THE POTENTIAL FOR AUSTRALIAN INVOLVEMENT IN ITER

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1. Introduction

Fusion, the process that powers the sun and stars, offers a solution to the world's long-term energy needs: providing large scale energy production with zero greenhouse gas emissions, short-lived radio-active waste compared to conventional nuclear fission cycles, and a virtually limitless supply of fuel.

Almost three decades of fusion research has produced spectacular progress. Present-day experiments have a power gain ratio approaching unity (ratio of power out to power in), with a power output in the 10's of megawatts in pulsed plasmas of duration seconds. The world's next major fusion experiment, the International Thermonuclear Experimental Reactor (ITER), will be a pre-prototype power plant. Since announcement of the ITER site in June 2005, the ITER project, has gained momentum and political support.

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Despite Australia's foundation role in the field of fusion science, through the pioneering work of Sir Mark Oliphant, and significant contributions to the international fusion program over the succeeding years, Australia is not involved in the ITER project.

In this talk, the activities of a recently formed consortium of scientists and engineers, the Australian ITER Forum will be outlined. The Forum is drawn from six Universities, ANSTO (the Australian Nuclear Science & Technology Organisation) and AINSE (the Australian Institute for Nuclear Science & Engineering), and seeks to promote fusion energy in the Australian community and negotiate a role for Australia in the ITER project.

As part of this activity, the Australian government recently funded a workshop that discussed the ways and means of engaging Australia in ITER. The workshop brought the research, industrial, government and general public communities, together with the ITER partners, and developed an opportunity for ITER engagement; with scientific, industrial, and energy security rewards for Australia

2. Opportunities for Contribution

The most systematic approach to describing potential Australian involvement in ITER is to work from the core plasma outwards and at each stage identify where current Australian research is currently having an impact and how that work can be extended. To achieve this the description will work through the following sequence:

- the collisions in the plasma
- the plasma theory development and integrated modelling
- plasma monitoring
- new generation plasma diagnostics
- the plasma wall interaction
- materials development and testing
- the power generating and management systems
- the project management level.

In all cases Australia has research teams who can contribute to the ultimate goal of proving fusion as a viable energy source if given the opportunity. Australia's capability in many of these fields is also enabled via an array of facilities, spanning basic plasma science experiments through to the H-1 Major National Research Facility, plasma – wall interaction experiments, super computer facilities and a suite of materials science research instruments.

2.1 Collisions in the Plasma

Fusion plasmas comprise energetic ions and electrons with an effective temperature of up to 100 million degrees, which corresponds to energies of the order of tens of keV. To achieve this plasma and its maintenance it is important to theoretically and experimentally study electron-atom and atom-atom collisions in the gaseous state. This is an active area of research for Igor Bray and Andris Stelbovics of Murdoch University. They have ongoing collaborative projects with The International Atomic Energy Agency. Their task is to provide electron impact data for the light atomic and ionic species in fusion plasmas, as well as alkali atoms injected into the plasmas for diagnostic purposes.

2.2 Plasma Theory Development and Integrated Modelling

Theory and modelling is one of few areas where Australia can make a low-cost, high-impact contribution to ITER science. One area of active research is in energetic particle mode physics (e.g. Alfvén waves), multiple-fluid modelling, 3D MHD equilibrium and stability studies, and integrated-modelling. The plasma theory group at ANU is also very active in turbulence studies, and dynamical systems modelling. These research efforts aim to understand the causes and conditions of turbulence suppression (which leads to higher performance), and develop dynamical system models to describe their behaviour.

Specific areas of research relate to the following:

1. *Turbulence.* Fusion plasmas are complex and turbulent environments. Confining a hot plasma provides free energy to small wavelength instabilities. At saturation, these instabilities can give rise to turbulent plasma mixing, reducing plasma confinement. Research by Dewar, Numata and Ball seeks understand the dynamics of turbulence, and explore predicted conditions under which turbulence can be suppressed (eg. Zonal flow). This fundamental research offers the promise of developing improved confinement configurations on ITER.
2. *Multiple-Fluid modelling.* Fusion plasmas are far from thermally equilibrated systems. They are driven systems, with multiple different energetic reservoirs, corresponding to: fusion-born alpha's, collisional heating (eg. beams), wave-particle resonant heating, magnetic reconnection, and cold gas puff injection. We have developed an energetically resolved fluid model, which treats the different energetic populations as different fluids. Steady-state model solutions provide a self-consistent description of the plasma. The importance of these equilibrium solutions is that they form the basis for all design, engineering, and interpretation. Initial working has been implemented into an existing numerical solver, providing energy resolved equilibria in realistic geometry [1]. The work has attracted interest from both UKAEA Fusion, and Princeton Plasma Physics Laboratories, whom have an interest in implementing the modified equilibrium code in the particle transport simulation, TRANSP.
3. *Energetic particle modes.* In addition to modifying the underlying magnetic equilibrium, energetic particles can drive a range of high frequency electromagnetic modes, with significant deleterious effects on plasma confinement. The field "energetic particle physics" is an active topical group of the ITPA. Work is underway to develop a self-consistent stability analysis of the multi-fluid models
4. *3D MHD Equilibrium and Stability.* According to ideal MHD theory 3D plasmas should not, in general, be able to support a continuous nonzero pressure gradient. In such plasmas theory predicts the pressure gradient to be zero in chaotic magnetic field regions, which arise due to the non-integrability of the magnetic field, viewed as a Hamiltonian dynamical system. In practice however, 3D plasmas, such as stellarators and weakly asymmetric tokamaks exhibit good performance, in which the observed pressure gradient appears to continuous and nonzero. The purpose of this research is overcome a long-standing problem in ideal MHD, by the development of a stepped pressure-profile model of 3D plasma

configurations. Practical outcomes include better tools for modelling non axisymmetric toroidal systems. The work also has a second application: an energetic basis for transport barrier formation. [2]

5. *Integrated Modelling.* Significant improvements in diagnostics and numerical models have lead to the need for more complicated data integration algorithms and approaches. Folding data together from thousands of diagnostics as input into numerical reconstruction codes is fraught with difficulty. In well diagnosed plasmas such as MAST (and ultimately ITER) the problem is heavily overconstrained: that is, the model inputs form a subset of the diagnostic data available. Applying these models in anger to a discharge normally means folding together highest-confidence data, and optimizing the data set to minimise a global measure of fit. The group at ANU has active research links with research staff at UKAEA Fusion in this topic area [3].

2.3 Plasma Monitoring

2.3.a The H-1 National Plasma Fusion Research Facility [4], established under the Major National Facilities Program, is a magnetic plasma confinement device with flexible geometry and a number of plasma generation and heating sources. It is suitable for basic plasma physics research in "hot" plasma, in the sense that the mean free path for collision is greater than the machine size, and for development of plasma measurement systems ("diagnostics"). H-1 plasma parameters (ion and electron temperatures Ti, Te ~ 10-100eV, electron density $0.1\text{-}5 \times 10^{18}$ m^{-3}) are similar to the edge plasma of reactor-sized machines, so it is particularly well-suited for development and testing of edge diagnostics.

The flexible magnetic geometry of H-1NF can be summarised by three quantities, the rotational transform (ι) or twist per turn of the magnetic field lines, the spatial derivative of this ("shear") and magnetic well, a measure of the decrease in average magnetic field in the centre of the plasma. These quantities are central to the stability of magnetically confined plasma, and their variation can be used to test fundamental stability theories over a much wider range of parameters than is possible in highly optimised machines. Magnetic field line resonances occur if the rotational transform is a low order rational number, such as $\iota = 3/2$. Such a resonance creates magnetic islands in the plasma, which can be harmful to plasma confinement. The flexibility of H-1 ($0.6 < \iota < 2$) allows exploration of plasma configurations ranging from those which are essentially free of islands, to configurations containing islands of low (ι =1/1, 3/2) to medium order (5/4, 9/7). Observations of magnetic islands are presented in another paper in this conference [BDB06], along with the benefits, characteristic of stellarators in general, of operation without the need for large currents in the plasma.

In addition to providing a "test-bed" for plasma diagnostics, and plasma conditions similar to edge plasma in a reactor, H-1 allows investigation of several fusion plasma phenomena on a smaller scale. Originally, transitions to a "high confinement" mode were reported by Shats[5], that reproduced most of the characteristics of those found in the largest machines, but were more conveniently accessed, and allowed detailed examination of the physics involved. The present design for ITER relies on a high confinement mode for successful operation of in a "burning plasma" mode.

