

Chapter 5 - Experimental Apparatus

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5.1 Introduction

Details of the experimental apparatus used in investigations on an R.F. plasma (to be discussed in chapter 7) are presented in this chapter. The apparatus discussed here includes only a description of the vacuum vessel, ancillary equipment, and a brief description of the radio-frequency oscillator and circuits used to couple the R.F. power to the plasma. Diagnostic procedures and theory are dealt with at length in chapter 6.

Preliminary experiments were carried out in a small pyrex glass tube of 2 inches diameter and 24 inches long (fig. 5.1). The majority of the wave experiments were carried out in a larger tube of 4 inches diameter and 48 inches long. As both tubes were similar in construction and had the same pumping system, the larger system will be fully described below, and the differences between results obtained in the two systems will be discussed in chapter 6 and chapter 7.

5.2 Large System

The discharge tube and the majority of the ancillary equipment are shown in figure 5.2, while figure 5.3 gives a schematic diagram of the tube, magnetic field coils, and pumping system. A framework of pressed angle steel housed the pumping equipment on which the vertical tube was mounted. A solenoid consisting of four modules surrounded the tube and was mounted on four supports attached to the frame. To ensure maximum stability, a framework which passed over the top module of the solenoid was bolted to the main frame. The tube comprised three sections of 4 inch internal diameter Q.V.F. pyrex tubing, the central section being 24 inches long and the top and bottom sections being 12 inches long.

Fig. 5.1 Schematic diagram of the small pyrex glass tube showing axial magnetic field coils and R.F. field coils.

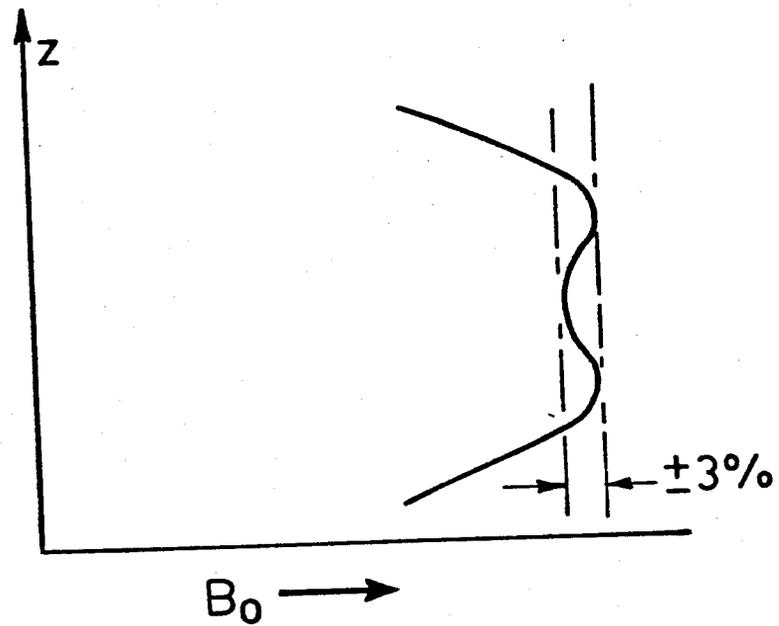
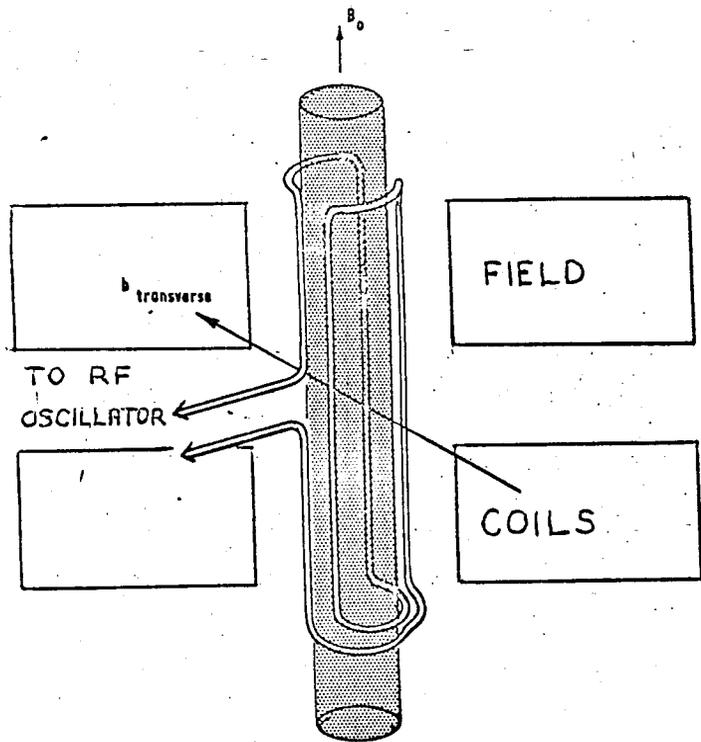


Fig. 5.2 General arrangement of the experimental apparatus and ancillary equipment for the large tube.

