

Experimental Studies of Magnetic Islands, Configurations and Plasma Confinement in the H-1NF Helic

A thesis submitted for the degree of
Doctor of Philosophy of
The Australian National University

by

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This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief, it contains no material previously published or written by any other person, except where due reference is made in the text.

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*“The difference between what we do and what we are capable of doing
would suffice to solve most of the world’s problems.”*

Mahatma Gandhi

Dedicated to my parents

Contributions

The majority of experimental results presented in this thesis have been obtained by the author, entirely during the course of this project, in cooperation with Boyd Blackwell. I draw special attention to the following contributions.

- The image warping technique (mentioned in chapter 3) and the method of calculation of t near a rational surface (appendix C.1) are developed by Boyd Blackwell for this project.
- The fast mapping system is developed by Mark Gwynneth, with the guidance of Boyd Blackwell, as a part of an engineering project.
- Figure 4.21 and the details about the Mirnov fluctuation experiments are provided courtesy of David Pretty.
- The spectroscopic results have been obtained in cooperation with John Howard.

Much of the experiments, data analysis, interpretation and theory have been done by the author, with guidance from Boyd Blackwell. Technical contributions are acknowledged in the acknowledgement section. Any other contributions are acknowledged in the usual fashion of referencing.

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Abstract

Rational magnetic flux surfaces in fusion (toroidal plasma confinement) devices can break the magnetic field lines and reconnect them in the form of magnetic islands. Formation of these magnetic islands can have a serious impact on the plasma confinement properties of the device. Islands can in general degrade the confinement by mixing up different regions of the plasma. However there has been experimental evidence of confinement improvement by island induced transport barriers, under certain conditions. Even though there are a large number of theoretical and experimental works on magnetic islands to date, there is clearly a paucity of convincing experimental understanding on the nature of behaviour of islands in plasma. This thesis reports detailed experimental studies conducted on the H-1NF heliac stellarator, to gain an in-depth understanding of magnetic islands and their influence in plasma confinement.

Work reported in this thesis can be mainly divided into three parts: (a) high resolution imaging of vacuum magnetic islands and flux surfaces of H-1NF, (b) accurate computer modeling of H-1NF magnetic geometry and (c) detailed experiments on magnetic islands in plasma configurations.

Electron-beam wire-tomography in the H-1NF has been used for the high resolution mapping of vacuum magnetic flux surfaces and islands. Point-to-point comparison of the mapping results with computer tracing, in conjunction with an image warping technique, has enabled systematic exploration of magnetic islands and surfaces of interest. A fast mapping technique has been developed, which significantly

reduced the mapping time and made this technique suitable for mapping at higher magnetic fields.

Flux surface mapping has been carried out at various magnetic configurations and field strengths. The extreme accuracy of this technique has been exploited to understand the nature of error fields, by point-by-point matching with computer tracing results. This has helped in developing a best-fit computer model for H-1NF magnetic configurations, which can predict rotational transform correct to three decimal places. Results from plasma experiments on magnetic configuration studies are best explained by the new model.

Experiments with low order magnetic islands in plasma configurations yielded some new results. It has been observed that the low order magnetic islands ($m = 2$) near the core of the plasma serve as ‘pockets’ of improved confinement region under favourable conditions. This results in significant profile modifications including enhancement of the radial electric field near the core to a large positive value. The characteristics of islands are found to be dependent on the plasma collisionality and the island width.

Experiments with a magnetic configuration which exhibits no vacuum islands, but the core rotational transform (t) very close to low order rational value, show a spontaneous transition of the radial electric field near the core to a large positive value ($E_r \sim 5$ kV/m), with a strong electric field shear (~ 700 kV/m²) and localised improvement in confinement, during the discharge. Evidence indicates that the transition is driven by the excitation of low order ($t = 3/2$) magnetic islands near the axis during the plasma discharge, due to the modification of rotational transform profile by toroidal plasma currents. The situation is similar to the Core Electron-Root Confinement (CERC) observed during high temperature ECH plasma discharges on other helical devices. This result provides an experimental evidence for the hypothesis that the threshold conditions for observing CERC can be reduced by exciting magnetic islands near the core of the plasma.

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Chapter 1

Introduction

Thermonuclear fusion has the potential to provide a safe, environmentally clean and virtually inexhaustible energy to satisfy the increased demands of the future. In this process, two light nuclei combine to form a heavier nucleus releasing an enormous amount of energy. At very high energies required for the fusion reaction to happen, fusion fuel is in the plasma state. Production, heating and confinement of this hot plasma, on sufficiently long time scales, poses major scientific and technological challenges. Magnetic confinement has come closest to meeting this. Experiments around the world with different magnetic geometries are providing an in-depth understanding of the complex behaviour of magnetically confined plasma. Even though we are on the verge of designing a prototype fusion power reactor, the physics of fusion plasma is not fully understood. The objective of this thesis is to explore one of the core physics issues concerning the fusion plasma: the effect of magnetic islands on plasma confinement.

1.1 Energy, fusion and plasma physics

World energy demand is increasing at an alarming rate. At least a 50% increase has been predicted by the middle of this century, mainly due to the increase in population [1]. Furthermore, about 1.7 billion people, most of them in Asia and sub-Saharan Africa, still live without electricity [2, 3]. The energy requirements

to provide them a decent standard of living is tremendous. Present day energy is mainly derived from fossil fuels, which is not a long term solution as the reserves are limited. Access and affordability of this energy source is looking less and less promising for much of the world's population. In addition, continuous burning of fossil fuels put the environment at risk. Global warming, acid rain etc. are near term concerns, the long term effects are still uncertain.

There are many alternatives to fossil fuels. However, many of them are not well suited for concentrated large scale energy production needed by future generations. Nuclear fusion, the same process which powers the Sun and the stars, is one of very few options left. As an energy source, the proposed nuclear fusion reactor is inherently safe as there are no chain reactions involved, virtually inexhaustible as the fuels are abundant, environmentally friendly as there is no green house gas emission or long lived radioactive waste, and has the right energy density for the large scale production of electricity [4] (Energy produced per unit mass of fuel from nuclear fusion is millions of times that of burning fossil fuels).

Nuclear fusion is the process of combining two light nuclei to form a heavy nucleus. The mass difference is converted into enormous energy according to Einstein's famous mass energy relation, $E = mc^2$. However, in order to make two nuclei fuse together, sufficient energy has to be supplied to overcome the Coulomb barrier of the like charges. Fusion reaction therefore requires high temperatures, in the order of millions of degree Celsius. At this high temperature, fusion fuel is fully ionised and in plasma state. In the Sun and stars, this hot plasma is confined by the intense gravitational force. Production, confinement and sustainment of such a high temperature plasma in laboratory are challenging, both scientifically and technologically.

Presently there are two schemes to the controlled thermonuclear fusion in laboratory: magnetic confinement and inertial confinement. In inertial confinement, a pellet of solid fusion fuel is ablated by strong laser pulses or charged particle beams to implode and fuse within the core disassembly time determined by inertia of the

particle [5]. The details of inertial confinement are not in the scope of this thesis, but more information can be obtained from the review articles [6, 7]. The magnetic confinement approach confines hot plasma of sufficient density and temperature in a magnetic bottle for a time scale sufficient for fusion reactions to occur. This aims to produce fusion in the steady state. At present, magnetic confinement is a much more developed technology than inertial confinement.

In laboratory, the most favourable fusion reaction is that between two hydrogen isotopes, deuterium (D) and tritium (T). This reaction has the highest cross-section and can be achieved at relatively lower temperatures (figure 1.1). In the D-T reaction, the products are an alpha particle (a He^4 nucleus) with a kinetic energy of 3.5 MeV and a neutron with kinetic energy of 14 MeV. In order for this reaction to happen, a temperature of about 10-100 keV (1eV=11600K) is needed. The condition on the ‘fusion triple product’, which is the product of plasma density (n), plasma temperature (T) and the time for which energy should be confined in the reactor (τ_E), for ignition¹ for this reaction is

$$nT\tau_E > 6 \times 10^{21} \text{ m}^{-3} \text{ keVs} \quad (1.1)$$

The presently achieved value is very close to ignition (at $1.5 \times 10^{21} \text{ m}^{-3} \text{ keVs}$) [8]. Up to 16 MW of fusion energy, with an energy amplification factor Q (ratio of fusion power to input heating power) ~ 0.65 lasting for a few seconds, has been demonstrated in a few devices around the world [9, 10]. The next generation fusion device, the International Thermonuclear Experimental Reactor² (ITER), is aiming to achieve $Q \geq 10$ and ~ 500 megawatts of fusion power for a burning time of nearly 400 seconds.

Even though ITER, which will be the predecessor to a prototype demonstration

¹Ignition is the point where energy released from the fusion reaction is sufficient to maintain the temperature of the plasma, and no external heating is needed. Often called the ‘burning plasma’.

²ITER is an international experimental project to build a fusion device which is capable of producing a self sustaining Deuterium-Tritium fusion reaction [<http://www.iter.org>].

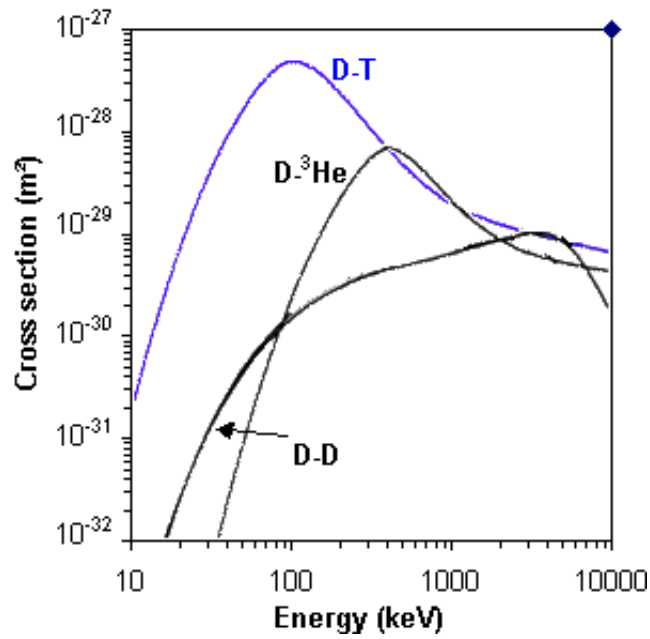


Figure 1.1: Cross sections for a few fusion reactions

reactor, has been designed based on empirical scaling laws, the physics of fusion plasma is not fully understood. There are many unresolved issues which have to be addressed to make the system more reliable, simple and economically viable. These include the understanding and control of anomalous particle and energy transport from the plasma core, physics processes governing the transition to the high confinement regime (H-mode), formation and effects of magnetic islands and transport barriers, and many issues related to MHD instabilities which can cause major disruptions etc. The goal of the current fusion experiments around the world is to have a better understanding of highly complex magnetically confined plasmas and also to try alternative geometries for magnetic confinement. As most of the physics information obtained from these machines is interchangeable between magnetic geometries, all these experiments contribute to enrich the fusion science database.

H-1NF (H-1 National Plasma Fusion Research Facility) heliac stellarator in the Australian National University is a medium sized plasma confinement device dedicated to investigation of basic plasma physics relevant to magnetic confinement fusion. Even though the plasma parameters are much lower than fusion conditions, flexibility of this machine to conduct controlled experiments makes this device suit-

able for exploring many physics issues which are not possible in bigger machines (Details are provided in chapter 2). This thesis exploits this opportunity to study the effect of magnetic islands on plasma confinement in a controlled fashion.

Presented below is a brief introduction to various magnetic confinement geometries and some basic magnetic properties of the fusion devices. Formation and importance of magnetic islands in fusion devices has also been explained. The objective of this thesis and thesis organization are given in the last two sections.

1.2 Magnetic confinement geometries

Plasma is a collection of charged particles. The motion of a charged particle can be influenced by a magnetic field. Charged particles can move freely along a magnetic field line whereas their motion across a field line is restricted. This property has been exploited to confine hot plasma in magnetic confinement devices.

The simplest approach is to use a linear device with field lines along the length of the device. Here particles are confined radially, but can escape axially. In order to reduce the end losses, field strength can be increased at the ends so that a fraction of particles reflect back (‘magnetic mirrors’) to the centre of the solenoid (figure 1.2). Even though increasing magnetic field near the end significantly reduces the end losses, confinement efficiencies of such mirror devices are not adequate for fusion purposes.

One obvious method to avoid the end losses is to close the field lines to form a ring, a ‘toroidal’ magnetic field geometry. However, a pure toroidal magnetic field is not sufficient to confine plasma. This is because the field line curvature and the field gradient (field strength of a torus decreases with distance from the centre of the torus) causes electrons and ions to drift in opposite direction giving rise to an electric field perpendicular to the toroidal magnetic field. This results in the ejection of plasma to the material walls. In order to cancel the charge separation and

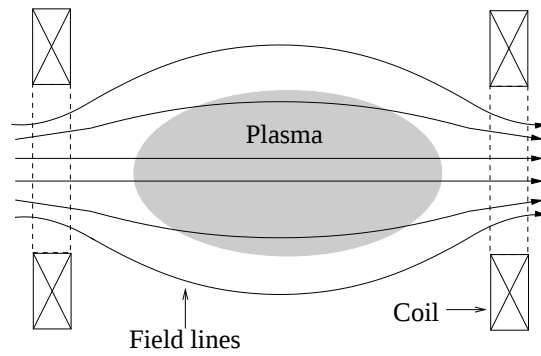


Figure 1.2: Schematic of a mirror device

the electric field, an additional component of magnetic field is required in poloidal direction (along the minor circumference of the torus). The resultant field lines are twisted and form well-nested magnetic flux surfaces which, in principle, can confine plasma indefinitely. An additional vertical field provides horizontal equilibrium of the plasma.

Toroidal plasma confinement devices are generally divided into two classes, based on the method of generating the poloidal magnetic field required to make the magnetic flux surfaces. Tokamaks are the most successful fusion devices at present. These devices (figure 1.3) drive a toroidal plasma current, in the order of kilo to mega ampere, by transformer action, which generates the required poloidal field and also heats the plasma (by ohmic heating). However, tokamaks are intrinsically non-steady state devices and the requirement of toroidal plasma current can lead to severe disruptions. Joint European Torus (JET) in UK [9], DIII-D in USA [11] and JT-60U in Japan [12] are some of the currently operating large tokamaks. ITER, the next step burning plasma experiment, is based on the tokamak concept.

Stellarators (figure 1.4) are toroidal plasma confinement devices which depend solely on external coils to generate the nested magnetic flux surfaces. Therefore, unlike in tokamaks, stellarators have vacuum magnetic flux surfaces. Stellarators are inherently non-axisymmetric devices. As there is no requirement of toroidal plasma currents and current drive, they are well-suited for steady-state fusion power plants. However the 3D magnetic geometry makes the system and coil design complicated.

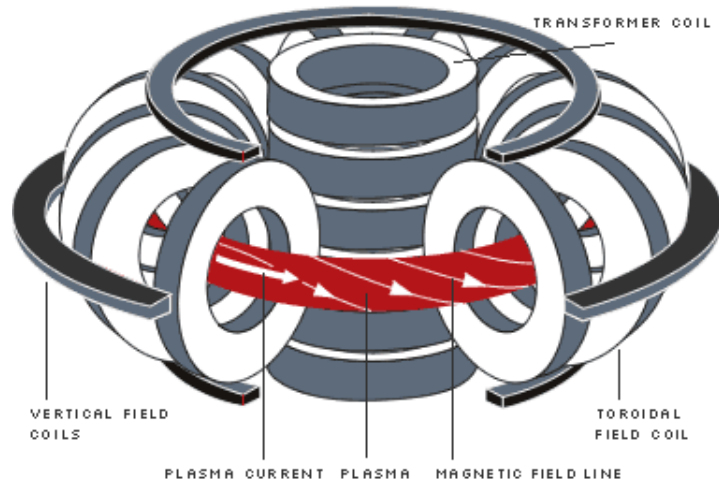


Figure 1.3: Schematic of a tokamak (Figure courtesy <http://www.ipp.mpg.de>)

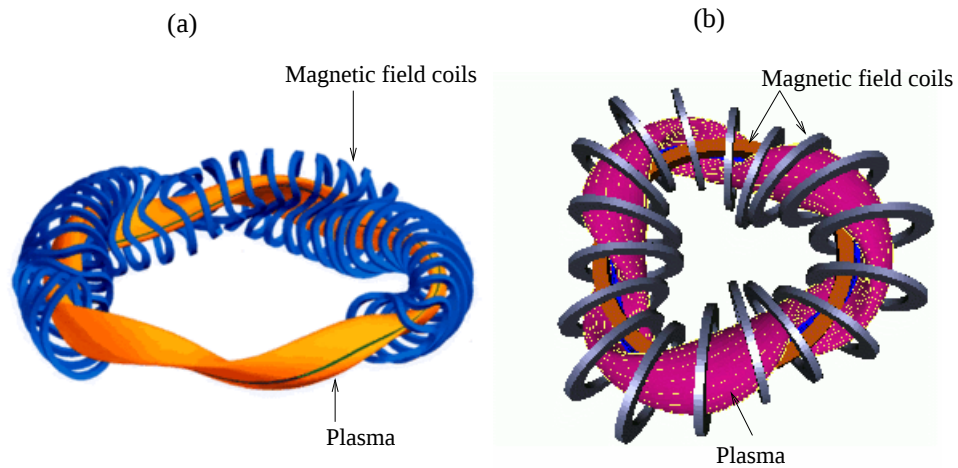


Figure 1.4: Schematic of stellarator. (a) W7-X stellarator being built in Germany (Figure courtesy <http://www.ipp.mpg.de>). (b) H-1NF heliac stellarator in The Australian National University

The performance of stellarators at present is not up to the standard of tokamaks in achieving conditions relevant to fusion. However the steady-state nature of these devices is promising. Results from two large stellarator experiments, the Large Helical Device (LHD) [13] in Japan and the W7-AS [14] in Germany have provided performance close to those of present day tokamaks. The physics of stellarators relevant to power plant capabilities is being explored in these experiments. Further, two large stellarators, the advanced stellarator W7-X [15] in Germany and the quasi-axisymmetric compact stellarator NCSX in USA [16], are being built to enable detailed investigations on stellarator physics.

1.3 Magnetic properties of fusion devices

As mentioned before, the twisted magnetic field lines of a toroidal confinement device form a set of well-nested toroidally and poloidally closed magnetic flux surfaces. Figure 1.5 gives a poloidal cross section (Poincaré section) of computed nested magnetic flux surfaces of the H-1NF heliac. Each point on a surface represents a toroidal transit of a field line, which forms a surface after many toroidal transits.

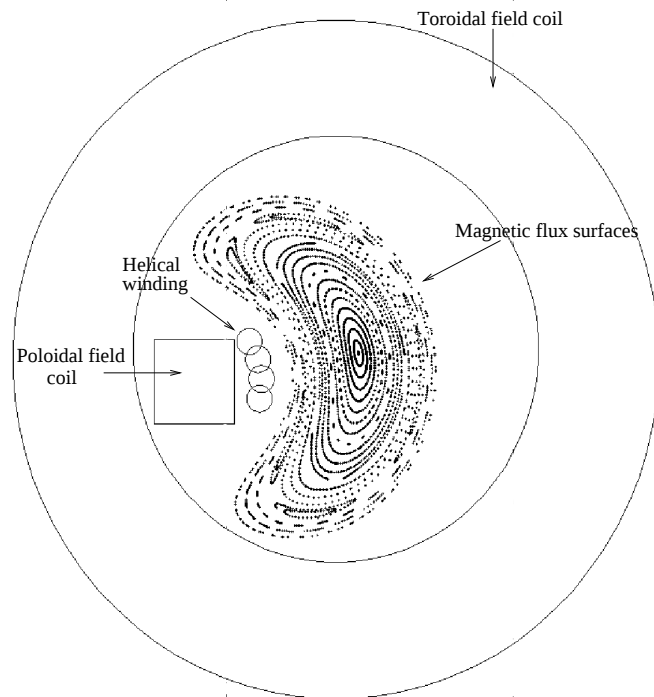


Figure 1.5: Magnetic flux surfaces of H-1NF heliac stellarator

The measure of twist of the field lines is given by the rotational transform (t), and its reciprocal, the safety factor (q), defined by [17]

$$t \equiv \frac{1}{q} = \lim_{N \rightarrow \infty} \frac{\sum_{k=1}^N \iota_k}{2\pi N} \quad (1.2)$$

Where ι_k is the poloidal rotation angle of a field line during one toroidal circuit (figure 1.6), N is the number of toroidal rotations. In general, t is used in stellarators and q in tokamaks. The rotational transform of a machine should be as high as possible to reduce the ∇B and curvature drifts. Rotational transform also has to

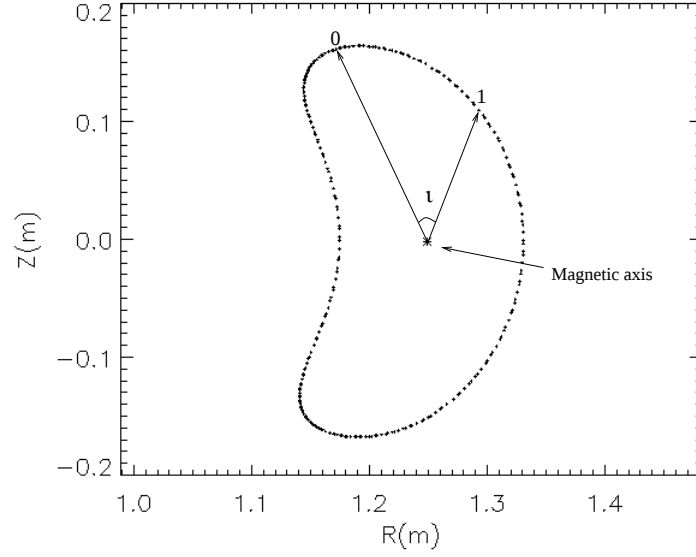


Figure 1.6: Figure explaining the concept of rotational transform. One computed flux surface of H-1NF heliac is shown. Assume that 0 is the starting point of the field line and 1 is the position of the field line after first toroidal transit. In actual case of H-1NF, the angle ι is more than 2π .

be large for MHD reasons, for example, to provide equilibrium for finite pressure plasma.

When the rotational transform of a magnetic surface is a rational number, $t = n/m$, where n and m are toroidal and poloidal mode numbers respectively, the flux surface is called a rational surface. In a rational surface, the field lines close on themselves after n poloidal and m toroidal excursions. Rational surfaces have a great importance in the confinement properties of a fusion device. The importance of rational surfaces to the formation of magnetic islands is outlined in the next section.

Magnetic shear is a quantity which measures the change in rotational transform from one surface to the next. Magnetic shear $s \equiv t' = \frac{dt}{d\psi_t}$ in magnetic coordinates, where ψ_t is the toroidal magnetic flux. In cylindrical coordinates, $t' = \frac{dt}{dr}$ where r is the averaged minor radius [17]. Magnetic shear has an important role in confinement, MHD instabilities and formation of islands. As a general rule, large shear

gives better stability. Magnetic shear has a strong effect on the development of magnetic islands. As explained in coming sections, low magnetic shear introduces large islands as the island width is inversely proportional to the square root of the shear. However, too much shear can accommodate wide range of rational surfaces and may introduce many islands.

Magnetic well is another parameter which is an important factor for plasma stability. It is evident that, unlike a linear device, a toroidal confinement geometry cannot have a magnetic well in real sense, i.e. field strength increasing in all directions from the magnetic axis. Toroidal effects introduce an additional $1/R$ dependence where R is the major radius of the machine. The Specific Volume (U) of a flux surface is the derivative of the volume (V) enclosed by the magnetic flux surface with respect to the toroidal flux ψ_t [18]

$$U = \frac{dV}{d\psi_t} \quad (1.3)$$

this reduces to

$$U = \lim_{N \rightarrow \infty} \frac{1}{N} \int_N \frac{dl}{B} \quad (1.4)$$

Therefore, if the specific volume decreases outward, it means that the magnitude B of the field increases in an average sense. Thus the plasma region has a minimum B configuration, in average sense (average magnetic well). The magnetic well depth can thus be written as

$$\frac{\Delta U}{U} = \frac{U_{axis} - U_{edge}}{U_{axis}} \quad (1.5)$$

Magnetic well is generally favourable for stability.

1.4 Magnetic islands

Magnetic islands are topological defects in fusion devices - an undesired and in many circumstances an inevitable feature generated by error fields. These are small

regions of nested flux surfaces inside the main confinement volume with their own local magnetic axis (figure 1.7). These snake-like structures close on themselves after a certain number of toroidal and poloidal circuits depending on the ι value (see figure 1.8). The standard notation of describing an island is using the poloidal mode number m . For example, islands formed on $\iota = 3/2$ have two lobes in a poloidal cross section and are called $m = 2$ islands.

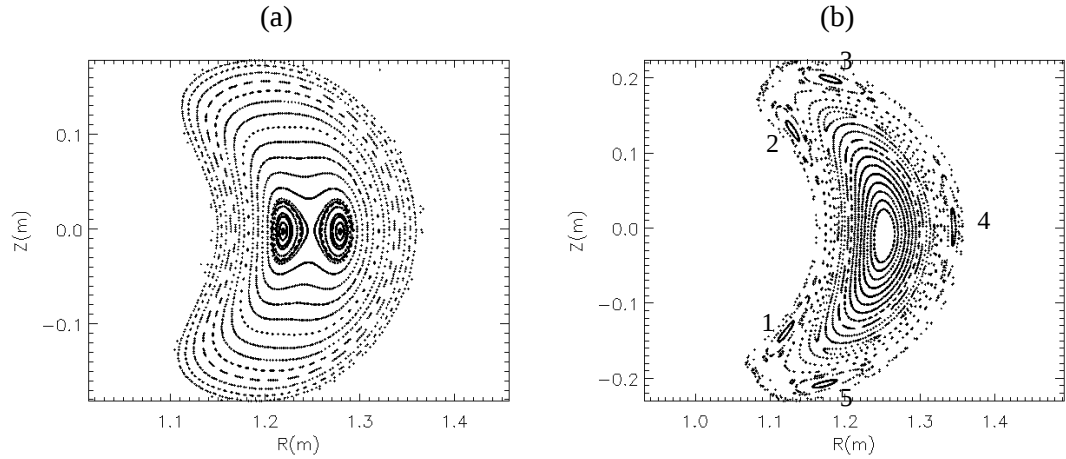


Figure 1.7: Magnetic flux surfaces of H-1NF heliac (computed using the *HELIAC* code) showing configurations exhibiting (a) $m=2$ islands and (b) $m=5$ islands

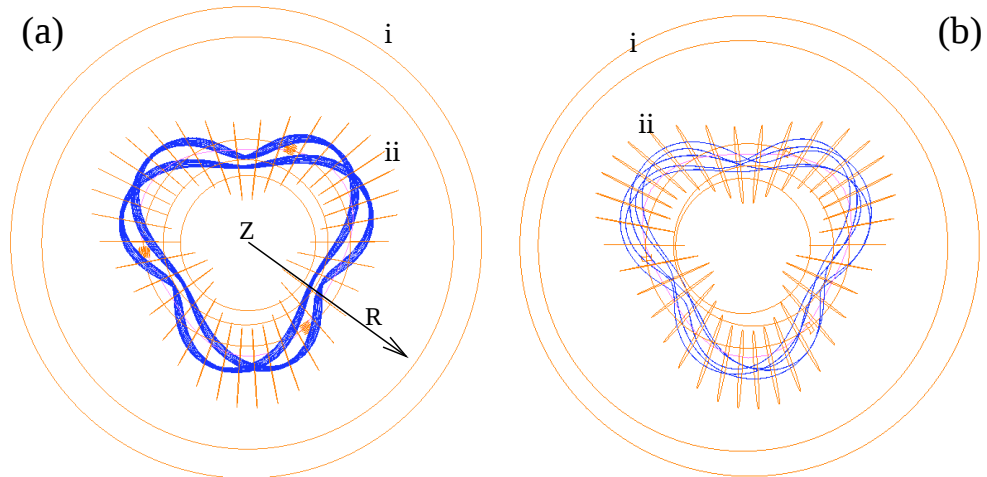


Figure 1.8: Top view of the magnetic island structure ('snake' in blue colour) of H-1NF heliac (computed using the *BLINE* code). (a) $m=2$ islands and (b) $m=5$ islands. Vertical (i) and toroidal (ii) field coils are marked.

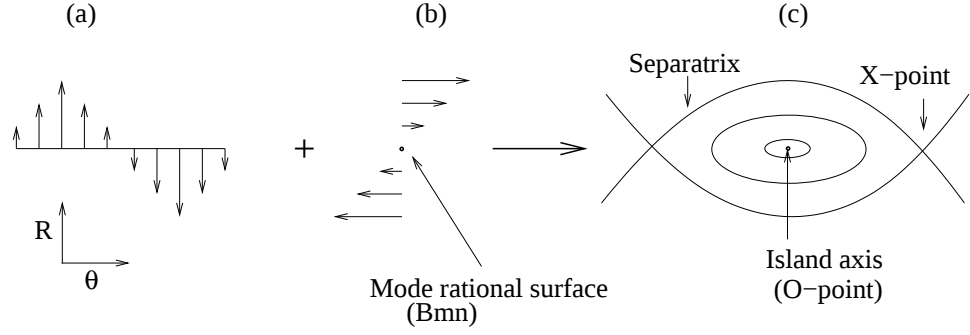


Figure 1.9: Formation of magnetic islands. (a) Radial component of the perturbation. (b) Poloidal magnetic field ($B^* = B_0 - B_{mn}$) showing the magnetic shear. (c) Magnetic island

1.4.1 Formation of islands

Islands are formed when a rational surface ($t = n/m$, where n and m are toroidal and poloidal mode numbers respectively) resonates with same mode number helical magnetic perturbation, if present.

Assume that there exists a perturbation field δB of the form $b_{mn} e^{i(n\phi - m\theta)}$ where b_{mn} is the Fourier component of the perturbing magnetic field with mode numbers m and n , and ϕ & θ are toroidal and poloidal angles respectively. Resonance of the Fourier components with rational surfaces having the same mode numbers ($t = n/m$) can break the field lines and reconnect in the form of island chains. The width of an island in toroidal flux [19] is given by the formula

$$\delta_{mn} \equiv 4 \sqrt{\frac{b_{mn}}{m \frac{dt}{d\psi_t}}} \quad (1.6)$$

where m is the poloidal mode number and $\frac{dt}{d\psi_t}$ is the magnetic shear. Alternatively, island width in cylindrical coordinates is given by [20]

$$\delta \approx 4r_s \sqrt{\frac{b_r L_s}{m B_\theta r_s}} \quad cm \quad (1.7)$$

where, r_s is the radius of the mode rational surface, b_r is the radial component of the resonant perturbation, L_s is the magnetic shear scale length and B_θ is the poloidal

magnetic field.

Each term b_{mn} in the Fourier expansion produces an island if there are rational surfaces with mode numbers m, n . If islands from different rational surfaces are big and close enough to overlap, the nested flux surfaces are destroyed and confinement property of the system in the region is lost. It can be seen from equation 1.6 that the width of an island decreases with increase in magnetic shear. Also the low order (low m number) magnetic islands are larger in size.

Error sources for the perturbation include stray magnetic field, coil placement errors, design imperfections, magnetic materials in the vicinity etc. In presence of plasma, any plasma current (self-consistent or RF induced) can modify the magnetic profile and lead to islands as mentioned in chapter 6. Due to the non-axisymmetric nature, stellarators can develop ‘natural’ islands. For example, H-1NF heliac is a three period heliac stellarator and any rational surface with n number 3 or its multiple are ‘natural’ modes ($t = 3/2, 6/5$ etc.). Islands developed on these rational surfaces are called ‘natural’ magnetic islands.

In tokamaks, there are two possibilities for resonant helical perturbation. Current driven Neoclassical Tearing Modes (NTM) [21] and static external field perturbations. In the former case, current perturbation at a particular rational q surface (where, $q = 1/t$) breaks and reconnects the field lines to form magnetic islands. When islands form, current separates into channels. These channels produce a poloidal field varying in strength and direction around the cross section. The latter case is similar to the island formation in stellarators.

1.4.2 Impact of islands on plasma confinement

The presence of magnetic islands can have serious impact on the plasma confinement properties of a fusion device. Islands radially connect different regions of plasma. Therefore plasma transport can much exceed the collisional-transport (and neoclas-

sical [18]) values in presence of islands. If there are many islands that are big enough on different rational surfaces, they can overlap and render the machine useless for confinement. There are many experimental evidences of confinement deterioration due to the presence of magnetic islands. For example, a decrease in the plasma density and stored energy has been observed in the Large Helical Device (LHD) when intrinsic magnetic islands ($m/n = 1/1$ & $m/n = 2/1$) are present [22]. Better plasma confinement was obtained experimentally by eliminating the islands, indicating that a magnetic configuration with no island is favourable for plasma confinement. A substantial deterioration of particle containment is observed in the Advanced Toroidal Facility (ATF) when external magnetic field perturbation is applied [23]. A dramatic drop in particle confinement is observed in Compact Helical System (CHS) [24] and Heliotron E [25] due to magnetic islands produced by externally applied field perturbation, when the magnetic axis is shifted outwards. Experimental studies of plasma transport across a magnetic island in the Compact Auburn Torsatron (CAT) indicates that increasing magnetic island size has little effect on ion diffusivity [26], whereas the electron diffusivity increases significantly above a critical size of island. Observed diffusion rates are found to be far exceeding neoclassical rates.

Magnetic islands can also improve the confinement if associated with an $E \times B$ sheared flow. The role of edge islands in the formation of edge thermal transport barriers and transition to improved confinement regime (H-mode) in the LHD has been experimentally confirmed [27]. Significant modification in the radial electric field profile and vortex like plasma flow ($E \times B$) have been observed due to magnetic islands [28], which is believed to be the main ingredient for confinement improvement. The heat transport inside the magnetic island in LHD was studied with a cold pulse propagation technique. The experimental results pointed to the possibility of magnetic islands forming internal transport barriers. Reduction in the heat transport inside the magnetic island O-point has been observed [29]. This is an indication that the generally observed ‘profile flattening’³ inside an island does not

³The $\nabla P = 0$ condition on a flux surface, where P is the plasma pressure, in principle requires the plasma parameters to be the same on both sides of an island. This may result in ‘flat’ regions in the radial profile, depending on the size of the island and plasma conditions.

always indicate the deterioration of the cross-field heat transport inside a magnetic island. The results also show that the heat diffusivity inside the island does not depend on the size of the island. The role of magnetic islands and low order rational surfaces near the core of the TJ-II plasma, in the development of recently discovered electron internal transport barriers, has been discussed [30, 31]. A density peak inside magnetic islands has been observed in some tokamak discharges [32, 33].

Even though magnetic islands improve confinement under some plasma conditions, in many situations, island suppression may be required. In tokamaks, the tearing modes and the associated magnetic island structures rotate (due to $E \times B$) in kilo Hertz range of frequencies. This rotation creates rotating perturbations in the magnetic field, density and temperature. Active rotation control during the plasma discharge, by the application of appropriate external magnetic field perturbations, has been considered as one method to suppress magnetic islands [34, 35]. A ‘seed’ island (or vacuum island in case of stellarator) can grow in the plasma or ‘self heal’ depending on the plasma conditions. In stellarators, a ‘coil healing’ method (healing of islands by external magnetic coils) can be applied to suppress vacuum magnetic islands [36]. ‘Self healing’ of an error field island by plasma has been experimentally observed in LHD when the plasma is collisionless ($\nu^* \lesssim 1$ where ν^* is the collision parameter⁴) and the plasma β (ratio of plasma pressure to magnetic pressure) is finite ($\gtrsim 0.1\%$) [37, 38, 39, 40]. Island widths in LHD are found to depend on plasma parameters and the magnetic axis position [37].

1.5 Objectives of this study

Experiments on magnetic islands have gained momentum after it was realised that islands can help in the transition to an improved confinement regime (H-mode). Even though there are a large number of experimental works on magnetic islands

⁴A dimensionless quantity represents the plasma collisionality, defined as $\nu^* = \frac{\nu_e R}{v_{th} \epsilon^{3/2} t}$, where the parameters are: the electron collision frequency (ν_e), the plasma major radius (R), the electron thermal velocity (v_{th}), the inverse aspect ratio (ratio of the plasma minor radius to the plasma major radius) of the device (ϵ) and the rotational transform (t).

to date, there is clearly a paucity of convincing experimental understanding on the nature of behaviour of islands in plasma. Furthermore, some of the experimental results on the effect of islands on the global plasma confinement scenario, from various devices, are conflicting and found to be sensitive to the magnetic configuration. Both self-healing (shrinking) and growth of islands have been experimentally observed, but favourable conditions for this to happen are not well understood. Some evidence of island current has been obtained in LHD, but the mechanism which generates this is poorly understood [37]. Understanding of the conditions of turbulent suppression by sheared flow and transport barrier formation is far from complete. The presence of islands in plasma configurations is normally inferred from flat profiles of density or electron temperature. However, in some cases, density peaks inside magnetic islands have been reported. It has to be noted in this context that the minimum size of an island in LHD for flattening to occur is expected to be ~ 2 cm [38]. Conditions for observing island signatures in plasma are not well understood. Some of these inconsistencies may be attributed to the lack of proper diagnostics. A recent study indicates that magnetic islands play a role in the generation of zonal flows [41]. Interplay between zonal flow and strong $E \times B$ shear flow [42, 43] and between magnetic island and $E \times B$ shear flow [28, 44] have been individually observed, but there is so far no direct experimental evidence of zonal flow generation due to magnetic islands. The role of magnetic islands in the generation of, and lowering the threshold conditions for generating, the recently classified ‘Core Electron-Root Confinement’ (CERC) in helical devices has been discussed [45, 46], but a detailed experimental study does not exist. Moreover, a large number of theoretical predictions on the interaction of magnetic island and plasma are awaiting convincing experimental verifications. (For example, see Ref [47, 48, 49, 50, 51, 52])

An in-depth understanding of magnetic islands and their effect on plasma confinement properties of a fusion device will help in controlling or making good use of the islands. This calls for a detailed, controlled experiment for different magnetic configurations and plasma conditions. As the larger fusion devices are not flexible enough for controlled magnetic island experiments, work on smaller devices like H-

1NF heliac has much importance. The coil system of H-1NF heliac (explained in detail in the next chapter) allows the magnetic configurations to be varied over a wide range to accommodate or avoid major rational surfaces and islands. Furthermore, low temperature argon plasma experiments on H-1NF will provide a different parameter window (for example, large ion gyro radius, high collisionality etc.) where island studies have not been done in the past. Feasibility of extensive high resolution localised diagnostics including Langmuir probes is an added advantage. The main objectives of the work reported in this thesis can be summarized as follows:

1. Devise a technique to obtain high resolution imaging of vacuum magnetic islands and flux surfaces of H-1NF.
2. Develop a suitable computer model for H-1NF magnetic geometry which can be used for further island / configuration studies.
3. Conduct detailed experiments on the effect of magnetic islands on H-1NF plasma using Langmuir probes and other diagnostic techniques. Of particular interest is to study the conditions for profile modifications, especially the radial electric field, and the effect of islands on plasma confinement.

