Princeton Plasma Physics Laboratory

PPPL- 4720

PPPL- 4720

Initial Investigation of Diagnostics in Support of Fusion Pilot Plant Studies

A.E. Costley

January, 2012

PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

November 22, 2011

Initial Investigation of Diagnostics in Support of Fusion Pilot Plant Studies

Work Carried out Under Subcontract S010486-G

A E Costley

Consultant, former Head of Diagnostics on ITER, Henley on Thames, UK.

Contact: Alan.Costley@physics.org

Abstract

An initial investigation of diagnostic aspects of a fusion pilot plant (FPP) has been undertaken as part of the on-going PPPL led FPP study. The diagnostic aspects of the spherical tokamak (ST) and advanced tokamak (AT), and to a lesser extent the compact stellarator (CS), FPP variants have been investigated. For the ST and AT, the requirements for first wall and plasma measurements have been derived in consultation with appropriate PPPL staff (J Menard for the ST and S Scott for the AT); candidate diagnostics to meet the requirements have been selected; and a first level integration with the machine has been attempted in cooperation with T Brown. For the CS, the measurement requirements have been derived in consultation with M Zarnstorff. The performance and reliability that could be expected of the diagnostic systems in the FPP have been assessed and critical areas identified. It is found that because of the relatively harsh environment - for example, approximately 10 - 40 x higher neutron radiation levels on the in-vessel diagnostic components than on ITER, and, in some cases, much higher thermal and mechanical loads - some diagnostics that conventionally provide quite basic measurements will probably not be feasible. Because of the central role that plasma and first wall measurements will play in the optimization and control of an FPP, it is essential that these critical areas be addressed in the next step development of the FPP. Some suggestions for potentially promising developments are made. Part of the work undertaken in this study has been peer reviewed and a summary of the response to the key matters raised in the review is included.

Table of Contents

1. Introduction

A potentially attractive next-step toward fusion commercialization is a fusion power plant (FPP). The goals of the FPP are to demonstrate the production of net electricity and tritium sustainability utilizing technologies and maintenance procedures that would be scalable to a reactor. Because of the central role that plasma and first wall measurements will play in the optimization and control of an FPP, study of existing measurements systems (diagnostics) and their potential applicability to an FPP is essential. In an FPP components of key diagnostic systems will potentially be subject to high levels of neutron radiation and high thermal and mechanical loads, and it is possible that the associated diagnostic systems will not be applicable. Adjustment of the FPP design and/or dedicated R&D on diagnostics will be necessary in order to achieve a credible integrated design. As part of an on-going PPPL led initiative to investigate the FPP an initial investigation of the diagnostic aspects has been undertaken. The results of the study are reported in this report.

In the FPP study three variants are being investigated - the spherical tokamak (ST), advanced tokamak (AT), and the compact stellarator (CS). A work program was established with the intention of investigating the diagnostic aspects of all three. The intended work program was completed for the ST and AT but because of the stage of the design of the CS at the time scheduled for completion of the diagnostic work program only a preliminary investigation of the CS was possible.

The results of the study are reported herein. The intended work program is presented in section 2 and the investigations undertaken for the ST and AT are reported in section 3. Part of the work undertaken in this study has been peer reviewed and a summary of the response to the key matters raised is given in section 4. The initial work carried out for the CS is presented in section 5. The performance and reliability that could be expected of the diagnostic systems in an FPP have been assessed and critical areas identified. The results of the assessment and some suggestions for next step work on diagnostics are presented in section 6.

2. Diagnostic Work Program

Basic Strategy: For each candidate machine configuration (ST, AT, CS), develop plasma measurement requirements, individual diagnostic system selection, high-level integration with access and space requirements, initially ignoring radiation and environmental effects. Then to identify and assess critical areas in view of expected radiation and environmental effects and adjust system to minimize risk. This will give a baseline diagnostic configuration and should enable the identification of the critical areas where R&D is needed and the next useful steps in this work.

For each machine configuration (ST, AT and CS), the following tasks will be undertaken.

Task 1. Determination of requirements for plasma and first wall measurements.

Inputs needed:

(a) High level machine performance requirements

(b) Expected values of key plasma parameters and outline plasma control requirements if possible.

Task 2. Selection of diagnostic systems and definition of space requirements for implementation.

Task 3. Integration of diagnostic systems into machine configuration.

Input needed:

(c) Machine configuration (dialogue with machine designers needed at this stage)

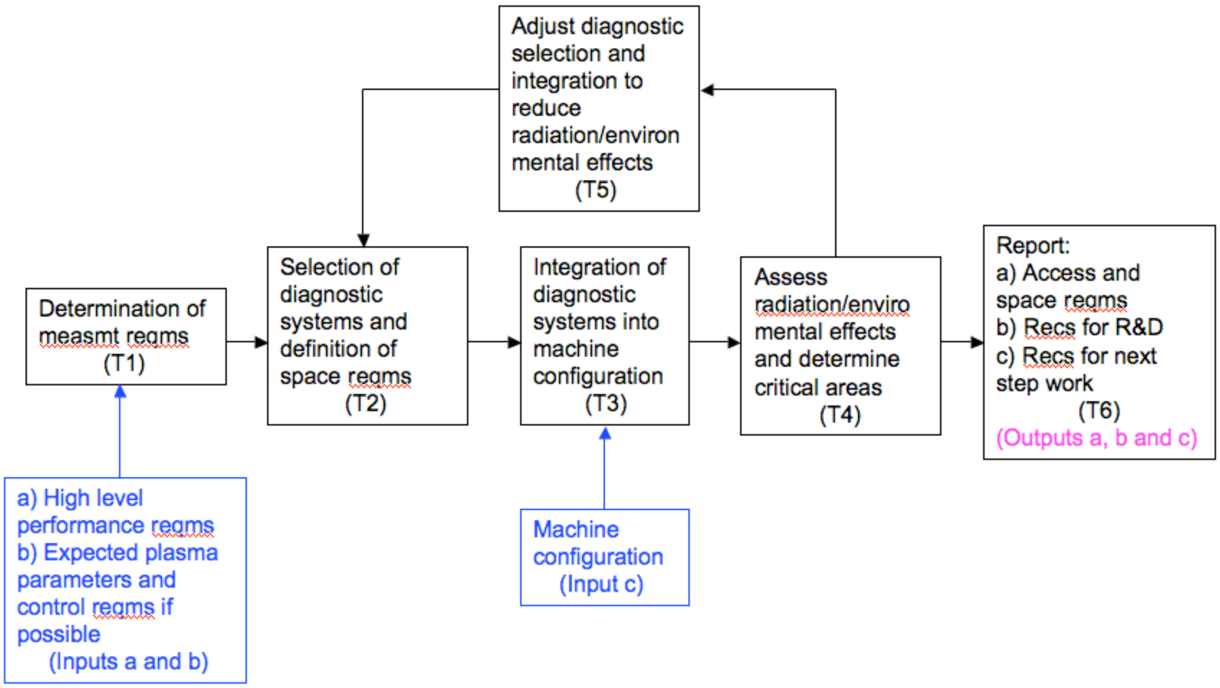
Task 4. Assessment of radiation and other environmental effects and determination of critical areas.

Task 5. Adjust selection and integration to reduce radiation/environmental effects.

Task 6. Prepare report with three principal elements (outputs)

(a) Access and space requirements
(b) Recommendations for R&D
(c) Recommendations for next step work

Total duration: 4 days per machine configuration. 12 days total.



Main Elements of Work Program for One Machine Configuration with Needed Inputs and Intended Outputs.

Identical Steps to be followed for each machine configuration.

3. Investigation of the AT and ST

3.1 Required Parameters that Must be Measured to Support Operation of a Fusion Pilot Plant Based on a ST and AT.

Assumption: It is assumed that the ST and AT will be operated in long pulse or steady state H mode and that measurements will only be needed for control and performance optimization and not for extensive scientific studies. This approach will give the minimum diagnostic set. It will give the minimum requirements on the integration of the diagnostic systems with the machine and therefore the least complication to the machine due to diagnostics.

Methodology: On the basis of experience on JET and ITER, A Costley (AC) developed a list of parameters for both the ST and AT that must be measured distinguishing between those that are expected to be required for real-time control and those required for optimization and set-up. The parameters for the ST were reviewed by Jon Menard (JM) and, after discussion, a modified list was developed. A similar process was followed for the AT with Steve Scott (SC). The small differences that emerged between the lists for the ST and the AT were reviewed (in response to a chit raised at the Peer Review) and it was agreed that they were not significant but rather reflected the method of development. A unified list was developed by AC, JM and SC working together. The list is as follows.

