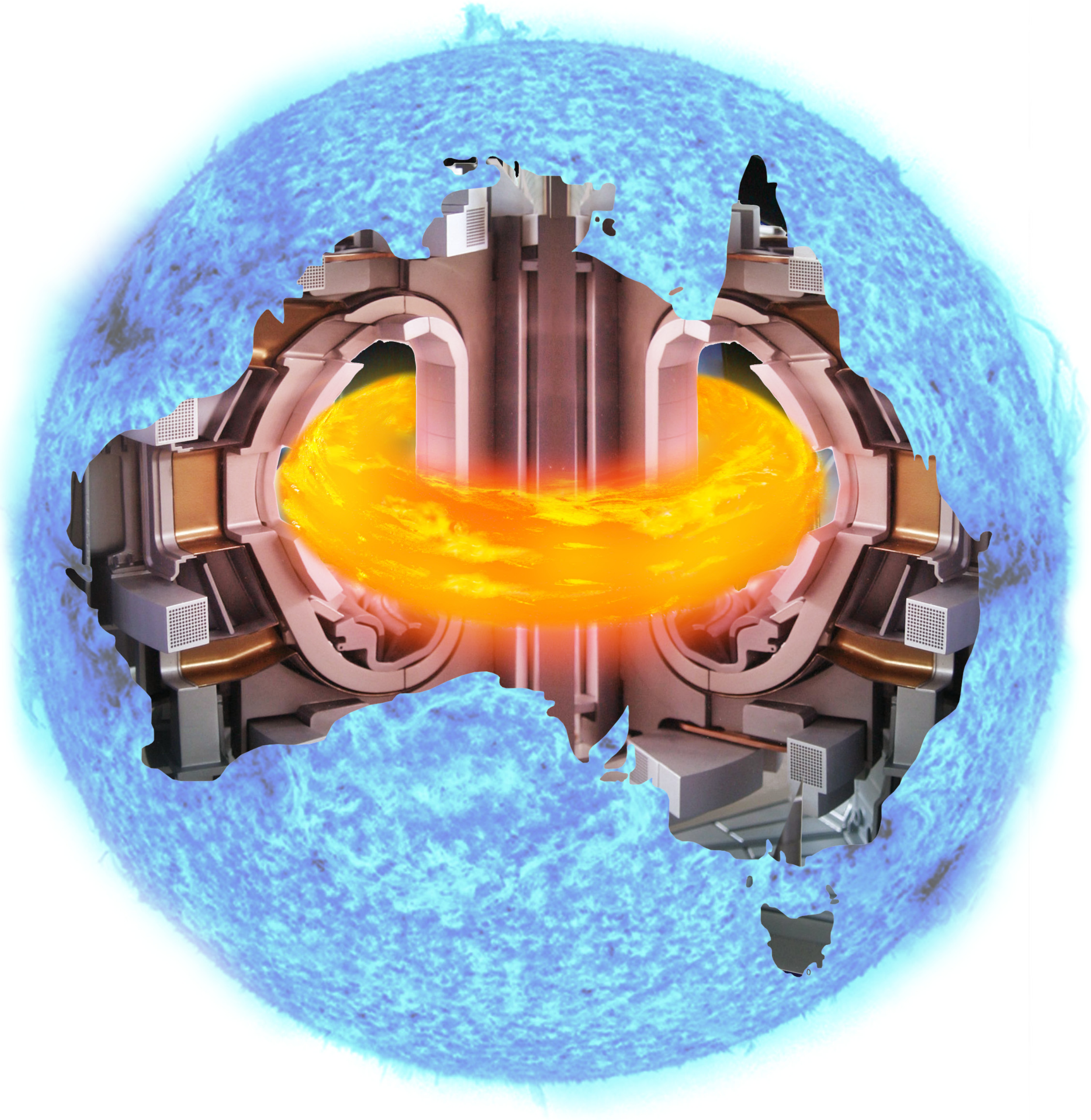
Powering Ahead

A National Response to the Rise of the International Fusion Power Program



> *"The problem I hope scientists will have solved by the end of the century is nuclear fusion. It would provide an inexhaustible supply of energy without pollution or global warming."*
>
> Stephen Hawking

Powering Ahead: A National Response to the Rise of the International Fusion Power Program

What problem do you hope scientists will have solved by the end of the century?
Stephen Hawking: Nuclear fusion. It would provide an inexhaustible supply of energy without pollution or global warming.

Brian Cox: I share that view, that the provision of clean energy is of overwhelming importance.

The Guardian, 11 September 2010

This document was commissioned by the ANU, ANSTO, and the Australian ITER Forum on behalf of the Australian fusion science and engineering community.

Contents

Preface

The urgent need to develop clean base-load power systems has sparked a global renaissance in fusion power research.

The next step ITER tokamak, now under construction in France, is designed to demonstrate the technical feasibility of fusion power generation. Supported by governments representing more than half the population of the planet, the ITER experiment will now commence operation in 2020. The slightly delayed starting date delivers a window of opportunity for Australia to make important research contributions to this largest of global scientific endeavours. It is expected that ITER will pave the way for a demonstration power plant, leading to commercial fusion power in the second half of this century. A strong Australian engagement with the international fusion program, including ITER, will see Australia well prepared for the coming fusion age.

In recent years, the Australian fusion science community, largely through the Australian ITER Forum, has worked hard to increase government and public awareness of the potential of fusion and to enhance the visibility of fusion science across the Australian scientific community. In 2007 the Forum released a strategic plan “A strategy for Australian Fusion Science and Engineering: Through ITER and into the Future”. Many elements of the plan have been realized, including Super-Science infrastructure upgrade for the Australian Plasma Fusion Research Facility (APFRF), and support for a fellowship scheme that is similar to the ARC Future Fellowships program.

There has also been growth in fusion plasma and materials science across the wider university research community. A new “Extreme Materials for Fusion” program embracing collaborations in the field of nuclear science was commenced in 2012 under the 2010 Memorandum of Understanding between the Australian Nuclear Science and Technology Organisation (ANSTO) and the Australian National University (ANU). The University of Newcastle has expanded its international collaborations in fusion related materials through its formal involvement in the CERAMAX consortium (which involves mainly European researchers).

In December 2012, it was agreed at a meeting of senior ANSTO representatives and the Australian fusion science community, including the Australian ITER Forum, that as Australia’s premier nuclear organisation, ANSTO would in future represent the formal interests of the Australian fusion community with the ITER organisation (see Appendix 2). In early 2013, ANSTO CEO Dr Adi Paterson met with ITER Director General, Dr Osamu Motojima, to identify pathways for future linkages between Australian science and ITER.

In concert with these developments, the ANU, ANSTO and Australian ITER Forum, on behalf of the Australian fusion community, have commissioned this new plan, with the goal of securing an Australian capability and preparedness for fusion power. Building on the work of the first plan, this will be achieved by expanding domestic research, maintaining world class facilities and infrastructure, and by broadening collaboration and engagement with international programs.

Executive summary

Fusion is the process that powers the Sun and the stars. If harnessed on Earth, it could provide millions of years of greenhouse gas-free, safe, base-load power. The ITER project, which will define fusion research for a generation, marks the next step in the development of a fusion reactor.

Australians were among the fusion research pioneers, and the nation today has word-class expertise in stellarator physics, plasma diagnostics, fusion theory and modelling, plasma-surface science, and advanced materials research. This expertise is the basis for deep and wide collaboration with fusion programs in the USA, Korea, Japan and Europe. The primary objectives of the proposed five year plan are, therefore, to secure Australia's research expertise in fusion science and develop programmatic engagement with the world's major international tokamak and stellarator fusion programs such as ITER.

Securing Australia's research expertise requires investment in human resources and capital infrastructure. The plan includes program fellowships to train and retain the next generation of fusion scientists, from theory and modelling to materials science.

To establish programmatic engagement with ITER, the community will seek formal participation in the International Tokamak Physics Activity (ITPA). The ITPA, which operates under the auspices of the ITER International Organisation (IO), is the primary channel through which fusion scientists share ideas and address physics and engineering problems vital to the success of ITER.

A material contribution to ITER is also planned through the design and construction of an optical "coherence imaging" system for plasma edge monitoring. This will showcase Australian capability in fusion science, open research opportunities for the wider domestic program and develop the skills base required for the future.

Consolidating the domestic program will also require operational and infrastructure support for APFRF operations beyond 2015. This would ensure full exploitation of the newly upgraded H-1 stellarator at the APFRF, and in so doing, meet the nation's commitment to the IEA Implementing Agreement on the Stellarator/Heliotron. The stellarator concept is an inherently steady-state plasma confinement modality suitable for base-load power.

Finally, the practical realisation of a fusion power plant will depend on the development of so-called "extreme materials" capable of withstanding the high neutron and heat fluxes at the edge of the fusion reactor. The plan envisages increased capabilities for community-wide basic and applied research into extreme materials for fusion through the development of a high-flux device capable of generating reactor-edge-plasma conditions.

This five-year plan will build and sustain a critical-mass domestic fusion science capability that will see Australia welcomed as a significant partner in future international fusion research. For modest investment, the Australian government will ensure that Australian industry and electricity suppliers will be well positioned to harness new opportunities in the emerging era of fusion power.

Recommendations

Recommendation 1

That the Australian government supports a national fusion program that will strengthen Australian engagement with the international effort and position Australia for the emergence of fusion power. This could be achieved with total funding of $16.3m spread over five years.

The funding would provide:

- Program fellowships in support of ITPA activities, stellarator physics and research into advanced fusion materials.
- Funding for the design and construction of a prototype optical "coherence imaging" system suitable for plasma flow measurements in the ITER edge "divertor" region.
- Operational support for the Australian Plasma Fusion Research Facility (APFRF) encompassing the H-1 Heliac and the materials testing facility, MAGPIE.
- Infrastructure funding (i) for high-power enhancements to the linear plasma device for fusion-relevant plasma-material and fundamental plasma physics studies, and (ii) to support to the development of the optical "coherence imaging" system ITER prototype.
- Travel funds for obligatory ITPA meetings, and secondment to either the ITER IO or associated international fusion agency.
- Appropriate management and outreach support.

Recommendation 2

That the Australian fusion science community establishes a Memorandum of Understanding between ANSTO and the ITPA Coordinating Committee to formally enable Australian participation in ITPA.

Recommendation 3

That the Australian government supports existing political commitments in fusion science, and provides the political will and vision that will deliver new opportunities to participate in large international fusion-oriented projects. For example, though we are signatories to the IEA Implementing Agreement on the Stellarator/Heliotron, Australia does not presently participate in Fusion Power Coordinating Committee meetings. The Government might also formally nominate fusion science as a research priority in new or existing bilateral or multi-lateral research agreements.

Recommendation 4

That the Australian government reinstates, or finds a suitable replacement for the international Science Linkages program. For international, goal-oriented endeavours such as fusion research, this program was a unique and essential source of funding for multilateral research undertakings.

1. The opportunity

1.1 The revolutionary prospect of energy from fusion

The fusion of light elements (see Figure 1), many of which are abundant and widely distributed, releases enormous amounts of energy, at levels needed for base-load power but without emissions of greenhouse gases that contribute to man-made climate change. The realisation of fusion power would enable nations to reduce their reliance on fossil fuels, such as coal, gas and oil.

Man-made climate change is an issue of fundamental significance to the long-term sustainability of our planet. An increased Australian investment in fusion-related research, development and education (RD&E) would demonstrate to the Australian community a medium to long-term response to address man made climate change.

"Why should Australia increase its investment in fusion-related R&D and education?"

Australia's current investment in fusion-related research, development and education (RD&E) is not sufficient to ensure a future capability and to capitalise on opportunities created by fusion power, Australians can also make a real contribution to realising fusion power.

Fusion would be ideal for electricity intensive processes such as aluminium refining, currently often powered by carbon emitting fossil fuel combustion. Fusion power plants produce high temperature heat which is useful, not only for electricity production with greater efficiency than today's power plants, but also directly for industrial processes (e.g. desalination and hydrogen production).

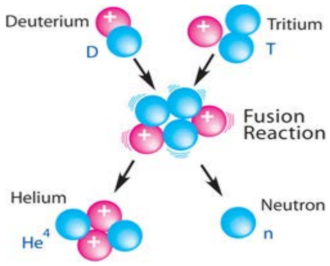


Figure 1: The fusion of isotopes of hydrogen: deuterium and tritium

Fusion power would therefore address Strategic Research Priority 5: Lifting Productivity and Economic Growth under program goal 2, Maximise Australia's Competitive Advantage in Critical Sectors, which includes the development of future energy resources.[1] The 2011 Strategic Roadmap for Australian Research Infrastructure has acknowledged that "A long-term solution for large scale, non-polluting energy supply may eventually come from nuclear fusion"[2].

The potential economic return from fusion energy is enormous. In 2011, a real options valuation of fusion energy showed the potential revenues from deployment of fusion technology substantially outweigh the R&D, demonstration and deployment costs.[3] To put the cost of developing fusion into perspective, Chen has argued recently that the cost of developing fusion would be less than, but comparable to, the cost of the Apollo program.[4]

---

[1] Department of Industry, http://www.industry.gov.au/research/Documents/SRP_fact_sheet_web.PDF

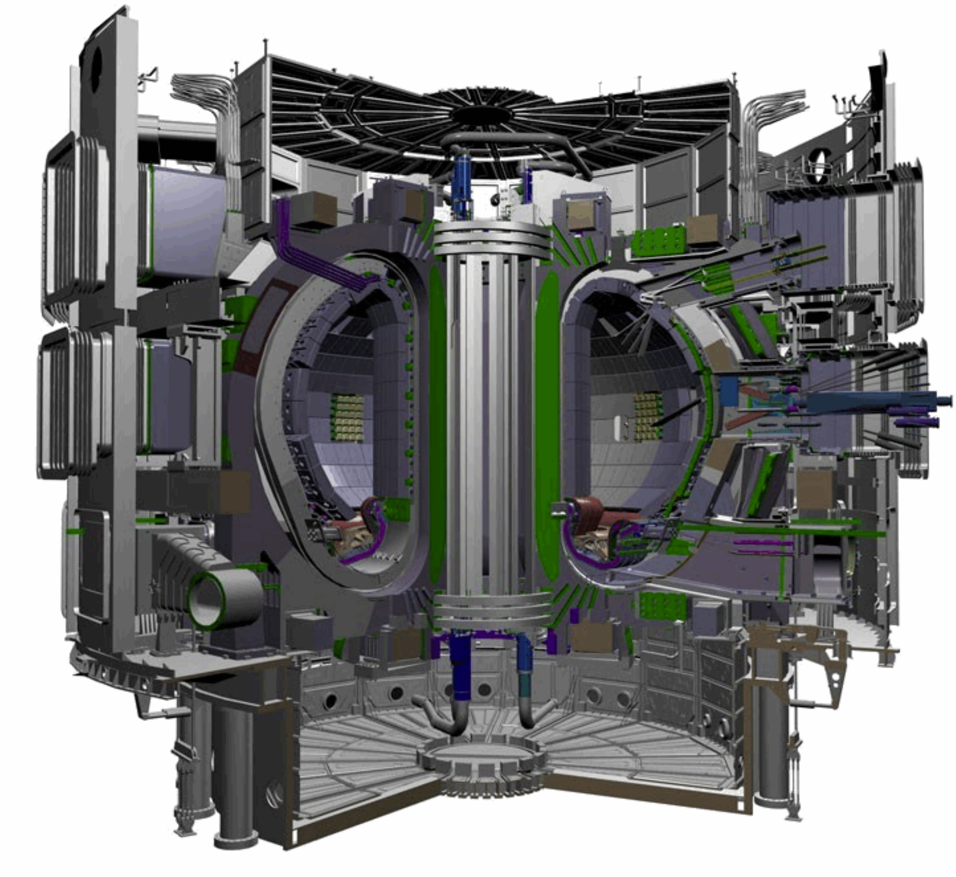
[2] 2011 Strategic Roadmap for Australian Research Infrastructure, September 2011, p47

[3] D Bednyagin, E. Gnansounou , *Real Options Valuation of Fusion Energy R&D Programme*, Energy Policy, 39(1), 116-130, 2011

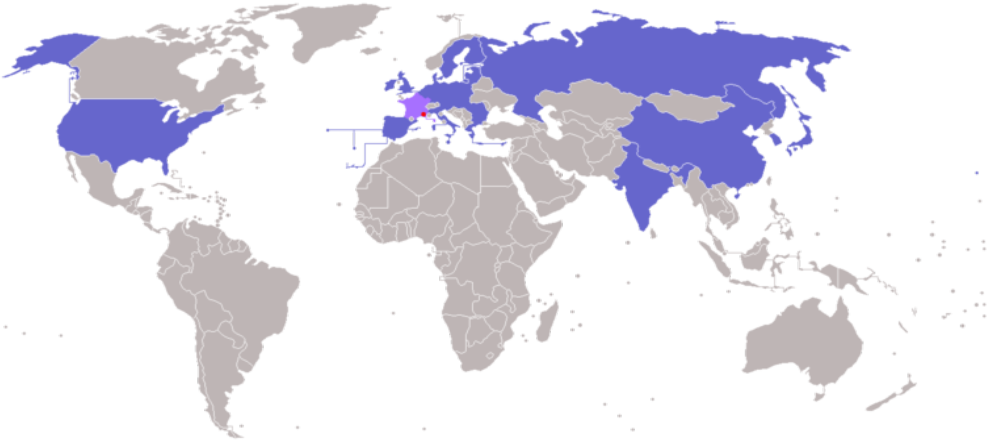
[4] F. F. Chen, *An Indispensible Truth: How Fusion Power Can save the Planet*, Springer (New York, 2011), ch 11.

What is ITER?

The ITER experiment, supported by a multinational consortium of the EU, Japan, the USA, the Republic of Korea, the Russian Federation, the People's Republic of China and India, marks the next step in the quest for fusion power. The goal of the ITER program is "to demonstrate the scientific and technological feasibility of fusion power for peaceful purposes". ITER has dimensions comparable to a power station and will demonstrate or develop all the new technologies required for fusion power stations, except for materials endurance. Construction and assembly of ITER in on site in Cadarache (France) commenced in 2010 and first plasmas are expected in 2020. With a total 20 year budget of $20bn, ITER is the world's largest science experiment. In contrast to earlier experimental research tokamaks, it is sharply focussed on humankind's most pressing issue – sustainable and clean power generation.



A cross section of the 60m high 23,000 ton machine.



The ITER member partners
Further information: www.iter.org

The fusion programs in most developed nations, as well as China and India, and now the international ITER program, provide clear evidence of the perceived importance of fusion as a long-term source of power that is sustainable, friendly to the environment and economically viable. Australia has a solid, long-standing base of scientific and engineering expertise that could contribute to the development of fusion power plants.

1.2 Options for energy security

It is generally recognised that our future society will depend on a portfolio of sources for base-load energy (such as provided by coal in Australia at present) and dynamic load (such as provided by hydro, wind, solar and other renewable energy technologies). An increased Australian investment in fusion-related research development and education (RD&E) will give the nation an option to adopt fusion as an electricity source when commercial systems become available. If this is to be a genuine option for Australia, the nation will need people with expertise and skills in this area, to help make decisions about its potential implementation and to advise on the selection of technologies. This expertise will be found in people who have detailed knowledge of the science and technology, solid experience in the field and personal relationships with key world players. They will be able to make intelligent judgements about available options and provide independent advice to Government. That capability will be achieved only if Australia increases its present RD&E in fusion-related science and engineering and trains the next generation of experts. The absence of such skills would seriously hamper efforts to adopt fusion power plants.

Regardless of whether the fusion option is eventually adopted, investment in this area will support other parts of the nation's energy options portfolio. A significant proportion of the knowledge and skills needed for fusion power plants is also relevant to all power generation involving high-temperature thermal cycles. This will be particularly relevant to Australia's involvement in developing renewable sources of energy such as solar and geothermal, as well as the next generation of advanced fission reactors (Generation IV). Participation in fusion research would strengthen the international linkages, most notably with the International Atomic Energy Agency, the International Energy Agency (IEA), and the OECD's Nuclear Energy Agency (NEA).

1.3 Spinoffs and Resources Opportunities

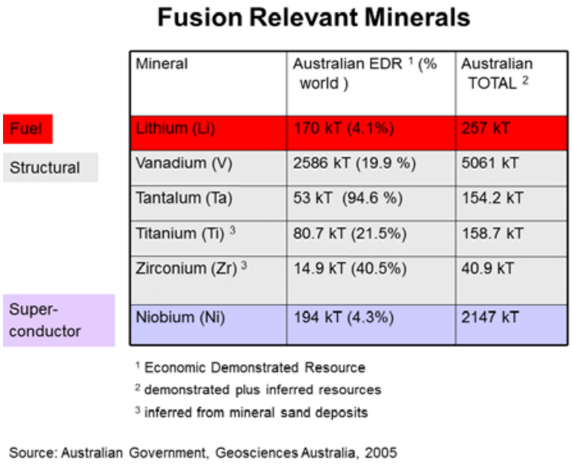
The enabling science of fusion power is plasma science, which is also fundamental to materials processing, astrophysics and space science. Plasma science contributes to a range of industries, including microelectronics, lighting, hazardous waste disposal, rocket thrusters and television screens. It is the basis for the new fields of plasma medicine, which promises new treatment modalities, and plasma chemistry, which promises new processes for producing innovative materials. In addition, the data processing demands of fusion systems will stimulate development of procedures that will be widely applicable.

The extraordinary *remote-sensing measurement* challenges posed by fusion plasmas give powerful impetus to innovations, new technologies and methods that are finding application in other areas of science and technology, as well as industry, defence and medicine. For example, plasma microwave techniques are being developed for breast cancer imaging, and advanced colour imaging technologies developed at the Australian National University (ANU) are being used to estimate iron and steel temperatures at Bluescope Steel. The ITER diagnostic systems for measuring plasma properties will be the most comprehensive to date, and will likely continue to spawn new technologies with applications further afield.

Fusion power plants will require *the development of new materials* due principally to the extremely high flux of neutrons and the localised high heat flux on internal surfaces facing the high temperature plasma. Materials developed for the extreme conditions imposed by a fusion plasma will be relevant not only for other forms of power generation, such as geothermal, solar thermal, fission and high-temperature fossil, but also to other industries that work with extreme conditions, such as the aerospace and mining industries.

The wider technology spin-offs are extensive. Superconducting magnet technology has been driven by development needs of fusion power and particle physics. Such technology has enabled Magnetic Resonance Imaging (MRI), now a routine medical diagnostic. Other spin-off technologies include remote handling systems, high power gyrotrons and microwave sources.

Finally, Australia has among the largest reserves in the world for several key minerals such as vanadium, lithium, tantalum, titanium, zirconium and niobium (see Table 1), all of which are candidates for critical components of a fusion power plant. In coming decades these minerals will be attracting international interest for their potential use in fusion energy systems, and the Australian RD&E base will give the Australian minerals sector a significant advantage in the exploitation of these resources.



Fusion Relevant Minerals

	Mineral	Australian EDR [1] (% world)	Australian TOTAL [2]
Fuel	Lithium (Li)	170 kT (4.1%)	257 kT
Structural	Vanadium (V)	2586 kT (19.9 %)	5061 kT
	Tantalum (Ta)	53 kT (94.6 %)	154.2 kT
	Titanium (Ti) [3]	80.7 kT (21.5%)	158.7 kT
	Zirconium (Zr) [3]	14.9 kT (40.5%)	40.9 kT
Super-conductor	Niobium (Ni)	194 kT (4.3%)	2147 kT

[1] Economic Demonstrated Resource
[2] demonstrated plus inferred resources
[3] inferred from mineral sand deposits

Source: Australian Government, Geosciences Australia, 2005

Table 1: Australian reserves of fusion-relevant minerals

1.4 Australian science engagement

The development of fusion energy has been an international cooperative effort since the late 1950s. This is exemplified in the ITER project, which is at present being developed by seven partners: the European Union (EU), Japan, the People's Republic of China, India, the Republic of Korea, the Russian Federation and the USA.

A number of recent reports have emphasised the benefits of increased Australian engagement in major international science activities. In 2011 the House of Representatives Standing Committee on Industry, Science and Innovation[5] presented a report on an *Inquiry into Australia's International Research Collaboration* in which it recognised that "Collaboration at the international level is not only desirable, but an absolute necessity".

---

[5] House of Representatives Inquiry into Australia's international research collaboration, Australian Parliament, 22 June 2010, http://www.aph.gov.au/Parliamentary_Business/Committees/House_of_Representatives_Committees?url=isi/intresearch/report.htm

The Committee provided strong recommendations that a successor program to the International Science Linkages program be established as soon as practicable (recommendation 8) and that the International Science Linkages program have its budget increased and indexed (recommendation 9).

The 2011 *Strategic Roadmap for Australian Research Infrastructure* expressed similar sentiments[6]:

> *"Australian investment in research infrastructure should not be limited to Australian-based facilities. There must be a high level of global connectivity to ensure Australia maintains international visibility and engagement with global research efforts."*

In relation to basic research and innovation across the broad range of energy sources and systems the *Roadmap* suggests that[7]

> *"…consideration could be given to continued support for research infrastructure related to fusion power to facilitate linkages with international activities such as the International Thermonuclear Experimental Reactor (ITER) project."*

Australian engagement with ITER will enable Australians to be fully informed of developments internationally, and to take advantage of the substantial investments that other countries are making in fusion-related science and engineering. ITER experiments will generate massive quantities of data, but access to that data will be restricted. Australian involvement should be used, in part, to gain access to this data and knowledge.

Australia has a prestigious position in fusion science, which goes back to the discovery of fusion reactions by an Australian, Sir Mark Oliphant (Figure 2), in 1933. Many Australian physicists who received their training in Australia, have or have had senior positions in international fusion programs. However, without an increased investment in fusion-related RD&E, this reputation and legacy will fade.

Figure 2: Sir Mark Oliphant, 1901-2000

The House of Representatives Industry and Resources Committee, in its *Australia's uranium — Greenhouse friendly fuel for an energy hungry world* report ("Prosser report"), was persuaded of the immense potential benefit that fusion energy represents for the world and, specifically, the potential benefits for Australian science and industry from involvement in the ITER project. The Committee believes that "involvement in this experimentation is simply too important for the nation to miss."[8]

---

[6] Strategic Roadmap for Australian Research Infrastructure, September 2011, http://www.industry.gov.au/science/Documents/2011StrategicRoadmapforAustralianResearchInfrastructure.pdf, p 10

[7] *ibid*, p37

[8] *Australia's uranium — Greenhouse friendly fuel for an energy hungry world*, November 2006 (Prosser report). http://www.aph.gov.au/Parliamentary_Business/Committees/House_of_Representatives_Committees?url=isr/uranium/report.htm. In Recommendation 14, the Committee recommended that Australia secure formal involvement in the ITER project.

