range the mean free path of any collision including charge exchange are larger than the dimension of the device and therefore collisionless plasma is obtainable. The measured plasma parameters at this working pressure were typically plasma
density $10^8 - 10^9$ cm$^{-3}$, ion temperature was in the range of 0.1 – 0.2 eV and electron temperature was controllable between 0.5 to 5 eV. Numerous experiments on plasma waves and instabilities such as ion acoustic waves, ion acoustic solitary waves, double layers, sheath and sheath induced instabilities, ion-beam interactions etc. have been carried out in the double plasma device [17,19]. The double plasma device is very advantageous for the study of ion acoustic waves because of its efficiency in wave excitation, ability of producing ion beams and lower damping effect on the propagating wave. The electron to ion ratio inside a double plasma chamber is very high due to which the effect of Landau damping on the propagation of ion acoustic wave is very small.

2.2 The multidipole double plasma device

The present experiments have been carried out in a double plasma device, made up of nonmagnetic stainless steel (SS304), 120 cm in length and 30 cm in diameter. The device photograph along with the other instruments used in the experiments are shown in fig. 2.1 (a) and (b). The device have nine ports of diameter 10 cm placed at equal distances and uniformly all over the body, two out of which are used as viewing window, others are used for gas inlet and pressure gauze. There are two removable flanges at each end of the device, one consists of a smaller window of 5 cm in diameter and another one consists of three Wilson sealed ports through which probes are inserted into the chamber. The device is placed horizontally on a supporting iron frame. The vacuum system is connected to the device by an extra port near one end of the removable flange. The schematic of the experimental setup is shown in fig. 2.2.
Chapter 2: Experimental setup and diagnostics

a) The vacuum unit

The vacuum unit consists of one rotary pump (Model: FD 20, Hind High Vacuum, Bangalore, India) and one turbomolecular pump (Model: HiPace 700, Pfeiffer vacuum). The two phase rotary pump FD 20 has pumping speed 333 L/min and it pumped down the chamber to $\sim 2 \times 10^{-3}$ Torr. After reaching this vacuum, turbomolecular pump is turned on and the chamber is pumped down to $\sim 10^{-7}$ Torr. The turbomolecular pump is capable of creating the high vacuum in lesser time because of its high pumping speed. In a turbomolecular pump a rapidly spinning fan rotor hits the gas molecules from the inlet of the pump towards the exhaust. The speed of the rotor fan in the turbomolecular pump used in the experiment is 50,000 rpm. The pressure is read by a penning gauge (Model: Pfeiffer Vacuum cold cathode gauge TYP TKR 251). For the present experimental device it takes nearly 5 hours to create a vacuum $\sim 10^{-7}$ Torr.
Figure 2.1 a): Photograph of the experimental setup along with the motor driver and excitation unit. b) The discharge unit and the Ar gas cylinder.

b) The magnetic cages

The double plasma device contains two magnetic cages namely source and target section. Each of the magnetic cage contains 20 axial (38 cm L × 1.8 cm B × 0.9 cm W) and 5 radial rectangular stainless steel tubes filled with small permanent magnets. These tubes are vacuum sealed. The schematic of the magnetic cages are shown on fig. 2.3 (a) and in fig. 2.3 (b) the cusp shape magnetic field for surface plasma confinement is shown. Both sides of the magnetic cages are fitted with two circular ring of stainless steel. One end of each cage is kept open and the other end is covered by the magnetic bars. The two magnetic cages are insulated from each other as well as from the chamber by using the ceramic insulator. Both the magnetic cages are separated by an insulated fine stainless steel mesh grid. The permanent magnets inside the magnetic cages are arranged with alternate pole orientation to form a cusp magnetic field. The strength of the magnetic field at the surface of the bars is ~ 1 K Gauss.
There are many advantages of using a multidipole double plasma device having cusp magnetic confinement.

i) The longer path length: The effective path length of the primary electrons are longer due to the bouncing back and forth in the multipole system and hence the plasma production rate could be increase substantially.

ii) The reduction of loss surface area: The surface field setup by the permanent magnets prevents the direct flow of plasma particles to the walls. Instead escaping particles must either
diffuse through the magnetic field or to be lost over small cusp surface. The condition for reflection from a magnetic barrier is the variation of the magnetic field in one cyclotron orbit be small as the particle approaches the surface. This condition much more likely to be satisfied by the electrons than ions. The dimension of loss area can be $10^2 – 10^3$ times lesser than the entire wall surface.

iii) High percentage of ionization: High fractional ionization rate can be achieved by a dc discharge in a multidipole device by increasing the efficiency of primary electrons and reducing the loss rate. Thus in a multidipole device a high density, highly ionized uniform and quiescent plasma can be produced.

In multipole cusp configuration, the magnetic field at the central region is zero, however at the edge region there is first reduce of magnetic field which confines the plasma. The radius of curvature of the confining magnetic field is in the wall side and not in the plasma confining volume (central region of the chamber). It is therefore free from many unstable modes that normally arise in magnetic confinement device.