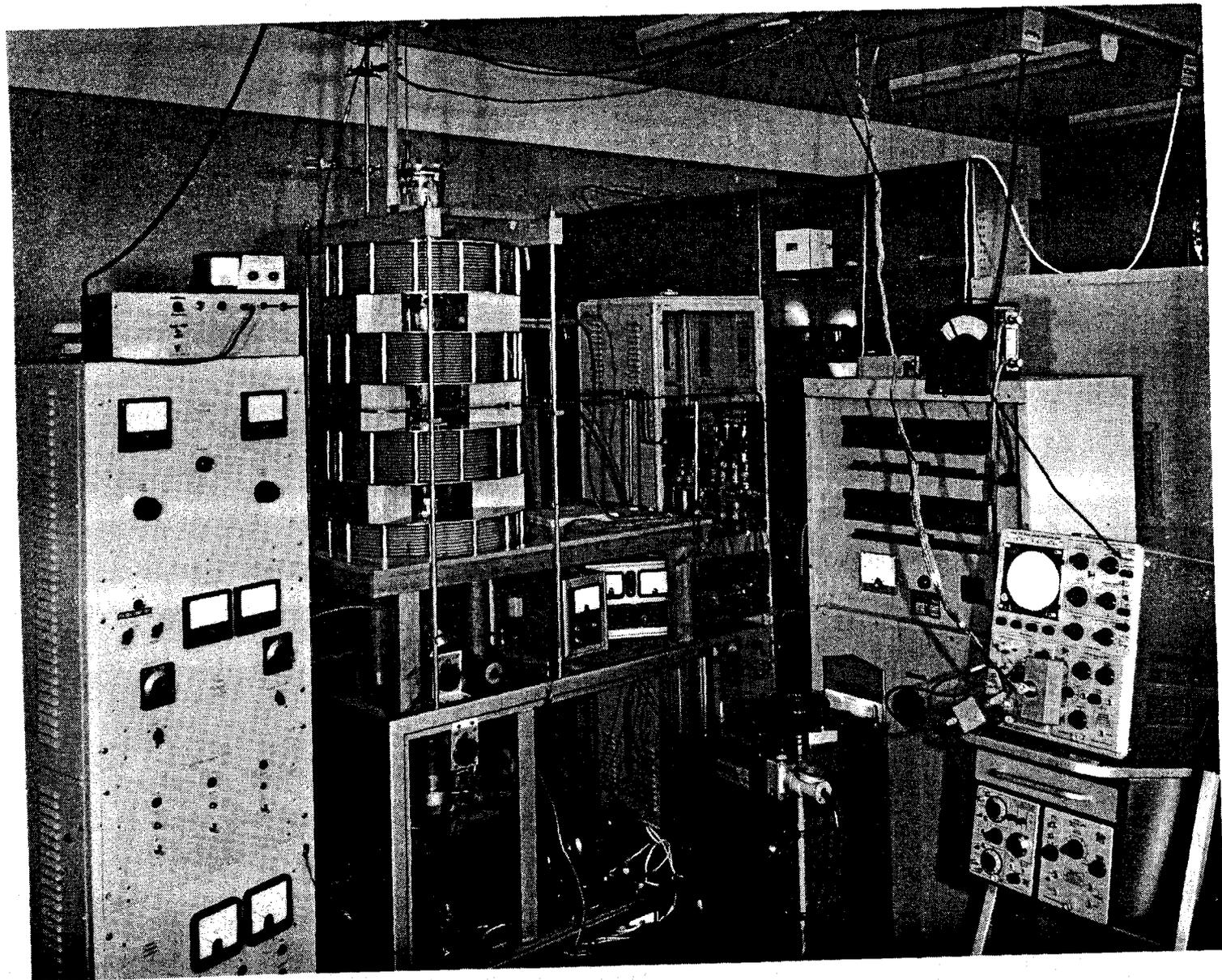
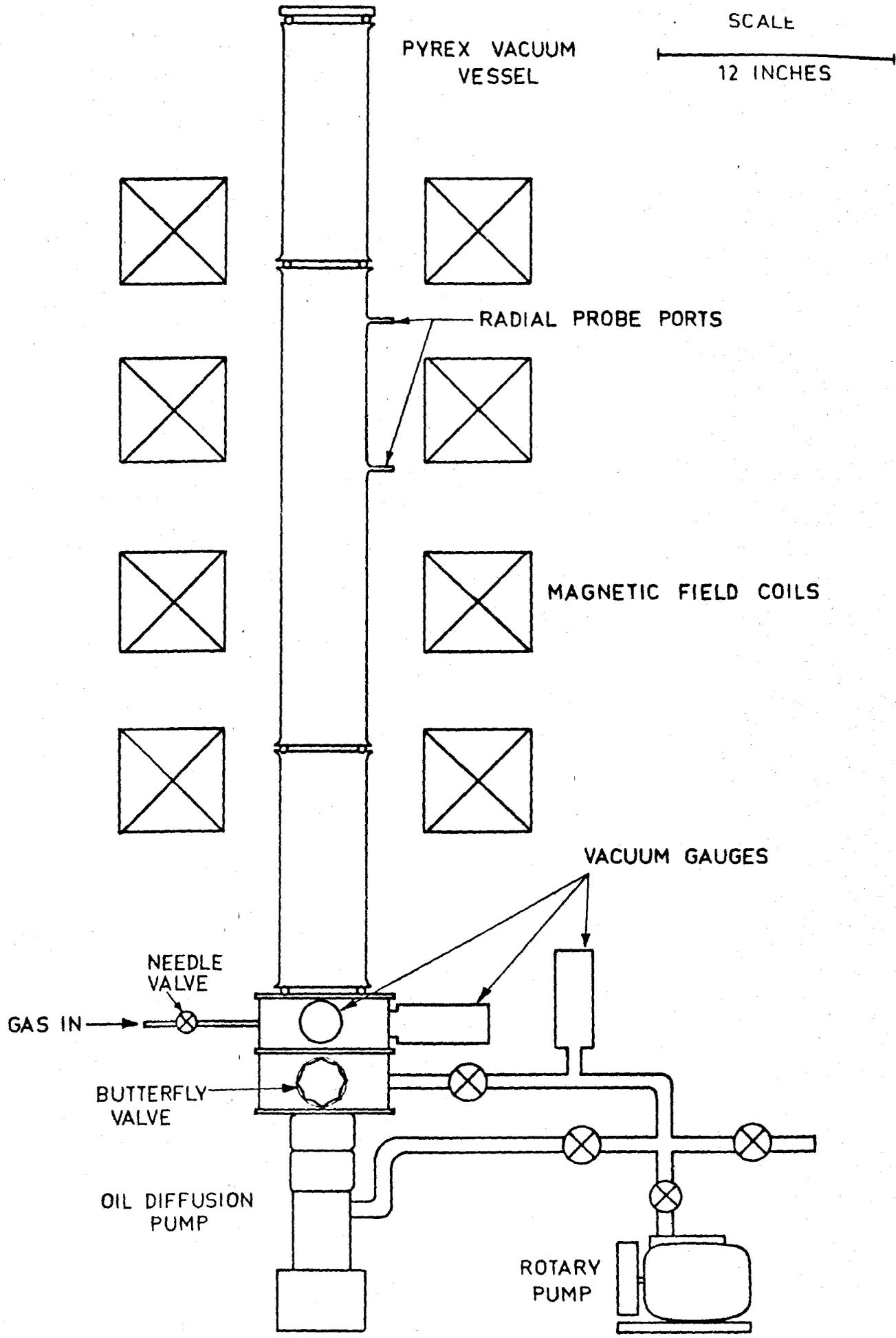