1.6 Thesis organisation

This thesis is organised as follows: Chapter 2 gives a brief account on the magnetic and geometric properties of H-1NF heliac. In chapter 3, the technique developed for experimentally mapping the vacuum magnetic islands and flux surfaces is described. Accurate modeling of H-1NF magnetic geometry and determination of new empirical magnetic parameters of H-1NF by error field analysis is explained in chapter 4. Chapter 5 presents experimental results from plasma configurations exhibiting ‘natural’ magnetic islands. Experimental observations of spontaneous bifurcations in the radial electric field and its implications in plasma confinement are described in chapter 6. Conclusions and future scope of study is outlined in chapter 7. A short description of the magnetic flux coordinate system is given in appendix A. The *HELIAC* code input file for the newly developed empirical magnetic parameters of

H-1NF (determined as explained in chapter 4) and the as-built measurements of the toroidal field coil positions are given in Appendix B. Appendix C describes the calculation of ι near a rational surface, from mapping results. Langmuir probe techniques used to obtain temporally and spatially resolved plasma parameters from experiments are detailed in Appendix D.

Chapter 2

The H-1 Heliac

A Heliac (helical axis stellarator) is a low magnetic shear stellarator device in which the rotational transform (t) is mainly due to the spatial torsion of the magnetic axis [19]. Three on-going heliac experiments at present are the TJ-II heliac in Spain [53], the TU-Heliac [54] at Tohoku University, Japan, and the H-1NF heliac in the Australian National University [55]. Experiments reported in this thesis have been conducted on the H-1NF heliac stellarator. Many controllable magnetic properties of this medium sized ‘flexible’ heliac make it an excellent experimental device for many basic plasma experiments which are not possible in large fusion devices.

2.1 Machine overview

2.1.1 The coil system

The H-1 National Facility [55] Heliac is a medium sized three period stellarator with major radius $R_0 \sim 1$ m and average minor radius $a \sim 0.2$ m. The coil system of H-1NF consists of 36 toroidal field coils of 10 turns each, one poloidal field coil (central ring conductor) having 36 turns, a three period helical winding of four turns wound over the central ring conductor, two inner vertical field coils of 16 turns each, and two outer vertical field coils of 12 turns each. There is a provision of tapping the outer vertical field coils at 4, 8 or 12 turns. Major machine components are shown

in figure 2.1. All coils except the outer vertical field coils are inside the vacuum tank.

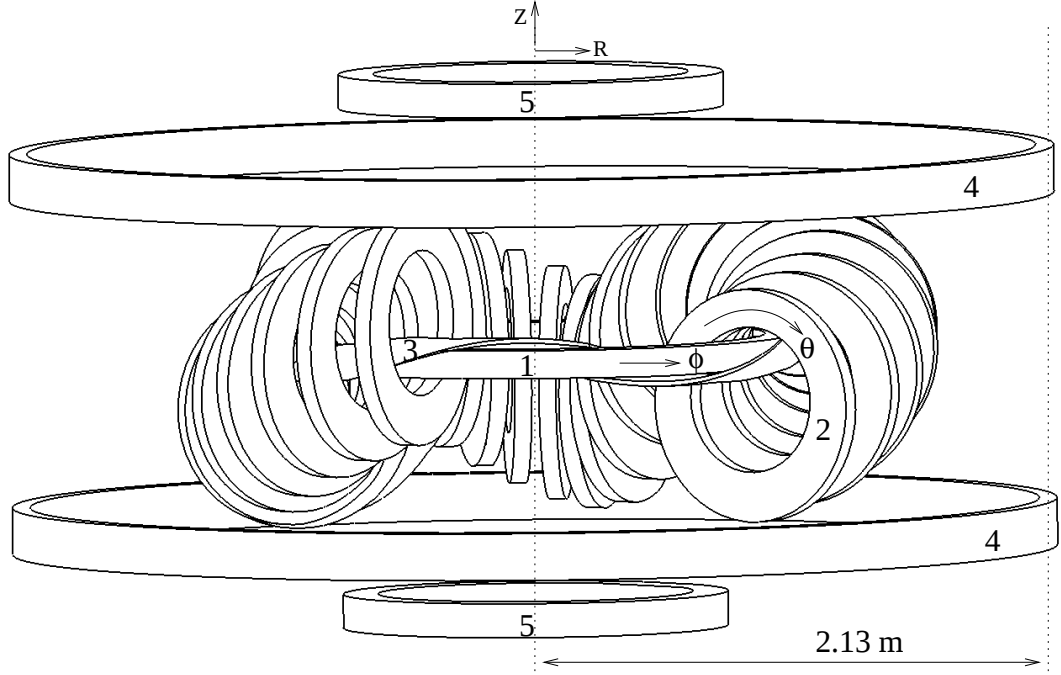


Figure 2.1: Coil structure of H-1NF showing the ring conductor(1), the toroidal field coils (2), the helical winding (3), the outer vertical field coils (4) and the inner vertical field coils(5). (Figure courtesy John Wach)

As mentioned before, in a heliac stellarator, the major source of the rotational transform is the torsion of the magnetic axis [19]. In the H-1NF, centres of the toroidal field coils are arranged in a three period helical path defined by [55]

$$R = R_0 + \rho_s \cos 3\phi \quad (2.1)$$

$$z = \rho_s \sin 3\phi \quad (2.2)$$

where ρ_s is the swing radius and ϕ is the toroidal angle. The vertical mid-planes are spaced according to

$$\phi = \phi' - 0.0097 \sin 3\phi' \quad (2.3)$$

where

$$\phi' = \frac{2\pi}{36}(j - \frac{1}{2}), j = 1 \text{ to } 36$$

Magnetic field coils are powered by either a motor-generator (MG) set or a dual

Table 2.1: Major machine parameters of the H-1NF

Major radius	1 m
Average minor radius	0.1 - 0.2 m
Aspect ratio	5+
Helical period	3
Vacuum chamber Volume	33 m ³
Magnetic field	≤1 Tesla pulse(0.2T DC)
Heating power	0.2 MW 28 GHz ECH 0.3 MW 7 MHz ICH

pulsed power supply (PPS). The MG set can provide up to 2500A at 100V giving a magnetic field strength of ~ 0.2 Tesla at the magnetic axis, and can be run in a continuous mode with currents up to 1500 A. The PPS can produce currents in the range of 1.5 to 14 kA providing a maximum field strength of 1T at the axis for a ‘flat-top’ of 0.5 sec. Thermal stresses in the coils limit the steady-state operation to lower magnetic fields.

Coil system of the H-1NF allows the magnetic configuration to vary in a broad range ($0.6 < t < 2.0$, $t = n/m$ is the rotational transform, n and m being the toroidal and poloidal mode numbers respectively), accommodating or avoiding major rational surfaces and islands in the main confinement volume [56]. This is done by selectively varying currents in some of the coils with respect to the central ring conductor (poloidal field coil). Two main configuration parameters of H-1NF are (a) $\kappa_h = I_{hw}/I_{ring}$, ratio of the currents in the helical winding to that of ring conductor and (b) $\kappa_v = I_{ovf}/I_{ring}$, ratio of the currents in outer vertical field coils to that of ring conductor. Some of the commonly used experimental configurations of H-1NF are:

1. The ‘standard configuration’ ($\kappa_h = 0$ & $\kappa_v = 1.0$). Here the helical winding is

not used. Outer vertical coils are tapped at 8 turns.

2. The ‘full helical’ configuration ($\kappa_h = \kappa_v = 1.0$). Here, the current through the helical winding is the same as that through the ring conductor. Again outer vertical coils are tapped at 8 turns.
3. The ‘half vertical’ configuration ($\kappa_h = 0$, & $\kappa_v = 0.5$). This is achieved either by halving the current through the outer vertical coils compared to the ring conductor (when 8 turns are used) or by tapping the outer vertical coils at four turns instead of eight.

Magnetic flux surfaces and rotational transform profiles for these configurations are shown in figures 2.2. Magnetic properties are detailed in coming sections.

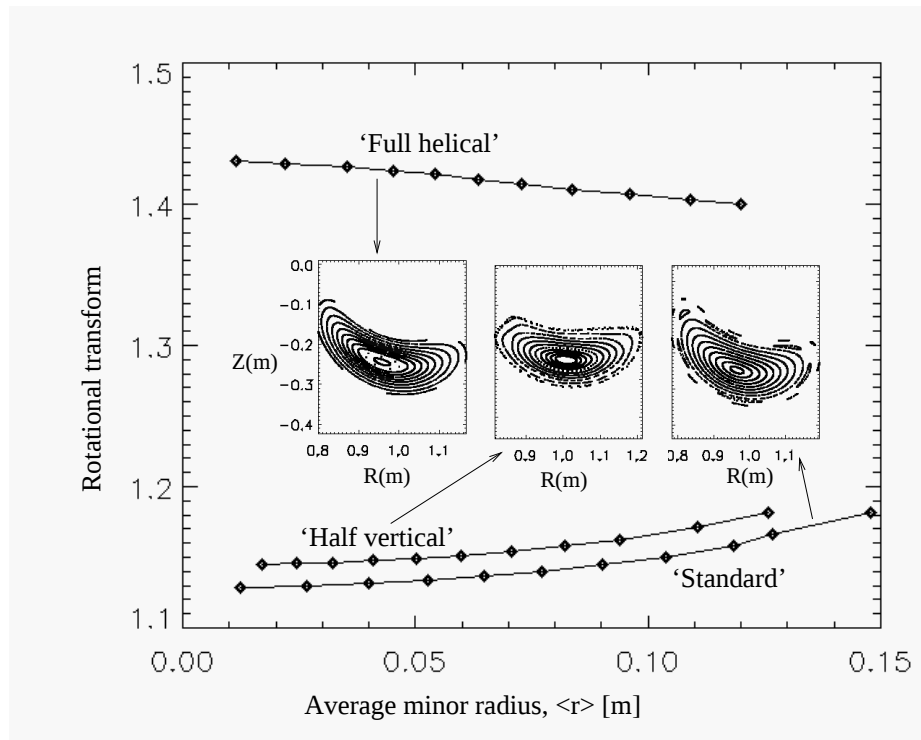


Figure 2.2: Rotational transform profiles and computed flux surfaces (at $\phi = 85^\circ$) for three different magnetic configurations of H-1NF: the ‘full helical’ ($\kappa_h = \kappa_v = 1.0$), ‘half vertical’ ($\kappa_h = 0.0$, $\kappa_v = 0.5$) and the ‘standard’ ($\kappa_h = 0.0$, $\kappa_v = 1.0$) configurations.

Apart from these three configurations, a wide range of κ values have been used for different experiments on H-1NF. The κ_h can be varied from 0 to ~ 1.30 in steps of $\Delta\kappa_h \sim 0.01$. Alternatively, the κ_v can also be varied in similar fashion. Also, both

values, κ_h and κ_v , can be changed simultaneously by connecting the outer vertical field coils and the helical windings in series ($\kappa_h = \kappa_v$). Many different values of κ_h and κ_v have been used for the mapping of vacuum magnetic flux surfaces and islands for accurate modeling of the H-1NF magnetic geometry (reported in chapters 3 & 4).

When separate power supplies are used for selectively varying the current ratios, differing ripple in the power supply (helical ripple may reach ~ 0.5 % in the worst case) currents can introduce a small ripple in the value of κ . This is important in the vacuum flux surface mapping process as the electron beam can dither or spread due to the power supply ripple. However, the $\Delta\kappa$ is found to be < 0.0035 , which has a negligible effect on our measurements. For the ‘standard’ ($\kappa_h = 0$ & $\kappa_v = 1.0$) and ‘full helical’ ($\kappa_h = \kappa_v = 1.0$) configurations, all involved coils are connected in series to a single power supply, either a motor generator (MG) or the large computer-controlled programmable power supply. This sets $\Delta\kappa = 0$ during measurements. For some configurations, different κ_v is achieved by tapping outer vertical coils at appropriate turns instead of using two power supplies, to achieve “ripple free” configurations. For example, for the ‘half vertical’ configuration ($\kappa_h = 0$, $\kappa_v = 0.5$), only 4 turns of the outer vertical coils are used, instead of eight.

2.1.2 Plasma production and heating

There are two plasma production/heating schemes in the H-1NF heliac. A 7 MHz radio frequency (RF) system delivers typically 60 kW power for 40-60 ms duration, with a maximum capacity of 300kW. This has mainly been used for low temperature (electron temperature, $T_e \sim 10$ eV and ion temperature, $T_i \sim 30 - 80$ eV) argon plasmas at low magnetic fields ($B \sim 0.1$ T) and Hydrogen/Helium plasma at $B \sim 0.5$ T. The electron cyclotron resonant heating (ECRH) system uses 28 GHz radiation from a gyrotron which is capable of delivering 200 kW of power. The core electron temperature for ECRH discharges in H-1NF is ~ 100 -200 eV. The RF system also serves as a pre-ionisation for the ECRH plasma. Typical fill pressure of the chamber is in the range of 10^{-4} to below 10^{-5} Torr.

2.1.3 Diagnostics

H-1NF is equipped with various vacuum and plasma diagnostic systems, some of them routinely operated. Summarised below some of the diagnostic systems relevant for the work reported in this thesis. An overview of the H-1NF diagnostic locations are given in figure 2.3.

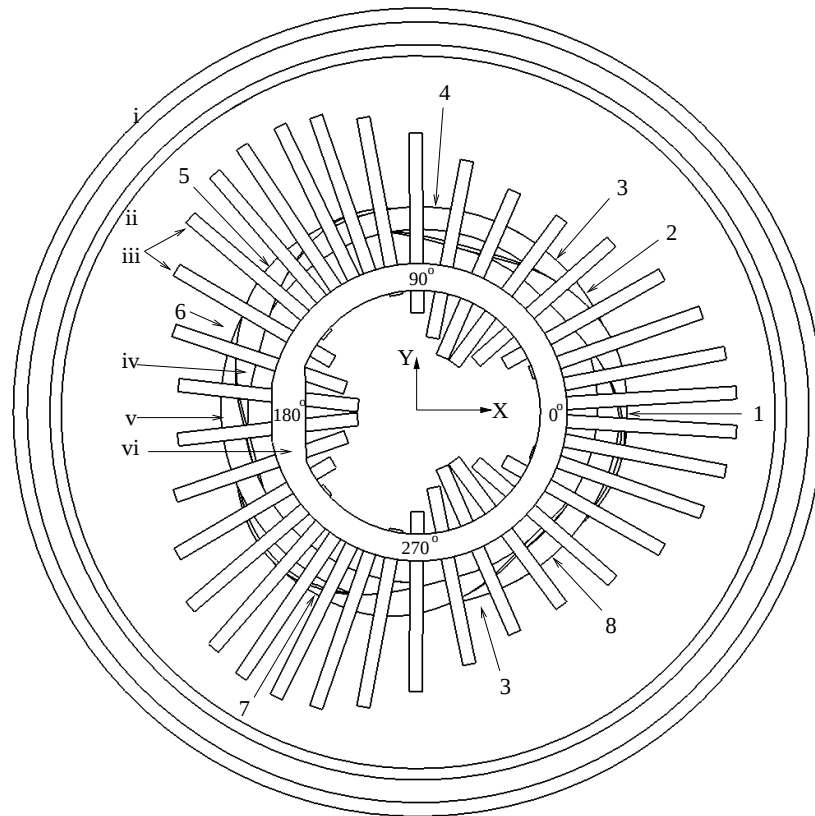


Figure 2.3: Plan view of the H-1NF coil structure showing the outer vertical field coils(i), vacuum tank(ii), toroidal field coils(iii), ring conductor(iv), helical winding(v), inner vertical field coils(vi) and the locations of various diagnostics and heating system. 1. Langmuir probe & Rogowski coil 2. Electron gun 3. Mirnov coil arrays 4. Multi-wire collector 5. RF antenna 6. Fast-ion camera 7. Microwave interferometer 8. Coherence imaging camera (Figure courtesy John Wach)

A major part of this work has been dedicated to accurately mapping the vacuum magnetic flux surfaces and islands and developing a computer model of H-1NF magnetic geometry by comparing it with the computer code results. The electron-beam wire-tomography [57, 58, 59, 60] has been used for mapping the vacuum flux

surfaces and islands. This gives a high resolution and accurate imaging of vacuum flux surfaces and islands. Details are given in chapter 3. The line averaged plasma density has been obtained from a 2mm interferometry. Alternatively, radial and temporal profiles of the plasma density have been obtained from the scanning interferometer [61]. Magnetic fluctuations associated with the magnetic islands have been studied using the Mirnov coil array [62]. Toroidal plasma current has been monitored from the Rogowski coil signals. A cylindrical Langmuir probe has been fabricated for the detailed experimentation of the local plasma properties of island configurations. (Details are given in Appendix D). Coherence imaging spectroscopy [63] has been used to determine the plasma rotation inside the magnetic islands and to verify some of the island features in plasma configurations.

2.2 Magnetic properties of H-1NF

The design criteria of H-1NF magnetic system consist of [64]

1. High rotational transform (t), though avoiding low-order rational surfaces
2. Formation of deep magnetic well
3. Flexibility in t and magnetic well
4. Reduced $|B|$ ripple
5. Insensitivity to magnetic field errors

Some of the magnetic properties H-1NF heliac, relevant to this thesis are discussed here. These have been computed using the *HELIAC* tracing code [65] and the best-fit model for the H-1NF magnetic geometry [60].

2.2.1 Rotational transform, magnetic shear and well

The flexibility of the machine to vary the coil current ratios with a good resolution allows access to various configurations with a wide variety of magnetic properties.

Computed rotational transform (t) profiles and flux surfaces for the three main magnetic configurations are given in figure 2.2. Rotational transform profiles for some of the possible configurations with different values of κ_h (keeping $\kappa_v = 1.0$) of H-1NF heliac are shown in figure 2.4. Major rational surfaces are marked.

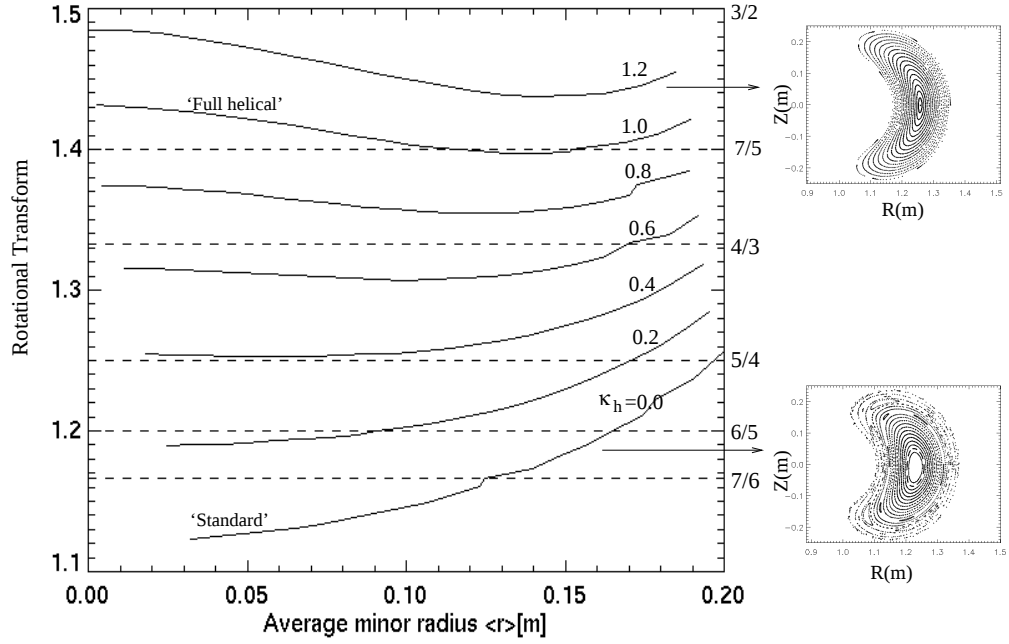


Figure 2.4: Radial profiles of rotational transform for various magnetic configurations of H-1NF. (different κ_h values, $\kappa_v = 1.0$). Major rational values are marked on the right axis. Magnetic flux surfaces for two configurations are also shown.

Although it is practically impossible to avoid all rational surfaces for any particular configuration, the magnetic configurations of H-1NF can be adjusted to avoid the dangerous low order rational surfaces and islands, or deliberately insert them into the main confinement volume.

The start and end points for the field line trace (in major radius, R) are kept the same for t calculations. Therefore it is apparent from figure 2.4 that the magnetic axis (average minor radius, $r=0$) moves radially outwards with an increase in the value of κ_h . In the plane $\phi = 0$, the magnetic axis moves radially out by ~ 22 mm and moves up by ~ 7 mm from the ‘standard’ configuration to the ‘full helical’

configuration. (For experimentally determined values, please see figure 4.6)

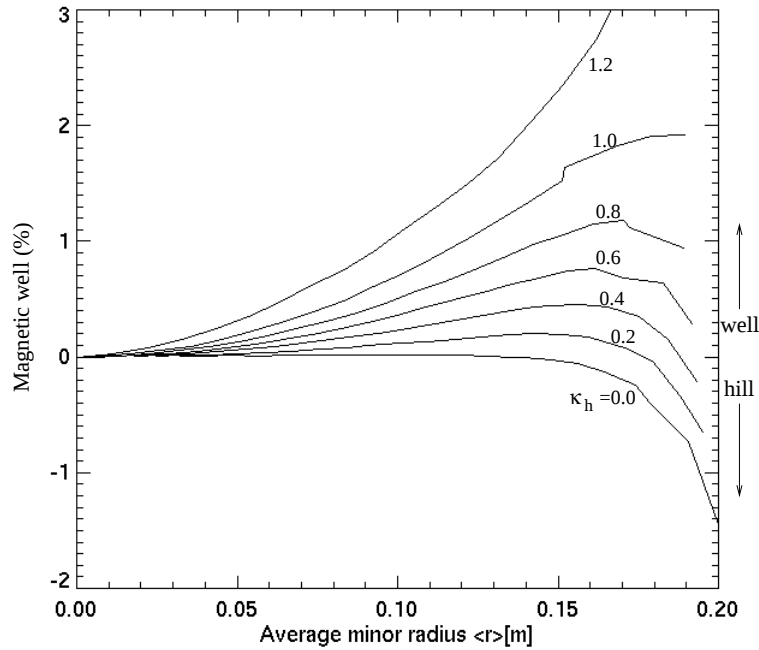
It can be seen from figure 2.4 that the magnetic shear ($t' = \frac{dt}{dr}$) of H-1NF can be varied over a broad range. The ‘standard’ configuration has relatively high magnetic shear. The ‘full helical’ configuration has a relatively lower shear and has a reverse magnetic shear with an inflection point at nearly $\langle r \rangle \sim 0.14$. This point coincides with the rational value of $t = 7/5$. Any increase in the helical current will make the on axis rotational transform close to the ‘natural’¹ mode of H-1NF, $t = 3/2$.

Radial profiles of the magnetic well for various magnetic configurations of H-1NF are shown in figure 2.5. It is apparent that changing configurations changes the magnetic well from a deep well to a magnetic hill. Even though large magnetic well configurations are good for stability, and can be obtained with larger values for κ_h , flux surfaces for these configurations become thinner, sacrificing up to 50 % of the plasma volume. Therefore, in many situations using κ_h more than 1.0 (the 3/2 island experiments, for example), it is necessary to increase the vertical field as well to maintain the plasma volume. This can be simply achieved by connecting the helical and outer vertical in series and changing both the κ values simultaneously ($\kappa_h = \kappa_v$).

2.2.2 Fourier spectrum of magnetic field

Fourier components of the magnetic field (B_{nm}) of H-1NF flux surfaces taken from two magnetic configurations are shown in fig 2.6. Various components are marked. There are three intrinsic components (‘ripples’) in the H-1NF [64]: (a) The ‘bumpy’ component ($B_{3,0}$) caused by the toroidal variation in B, largely due to the $1/R$ (R = major radius) dependence of the magnetic field encountered as the magnetic axis follows a helical path, (b) the helical component ($B_{3,1}$), (c) $B_{0,1}$ due to interaction between helical and toroidal curvatures and (d) side bands (for example, $B_{6,1}$) due

¹Any rational rotational transform in H-1NF ($t = n/m$) with the numerator 3 or its multiple are ‘natural’ or intrinsic modes due to the three period helical structure.

Figure 2.5: Magnetic well profiles for κ_h scan

to other interactions. Resultant magnetic field $|B|$ in flux coordinates² for the same surface is plotted as a function of the toroidal angle in fig 2.7. The toroidal (slow) and helical (fast) components are marked.

2.2.3 Magnetic islands in H-1NF

Being a three period heliac, H-1NF has a ‘natural’ poloidal mode number of $n = 3$ or its higher harmonics. These can resonate with the same mode number rational surfaces to form magnetic islands. Islands formed on $t = 3/2, 6/5$ in H-1NF are thus ‘natural’ magnetic islands. Shown in figure 1.7 are computed flux surfaces of configurations which accommodate these ‘natural’ islands. Width of the $6/5$ islands is ~ 1.5 cm, whereas the width of the $3/2$ islands can be varied by changing the values of κ , from zero to an appreciable fraction of the plasma volume, and finally splitting the whole flux surfaces into two separate big islands as shown in figure 2.8.

²Magnetic flux coordinates are explained in appendix A

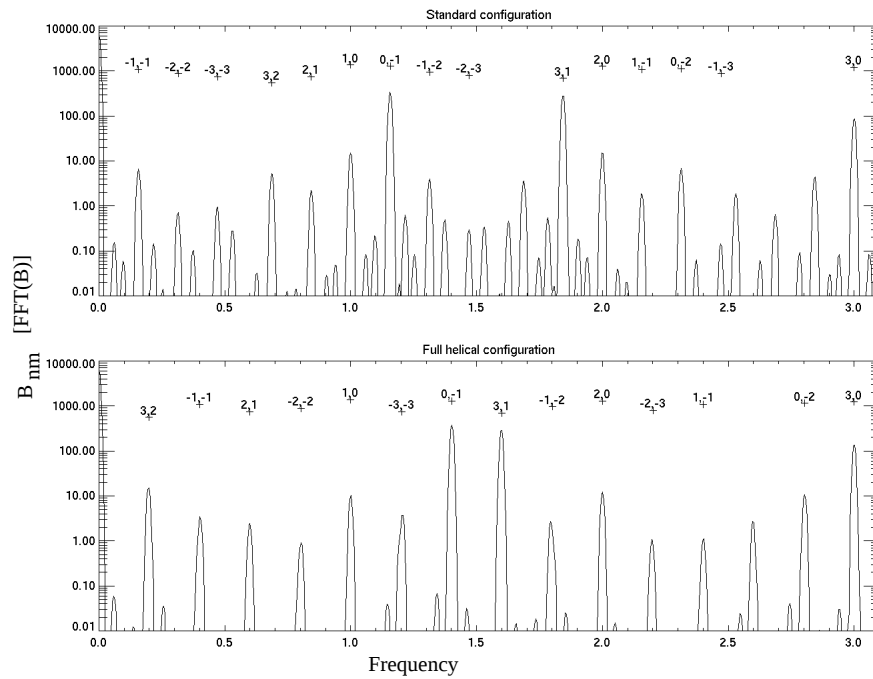


Figure 2.6: Fourier components of magnetic field, $[B_{nm} = \text{FFT}(B)]$ for the ‘standard’ (at $\langle r \rangle = 0.118$ m, $t = 1.157$) and ‘full helical’ (at $\langle r \rangle = 0.130$ m, $t = 1.401$) configurations. Negative values reflect the left handed helicity in the H-1NF and n values are not normalised to the field period. (File name: ‘modelSTByoffmodb.spec’ & ‘modelFHByoffmodb.spec’).

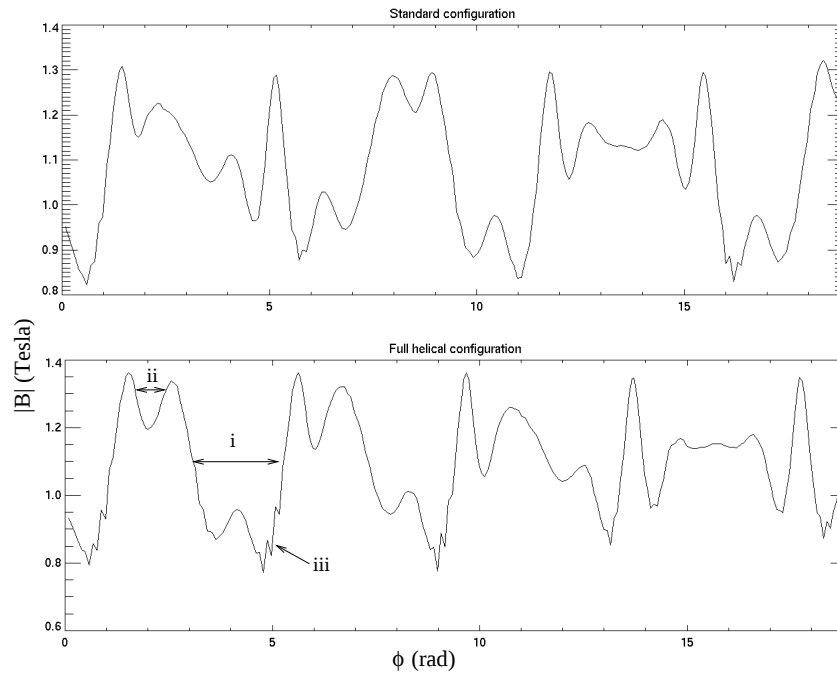


Figure 2.7: Variation of $|B|$ on a surface for the ‘standard’ and ‘full helical’ configurations. i & ii are magnetic mirrors formed by toroidal and helical ripples respectively, and iii is the ripple due to discrete toroidal field coils.

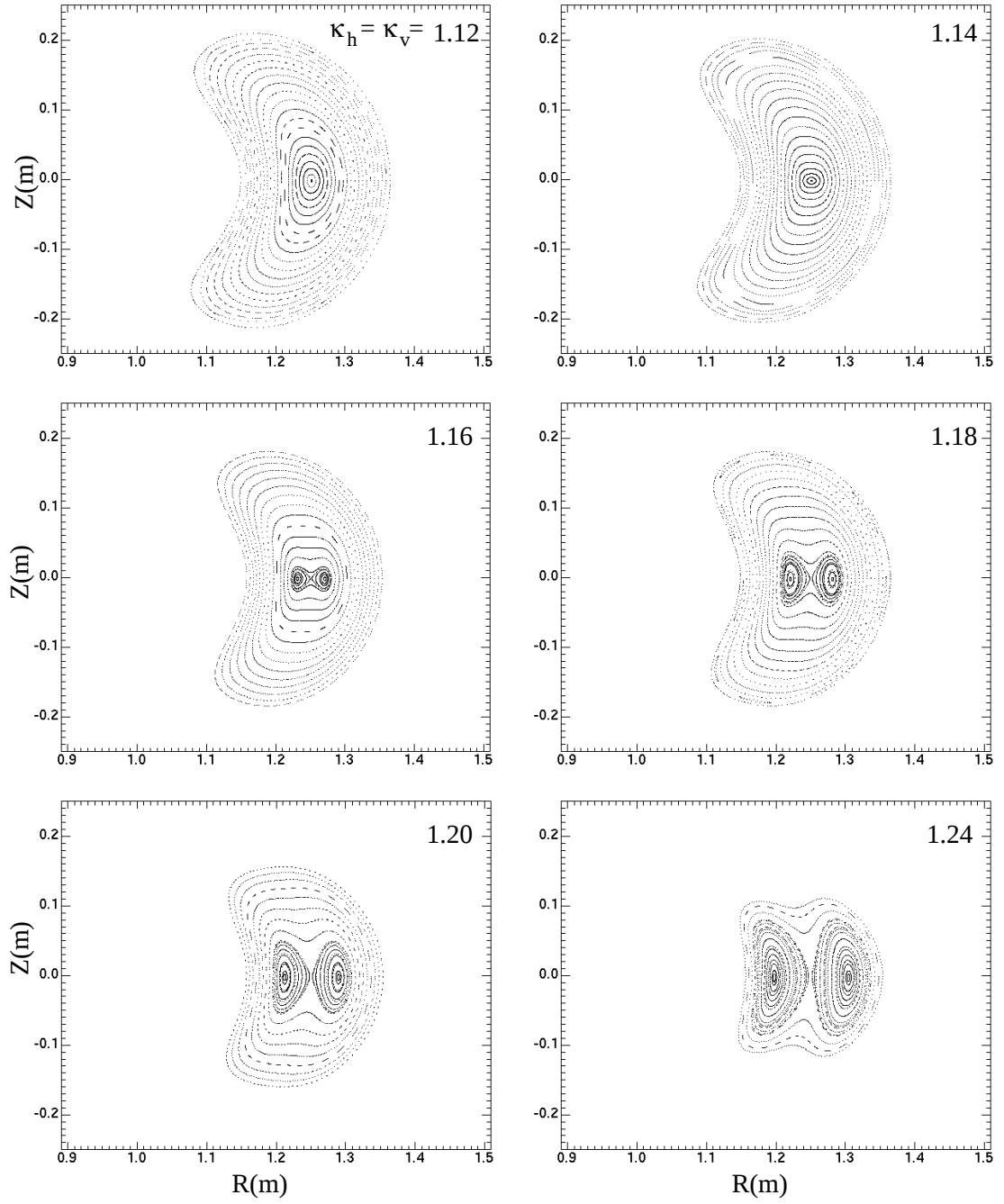


Figure 2.8: Evolution of the $m=2$ magnetic islands as the values of κ_h and κ_v are increased.

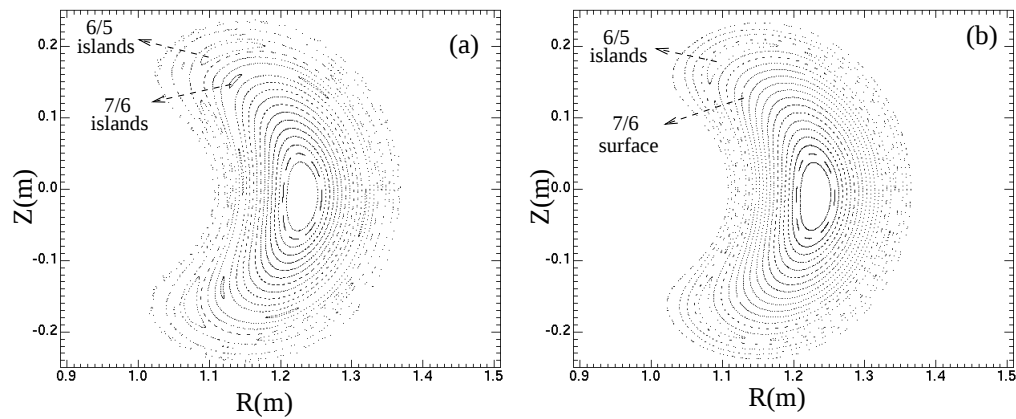


Figure 2.9: Computed flux surfaces of the ‘standard’ configuration (a) with and (b) without current cross-overs. The $m = 6$ islands appear only when the winding cross-overs for the ring conductor are included in the model.

Apart from the ‘natural’ islands, some configurations of H-1NF exhibit islands on other low order rational surfaces. These are observed in computation results; however their existence has not been experimentally confirmed, mainly due to the small size. Computation results show that the 7/6 islands formed in the ‘standard’ configuration are mainly due to the inclusion of current cross-overs for the central ring conductor³ (see figure 2.9). The 7/5 islands in the ‘full helical’ configuration seem to depend on the helical winding parameters.

³The ring conductor consists of 36 circular segments effectively connected to adjacent conductors by short (~ 60 mm) cross over segments approximately at $\phi = 35^\circ$, 155° and 275° .

Chapter 3

Mapping of vacuum magnetic islands and surfaces

Electron-beam wire-tomography in the H-1NF heliac enables high resolution mapping of vacuum flux surfaces with minimal disruption of the plasma operations schedule. Recent experimental results have proved this technique to be a highly accurate and high resolution method for mapping vacuum magnetic islands. Islands of width as small as $\delta \sim 8$ mm have been measured, providing estimates of the internal rotational transform of the island. Point-to-point comparison of the mapping results with computer tracing, in conjunction with an image warping technique, has enabled systematic exploration of magnetic islands and surfaces of interest. Development of a fast mapping technique has significantly reduced the mapping time and made this technique suitable for mapping at higher magnetic fields.¹

3.1 Introduction

Characterisation of vacuum magnetic islands provides information about errors of magnetic field structure, essential in verifying the magnetic geometry of a newly constructed device. Accurate mapping of vacuum magnetic flux surfaces and islands is crucial for an in-depth understanding of the magnetic geometry. Many different

¹A large part of this chapter has been published in *Review of Scientific Instruments* [60]

techniques have been used to map flux surfaces on different machines, worldwide. These include the emissive filament technique, fast-rotating fluorescent wire, highly transparent screen and resistive wire systems in the Auburn torsatron [66, 67, 68], a fluorescent mesh technique on the Compact Helical System [69], a phosphor-coated screen method on the ATF torsatron [70], a fluorescent rod technique on the W7-AS stellarator [71] and on the Columbia Non-neutral Torus (CNT) [72], an image-intensifying fluorescent probe on SHEILA [73] and a movable fluorescent rod on the H-1NF heliac [74, 75].

Electron beam multi-wire tomography in the H-1NF heliac [59, 58, 57] provides high resolution imaging of flux surfaces. Unlike many other techniques, this is free from inaccuracies arising from optical distortion due to viewing optics and non-ideal viewing angles. As low electron energies are used (~ 20 eV, compared to 100 - 200 eV in other techniques), drift effects are minimised (important at lower magnetic fields), and the mapped drift surface is a very good approximation to the actual flux surfaces. Tomographic inversion produces electron beam images directly in machine coordinates. Therefore, a point to point matching with computer tracing is possible. This increases the accuracy of error field estimation and magnetic modeling of the device. Because individual transits are resolved in sequence, the rotational transform of a surface can be calculated accurately from the mapped surface. This technique has recently been specifically modified and improved for accurate mapping of magnetic islands in H-1NF.

3.2 Experimental setup

The electron beam for wire tomography is generated from a specially made electron gun. (figure 3.1). This uses a heated thoriated tungsten filament of length ~ 2 cm and diameter ~ 0.1 mm. The interchangeable biasing shield has a beam aperture of 1 mm in diameter and a conical shaped tip which improves scanning of islands in two ways: (a) the shield diameter at the aperture is much reduced, which reduces the chance of the electron beam hitting the back of the gun in case of near-rational

surfaces and islands (b) the projection beyond the aperture (to the tip) determines the smallest width of the island which can be scanned without intersecting the other side of the island. A beam current of $\sim 6\text{--}10\ \mu\text{A}$ is obtained with a filament current of 1.25 A. During mapping, the base pressure of the chamber is kept as low as possible $\leq 3 \times 10^{-7}$ Torr to increase the number of toroidal beam transits. The typical number of toroidal transits at this base pressure is 20-25 (this is probably also limited by the transparency of the wire grid) and the collected wire current for the first electron transit is $\sim 1\ \mu\text{A}$. The electron gun is installed in the H-1NF at toroidal angle $\phi = 35.2^\circ$, and is movable both radially and vertically.