Figure 2.3: (a) End plate arrangement of magnetic cage. (b) Cusp shape magnetic confinement
c) **Plasma production by filamentary discharge**

The plasma is generated inside the two magnetic cages as independent sources. The cages are named as source and target chambers. Both the chambers are separated from each other by a fine stainless steel mesh grid (50 lines per inch) of 83% transparency. Each chamber contains 5 thoriated tungsten filaments of diameter 0.1 mm and length 5 cm placed symmetrically at 6 cm from the surface of the magnetic cage. After achieving the base pressure ($\sim 10^{-7}$ Torr), Argon is inserted into the chamber to raise the neutral pressure up to $\sim 10^{-4}$ Torr by using a double valve system consisting a stop valve and a needle valve for fine control. The filament power supply (Model: Elnova 0 – 30 V, 0 – 20 A) is then turned on and the filament voltage is gradually turned up till the filaments turned red glow. The filaments are hot enough to emit electrons and act as cathode. These primary electrons are accelerated by dc electric field such that they have sufficient energy to ionize the neutral gas. A minimum energy of 20 eV is required to remove the first valance electron from the neutral atom for the Ar gas at room temperature. A discharge voltage above this must be applied between the cathode (filaments) and anode (the magnetic cages) to obtain the discharge. The secondary electrons (removed valance electrons) are scattered with less energies than the corresponding incident primary electrons at any given time and thus most of the electrons in plasma are secondary electrons. The discharge voltages of the source and target chamber are set to the desired value and then filament voltages are carefully increased until the preferred discharge currents are obtained. Usually, the discharge voltages of the source and target sections are maintained at 40 – 70 V and discharge currents are varied from 0 – 500 mA to
perform our experiments in multidipole device by using a dc power supply (Model: Tektronix PWS 2721, 0 – 72 V, 1.5 A).

This arrangement makes the complete insulation between the chambers so that a relative potential could be applied to the two plasmas. For this purpose, a bipolar power supply (Model: POW 35 – 1 A, – 35 → + 35 V, Kikusui Electronics Corp.) is used. As the mesh grid floats at a negative potential typically ~ – 20 V, it prevents the cross flow of plasma electrons between the two chambers. However, the flow of the ionizing electrons are not necessarily prevented due to this potential. The ions flow between the two chambers through the grid and subject to small interception due to finite wire size. The plasma thus produced contains Ar⁺, electrons and neutrals.

2.3 Measurement of different plasma parameters

2.3.1 The Langmuir Probe

Irving Langmuir invented the electrostatic probe to measure different plasma parameters commonly known as Langmuir probe. Out of all the diagnostics, Langmuir probe measurement is perhaps the simplest and easiest way to measure the plasma parameters such as density, temperature, plasma potential and distribution function of charged particles inside the plasma. A Langmuir probe is a small metallic electrode with a well-defined geometry (planar, cylindrical or spherical). For the present work, a disc shape plane Langmuir probe of 6 mm diameter is used in the experiments. The plane Langmuir probe is constructed by using a stainless steel plate of 6 mm diameter which is spot welded at one end of a Teflon coated silver wire. The back side of the probe connected to the wire is covered with ceramic
Chapter 2: Experimental setup and diagnostics

Figure 2.4: The schematic of the Langmuir probe. A stainless steel disc of 6 mm diameter is used to construct the probe tip.

...paste to make the probe one sided. The connecting wire then passes through a stainless steel pipe (6 mm in diameter) acting as shaft. The front part of the wire is supported with a stainless steel rod (1 mm diameter) in order to bend the probe and then to fix it at desired position (center of the chamber). This part of the probe shaft exposed to the plasma is covered with Teflon tape. The schematic of the plane Langmuir probe is shown in fig. 2.4.

2.3.2 The current – voltage (I – V) characteristics curve

In order to obtain the I – V characteristics curve, first the surface of the probe is cleaned by the bombardment of ions by applying a negative voltage from a dc power supply ~ 75 – 150 V for about an hour. We have used two methods to draw the I – V characteristic curve, first one is the X – Y recorder (Model: YOKOGAWA 3036) and secondly the Automated Langmuir Probe (Model: Impedans ALP 150) system. Both the method gives similar results. In order to draw the I – V curve, a voltage ranging from – 50 V to + 50 V is swept to the probe which manually form a voltage divider unit and the probe current is obtained from the voltage drop across a resistor (~ 100 Ω), which are then fed into the X and Y axis of the X – Y recorder. In ALP, voltage sweeps in few microseconds in the range of – 150 V to + 150
Chapter 2: Experimental setup and diagnostics

V and corresponding current voltage data are stored in the computer. Digitized data are useful for analysis because of its high resolution. A typical Langmuir probe I – V characteristics curve taken by using the ALP system is shown in fig. 2.5. The probe collects the current against the biasing voltage which gives a picture about the plasma conditions. We can consider the plasma space potential as $V_s$ and the probe potential as $V_P$. When $V_P = V_s$, the charged particle feel no external field and eventually the probe collects electron current $I_e$ due to the electron thermal motion which is much faster than the ions. With further increase of $V_P$ above $V_s$ (region a), the electron current reaches a saturation level and the ions are repelled by the probe. For the negative bias voltage i.e. When $V_P < V_s$ (region b), an increasing fraction of the electron current is repelled and the probe collects ion current. In this region, electron current decreases exponentially with the decrease in probe voltage indicating the Maxwellian distribution for electrons. The total current received by the probe becomes zero ($I = I_i + I_e$) at probe potential $V_P = V_f$, known as floating potential. When $V_P << V_s$, the probe collects only ion current at almost constant rate providing the ion saturation current (region c).
Chapter 2: Experimental setup and diagnostics

Figure 2.5: A typical I – V characteristic taken by the plane Langmuir probe of diameter 6 mm. Ar neutral pressure is $3.8 \times 10^{-4}$ Torr. Discharge voltage $V_{ds} = V_{dt} = 60$ V and discharge current $I_{ds} = 40$ mA and $I_{dt} = 30$ mA. Floating potential $V_f = -10$ V and plasma space potential $V_s = 2$ V.

