The Australian Plasma Fusion Research Facility

The completion of 4 milestones, one 3 months early, and the progress on milestone 15 keeps the
project one milestone ahead of the number originally agreed to for this quarter.  As foreshadowed
in the first Annual Business Plan, adjustments in priorities and other factors have led to moving
some milestones forward and others back, as evidenced by the milestone number being out of
order in some cases.  For simplicity the numbers relate directly to the original agreement, but dates
reflect any changes in the ordering of milestones.

**Milestone 12:  Commission new fast timer and trigger system  31st December 2010**

The trigger and timing system is an essential part of H-1 infrastructure, which required upgrade to
provide a wider range of timing signals, and integration with the upgraded control system.  The
existing “TTL” based system was limited to 3 digits accuracy and was the only remaining function of
the obsolescent ring-bus control stations.  Requirements for a new system were compiled allowing
for future expansion, resulting in the 24+ channel fibre optic based design summarised in
Attachment A.

This milestone was considered to be 80% complete in the December milestone report.  It has now
been modified as indicated in the previous milestone report, and is now installed, commissioned
and operational.  **Complete**

**Milestone 15:  Create a database of Magnetic Configurations  31st March 2011**

This milestone was affected by delays in filling the position responsible for this task.  An
international applicant was found to be the best-qualified for the position, but visa and other delays
meant that Dr. Siewald arrived just one month before the deadline.  As explained in more detail in
Attachment B, the project has now been defined, and a database of more than 100 configurations
has been generated, but work remains on the provision of programming interfaces and developer
tools.  **1/3 Complete**

**Milestone 17:  Commission Current Controller  31st March 2011**

The precision current controller allows more flexible access to plasma configurations by providing a
third current parameter to supplement the two controls parameters of the dual 14000 A power
supply.  Commissioning has been completed including in-situ operation of the complete system at
the maximum continuous current with cooling turned off to highlight any overheating, and
extensive bench tests of the solid state regulator at currents up to 89A, well above the
requirement.  Stable operation was observed, and thermal imaging showed no unexpected
temperature increases.  A brief report is in Attachment C.  **Complete**
Milestone 22: Specify Components required for the Vacuum System Upgrade  31st March 2011

Milestone 22 was brought forward in accordance with the Annual business plan 1. The milestone has been expanded in scope to include a plan for the vacuum upgrade process, which prioritises the upgrade, and coordinates it with the long break in operations for the upgrade of the radiofrequency heating system. The major items required for the vacuum upgrade are turbo-molecular pumps. Changes in the design of these, in particular magnetic bearings, have required re-evaluation for use on H-1. Suitable replacements now have been identified and the plan for the remaining aspects of vacuum enhancement described in the agreement is outlined in Attachment D. Complete

Milestone 20: First plasma produced in satellite prototype  30th June 2011

This milestone has been completed three months ahead of the original schedule because of increasing interest in this facility, the appointment of Future Fellow Dr. Cormac Corr and the efforts of two graduate students. The Materials Diagnostic Development Facility (MDF) is intended to provide a test-bed specifically for developing and testing diagnostics for plasma-materials interaction under conditions relevant to the edge of fusion reactors. Infrastructure including powerful computer controlled magnet system and power supplies, radio frequency source and vacuum system was commissioned early this year, enabling first plasma in early March. Interest has already been shown by material scientists and engineers at ANSTO. The final version will leverage the extensive power system and diagnostic infrastructure of the H-1 Facility as described in more detail in Attachment E Early Completion

Upcoming Milestones

At this stage, we expect to meet the milestones for June 30th and complete the outstanding work in milestone 15. Proposed adjustments to some milestones beyond that are detailed in the Second Annual Business Plan.

Draft

Attachment A: Brief Report on the Commissioning of the Fast Timer and Trigger System
Attachment B: Progress Report on the Creation of a Magnetic Database
Attachment C: Brief Report on the Commissioning of the Current Controller
Attachment D: Vacuum Upgrade Plan
Attachment E: Brief Report on Milestone 20: First Plasma in the MDF Prototype
Milestone 12: Commission new fast timer and trigger system

The trigger and timing system is an essential part of H-1 infrastructure, which required upgrade to provide a wider range of timing signals, and integration with the upgraded control system. Requirements for a new system were compiled allowing for future expansion, resulting in a 24 channel fibre optic based design, with a second controller (PB2) for redundancy, supporting 20 additional channels in normal use. The new Fast Timer and Trigger System is now installed, commissioned and operational.

The figure shows the two control units (PB1, PB2) located in the screened data room, and the five “patch” panels which send the pulses to five remote stations around H-1, via optical isolation for best noise immunity. The remote stations echo the pulses from the control units and like the control units, show the presence of output by pulsing a green indicator light. Control of signal paths and optical fibre lengths keep timing errors between channels to no more than 15ns, and the time resolution is 16.7ns.

Each of the 20 channels can generate up to thousands of pulses with minimum width and separation of 90ns. A user-friendly interface screen is shown in Figure 2,
displaying programming for a 6 pulse sequence with pulse times of 10μs, 100μs, 10μs, 10μs, 1ms, and 10μs.

Figure 2: User Interface for defining a pulse train.

As part of the project, a design, commissioning and test report was generated. The block diagram from this report is shown in Figure 3 (over), and can be compared with the photograph in Figure 1, which shows hardware to the left of the fibre optic links. Work is now underway on the second generation of software, based on user experience with the commissioning software and final integration into the control system.
Figure 3: Trigger and Timer System Block Diagram. The "FIBRE OPTIC" links in column 3 mark the division between the control station left of the links and the five remote stations on the right.
Milestone 15: Create a database of Magnetic Configurations

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Introduction
The Magnetic Configuration database provides user-access to various data related to the H-1 magnetic geometry. The target users of the database are experimentalists and theorists working on H-1. Most research carried out on, or using models of, H-1 requires accurate and specific information about aspects of a magnetic configuration. Supplying this information from a central database reduces duplication of work by individual researchers, and provides reference configuration data for collaboration. The database consists of a set of pre-calculated standard configurations, an API for on-the-fly computation of user-requested configurations, and additional developer tools. For the first stage, a data base of vacuum (or low plasma pressure) configurations will be implemented. Following this, and taking into account user feedback, a similar project will be undertaken for finite pressure configurations. This introduces an extra parameter (plasma pressure ratio $\beta$) and considerably increases the computational requirements, because a magnetic equilibrium has to be calculated in three dimensions for each configuration. The for each database, the task has been divided into three parts, the main database of pre-computed configurations, provision of a library of subroutines to simplify common analysis techniques (API below), and more advanced software tools (Developer Tools below).

Pre-computed configurations

Overview
Some magnetic configurations are so frequently used that it is convenient to provide quickly accessible pre-computed reference data. The most frequently accessed configurations of H-1 are those with all field coils connected in series apart from the helical winding. The ratio...
currents in the helical winding to the poloidal field coil is known as "kappa h". The pre-computed configurations are those accessed in a typical "kappa h scan", where kappa h ranges from 0 to 1.2 in 0.01 increments, a total of 121 configurations. The HELIAC code has been used to compute the configuration data and key magnetic configuration data including rotational transform, magnetic well and Poincare plots in various image formats along with input files are contained in the database for each of the pre-computed configurations as described below.

The front page of the configuration database website (http://h1svr.anu.edu.au/configurations/) shows summary information for the most commonly used H-1 configurations, "Standard configuration" and "Full helical configuration". For both configurations, the phi=0 Poincare plot is shown along with the rotational transform profile. Below the summary information table is a list of all pre-computed configurations. Each configuration has a unique configuration identifier string (config_id), which serves as a URL path component of the configuration description webpage http://h1svr.anu.edu.au/configurations/config_id.

The configuration description page

The pre-computed kappa h configurations have config_id values in the format "kha.bc", where a.bc is the value of kappa h. For example, the kappa h = 0.47 configuration has config_id = "kh0.47", and the configuration description URL http://h1svr.anu.edu.au/configurations/kh0.47 The configuration description page contains: links to HELIAC input files and plots of rotational transform and magnetic well profiles as well as Poincare plots for constant phi surfaces from phi=0 to phi=120 at 10 degree intervals. For each plot, links are provided to high-resolution raster (PNG) and vector (SVG) image files.

Application Programming Interface

An Application Programming Interface (API) is essentially a user interface for programming languages. The API is being developed to allow access from H1 data system client libraries (for IDL, Python, etc) and the H1 data web interface.

Coordinate transform

Manipulation of coordinate systems is required for experimental work, e.g. transform from laboratory (cartesian/cylindrical) to plasma coordinates, and theoretical work, e.g. transform to and from VMEC coordinates. The parameters required for a transform are: the configuration descriptor, the input and output coordinate systems, and the input coordinate values. The function call will return the coordinates in the specified output coordinate system. The supported coordinate systems are: cylindrical (lab coordinates) (phi, R, z), PEST coordinates (s,theta, phi), Boozer coordinates and VMEC coordinates.

transform_coords(config_descriptor, from_system, to_system, input_coords)

- input:
  - config_descriptor is the magnetic configuration descriptor
  - from_system is the input coordinate system
  - to_system is the output coordinate system
Poincare plots

A Poincare plot is a mapping of the intersection of periodic orbits with a lower dimensional space. Here we map the intersections of magnetic field line 'orbits' with a user specified two-dimensional plane. Usually, a constant phi surface is used but the API allows for an arbitrary surface to be specified. The required parameters are: the configuration descriptor, a plane descriptor, the starting locations of the field 'orbits' and the number of orbits. The function returns a list of intersection points.

\[ \text{get_poincare}(\text{config\_descriptor}, \text{plane\_descriptor}, \text{starting\_locations}, \text{n\_orbits}) \]

- **input:**
  - \( \text{config\_descriptor} \) is a magnetic configuration descriptor
  - \( \text{plane\_descriptor} \) representation of plane in some coordinate system
  - \( \text{starting\_locations} \) list of starting points for field line traces, optional with sane defaults.
  - \( \text{n\_orbits} \) for each starting point, with sane default (e.g. 100)

- **output:**
  - list of points intersecting the plane.

Surface quantities

Several properties of toroidal magnetic geometry are functions of, or defined by, the nested magnetic surfaces. These properties include toroidal flux, average minor radius, rotational transform and magnetic shear. In order to return a list of surface properties, the required input parameters are: configuration descriptor, a list of surfaces and the requested surface properties.

\[ \text{get\_surface\_quantity}(\text{config\_descriptor}, \text{surface\_list}, \text{surface\_properties}) \]

- **input:**
  - \( \text{config\_descriptor} \) is a magnetic configuration descriptor
  - \( \text{surface\_list} \)
  - \( \text{surface\_properties} \) list from, e.g. iota, ripple, mag well, etc

- **output:**
  - requested surface quantities for each surface.

Developer tools

Precomputed arbitrary magnetic field mesh

While the pre-computed configurations and API are sufficient for most users, some researchers may require more sophisticated modelling. Ultimately, they can use the vacuum field codes (Bline and HELIAC) for modelling. However in many cases a pre-computed grid of field values can be used for interpolation of field properties. A three-dimensional grid with individual field components calculated for each vertex can be downloaded from the.
configurations database website. By using linear superposition of the field grids, any arbitrary configuration can be modelled.

The first step is to create the mesh for the most accurate and detailed models of H-1. The dataset size ranges up to a few Gigabytes for precisions in the order of one part per million, so compression is important for storage and for transferring the files.

The next stage is to make the data available in standard formats such as netCDF, to enhance portability, while retaining a high level of compression.

The final step is to provide user-friendly input file generation software to produce input data files in all required formats including the precomputed binary mesh file, and BLIne, Heliac, Gourdon, xBase/Mag3D/xml and VMEC and AVEC text input format.