Fig. 5.3 Schematic diagram of the large pyrex glass tube showing axial magnetic field coils and vacuum pumping apparatus.



PYREX VACUUM VESSEL

SCALE

12 INCHES

RADIAL PROBE PORTS

MAGNETIC FIELD COILS

VACUUM GAUGES

NEEDLE VALVE

GAS IN

BUTTERFLY VALVE

OIL DIFFUSION PUMP

ROTARY PUMP

Ease of dismantling was achieved by using Viton 'O' rings in aluminium cages to seal the three sections together, and to provide a degree of stability to the vertical structure. The bottom section of the tube was sealed by one of the 'O' rings to a manifold which was bolted to the frame and supported the vacuum system and pressure gauges. The top section of the tube was sealed with a removable pyrex disc. Alternative discs had vacuum seals allowing small pyrex sheathed probes to be inserted into the tube. A single stage mechanical pump maintained a backing line pressure of about 50 millitorr, while a 3" oil diffusion pump fitted with a baffle valve could maintain a base pressure of below 10^{-2} millitorr in the tube. The diffusion pump used silicon type 504 oil.

The base pressures were measured with a Penning vacuum gauge, while the gas pressure and backing pressure were measured with Pirani gauges. Since Argon is a monatomic gas, a higher degree of ionization can be achieved far more easily than with Hydrogen and the majority of experiments were therefore carried out using Argon gas. Although the discharge was insensitive to small amounts of impurities, hydrocarbons could break down and build up on the walls and electric probes as a layer of carbon, resulting in incorrect measurements. Using silicon oil in the diffusion pump helped reduce this problem.

Welding grade Argon was used due to its low proportion of impurities which are set out below.

Welding Grade Argon

<u>Gas</u>	<u>Percentage</u> (volume basis)
Argon	99.99
Nitrogen	<0.01
Oxygen	<0.001
Hydrogen	<0.0001
Carbon dioxide	<0.0005
Water vapour	<0.0025

Measured at 16°C.

(This information was supplied by C.I.G. Ltd.)

The Argon was taken from the cylinder via a ballast tank with a volume of about two litres and a needle valve to the manifold. The pressure in the ballast tank was generally kept at 5 p.s.i. above atmospheric pressure. Hydrogen gas could be introduced from a cylinder in a similar manner, either separately or mixed with the Argon as a trace gas. As can be seen from the table above, the impurity content of the Argon was low and since the gas was continuously passing through the discharge tube, no trapping of any kind was employed. Gas pressure was determined by the phenomena being investigated and was generally 1.5 millitorr, but some experiments were carried out in the pressure range 0.2 to 10 millitorr. The pressure was continuously monitored with a Pirani gauge and since very accurate values of the neutral gas pressure were not required, the manufacturer's pressure calibration was used.