Parameters required under real-time control

Plasma shape and position, vert speed, Btor, Ip, Vloop, β

Existence of locked modes, m = 2 modes, low m/n MHD modes

ELM occurrence and type, H/L mode indicator

Line-average density

Zeff (line average)

Runaway electrons

Surface temperature of first wall and divertor plates (Note 1)

Divertor detachment

q(r)

nT/nD in core

Prad from core – single chord

Pfus

Impurities in divertor

Other essential parameters that must be measured for optimization and set-up

Prad(r) from core

Te(r) and ne(r) in core

Impurities in core

ne and Te in divertor

Ti(r) in core

vtor(r)

ne(r) in edge

Impurity influx

D,T influx

RWMs

Energetic particle modes

He content in divertor exhaust

Gas pressure and composition

Erosion of first wall and divertor, and dust (Note 2)

Notes

(1) Maybe the bulk or near surface temperature would be sufficient.

(2) Parameters such as these merge with machine engineering parameters.

(3) Possibly add measurement of halo currents flowing in internal structures, especially the blanket module supports.

3.2 Candidate Diagnostics for the ST and AT Fusion Pilot Plant Variants

Based on the experience gained in preparing diagnostics for ITER, it is possible to identify candidate diagnostics for each of these parameters. These are shown in the following table. Some of these diagnostics will require components mounted in the vacuum vessel while others will require components in ports or in the divertor. Even at this stage it is clear that some will require dedicated R&D. These aspects are highlighted in the table.

Diagnostics that need a labyrinth in an upper-port
Diagnostics that need a labyrinth in a mid-plane port
Diagnostics that need optical viewing at the divertor level
Diagnostics that need sensors on inboard side
Already clear R&D topic

Role	Parameter	Candidate Diagnostic	Comment
Measurements for Real-time Control	Plasma shape and position, vert speed, Btor, Ip, Vloop, β	A complete set of magnetic sensors both inside and outside the VV (normal and tangential coils, flux loops, Rogowskis, diagmagnetic loops, MHD saddles); inductive operation (inner), steady state operation (outer). Inner sensors designed for minimum effect due to radiation and probably requiring active cooling.	The basic approach is the same as that used on ITER, ie inductive operation for the inner set and steady-state operation for the outer set, both sets working in unison (how to do this is a current R&D topic within ITER). For the inner set, need good e.m coupling with the plasma and this probably means that gaps will be required between the blanket modules. The absence of blanket modules on the high-field of the ST probably means that sensors cannot be mounted in this location with the consequence that there will be significant degradation of the information, especially of plasma shape and position, that can be obtained from magnetics. The development of alternative means to obtain this information would be required.
	Existence of locked modes, m = 2 modes, low m/n MHD modes		
	ELM occurrence and type, H/L mode indicator	Reflectometry from low field side	
	Line-averaged density	Single line of sight interferometer	Use longest wavelength possible to avoid problems from plasma facing mirrors
	Zeff (line average)	Visible continuum emission	Have to mitigate against first mirror damage, eg use

Role	Parameter	Candidate Diagnostic	Comment
			active shutter if measurement not required continuously.
	Runaway electrons	Vis/IR viewing, Hard X-ray monitors	
	Surface temperature of first wall and divertor plates	Vis/IR viewing (x8), Thermocouples in key components	Aim for high fractional coverage of the first wall.
	Divertor detachment	Vis/UV spectroscopic influx monitor	Could be very difficult to implement. Potential R&D topic; how to operate without it?
	q(r)	Multiple chord polarimetry (say 10 channels). Possibly MSE on the heating beams.	Upgrade capability to 20-30 channels maybe needed. Choose longest wavelength for operation possible consistent with getting a good measurement, probably λ in range 10 – 100 microns. Will require retroreflectors mounted on first wall on inboard side. For MSE, have to take care to maintain polarization in the in-vessel optical labyrinth that will inevitably be needed to shield the neutron flux. Possibly perform MSE using spectroscopic approach, which will not require polarization measurements.
	nT/nD in core	Neutral Particle Analyser	This is going to be difficult to implement. Could be another area where either R&D is needed to manage without or a new technique is needed. Potentially one exists – Fast Wave Reflectometry and should be much easier to implement but needs R&D.
	Prad from core – single chord	Bolometers	A port based system could give a single chord measurement but radiation hard bolometers will be needed. Such bolometers are currently under development for ITER but on an FPP they will have to operate at higher levels of neutron flux. For conventional resistive foil type bolometers lifetime will be a problem. Other potentially more rad. hard options exist but will require dedicated R&D.
	Pfus	Neutron flux monitors (x4) Activation system	To cover the wide range of neutron flux from calibration source to the plasma emission (many orders of magnitude) several different types of neutron

Role	Parameter	Candidate Diagnostic	Comment
			detectors will be needed with different degrees of coupling to the plasma.
	Impurities in divertor	Vis/IR cameras, dedicated Vis/UV systems viewing the divertor plasma (lower and upper)	Exactly what is implemented for this measurement will depend on what impurities are expected. At this stage probably just make some access provision at the upper and lower levels for the divertor viewing.
Additional Parameters for Optimization and Set-up	Prad(r) from core	Bolometers	In principle, Prad(r) measurement requires bolometers mounted on the inboard and outboard sides viewing the plasma through gaps in the blanket modules (as on ITER), but likely to be very difficult/impossible to implement on a PP. For conventional resistive foil type bolometers lifetime will be a problem. Other potentially more rad. hard options exist but will require dedicated R&D.
	Te(r) in core	ECE or Thomson Scattering	For the AT, ECE should operate satisfactorily but it may not be possible to measure the full profile due to harmonic overlap and there might also be limitations on the spatial resolution due to intrinsic line broadening at the high electron temperatures expected. For the ST, it probably wont be possible to use conventional ECE measurements because of harmonic overlap. Th Sc will require large apertures for access and have potentially severe first mirror problems. The first mirror problems could be so severe that measurements at only a few times during the plasma pulse may be possible (may have to limit exposure of first mirror to the plasma using a shutter). But expect plasmas to be collisional and so a measurement of Ti(r) may be enough.
	ne(r) in core	Multiple chord interferometry, Thomson Scattering	Combine with polarimetry and/or use multiple lines of sight in the mid-plane used for line-averaged density. Outer profile can be obtained from reflectometry.
	Impurities in core	Vis/IR cameras, dedicated Vis/UV	Exactly what is implemented for this measurement will

Role	Parameter	Candidate Diagnostic	Comment
		systems viewing the main plasma	depend on what impurities are expected. At this stage probably just make some access provision at the mid-plane.
	ne and Te in divertor	Spectroscopy and/or dedicated Thomson scattering system. (viewing through mid-plane and/or upper, and/or divertor ports) (lower and upper)	With the severe access restrictions at the divertor level it is not easy to see how these measurements can be made. Possibly passive spectroscopic viewing from upper or lower ports might give estimates. A high resolution LIDAR type system could, in principle, be implemented in one of the outboard ports (upper or lower) but it would be a significant installation.
	Ti(r) in core	X-ray crystal spectrometer High res. neutron spectrometer	XCS may require R&D to achieve necessary radiation hard detectors.
	vtor(r)	X-ray crystal spectrometer	ditto
	ne(r) in edge	Reflectometry	Implementation should be relatively straightforward.
	Impurity influx D, T influx	Vis/IR cameras, dedicated Vis/UV systems viewing the main plasma especially the edge region.	Exactly what is implemented will depend on impurities expected. Measurement of the D, T influx is a specific case.
	RWMs	In-vessel magnetics	See comments above regarding in-vessel magnetics.
	Energetic particle modes	In-vessel magnetics, reflectometry, ECE	It should be possible to detect the modes fairly straightforwardly but detailed modeling would be needed to extract details of the energetic particle population.
	He content in divertor exhaust	RGAs	
	Gas pressure and composition	Pressure gauges, RGAs	
	Erosion of first wall and divertor, and dust		Need a discussion with machine engineers to determine the minimum required measurements. Potentially an important but difficult topic. Overlaps with machine engineering requirements and systems.

3.3 *First Level Integration of Diagnostics for the AT and ST Variant of Fusion Pilot Plant*

Diagnostics have been chosen to meet the identified measurement requirements for the ST and AT. Reasonably optimistic assumptions have been made of the measurement capability of the individual diagnostic systems in order to find the minimum number of diagnostic views and ports needed. The number of ports that are needed to accommodate these diagnostics is based on the experience gained installing similar diagnostics on ITER. It is assumed that optical systems that require significant optical throughput will utilize mirror optical labyrinths imbedded in shielding blocks and view the plasma through apertures in the first wall. It assumed that the AT and ST will have ports at the mid-plane and above and below the mid-plane. If this is not the case then the integration will have to be revisited. High optical throughput systems are highlighted in blue.