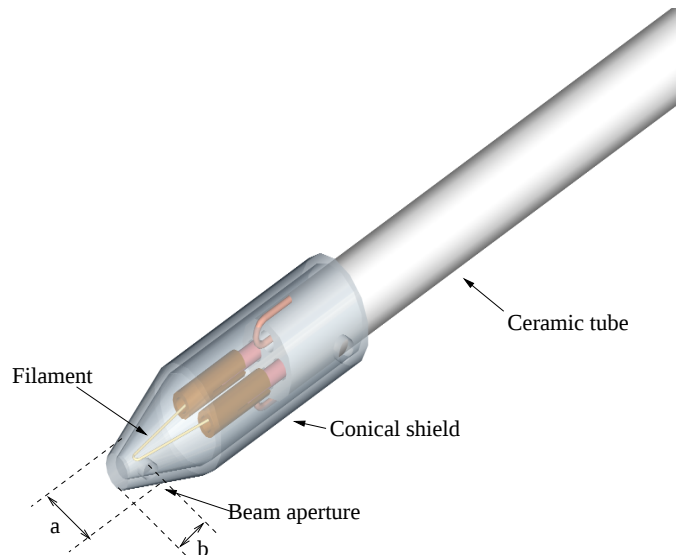


Figure 3.1: Electron gun. The shield diameter at the aperture, $a=2.9\text{ mm}$, the projection beyond the aperture (tip), $b=1.5\text{ mm}$ (Figure courtesy John Wach)

The multi-wire assembly (described in detail in ref [57, 59]) consists of 64 fine Molybdenum wires (diameter $\sim 0.15\text{ mm}$, spacing $\sim 4\text{ mm}$) stretched on a circular rotating frame (figure 3.2). This is permanently installed in the H-1NF vacuum chamber at toroidal cross section $\phi = 85^\circ$. Rotation of this assembly with minimum wire vibrations and required angle steps is achieved by a computer-controlled micro-stepping stepper motor. For a typical high resolution full surface scan, the wire grid

is rotated at an angle step of $\sim 0.5^\circ$, to make a total angular rotation of $\sim 220^\circ$. When not in use, the whole wire assembly can be moved to ‘park’ position, leaving the magnetic flux volume free for the plasma experiments.

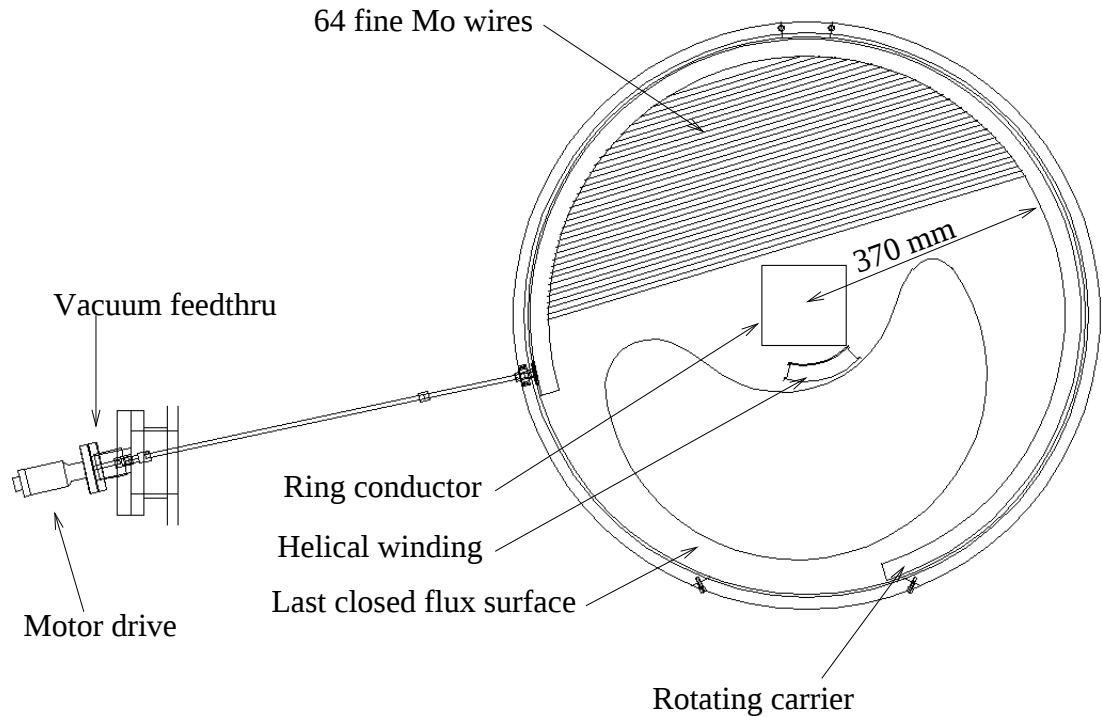


Figure 3.2: Rotating multi-wire assembly in park position. (Figure courtesy John Wach)

A typical full surface mapping using wire tomography takes 5-8 minutes. Thermal stresses in the coils limit the steady-state operation to lower magnetic fields (<0.1 T). Therefore, for most of the mapping results reported in this chapter, the main coil (ring conductor) current was chosen to be ~ 1000 A ($= 0.07$ T). The fast mapping system enables mapping at higher coil currents (up to 6500 A $= 0.5$ T) and fast iteration to optimize the launch position for island investigations, which is discussed in section 3.5.

3.3 Mapping and reconstruction

Electrons are injected along a field line of a magnetic flux surface from the electron gun situated at toroidal angle $\phi = 35.2^\circ$. The wire grid, which is at $\phi = 85^\circ$, is rotated in steps (inwards or outwards) to intercept the beam transits. In each orientation of the grid (θ_j), the amount of current the k^{th} wire draws is a function of current density of the electron beam (S) and the perpendicular distance between the wire and the beam (d)

$$R_{k\theta_j} = R(S, d) = R_{kj} \quad (3.1)$$

The collected electron current in each wire is line integral along the length of the wire (a projection). The data consists of $k \times j$ projections. Current collected by each wire is recorded at each rotation angle using a 64 channel multiplexer. The data is then subjected to various inversion techniques as explained below.

3.3.1 Sinogram

In the first step of reconstruction, a sinogram is formed (collected wire current as a function of wire rotation angle and wire number). Sinograms can give fairly good information about the flux surface mapped, *viz* the number of toroidal beam transits, signature of magnetic islands/rational surfaces etc. Sinograms from two different configurations are shown in figure 3.3(a) and (b). Each trace (partial sinusoid) in a sinogram represents one toroidal beam transit or ‘puncture’. It can be observed that figure 3.3(a) has five distinct groups of traces in it, indicating that this surface is near a rational surface with poloidal mode number m of 5. (For a surface with $m = 5$ precisely, each group reduces to one curve (transit) and the sixth transit will coincide with the first (launch) point, thus hitting the gun). Figure 3.3(b) represents two $m = 2$ islands with ~ 12 toroidal transits (which, for the 3 period H-1NF, are connected toroidally). The clarity of this sinogram and the absence of a ‘cloud’ effect indicate that the beam path is most likely terminated by hitting the gun. The island encountered between 130° and 240° in figure 3.3(b) is only partially scanned, so its reconstruction in 3.4(b) and 3.5(b) is faint and diffuse.

Two inverting techniques have been used to reconstruct the flux surface from the sinogram.

3.3.2 Simple back-projection

Simple back projection is used for a quick analysis for an initial assessment of the ‘puncture’ plot. This is a summation method, which involves distribution of the projections over an array of two dimensional pixels. The back-projected image is represented by the equation

$$\mathbf{I} = \sum_{k,j} R_{kj} \quad (3.2)$$

where R_{kj} is the collected current of k^{th} wire at j^{th} angular step. In practice, a discrete back-projection is employed, instead of unfiltered simple back-projection. This involves the distribution of the projections over an array of two dimensional pixels. The digitisation process is necessary to numerically process the image from projections. This involves choosing a set of basic pictures $(p_1, \dots, p_i)$, whose linear combination would approximate the image to be reconstructed. The basic picture is defined as

$$p_i = \begin{cases} 1, & \text{if } W_{k,j} \text{ is inside the } i^{th} \text{ pixel} \\ 0, & \text{otherwise} \end{cases}$$

Where $W_{k,j}$ is the k^{th} wire at j^{th} angle. The digitised image $\mathbf{I}$ is described as an array given by the equation,

$$\mathbf{I} = \sum X_{ir} p_i \quad (3.3)$$

where, X_{ir} is the value of $\mathbf{I}$ in the i^{th} pixel due to r^{th} wire. X_{ir} is proportional to the current through the r^{th} wire and the perpendicular distance between the wire and the i^{th} pixel. Good approximation of the image depends on the appropriate selection of the grid size.

Simple back-projection is computationally cheap. Reconstruction using this

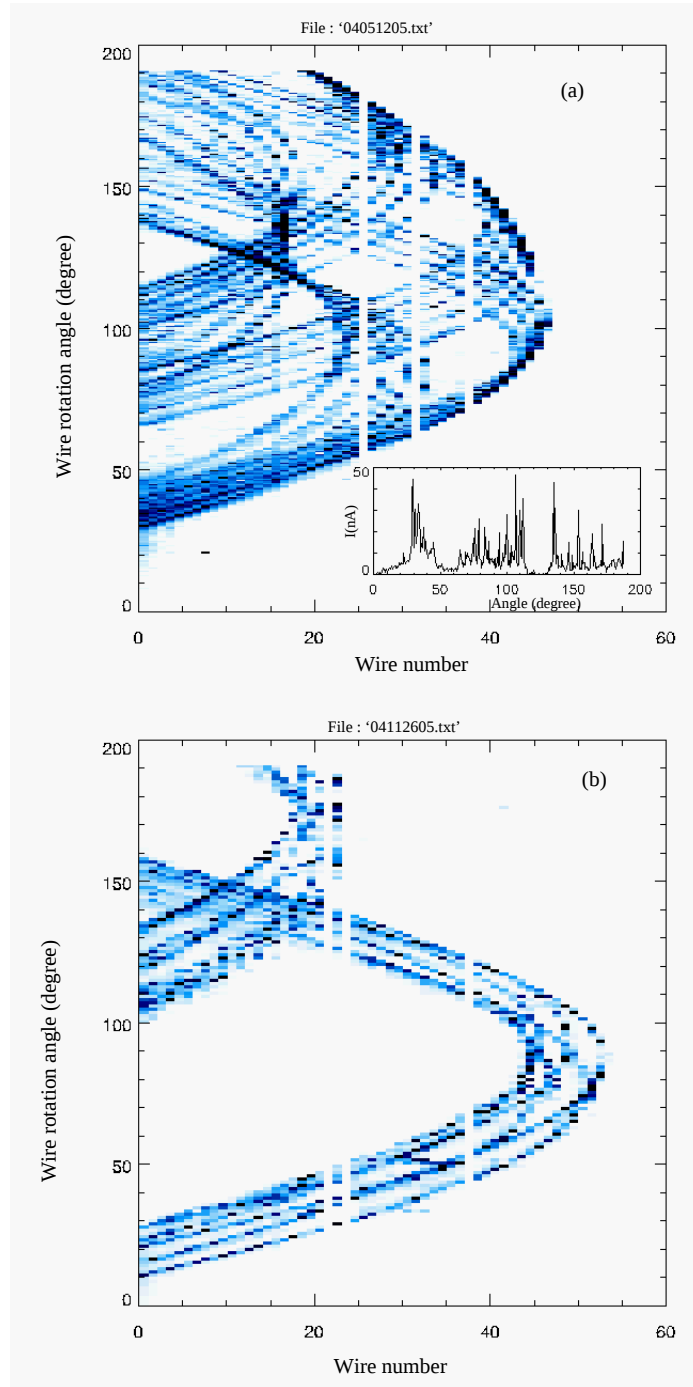


Figure 3.3: Sinograms of flux surfaces for (a) ‘full helical’ configuration ($\kappa_h = \kappa_v = 1.0$) (b) configuration exhibiting $m=2$ islands ($\kappa_h = \kappa_v = 1.27$). Shown in inset of figure (a) is the current through the longest wire (wire number 0) as a function of wire rotation angle.

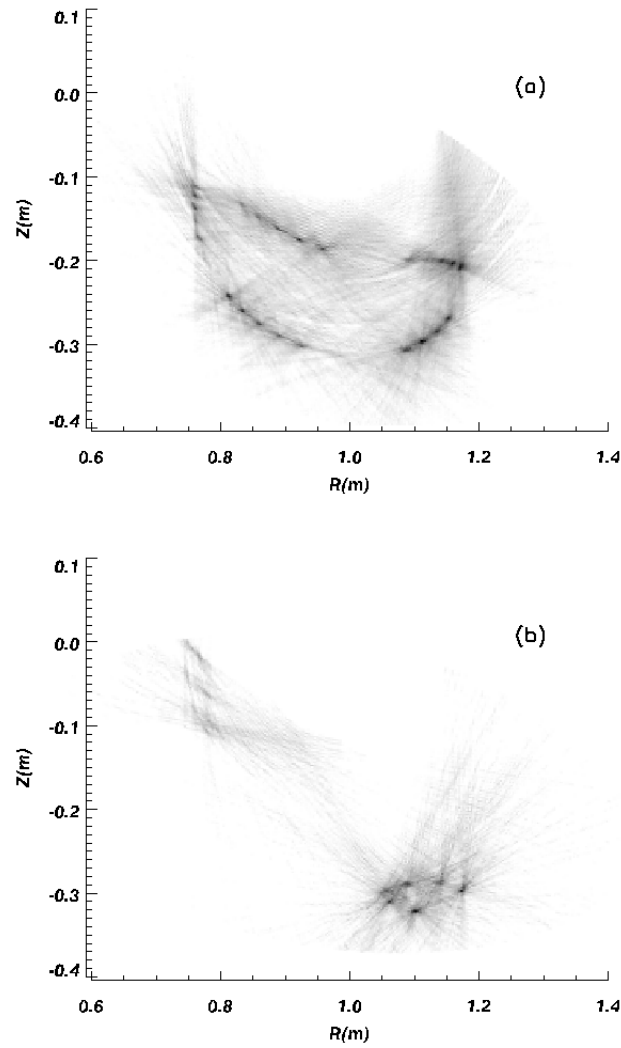


Figure 3.4: Simple back projections (a) & (b) of data shown in figure 3.3

method takes less than a minute. This is therefore used for a quick analysis soon after the data acquisition for an initial assessment. However, simple back-projection is problematic for noisy projections, or projections with reduced spatial resolution. There is a tendency of the image to be blurred. Blurring of the image is inherent of back-projection because the projection is uniformly distributed along a wire in the reconstruction plane (See figures 3.4(a) & (b)). Also artifacts (eg: wing-like) can confuse the analysis of the final image. This is more severe for large flux surfaces as the wire grid doesn't cover the surface fully.

3.3.3 Algebraic Reconstruction Technique (ART)

In order for the mapped results to be compared with field line tracing, background ‘noise’ and the artifacts have to be removed from the image, and each ‘puncture’ point has to be separately identified. The Algebraic Reconstruction Technique (ART) [76, 77] is used for this purpose. ART is an iterative back-projection algorithm with corrections applied in each iteration to remove unwanted pixels and enhance the image. ART results for the above mentioned mappings are given in figures 3.5(a) & (b). (For a full explanation of the ART procedures used in this thesis, see the Ph.D thesis by Roy Tumlos [59] and the vacation scholar report by Aska Dolinska [78]). Several characteristics of wire tomographic data, the limited angular range, the sparse radial grid (64 elements), its multiple delta function character and the slightly perturbing nature of the measurements, prevent significant improvements by typical convolution methods used on CT X-ray data, for example, Ram-Lak, Shepp-Logan etc. [58, 79].

3.4 Image warping technique

Being a fully three dimensional configuration, H-1NF flux surfaces have different shapes and sizes at different toroidal cross sections in any of the three periods for a particular configuration. The electron gun is toroidally separated from the multi-wire assembly by 49.8° . Computed flux surfaces for the configuration exhibiting $m=2$ islands at the gun and wire grid locations are shown in figure 3.6. Exploring a particular flux surface, islands or island axis requires knowledge of the gun position with respect to the surface at the gun port location ($\phi = 35.2^\circ$). A technique has therefore been developed to warp the scanned image from $\phi = 85^\circ$ to $\phi = 35.2^\circ$. This uses the computed mapping of a two dimensional grid of points from one cross section to the next as a base and transforms the experimentally mapped image from one grid to other using the ‘warp_tri’ procedure in IDL (Research Systems, Boulder, CO), which warps images based on tie-points according to a Delaunay triangulation, with Thin Plate Spline (TPS) interpolation. This technique does not rely on the

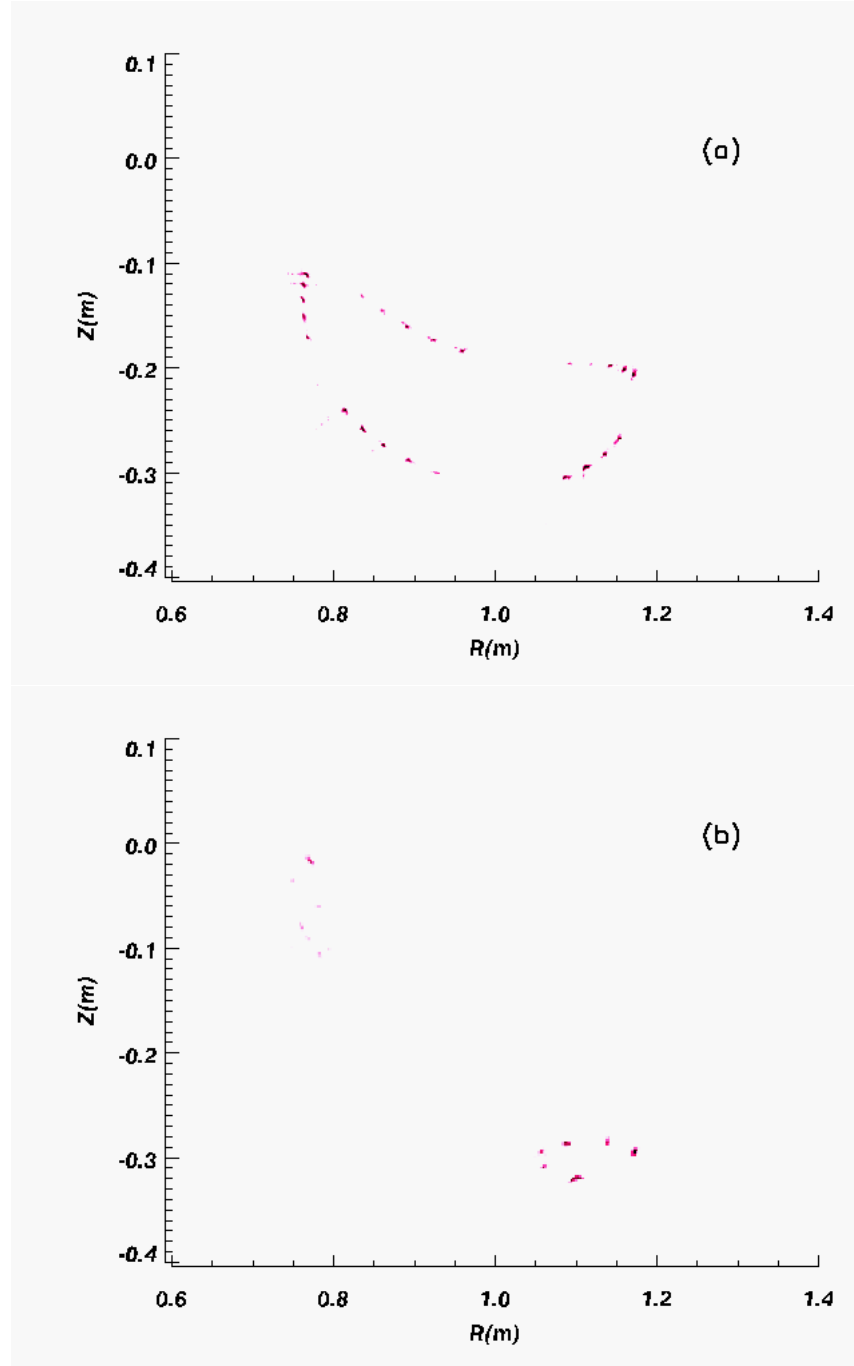


Figure 3.5: ART images (a) & (b) of data shown in figure 3.3. Width of the island lobe in (b) is ~ 8 mm

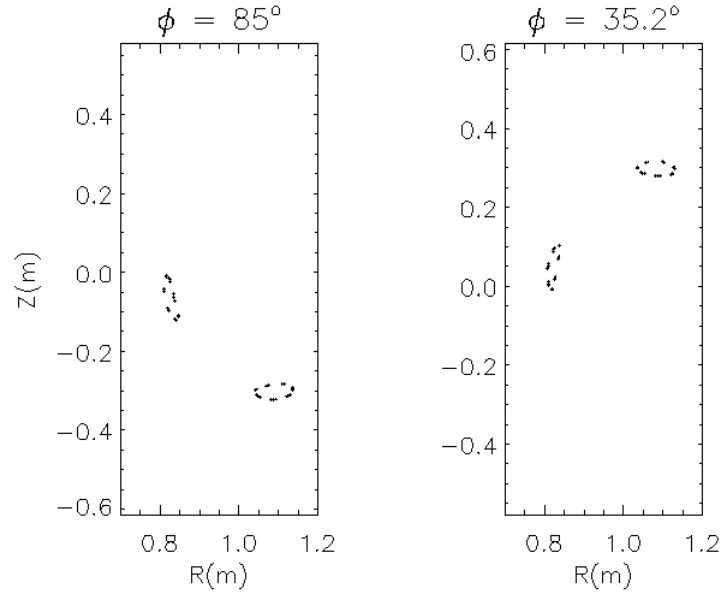


Figure 3.6: Computed flux surfaces of the $m=2$ islands at the wire ($\phi = 85^\circ$) and the gun ($\phi = 35.2^\circ$) cross sections. Note that warping is not just a rotation - the thinner island at 85° becomes the thicker island at 35.2° , and vice-versa.

existence of closed flux surfaces. Also, a highly accurate computer model is not essential as the distance over which the image is transformed is small ($\sim 50^\circ$). This is important, because the technique is used in developing the computer model. Warped images for the ‘full helical’ and the configuration exhibiting $m=2$ islands ($\kappa_h=\kappa_v=1.27$), produced by a simplified three fold symmetric magnetic coil model that ignores most of the error terms and by the best-fit magnetic model which includes various error field corrections, are shown in figure 3.7. Even though the magnetic flux surfaces of the simple model differs significantly from that of the best-fit model, the images transformed by “warping” over this short distance are accurate enough to guide the electron gun for island/surface exploration.

Shown in figure 3.8 is a warped image of the data presented in figure 3.5 (b). Smearing of the warped points is due to the effect of magnetic shear on the unphysical width (in the minor radial direction) of the ART processed ‘puncture’ points at the wire grid cross section. Fading of the points usually indicates beam attenuation over successive toroidal transits. Thus the first point (brightest) can be identified as the gun location. Knowledge of the gun location in relation to the local magnetic

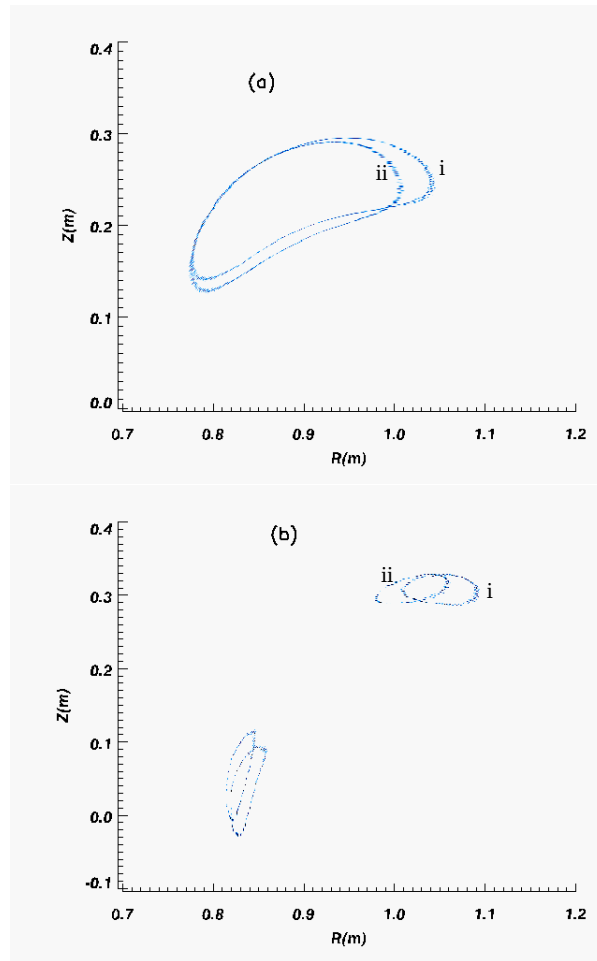


Figure 3.7: Warping by the best-fit (i) and the simple (ii) models. (a) ‘Full helical’ configuration. (b) Configuration exhibiting $m=2$ islands. In practice, we use a much more accurate model than the ‘simple’ model, and images (i) and (ii) would be almost indistinguishable from each other.

surfaces is essential to the successful optimization of the launch position, especially when mapping complicated surfaces, such as magnetic islands.

3.5 Fast mapping

As mentioned before, a normal full surface mapping with controlled acceleration and deceleration, and pausing the wheel for each measurement, takes 5-8 minutes. This makes the island exploration too time consuming and limited to low magnetic fields. (Even though the warping technique helps in guiding the electron gun movements for exploring the islands, it takes several full surface mappings before the optimum

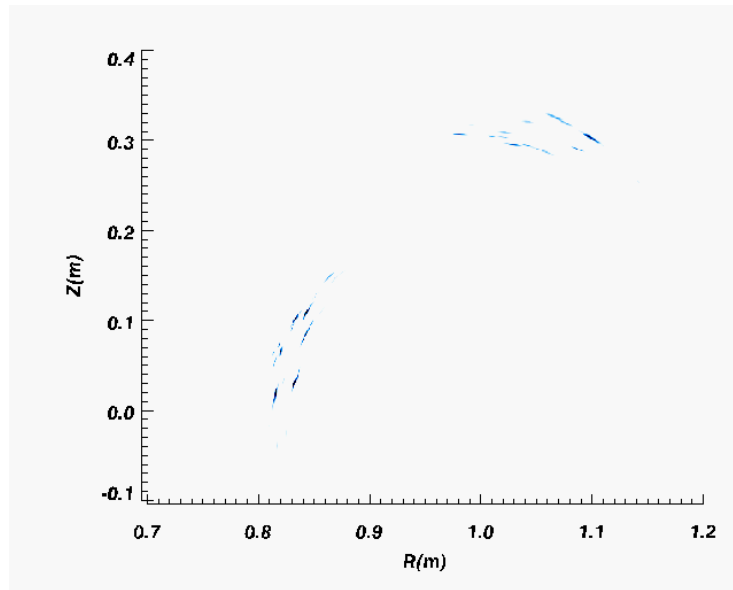


Figure 3.8: Warped image of the $m=2$ islands. The original data at $\phi = 85^\circ$ are shown in Fig 3.5(b)

launch point for the island is found.) A fast mapping technique has therefore been developed. This involves continuous running of the wheel at the maximum possible speed and taking data on the run. The position (angle), time, wire number and the wire current are recorded continuously as the wheel rotates. A high speed programmable power supply is operated in an approximately constant current mode to compensate for the induced back e.m.f of the motor windings at high speeds. In order to make the rotation of the wheel uninterrupted during the data collection, a separate buffered output Digital to Analog Converter (DAC) module (combination of hardware & software buffering) is used for controlling the stepper motor. A Lab-view routine has been developed to perform this task.

The fast mapping technique significantly reduces the mapping time from 5-8 minutes to less than 15 seconds for a full surface. This is therefore very helpful in exploring the islands and also in mapping surfaces and islands at higher magnetic fields where the operation is limited to only a few seconds. Even though this method partly sacrifices the resolution of the measurement and sensitivity to fainter punctures, the results indicate this technique to be almost as accurate as the normal (incremental) mapping one, especially for large surfaces. Simple back-projections of

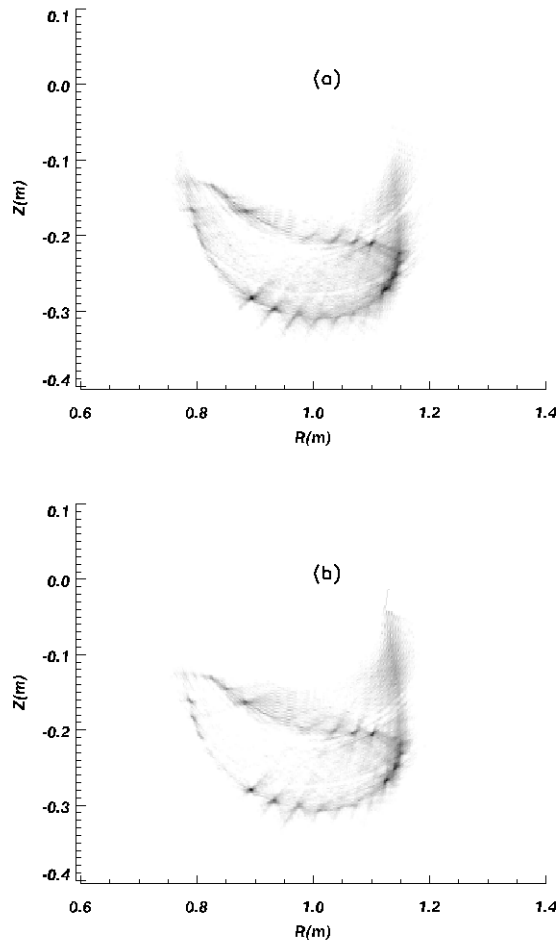


Figure 3.9: Simple back-projections of slow(a) and fast (b) mapping of a flux surface. The image is clipped to make the points more distinct.

surfaces with normal and fast mapping are shown in figures 3.9 (a) & (b) respectively for comparison. The ART processed images are much sharper, but the differences are not so apparent.

3.6 Critical issues

As mentioned above, the electron gun should be as small as possible to map islands. This requirement relates not only to the size of the islands, but the internal rotational transform (t_i) of the islands also; the rate at which field lines twist about the island axis, or O-point. Typical values in H-1NF range from $t_i = 0.01$ to 0.1 . At present, the conical electron gun shield radius at the beam aperture is $\sim 1.5\text{mm}$.

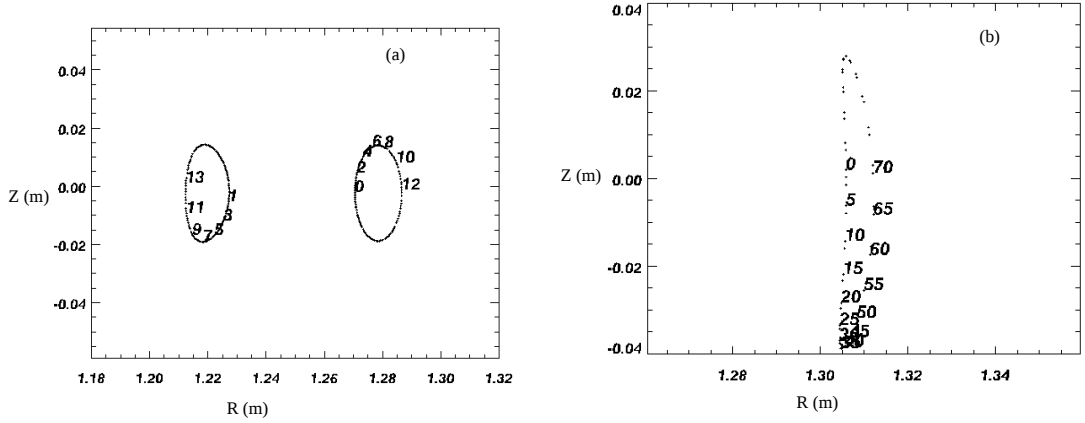


Figure 3.10: Figures showing the internal rotational transform (and the half connection length) of islands. (a) $m=2$ islands and (b) One of the $m=6$ island lobes

If the distance between two adjacent beam transits (which depends on the internal rotational transform of the island) is less than or equal to 1.5mm, the electron beam will hit the back of the gun after just one transit. Also, if the internal rotational transform of the island is small (or, in principle, near an integer; but this has not been observed in H-1NF), it takes many toroidal rotations for the beam to reach the other side of the island (half connection length), so that it can be unambiguously identified as an island from the mapping results. For example, it is relatively easy to detect the $m=2$ islands as the half connection length is ~ 10 -12 transits ($t_i \sim 0.08$ -0.1) [see figure 3.10]. However, for the $m=6$ islands in H-1NF, the half connection length corresponds to ~ 65 toroidal transits ($t_i \sim 0.07$). The maximum toroidal transits we have detected so far is ~ 25 -30. Our attempts to map $m=6$ islands have therefore been unsuccessful, even though their existence is predicted by the computer code, and we have no reason to doubt their existence.

A unique feature of the wire tomography is the point-to-point matching of the ‘puncture points’ with the computer model. This has helped us to obtain a best-fit empirical computer model for H-1NF magnetic parameters. A detailed error analysis and computer modeling of the H-1NF magnetic configurations is discussed in the next chapter.

Chapter 4

Accurate determination of H-1NF magnetic geometry

High precision mapping of the vacuum flux surfaces of the H-1NF heliac is carried out using electron-beam multi-wire tomography, at various magnetic configurations and field strengths. The extreme accuracy of this technique has been exploited to understand the nature of error fields, by point-by-point matching with computer tracing results. This has helped in developing a best-fit computer model for H-1NF magnetic configurations, which can predict rotational transform correct to three decimal places. Results from plasma experiments on magnetic configuration studies are best explained by the new model.

4.1 Introduction

Laboratory magnetic fields of a fusion device can vary significantly from the designed values due to various reasons (e.g. stray magnetic fields, coil placement error, magnetic materials in the vicinity, design imperfections etc). Unlike in tokamaks, in stellarators, it is possible to map the magnetic flux surfaces in the absence of plasma. This can shed light on the error fields present - essential in verifying the magnetic properties of a newly constructed device, and help in accurate modeling of the magnetic geometry. The goal of the work reported in this chapter is to produce

an accurate model for the magnetic field of the H-1NF heliac stellarator which can be used in future research, and provide some insight into the effect of the magnetic environment. One of the aims was to calculate the magnitude of positional errors in construction and the corresponding effect on the magnetic surfaces. To this end, a coil configuration was chosen which comprises a majority of simple circular elements for which errors could be easily quantified and a single helical winding which is not required in the ‘standard’ configuration (see section 4.2). As will be described, the key parameters are optimised manually by examination of the most critical configuration for each parameter.

Wire tomography in H-1NF heliac provides high resolution images of vacuum magnetic flux surfaces and islands (detailed in chapter 3). Tomographic inversion produces electron beam images directly in machine coordinates. Therefore, a precise point to point matching with computer tracing is possible. This has helped in understanding the actual error fields and determination of the best-fit empirical values for the H-1NF magnetic parameters. The main improvements over the previous model of H-1NF are the point-by-point matching, which includes ι in the fitted parameters (where $\iota = n/m$ is the rotational transform, n and m are the toroidal and poloidal winding numbers respectively), and a more accurate location of the ‘punctures’ by eliminating the image mapping step that was required when using a camera.

4.2 Experiment

For the experiments reported in this chapter, three magnetic configurations which are most relevant to plasma experiments, and insensitive to power supply ripples (as explained in section 2.1.1), are mainly used:

1. ‘standard’ ($\kappa_h = 0$ and $\kappa_v = 1.0$)
2. ‘full helical’ ($\kappa_h = \kappa_v = 1.0$), and
3. ‘half vertical’ ($\kappa_h=0$, $\kappa_v=0.5$)

Table 4.1: Mapped flux surfaces from each of the following configurations at various coil currents (magnetic fields) as tabulated below are used for the work reported in this chapter.

Configurations	Coil (ring conductor) currents
‘Full helical’	500A, 1000A, 1500A, 3000A, 4500A, 6500A
‘Standard’	1000A, 1500A, 2200A, 3000A, 4500A, 6500A
‘Half vertical’	1000A
$\kappa_v = \kappa_h = 1.18, 1.20, 1.22, 1.25, 1.27$	1500A
$\kappa_v = 1.0$ & $\kappa_h = 0.67, 0.77, 1.20, 1.25$	1500A
$\kappa_h = 1.0$ & $\kappa_v = 1.3$	1000A
$\kappa_h = -0.5$ & $\kappa_v = 1.0$	1000A
$\kappa_h = -0.4$ & $\kappa_v = 1.0$	1000A

Rotational transform profiles and computed flux surfaces for these three magnetic configurations are shown in figure 2.2.

Flux surfaces from each of these configurations were mapped using wire tomography and compared with the computer model. Many different magnetic configurations were used for verifying the results, and the corresponding values of κ are given (see table 4.1 for the list of configurations used for the work reported in this chapter). As the thermal stresses in the coils limit the steady-state operation to lower magnetic fields (< 0.1 T), the main coil (ring conductor and also the TFC current) current was chosen to be $\sim 1000\text{A}$ - 1500A for most of the initial studies. However, the model results have been compared with mapping at higher magnetic fields (up to $6500\text{A} = 0.5\text{T}$) using the fast mapping system [60].

The *HELIAC* code [80, 65] has been used for the computer modeling of H-1NF vacuum configurations. Originally from Princeton Plasma Physics Laboratory, this is a field line tracing code, in which coils are represented as current-carrying (piece-

wise linear and circular) filaments, and an analytical function for external vertical field with specified index and radius of curvature. Calculations include location of magnetic axis, flux surfaces, rotational transform, magnetic well, magnetic flux, shear etc. A three-fold and stellarator symmetric *HELIAC* model for H-1NF includes 36 circular filaments for the toroidal field coils, 36 circular filaments for the poloidal field coil (central ring conductor) representing 36 turns, four separate piecewise linear filament models for the three period helical winding of four turns over the central ring conductor, and two lines each for the inner and outer vertical field coils. (The inner vertical field coils consist of 16 turns each, and the outer vertical field coils of 12 turns each. They are represented in the model by single turn circular conductors). This model contains the designed values of the coil parameters, and does not include any error terms. For the ‘basic’ model referred in this chapter, the coil parameters are updated with the best available as-built measurements (see appendix B and the table B.1 therein for the as-built measurements). A more recent H-1NF model (used in Ref [75] and afterwards, called ‘intermediate model’ from here onwards) includes the current cross-overs for the ring conductor and positional offset in the ring conductor as explained in coming sections.