For reasons explained in Milestone Report 5, this milestone is considered to be 1/3 complete as of 31 March 2011. Although a database of over 100 configurations has been generated, considerable work remains to be done on the API and Developer tools.
Milestone 17: Commissioning the Precision Current Controller

The precision current controller allows more flexible access to plasma configurations by providing a third current parameter to supplement the two controls parameters of the dual 14000 A power supply. The design current rating is 1500A, consistent with the continuous rating of the smaller windings on H-1. The device is capable of higher shunt currents on a pulsed basis.

Coarse current control is achieved with an approximate “binary tree” of high power resistors. Fine control is achieved by a pulse width modulation (PWM) controller employing a 300 A Field Effect Transistor.

Stable operation at 1500A was demonstrated as shown in Figure 2.

![Figure 1: The Precision Current Controller showing the PWM filter inductors (blue), the switched high power resistors (red), and the high current switches (grey, three phase contactors) PWM controller (seen in Fig. 3) was removed for bench tests.](image)

The commissioning consisted of checking the resistance values, the switch operation, the pulse width modulation (PWM) controller operation and confirming stable operation at full current, while checking for excessive temperature rise.

PWM operation was checked on the bench to operate at 50A continuously and for 10s of seconds up to 89Amps. This is much higher than required for normal operation. The PWM ripple was small, and the transient response was free of ringing.

Resistance values were checked against nominal, which also provided confirmation of the correct operation of the high current switches (contactors) which select various combinations of resistors.

Stable operation at 1500A was demonstrated as shown in Figure 2.

![Figure 2: The first 8 seconds of current flowing through the shunt during a 120 second test, showing stable operation at 1500A](image)
Temperature monitoring with a thermal imaging camera (Figure 3) showed that the only hot spots were on the surface of the high power resistors, and that the maximum temperature (about 90°C) was well within the resistor’s limit of 200°C. No hot spots on the connecting wires or connectors were visible confirming good contact. Cooling fans were disabled for these tests to expose the components to worst case conditions.

These tests demonstrate the successful commissioning of this controller, and will allow its use in the near future on H-1 in certain applications, once suitable operating procedures have been established, and additional testing is complete. The next milestone for this system is the completion of integration into the H-1 power and control system, due at the end of next year. The success to date suggests that this milestone may be achieved ahead of time.
Milestone 22: Vacuum Upgrade and Enhancement Plan: Specify Components required for the Vacuum System Upgrade

The major items required for the vacuum upgrade are turbomolecular pumps. Changes in the design of these, in particular magnetic bearings, have required re-evaluation for use on H-1. Replacement pumps have been identified which are suitable for H-1, and fit within the budget, allowing for some savings in the purchase of other vacuum items flowing in part from exchange rate improvements. The optimum time for replacement in consideration of cash flow is in year 3. A working spare which has been used for less than one year is on hand in case of early failure, and it is likely that more benefit will be gained from other vacuum upgrades in the short term.

A plan has been developed for the other aspects of vacuum enhancement described in the agreement, and is outlined here. Several strategies for improving the vacuum quality in H1, and reducing the impurity content of the plasma have been investigated. Considering the special features of the “coil in tank” construction, the techniques have been prioritised as below. Priorities A-D will be implemented initially, and the remaining schemes reconsidered once results of A-D are known.

This plan takes advantage of a valuable opportunity for evaluation and tests of suitable vacuum improvement technologies (that do not rely on plasma operation) during the ~6 month down time while the RF heating system is being upgraded, from June to December 2011. However our technical resources will be stretched very thin during this period, in order to prepare a larger laboratory area for the MDF, so a number of items may have to be postponed until a later vacuum break.

Glow Discharge Cleaning (Priority A)

The glow discharge cleaning (GDC) power supply has been dismantled and relocated and is yet to be re-assembled. It is known to have sustained some physical damage during the move. There is also an issue with the specification of suitable cabling and the safety interlocking of that cabling. The final disposition of the internal electrodes is yet to be specified.

The RF upgrade break will allow some vacuum modifications to investigate the viability of GDC, to evaluate the efficiency of the process and to estimate the requirements for implementation of the final system. A high current, high voltage electrode has been mounted in the vacuum system above the interferometer. A glow discharge will be created under the appropriate pressure and gas mixture conditions. This procedure will require viewing access to assess the distribution and extent of the discharge.

Initial tests ahead of the RF upgrade break will allow determination of details of the vacuum system modifications to be made during that break.

UV Baking (Priority B)

This technique employs UV discharge lamps internally and is claimed to be very efficient. Advantage of directing UV energy straight onto internal surfaces to photo-desorb water vapour. High temperatures are possible, requiring monitoring. There are probable shadowing effects on surfaces not in direct or reflected exposure.
Initial tests will be performed in a test tank, and depending on the results, a small pilot system will be installed in the RF upgrade break.

**Cryopump (Priority C)**

Cryopump reliability continues to be an issue. Whilst we can continue to top up the refrigerant the long term stability of operation will eventually be compromised under the present arrangement.

There was an improvement after the last opening but this only lasted a few months. Presumably, the problems are associated with small refrigerant leaks over extended periods of time. It appears that the present leak testing methods are not as effective as hoped. Improvements, whilst possible will take a major strip down of the cryolines and their modification in order to allow a more accurate leak test, possibly a review of the present insulation should be performed. An extensive leak test of the internals of the cabinet would also be required.

In the short term some modifications to the cryoline will be performed in order to maximise the short term benefit from the point of view of re-filling with new refrigerant and using the opportunity to isolate the cryolines as the possible source of the leak problems.

**Non Evaporable Gettering (NEG) (Priority D)**

This is a promising alternative to titanium (Ti) gettering, using alloyed materials, functioning as a controllable sponge though diffusion and trapping. It is re-generable by heating electrically in-situ. Regeneration for 10s of cycles is possible for heavy molecules contaminants, unlimited regeneration is possible for hydrogen. Products are available in cartridge form, foils, pellets, or custom deposited on selected surfaces. It is usually used internally but may be configured as an appendage pump on a port through a valve although with far from optimal pumping speed. This is planned to be evaluated in the test tank, but given time constraints, it is unlikely to be ready for tests in H-1 before operations resume in 2012.

**The following are not prioritised and are in no particular order**

**Gettering (Ti)**

Works by subliming Titanium onto the inside of an open volume. Possibility of a re-entrant “Ti-ball” style of pump that is inserted from the outside. Limited although high pumping speed, limitation would be due to fixed surface area that would be inserted through a port. Alternative is to have fixed pump internal, of large surface area. Possible disadvantage of vapourised Ti condensing in unintended locations.

**Shutters**

There are two commercially obtained shutters in stock (6”CF size). These are designed to be interspersed between the port and whatever is on the port. Their use will move the window in question radially out by 20mm.

Other shutter locations have yet to be specified. Custom made shutters will likely require considerable design and installation time.

**Antennae**

The existing antenna has associated Rogowski current monitors and TFC coil shields. These would presumably have to be replicated for the new antennae.
Presently the plan is to install the new fixed antenna at 275 deg. (south of the interferometer). The moveable antenna would be installed at the existing RF port.

**Hot Baking**

This is the conventional approach. Requires external heating mechanism of high power with copious external insulation. Very inefficient unless the vessel is comprehensively thermally insulated since heating effect has to penetrate through the tank wall to work. Safety issues when in use with probable very long baking cycles required, including overnight operation.

**Fiducial Markers**

Fiducial markers are present in the machine but the present series are not visible though any port. We plan to install new ones expediting the extensive setup and surveying required traditionally by the use of a laser survey instrument.

**Test Samples**

There have been long-standing problems with unknown sources of contamination inside H1. The result of these have been the premature spoiling of both the ion gauges and the RGA. Our gauges and RGA typically last only 3 months or so before they require either replacement or cleaning. For some time there have been some small stainless steel test samples attached to the top of some of the TFC’s. During the RF break these samples will be replaced and the exposed ones analysed using some appropriate surface techniques in order to formulate a possible remedy.

**Internal Camera**

It is proposed to install one or more cameras either inside H1, or in a re-entrant window port. For the fully internal option, it should be possible, once an appropriate port is identified, to fabricate a tubular pipe (“snake”) of irregular shape to house the camera. The snake could then be installed during a vent of the tank without having to take the lid off. It may be possible to install these in multiple locations if the ports are available.

It is unlikely that the fully internal option will be possible to implement during the RF installation break. In this case, suitable locations will be identified for future implementation while there is access to the inside of the vessel, and the rentrant port camera option will be installed.

There have been long-standing observations of small arc tracks around the structure outside the TFC’s. An internal camera will permit further observation.
Milestone 20: Material Diagnostic Development Facility: 
First plasma produced in satellite prototype

The Materials Diagnostic Development Facility (MDF) is intended to provide a test-bed specifically for developing and testing diagnostics for plasma-materials interaction under conditions relevant to the edge of fusion reactors. The device aims to achieve high plasma densities (~10^{19} \text{m}^{-3} \text{ H}^+) and power densities, but cannot provide the neutron flux.

A prototype plasma source has been constructed with EIF funding using RF production from a 4.5 kW peak power source, magnetic field coils from the University of Sydney, and two 1000A power supplies. The device has a flexible magnetic field configuration and will be equipped with a target holder and multiple diagnostics. A high-power dye laser from the University of Sydney will be the central part of one of the key diagnostic tools.

The first milestone for this device, first plasma, was achieved 3 months ahead of schedule. First results are shown below. The machine is now ready to conduct experiments and it is expected to produce research results in the near future. Strong interest in the facility has already been shown by material scientists and engineers at ANSTO. The final version will leverage the extensive power system and diagnostic infrastructure of the H-1 Facility.

Infrastructure commissioned early this year includes computer controlled magnetic field power supplies, radio frequency source and vacuum system enabling first plasma to be produced in early March. Early measurements show reasonable plasma density, given the initially low plasma heating power. It is expected that density can be increased by 1-2 orders of magnitude.

![Figure 1: An Argon plasma inside the MDF. A round diagnostic port can be seen on the left through the glass window on the vacuum vessel. The plasma glow is strongest under the helicon antenna, part of which can be seen at top right (the helical copper conductor) See also fig 2.](image)

First Plasma Results

The first measurements carried out on the MDF were the initial characterisation of the plasma properties. To begin this process, an rf-compensated Langmuir probe was inserted into the target chamber. The probe itself is a very small piece of wire that it biased to a particular potential. Depending on whether the probe is
biased to positive or negative voltage, it will attract either positive Argon ions or the negatively charged electrons that will hit the probe tip and be collected. The observed current as a function of applied bias forms an IV characteristic from which a variety of plasma properties can be determined including ion density, electron temperature and plasma potential.

Below is a graph of the first current-voltage (IV)-characteristic taken in the MDF.

![Langmuir Probe IV Characteristic](image)

*Figure 2: A Langmuir probe IV characteristic. At negative bias voltages, the probe is collecting positive Argon ions. At positive voltages, electrons are attracted to the probe. The electron current is much higher than the ion current due to the much smaller mass and higher mobility of electrons in comparison to the relatively massive Argon ions.*

![Cross sectional view of MDF](image)

*Figure 3: cross sectional view of MDF. The direction of view of the photograph in Figure 1 is indicated by the arrow.*

Figure 3 shows how the magnets are positioned on the machine, it also shows the location of the antenna and the vacuum chamber, both of which are shown in cutaway view.

Attachment E to Fusion Milestone Report 5: Page 2
Figure 4 shows the magnitude of the axial magnetic field along the axis of MDF. The line represents the calculated field, and the points are Hall Effect probe measurements.

The rectangles above represent the position of the coils in MDF. Two power supplies energizing the coils in MDF to provide flexibility to change the shape of the magnetic field.

The Axial magnetic field in MDF allows radial confinement the plasma inside MDF and slows diffusion of the plasma to the chamber walls.