2.3.3 Electron temperature measurement from I – V curve

The total current received by the probe is given by the sum of electron and ion current,

$$ I = A \sum_{\alpha} n_\alpha q_\alpha v_\alpha. $$

(2.1)
The subscript $\alpha$ represents ‘i’ and ‘e’ for ions and electrons respectively. $A$ is the total collecting surface area of the probe, $n_\alpha$, $q_\alpha$ and $v_\alpha$ are the density, charge and average velocity of the species $\alpha$.

In the region of the probe characteristics where $V(=V_p-V_s)<0$ (region b and c), the total probe current is given by

$$I = I_{is} + I_e.$$  \hspace{1cm} (2.2)

As the electrons are Maxwellian, the total electron current $I_e$ can be expressed by using the Boltzmann distribution law as given below

$$I_e = -neAv_e \exp(eV/K_BT_e).$$ \hspace{1cm} (2.3)

Where, $v_e$ is the average thermal velocity of electron, $T_e$ is the electron temperature and $K_B$ is the Boltzmann constant. Also as the plasma is quasineutral, we consider $n_e \sim n_i = n$ and $q_e = -e$ for electrons. Therefore, eq. 2.2 becomes,

$$I = I_{is} - neAv_e \exp(eV/K_BT_e)$$

Or,

$$I = I_{is} + I_{es}\exp(eV/K_BT_e)$$ \hspace{1cm} (2.4)

where $I_{is}$ and $I_{es}$ represents the ion and electron saturation current respectively.

For very small ion current $I_{is} \ll I$, eq. 2.4 becomes

$$I = I_{es}\exp(eV/K_BT_e)$$  \hspace{1cm} (2.5)

Or,

$$\ln I = \ln(I_{es}) + \frac{eV}{K_BT_e}$$ \hspace{1cm} (2.6)

$$\frac{d\ln I}{dV} = \frac{e}{K_BT_e}$$ \hspace{1cm} (2.7)
Figure 2.6: Semi logarithmic plot of Langmuir probe I – V characteristic (fig. 2.5) showing the evaluation of different parameters required for the calculation of electron temperature and density. The electron saturation current ($I_{es}$) is 0.46 mA and the effective electron temperature is 0.9 eV.

which shows that the inverse of the slope of the line $ln I$ vs $V$ gives the electron temperature. The Langmuir probe I – V characteristic curve (fig. 2.5) is plotted in a semi logarithmic scale for better visualization of the exponential part to measure the electron temperature. The semi logarithmic plot is shown in fig. 2.6. The electron saturation current $I_{es}$ and the plasma
potential are determined from the intersection of two straight lines. The temperature $T_h$ of the high component is calculated from the straight line (h) and its saturation current $I_h$ is obtained from the intersection point of the line (h) with the vertical line at the plasma potential. The low temperature component $T_l$ is marked as line (l) in fig. 2.6 is obtained by subtraction of the extrapolation of line (h) from the curve (red line). Therefore, the effective electron temperature ($T_{eff}$) is calculated from the following expression,

$$\frac{I_{es}}{T_{eff}} = \frac{I_h}{T_h} + \frac{I_l}{T_h}. \tag{2.8}$$

The effective electron temperature obtained from the Langmuir probe $I - V$ characteristic curve is $T_{eff} = 0.9$ eV.

2.3.4 Electron density measurement from $I - V$ curve

For a planar one sided Langmuir probe, the electron saturation current is given by

$$I_{es} = -\frac{1}{4} (n_e e A v_e). \tag{2.9}$$

Where $v_e = (8k_B T_e/\pi m_e)^{1/2}$ is the thermal speed of electron, A is the area of the planar Langmuir probe that is exposed to plasma. Once $T_e$ is calculated and $I_{es}$ is obtained from the graph, electron density $n_e$ can be calculated from eq. 2.9. In the semi logarithmic $I - V$ plot (fig. 2.6), straight line fit to the electron reduction and saturation currents are drawn. The intersection point of the two straight lines (fig. 2.6) provides the plasma potential and the electron saturation current values. The measured value of plasma density for $T_e \sim 0.9$ eV is $6.4 \times 10^8$ cm$^{-3}$.
2.3.5 Floating potential

On the I – V characteristic curve, the floating potential represents the point where the net probe current is zero. It means that when the probe biasing voltage \( V = V_p - V_s \) equals with the floating potential of the plasma, the ion and electron currents are equal and the net probe current is zero. The floating potential can be expressed as,

\[
V_f = -(kT_e/e) \ln (m_i/4\pi m_e)^{1/2}.
\]

Where, \( m_i \) is the mass of ions. In the experimental I – V, the \( V_f \) is marked and its value is –10 V.

We measure different plasma parameters analyzing the I – V characteristic curve. Typical values obtained from I – V curve shown in fig. 2.5 are listed below.

<table>
<thead>
<tr>
<th>Plasma Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron temperature ( T_e )</td>
<td>1.2 eV</td>
</tr>
<tr>
<td>Electron density ( n_e )</td>
<td>( 6.4 \times 10^8 ) cm(^{-3} )</td>
</tr>
<tr>
<td>Electron plasma frequency ( f_{pe} = \omega_{pe}/2\pi )</td>
<td>227 MHz</td>
</tr>
<tr>
<td>Ion plasma frequency ( f_{pi} = \omega_{pi}/2\pi )</td>
<td>837 kHz</td>
</tr>
<tr>
<td>Debye length ( \lambda_D )</td>
<td>0.027 cm</td>
</tr>
<tr>
<td>Ion acoustic speed ( c_s )</td>
<td>( 1.46 \times 10^5 ) cm/s</td>
</tr>
</tbody>
</table>

Table I: List of different plasma parameters.