Location	**Diagnostic**	**Number of ports**
Ex-vessel	Sets of magnetic pick-up coils normal and tangential to the vessel; Sets of steady-state sensors; A small number of continuous flux loops.	No port requirements but cabling for the electrical signals will be needed.
In-vessel	A complete set of magnetic sensors - normal and tangential coils, flux loops, Rogowskis, diamagnetic loops, MHD saddles. Bolometers on in-board side viewing through gaps in the BMs.	No port requirements but feedthroughs and external cabling for the electrical signals will be needed.
Upper	Vis/IR first wall and divertor viewing (x4) Vis/UV spectroscopy Port-based bolometry Neutron Flux Monitors (NFMs) Activation system MSE viewing of the heating beams Th. Sc. System for upper div. Te and ne measms.	5 ports
Mid-plane	Reflectometer Toriodal (multichord) interferometry Multi-channel polarimeter NPA NFM ECE/Thomson Scattering X-ray crystal spectrometer High resolution neutron spectrometer Hard X-ray monitor Visible continuum array.	2 ports
Lower	Vis/IR first wall and divertor viewing (x4) Vis/UV spectroscopy Port-based bolometry NFMs Th. Sc. System for lower div. Te and ne measms.	5 ports

Others	Thermocouples in divertor Erosion/dust monitor (Note 1) RGAs and pressure gauges	

Note 1. Erosion and dust monitors may require port views.

3.4 Identification and Assessment of Critical Areas in Diagnostics for the ST and AT and Possible Impact on the Measurement Capability

Thus far, for the ST and AT, we have defined the physical parameters that must be measured, selected the candidate diagnostics techniques, recommended the locations where the front end diagnostic components should be located, and estimated the number of ports needed. On the basis of the experienced gained with the ITER diagnostic system, it is now possible to assess this preliminary integration and to identify the critical diagnostic areas. This initial assessment has been made and is summarized below. The possibilities where further work could be fruitful are identified. To a large extent the assessment is the same for both the ST and the AT but there is one significant difference arising from the different situation regarding blankets on the in-board side.

1. In-board Magnetic Diagnostic Sensors

For the ST, the lack of a blanket on the in-board side makes the magnetic diagnostic sensors (loops and pick-up coils) that would, from a diagnostic perspective, ideally be mounted in this location, the most critical diagnostic components. The neutron flux levels at the location of the sensors would be much higher than on ITER – a rough estimate puts it at least 40 times higher - and this would give rise to several different radiation and thermal effects in the sensors, and these would generate spurious signals (prompt effects) that would compete with the signals that are intended to be measured. The spurious signals would be significantly higher that on ITER because of the relatively higher neutron fluxes. It is estimated that the ITER magnetics diagnostics system will start having difficulty from the radiation induced signals after a few hundred seconds of high power plasma operation in a long pulse, and so, by extrapolation, the limiting pulse length on the Pilot Plant would therefore be much shorter (assuming inductive magnetics diagnostics as used on ITER for the in-vessel sensors). There would also be long-term changes/damage to the sensors due to the high fluence (accumulative effects). Moreover, in this location, the sensors would potentially be subject to high mechanical and thermal loads from plasma disruptions. Taken together, these perturbing effects and risks almost certainly mean that it is unrealistic to have magnetic diagnostic sensors on the in-board side of the vacuum vessel with a consequential reduction in the measurement capability.

Potentially, the sensors could be located in the skins of the vacuum vessel and/or be integrated into the Central Solenoid. In these locations they would be protected from the plasma disruption loads. However, the radiation levels would still be high since the screening given by the vacuum vessel is only moderate, and there would be a conducting surface between the sensors and the plasma – eddy currents in this structure could disturb the measurements. Detailed modeling would be required to determine the impact on the measurement capability but it is unlikely that the full capability would be available.

Also for the AT probably the most critical diagnostic components would be the diagnostic sensors mounted on the back-wall on the in-board side. The AT has blanket modules on the in-board side and so there would be some shielding from the neutron flux. Relative to ITER, approximate calculations suggest that the neutron flux levels would be about 10 times higher on the inboard side (because of the thinner blanket module) but about the same or lower on the outboard side. The sensors would have to couple to the plasma through gaps between the blanket modules and/or directly through the modules. The details of this coupling could well have a significant impact on the measurement capability.

Currently, magnetics diagnostics operate inductively but this type of operation is difficult/inconsistent with the intended steady-state operation of both the ST and the AT (requires special integrators). In principle, steady-state sensors could be used but those currently available are thought not to be able to operate in the harsh in-vessel environment. An R&D option is to develop steady-state sensors that could withstand this environment. An alternative is to install an additional set of sensors utilizing steady-state sensors external to the vacuum vessel where the radiation levels are lower. In principle, if the vessel currents can be accurately modeled, the external set alone would be sufficient. A possible approach is to use the two sets - inductive in-vessel and steady-state ex-vessel – and during the low activation phase develop and validate the models of the currents in the vessel. Then, during the active phase, the external set and the validated models should be sufficient. This is the method being adopted for ITER and, in principle, the experienced gained could be available for the PP.

2. Out-board Magnetic Sensors

In principle, on the out-board side, the magnetic sensors could be located behind the blanket modules on the back-wall. Here they would be shielded by the modules against the neutron flux and protected against the thermal and mechanical loads arising from disruptions. They would couple to the plasma through the gaps between the blanket modules and through the modules directly. For ease of maintenance, the modules on the ST are planned to be large, banana-shaped, poloidal segments. In the current ST design, there are vertical, poloidal-going gaps, with a labyrinth to reduce neutron streaming, between adjacent modules, but no horizontal, toriodal-going, gaps. The coupling of the sensors to the plasma would be influenced by the presence of the modules and the size, direction and location of the gaps. A detailed analysis would be needed to determine the impact on the measurement capability. It is likely that there would be significant impact. Compensation by using data from other diagnostics to make up for the reduction in measurement capability might be possible and could be explored in future work.

On existing tokamaks, and also planned for ITER, the measurements provided by the magnetic sensors on the in-board and out-board sides are used in the determination of several plasma parameters and especially the plasma shape and position, and these parameters are used in real-time plasma control. If these parameters cannot be measured using magnetics diagnostics, then alternative diagnostic means would be needed. There are possibilities, for example, visible or near visible tangential viewing of the plasma to obtain the position and shape of the plasma boundary, but this would be new territory for diagnostics and would need extensive development on existing machines.

3. Bolometry

Both the ST and the AT require a measurement of the spatial profile of the radiated power for optimization and set-up. This can only be obtained with bolometers mounted at different poloidal locations and some sensors will be required to be mounted inside the vacuum vessel on the in-board side. In principle, for the AT these sensors could view the plasma through gaps in the blanket modules. In this location, there are potential perturbing/damaging hazards arising from the high levels of neutron flux and, of course, significant maintenance issues. A similar situation exists on ITER and so in this case too ITER may provide the experience and development base that is needed, although the neutron flux at the location of the bolometers will probably be higher on the PP as mentioned above.

For the ST, the absence of blanket modules means that it is not feasible to mount bolometers on the inboard side and so the measurement of the radiation profile cannot be made independently. If the magnetic surfaces are known, and it is assumed that the radiation is a constant on a magnetic surface, then possibly the radiation profile could be unfolded from port-based measurements made on multiple lines of sight. R&D would be needed to establish this approach.

4. Optical Diagnostics

Diagnostics that use e.m. radiation in the UV to submillimeter range, and especially those that require a high optical throughput, will probably have to view the plasma via a mirror: high levels of neutron radiation prohibit the use of refractive components near the plasma. The mirror would be the first component in an optical labyrinth embedded in neutron shielding and located in ports dedicated to diagnostics. This is the technique being adopted on ITER. The problem with this approach is that there will be high levels of erosion of the first wall and divertor and this will lead to deposition of first wall material on the plasma facing mirror. Depending on their location, the mirrors could also be eroded. The deposition and erosion will lead to degradation in the reflectivity of the mirrors. Estimates based on ITER work suggest that the degradation could be quite rapid and possibly, in some cases, severe in less than one plasma pulse.