4.3 Error estimation and computer modeling

The computed magnetic flux surfaces are compared with the experimentally mapped surfaces by overlaying one on the other. For a perfect-fit computer model, the computed points should exactly superimpose on the mapped points (‘puncture points’), if the starting points are the same. A best-fit model gives a flux surface with the same rotational transform and surface area as the mapped one. Surfaces with ι near a rational value are good for comparing rotational transform, and whether the surface is above or below the resonant surface can be distinguished by the rotation of the points in clockwise or anti-clockwise directions. It is also possible to very accurately calculate rotational transform of a near-rational surface from the mapped surface, if the rational number is known (explained in appendix C).

Super-imposition of the experimentally mapped flux surfaces for the three magnetic configurations on the corresponding computed flux surfaces from the ‘basic’ model is shown in figure 4.1. It is observed that the rotational transform (t), shape and the position (in the R-Z plane) of the mapped surfaces are a little different from the computer code predictions. The extent of deviation from the model differs for different configurations, as apparent from the figure.

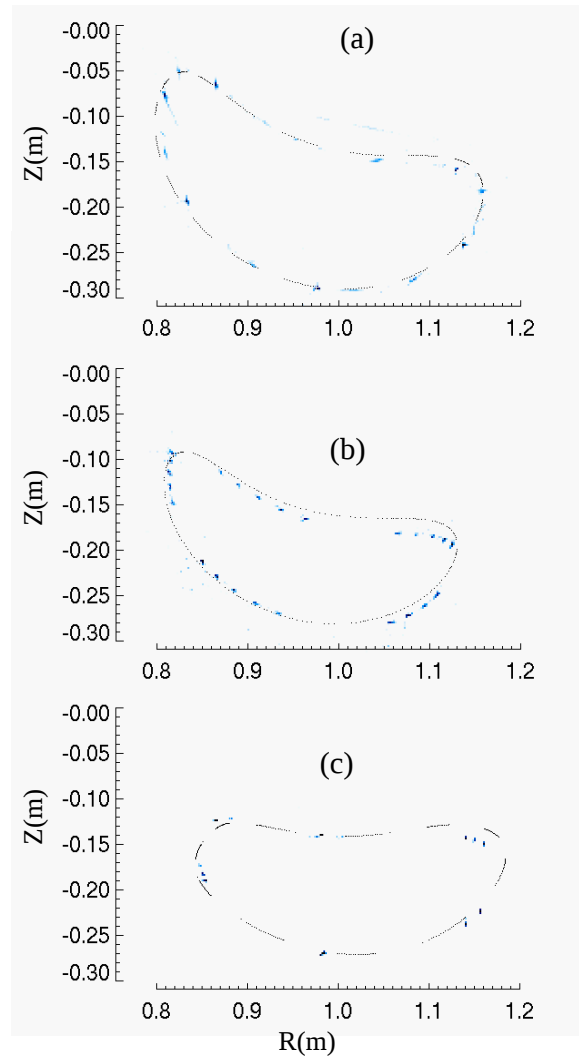


Figure 4.1: Super-imposition of experimental mapping results (blue) for the (a) ‘Standard’, (b) ‘Full helical’ & (c) ‘Half vertical’ configurations on the corresponding computed flux surfaces (black) from the basic model. For best reproduction, overlayed figures in this chapter have been created so that image pixels are aligned with vertical and horizontal. Consequently, although the coordinate system is consistent within the figure, there are small angle ($\sim 3^\circ$) and offset ($R \sim 5$ mm, $Z \sim 15$ mm) errors when compared with the other figures.

The deviations of the experimental results from the computer predictions are due to (a) small systematic changes in the coil parameters from the designed values which are used in the code and (b) stray magnetic fields in the laboratory due to the magnetisation of ferromagnetic materials around the laboratory and in the floor, possibly exacerbated by recent high field operations (0.5 T) of the machine. In the former case, two possible candidates are the positional offset in the ring conductor and the swing and the major radii of the helical windings. An offset in the position of the ring conductor in X and Y directions, relative to the centre of the toroidal field coil (TFC) support structure, of -1.5 mm and 2.0 mm has been introduced in the past to match with the mapping results from a fluorescent rod [75] (please see figure 2.3 for X & Y directions). The helical winding is the only non-circular coil in H-1NF. Therefore, its parameters cannot be measured very accurately like that of all other coils in H-1NF.

The effects of the main error sources on the basic model have been computed separately for each of the three configurations. Displacement of the magnetic axis due to the error fields is summarised in table 4.2. Here, effects of stray magnetic fields in the X, Y and Z directions are modeled by including appropriate Helmholtz coils in the basic model. (Please note that the values are evaluated at toroidal angle $\phi = 0^\circ$, and may be different at other toroidal locations. For example, see figure 4.2.) Figures 4.3, 4.4 and 4.5 show the effect of various error fields on the three configurations. The percentage change in rotational transform ($\delta t/t \times 100$) from the basic model, for a constant flux surface area¹, due to various error fields are tabulated in table 4.3. It may be noted that some of the error sources have similar effects on the t and the surface area for a particular configuration. As horizontal stray error fields (B_x and B_y) are asymmetric to the three-period H-1NF, they can have different effects at various toroidal cross sections. Because of the difficulty in determining this with only one mapping location on the machine, we have used more symmetric error fields as far as possible to obtain an empirical model.

¹Although magnetic flux is conventionally used to label flux surfaces, when mapping magnetic surfaces, flux surface area is a more practical experimental quantity because magnetic field values cannot be obtained from mapping images.

Table 4.2: Effects of various possible error fields on the magnetic axis, for three configurations used for study. (Evaluated at toroidal angle, $\phi = 0^\circ$). Reference is the basic model for the corresponding configurations. Movement of less than 0.1 mm is omitted.

Error Sources	‘Standard’ ($\kappa_h=0, \kappa_v=1.0$)		‘Full helical’ ($\kappa_h=1.0, \kappa_v=1.0$)		‘Half Vertical’ ($\kappa_h=0, \kappa_v=0.5$)	
	ΔR (mm)	ΔZ (mm)	ΔR (mm)	ΔZ (mm)	ΔR (mm)	ΔZ (mm)
Stray fields ^a						
$+B_x$	-0.2	8.4		3.2	-0.1	7.2
$-B_x$	-0.1	-8.4		-3.2	-0.1	-7.2
$+B_y$	3.1		0.5		2.2	
$-B_y$	-3.1		-0.5		-2.2	
$+B_z$	0.8		0.6		0.8	
$-B_z$	-0.8		-0.6		-0.8	
Ring offsets ^c						
$+\Delta_x$	7.2		2.8		6.3	
$-\Delta_x$	-7.3		-2.8		-6.26	
$+\Delta_y$	-0.2	-12.3		-2.9	-0.2	-11.0
$-\Delta_y$	-0.3	12.2		2.9	-0.3	11.0
$+\Delta_z$		1.3		1.2		1.3
$-\Delta_z$		-1.3		-1.2		-1.3
Ring radius ^d						
$+\Delta_R$	2.1		1.7		2.1	
$-\Delta_R$	-2.1		-1.7		-2.1	
Cross-overs ^e						
	-0.2		-0.1	-0.3	-0.2	0.2

^a 0.1% of B_0 in each direction. ^b At a different toroidal cross section, this value is up to 8.5 mm.

^c By 2 mm in each direction. ^d Increase and decrease in the radius of the ring conductor by 2

mm. ^e Current cross-overs for the ring conductor.

The stray magnetic fields in the laboratory have been measured at zero coil current using a three-axis Hall probe. It has been observed that the vertical and radial (horizontal) components of the stray magnetic field are ~ 9.5 and 2 gauss respectively just above the floor at $R \sim 1$ m from the machine centre (corresponds to the major radius of H-1NF). The radial component of the stray field at the device mid plane (about 2.1 m above the floor) reduces to less than one gauss whereas the vertical component remains at a significant value of ~ 4 gauss. This shows that the

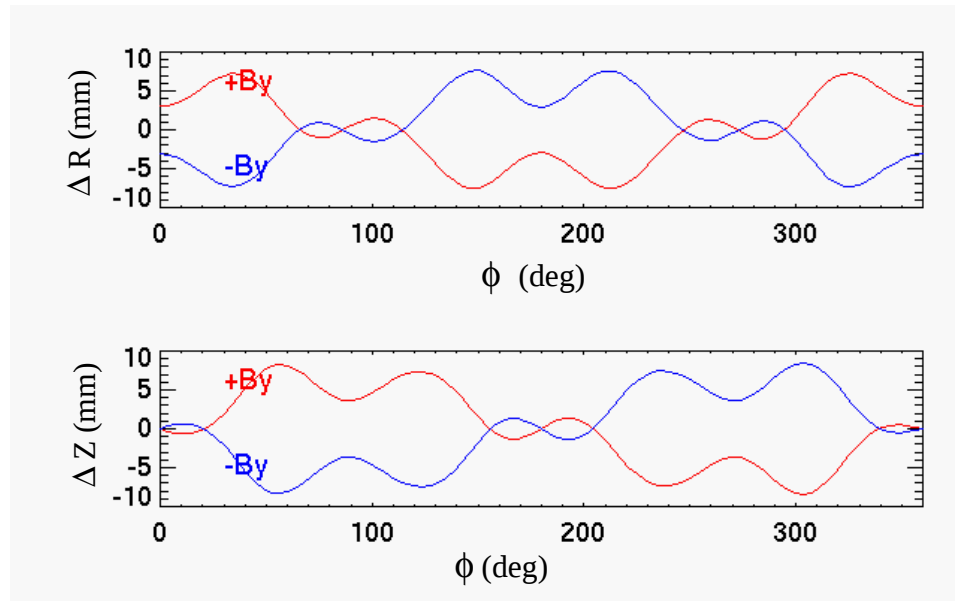


Figure 4.2: An example of variation of the axis displacement (ΔR and ΔZ) given in table 4.2, as a function of toroidal angle (ϕ). Plotted is the displacement of magnetic axis of the ‘standard’ configuration, for a stray error field of 0.1% each in $+B_y$ and $-B_y$ directions.

Table 4.3: Computed values of the percentage change in the rotational transform $[(\delta t/t) \times 100]$ of a flux surface, for a constant surface area, due to various error fields. Reference is the basic model for the corresponding configurations. Stray fields and offsets have the same magnitude as mentioned in table 4.2.

Error Sources	‘Standard’ ($\kappa_h=0, \kappa_v=1.0$)	‘Full helical’ ($\kappa_h=1.00, \kappa_v=1.0$)	‘Half vertical’ ($\kappa_h=0, \kappa_v=0.5$)
Stray fields			
$+B_x$	0.02		0.02
$-B_x$	0.02		0.01
$+B_y$	0.01		0.01
$-B_y$	0.02		0.01
$+B_z$	0.03	0.07	0.17
$-B_z$	-0.03	-0.07	-0.17
Ring offsets			
$+\Delta_x$	0.02		0.02
$-\Delta_x$	0.03		0.02
$+\Delta_y$	0.02		0.01
$-\Delta_y$	0.03		0.03
$+\Delta_z$			
$-\Delta_z$			
Ring radius			
$+\Delta_R$	0.09	-0.01	0.06
$-\Delta_R$	-0.09	0.01	-0.06

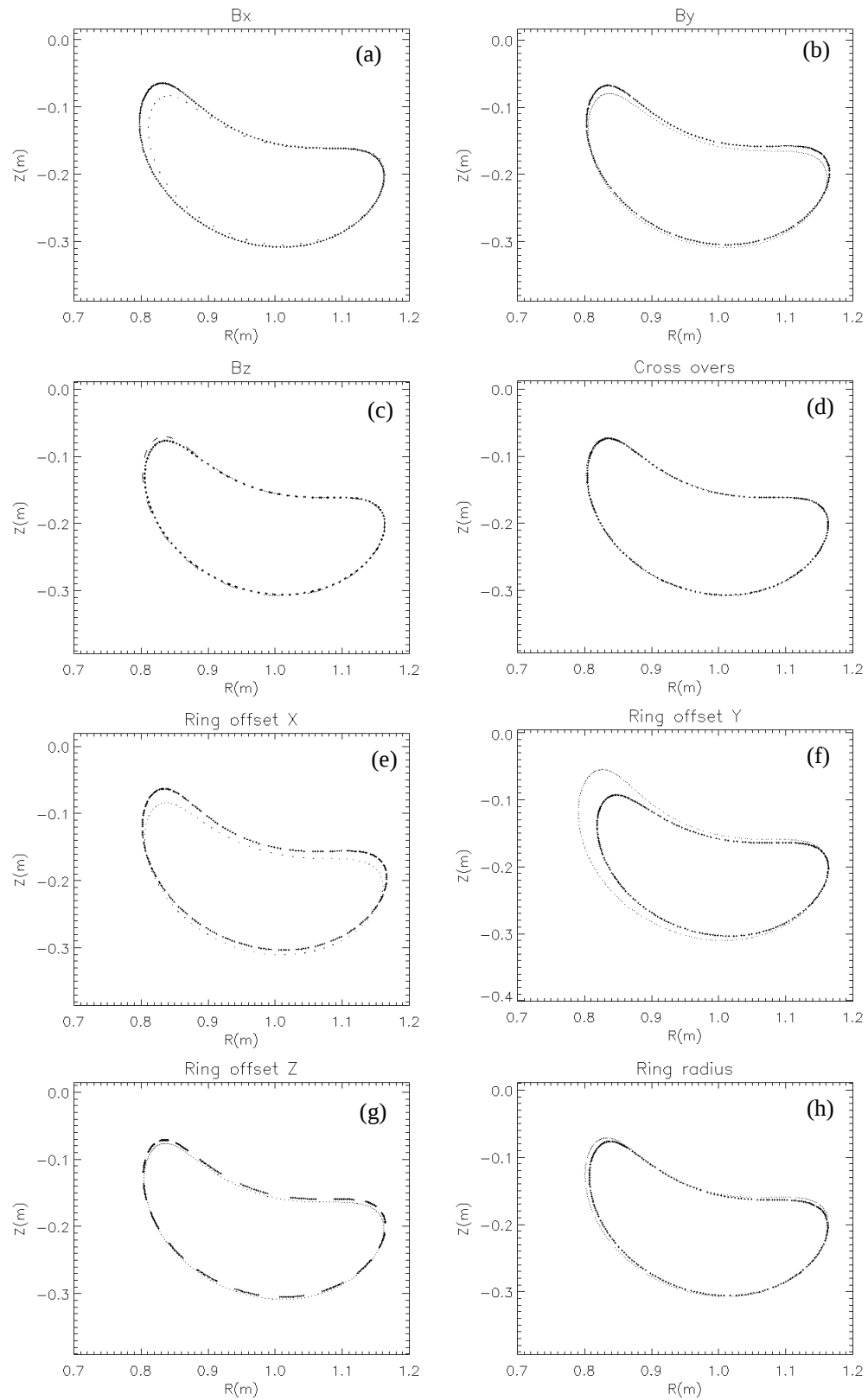


Figure 4.3: Effect of various error fields on the ‘standard’ configuration. Stray fields have the same amplitude as mentioned in table 4.2. Thick line represents positive and the thin line represents negative directions for the error field, except for (d) where thick and thin lines are (indistinguishable) flux surfaces with and without cross-overs. See table 4.2 for details.

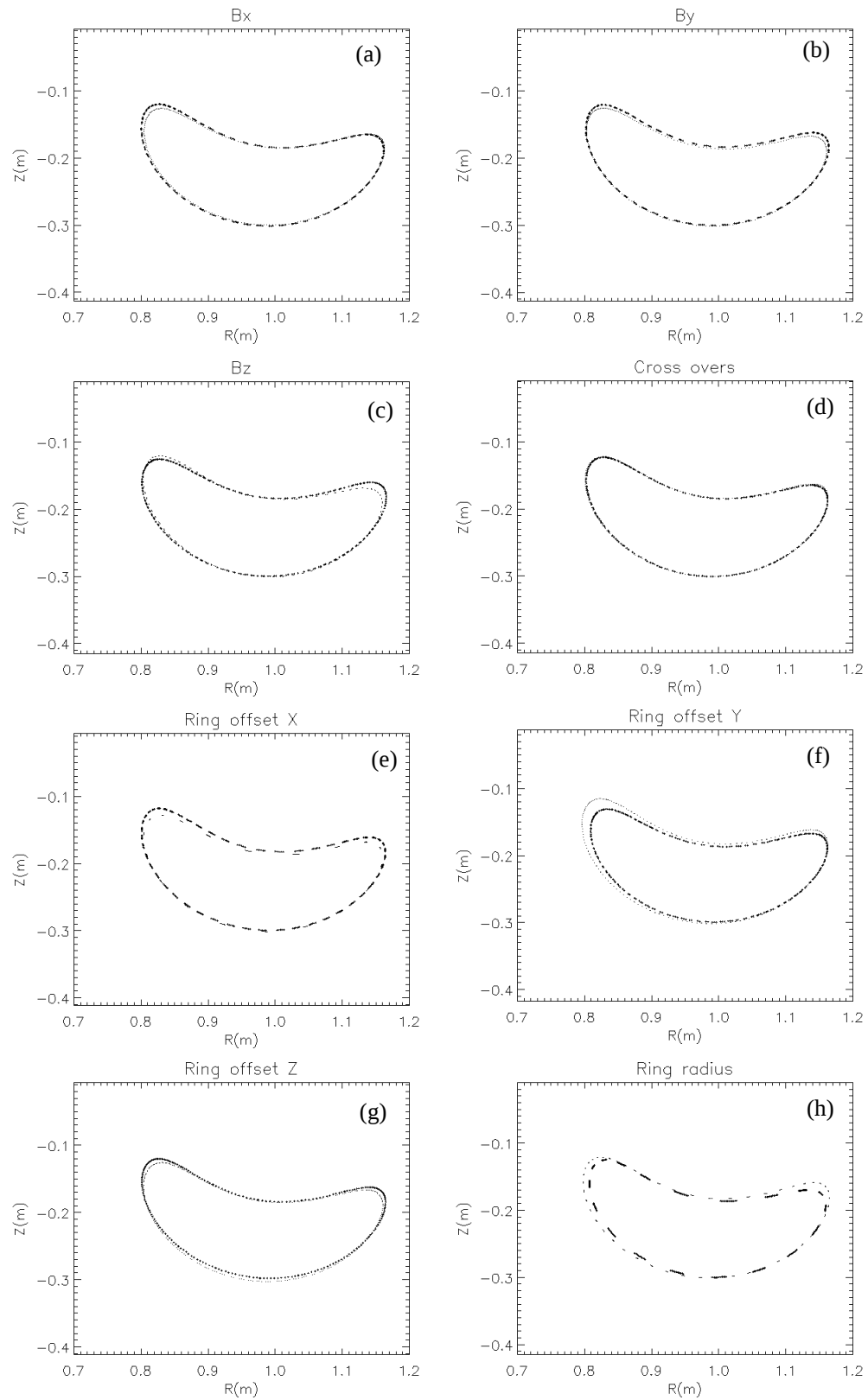


Figure 4.4: Effect of various error fields on the ‘Full helical’ configuration. Error amplitudes have the same value as mentioned in table 4.2. Thick line represents positive and the thin line represents negative directions for the error field, except for (d).

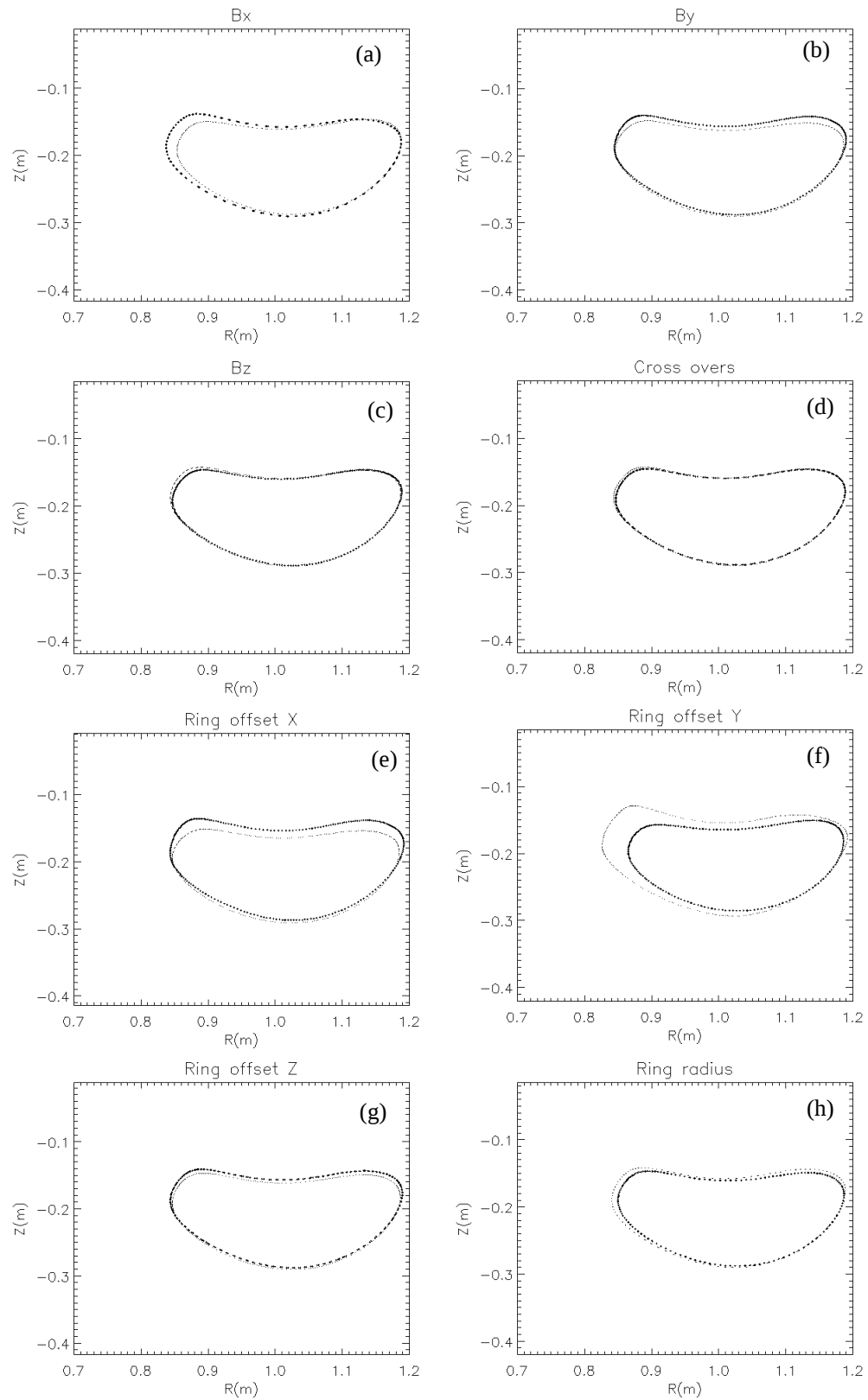


Figure 4.5: Effect of various error fields on the ‘Half vertical’ configuration. Error amplitudes have the same value as mentioned in table 4.2. Thick line represents positive and the thin line represents negative directions for the error field, except for (d).

previously demagnetised floor may have acquired a significant residual magnetisation due to high field (0.5T) operations. Because of the helical magnetic axis, during a toroidal transit, the flux surfaces move both above and below the mid plane. The amplitude of the vertical error field due to the magnetised floor at the position of the plasma is therefore different at different cross sections. Thus the magnetic field lines experience a toroidally varying error field with the toroidal wave number $n \neq 0$. The varying component of this field can resonate spatially with surfaces of rational rotational transform ($t = n/m$ where m is the poloidal mode number) and produce magnetic islands.

The locations of magnetic axes for each of the three configurations have been determined using a Langmuir probe and electron beam. (Axis measurements could not easily be made with the surface mapping technique, as when the gun is near the axis, the electron beam hits the back of the electron gun after just one transit). Electrons launched from an electron gun situated at a toroidal cross section $\phi = 35.2^\circ$ are collected by a Langmuir probe at $\phi = 0^\circ$. For a fixed gun position (a flux surface), two dips in the floating potential are obtained when the Langmuir probe is moved radially, corresponding to two intersections of the probe with the electron beam (flux surface). The midpoint between these dips gives a good approximation of the magnetic axis (see figure 4.6). Measurements have been repeated for many different surfaces (different gun positions) for each configuration. The position of the magnetic axis has thus been obtained. The radial shift of the magnetic axis (ΔR) between these configurations has served as a valuable input for the modeling.

Identification of the error sources to develop a best-fit model demands an iterative approach, as the effect of various errors are not the same on all the magnetic configurations because of differing amplitudes of error fields in the configurations and different profiles of rotational transforms. Also the best-fit coil parameters for a particular configuration are not unique, especially for the configurations using helical windings, as will be discussed later. As mentioned before, three magnetic configurations which are very different in their κ values and relevant to plasma operations

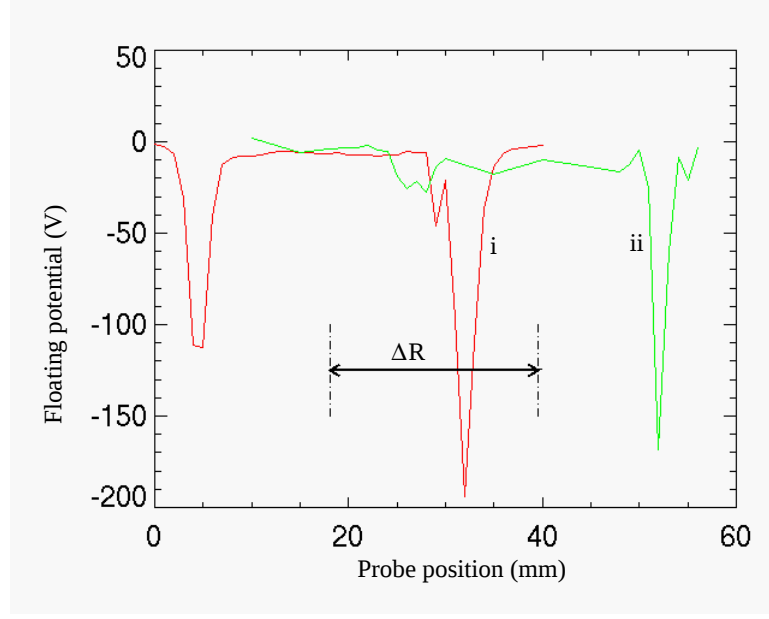


Figure 4.6: Determination of magnetic axis (dashed lines) using Langmuir probe and electron beam. i- ‘standard’ configuration, ii-‘full helical’ configuration. Axis shift from ‘standard’ to ‘full helical’, $\Delta R = 21.5$ mm.

of H-1NF- the ‘standard’, the ‘full helical’ and the ‘half vertical’ - are mainly used for this process. However, flux surfaces from many other configurations have been mapped and compared with the computer model at various stages of the modeling, including the $m=1$ and $m=2$ islands (see table 4.1 for a complete list).

4.3.1 Stage I: $\kappa_h = 0$

Initially, ‘standard’ ($\kappa_h = 0$ and $\kappa_v = 1.0$) and ‘half vertical’ ($\kappa_h = 0$ and $\kappa_v = 0.5$) configurations are chosen for the study. These two configurations do not energize the helical winding, which simplifies the problem as the number of variables in the model is reduced by two; the effective major radius (R_{hw}) and the swing radius (ρ_{hw}) of the helical winding. The effects of the winding cross-overs for the ring conductor are included in the model. As explained in figure 2.9, the 7/6 islands formed in the ‘standard’ configuration is due to the inclusion of current cross-overs for the central ring conductor in the model. The effects of the current carrying conductors (buss bars) and the ferromagnetic components in motors used for various diagnostics were found to be insignificant. The stray field measurements, locations of magnetic axis

measured with the Langmuir probe, and the previous setting of the X and Y offsets in the ring conductor served as guiding factors in the process of iteration.

After a large number of iterations, very good agreement with the experimental results has been obtained for both the ‘standard’ and ‘half vertical’ configuration with the following modifications in the basic model.

1. Addition of a vertical error field of $\sim 0.75\%$ to $\sim 0.85\%$ of B_0 , depending on the configuration and operating coil current, where B_0 is the nominal magnitude of the total field on the axis ($B_0 = 1.0$ T for a coil current of 14 kA for the ‘standard’ configuration). This corresponds to ~ 6 gauss at 1000A coil current.
2. Positional offsets in the ring conductor by -0.5 mm and +2 mm in the X and Y directions respectively. Vertically the ring conductor remains at the mid plane. (Discussed in relation to figure 4.12).
3. Reduction of the ring conductor radius by 2 mm.²

Shown in figure 4.7 and 4.8 are the best-fit surfaces for the ‘standard’ and the ‘half vertical’ configurations respectively, overlaid on the mapped surfaces.

The error field of 0.85% of B_0 changes the vertical component of the total magnetic field at the axis by 1.7% at $\phi = 0^\circ$ and by 5.8% at $\phi = 85^\circ$ for the ‘standard’ configuration. This has been experimentally confirmed by a careful magnetic field measurement using a 3-axis Hall probe at lower coil currents (~ 1500 A). An attempt has also been made to understand the source of the error field. Two factors point to the outer vertical field (OVF) coils: the main component of the error field is vertical and the OVF coil set has by far the greatest flux linkage with the reinforcing steel in the floor and walls. A scaled model (1:10) of the H-1NF outer vertical

²The deduced effective ring radius of 0.998m is just outside the range of estimated effective radius as-built, which was between 1.000 and 1.003 m. This choice is driven mainly by correction of the transform in standard configuration. The small discrepancy may be because there are undiscovered small deviations in the conductor and feed paths, in addition to the effects already included (36 conductors, 3 coaxial feed points and associated crossovers). However the dimension is not beyond the bounds of reasonable possibility, and it currently produces the most accurate magnetic model.

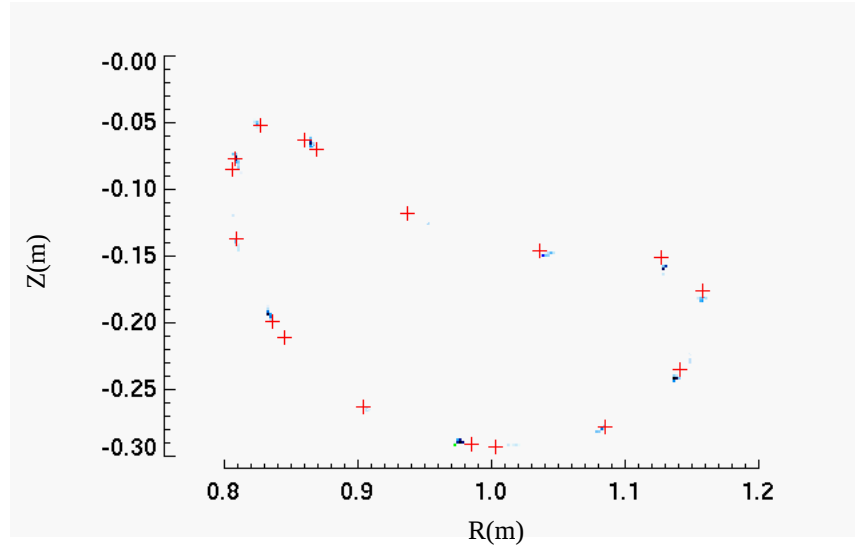


Figure 4.7: Mapped flux surface from the ‘standard’ configuration overlaid on the best-fit computer code result (‘+’ points)

field coils was made using two circular coils of ~ 200 mm in radius. The effect of magnetic materials around the device has been modeled using appropriately scaled iron rods, mesh and loops. It has been observed that the presence of these magnetic materials increase the vertical component of the magnetic field at the centre of the coil assembly by $\sim 5\%$. Our experiments on H-1NF by powering the different coils individually indicate that the error field could not be explained solely by the vertical field coils. Evidence indicates that the observed additional vertical field can be largely attributed to the magnetic materials around the machine, including the reinforcing in concrete floor.

4.3.2 Stage II: The helical winding

Having obtained a best-fit model for the ‘standard’ and the ‘half vertical’ configurations, which do not use the helical winding, a model for the ‘full helical’ ($\kappa_h = \kappa_v = 1.0$) configuration can then be developed. This configuration has the helical winding in series with other coils, *i.e.* $\kappa_h = 1.0$. As mentioned earlier, the helical winding is the only non-circular magnetic coil in the H-1NF and the two helical parameters, the major radius R_{hw} and the swing radius ρ_{hw} , are difficult to measure accurately. These two parameters are empirically obtained using the procedure outlined next.

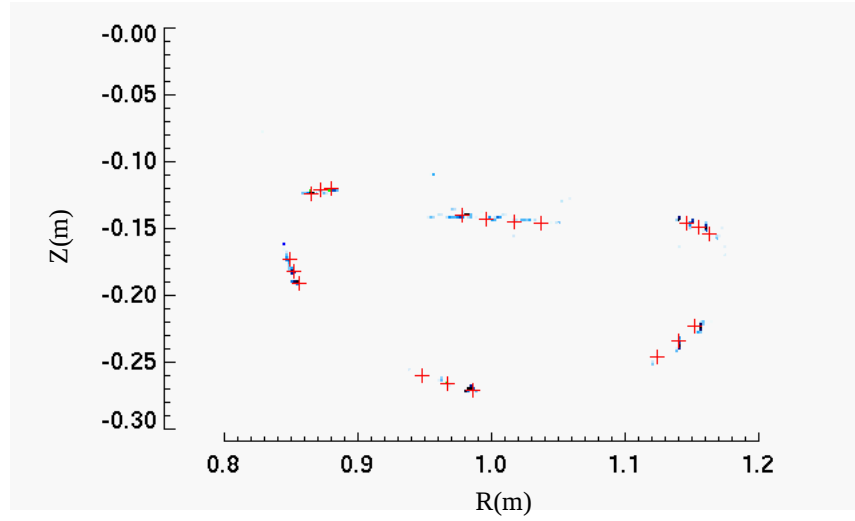


Figure 4.8: Mapped flux surface from the ‘half vertical’ configuration overlaid on the best-fit computer code result (‘+’ points)

From the design data for the helical winding and estimates of the as-built deviations, the swing radius ρ_{hw} lies between 0.0900m and 0.100m and the major radius R_{hw} is essentially same as the radius of the ring conductor *i.e.* 1.0 m. For the basic model, 0.0950m and 1.0 m have been used for ρ_{hw} and R_{hw} respectively. As a first step, the X and Y offsets of the ring conductor, -0.5 mm and +2 mm respectively, have been applied to the helical winding as well, because this winding is intimately connected by spot welding to the ring conductor. The sensitivity of the rotational transform for this configuration to the helical winding parameters is explained in table 4.4. It can be shown that more than one combination of R_{hw} and ρ_{hw} can provide the rotational transform and the surface area which is in good agreement with the mapped results. In order to get a unique value for these two parameters, this process has been repeated for the configuration exhibiting the $m=2$ islands ($\kappa_h = \kappa_v = 1.27$). (The location of the magnetic islands is sensitive to the helical parameters, as explained in coming sections). A set of values for R_{hw} and ρ_{hw} for each of these two configurations has been obtained. From these, the common values have been deduced to be $R_{hw} = 1.000\text{m}$ and $\rho_{hw} = 0.0973\text{m}$ respectively. These values are then used to model various other configurations having different values of κ ($\kappa_h=1.0$ & $\kappa_v = 1.3$, $\kappa_h=-0.4$ & $\kappa_v = 1.0$, $\kappa_h=-0.5$ & $\kappa_v = 1.0$, $\kappa_h = \kappa_v = 1.18$, 1.20,

Table 4.4: Table showing the sensitivity of the rotational transform (t) to the helical winding parameters, for the ‘full helical’ configuration. Reference is the basic model for the same configuration.

Parameters	$(\delta t/t) \times 100$ (For a constant flux surface area)
Increase in the swing radius (ρ_{hw}) by 1 mm	0.31
Decrease in the swing radius (ρ_{hw}) by 1 mm	-0.30
Increase in the major radius (R_{hw}) by 2 mm	0.07
Decrease in the major radius (R_{hw}) by 2 mm	-0.07

1.25.) and found to match very well with the mapping results. It has to be noted that any slight differences in the swing radius in each swing period, if present, have not been accounted in the model at present. The estimated effective helical swing radius of 0.0973 was subsequently found to be consistent with the design engineer’s log book estimating an “as-built” increase of between 1.7 and 2.2mm above the design target of 95.5mm. Shown in figure 4.9 are the experimentally mapped surfaces from the ‘full helical’ configuration overlaid on the best-fit computed surfaces using the new empirical values for R_{hw} and ρ_{hw} .

4.3.3 Stage III: Magnetic islands

The characterisation of configurations exhibiting magnetic islands provides additional information of the magnetic field errors in fine details. As mentioned before, configuration exhibiting the ‘natural’ $m = 2$ islands ($\kappa_h = \kappa_v = 1.27$) has been used to obtain a unique value for the helical winding parameters, as the location and size of these islands are highly sensitive to the swing and the major radii of the helical winding (figure 4.10). Mapping of the $m = 2$ islands has also provided information about the internal rotational transform (t_i) of the island. Comparing this with the computer code results has helped in verifying/fine tuning the parameters obtained earlier. Experimentally mapped $m = 2$ surfaces are overlaid on the best-fit computed results in figure 4.11.