2.4 Production of multicomponent plasma with negative ions

In plasmas, negatives ions are omnipresent in the D-layer of lower ionosphere and in a small current regime of DC discharge of halogens and oxygen. In a laboratory, artificial production of negative ion plasma has been made by cesium chloride (CsCl), sulfur hexafluoride (SF\(_6\)), iodine (I\(_2\)) and oxygen (O\(_2\)). It is important to study the plasma phenomena in presence of
negative ions. The addition of negative ions in plasmas have many applications such as in semiconductor manufacturing. In fusion reactors negative ion sources are investigated for neutral ion beam injections. The ion acoustic wave behavior changes with the addition of negative ions. Negative ions play an important role in the charging of dust grains in a dusty plasma. Addition of electronegative gas in plasmas produces negative ions with different processes such as electron attachment, dissociative attachment, charge transfer and clustering reaction.

The production of multicomponent plasma with negative ions has been studied by a number of researchers. In a Q-machine plasma, D'Angelo et al produced a plasma containing Cs\(^+\), Cl\(^-\) and electrons by directing a beam of CsCl onto a hot tungsten plate [58]. Wong et al produced negative ion plasma by inserting SF\(_6\) gas into Argon discharge [52]. The electron attachment process mainly produces plasma with SF\(_6^-\) ions as a third primary species. Goeler et al bombarded hot tungsten plates with CsCl creating a plasma composed of Cs\(^+\), Cl\(^-\) and electrons in a Q-machine [50]. Douchet produced negative ion plasma by introducing a high concentration of I\(_2\) into a standard gas discharge where I\(_2\) is dissociatively ionized to I\(^-\). Sheehan et al described two classes of negative ion plasma sources in a Q-machine [51]. The effective method was the insertion of metal hexafluoride such as SF\(_6\) in a Q-machine metal-electron plasma (Ba or Cs). Since SF\(_6\) has a large electron capture cross-section for low energy electrons (0.2 eV), this method is particularly effective in production of negative ion plasma even at partial pressure of SF\(_6\) is below 1 × 10\(^{-5}\) Torr. Song et al used this method to produce negative ion plasma composed of K\(^+\), SF\(_6^-\) and electrons in a Q-machine [153]. In a Q-machine using this method, at the
Chapter 2: Experimental setup and diagnostics

environment of low temperature (0.2 eV) potassium plasma, Sato introduced a small amount of SF₆ and produced negative ion (SF₆⁻) plasma.

2.4.1 Multicomponent plasma with F⁻ negative ions using SF₆ gas

The multicomponent plasma in the present experiment, is produced by introducing sulphur hexafluoride (SF₆) gas into the argon plasma through a double valve system consisting a fine control needle valve. The partial pressure of SF₆ is maintained at $\sim 1 - 5 \times 10^{-5}$ Torr. The SF₆ molecules are bombarded by 50 – 70 eV primary electrons mainly forms F⁻ ions due to dissociative attachment process [154],

$$\text{SF}_6 + e \rightarrow \text{SF}_5^- + F^-$$

in which negative fluorine ion is produced by dissociation of a SF₆ molecule in electron molecule collision.

In resonance capture

$$e + \text{SF}_6 \rightarrow \text{SF}_5^- + F^- \leftrightarrow \text{SF}_6^-,$$

electron is attached to the SF₆ molecule to form a vibrationally excited ($\text{SF}_5^-)^*$ ion. This ion has a very short life time and is less than few tens of microsecond, it may follow any of the following three processes.

i) auto detaches, returning to a neutral molecule and free electron,

ii) collides with a neutral SF₆ molecule and is stabilized according to

$$ (\text{SF}_5^-)^* + \text{SF}_6 \rightarrow \text{SF}_6^- + \text{SF}_6^*$$

iii) dissociates into stable SF₅⁻ ion and fluorine atom.
Chapter 2: Experimental setup and diagnostics

Negative ions such as SF$_5^-$ and SF$_6^-$ are also formed by the capture of low energy plasma electrons. For electron temperature 2 eV, the production rate of SF$_5^-$ is much higher than SF$_6^-$ ions [67]. In addition to this, the ionization of SF$_6$ molecules by primary electrons leads to the formation of positive ions such as SF$_5^+$, SF$_4^+$, SF$_6^+$ etc. Hence the plasma consists of several species of positive and negative ions. In case of propagation of ion acoustic waves in multicomponent plasma with negative ions, the dominant contribution is from the lighter ion species i.e. from F$^-$ ions [67,155]. Therefore, the contribution from the heavier species in the propagation of ion acoustic waves can be neglected and the multicomponent plasma is considered to be composed of Ar$^+$, F$^-$ and electrons.

2.4.2 Negative ion density control and measurement

To perform the experiments with negative ions, the SF$_6$ gas is inserted in the argon plasma environment with a double valve system. With the help of a needle valve the SF$_6$ gas is controlled from outside. The density profile for negative ions are measured with the already existing planar Langmuir probe inside the plasma. Introduction of negative ion into the Ar plasma indicates reduction in electron saturation current in the I – V curve. In context of measurement of negative ion concentration by Langmuir probe, a number of research work have been performed [156–158]. *Shindo et al* investigated the negative ion density using a Langmuir probe considering the change in the electron as well as ion saturation current [157]. They showed that the sheath structure in front of the probe has modified with presence of negative ions results in the reduction of the ion saturation current. The propagation characteristic of the ion acoustic waves in multicomponent plasma with negative ions is also considered as a diagnostic tool for the determination of negative ion concentration.
as the phase velocity of the ion acoustic wave depends on the ratio of negative to positive ion density \[65,159-161\].

