Chapter 3

Operation System, Diagnostics and Data Analysis

In order to carry out experiments in LVPD, several operations have to be accomplished. These include tasks such as bringing the vacuum vessel to a base pressure of $10^{-7}$ mbar, producing large volume plasma, launching of EMHD perturbations from appropriate antennas, acquisition and analysis of the relevant data and safe termination of the experiment. These operations are facilitated by a VXI-based 12-channel data acquisition and control system and various diagnostic heads. In this chapter, we shall discuss the data acquisition system [40], diagnostics, data analysis techniques and grounding and shielding techniques. The data acquisition and control system is described in Section 3.1. Different diagnostics used in the present thesis are described in Section 3.2. The data analysis techniques used for data reduction to meaningful form are described in Section 3.3. Grounding and shielding techniques are discussed in Section 3.4.

3.1 Data Acquisition and Control System

Basic plasma physics experimental devices have grown in status from handling very simple experiments yielding data which can be handled by simple recording systems such as oscilloscopes and recorders to complex experiments which can be meaningfully understood only when a large volume of data is acquired [30, 4] assisted by computers [41]. In the past, this need was satisfied by modern and powerful oscilloscopes with a general purpose interface bus for the transport of data. However, such systems cannot provide high throughput. The performance was enhanced by
basing the data acquisition system on a VXI interfaced CAMAC [42] crate using FORTRAN code and VMS. While this system provided useful assistance in data acquisition, its poor upgradability has been a major concern. Now client CAMAC has given way to VXI. This has led to at least an order of magnitude increase in the capability of data transfer rates, as has been demonstrated on a large plasma device (LAPD) by Mandrake and Gekelman [43]. However, performance of this system can be further improved by making use of the relational database management system RDBMS on network. This results in reduced need for permanent storage systems, ease of operation from any terminal point, and increased capacity of data management [44]. A network based data acquisition and database management solution eases operations with regard to acquisition, data processing, and management [45]. In the following, we shall describe the need for a data acquisition system, hardware configuration, and software developed for this program. Examples are given to demonstrate the capability of the data acquisition and control system.

3.1.1 Experiment and Data Acquisition and Control Requirement

The nature of the experiment is such that it requires high sampling techniques as the phenomena of study is related to high frequency oscillations. A full understanding is realizable only when topology of the field parameters can be mapped with a high spatial resolution. To achieve this end, there is a need to have not only a drive system which can scan the desired plasma volume, but also to have a matching acquisition which can acquire data at a fast sampling rate, store it in appropriate system and make use of software programs for efficient data processing and management. In addition, the plasma is pulsed. The repeatability of the discharge pulse is therefore important and entirely depends upon the control parameters such as arc current, filament heater current, gas throughput, etc. Further, safety of the device requires various parameters to be monitored and interlocked.

Another design issue arises purely from various time scales that exist in the system. These scales vary from a few hundred of ms for plasma discharge pulses to a few ns for excitation of high frequency oscillations. Figure 3.1 shows a schematic of LVPD with the control system.
Figure 3.1: Schematic of LVPD with control system