As mentioned before, the X and Y offsets in the ring conductor mainly affect the $m=1$ islands. Shape and locations of the $m=1$ islands for different X and Y

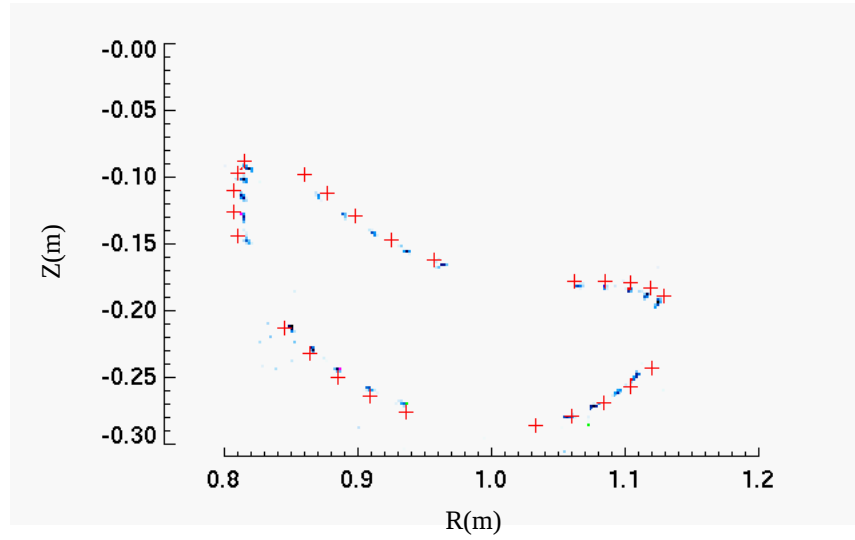


Figure 4.9: Mapped flux surface from the ‘full helical’ configuration overlaid on the best-fit computer code result (‘+’ points)

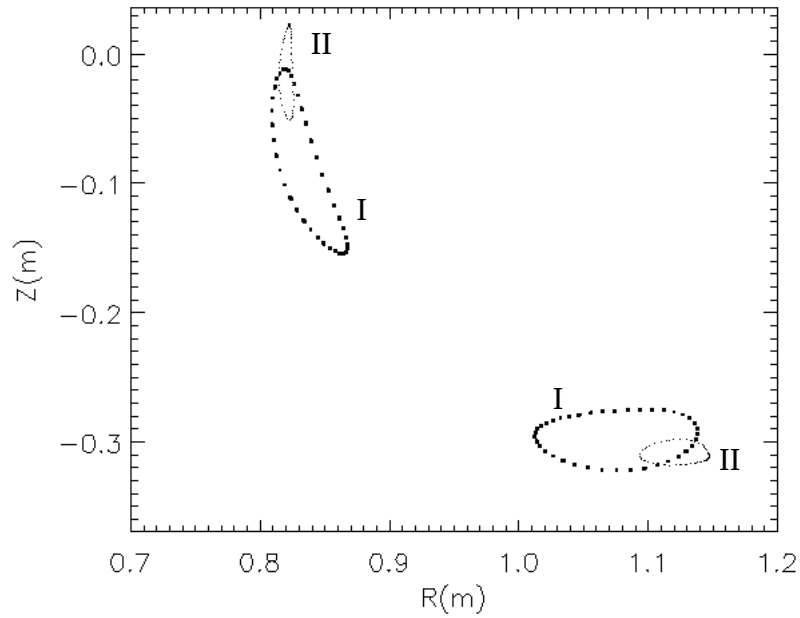


Figure 4.10: Effect of the helical winding parameters on the configuration exhibiting $m=2$ islands. ($\kappa_h = \kappa_v = 1.27$). I. $R_{hw} = 1.0080\text{m}$, $\rho_{hw} = 0.0900\text{m}$ II. $R_{hw} = 1.000\text{m}$, $\rho_{hw} = 0.0930\text{m}$

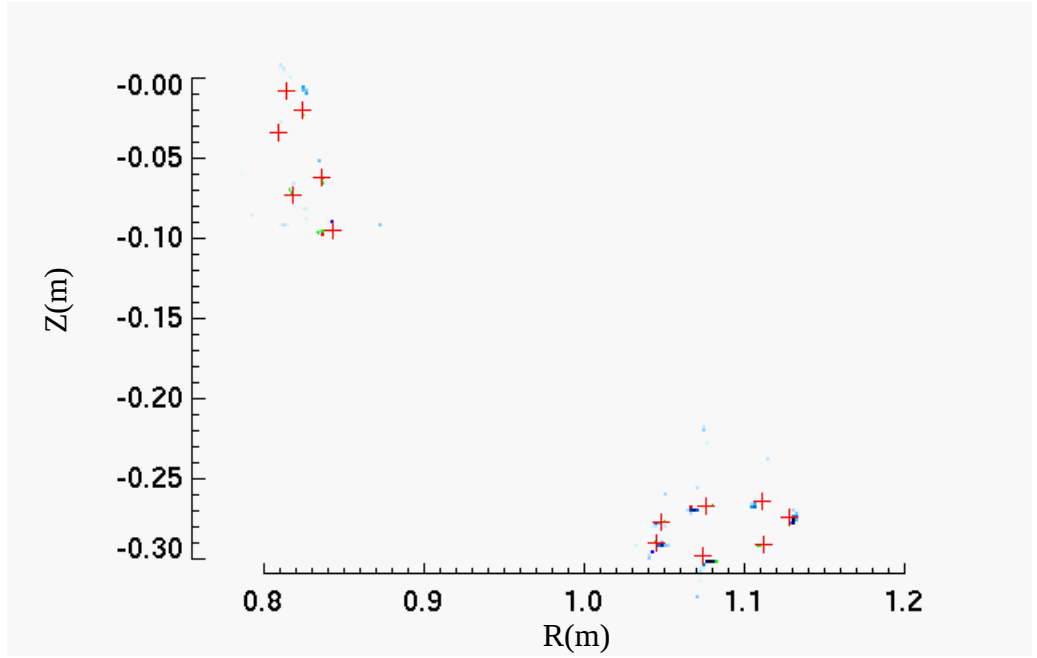


Figure 4.11: Mapped flux surface from the configuration exhibiting $m=2$ islands ($\kappa_h = \kappa_v = 1.27$) overlaid on the best-fit computer code result ('+' points)

offsets are shown in Fig 4.12. This configuration requires the current through the helical winding in reverse direction compared to the normal ‘full helical’ configuration ($\kappa_h = -0.4$ to -0.5). Mapping of the $m=1$ islands has been done using the wire tomography and found to be in good agreement with the new model predictions, as shown in figure 4.13 (a) and (b). There was no attempt to match the internal rotational transform of the islands because accurate mapping is difficult as the rotational transform is close to unity (the successive transits are so close that they cannot be unambiguously resolved. Computed ι for the matching surface is 1.04). However, the result produced in figure 4.13 is good enough to confirm the new magnetic parameters of H-1NF.

Modifications in the new magnetic model in comparison with the basic and an intermediate model are tabulated in table 4.5. The *HELIAC* code input file for the new model is given in the appendix B.

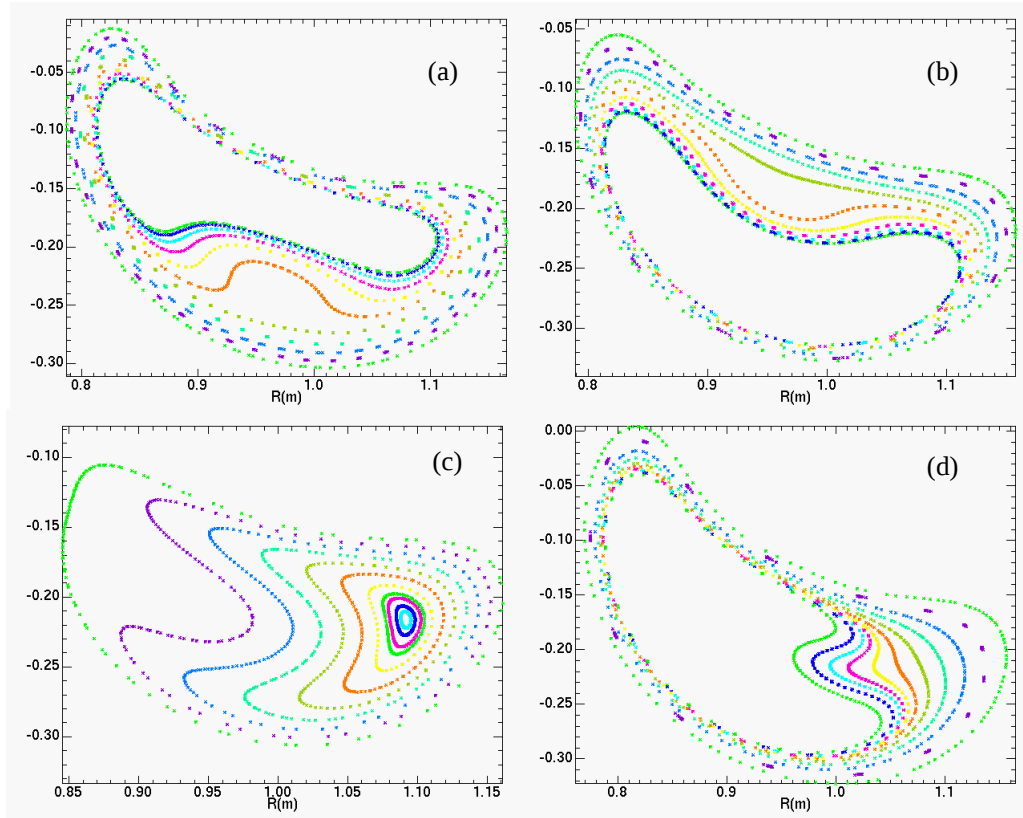


Figure 4.12: Effect of ring conductor offsets in X and Y directions on $m=1$ islands ($\kappa_h = -0.4$, $\kappa_v = 1.0$). (a) $\Delta X = 2\text{ mm}$, $\Delta Y = 0\text{ mm}$ (b) $\Delta X = -2\text{ mm}$, $\Delta Y = 0\text{ mm}$ (c) $\Delta X = 0\text{ mm}$, $\Delta Y = 2\text{ mm}$ (d) $\Delta X = 0\text{ mm}$, $\Delta Y = -2\text{ mm}$

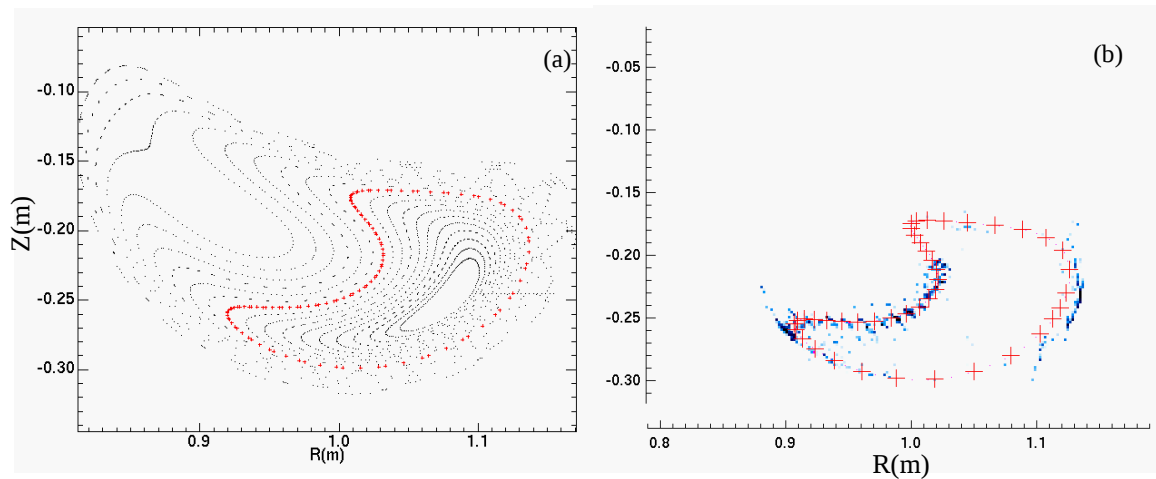


Figure 4.13: (a) The best-fit model predictions for $\kappa_h = -0.4$ ($m=1$ island) and (b) Mapped island surface for this configuration (blue) overlaid on the best-fit model result ('+'). The best-fit surface has been marked on figure(a).

Table 4.5: Summary table showing the modifications in the new model in comparison with the previous models

Parameter	Basic model	Intermediate model ^a	New (best-fit) model
Stray field (B_X, B_Y, B_Z)	0, 0, 0	0, 0, 0	0, 0, 0.75-0.85%
Ring conductor offsets $\Delta X, \Delta Y, \Delta Z$ (mm)	0, 0, 0	-1.5, 2.0, 0	-0.5, 2.0, 0
Radius of the Ring conductor(m)	1.000	1.006	0.998
Major radius of helical winding (m)	1.000	1.003	1.000
Swing radius of helical winding(m)	0.0950 ^b	0.0927 ^b	0.0973
Helical winding offsets $\Delta X, \Delta Y, \Delta Z$ (mm)	0, 0, 0	0, 0, 0	-0.5, 2.0, 0
Ring conductor cross-overs	No	Yes	Yes

^a Used in Ref [75] and afterwards.

^b Helical winding for the basic and intermediate models was essentially a single filament. This has been corrected in the best-fit model by putting 12.5 degree angular separation between the four windings.

4.4 Modified magnetic properties of H-1NF

The rotational transform profiles and the magnetic well profiles of H-1NF with the basic, intermediate and the best-fit models are shown in figures 4.14 and 4.15 respectively. It can be seen that the error fields have significant effect on the magnetic properties of H-1NF. The rotational transform near the magnetic axis for the ‘full helical’ and ‘half vertical’ configurations is reduced by $\Delta t \sim 0.03$ and 0.015 respectively from the basic model with a slight modification in the magnetic shear. The ‘standard’ configuration exhibits almost the same rotational transform profile as the corresponding basic model. A significant change in the magnetic well has been observed for the ‘full helical’ and the ‘standard’ configurations. One flux surface each for these three configurations, computed from the three models, is given in figure 4.16 for comparison. Starting point for the field line tracing is kept the same

for a particular configuration. It can be seen that the best-fit model has a flux surface area very close to that of the basic model for all the three configurations. It is apparent that if we simply overlay surfaces, without matching individual punctures or rotational transform, the conclusion would be in error. For the ‘half vertical configuration [figure 4.16(c)], the best-fit model shows larger islands than the basic model.

4.5 Mapping at higher magnetic fields

All the flux surface mappings mentioned above have been carried out at lower magnetic fields (1000 -1500 A coil current, $B_0 \sim 1$ k gauss) as high field operations in steady state operation are limited to a few seconds duration because of coil heating. A fast mapping scheme has recently been developed which reduced the mapping time from ~ 5 -8 minutes to ~ 15 seconds [60]. Flux surfaces from the ‘full helical’ and the ‘standard’ have been mapped at various magnetic fields up to ~ 0.5 T at the axis (=6500 A coil current).

Figure 4.17 presents mapping results from the ‘full helical’ configuration at different magnetic fields, for a fixed electron gun position. It is apparent that the rotational transform of the mapped surface is slightly different at higher magnetic fields. The rotational transform has changed from $t \sim 1.408$ at 1500 A coil current [$B \sim 0.1$ T, figure 4.17(a)] to $t \sim 1.400$ ($t = 7/5$) at 6500A [$B \sim 0.5$ T, figure 4.17(d)] which is consistent with the observation of 5 transits. (Observation of only five ‘punctures’ in figure 4.17(d) is attributed to the fact that the electron beam is hitting the back of the gun after five transits, because the surface is a near rational one. Our calculations, taking into consideration of the width of the electron gun, show that the Δt above which the beam could avoid hitting back of the gun is ~ 0.0006). As the surface area of these flux surfaces is almost the same, electron gun movement due to deflection or vibrations at higher magnetic fields is ruled out. This is particularly clear in this configuration because the shear is very low - to explain the change in rotational transform, the area would have to change by $\sim 40\%$. It was

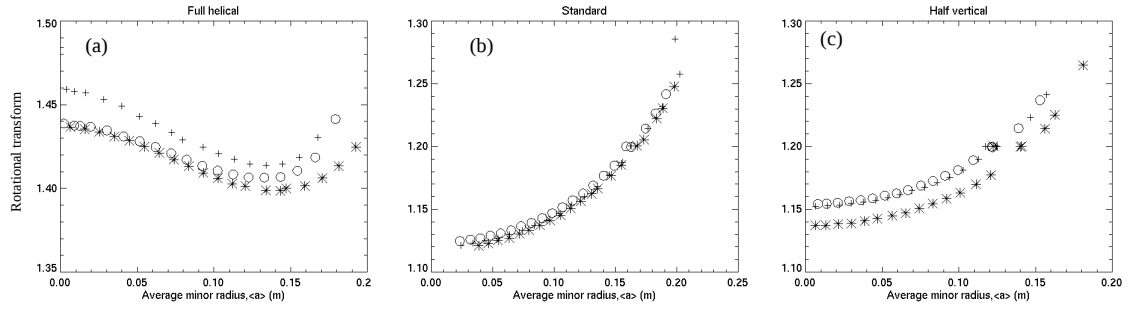


Figure 4.14: Rotational transform profiles with the best-fit (*), intermediate (o) and the basic (+) models

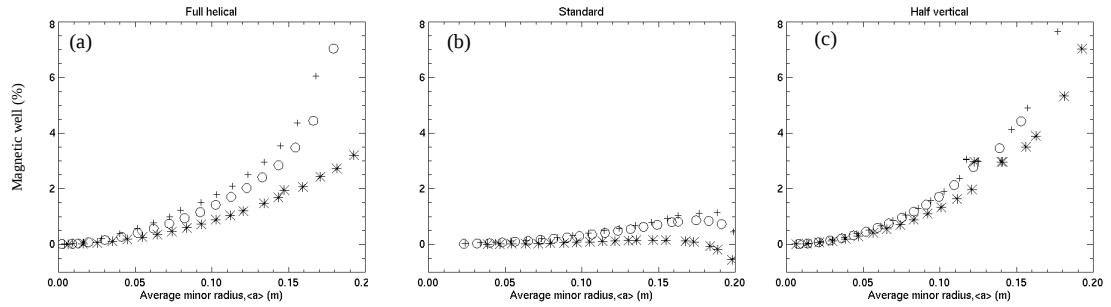


Figure 4.15: Magnetic well profiles with the new (*), intermediate (o) and the basic (+) models

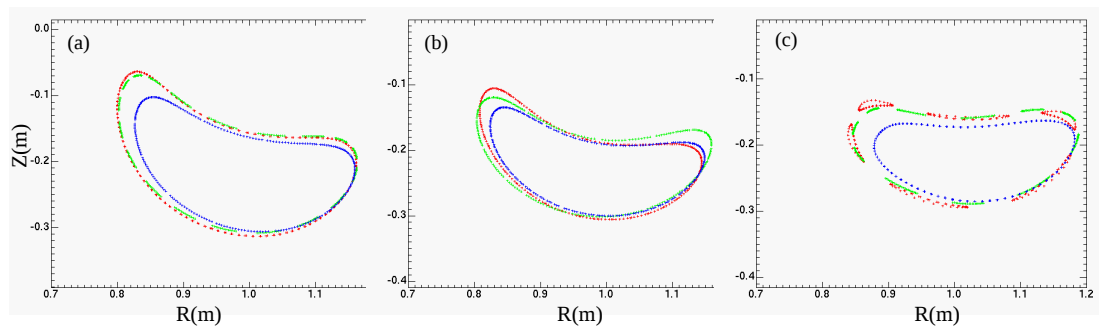


Figure 4.16: Comparison of the three models for the three magnetic configurations. Red-the best-fit model, Green- the basic model, Blue- the intermediate model. (a) ‘Standard’ configuration (b) ‘Full helical’ configuration (c) ‘Half vertical’ configuration

assumed that the effect of stray magnetic field will be less on high field operations, if the contribution is from the magnetised floor. Contrary to our assumption, lowering the vertical error component could not explain this change in rotational transform at higher field. Also, a lower vertical error field at high field operation should rotate the flux surface as shown in figure 4.18. However the mapped surfaces do not show any rotation. This shows that the vertical error field due to the magnetisation of the floor is not ‘permanent’ in nature, but changes with the coil current almost linearly, in the normal operating range of H-1NF (coil current from $\sim 1000\text{A}$ to $\sim 6500\text{A}$). This is in good agreement with our magnetic field measurements with a Hall probe, at different coil currents. There is a potential ambiguity between the effect of drift in the origin of the rotation of the wheel and stray magnetic field. This degeneracy is largely removed by including rotational transform in the matching procedure. Although effects of the earth’s field and the ‘permanent’ part of the stray fields from nearby structures is noticeable at very low fields (eg. 500A), the best-fit model for currents from 1000A - 6500A has zero constant component within experimental uncertainties.

Two possible explanations for this change in rotational transform at high field operations are, (a) the coil movements (in particular the toroidal field coils) due to the dynamic load at high coil currents and (b) slight deformation of the ring conductor due to the electro-magnetic forces. Finite Element Analysis carried out in the past on H-1NF predicted displacements of toroidal field coils of $\pm 1\text{ mm}$ at high coil currents. Images taken during high field operations ($B \sim 0.5\text{ T}$) with open vacuum chamber showed some coil displacements higher than these predictions [81]. Further, the Δt observed for the ‘full helical’ configuration scales as I^2 , where I is the coil current, as shown in figure 4.19(a). Similar behaviour has been observed for the ‘standard’ configuration as well (figure 4.19(b)). It has also been found that a computer model where the ring conductor is replaced with a helical winding with same major radius ($R = 1\text{m}$) and a swing radius of $\sim 0.8\text{ mm}$ could explain the observed rotational transform changes, as shown in figure 4.20. (The difference between a single circular filament model and the model having 36 circular turns in

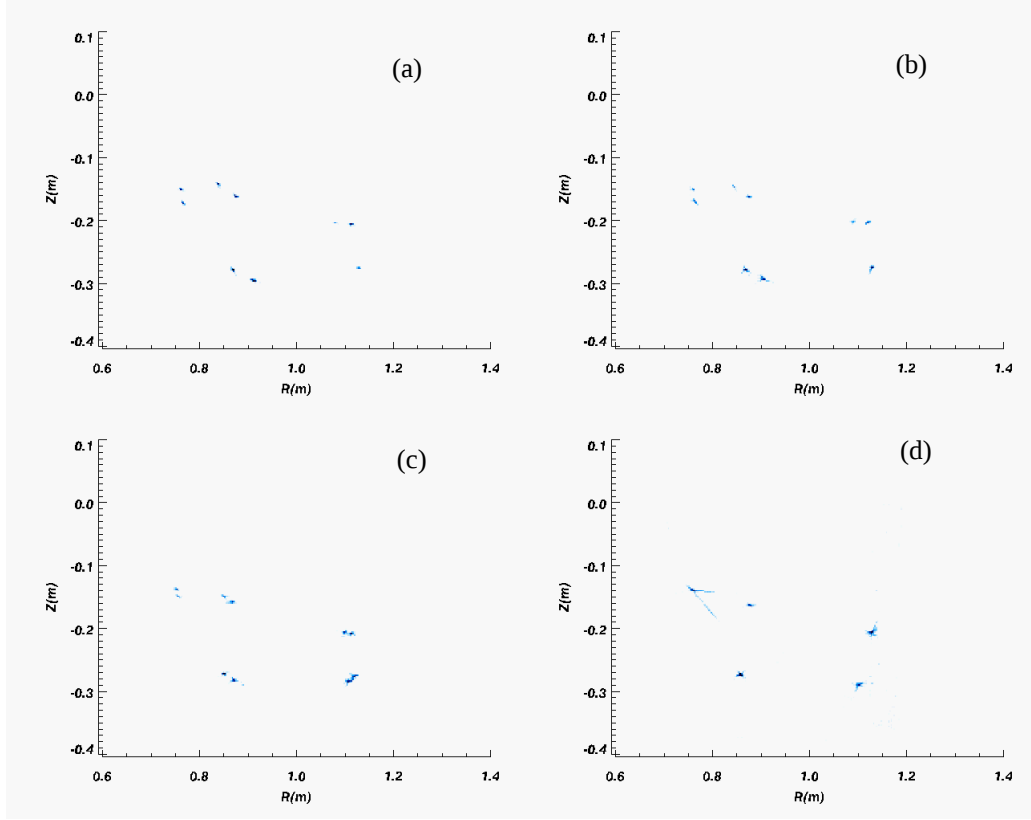


Figure 4.17: Mapping results of full helical configuration at different magnetic fields (a) 1500A (b) 3000A (c) 4500A (d) 6500A

the ring conductor, is indistinguishable inside average minor radius $\langle r \rangle \sim 0.18$ m). A detailed analysis of this is not within the scope of this thesis. (Plasma experiments reported in this thesis are carried out at lower magnetic fields). However, this has to be taken into account when configuration effects are dealt with fine detail.

4.6 Verification from plasma experiments: Mirnov fluctuations

Configuration scans in H-1NF plasma, through variation of the parameter κ_h , have yielded very reproducible MHD spectra with clear resonances related to low-order rational values of rotational transform [62]. MHD modes exist which exhibit the properties of global Alfvén eigenmodes (GAE) [82] up to a scaling factor λ in the dispersion relation $\omega_{GAE} = \lambda k_{||} v_A$, where $v_A = B/\sqrt{4\pi\rho}$ is the Alfvén velocity, the

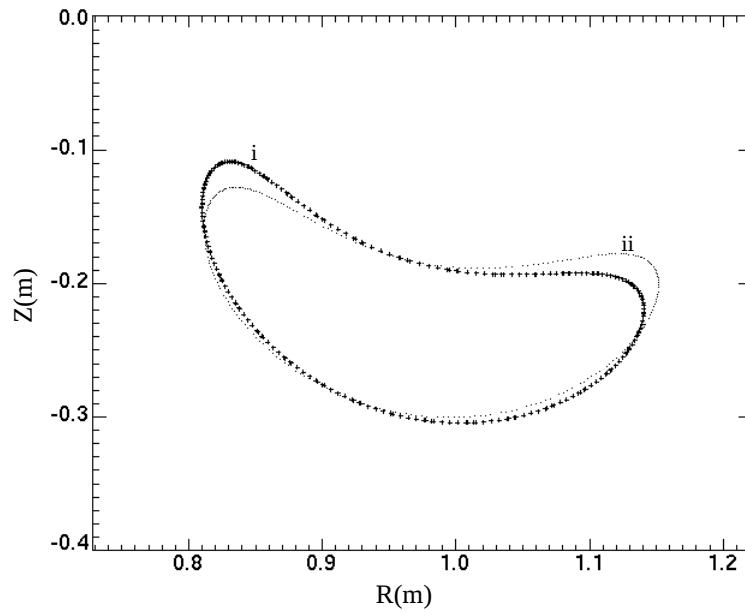


Figure 4.18: Rotation of surface with different vertical error fields (i) with a vertical error field of $\sim 0.85\%$ (ii) with a vertical error field of $\sim 0.25\%$ of B_0

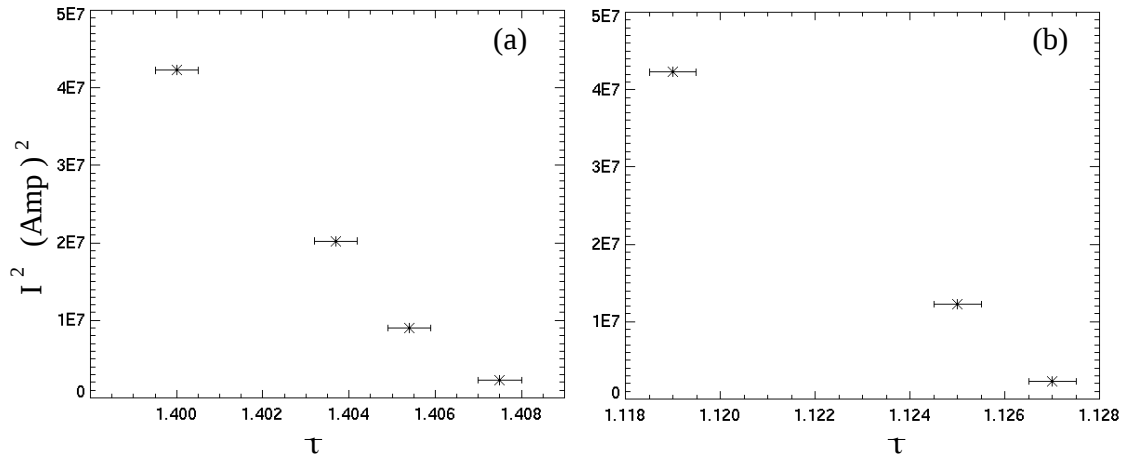


Figure 4.19: Rotational transform (t) of a flux surface as a function of the square of the coil current (I^2). (a) The ‘full helical’ configuration. (b) The ‘standard configuration’

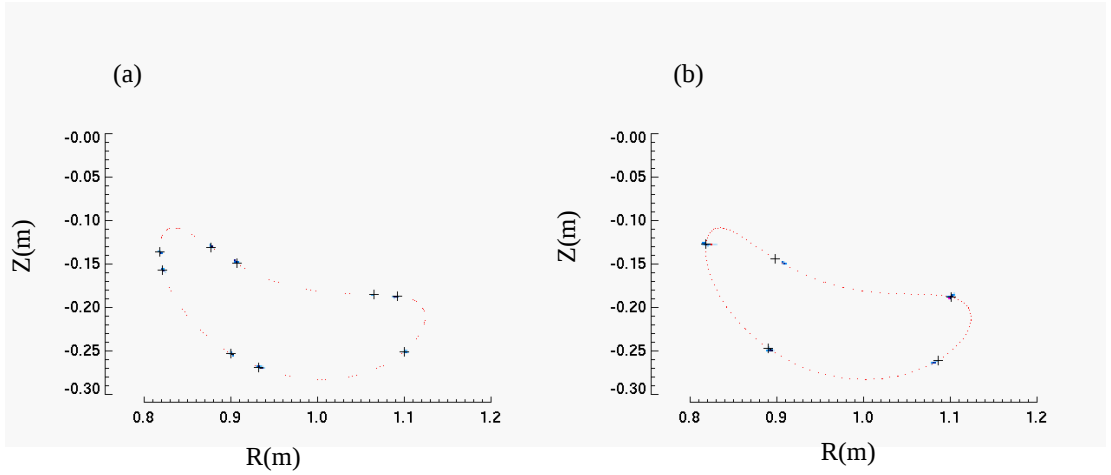


Figure 4.20: (a) Mapping result from the ‘full helical’ configuration for different coil current overlaid on model with ring conductor replaced by a helical winding (a) $I_{coil} = 1500A$, $R_{helix} = 1.000m$, the helical swing radius, $\rho = 0m$ (b) $I_{coil} = 6500A$, $R_{helix} = 1.000m$, $\rho = 0.0005m$

parallel wave number is $k_{||} = \frac{m|\tau - \frac{n}{m}|}{R}$, ρ is the density, R is the major radius and n and m are the toroidal and poloidal mode numbers respectively. Taking frequency measurements f_M from two poloidal arrays of Mirnov coils and electron density n_e from a 2 mm interferometer, we see the scaling of $f_M \sqrt{n_e} \propto |t_{zs} - n/m|$ given by the dispersion relation. Here we use $t_{zs} = t(t'=0)$, the rotational transform at zero shear point, which gives a close approximation to the Alfvén resonance conditions for the non-monotonic rotational transform profiles for these configurations ($0.55 < \kappa_h < 0.95$) [62].

Shown in figure 4.21 (a), (b) and (c) are the observed Alfvén scaling with t_{zs} obtained from the basic, best-fit (low magnetic field) and the high field (ring conductor replaced by a helical winding) models respectively. The mode structure has a dominant $m = 3$ component, therefore it is expected to be resonant with $t_{zs} = 4/3 = 1.333$. It is apparent that the resonant t_{zs} is far from the expected value for the basic model (figure 4.21 (a)). As these experiments have been performed at higher coil currents ($6500A = 0.5 T$), the small difference in the resonant t_{zs} from $4/3$ for the best-fit model ($\Delta t_{zs} \sim 0.005$) figure 4.21 (b)) is as expected. The high field model with a helical winding replacing the ring conductor gives very good agreement with

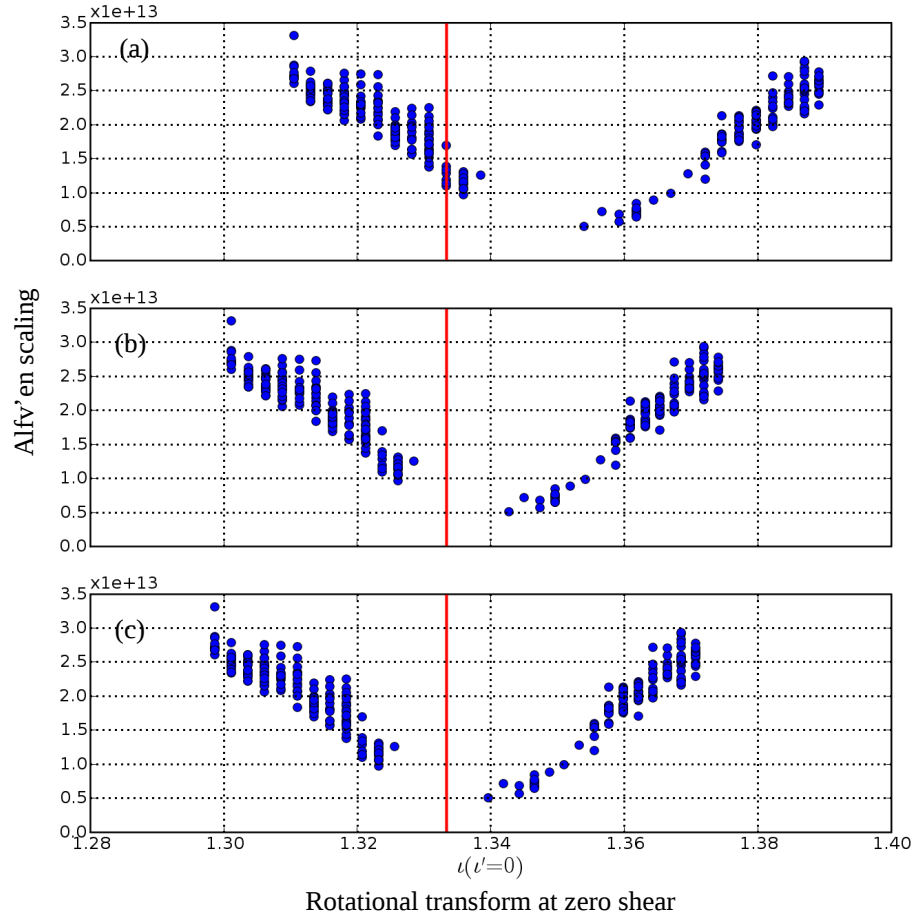


Figure 4.21: Frequency scaling of Mirnov fluctuations (a) with the basic model (b) with the best-fit (low magnetic field) model (c) with the high field (ring conductor replaced with a helical winding) model. The vertical line shows the resonant value of rotational transform. (Courtesy of David G. Pretty)

the experimental observation (figure 4.21 (c)).

In conclusion, the point-to-point matching of the mapping results with the computer code has helped in pin-pointing the error fields present in the laboratory and in determining the best-fit empirical values for the H-1NF coil parameters³. The new H-1NF magnetic model gives rotational transform of any H-1NF configuration correct to three decimal places. We speculate that the observed small difference in rotational transform at high magnetic field is due to slight coil deformation due to electro-magnetic load.

³Manual optimisation was used in this work because of the complex and critical nature of a point-by-point fit between mapped and computed surfaces. With several innovations, a machine-optimised fit may be possible in future.

Chapter 5

Islands in plasma configurations

‘Natural’ magnetic islands in the H-1NF (both $m = 2$ & $m = 5$) have been used to study the effect of islands on the plasma confinement. Of particular interest are island-induced modifications in the radial profiles of plasma parameters, and the conditions for observing island signatures in the plasma. Experimental results indicate that, under favourable conditions, the low order ($m = 2$) islands near the core of the plasma serve as ‘pockets’ of improved confinement regions. This results in significant profile modifications including enhancement of the core radial electric field to a large positive value. These effects are found to be dependent on the plasma collisionality and the island width. In the case of the edge islands ($m = 5$), no significant changes in the radial profiles within the island have been observed under our experimental conditions.

5.1 Introduction

Islands in plasma configurations have been inferred from the ‘flattening’ of the radial profiles of the plasma temperature or density (for example, see Ref. [37, 83]). In the Large Helical Device (LHD), it has been observed that there is a minimum size of the island, below which the profile flattening does not occur [38]. This was interpreted in terms of the balance between cross-field and parallel transport. Flattening of the radial profile may be attributed to the poor confinement inside the island or to the poor resolution of diagnostics. However, in a separate experiment on LHD, it has

been observed that the heat transport inside an island is much reduced [29], which indicates that the profile flattening does not necessarily imply deterioration of the confinement within the island. Further, a local density peak inside magnetic islands has been observed in some tokamak discharges [32, 33]. The parametric conditions required for observing any of these island signatures remain unclear.

A simple hypothesis is in terms of the relation between the island width, gyro radius of the particles, collision scale lengths and the ‘half connection length’ (the toroidal distance from one end of the island to the other) of the island. The $\nabla P = 0$ condition on a flux surface, where P is the plasma pressure, in principle requires the parameters to be the same on both sides of an island, if collisionality conditions are satisfied: If the collision mean free path is much less than the half connection length of the island, the probability of observing same plasma conditions on both sides of the island is less. Also, if the gyro radius of particles is more than the half width of the island ($\delta/2$), particles do not feel the island: the kinetic effects may ‘smooth out’ any profile modification that would occur otherwise. A more complete picture should include drifts and trapped particle effects.

The aim of the present experiment has been to gain an understanding of the conditions for observing island signatures in the H-1NF plasma and study the effect of islands on the plasma confinement. Low order ‘natural’ $m = 2$ ($t = 3/2$) islands in the H-1NF provide an excellent opportunity. These islands are relatively easily observed in vacuum configurations and the size of the island can be varied in a controlled fashion.

5.2 Experimental setup

Three magnetic configurations (shown in figure 5.1) have mainly been used for the initial experiments :

- Case I: $\kappa_h = 0.8$, $\kappa_v = 1.0$ ($t \sim 1.35$ - 1.38). This configuration has well-nested (unperturbed) magnetic flux surfaces as shown in figure 5.1. Profiles

obtained from this configuration are used for comparison with that of the island configurations.

- Case II: $\kappa_h = \kappa_v = 1.18$ ($t \sim 1.44$ -1.50). This configuration exhibits vacuum magnetic islands with width $\delta \sim 0.4\rho$ (~ 40 mm) where $\rho = r/a$, the radial distance from the magnetic axis normalised to the radial location of the last closed flux surface ($r=a$) as shown in figure 5.1.
- Case III: $\kappa_h = \kappa_v = 1.24$. For this configuration, the vacuum islands cover most of the plasma region with width $\delta \sim 0.8\rho$, results in a (toroidally connected) ‘doublet’ like configuration.

