DIVERTOR MEASUREMENT REQUIREMENTS: UPDATE FOLLOWING DISCUSSIONS AND FEEDBACK FROM THE ITER DIVERTOR EXPERT GROUP, Part II

Presented at the 1st ITPA meeting on Diagnostics
by G. Vayakis on behalf of the ITER IT incorporating large contributions from R. A. Pitts (CRPP / EPFL)

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Background and introduction

Following the presentation on the mismatch between divertor measurement[1] requirements and expected performance and resulting action[2] item at the 13th Expert Group, the JCT prepared a presentation for the 13th ITER Scrape off layer and Divertor Expert Group Meeting[3] The aim was to identify the minimum measurement requirements for each measurement in difficulty.

Feedback received from the SOL & Div. group was summarised and presented at the last (14th) meeting of the ITER Diagnostics Expert Group, with some key issues identified.[4] As a direct result one change was made to the divertor measurement requirements before the ITER FDR was delivered. An action was placed to give feedback to the SOL & Div. EG.[5] This was done, in a presentation[6] that focused the discussion to the 6 key points where the minimum measurement requirement was still uncertain. R. A. Pitts of the SOL & Div. group provided a response. An abstract of comments (included as an appendix[7] for the record) follow each of the points below, together with a suggestion for action by the ITPA Diagnostic group where appropriate.

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[1] G. Vayakis, "Divertor Session Discussion Prompter". presented at the at the IEA Large Tokamak Workshop on Diagnostics For Burning Plasma Experiments, Naka, Japan, 19 September 2000, N 55 RI 11 00-09-19 F 1

[2] 13a069: "JCT, Diagnostic and Divertor Experts to propose a set of minimum requirements for the ITER divertor to be compared with the capabilities of the diagnostics under consideration.", from Minutes of the 13 the Meeting of the 13th ITER Diagnostics Expert Group, N CX MI 4 00-11-24 F 1

[3] A. E. Costley and G. Vayakis, "Brief review of the measurement of Divertor Plasma and Target Parameters", presentation to the Scrape Off Layer and Divertor Expert Group, Garching, 13th October 2000, N 55 RI 12 00-10-13 F 1

[4] G. Vayakis on behalf of the ITER JCT, "Divertor Measurement Requirements: Update Following Discussions And Feedback From The Iter Divertor Expert Group", presentation to the 14th ITER Diagnostic Expert Group, Julich, 19-23 March 2001. Annex 5 to , N CX MI 5 01-05-18 F1

[5] 14a076 in Minutes of the 14th Meeting of the ITER Diagnostics Expert Group, N CX MI 5 01-05-18 F1

[6] A. Costley and G. Vayakis, "Divertor Measurement Requirements: Update Following Discussions And Feedback From The Iter Divertor And Diagnostic Expert Groups" , Presented at the 14th ITER Expert Group Meeting on SOL and Divertor Physics, Naka, 9 - 11 July, 2001, N 55 RI 13 01-07-11 F 1

[7] Commenta on Alan's discussion points, N 55 LR 8 01-11-09 W 0.1

Discussion Point # 1

A spatial resolution of 5 cm in the radiated power profile measurement is all that is likely to be available. Is it enough? What are the consequences if it is > 5 cm, say 10 cm?

. Radiation Profile	Main plasma P_{rad}		0.01 – 1 MW/m^3	10 ms	a/15	20 %
	X-point/MARFE region P_{rad}		TBD – 300 MW/m^3	10 ms	a/15	20 %
	Divertor P_{rad}		TBD – 100 MW/m^3	10 ms	5 cm	30 %

RAP: "… partially detached state leads to an extremely wide variation in the 2- D distribution of T_e and n_e throughout the divertor volume … Conclusion: chordal resolution of 10 cm along the divertor legs inadequate, 5 cm adequate, less would be better in the zones near the targets if possible. This measurement is potentially the most valuable of the divertor diagnostic set and every effort should be made to provide the best resolution possible."

The resolution achieved by the present set is not ideal (chordal 5 cm, inverted >10 cm). Performance improvements should concentrate near the target (within 10 cm)

→ Performance improvements at present limited by cash.

RAP: “If possible ITER should consider the use of zero dead layer AXUV * (Absolute Extreme Ultraviolet) diodes as a complementary diagnostic during the low activation phase)

- On present plans and expectations, low activation (hydrogen) phase is short, intended for commissioning and may not reach H-mode. We can consider AXUV diodes if their radiation hardness improves so they can survive a significant way into DT operation (~ the divertor maintenance interval)

- Access, wiring requirements etc. similar or less than bolometers

- Divertor modules can be swapped if required

→ No need for immediate decision, but should encourage development of rad-hard diodes.

Discussion point # 2

We have been asked to consider increasing the time resolution in the target plate measurement to 20 μs (presently 2 ms). On this time scale we expect the accuracy to be poor ($\Delta T > 200$ °C). Is this serious? What is the minimum requirement?