When inserting probes into the tube or cleaning parts of the apparatus, the tube had to be let down to atmospheric pressure and exposed to air. Most of the gases consequently adsorbed by the walls were removed by maintaining a R.F. discharge for a few hours. The pyrex walls became quite hot, driving off most adsorbed gas, this being seen by the change in colour of the discharge from the white characteristic of air, to the light pink of Argon.

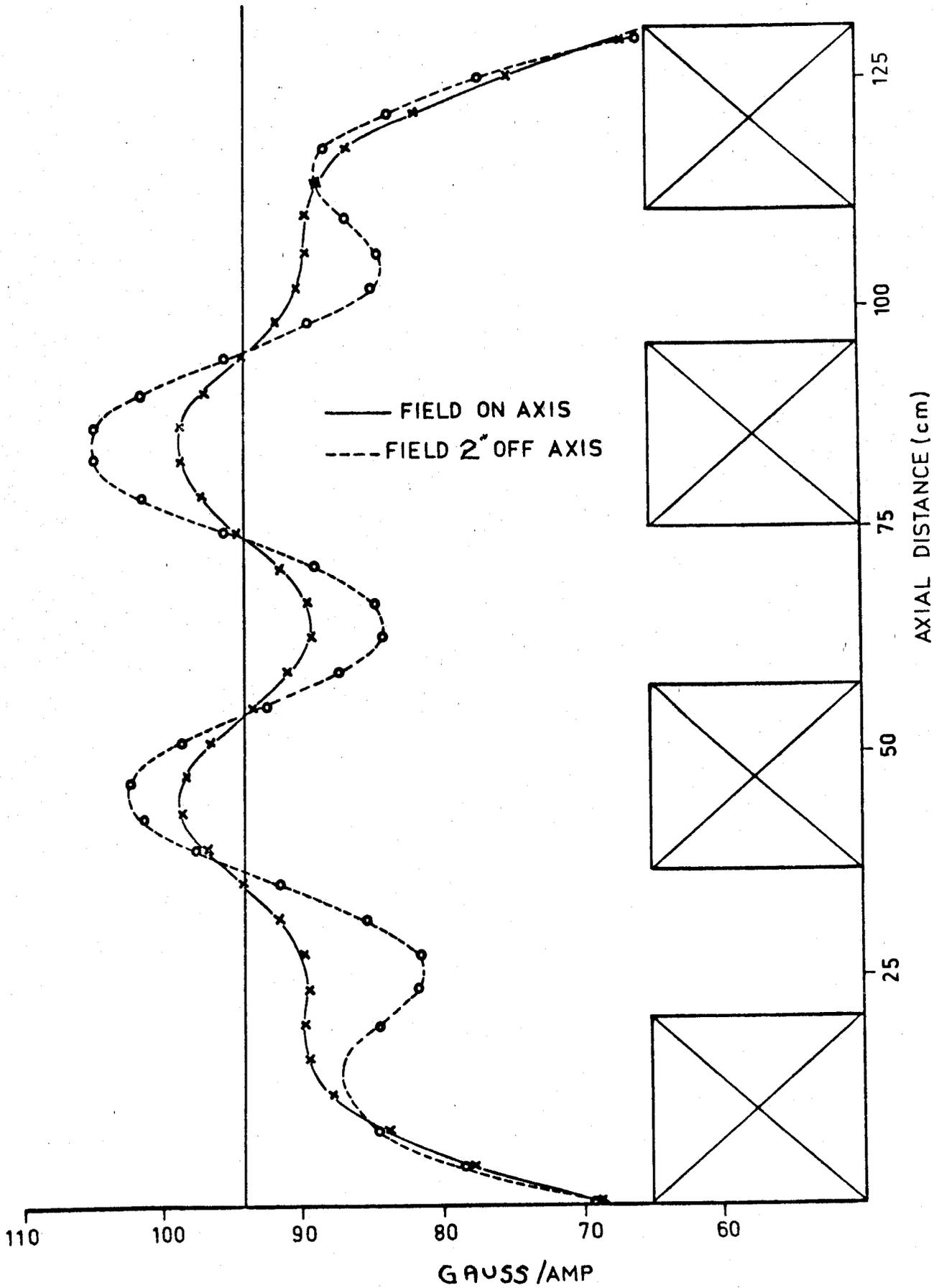
Small pyrex side arms joined to the main tube allowed magnetic probes to be inserted radially into the plasma using a floating vacuum seal. As the main tube was vertical, axial probes of up to 4 feet long could easily be inserted through a vacuum seal, bonded to the top sealing disc with Araldite. Both types of vacuum seals allowed longitudinal and rotational movement of the probes.