The negative to positive ion density ratio in a multicomponent plasma with negative ions are defined as the concentration of negative ions \(r = n_/-n_+\) where \(n_-\) and \(n_+\) are the unperturbed densities of negative and positive ion respectively. This is experimentally determined by using the method proposed by \textit{Shindo et al.} \[162\]. The \(r\) is given by the relation

\[
r = 1 - \frac{I_{es}(SF_6)}{I_{es}(Ar)} \frac{I_{is}(Ar)}{I_{is}(SF_6)} \sqrt{\frac{m_i(Ar)}{m_i(SF_6)}} \Omega(SF_6). \tag{2.7}
\]

In order to measure the experimental effective negative ion density ratio \(r (= n_-/n_+)\), so that the mass ratio \(\mu = 0.476\), first a current voltage (I – V) characteristics of the Langmuir probe is taken. The typical I – V characteristic taken by ALP system at different pressure of SF\(_6\) is shown in fig. 2.7. The charge neutrality condition in plasma is modified in presence of negative ions.

In Ar plasma, the charge neutrality condition is

\[
n_+ \cong n_{eo}, \tag{2.8}
\]

where \(n_{eo}\) is the unperturbed density of electrons. In Ar + SF\(_6\) plasma the charge neutrality condition is modified as,
Figure 2.7: The typical I – V characteristics taken at different pressure of Ar and SF₆ by the plane Langmuir probe.

\[ n_+ \approx n_{eSF_6} + n_- . \] (2.9)

Here, \( n_{eSF_6} \) is the electron density in presence of negative ions. Then the negative ion density ratio \( r = n_- / n_+ \) is mathematically calculated by dividing eq. 2.9 by \( n_+ \). Equation 2.9 becomes,

\[ 1 \approx \frac{n_{e(SF_6)}}{n_+} + \frac{n_-}{n_+} . \]

or,

\[ 1 \approx \frac{n_{e(SF_6)}}{n_{e0}} + r. \]

Substituting \( n_{e0} \propto I_{es(0)} \) and \( n_{eSF_6} \propto I_{es(SF_6)} \), the above equation is written as,
1 \simeq \frac{I_{es(SF_6)}}{I_{es(0)}} + r.

Thus negative to positive ion density ratio can be calculated by measuring the reduction in the electron saturation current by the above equation as,

\[ r = 1 - \frac{I_{es(SF_6)}}{I_{es(0)}}. \]  

(2.10)

In this assumption we assume no perturbation in the ion saturation current and that the ratio of the total positive contaminating ions such as SF$_5^+$ to total positive Ar$^+$ is negligible.

2.4.3 Dispersion relation of ion acoustic wave

In order to observe the propagation characteristic of ion acoustic wave, first experimentally excite the linear ion acoustic wave and measure the linear dispersion relation. The experimental measurement of dispersion relation is performed by using the interferometer method. The peak to peak amplitude is kept as low as 200 mV to excite the linear waves. The block diagram of the experimental arrangement is shown in fig. 2.8. From a function generator (Model: Tektronix AFG 3021B) continuous sinusoidal signal of frequencies from $f = 100$ to $700$ kHz ($\omega = 2\pi f$) are used to excite linear waves in plasma. The excited wave propagating through the plasma are collected by the Langmuir probe. The signals collected by the probe are amplified by a low noise differential preamplifier (Model: KROHNHITE 7000, 1 Hz – 1 MHz) and then attenuated and mixed with the input signal. The probe is slowly moved with the help of a motor driver and the voltage, which is proportional to the distance of the motor driving system of the movable probe, is applied to the X axis of the recorder. The interferometer output from the mixer is fed to the Y axis of the X–Y recorder. The raw data of interferometer phase plot of ion acoustic wave is shown in fig. 2.9. In Ar
plasma, the experimentally obtained dispersion relation i.e. the plot of angular frequency \( \omega \) (normalized to the ion plasma frequency \( \omega_{pi} = 2\pi \times 700 \text{ kHz} \)) vs wavenumber \( k \) (normalized to inverse of Debye length \( 1/\lambda_D, \lambda_D = 0.04 \text{ cm} \)) is shown in fig. 2.10. To calibrate the experimental dispersion relation in presence of negative ions, a theoretical relation is calculated for different negative ion concentration \( r \) from the following relation

![Figure 2.8: Block diagram of the experimental arrangement to obtain the dispersion relation by interferometry.](image-url)
Figure 2.9: Typical interferometer output for applied frequencies 100 to 700 kHz. Excitation amplitude 200 mV. Ar pressure \(3.8 \times 10^{-4}\) Torr.

\[
(1 - s - r)(1 + 1/k^2) + s/Uk^2 = 1/(\Omega^2 - 3k^2T) + r/(\mu\omega\Omega^2 - 3kT).
\]  

Here \(k = k\lambda_D\) and \(\Omega = \omega/\omega_{pi}\). \(\omega\) and \(k\) represents the angular frequency and wavenumber respectively. Also \(s = n_{h0}/n_+\), \(n_{h0}\) is the unperturbed density of electrons of high temperature \(T_e\). \(r = n_-/n_+\), \(n_-\) and \(n_+\) are the unperturbed density of negative ions and positive ions respectively, \(T = T_i/T_e\) is the ion to electron temperature ratio. This dispersion relation indicates that for \(k \gg 1\), the phase velocity \(\omega/k\) has two values. When \(s = 0\) and
\( \mu > 3T \), the mode is called a fast mode and becomes the ion-acoustic wave of the positive ions. The slower mode is a virtual mode with \( \omega/k = (3 K T_i/M_i)^{1/2} \). The theoretically obtained dispersion relation with variation of negative ion density ratio \( (r = 0 - 0.4) \) is shown in fig. 2.11. The experimentally obtained dispersion relation for different SF\(_6\) pressures i.e. at different values of \( r \) \((0 - 0.3)\) is shown in fig. 2.12. When \( k\lambda_D \ll 1 \), the dispersion curve is linear and wave phase velocity \( \omega/k \) is obtained from this region. For \( k\lambda_D > 1 \), the dispersive nature is prominent and the phase velocity reduces with increasing wavenumber.

