The Australian Plasma Fusion Research Facility
Annual Report 2009-2010
Fusion: the clean energy source for the third millennium

The world is facing an energy crisis; oil prices continue to rise, and there are increasing concerns over Greenhouse Gas emissions and dwindling fossil fuel reserves. Whilst many sustainable energy technologies such as wind and solar power show promise, it seems unlikely that they will be able to meet all of the world’s ever-increasing demands. Although conventional nuclear fission reactors have the advantage of very low Greenhouse Gas emissions, they create long half-life hazardous waste and provoke strong public concerns over their safety. For all these reasons scientists have been exploring an alternative nuclear technology, fusion. The basic principle of a fusion reactor is to heat a gas of hydrogen isotopes, deuterium and tritium, to many millions of degrees, causing them to fuse together into helium, and releasing vast amounts of energy in the process. Fusion is the process that powers the sun.

Fusion has several significant advantages over fission. The raw materials can be extracted from seawater, and the reaction product is helium, not a long-lived radioactive isotope. The reactor does not contain enough fuel at any given time for a catastrophic runaway reaction of the type that can occur in fission reactors. All of these factors coupled with its zero Greenhouse emissions, make fusion power a very attractive option for massive scale power generation.

The technical difficulty in achieving fusion is great but not insurmountable. Since work began in the 1950s prototype reactors have shown a steady increase in the ratio of power out to power in, and current generation experimental reactors are beginning to reach “break-even point”. Within a decade or two, most scientists expect experimental reactors will be producing significant power.

Naturally, given the complexity of developing a working fusion reactor and the size and expense of such a project, most work in this area is carried out by many nations in partnership. Through the H-1 National Facility (H-1NF) based in Canberra (left), Australia is able to actively participate in this international effort.

H-1 NF is a toroidal stellarator capable of holding super-heated plasma in a twisted magnetic loop. Although on a much smaller scale that prototype reactors such as ITER (right), H-1 offers excellent flexibility in its configuration and is particularly suited to the development of advanced diagnostic instrumentation. Some of this instrumentation has been employed on large scale reactors overseas and some has also been adapted to service other industries at home. In addition to its scientific value to Australia, H-1 also offers an excellent training ground for young Australian scientists and engineers.

The development of H-1 was supported by an $8.7M establishment grant from the Department of Industry Science and Resources (1997-2010) and EIF funding for a $7M upgrade (2010-2013). The facility is operated by the Australian National University and is available through the Australian Institute of Nuclear Science and Engineering (AINSE) to researchers from around the country and internationally through collaborations.

Front Cover – Tim Wetherell and Martin Conway: H-1 toroidal and helical magnetic field coils (stainless steel) above the copper 14,000 Amp bus bar and cooling pipe work.

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The Australian Plasma Fusion Research Facility, operated by the Plasma Research Laboratory,
Research School of Physics and Engineering in the College of Physical and Mathematical Sciences,
The Australian National University, Canberra, Australia. http://h1nf.anu.edu.au

This report covers January 2009 to September 2010 to bridge the change in reporting requirements.
Research Highlights

High-speed synchronous imaging has revealed the detailed helical structure of density perturbations associated with unstable modes in the H-1 heliac.

A data mining technique developed on H-1NF and applied to experiments in Kyoto, Madrid and Germany, is now being applied on a large scale to the world’s largest stellarator experiment LHD.

An International Science Linkages research collaboration has led to the development of Bayesian inversion methods for analysing currents, temperature, density and magnetic field oscillations, providing a framework for comparing different force-balance models and identifying mode-structures.

New spatial heterodyne coherence imaging systems developed on the facility have been deployed on frontline tokamaks in Europe and the USA to produce the world’s first 2D images of plasma internal current distribution, ion temperatures and toroidal flows.

The Physics of Fluids group has shown that the interaction between large-scale coherent structures and turbulence are at the heart of spectral condensation and of the plasma confinement bifurcations during L-H transitions, and in many cases that turbulence feeds coherent structures.

Upgrade Highlights

The new website and data server provides user-friendly access to summary data, with access to raw data coming soon.

A high speed imaging system has been commissioned for investigating short timescale phenomena – see sample results in Research Highlights.

Assembly has begun on the Materials Diagnostic Development Facility (MDF) which will allow development of diagnostics for fusion plasma-material interactions, and to a limited extent, the testing of materials under high heat and plasma flux.
Executive Summary

The Super Science Initiative Scheme, announced in the 2009-10 Federal Budget, provided for a major infrastructure upgrade to the H-1 facility, which is now known as the Australian Plasma Fusion Research Facility (the Facility). The proposed outcomes of this financial support are:

- Significant improvements to the plasma formation and heating systems, vacuum systems and plasma diagnostic and data systems.
- Enhanced accessibility of plasma data and diagnostic information.
- Dual use of heating, magnet supply and diagnostic systems with a new high power and high plasma density Materials Diagnostic Development Facility (MDF).
- The development of diagnostic tools, which it is hoped, will ultimately be installed on the international fusion experiment ITER, identified as a central plank of the “Strategy for Australian Fusion Science and Engineering” developed by the Australian ITER Forum in consultation with the Australian fusion community.

All upgrade project milestones for this year were met on time, including detailed planning of the upgrade, and first steps of the heating, diagnostic, data system and safety upgrades. These include:

- Procurement of a power amplifier system to upgrade the radiofrequency (RF) plasma heating system for installation in 2011-12.
- Work has begun on the design of upgrades to the RF transmission and launching system.
- A detailed plan for the Fire Protection upgrade was developed and implemented in all areas except the transmitter hall. The fire protection for this area will be upgraded during the radiofrequency source upgrade.
- A scoping study for a small-scale electron heating system.
- Significant upgrades to diagnostics include the recent installation of a new high speed fluctuation-imaging camera.

Central to our aim of improving access to experimental data is the upgrade of the data server, acquisition hardware and experiment timing systems.

- The existing experimental database is undergoing a total redesign to improve accessibility to new users without detailed knowledge of the data structures.
- A new web interface provides a simple means of data access, and efficient server protocols will soon allow access to more detailed data for more complete analysis.

Additional staff have been recruited, including two short term appointments to assist in assessment of heating and database options. The filling of three fixed term positions to perform work on the upgrade of the diagnostic system and databases is currently underway.

The following document consists of the EIF Upgrade Annual Report 1 followed by the Facility Annual Report (Section II onwards) which focuses on research and outputs.
Section I: Educational Infrastructure Fund Upgrade Annual Report 1

1.1 Facility Mission and Outcomes

The Facility, built around the H-1 heliac is the Australian focus of basic experimental research on magnetically confined plasma, important in developing fusion energy, a clean, virtually inexhaustible energy source that powers the sun and stars.

The mission of the Facility is to:

- perform research into the basic properties of magnetically-confined, high-temperature plasma as part of an international program, whose ultimate aim is ecologically sustainable power generation by the controlled fusion of hydrogen isotopes
- ensure that Australia is intellectually and technologically equipped to benefit from a future fusion power industry, with emphasis on the export of high-technology components needed by fusion power stations
- maintain Australia’s internationally recognised position of excellence in basic plasma physics and applications such as plasma diagnostics and plasma processing of semiconductors.

The proposed research outcomes of the Facility include:

- a detailed understanding of the behaviour of hot plasma which is magnetically confined in the helical axis stellarator configuration – this forms part of an international program under the International Energy Agency (IEA) Implementation Agreement on Stellarators, to which Australia is a party
- the development of advanced plasma measurement systems (‘diagnostics’), integrating real-time processing and multi-dimensional visualisation of data
- fundamental studies of turbulence and transport of particles and energy in confined plasmas
- significant contributions to the global fusion research effort and an increased Australian presence in the field of plasma fusion power into the 21st century
- improvements in knowledge of basic plasma physics for applications such as plasma processing of semiconductors
- an important performance indicator was identified as ‘technological spin-off activities’ in areas including instrumentation and techniques.

More detail on the Facility and its existing infrastructure and power and instrumentation systems, and research is provided in the Facility Annual Report, beginning in Section II.
I.2 The Education Infrastructure Fund Facility (EIF) Upgrade

In its 2009-10 Budget the Australian Government announced a $1.1 billion Super Science Initiative to build on the National Collaborative Research Infrastructure Strategy (NCRIS) investments in research infrastructure. As part of this initiative, $7 million has been allocated to the upgrade of Australia’s plasma fusion research capabilities, the need for which was identified in the 2008 Strategic Roadmap for Australian Research Infrastructure.

The Australian Plasma Fusion Research Facility (APF RF, formerly the National Plasma Fusion Research Facility) is a uniquely versatile plasma research facility, located in the Research School of Physics and Engineering within the College of Physical and Mathematical Sciences of the Australian National University in Canberra. It is capable of accessing a wide range of plasma configurations or shapes, and utilising associated state-of-the-art power and measurement systems that allow fundamental studies of plasma, the fourth state of matter. The facility is operated by the staff from the Plasma Research Laboratory, and serves both national and international collaborators including researchers from China, Japan, Korea, Germany, and the United States.

A core component of the Facility is the H-1 Heliac plasma confinement device (Heliac). The Heliac allows investigation of basic plasma physics and exploration of ideas for improved magnetic design of the fusion power stations that will follow the ITER international fusion experiment in France. While the Heliac’s shape prevents its use in a reactor, its high degree of flexibility allows testing basic plasma theory over a wide range of conditions, making it ideal for a university or research environment. Similarly, the Facility provides a convenient, flexible and well diagnosed test-bed for development of plasma measurement systems for both stellarators and tokamaks, an area where Australia is at the international forefront.

The objectives of the upgrade are to:

- upgrade the technical capabilities of the APF RF by replacing or upgrading various components of the Heliac system such as the plasma generation and heating system and associated antennas, the vacuum system, the plasma measurement systems, precision current regulator, and fast cameras
- boost Australian capability in fusion science and engineering by making the facility more accessible to national and international researchers
- offer open access to data arising from the Facility upgrades to relevant research communities
- offer merit-based access to the research infrastructure upgraded and built through the Project

In the 2008 Strategic Roadmap for Australian Research Infrastructure, fusion was included under the Sustainable Energy Future capability among long timescale candidates as a potential large-scale, non-polluting energy source. The Roadmap identified that plasma fusion required concerted international collaboration, investment in local capabilities including...

experimental facilities, and co-operation to bring to commercial reality. The upgrade of the APFRF is part of this investment.