5.3 The Solenoid

The vacuum vessel was surrounded by a solenoid which, when energised, supplied an axial magnetic field of up to 1.6 kilogauss, uniform to within $\pm 10\%$ over the volume occupied by the plasma (fig. 5.4).

The D.C. power supply for the solenoid was rated at 100 volts and 190 amperes, and consequently for maximum power the optimum matching resistance of the solenoid had to be about 0.5 ohms. To achieve the best matching for the solenoid to dissipate up to 19 kilowatts of power and to produce the most uniform field, the following factors had to be taken into account in

Fig. 5.4 Axial magnetic field produced by the solenoid on-axis and 2 inches off-axis.



the design of the solenoid:

1. The number of modules constituting the solenoid.
2. The diameter and length of the modules.
3. The number of turns on each module.
4. The type and diameter of the conducting cable.
5. The thickness and type of insulating material covering the cable.

It was decided that four modules would be used, this configuration allowing easy accessibility to the tube and a large surface area to dissipate the heat arising from ohmic losses in the cable. After considering both the required field specification for maximum magnetic induction, minimum ripple, and physical limitations on the apparatus, a basic rectangular coil of 5 inches width and 9 inches inside diameter was chosen. The large inside diameter was needed as probes were to be inserted radially into, and axially down the outside of the tube. A spacing of 4 inches between the modules was about the minimum permissible in order to retain easy accessibility. Preliminary investigations with the small tube showed that an axial magnetic field of at least 1.5 kilogauss was required over an axial distance of two feet. A simple solenoid approximation implied that a total number of about 780 turns was required for this field strength. This meant that each module had to have approximately 14 layers with 14 turns in each layer. This obviously imposed a restriction on the maximum diameter of the cable.

The paucity of available cables capable of carrying the required current of 190 amps meant that a compromise had to be reached. Single

wires of large diameter were not sufficiently flexible to be wound onto the formers and so multistrand cable had to be used. A cable consisting of 19 strands of 0.052 inch diameter wires with an overall diameter of 0.260 inches was finally selected. This cable was covered with a thin plastic insulation of 0.030 inch thickness, giving a total diameter of about 0.320 inches. The total length of the cable was about 1000 yards and it had a resistance of 0.6 ohms.

The field of the basic module was computed by adding contributions from each single turn in the coil. The on-axis magnetic field for a single turn at a radius R cm from the axis is:

$$G_1(x) = \frac{2\pi}{10} \frac{R^2}{(R^2+x^2)^{3/2}} \text{ gauss/amp,}$$

where x is the distance in centimetres along the axis from the centre of the turn.

The total field, $G_2(x)$, of the whole coil module is found by adding the field due to the 14 layers, each of 14 turns:

$$G_2(x) = \frac{2\pi}{10} \sum_{n=0}^{13} \sum_{i=1}^{14} \frac{R_i^2}{(R_i^2+(x+na)^2)^{3/2}} \text{ gauss/amp}$$

where R_i are the radii of successive turns of the layer, a is the overall diameter of the conductor including insulation and n is the number of layers.

The field due to the four modules was calculated and gave an on-axis magnetic field of 9.26 gauss/amp at the centre of the modules

when they were spaced 4 inches from each other. The modules were wound on brass formers which had been coated with 'Glypolin', a high melting point insulating varnish. They were strengthened with brass rods arranged around the inner and outer diameters and screwed between the two end flanges of the formers. With the modules constructed and each separated by 4 inches, the field on-axis at the centre was measured to be 9.2 gauss/amp. The axial variation of the field was too large with this separation of the modules and the optimum spacing between the modules was determined empirically using the D.C. power supply and a Hall effect gauss meter. The most uniform field was found at a spacing of 4.5 inches between the centre two modules and 3.75 inches between these and the outside modules.

The field variation of the full solenoid was measured on-axis, and 2 inches off-axis where the wall of the tube would be and are shown in figure 5.4. Along the central axis the average magnetic field is 9.4 gauss per amp over the central axial two feet of the solenoid with a maximum variation of $\pm 5\%$. The inductance of the coils reduced the ripple in the current from the supply to below 0.2%, yielding a magnetic field quite constant in time. The wave experiments were carried out in this central region and the decrease in the magnetic field beyond this section was considered less important.

5.4 Production of the R.F. Magnetic Field

The simplest way to excite an $m = 1$ helicon wave is with a high-frequency current loop which produces a magnetic field which couples with radial component of the wave magnetic field (Christiansen (1969)). A

simplified diagram of the wave fields for the $m = 1$ helicon is given in figure 5.5.

Most previous work on helicon wave propagation has employed 'ringing' capacitors and a spark gap to obtain the required frequency and wave amplitude. This work is concerned with the production of a continuous plasma with a standing helicon wave and consequently a vacuum tube oscillator was employed as a source of R.F. energy. A block diagram of the R.F. system is given in figure 5.6. To prevent frequency 'pulling' on the oscillator by impedance changes in the load, the output stage was isolated from the oscillator valve by two amplifier buffer stages. The oscillator consisted of a triode (half a 12 AX7) with a tuned anode-grid circuit. The low R.F. power from this stage was amplified by a tuned buffer to about 50 watts which in turn was used to drive the 600 watt final stage. A pair of Philips type TB2.5/400 tetrode valve operating in push-pull class C mode with 2.3 kV applied to the anodes constituted the final amplifying stage. The average D.C. anode current drawn by these valves was in the range 200 to 400 milliamps.