The continuous sinusoidal signal of frequencies from 100 – 700 kHz \((100 \text{ kHz in step})\) is used to excite the waves in plasma. From the theoretical curve which coincide best with the experimental one at same temperature ratio gives the value of \( r \).

![Figure 2.10: Experimentally obtained dispersion relation for Ar plasma. Ar pressure 3.8 × 10^{-4} \text{ Torr.}](image)
Chapter 2: Experimental setup and diagnostics

Figure 2.11: Theoretical plot of dispersion relation obtained from eq. 2.11 varying the negative ion density ratios from $r = 0$ – 0.4 keeping the temperature ratio ($T_i/T_e$) fixed at 0.05.

Figure 2.12: Experimental plot of the dispersion relation for different negative ion densities $r = 0$ – 0.3.
Figure 2.13: Comparison of experimentally obtained dispersion relation to the theory at $r = 0.2$.

In fig. 2.13, comparison between the experimental and theoretical graph is presented. The theoretical graph is calculated from eq. 2.11. The experimental measurement of $\omega/\omega_{pl}$ vs $k\lambda_D$ is in good agreement with the theoretical solid line. The calculations are done considering $r = 0.2$, ion plasma frequency $\omega_{pl} = 2\pi \times 750$ kHz and Debye length $\lambda_D = 0.04$ cm. From the comparison of theory and experimental graph, the exact density ratio can be measured. Also at different Ar + SF$_6$ partial pressures, the phase velocity of the ion acoustic waves can be measured from the dispersion curves.

2.5 **Excitation of ion acoustic waves in double plasma device**

In a double plasma device, different methods of excitation of ion acoustic waves are used. For ion acoustic wave excitation, normally a localized density perturbation is created by
applying a short positive voltage pulse to an exciter. The duration of the pulse is chosen below the ion plasma period ($\omega_{pi}^{-1}$) and applied voltage is in the range of $e\phi/K_B T_e \geq 1$.

2.5.1 Excitation from a solid metal surface

In this method a solid metal plate is immersed in plasma and then a very large voltage pulse is applied to the plate to excite the ion acoustic waves [163,164]. One can use the metal object as wave exciter of different shapes like a sphere, a long cylindrical rod or a large flat plate. Close to the metal object, a group of ions are pushed away by the applied voltage to the separation grid creating a compressions of ions in a small region and leaving behind a region of electron rarefaction. Thus an initial applied perturbation can propagate as ion acoustic waves throughout the plasma. This method of wave excitation need a pulse or a sine wave of very high amplitude (~ 10 – 100 times the electron temperature) to excite a linear or nonlinear ion-acoustic waves [165–167].

2.5.2 Excitation from a mesh grid

In this method, inside a uniform plasma a voltage (pulse or sine) is applied as initial perturbation to a fine mesh grid to excite the ion acoustic waves [8,22,168,169]. The grid in which the voltage pulse applied may be the separation grid inside the DP device. The exited perturbation propagates through the plasma. In this method of wave excitation, it was observed that large density perturbation can be excited by applying voltage pulses of amplitude nearly 3 – 4 times the electron temperature [34,170,171]. However, in this method of grid excitation, a bunch of free ions identified as pseudowaves are also observed in front of the propagating wave [172]. These pseudowaves are generated by the reflection of ions from the wave potential can cause significant wave damping.
2.5.3 Anode excitation

The widely used method of wave excitation in a double plasma device is the anode excitation. In this technique, the plasma potential of the source is suddenly increased with respect to the target plasma by applying a positive voltage pulse to the anode of the source chamber. As a result, some of the plasma ions flow from the source to the target during the pulse period which in turn sets up a density perturbation in the target through the grid. Compared to the former two methods, this wave excitation method is very efficient as a wave of comparatively large amplitude ($\delta n/n$) can be achieved by applying a relatively small voltage signal to the source anode with minimum amplitude of pseudowave.

2.6 Excitation of ion acoustic solitons in plasma

To study the propagation of waves, particularly ion acoustic solitons in laboratory, an infinite homogeneous quiescent collisionless plasma whose parameters are controlled easily, must be produced. Within this large plasma, a uniform localized density perturbation of sufficient amplitude $\delta n(x,t)/n_0 \approx 0$ (10%) must be excited. This perturbation then evolve into a nonlinear wave which has the characteristic of a soliton and called as ion acoustic soliton. In order to create a large localized density perturbation in the target chamber of the DP device, the plasma potential of the source chamber is suddenly increased or decreased with respect to the target chamber by applying a tone burst signal to the anode of the source chamber. The tone burst (sinusoidal voltage pulse) signal of frequency 60 – 100 kHz and amplitude of a few volts is produced by using an arbitrary function generator (Model: Tektronix AFG 3021B) and applied to the anode (magnets) of the source section through a capacitor (1$\mu$F/400V) to increase the plasma potential. This result the flow of ions from the source to
Chapter 2: Experimental setup and diagnostics

the target section through the separation grid. The capacitor is used here to block the
discharge voltage from anode to the function generator. The possibility of a steady state beam
is eliminated by adjusting the dc bias between source and target plasma by using the bipolar
power supply. The fine mesh grid between the source and target plasma is kept floating at a
negative potential (about $-20$ V) and separates the two (source and target plasma) by
shielding the electrons.