In addition to increased technical capabilities, the upgrade will develop capabilities and expertise by fostering student, post-graduate and post-Doctoral training. It will also facilitate the development of measurement systems suitable for application to current and next generation fusion power experiments such as the ITER experimental fusion reactor.

**Scope of the Upgrade**
The APFRF upgrade will include a number or technical upgrades and additions to the existing facility. These include:

**Upgrading the RF heating system:** The RF system used to generate plasma in the H-1 has proven to be the most often-used method of plasma formation and heating, because of its flexibility of frequency, modulation and the phasing of elements in the antenna. The upgrade will double the available power, improve reliability and facility uptime, and reduce electric power costs. In particular, the ability to vary frequency over a wide range will allow properly controlled magnetic field scans while using resonant heating.

The upgrade may include a medium power continuous or long pulse gyrotron, contingent upon availability of funds after the procurement of the RF upgrade above. This could provide a more reliable, routine source of electron heating than the present high power pulsed gyrotron, applicable to both H-1 and the satellite test chamber.

**Installation of new RF antennas:** This will allow more frequent pulses, control of antenna position and enable RF plasma to be used as a cleaning method to remove oxygen and carbon impurities from the chamber walls and internal structures.

**Installation of a precision current regulator:** This will allow better and more controlled access to island divertor plasma configurations.

**Upgrade of the vacuum system:** This upgrade will allow better impurity control, which is necessary for achieving higher ionisation states, and for dealing with material ablated or sputtered from wall material tests.

**Upgrade of the data system:** The upgrade will make data more readily available, especially to users not intimately familiar with details of H-1 operation. In conjunction with this, a greater degree of automation of measurement systems (diagnostics) will ensure that key diagnostics are available on all shots.

**Installation of fast cameras and photomultiplier arrays:** This installation will provide important infrastructure for development of plasma edge and divertor diagnostics, both of which require detailed measurements because of their complexity.

**The use of the various H-1 power, heating and diagnostic systems on a small satellite device:** This small device (described in Upgrade Highlights) will allow tests of plasma edge and wall diagnostics under conditions approaching fusion reactor edge plasma, for example, under higher power and plasma density.
Status of the Upgrade Project

Following is a brief summary of the progress made on the Facility upgrade, grouping associated milestones together. Some of the topics are treated in more detail in Upgrade Highlights, and the complete list of Milestones into next year is provided in Section IX.

A Detailed Upgrade Plan was compiled and a total project risk assessment was performed. This will be updated in future Facility Upgrade Annual Business Plans.

A request for tender was issued for the supply of Radio Frequency Heating Equipment for the RF Heating Upgrade. Of four interested parties, the successful tenderer was Thomson/Grass Valley, to supply two 40kW CW/ 160kW PEP power amplifiers of the DRM type, and associated equipment in 2011.

A comprehensive survey of fire safety was completed, resulting in a Fire Protection Upgrade Plan in April. With significant financial assistance from the School, most of implementation has since been completed, apart from work to be performed immediately prior to the RF heating source upgrade in 2011.

A new website and server are in operation to provide better access to information and databases in particular, presented in a more user-friendly manner. In particular data, and the meta-data required for its interpretation can be accessed simply through a number of interfaces, without knowledge of the detailed data storage structure. Data access regimes in several leading international laboratories were surveyed, and the features most appropriate to our situation were combined with current best practice in the design of our “RESTful” data access strategy.

A Princeton Instruments PI-Max 3 high speed intensified CCD camera was purchased and installed on H-1 for the observation of short timescale phenomena. With exposures down to nanoseconds, both single frame events and periodic phenomena can be observed. This provides a unique imaging diagnostic capability for the heliac. By synchronising with various instabilities it is possible to "freeze-frame" these structures at various phases of their evolution. By combining with novel front-end components developed over a number of years at ANU, we have the ability to measure the fluid displacements produced by these instabilities for the first direct comparison with 3D magnetohydrodynamic modelling codes. An example of the application of this instrument is given in Section III.1

Upgrade Highlights

The following is a selection of equipment and diagnostic projects enabled by the EIF upgrade funding in 2010, and which are close to operation. The high speed camera project is described more fully in the research results section, and all current and completed upgrade projects are briefly described in time sequence in the following section.
The Toroidal Mirnov Array

H-1 is well-suited to the study of instabilities in the Alfvénic range of frequencies because of its low magnetic shear and precisely controllable rotational transform. The existing two poloidal arrays have provided an extensive database of wave dispersion and poloidal mode structure information. Optical techniques show promise to provide information on the toroidal (the long way around) structure, but to better characterise these fluctuations, a toroidal array has been designed and constructed by PhD student Shaun Haskey, John Wach and workshop staff. The array consists of 16 sets of 3 mutually perpendicular coils to detect all 3 components of the fluctuation field, housed inside a vacuum-tight bellows. The bellows is largely transparent to magnetic field in the desired frequency range, and snakes in a toroidal helix near the ring conductor.

Being close to the plasma, the array produces large signal amplitudes, and because it traverses regions of both good and poor curvature it may be possible to distinguish interchange modes by their localisation. A set of 48 programmable variable gain and bandpass amplifiers is under construction to complete the fluctuation diagnostic.

The Materials Diagnostic Development Facility (MDF)

The plasma conditions in H-1 are closer to conditions at the edge of a fusion reactor where the plasma is cooler and more collisional than in the hot core. Furthermore, the complex, three dimensional nature of the magnetic fields in H-1 provides a diagnostic challenge similar to the problem of unravelling plasma measurements in the comparably complex magnetic field of a fusion reactor “divertor”: a small auxiliary chamber loosely connected to the confined plasma region to extract impurities including the fusion end product, helium. The magnetic field in this region, usually based on one or two “X” points (stagnation points), is carefully designed to provide a controlled exit path from the confinement volume, to avoid concentrated heat loads on wall materials, and to provide a high pumping capacity for impurity removal.
Australia has developed world leading diagnostic techniques which are already being applied to edge plasma and divertor regions in leading international devices. These were developed on H-1 and/or in small general purpose plasma devices at the University of Sydney. The Materials Diagnostic Development Facility is intended to provide a test-bed specifically for developing and testing diagnostics for plasma-materials interaction under conditions relevant to the edge of fusion reactors. The device aims to achieve high plasma densities (~10^{19} \text{m}^{-3} \text{H}^+) and power densities, but cannot provide the neutron flux. This is not a significant problem for materials diagnostic development, but does mean that testing of materials per se is possible, but is limited to high power and high incident plasma flux tests.

It is planned to include three different sources – RF helicon wave source, an electron beam source and a plasma gun source. Initial enquiries about a commercial plasma gun indicate that it is no longer available, and alternatives are being explored. Recent results show that plasma densities of ~10^{19} \text{m}^{-3} can be achieved in hydrogen if helicon waves are launched into an increasing magnetic field.

A prototype MDF using this approach is under construction using RF production from a 5kW PEP source, magnetic field coils from the University of Sydney, and two 1000A power supplies. Figure 2 shows a 3D rendering of the prototype, which can be compared with the photograph (Figure 3) showing the coils being tested prior to assembly which is planned for late 2010.
When complete, this device will provide a diagnostic test-bed capable of much higher repetition rates, and a much faster vacuum opening/closing cycle for installation of different diagnostics, probes and material targets. It will also be more practical to clean the device if contaminated with carbon or metal deposits, compared to H-1, so it will allow a wider range of materials to be tested, under higher power conditions, without fear of contaminating H-1.

**The Precision High Current Controller**

H-1 achieves a wide range of magnetic configurations by precise control of two power supplies connected to various combinations of five magnetic field coil systems. The object of this new controller is to add a third control variable to the existing two currents controllers so that a larger part of the five dimensional magnetic field parameter space can be accessed. Another advantage is access to a wider range of currents below 1000-1500 Amps, the present lower limit of the two supplies. For example, this will allow the ratio of helical conductor to ring current, our most common shape parameter, to be varied from +1 through zero to -1. Previously it was not possible to access values between +0.16 and 0 and -0.16 at high fields. The inaccessible range was larger still at lower fields.

The controller is a development of an M. Phil. project by Mr Tony Lin, and combines a binary tree of high power, low value resistors for coarse control with a pulse-width modulated controller for fine, continuous adjustment of current. Almost all components are in place (Figure 4) and the unit is integrated with the high current patch panel for the two power supplies. The controller project commissioning milestone of March 2011 should be comfortably achieved.

![Figure 4: CAD rendering of the Precision High Current Controller. (Replace by photo). The resistors are red, and contactors are shown in green. The PWM regulator is front centre, and two filter inductors are in the rear.](image-url)
I.3  Financial and Performance Summary

The financial statement in Section X shows that at June 30th 2010, of the initial instalment of $1M, the EIF fund balance was $691,323.92, of which $454,000 was allocated for the initial payment on the RF heating upgrade contract. The next instalment of $2M will follow the acceptance of the September Milestone report. Funding will be completed by two more instalments of $2M at similar times in the next two financial years.

Co-investment in kind from the University of Sydney in the form of equipment and high current magnetic field solenoid modules to the value of $220,000 has been delivered. These are undergoing testing before forming the basis of the Materials Diagnostic Development Facility. The in-kind contribution of the Helium Beam diagnostic was already at ANU, and the data acquisition and other components were delivered in 2009, making the total provided in kind value of $400,000.

The ANU in kind contributions below reflect the planning and start-up phase of the upgrade, with reduced emphasis on operations and increased emphasis on project management. The ANU contributions in kind were:

<table>
<thead>
<tr>
<th>The Australian National University – Direct Facility Support Q3&amp;4/FY2009/10</th>
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<tbody>
<tr>
<td>• Director, Head Diagnostics, Operations Manager (Pro rata salary) $109,000</td>
</tr>
<tr>
<td>• Other Support Staff (Pro rata salary) $18,700</td>
</tr>
<tr>
<td>• Operation and Maintenance costs $11,200</td>
</tr>
<tr>
<td>Total ANU in kind contribution to direct facility support $139,000</td>
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</table>

Table 1: ANU in-kind contributions

The table in Section IX lists the project Milestones, completed and pending. Performance indicators for the upgrade project were developed in September, and will be fully implemented in the next Annual Report. The Table below is a composite of some of these and some research performance indicators.