Within the ITER program, there is an extensive R&D program to deal with the problem. The main elements of the program are the development of design solutions which minimize the degradation; use of materials that are resistant to erosion; development of mitigation measures such as in-situ cleaning and calibration, and use of shutters and baffles. Designs that enable replacement of the mirrors without changing other parts of the diagnostic are also incorporated.

Estimates of the expected level of erosion and deposition in an FPP have not been made but since the first wall fluxes will be higher than on ITER we can expect that they will be higher too. The diagnostic first mirror problem will therefore likely be even more severe than is expected on ITER. Diagnostics that utilize first mirrors should therefore be avoided if possible and this was done in the diagnostic selection (Section 3.3). Nevertheless, it was not possible to avoid them entirely: for example, systems that view the first wall and divertor in the visible and IR are required, and visible and near UV spectroscopy is required for several measurements.

In principle, the first mirror problem could be avoided by viewing the plasma through very long and narrow viewing pipes, but the solid angle of view would be small and the associated reduction in measurement capability may not be acceptable. This is an area where further investigation is required.

5. Access at Divertor level: Divertor Diagnostics

Several critical measurements are required of the divertor plasma, for example measurements of the divertor detachment, but access for diagnostic systems at this level is very limited. There are also high levels of erosion and deposition in the divertor region and this will potentially degrade diagnostic components at this level. Significant design and targeted R&D would be needed to develop dedicated diagnostics for this region.

Both the current ST and the AT designs incorporate both upper and lower divertors and both will need to be diagnosed. On ITER systems located in the upper ports are used to diagnose the divertor at the lower level but with two divertors such an approach would not be possible. Some of the divertor viewing systems would have to be located in the mid-plane ports putting additional requirements on an already busy location.

6. Additional Diagnostic Problem Areas

With the existing machine design only one radial port is allocated to diagnostics whereas the initial diagnostic integration shows that two are needed. In principle, this could be overcome by allocating an additional port but there is great pressure on the radial ports and it is not clear if another port can be allocated. Other ports (five above the mid-plane and five below) are also needed and are presently not included in the machine design, but Dr T Brown has indicated that probably these can be accommodated.

Other difficult diagnostic areas are the measurement of first wall and divertor erosion and dust. These also are difficult areas for ITER and are topics of R&D in the ITER programme. Hopefully, a diagnostic base will emerge from this work that can be applied to the FPP.

7. Overall Assessment.

Fortunately, not all diagnostic systems will have difficulty under Pilot Plant conditions: for example, the microwave and neutron based diagnostics will be readily applicable. The measurement capability for these systems has therefore been maximized in the diagnostic selection. Further development of these techniques could be fruitful.

Based on the above considerations, it is possible to make a first level assessment of the measurement capability. This can be summarized by returning to the list of measurement parameters and highlighting in red those that are likely to be very difficult/impossible to measure, and in blue those that are difficult to measure but probably could be measured with reduced capability. No highlight means that the measurement should be possible at the required level. This is, of course, an oversimplification but it does give a summary view of the situation.

The assessment for the ST is shown below.

Red: signifies very difficult/impossible to measure; blue signifies difficult to measure but probably could be measured with reduced measurement capability.

Parameters required under real-time control

Plasma shape and position, vert speed, Btor, Ip, Vloop, β

Existence of locked modes, m = 2 modes, low m/n MHD modes

ELM occurrence and type, H/L mode indicator

Line-average density

Zeff (line average)

Runaway electrons

Surface temperature of first wall and divertor plates

Divertor detachment

q(r)

nT/nD in core

Prad from core – single chord

Pfus

Impurities in divertor

Other essential parameters that must be measured for optimization and set-up

Prad(r) from core

Te(r) and ne(r) in core

Impurities in core

ne and Te in divertor

Ti(r) in core

vtor(r)

ne(r) in edge

Impurity influx

D,T influx

RWMs

Energetic particle modes

He content in divertor exhaust

Gas pressure and composition

Erosion of first wall and divertor, and dust

The assessment for the AT is very similar except, because of the existence of blanket modules on the in-board side, the situation for the measurements of plasma shape and position and Prad(r) from the core will be better. Blue would be the appropriate color for these parameters in the case of the AT.

4. Peer Review

On 2 August 2011 a review of the work carried out thus far was performed. The charge to the review board was to address the questions:

1. Have the appropriate plasma measurement requirements been identified?
2. Have the appropriate diagnostic system choices been made?
3. Are the diagnostic space allocations and machine integration approaches reasonable?
4. Have the key performance and integration issues been identified?

The review was chaired by Dr Ken Young and the panel members have extensive experience in diagnostics. A full report on the review has been prepared – "Report of the Board of the Peer Review of the Pilot Plant Diagnostic Integration, August 2, 2011". By early August only the ST and AT had been examined and so the review was limited to the work on these machines. The review raised 54 chits, which have subsequently been answered. A summary of the chits and the responses is included in the Appendix.

5. Investigation of the CS

5.1 Required Parameters that must be measured to Support Operation of a Fusion Pilot Plant Based on a CS

Assumption: It is assumed that the CS will be operated in steady state and that measurements will only be needed for control and performance optimization and not for extensive scientific studies. This approach will give the minimum diagnostic set. It will give the minimum requirements on the integration of the diagnostic systems with the machine and therefore the least complication to the machine due to diagnostics.

Methodology: On the basis of his extensive experience with stellarators, Mike Zarnstorff developed an initial list of measurements needed for plasma control and for optimization and set-up. This was then reviewed by AC and after a short dialogue a revised list was agreed. This is as follows.

Parameters required under real-time control

Btor, Ip, β

Line-average density

Surface temperature of first wall and divertor plates (Note 1)

Divertor detachment

nT/nD in edge

Prad from core – single chord

Pfus

ne in divertor

Other essential parameters that must be measured for optimization and set-up

Low m/n MHD modes

Prad(r) from core and divertor

Te(r) and ne(r) in core

Impurities in core

ne(r) and Te(r) in divertor

Gas pressure and composition

Erosion of first wall and divertor (Note 2)

Notes
(1) Maybe the bulk or near surface temperature would be sufficient.
(2) Parameters such as these merge with machine engineering parameters.

5.2 Candidate Diagnostics for the CS

The candidate diagnostics for the required measurement parameters of the CS would, to first order, be a subset of those already identified for the ST and AT (section 3.2), with the selection being made appropriately through the measurement parameter. Because of the quite different machine configuration, the implementation and integration details would be different. The number of parameters to be used in control is significantly less for the CS and so possibly the integration would be easier. On the other hand, the complicated geometry of the CS may require multiple systems for some parameters, for example first wall and divertor viewing. The design of the CS had not matured sufficiently by the time of closure of this contract for the integration work to be undertaken.

6. Diagnostic Readiness: Critical R&D Areas

Because of the step in environmental conditions from existing tokamaks, R&D is needed in the preparation of diagnostics for ITER and is in progress. Some of this R&D will provide the basis for the diagnostics for a FPP. However, the FPP environment will be more severe than ITER, access will be more restricted and engineering requirements will be even higher. Diagnostic dedicated R&D beyond that for ITER will therefore be required. The initial work undertaken in this study suggests that the most critical areas are as follows.

In-vessel magnetics provides many key parameters such as plasma shape and position but in a FPP, and particularly in a ST FPP, the sensors will be subject to very high levels of radiation and potentially severe thermal and mechanical loads. It is quite possible that the resulting spurious signals will be so high as to make measurements by the in-vessel sensors intolerably inaccurate. Alternative means of determining the key control parameters that are currently provided by in-vessel magnetics should developed. Concepts exist, for example tangential viewing through a small aperture, filtered on an impurity line known to exist in the plasma boundary, could potentially be a method for obtaining the plasma boundary with sufficient accuracy for control. Dedicated R&D is needed to find and develop such possibilities.

In any case, both the ST and AT FPPs under consideration are intended to be steady state. Magnetic diagnostics typically operate inductively. Steady state sensors that can withstand the harsh environment need to be developed.

All three FPPs are calling for a measurement of Prad(r) as an optimization parameter. To make this measurement independently requires bolometers on the in-board side as well as in the ports.

For the ST, such an installation is probably not feasible but even for the AT the lifetime of existing devices would probably be too short and/or radiation induced spurious signals too high. Within the ITER program bolometers that have the potential to be radiation resistant have been identified and will be developed to a certain extent. Possibly these could be used for the AT and the CS. Otherwise a means to optimize the operation of these machines without these measurements will have to be developed.