Table 3.1 gives an account of the experimental requirement with regard to the time scales involved. The maximum sampling rate required is 1 GS/s. Hence the data acquisition system has to handle multiple time scales. To get statistically meaningful data, the data acquisition has to be executed in a burst mode of \( \approx 10 \) plasma discharge pulses. To reduce the campaign time and therefore to obtain stable operation of the cathode of the device during the period of campaign, the plasma discharge frequency must be 1 Hz with a duty cycle of 10 ms ON/1 s OFF. The lower limit of 4 ms is imposed by rise and fall times \( \approx 1 \) ms of plasma density observed in plasma discharges of our device. Further, the plasma device has to be prepared for repeating the experiment and the data acquisition has to be armed for the next acquisition.
Table 3.1: LVPD Diagnostics and Sampling Rate Requirement.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Diagnostics</th>
<th>Sampling rate</th>
<th>Record length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langmuir probe</td>
<td>Steady state density</td>
<td>250 kS/s</td>
<td>2048</td>
</tr>
<tr>
<td>Langmuir probe</td>
<td>Afterglow density</td>
<td>1 GS/s</td>
<td>30000</td>
</tr>
<tr>
<td>Langmuir probe</td>
<td>Fluctuations</td>
<td>1 GS/s</td>
<td>15000</td>
</tr>
<tr>
<td>Magnetic probe</td>
<td>Whistler wave magnetic field</td>
<td>1 GS/s</td>
<td>2048</td>
</tr>
<tr>
<td>Electric dipole probe</td>
<td>Electric field</td>
<td>250 MS/s</td>
<td>2048</td>
</tr>
<tr>
<td>Diamagnetic probe</td>
<td>Beta effects</td>
<td>250 kS/s</td>
<td>2048</td>
</tr>
<tr>
<td>Emissive probe</td>
<td>Plasma potential</td>
<td>250 kS/s</td>
<td>2048</td>
</tr>
</tbody>
</table>

3.1.2 Data Acquisition Hardware Configuration

We are using three TVS641 Tektronix Inc. Make VXI based digitizer modules. These modules have four channels each with 1 GHz single shot sampling rate. Using segmented memory of this module, the auto advance acquisition mode using segmented memory of this module offers the additional advantage of scaling down the time interval between consecutive pulses. As and when required this module also offers flexibility over triggers internal, external and VXI burst, record length, gain and sampling rate. The VXI mainframe provides power to these modules. All the VXI data acquisition modules and controller module share the single VXI bus. All these modules are controlled by the MXI2 National Instruments product slot “0” controller which is in turn controlled by a PC add on card. This card is a MXI bus controller and resides on a PCI slot of a standard computer. This computer controls the whole VXI system. The MXI-2 bus has a throughput of 33 Mbytes/s in block transfer mode and 23 Mbytes/s in sustained mode. Our VXI data acquisition modules are message based. These modules have their own command processing time. The effective transfer rate, which is system dependent, is 500 Kbytes/s for our system, irrespective of the operating system.

Triggering and Data Acquisition

For triggering the wave excitation in the afterglow plasma, a Langmuir probe signal is compared in a comparator circuit incorporated inside the I–V card (see Appendix A). This produces a transistor-transistor logic TTL signal when density crosses a
reference signal. One of the TVS641 modules is triggered by the TTL pulse VXI backplane TTL trigger line. Remaining modules are triggered from the VXI backplane TTL trigger line. Thus all three modules get triggered at a specific plasma density that can be changed by changing a reference signal and capture signals for 10 s.

**Burst Mode Data Acquisition Operation**

In this mode of data acquisition, we capture the signals for the multiple triggers. Data are acquired and stored in the segment of a VXI digitizer module. In any one particular shot the data for 10–15 triggers is acquired every 1 s. Each trigger data is kept in one of the segments of the VXI digitizer module. The trigger data are stored in different segments of memory. These segments are not physical segments, but logical. Finally, all the data are simultaneously transferred to the computer. This burst mode data acquisition is accomplished by using the Auto-Advance data acquisition facility of the TVS 641 Tektronix VXI data acquisition module.

**Monitoring and Control System**

The requirements regarding the control and monitoring input/output signals are listed in Table 3.2. In LVPD, the temperature at various places of the cathode structure which dissipates about 90 kW, the walls of the chamber and the magnetic field coils of 180 kW have been continuously monitored. In case of the coils, which are 60 in number, RTDs (PT-100) have been mounted on each and the temperature is compared with the predefined set limits. The temperature of the hot cathode and chamber wall is monitored with the help of K-type thermocouples. Special thermocouples have been designed for this purpose. These thermocouples are non-grounded, potential free and vacuum compatible. The vacuum of the chamber is also monitored through the output signal of vacuum gauges. All these signals travel 20 m and terminate at a 96-channel microprocessor based monitoring, logging and control system datalogger with a computer interface. Datalogger scans all these channels within 2 s.