<table>
<thead>
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<th>Summary of outcomes 2009 – 9/2010</th>
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<tbody>
<tr>
<td>Milestones Completed on Time 11</td>
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<tr>
<td>Milestones Overdue 0</td>
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<td>Publications</td>
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<tr>
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<td>Refereed Journal Articles 30</td>
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<td>Invited Talks 7</td>
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<td>Patents -</td>
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<td>HDR Completions/submissions 1/1</td>
</tr>
<tr>
<td>Workshops and Conferences held 1</td>
</tr>
<tr>
<td>Workshops and Conferences attended 6</td>
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<tr>
<td>Grants won: active in 2009/10 2:9</td>
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<tr>
<td>Pulses processed 1613</td>
</tr>
<tr>
<td>Gigabytes data acquired 31.6</td>
</tr>
</tbody>
</table>

Table 2: Performance Indicators for 2009—9/2010 Details are provided in Sections V.1, V.2
Section II: Facility Annual Report

II.1 The Facility: Background and Overview of Systems

The Australian Plasma Fusion Research Facility (APFRF) is the Australian focus of basic experimental research on magnetically confined plasma, important in developing fusion energy, a clean, virtually inexhaustible energy source that powers the sun and stars. Plasma phenomena are important in everything from stars and space exploration to the processing of electronic materials. Plasma physics is thus a highly interdisciplinary endeavour because of the range of physics areas it encompasses (fluid, atomic, electromagnetic, optical and surface physics) and the diverse technologies employed in plasma experiments (electronics, radio-frequency technologies, magnetics, lasers, microwaves and spectroscopy).

The Facility mission was defined in Section I. The Facility was developed from the “H-1 Heliac” toroidal stellarator experiment in the Research School of Physical Sciences and Engineering at the Australian National University. The innovative plasma geometry of the heliac allows investigation of basic plasma physics, and exploration of ideas for improved design of the fusion power stations that will follow the ITER international fusion experiment. The Heliac itself was originally funded through the ANU Block Grant and Major Equipment Grants, and was established as a national facility in the first round of the Major National Research Facility (MNRF) program in 1997. MNRF funding was used to provide two precision 14,000 Amp magnet power supplies, high power pulsed electron and RF heating sources, and a set of plasma diagnostic systems to improve the versatility of this national facility. More recently a variation of the MNRF funding agreement allowed the automation of the operating system to improve operational efficiency, and to allow greater control of plasma parameters.

The Facility is operated by the Plasma Research Laboratory’s Toroidal Plasma Group at the Australian National University, on behalf of the proponent organisations, and under the auspices of the Australian Institute of Nuclear Science and Engineering (AINSE). Users include researchers in plasma physics from the Australian National University, the University of Canberra, the University of Sydney, and Flinders University. Recently, interest in plasma fusion has increased, and more than 100 scientists, engineers, students and others have come together to form the Australian ITER Forum. The forum aims to promote Australian research into fusion science and materials, and involvement in the international fusion experiment (ITER).

The heart of the H-1NF, shown in block diagram form in Figure 5, is the H-1 Heliac, a large toroidal helical-axis stellarator device which was designed for fundamental research in the physics of plasma confinement. The Heliac magnetic field is produced by a three-dimensional magnetic coil system. This magnetic field is precisely controlled by a precision computer-controlled 14MW dual power supply, which by control of currents, allows a wide range of plasma shapes to be produced (see Section III.4). The plasma is produced by high-power radio and micro-waves, and its properties are measured by electric and magnetic probes, optical and microwave interferometry and scattering instruments.
These measurement systems, many of them based on advanced remote sensing techniques, are called ‘plasma diagnostics’. Australia has an outstanding international reputation in the development of innovative diagnostics, and a central aim of the Facility is to exploit and build upon this capability. A particular focus of research on the heliac is the study of turbulent transport, flows, instabilities and the effect of magnetic configurations on plasma stability and confinement. These aspects are expanded upon in Sections III.1-4.

Technologies originating in research on the heliac are also being applied to plasma diagnostics for experiments around the world, instruments for industry and defence, and wireless communication and medical imaging (Section VI). International collaborations include work with scientists from Japan, the United States, and Europe, and are elaborated on in Section V. In addition, the Laboratory also carries out research in plasma theory, simulation, and visualisation, in collaboration with staff from the Department of Computer Sciences in the Faculty of Engineering and Information Technology.

The Laboratory is deeply involved in educating young scientists and engineers, through the supervision of post-graduate and fourth-year undergraduate research and advanced studies projects described in Section V. We also regularly host students from around the world who can take advantage of the Laboratory’s special capabilities. Members of the Laboratory staff also have introduced new or contribute to existing undergraduate lecture and laboratory courses offered by the Department of Physics and the Department of Engineering in the ANU Faculties.

Figure 5: The Facility, built around the H-1 Heliac. Power systems for the magnetic field (ABB and motor generator) and electron and ion heating are shown.
III RESEARCH

III.1 Advanced Imaging and Inverse Methods

The Advanced Imaging and Inverse Methods (AIIM) Group in PRL (Toro Division) undertakes research into passive (optical) and active (laser-based) techniques for plasma diagnostics, and their associated inverse methods, with applications in industry and medicine. To complement this work, we also investigate issues relating to inverse methods and tomography whereby useful information can be extracted from line-of-sight integrated measurements by applying appropriate mathematical transformations.

Figure 6 AIIM team members as of Sept 2009. L-R: Mr Mark Gwynneth (engineer), Dr Ahmed Diallo, Dr Shantanu Padhi, Mr Matthew Creese (BSc Hons), Prof John Howard, Mr Jesse Read (MPhil), Mr Sebastian Bengsston (MPhil, Chalmers Uni). Not shown: Ms Nandika Thapar, Dr Sean Ma, and Mr Stuart Henderson.

Research on H-1NF

Synchronous imaging of plasma instabilities

During 2009-2010 we installed dual fast gated intensified CCD cameras viewing the plasma both radially and tangentially. A photo of the new radial-viewing installation is shown in Figure 7.

Figure 7 Photograph of the radial high speed camera showing mounting rails and calibration integrating sphere mounted at front of rail. The elongated view port on the H-1 device can be seen in the background.
Phase-synchronous radial projections of Alfven-like plasma instabilities have been tomographically inverted to obtain information about the perturbation structure. As expected for resonant eigenmodes, it is found that the mode helicity depends on magnetic configuration which is set by the current the helical control winding. Example projection images are shown below in Figure 8, with tomographic reconstruction shown in Figure 10.

To confirm these findings, a second camera that tangentially views the plasma via an internal mirror in the toroidal direction has been installed to image light from an impurity gas (neon) injected across a poloidal plasma cross-section by a high speed nozzle. The direct synchronous "gas puff" image is compared with the tomographic reconstruction in Figure 10 (Jesse Read, MPhil)

These cameras now provide a unique imaging diagnostic capability for the heliac. By synchronising with various instabilities it is possible to "freeze-frame" these structures at various phases of their evolution. By combining with novel front-end components developed over a number of years at ANU, we now have the ability to measure the fluid displacements produced by these instabilities for the first direct comparison with 3D magnetohydrodynamic modelling codes.

Based on ratios of helium atom emissivity fluctuations at different wavelengths, and interpreted using a collisional radiative model being developed at ANU by Dr Sean Ma, we will be able to image the temperature and density fluctuations associated with the modes (Ms Nandika Thapar, MPhil).
The aim of these studies is to validate the predictions of fully 3-D modelling of Alfvén eigenmodes in stellarator magnetic fields. This would be the first such detailed comparison and would help establish confidence in model predictive capabilities ahead of next generation devices such as W7-X.

Figure 10: Left: tomographic reconstruction of the 4/3 Alfvén eigenmode snapshot projections shown above in Figure 8. Given that there is only a single projection, there remains some uncertainty about the fine detail of the mode structure. This will be resolved by making measurements at other viewing angles. Right: direct synchronous imaging of the same mode using the tangential fast camera and a neon gas-puff to locally illuminate the mode in a poloidal cross-section. Though the image remains to be spatially calibrated and corrected for viewing distortions, there is reasonable qualitative agreement between the reconstructions and direct imaging.

International collaborations

Based on new optical technologies and methods developed at ANU, our international collaborations in Europe, the USA and Asia are supported by a large (>$500K) International Science Linkages grant (2008-2010). The following sections summarise aspects of this work completed to date.

Heating neutral beam imaging experiments on the TEXTOR tokamak in Germany (Howard, Diallo, Creese)

These experiments include Motional Stark Effect (MSE) imaging of internal plasma currents and charge exchange recombination spectroscopic (CXRS) imaging of ion temperatures and flows. The work has generated invited talks at the International Workshop on Active Beam Spectroscopy for control of the fusion plasma, Lorentz Center, The Netherlands (2009) and at the 18th International Toki Conference, Toki, Japan (2008).
Passive Doppler tomographic imaging of divertor flows on the DIII-D tokamak in San Diego USA. (Howard, Diallo).

This work has yielded the first 2-D resolved images of ion flows in a tokamak divertor, and was the subject of invited talks at the 18th APS Topical Conference on High Temperature Plasma Diagnostics Wildwood, New Jersey May 2010 and also at the International Conference on Plasma Diagnostics, Pont-à-Mousson, France, April 2010. Some representative results are included below:

Figure 11: False colour raw interferometric projection image for DIII-D discharge # 141170 at time 3860ms into the discharge. The white wire-frame lines superimposed on the fringes show outlines of the divertor floor structure and the inside centre-column of the tokamak.