The oscillator could be tuned from 6 MHz to 30 MHz in two switched bands, but the final amplifier required changes of the tuning inductors in the output stage. Although the output coil was designed for use with a balanced transmission line, experimental considerations dictated the use of a single unbalanced coaxial line. Consequently, one side of the final coupling inductance had to be earthed and the power then fed into a 71Ω high-voltage coaxial cable.

Magnetic probes inserted into the plasma very rapidly became overheated, causing the insulation on the wire coil to break down.

Fig. 5.5 Simplified diagram of the wave fields for the $m = 1$ helicon wave. The applied transverse R.F. field is also shown.

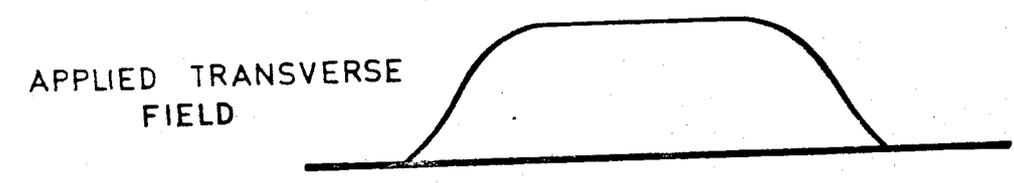
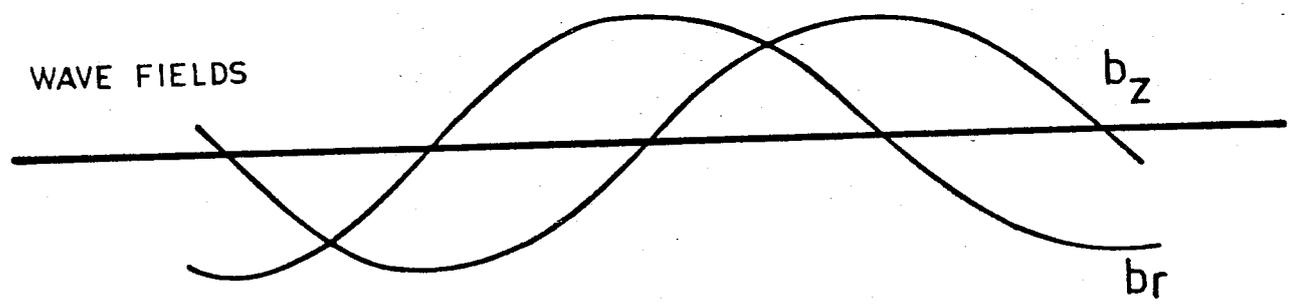
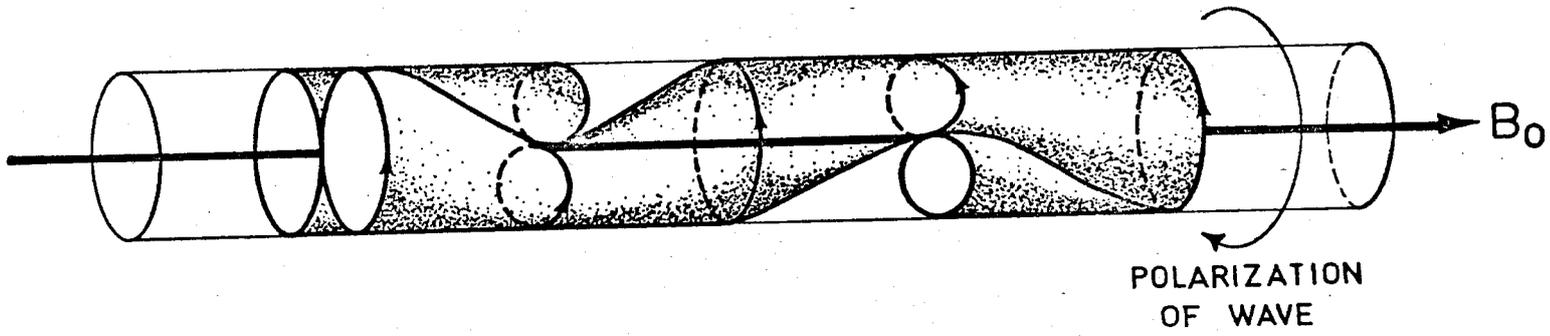
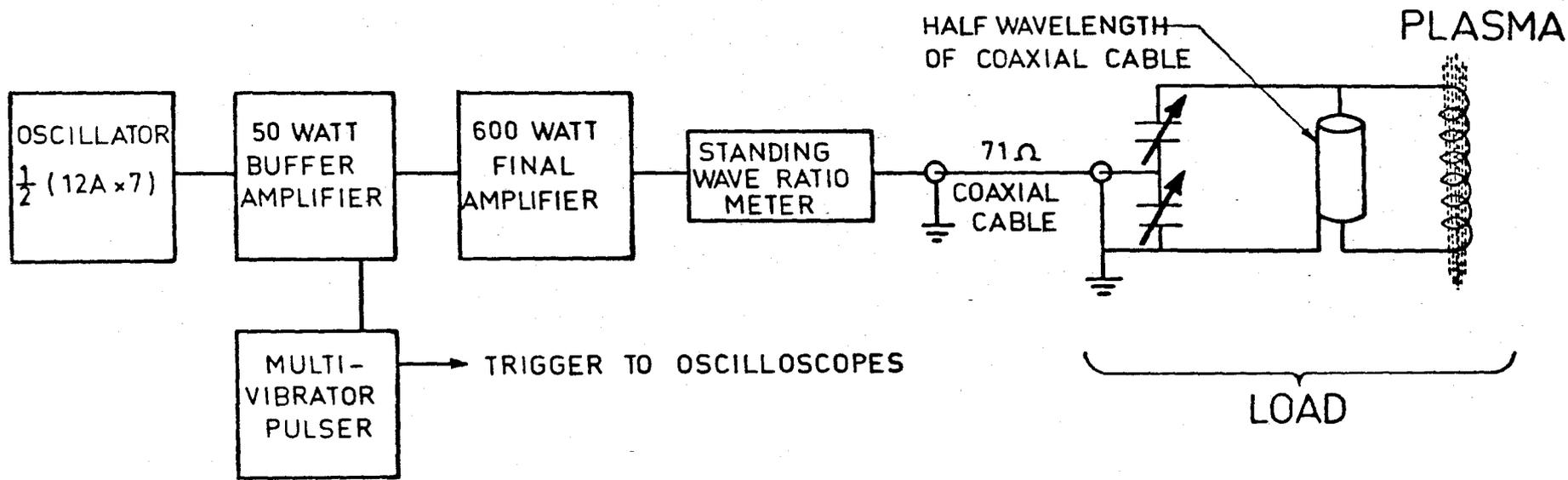