Most optical systems have to view the plasma via a mirror – the mirror forms the first element in the optical labyrinth imbedded in shielding which is necessary to prevent neutron streaming. The first mirror is potentially exposed to erosion and deposition and could have a short lifetime. Within the ITER program there is an extensive R&D effort to find a means to reduce the amount of erosion and deposition, eg by the use of baffles and shutters, and methods of mitigation and recovery, eg in-situ cleaning. Perhaps these methods could be extended to a FPP but in any event, it would be prudent to seek alternative methods to make the required measurements without the use of optical systems. In some cases, this will not be possible, for example for first wall and divertor viewing, in which case R&D should be focused on this specific measurement.

It is clear that the diagnosis of the divertor is going to be especially difficult and the problem becomes even more severe with a double divertor because the access is even more restricted. On the other hand, effective operation of the divertor is essential and good diagnostics are needed to ensure this. A critical investigation of this problem is required. It could be that the diagnostic limitations become a constraint on the operation of the divertor and thereby possibly on the operation of the machine.

Several diagnostics, eg measurements of dust and divertor erosion, overlap with engineering requirements and systems. This functional interface should be carefully developed in any future work.

These are some of the most critical and somewhat generic problems that have arisen in this work. There are many specific areas, for example the impact of neutrons on specific components such as x-ray crystals, need to be evaluated in dedicated R&D. These specific needs and hopefully potential solutions will arise with dedicated work on specific machine designs.

7. Publication

During the course of this work a contribution was made to the paper:

T Brown et al, "An Overview of Pilot Plant Designs Based on the Advanced Tokamak, Spherical Tokamak and Stellarator" presented at the SOFE 11, Chicago, June 2011.

8. Acknowledgement

This study relied heavily on discussions and contributions from many colleagues and especially Tom Brown, Hutch Neilson, Jon Menard, Steve Scott and Mike Zarnstorff, PPPL; George Vayakis, ITER Organization; David Ward, Nick Hawkes, Neil Conway and Paddy Carolan, Culham Laboratory. I thank them for their constructive cooperation.

9. Appendix: Summary Of Response To Chits Raised In The Peer Review

Chit Number (Originator)	Issue	Who to Resolve	Response
A1 (JT)	What is driving the designs for the amount of first-wall surface area that is available for diagnostics, heating ports, and blanket test modules? KY: This chit identifies the most pressing issue for the incorporation of diagnostics onto a Pilot Plant (and other similar tritium-burning devices). Chits A2, A3 and A4 all bring up aspects of the tritium-breeding problem. The PP program management should provide a plan for resolving the challenge.	TB/AC/HN	Main requirement is indeed the requirement that TBR > 1. Approach being adopted is that each system that uses FW space is designed (pre-concept level) using as little FW space as possible and then the TBR is assessed. If TBR is not sufficient then systems designs have to be modified. Currently still in first iteration loop. Pre-allocation of FW space to individual systems may not produced the best integrated design.
A2 (KY)	There was very little information available on the size and location of ports for either device. Nor was there information on the requirements of other auxiliary systems, apart from some rather unrealistic neutral beams, all on the midplane. A major future part of this PP study should be working on integration of all these systems, and evaluating the possible tritium breeding ratio (tbr) with these intrusions into the blanket. Once this has been done, another Peer Review should be held. (My personal view is that this should take priority over work on the CS design.) KY: See response to chit A1, but ensure that realistic ports are incorporated into the design. Costley asked for 10 ports (ST) and 12 ports (AT) and other auxiliary systems must be accommodated.	TB/AC/HN	Agreed. This should form part of the next phase of the work. Note. In response to chits A6a and A6b the parameters to be measured for both the ST and the AT have been reviewed and are now the same. Hence, the number of ports needed by diagnostics will be the same and is 2 upper, 5 mid-plane and 2 lower. Details are given in the final report of the work undertaken for the diagnostic study.
A3 (LR)	It is really critical to have a breeding ratio of more than 1. I do not think there is enough tritium in the world to operate ITER and a PP at the same time, especially after ITER has operated for several years.	AC/TB/HN	Agreed. The TBR for the PP is indeed > 1.

Chit Number (Originator)	Issue	Who to Resolve	Response
A4 (KY)	Since tritium sustainability is essential, the “permanent” part of the blankets must produce a tbr > 1.0. Hence the value of testing blankets in small ports on the PP rather than with more capability on a test facility should be considered. Consider the optimum use of ports on the tokamaks in light of other testing facilities. KY: Consider the optimum use of ports on the tokamaks in light of other testing facilities.	TB	We are following the philosophy proposed by Malang and El-Guebaly that TBR > 1 will be achieved with a combination of both base blanket plus local test blanket modules.
A5 (KY)	The requirements for the control for the present AT and ST configurations with their blanket, heating and fuelling interactions appear very difficult to meet. Some effort should go into studying a more conservative larger device.	HN	We will do the best we can at (or near) the present design point, evaluate any shortfalls, and identify possible improvement strategies for a follow-up study, should there be one. It is not clear that making an AT or ST larger solves the problem.
A6a (SS)	Comparison of diagnostic requirements for AT versus ST pilot plants: Alan did the sensible thing, which was to ask an ST expert about the minimum diagnostic requirements for an ST pilot plant, and ask an AT ‘expert’ (just me for want of a real expert) for the corresponding requirements for an AT tokamak. Given that the two experts didn’t consult with one another, it’s reassuring that their lists of required diagnostics are so similar. But we should have a conversation about each of the differences in parameter-measurement requirements between the AT and ST, to make sure that the differences are really specific to the device, and not due to the experts’ perceptions of e.g. acceptable risk. KY: This detailed comparison of the different device needs should be made soon. (See also chit A6b.)	AC/JM/SC	Following the Peer Review AC, JM and SS together reviewed the measurement parameter list for both the ST and AT and found that indeed the small differences between the original lists were due to the method used to produce them. A common list was produced and is included in the final report on the diagnostic work.

Chit Number (Originator)	Issue	Who to Resolve	Response
A6b (SS)	I compare Alan's requirements for the ST versus AT (table 1 of the report). In the discussion below, I assert that most of the purported ST/AT differences are spurious, i.e. you can argue that a particular parameter measurement might or might not be needed, but if it is needed in the ST it will be needed in the AT and vice-versa. Some examples are given below, others appear as chits in section B. Prad(r) Should be the same for ST and AT [original listing: not required for ST; required for real-time control in AT]: might be needed to properly feedback-control impurity gas puff rate to control Prad (see discussion below). . Impurities in core/divertor: Should be the same for ST and AT [original listing: not required for ST; required for real-time control in AT]: might be needed for control of Prad. Ne, Te in divertor: Should be the same for ST and AT [original listing: not required for ST; required for real-time control in AT]: possibly useful to assure that erosion rate at divertor is acceptable low (note: maybe divertor Te is sufficient?) If we have measurements of the edge density and temperature, and if we know the power flow thru the edge (a power plus current-drive power minus Prad), then research might provide validated physics models that allow us to compute the density and temperature in the divertor, i.e. eliminate need for this measurement. KY: These comparisons should be carried out in conjunction with chit A6a.	AC	See response to chit A6a
B1 (JT)	For the measurements Alan has identified as necessary for the PP, I would like to see an annotation added to those that require continuous real-time measurement and another annotation added to those that could be discontinuously sampled/shuttered.	AC	Good suggestion. It should reduce the operational requirements and so might help alleviate some of the diagnostic implementation difficulties. More details on the planned operating scenarios will be needed to do it. If these are available, it is recommended that this should be attempted in the next phase of the work.

Chit Number (Originator)	Issue	Who to Resolve	Response
B2 (MB)	Distinction between requirements for real-time measurements in ST and AT seems artificial. Achieving necessary plasma performance in either will require a similar level of real-time control.	AC	Essentially the same point as in chits A6a and A6b. See response to A6a.
B3 (SS)	Ne(r) in edge: Should be the same for ST and AT [original listing: required for optimization in ST; not required in AT]. Maybe this is a definitional difference, since Ne control in the divertor was listed as mandatory for the AT but not for the ST. I assume that one might want control of edge density because it affects (a) edge Prad; (b) edge temperatures, that then propagate to core temperatures thru profile stiffness; (c) bootstrap current near the edge, which might affect stability. The needs to control Prad; core temperature profiles; bootstrap currents are similar for the ST and AT, so I think the need for edge density control for AT and ST should also be similar. The actuators for edge density control – as opposed to core density control – aren't so clear to me. Maybe 3D fields and/or ELM timing control? KY: This is an example of the issue raised in chit B2, and should be considered at the same time.	AC	Similar point to that raised in chits A6a, A6b and B2. See response to A6a.