2.6.1 Excitation of ion acoustic Korteweg-de Vries solitons

In the double plasma device, ion acoustic KdV solitons are excited and the perturbation are
received by the Langmuir probe biased above the plasma potential to obtain the perturbation
in electron saturation current and recorded in a digital oscilloscope. A sinusoidal voltage
pulse of duration $20 \mu s$ and excitation amplitude $2$ V is applied at the source anode as initial
perturbation. The soliton profile recorded at different probe distances ($x$) from the grid is
shown in fig. 2.14 (a). At $2$ cm the perturbation is almost like the excitation pulse. Form $4$
cm onwards, the steepening occurs. At $6$ cm, the ion acoustic soliton forms and number of
peaks appear behind the main soliton as the perturbation propagates further. However, at
probe position $12$ cm, the amplitude of the soliton decreases for the inherent Landau damping
in the system. The density perturbation recorded at $6$ cm from the floating grid due to the
applied pulse of $20 \mu s$ duration are shown in fig. 2.14 (b). The amplitude of the applied pulses
are increased from $1$ to $2.5$ V ($0.5$ V in step). For small initial amplitude ($1$ V) the wave
propagates with dispersion. As the excitation amplitude increases, the leading part of the
perturbation steepens due to nonlinearity and the solitons appears. The velocity of the solitons
increases with wave amplitude whereas the width of the solitons decreases with wave amplitude. The density perturbation of the soliton as measured is $\delta n/n \sim 0.06$ i.e. 6%.

In fig. 2.15 (a) and (b), the theoretical and measured Mach number $M$ and width of the KdV solitons are plotted as a function of normalized amplitude respectively. The Mach number (velocity of soliton divided by the ion acoustic speed $c_s$) of the solitons increases linearly with amplitude. The experimental results nearly agree with the prediction of KdV equation in small amplitude region ($\delta n/n < 0.08$), however at large amplitude region ($\delta n/n > 0.08$), the experimentally measured $M$ is greater than the theoretically obtained value (fig. 2.15 (a)). The ion acoustic speed calculated through time of flight technique and found to be $1.5 \times 10^5$ cm/s. The temporal full width of the soliton is measured at 50% of the soliton amplitude which is multiplied with the soliton speed to get the spatial width. The measured spatial width of the solitons decreases with amplitude ($\delta n/n = 0.02 – 0.1$), which is a universal characteristics of the solitons. The spatial width of the solitons are normalized to the electron Debye length $\lambda_D$. The theoretical graph is obtained from the solution of KdV equation (eq. 1.15) which is in agreement with the experimental results (fig. 2.15 (b)). These observation confirms the wave formation as solitons.
Figure 2.14: The KdV solitons. a) The top trace is the applied sinusoidal pulse of excitation amplitude 2 V. The perturbations are recorded at different probe distances from $x = 2$ cm to $x = 12$ cm. b) The perturbations are collected by the Langmuir probe at a distance 6 cm at different excitation amplitudes.
Figure 2.15: (a) Measured Mach number vs normalized amplitude of the compressive ion acoustic solitons and (b) measured width of the solitons normalized to $\lambda_D$ as a function of normalized amplitude. In both (a) and (b) the solid line represents the theoretical results calculated from the KdV equation (eq. 1.15).
2.6.2 Excitation of ion acoustic modified KdV solitons

In multicomponent plasma composed of Boltzmann electrons, Ar$^+$ positive ions and F$^-$ negative ions the ion acoustic solitons are excited by the usual anode excitation method. A sinusoidal positive/negative voltage pulse of duration $\sim 20 \mu s$ is applied to the anode of the source plasma. The perturbations are received in the target section by the Langmuir probe biased above the plasma potential and recorded in the oscilloscope. In fig. 2.16 a) and b), the modified KdV (mKdV) solitons are shown at different probe positions at a fixed excitation amplitude $\pm 4 \text{ V}$. The negative ion density ratio $r = 0.09$ for this experiment which is close to the theoretically calculated critical concentration value $r = 0.103$. 

![Graph showing modified KdV solitons at different probe positions](image)
Figure 2.16: Detected signals at different probe positions for a fixed excitation amplitude $V_{ex} = 4 \text{ V}$ and $-4 \text{ V}$ when $r = 0.09 \sim r_c$. (a) Compressive (b) Rarefactive mKdV solitons.

The mKdV soliton has the unique characteristics that the excitation is independent of the sign of initial perturbation (voltage, density etc.). This means that both compressive (positive) and rarefactive (negative) solitons are excited simultaneously depending on the sign of initial voltage. The temporal evolution profiles in fig. 2.16 (a) (for the $+$ ve initial voltage) and in fig. 2.16 (b) (for the $-$ ve initial voltage) confirms this unique characteristic of mKdV solitons.

In normal two component plasma (electron and ion), however only positive initial perturbation excites compressive KdV solitons.

In this same negative ion concentration i.e. $r = 0.09 \sim r_c$, the evolution of mKdV solitons are examined varying the excitation amplitude and are shown in fig. 2.17 (a) and (b). For $V_{ex} = 1 – 2\text{V}$, steepening is observed at the leading edge of the formation which appear more prominent with higher excitation voltages, creating the solitary peak. As the
Figure 2.17: The mKdV solitons at a fixed probe position 6 cm from the grid. The top trace is the applied sinusoidal pulse of duration ~ 20 µs. (a) positive applied pulse (b) negative applied pulse.
excitation amplitude is increasing, the amplitude and velocity of the solitons are increased and width of the solitons are decreased. In fig. 2.17 (b), the evolution of rarefactive solitons are shown for excitation amplitude $V_{ex} = -1$ to $-4$ V at a probe position 6 cm from the floating mesh grid. At critical density $r = r_c = 0.09 \sim 0.1$, the rarefactive solitons are evolved simultaneously with the compressive solitons. The amplitude of the solitons are measured and found that the rarefactive solitons are smaller than the compressive solitons for a fixed $V_{ex}$.
Chapter 2: Experimental setup and diagnostics

2.6.3 Excitation of envelope solitons in multicomponent plasma

In the double plasma device the envelope soliton is excited by applying an amplitude modulated sinusoidal wavepacket to the anode of the source plasma. For this purpose, two
function generators (Tektronix AFG 3021B and Tektronix AFG 3021C) are used to apply the amplitude modulated sinusoidal wavepacket of carrier and modulation frequencies lies between 300 – 400 kHz and 5 – 35 kHz respectively. The amplitude of the carrier signal is varied from 0.5 – 10 V for different types of soliton excitation. The perturbations are collected by the Langmuir probe biased above the plasma potential in the target section and then recorded in a digital storage oscilloscope (Model: Tektronix TDS 2001C). The block diagram of the excitation circuit is shown in fig. 2.19.

![Block Diagram of Excitation Circuit](image)

Figure 2.19: The block diagram for excitation of envelope like solitons. FG: Function Generator, LP: G: Grid, Langmuir Probe, DSO: Digital storage oscilloscope, C: Blocking capacitors.

### 2.7 Role of negative ions on the propagation of ion acoustic solitons

The introduction of negative ion in a plasma drastically modifies the propagation characteristic of ion acoustic waves. First, the charge neutrality condition is modified to \( n_+ = n_e + n_- \) and therefore, electron density reduces. The shielding of positive ions hereby reduces and phase velocity of ion acoustic mode increases. At critical density, negative ions
also start taking part in wave propagation, which alternately means that they take part in shielding positive ions. Above critical density, negative ions are dominated and only rarefactive (negative) KdV solitons can propagate. For the experimental investigation on the propagation of ion acoustic waves with addition of negative ions, at first the ion acoustic wave compressive solitons are excited in Ar plasma by using the usual anode excitation method. The probe is fixed at \( x = 6 \) cm form the separation grid. The initial positive perturbation applied to the plasma is of duration 20 \( \mu \)s and excitation amplitude 3 Volts. The Ar neutral pressure is \( 3.6 \times 10^{-4} \) Torr. Now, keeping all other parameters fixed, slowly SF\(_6\) gas is inserted into the Ar plasma using a double valve system. Due to the introduction of the SF\(_6\) gas, the total pressure of the system increases and successive oscilloscope traces are recorded at different total pressure. The initial compressive ion acoustic soliton changes its

\[ P_{Ar} = 3.6 \times 10^{-4} \text{ Torr} \]

\[ P_{Ar+SF6} = 3.7 \times 10^{-4} \text{ Torr} \]

\[ P_{Ar+SF6} = 3.8 \times 10^{-4} \text{ Torr} \]

\[ P_{Ar+SF6} = 3.9 \times 10^{-4} \text{ Torr} \]

Figure 2.20: The compressive ion acoustic solitons in presence of negative ions at 6 cm probe distance (SF\(_6\) pressure \( 1 - 3 \times 10^{-5} \) Torr). The top trace is the applied pulse of excitation voltage 3 V. Second trace is for Ar only with \( P_{Ar} = 3.6 \times 10^{-4} \) Torr.
Chapter 2: Experimental setup and diagnostics

characteristics throughout the process. The observed signals are shown in fig. 2.20. When the total pressure is increased to $3.7 \times 10^{-4}$ Torr, i.e. SF$_6$ partial pressure is $1 \times 10^{-5}$ Torr, the initial steepening of the compressive wave decreases. The solitary peak almost disappears at the pressure $3.8 \times 10^{-4}$ Torr. The reason behind this is the reduction of nonlinearity and strong dispersion caused by the reduction in electron density. Further increase in total pressure, the perturbation completely disappears with a sign of growth of a rarefactive oscillatory pulse (also known as Air function oscillation).

2.8 Conclusion

In this chapter the experimental arrangements of the double plasma device are thoroughly discussed along with the diagnostics tools. The various plasma parameters like the electron temperature, electron density, floating potential etc. are measured from the I – V characteristics curve taken by the planar Langmuir probe. The production of multicomponent plasma with negative ions in a double plasma device has been discussed in this chapter. The control and measurement of negative ion density in plasma through different technique have been deliberated. In a multicomponent plasma with negative ions, the Langmuir probe I – V characteristics curve has been taken at different SF$_6$ partial pressures to obtain negative ion density ratio, which is a critical parameter for the thesis work. The dispersion relation of ion acoustic waves in a normal as well as in negative ion plasma has been evaluated. The theoretical linear dispersion relation has also been obtained from the fluid model of plasma. From the comparison of experimental and theoretical dispersion relations, the negative ion density in plasma can be measured. The evolution of ion acoustic KdV and mKdV solitons have also been observed. The Mach number and width of the solitons are measured. These
Chapter 2: Experimental setup and diagnostics

are plotted with variation of normalized amplitude and compared with the theoretical one obtained from the KdV and mKdV equations. All the results are in good agreement with theory. The excitation of mKdV soliton substantiate the production of multicomponent plasma with critical concentration of negative ions.

In next chapter, the characteristics of Peregrine solitons (first and second orders) in multicomponent plasma and their theoretical formulation within the framework of NLSE will be discussed.