Fig. 5.6 Block diagram of the R.F. system including optimum matching section to plasma.



To eliminate this problem, a simple free-running multivibrator was constructed which pulsed the buffer stages of the oscillator off and on. Although the frequency and pulse length could be varied, a duty cycle of 10% was chosen, with the oscillator being on for 10 milliseconds and off for 90 milliseconds. This mode of operation prevented the probes from overheating while still allowing the behaviour of the plasma to be easily observed. An added advantage was that the signals from the microwave interferometer could be continuously monitored. The plasma was exceptionally reproducible and changes in the electron density could be simply measured. A triggering voltage could be taken from the pulse unit when required in some experiments.

Variable high-voltage capacitors were used to match the coaxial cable to the load coil on the vacuum tube. As the load coil is in effect a balanced circuit, a half wavelength section of coaxial cable connected across the coil was used to achieve optimum matching to the unbalanced line (see fig. 5.6). A standing wave meter measured the degree of matching between the oscillator and the load. This meter was checked using a length of coaxial cable somewhat over a half wavelength long inserted between the oscillator and the input of the coaxial cable to the load. The inner and outer conductors were exposed at a number of points along the length of the cable to allow measurements of the voltage and current to be taken. A vacuum tube voltmeter with a linear high-frequency response up to 700 MHz (Hewlett-Packard type 410B) was used for voltage determination.

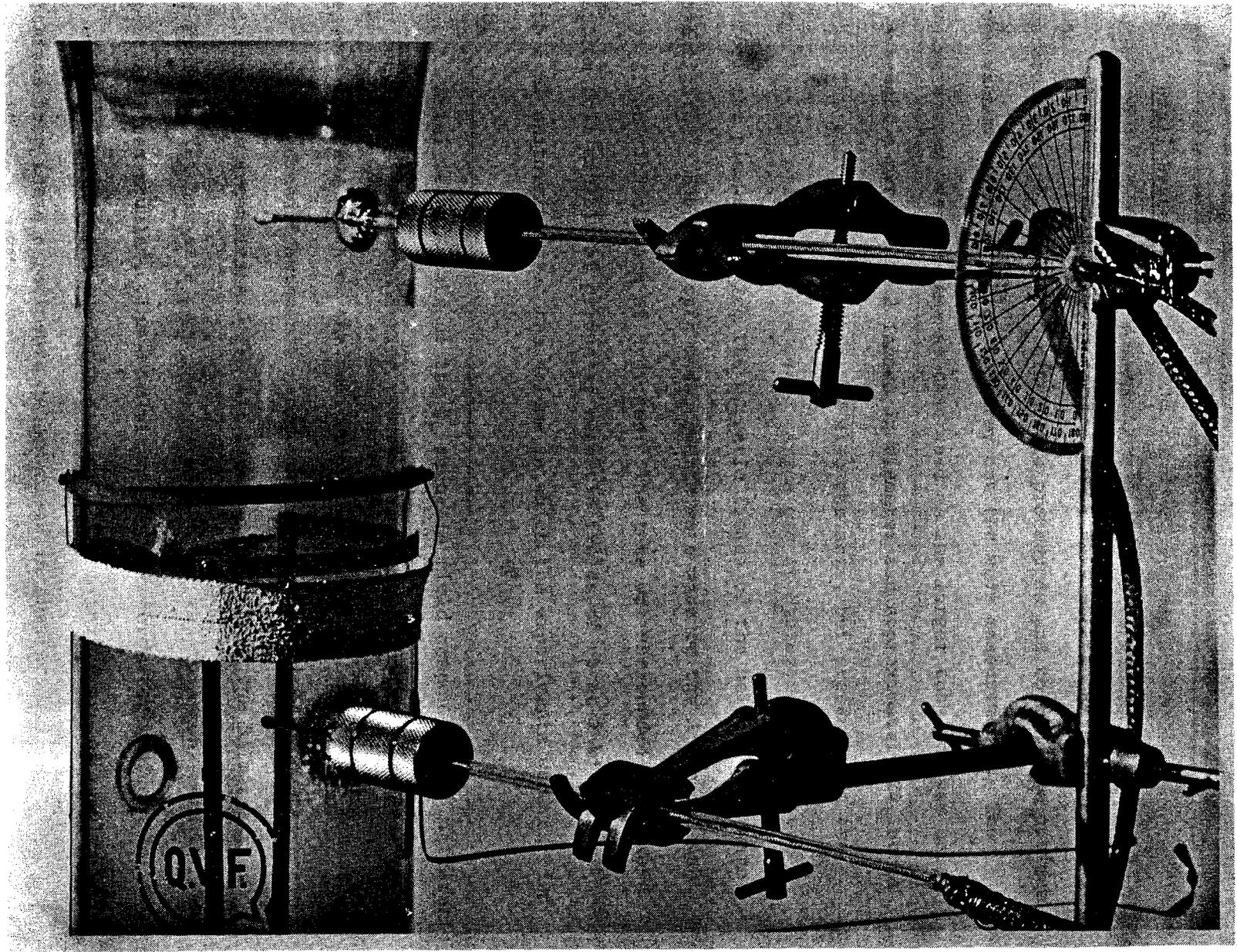
The large R.F. voltages on the line (above 1 kV peak to peak at standing wave maxima) required the construction of a high-voltage R.F. probe for the voltmeter. A graph of voltage against length yielded the

voltage standing wave ratio (V.S.W.R.) which was used to check the standing wave meter. Differences between the two methods of measurement were less than 10% over the range of interest (i.e. V.S.W.R.'s ratios between 1:1 and 10:1).

The D.C. power being drawn by the final anodes could easily be measured and the power in the coaxial line was derived from absolute measurements of the voltage and the standing wave ratio. The efficiency of the final amplifier was calculated to be 65%. The power reflection coefficient was calculated using a Smith chart, and the power being delivered into the matching section load was calculated to be 180 ± 20 watts. The power dissipated in the plasma is quite difficult to measure, but would be less than 180 watts by an amount equal to the heating of the matching components and the power being radiated other than into the plasma.

For all conditions of the plasma, the power delivered into the matching section-load was measured to be within the limits mentioned above. The geometrical arrangement of the coil surrounding the vacuum vessel used to produce the transverse R.F. magnetic field is shown in figure 5.7. The axial length of the coil for the experiments described in this thesis was 25 cm ($\sim \frac{1}{2}$ plasma wavelength). To minimize electrostatic pickup in the magnetic probes, power was fed into the centre of the coil, rather than at the ends. Typical radial probes are also shown in figure 5.7.

Fig. 5.7 Geometrical arrangement of R.F. coil surrounding vacuum vessel. The uppermost probe was used to measure b_{θ} while the lower probe was used to measure b_r .



5.5 Small System

A number of preliminary experiments were carried out on a small apparatus (fig. 5.1) to test diagnostic procedures and to find the optimum sized vacuum vessel in which to carry out the wave measurements. The pumping system was the same as that used on the larger tube and was used to evacuate a pyrex tube 2 inches in diameter and approximately 24 inches long. The gas handling system was also the same, but pressures in the range 4 - 100 millitorr were used. Argon gas or Hydrogen gas were used to form the plasma in which the magnetic fields of the helicon wave were investigated. Spectroscopic measurements were made on the Argon plasma or on Argon with a trace of Hydrogen. The tube was surrounded by a two-section coil capable of producing magnetic fields of up to 2 kilogauss with $\pm 3\%$ uniformity over the volume in which the experiments were carried out.

Axial measurements of the b_z magnetic field component with different end conditions, i.e. conducting plates or a vacuum boundary were made to measure the wavelength of the helicon wave. Electron temperature measurements were deduced from double Langmuir probes and also from spectroscopic relative line intensities. The AII lines of Argon and the Balmer series of Hydrogen (either as a pure gas, or as a trace gas in Argon) were the spectral lines studied. The 8 mm microwave interferometer was used to give an estimate of the electron density. The significance of results obtained from these experiments is discussed in chapter 7.