Chit Number (Originator)	Issue	Who to Resolve	Response
B4 (JS)	The diagnostics which are assumed to be developed by ITER seem (to me) to be inconsistently applied. Specification (explicit) of what is developed for ITER would help me understand better. KY: A present day assessment of the current issues in development of ITER diagnostics should be made. The assessment could be sought from people working on ITER diagnostics.	AC	The diagnostics for the FPP have been selected to meet the measurement requirements for the AT and ST. These are different from ITER and so there will be differences in the diagnostics between the FPP and ITER. Also, allowance has been made for the FPP environment, which is harsher than that in ITER. An assessment of the ITER diagnostics was made a few years ago and published in the "Progress in the ITER Physics Basis", Chapter 7, Nucl Fusion, vol 7, no 6, S337 – S384, (2007). It is continuously under review and updated in internal ITER documents. It would be useful to update the published version.
B5 (JS)	Is the ST divertor concept the same as the AT? Currently some ST divertors are different than normal tokamak. If these differences continue to pilot plant, then these differences might imply different diagnostic requirements. KY: This is the first of a number of chits relating to the double-null divertor arrangement. Some effort should be put into assessing the appropriate divertor arrangement for the PPST and the resulting requirements on measurement.	TB/HN	TB: As I understand it the heat loading is a somewhat different for the ST so there will be some design differences with respect to an AT. Also the defined in-vessel maintenance scheme may be different which can have an impact on the placement of diagnostics. Further details are needed. HN: The relevant configurational distinctions are ITER-like vs. Super-X vs. Snowflake, and SN vs. DN. These may be more important than ST vs. AT, and may imply different diagnostic requirements. This issue should be examined at some point, but we may not get to it in this study.

Chit Number (Originator)	Issue	Who to Resolve	Response
B6 (JT)	How does the double-null configuration of the design affect the diagnostics considerations? Alan Costley has already noted that this will mean a doubling of the divertor diagnostics and including views from below (of the upper divertor) and views from above (of the lower divertor), but are there possibly other consequences of the DN for the diagnostics, for example, stray light from the nearest divertor, or increased deposition on optical components due to the proximity of a divertor? KY: The impact of the double-null configuration on measurement requirements and, hence, diagnostics, should be assessed and any differences on requirements should be detailed.	AC/HN	AC: It drives a requirement for additional diagnostic systems. Basically all divertor diagnostics have to be doubled. It also causes access difficulties. The divertors have to be diagnosed using mid-plane or near mid-plane ports. On ITER there are upper ports that can view down into the divertor. Obviously this is not possible with a double null arrangement. Also, diagnostics in the divertor themselves, eg erosion monitors, will have to be doubled. Additional problems, such as enhanced stray light and/or deposition, could emerge but design at a more detailed level would be needed to find this. HN: For this study we will focus on whatever divertor configuration is chosen for the design (DN I believe), but this issue should be the subject of a future trade study.
B7 (JM)	Magnetics in divertor region could be as difficult or more so than magnetics on in-board wall – need to assess how close sensors need to be to plasma for control.	AC	This is a very good point, both the ST and the AT will potentially be troubled by this. Experience on ITER shows that the sensors need to be close to the divertor plasma and therefore will, in a FPP, be subject to high radiation loads. At the divertor location they will not have protection from blankets. There could be significant consequences for plasma control.
B8 (KY)	Control of the plasma/surface interface in the divertor will be very difficult. Some expert advice on the measurements and control responders that are likely to be usable should be sought.	AC	Agreed but the current study has not gone to sufficient detail to handle this. Important to include in the next phase work along with the points raised in chits B6 and B7.

Chit Number (Originator)	Issue	Who to Resolve	Response
B9 (KY)	Balancing detachment in two divertors concurrently will need specific control, probably using a noble gas. Spectroscopy should be provided to support this control. KY: The control requirements for double-null operation should be detailed and the duplication of diagnostics top and bottom should be defined.	AC/HN	AC: Spectroscopic views of the divertor are already included. Need to go to next level of study to determine in more detail what is needed. Detailing of control requirements will be needed at a later phase in the project but concept guidance of the need for measurements, and especially any duplication of measurements, is needed early. HN: I agree.
B10 (KY)	The measurement requirement for nHe(r) in the divertor for both the ST and AT was not well defined. If it is a measurement of the helium ash, then spatial dependence is not required. But it is not clear whether the divertor regions are being pumped, so the measurement of the ash needs to be considered carefully. KY: Clarify where and how He-ash is to be measured.	AC/TB	AC: As stated in the report and presentation to the Peer Review Committee, it looks very difficult/impossible to make measurements of nHe in the divertor plasma. In the follow up discussions, JM and SC have agreed that measurement of the He in the exhaust should be sufficient. TB: Although the models currently do not show this, I assume that the divertors will be pumped in a fasion similar to ITER although maybe not using cryo pumps.
B11 (SS)	q-profile measurement: The physics of current drive is reasonably well understood, so the range of q-profiles that would be expected in nominal operation should be known – and should not be too large. For both the ST and AT, could we possibly get by with a sparse, 'conglomerate' q-profile using (a) qedge from magnetic; (b) radius of q=3/2 and q=2 from the radius of 3/2 and 2/1 NTMs again using magnetic pickup and/or ECE or VBI ; (c) radius of q=1 sawteeth; and, if necessary (d) q(0) and or qmin from techniques TBD? KY: Provide an assessment of the measurement quality required for q(r).	AC	This kind of approach is reasonable for an optimization or set up parameter but both the AT and ST have q(r) as a control parameter. Probably a direct measurement will be needed for this function.

Chit Number (Originator)	Issue	Who to Resolve	Response
B12 (KY)	Measurement of q(r) with MSE and/or multiple-chord polarimetry looks very challenging. One requires localization on a suitable beam and access to it. The other requires retro-reflectors which may be impossible with the present ST design. KY: Provide an assessment of the measurement quality of q(r). Is this an area where R&D is needed?	AC	Agree. Measurement by polarimetry could be possible using long wavelengths (10 microns or longer) and embedded retroreflectors, but can only measure monotonic ql. If heating beams are used then in principle MSE could be applied but the diagnostic first mirror will be a critical components. R&D will be needed at least to determine the lifetime of the retroreflectors for the polarimeter and the first mirror for the MSE system. Alternative ways of measuring ql in a FPP environment should be sought.
B13 (MB)	Retroreflectors (corner cubes) involve 3 reflections. If reflectivity is 65% (as shown in results for Mo) overall reflector will be <30%. KY: This chit points out a significant operational challenge. Is data available from current operations?	AC	The results shown were for a wavelength of 600 nm. The polarimeter would use a wavelength of 10 microns or longer. At these long wavelengths the degradation will be much less.
B14 (MB)	q(r) may be required for real-time control in AT regimes. Polarimetry will require density profile information also, which was not included. KY: Determine whether q(r) will be required for the AT and, if so, add the density profile.	AC	In response to chits A6a and A6b the parameters to be measured for both the ST and the AT have been reviewed and are now the same. ne(r) is now included as a set-up and optimization parameter for both the ST and AT. Systems for measuring ne(r) are therefore included in the diagnostic set. Depending on how polarimetry is implemented one can also get ne(r) from the same system. A good part of ne(r) can be obtained from reflectometry, which is planned. So ne(r) will be available although not used as a direct control parameter.

Chit Number (Originator)	Issue	Who to Resolve	Response
B15 (LR)	The NPA will have to look across a neutral beam in order to have any chance of measuring the nT/nD ratio, and even then, it is very doubtful if the measurement can be made. KY: This chit and chit B16 suggest that an NPA is unlikely to perform the measurement requirements for the fuel densities. Suggest alternative possibilities. Is this an area for R&D?	AC	The NPA should be able to measure nT/nD in the edge region and usually this ratio does not change much with radius. Yes, this is an area where R&D is needed.
B16 (KY)	The measurement of the deuterium and tritium fuels is important. The measurement should include hydrogen as an impurity. It does not seem possible to do this measurement with an NPA, if there is only a high-energy beam. A diagnostic beam is unlikely to penetrate. KY: See chit B15.	AC	The NPA is expected to work in ITER at least in the edge region. Detailed calculations would be needed for the FPP plasmas to determine if it could work for these plasmas too. In principle, a measurement of hydrogen could be included.
B17 (SS)	nD/nT measurement: (listed as being difficult) Would it be possible to measure the ratio of dd/dt neutrons and from that infer a ratio of deuterium to tritium in the core? A more speculative approach would be to compare the total fusion power to calculations based on the measured temperature & density profiles and Zeff. KY: Evaluate the feasibility of measuring the fueling ratio using neutron techniques.	AC	A measurement of nD/nT using neutron spectroscopy has been looked at for ITER and it appears to be very difficult due to the intense background coming from neutrons scattered from the tokamak structure. The more speculative approach could be attempted but is unlikely to be accurate. It should at least be attempted for consistency.
B18 (SS)	D,T influx: measurement requirement should be the same for ST and AT [original listing: required for optimization in ST; not required in AT]. I would argue that what is really needed is control over the ratio of nD/nT in the core; the actual D,T influx is important only to the extent that it affects the value of core nD/nT. I would argue that if a core measurement of nD/nT indicates that more tritium is needed, the control system needs to add more tritium to the plasma (thru pellets or NBI) irrespective of what a D/T influx measurement might say. KY: Consider whether DT influx is a necessary requirement.	AC	In response to chits A6a and A6b the parameters to be measured for both the ST and the AT have been reviewed and are now the same. D,T influx has been reduced to an optimization parameter. Instead impurities in the divertor are included as the control parameter.

