AU9816848

Nuclear Fusion Research in Australia

A D CHEETHAM and the Australian Fusion Research Group
Plasma Instrumentation Laboratory, University of Canberra
PO Box 1, Belconnen ACT 2616

SUMMARY: In this paper the recently formed National Plasma Fusion Research Facility at the Institute of Advanced Studies is described in the context of the international Stellarator program and the national collaboration with the Australian Fusion Research Group. The objectives of the Facility and the planned physics research program over the next five years are discussed and some recent results will be presented.

1 INTRODUCTION

Nuclear fusion, in which light elements in a hot ionized plasma combine to form heavier elements, is the ultimate source of energy in the universe: it powers stars. Research to develop a terrestrial fusion reactor has been pursued since the 1950s in laboratories all over the world, including Australia.

Although conditions for fusion—temperatures of 10 keV (100 million degrees C), densities of 10^{14} particles/cm^3, and energy confinement times of the order of 1 second—are difficult to achieve, recent experiments on large toroidal magnetic fusion devices in the US, Europe, and Japan have demonstrated plasma conditions like those required in a reactor. But much further work is needed to develop toroidal magnetic confinement schemes that would be attractive for commercial reactor applications.

Australia has participated in fusion research with fundamental plasma physics experiments in universities for many years, and Australian scientists have long worked on the world's large fusion experiments in many countries.

In the 1995 Major National Research Facility funding round, the ANU and the Australian Fusion Research Group (AFRG) submitted a proposal which won $8.7M to upgrade the H-1 toroidal Heliac experiment at the ANU Research School of Physical Sciences and Engineering to the status of the National Plasma Fusion Research Facility. During 1996 work proceeded in setting up the Facility, in particular in setting up the contract with Department of Industry Science and Tourism (DIST), which oversees the MNRF program, and the strategic plan for the funding period. At the same time work has continued on the H-1 experiment with full experimental and diagnostic development programs. In April 1997 the contract between DIST and the Host organisation (ANU) was signed and the serious upgrade work could begin.

In this paper we describe the current status of the Facility: the administrative structure, the experimental plan for the next five years and the projects that have so far been undertaken by the AFRG teams.

The AFRG is a grouping of six university plasma physics research groups from around Australia acting under the umbrella of the Australian Institute for Nuclear Science and Engineering (AINSE). The Group was formed in late 1994 with the specific aim of consolidating fusion research in Australia on the large Heliac device at the ANU. An application for MNRF funding for a significant upgrade to the Heliac was compiled by the AFRG in 1995. This application was successful, (announced in December 1995) as was the application for ARC REIFP funds in 1995 ($120k) and again in 1996 ($250k). The MNRF funds go mostly towards capital costs of the machine upgrade but the ARC infrastructure money goes almost entirely to the AFRG collaborative teams to help fund the experiments and diagnostics that they are constructing for the Heliac. The AFRG acts with AINSE to coordinate national collaboration on the Heliac, now recognised as an AINSE facility for the purpose of AINSE Research Grants. At present the AFRG has participating members from the Australian National University, Central Queensland University, Flinders University, University of Canberra, University of New England and University of Sydney. Three of these institutions have donated funds to facilitate the employment of a technician to work at the Facility for three years to help with the construction and installation of AFRG equipment.

2 THE H-1NF DEVICE

The H-1 Heliac (shown with the vacuum tank removed in Fig. 1) is a medium sized device from the Stellarator family representing an alternative approach to fusion from the widely researched Tokamak. The Stellarator differs from the Tokamak in that the poloidal field and hence the rotational transform is provided by external coils rather than by plasma current, thus avoiding some of the operational problems associated with the tokamak design. These external coils do, of course, make design and construction of these machines more complicated as the poloidal windings must thread the toroidal coils or complex three dimensional coil structures must be designed It was for this reason that early stellarators failed, the required accuracy of construction was not appreciated and the computing power to model such structures was not yet available.

