Chapter 2
Electrode and Probe Diagnostics

2.0: Introduction

To study the dynamics of plasma biasing and rotation, a suite of electrode and Langmuir probe tools has been developed. The technical details of these tools are described in this chapter. The first section deals with the design of the plasma biasing electrode and its associated power supply. The second section discusses the Mach probes used to measure flows, including the models used to analyze the data.

2.1: The Biased Electrode and Power supply.

To induce plasma flows in HSX, we use a biased electrode system. The electrode itself is a molybdenum cylinder, 0.75" long and 0.75" in diameter. This cylinder is captured inside a boron nitride shroud, allowing only 0.25" of the length of the electrode to be exposed to the plasma. This electrode assembly is mounted on a ¼" diameter OFHC copper shaft, which is in turn joined to a single pin, medium current feedthrough. The shaft and feedthrough are protected from plasma by boron nitride armor. This entire assembly is mounted inside a welded bellows, and can be positioned in the plasma using a linear positioning stage. Figure 2.1 shows a drawing of the assembled electrode.

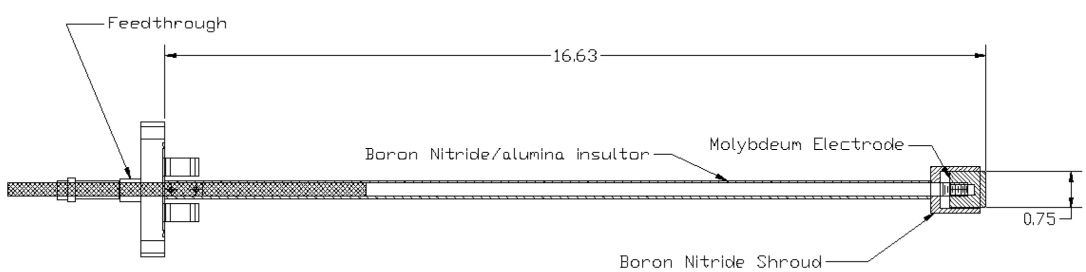

Figure 2.1: Electrode used to bias the plasma; all dimensions are in inches.

The power supply consists of a capacitor bank, control electronics, and diagnostic outputs. The individual capacitors are each 1000μF, rated for 450V. 20 of these capacitors are combined in parallel into two 20,000 μF banks, which are then stacked to provide 10,000μF of capacitance with a maximum voltage of 900V. To charge the bank, a 600V and 1.6A (Sorenson DCS 600-1.7) power supply is used, setting the upper limit on what bias voltages can be applied. The bank is charged before each shot, and the voltage remaining on the capacitors is removed via a shorting bar at the end of each discharge.

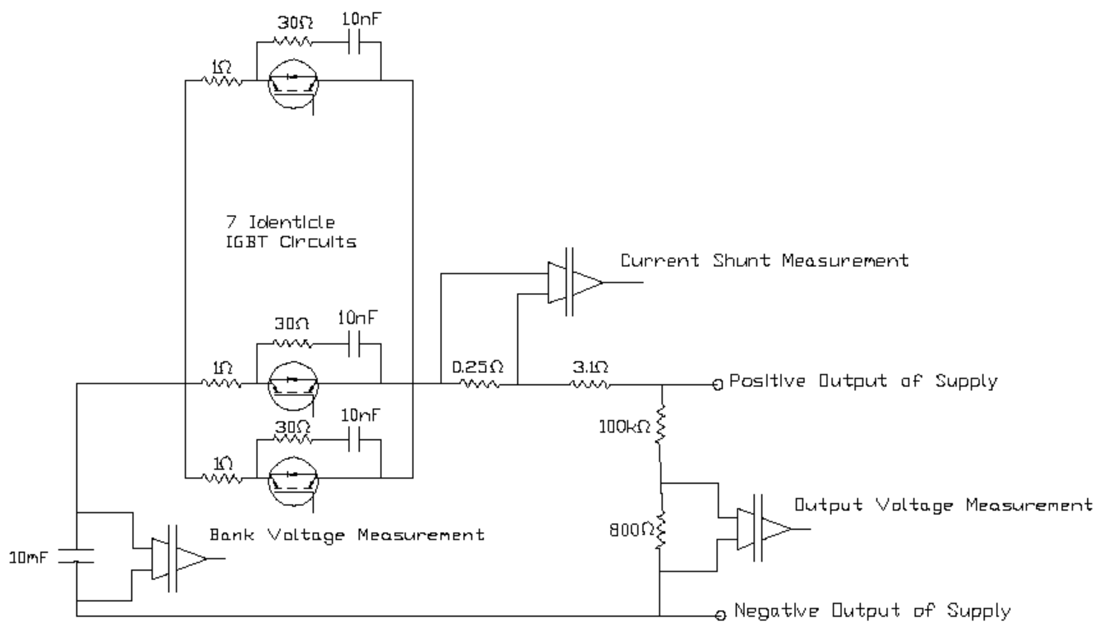

Figure 2.2: Circuit of the bias electrode power supply

The firing circuit is shown in figure 2.2. Each IGBT (International Rectifier, IRG4PH50UD) is capable of standing off 1200V and conducting 45 A DC. The large amount of series resistance, 3.35Ω, limits the current to at most 180A in the case of a fault. Using these IGBT switches, the bias voltage can be turned on in ≈1μs at the beginning of the pulse, while the current can be stopped on a similar time scale at the end. This switching system also allows the bank to be pulsed multiple times during each discharge, increasing the amount of data taken during each plasma shot. The combination of 30Ω resistor and 10nF capacitors is used to snub out ringing when the current is shut off, while the 1Ω resistors cause the current to distribute evenly between the seven IGBT circuits.

In normal operation, the voltage at the electrode, the voltage on the capacitors, and the voltage at the output of the supply are monitored using voltage dividers and Analog Devices AD215BY transformer coupled isolation amplifiers. This system enables the voltage to be monitored with ≈120 kHz of bandwidth. The current drawn by the bank is monitored via a Pearson current transformer, enabling very high bandwidth (>1MHz) measurements of the electrode current. A 0.25Ω current shunt is also installed in the supply. This measurement is limited by both the inductance of the wire wound resistor and the comparatively low bandwidth of the necessary isolation amplifiers (also AD215BY with 120kHz of bandwidth). Hence, the current shunt is a less attractive measurement than the current transformer, and is generally not used.

It will be shown in chapter 4 that the plasma typically provides approximately 50Ω of resistance to the electrode. To test the power supply under similar impedance, the system was discharged into a 50Ω resistor. The waveforms for this case are shown in figure 2.3. The decay time for the voltage and current at the end of the pulse are ≈3.5μsec. This implies the presence of a capacitance of 70nF in the system (using $\tau=RC$). This is exactly the parallel capacitance of the seven 10nF capacitors used as snubbers on the IGBTs.

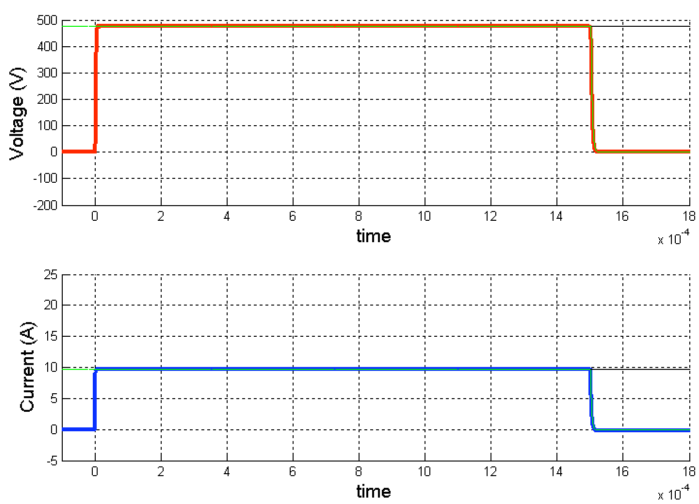

Figure 2.3: Bias power supply characteristics when discharged into a 50Ω resistor.

2.2: Multi-Sided Mach Probes

2.2.1 Flow Measurements in Plasmas

There are multiple means to measure the mass flow of a hot plasma. A typical technique is to measure the Doppler shift of impurity light emitted by the plasma.[1] It is possible to deduce the average flow speed of that impurity along the line of sight using this method. Unfortunately, the spatial resolution of this diagnostic is usually compromised by the line integrated nature of the measurement, and the time resolution is often limited by the speed of multi-element detectors such as CCDs and photodiode arrays. The time resolution of these systems has been improved in some systems by using multiple photomultiplier tubes as detectors, at the expense of a more complicated detector system.[2,3] The spatial limitation of these systems has been improved by viewing the spatially localized charge exchange light from a diagnostic or heating neutral beam.[4] This method has been used successfully on many large experiments,[5,6] but is difficult for a small stellarator like HSX.

In the interest of making spatially and temporally resolved measurements of flow in HSX without the complicated spectroscopic systems noted above, we have build a system of Mach probes. These Mach probes have the advantage of good spatial resolution and time resolution On the down side, they are a local perturbation to the plasma, and the interpretation of the data from these types of probes is a matter of some controversy. The following sections describe in detail the design and use of the Mach probe system.

2.2.2 Introduction to Mach Probes

In its simplest manifestation, a Mach probe is composed of two probe tips, separated from each other by an insulator, and each biased into ion saturation current (I_{sat}). An example of this type of probe is shown in figure 2.4.

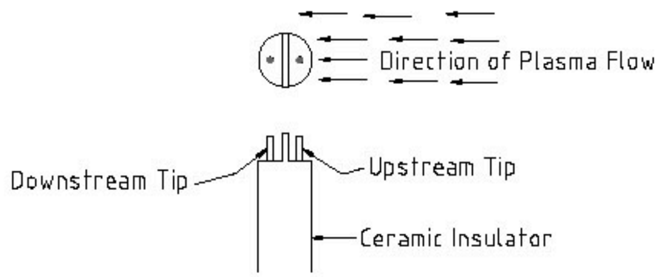

Figure 2.4: Simple Mach Probe.

If the plasma is not flowing, then the two tips should collect the same I_{sat}. If the plasma is flowing across the probe as indicated in the figure, then the tip facing the flow (I_{up}) will draw more current than the tip facing away from the flow (I_{down}). The relationship between the current drawn by the tips and the plasma flow speed is known as the Mach probe calibration problem. In general, the models which relate the upstream and downstream currents to flow speed reduce to an expression of the form

$$\frac{I_{up}}{I_{down}} = \mathbf{exp(}kM\mathbf{)}\,. \tag{2.1}$$

Here, M is the Mach number of the flow ($M=V_{flow}/c_s$, $c_s=\mathrm{sqrt}(2T_e/m_i)$) and k is a constant determined by the model used.

The picture is complicated by the need to consider the extent to which ion collection is impacted by the presence of the magnetic field.[7] If the ion gyroradius (ρ_i), is much greater than the characteristic dimension of the probe (r_p), ions are considered to be unmagnetized. If the opposite limit holds, the ions are considered to be magnetized. For the highly magnetized case ($\rho_i/r_p<<1$), the magnetized model by Hutchinson[8] is by far the most widely used. In the unmagnetized case, the one dimensional model of Hudis and Lidsky[9] has been the most widely used in the past. Recent work by Hutchinson has criticized[10] the Hudis and Lidsky model for its one dimensional nature, and provided a two dimensional model[11] for the interpretation of data; this model will be used for the interpretation of HSX data, and will be discussed in greater detail below. Other expressions can be found in work by Shats, et. al., [12] or Hsu, et.al.[13]

The probe shown in figure 2.4 is only sensitive to flow along the line made by connecting the two tips. Hence, it is necessary to rotate it on a shot to shot basis to measure the total flow vector. This problem has been addressed by the construction of multi-tipped Mach probes. These probes are composed of many outward facing tips insulated by the body of the probe, and are known as "Gundestrup probes".[14] This style of probe has been selected for making flow measurements in HSX.

Figure 2.5: Photograph of HSX Mach probe. Note the outward facing tips used for the flow measurements (two are easily visible) and the proud pin used for measuring the floating potential. The tips are made of tungsten and the white body of the probe is boron nitride.

2.2.3 Mach Probes on HSX

In HSX, we have constructed two “Gundestrup” style probes. The geometry is demonstrated in figure 2.5. Six tips are mounted in a circle facing outward from the insulating body of the probe; the seventh tip is a "proud" tip extending beyond the insulating body. This tip is sensitive to the plasma in all directions and is generally used to measure the floating potential (V_f). The tips of the probes are composed of 0.75mm diameter tungsten wire; the six outward facing tips have been ground down so that a flat surface faces the plasma. On probe #1, each of the outward facing tips is .20" long; the proud tip is .146" long. The ceramic probe head is made of .375" diameter boron nitride. For probe #2, the length of the outward facing tips is 0.2" and the proud pin is 0.05" long; this probe head is mounted in 0.5" diameter boron nitride. In each case, the probe head is mounted in a stainless steel tube, which is attached to a rotatable feed through via a helical beam coupling. This allows the probe to be rotated ±90°. The entire assembly is placed inside a welded bellows and mounted on a sliding assembly to allow precise insertion into the HSX plasma. The signals are carried inside the vacuum using kapton coated wire, and brought out of the machine using a 15 pin D-connector feedthrough.

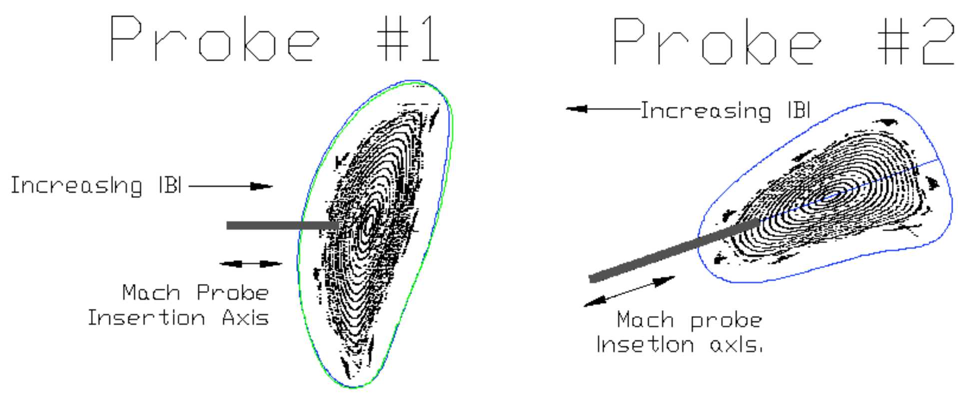

Figure 2.6: Locations of Mach probes on HSX.

The six radial tips are biased with respect to the HSX vessel at –180V, so that ion saturation current is collected. The local floating potential is digitized from the proud pin as a measure of local electric field behavior. For signal isolation and conditioning, special amplifiers have been constructed. Isolation is provided by Analog Devices AD215BY isolation amplifiers. This is followed by a four pole low pass filter with a cutoff at 100 kHz. All six Mach probe signals are recorded on the same digitizer, typically at 180 kHz, while the floating potential signals are recorded separately at typically 600 kHz. The amplitude and phase response of the amplifiers are shown in Appendix 1.

The two probes constructed for HSX are inserted into very different locations in the machine, as shown in figure 2.6. Mach probe 1 is inserted from the outboard side of the machine near the box port. At this location, the outboard side of the machine is the low |B| side. Mach probe 2 is inserted from the outboard side of the machine near the joint flange, into the end of the approximately triangular surfaces. At this location, the high |B| region corresponds to the outboard side, due to the helical structure of |B|. Note that the two ports chosen for the probes in HSX are ~135^o toroidally separated.

2.2.4: Examination of Magnetization

As stated in the introduction to this section, the solution to the Mach probe calibration problem depends on the degree to which the magnetic field impacts collection of the ions by the probe. A 20eV proton, typical of HSX parameters, has a gyroradius of ≈ 1mm at the HSX field of B=0.5 Tesla. Hence, neither of the limits ρ_i/r_p>>1 or ρ_i/r_p<<1 strictly hold, and some experiment needs to be done to determine how much the magnetic field impacts ion collection.

A simple experimental means of determining the magnetization is provided by Peterson.[7] Define I_{is0} as the average of signals from an opposing pair of pins:

$$I_{is0} = \left(I_{is}^{+} + I_{is}^{-}\right)/2. \tag{2.2}$$

The gundestrup probe on HSX has 6 symmetrically spaced outward facing tips, allowing three I_{is0} measurements to be made simultaneously. If the collection is perfectly unmagnetized, then the curve of I_{is0} vs. angle should be a circle. If the collection is strongly magnetized, then the I_{is0} vs. angle curve will be an ellipse elongated along the direction of the magnetic field.

To resolve this issue, the set of experimental data can be fit to an ellipse of the form

$$I_{is0} = 1/\left(K_1 + K_2\right), \tag{2.3}$$

where

$$K_1 = \frac{C^2\cos^2(\theta) + 2CS\cos(\theta)\sin(\theta) + S^2\sin(\theta)}{\delta_1^2}, \tag{2.4}$$

$$K_2 = \frac{S^2\cos^2(\theta) - 2CS\cos(\theta)\sin(\theta) + C^2\sin(\theta)}{\delta_2^2}. \tag{2.5}$$

Here, C=cos(α) and S=sin(α), where α is the tilt of the ellipse, θ is the angle of the tips of the Mach probe, and α, δ_1, and δ_2 are treated as fit parameters.

Examples of the data and fit are shown in figure 2.7, for two time slices in a QHS discharge. The time slice at 815 ms refers to a time before the bias probe is energized; the plasma is only slowly flowing at this time. The time slice at 819 msec. corresponds to well into the bias pulse, when the plasma has begun to flow. It can be seen that there is a slight ellipticity to the curves; comparison of this figure and figure 2.8 reveal that the slight elongation is actually along the direction of flow.

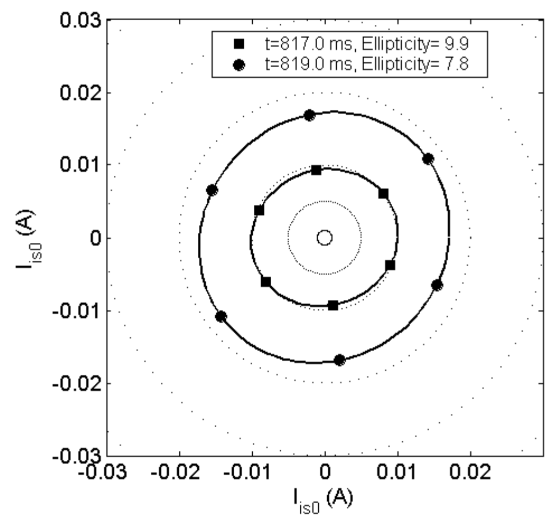

Figure 2.7: Magnetization curves for two time slices in a discharge.

Following Peterson, an ellipticity figure of merit can be defined as

$$\text{Ellipticity} = 100\left(\frac{\delta_1}{\delta_2} - 1\right). \tag{2.6}$$

If $\delta_1 = I_{is0||}$ is the I_{is0} current collected when the faces are aligned parallel to the field and $\delta_2 = I_{is0\perp}$ is the I_{is0} current drawn when the faces are aligned perpendicular to the field, then this figure of merit corresponds to the degree of magnetization. This would be the case if the ellipse were extended along the magnetic field. The calculated ellipticity is illustrated in the legend of figure 2.7, showing that the deviation of the curves from a circle is small. Hence, an unmagnetized collection model will be used for analyzing HSX data.

2.2.5: Mach Probe Modeling for HSX.

The Mach probe data in this work is analyzed using the unmagnetized model proposed by I. Hutchinson.[11] In this model, the ion flux to a negatively biased sphere in a flowing plasma is calculated as a function of angle using a specialized Particle in Cell (PIC) code. In particular, the sphere is situated at the origin, and plasma uniformly flows toward the sphere from the z direction. By symmetry, the flux is independent of the polar angle (angle in the x-y plane); The flux is, however, a function of the azimuthal angle (angle from the z-axis). The calculations are repeated for different values of T_i/T_e and ion flow speed, $M=V/(ZT_e/m_i)^{1/2}$, where V is the flow speed in m/s, under the assumption of vanishingly small Debye length ($\lambda_D/r_p<<1$). This assumption is well satisfied for HSX, where $\lambda_D/r_p=\sim.01<<1$ The code can reproduce previous analytical results for a spherical probe in a finite T_i, stationary plasma. It is shown that a reasonable fit for the ion flux to the sphere in a flowing plasma as a function of azimuthal angle and flow speed is given by the expression

$$\Gamma_{IH}(M,\theta)=\Gamma_o \exp\{M[(1-\cos(\theta-\theta_f))K_u-(1+\cos(\theta-\theta_f))K_d]\}, \qquad (2.7)$$

where K_u=.64 and K_d=.7; these two numbers can be considered the calibration factors for this model. This expression is shown to be appropriate for T_i/T_e ratios from .1 to 10 and flow speeds M from 0 to 2.5. In the analysis of data from HSX, the three parameters Γ_o, M, and θ_f are treated as fit parameters, which are used to fit (2.7) to the six I_{sat} measurements at each time point using the Levenberg-Marquardt algorithm.[15] This algorithm has the advantage of providing uncertainty estimates for the fit parameters, provided the uncertainties in the signal are known.

An example of these fits is shown in figure 2.8, for the same discharges and time slices as in figure 2.7. Note that the set of six I_{sat} points is pulled farther to the bottom left when the bias is on (t=.001), corresponding to greater plasma flow from that direction. The fit function represents the data well, both before and during the biased electrode pulse. The uncertainty in the flow speed parameter is also illustrated in the legend.

In the daily use of these probes, the fit in equation (7) is applied to the six I_{sat} points at each time sample. This fit procedure yields the three fit parameters as a function of time, as well as the uncertainties in the fit parameters. This data is stored in the HSX database where it can be accessed with any of the standard data access routines. The time dependent magnetization parameters can also be stored in the database if desired.

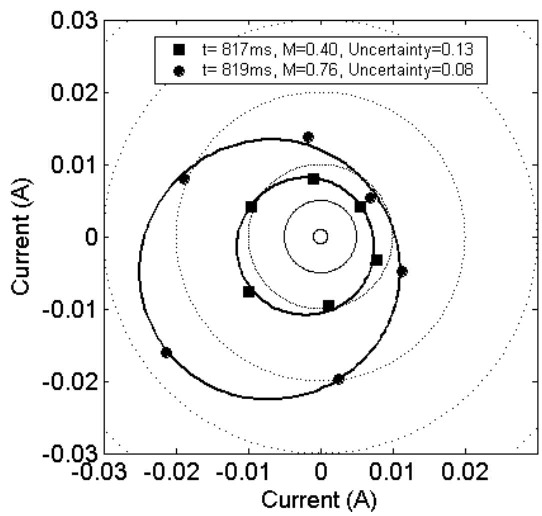

Figure 2.8: Flow fits for two time slices.

As a final comment on the Mach probe models, it should be noted that the purely geometric arguments by Nagaoka, et al.[16] suggest that if Mach probe ion collection is unmagnetized, then the ion saturation current as a function of angle can be written as

$$I_{sat}(\theta) = I_{sat}^{(0)}\left(1 - \alpha \frac{V}{c_s} \mathbf{cos}(\theta - \theta_F)\right). \tag{2.8}$$

In their purely geometric arguments, the coefficient α is left to be determined by some appropriate calibration procedure. It can be noted that this is exactly the Hudis and Lidsky[9] expression as written by Peterson[7], where

$$\alpha = \frac{\sqrt{2T_i(T_i + T_e)}}{T_e}. \tag{2.9}$$

The expression (2.8) can be shown to fit the HSX mach probe data well, giving further indication that an unmagnetized collection model is appropriate for HSX. In general the Hudis & Lidsky model as written in (2.8) fits the raw I_{sat} points as well as the Hutchinson model. The Hutchinson model was chosen because of its wide range of applicability as calculated by the PIC code, and because the calibration factors do not have the extra T_i and T_e dependencies found in (2.9).

2.3: Summary

A fast switching electrode system has been constructed for plasma biasing experiments in HSX. The electrode power supply consists of a capacitor bank and solid state switches, which can turn on the voltage or turn off the current in a few microseconds. The electrode is a cylinder of molybdenum encased in boron nitride armor.

Two Mach probes have been constructed to measure plasma flows in a flux surface. The Mach probes have 6 tips for the flow measurements, as well as a seventh tip for floating potential measurements. An unmagnetized collection model appears to be appropriate for analyzing data from HSX, and the unmagnetized model by Hutchinson is used in this research.

[1] A. Thorne, U. Litzen, and S. Johansson, *Spectrophysics*, (Springer, Berlin, 1999), p. 191.

[2] D.J. Den Hartog and R.J. Fonck, Rev. Sci. Instrum. **65**, 3238 (1994).

[3] R.A. Bamford, P.G. Carolan, and C.A. Bunting, Rev. Sci. Instrum **63**, 4926 (1992).

[4] R.P. Seraydarian, K.H. Burrell, N.H. Brooks, R.J. Groebner, and C. Kahn, Rev. Sci. Instrum. **57**, 155 (1986).

[5] R.E. Bell, L.E. Dudek, D.W. Johnson, and R.W. Palladino, Rev. Sci. Instrum. **70**, 821 (1999).

[6] J. Baldzuhn, M. Kick, H. Maassberg, and the W7-AS Team, Plasma. Phys. Control. Fusion **40**, 967 (1998).

[7] B.J. Peterson, J.N. Talmadge, D.T. Anderson, F.S.B. Anderson, and J.L. Shohet, Rev. Sci. Instrum **65**, 2599 (1994).

[8] K.S. Chung and I.H. Hutchinson, Phys. Rev. A. **38**, 4721 (1988) and references therein.

[9] M. Hudis and L.M. Lidsky, J. Appl. Phys **41**, 5011 (1970).

[10] I.H. Hutchinson, Phys. Plasmas **9**, 1832 (2002).

[11] I.H. Hutchinson, Plasma Phys. Control. Fusion **44**, 1953 (2002).

[12] M.G. Shats, D.L. Rudakov, R.W. Boswell, and G.G. Bork, Phys. Plasmas **4**, 3629 (1997).

[13] S.C. Hsu, T.A. Carter, G. Fiksel, H. Ji. R.M. Kulsrud, and M. Yamada, Phys. Plasmas **8**, 1916 (2001).

[14] C.S. MacLatchy, C. Boucher, D.A. Poirier, and J. Gunn, Rev. Sci. Instrum. **63**, 3923 (1992).

[15] P.R. Bevington and D.K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, (McGraw-Hill, Boston, 1992), p. 161.

[16] K. Nagaoka, A. Okamoto, S. Yoshimura, and M. Tanaka, Journal of the Physical Society of Japan **70**, 131 (2001).