Chit Number (Originator)	Issue	Who to Resolve	Response
B19 (KY)	The measurement of RWMs was not clearly defined, and nor was the technique for responding to the measurement. Should the measurement be upgraded to "Real Time Control"?	AC	This is a valid comment but better definition of the requirement cannot be given at this stage. This definition should come later when more details are known of the intended plasma operation scenario.
B20 (SG)	Do you have the capability to detect slowly growing n=1 perturbations? Assuming that there is the capability to apply n=1 fields, the slow n=1 perturbation could be important to measure for RFA control. KY: Define the measurement requirements in more detail to include specific mode responses.	AC	Yes we do. The magnetics should pick these up. It is expected that the measurement requirements will be better defined in the next stage of the work.
B21 (JS)	ST should feature different α stability than other devices. Is the measurement requirement higher? KY: Re-examine the measurement requirements in the ST in the light of different alpha-effects.	AC	AC: Correct. JM has confirmed that the ST will be more prone to various modes, but quite good mode diagnostics – magnetics, ECE, reflectometry – are already included in the diagnostic set. Suggest closer examination of requirements in next phase to determine if additional diagnostics would be needed.
B22 (SS)	EPMs: For STs in particular, is it necessary to be able to identify energetic particle modes that could generate fast ion losses that could damage PFCs? KY: Consider the issue of energetic particles and their effects for the ST.	AC	In discussion following the Peer Review, JM and SS agreed that this is a valid point and measurement of EPMs is needed for both the ST and AT. The requirement for measurement of EPMs has been added to the parameter list as an optimization parameter.
B23 (RB)	Tangential views for the Ti(r) and Vtor(r) measurements using the x-ray crystal diagnostics are required. The profiles require an inversion and radial views would require information on plasma shape (which might not be available for the ST). Inverting a tangential view is trivial. KY: Consider the detailed implementation of the x-ray crystal diagnostics.	AC	This is a good suggestion. Thank you. Implementation points such as this should be investigated in the next stage of the work.

Chit Number (Originator)	Issue	Who to Resolve	Response
B24 (MB)	Thomson scattering may be impossible due to limitations of f – number of collection optics in high-neutron regions. KY: A conceptual design of the Thomson scattering system should be made to determine its feasibility. (The ITER design may be relevant.)	AC	Agreed. But we wont know until we get to the details.
B25 (RB)	More than one line-averaged Zeff measurement could add information on impurity accumulation that one view would not provide, e.g. a central view and another at ~ a/2. KY: In the list of diagnostics, indicate how many channels (sightlines) are required.	AC	Good suggestion. Thank you. Also, a point for the next phase of the work.
B26 (RB)	For the ST Zeff (line averaged) is listed as a real-time diagnostic. Zeff is proportional to g ne2 Te -1/2 where g is the gaunt factor that also depends on Te. Te(r) is listed as an additional diagnostic. Assuming ne is provided from a line-averaged measurement, Te would need to be inferred by other means to get Zeff. KY: Provide more detail on the optimal way for obtaining the Zeff measurement.	AC	Formally this is correct. However, no other reason to measure Te(r) for real time control has been identified. Also, the dependence of the Zeff determination on Te is weak (Te-1/2). It is assumed that the FPP operating plasma will be well characterized through the set-up process and both Te(r) and Ti(r) will be known at that time. In discussion following the Peer Review, JM and SS agreed to reduce Te(r) to an optimization measurement for both machines.
B27 (JT)	Alan has appropriately noted that neutron and microwave diagnostics should have an easier time fulfilling their respective measurement requirements, than, say, magnetic or optical diagnostics. As a cautionary note (and Alan is well aware of this), I mention that the calibration of the neutron diagnostics is difficult and very time-consuming on ITER (and will be more so on a PP device), and that scattered microwave radiation from microwave-based heating systems is a serious problem still under investigation for ITER and W7-X.	AC	Agreed.

Chit Number (Originator)	Issue	Who to Resolve	Response
B28 (JS)	The Prad(r) requirements seem overly restrictive → should be defined more. KY: Give a better, and possibly less demanding, definition of the Prad(r) coverage.	AC	Following the Peer Review, JM and SS agreed that Prad(r) can be reduced to an optimization parameter for both the ST and the AT. The needed control parameter is Prad from core – single chord. This should be measurable by port based bolometers but, of course, they would need to be rad hard.
B29 (SS)	Is core Prad profile required? Detailed discussion of this question.	AC	See response to B26.
B30 (LR)	A dedicated disruption monitor should be included utilizing all of the precursor information and a mitigation scheme should be part of the measurement and control scheme. There are many diagnostics that give some precursors to disruptions but are used as a measure of plasma performance (Locked modes, low m numbers, Prad). I was concerned that the term “disruption monitor” was not specifically called out, as this is especially important for high power operation. It is critical for ITER, so even more important for a PP. KY: Mitigating disruptions is vital for a PP. Identifying the set of measurements which could form a package to protect against disruptions would be valuable and might lead to possible R&D including testing on operating devices.	AC	Because there are potentially several different causes of disruptions no one single measurement can perform the function of a “disruption monitor”. A device more likely to succeed is a software device that takes input from several different diagnostics, applies some intelligence (possibly based on “training”), and then issues instructions to actuators via the control scheme. Maybe this is what LR has in mind. If so, then what we need to cover this function at this stage is the basic measurements and then the “disruption monitor” would be part of the control system. I believe we have the basic measurements covered. R&D is underway on current devices for both disruption monitoring and mitigation.
B31 (SS)	Disruption diagnostics. The question is whether we need to implement additional pilot-plant diagnostics to provide information that informs the decision to quickly restart (after a disruption).	AC	This is really a question of measurement requirement and underlying that is the question of risk. It needs to be answered at the project requirements level or possibly even higher. Also one for the next phase of the work.

Chit Number (Originator)	Issue	Who to Resolve	Response
B32 (LR)	A neutron camera may be utilized as a control device (as per Strachan). Two neutron cameras displaced by 180 degrees would yield mode information as well. Only a subset of central channels would be required. KY: We suggest you include two cameras in your initial layouts of diagnostics on the PPs.	AC	Currently there is no requirement to measure the neutron source profile and so no cameras are included. However, one or two cameras could be added in mid-plane ports. Being a neutron measurement they would be rugged in the FPP environment. Suggest reconsider in the next phase.
B33 (JT)	Demonstration of a high “availability” is one of the goals of the planned PP. Yet in constructing the minimal set of diagnostics, with little or no redundancy, the risk of failing to achieve the desired “availability” is significantly increased. I realize that at this stage of the planning the motivation was to define and determine the functionality of a minimal set of diagnostics. However, if the minimal set cannot deliver the desired “availability”, then it is not the “minimal” set. Thus, I encourage the design team to include in the minimal set enough redundancy to support the “availability” mission.	AC	This a fine balance. Adding diagnostics adds complexity and therefore can be negative for availability. Also, there is competition for first wall space and access and too many diagnostics could make it difficult to achieve the required TBR. A full assessment is required to get this balance right and is something that would have to be done in future work. At this stage we are trying to determine whether we can meet the minimum requirements under reasonably optimistic assumptions. If we can’t do that then we have to go much further back in our thinking. This issue is one that should be addressed in future work.