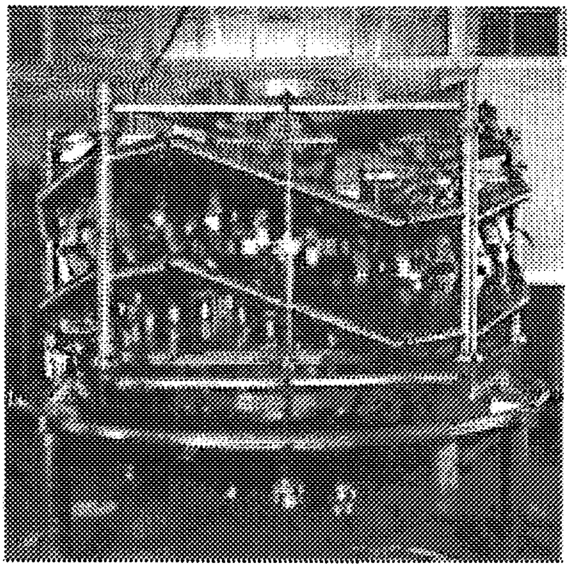

Fig. 1. H-1NF with the vacuum vessel removed.

Since the plasma in a Stellarator is not heated by a current, auxiliary heating power is required. A second factor in the renewed interest in the Stellarator family is the development and successful use of powerful auxiliary heating methods over the past decade: methods such as RF heating at the ion cyclotron frequency and high power neutral beam injection.

The H-1 machine has been operational at low powers for some three years and has already produced some interesting and important papers [eg 1]. The MNRF funding will be used to upgrade the machine systems to higher power levels to allow access to higher plasma temperatures and densities enabling research into the stability and confinement of fusion relevant plasmas.

The H-1NF parameters are shown in the table below [2]:

H-1NF Parameters	
Major Radius:	$R = 1.0$ m
Avg. Minor radius:	$<a> = 0.2$ m
Toroidal Field:	$B_T < 1.0$ T $B_T < 0.2$ T (Continuous)
RF Heating:	4-28 MHz, 500 kW
Microwave Heating:	28 GHz, 200 kW
Vacuum Vessel:	Diameter = 4 m Height = 4 m
Gas Feed:	Ar, H, He and Ne gas puffing up to 300 Torr.Litres/sec

The resulting plasma has a bean-shaped cross section and a helical axis of 3 periods about the major axis as shown in Fig. 3. Although this geometry seems rather complicated and difficult to model; most of the coils can be circular, which greatly simplifies construction. There is a central conducting ring coil, and simple circular toroidal field coils arranged, offset, around the ring to generate the plasma shape shown in Fig.2. An additional helical winding is wrapped around the central ring coil. The major constructional difficulties in this geometry are the threading of the central current conductor through all the toroidal coils and the accurate positioning of the coil components.

The main advantages of this geometry are that the construction is relatively easy. It is flexible in that the magnetic geometry can be varied by changing the relative currents in the various coil sets. From a physics point of view, the geometry has an inherent "magnetic well" that has a stabilising influence on the plasma. Theoretical studies of a linear Heliac have shown beta up to 30%, although this would be significantly reduced due to pressure-driven "ballooning" instabilities in the toroidal case. The strong breaking of axisymmetry, combined with a highly non-circular plasma cross section, requires a theoretical effort combining the development of new analytical tools and advanced computational methods. Advanced data analysis methods for plasma diagnostics are also required.

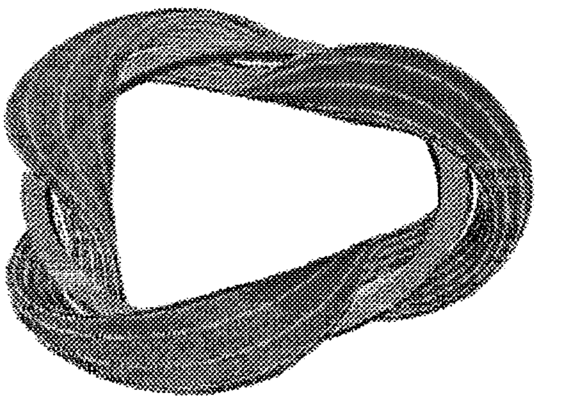

Fig. 2. The H-1NF helical-axis plasma.

The H-1NF device was designed using state-of-the-art, three-dimensional, computer design tools, and the magnets and supporting structure were constructed and assembled with component location tolerances of ±1 mm using the facilities available in the Research School of Physical Sciences and Engineering at the Australian National University. Figure 3 shows a comparison of the nested surfaces of twisted magnetic field lines for the vacuum magnetic field configuration as calculated by a computer program, and as measured in the actual device by launching an electron beam along the field lines and imaging successive transits of the beam using a fluorescent rod.

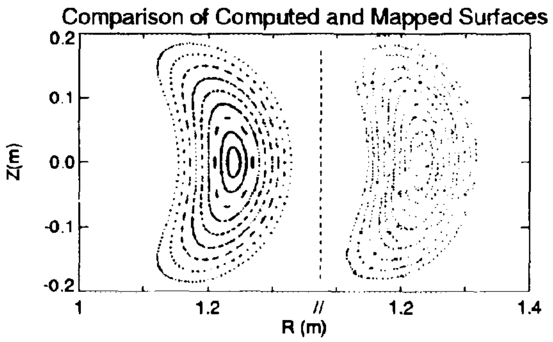

Fig. 3. Calculated and measured magnetic surfaces in the H-1NF device.

4 RESEARCH PROGRAM

The facility objectives are fourfold:

- To provide a high temperature plasma National Facility of international standing on a scale appropriate to Australia's research budget.
- To provide a focus for national and international collaborative research, to make significant contributions to the global fusion research effort and to increase Australia's presence in the field of plasma fusion power into the next century.
- To gain detailed understanding of the basic plasma physics of hot plasma confined in the helical axis Stellarator configuration.
- To develop advanced plasma and fusion measurement systems, integrating real-time processing and multi-dimensional visualisation of data.

The first two of these objectives emphasise national and international collaboration. Such collaboration is already well under way in the form of the AFRG nationally and in the formal agreement between H-1NF and the Japanese National Institute for Fusion Science (NIFS). This collaboration is discussed in detail in section 6.

The latter two objectives concern the work to be carried out on H-1 emphasising the fact the this machine is not a device that will reach fusion conditions and is not intended to be used for "parameter pushing" towards temperatures and densities appropriate for fusion to occur. The machine will be used to gain understanding of the fundamental physics of plasma (particle and energy) transport and confinement in the Heliac geometry as well as a test bed for the development of advanced diagnostics for which Australian plasma physicists are justifiably renowned in the world's major laboratories. In particular the complicated axially asymmetric nature of the nature the Heliac plasma will require the development of two and three dimensional visualisation and advanced tomographic processing techniques.

The facility has three broad regimes of operation that broadly depend on the plasma heating system that is installed. Scheduling of experimental work in these different regimes is therefore dependent on the installation program of the different heating systems:

- High-temperature plasma heated by Electron Cyclotron Heating (ECH). Only fixed frequencies are available (28 GHz) which restricts operation to high field (0.5 to 1.0T)and hence moderate beta.
- High-pressure plasma heated by high power RF in the MHz range giving moderate temperatures and high densities and thus higher beta.
- Low-temperature plasmas in the edge of the discharge. An important region where probes can be used. Experiments carried out in this regime links well to many of the plasma processing research areas in Australia.

It is planned that these different operating regimes will support investigations in the following research areas:

- Finite pressure equilibrium and stability
- Transport in high temperature plasmas
- Plasma heating and formation
- Instabilities and turbulence
- Edge plasma physics
- Advanced diagnostic development.

It should be noted that all these areas will require the development of advanced diagnostics to measure plasma density, temperature, flow, electric fields etc. Nearly all will require diagnostics with good spatial resolution in more than one dimension as well as good temporal resolution.

To support the above research areas and objectives, the H-1NF experiment will be scheduled to run a program in two main branches:

Physics Program.
This program has been mapped out and will be pursued by the H-1NF team. It will be concerned with investigating the effect of configuration, well, transform and shear on equilibrium, transport and stability.

The staging of the physics program for the National Facility over the next five years is determined by the major equipment upgrade schedule. This has been arranged as shown below. The schedule may change as the experimental results unfold.

H-1NF Experimental Program:

1997-1998:	Low temperature plasma physics.
1998-1999:	ECH Phase 1
1999-2000:	ICH Phase 1
2000:	ECH Phase 2
2001:	ICH Phase 2

During the phase 1 periods of operation, H-1 will be run with an available magnetic field of 0.5T and low heating power. These periods of operation will be used to assess operational requirements and the possibility of mixing ECH and ICH heating, ready for the second phase, when fields of 1T will be available as well as at least double the heating power.

Support for AFRG Collaboration.
Several of the AFRG projects are diagnostic developments that are essential to the main physics program. Others make special use of the Facility for the fundamental physics studies or development of technological spin-offs.

4 MANAGEMENT STRUCTURE

The management structure of the Facility is shown in Fig. 4. This structure involves three high level organisations DIST, AINSE and the ANU all of which have input to the Board which otherwise acts autonomously. It is only the Board and the Steering and Operations Committees that have direct impact on the Facility.

The role of AINSE through its Plasma Specialist Committee lies mainly in the allocation of travel funds to- and co-ordination of- the AFRG collaborations. The AFRG has input at all levels as the collaboration with these external bodies is crucial to the objectives and success of the project.

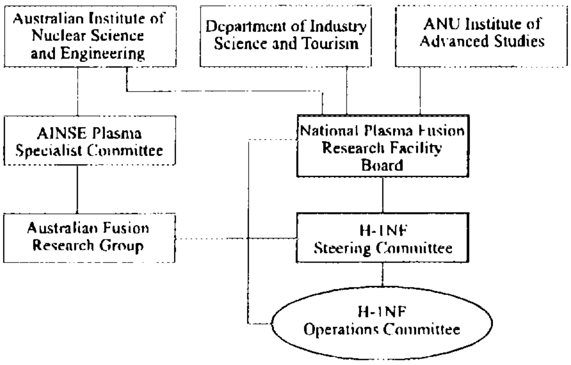

Fig. 4. Management structure of the National Plasma Fusion Research Facility

The Board guides the operation of the Facility as a whole. As shown in the table, the Board comprises almost entirely *ex officio* positions with members from institutions with an interest in the operation of the Facility.

H-1NF Board:	
Chair	Dr J. Baker
Executive Secretary	Dr R B Gammon
Minutes Secretary	Ms H P Hawes
AFRG Chair	A/Prof A D Cheetham
AINSE President	Professor T Ophel
ANU - IAS Director	Professor S Sergeantson
ARC Chair	Professor M H Brennan
H-1NF Director	Professor J H Harris
NIFS Director	Professor A Iiyoshi
RSPhysSE Director	Professor E Weigold

The Steering Committee plans the various programs: construction, installation, commissioning and experiments. The Operations Committee is more or less the shop floor organisation of the actual experimental work. This committee will become more important as more AFRG collaborative experiments require scheduled running time.

5 CURRENT AFRG PROJECTS

Soft X-ray diagnostics
University of Canberra
This project comprises two separate but dependent parts. Work is under way on the installation of a pair silicon surface barrier detectors. These two detectors view the plasma soft x-ray emission through a pinhole covered with thin beryllium foil. The results of this experiment will estimate the global electron temperature by the ratio method as well as acting as a pilot experiment to determine the level of x-ray flux from the Heliac plasma. The next phase will be the installation a pair of 16 channel detector arrays that will give 32 views of the plasma. This system will allow tomographic reconstruction of the emission profile through the cross séction of the plasma.

Real Time Tomography
Central Queensland University.
Work is well under way in the development of a transputer based data acquisition system for real time tomography. The system under development is specifically for the multi-view multi-channel FIR interferometer developed at the ANU. It will however, with little modification be applicable to several other diagnostics such as the soft x-ray detector arrays, spectroscopic Doppler vector tomography etc. [3 & 4]

Alfven Wave Propagation
University of Sydney
This experiment is designed to measure the low frequency modes of oscillation of the H-1 plasma at frequencies between 20kHz and 20MHz providing information on the q and ion density profiles. This is not a new measurement but the interpretation will prove interesting in the complicated geometry of the Heliac with the wide variety of q profiles available.

Laser Induced Fluorescence
University of Sydney and Flinders University:
This measurement is being developed jointly although initially the laser and associated equipment will reside at the University of Sydney. This diagnostic is used to measure electric field in the plasma, and the densities of various species.

Transport Theory and Optical Fibre Diagnostics
University of New England.
The two projects here involve a theoretical study of energy confinement and transport in the ECH heated H-1NF plasma and the application of fibre optic transducers developed in the Physics Department of the UNE to plasma diagnostics in the low temperature region of H-1NF.

6 INTERNATIONAL COLLABORATION

The most developed international collaboration for H-1NF is with the Japanese stellarator/helical system research program. The National Institute for Fusion Science (NIFS) in Toki operates a medium-sized (R = 0.9 m) stellarator, the CHS (Compact Helical System) experiment, and is constructing a large (R = 4 m) experiment, the LHD (Large Helical System), which will be the largest magnetic fusion experiment in the world when it is completed in 1998. Kyoto University operates the Heliotron-E experiment (R = 2.2 m) and is designing a new device that is related to H-1NF by virtue of having a helical magnetic axis.

NIFS and Kyoto University have joined together to collaborate with the Australian fusion program by loaning a 28 GHz gyrotron for use in electron - cyclotron heating experiments on H-1NF. This system, which is worth about A$1M, has been installed at the ANU, and awaits the upgrade of the H-1NF magnetic field system to be used in plasma experiments. Japanese researchers will also contribute to the planning and analysis of heating experiments on H-1NF.

NIFS and Australian fusion researchers are also collaborating on low-frequency plasma heating, equilibrium, stability and transport theory, and 3-D computation.

Additional collaborations in theory and experiment are being developed with laboratories in the US and Europe.

7 RECENT EXPERIMENTAL RESULTS

During the low temperature phase of operation before the magnetic field and heating power are increased, the temperature and energy content of the H-1NF plasma are low enough that small metal probes can be inserted into the plasma. By measuring the current-voltage characteristics of these probes, the plasma density, temperature and electric field can be determined.

Experiments on H-1NF in this regime have already revealed interesting plasma confinement phenomena [1]. For discharges in which the magnetic field exceeds a critical value that depends on the pressure and the magnetic configuration, the density suddenly increases by a factor ~2, the profiles of density and electric field change (Fig. 5), and the energy of the ions increases. The outward transport of particles due to plasma turbulence decreases. This is evidence of a transition to an improved mode of plasma confinement; one model for this transition involves reduction of turbulence and transport due to shear in the plasma drift induced by the radial electric field. Such transitions are of critical interest in magnetic fusion research because improvements in confinement directly affect the overall size (and therefore cost) of a magnetic fusion reactor that produces electric power. Typically, the transitions to improved confinement occur in large devices with megawatts of heating power. In H-1NF, qualitatively similar regimes can be attained at low powers ~50 kW and low temperatures, which permits detailed measurements with relatively simple diagnostics.

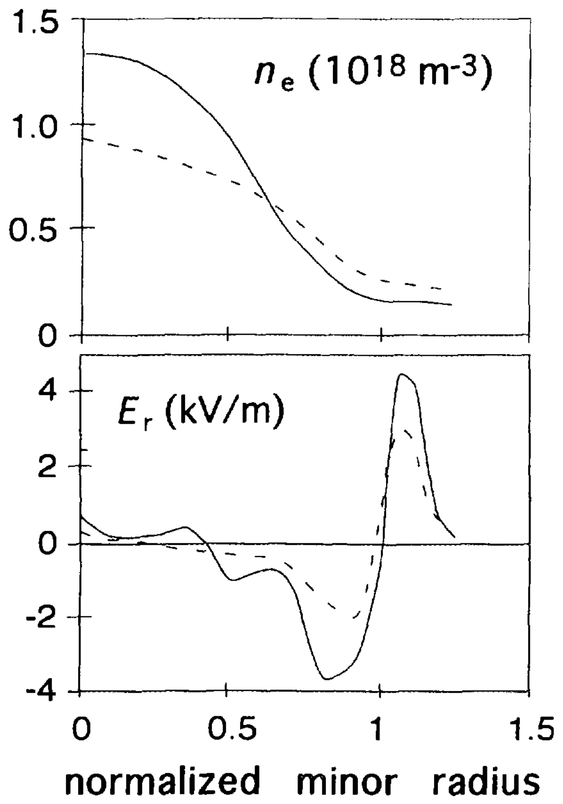

Fig. 5. Radial profiles of plasma density (n_e) and radial electric field (E_r) in H-1NF plasma. Profiles taken before (dashed) and after (solid) the transition to improved confinement.

8 CONCLUSIONS

The Australian fusion program is centred around the H-1NF Heliac, an innovative and flexible experimental facility located at the ANU. Promising experimental results are being obtained in low-power operation, work to increase the heating power and magnetic field is underway, and an network of research collaborations involving Australian and overseas scientists is being developed.

Further information concerning AFRG, its members and the H-1 National Facility can be obtained starting from the AFRG web page:
http://online.anu.edu.au/AFRG/AFRG.html

9 ACKNOWLEDGEMENT

The author would like to thank the members of the AFRG teams that supplied the information included in this paper and the director of the H-1NF Facility, Prof Jeffrey Harris for his collaboration. Some of the work presented here has been supported by the Australian Research Council.

10 REFERENCES

[1] M G Shats, D L Rudakov, B D Blackwell, G G Borg, R L Dewar, S M Hamberger, J Howard and L E Sharp. *Physical Review Letters* 77 (1996) 4190.

[2] S M Hamberger *et al., Fusion Technology* 17 (1990) 123

[3] J W Waller, X H Shi, N C Altoveros, J Howard, B D Blackwell and G B Warr, *Reviews of Scientific Instruments*, 66 (1995) 1171.

[4] J Howard, *Reviews of Scientific Instruments* 61 (1990) 1086-1094