**It compares input signals with predefined set limits. Crossing of the set limit by any of the signals produces a TTL pulse. This pulse is isolated using opto-couplers**
Table 3.2: Control and monitoring signals in LVPD.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Type</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump ready signal from three difstacks</td>
<td>digital input</td>
<td>3</td>
</tr>
<tr>
<td>Roughing pump valve status</td>
<td>digital input</td>
<td>3</td>
</tr>
<tr>
<td>Roughing pump valve ON/OFF</td>
<td>digital output</td>
<td>3</td>
</tr>
<tr>
<td>Baffle-valve status of three difstack pumps</td>
<td>digital input</td>
<td>3</td>
</tr>
<tr>
<td>Gate valve status of roughing pump</td>
<td>digital input</td>
<td>1</td>
</tr>
<tr>
<td>Gate valve of roughing pump ON/OFF</td>
<td>digital output</td>
<td>1</td>
</tr>
<tr>
<td>Status thermal snap switches of three difstack pumps</td>
<td>digital input</td>
<td>3</td>
</tr>
<tr>
<td>Water flow switches</td>
<td>digital input</td>
<td>8</td>
</tr>
<tr>
<td>Difstack heater status</td>
<td>digital input</td>
<td>3</td>
</tr>
<tr>
<td>Penning gauges relay signal</td>
<td>digital input</td>
<td>3</td>
</tr>
<tr>
<td>Pirani gauges relay signal</td>
<td>digital output</td>
<td>5</td>
</tr>
<tr>
<td>Ionization gauge relay signal digital input</td>
<td>digital input</td>
<td>2</td>
</tr>
<tr>
<td>Power supplies’ OFF signal for magnet, filament, and discharge</td>
<td>digital output</td>
<td>3</td>
</tr>
<tr>
<td>RTD PT-100 signal</td>
<td>analog input</td>
<td>50</td>
</tr>
<tr>
<td>K-type thermocouples</td>
<td>analog input</td>
<td>5</td>
</tr>
<tr>
<td>T-type thermocouples</td>
<td>analog input</td>
<td>4</td>
</tr>
</tbody>
</table>

and it drives a relay which trips the filament and magnet power supply of the system.

The vacuum system for LVPD is a complex system with multiple vacuum pumps, requiring a certain fixed procedure of turning ON and OFF and a protocol has to be observed for obtaining the vacuum. These procedures and protocols may change with the experimental condition. Hence there has to be a full online monitoring of the whole vacuum system.

The power of all the vacuum pumps is monitored along with the valve position open/close with the help of electrical signals obtained from these devices. Other signals from thermal snap switch and pump ready switches are also monitored. Opto-isolaters are put in these monitoring lines to isolate the power side from the monitoring and control side. Signals from the Penning, Pirani, and ionization gauges are analog output signals. These signals are interlocked with a vacuum control system. All the power supplies are interlocked with vacuum, temperature and flow signals using the datalogger.
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Probe Drive Control System

A three axes probe drive control system PDCS is a recent addition to LVDP. High
accuracy (~ 0.1°), error correction, protection and flexibility are its main features.
Power supplies, motor drives, stepper motors, encoders, limit switches and a com-
puter with software are the main components of the PDCS.

Overall operation of PDCS is controlled by the computer which provides enough
flexibility to change the sequence of operation as per requirements. While PDCS is
only a recent addition to the experimental system, most of the experiments described
in this thesis have been carried out using a string-pulley based manually operated
probe drive earlier installed on the system (see Chapter 2).

3.1.3 Software System

The LVDP software system is modular and distributed, each module performs a
specific task. With modular architecture of the software system we can easily modi-
fy the code without affecting other modules. This is very important to provide
flexibility in the operational sequence of experiments. The LVDP software system
consists of a VXI graphics user interface, a database graphics user interface (Figure
3.2), and a database management system.

3.1.4 Operational Experience

The LVDP, along with the VXI based data acquisition system, has been operational
for the last three years. The plug and play nature of the VXI platform provides
future expandability in terms of more channels for data acquisition. Due to its open
vendor architecture and VISA library, there is no single vendor dependence making
the system highly flexible. Any new operational requirement can be fulfilled in a
short time by making a relevant alteration in the software.

Operational reliability

All the control logic in LVDP are hardwired. The control signals from vacuum
system, power supplies, and PDCS are interlocked by various hardware gates, thus
providing a high level of reliability. Various test utilities have been developed for
the VXI system, where by it is possible to read the data from all the VXI modules
memory and display it in graphical form simultaneously. This allows the user to make an online assessment of the shot. A utility program for the database further confirms the proper storage of the shot data. Various features of the SQL server database system like backup and network support allow one to keep the backup of the data on other auxiliary storage as well as on other computers on the network.

Future Upgrades

The system has been supplemented by another four channel VXI module with the same specifications. To incorporate this module we have modified our existing acquisition software as well as database design. Development of a 16-channel data acquisition system is almost complete. Features of this system is being enhanced to include a software for online processing of the data as well as utility programs which read the data from the database server, process it, and give us a graphical output.

Figure 3.2: Database graphic user interface.
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The existing database shall be modified to facilitate storage of processed data.

For full automation of the LVPD, a PC based monitoring system shall be provided in which status of all the control signals will be displayed. With a provision of automation in ordering the discharge duty cycle and arming of magnet and filament power, all the operational processes related to LVPD experiments can be made fully automatic and left unattended around the clock.

3.2 Diagnostics

3.2.1 Plasma Density and Temperature

The plasma density and temperature are obtained using measurements from Langmuir probes [46]. The Langmuir probes are cylindrical SS304 tips of length 10 mm and diameter 2 mm. A schematic of the Langmuir probe is shown in Figure 3.3.

![Figure 3.3: Schematic of the Langmuir probe is shown](image)

We cannot employ the conventional method of obtaining the plasma density and temperature by sweeping the voltage of Langmuir probe because the plasma is pulsed with $t_{\text{on}} \approx 5$ ms. It has been reported in previous work [47], and observed by us as well, that fast sweep of the probe can enable the probe to collect currents in excess of the Langmuir limit and can result in erroneous $I-V$ traces. However, voltage sweeps $\sim 10$ $\mu$s have been used [48, 49, 50] in other experiments to study EMHD turbulence. But it is our observation that at these sweep rates Langmuir probes show signature of hysteresis which can again lead to erroneous results for the estimation of density and temperature. However these results are out of the scope of this thesis and will be reported elsewhere. On the other hand, slow sweeps of few hundreds of $\mu$s to few ms are not desirable since discharge pulse is limited to
5 ms and there is considerable variability of plasma parameters in the rise and fall portion of the discharge pulse.

In the experiments described in this thesis, the Langmuir probe traces are obtained at each spatial location by fixing the voltage bias on the probe for one plasma shot and then varying the bias voltage in appropriate steps in several repeatable plasma shots. Current-voltage (I-V) characteristics are shown in Figure 3.4 in the main glow of the plasma and \( \sim 500 \mu s \) in the afterglow. Taking the logarithm of I and obtaining the slope \( \partial \log(I)/\partial V \), we get \( T_e = 1/\text{slope} \approx 9 \text{ eV} \) for main glow and \( \approx 2 \text{ eV} \) for \( \sim 500 \mu s \) in the afterglow. Using the value of the ion saturation current \( I_s \) we obtain the plasma density from \( n_e = 4I_s/eAC_s \) as \( \approx 9 \times 10^{11} \text{ cm}^{-3} \) in the main glow and \( \approx 3 \times 10^{11} \text{ cm}^{-3} \) at \( \sim 500 \mu s \) in the afterglow.

The I-V curves are then reconstructed for all times at each spatial location and the plasma density and temperature are obtained. Radial and axial density profiles and temporal evolution of density and temperature have been shown in Chapter 2.

### 3.2.2 Magnetic Field

Several methods exist for measuring magnetic fields in a plasma, e.g. deflection of injected beams of fast charged particles, Hall effect etc. While the interpretation of the measurements from the former technique becomes a very difficult task, the latter is generally used for measuring dc fields. In most cases the magnetic probe [51, 52] is an ideal sensor for measuring time varying magnetic fields. A magnetic probe should have the following characteristics (i) good sensitivity i.e. high signal to noise ratio (ii) excellent frequency response so that it can measure rapid fluctuations of the magnetic field (iii) minimal perturbing effect on the plasma. Since each of the above requirements requires conditions in conflict with the other, there is a trade-off between them and a design has to be worked out so that each condition can be optimally met. In addition to all these, appropriate electrostatic shielding is required to minimize the capacitive pickup.

In our experiments, we have excited electromagnetic structures of dimensions \( \sim \) skin depth \( \approx 1 \text{ cm} \). Therefore the magnetic probe used is miniature with minimal perturbing effect on the plasma. But this leads to a compromise over the sensitivity of the probe. Secondly, it is almost impossible to provide an electrostatic shield in
Figure 3.4: Typical I-V characteristics of the LVPD plasma in the (a) main glow, where plasma density and temperature are respectively $\approx 9 \times 10^{11}$ and 9 eV, and (b) afterglow where $n_e \approx 3 \times 10^{11}$ cm$^{-3}$ and $T_e \approx 2$ eV.

the form of a metallic cover with a cut, both because of the small size of the probe and the decreasing sensitivity due to formation of eddy currents.

We have therefore constructed a miniature magnetic probe with a modified center-tapped design [53], which requires no metallic cover as an electrostatic shield but at the same time acts to minimize the electrostatic pickup. The magnetic probe used in the experiments in this thesis is a 3-axes magnetic probe. A photograph of the magnetic probe is shown in Figure 3.5. Each probe is orthogonal to the other two so that all three magnetic field components $B_x$, $B_y$ and $B_z$ can be measured simultaneously. Each probe is bifilar with total 30 turns. The probe is wound using 0.13 mm insulated copper wire on a ceramic formar of 2 mm diameter and 5 mm
Figure 3.5: Photograph of the 3-axes magnetic probe: The metric scale is shown to indicate the probe dimensions.

length. Two sets of 15-turn windings are wound close to each other. One of the sets is connected to ground across a miniature SMD (surface mountable device) resistor of 50 Ω. The inductive signal is picked up by the other set which is grounded at the opposite end. The signal is carried to an amplifier (ZFL 500LN, Minicircuits) via a miniature semi-rigid coaxial cable (EZ 34, 50 Ω) and ultimately to the acquisition system. A schematic of the magnetic probe is shown in Figure 3.6.

Due to the close winding of each set of 15 turns with the other, the self-inductance of each set is equal to the mutual inductance. Therefore this serves to cancel the unwanted capacitive currents at the probe tip itself. This design [53] has certain advantages over the regular center-tapped design in the sense that only two connections need to be taken out, unlike three in the centre-tapped. Thus it does not require the use of a subtraction transformer or a differential amplifier before acquisition. The magnetic field is obtained from the probe voltage signal using methods described in Section 3.3. The electrostatic rejection is done right at the probe tip itself instead of a remote distance (the acquisition system) from the probe tip as in the case of a singly wound or a regular center-tapped magnetic probe.
15 effective turns

Figure 3.6: Schematic of a single magnetic probe. A resistance of 50 Ω is connected right across one set of coils and grounded at the end opposite to that of the other set in order to reject the electrostatic signal at the probe tip itself.

### 3.2.3 Electric Dipole Probe

While space charge electric fields $E = -\nabla \phi$ can be derived from local measurements of the plasma potential [46], inductive electric fields can be obtained only from knowledge of currents all over the volume in space and time. When both space charge and inductive electric fields are present, dipolar probes [54] are used.

Figure 3.7: Photograph of the electric dipole probe

In the experiments presented in this thesis, both types of electric field may be
associated with the excited electromagnetic structures. Besides, fast time scales \( t^{-1} \sim 0.1 - 10 \) MHz are involved. Therefore, the small amplitude time varying electric fields \( \mathbf{E} = -\partial \mathbf{A}/\partial t - \nabla \phi \) are measured using an electric dipole probe capable of measuring even high frequency \( (\leq 10 \) MHz\) electrostatic and inductive electric fields \( (\geq 150 \) mV/cm\). Such probes [55] have been used by earlier workers in their experiments [56]. For our experiments, we have constructed one such probe where the major feature is the method of measuring a small open-loop voltage and transferring the information from an \textit{in situ} dipole to an external instrument. This design is similar to that of the dipole probes used earlier [55], the only difference being that the resonant frequency is halved to \( \sim 418 \) MHz because we have used a varactor diode of different specifications. This has led to a decrease in the Q-factor and hence the sensitivity \( \partial V/\partial f \) of the probe. Also, the signals are demodulated numerically due to lack of availability of an appropriate detector.

The dipole probe (Photograph shown in Figure 3.7) consists of two copper spheres of \( 6 \) mm diameter separated by a distance of 28 mm. In the presence of an electric field \( \mathbf{E} \), an open-loop voltage \( V = \int \mathbf{E}.d\mathbf{l} \approx 2 \mathbf{E}d \) is developed across the spheres. The voltage developed across these two spheres is applied to a Gallium Arsenide varactor diode \( (1.25 \) pF to 2.25 pF for -4 to 0 V\) which is part of the resonance circuit tuned to a frequency of around 418 MHz. The dynamic range of varactor allows resonance frequency to be shifted from 401 MHz to 425 MHz corresponding to voltage difference across the spheres to be \( \pm 100 \) mV. Since transmission line \( (EZ 34, 50 \) \Omega, semi-rigid coaxial cable\) carries frequency modulated RF signal, there is no introduction of noise. Again, since resonator is magnetically coupled to the transmission line, no ground interference affects the signal. A schematic of the electric dipole probe is shown in Figure 3.8.

The probe is separately calibrated against a known electric field produced by a capacitor and a linear wire antenna. Figure 3.9 shows one such result from a setup involving the electric dipole probe placed between the plates of a capacitor. We have plotted the displacement current \( I = C\partial V/\partial t \), the electric field \( E_z \) as measured by the dipole probe and the numerically demodulated signal. The results show that the electric dipole probe can measure electric field \( \geq 2 \) mV/cm at a frequency up to 10 MHz.
3.3 Data Analysis

The data acquired from different diagnostics are analyzed for obtaining different plasma and field parameters. The plasma density and temperature are obtained from I–V curves of the Langmuir probes. As stated earlier, these curves are reconstructed from the data obtained for each spatial location and each time in the pulsed plasma.

In the absence of an appropriate video detector, the voltage signals obtained from the electric dipole probe are numerically demodulated to obtain the electric fields. In order to obtain the magnetic fields from the voltage signals, they have to undergo a series of numerical manipulations. This is because the probe/amplifier circuit has an intrinsic frequency dependence and this leads to distortion of the signal as recorded by the acquisition system. Distortion removal as well as integration of the signal are the tasks to be carried out on the detected signal. In what follows, we shall discuss
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Figure 3.9: Results from a calibration setup for measuring small time-varying space charge electric fields (a) Voltage across the capacitor plates (b) Capacitive current measured by current monitor (c) Signal picked up by the dipole probe (d) Numerically demodulated signal to yield the electric field.

in detail the conventional technique, its disadvantages and the currently used Probe Transfer Technique to analyze the magnetic probe data.

3.3.1 Conventional Techniques : Disadvantages

The conventional technique is spread over several steps. First, the probe is calibrated in a known configuration, which in most cases, is a Helmholtz coil. The usual procedure is to vary the frequency of the applied current signal in the Helmholtz coil and acquire the corresponding magnetic probe voltage signals. A severe limitation to this method is the frequency step which is decided by the waveform generator.
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There is every chance that resonances, if any, might be missed. Also, this procedure is long and readings have to be taken at several frequencies of interest. The voltage induced in the probe \( V_p = uA dB/dt \), as observed on the acquisition system, is not the actual voltage induced in the pickup coil. Alternatively, an attenuation factor \([57]\), which is the ratio of the voltage observed \( |V_r| \) to the voltage induced in the coil \( |V_p| \), \( A = |V_r|/|V_p| \), has to be introduced to account for the frequency response of the probe circuit, where \( |A| = [(R + r)/R - \omega^2 LC]^2 + [\omega(L/R + Cr)]^2 \)^{-1/2}, and \( R \) is the input impedance of the acquisition system and the probe and its leads are an inductance \( L \) in series with a resistance \( r \) plus a parallel capacitance \( C \) for a given frequency \( \omega \). In order to carry out the above analysis, the parameters \( R, L, \) and \( C \) of the probe/amplifier circuit must be known accurately. After these analyses, the data is integrated to obtain the magnetic field. The integration in time can lead to erroneous results if unwanted high-frequency noise or a dc shift, if any in the acquisition system, is not taken care of.

3.3.2 Probe Transfer Function Technique

This technique is based upon the use of a Probe Transfer Function (PTF) \([58]\). In this method, both the operations of integration and frequency response correction are carried out simultaneously. The technique is first established by carrying out tests on simulated data. We have chosen a simulated current and corresponding voltage waveforms (shown in Figure 3.10a). The PTF is calculated by taking the FFT of these waveforms and dividing the FFT of the former by that of the latter

\[ \text{PTF}(\omega) = I(\omega)/V(\omega). \]

Figure 3.11a shows some voltage waveforms on which the PTF technique is applied. The results are shown in Figure 3.11b. The first waveform is the same voltage waveform delayed in time and the second a different waveform. Clearly, the obtained waveforms for the current are not the expected (true) current waveforms. This is due to the assumptions built-in in the convolution theorem. First, the input data is assumed periodic. Secondly the data is assumed to be of the same length as the PTF. Both these problems can be overcome by treating the input data and/or the PTF by zero padding, which essentially means extending the data to a larger length by putting the extra data points to zero. This treatment ensures that during
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Figure 3.10: (a) Waveforms of voltage, current, (b) real and imaginary components of their Fourier spectra. The amplitude is negligible at higher modes (frequencies). (c) Spectrum of PTF. Note the spurious power at higher modes not present in the current and voltage spectra. (d) PTF spectrum at lower frequencies.

deconvolution the signal is not corrupted. Figure 3.11c shows the deconvolved signals where zero padding has been carried out before taking the inverse FFT. It is clear that the obtained waveforms represent the true current profiles corresponding to the given voltage profiles.

We now investigate the effect of noise on the input data. This exercise is imperative since experimental data always contains noise. Figure 3.12 shows some waveforms where Gaussian white noise has been added to a simulated waveform with signal to noise ratio $\approx 1 - 10\%$. Figure 3.12b shows the resulting data after deconvolution of the signal with the PTF.
Figure 3.11: (a) Test voltage waveforms. (b) Deconvolved waveforms. Note that these waveforms do not represent the expected current waveforms. (c) Deconvolved waveforms after zero padding. The resulting waveforms truly mimic the current waveforms.

It is clear that nothing can be made out from the resulting waveforms where the noise seems to be predominant over the signal. We plot the real and imaginary components of the current and voltage waveforms and the PTF in Figure 3.10. A careful examination of the PTF shows that amplitude is finite even for modes having negligible amplitudes in the current and voltage spectra (Figure 3.10b). We find that the operation $I(\omega)/V(\omega)$ leads to spurious power at these modes, corrupting the deconvoluted signal. Therefore, the PTF is truncated up to these modes. The test waveforms with noise are again deconvolved with the truncated PTF to obtain meaningful waveforms as shown in Figure 3.12c. Thus, in the PTF technique, two steps are absolutely necessary (i) Zero padding (ii) Truncation of PTF up to modes of interest after careful examination of the PTF as well as the current and voltage...
Figure 3.12: Plots showing results after application of PTF on noisy data. (a) Noisy data (b) Deconvolved signals using the full PTF (c) Deconvolved signals using the truncated PTF.

spectra. We have incorporated these steps while analyzing the actual experimental data. When applied to actual experimental data, truncation can also be done up to relevant frequencies of interest.

The PTF used to analyze experimental data is obtained from a calibration setup in vacuum. The setup consists of a magnetic probe placed on the axis of a magnetic loop antenna in vacuum in the actual experimental arrangement in which data in plasma is to be taken. A current waveform I(t) (Figure 3.13) is applied to the loop antenna.

It is measured accurately using a precalibrated current monitor. The waveform applied is a pulse consisting of several frequencies of interest. The voltage V(t), as
measured by the probe is acquired on the acquisition system at the desired sampling rate $\Delta t$ and record length $T$. $I(t)$ and $V(t)$ are converted to $I(\omega)$ and $V(\omega)$ (See Figure 3.13) respectively using standard FFT techniques. We can see that in the present context both real and imaginary components of both $I(\omega)$ and $V(\omega)$ exhibit a $1/\omega$ dependence and frequencies of $f \geq 20$ MHz are not part of the physical phenomena (low-frequency whistler waves) and only act as high frequency noise.

The PTF (Figure 3.14) is then calculated $T(\omega) = I(\omega)/V(\omega)$. A calibration factor $\kappa$ is obtained from $\kappa = \mu_0/2r$, where $\mu_0$ = permeability of free space, and $r$ = radius of the loop.

Figure 3.15 shows a typical experimental magnetic probe data curve containing information about the whistler wave field at one spatial location. $V_p(t)$ is converted to $V_p(\omega)$ and is multiplied by $T(\omega)$ to obtain $I_p(\omega) = T(\omega)V_p(\omega)$. $I_p(\omega)$ is converted
Figure 3.14: The probe transfer function (PTF) is calculated by taking the fast Fourier transforms of the current and voltage and then dividing the former by the latter to \( I_p(t) \) using inverse FFT techniques. It is multiplied by the calibration factor \( \kappa \) to obtain \( B(t) = \kappa I_p(t) \). Figure 3.16 shows \( B(t) \) obtained using two types of transfer functions, one with the complete information and the other truncated to frequencies of interest. Also, the dc zero-frequency component can be removed by putting the first component of \( T(\omega) \) to zero. This method, which combines frequency response fitting and integration into one, also takes into account other constants such as number of turns and area of the probe which need not be known.

Thus, the Probe Transfer Function (PTF) technique offers several advantages over the conventional techniques by combining frequency response fitting and integration into one and taking into account several unknown constants. When large data sets are involved, this can save precious computational time over the conventional techniques. Also, noise in the data can be handled easily leading to easy
Figure 3.15: Experimental magnetic probe data curve containing information about the whistler wave field

3.4 Grounding and Shielding Techniques

Separate electrical ground pits have been constructed, viz. system, power and signal grounds. This is done to avoid mixing of grounds. Different signals from various diagnostics are carried to the acquisition system through coaxial cables RG 58C/U, RG 188, RG 196, or miniature semi-rigid coaxial cable EZ 34, each of characteristic impedance 50 Ω. Signals from magnetic probes are carried through triaxial cables of characteristic impedance 50 Ω. Multiple grounding technique is used in case of magnetic probes. Single grounding technique is used for other diagnostics. The signals are carried to a shielded room which has provisions for EMI/RFI shielding. The room offers > 100 dB attenuation from 10 kHz to 1 GHz for plane as well as electric waves. It has been tested as per MIL-STD-220 and MIL-STD-285 standards.
Figure 3.16: Magnetic field obtained using two different PTFs. The interpretation of $B(t)$ becomes much easier when the improved (truncated) transfer function is used.