Chit Number (Originator)	Issue	Who to Resolve	Response
B34 (SS)	Diagnostic redundancy: This issue was raised in the call yesterday by someone other than me, so I assume this is a duplicate chit. The issue is diagnostic redundancy: Alan has a list of ~20-30 physical parameters whose values must be measured to operate the pilot plant. If one of diagnostics breaks or drifts out-of-calibration, then presumably the plant must stop operating until a fix is implemented. If redundant diagnostics aren't provided, it seems highly unlikely that we could achieve the target 10-30% availability. The costs of providing redundancy are: (1) port space; (2) loss of tritium breeding; (3) dollar cost of the actual additional diagnostics. I think this is a big issue, since it is likely to double the required port space with a commensurate effect on loss of TBR. The issue may even be more serious for beam-based diagnostics, since obviously the loss of the beam or the diagnostic leads to the loss of the measurement.	AC	Agreed. Diagnostic redundancy is closely related to diagnostic availability, which is the point raised in chit 33, and essentially the same reply applies.
B35 (KY)	An important area of study should be optimizing the diagnostic performance by providing redundancy or rapid replacement capability. This is an area where engineers in other fields might be able to provide insight.	AC	This chit is also closely related to chits B33 and B34 and essentially the same reply applies. Good suggestion to check for experience in other fields. Should be followed up.

Chit Number (Originator)	Issue	Who to Resolve	Response
B36 (KY)	Monitoring the first-wall and divertor surfaces for damage will be essential. Is the diagnostic viewing system to be used for this or will a robotic inspection system be required? If the plasma diagnostic system is to provide the capability, it will need a lighting system, 100% coverage and, probably, the capability for better spatial resolution. If a robotic system is required, how will it be implemented and stored when not in use? KY: The requirements for in-vessel inspection and its implementation should be addressed at the same time as chits A1 and A2 are considered.	AC	As far as I am aware, the requirements for in-vessel inspection of the FPP have not yet been determined. On ITER we looked at trying to meet the in-vessel inspection requirements with the diagnostic real-time first wall viewing system. We could not meet the spatial resolution requirements. Further, the in-vessel inspection system on ITER has a metrological function as well. Obviously that can't be met with just a viewing system. This is a good example of where plasma and first wall diagnostics interface with engineering measurement systems. This is already emerging as a significant interface on ITER. For an FPP, even more attention will have to be paid to it.
B37 (GL)	1.Design the diagnostics as a modular set for ease of installation and change. 2. Mirrors are to be remotely operable for realignment and calibrations 3. Need to design a new motion feed-through 4. Need robust and accurate remotely operable metrology system. KY: These specific recommendations should be implemented in a future stage of the design.	AC	Agree with comment by KY.
B38 (RB)	The x-ray crystal measurements may also be compromised by neutron damage to the crystal itself as well as issues with the detector (which were addressed in the presentation). This is an area for R&D. KY: The x-ray crystal systems should be considered in a list of proposed R&D.	AC	ITER will be a good test bed for this – a state of the art x-ray crystal spectrometer is planned. Thus far the indications are that neutron damage will not be a problem under ITER conditions but the FPP will go to higher neutron loads and so further investigations will be needed. Agree with KY comment.

Chit Number (Originator)	Issue	Who to Resolve	Response
B39 (KY)	Some effort should be made to define essential diagnostic R&D based on the challenges that Alan has identified. This should include such things as asking device operators to try operating their devices without some “essential” techniques, e.g. magnetic position. KY: Prepare a list of necessary R&D for the next few years. This detail should supplement recommendations being made in the FNS-PA study.	AC	AC: Agree. Critical areas of R&D have been identified in the final report. More in depth R&D listing would form part of the next phase of this work. HN: I agree that this should be an output of the present study.
B40 (GL)	I think a separate design effort is warranted to develop suitable actuators, feed-throughs and limit switch packages with an effort to standardize. KY: This chit proposes a strong engineering R&D program for plasma diagnostics in addition to the more common physics-oriented program.	AC/TB	AC: For sure such developments will be needed before an FPP can be built. But are there any feasibility issues here? If not, as I suspect, it can wait until a later stage. TB: I agree with the comment. To meet the availability goals will require larger design and R&D efforts to arrive at creditable robust solutions.
B41 (SS)	Neutron damage to mirrors: Erosion, deposition and neutron damage to plasma-facing mirrors are known high-priority issues for ITER and pilot plants, but the papers I’ve seen focus almost exclusively on erosion and deposition – neutron damage doesn’t get much attention. Is there a reason to believe that neutron damage will be sufficiently small that it can be ignored, assuming that the mirrors are replaced every time the divertor is replaced?	AC	Yes. It is believed that for metallic mirrors under ITER conditions neutron damage will not be a problem. There is an intention to check this. Dielectric mirrors have been shown to be not much affected by irradiation by neutrons but the coatings can be damaged by ionizing radiation; for example, the coatings can swell which together with the refractive index change affects the reflectivity. If such mirrors were to be used in an FPP, dedicated R&D would be needed.

Chit Number (Originator)	Issue	Who to Resolve	Response
C1 (LR)	One of the midplane diagnostic ports should view tangentially to avoid problems with first-mirror coatings. KY: Implement if this is possible. Treat the response as part of responding to chit A1.	AC	Such viewing may give some reduction in deposition on first mirrors – presumably because the mirrors can be set back – but it wont alleviate it totally: the mirrors still have to face the plasma. Many diagnostics require a fairly wide solid angle of view and so the extent to which they can be set back is limited. Prevention and mitigating methods are being extensively investigated in the ITER programme and hopefully will produce a result that can be applied to an FPP. Combining with tangential viewing might be an effective solution.
C2 (LR)	If there are no breeding blankets on the top divertor, at least a shielding blanket should be installed to reduce background radiation. KY: Implement in consideration of the allowable site fluxes, fluences and doses.	TB	We will be considering the possibility of locating blankets on top of the divertors if the TBR warrants this. Adding the space is a cost issue not a feasibility issue.
C3 (JS)	What are the relocation specs (centimeters of displacement) when replacing segments. Will all the segments be replaced simultaneously? What is involved in “maintenance”?	TB	Although general maintenance schemes have been defined for each option, details of placement schedule, alignment requirements and displacements have not.
C4 (GL)	Modularization will be an important element of reducing down-time for replacing failed components. The facility should have duplicate modules containing multiple system instrumentation. When a failure occurs replace the failed module. The failed module is then repaired during the run period. The D3D vessel design of raising the vessel shell to 350°C permits a very quick recovery after a vessel entry.	TB	Very good comment and suggestion.

Chit Number (Originator)	Issue	Who to Resolve	Response
C5 (JS)	What are the DPA influences on the segments? Are there size distortions to segments or port plugs due to DPA? Are there size distortions to segments or port plugs due to DPA? Are there size distortions due to blanket temperatures? What are the diagnostic impacts of these site distortions? KY: Detailed analyses at a more detailed design level is needed to determine the impacts on components (especially for diagnostics for this review).	TB	Good questions that will need to be addressed in the follow up design effort.
C6 (JS)	Does the scope include diagnosing the causes for the availability & DPA required maintenance. For example, if accumulation of tritium reached a level such as to cause a maintenance cycle, then how is that measured? Similarly for DPA induced component weakening. KY: This is a consideration for the detailed engineering design of the PP device.	AC/TB	AC: Presently the measurement of retained tritium is not in the diagnostic scope but maybe it should be. It is in the diagnostic scope for ITER. TB: Agree with comment by KY.
C7 (KY)	The use of so many JT-60 neutral beams as the only heating/current drive system on the ST needs to be reconsidered (much of the problem exists for the AT). A) Shielding will have to be provided to the outside of the coils and on top of the beams; b) access to the whole outside of the tokamak for any other components will be nearly impossible; the radiation levels inside the beams would be very high if a single shield arrangement were used. As shown, with two sources on each beamline, the beams will not reach the plasma. Unless a new neutralizer is developed and used, the gas load to the tokamak is likely to be unacceptable. Note that the power supplies would not need to be close to the beam boxes, so that the shielded volumes need not be so large. KY: More realistic arrangements for the heating and current drive systems should be included in the design of the whole facility (see also chit A1). The full impact of the beams, with their orientation and shielding would need to be understood.	JM	JM: This is a valid issue although strictly outside the scope of this review. In the next iteration of the ST machine design an attempt will be made to shift the beams off the mid-plane and possibly reduce the number of beams. EBW current drive has the potential for efficient off-axis current drive in the ST with reduced requirements for blanket penetrations, but substantially more R&D is required to increase the coupling efficiency and reliability.

November 22, 2011

KY – Ken Young; JT – Jim Terry; LR – Lane Roquemore; SS – Steve Scott; JM – Jon Menard; MB – Mike Bell;
RB – Ron Bell; JS – Jim Strachan; SG – Stephan Gerhardt; GL – George Labik

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2245
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov