# BOUNDARY AND DIVERTOR DOPPLER COHERENCE IMAGING

## THE ITER-AUSTRALIA INTEGRATED TEAM

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# 1 SCOPE

This document provides a complete description of the ITER flow monitor project, including a detailed Work Breakdown Structure (WBS), a description of management and governance provisions, a feasible schedule and detailed budget which includes manpower, hardware and travel costs for the for the period 2018-2027 when the system will be installed on ITER.

The project will be managed by the ITER-Australia Integrated Team, with the primary responsibility for the Project being borne by the Australian Team (Aust-team) with assistance and guidance from the ITER Organization central teams (IO-CT).

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# 2 Definitions and Acronyms

For a complete list of ITER abbreviations see: ITER Abbreviations (ITER_D_2MU6W5).

| | |
|---|---|
| ANSTO | The Australian Nuclear Science and Technology Organization |
| ANU | The Australian National University |
| Aust-team | The Australian team |
| CAD | Computer Aided Design |
| CI | Coherence Imaging |
| CDR | Conceptual Design Review |
| CODAC | Control, Data Access and Communication |
| CMM EP8 | Configuration Management Model for Equatorial Port 8 |
| DR | Deviation Request |
| FAT | Factory Acceptance Test |
| FDR | Final Design Review |
| I&C | Instrumentation and Control |
| IDM | ITER Document Management |
| IO-CT | ITER Organization Central Team |
| IS | Interface Sheet |
| IT | Integrated Team |
| MRR | Manufacturing Readiness Review |
| P&ID | Piping and Instrumentation Diagram |
| PDR | Preliminary Design Review |
| PBS | Plant Breakdown Structure |
| PCR | Project Change Request |
| PFD | Process Flow Diagram |
| PIC | Protection Important Components |
| RAMI | Reliability, Availability, Maintainability and Inspectability |
| SAT | Site Acceptance Test |
| SIR | Structural Integrity Report |
| SLD | Single Line Diagram |
| SLS | System Load Specifications |
| WBS | Work Breakdown Structure |

# 3 Applicable and Reference Documents

The references are embedded throughout the text.

# 4 BACKGROUND

A recently signed Cooperation Agreement between the Australian Nuclear Science and Technology Organisation (ANSTO) and the ITER Organization (IO) may see advanced imaging systems developed at the Australian National University (ANU) deployed for detailed measurement of the impurity ion flows and temperatures in the ITER plasma boundary and divertor. These measurements are essential for benchmarking models of edge and divertor transport. So-called "coherence imaging" (CI) instruments are uniquely capable of meeting the measurement requirements for impurity ion flow speeds and temperatures expected in the ITER divertor, but in addition, can potentially image plasma electron density, hydrogen isotope fractions and other quantities of interest for the ITER physics program.

## 4.1 THE NEED FOR BOUNDARY FLOW MEASUREMENTS

Recent studies indicate that managing the plasma exhaust power from the ITER tokamak will be a great challenge, and that present strategies may well be inadequate for future fusion power reactors. Even for standard axisymmetric poloidal divertors, our understanding of heat and particle transport, including the various source distributions and dissipation processes along open field lines in the plasma scrape-off-layer (SOL) and divertor, is incomplete [1, 2]. Moreover, the layered co-deposition of beryllium and isotopes of hydrogen in the ITER divertor is a safety issue because of possible tritium retention and the production of dust. A measurement of ion flows between the inner wall and the inner divertor baffle, combined with erosion/deposition measurements and Langmuir probe measurements at the inner baffle will allow validation of Be migration models. Validated models will provide a predictive capability for divertor performance and control, and engineering safety in ITER and future fusion devices.

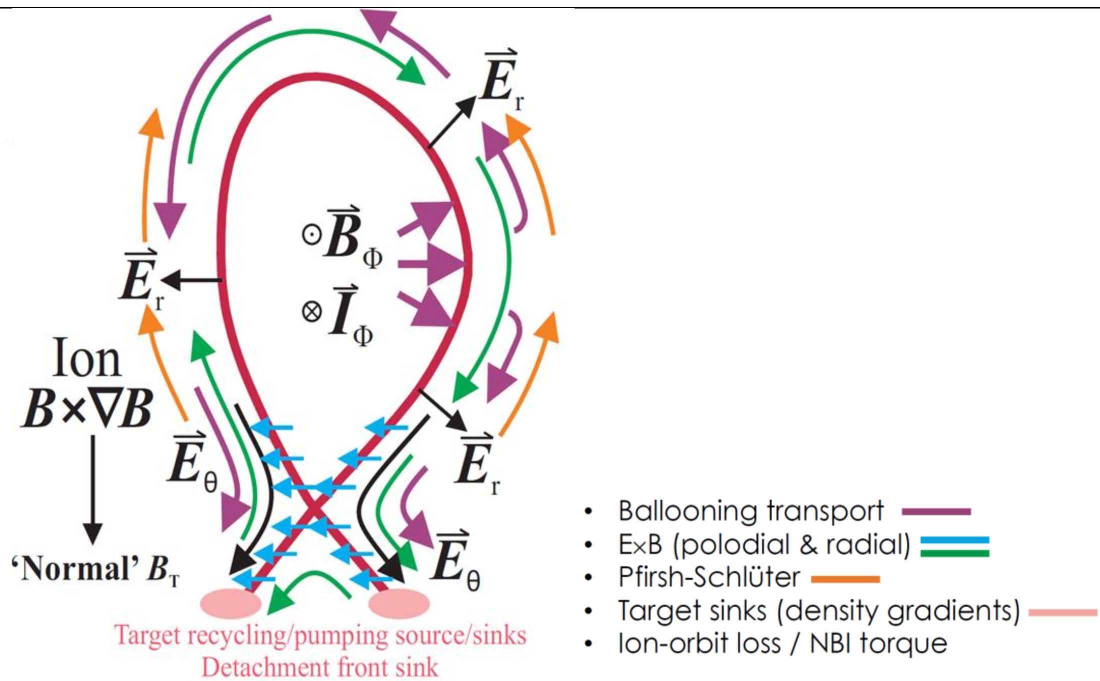



*Figure 1 Cartoon showing the many transport mechanisms that drive ion flows in the scrap-off-layer (SOL) and divertor in a tokamak (Courtesy LLNL)*

## 4.2 COHERENCE IMAGING RESULTS TO DATE

Capturing orders of magnitude more information than traditional spectroscopic/polarimetric systems, coherence imaging systems have the capability to deliver detailed images of plasma flows, temperatures, densities, internal fields and structures. CI systems use polarization-based interferometers and various modulation strategies to encode in one or more snapshot images, the polarization state (Stokes vector) and/or the complex optical coherence of the spectral emission at one or more optical delays. For sufficiently simple spectral scenes, the decoded images, for extended plasmas, can be linked to line-integral projections of simple scalar and vector field quantities that yield to tomographic techniques [3]. Example applications include [4]:

- Doppler, including CXRS (velocity distribution function)
- Stark effect (electron density) [5]
- Line intensity ratios (e.g. isotope fractions)
- Thomson scattering (electron density and temperature)
- Motional Stark effect (toroidal current density) [6]

Coherence imaging systems for optical spectroscopy and polarimetry have been validated through installation and operation on numerous devices around the world, including Italy (RFX), Germany (ASDEX-U, VINETA, W7-X, WEGA), Netherlands (Pilot PSI), UK (MAST), Japan (RT-1), Korea (KSTAR), China (HL-2A), USA (DIII-D, CTH) and Australia (H-1, MAGPIE). [7, 8]New systems are presently being planned for other machines. A photo of the system installed on the MAST tokamak is shown in Figure 2, while an example of a raw plasma image and the reconstructed ion flow field in the MAST divertor are shown in Figure 3.