Another critical issue for fusion reactors is the effect of the energetic fusion-generated alpha particles on the stability of hot plasma. If the velocity of the alphas is near the Alfvén velocity, they can drive an instability at the Alfvén resonant frequency. As a burning fusion plasma relies on the power from fusion alphas for heating, the effect of this instability on plasma confinement in general, and the confinement of the energetic alphas in particular, is crucial. Results from an "analogue" experiment driven by fast plasma particles in H-1 are given in [6]. Using this facility we are able to explore a wider range of parameters, with more detailed measurements than the limited experiments performed to-date with fusion alphas. For example, the absence of significant plasma current, and the ability to map the magnetic configuration in vacuum means that the rotational transform is much more precisely known than in a tokamak such as ITER. This, in conjunction with the world's only fully tomographic 2-d imaging plasma interferometer for plasma density measurement [7], allows unequalled precision in the prediction of the Alfvén dispersion relation which is at the heart of these instabilities. Another advantage of the configurational flexibility in H-1NF is access to the low shear or reversed shear configurations of next-generation fusion reactors such as advanced tokamaks or stellarators.

2.3b Recently, there is a significant increase in interest by the fusion community in the role of dust in fusion plasmas. It is well known that fusion devices are rather "dusty" in the periphery regions; however, the impact of dust on the performance of fusion plasmas is not clear at the moment. The dust can affect the transport and re-distribution of eroded material of first wall components as well as the plasma auxiliary heating. As we advance to high-power, burning plasma experiments such as ITER, it becomes more crucial to understand the physics of radioactive, mobile, and, therefore, potentially hazardous substances like dust. Research in dusty plasmas done in the Complex Systems Group (S. Vladimirov) which includes theoretical/computational/modelling studies as well as dusty plasma experiments at the Complex Plasma Laboratory (A. Samarian) can be related to such priority research areas (designated as the International Tokamak Physics Activity (ITPA) High Priority Physics Research Areas in ITER Physics Design) as the Compatibility with impurity exhaust and divertor (within the high priority research area of Internal transport barrier (ITB) properties), the scaling of pedestal properties and ELMs (within the high priority research area of Pedestal physics), and the Carbon chemical sputtering, redeposition and deuterium retention/cleaning methods (within the high priority research area of Scrape-off layer (SOL) and divertor). The world-class quality of dusty plasma research at the Complex plasma Group of the University of Sydney can be exemplified by recent invitation of Prof. S. V. Vladimirov to the Japanese National Institute for Fusion Science as a Visiting Professor in January-March, 2006.

2.3c Space Plasma Propulsion

The Space Plasma Power and Propulsion group in the RSPhysSE at ANU carries out research into the physics of high beta plasmas and the behaviour of instabilities both parametric and pressure driven. Primarily the research is experiment driven but we do use analytical modelling and a variety of PIC and hybrid computer simulations.

Initial visits to American and German Laboratories show that we have the opportunity and the plasma system to fit into their programs that are related to fusion and in particular ITER. We are starting immediately on collaborative programs with W7X in Greifswald and the Ruhr University in Bochum. The research would be greatly aided by funding for bilateral exchange of staff between these institutions and appropriate funding of travel and bench fees required for new experiments.

2.4 New Generation Plasma Diagnostics

Systems under development by the Australian National University and the University of Sydney will allow improved monitoring of the state of the plasma. The first method is the supersonic helium beam probes, capable of measuring plasma density and temperature at the plasma edge of ITER. The extension of the system to metastable He ions will enable electric fields to be included in the measurements.

The second is the advanced interferometric techniques to measure the distribution of ion velocities and temperatures . Research on the tomography of vector fields, especially in relation to Doppler spectroscopy of plasma flow fields [8] in the H1-NF national fusion plasma research facility at ANU has led to the development of novel optical “coherence imaging” systems (CIS). This work, undertaken by John Howard and his group, at ANU [9,10], has spawned a couple of patents, and generated sales of optical systems to fusion labs in the US, Korea, Germany and Italy totaling $0.5M.

The CIS technology, which is based on the use of spatial and/or temporal multiplex techniques to image the optical coherence of a given spectral scene, has also led to the development of “coherence pyrometry” systems for measuring temperature, emissivity and emissivity-slope in thermography applications. A 4-quadrant system has been recently trialled successfully under contract to Bluescope Steel to monitor the molten iron stream at their blast furnaces in Wollongong.

Based on polarizing interferometric techniques, CIS offers the important advantages of high light throughput and the capacity to spectrally image simple two-dimensional scenes. A variant of this technology [11] is presently being developed under contract for trial on the laser Thomson scattering system at the JT-60U tokamak in Japan – the world’s second largest fusion device. Successful operation will almost certainly see this technology adopted for the Japanese laser Thomson scattering systems on the ITER tokamak.

2.5 Plasma Wall Interaction

The plasma particles have kinetic energies to over 50keV. At the low energy end (~1keV) this covers the energy range which is a maximum for sputtering erosion of the surface and over the whole energy range there is the potential to modify the surface and near surface composition. The plasma particles interacting with the surface will lose energy (become colder) and have a significant chance of being neutralised which eliminates the capacity to control them with magnetic fields. This form of interaction has been an ongoing study of researchers at the University of Newcastle for over 30 years where such low and medium energy ions have been used routinely for surface analysis and modification. Currently research is underway on the effect of low energy bombardment of TiSiC alloys to ascertain what enrichment and sputtering processes dominate.

2.6 Materials Development and Testing

ITER will place extreme demands on materials in that the first wall will face a high temperature plasma, high heat loads, radiation damage from 14MeV neutrons and potential neutron activation. As well, there has to be the capacity to remove heat from the reaction products, minimize plasma contamination from heavy elements, maintain structural integrity and allow lithium to be exposed to the maximum neutron flux to allow the production of tritium as a fuel. No one material can meet all these demands so there will be different materials at various stages through the process. Australia has a wealth of experience in materials synthesis and characterization which can benefit the develop of new alloys with extreme properties.

One area of particular interest and current research is the production and characterization of MAX phase alloys which combine the electrical properties of metals with the oxidation and thermal resistance of ceramics. A variety of production process options are available including Self-propagating High temperature Synthesis, plasma deposition and Hot Isostatic Pressing. This work involves collaborative research by ANSTO and the Universities of Sydney and Newcastle, with additional research activities at UTS and UNSW. Advanced materials growth and growth facilities have been developed at these sites to explore new materials combinations expanding the capability envelope of materials.

World-class facilities for the sophisticated probes (electron, x-ray, neutron) required for the micro-structural analyses of these advanced materials is readily available at the Australian Key Centre for Microscopy and Microanalysis (electron), the Australian Synchrotron (x-ray) and ANSTO-OPAL (neutron)

Relatively low level fusion neutron fields have the potential for causing defects in semiconductor electronics that will be used for a wide range of diagnostics and monitoring on ITER. Moreover, dosimetery and other radiation health effect issues need to be considered in this environment. Australia has the local expertise for producing small scale fusion neutron sources, based on the electrostatic confinement of an energetic plasma, which will enable these studies to be carried out. A prototype device, using hydrogen plasma has been demonstrated by Dr. Khachan of the School of Physics, University of Sydney, and an improved deuterium device is under construction. In such a device electrostatic confinement results when a deep electrostatic potential is created in a plasma. Ions that are accelerated and trapped by the potential have a much increased chance of fusion events taking place. It has been shown [112] that with a modest power input (i.e. 5 - 10 kW, in D-D plasma) it is possible to produce 10^8 2.45 MeV neutrons per second operating in the electrostatic confinement mode. Consequently, it is also possible to produce 14 MeV neutrons at a factor of a hundred higher (i.e. 10^{10} neutrons/second) in a D-T plasma [113]. In addition, these devices are on a scale such that they can be built to a desktop size with matching small scale costs.

2.7 Project Management

Due to the complexity of a large scale fusion research machine, significant management effort is required for all stages of its life cycle. While sound project management methodologies are universally available, experience in project management of large fusion machines is relatively limited. Australia is in a good position to make a strong contribution to the project management effort on the ITER project because of its experience in, and successes achieved from, this type of work on the JET project. This experience gained between 1980 and 1997, and available in Bovis Lend Lease, included the following:

Stage of Project	**Major Non-Technical Management Experience**
Design, manufacture, assembly, installation, commissioning	➢ planning and scheduling ➢ contingency planning ➢ resourcing ➢ detailed coordination ➢ performance monitoring and reporting
Operations	➢ shift planning and resources ➢ intervention coordination and access control ➢ feedback on operational performance ➢ planning and preparation for active gas introduction
Planned shutdowns (and decommissioning)	➢ overall planning and preparation ➢ activity/shift scheduling ➢ resourcing ➢ detailed coordination ➢ performance monitoring and reporting

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