1.5 Boost for science and engineering education

There is a well-documented need for more Australian scientists and engineers. Australia's involvement in fusion energy, especially the iconic ITER project, but also other major national programs, provides an exciting, big science project to encourage Australian students to take up the study of science and engineering. Fusion will be a significant part of the 2014 ANU summer physics school, while there was strong interest in the *Winter School on Industrial and Fusion Plasmas* held at the ANU, which attracted over 30 students (see Figure 3). ANU also hosts international fusion conferences such as the joint stellarator and plasma theory conference held in 2012 (Fig. 3).

Fusion captures student interest as a new technology addressing man-made climate change in the long term and calling for robust systems performance in demanding physical conditions. At the same time such projects provide opportunities to work internationally and the personal fulfilment of contributing to a major enterprise of fundamental significance to civilisation with obvious rewards for the nation as a whole.

Figure 3: **Participants of the international Stellarator and plasma theory conference held at ANU in 2012**

1.6 Urgency of action

The development of fusion energy is entering a major new phase, with the construction of ITER having commenced in 2010 and first plasmas scheduled for 2020 (see Table 2). Its design and the experiments conducted on it will define the path of fusion energy development over the next 30 to 40 years.

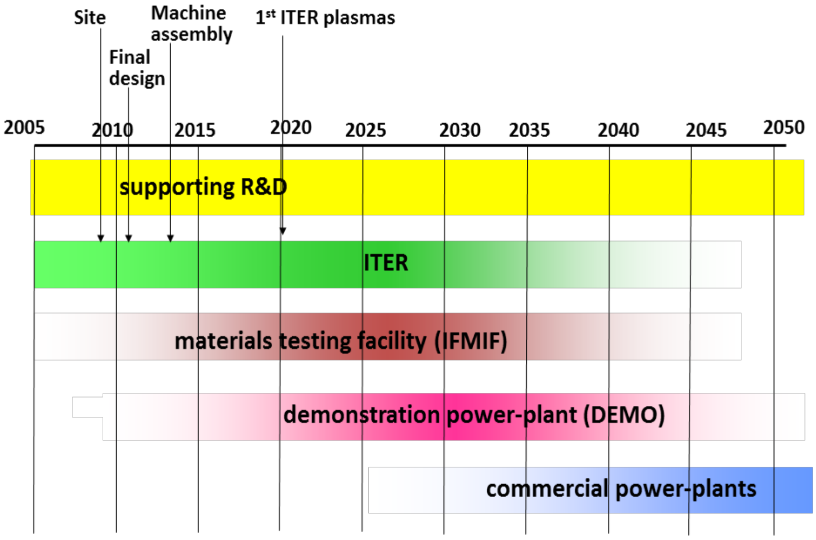


Table 2: Illustrative timeline for fusion power development. It assumes the timely provision of appropriate resources (both financial and human)

It has been identified that a deeper understanding of the science and technology of materials under extreme heat loads is critical[9] to the success of steady-state plasma fusion reactors that will follow ITER. The International Fusion Materials Irradiation Facility (IFMIF)[10], in which materials developed for the ITER device will be tested, is under design, and a Fission, Fusion Materials Facility (F^3) has been proposed at Los Alamos as part of its Matter-Radiation Interactions in Extreme Experimental Facility (MaRIE)[11]. At the same time fusion advocates are looking towards DEMO[12], which will be a prototype commercial fusion power plant. Deciding on a material for DEMO represents a significant challenge. There is an urgent and outstanding need for dedicated experiments on purpose-built facilities, equipped with state-of-the-art diagnostic systems, to validate models for fusion-relevant material performance under extreme conditions.

In fact, only the partners of the ITER Project have access to the advances flowing from ITER towards the further development of fusion energy. Should Australia not gain access to the ITER project, its participation in the main international development program to realise fusion power and gain the benefits of the associated science and technologies will be impossible. We are, therefore, at a critical point in the development of fusion power. Unless Australians take roles in these developments, the nation will become a backwater of research and engineering in this area.

Although Australian fusion research personnel have experienced some growth since 2007, this has occurred in short term positions. This new skills set will vanish if there is no sustainable research environment to retain them, and these Australians will move to take up opportunities overseas. It is time to convert this growth into a sustainable fusion activity, provide security enabled by a program, and build support for the next generations of researchers with expertise in this area, looking towards the future when commercially viable fusion power plants will be built.

While the Future Fellowship, Super Science Fellowship, and ARC Discovery Early Career Researcher schemes have provided some capacity to support excellence in fusion research and attract expatriate researchers to return to Australia, the number of tenured staff remains critically low. The capacity to teach basic plasma physics has become sub-critical with only two universities – Sydney and the ANU – teaching the subject at the undergraduate level. The Prosser Report recommended that Australia “seek to consolidate and coordinate Australia’s efforts in fusion related research and examine the merits of establishing fusion science as a national research priority”[13].

The construction timetable for ITER is an imperative for action. The ITER parties have established their own responsibilities for the construction of ITER but some elements have not yet been allocated to any party. These unallocated, or “uncredited” systems offer the best avenues for a non-party, such as Australia, to be involved by making a “machine contribution”, as is further discussed in Chapter 3. In a few years Australia will be unlikely to be able to play a significant role in the development of ITER diagnostic systems.

---

[9] The US Fusion Energy Sciences Advisory Committee “Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy”, DOE/SC-0102 (2007)

[10] IFMIF has been pursued under an IEA Implementing Agreement since 1995 by the EU, Japan, the USA and Russia. http://www.ifmif.org/c/index.htm

[11] http://marie.lanl.gov/f3.shtml

[12] http://www.iter.org/proj/iterandbeyond

[13] *Australia's uranium — Greenhouse friendly fuel for an energy hungry world*, November 2006 (Prosser report), *Op cit*, Recommendation 8

2. Australia's capability in fusion research

Since the discovery of fusion in 1933 by Australian physicist Sir Mark Oliphant, Australian-based scientists have made many significant contributions to fusion science, encompassing magnetic confinement concepts, plasma theory and measurement techniques.

While ITER is in its early construction phase, national programs, particularly those of the ITER partners, continue to provide opportunities for Australian-based scientists to make innovative contributions to fusion science at an international level. As these contributions invariably involve postgraduate research students, they also provide an opportunity for training young scientists and thereby extending national expertise in fusion science. They also increase the chances that upon graduation such students find positions in other national programs. As a certain fraction of these people are likely to return to Australia at some time in their careers the initial collaborations can be expected to lead to long-term contact with global developments in fusion science.

Australian capabilities in fusion-related research are described below, along with examples of current international collaborations undertaken by Australian-based scientists.

2.1 The H-1 Heliac

The H-1 Heliac, located at the ANU, is the focus of experimental fusion research in Australia. This device, which produces a magnetized plasma of complex topology (see Figure 4) was upgraded under the Super Science scheme – a welcome outcome of the 2007 strategic plan. The upgrades have increased heating power by a factor of 5, improved vacuum system quality and enhanced measurement systems and supporting infrastructure.

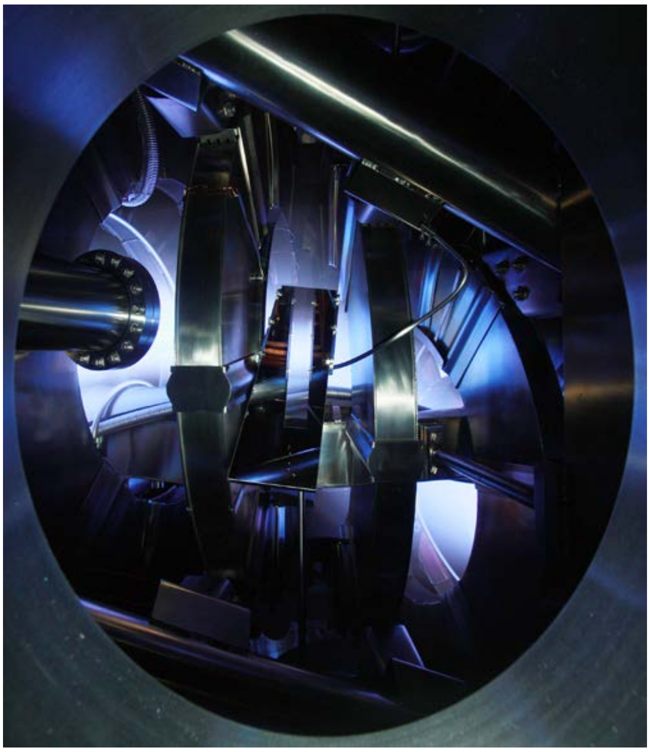


Figure 4: A section of the H-1 magnetic field coil structure needed to generate the helical magnetized plasma (blue emission)

While ITER is a tokamak, H-1 is an example of a stellarator confinement device. Stellarators have inherent advantages over tokamaks: they do not require a large toroidal electric current to flow in the plasma in order to produce an effective magnetic container for holding the hot fusion plasma. As a result, they are free from current-driven instabilities that can potentially damage a tokamak, and are, in principle, also capable of continuous operation. On the other hand, stellarators require a more complex set of magnets to produce the confining field, and this has slowed their development compared with tokamaks, which have a simpler axisymmetric geometry. It is somewhat ironic that large present-day tokamaks are now installing symmetry-breaking magnetic coils in an attempt to suppress the damaging edge localized modes that afflict high pressure tokamak operations. Stellarator research is therefore an essential component of the study of toroidal, magnetically confined plasmas.

In spite of the stellarator's complexity, the Large Helical Device (LHD) stellarator, operating since 1998 at the National Institute of Fusion Science (NIFS) in Japan, has achieved, in continuous operation and without disruptive instabilities, values of beta (the figure of merit which indicates the efficiency of the plasma confinement) superior to those of comparable-sized tokamaks. In Germany an even larger super-conducting stellarator, Wendelstein 7X is under construction at Greifswald and is expected to begin operation in 2016.

Unlike most other stellarators, H-1 has the design flexibility to explore many different non-axisymmetric 3D confinement configurations. Its unique construction also provides unparalleled observational access to the plasma. As a university-scale device, it also has the operational flexibility to adapt quickly to new challenges and changing priorities. Given the resurgence of interest in the physics of non-axisymmetric confinement systems, the H-1 Upgrade is well poised to make contributions to the international fusion program. Its inherent non-axisymmetry and diagnostic access also makes it an ideal test bed for developing 3D imaging systems of the kind proposed for the divertor region of ITER. Study of stellarator plasmas also provides information of general value to the confinement of toroidal plasmas as in tokamaks.

2.2 Coherence imaging technology

Optical instruments developed at the ANU are uniquely capable of producing fast, high-spatial-resolution 2D images of the temperature and flow speeds, and the internal current distribution inside fusion power plants. These "coherence imaging" (CI) systems utilize advanced interferometric concepts to optically process subtle changes in the spectrum and polarization of light emitted by the plasma and to encode those changes on an image captured by a fast camera.

CI cameras have been installed and operated on major devices in Germany, England, Italy, the Netherlands, Korea, Japan and the USA. In a parallel development, in November 2012, these systems were successfully deployed to obtain the world's first and only images of the internal magnetic field on the KSTAR tokamak in Korea (see Figure 5). This represents a breakthrough in fusion plasma measurement capability. A Memorandum of Understanding with the National Fusion Research Institute (NFRI) in Korea spanning diagnostic development and MHD plasma interpretation was initiated as a result of the CI-based collaboration, and multiple dedicated operational run days on the superconducting KSTAR tokamak have been allocated annually for such experiments since 2010.

In collaboration with US teams from General Atomics and Lawrence Livermore National Laboratory, coherence systems were also used in 2010 to obtain the world's first tomographic reconstructions of sonic ion flows in the plasma edge. These flows insulate the core plasma from the wall and also transport exhaust plasma to the "divertor", a pumped magnetic funnel that channels lost plasma onto refractory target plates that dissipate waste energy prior to exhaust. Similar systems have now been deployed on the UK's Mega Ampere Spherical Tokamak (MAST).

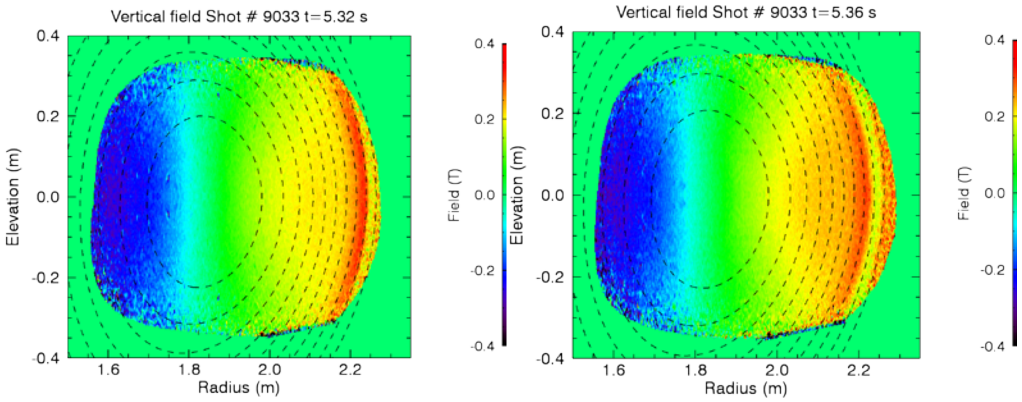


Figure 5. World's first images of the internal magnetic field inside a tokamak. Left: Measured vertical magnetic field structure for a high-confinement-mode KSTAR discharge just prior to the onset of an edge localised mode eruption, and Right: during the edge relaxation event. The dashed curves are the magnetic flux contours. The strong edge gradients in B_z indicate large edge toroidal currents.

Measurement of plasma flows in the divertor is "Requirement Number 43" in the ITER diagnostic baseline specification, but is presently unallocated due to the lack of availability of a suitable technique. *Australia now has that unique capability and is ideally positioned to make a vital contribution to the ITER project.* With modest funding support, CI systems could be a pathway to Australian participation in the ITER project.

2.3 Theory and modelling

Australia has a well established reputation in the science of plasma physics - magnetohydrodynamics (MHD), and has a growing footprint in modelling plasma configurations and wave activity, as well as integrated modelling using probabilistic techniques. A core activity is the inference of magnetic equilibrium and interpretation of wave physics in international experiments, MAST and KSTAR. Both activities are captured by recent MOU's between the ANU and the Culham Centre for Fusion Energy (CCFE) in the UK, and the ANU and the NFRI in Korea, and supported by the competitive time allocated to MAST and KSTAR experiments.

Models of plasma rotation and anisotropy that arises in a burning plasma such as ITER, a routine situation for ITER where a significant fraction of the plasma energy resides in energetic fusion products, are being developed in collaboration with CCFE and the University of Texas, Austin. This additional physics will be incorporated into standard magnetic reconstruction codes used the world over to infer the magnetic field configuration.

Modern fusion experiments are characterised by the wide diversity, and unprecedented accuracy and resolution of plasma measurement systems ("diagnostics"). There is a great need to maximize the information retrieved from these expensive systems. In collaboration with Germany's Max Planck Institute for Plasma Physics and CCFE, a "probabilistic inference engine", that combines plasma models with diagnostic models and data to reconstruct the plasma parameters without prior assumptions has been developed. This approach has already been implemented successfully for current tomography measurements on the UK experiment MAST.

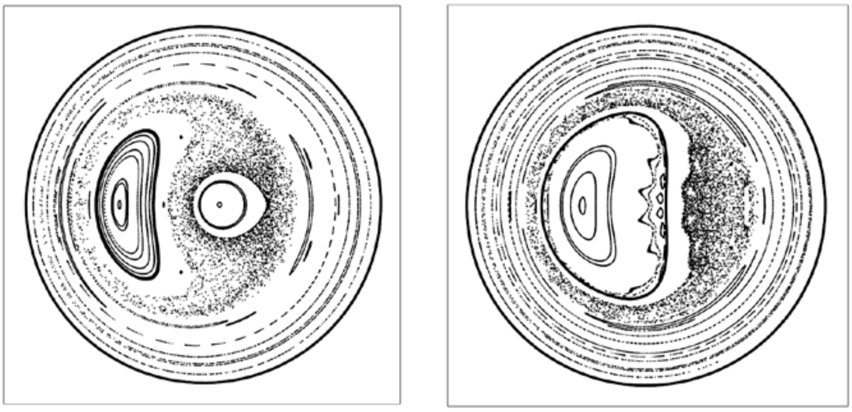


Figure 6: An example of Reverse field pinch fields computed generated by the SPEC code. The left image shows a double axis and the right a single helical axis.

In practice, all donut shaped fusion power plants will have a twist to their magnetic shape. In tokamaks like ITER, this twist is produced by the large internal electric currents. Stellarators like H-1 Heliac have an externally imposed twist, intended to make the plasma more stable but at the same time making the field much more complicated. A new magnetic field model describing regular field lines, magnetic islands and chaotic fields has been developed. In collaboration with the US Princeton Plasma Physics Laboratory this model has been incorporated in a new code, SPEC (Stepped-Pressure Equilibrium Code – see Figure 6*)***,** to describe fully three-dimensional toroidal magnetic fields. SPEC has been deployed to RFX, a reversed field confinement device in Italy, and will be further developed with UK collaborators to try to understand the properties of edge modes that can damage the power plant wall.

The Curtin University Institute of Theoretical Physics has extensive contacts with the IAEA through coordinated research projects to provide collision data for the reactants in fusion plasmas. The locally developed Convergent Close Coupling (CCC) theory is providing accurate data for electron-impact excitation and ionization processes at all of the energies of interest for many of the lighter elements relevant to fusion plasmas.

Theory and modelling activities are large users of high performance advanced computing infrastructure, including the Australian National Computational Infrastructure. More widely, computational projects in the Department of Computer Science at the ANU include model coupling, plasma visualisation, and the development of fusion data grids.

2.4 Materials for fusion power plants

The challenging environment associated with a fusion reactor (radiation, heat flux, chemical compatibility, thermo-mechanical stresses) will require the utilization of advanced materials in order to enable the successful development of fusion energy. New materials to meet the unique requirements of fusion power plants are the subject of increased international research. Recognition of the importance of materials to the practical achievement of fusion power has been the motivation for the design and construction of the International Fusion Materials Irradiation Facility (IFMIF) as part of the ITER Broader Approach program (an agreement between Japan and the European Union, but accessible only by the ITER partners). In Australia materials research relevant to fusion is being undertaken at ANSTO, the ANU and the Universities of Sydney, Newcastle and Melbourne.

Materials for extreme environments

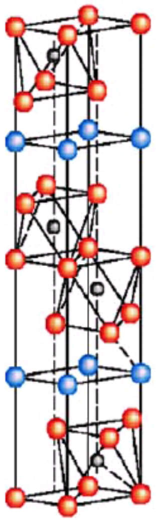


Figure 7: The structure of Ti_3SiC_2

Australia possesses a strong capability in the synthesis, modelling and characterisation of materials that are of potential interest for the demanding environment of a fusion power plant. In the 1970's and 1980's there was considerable interest in the potential roles of TiC and SiC as materials for high radiation environments such as the first wall of fusion power plants. While it is now believed these material would not be the optimal choice for first wall applications, there is renewed interest in these three elements (Ti, Si and C) as they form one of the possible combinations in MAX phase materials. There are over 600 possible combinations in this ternary family and the most studied has been Ti_3SiC_2 (see Figure 7), a material with high melting point, good high temperature strength, high resistance to thermal shock and high electrical and thermal conductivity characteristics, make it essentially both metallic and ceramic in nature.

More importantly it has been discovered to be resistant to radiation damage which is key to applications such as fusion or fission reactors where structural materials are exposed to radiation which can result in atoms being displaced from their regular lattice sites between 10 and 100 times during the material's operational lifetime. Ti_3SiC_2 has demonstrated that it can retain its properties longer than expected under such conditions. Australian research on MAX phase materials has gained international interest and Australian groups are already collaborating with groups in the USA, Europe and China.

Facilities across Australia available to support fusion related materials research also include

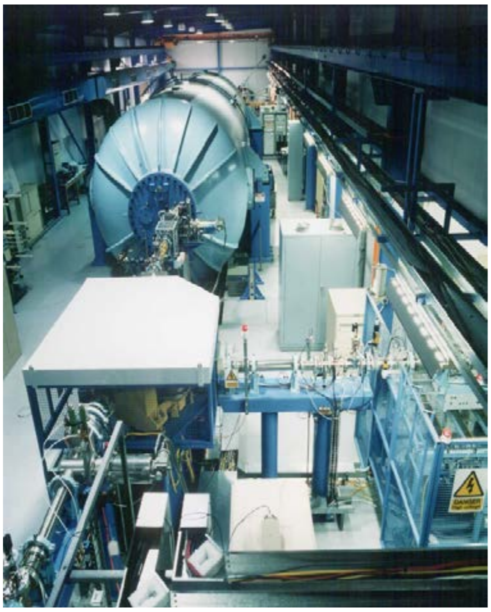


Figure 8: ANSTO ion beam irradiation and analytical facilities; member of Centre for Accelerator Science (CAS).

- Ion and plasma irradiation and characterisation facilities at the Australian National University.
- ANSTO capabilities in modelling and synthesis, as well as ion irradiation facilities (see Figure 8) and the OPAL reactor for neutron diffraction studies.
- Studies of the high temperature stability of MAX phase materials at Curtin University
- Capabilities in synthesis, transmission electron microscopy and a background in the effects of radiation damage in materials at the University of Newcastle
- The ability to grow thin films of MAX phases using magnetron sputtering and to model their properties using first principles methods at the University of Sydney.
- The Australian Synchrotron for materials analysis.

The *Materials for Extreme Environments* (MEE) program at ANSTO focuses on improving material performance for extreme conditions of temperature, pressure, stress or corrosive agents. Although applicable to a broader range of industrial applications, the MEE research program includes investigation of materials for magnetically confined fusion. ANSTO is presently investigating materials suitable for plasma-facing applications where macroscopic erosion and thermally induced failure are challenges any perspective material must withstand. ANSTO has established research projects aimed at investigating and improving the performance of refractory metal alloys, oxide dispersion strengthened (ODS) and enhanced stainless steels, ultra-high temperature materials and novel composite materials. ANSTO has the potential to offer support in the design, synthesis, fabrication and testing of materials and components to complement fundamental research programs in Australia and internationally.

The significance of materials under extreme environments was stated in ANSTO's corporate plan (2010-2015), *"ANSTO, in partnership with the Australian National University, will give strategic priority to providing the Australian Government with insight into the importance of fusion research (and plasma research more generally) and ensure that a new generation of Australian scientists and engineers can participate locally and globally in this important endeavor."*

MAGnetised Plasma Interaction Experiment (MAGPIE)

As part of the infrastructure upgrade to the Australian Plasma Fusion Research Facility, the prototype plasma-material interactions facility (MAGPIE) began operation in early 2011 (see Figure 9). Linear plasma devices (or plasma simulators) such as MAGPIE provide a cost-effective solution for plasma-material interaction studies as they provide:

- Sufficient access to the plasma-material interaction region to deploy a comprehensive set of diagnostics (laser, optical emission spectroscopy, imaging)
- Controlled access to a wide range of fusion-relevant plasma conditions
- Key plasma conditions to study the mechanisms relevant to the degradation of plasma-facing materials in a steady-state fusion device.

The physics of plasma-surface interactions in this complex magnetised boundary plasma could affect future choices in fusion device engineering, and is therefore of great importance to the success of ITER and ultimately of fusion power reactors. Tests of materials began in 2012 in a collaboration between ANU and ANSTO. Building on the success of this program, it is proposed that a steady-state linear plasma device will be constructed that is capable of producing the high-flux conditions that will be generated in a fusion power plant.

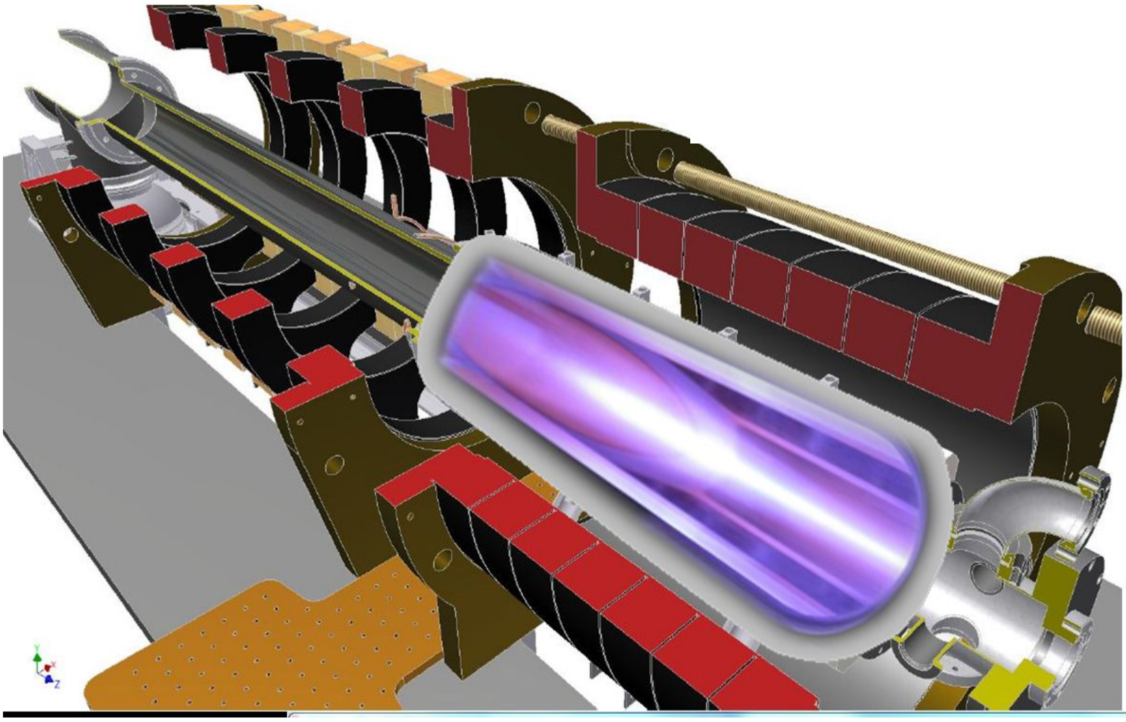


Figure 9: MAGPIE cross-section, with a photograph of argon plasma superimposed, showing the compression of the plasma beam towards the target area in the foreground.

2.5 Data mining of plasma fluctuations

Over the wide range of magnetic configurations accessible in H-1, a great variety of phenomena are observed. Interpretation requires knowledge of the spatial variation (mode structure) parallel and perpendicular to the magnetic field, and the fluctuation frequency spectrum. To distil this information from the gigabytes of data produced by H-1 and other leading international experiments, a data mining technique has been developed.

Data mining is the process of extracting useful information from large databases, such as those encountered in bio-informatics research where it has been used to discover useful information in relation to genetic codes. The data mining technique developed on H-1 is largely automated and groups the thousands of structures found into a small number of clusters of similar mode structure. Based on similarity of the spatial variation in phase, rather than a fit to a pre-determined model, the technique does not rely on prior knowledge. This was important for H-1 as the highly three-dimensional nature of the magnetic field leads to complex mode structures that are not easily represented analytically.

With this technique, it was possible to extract the detailed dependence of mode structure and frequency on the rotational transform or “twist per turn” of the confining magnetic field, producing a very clear result, which has not been matched elsewhere, either in range or level of detail. Following the success on H-1, the technique has been implemented on all the large stellarators in the international program, including the flagship of stellarators, the superconducting LHD device at the National Institute for Fusion Science, Japan. In addition to the physics understanding provided, such projects help to strengthen existing collaborations and to build new ones.

2.6 Basic Plasma Science and Technology

Australia's capability in fusion science and technology is strengthened by a range of basic plasma physics research and technology development that is not orientated specifically toward fusion science, but is fusion relevant. Plasma technology underpins basic plasma physics research, nanoscience and nanotechnology, solar energy, material science and engineering, and ion propulsion.

The Australian Government, through the National Collaborative Research Infrastructure Strategy (NCRIS), has committed $41 million over five years to establish The Australian National Fabrication Facility Limited (ANFF), a comprehensive source of equipment and expertise to service the nation's fast emerging nanotechnology industry. The funding has been augmented significantly with co-investments from several state governments, CSIRO and a number of universities and industry partners. A large portion of this research infrastructure uses plasma-based material processing techniques. As an example, the ANFF node at the ANU has several plasma systems for materials processing. The Department of Electronic and Materials Engineering at the ANU also use reactive plasma etchers, ion implantation systems and plasma deposition tools. The ANU Space Plasma Power and Propulsion Group (SP3) is well known for its particle-in-cell numerical simulations, and has research programs involving experimental and theoretical aspects of applying radiofrequency helicon plasmas to material processing, space science, space propulsion and hydrogen fuel cells.

Groups at the University of Sydney are developing technological plasmas for industry, space and medicine. The School of Physics at the University of Sydney has many years of experience in developing diagnostic techniques, particularly spectroscopy and laser techniques, which contribute to Australia's reputation in plasma diagnostics. It also has magnetic-filtered cathodic arcs, magnetron sputtering, plasma immersion ion implantation and a range of rf plasmas used for surface modification of materials for industrial and medical applications as well as advanced surface characterisation instruments. In addition, electrostatic fusion devices are being developed as alternative hot fusion concepts and novel micro plasma thrusters for maintaining satellite orbits. Other basic plasma science research at the University of Sydney includes the recent study of particulate or dusty plasmas. The latter includes the development of physical concepts for the mechanisms of dust formation, charging and transport in fusion plasmas. In ITER, dust is expected due to ablation and sputtering of the first wall, and tracking this dust is important for maintaining the inventory of tritium in the machine. Macquarie University is well-known for experimental and computational studies of gas discharges used in lasers and ultraviolet light sources.

CSIRO has a wide range of activities in the applications of plasmas. These include experimental, computational and theoretical studies of the formation of nanostructures and deposition of nanostructured coatings by low-pressure plasmas, computational modelling of atmospheric-pressure thermal plasmas, and development of applications of atmospheric-pressure non-equilibrium plasmas. This research has found applications in gas-metal arc welding, a joining method widely used in the automotive industry and elsewhere and in plasma arcs for toxic waste disposal. Welding technology poses a research challenge for ITER, due both to the high neutron and heat flux expected, and restricted access.

The Mawson Institute of University of South Australia promotes a strategy based on strong basic and applied research that will encourage scientific and technological innovation for Australian manufacturing. The institute has a focus on the basic plasma science and engineering that underpins "next generation" manufacturing, providing technology platforms based upon new knowledge and innovation that can be readily integrated into new products

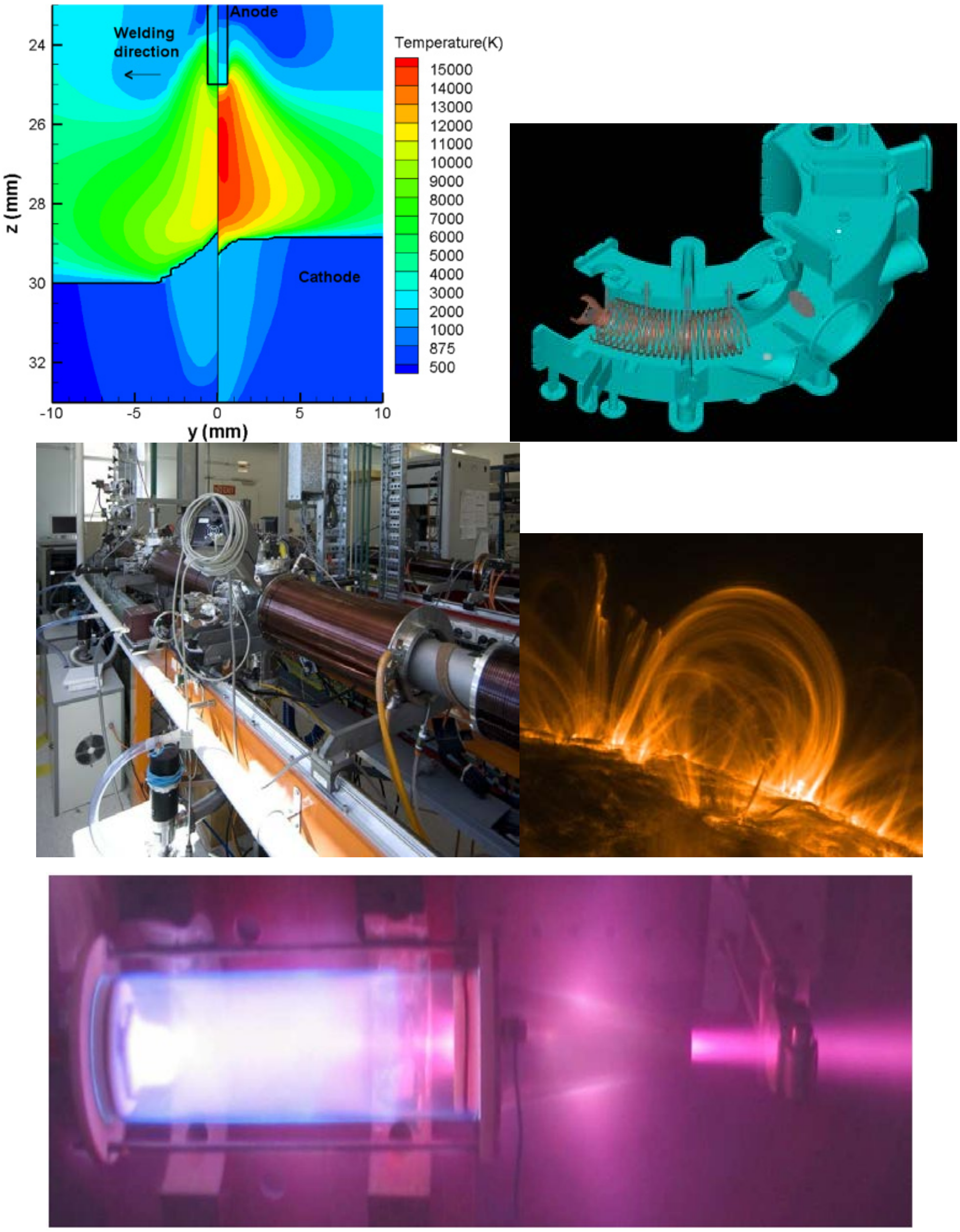


Figure 10: Clockwise from top left: , three-dimensional modelling of the gas-metal arc welding at CSIRO, quasi-toroidal cathodic arc at the University of Sydney, and a solar flare, a space thruster under development at the University of Sydney, and the Australian Positron Beamline Facility, part of the Centre for Anti-Matter matter at the ANU.

and processes. Fundamental to this is the Institute's multidisciplinary approach, building research teams in concentrations that encompass a diverse range of disciplines and collaboration with a range of partners from academia, industry and knowledge-intensive enterprises.

The Institute for Frontier Materials at Deakin University has been created to meet key challenges in material development for areas such as energy, health, environment, and manufacturing. The Institute brings together a wide range of specialised laboratories in chemistry, engineering, biology, physics, materials, mathematics, to name a few, in order to develop new materials that are not only affordable, but also have a low societal cost of manufacture, usage and recycling. Since 2009, a new plasma research laboratory has been developed to produce new materials by tailoring the plasma-surface interface and nanofabrication. The research tackles key areas of energy, biomedicine, nanotechnology, composites, and textile and transport industries.

The Centre of Excellence for Antimatter-Matter Studies is involved in experimental and theoretical atomic and molecular physics, about 10 per cent of which is fusion-related. This centre is hosted at the ANU, and includes ANSTO, Flinders, Curtin, Charles Darwin and James Cook universities, and the University of Western Australia. Research outcomes from this work, especially from Curtin University, feed into the IAEA and NFRI collision databases pertinent to diagnostics and beam heating in fusion plasmas.

Finally, there are many **astrophysics and space science groups** around Australia, including the ANU, University of Sydney, University of Melbourne, University of Newcastle, University of Western Australia, Curtin University and CSIRO. These programs contain a large plasma physics content, much of which is dedicated to the study of magnetised plasmas in space. Particularly relevant to fusion research are activities focused on the Sun, heliosphere and magnetospheres.

2.7 Superconducting Magnet Technology

A key requirement for the realisation of fusion power is the provision of strong (~5T) steady state magnetic fields for confinement. Such fields can only be produced using superconducting coils. Low Temperature Nb-based superconducting coils and the associated cryogenic cooling systems represent about 30% of the ITER construction cost. In ITER, 112 tonnes of low temperature Niobium Tin (Nb_3Sn) superconducting magnets will be used. These will be cooled down to 4K using liquid helium which is expensive, not-readily available in the volumes required and difficult to recycle. The magnet system in ITER is Nb-based technology, and made up of 18 Nb_3Sn toroidal field coils, a 6-module Nb_3Sn central solenoid, 6 Nb–Ti poloidal field Coils, 9 Nb–Ti pairs of correction coils, all operating at 4.2K. A challenge to successor fusion power plants is to reduce the both total cost of the superconducting coils, and the cryogenic cooling requirements

Over the last 20 years researcher scientists at the University of Wollongong's Institute for Superconducting and Electronic Materials (ISEM), have made significant breakthroughs in both Type I (low temperature) and Type II (high temperature) superconductors. A key breakthrough is in the fabrication of wires from the superconductor magnesium diboride (MgB_2) by using silicon carbide (SiC) nanoparticle doping. They have achieved a world record high critical current carrying capacity in superconducting MgB_2 wires (Dou S X *et al.*, *Phys. Rev. Lett.* 98 (9) 097002 (2007)), which can carry one million Amperes per square centimeter in the superconducting state. Due to its higher critical temperature, lower material and manufacturing cost, there is great potential in this emerging superconductor for various practical applications, such as magnets for magnetic resonance imaging (MRI), fault current limiters, power cables, motors, energy storage, generators, magnetic separators, transformers, and fusion.

Helium-free MgB_2 superconductors are a viable option for next generation fusion machines. The massive advantage is that MgB_2 superconductors have acceptable performance at temperatures as high as 20K, well above 4.2K required for conventional Nb-based low temperature superconductors. This temperature difference would provide equivalent poloidal field and correction coils operation, but with one-tenth of the cooling power needs if compared to a conventional system. It is estimated that this development approach could reduce operating costs of the superconducting magnet system by approximately 50%.

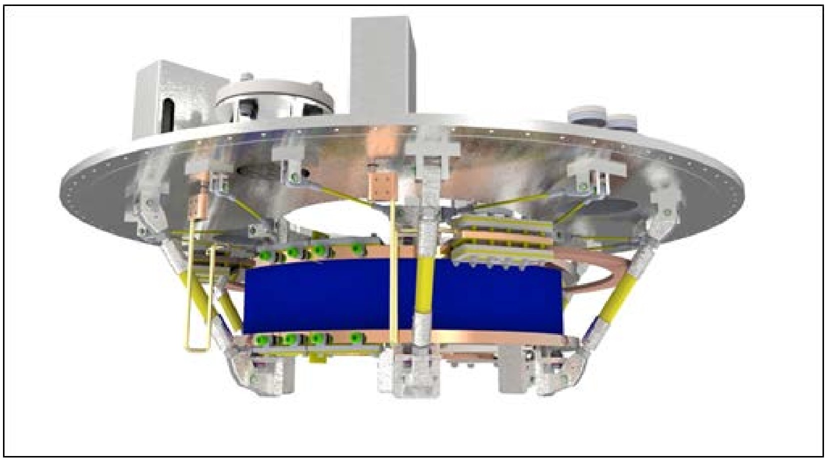


Figure 11: Design of the MgB_2-based coil (cryostat base removed for clarity)

2.8 Inertial Confinement Fusion

Inertial confinement, an alternative to magnetic confinement (which is the focus of this document) employs pulsed high power lasers to compress small pellets of fusion fuel to extremely high densities. Although magnetic confinement is by far the dominant approach, there have been Australian contributions to the theory of compression mechanisms over many years by Professor H. Hora and his colleagues and students at UNSW. [14]

---

[14] H. Hora et al., Shock studies in nonlinear force driven laser fusion with ultra high plasma block acceleration, 24th IAEA Fusion Energy Conference, San Diego, USA, October 2012, Program & Book of Abstracts, p529 (IFE/P6-03)

3. Strategy for Australian fusion Science

Most national fusion programs are supported and coordinated by a central programmatic funding body. Examples include the US Department of Energy, the UK Culham Centre for Fusion Science, the Max Planck Institute for Plasma Physics in Germany, the Korean National Fusion Research Institute, and the European Commission, which coordinates the fusion programs of EU member states. As for these nations, an Australian fusion program will require dedicated program funding. Domestic program analogs include the renewable energy research agency ARENA and our participation in international telescope facilities such as the Square Kilometre Array.

The achievement of some of the major objectives of the 2007 strategic plan has delivered a powerful impetus for future ITER engagement. This updated strategy builds on the achievements of the first plan to strengthen our domestic program and to widen our international linkages. It also proposes the establishment of a formal Memorandum of Understanding between ANSTO and the International Tokamak Physics Activity (ITPA), which operates under the auspices of the ITER International Organisation (IO) and is the primary channel through which fusion scientists share ideas and address physics and engineering problems vital to the success of ITER and the future fusion development program. Membership of ITPA will facilitate collaborations with ITER scientists, including preparing for the possibility of a flagship contribution to the ITER project.

3.1 Building on success – towards an integrated domestic fusion program

To secure a bright future for Australian fusion science, the Australian fusion community is leveraging the success of the first plan:

a) The upgraded H-1 device now underpins a world-class facility capable of attracting some of the world's best scientists. High profile research leaders are being sought to harness these opportunities through mechanisms such as the ARC Laureate Fellowships scheme.

b) The community is fortunate to have two Future Fellows, and is actively seeking new Future Fellowship candidates to grow and sustain capability.

c) With SuperScience seed funding and backed by the ANU-ANSTO MoU for research cooperation, a new "extreme materials" research activity has been established, building on existing activities at ANSTO and some universities. The ANU and ANSTO have committed institutional funds for operational support of new experimental facilities and the hire of research personnel.

Internationally competitive Australian-based fusion research is an essential pre-requisite for credible international collaboration. It is clear that it will be based on the capabilities described in the previous chapter, with the upgraded H-1 and the new materials diagnostic facility as essential components. A vibrant and world-class sustainable domestic program requires ongoing support for technical operations and infrastructure of the Australian Plasma Fusion Research Facility.

3.2 Expanded participation in international fusion programs

International collaboration is widely recognised as an essential component of any Australian-based research program. In the case of fusion science, which has long been an endeavour noted for international collaboration and exchange, there is no place for national activities that are not also enmeshed in broader international programs. International collaboration allows Australia to leverage its investments by gaining dedicated machine run-time on international facilities and access to international databases.

In a recent position paper, *Australian science in a changing world: innovation requires global engagement*[15], the Australian Academy of Science makes a strong case for[16]

> *"...ongoing investment in Australia's links to the global scientific frontiers that enable the nation's researchers and innovators to contribute to, shape and access the best knowledge available around the world, and then apply it in the national interest."*

Our international research engagement is built on activities spanning basic plasma physics, the physics and engineering of fusion materials, fusion theory, integrated modeling and data analysis, and advanced measurement systems. The Australian community now actively and formally participates in programs in Europe, the USA and Asia. These programs span high performance compact tokamaks (MAST, UK), high power advanced tokamaks (DIII-D, US), the next generation superconducting tokamaks in Asia (JT60-SA, Japan and KSTAR, Korea), and the global stellarator program including the billion-dollar class LHD in Japan and the superconducting Wendelstein 7-X experiment under final stages of construction in Germany. These activities also form the backbone of our strategy for participation in ITER.

An outward looking Australian fusion program will provide support for

- program-focused fellowships
- international exchange of scientists and research students
- travel associated with membership of international fusion-related committees

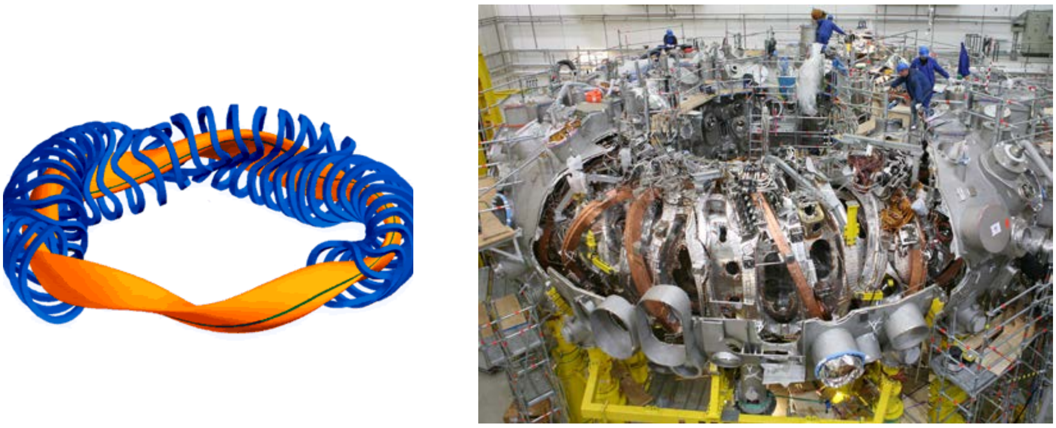


Figure 12: Wendesltein 7-X plasma cross-section and field coils (left), experiment under final stages of construction (right).

---

[15] *Australian Science in a changing world: innovation requires global engagement*, Australian Academy of Science, November 2011, www.science.org.au/sites/default/files/user-content/innovationrequiresglobalengagement.pdf

[16] ibid, p4.

3.3 Engagement with ITER

To facilitate a structured and staged ITER engagement, we would establish a memorandum of understanding (MoU) between the ANSTO and ITPA to formalise Australian participation in ITPA. This important forum allows fusion scientists to share ideas and address physics and engineering problems of relevance to ITER. Such Australian participation will be essential to ensure relevance and currency of the national RD&E efforts. The MoU will define a general enabling framework for collaboration between Australian institutions and the IO and its partner organisations. It will allow Australian scientists to apply for grants, from schemes such as ARC Discovery, jointly with scientists from ITER as partner investigators, under established guiding principles and a common understanding.

3.4 An Australian flagship contribution to ITER

The 2007 strategic plan identified that an ITER machine contribution or diagnostic would be a well-defined Australian contribution in scope, funding, and scale. It would represent a flagship for Australia's national effort in fusion science and would draw on researcher, industry and wider community interest and support. As the national hub of high temperature experimental fusion science, the Australian Plasma Fusion Research Facility will likely play a key supporting role in the design, construction, and testing of any ITER diagnostic contribution.

The Australian fusion science community remains committed to supporting a machine contribution to ITER. Such a contribution will ultimately require dedicated funding which is most likely beyond the scope of existing grant mechanisms.

Some of the diagnostic requirements for ITER have not been allocated to any of the ITER partners. Taking account of the special expertise in Australia and the requirements noted above it is appropriate that several of these be considered for an Australian contribution:

- measurement of flow in the ITER divertor
- measurement of erosion of plasma facing tiles
- measurement of wall surface contamination by tritium

The first of these is perfectly suited to the ANU's coherence imaging technology and is clearly a case where Australia's contribution would exceed any possible contribution by another party. All three measurements relate to plasma-wall interaction, and it is conceivable that a contribution that is initially focussed on imaging could be expanded to encompass other aspects of plasma-wall interaction.

A contribution to ITER based around the above systems would exploit a number of favourable synergies that exist across the breadth of Australian fusion science:

- With its complex magnetic structure, the ability to rapidly vary it and the ability to provide enviable diagnostic access, the upgraded H-1 Heliac at the APFRF will provide a toroidal plasma confinement environment suitable for developing ITER diagnostic systems.
- Our modeling and theory capabilities are well matched to the challenges of understanding the physics of the fusion reactor plasma edge and divertor flows. In particular

  - We have the necessary expertise in probabilistic and other advanced inverse procedures required to interpret the imaging data
  - The locally developed Convergent Close Coupling (CCC) theory can compute the essential cross-sections required to develop credible plasma divertor and boundary layer transport models and
  - We have the experience in integrated modeling, 3D physics and burning plasma science required to couple boundary and plasma core physics models. The plasma edge in ITER is likely to be fully 3D owing to the use of resonant magnetic field perturbation coils, which are proposed to mitigate edge localised modes (ELMs).
- Materials expertise at ANSTO and at universities across Australia, together with the new materials diagnostic facility at the ANU could deliver improved plasma-facing materials. Using divertor plasma and materials transport models validated by coherence imaging results on ITER, it may be possible to extrapolate the performance of locally developed and tested advanced materials to the extreme environments encountered at the boundary of next step fusion power plants such as DEMO.

A case study of a divertor coherence imaging diagnostic for ITER is given in Appendix 1.

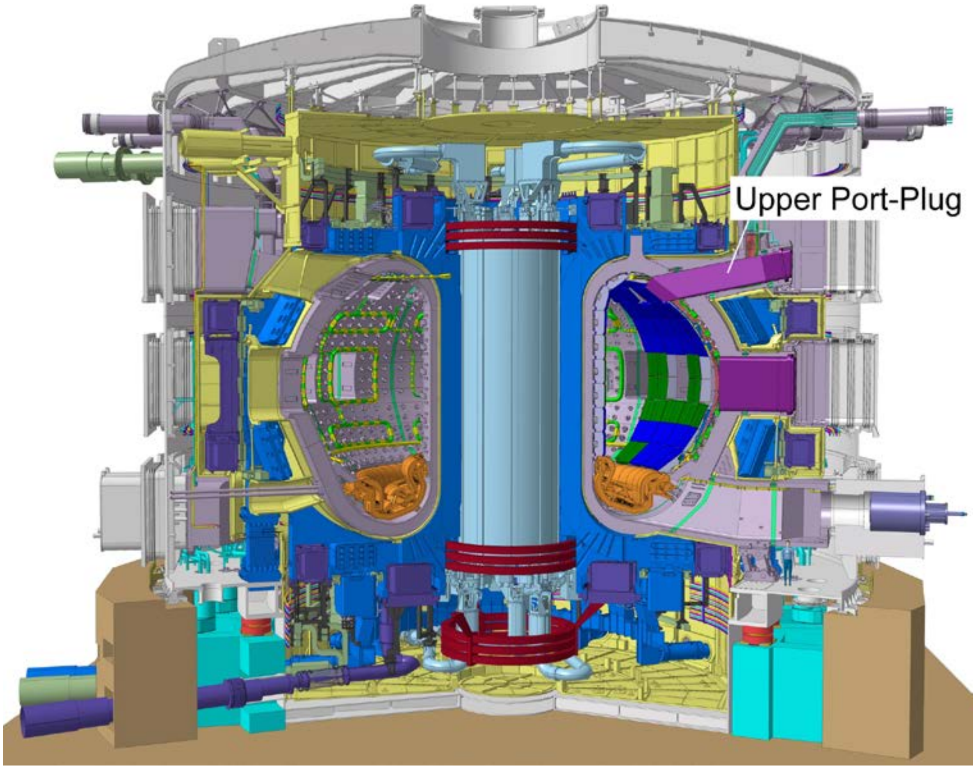


Figure 13: ITER and diagnostic port plugs (purple), which slot into the vacuum chamber. A divertor coherence imaging diagnostic would slot into one of the upper ports.

3.5 Budget for the program over 5 years

The proposed fusion science program will cement a sustainable national capacity in the field and will enable high profile Australian programmatic contributions to ITER through targeted ITPA topical groups, as well as the development of the stellarator concept and new fusion materials ahead of a demonstration fusion power station.

This budget comprises support for the domestic program through APFRF infrastructure and operating costs and research fellowships. The international components include the conceptual design of an ITER diagnostic and prototype, and travel and research funding in support of ITPA activities. APFRF budget items and the diagnostic system conceptual design/prototype would be allocated to, and managed by the APFRF. The remaining items would be managed by ANSTO through a management committee drawn from the fusion science community as described in Appendix 2.

Five year costing in support of the domestic program, including research engagement with ITER is given in Table 3.

Program fellowships	7 x 5 year ($157k per year)	**$5.5m**
APFRF: operating and research support	($600k per year x 5)	**$3m**
APFRF: enabling infrastructure	high power, high flux plasma fusion materials facility.	**$5m**
ITER machine contribution: Conceptual design and prototype	Engineering/modeling support, travel and hardware systems	**$1.8m**
Secondment and Travel (ITER/ITPA)	ITPA/IEA meetings and secondments	**$0.5m**
Management and Outreach	(.5FTE mgmt, .25 FTE outreach)	**$0.5m**
TOTAL		**$16.3m**

Table 3: Prospective five-year costing in constant 2015 $A for the proposed Domestic Fusion RD&E program

Program fellowships

These competitive appointments will support work in targeted ITPA topical groups, strategic development of the stellarator concept, and collaborative fusion materials research. ITPA topical groups where Australians have globally recognised expertise include Diagnostics; Energetic Particle Physics; MHD, Disruption and Control; and Divertor and Scrape off Layer. At least three fusion program fellows will be employed in support of the research tasks and activities that will attend participation in the ITPA program.

The stellarator concept has the potential to provide steady-state plasma confinement suitable for base-load power generation. Program fellows may be appointed in support of the IEA Implementing Agreement on the Stellarator/Heliotron concept, to which Australia is a signatory, thereby capitalize on recent major H-1 stellarator infrastructure improvements.

A challenge for fusion power is the development of so called “extreme materials” capable of withstanding the high neutron and heat flux of a power plant. Program fellows may be appointed in support of the community-wide program in advanced materials, including the joint ANSTO-ANU collaboration on “Extreme Materials for Fusion”.

The experience required for these positions indicates appointment at a level comparable to ARC Fellow step 2, which is costed at $157k/pa including 28% salary overheads and a small allowance for incidentals.

APFRF operations

Approximately $600k per annum is required to maintain and operate the enhanced world-class Australian Plasma Fusion Research Facility. This includes support for a half-time Facility manager, three dedicated engineers to maintain electrical, mechanical, vacuum, diagnostic and software systems, and to provide for routine maintenance and consumables.

APFRF infrastructure

The prototype MAGPIE device was designed as a “proof-of-principle” pulsed plasma-material interaction device. The next-step materials testing facility will access the power and RF heating systems available to H-1 for continuous operation that will allow materials testing under sustained high-power fluxes. The proposed budget will allow for high temperature components including the vessel, target, antenna chamber and the vacuum system, connection to the existing high capacity H-1 power and cooling systems, and steady state thermal, optical and microwave diagnostics.

The design criteria for the high-power linear plasma device include high plasma density and low electron temperature, providing reactor relevant heat and particle fluxes, a system size that is larger than that of important length scales of relevant physical processes and the simulation of the complex geometry of the Fusion reactor divertor. An important aspect of this enhanced device, not available on MAGPIE, is continuous operation and a target exchange and surface analysis chamber so that surface analysis can be performed without breaking vacuum. This high-power plasma device, with a much simpler magnetic configuration than the H-1 Stellarator, will increase capacity to conduct research in nanoscience, diagnostics, astrophysics, material processing and plasma thrusters.

Budgetary estimates for an indicative design:	**$M**
High temperature vacuum vessel, vacuum pump system with high pumping speed, throughput and tolerance of particulates, and sample exchange system.	**0.8M**
Heating and Power systems:	
RF Antenna and motorised matching system including instrumentation Connection to H-1 power and RF systems (total value > $5M) 28GHZ 40kW continuous electron heating system for dual use between H1 and the new materials facility Auxiliary power supplies for magnetic field tailoring/modulation.	**1.1M**
Plasma Composition Diagnostics:	
In-situ surface analysis, Energy resolving Mass Spectrum Analyser, Residual gas analysis system, Langmuir probe systems	**0.8M**
Optical Diagnostics:	
Laser diagnostics: Thomson scattering system, Tuneable scattering system and associated cameras/detectors Passive optical diagnostics (imaging spectrometer, Coherence imaging systems) Electronic instrumentation	**1.1M**
Fabrication and construction	**1.2M**
Total	**$5M**

Coherence imaging system for ITER

A description of the Coherence Imaging system proposed for ITER is detailed in the Appendix 1. The $1.8 m budget will provide for engineering and research support ($270K x 5 years = $1.35m) to develop the conceptual design of a system that could be installed on ITER. The balance of the budget will be used to build a working prototype of the ITER real-time imaging system that will be tested and benchmarked on the H-1 Heliac at the APFRF. It is anticipated that this work will be conducted with input and guidance from the ITPA Diagnostics committee.

ITPA Secondment and Travel

ITPA membership requires attendance at topical group meetings held twice yearly. Over five years to support four ITPA topical groups and the relevant IEA Implementing Agreements will require an average of 2 working group/executive council meetings per year for each group at $5k per person. Much of the work of the ITPA is highly collaborative, necessitating secondments of staff abroad for periods of 3-6 months. The budget for this activity is estimated as follows: Assuming half the IEA council meetings can be combined in the same travel with ITPA meetings, allowance is made at $5k per person for 2 meetings of 4 ITPA groups and one IEA executive council over 5 years = (2 × (4+1) × 5y × 5k) = $250k + 8 x 3month secondments ($20k each) + 3 x 6month secondments ($30k each) = $0.5m total.

Management and Outreach

A skilled cognizant manager will be required to oversee and report on the program. Duties of the manager would include facilitation of domestic and international collaboration, oversight of the fusion fellowship program, coordination of international travel and secondments totalling 0.5FTE, and publicity and outreach totalling 0.25 FTE.

3.6 A timetable for action

Leading into the program, we will consolidate recent gains and seek an MoU agreement with the ITPA. This incremental approach will hopefully allow the Australian community to establish and grow scientific linkages with ITER using existing funding schemes.

The launch of the 5-year program in 2014 will follow the successful completion of the APFRF Super Science upgrade. It will see the commencement of ongoing operational support for the Australian Plasma Fusion Research Facility and its activities, the construction of a new plasma materials diagnostic testing facility, formal engagement with ITPA and expansion in ITER-related research activities, and the first steps towards the development of the flagship ITER contribution. The 5-year duration of the program see the development of a fully tested prototype ITER machine contribution based on coherence imaging technologies.

2014	Release of Fusion Science Strategic plan (this document). MoU negotiations with ITER initiated
2015	MoU with the ITPA coordinating committee signed. Commence design of divertor imaging diagnostic system. First full-participation in ITPA meetings
2016	Program launch. Program management and governance arrangements established. First call for applications for Australian Fusion Program Fellows (ongoing). First call for travel and exchange grants (ongoing). First annual conference (ongoing).
2017	Divertor diagnostic conceptual design review. Commence construction and testing of prototype diagnostic system.. Development of high-power Materials Diagnostic testing Facility. Engagement with ITER research program in key areas of Australian expertise.
2018	Complete detailed design of full-scale ITER machine contribution.
2019	Conclusion of first phase of Australian ITPA contributions. Review of program outcomes. Preparation of revised fusion strategy.
2020	**First ITER plasmas**

Table 4: Time line for the proposed fusion RD&E program

Appendix 1: Case study of an ITER divertor imaging diagnostic

The main function of the ITER divertor is to exhaust helium “ash” and plasma impurities, and to handle the associated waste heat loads. Maintaining its critical operational function in an extreme environment poses a range of unmet materials and diagnostics challenges. In this “case study” we consider divertor-plasma flow imaging – an area where Australia has a unique and world-leading capability.

As described elsewhere in this document, advanced optical “coherence imaging” (CI) systems developed at the Australian National University are now deployed on frontline fusion devices in the United States (DIII-D tokamak), Korea (KSTAR superconducting tokamak), UK (the MAST tokamak) and Germany (ASDEX-Upgrade)[17]. These systems are used for fast 2D imaging of essential plasma properties such as ion flows (Doppler CI) and temperature and internal magnetic and electric fields spanning the region from the plasma edge to the core. Displacing now obsolete and expensive multiple-discrete-point measurement systems, they represent a step-function leap in measurement capability.

In his extensive report on proposed ITER infrared and visible imaging measurement systems R. Reichle from the ITER organisation notes that[18]:

“The measurement of divertor flow is one of the required measurements for which no diagnostic concept has yet been identified in the ITER baseline. Oblique views into the divertor - not entirely dissimilar to the ones envisaged for the upper port visible infrared system - have been used recently for Doppler and Motional Stark Effect Imaging on the DIII-D and TEXTOR tokamaks. It might be interesting to study whether it is applicable to the geometry of the upper port visible infrared and thus become a useful add-on to the planned system. 19”

For example, Doppler coherence imaging of the divertor region of DIII-D has produced the first images of the impurity carbon ion flow in the plasma edge[20]. These studies are very important for validating transport models and for understanding material erosion and deposition patterns in the divertor. A CI system (Figures 14 and 15) has also been deployed on MAST tokamak in the UK to image the edge ion temperature and flow and also in the core of the TEXTOR rokamak in Germany[21]. Coherence imaging is the only technically feasible diagnostic concept that can deliver images of the divertor and edge flows with the spatial, temporal and flow-speed resolution specified in the ITER baseline diagnostic description. As such, CI optical systems represent a natural pathway for Australia to make a valuable technical contribution to ITER.

---

[17] J. Howard, *Coherence imaging spectro-polarimetry for magnetic fusion diagnostics,* J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 144010

[18] R. Reichle, ITER document: DDD_Upper_Port_VIS_IR_35L5US_v1_7

[19] J. Howard, et al, "Doppler coherence imaging and tomography of flows in tokamak plasmas" Review of Scientific Instruments, Vol 81, 10E528 (6pp) (2010)”

[20] ibid

[21] J. Howard, R. Jaspers, O. Lischtschenko, E. Delabie and J. Chung, *Imaging charge exchange recombination spectroscopy on the TEXTOR tokamak* , Plasma Phys Controlled Fusion, Vol 52, 125002 (10pp) , (2010)

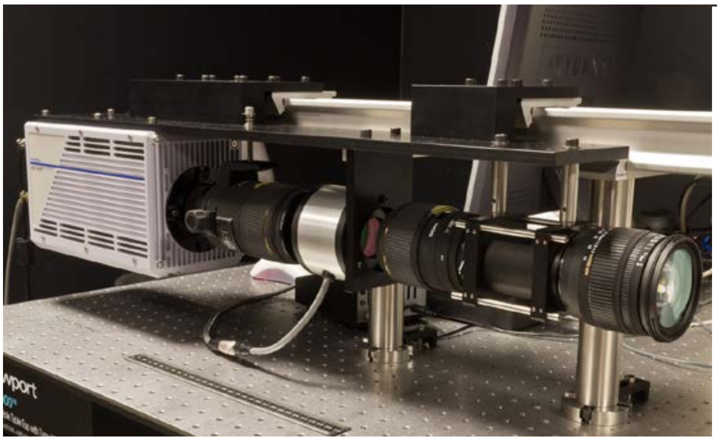


Figure 14: Photograph of the optical CI system used for flow and temperature measurements on the MAST tokamak in the UK. The optical cell replaces a large spectrograph and produces a 2D image of flows and temperature rather than a set of point measurements. (Courtesy Scott SIlburn)

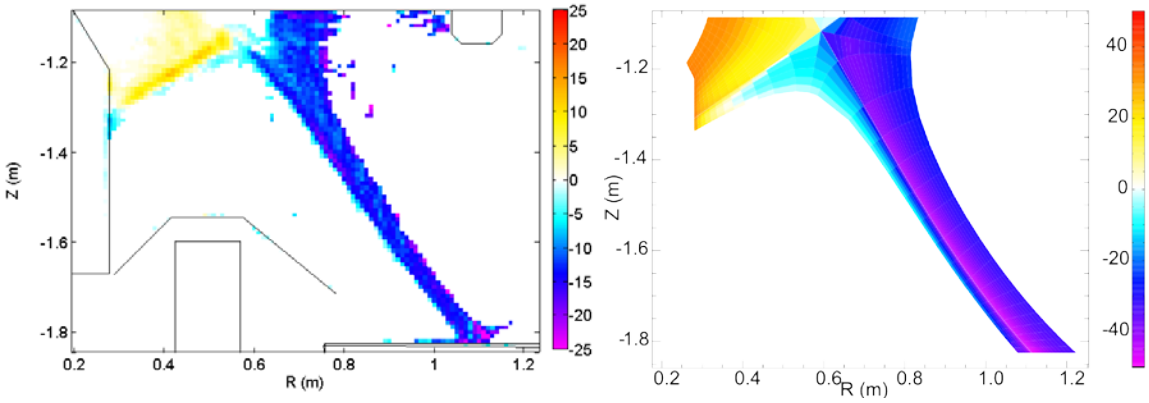


Figure 15: Tomographic reconstruction of the carbon ion flow speeds in km/s (left) in the MAST divertor compared with modelling (right) The "X" contour separates the high temperature plasma (top) from the divertor plasma. Supersonic plasma flows parallel to the magnetic field lines transport exhaust plasma onto the divertor floor and to the pumping ducts. (Courtesy Scott SIlburn)

Phase I: Coherence Imaging System Conceptual Design Study

Figure 16 shows a cross-section of the ITER core, the three primary diagnostic access ports (pink) and the surrounding building and infrastructure. An Australian CI system would be an add-on instrument that would take advantage of the optical access being developed for the upper and equatorial port visible/infrared wide angle viewing systems. The CI instrument would be stationed in the Port Cell region outside the Bio-Shield. Details of the upper port optical layout and the resulting internal views of the machine wall and divertor are shown in Figures 17 and 18 respectively.

The first step in developing a system for ITER would be to undertake, in collaboration with the ITER Organisation (IO), a conceptual design study of the divertor and wall Doppler imaging systems. With an appropriate Australia-IO Collaborative Agreement in place, the Australian community would seek support from domestic programs such as ARC Linkage and Discovery to undertake the conceptual design study.

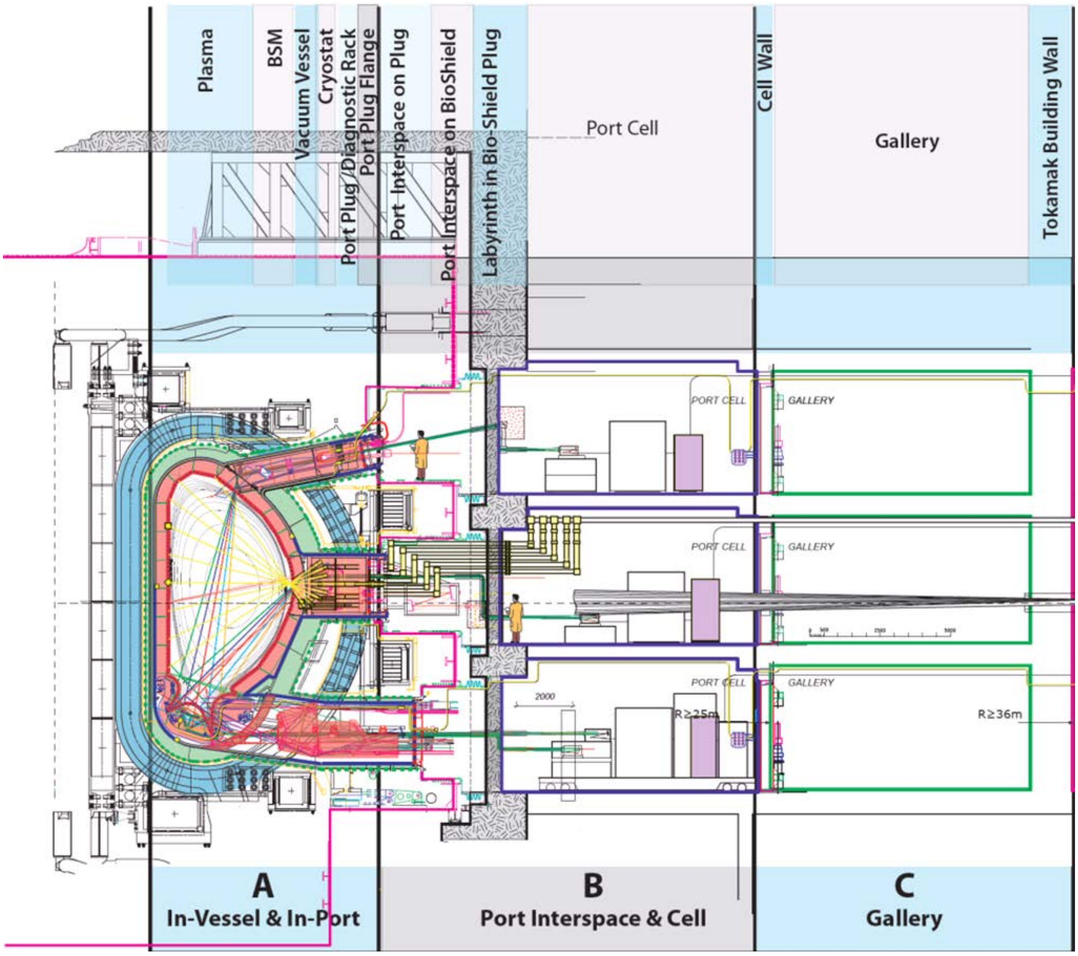


Figure 16: Cross-section of the ITER tokamak showing the three primary access port levels and associated diagnostic zones. The divertor resides at the bottom of the machine. (Courtesy R Reichle, ITER).

Among many important issues, the conceptual design study would

- Define the measurement scope: what species and ionization states should be targeted?
- Develop a full optical model in order to optimize the viewing requirements and required infrastructure.
- Ascertain the expected spatial, temporal and velocity-space resolution
- Explore options for simultaneous ion temperature measurements.
- Optimize the instrument design (robustness, alignment, thermal effects, calibration etc) + integration + costs
- Assess the possibility of accurate helium exhaust estimates
- Examine the feasibility of flow tomography in the presence of contaminating wall reflections. How many measurement stations are required?
- Assess the need for internal port plug polarization discrimination optics for Zeeman-effect spatial tagging
- Address key materials issues relating to mirror degradation under plasma exposure and neutron bombardment.

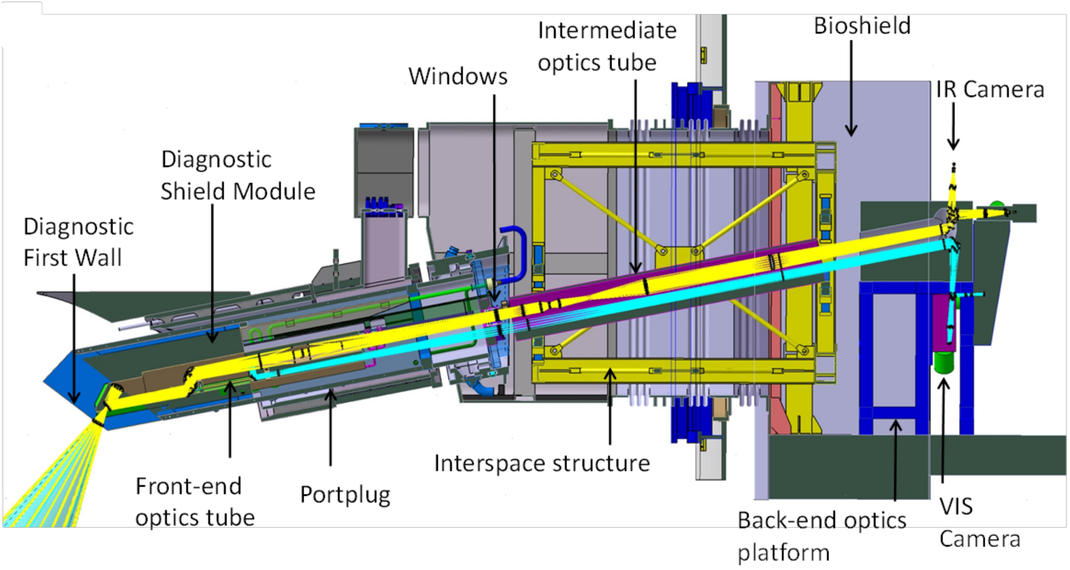


Figure 17: CAD drawing of the Upper Port optical layout and optical ray paths (shown in cyan). The CI system would be stationed outside the bio-shield.

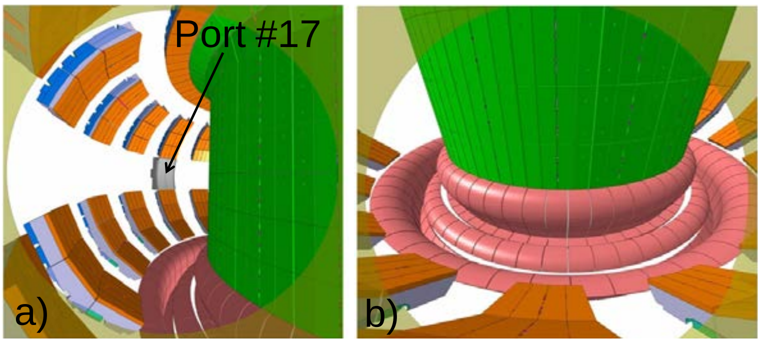


Figure 18: Wide angle divertor views from an equatorial port. a) Tangential view direction and b) direct view. (Courtesy R Reichle, ITER).

The conceptual design would be subject to a formal ITER Design Review. Assuming a favourable outcome, a decision would be required on how best then to proceed.

Phase II: Implementation and Operation

Implementation would require Australian scientists and engineers to undertake device construction, integration and installation. Challenges would include interfacing and compliance with ITER machine engineering constraints, nuclear qualification, remote calibration and operations. Theoretical and computational support would allow the measurement results to be compared with models in order to secure physics outcomes that would inform the ITER program and guide the design of future commercial power plants.

Potential outcomes

Provision of a baseline diagnostic system for ITER would

- Leverage a multi-billion dollar science experiment at relatively low cost, ensuring knowledge-sharing and future high-impact outcomes for Australian science.
- Secure an Australian readiness and technical capability in fusion science
- Provide opportunities for ANSTO advanced materials and Australian industry

Appendix 2: A Framework to Advance Australian Fusion Science and Technology

Preamble

The international commitment to construct the ITER device has seen a rapid expansion in the international effort to harness fusion energy. The Australian Fusion Strategic Plan (AFSP) "*Powering Ahead: A National response to the rise of the International Fusion Power Program*" (January 2013) aims to ensure Australian is ready to participate in and benefit from the emergence of fusion power. Achieving this will require sustained investment in the national fusion program and expanded engagement and collaboration with the international effort, including a significant Australian involvement with the ITER project through the framework for internationally coordinated fusion research activities on ITER science, the International Tokamak Physics Activity (ITPA).

The purpose of this document is to articulate the roles and responsibilities of the key Australian fusion research entities and to establish a set of guiding principles, or a framework, that will ensure that key elements of the AFSP are supported and implemented in a coherent and coordinated fashion.

The Parties:

- The Australian Nuclear Science and Technology Organisation (ANSTO) is Australia's premier nuclear science and technology institution. It is the formal Australian contact organisation for the International Atomic Energy Authority (IAEA).
- The Australian National University (ANU) Research School of Physics and Engineering supports a critical mass of research in fusion science and hosts the Australian Plasma Fusion Research Facility (APFRF). The APFRF, comprising the toroidal plasma experiment, the H-1 Heliac, and the linear materials facility MAGPIE, is Australia's premier plasma fusion research facility.
- The Australian ITER Forum represents the interests of the wider Australian fusion science community including scientists, engineers, research managers in advancing Australian fusion research and building towards participation in ITER.
- The Australian Institute for Nuclear and Science Engineering (AINSE) has traditionally helped coordinate and fund fusion-related activities and meetings between Australian universities and research institutions.

Roles and Responsibilities of the Parties:

ANSTO

The AFSP identifies ANSTO, as Australia's formal authority on nuclear issues, as the appropriate Australian legal entity to negotiate and conclude any collaborative agreement with the ITPA Coordinating Committee to enable formal Australian participation in ITPA. The parties endorse ANSTO's role to undertake negotiations with the ITPA Coordinating Committee and ITER Director-General on behalf of the Australian fusion science and technology community (hereafter simply the Community) to achieve this goal. ANSTO would also constitute a management committee drawn from the fusion science community to oversee and manage any new non-APFRF budget. In later years, ANSTO would also be the body through which any formal Australian participation in ITER is negotiated.

ANU

As the national centre for fusion research, the ANU will

a. Expand and promote the domestic fusion research effort through new domestic collaborations and outreach.
b. Consolidate already extensive international linkages and take advantage of new opportunities to showcase Australian fusion technology and knowhow.
c. Through the auspices of the APFRF Board, secure and grow future operations of the APFRF.

In so doing, the ANU together with the APFRF Board, will advance and promote the goals of the AFSP.

Broader Australian fusion science and plasma research community

The broader Australian research activity in fusion science, the underpinning plasma science and technology, and fusion materials spans the University of Sydney, University of Newcastle, Curtin University, the Mawson Institute, CSIRO, and Macquarie University. Fusion-relevant activities in these institutes will expand and further develop international links.

Australian ITER Forum

The Australian ITER Forum (www.ainse.edu.au/fusion) will continue to promote Australian Fusion Science and Technology on behalf of the Community both domestically and abroad. These activities will also promote and advance the AFSP.

AINSE

AINSE will continue to support fusion-science engineering related activities across the nation through student support and advocacy. Consistent with its institutional coordinating role, AINSE will remain an important conduit or mechanism for new collaborators to participate in the national fusion science plan.

Glossary

ANSTO	Australian Nuclear Science and Technology Organisation
ANU	Australian National University
APFRF	Australian Plasma Fusion Research Facility
ARC	Australian Research Council
CCFE	Culham Centre for Fusion Energy, UK
CI	Coherence imaging
DIII-D	Doublet IIID, a large tokamak in San Diego, USA
EU	European Union
H-1	H-1 National Facility
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFMIF	International Fusion Materials Irradiation Facility
IFERC	International Fusion Energy Research Centre
IFRC	International Fusion Research Council
ISL	International Science Linkages
ITPA	International Tokamak Physics Activity
LHD	Large Helical Device, National Institute for Fusion Science, Japan
MAST	Mega Amp Spherical Tokamak
MHD	Magnetohydrodynamics
MoU	Memorandum of understanding
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Cooperation and Development
PMSEIC	Prime Minister’s Science, Engineering and Innovation Council
RD&E	Research, development and education
SP3	Space Plasma Power and Propulsion Unit, Plasma Research Laboratory, ANU

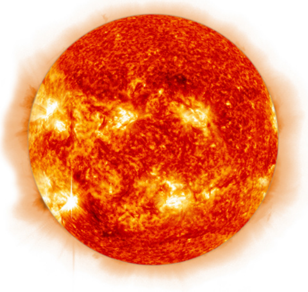
Acknowledgements

This document was commissioned by the ANU, ANSTO, and the Australian ITER Forum on behalf of the Australian fusion science and engineering. Honorary Associate Professor Brian James from the University of Sydney was appointed as convenor, and a working group appointed to assist with compilation of the document. The working panel comprised:

- Honorary Associate Professor Brian James, University of Sydney (Convenor)
- Dr Richard Garret, Australian Nuclear Science and Technology Organisation
- Dr Barry Green, University of Western Australia
- A/Prof. Matthew Hole, Australian National University
- Prof. John Howard, Australian National University
- Prof. John O'Connor, University of Newcastle

What is fusion and why fund it?

Fusion is the process that powers the Sun and the stars



Fusion power offers millions of years of clean, safe, base-load power

Australia has world-class fusion facilities

Our international research collaborations address key challenges to realise fusion power

We have an opportunity to contribute to the $20 billion international fusion program, ITER