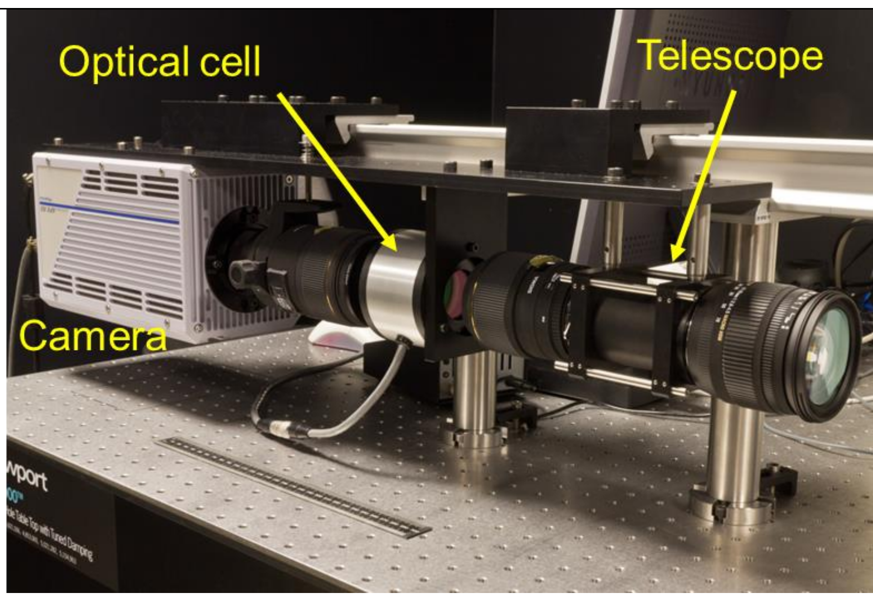



*Figure 2. The Doppler CI camera used for measurements on MAST (Courtesy Scott Silburn)*

These cameras are also capable of synchronously locking to periodic plasma structures and to produce differential measurements of flow perturbations. Figure 4 shows carbon ion velocity projections of structures associated with RMP-generated n=1 island chains in DIII-D. Double-vortex flows of order 5 m/s associated with m=1 drift waves have also been observed on the MAGPIE device at the ANU.

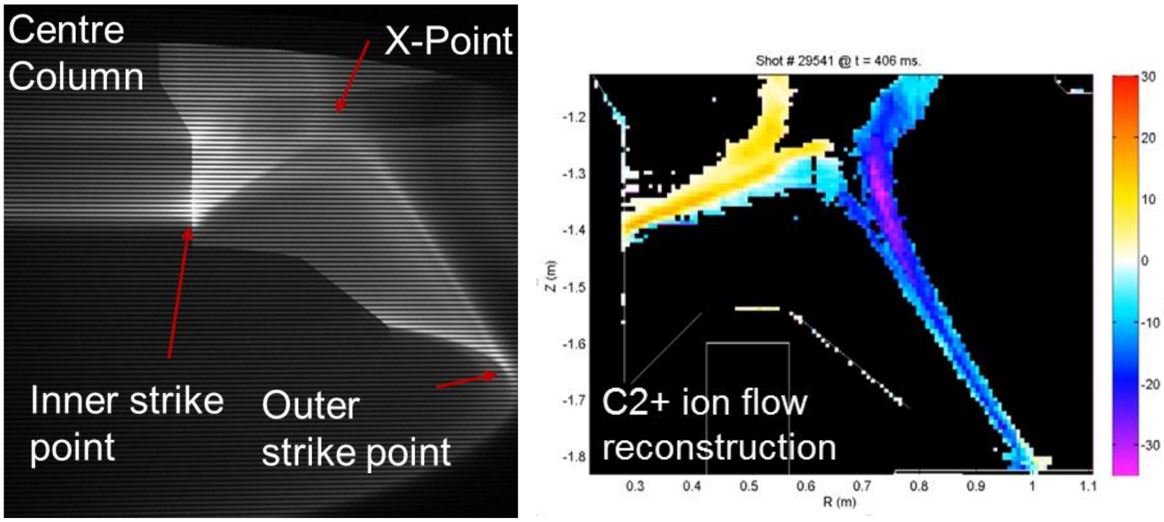



*Figure 3. Left: The raw spatial heterodyne snapshot interferogram of the 465nm CIII ion emission in the MAST divertor. Right: tomographic reconstruction of the associated demodulated phase image showing oppositely directed flows into the inner and outer divertor plates. (Courtesy Scott Silburn)*

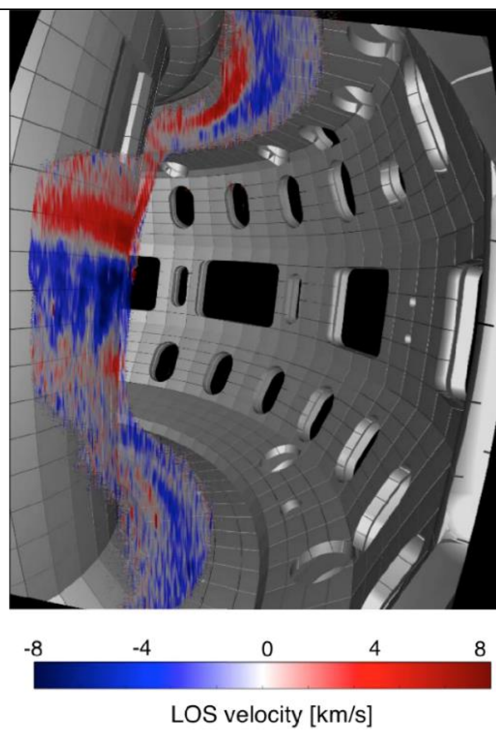



*Figure 4. CI systems can reveal complex flow structures. Image shows the change in CIII velocity near RMP magnetic islands superimposed on a CAD model of DIII-D. (Courtesy Cameron Samuel, LLNL)*

# 5 THE ITER BOUNDARY COHERENCE IMAGING SYSTEM - OVERVIEW

The ITER boundary coherence imaging system, or simply ‘flow monitor’, (55.GE in the ITER Plant Breakdown Structure, PBS) is an advanced imaging system for detailed measurement of the impurity ion flows and temperatures in the ITER plasma boundary and divertor. The schematic of the ITER flow monitor is shown in Figure 5. The diagnostic consists of an optical system with a ‘front end’ located inside one of the ITER port plugs and extending through interspace to the port cell which contains the processing optics and CCD camera. The CI flow monitor is slated for installation in the ITER equatorial port #8

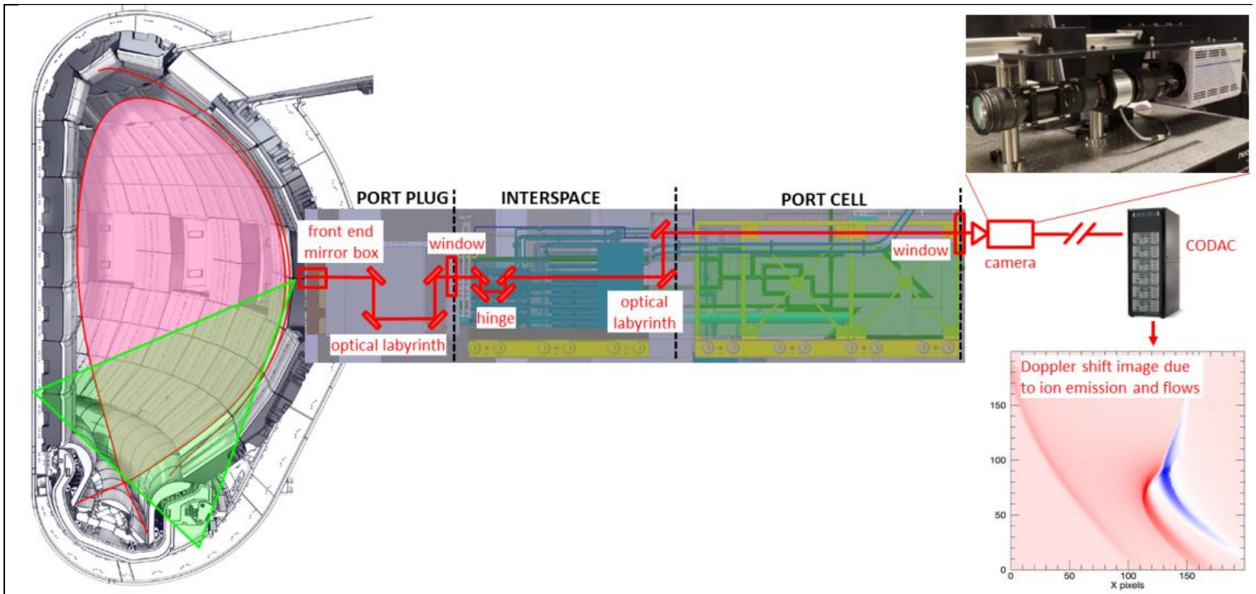



*Figure 5. Schematic of the ITER flow monitor experimental layout.*

The Australian Team will be responsible for executing the elements of the Work Breakdown Structure (WBS) that are particular to the CI system, including for example, the development and validation of the flow monitor design, the development of operation and processing software, as well as for the manufacturing of the diagnostic components and ultimately for the support to installation and commissioning of the flow monitor on ITER.

In coming years, the project will allow the Aust-team to implement, in close collaboration with ITER Organization (IO), its own high-impact scientific and engineering program on the world’s largest physics experiment, including opportunities for domestic industry through the WBS.  For the purposes of this document, it is assumed that the Aust-team is comprised of experts from the Australian National University (ANU), the Australian Nuclear Science and Technology Organisation (ANSTO) and the broader Australian fusion science community.

## 5.1 Preliminary scoping study

A scoping study for the CI flow monitor was commenced in 2016 under Task Request ref. IO/TR/15/11378/IDS "Imaging Divertor Flow Measurement for ITER Diagnostics". Main results of the scoping study include:

1. Identified need to account for Zeeman polarization effects for Doppler tomography in ITER
2. Obtained the analytic relationship between the Doppler-Zeeman spectrum and the measured Stokes vectors for an inhomogeneous plasma radiator
3. Completed and benchmarked a Stokes-Doppler forward projection model (see Figure 6)
4. Finalised camera location and orientation using the model
5. Completed preliminary characterisation of polarization reflection properties of plasma-damaged tungsten
6. Experimentally demonstrated the utility of polarization filtering for suppression of diffuse background reflections – extremely important for optical diagnostics in a metal wall machine

A key report recommendation is for a prototype spectro-polarimetric imaging system to be installed on a present-day all-metal-wall machine in order to test the utility of polarization filtering for suppression of background unpolarised emission. Suppression of the background component will greatly enhance the reliability of Doppler tomography on ITER.

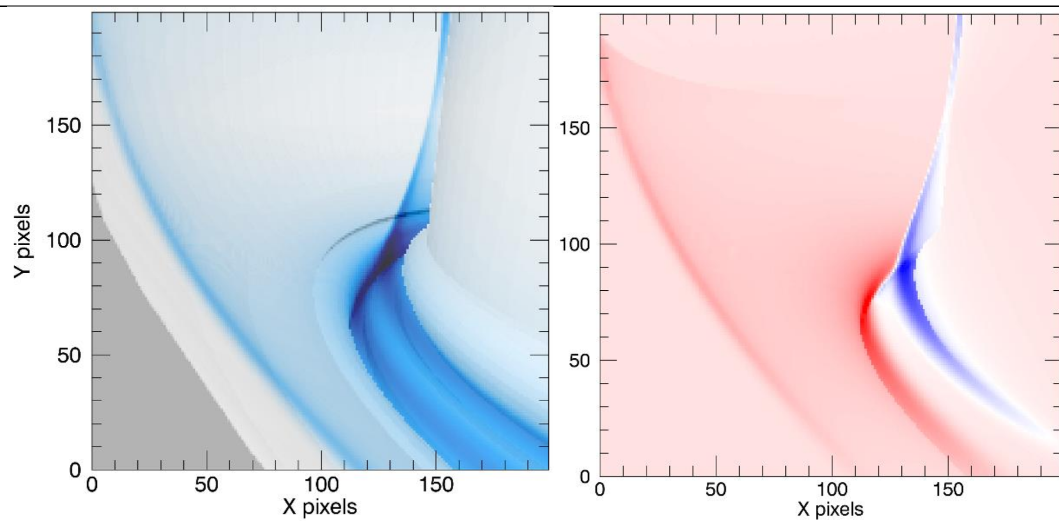



*Figure 6. Forward models of the brightness (left) and Doppler shift (right) images due to ion emission and flows in the ITER boundary and divertor. Blue: flows towards the camera, Red: flows away from the camera.*

# 6 WORK BREAKDOWN STRUCTURE

The work breakdown structure (WBS) defines and includes all of the work elements necessary to complete the project. This includes project management (Column 1 – see Sec. Organization and Management), project scheduling (Column 2 – see Sec. Project plan and ) and the work packages required to complete the project (Columns 3-8). The workforce requirements and budget are set by the WBS and the budget profile is dictated largely by the Project schedule.

*Figure 7* shows the broad decomposition of the flow monitor project into the primary work packages (under the various column headings) to be carried out by the Integrated Team. The detailed allocation and breakdown of the various tasks and responsibilities within the work packages will be agreed by the IO and the Australian partner organizations and documented in a number of *Implementing Agreements* (IAs). Nevertheless, it is relatively straightforward to separate the tasks into those that remain the primary responsibility of the Aust-team and those that are more conveniently shared.

It is natural for the Aust-team to assume primary responsibility for the flow monitor hardware and software development and the underpinning modeling (the final three columns of the WBS). This work will include construction and characterization of various prototype systems, including deployment at one or more of the world’s largest tokamaks for in-situ testing and validation of various sub-systems. The use of realistic physical model data is required for finalising the optical and mechanical design. An Australian scientist will work with IO experts to develop these models. It will also be necessary to develop the ITER-specific software for operation, real-time demodulation and offline analysis.

The Aust-team will also be primarily responsible for some of the sub-systems (Column 5) including automated calibration and alignment systems that will be required to ensure correct interpretation of the interferometric measurements. Light and polarization transport issues as well as development of an appropriately thermally stable enclosure for the CI optics will be the responsibility of the instrument physicist working with the Aust-team.

Responsibility for many elements of Integration and Interfaces, Engineering and some of the major Sub-systems (Columns 3-5) will be shared between the IO-CT and the Aust-team. Examples include the complex interfaces with the port structures as well as with auxiliary systems (electrical, water, gas), buildings and CODAC. Joint responsibility for these tasks ensures that the project efficiently taps into the pre-existing and unique knowledge and expertise of the IO team and will ensure safe integration of the flow monitor project with other Equatorial Port 8 systems. Some engineering tasks, include manufacturing, installation and operations support will remain the primary responsibility of the Aust-team.

The IO-CT will provide guidance for the development of the major hardware subsystems, including for example the front end mirror box with on-board mirror cleaning system and a ‘hinge’ in the interspace for optical realignment.

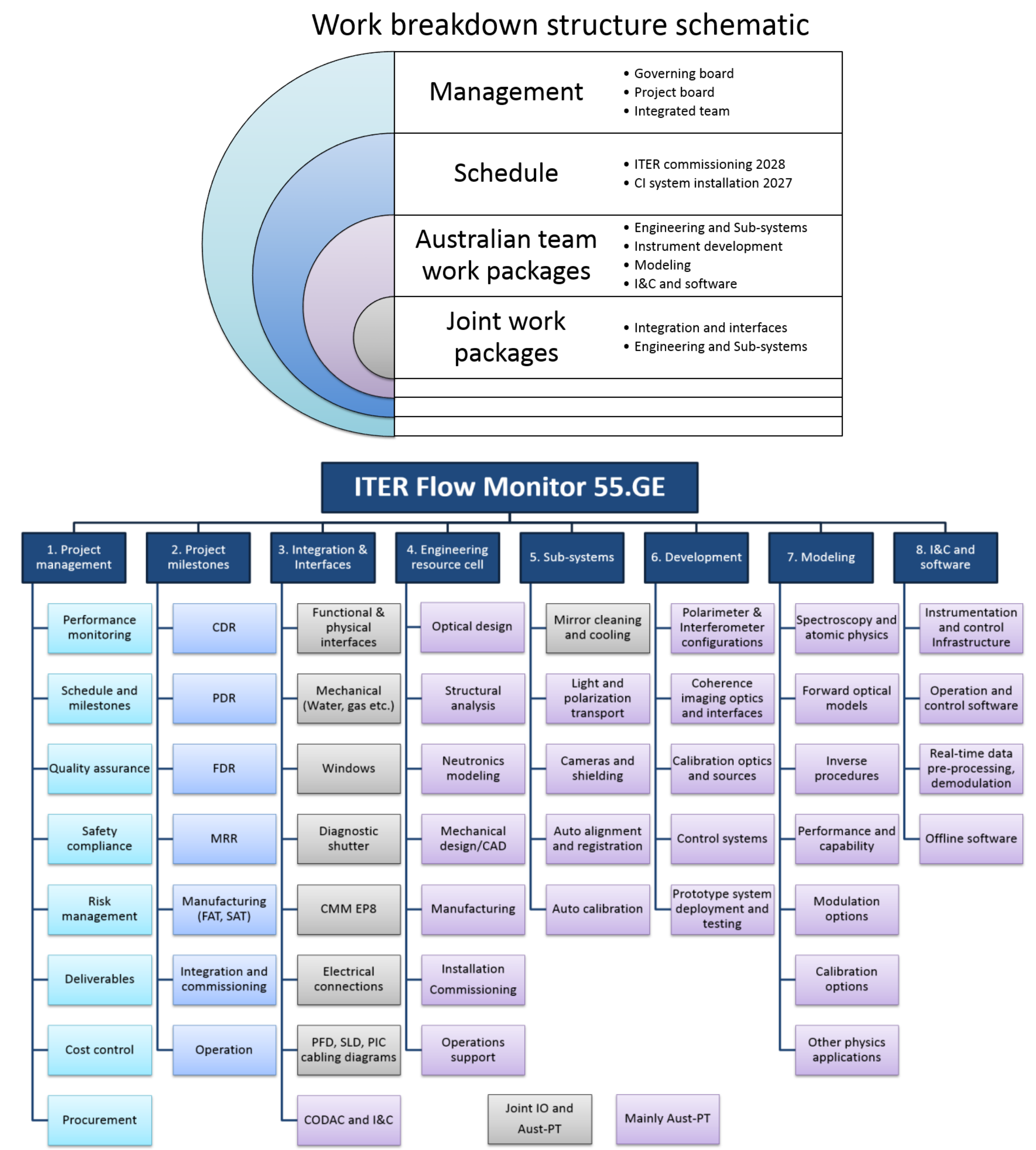



*Figure 7 Top: Schematic breakdown of the Work Breakdown Structure for the Boundary Coherence Imaging system and Below: Detailed description of the WBS. The Coordination Committee and Project Boards will control and monitor the project management (Column 1). Column 2 indicates the key Project Milestones as detailed below. The detailed allocation of tasks indicated in grey (Joint IO and* Aust-team*) and mauve (mainly* Aust-team*) will be covered by the Implementing Agreement.*

# 7 ORGANIZATION AND MANAGEMENT

The physical and financial scale and complexity of the ITER tokamak is unprecedented for a scientific undertaking. In turn, IBIS in its own right, is a significant instrument that must operate safely, reliably and autonomously in a nuclear environment. Maintaining project discipline in an environment of multiple complex technical, financial and administrative interfaces and constraints, poses formidable challenges. The proposed multi-layered governance model has been approved by the ITER Organisation. Multiple clear lines of responsibility and authority, with frequent review and accountability, will ensure timely and cost-effective delivery of IBIS.

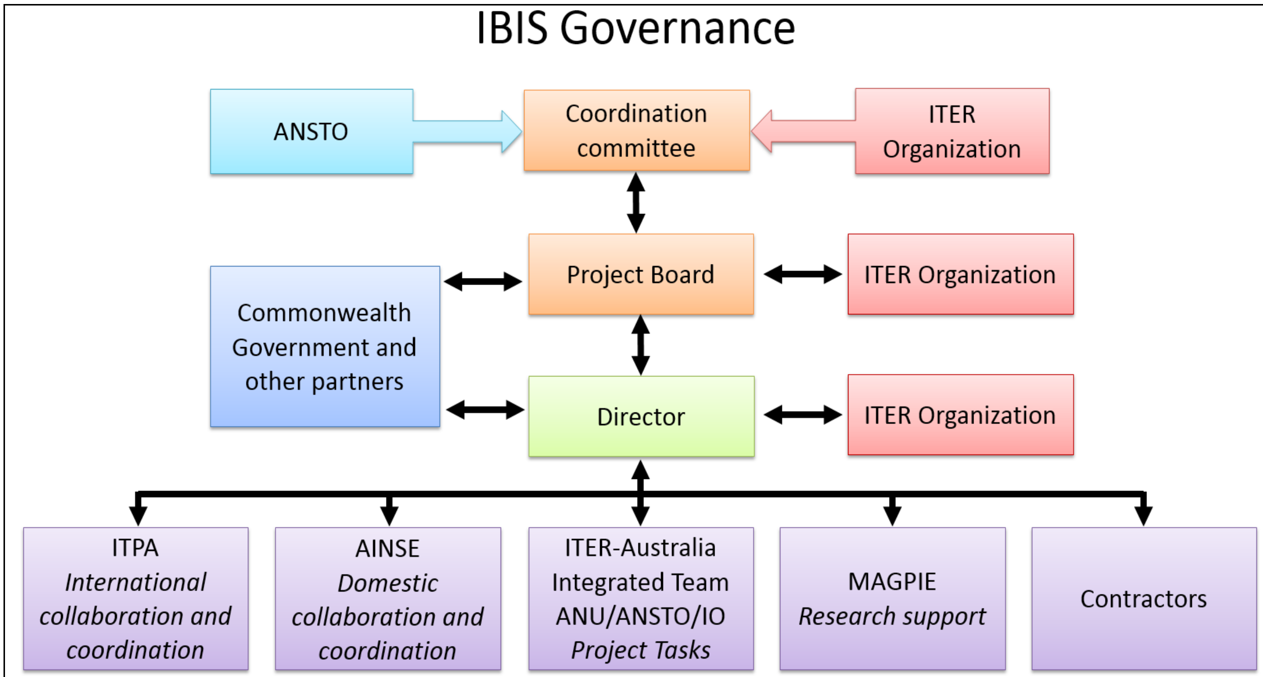



*Figure 8 Schematic diagram showing the proposed governance model.*

**Error! Reference source not found.** illustrates the likely governance and operational structure of the TER-Australia IT. The Coordination Committee oversees all collaborations and joint activities undertaken under the banner of the ANSTO-ITER Collaboration Agreement. The Coordination Committee will have three delegates from Australia and a matching number from IO with the IO Director General or his nominee as Chair. This committee will meet once per year in relation to the IBIS project. It will be ultimately responsible for the satisfactory execution of Implementing Agreements (IAs) which define the joint project tasks.

The IBIS Project Board will be drawn from senior staff from the IO, ANSTO and ANU, and will include the IBIS Director, representatives from government and other stakeholders, and experts from the Australian business, research and higher education communities.

The Project Board will meet two or three times per year. It will select the Director and periodically review his or her performance. It will provide oversight and assistance to the Director in the management of the project as outlined broadly in the Work Breakdown Structure. This will include monitoring of the project planning and scope, resources and budget, relevant policies and resolution of other major issues as required.

The Director will be responsible for all aspects of the IBIS project, including the staffing, budget and resources, scheduling and the management of external contractors. The Director will put in place risk management strategies, ensure necessary safety and compliance measures and monitor the project documentation. In addition the Director will facilitate and foster relevant international and domestic collaborations and joint activities associated with the ITPA, AINSE and the MAGPIE research support program.

To ensure compliance with the project requirements, the IO will retain an independent position in its interactions with the Project Board and the Director. In practice, the Project Director will work directly with the IO-CT Technical Responsible Officer (TRO) who will then address IO-CT related actions with the IO Central Team. The details of the integrated team coordination will be developed in the primary Implementing Agreement that describes and governs the project.

The Director will conduct regular meetings with the Integrated Team to pilot and review the technical progress. The Director will prepare interim and annual reports as required, including an assessment of

## 7.1 THE INTEGRATED TEAM

The work package requirements as defined in the WBS determine the required workforce skills. The skills and manpower requirements for the Aust-team are shown in *Figure 9* while *Figure 10* depicts the equivalent breakdown for the IO team.

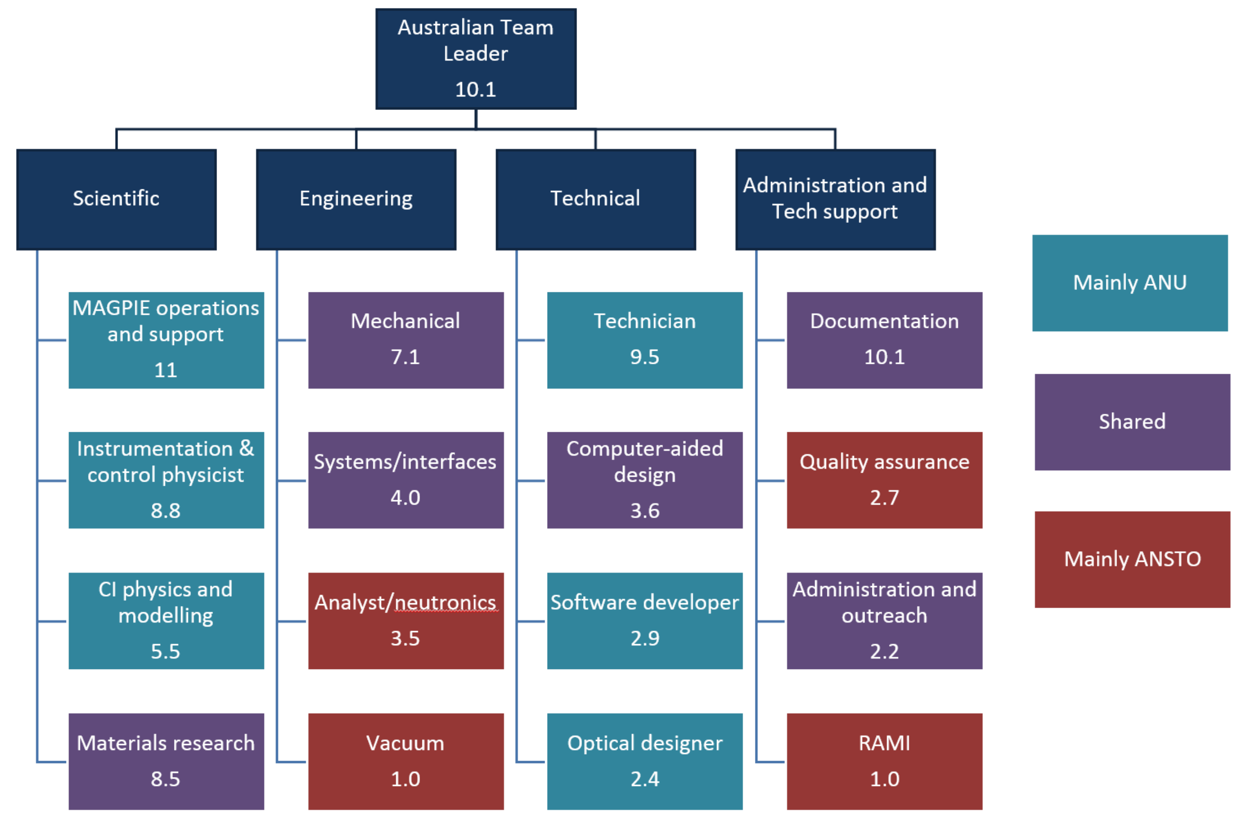



*Figure 9. Skills and manpower requirements for the Aust-team. The numbers correspond with the man-years attributed to each task and correspond with those listed in the detailed budget table.*

There is considerable overlap between the various work categories (scientific, engineering, technical and administration). Roles are colour-coded according to whether they are associated mainly with ANU or ANSTO or are effectively joint. A number of the staff (for example the technician) will be required to provide support across the flow imaging project as well as supporting programs on the MAGPIE Facility and elsewhere. Some justification for the manpower requirements is found in the budget spreadsheet, though this will be developed in more detail in due course.

The IO-CT will oversee relevant activities of the Aust-team to ensure compliance with the applicable rules (e.g. CAD rules), procedures and requirements (e.g. ITER_D_2832CF - Design Review Procedure, ITER_D_NSADBC - Port Integration Engineering Guidelines). These will include, but are not limited to

- Measurement Requirements
- Safety Requirements
- Design Requirements
- Operation and Maintenance Requirements
- Quality Requirements
- Applicable Codes and Standards

Further information on the system requirements can be found in ITER_D_28B39L - SRD-55 (Diagnostics) from DOORS.

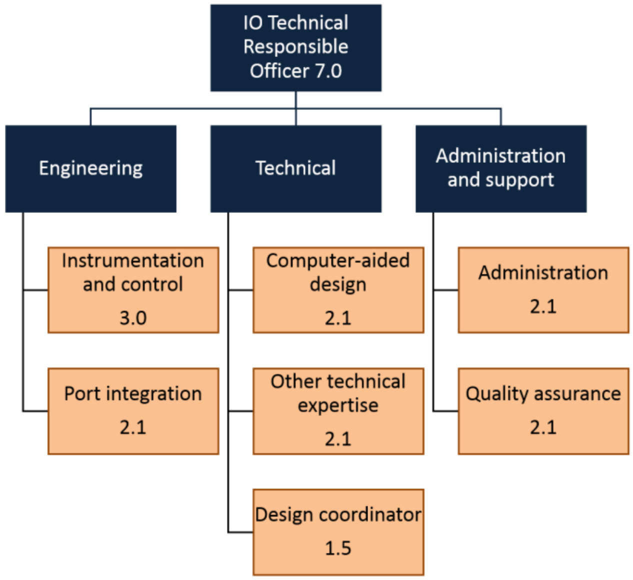



*Figure 10 The IO Project Team. The numbers correspond with the man-years attributed to each role and correspond with those listed in the budget table.*

### 7.2 RELATIONSHIP TO THE WIDER COMMUNITY

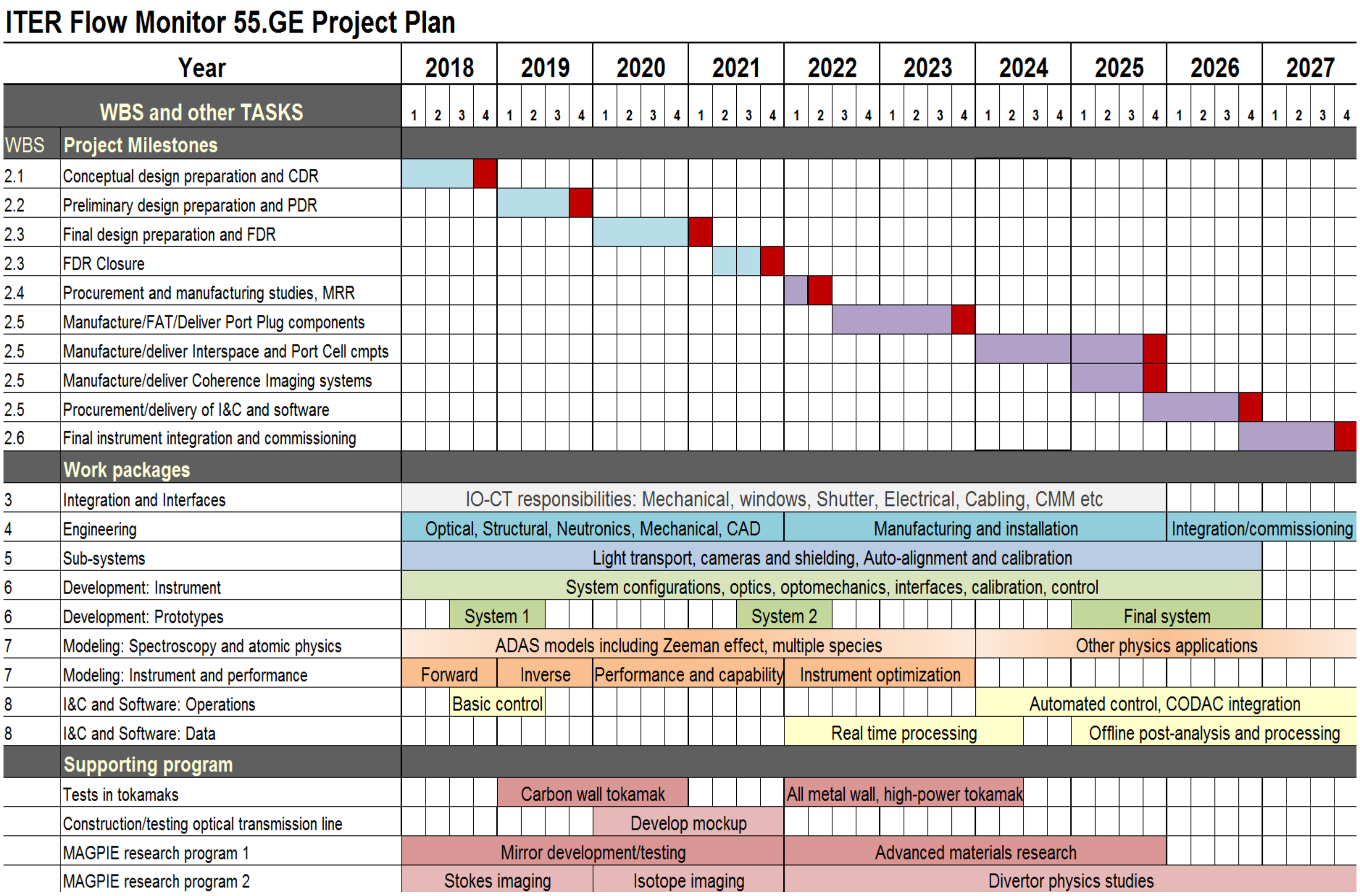
The program will work with and report to the international and domestic fusion science communities through bodies such as the ITPA and the Australian Institute of Nuclear Science and Engineering (AINSE). This will help ensure an appropriate level of scientific and technical scrutiny and accountability.

## 8 PROJECT PLAN AND MILESTONES

The IO has recently adopted the "staged approach" which envisages several assembly phases and plasma operation campaigns before the start of Deuterium-Tritium (DT) Operation [ITER_D_TSYX4X - IC/STAC-21/2.2.1-2. The ITER Staged Approach to DT Operation ]. The flow monitor is required to be operational for the Pre-Fusion Power Operation I, or simply the "second plasma" (following the engineering first plasma), of which start is planned for December 2028. This date constrains the schedule of the flow monitor design development, manufacturing and delivery to IO. The design development of the flow monitor must be also synchronized with the development of the port (this concerns in particular the interfaces with the port).

Table 1 shows the Project Plan for the period 2018-2027. The schedule assumes the start of the project activities in Q1 2018 and the delivery of the flow monitor components to IO in Q4/2023 (port plug components) and Q4/2025 (interspace and the port cell components).

*Table 1. The Project Plan. The Project Milestones correspond with Column 2 of the WBS (Blue-filled Colum). The Teams and Work Breakdown Structure (WBS) tables will later be combined in a Gantt chart representation that addresses resources/workflow/milestones.*




## 8.1 DESIGN/TECHNICAL REVIEWS

The design and technical reviews will include the Conceptual, Preliminary and Final Design Reviews (CDR/PDR/FDR) to be convened at IO in accordance with the applicable guidelines [ITER_D_2832CF - Design Review Procedure] and the Manufacturing Readiness Review(s) to be organized at the Aust-team premises.

# 9 PROJECT WORK PACKAGES

The allocation of work packages is indicative only. The responsibilities within each work package will be detailed in a number of Implementing Agreements.

## 9.1 INTEGRATION AND INTERFACES

Apart from CODAC, these elements will be managed largely by the IO-CT.

### 9.1.1 Physical and functional interfaces

The flow monitor will be installed in EP8 and the most important interfaces will be thus the physical interfaces with this port. These interfaces will be described in a dedicated interface sheet (IS). This IS will specify e.g. (i) the main components of the flow monitor (weight, materials, CAD model location), (ii) assembly tolerances of the flow monitor components inside the DSM, interspace and port plug, and (iii) requirements for electrical, gas and water services. Additional interfaces will include e.g. interface with CODAC, diagnostic electrical services, cable trays, and machine assembly and installation. All these interfaces will be specified through dedicated interface sheets.

### 9.1.2 Mechanical requirements (Water, gas, electrical, alignment, etc.)

Aust-team will specify the needs for the water (for the mirror cooling), gas (for the mirror cleaning and shutter actuation) and electrical supply. This will include the water flow rate, type of gas, number of electrical pins and specific cables (if required e.g. for the mirror cleaning). These requirements will be formalized through the interface sheet with EP8, cabling collection list, cabling diagrams, Piping and Instrumentation Diagram (9.1.6), etc. See e.g. ITER_D_46NXUU - Window Assemblies Design Description Document

### 9.1.3 Windows

In order to standardize the design of the vacuum windows assemblies, IO-CT performs the qualification test program for the windows assemblies and manages the catalogue of standard diagnostic window assemblies for the use in ITER. IO-CT specifies the main technical features of these catalogue windows (e.g. fixation types, SVS connection). The specification of the functional requirements (material, diameter, optical surface requirements, coating requirements, etc.) will be in the responsibility of the Aust-team. These functional requirements will be formalized through a dedicated interface sheet with the windows assembly. The windows will be procured by the Aust-team. (See e.g. ITER_D_46NXUU - Window Assemblies Design Description Document )

### 9.1.4 Diagnostic shutter

The system can take advantage of standardized solutions, e.g. pneumatic shutter, already used for a number of other diagnostics.

### 9.1.5 Configuration Management Model (CMM) for Equatorial Port 8

The management of the CMM will be in the full responsibility of IO-CT. The CMM constitutes the design envelope for a diagnostic system. The purpose of the CMM is to avoid clashes with other diagnostics sharing the same port or with the port structures. The CMM will be allocated to the CI flow monitor in a way to provide some flexibility in the diagnostic design whilst avoiding excessive space demands. If necessary, the update of the CMM will be done through a formal process managed by IO-CT. (see ITER_D_NSADBC - Port Integration Engineering Guidelines ).

#### 9.1.6 Electrical connections

IO-CT will develop and qualify standard vacuum electrical feedthrough for the port plug electrical services. Aust-team will specify the electrical needs for the flow monitor port plug components.

#### 9.1.7 Process Flow Diagram (PFD), Single Line Diagram (SLD), Piping and Instrumentation Diagram (P&ID) and Cabling Diagrams

These diagrams defines the flow monitor diagnostic on the system engineering level. The CCL specifies the type and the number of cables allocated to the flow monitor diagnostic and the requirement regarding the cable segregations in the cable trays. Preliminary system diagrams and the cable collection list (CCL) for the flow monitor diagnostic have already been prepared by IO-CT. These diagrams will be updated and maintained by the Aust-team as the diagnostic design evolves. IO-CT will provide training and expert support for the update and the review of the diagrams and the CCL.

The preliminary diagrams and the cable collection list were prepared based on the existing similar CI systems (with some conservative assumptions about the number of cables needed) so are OK to the first order. Later Aust-team will update and maintain them.

ITER_D_TPCYN8 v1.1 - 55-GE-00 Divertor Flow Monitor PID

ITER_D_TPCTCJ v1.2 - 55-GE-00 Divertor Flow Monitor PFD

ITER_D_TPAPDD v1.3 - 55-GE-00 Divertor Flow Monitor SLD

ITER_D_UANTKG - 55-GE-00 Flow Monitor CCL

#### 9.1.8 Control, Data Access and Communication (CODAC and I&C)

This work package includes (i) the definition of the flow monitor instrumentation and control functions and architecture (including high level functional analysis, functional breakdown and the physical and functional architecture), (ii) the specification of the I&C controller type and the network interface configuration, (iii) the list of signals to plant system I&C, including signal name, type, sampling rate, allocation to I&C cubicle, (iv) hardware configuration of I&C cubicles showing the cubicle interfaces with CODAC infrastructure, buildings, power supply and HVAC, etc.

### 9.2 ENGINEERING RESOURCE CELL

#### 9.2.1 Optical design

While this is mainly an Aust-team responsibility, expert support (e.g. to review the proposed design or to advise on standard design solutions) will be provided by IO-CT. The task is to use existing designs as a basis for optimizing the optical transmission line subject to various constraints:

- Set viewpoint and field-of-view (done)
- minimize number of mirrors while avoiding low incidence angles
- maximize and preserve light throughput
- maintain a well-behaved optical polarization response
- satisfactory neutron shielding (avoid straight paths by using ‘dog legs’ in the optical design)

- possible in-situ calibration options
- assessment of the alignment tolerances to identify acceptable misalignment and required precision for mounting or individual mirrors and mirror assemblies

#### 9.2.2 Structural analysis

Aust-team will develop the system load specifications (SLS) document for the flow monitor CI system, following the IO SLS requirements. Aust-team will also perform and update the structural analysis of the flow monitor diagnostic in accordance with the IO requirements to demonstrate that the design is compliant with the loads specified in the SLS. IO-CT will provide onsite IO training for suitable engineers to facilitate the development of load specifications and Structural Integrity Report (SIR). IO will also provide expert support for the review of the SLS and SIR.

#### 9.2.3 Neutronics modeling

Aim to achieve lowest possible neutron leakage whilst maintaining acceptable optical performance and staying within the specified neutron budget. The neutronics analysis will be performed by the Aust-team. IO-CT will also provide onsite basic neutronics training for the appropriate person if needed.

#### 9.2.4 Mechanical design and CAD

Within this WP, Aust-team will develop the complete mechanical design of the flow monitor inside the IO CAD database. IO-CT will propose standard solutions for the mirror mounts, in particular inside the DSM, which may be adopted in the flow monitor. IO-CT will provide support and expert advice regarding the integration of the mechanical structures inside the port (DSM, interspace, port cell). Aust-team will establish the CAD infrastructure to work on the CAD design in a synchronous manner and will train the CAD personal to ensure that the IO CAD rules are followed. IO-CT will provide the support for installation of the CAD replicator and training.

#### 9.2.5 Manufacturing

This work package will include the pre-manufacturing studies, management of the tender process and the qualifications, procurement of the system and it's shipment to IO-CT. IO-CT will also exercise a close oversight of the Aust-team manufacture and qualification activities through the reviews and control points.

#### 9.2.6 Integration and Commissioning

This will involve the testing operational performance of all diagnostic sub-systems and instrumentation and control software prior to shipping. It will involve the in-situ installation of the optics and instruments and satisfactory integration with ITER interfaces and services. The system will then be tested against a set of performance criteria which will include auto-calibration, registration and real-time data processing and archival requirements.

#### Operations support

Australia will be seeking ongoing operations (technical) and an appropriate level of research support for maintaining and operating the system(s) and for using the results to help understanding of divertor physics and impurity transport.

## 9.3 SUB-SYSTEMS

### 9.3.1 Mirror cleaning and cooling

While the Aust-team can investigate these issues, it will make sense to build off existing solutions to first mirror problems.

### 9.3.2 Light and polarization transport

Specify and characterize the polarization properties and response of all optical components (mirrors, windows, lenses, fibers) from the Port Plug through to the Interspace, Port Cell and Gallery outside the port cell (see Figure 5). This includes accounting for Faraday Effect, stress-induced birefringence, plasma and radiation effects etc.

### 9.3.3 Cameras and shielding

It is planned to locate the camera outside the port cell in the Gallery. For the moment there is available space and this would have a number of additional advantages including lower radiation, better access which is very limited for equipment inside the port cell. The shielding enclosure must exclude EM and neutron radiation and provide a thermally controlled environment for CI system and camera. The camera choice will represent a compromise between resolution, readout time and read noise. IO-CT will provide information about existing shielding designs used for other camera-based diagnostics.

### 9.3.4 Auto-alignment and registration

The optical "hinge" used for optical alignment is located just outside the port plug closure flange in the interspace. An advantage of the imaging system is that alignment is not critical as the viewing geometry (i.e. image registration) can be determined in-principle from the location in the image of known fiducial markers in the field-of-view. A numerical procedure will be required to perform this registration.

### 9.3.5 Auto-calibration

Investigate methods for calibration of optical light throughput and polarization response of optics in Port Plug through to Port Cell. An in-situ first mirror calibration system may be required. Explore currently proposed solutions. Spectral calibration systems required at location of CI instrument.

## 9.4 DEVELOPMENT

### 9.4.1 Polarimeter and interferometer configurations

Develop and test a range of optical systems for Stokes-Doppler imaging and compare with modeling. Develop a flexible system that offers choice of configuration depending on experimental requirements (for example speed, spatial resolution, precision). Allow for simultaneous multi-colour imaging of various species and ionization states. Allow for simultaneous measurement of flows and temperatures at multiple optical delays.

### 9.4.2 Coherence imaging optics and interfaces

Develop and characterize:

- polarization optical components (Wollaston prisms, Savart plates, delay plates etc.), including liquid crystal modulators and switches (materials, coatings, dimensions, orientation, delay, switching times etc.)

- mirrors, windows, lenses, filters and other optics from Port Plug through to CI system
- robust opto-mechanical mounting solutions
- Thermally and mechanically stable and rad-hard enclosure.

### 9.4.3 Calibration optics and sources

A range of monochromatic calibration sources will be investigated, including discharge lamps and lasers, including custom manufactured fixed wavelength diode lasers and optical frequency combs. To obtain a robust calibration, these sources will be required to illuminate the interferometer in the same way as the plasma emission (in-situ first mirror calibration or self-consistent plasma-emission-based strategy). Various approaches combined with modeling and bench tests will be explored to achieve this challenging goal.

### 9.4.4 Control systems

Develop DAQ hardware and software solutions for system switching, timing, actuation etc.

### 9.4.5 Prototype system deployment and testing

Various prototype systems will be deployed on frontline tokamaks such as MAST or DIII-D (carbon walls) and JET or WEST (metal walls). Some of the more important aims include

- Validating forward and inverse imaging models,
- Investigating the effects of wall reflections
- Benchmarking spectroscopic models for various impurity species
- Testing system hardware and electrical properties such as shielding, remote control, automated spectro-polarimetric calibration systems, performance of thermally stable enclosures and optical mounting systems.
- Deployment and testing of software systems.

## 9.5 Modeling

### 9.5.1 Spectroscopy and atomic physics

There are a range of important spectroscopic issues that need to be considered for proper interpretation of impurity radiation. For example, quantum mechanical models of Zeeman splitting in strong and intermediate field regimes will be required. Survey spectra on current day machines should reveal suitable emission line targets for common ionic and atomic impurity species (Be, C, N, etc) in the range 400nm-700nm. The structural details of these spectra and their dependence on plasma conditions, including possible self-absorption effects will be required.

### 9.5.2 Forward optical models

Simple forward models that compute the expected Stokes intensity images (phase and contrast) have been already developed as part of the preliminary scoping study. A number of important issues remain to be properly accommodated, including

- Realistic plasma emission models that accurately account for Zeeman splitting.
- The polarization properties of the optical transmission line
- Optical aberrations and vignetting
- Polarization dependent scattering and reflections from the material walls

- Non-ideal polarization response of the various optical Doppler-Stokes interferometer/polarimeter configurations (see Sec. Modulation options below).
- Symmetry-breaking effects of RMP fields.

### 9.5.3 Inverse procedures

Assuming toroidal symmetry, it is possible to retrieve local information using tomographic techniques. Inverse procedures will be required for the emission intensity, the flow field component parallel to the magnetic field, and the species temperature. The inverse models will also assist with the optimization of the instrument design parameters and used to assess the likely efficacy of polarization filtering for background reflection suppression. Some considerations include:

- The weighting kernels for the Stokes intensities must account for the time-varying vector magnetic field.
- The utility of stabilizing a priori assumptions (for example flux surface constraints).
- The impact of higher order terms in the integral kernels needs to be assessed.
- Sensitivity to registration errors.

### 9.5.4 Performance and capability

Models will be developed to test system performance against measurement requirements. Models will investigate and optimize trade-offs between system optical design (OTF, modulation options etc), and the resulting temporal and spatial resolution of the Doppler-based quantities (flows and temperatures) subject to expected light fluxes, random noise sources and reflection contamination.

### 9.5.5 Modulation options

Spatial heterodyne systems require no modulating components, but suffer from a loss of spatial resolution. Temporal multiplex methods risk inconsistencies produced by changing plasma conditions. Multiplexing of multiple images onto a single CCD capture reduces light sensitivity and is subject to aberrations and registration errors. All these options, including possible hybrid systems, need to be explored using realistic forward and inverse models.

### 9.5.6 Calibration options

An accurate and reproducible calibration is required to determine the instrument Doppler-Stokes response (i.e. 'instrument' temperature and flow speed images and mapping and modeling of the ellipticity and polarization orientation response). An assessment of vignetting effects, polarization distortion is also required. Availability of suitable 'monochromatic' calibration sources and illumination options will need to be explored. Calibration reproducibility in the light of possible thermal drifts and other effects needs to be assessed.

### 9.5.7 Other physics applications

A variety of other important spectroscopic applications can take advantage of the polarization-preserved optical emission seen by the EP8 system. These include intensity ratio imaging for monitoring H/D/T ratios and possible Stark-broadening for electron density measurements. There is a need to explore the utility of multiple systems sharing the same light source for simultaneous optimized measurement of flows and temperatures, or multiple radiating species.

## 9.6 Instrumentation and control, and Software

### 9.6.1 Infrastructure

This is instrumentation associated with system control and data acquisition. It includes

- Electro-optical and electro-mechanical components,
- DAQ hardware for system control (triggers, switches, motors, actuators, interlocks etc)
- Image and data acquisition hardware
- Real-time FPGA and/or GPU hardware for image conditioning
- Communication interfaces to the ITER CODAC system.

Where possible these systems will be located in the diagnostic building or shielded corners of the tokamak building. Electro-optical equipment and some actuators (e.g. filter wheels, stepper motors and optical flippers) will likely be located together with the CI instrument and calibration equipment in the Gallery.

### 9.6.2 Operation and control software

To be specified.

### 9.6.3 Data real-time pre-processing and demodulation

Explore FPGA and/or GPU-based systems for real-time noise-reduction and/or binning pre-processing, including demodulation and compression of spatially and/or temporally encoded interferograms. This will include the application of suitable calibration and flat-field corrections, and image registration.

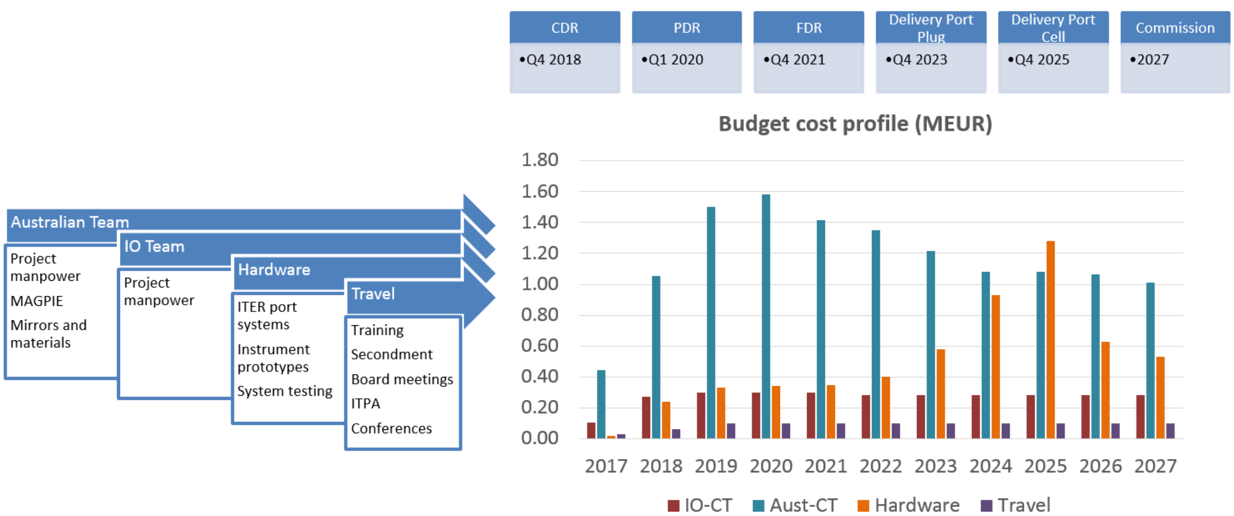
### 9.6.4 Offline software

This will involve post processing analysis of the de-noised, demodulated and calibrated Stokes vector and Doppler images. It will involve application of various tomographic inversion routines, benchmarking against other available diagnostic measurements, and comparison with various physical models.

# 10 PROJECT BUDGET

The budget will be set by the requirements of the WBS and associated schedules as agreed and detailed in various Implementing Agreements. The largest components of the budget are the manpower and hardware costs. A summary of these costs for the flow monitor project from the CDR preparation phase (2018) until installation and commissioning (2027) is shown in Table 2. The spending rate takes into account the project scheduling from **Error! Reference source not found.** which will dictate different xpertise and hardware costs (broken into infrastructure/R&D and the system manufacturing cost) according to the project phase/deliverables etc. The full breakdown of costs and their justification is given in the accompanying budget spreadsheet.

*Table 2. Project budget for manpower, hardware and travel costs.*




| Budget components | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2018-2027 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IO-CT Manpower (MEUR) | 0.11 | 0.27 | 0.30 | 0.30 | 0.30 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | **2.97** |
| Aust-PT Manpower (MEUR) | 0.45 | 1.05 | 1.50 | 1.58 | 1.42 | 1.35 | 1.22 | 1.08 | 1.08 | 1.07 | 1.01 | **12.80** |
| Hardware (MEUR) | 0.02 | 0.24 | 0.33 | 0.34 | 0.35 | 0.4 | 0.58 | 0.93 | 1.28 | 0.63 | 0.53 | **5.63** |
| Travel, secondment and training (MEUR) | 0.03 | 0.06 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | **0.99** |
| **Total** | **0.60** | **1.62** | **2.23** | **2.32** | **2.16** | **2.13** | **2.18** | **2.39** | **2.74** | **2.08** | **1.93** | **22.39** |

The budget assumes the average person cost per year equivalent is 135 kE. As can be seen from the table, excepting 2018, the project will require approximately 2.0 ME per year, with slight peaking during the preliminary design stage (mainly labour costs) and later during the manufacturing phase (peaking of hardware cost).

The budget includes elements that are specific to the needs of the Australian Team, including provision for outreach, project-specific travel, including broad-based ITPA participation and support for the MAGPIE Facility operations (ANU) and materials research. These elements allows for testing instrument concepts and fusion-materials developments, including essential mirror research. Funding for additional elements such as associated research programs and student support will also be sought through domestic research support agencies such as the Australian Research Council.

The Aust-team budget also allows for promotion and outreach. This will include press and media releases, maintenance of a web presence and portal, and an outreach program to other Australian universities and institutions, engineering associations, industry, schools and the public.

Beyond 2027, following delivery, installation and commissioning of the diagnostic system, it is anticipated that the required budget will fall substantially as the project enters the operations and research phase. There will no longer be a requirement for engineering services in this phase, while required technical and administrative support will also reduce substantially.

# 11 Design changes

Design changes will be managed using Deviation Request (DR) or Project Change Request (PCR) procedure.

# 12 Risks and mitigation strategies

There are wide range of risks encompassing scientific and technical feasibility, engineering reliability, work delays, budget creep and so on. In due course, a full risk assessment based on established IO processes (e.g. RAMI - Reliability, Availability, Maintainability and Inspectability - https://www.iter.org/newsline/55/1193 ) will be determined and risk mitigation strategies developed. The budget presented here is comparable to budgets for diagnostic systems of similar scale already under development, and has been prepared in close consultation with the IO-CT.

# 13 Documentation and Records

The documents specified in the IO Document Production Plan [ITER_D_RZJ4LM - Documentation Production Plan (DPP) Template for PBS 55] will be kept on IO IDM. Other routine records and documents such as workbooks, data files, meeting minutes, correspondence, budget documents and so forth will be retained in electronic format by the Aust-team management and administration.

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