Chapter 7
Conclusions

The present thesis concerns experimental studies of the role of electron inertia in EMHD. The experiments were performed in LVPD. Fabrication, erection and commissioning of LVPD has been an experience of its own.

Mid-term corrections were made to the original plan for plasma source. An indirectly heated oxide coated cathode was envisaged in the original plan. Due to non-availability of cathode grade nickel used in oxide coated cathode, a cathode of multiple electron emitting tungsten filaments was adopted. Such electron emitters are widely used by workers worldwide. A matrix of 26 filaments of 45 cm length each spread over 60 cm × 60 cm forms the cathode. This provided plasma of desired characteristics. Since magnetic field at the filaments has to be kept less than 10 G, it becomes imperative to change the current distribution in the magnetic field coils for the different desired values of background magnetic field.

We identified a regime in the afterglow plasma where the plasma was of low temperature and quiescent for our experiments. This source is user-friendly and nearly maintenance-free.

Magnet coil system, giving uniform magnetic field in the plasma volume of ~ 6 m³, required attention to details right from the design stage to fabrication, erection, alignment and commissioning and field measurements.

Discharge power supply capable of delivering 4000 A current pulses of 5 – 20 ms duration at 70 V over an interval of 1 s was specifically developed for LVPD. Significant features of this supply are a turn-off time ~ 50μs and 2% repeatability. These features allow afterglow plasma to be devoid of fast electrons and delineation of field topology to use a large number of discharge pulses.

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Magnetic probes were extensively used for the work presented in this thesis. They formed the window for whistlers excited in LVPI. Without them, whistlers in laboratory plasma are undetectable. So considerable effort was needed to refine the technique for obtaining calibrated, interference free spatially resolvable measurements. Present set does not have desirable spatial resolution for studying the region around the null-point. Electric dipole probes provided supporting measurements wherever required.

Without 12-channel fast (1 GSamples/sec) data acquisition and control system experimental studies presented in this thesis could not have been attempted even when scope is limited to not obtaining field topologies.

We have designed a 3-axes probe drive system complete with computer control. Despite repeated attempts industry has not responded to our query. Industry is apprehensive about existence of temperature gradients over a distance of 3 m, securing nonmagnetic bearings and vacuum interface. We have now awarded the contract to a fabricator and hope to get it installed on LVPI very soon.

We have an alternative manually driven probe drive based on a simple but novel idea. This allows us to obtain one dimensional field profiles. Complete mapping of fields with desired accuracy cannot be carried out with this drive. Even with this handicap, we could make reliable conclusions from our experiments.

Initial experiments were aimed at learning the basic excitation mechanism of electromagnetic structures in the context of EMHD. The electromagnetic structures were excited from both insulated antennas as well as biased electrodes in touch with the plasma. Dispersion and polarization characteristics of the electromagnetic structures have revealed that they propagate in the form of whistler waves. Specifically, an experiment was carried out to delineate the role of return current system in the excitation of the structures by biased electrodes. Until now, the role of return current system was thought to be limited to provide only current closure paths for the currents in the plasma. Our work has demonstrated that it plays a much larger role in determining the characteristics of the EMHD structures. It has been shown that the EMHD structures are excited in the regions where return currents are formed parallel to the background field.

The experiments aimed at investigating the role of electron inertia were per-
formed using simple wire-loop antennas. For the first time, EMHD structures with \( k_d \sim 1 \) were excited in a laboratory plasma. Previous attempts to launch such structures with dimensions of the order of an electron inertial skin depth \( c/\omega_{ce} \) have been reported to be unsuccessful. No extra effort has been put in our experiments. Experimental conditions are almost the same as earlier experiments.

Presence of null-points in the propagation path leads to significant changes in the propagation properties of linear EMHD structures. A significant result is while \( B_{\text{toroidal}} \) is transmitted across the null-point, \( B_{\text{poloidal}} \) is not. \( B_{\text{poloidal}} \) is missing beyond the null-point. Hence there is no helicity reversal of the wave packet. This is not in agreement with theoretical predictions. Theory predicts that one component gets generated from the other self-consistently. Our experiments have shown that \( B_{\text{poloidal}} \) does not get generated from \( B_{\text{toroidal}} \) beyond the null-point. However, we have shown that \( B_{\text{poloidal}} \) signals are contaminated by the contribution from induced currents in the Helmholtz coil due to its mutual coupling with the antenna.

Another important result is that electron inertia does not manifest itself significantly in linear EMHD structures. On the other hand, role played by electron inertia in nonlinear EMHD is significant, as evidenced from experimental results. In earlier works, nonlinearity manifested itself through the breakdown of EMHD conditions near null-point. Nonlinear effects are weakened on the inclusion of electron inertia, probably pointing to the fact that EMHD conditions are valid even in the region around the null-point inspite of \( \omega > \omega_{ce} \). Electron inertia also reduces flux decay rate during propagation of EMHD structures across null-points. Inclusion of finite electron inertia enables the electron fluid to be frozen to the generalized vorticity rather than the magnetic field. To the best of our knowledge, this is probably the first experimental verification of theoretical predictions that finite electron inertia does not destroy the freezing-in constants but only changes their form. Reconnection rates in EMHD may have sensitive dependence on the electron inertial skin depth, which is not in agreement with theoretical models.

In brief, this thesis has made the following contribution:

1. A multifilamentary, nearly maintenance-free plasma source capable of producing high density, low temperature, quiescent plasma over a large volume has been developed.
2. Return current system has been shown to play a role not only in current
closure, but also in the determination of the characteristics of the excited
EMHD structures.

3. Linear EMHD structures, propagating in the form of whistler wave packets,
change character across a null-point embedded in the background magnetic
field. Specifically, $B_{poloidal}$ component is missing beyond the null-point. It is
not transmitted across the null-point, whereas $B_{tangential}$ is.

4. $B_{poloidal}$ signal on probe is contamination by the contribution arising from the
mutual coupling between the Helmholtz coil and the antenna.

5. Electron inertia effect is not important in linear EMHD structures.

6. Electron inertia is found to weaken nonlinearities in EMHD structures with
$k_d \sim 1$.

7. Electron inertia leads to freezing-in of electron fluid to generalized vorticity
rather than magnetic field, in agreement with theoretical predictions.

8. Rate of reconnection in EMHD has sensitive dependence on skin depth.

7.1 Future Scope of Work

Obvious extension of the work presented in this thesis are in the following areas.
Transmission of wave field components of whistler waves across a null-point needs
a resolution to the contradictory results from two different devices (UCLA and
LVPD). An experiment with compensation arrangement for coupling between the
antenna and the Helmholtz coil is desirable. Weak transmission across the null-
point, particularly for $k_d \sim 1$ is not understood. In this situation, region around
the null occupies a significant fraction of the size of the EMHD structure. Loss of
energy has been attributed to the curving of the field lines around the null region.
But that does not explain how even a small fraction of the energy gets across the
null-point. There is a speculation that the EMHD structure may be evanescent in the
region around the null-point and it may tunnel through. Though this explanation
cannot be ruled out, there are theoretical works which indicate that EMHD can be
sustained and the structures propagated in plasma without background magnetic field.

LVPD plasma has detectable EMHD turbulence. It is broadband and spectral distribution has power law. If the nonlinearity manifests itself only through the presence of null-points, a detailed study needs to be carried out on how energy contained in a single mode can be distributed over various modes of EMHD turbulence. In this context, it may be important to do some simulation experiments. They may point to the nature of the experiments in a laboratory device. This is because right now there is no clear indication of how EMHD turbulence can be generated from a large energy poured in a single mode.

EMHD structures with dimensions of the order of skin depth can pave way for investigations into the regime of truly inertial EMHD vortices. They are coherent structures representing exact solutions to the nonlinear EMHD equation and propagate in the plasma as robust entities even in the absence of background magnetic field. They are confined within a skin depth and do not allow their own fluid to mix with the surrounding plasma. Experiments pertaining to their excitation, their characteristics, their interaction among themselves form a series of interesting investigations which may throw light on EMHD turbulence.