Figure 12: Reconstructions of the emissivity and parallel flow speed at times (L-R) 500ms, 2000ms and 4000ms during DIII-D discharge #141170. The equilibrium flux surfaces in the divertor are over-plotted for reference. While the observed flow speeds and flow field structure are in broad agreement with modelling expectations, further systematic studies are planned to resolve the reason for some important discrepancies.
Neutral beam imaging on the KSTAR superconducting tokamak in Korea (Howard, Henderson)

We have been allocated three full days of operational time during November 2010 on the superconducting KSTAR tokamak in Korea to install MSE and CXRS imaging systems for measurement of the fundamental plasma parameters: internal current, ion temperature and toroidal flow velocity. In the longer term we aim to develop real-time image processing for active control of the KSTAR device.

It is worth mentioning that our spatial heterodyne imaging systems provide effectively thousands of image pixels at a cost of around $10-$50 per pixel. This compares with standard MSE systems where the cost is three to four orders of magnitude greater. We are presently in the process of negotiating an agreement with the Max Planck Institute for Plasma Physics for the development of an imaging MSE system for either of the ASDEX or MAST tokamaks in Europe.

Figure 13 Photograph of the coherence imaging system installed for CXRS measurement on the TEXTOR tokamak in Germany.
III.2 Plasma Theory and Modelling

The Plasma Theory and Modelling group in PRL focuses on understanding the fundamental properties of plasmas. With a particular focus on magnetically-confined plasma physics, the group has an eclectic range of expertise including modelling and computer simulation of plasma turbulence and equilibria, fluid dynamics, mathematical theory of dynamical systems, plasma diagnostic design and using advanced statistical techniques in analysing experimental data. The group also actively fosters international collaboration in plasma research and is currently engaged in research with scientists in the UK, France, Germany, Korea, Japan, and the United States. Beyond fusion, the Plasma Theory and Modelling group has members whose interests also include the dynamics, modelling and computer simulation associated with weather, fluid flow and space plasma phenomena, to name just a few.

Bayesian inference of equilibrium physics and mode structure

During 2009-2010 our group in collaboration with the Toroidal Plasma Group commenced a Bayesian mode structure identification project using the H-1 Facility. This is a collaborative $395k International Science Linkages project with the Culham Centre for Fusion Energy and IPP Greifswald. The purpose of the project is to use a new probabilistic framework, based on Bayesian principles, to develop inversion tools that aim to (1) distinguish between competing equilibrium theories, which capture different physics, using the MAST spherical tokamak of the UK; and (2) test the predictions of MHD theory, particularly mode structure, using the H-1 Heliac. Dr Greg von Nessi is a new research scientist focusing on Bayesian inference.
The overarching aim of the project is to develop a better understanding of plasma equilibrium and stability en route to burning plasmas. As fusion plasmas increase in auxiliary heating, magnetically confined fusion plasmas have drifted far from the simple picture of static ideal magnetohydrodynamics (MHD), which describes the plasma as a single, stationary, isotropic Maxwellian fluid. A parallel development has been in the diversity, accuracy and resolution of plasma measurement systems (“diagnostics”). Our work takes the recent concept of “data fusion,” in which data from disparate sources are merged, formalises this fusion through "Bayesian Inference,” and provides a framework for comparison with theoretical models without bias from unjustified, hidden assumptions, or overly simplistic models such as static ideal MHD.

The Bayesian approach to inference in fusion plasmas involves the specification of an initial prior probability distribution function (pdf), $P(I)$, which is then updated by taking into account information that the measurements provide through the likelihood pdf $P(D|I)$. The result is the posterior distribution $P(I|D)$ given by Bayes’ formula $P(I|D) = P(D|I)P(I)/P(D)$.

As an illustration, Figure 15 shows poloidal flux surfaces obtained by Bayesian inference techniques on data from pickup coils, flux loops and motional Stark effect measurement from MAST discharge # 24600 at 280 ms. This discharge is a deuterium plasma in a double-null configuration, which was heated with 3 MW of neutral beam heating and a plasma current of 800 kA. The figure shows a contour plot of $(R, Z)$ which is calculated from the maximum of the posterior of the distribution of toroidal current beams. Overlaid on the contours are traces of the poloidal field coil cross sections and conducting surface cross sections for the MAST experiment. One outcome of the Bayesian approach is generation of pdfs of inferred quantities from which the uncertainty can be inferred. For instance, Figure 16 shows the corresponding

![Image](62x421 to 190x652)

Figure 15: Poloidal flux surfaces inferred for MAST #24600 at 280 ms.

![Image](81x195 to 307x360)

Figure 16: Safety factor $q$ profile as a function of normalised poloidal flux for #24600 at 280ms found by sampling the posterior. The right axis shows the correction in $q$ due to the inclusion of poloidal currents.
safety factor or $q$ profile and its uncertainty. This research has created strong international interest, as has related research which quantifies the information content of diagnostics, and hence is useful to remove incongruous diagnostic data.

In April 2010, expert scientist Dr Lynton Appel of the Culham Centre for Fusion Energy visited the ANU to develop a poloidal current model for the Bayesian inference framework, MINERVA.

**3D MHD Physics**

Understanding the physics of fully 3D MHD configurations has been a rich vein of group research, and is an area in which Prof. Dewar has strong international recognition. In partnership with Dr Stuart Hudson of Princeton Plasma Physics Laboratories, we have been building a stepped pressure profile equilibrium code, based on MRXMHD, a relaxed multi-region MHD model developed by Prof. Dewar. The code SPEC, which has largely been written by Dr Hudson, will be the first to compute fully 3D MHD equilibria with islands and chaotic field regions. As an illustration, Figure 17a shows a Poincaré section of field lines in the poloidal plane of an illustrative stellarator computed using SPEC. For comparison, the bean shaped Poincaré section of H-1 is shown in Figure 17b. Magnetic islands are evident in both field configurations. Apart from important applications to field representation in stellarators, the MRXMHD model also has application to tokamaks with field ripple and ergodising field coils needed to quench damaging Edge Localised Modes.

In 2009-2010, ANU work focused on the understanding of stability of the MRXMHD model, development of the underlying algorithm of SPEC, studying the maximum pressure that stepped pressure surfaces can support, and identifying optimal coordinate representations in chaotic magnetic field line regions.

![Figure 17a: Magnetic field Poincaré section of the stepped pressure profile of the new 3D MHD code, SPEC.](image)

![Figure 17b: A Poincare section of H-1 field lines, courtesy S. Kumar and B. Blackwell.](image)
Burning Plasma Physics

Building on two large ARC grants in 2009 (~$0.97M total) in burning plasma physics, the PTM group commenced a collaboration into burning plasma physics with the Culham Centre for Fusion Energy. The project seeks to resolve the effect of energetic fusion particle populations both on equilibrium and force balance.

Burning plasmas such as ITER will be energetically complex nonthermal systems, in which a significant fraction of the stored energy resides in beam heating driven fast ions (~1 MeV) and charged fusion product alphas ($\alpha$s) of reaction (3.5 MeV). As both beam and $\alpha$ particles undergo collisions with the background plasma they slow and can drive electromagnetic modes of the plasma, which, in turn, can eject the same driving particles from confinement. Unchecked, confinement loss of the 3.5MeV fusion products halts the fusion process, and loss rates in excess of a few percent are unacceptably high for future commercial fusion plants, primarily due to associated reactor first-wall damage.

Our project seeks to understand how energetic particles modify the plasma, explain the stability and structure of modes in plasmas with multiple energetic ion populations, and assess the confinement implications for deleterious Alfvénic modes.

In 2009 Dr Hole completed analysis begun by former ANU Honours student, Graham Dennis, and computed the impact of mock neutral beam particles on the plasma configuration through a multiple fluid generalisation of a Rochester University code, FLOW. In 2010 Dr Hole and new research scientist Dr Fitzgerald commenced research examining the effect of anisotropy on the plasma, and are presently examining the rotation profile of high elongation compact torii, for which the effect of flow and anisotropy is expected to be large. Expert scientist Dr Sergei Sharapov of the Culham Centre for Fusion Energy visited the group in July 2010 to commence work with Dr Fitzgerald.

Other international linkages

As part of a well established collaboration with the Culham Centre for Fusion Energy, Dr Hole completed work on wave modulation physics models, exploring the coupling between high frequency MHD and low frequency tearing modes shown in Figure 18. In other work, Dr Hole completed a publication on development of a new high frequency Mirnov coil array for MAST. Elements of the physics design of the array have fed into the design of the new toroidal array for H-1.

Figure 18: Spectrogram of magnetic fluctuation activity in MAST, showing low frequency (~20 kHz and multiples) tearing modes and high frequency (~300 kHz) MHD Alfvénic activity.
III.3 Physics of Fluids Laboratory Research

Physics of Fluids Laboratory (PFL) led by Professor Michael Shats conducts research into fundamental aspects of turbulence and self-organization in fluids and plasmas.

Research facilities of the PFL were initially partly supported by the MNRF. This included turbulence facility. Recently a new Surface Wave Experiment has been set up founded by an ANU Major Equipment Committee grant. Also, a new rotating tank platform has been commissioned in 2009-2010.

Among the research highlights in 2009 were comparative studies of spectrally condensed fluid turbulence and L-H transitions in plasma by M Shats and H Xia. An overview was presented by Prof Shats as invited talk at the 14th International Congress on Plasma Physics (Fukuoka, Japan). The extended version of the review was published in Plasma and Fusion Research. Main results of these studies indicate that the interaction between large-scale coherent structures and turbulence are at the heart of spectral condensation and of the plasma confinement bifurcations during L-H transitions. In many cases turbulence feeds coherent structures. On the other hand, turbulence is affected by coherent shear flows. Such a complex interplay between the two is rather difficult to describe theoretically, but it has been successfully studied in model laboratory experiments.

The role of strong shear flow in plasma is played by zonal flows, turbulence-driven anisotropic structures of the electrostatic potential. These structures were found at the pedestal, a region in plasma characterized by a sharp increase in the density gradient, a universal feature of confinement improvement.

Among other plasma-related highlights of the PFL in 2009 were studies of turbulence-flow interactions in fluid layers (Figure 21). This work has been published in several Physical Review Letters (a physics journal with the highest impact factor) and has been summarized in...
the Physics of Fluids paper. Dr H Xia has been invited to give a talk to overview these studies at the 20th International Toki Conference (Japan 2010).

![Figure 20: Power spectra of the fluctuations in the electrostatic potential measured at the transport barrier in (a) L-mode and (b) H-mode. Zonal flow is represented by the large low-frequency spectral feature at the far left of (b). Its onset in H-mode coincides with the strong turbulence reduction over a broad spectral range.](image)

Figure 21: Visualization of turbulent flow in a thin fluid layer.

Also in 2009 the group has published very important results on the physics of turbulence formation in nonlinear capillary surface waves (Punzmann, Shats, Xia, Phys. Rev. Lett. 2009). The Letter reported the first observation of the modulation instability of capillary waves and the formation of the envelope solitons. These results have later led to the discovery of extreme wave events in capillary waves. This work was funded by an ARC Discovery grant.
III.4 Plasma Configuration Research

Being a flexible heliac, H-1NF is uniquely equipped to study magnetic configurations because of its combination of precisely controllable power supplies, the flexible coil set and the permanently installed wire-tomography mapping system. This precision and flexibility in magnetic configuration make H-1 ideal for magnetic island studies, exploring the range of magnetohydrodynamic (MHD) instabilities appearing in H-1, and mapping out their dispersion relations.

MHD Fluctuations in H-1NF

In H-1 hydrogen/helium plasma at $B_0 \sim 0.5T$, fluctuations in the Alfvén frequency range are observed to dominate the magnetic fluctuation spectrum. In many cases these have been identified as torsional Alfvén eigenmodes by virtue of their phase velocity scaling with plasma density and their resonant dependence on rotational transform. The phenomenon is typical of toroidal confinement devices, and because plasma density tends to scale as the square of the magnetic field, the frequencies are similar across a range of devices, extending even to fusion reactors. The instability is particularly important in fusion reactors, as the correspondence between the fusion alpha particle velocity and the Alfvén velocity provides a channel for significant energy transfer into the instabilities, and back to the alphas, possibly affecting their confinement. As the power into the alpha particles is the main source of energy to sustain the plasma, such instabilities could prevent the achievement of a “burning plasma”.

An example is shown in Figure 23 in which the frequency changes from $\sim 22kHz$ to $\sim 50kHz$ midway into the discharge. This figure illustrates the automated mode identification by a datamining method developed at the Facility. This example uses clustering of von Mises distributions of the phase differences between magnetic probes to automatically classify wave modes.

It can be seen in Figure 23c that when the mode frequency abruptly changes at $t=40ms$, the mode also changes.

![Figure 23: Spectrogram of MHD fluctuations in H-1, showing a) mode transition, b) mode extraction and c) identification.](image-url)
Application of the Datamining Technique to the Large Helical Device in Japan

The datamining techniques have been applied to all of the world’s large stellarators. Initial results from the flagship Japanese stellarator “LHD” are shown in Figure 24, demonstrating that even the very fast-sweeping energetic particle modes can be captured and identified. This is part of a study of the LHD high performance database by a working group under the IEA Implementing Agreement for Cooperation in Development of the Stellarator Concept.

Spontaneous Bifurcations and Generation of Radial Electric Fields in H-1NF

Magnetic islands are studied in H-1NF in argon plasma, at the relatively low temperature of ~10eV, so that Langmuir probes can be used. Such probes provide highly localised measurements of electron temperature and density, and plasma potential. The result in Figure 25 shows the what appears to be the bifurcation of a relatively smoothly varying plasma profile (red curves) into a double peaked structure in electron density. The effect is particularly noticeable in the electric field, and is suggestive of a phenomenon observed in some other stellarators – an improvement in confinement due to a switch in equilibrium to the electron root of the radial transport equation.

Figure 25: Radial profiles of plasma parameters at ~10 ms (red+) and ~30 ms (green⋄) into the discharge. The twin island bifurcated equilibrium is indicative – the magnetic configuration is not bifurcated in the absence of current, so a plasma current of ~10-20 amps must be present for this degree of bifurcation.
IV  FACILITY PROMOTION

In 2009, the main outreach was jointly with the Australian ITER Forum, in addition to promotional and awareness activities undertaken by staff to promote the Facility. These include the publishing of recent research results in a number of refereed journals (see Section IV.1) and presentations by researchers at several national and international conferences (Section IV.2). A number of collaborative ventures with national and international partners, government and private industry were also undertaken (see Section VI). Visits to the Facility by national and international researchers and by prospective science students were organised, and service was provided by staff to a number of outside organizations.

H-1 Facility, JET on Catalyst segment on Fusion 18th Feb 2010

The ABC popular science program “Catalyst” featured fusion energy research in February, and visited the Facility. The program, filmed in Canberra and in Oxford, UK, explained the basic principles, and provided a glimpse of current research and anticipated progress. After quickly mastering the difference between stellarators (H-1) and tokamaks (JET, UK), presenter Graham Philips just as quickly decided that if it couldn’t be explained well in one sentence, it shouldn’t be on TV, and chose to demonstrate basic magnetic confinement instead (Figure 26).

Figure 26: Clockwise from top left - Graham Philips is shown the H-1 magnetic field coils by Dr Blackwell; Prof. Howard and Dr. Barry Green explain fusion energy; Graham Philips demonstrates principle of magnetic confinement on a low temperature demonstration plasma.

Minister for Science and Innovation Operates H-1

The Minister for Innovation, Industry, Science and Research, Senator Kim Carr visited ANU in October 2009 to witness a Memorandum of Understanding between The Australian National University and the Australian Nuclear Science and Technology Organisation, and to
visit the laboratories involved. The memorandum formally enables the two institutions to collaborate across research fields which underpin Australia’s capacity for international engagement in nuclear science and technology including key accelerator facilities, future energy sources and nuclear non-proliferation. ANSTO Chief Executive, Dr Adi Paterson, said the MOU represented a renewal of nuclear research and collaboration in Australia. “It is important that we engage the next generation in research leadership and innovation. To develop the kinds of skills we need to bring the full benefit of nuclear technology in Australia will need commitment, vision and sustained investment. Foundational research and enhanced innovation into areas such as nuclear fusion and environmental challenges using nuclear techniques will underpin our collaboration and its impact”.

After signing the agreement, the parties visited the Australian Plasma Fusion Facility control room, where Senator Carr fired a plasma pulse in the H-1 Heliac (Figure 27).

Figure 27: left: Senator Carr at the H-1 control desk; right: Dr Adi Paterson, Vice Chancellor Prof. Ian Chubb and Senator Carr inspecting the Facility.

Australian ITER Forum Workshop 2009
Two sessions of the Japan-Australia Diagnostics workshop were devoted to a workshop on scoping possible remote diagnostic systems for and Australian in-kind contribution to the ITER international fusion experiment. The head of ITER diagnostics, Dr. Alan Costley, accompanied by Dr. H. Matsumoto discussed several options with the Australian plasma diagnostic community, including divertor imaging and dust and erosion monitors.

The 2010 Joint Gaseous Electronics Conference and AINSE Plasma Conference
GEM XVI was held jointly with the AINSE plasma physics conference from January 31st to February 3rd 2010, at the Murramarang Conference Centre, near Batemans Bay. The conference covered all aspects of gaseous electronics and related multidisciplinary topics and applications, including basic studies and diagnostics of low-temperature plasmas, physics of laboratory and space plasmas.
Winter School on Industrial and Fusion Plasmas, July 7-9 2010

The school convened by Dr M Hole, attracted 35 students, drawn from the ANU, the Univ. of Western Australia, Univ. of Sydney, Queensland Univ. of Technology, Univ. of South Australia, Curtin University, and Murdoch University.

The lecture series on "Fundamental plasma processes in low temperature plasmas", "Electrodynamics for plasma Physics", and "Toroidal Magnetic Confinement" were well received by students. Many students identified the laboratory tours of ANU plasma physics facilities, including the H-1 National Facility and SP3 laboratories as a highlight, as well as the opportunity to talk with scientists about plasma research at the ANU. The overwhelming feedback was that the students found the School very useful to their research, and a great opportunity to learn more about plasma physics - from basics through to cutting edge research, as well as meet others with similar interests. On the basis of strong support we are now considering future schools.

KSTAR Research Collaboration Delegation

In 2010 Prof Dewar organised and led an expedition of seven Australian scientists to KSTAR to conduct a Department of Foreign Affairs and Trade supported a feasibility study of Australia-Korean research in fusion science centred on the KSTAR superconducting tokamak. The two day workshop discussed the research strengths of scientists from the ANU, Sydney, the Korean National Fusion Research Institute, and POSTECH University, Korea. Bi-lateral collaboration possibilities and access arrangements for KSTAR were discussed.

In the initial competitive time allocation, Prof Howard and Dr Hole, were awarded a total of 3 days run time on KSTAR.

Prof Chang Mo Ryu and Mr Minhao Yu of POSTECH University, Korea, visited the ANU in February, to collaborate with Dr Hole on the energetic particle driven internal “sawteeth” modes observed in KSTAR.
Outreach activities are listed in summary below:

IV.1 Publications

Books Edited
Dewar R, Detering F
*Complex Physical Biophysical and Econophysical Systems*

Book Chapter
Dewar R
*The Screened Field of a Test Particle**

Refereed Journal Articles


Collis SM, Dall RG, Howard J, Andruczyk D, James B
*Validation of collisional radiative modelling of emission line ratios for helium beam plasma diagnostic*

Dewar R, Mills R, Hole M
*MHD Memes*

Dewar R, Yap J (Chun-Chiat)
*Adiabatic Wave-Particle Interaction Revisited*
Plasma and Fusion Research 4 (2009) 001

Fhager A, Padhi S, Howard J
*3D Image Reconstruction in Microwave Tomography Using an Efficient FDTD Model*
IEEE Antennas and Wireless Propagation Letters, 8 (2009)

Hatae T, Howard J, Ebizuka N, Hirano Y, Koguchi H, Kiatmura A, Sakuma T, Hamano T


Hole M, Appel LC, Martin R
*A high resolution Mirnov array for the Mega Ampere Spherical Tokamak*
Review of Scientific Instruments 80 (2009) 123507
Hole M, Appel LC
A Modulation Model for Mode Splitting of Magnetic Perturbations in the Mega Ampere Spherical Tokamak

Hole M, Dennis GR
EnergeticallyResolved Multiple-Fluid Equilibria of Tokamak Plasmas

Model Data Fusion: developing Bayesian inversion to constrain equilibrium and mode structure,

Hole M, Mills R, Hudson SR, Dewar R
Relaxed MHD states of a multiple region plasma
Nuclear Fusion 49, 7 pages (2009) 065019

Howard J
Coherence imaging spectro-polarimetry for magnetic fusion diagnostics,

Howard J, Diallo A, Jaspers R, Chung J
Spatial heterodyne spectro-polarimetry systems for imaging key plasma parameters in fusion devices,

Hudson SR, Dewar R
Are ghost surfaces quadratic-flux-minimizing?

Kumar S, Blackwell BD, Harris, J
Determination of error field sources by accurate mapping of the magnetic geometry of the H-I heliac,
Nuclear Fusion, 49 (2009), 035001

Kumar S, Blackwell B, Howard J and Harris J
Core magnetic islands and plasma confinement in the H-INF heliac

Meyer H, Akers RJ, Alladio F, Appel LC, Axon KB, Ben AN, Boerner P, Buttery RJ, Carolan PG, Ciric D, Hole M
Overview of physics results from MAST
Nuclear Fusion 49 (2009) 104017

Mills R, Hole M, Dewar R
Magnetohydrodynamic stability of plasmas with ideal and relaxed regions

Blackwell B and Sano F
ECCD Experiments Using the Upgraded Launching System in Heliotron J

Pretty DG, Blackwell BD
A data mining algorithm for automated characterisation of fluctuations in multichannel timeseries
Computer Physics Communications, 180(10) (2009)
Pretty D, Vega J, Ochando MA, Tabares FL
Empirically derived basis functions for unsupervised classification of radial profile data
Fusion Engineering and Design, 5072 (2 pages) (2010)

Punzmann HH, Shats M, Xia H
Phase Randomization of Three-Wave Interactions in Capillary Waves

Confinement transitions in TJ-II under Li-coated wall conditions
Nuclear Fusion, 49 (2009), 104018

Shats M, Punzmann H, Xia H
Capillary Rogue Waves

Shats M, Xia H
Spectrally Condensed Fluid Turbulence and L-H Transitions in Plasma
Plasma and Fusion Research, 4 (2009)

Xia H, Shats M, Punzmann HH, Falkovich G
Comment on "Melting Line of Hydrogen at High Pressures*,

Xia H, Shats M, Punzmann H
Modulation instability and capillary wave turbulence
Europhysics Letters 91, 14002 (2010)

Xia H, Shats M, Falkovich G
Spectrally condensed turbulence in thin layers
Physics of Fluids, 21(12) (2009)

IV.2 Invited Talks
Blackwell, BD et al. Configurational Effects on Stability and Confinement in the H-1NF Heliac,
Third International Meeting on Frontiers of Physics, Kuala Lumpur January, 2009


Blackwell, BD et al. Initial Results from an International MHD Data Mining Collaboration, 15th International Congress on Plasma Physics, Santiago, Chile, August 2010

Hole M - Recipient’s address - IUPAP C.16 2010 Young Scientist Prize, 15th International Congress on Plasma Physics, Santiago, Chile, August 2010


Howard J et al. Doppler coherence imaging and tomography of flows in tokamak plasmas, 18th APS Topical Conference on High Temperature Plasma Diagnostics Wildwood, New Jersey May 2010


**IV.3 Published Conference Presentations**

**Dewar R, Mills R, Hole M**  
*MHD memes*  

**Padhi S, Fhager A, Howard J, Persson M**  
*Experimental performances of Antennas for a proposed Microwave Tomography System using the time-domain approach*  
Antennas and Propagation Society International Symposium *(APSURSI 2009)*, IEEE Inc, Charleston, USA

**Newspaper / Magazine Article**

**Green B, Hole M, Blackwell B, Howard J**  

**IV.4 Service to Outside Organisations**

**B Blackwell**  
Member, IUPAP Commission on Plasma Physics (C16)

Member, Executive Committee, IEA Implementing Agreement for Cooperation in Development of the Stellarator Concept

**J Howard**  
Chair, ACT Branch of the Australian Institute of Physics.  
Member, Editorial Board, Plasma Physics and Controlled Fusion

**M Hole**  
Member, Editorial Board, Plasma Physics and Controlled Fusion  
Member, International Fusion Research Council, IAEA  
Chair Australian ITER Forum

**IV.5 Outreach Activities**

Some of these are covered in more detail in the preceding paragraphs.

Catalyst: H-1 Facility, JET on Catalyst segment on Fusion 18th February 2010

Visit by Minister for Science and Innovation to H-1 after witnessing ANU/ANSTO Memorandum of Understanding 29th October 2009

Australian ITER forum workshop on scoping and ITER diagnostic scope, February 2009

The Joint Gaseous Electronics Conference and AINSE Plasma Conference, February 2010

Winter School on Industrial and Fusion Plasmas, July 7-9 2010
Members contributed to various submissions:
Submission to policy paper: "A process to identify and prioritise Australia's Landmark Research Infrastructure needs" July 16, 2010
Comment on the recommendation on the Henry Tax review and the government's response on fuel and energy security May 31, 2010
Submission to the Inquiry into Australia's International Research Collaboration January 29, 2010
Submission to Fuel and Energy, July 21, 2009
Submission on Clean Energy Program Guidelines 9 April 2009
Submission to Energy White Paper Consultation Process 29 May 2009

Teaching
B. Blackwell: taught Power Electronics ENGN4625/6625, ANU, 2010
M. Hole: taught Advanced Electrodynamics, Phys 4003F, 2009/2010
M. Shats: taught Physics of plasma and turbulence, Phys 3041/42 ANU, 2009

IV.6 Visitors
Professor Elena Kartashova, Johannes Kepler University, Austria
Professor Mikael Persson, Chalmers University of Technology, Sweden
Professor Chang Mo Ryu, Pohang University, Korea
Dr Kanti Aggarwal, Queens University, Northern Ireland
Dr Lynton Appel, Culham Centre for Fusion Energy, United Kingdom
Dr Andrea Fhager, Chalmers University of Technology, Sweden
Dr Li Haibin, Shenyang Aeroengine Research Institute, China
Dr Leon Kamp, Eindhoven University of Technology, the Netherlands
Dr Jay Larson, Argonne National Laboratory, USA
Dr Raffi Nazikian, Princeton Plasma Physics Laboratory, USA
Dr Sergei Sharapov, Culham Centre for Fusion Energy, United Kingdom
Dr Satoshi Yamamoto, Institute of Advanced Energy, Japan
Dr Andrey Yaroshchuk, Polytechnic University of Catalonia, Spain

Off-site presentations were made by staff and ITER Forum members to:
B Blackwell, University of Sydney Colloquium, November 2009
M Hole, Presentations and Lectures at UWA and Curtin Univ. Tech, June 2009/10
V COLLABORATION, EDUCATION AND TRAINING

V.1 Collaborative Ventures

B Blackwell

Project: Data mining and Analysis of MHD fluctuations in Heliotron-J
Partners: Dr K Nagasaki, Dr S Yamamoto - Kyoto University

Project: An International MHD Data mining project
Partners: Dr D Pretty - ANU, Dr S Yamamoto, Dr K Nagasaki - Kyoto University,
Dr E Ascasibar - CIEMAT, Madrid, Dr A Werner – IPP, Greifswald,
Dr S Sakakibara - National Institute of Fusion Science, Japan.

Project: Observations of plasma effects in detonations
Partners: Dr J Waschl - DSTO

B Blackwell, J Howard

Project: MHD Instabilities in toroidal devices
Partners: Dr R Nazikian - Princeton University, Dr J Harris - Oak Ridge National
Laboratory

G Borg

Project: Collaboration with Standard communications on ARC grant and application
for Scientific License for Radio Emission
Partners: Mr Z Zhao, Mr D Dries, Mr G Long, Mr J Leong

J Howard

Project: Installation of Coherence imaging system
Partners: University of Sydney

Project: Microwave tomography of human tissue
Partner: Prof Persson - Chalmers University, Sweden

Project: Optical coherence imaging for Thomson scattering
Partner: Dr T Hatae - Japan Atomic Energy Agency

Project: Optical imaging systems for thermography and slag/iron discrimination at a
molten iron furnace
Partner: Mr B Scott, Dr R Nightingale - BlueScope Steel Limited, Port Kembla

Project: Coherence imaging studies of the Hanbit Mirror and KSTAR tokamak
Partner: Dr J Chung - Korean National Fusion Research Center

J Howard, M Shats, B Blackwell

Project: Development of Diagnostic Imaging Systems for the Sydney University High
Current Pulsed Arc
Partners: Prof M Bilek, Dr R Tarrant and Prof D Mackenzie - University of Sydney

M Shats

Project: Confinement Studies in Stellarators
V.2 Higher Degree Research Completions

D Pretty
*A Study of MHD Activity in the H-I Heliac Using Data Mining Techniques.*
*Awarded March 2009*

Pending

B Heslop
*Entrepreneurial Knowledge Transfer* – Under revision

VI CONTRIBUTION TO AUSTRALIAN INDUSTRY

The Heliac program at the ANU has produced several technological spin-offs that are now attracting support independent of the fusion program. These include technology for long distance, non-line-of-sight VHF digital wireless communications in rural Australia (the BushLAN project), and optical coherence imaging (CI) spectroscopy systems for use in process control in steel production. A variant of the 4-quadrant solid-state CI system promises to be able to provide accurate surface-temperature estimates without the need for emissivity corrections.

The AIIM group has also developed imaging techniques in the microwave range of frequencies which have potential for relatively non-invasive detection of breast cancer, taking advantage of differences in refractive index and attenuation as described below.

New research areas and opportunities for collaboration will be opened up by the Material Diagnostics Facility. One new collaboration with DSTO has already begun with Dr. John Waschl. A student recently enrolled in an M. Phil degree on the Material Diagnostics Facility is using the probe technology being developed for that facility to measure plasma parameters in detonations for investigation of MHD phenomena. That environment has a similar high plasma density to that of the Materials Diagnostic Test Facility and a very peak high heat flux.

**Microwave imaging for human breast cancer detection**

Supported by an Australian Research Council (ARC) Discovery Grant (2006-2009) and in collaboration with researchers at Chalmers University in Sweden, the group conducted research into suitable inverse techniques for microwave imaging of human tissue. Within the ANU-Chalmers collaboration we:

- Extended the finite-difference-time-domain (FDTD) inverse algorithms from 2d to 3d, with clear improvement in reconstruction fidelity (Fhager et al. 2009).
• Successfully implemented, realistic antenna models in the numerical FDTD model of the microwave scanner (Padhi et al. 2008).

• Combined 3D reconstruction techniques and realistic antenna modelling in a third paper on "Reconstruction Quality and Antenna Modeling Accuracy in an Electromagnetic Time-Domain Inversion Algorithm" (submitted to IEEE Transactions on Antennas & Propagation (2010).

• Constructed a fully functioning, dual-polarization wideband microwave scanner. A paper that describes the system entitled "Design and implementation of a PC based Labview controller for microwave tomography scanning system for breast imaging", Padhi et al. is in preparation.

• Obtained co- and cross-polar scattering data on various test objects. The analysis of these results will be the subject of a future paper.

While the ANU program is now no longer funded, the project has seen numerous personnel exchanges: Padhi to Sweden for 6 months, Fhager to Australia (3 months), Bengsston (MSc, 6 months training in Australia), and a 1 month short visit by Prof Persson to Australia. These exchanges stimulated new ideas and methods, including the development of a full vector field (co- and cross polar) imaging capability and the implementation of novel heuristic reconstruction methods. These activities will now continue at Chalmers University but without formal collaboration with ANU.

![Image: The microwave scanner with index matching water inside the container and antennas mounted, ready for radiation pattern measurements (From thesis by S. Bengsston).]
VII STAFFING AND ADMINISTRATION

VII.1 Management Structure of the H-1 National Facility

The management structure involves four major organisations:

- The Department of Innovation, Industry, Science and Research (DIISR)
- The Australian Nuclear Science and Technology Organisation (ANSTO)
- The Australian Institute of Nuclear Science and Engineering (AINSE)
- The Australian National University (ANU)

all of which have input into the decisions made by the H-1NF Board.

At annual meetings, scientific and technical operational plans and associated budgets are developed, including Facility upgrades, collaborations, and research training plans.

At weekly meetings, the reduced Management Committee executes the operational plan and schedules experiments.

The role of AINSE lies mainly in the facilitation and coordination of Australian collaborations and the allocation of travel funds in support of this.

The Director oversees the implementation of the operation plan in accordance with the contract, including reporting to the Board.

The Board, and the Management Committee, provides strategic and technical guidance to the Facility.

Figure 30: H-1NF Management Structure

Figure 31: Board members and attendees at the AGM held on 19 May 2009. BACK ROW: J Howard, B Blackwell, M Hole, J Söderbaum, H Punzmann, J Soria, M Shats, D Mather, R Dewar, R Storer. FRONT ROW: M Hewitt, H Rubinsztein-Dunlop, J O’Connor (Chair), J Baker, M Bilek. MISSING: G Collins, J Williams, A Paterson
Committees, have a direct impact on Facility policies.

The higher level role of the Australian Fusion Research Group has been subsumed by the larger entity presently known as the Australian ITER Forum, and at the lower levels, by incorporating active external researchers in the management committee.

The Management Committee consists of the Facility Director and Manager, leaders of Facility research pursuits, and representatives or nominees of users’ organisations and proponent organisations, one per organisation. The structure provides a clear mechanism for proponent organisations and users to have effective input to Facility operations planning, and equitably allows for the Director to also be a Facility user. This Committee meets annually, in conjunction with a conference or workshop if convenient, with (as close as possible) full membership, and weekly, in a reduced form with the members that are on site or wish to join via teleconference.

As part of the upgrade process, a Annual Business Plan is developed. Scientific and technical operational plans and associated budgets are developed, including Facility upgrades, collaborations, and research training plans, consistent with the Facility Business Plan and this Project Plan. If a vote is required, sufficient members will abstain from voting so that an equal number of ANU and non-ANU representatives cast votes. At weekly meetings, the reduced Management Committee executes the operational plan and schedules experiments.

VII.2 Board Membership

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professor John O’Connor (Chair)</td>
<td>University of Newcastle</td>
</tr>
<tr>
<td>Dr Boyd Blackwell</td>
<td>Director, APFRF</td>
</tr>
<tr>
<td>Dr Horst Punzmann</td>
<td>Facility Manager, APFRF</td>
</tr>
<tr>
<td>Professor Michael Shats</td>
<td>ANU</td>
</tr>
<tr>
<td>Professor Richard Banati</td>
<td>ANSTO</td>
</tr>
<tr>
<td>Dr Dennis Mather</td>
<td>AINSE</td>
</tr>
<tr>
<td>Emeritus Professor Robin Storer</td>
<td>Flinders University</td>
</tr>
<tr>
<td>Professor Joe Baker</td>
<td>Visiting Science Fellow, Agri-Science, Queensland</td>
</tr>
<tr>
<td>Professor Robert Dewar</td>
<td>ANU</td>
</tr>
<tr>
<td>Dr John Söderbaum</td>
<td>ACIL Tasman Pty Ltd</td>
</tr>
<tr>
<td>Professor Julio Soria</td>
<td>Monash University</td>
</tr>
<tr>
<td>Professor Jim Williams</td>
<td>ANU</td>
</tr>
<tr>
<td>Professor John Howard</td>
<td>ANU</td>
</tr>
<tr>
<td>Professor Halina Rubenstein-Dunlop</td>
<td>University of QLD</td>
</tr>
<tr>
<td>Professor Marcela Bilek</td>
<td>University of Sydney</td>
</tr>
<tr>
<td>Dr George Collins</td>
<td>CAST CRC</td>
</tr>
<tr>
<td>Dr Brian James</td>
<td>Chair, Technical Reference Group</td>
</tr>
<tr>
<td>Mrs Maxine Hewitt (Board Secretary)</td>
<td>ANU</td>
</tr>
</tbody>
</table>
VII.3 ANU Facility Staff

**Academic Staff**
- Dr Boyd Blackwell BSc PhD Sydney
- Dr Gerard Borg BSc PhD Sydney
- Dr Ahmed Diallo (left 7 September 2009)
- Professor Robert Dewar BSc Melb, MSc Melb, PhD Princeton, FAA
- Dr Matthew Hole
- Professor John Howard BSc PhD Sydney, FInstP
- Dr Shuiliang Ma (arrived 17 February 2010)
- Dr Shantanu Pahdi (left 4 April 2010)
- Dr Michael Shats MSc KPI, PhD GPI Moscow
- Dr Greg von Nessi
- Dr Michael Fitzgerald (arrived 28 June 2010)

**General Staff**
- Mr Rais Ahmed
- Mr Dhammika Amarasinghe
- Mr Michael Blacksell
- Mr Mark Gwynneth
- Mrs Maxine Hewitt BA CCAE (Departmental Administrator)
- Dr David Pretty BSc Melb PhD
- Dr Horst Punzmann BSc Regensburg, PhD (Research Engineer)
- Mr John Wach BAppSci CAE Ball, GradDipEl CCAE

**Visiting Fellows**
- Dr Jay Larson
- Dr Li Haibin

**Postgraduate Students**
- Mr Farzand Abdullatif
- Mr Jason Bertram
- Mr David Byrne, BSc ANU
- Mr Juan Caneses
- Mr Ashley Gibson
- Mr Shaun Haskey
- Mr Lei Chang
- Mr Mathew McGann
- Mr Jesse Read BSc RMIT
- Dr Indrajit Ghosh Roy
- Ms Nandika Thapar

**Honours Students**
- Mr Tam Chung FEIT Gerard Borg
- Mr Michael Gill FEIT Gerard Borg
- Mr Andrew Kerrigan FEIT Gerard Borg
- Mr Yinzhu Quan FEIT Gerard Bog
- Ms Lucinda Teague FEIT Gerard Borg
- Mr Da Wang FEIT Boyd Blackwell
Summer Scholars
Mr Daniel Leykam
Mr Rufus Boyack
Mr Romesh Abeysuriya

PhB/Advanced Studies
Mr Gabriel Collin
Mr David Johnson

Visiting Overseas Students
Mr Sebastin Bengtsson, Chalmers University of Technology, Sweden
Mr Martin Olesen, BSc, Technical University of Denmark
Mr Stuart Henderson, MSc, University of Strathclyde, Scotland
VIII GRANTS AWARDED

2009-2010 Awards

Department of Innovation, Industry, Science and Research

B Blackwell, RL Dewar, M Hole, J Howard, H Punzmann
Plasma Fusion Education Investment Fund Project
2010-2012 $7,000,000

Australian Research Council

M Hole, R Dewar, K McClements, SD Pinches, S Sharapov
2010 Discovery Project Grant
Burning Plasmas: resolving energetic particle physics for ITER
2010-2012 $285,000

Continuing grants

Prof J Harris et al.
National Plasma Fusion Research Facility
April 1997 – May 2005
June 2005 – June 2010 $8,700,000

M Hole, Appel, Blackwell, De Bock, Dewar, Howard, Martin, Michael, Nuehrenberg, Scannell, Svensson, Wisse
International Science Linkages Competitive Grant
Model/data fusion: using Bayesian inversion to constrain equilibrium and stability theory of advanced magnetic confinement experiments ahead of the International Thermonuclear Experimental Reactor
2008-2012 $395,051

M Shats

Australian Research Council
2008 Discovery Project Grant
Structural transitions in turbulent fluids and plasma through self-organization
2008-2010 $360,000

M Shats

Australian Research Council
2008 Discovery Project Grant
New method of remote characterization of hydrocarbon films on the ocean surface through studies of wave turbulence
2008-2010 $246,000
Department of Education, Science and Training

J Howard, R Boivin, J Chung, R Jaspers
International Science Linkages
Using advanced optical technologies to help control and optimize performance of fusion reactors
2007-2011 $505,279

Australian Research Council

J Howard, M Persson
2006 Discovery: Project Grant
Development of Microwave Tomography Techniques and Inverse Methods for Biomedical Imaging Applications
2006-2009 $370,000

Australian Institute of Nuclear Science and Engineering (AINSE)

M Hole
From Stellarators to Tokamaks: The Effects of 3D Structure on Alfven Eigenmodes
2009 $4,920
IX  PROJECT PROGRESS VERSUS MILESTONES

Milestones up until 30th September 2011 are shown. All milestones to date have been completed on time. Milestone numbers refer to the original agreement. In Annual business plan 1, it was proposed (with the agreement of the Department) that deadlines for Milestones 22 and 16 be exchanged for more efficient integration with the RF upgrade.

Project Milestones

<table>
<thead>
<tr>
<th>Milestone Number</th>
<th>Milestone Description</th>
<th>Deadline</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sign Agreement</td>
<td>22 December 2009</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>Finalise Detailed Facility Infrastructure Upgrade Schedule</td>
<td>6 January 2010</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>Put new Radio Frequency system out to tender</td>
<td>31 March 2010</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>Define scope of Fire Protection upgrade in Plant and Machine Area</td>
<td>31 March 2010</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Submit Annual Business Plan 1</td>
<td>31 March 2010</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Submit Milestone Report 1</td>
<td>31 March 2010</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>Select Radio Frequency System Supplier</td>
<td>30 June 2010</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td>Define Data Access and Metadata Format</td>
<td>30 June 2010</td>
<td>✓</td>
</tr>
<tr>
<td>7</td>
<td>Launch new Website</td>
<td>30 June 2010</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Submit Milestone Report 2</td>
<td>30 June 2010</td>
<td>✓</td>
</tr>
<tr>
<td>8</td>
<td>Commission new server for H-1NF Data storage</td>
<td>30 September 2010</td>
<td>✓</td>
</tr>
<tr>
<td>9</td>
<td>Finalise performance indicators</td>
<td>30 September 2010</td>
<td>✓</td>
</tr>
<tr>
<td>10</td>
<td>Create database for Summary Data in a more generally accessible form (Metadata)</td>
<td>30 September 2010</td>
<td>✓</td>
</tr>
<tr>
<td>11</td>
<td>Commission high speed camera (imaging system) for investigating short time scale phenomena</td>
<td>30 September 2010</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Submit Annual Report 1 (including Milestone Report 3)</td>
<td>30 September 2010</td>
<td>✓</td>
</tr>
<tr>
<td>12</td>
<td>Commission new fast timer and trigger system</td>
<td>31 December 2010</td>
<td>✓</td>
</tr>
<tr>
<td>13</td>
<td>Web data access to &quot;raw data&quot; via metadata server</td>
<td>31 December 2010</td>
<td>✓</td>
</tr>
<tr>
<td>14</td>
<td>Complete Data System Interface for the Coherence Imaging Camera</td>
<td>31 December 2010</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Submit Milestone Report 4</td>
<td>31 December 2010</td>
<td>✓</td>
</tr>
<tr>
<td>15</td>
<td>Create a database of Magnetic Configurations (magnetic coordinate transformation)</td>
<td>31 March 2011</td>
<td>✓</td>
</tr>
<tr>
<td>22</td>
<td>Specify Components required for the Vacuum System Upgrade</td>
<td>31 March 2011</td>
<td>✓</td>
</tr>
<tr>
<td>17</td>
<td>Commission Current Controller to provide more flexible access to various plasma configurations.</td>
<td>31 March 2011</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Submit Annual Business Plan 2</td>
<td>31 March 2011</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Submit Milestone Report 5</td>
<td>31 March 2011</td>
<td>✓</td>
</tr>
<tr>
<td>18</td>
<td>Decommission radio frequency source and begin installation of the upgraded sources</td>
<td>30 June 2011</td>
<td>✓</td>
</tr>
<tr>
<td>19</td>
<td>Commission Spectral Line Monitors dedicated to monitoring specific impurities (e.g. C, O)</td>
<td>30 June 2011</td>
<td>✓</td>
</tr>
<tr>
<td>20</td>
<td>First plasma produced in satellite prototype</td>
<td>30 June 2011</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Submit Milestone Report 6</td>
<td>30 June 2011</td>
<td>✓</td>
</tr>
<tr>
<td>21</td>
<td>Commission new Radio Frequency Heating Antenna</td>
<td>30 September 2011</td>
<td>✓</td>
</tr>
<tr>
<td>16</td>
<td>Upgrade multi-channel interferometer - Phase I complete</td>
<td>30 September 2011</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Submit Annual Report 2 (including Milestone Report 7)</td>
<td>30 September 2011</td>
<td>✓</td>
</tr>
</tbody>
</table>
X    FINANCIAL STATEMENTS

This transition year requires two sets of statements, audited copies to be supplied separately, from Jan 2009 - June 2010

Income and Expenditure Statement 2009/2010
Plasma Fusion Education Investment Fund Project

<table>
<thead>
<tr>
<th>Income</th>
<th>Funds Allocated</th>
<th>2009-2010 Actual</th>
<th>Total Expenditure</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIF Cash Contribution</td>
<td>7,000,000</td>
<td>1,000,000.00</td>
<td>1,000,000.00</td>
</tr>
<tr>
<td>EIF Cash Contribution Interest</td>
<td></td>
<td>8,824.98</td>
<td>8,824.98</td>
</tr>
<tr>
<td><strong>Total Income</strong></td>
<td>7,000,000</td>
<td>1,008,824.98</td>
<td>1,008,824.98</td>
</tr>
</tbody>
</table>

**Expenditure**

<table>
<thead>
<tr>
<th>Facility Infrastructure and Upgrade</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Management</td>
<td>332,000</td>
<td>71,161.00</td>
<td>71,161.00</td>
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<tr>
<td>Plasma Heating</td>
<td>3,007,000</td>
<td>27,595.73</td>
<td>27,595.73</td>
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<tr>
<td>Data Access</td>
<td>598,000</td>
<td>26,228.45</td>
<td>26,228.45</td>
</tr>
<tr>
<td>Plasma Diagnostics</td>
<td>1,325,000</td>
<td>140,936.64</td>
<td>140,936.64</td>
</tr>
<tr>
<td>Advanced Operation</td>
<td>887,000</td>
<td>46,824.64</td>
<td>46,824.64</td>
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<tr>
<td>Infrastructure Replacement</td>
<td>851,000</td>
<td>4,754.60</td>
<td>4,754.60</td>
</tr>
<tr>
<td><strong>Total Expenditure</strong></td>
<td>7,000,000</td>
<td>317,501.06</td>
<td>317,501.06</td>
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<tr>
<td><strong>Unspent Cash Balance</strong></td>
<td></td>
<td>691,323.92</td>
<td>691,323.92</td>
</tr>
<tr>
<td></td>
<td>This Period</td>
<td>Next Quarter</td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td><strong>Cash Carried over from previous quarter</strong></td>
<td>A1: 466,700.19</td>
<td>A2: 293,093.22</td>
<td></td>
</tr>
<tr>
<td><strong>RECEIPTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MNRF Program Funds</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Non-MNRF Program Funds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partner Contributions</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Sources</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interest</td>
<td>0.375.09</td>
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<tr>
<td><strong>TOTAL RECEIPTS</strong></td>
<td>B1: 6,375.09</td>
<td>B2: 0.00</td>
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<tr>
<td><strong>EXPENDITURE</strong></td>
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</tr>
<tr>
<td>Power Supply</td>
<td>5,022.55</td>
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<tr>
<td>Heating Systems</td>
<td>11.97</td>
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<tr>
<td>Plasma Diagnostics</td>
<td>78,303.75</td>
<td>0.00</td>
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<tr>
<td>Heltec Infrastructure</td>
<td>6,875.04</td>
<td>0.00</td>
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<tr>
<td>Other Support Costs</td>
<td>90,159.75</td>
<td>0.00</td>
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</tr>
<tr>
<td><strong>TOTAL EXPENDITURE</strong></td>
<td>C1: 152,012.08</td>
<td>C2: 0.00</td>
<td></td>
</tr>
<tr>
<td><strong>CASH BALANCE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CASH BALANCE OF ACCOUNT</td>
<td>D1: 266,093.22</td>
<td>D2: 293,093.22</td>
<td></td>
</tr>
</tbody>
</table>
ACRONYMS

ABC    Australian Broadcasting Commission
AFRG   Australian Fusion Research Group
ANU    Australian National University
AINSE  Australian Institute of Nuclear Science and Engineering
ANSTO  Australian Nuclear Science & Technology Organisation
CDX-U  Current Drive Experiment-Upgrade
COSNet Complex Open Systems Research Network
CQU    Central Queensland University
DC     Direct Current
DISR   Department of Industry, Science and Resources
DRM    Digital Radio Mondial
DSTO   Defence Science and Technology Organisation
DT     Deuterium-Tritium
ECH    Electron Cyclotron Heating
ECRH   Electron Cyclotron Resonance Heating
ELSI   Electronically Swept Interferometer
FEIT   Faculty of Engineering and Information Technology
GAE    Global Alfvén eigenmode
GAM    Geodesic Acoustic Mode
H-1NF  H-1 (Heliac) National Facility
IAS    Institute of Advanced Science
ITER   International Fusion Experiment
JET    Joint European Torus
LCD    Liquid Crystal Display
LHD    Large Helical Device
MAST   Mega-Ampere Spherical Tokamak
MEMS   Micro-Electronic Mechanical Switch
MDS    Model Data System
MHD    Magneto-hydrodynamic
MOSS   Modulated Optical Solid State
NIFS   National Institute for Fusion Science
OVMS   Open Virtual Machine Operating System
ORION  Oak Ridge Ion
PIN    P-type (intrinsic layer) n-type diode
RF     Radio-frequency
RIEFP  Research Infrastructure Equipment and Facilities Scheme
SOFT   Spread-Spectrum Optical Fourier Transform
SPIRT  Strategic Partnerships with Industry - Research and Training Scheme
SP3    Space Plasma and Plasma Processing
TFTR   Tokamak Fusion Test Reactor
TJ-II   Torus de la Junta de l’Energia Nuclear, the second device (a Heliac)
UKAEA  United Kingdom Atomic Energy Authority
UC     University of Canberra
VNC    Virtual Network Computer
WiMAX  Worldwide Interoperability for Microwave Access
WKB    Wentzel-Kramers-Brillouin