Experiments have been conducted in a low magnetic field (~ 0.1 Tesla at the axis) argon plasma, produced by Radio Frequency (RF) waves of power ~ 60 kW for a discharge duration of 40 ms. Typical chamber fill pressure for the discharges is 3.0×10^{-5} Torr, although this is varied for some of the experiments. A radially movable Langmuir probe (tip length ~ 1.4 mm and diameter ~ 0.5 mm) has been used to obtain local plasma parameters. The probe position has been calibrated using an electron beam in vacuum (please see section 4.3, figure 4.6). A more accurate determination of the magnetic axis is obtained later on from the symmetry point of the density profile of a no-island configuration. Low electron temperature (~ 10 eV) of these low magnetic field argon plasmas allows the use of Langmuir probes. argon plasmas in H-1NF are highly reproducible and less affected by the insertion of probes [43]. The probe is biased with a sine wave of frequency 30 kHz and bias voltage up to ± 150 Volts. Plasma parameters (n_e , T_e , ϕ_f) are thus temporally ($\Delta t \sim 16 \mu s$) and spatially ($\Delta r = 5$ mm) resolved. Plasma potential (ϕ_p) is calculated from the floating potential (ϕ_f) using the relation $\phi_p = \phi_f + 4.7 T_e$. Electric field is calculated ($E_r = -\nabla \phi_p$) from the fitted curve of ϕ_p . Radial profiles are averaged over two sets of measurements and the error bars in density and plasma potential are not bigger than the size of the symbols shown in the figures. Details of the Langmuir probe techniques used are outlined in appendix D. A reference Langmuir probe has been positioned near the edge of the plasma (last closed flux

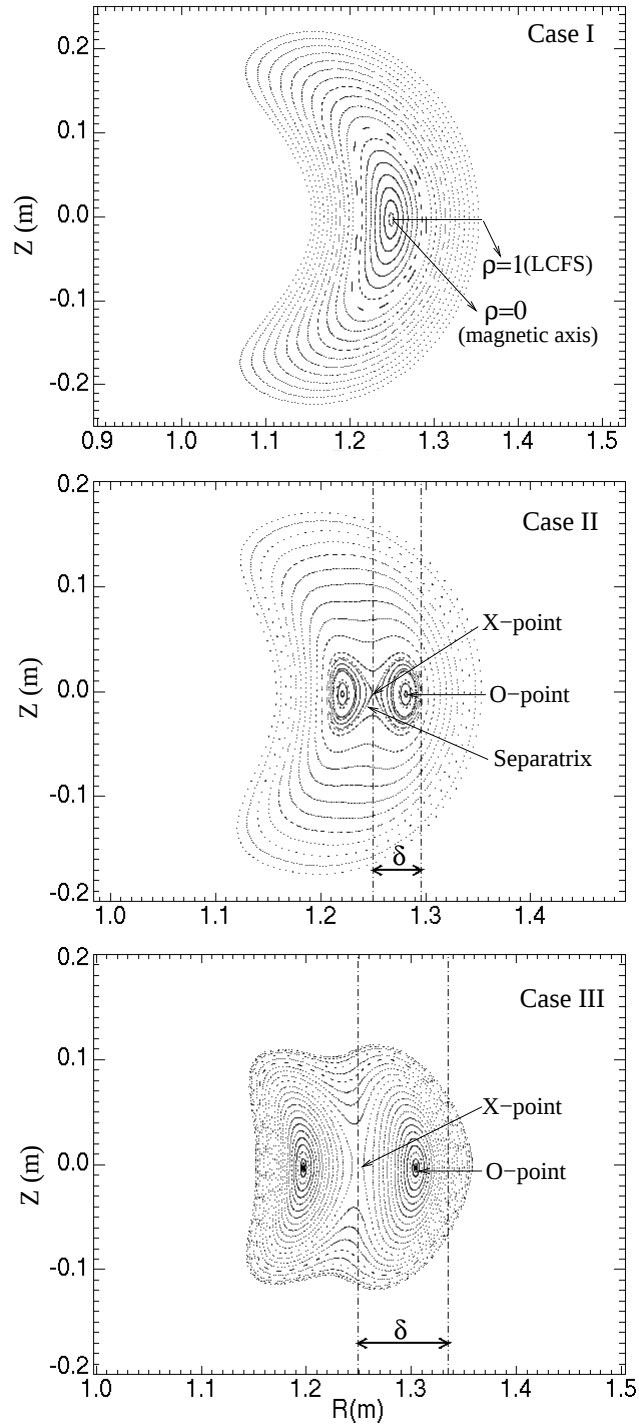


Figure 5.1: Computed flux surfaces of the three configurations used for study. δ is the width of the vacuum magnetic island. The islands (Case II & III) are toroidally connected, as explained in section 1.4

surface) to monitor any perturbation in the plasma parameters due to the insertion of the probe.

5.3 Experimental results

Radial profiles of plasma parameters for the three configurations are shown in figure 5.2, 5.3 and 5.4 respectively. Major experimental observations can be summarized as follows:

- Case I: The electron temperature has a ‘flat’ profile ($T_e \sim 8$ eV) for most of the plasma minor radius with an increase at the edge. This is the typical behaviour of T_e for the RF argon discharges of H-1NF, as the most of the energy deposition is at outer radii, near the RF antenna. A plasma density of $\sim 1.5 \times 10^{18}/\text{m}^3$ has been obtained near the core with a centrally ‘flat’ profile that decreases monotonically towards the edge. The plasma potential is almost ‘flat’ near the core and increases towards the edge. The radial electric field calculated from the plasma potential is in the range of 0 to -4 kV/m. The sharp potential gradient near the edge coincides with the density gradient (figure 5.2).
- Case II: Magnetic islands manifest in the form of density peaking close to the island O-point (figure 5.3), throughout the discharge. The electron temperature is ‘flat’ ($T_e \sim 10$ eV) at the core which increases towards the edge. The plasma potential has a dip near the island O-point. The resultant electric field becomes positive ($E_r \sim 2\text{-}4$ kV/m) near the core with a large electric field shear (~ 300 kV/m²) inside the island with a shear layer thickness of $\sim \delta/2$ where δ is the full width of the island. The E_r has a minimum point inside the island which coincides with the island O-point. The dip in the E_r at $\rho \sim 0.8\text{-}0.9$ corresponds to the density gradient. A similar behaviour is observed when the neutral density (chamber fill pressure) is halved. However, when neutral pressure is doubled, these potential, density and electric field structures disappear as shown in figure 5.5.

- Case III: For this ‘doublet’ configuration, the plasma confinement is poor, as indicated by the low plasma density (figure 5.4). Nearly 50% decrease in the plasma density has been observed. The density profile in this case does not peak at the island O-point, as observed in the case II, but exhibits two inflections ($\rho = 0.4, 0.85$) with a peak near the magnetic axis. The T_e increases towards the edge with a core value of $T_e \sim 11$ eV and edge $T_e \sim 13$ eV. The plasma potential is ~ 10 V near the core, and increases towards the edge of the plasma to just past the island O-point, and remains rather flat after that. The resultant E_r has a minimum point (~ -1.5 kV/m) which coincides with the island O-point, and has a symmetry around the O-point (figure 5.4).

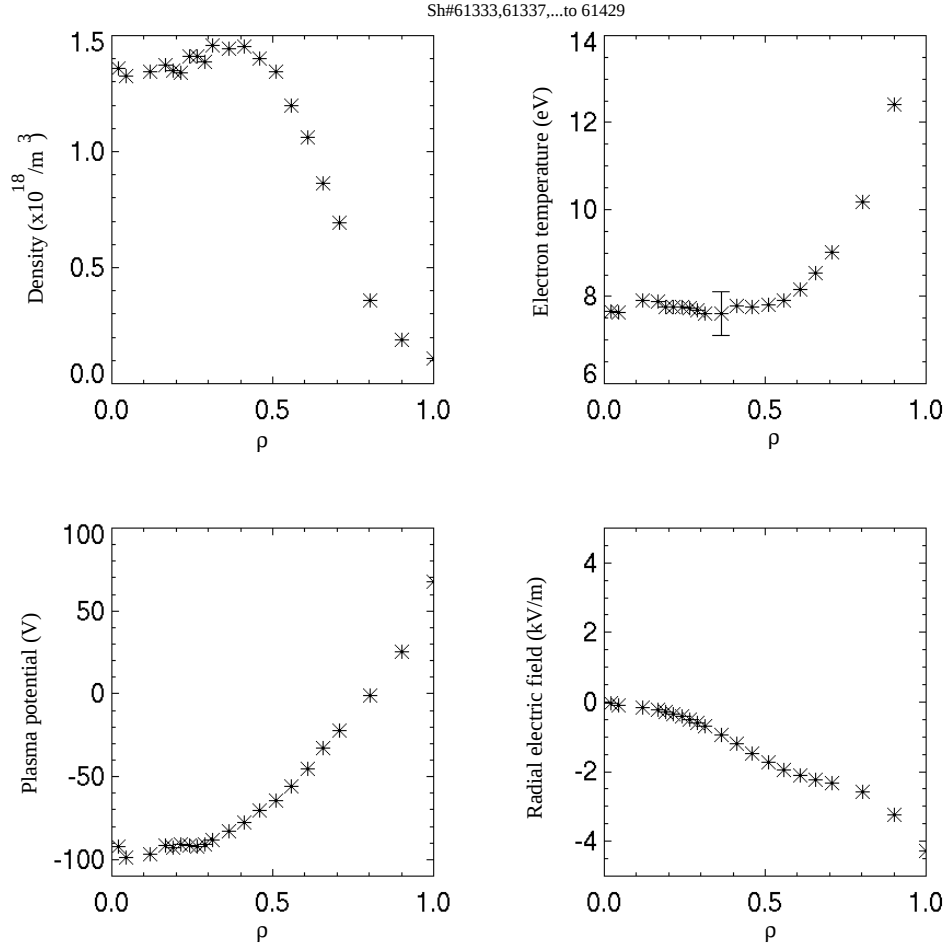


Figure 5.2: Radial profiles of plasma density (n_e), electron temperature (T_e), plasma potential (ϕ_p) and radial electric field (E_r) for the no-island configuration (Case I) at ~ 20 ms into the discharge.

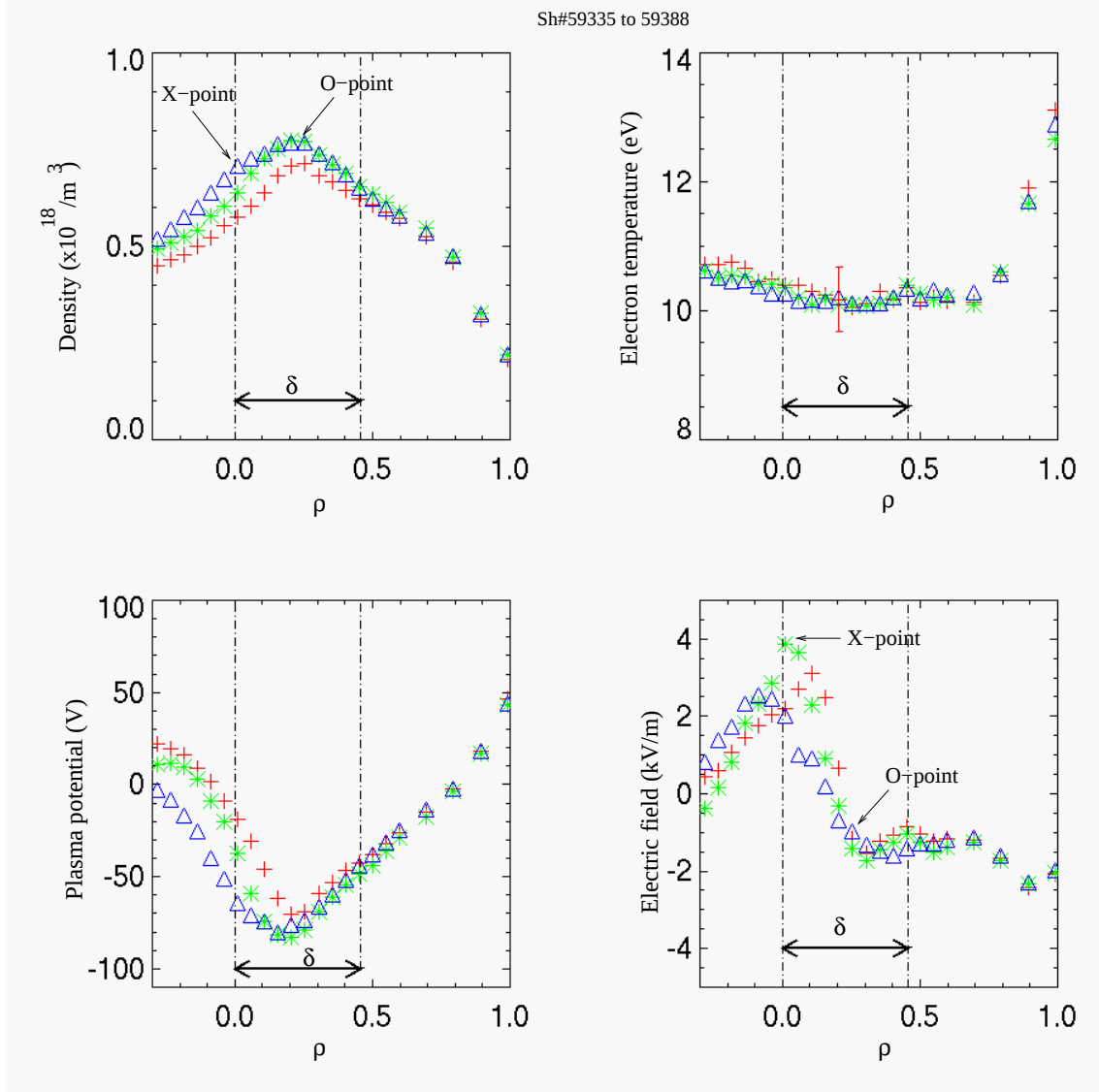


Figure 5.3: Radial profiles of plasma density (n_e), electron temperature (T_e), plasma potential (ϕ_p) and electric field ($-\nabla\phi_p$) for the island configuration (Case II) at ~ 10 ms (+), ~ 20 ms (*) and ~ 30 ms (Δ) into the discharge. δ is the width of the vacuum magnetic island. (Note that the radial coordinate axis is extended to negative values to explore symmetries. The electric field is plotted as if the coordinates were Cartesian, and therefore would be expected to have odd symmetry about $\rho = 0$. The asymmetry about $\rho = 0$ is discussed in section 5.5)

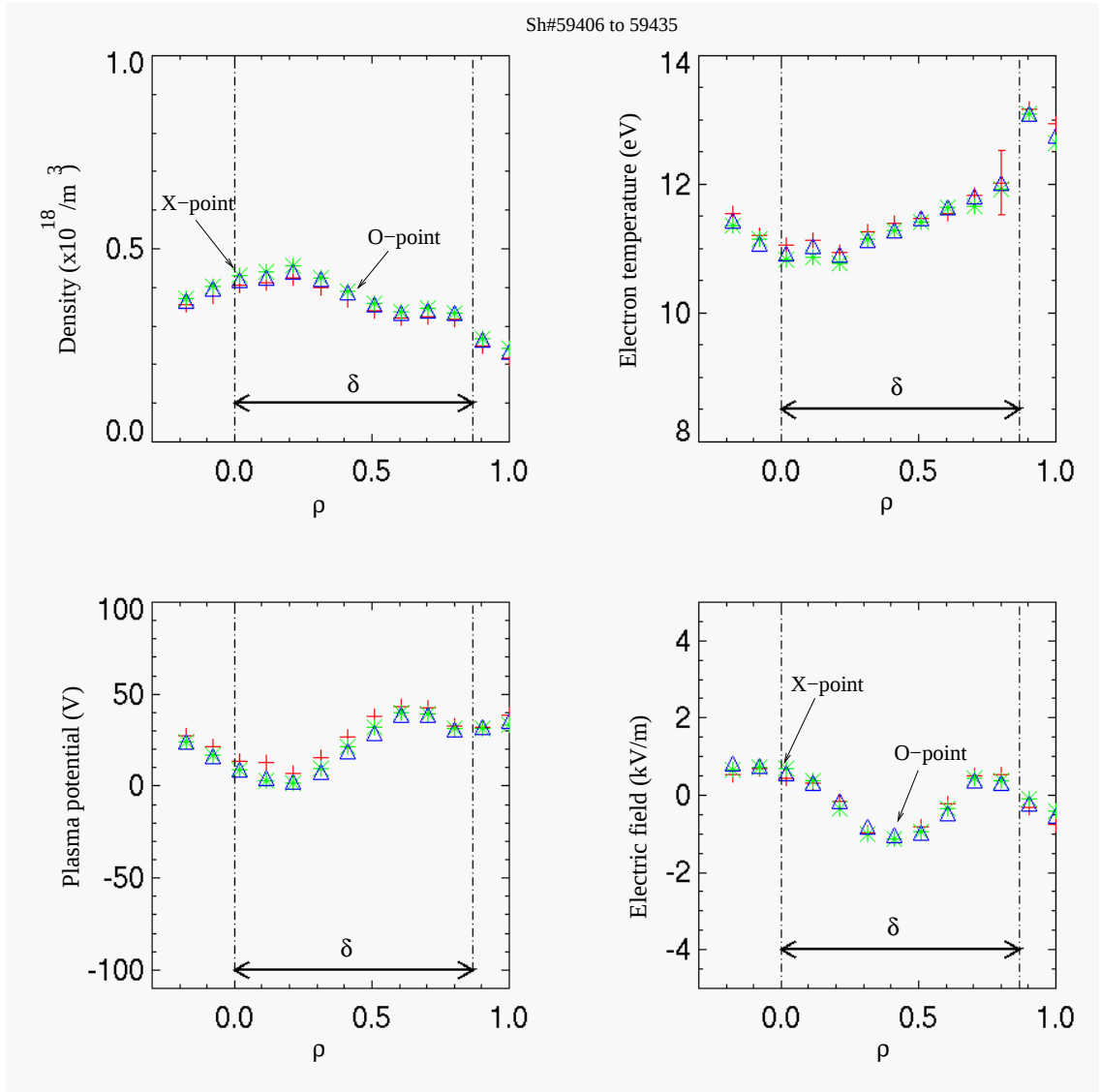


Figure 5.4: Radial profiles of plasma density (n_e), electron temperature (T_e), plasma potential (ϕ_p) and electric field ($-\nabla\phi_p$) for the ‘doublet’ configuration (Case III) at $\sim 10 \text{ ms}$ (+), $\sim 20 \text{ ms}$ (*) and $\sim 30 \text{ ms}$ (Δ) into the discharge. δ is the width of the vacuum magnetic island.

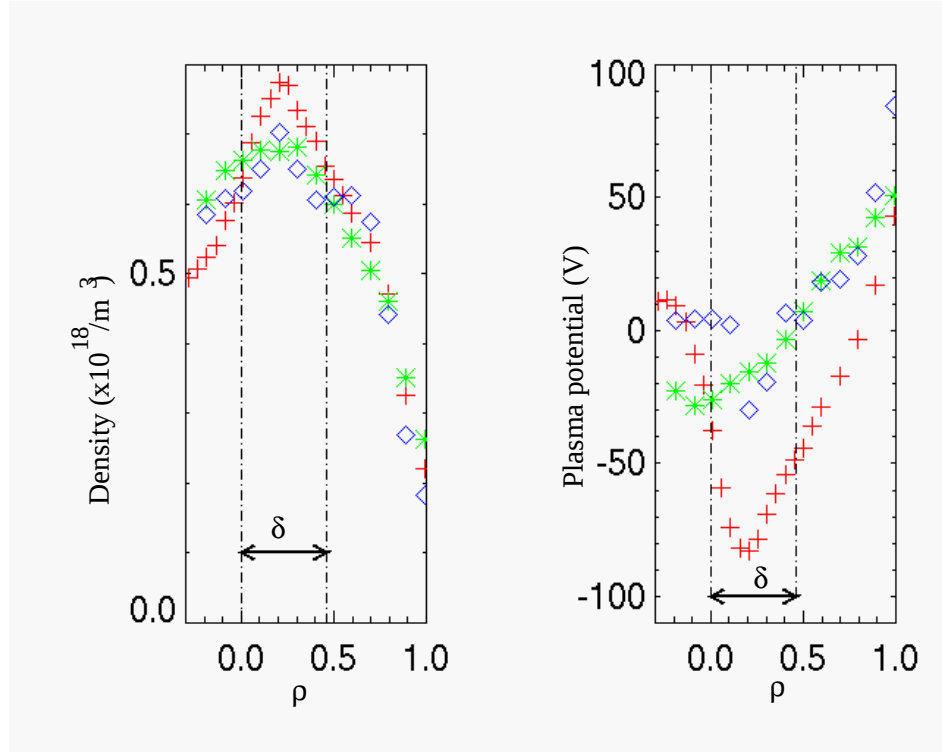


Figure 5.5: Radial profiles of plasma density and plasma potential for the island configuration (Case II) at three different neutral pressures. (+ Normal neutral pressure [Sh#59335-59388], * double neutral pressure [Sh#59471-59501], ◇ half neutral pressure [Sh#59503-59532])

5.4 Results from spectroscopy

The spectral light intensity (I) of the plasma radiation from singly charged ion lines has a simple functional dependency on the plasma density (n_e) and the electron temperature (T_e) [84]:

$$I \propto n_e^2 \xi(T_e) \quad (5.1)$$

where ξ is the distribution averaged rate coefficient for collisional excitation from the ground state. Evidently, the electron density has a strong effect on the spectral light intensity. Assuming that the temperature does not vary much during a discharge (for example, see figure 5.3), the spectral intensity can give a direct indication of the plasma density. It has to be noted that spectroscopic measurements are line of sight averaged, unlike the Langmuir probe measurements which are localised.

A coherent imaging camera [63] has been used to obtain the spectral light in-

tensity from the argon plasma. The camera was used to measure the bulk rotation velocity from Doppler shift of the Ar II line at $\lambda = 488$ nm [84, 63, 85], and with the coherence feature disabled to measure the light intensity. The lines of sight (viewing chords) for this 16 channel camera, calibrated using an electron beam, are illustrated in figure 5.6. The spectral light intensity contours obtained for the configuration exhibiting vacuum islands (case II) are shown in figure 5.7. The density peak inside the island, throughout the discharge, is apparent from figure 5.7. It can also be noted that one of the two $m=2$ island lobes is much brighter than the other, which will be discussed in the coming section.

5.5 Discussion

The typical plasma parameters for the discharges mentioned above (except the high neutral pressure discharges) are listed in table 5.1. It can be seen that, for the experimental conditions, $\omega_{ci} \lesssim \nu_{ei} \ll \omega_{ce}$ where ω_{ci} , ν_{ei} and ω_{ce} are the ion gyro frequency, electron-ion collision frequency and electron gyro frequency respectively. Electrons are therefore highly magnetised and ions are nearly unmagnetised. Also, for the case II, $\rho_e \ll \delta/2 < \rho_i$ where ρ_e , ρ_i & δ are the electron and ion gyro radii and the island width respectively. Therefore ion dynamics is not much affected by the presence of island (as $\rho_i > \delta/2$, ions do not ‘feel’ the presence of these islands).

The radial electric field can be calculated from the radial force balance equation [90]

$$E_r = \frac{\nabla P_i}{n_i Z_i e} - (v_\theta B_\phi - v_\phi B_\theta) \quad (5.2)$$

where B_ϕ and B_θ are the toroidal and poloidal magnetic fields, v_ϕ , v_θ are toroidal and poloidal plasma rotation velocities and $Z_i e$, n_i and P_i are ion charge, density and ion pressure, respectively. In the absence of plasma rotation, the radial electric field can be approximated to the ion pressure gradient term, $\frac{\nabla P_i}{n_i Z_i e}$. Figure 5.8 compares the E_r profile calculated from the pressure gradient ($\frac{\nabla P_i}{n_i Z_i e}$) to the E_r obtained from the Langmuir probe, for the case II. It can be shown that the dip in E_r observed

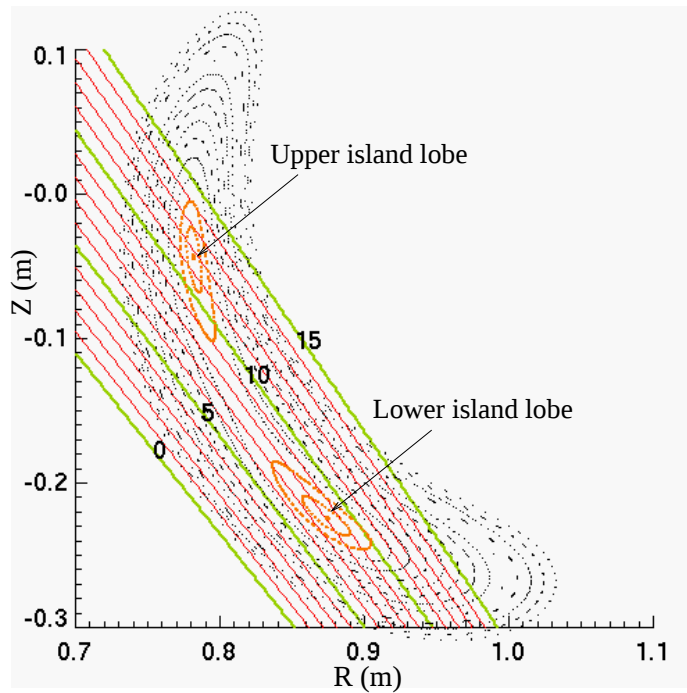


Figure 5.6: Viewing chord positions for the 16 channel imaging camera, overlaid on the flux surfaces from the configuration exhibiting $m=2$ vacuum magnetic islands (Case II). Channel numbers (0-15) are shown.

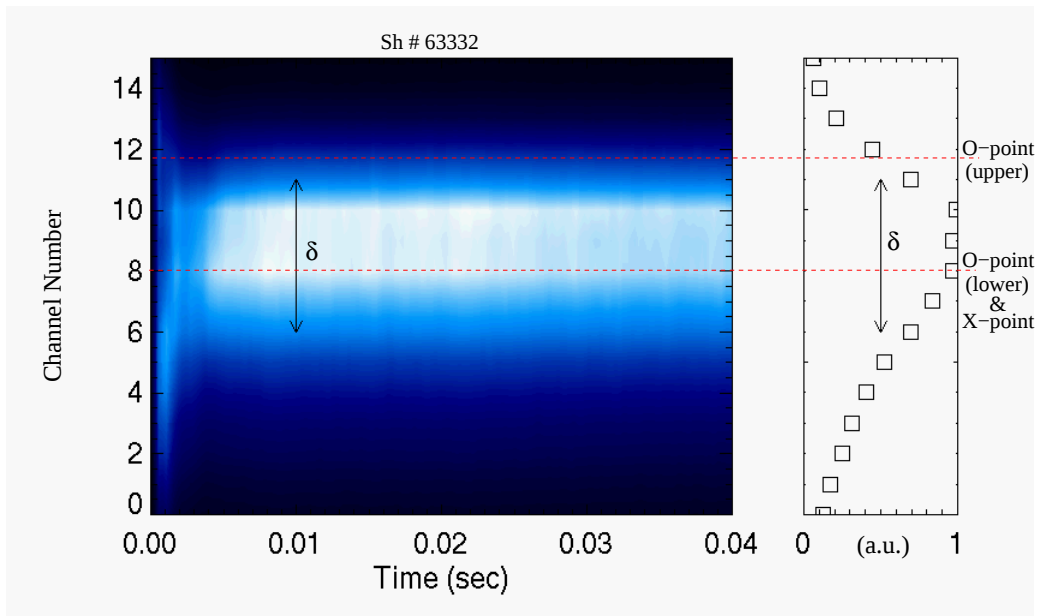


Figure 5.7: The spectral light intensity (normalised to the maximum brightness) for a configuration exhibiting vacuum islands (Case II), showing the lower island lobe is 'brighter' throughout the discharge. δ is the approximate width of one of the vacuum island lobes (the lower island lobe in figure 5.6). Plotted on the right side is the normalised brightness (arbitrary units) at ~ 20 ms into the discharge, and the O-points are shown.

Table 5.1: Typical plasma parameters for the usual neutral pressure discharge.

Electron temperature	10 eV
Ion temperature ^a	$\sim 30\text{-}80$ eV
Neutral (fill) density ^b (n_n)	$\sim 0.81 \times 10^{18}/m^3$
Plasma density	$\sim 1 \times 10^{18}/m^3$
Electron thermal velocity (V_{the})	1.3×10^6 m/sec
Ion acoustic velocity(C_s)	1×10^4 m/sec
Electron gyro radius(ρ_e)	0.075 mm
Ion gyro radius (ρ_i)	$\sim 35\text{-}55$ mm
Electron gyro frequency (ω_{ce})	1.7×10^{10} rad/sec
Ion gyro frequency (ω_{ci})	2.5×10^5 rad/sec
Electron-ion collision frequency(ν_{ei})	9.2×10^5 /sec
Electron-neutral collision frequency(ν_{en}) ^c	1.6×10^5 /sec
Collision mean free path (λ_{ei})	~ 2.5 m
Collision mean free path (λ_{en})	~ 8.2 m

^a From previous measurements on similar discharges [86]. $T_i = 30$ eV is taken for most of the calculations, unless otherwise mentioned.

^b The background neutral density is expected to drop by $\sim 1\%$ by virtue of plasma pumping [87]. The central neutral density (in plasma) depletes to $\sim 30\%$ of the background neutral density [88, 85].

^c $\nu_{en} = n_n \sigma V_{the}$, where σ is the momentum transfer collision cross-section.
 $\sigma = 1.5 \times 10^{-15} \text{cm}^2$ for 10 eV electrons [89]

at $\rho \sim 0.8\text{-}0.9$ for the case II can be explained in terms of the pressure gradient, when a radially flat ion temperature of 60 eV is assumed. (We do not have measurements of ion temperature for this experiment, but ion temperature measured previously for similar discharges is $\sim 30\text{-}80$ eV [86]. Doppler measurements under similar conditions [84, 85] indicate a two component ion distribution with a smaller cold component [$\sim 20\%$, < 10 eV] and a majority ion temperature of ~ 30 eV near the core and ~ 60 eV near the edge.) However the E_r and the sharp gradient near the core in the case II cannot be attributed solely to ∇P . We posit that an $E \times B$ shear flow is set up inside the island, the sign of which reverses (in the coordinate system shown in figure 5.8) across the centre of the island as the sign of the electric field reverses. This observation is in line with the previous observation of vortex-like plasma flow inside an island in LHD [28], although the plasma parameters are quite different.

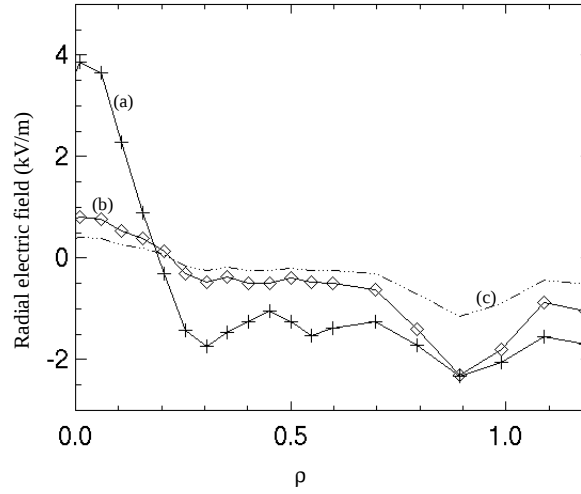


Figure 5.8: The radial electric field for the island configuration (Case II), calculated from the pressure gradient using a radially flat ion temperature of 60 eV (b) and 30 eV (c), over plotted on the measured E_r (a).

It should be noted that the calculated $E \times B$ velocity (in the range of -2×10^4 m/sec to 4×10^4 m/sec) is much higher than the bulk poloidal rotation velocity obtained from the imaging camera ($v_\theta \sim 1000 - 2000$ m/sec). This could be due to the fact that the zeroth order radial force balance equation (5.2) may not be adequate in this case, as the scale length of parameter variations is less than the ion gyro radius (ρ_i). Also, the camera may not resolve the contribution of the island to the line of sight. The radial force balance equation in low temperature argon plasma in H-1NF has been much discussed in the past. It had been reported that the radial electric field obtained from the Langmuir probe measurements disagrees with spectroscopically inferred values [84]. This discrepancy was attributed to the non-Maxwellian features of the ion temperature distribution. In another study using Langmuir probes, a large deficit between the measured and inferred radial electric field has been reported [90]. It was suggested that fluctuation driven radial current may be responsible for the balance deficit. A complete understanding of the radial force balance equation of H-1NF argon plasma is not yet available.

We consider two ways in which the radial electric field can be modified due to the presence of islands: (a) The flows associated with the ambipolar condition

$\Gamma_i = \Gamma_e$, where Γ_i and Γ_e are radial flux of ions and electrons respectively, is significantly modified in the vicinity of magnetic islands. As the island radially connects different regions of the plasma, parallel transport in the vicinity of the island (especially near the separatrix) eventually results in radial flux. For the vacuum island configuration (case II), the island X-point is close to the position of the magnetic axis in the absence of the 3/2 perturbation. As the ion gyro radius (ρ_i) is more than the half width of the island, the ion dynamics (and therefore, Γ_i) are likely to be less affected by the presence of island. Therefore, an enhanced preferential flux of electrons is expected from the core of the plasma, due to the rapid electron transport along the magnetic field lines near the island boundary, especially from within one ρ_e of the island separatrix. Plasma could thus set up a positive radial electric field so that the electron and ion flux are balanced. However, it has to be noted that, due to the high collisionality in our experimental conditions and the extremely long half-connection length near the X-point region (~ 10 -50 toroidal transits), electrons from the X-point region are very unlikely to reach the other side of the island before making a collision. Even though this effect is expected to play an important role only at lower neutral pressures or long mean-free-path regimes, a preferential loss of electrons from the X-point region is still expected to create a charge separation in our experimental conditions. Our field line trace based on the most realistic model of error fields (chapter 4) does not show any significant ergodic region in the vicinity of the separatrix, which under different circumstances might have provided another path for the rapid electron loss from the X-point region. As the X-point is very sensitive to perturbations (drift effects, electric field effects etc), there may be some other mechanisms which can take electrons out of this region. (b) The flux surfaces inside the island are still well nested. Therefore these islands would behave as regions of good electron confinement leading to the development of a potential well inside the island. This modifies the radial electric field. The good electron confinement inside the island (evidenced by the density peak), and to some extent the ‘leaky’ X-point, lead to the development of a non-flat plasma potential in the vicinity of the island in our experimental conditions.

Positive radial electric field due to the presence of magnetic islands has been observed elsewhere also. For example, in LHD, a non-flat space potential and positive radial electric field is observed when the low order ($n/m=1/1$) externally imposed magnetic islands become large enough [28, 44]. Positive radial electric field due to magnetic islands has also been observed in tokamaks [91]. It has also been theoretically predicted that in the vicinity of a magnetic island in a tokamak, the radial electric field can bifurcate to a large value [47].

When the neutral density is doubled (from the usual value of $\sim 0.81 \times 10^{18}/m^3$) for the Case II, the electron neutral collision frequency (momentum transfer) doubles ($\nu_{en} \sim 3.2 \times 10^5$ /sec). There are two effects due to this [92]: (a) The perpendicular collisional (classical) diffusion increases as the diffusion coefficient $D_{\perp} \propto \nu$. This results in degradation of the electron confinement within the island. (b) The parallel transport of electrons along the magnetic field lines near the separatrix (which is essentially the Γ_e because of the radial connection of the island) is much reduced due to the increased collisions with neutrals, as the parallel diffusion coefficient $D_{\parallel} \propto 1/\nu$. As a result, the structures in the density, potential and electric field disappear. This is well supported by our experimental observations (see figure 5.5). When the neutral density is halved, the potential and density structures are still present (although the electric field effect is smaller), as shown in figure 5.5. This indicates that island signatures depend on collisionality. However, our simple hypothesis in terms of collision scale lengths and the half connection length of the island may not be valid, as explained later in this section.

When the half width of the island becomes much larger than the ion gyro radius as in Case III, ($\rho_e, \rho_i \ll \delta/2$), there is no preferential diffusion due to the presence of island. The situation is not very different from the no-island case as far as the transport process is concerned. This is in good agreement with the experimental observations of much reduced E_r in the case III. A decrease in plasma density by a factor of ~ 2 is observed in case III, even though the plasma volume in this configuration is not different from other cases. This may indicate that the RF ionisation

process is affected by the presence of islands in vacuum configuration: in a separate experiment detailed in the next chapter, we analyse a situation where it is proposed that the core magnetic islands are spontaneously generated during the discharge due to toroidal plasma currents. That situation is free from vacuum magnetic islands, at the time of plasma formation.

As mentioned before, it has been observed, both from the Langmuir probe results and from the spectroscopy, that the radial profiles for the island configurations ($\kappa_{hv} = 1.18$) are not symmetric about the magnetic axis (for example, see figure 5.7 where only one lobe of the island is ‘bright’). Even though the two $m = 2$ island lobes are toroidally connected, one of the island lobes is relatively dense. (It can be shown, by tracing the field line, that figures 5.3 and 5.7 agree as to which island lobe is stronger). Though not well understood, a similar imbalance was observed in previous experiments in a related magnetic configuration [93, 94]. The asymmetry of H-1NF discharges is much discussed in the past. For example, it has been reported that the argon light intensity and density profiles often violate flux symmetry on H-1NF discharges [84], and this asymmetry is attributed to be driven by the heating mechanism.

By tracing the field line back to the RF antenna port, it can be shown that the two island lobes are approximately at equal distance from the RF antenna. Due to subtle effects, an imbalance in the plasma density may be occurring at the initial phase of the discharge. As the flux surfaces inside the magnetic islands are well-nested, plasma confinement inside the island is good. As both the dielectric constant and collision rate increases with electron density, for wave heating, ionisation may be more effective in the regions of higher density (at the O-point of the stronger island lobe), reinforcing any imbalance at the initial stages of the discharge and leading to much higher density in one island lobe. As the electron-neutral collision mean-free-path is less than or comparable to one toroidal transit under our experimental conditions, this imbalance is unlikely to be corrected by toroidal connection. Further, if the ionisation is more effective at the O-point, the density profile inside

the island is expected to be symmetric around the island O-point (see figure 5.3), even though the collisionality conditions for $\nabla P = 0$ on a flux surface (mentioned in section 5.1) are not satisfied: both the electron-ion and electron-neutral collision mean free paths (λ_{ei} & λ_{en}) are less than or comparable to one toroidal transit, and therefore, much less than the half connection length of the island (10-12 toroidal transits, which is about 70-90 meters). Cross-field diffusion with a source peaked at the O-point determines the density profile inside the island. For this reason, our simple hypothesis for observing island signature in terms of the collision scale lengths and the half connection length of the island is not applicable.

A positive radial electric field near the core of the plasma and associated enhancement of plasma confinement in helical devices has recently been classified as ‘Core Electron-Root Confinement’ (CERC) [46]. However, this has been observed only in high temperature electron cyclotron heated (ECH) plasmas which satisfy some threshold conditions (conditions on ECH power per particle). Our experimental results may indicate that magnetic configurations with islands near the core of the plasma could help in achieving the CERC equivalent scenario (as mentioned in Ref [95]), in low temperature RF plasmas as well. The next chapter details an experiment concerning this issue.

5.6 Islands at the edge

Magnetic islands and ergodic field lines at the edge of the plasma are of great importance in fusion devices. By positioning chaotic field lines and magnetic islands at the edge, the undesirable concentration of heat load to the walls can be avoided and the Edge Localised Modes (ELMs) can be suppressed. This also improves the core confinement [96, 97].

Experiments have been conducted on H-1NF to understand the behaviour of edge islands. Some of the H-1NF magnetic configurations exhibit the ‘natural’ $m = 5$ islands ($t = 6/5$). These islands can be located near the last closed flux surface,

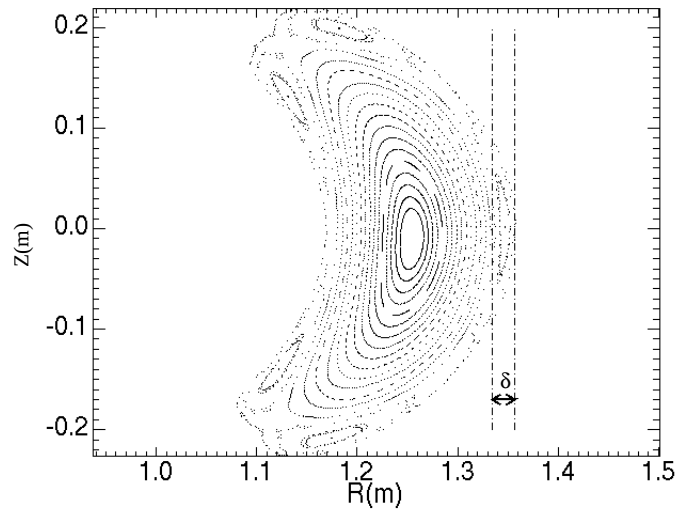


Figure 5.9: Computed flux surfaces of the configuration exhibiting the 6/5 magnetic islands at the edge. δ is the width of vacuum magnetic island.

and are reasonably wide ($\delta \sim 2$ cm) yet inside the LCFS, for the ‘half vertical’ configuration ($\kappa_h = 0.0, \kappa_v = 0.5$). Computed flux surfaces for this configuration are reproduced in figure 5.9. Island width is marked. As discussed in chapter 3, we could not confirm the presence of these islands in vacuum configurations due to the small internal rotational transform. However, the accuracy of other aspects of the computer model eliminates any doubt on their existence (section 3.6).

Radial profiles of density, plasma potential and the radial electric field at nearly 20 ms into the discharge for the ‘half vertical’ configuration are shown in figure 5.10. Location of the vacuum magnetic islands is marked. Electron temperature has a hollow profile with ~ 12 eV at the centre and ~ 20 eV at the edge. It is apparent that these islands do not show up in the plasma profiles even though the measurement resolution is sufficient. This may be because of the extremely long half connection length for this island (~ 65 toroidal transits which is about 450 meters) and the small island width ($\delta \sim 2$ cm): cross-field transport across the island may dominate parallel transport around the island. Because of difficulties of plasma production under standard conditions, these experiments are conducted at a magnetic field of ~ 0.18 T at the axis (corresponds to 2500A through the ring conductor) and a neutral

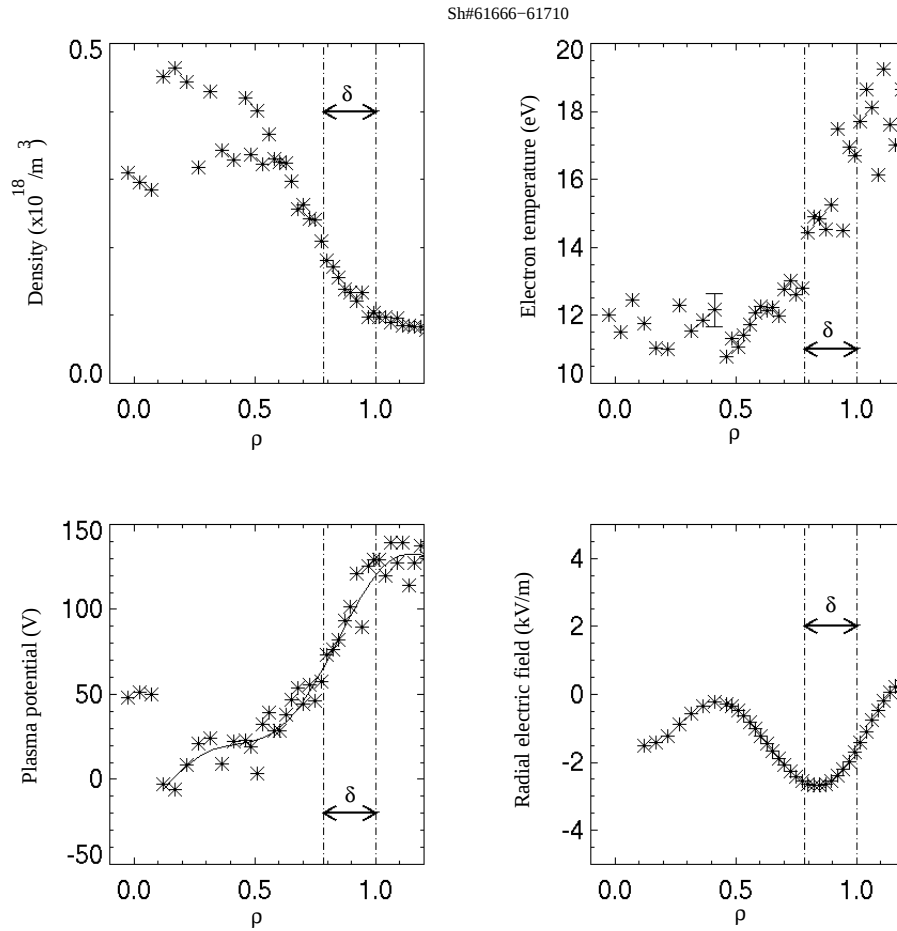


Figure 5.10: Radial profiles of plasma parameters for configuration exhibiting vacuum islands (6/5) at the edge, at ~ 20 ms into the discharge. Scatter in density is due to fluctuation in the plasma as explained in the text.

pressure $\sim 4 \times 10^{-5}$ Torr. Detailed experiments with a range of neutral pressures or magnetic fields were not possible, as the whole plasma readily breaks into large amplitude global modes in this configuration and measurements and interpretation become difficult. It has to be noted from the density profile that the density near the core for this configuration is highly oscillating and seems to jump between two distinct states. This scatter in density is due to a low frequency fluctuation in the plasma. This behaviour is similar to the previous observation of low frequency dithering prior to the H-mode transition in the H-1NF argon plasma [98], but different from the single step L-H transition [99]. Any relation of this behaviour to the presence of magnetic islands near the edge is not understood at present. A detailed experimentation could be a topic of future research.

In conclusion, the low order magnetic islands near the core are found to behave as regions of improved electron confinement, under favourable conditions. A model has been put forward to explain the radial profile modification by the island, especially the radial electric field: when the ion gyro radius is larger than or comparable to the half width of the island, the ion dynamics are less affected by the presence of island, but the electron dynamics are significantly modified. Nested flux surfaces inside the island leads to a good electron confinement which creates a potential well inside the island. Electrons near the core of the plasma (near the island X-point) are expected to undergo a rapid radial transport moderated by collisions, along the magnetic field lines near the island boundary, especially within one ρ_e of the island separatrix. This enhanced preferential electron flux from the core leads to the development of an ambipolar radial electric field, which is positive near the core. This simple model is supported by our experimental evidence of much reduced radial electric field structure in the vicinity of the islands when the island width or the neutral collisions are increased.

Chapter 6

Spontaneous bifurcation of the radial electric field

Experiments with a magnetic configuration which exhibits no vacuum islands, but with core t close to the low order rational value of $3/2$, show a spontaneous transition of the radial electric field near the core of the plasma to a large positive value ($E_r \sim 5$ kV/m), with a strong electric field shear (~ 700 kV/m²) and localised improvement in confinement. Evidence indicates that the transition is driven by the excitation of low order ($t = 3/2$) magnetic islands near the axis during the plasma discharge, due to modification of the rotational transform profile by toroidal plasma currents. This is the first experimental observation of this kind in a RF collisional plasma.

6.1 Introduction

The radial electric field (E_r) and its shear play an important role in plasma confinement in fusion devices. Role of E_r in the transition to the improved confinement regime (H-mode) and the formation of transport barriers has been recognized both theoretically [100, 101, 102] and experimentally [103, 104, 105].

Recently, an improved plasma confinement near the core in helical devices, with a large positive radial electric field (E_r), has been classified as Core Electron-Root

Confinement (CERC) [45, 46]. This is one of the two stable solutions of the electric field that satisfy the ambipolar conditions, other being the normally observed ion-root situation where the core radial electric field is usually negative, and smaller in magnitude. The highly positive core E_r suppress the neoclassical $1/\nu$ transport, where ν is the collision frequency. CERC has been observed in many helical devices with various power levels of electron cyclotron heating (ECH) and various magnetic geometries [106, 107, 31, 108, 109]. Experimental observations with similar features in the ‘transition layer’ [110] between the two neoclassical regimes (electron-root and ion-root) have also been reported. All these experiments require strongly heated electrons to make electron losses from the core exceed the ion loss and suggest that there is a threshold ECH power per particle required to achieve this improved confinement regime. It has also been reported that presence of a low order rational surface close to the plasma core is a necessary condition for triggering CERC [108]. Reduction of the threshold conditions due to the presence of low order magnetic islands at the centre has also been discussed [31, 46]. Experiments on LHD have shown that the existence of $m/n = 2/1$ islands facilitate a confinement transition to a high- T_e state [95]. This chapter reports the first experimental observation of a spontaneous transition of the E_r near the core to a large positive value (a CERC equivalent scenario) in a low temperature collisional RF plasma, possibly triggered by low order magnetic islands.

6.2 Experiment

Experiments reported in this chapter have been conducted in a low magnetic field (~ 0.1 Tesla at the axis) argon plasma, produced by radio frequency (RF) waves of power ~ 60 kW for a discharge duration of 40-60 ms. A magnetic configuration having on-axis rotational transform of ~ 1.475 , very close to the ‘natural’ $t = 3/2$ resonance of H-1NF, has been chosen so that a very small toroidal current in the right direction can take the on-axis t to the resonance value and may spontaneously create $m = 2$ magnetic islands during the discharge. A radially movable cylindrical Langmuir probe (length ~ 1.4 mm and diameter ~ 0.5 mm) has been used to obtain

local plasma parameters, as detailed in chapter 5 and in appendix D.

6.3 Results and discussion

Temporal and spatial evolution of the plasma potential (ϕ_p) obtained from the Langmuir probe measurements are shown in figure 6.1. Radial profiles of plasma parameters at two different times of the discharge are shown in figure 6.2. Major experimental observations are as follows: Global plasma parameters at the initial phase ($t < 20$ ms) of the discharge have the typical behaviour of the high confinement mode (H-mode) plasma of H-1NF (see for example Ref [42]). The region beyond the characteristic kink in the density profile (at $\rho \sim 0.6$) forms the density pedestal [figure 6.2(a)] of the H-mode. Electron temperature remains flat (~ 10 eV) inside and increases towards the edge. The dip in the observed electric field at $\rho \sim 0.8-0.9$ of about 3kV/m is matching with our calculations, $E_r = \frac{\nabla P_i}{n Z_i e}$, as explained in the previous chapter. Towards the end of the discharge ($t > 20-25$ ms), the plasma potential bifurcates and a large potential well develops near the core [figure 6.2(c)]. The cause of the asymmetry about the magnetic axis ($\rho = 0$), towards the end of the discharge in figures 6.1 and 6.2, is not understood at this time. (A shift in the magnetic axis ~ 6 mm [$\rho \sim -0.055$] inward would remove this asymmetry, but we cannot find a mechanism that would cause this.) There is a corresponding local improvement in the plasma density, whereas the electron temperature remains the same. The electric field calculated from the fitted profile of the plasma potential has a large positive value of ~ 5 kV/m near the core and the sign of the electric field reverses in a narrow region. A strong shear layer (~ 700 kV/m²) has thus been developed with a thickness of $L_s \sim 20-25$ mm which is much larger than the electron gyro radius, ρ_e (~ 0.07 mm) but less than or equal to the ion gyro radius, ρ_i ($\sim 25 - 35$ mm) for this discharge. The floating potential fluctuations ($\tilde{\phi}_f$) measured using an unbiased Langmuir probe at $\rho \sim 0.5$ (outside the shear layer as the insertion of the probe into the shear layer seems to slightly modify the fluctuation pattern) show a highly coherent ($f \sim 3$ kHz) mode, once the shear layer has been formed (figure 6.3). Similar fluctuations have been observed in the chord-averaged

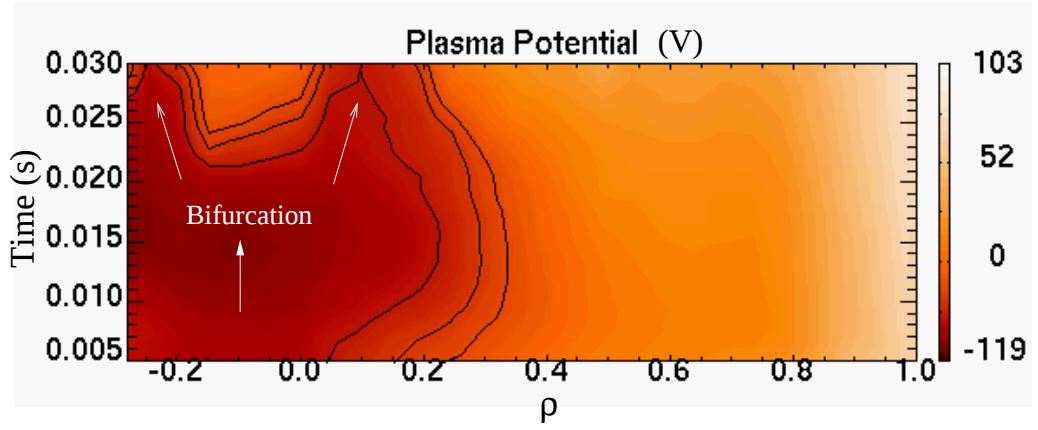


Figure 6.1: Spatial and temporal evolution of the plasma potential (ϕ_p) for the $\kappa_h = \kappa_v = 1.12$ configuration, showing the bifurcation at ~ 20 ms into the discharge (Sh#59712-59773).

density measurements (2 mm interferometry) and magnetic fluctuations obtained from Mirnov coils.

Shown in figure 6.4 is the spectral light intensity, for the configuration under test, obtained using a coherent imaging camera. The spontaneous transition of the core light intensity (corresponds to the electron density, assuming a constant T_e) is clearly visible from the figure. This has to be compared with the spectroscopic results shown in the previous chapter for the vacuum island configuration (figure 5.7), where the islands manifest in the form of bright regions.

Observed plasma parameter profiles towards the end of the discharge have similar features to that obtained for a configuration with vacuum magnetic islands (case II, chapter 5). The plasma potential and radial electric field for this configuration at 10 ms and 35 ms into the discharge, along with the vacuum flux surfaces, are reproduced in figure 6.5. Radial electric field is positive at the core (~ 4 kV/m) which reverses sign inside the island. As explained in the chapter 5, the positive electric field is possibly due to the rapid electron transport from the core, which coincides with the X-point of the island, along the magnetic field lines near the island boundary.

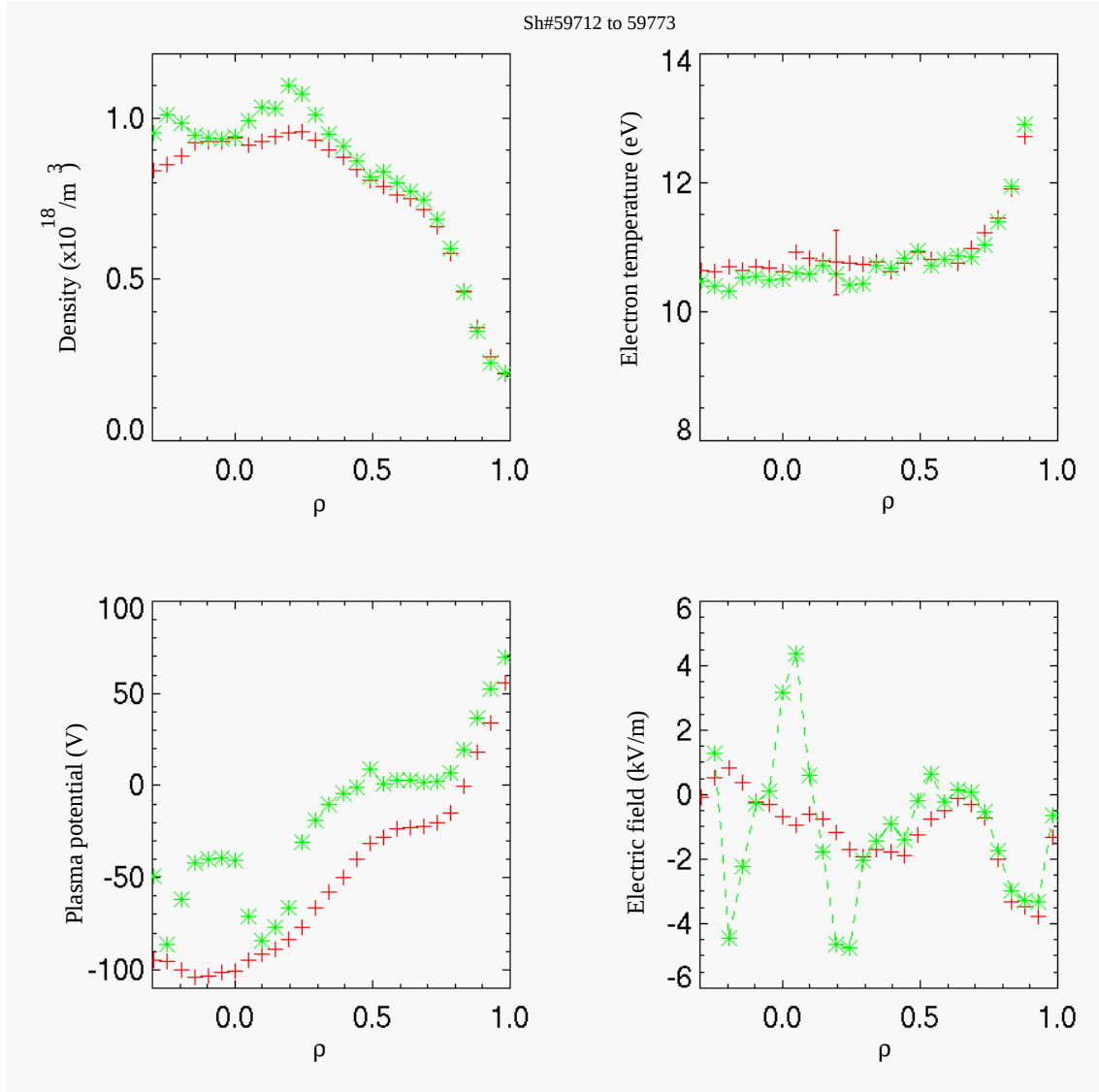


Figure 6.2: Radial profiles of plasma density (n_e), electron temperature (T_e), plasma potential (ϕ_p) and electric field ($-\nabla\phi_p$) at ~ 10 ms (+) and ~ 30 ms (*) into the discharge. (Note that the radial coordinate axis is extended to negative values to explore symmetries. The electric field is plotted as if the coordinates were Cartesian, and therefore would be expected to have odd symmetry about $\rho = 0$.)

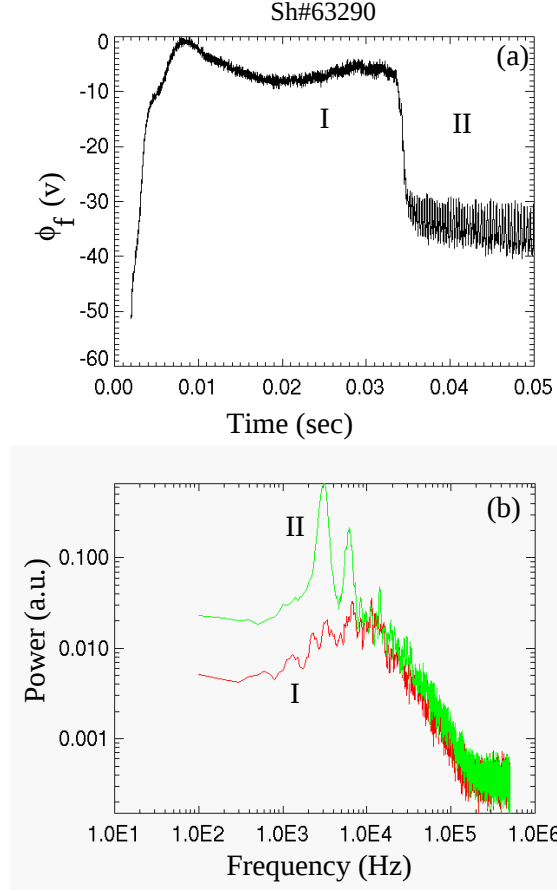


Figure 6.3: Fluctuations in the floating potential (at $\rho \sim 0.5$) before (I) and after (II) the shear layer excitation. (a) Time series of the floating potential (b) Power spectrum at two time intervals

All this evidence suggests that the vacuum rotational transform in the present experiment has been modified during the discharge so that the central ι reaches the resonant value ($3/2$) and $m=2$ islands spontaneously develop near the core of the plasma. Our measurements with Rogowski coil show a net toroidal current of ~ 10 - 15 A during these discharges (figure 6.6), which is believed to have a contribution from the RF antenna sheath current as well. We presently do not have information about the radial distribution of the toroidal current and its evolution near the core of the plasma. (Such changes may explain the contradictory observation that the bifurcation occurs at ~ 30 ms whereas the toroidal current is nearly constant after ~ 10 ms). However, previous measurements using a movable Rogowski coil on similar discharges, and theoretical predictions of Pfirsch-Schlüter and diamagnetic currents, show a toroidal current up to 9 A [111]. Computer simulation with *HELIAC* code

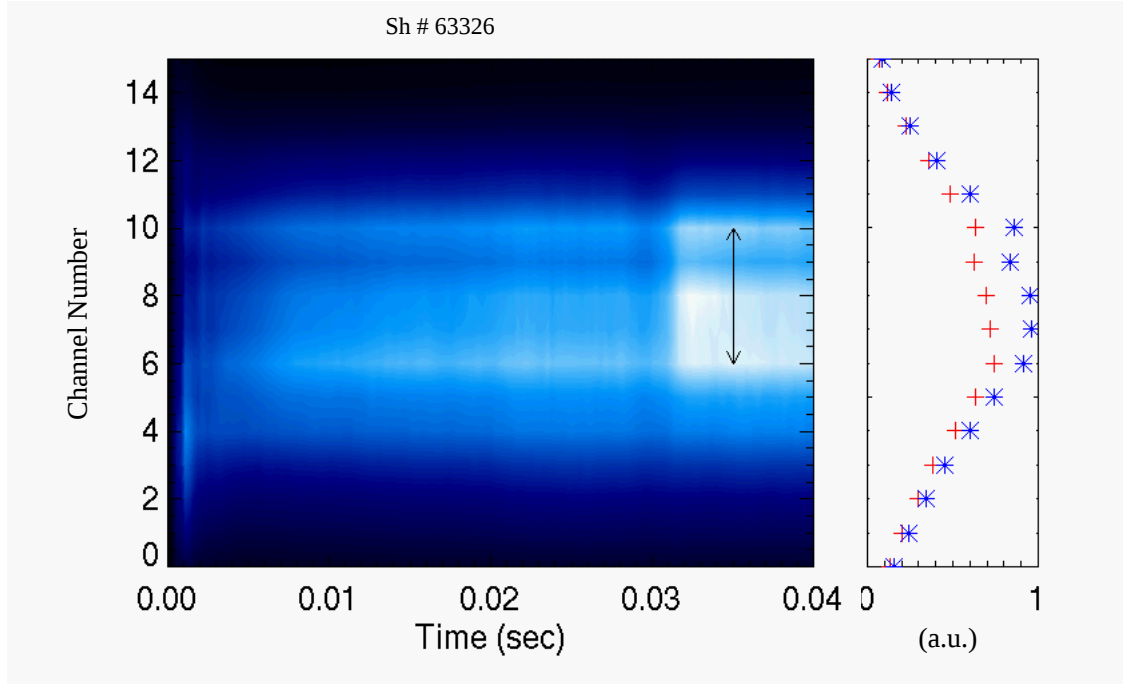


Figure 6.4: Spectral light intensity measured from a 16 channel imaging camera which shows a sudden transition nearly at 30 ms into the discharge. (see figure 5.6 for viewing chords). Plotted on the right side is the normalised brightness (arbitrary units) at ~ 10 ms (+) , ~ 35 ms (*) into the discharge

shows that a toroidal current much less than this value (~ 1 A) through the magnetic axis is sufficient to increase the core t by 1.7% and create 3/2 magnetic islands near the core for this configuration. The vacuum t profiles with and without ~ 5 A current through the magnetic axis, computed using the *HELIAC* code, are shown in figure 6.7. Shown in figure 6.8 are the unperturbed and the modified flux surfaces showing the development of the $m=2$ islands. It has to be noted that the toroidal current in this calculation is unrealistically concentrated at the magnetic axis. A more accurate and realistic computation with a radial profile of toroidal current is not possible with the *HELIAC* code at present.

In our experiment, $\nu_{eff} \gtrsim \omega_b$, where ν_{eff} ($\sim 4.6 \times 10^6$ /sec) and ω_b ($\sim 2.8 \times 10^5$ /sec) are the effective collision frequency and the bounce frequency from the helical ripple, respectively. Therefore, our plasma is not in the $1/\nu$ regime. Electrons are highly magnetised whereas ions are not : $\omega_{ci} \lesssim \nu_{ei} \ll \omega_{ce}$ where ω_{ci} , ν_{ei} and ω_{ce} are the ion gyro frequency, electron-ion collision frequency and electron gyro frequency

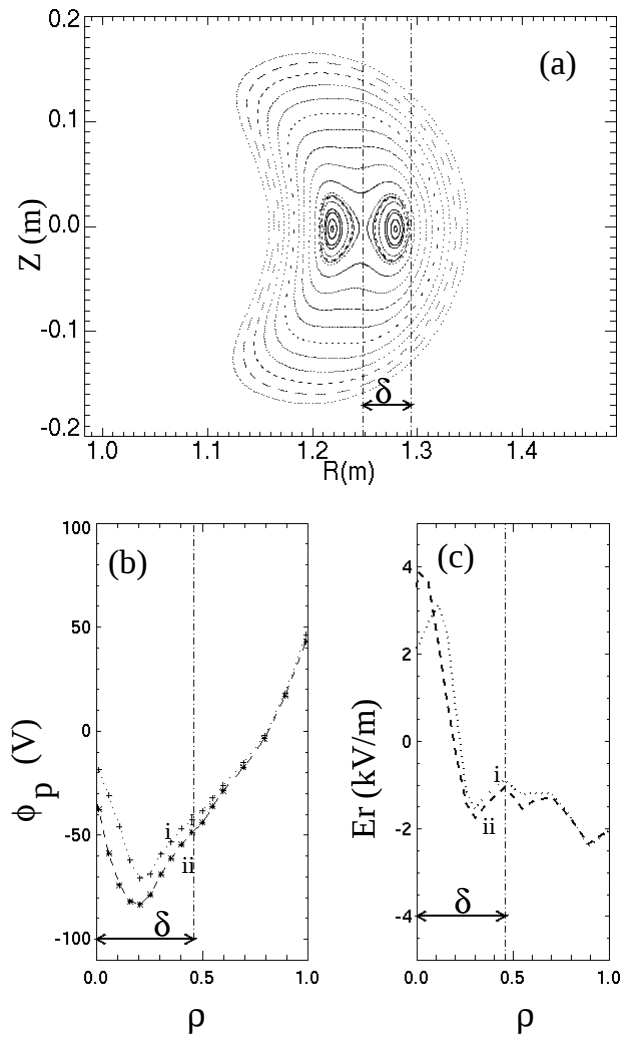


Figure 6.5: Computed flux surfaces (a) and radial profiles [at ~ 10 ms (i) and ~ 35 ms (ii) into the discharge] of plasma potential (b) and electric field (c) for configuration exhibiting vacuum magnetic islands (case II, chapter 5). δ shows the vacuum island width.

respectively. Also the half width of the island (approximately equal to the shear layer thickness) $\delta/2 \lesssim \rho_i$. So, ion dynamics are not much affected by the presence of the island. The ambipolar electric field is therefore modified by the island to balance the enhanced electron flux, as in the case of vacuum magnetic islands (explained in chapter 5).

In the case of vacuum magnetic islands (case II, chapter 5 and figure 6.5), the observed electric field shear is much less (~ 300 kV/m² compared to ~ 700 kV/m²

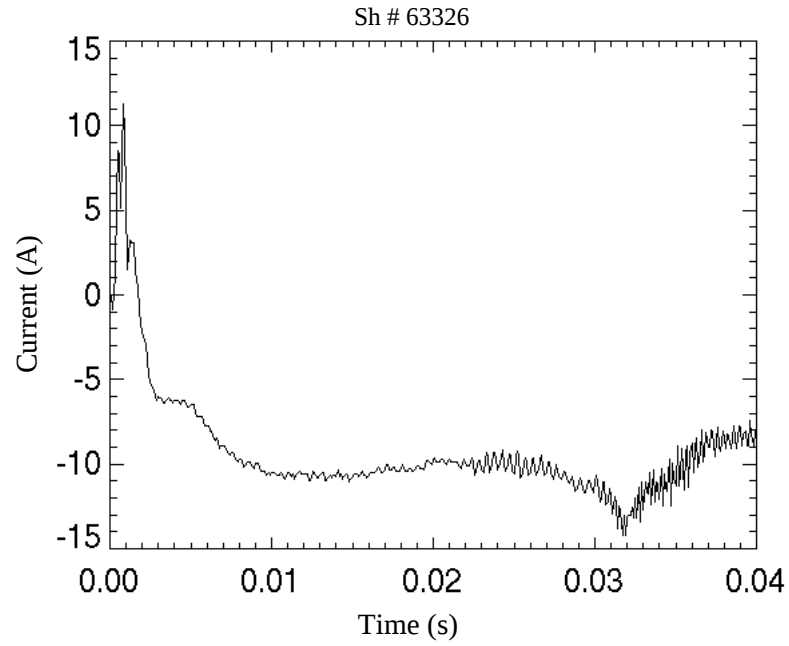


Figure 6.6: The Rogowski coil signal for the plasma discharge of figure 6.4, typical of discharges discussed in this chapter.

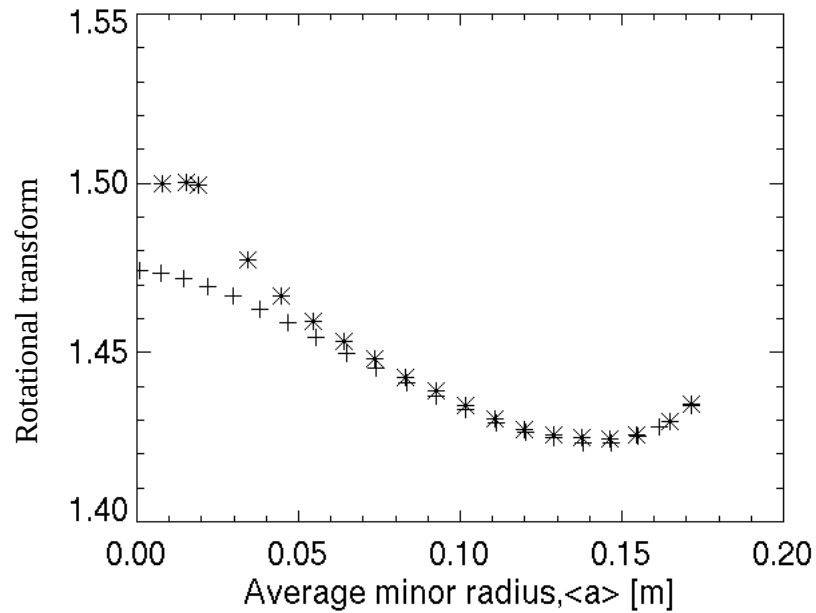


Figure 6.7: Rotational transform profiles computed using the *HELIAC* code, with (*) and without (+) a toroidal current of ~ 5 A, through the magnetic axis.

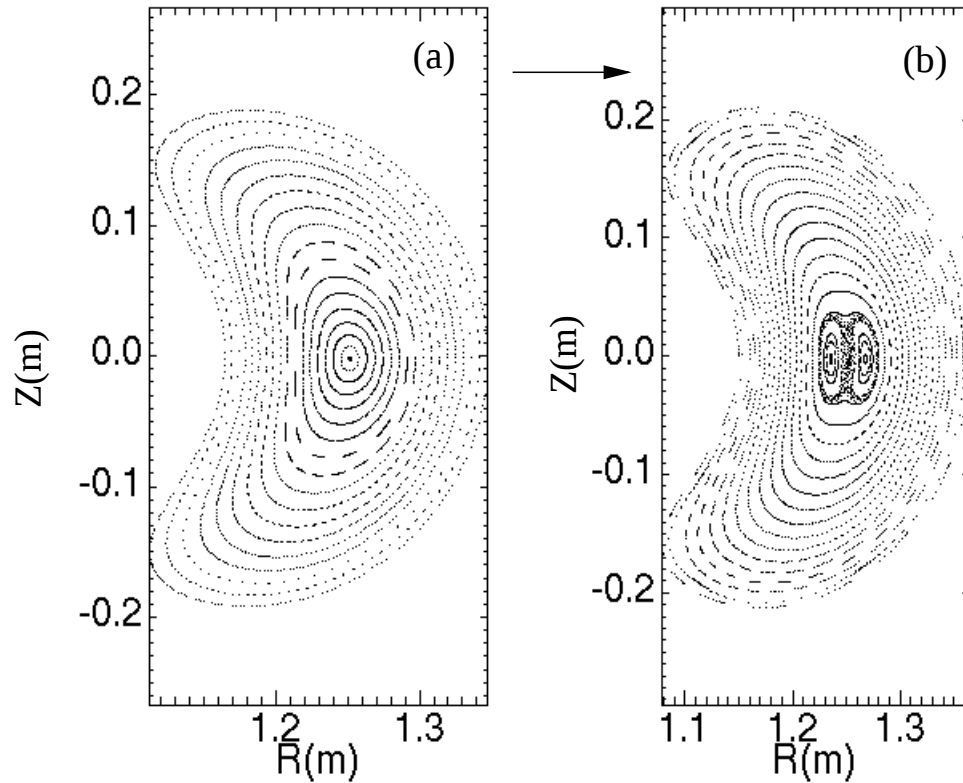


Figure 6.8: Modification of the flux surfaces due to a toroidal plasma current of ~ 5 A through the magnetic axis, computed using the *HELIAC* code. (a) Unperturbed vacuum flux surfaces (b) Modified flux surfaces.

in the present case). Further, the plasma density for case II is lower by $\sim 30\%$ and one of the two island lobes is relatively dense. As mentioned in chapter 5, this may be due to the fact that RF ionisation process is affected by the presence of islands in vacuum configuration. This chapter reports a scenario where the islands are excited during the discharge, after the plasma is fully developed. This situation is free from the effect of the presence of vacuum magnetic islands on the plasma production, at the time of plasma formation. Therefore, both of the induced island lobes are evenly populated as evidenced from the Langmuir probe results (figure 6.2) and spectroscopy (figure 6.4).

In previous experiments on similar plasma in H-1NF, highly coherent low frequency fluctuations have been observed and understood to be due to the $E \times B$ driven instability [43]. Strong $E \times B$ sheared flow in the transport region of H-mode plasma

in H-1 heliac has recently been related to zonal flow [42]. It has been theoretically shown that magnetic islands can generate zonal flows [41]. Therefore, the observed coherent mode ($f \sim 3$ kHz) in potential, density and magnetic fluctuations in the present experiment may point to zonal flow generation by magnetic islands.

In conclusion, this chapter presents an experimental observation of spontaneous bifurcation of the radial electric field near the core in a collisional RF plasma. We posit that the core rotational transform is modified during the discharge to spontaneously develop the 3/2 magnetic islands near the core. The large positive electric field is set up in the core to balance the enhanced radial transport of electrons due to the magnetic islands. Experimental evidence has thus been obtained that positioning low order magnetic islands near the core can facilitate the generation of a CERC equivalent scenario even in a low temperature collisional RF plasma.

Chapter 7

Conclusions and future scope of study

In fusion devices, magnetic islands are topological defects in the magnetic geometry. These are generated by error magnetic fields, including fields due to induced or self-consistent plasma currents, and are inevitable in many situations. Magnetic islands have serious impacts on plasma confinement. Due to radial connection, islands can in general degrade the confinement by mixing up different regions of the plasma. There has also been experimental evidence of confinement improvement by transport barriers induced by the formation of islands, under favourable conditions. Even though a number of theories have been put forward, there is a paucity of convincing experimental evidence. This thesis has reported detailed experimental work on magnetic islands in vacuum and plasma configurations of the H-1NF, addressing a few fundamental questions on the effect of island in plasma confinement.

A large part of the thesis has been dedicated to the accurate mapping of vacuum magnetic flux surfaces and islands and accurate determination of the H-1NF magnetic properties by computer simulation. Electron-beam wire-tomography has been specifically modified and improved for accurate mapping of magnetic islands in H-1NF. Point-to-point comparison of the mapping results with computer tracing, in conjunction with an image warping technique, enabled systematic exploration of

magnetic islands and surfaces of interest. Development of a fast mapping technique significantly reduced the time of island exploration and made this technique suitable for mapping at higher magnetic fields.

Vacuum mapping of islands and surfaces has been carried out at various magnetic configurations and field strengths. This has been used to study the error fields arising from the laboratory environment, by point-by-point iterative matching with computer tracing results. This has helped in developing a best-fit computer model for H-1NF magnetic configurations, which can predict detailed magnetic surfaces and rotational transform for any H-1NF magnetic configurations.

Experimental studies of magnetic islands in plasma configurations have been carried out using Langmuir probes and other diagnostic techniques. This has yielded very interesting results. Contrary to the general concept that the magnetic islands tend to flatten the radial profiles, under favourable conditions, islands in H-1NF are found to behave as pockets of improved confinement regions. This results in significant profile modifications including a large positive radial electric field near the plasma core, possibly due to the preferential loss of electrons from the island X-point which coincides with the magnetic axis. A spontaneous transition of the radial electric field near the core and localised improvement in confinement are observed for a configuration with the core t close to $3/2$, but exhibiting no magnetic islands in the absence of plasma. This is identified as an ‘electron-root’ scenario triggered by the sudden excitation of the low order magnetic islands at the core due to modifications in the rotational transform, by the toroidal plasma current. These results are first of this kind in a collisional RF plasma.

This thesis opens up a range of experimental opportunities on magnetic islands on this very ‘flexible’ (in magnetic configurations) H-1NF heliac. Island studies in fusion devices are generally concentrated on magnetic islands near the edge, which on H-1NF, are relatively difficult to map in vacuum. Further, RF plasma discharges for the configuration exhibiting ‘natural’ vacuum islands at the edge are found to be

highly oscillating, making it difficult to study with available diagnostic techniques. Until the work reported in this thesis, the core islands were not considered as an important topic of research. There are now a variety of physics issues which could be addressed on the low order core magnetic islands on H-1NF. A simple extension of this study would be to carry out island experiments with ECH plasma in which the power deposition layer coincides with the island X-point (magnetic axis). This would possibly provide a better understanding of the CERC, creating an additional channel for local electron transport from the core (X-point), conditions which have not so far been explored. For typical plasma parameters for ECH plasma in H-1NF ($n_e \sim 1 \times 10^{18} / \text{m}^3$, $T_e \sim 100$ eV, $T_i \sim 30$ eV), the collision scale lengths ($\lambda_{ei} \sim 250$ m, $\lambda_{en} \sim 80$ m) are much more than one toroidal transit, and comparable to the half-connection length of the $m = 2$ island. Further, when the ECH resonant layer is at the X-point, it is less likely that there will be preferential heating of one of the island lobes. These would avoid the situation of density imbalance in the island lobes. However, this experiment requires development of new diagnostic techniques as Langmuir probes cannot be used in such a high temperature plasma. Measurement of the radial profile of the toroidal plasma current (assuming that plasma perturbation can be minimised) and provision of including this in the computer model (*HELIAC*, *VMEC* etc.) could help in a better understanding of the modification of t profiles during a discharge.

In summary, this thesis looked at some fundamental properties of magnetic islands in a low temperature RF plasma and made some connections with the behaviour of islands in a more fusion relevant plasma. In fusion science, the physics of magnetic islands is expected to be an area of increased interest, as more progress is made with the understanding of island induced transport barriers, ergodic limiters in tokamaks, island divertors in stellarators etc. There are now three 3-D equilibrium codes capable of dealing with magnetic islands and stochastic regions, *viz.* PIES [112], HINT [113] and SIESTA [114]. The resulting increased realism could flow on to transport codes to produce a better understanding of fusion plasma.

The physics of magnetic islands, its evolution, merging and interaction with background plasma, is of great importance in solar and astrophysical plasmas as well. Controlled laboratory experiments could lead to an in-depth understanding of these issues which could answer some long-standing fundamental physics questions such as why is the solar corona so much hotter than the Sun's surface. On this note, a further extension of the work reported in this thesis could involve merging of the two $m=2$ island lobes during a discharge, by dynamically changing the coil current ratios or by driving a toroidal plasma current. In conjunction with suitable diagnostic techniques, these would make H-1NF an excellent experimental test bed for studying a rich array of magnetic reconnection physics issues, both fusion and space plasma related.

Appendix A

Flux coordinates

‘Magnetic flux coordinates’ are non-orthogonal curvilinear coordinates chosen in such a way that the magnetic field lines are straight. This is instrumental in various calculations, for example plasma equilibrium and stability, etc. The use of straight field line coordinates simplifies the equations of particle motion where only the magnitude of the fields and the corresponding derivatives appear, not the vector components [115].

In Clebsch representation, a vacuum magnetic field can be written as [17, 116, 117]

$$B = \nabla\psi_t \times \nabla\vartheta \tag{A.1}$$

where ψ_t, ϑ are scalar functions of position. A magnetic field line lies on the surface $\psi_t = \text{constant}$ (that corresponds to a magnetic surface) and $\vartheta = \text{constant}$ (that corresponds to a poloidal angle line). The toroidal magnetic flux ψ_t is a radial-like variable (but varies as $\sim r^2$) and the function ϑ is a poloidal angle-like variable. There are various choices for the third coordinate of the Clebsch coordinates, which should be a length-like variable in the toroidal direction. The widely-used coordinate system, commonly known as Boozer coordinates, chooses the magnetic scalar product, $\chi \equiv \int B dl$ along each field line, as the third coordinate. The Jacobian of the transformation for this coordinate system is

$$J = \frac{1}{(\nabla\psi_t \times \nabla\vartheta) \cdot \nabla\chi} = \frac{1}{B \cdot \nabla\chi} = \frac{1}{B^2} \quad (\text{A.2})$$

In order to get the magnetic spectrum of a flux surface, we expand the Jacobian in Fourier series as

$$J = \Re \sum_{m,n} J_{mn} e^{i(m\theta - n\phi)} \quad (\text{A.3})$$

where J_{mn} are Fourier components, n and m are toroidal and poloidal mode numbers respectively, ϕ and θ are toroidal and poloidal angles respectively. This gives a series representation of the field strength ,

$$B(\psi_t, \vartheta, \chi) = \sum_{m,n} B_{mn}(\psi_t) \cos(m\theta - n\phi) \quad (\text{A.4})$$

The *HELIAC* code input file and TFC locations

```
&INPUT
NEQ=2,      IDL=1,      ITERM=0,      IBAUD=110,
RMIN=0.60,  RMAX=1.6,   ZMIN=-0.6,   ZMAX=0.6,
RMAG=1.24,  MXITER=8,   DRMIN=1.0E-4, LASTSF=0, NRDTH=5,
IFPLOT=0,   IMAG=2,     IBLINE=0,   NAXIS=5,
JFLAG=1,    MXSAVE=1,   IFSYM=0,    ZMAG=0.0,
NSV =       0,  1,  3,  3,  3,  3,  6,  6,
THPIC=0.00,7.2,35.2,85.0,
thi=85.0,
MSV =      -1, -1, -1, -2, 0, -3, -2, -3,
IFFT=0,     IBETA = 0,
ETA=4.0,    DW=0.1,
MXITER=4,   DRMIN=1E-9,  NRDTH=2,  NAXIS=5,
&END
3.000
New Coil Parameters
(total) Main current = 500000, Hel curr = -1.3514e4, OV curr = 1.11111e05
Kappa helical = 1.000, Kappa (outer) vertical = 1.000
1.000      480.0      1.000      0.2200
8.500E-03  1.000      0.0000
-13888.89
0.866680    0.611600    0.027750
0.886540    0.558300    0.027750
0.846180    0.615500    0.027750
0.871430    0.547640    0.027750
0.831070    0.604830    0.027750
0.856310    0.536970    0.027750
0.815950    0.594160    0.027750
0.841200    0.526300    0.027750
0.800840    0.583500    0.027750
0.826080    0.515640    0.027750
0.785720    0.572830    0.027750
0.810970    0.504970    0.027750
0.770610    0.562160    0.027750
0.776020    0.547630    0.027750
0.776020    0.547630    0.046250
```

```

0.787900 0.537650 0.046250 99
0.747540 0.594850 0.046250 99
0.803020 0.548320 0.046250 99
0.762660 0.605510 0.046250 99
0.818140 0.558990 0.046250 99
0.777770 0.616180 0.046250 99
0.833250 0.569650 0.046250 99
0.792890 0.626850 0.046250 99
0.848370 0.580320 0.046250 99
0.808010 0.637510 0.046250 99
0.863480 0.590990 0.046250 99
0.823120 0.648180 0.046250 99
0.866680 0.611600 0.046250 99
0.866680 0.611600 0.027750 99
**Crossover II
-13888.89 2
-0.963000 0.444770 -0.009250 99
-0.926780 0.488620 -0.009250 99
-0.956130 0.425070 -0.009250 99
-0.909980 0.480860 -0.009250 99
-0.939330 0.417310 -0.009250 99
-0.893190 0.473100 -0.009250 99
-0.922540 0.409550 -0.009250 99
-0.876390 0.465350 -0.009250 99
-0.905740 0.401800 -0.009250 99
-0.859600 0.457590 -0.009250 99
-0.888950 0.394040 -0.009250 99
-0.842800 0.449830 -0.009250 99
-0.872150 0.386280 -0.009250 99
-0.862270 0.398240 -0.009250 99
-0.862270 0.398240 0.009250 99
-0.859570 0.413520 0.009250 99
-0.888920 0.349970 0.009250 99
-0.876370 0.421280 0.009250 99
-0.905720 0.357730 0.009250 99
-0.893160 0.429030 0.009250 99
-0.922510 0.365480 0.009250 99
-0.909960 0.436790 0.009250 99
-0.939310 0.373240 0.009250 99
-0.926750 0.444550 0.009250 99
-0.956100 0.381000 0.009250 99
-0.943550 0.452300 0.009250 99
-0.972900 0.388750 0.009250 99
-0.963000 0.444770 0.009250 99
-0.963000 0.444770 -0.009250 99
**Crossover III
-13888.89 2
0.096320 -1.056370 -0.046250 99
0.040230 -1.046920 -0.046250 99
0.109940 -1.040570 -0.046250 99
0.038550 -1.028500 -0.046250 99
0.108260 -1.022140 -0.046250 99
0.036870 -1.010070 -0.046250 99
0.106580 -1.003720 -0.046250 99
0.035190 -0.991650 -0.046250 99
0.104900 -0.985290 -0.046250 99
0.033510 -0.973230 -0.046250 99
0.103220 -0.966870 -0.046250 99
0.031830 -0.954800 -0.046250 99
0.101540 -0.948450 -0.046250 99
0.086250 -0.945870 -0.046250 99
0.086250 -0.945870 -0.027750 99
0.071670 -0.951170 -0.027750 99
0.141380 -0.944820 -0.027750 99
0.073350 -0.969600 -0.027750 99
0.143060 -0.963240 -0.027750 99
0.075030 -0.988020 -0.027750 99
0.144740 -0.981660 -0.027750 99
0.076710 -1.006440 -0.027750 99
0.146420 -1.000090 -0.027750 99

```

```

0.078390 -1.024870 -0.027750 99
0.148100 -1.018510 -0.027750 99
0.080070 -1.043290 -0.027750 99
0.149780 -1.036930 -0.027750 99
0.096320 -1.056370 -0.027750 99
0.096320 -1.056370 -0.046250 99
**36 Toroidal field coils. Single turn, as-built positions
0.1389E+06 01
1.210616 0.074405 0.039700-90.000000-86.482994 0.383000 20
1.159895 0.224389 0.111500-90.000000-79.050995 0.383000 20
1.050229 0.371204 0.174000-90.000000-70.533997 0.383000 20
0.877091 0.495547 0.204500-90.000000-60.533997 0.383000 20
0.666271 0.588410 0.166500-90.000000-48.550999 0.383000 20
0.475905 0.643548 0.067200-90.000000-36.482998 0.383000 20
0.319576 0.734379 -0.074000-90.000000-23.517000 0.383000 20
0.167694 0.866828 -0.176000-90.000000-10.948996 0.383000 20
-0.009389 1.007356 -0.206500-90.000000 0.533993 0.383000 20
-0.203642 1.095127 -0.177000-90.000000 10.533997 0.383000 20
-0.386273 1.118583 -0.115000-90.000000 19.050997 0.383000 20
-0.525719 1.090269 -0.047000-90.000000 25.742990 0.383000 20
-0.669468 1.010805 0.038500-90.000000 33.516987 0.383000 20
-0.769832 0.902983 0.109500-90.000000 40.449001 0.383000 20
-0.845447 0.722948 0.174500-90.000000 49.466000 0.383000 20
-0.869596 0.512927 0.203500-90.000000 59.465992 0.383000 20
-0.841766 0.282484 0.164500-90.000000 71.448997 0.383000 20
-0.795282 0.090372 0.069000-90.000000 83.516991 0.383000 20
-0.798461 -0.090733 -0.071500 90.000000 83.516991 0.383000 20
-0.835960 -0.288677 -0.175000 90.000000 70.949013 0.383000 20
-0.865548 -0.510539 -0.208000 90.000000 59.466000 0.383000 20
-0.846207 -0.723598 -0.177000 90.000000 49.466000 0.383000 20
-0.773947 -0.891926 -0.115000 90.000000 40.949005 0.383000 20
-0.674262 -1.007011 -0.043000 90.000000 33.804981 0.383000 20
-0.540737 -1.085358 0.039000 90.000000 26.482990 0.383000 20
-0.385621 -1.116693 0.115500 90.000000 19.051008 0.383000 20
-0.203642 -1.095127 0.175500 90.000000 10.534008 0.383000 20
-0.009391 -1.007556 0.204500 90.000000 0.534011 0.383000 20
0.176344 -0.870722 0.163500 90.000000-11.449009 0.383000 20
0.320145 -0.733585 0.067500 90.000000-23.576992 0.383000 20
0.475311 -0.642744 -0.074000 90.000000-36.482990 0.383000 20
0.669492 -0.580935 -0.173500 90.000000-49.051003 0.383000 20
0.876394 -0.495154 -0.207500 90.000000-60.533997 0.383000 20
1.054943 -0.372871 -0.177000 90.000000-70.533997 0.383000 20
1.160091 -0.224427 -0.115500 90.000000-79.050995 0.383000 20
1.211115 -0.074435 -0.043000 90.000000-86.483002 0.383000 20
**36 individual turns of the ring conductor. This is removed for the high field model
-13.8888e3 01
-0.0005 0.0020 -0.0458 180.0000 180.0000 0.9522 20
-0.0005 0.0020 -0.0275 180.0000 180.0000 0.9522 20
-0.0005 0.0020 -0.0092 180.0000 180.0000 0.9522 20
-0.0005 0.0020 0.0092 180.0000 180.0000 0.9522 20
-0.0005 0.0020 0.0275 180.0000 180.0000 0.9522 20
-0.0005 0.0020 0.0458 180.0000 180.0000 0.9522 20
-0.0005 0.0020 -0.0458 180.0000 180.0000 0.9705 20
-0.0005 0.0020 -0.0275 180.0000 180.0000 0.9705 20
-0.0005 0.0020 -0.0092 180.0000 180.0000 0.9705 20
-0.0005 0.0020 0.0092 180.0000 180.0000 0.9705 20
-0.0005 0.0020 0.0275 180.0000 180.0000 0.9705 20
-0.0005 0.0020 0.0458 180.0000 180.0000 0.9705 20
-0.0005 0.0020 -0.0458 180.0000 180.0000 0.9888 20
-0.0005 0.0020 -0.0275 180.0000 180.0000 0.9888 20
-0.0005 0.0020 -0.0092 180.0000 180.0000 0.9888 20
-0.0005 0.0020 0.0092 180.0000 180.0000 0.9888 20
-0.0005 0.0020 0.0275 180.0000 180.0000 0.9888 20
-0.0005 0.0020 0.0458 180.0000 180.0000 0.9888 20
-0.0005 0.0020 -0.0458 180.0000 180.0000 1.0072 20
-0.0005 0.0020 -0.0275 180.0000 180.0000 1.0072 20
-0.0005 0.0020 -0.0092 180.0000 180.0000 1.0072 20
-0.0005 0.0020 0.0092 180.0000 180.0000 1.0072 20
-0.0005 0.0020 0.0275 180.0000 180.0000 1.0072 20
-0.0005 0.0020 0.0458 180.0000 180.0000 1.0072 20

```

```

-0.0005  0.0020  -0.0458  180.0000  180.0000  1.0255  20
-0.0005  0.0020  -0.0275  180.0000  180.0000  1.0255  20
-0.0005  0.0020  -0.0092  180.0000  180.0000  1.0255  20
-0.0005  0.0020  0.0092  180.0000  180.0000  1.0255  20
-0.0005  0.0020  0.0275  180.0000  180.0000  1.0255  20
-0.0005  0.0020  0.0458  180.0000  180.0000  1.0255  20
-0.0005  0.0020  -0.0458  180.0000  180.0000  1.0438  20
-0.0005  0.0020  -0.0275  180.0000  180.0000  1.0438  20
-0.0005  0.0020  -0.0092  180.0000  180.0000  1.0438  20
-0.0005  0.0020  0.0092  180.0000  180.0000  1.0438  20
-0.0005  0.0020  0.0275  180.0000  180.0000  1.0438  20
-0.0005  0.0020  0.0458  180.0000  180.0000  1.0438  20
**Deformed ring conductor. This is removed for the low field model
  1.0000  -0.0008  0.000  3.0000  0.0000  3.0000 -5.000e05  999.0 06
-0.0005  0.0020  0.000  0.0000  0.00  0.000  0.0000  999.0 06
**Outer vertical field coils (as-built measurements)
1.11104e05  01
  0.0000  0.0000  -0.6949  180.0000  180.0000  2.1300  20
  0.0000  0.0000  0.7622  180.0000  180.0000  2.1300  20
**Inner vertical field coils
2.2222E+05  01
  0.0000  0.0000  -1.0700  180.0000  180.0000  0.7200  20
  0.0000  0.0000  1.0700  180.0000  180.0000  0.7200  20
**The four turns of the helical windings, each represented by 400 segments
  1.0000  0.0973  -18.750  3.0000  0.0000  3.0000 -1.3888e4  400.0 06
-0.0005  0.0020  0.000  0.0000  0.00  0.000  0.0000  999.0 06
  1.0000  0.0973  -6.250  3.0000  0.0000  3.0000 -1.3888e4  400.0 06
-0.0005  0.0020  0.000  0.0000  0.00  0.000  0.0000  999.0 06
  1.0000  0.0973  6.250  3.0000  0.0000  3.0000 -1.3888e4  400.0 06
-0.0005  0.0020  0.000  0.0000  0.00  0.000  0.0000  999.0 06
  1.0000  0.0973  18.750  3.0000  0.0000  3.0000 -1.3888e4  400.0 06
-0.0005  0.0020  0.000  0.0000  0.00  0.000  0.0000  999.0 06
09
0  1.1340  -.239  0.250360000 320  1.143005

```

Table B.1: As-built measurements of the TF coil locations

No.	$\phi(\text{deg})$	R(mm)	Z(mm)
1	3.517	1212.9	39.7
2	10.949	1181.4	111.5
3	19.466	1113.9	174.0
4	29.466	1007.4	204.5
5 [†]	41.449	888.9	166.5
6	53.517	800.4	67.2
7	66.483	800.9	-74.0
8	79.051	882.9	-176.0
9	90.534	1007.4	-206.5
10	100.534	1113.9	-177.0
11	109.051	1183.4	-115.0
12 [‡]	115.743	1210.4	-47.0
13	123.517	1212.4	38.5
14	130.449	1186.6	109.5
15	139.466	1112.4	174.5
16	149.466	1009.6	203.5
17 [†]	161.449	887.9	164.5
18	173.517	800.4	69.0
19	186.483	803.6	-71.5
20	199.051	884.4	-175.0
21	210.534	1004.9	-208.0
22	220.534	1113.4	-177.0
23	229.051	1180.9	-115.0
24	236.195	1211.9	-43.0
25	243.517	1212.6	39.0
26	250.949	1181.4	115.5
27	259.466	1113.9	175.5
28	269.466	1007.6	204.5
29 [†]	281.449	888.4	163.5
30	293.577	800.4	67.5
31	306.483	799.4	-74.0
32	319.051	886.4	-173.5
33	330.534	1006.6	-207.5
34	340.534	1118.9	-177.0
35	349.051	1181.6	-115.5
36	356.483	1213.4	-43.0

[†] Angular displacement of +1 degree (three-fold symmetry preserved).

[‡] Angular displacement of -1 degree (does not preserve three-fold symmetry)

Appendix C

Calculation of t near a rational surface

Rotational transform (t) of a near-rational surface can be accurately calculated from the mapped flux surface, if the rational number is known. The procedure is outlined in this section.

Shown in figure C.1 is a mapped flux surface from the ‘full helical’ configuration. Observation of five distinct groups indicates that this surface is close to a rational flux surface with a poloidal mode number $m=5$. From the rotational transform profile obtained from computation, this near-by rational rotational transform is found to be, $t = 7/5$. Further, it can be shown that, around a rational surface, for a surface having t above (below) the rational value, the successive points move in anti-clockwise (clock-wise) direction, when viewed in the direction of toroidal angle (ϕ). Therefore the surface shown in figure C.1 has rotational transform $t = 7/5 + \Delta t$.

Rotational transform is the measure of twist per turn. It is the poloidal displacement of a field line in a toroidal transit. Therefore, Δt can be written as:

$$\Delta t \equiv \beta / \Delta \phi$$

where $\Delta \phi = 2\pi \times 5$ is the toroidal angle traversed by the field line between 18th

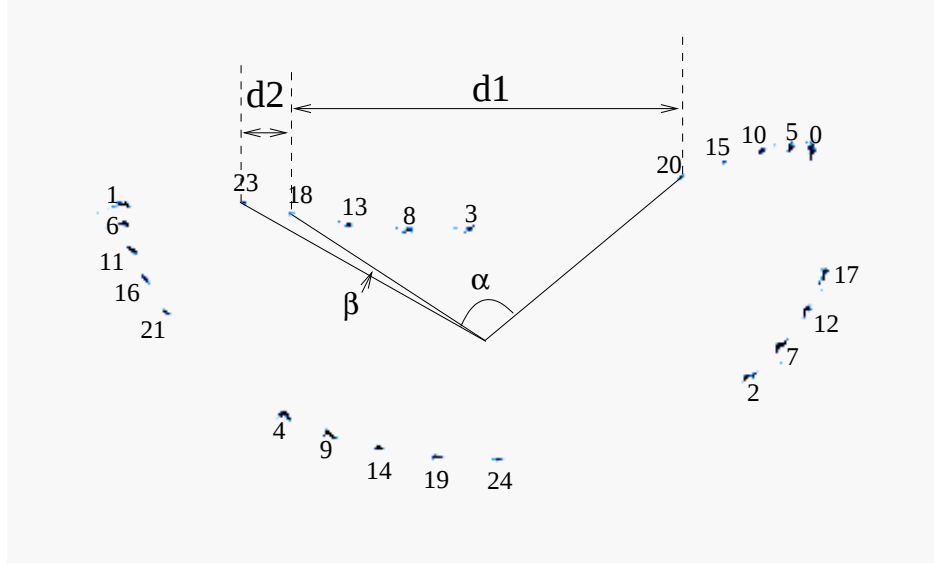


Figure C.1: A mapped surface having $t \sim 7/5$. Successive transits are numbered in time sequence, taking the brightest one as the first transit (0). This is confirmed by introducing a large gas fill ($\sim 10^{-5}$ Torr) which attenuates all but the first few transits, and increases the contrast of the surviving transits.

and 23^{rd} transit (please see figure C.1), which are adjacent in the puncture plot and separated by magnetic poloidal angle β . The poloidal angle is best measured in magnetic coordinates in which field lines are straight. This allows t to be measured over a finite interval instead of requiring a limit over many rotations. The PEST-3 coordinate system [118] is such a coordinate system, and is suitable for this work as the planes of constant toroidal angle are vertical, corresponding to the measurements from the wire-tomography wheel. For a rational rotational transform, the magnetic field line ‘punctures’ set out an equi-spaced coordinate grid in the magnetic poloidal coordinate. Slightly away from this resonance, the grid is approximately equi-spaced, and can be used to construct the relationship between magnetic poloidal angles α and β , and the measured distances shown in the diagram. As there are five groups of points, the magnetic poloidal angle α between the corresponding points of any adjacent group (for example, angle between 20^{th} and 23^{rd} transit) is given by

$$\alpha \approx \frac{2\pi}{5}$$

and, from the figure, as the equi-spaced points are approximately equi-spaced in

distance in the region. Therefore,

$$\frac{d2}{d1} \approx \frac{\beta}{\alpha}$$

By measuring the values of $d2$ and $d1$ from the mapped surface, Δt can be calculated.

For the surface shown in figure C.1, $d1 = 0.225$ and $d2 = 0.0250$

$$\Delta t = \frac{d2/d1 \times 2\pi/5}{2\pi \times 5} = 0.0044 \pm 0.001$$

Therefore the rotational transform of the mapped flux surface is $t = 7/5 + 0.0044 = 1.4044 \pm 0.001$. As the accuracy of the computer model is improved, this can be confirmed by overlaying traces with computed punctures. A best-fit computed flux surface matching with this mapped flux surface has rotational transform $t = 1.405$, as shown in figure 4.9.

Appendix D

Langmuir probe

The Langmuir probe is one of the simplest plasma diagnostics. A small metallic electrode, generally Tungsten, in the form of a wire or a disc inserted into the plasma can measure the plasma parameters: the plasma potential (ϕ_p), the floating potential (ϕ_f), the electron temperature (T_e), the plasma density (n_e) and fluctuations in many of these parameters (for example, $\tilde{\phi}_f$ & $\tilde{n}_e$).

A cylindrical Langmuir probe with a tip comprising a Tungsten wire of length 1.4 mm and diameter 0.5 mm, has been used to measure plasma parameters reported in this thesis. The probe has been moved in and out in the horizontal plane (at $\phi = 0^\circ$, $Z=0$) to get the radial profiles. The position of the probe has been calibrated with respect to the magnetic axis, using an electron beam from electron gun situated at $\phi = 35^\circ$ (see figure 4.6). A more accurate determination of the magnetic axis is obtained later on from the symmetry point of the density profile of a no-island configuration, for example the density profile at ~ 10 ms in figure 6.2. In order to minimize the RF contamination of the probe data, a two layered ceramic tubing, with a stainless steel tubing in between, has been used, as shown in figure D.1.

The probe is biased with a sine wave at 30 kHz, up to ± 150 V, using a function generator and a high voltage amplifier. The 30 kHz biasing voltage enables good temporal resolution of measurements (measurement frequency $f=60$ kHz as a single

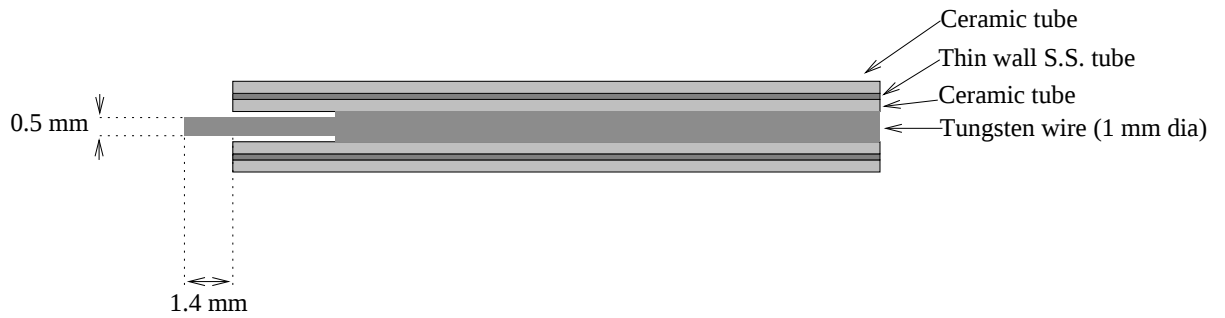


Figure D.1: Schematic of the Langmuir probe design. (Although the assembly is a tight-fit, there may be small gaps between all four concentric components).

sine wave can provide two probe traces). A schematic diagram of the probe circuit has been given in figure D.2. The bias voltage is measured using a voltage divider circuit and the probe current is measured across a 50Ω resistor, as shown in figure D.2.

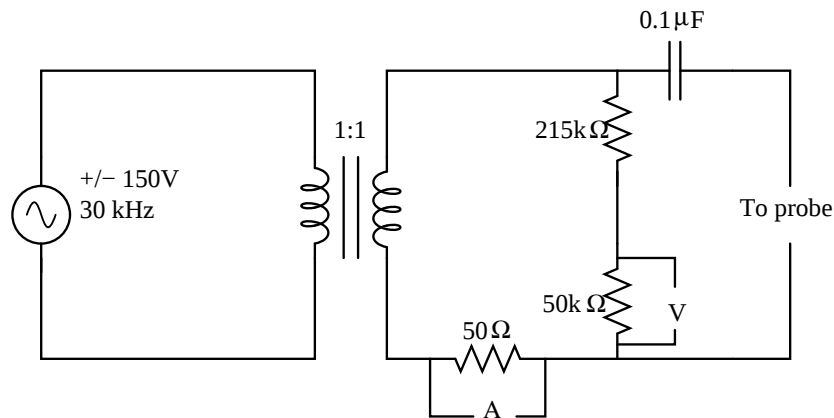


Figure D.2: Schematic of the probe circuit

The floating potential of the plasma changes largely during a discharge. Therefore it is not possible to get the full probe characteristics with a constant bias voltage range ($\pm 150V$). A capacitor has been added to the circuit in series (see figure D.2) so that the bias voltage is dynamically adjusted to get equal parts of the characteristics on both sides of the floating potential¹ (total electron current = total ion current in a cycle, so that the D.C. current through the capacitor equals zero). The $0.1\mu\text{F}$ capacitor ensures that the probe responds to the change in floating potential

¹Courtesy of Prof. I. H. Hutchinson

as fast as $\frac{dV}{dt} \sim 500$ V/ms.

The measured probe current is corrected for the capacitive current due to the cable capacitance (important at 30 kHz bias voltage) and the current through the voltage divider as

$$I_p = I_{meas} - (C \frac{dV_b}{dt} + I_{res})$$

where I_{meas} is the measured probe current, C is the cable capacitance (~ 0.76 nF), V_b is the probe bias voltage and I_{res} is the current through the voltage divider. A typical probe signal is shown in figure D.3.

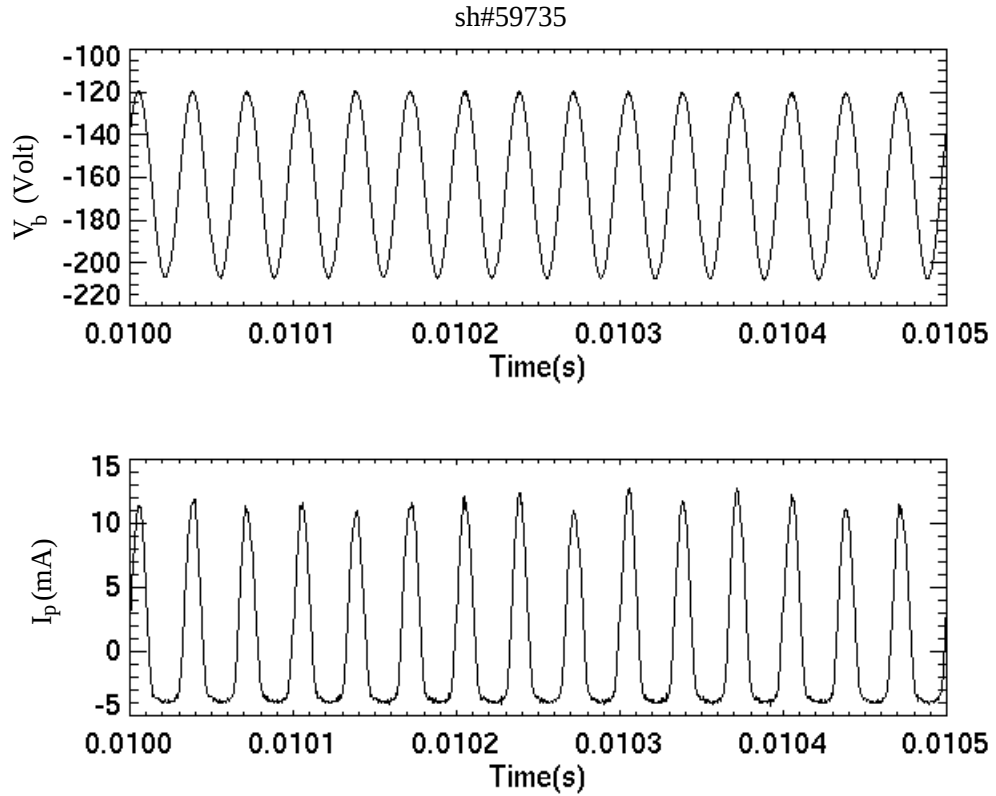


Figure D.3: Typical probe bias voltage (V_b) and probe current (I_p) traces for H-1NF argon plasma

Standard analysis techniques [119, 120] have been used for obtaining the plasma parameters. A typical current-voltage characteristics obtained in H-1NF is shown in figure D.4. The part-A of the curve is the ion saturation region and part-C ap-

proaches the electron saturation region (which is rarely observed in experiments). The shape of the part B of the curve is related to the distribution of electron energies, and can be used to calculate electron temperature. If the electron exhibits Maxwellian distribution, the probe current for this portion of the trace can be written as

$$I = I_{sat}(1 - e^{-e\phi/KT_e}) \quad (D.1)$$

Where I_{sat} is the ion saturation current, $\phi = V_b - \phi_f$, V_b is the probe bias voltage and ϕ_f is the floating potential and $\frac{KT_e}{e}$ is the electron temperature in eV. Taking logarithm, equation D.1 can be written as

$$\log\left(\frac{I - I_{sat}}{I_{sat}}\right) = \frac{-eV_b}{KT_e} + \frac{-e\phi_f}{KT_e} \quad (D.2)$$

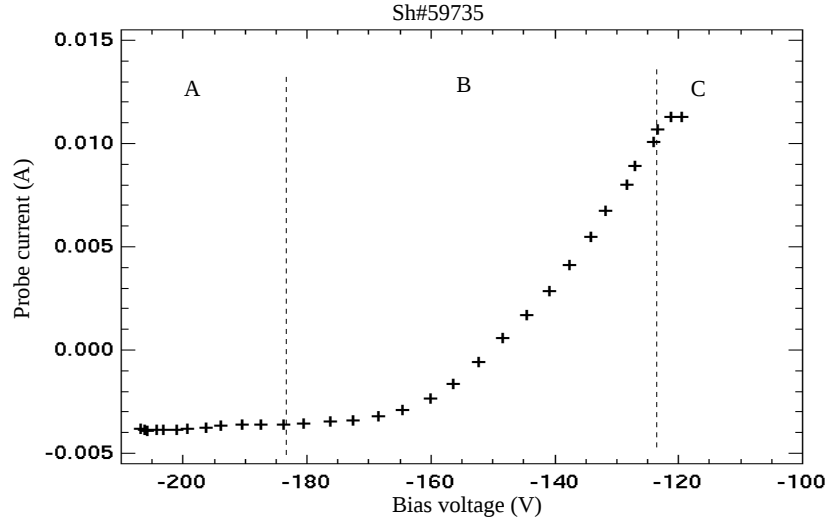


Figure D.4: Current-voltage (I-V) characteristics of a Langmuir probe. Data from H-1NF argon plasma.

The above expression is a straight line equation having its slope $\frac{e}{KT_e}$, from which the electron temperature can be estimated. The floating potential (ϕ_f) is the potential acquired by a ‘floating’ (unbiased) probe in the plasma. This is the point in the probe trace where the ion current is equal to the electron current (bias voltage at which probe current is zero). Alternatively, floating potential can also be calculated from equation D.2. Plasma potential (ϕ_p) is calculated from the floating potential

and temperature using the relation

$$\phi_p = \phi_f + \alpha \frac{KT_e}{e} \quad (\text{D.3})$$

where $\alpha = 4.7$ for argon [120]. Electron density is determined from the ion saturation current. The negative current to the probe in the ion saturation region, for a cylindrical probe is given by the relation [92]

$$I_{sat} = 0.61 n_e e A C_s \quad (\text{D.4})$$

where n_e is the electron density, e is the electronic charge, A is the effective collection area of the probe and C_s is the ion acoustic velocity ($C_s = \sqrt{\frac{KT_e + KT_i}{m_i}}$ where T_i is the ion temperature and m_i is the ion mass. A radially flat ion temperature of 30 eV is taken for the density calculations). At large negative voltages, probe sheath thickness may become comparable to probe dimensions and the effective probe collection area becomes larger than the probe area. The probe sheath thickness has been calculated for each trace, from the formula [120]

$$d = 1.1 \eta^{(3/4)} \lambda_D \quad (\text{D.5})$$

where d is the probe sheath thickness, λ_D is the Debye length and $\eta \equiv \frac{e(\phi_p - V_b)}{T_e}$. The sheath thickness has been added to the probe radius for calculating the effective collection area. Also, instead of taking probe current at a fixed negative bias, the ion saturation current is averaged around the bias voltage of $V_b = \phi_f - 4.7 \frac{KT_e}{e}$. Comparison of the line integrated density from probe measurements with the line integrated density from the 2 mm interferometry shows agreement within $\pm 15\%$ for most of the configurations.

Magnetic field can affect the probe measurements in a strongly magnetized plasma. In consideration to probe measurements in a magnetic field environment, plasma is considered to be strongly magnetised if $\rho_i/a \ll 1$ where ρ_i is the ion gyro

radius and a is the probe radius [121]. For the 0.1 Tesla argon plasma in H-1NF, $\rho_i \sim 34$ mm. Therefore the plasma is not magnetized in our case ($\rho_i/a \gg 1$) and the probe measurements are not affected by magnetic field effects.

Great care has been taken in calculating the electron temperature from the probe trace. For example, the calculated parameters are used to back-calculate the exponential part of the probe trace. Only those values for which the calculated trace shows a good correlation to the measured probe trace (correlation coefficient more than 0.95) are used for further analysis (the correlation coefficient is computed using the ‘correlate’ procedure in IDL, which computes the linear Pearson correlation coefficient). Some of the points are thus lost in between from the 60 kHz measurement. For this reason, the frequency spectrum of fluctuations could not be reliably obtained from the biased probe measurements. The floating potential fluctuations are separately measured using an unbiased probe. Typical time evolution of plasma parameters is shown in figure D.5.

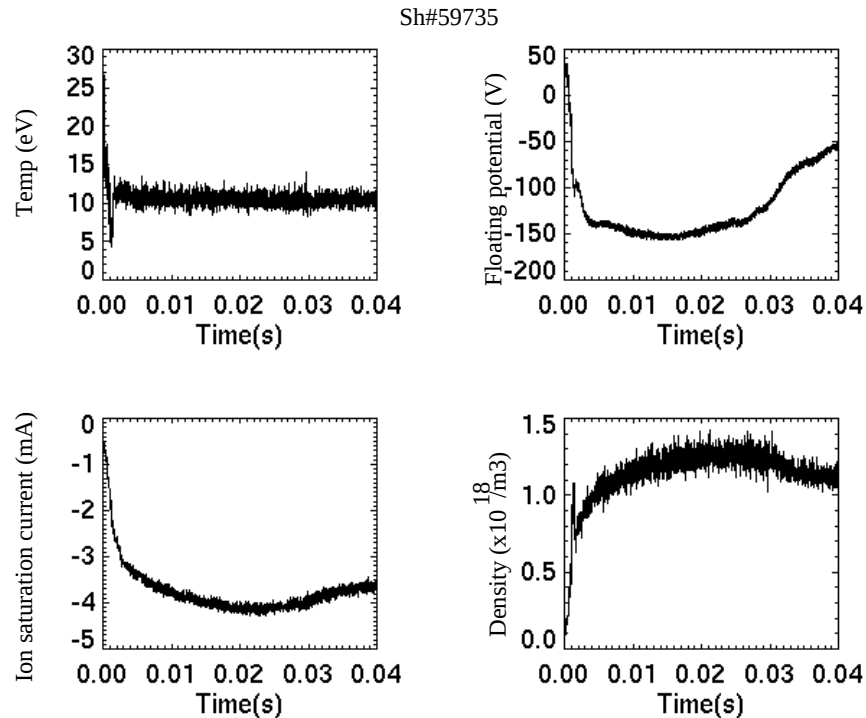


Figure D.5: Typical temporal profiles of plasma parameters obtained from the Langmuir probe for a 40 ms argon discharge. The sheath thickness correction in this case is ~ 0.12 mm to 0.15 mm.

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