6. Divertor Operational arameters	Max. surface temperature		200 – 2500°C	2 ms	–	10 %
	Real-time net erosion		0 – 3 mm	1 s	1 cm	10 %
	Gas pressure		$1 \cdot 10^{-4}$ – 20 Pa	50 ms	Several points	20 % during pulse
	Gas composition	A = 1-100 ΔA = 0.5	TBD	1 s	Several points	20 % during pulse
	Position of the ionisation front		0 – TBD m	1 ms	10 cm	–

8. Heat Loading Profile ı Divertor	Surface temperature		200 – 2500°C	2 ms	3 mm	10 %
	Power load	Default	TBD – 25 MW/m^2	2 ms	3 mm	10 %
		Disruption	TBD – 5 GW/m^2	0.1 ms	TBD	20 %

RAP: “Surface temperature rise to max. value occurs in ~ 100 μs for C and W [...] Starting temperature depends on assumed heat flux in between ELMs [which is] ~1000 ºC for assumed worst case 10 MW / m^2. Max. temp. excursion at peak of power deposition close to or exceeding values for sublimation (C) or melting (W) . W melts at ~ 3650 K, C suffers enhanced erosion […] above 2000 K.”

RAP: “Conclusion: resolution of [even] 0.2 ms insufficient for studying target power deposition due to Type I ELMs. Better 0.02 ms for fast rise phase. Given the high initial target temperature, currently proposed system might suffice for resolution of ELMs if a fast enough detector is available.”

- Starting temperature could be as low as 400 °C for design value of heat flux on target.
- Key temperature range appears to be 400 – 2500 °C for present C target. Large ELMs could be expected to breach 1000 °C but this needs confirmation (with code).
- Instrumental performance of ITER-98 design gives time resolution (for better than 10 % noise on T_{plate}) of << 10 μs at 1000 °C.

- Divertor Operational Parameters: present instrument OK for conditions near limits since all above 1000 °C. No change required.
- Poor performance at 200 °C not serious;
- present instrument design good above 1000 °C; dedicated simulation needed to determine if minimum detectable ELM at low starting Tplate is OK.
- (RAP) Errors due to poor surface at transient events will dominate the total error, so noise of the instrument may be unimportant.

→ suggest changing specification as follows:

38 Heat Loading Profile in Divertor	Surface temperature		200 – 1000 °C	2 ms	3 mm	10 %
			1000– 2500 °C	20 μs	3 mm	10 %
	Power load	Default	TBD – 25 MW/m^2	2 ms	3 mm	10 %
		Disruption	TBD – 5 GW/m^2	0.1 ms	TBD	20 %

with the lower limit to be reviewed in the light of simulations of type I ELMs when these become available. FEAT IR thermography adaptation is likely to meet these specifications. Its performance could be used as an input to the simulations.

→ should encourage experiments to investigate effect of non-ideal surfaces

Discussion point # 3

It is suggested that the resolution in the measurement of target plate erosion should be 0.1 micron for single type 1 ELM in real time. It will not be possible to meet this. 100 micron is more likely. How serious is this? (Presently have not chosen an erosion measurement system and have no developed design but several concepts exist.)

16. Divertor Operational Parameters	Max. surface temperature		200 – 2500°C	2 ms	–	10 %
	Real-time net erosion		0 – 3 mm	1 s	1 cm	10 %
	Gas pressure		$1 \cdot 10^{-4}$ – 20 Pa	50 ms	Several points	20 % during pulse
	Gas composition	A = 1-100 ΔA = 0.5	TBD	1 s	Several points	20 % during pulse
	Position of the ionisation front		0 – TBD m	1 ms	10 cm	–

- So by implication asked to consider real time vs not, 300 *μ*m vs 100 *μ*m vs micron vs sub-micron resolution. A difficult task

RAP: Current expected erosion and redeposition rates 3- 10 nm / s on the currently planned graphite plates for “standard” ITER divertor target plasma without ELMs or disruptions.

- For ITER pulse length of ~ 500 s, ~ 1.5 - 5.0 µm changes in target “height ”.
- […]300 µm “change ”in target height but […] 500 g T codeposited

Loked at proposed methods: Ellipsometry, Colourimetry, Visible spectroscopy combined with depth markers, Speckle interferometry [but not standard interferometry (proposed several years ago by N. Bretz)

Conclusion: real time measurements appear impossible, so individual ELM effects on erosion and redeposition could not be diagnosed. Resolution of 100 µm is too coarse for a serious study and is not useful for D-T phase. Suggest an attempt to provide “global” measurement at target areas such that the effects of a single or at most a handful of discharges can be quantified. Specialised measurements could occasionally provide higher resolution. But this is a critical issue and ITER should drive research in this area now.

→ The natural question is, too coarse for serious study of…? What is missing is a list of functions for this system and a scenario for its use in various modes (protection, T monitoring, Physics…)

- What measurement specification is provided now (in DRG1 document) is intended only for tread wear indicator for divertor protection and maintenance. There is more than 3 mm of “tread”, and 10% of full scale was a good first guess of how close we should monitor for the signs of the divertor end-of-life (FUNCTION 1). This measurement demands around 300 μm accuracy. It need not be real-time under known conditions.

- Erosion measurement is suggested as indirect measurement of T retention (FUNCTION 2). This implies an erosion measurement accurate to the equivalent of a fraction of the inventory limit. Setting that arbitrarily at ~ 20 gT for the “no ELM” condition gives an accuracy requirement of ~12 μm. Again this measurement need not be real-time under known conditions.

- However high erosion rates predicted for the divertor and cost of divertor replacement probably mean that there will be an erosion budget for each task. So both these measurements must at least be known once a pulse to guide operations.

- In the same context, it is much better to prevent erosion than to find out after the pulse. Similar arguments will certainly apply to T retention. This is the argument for some kind of real-time measurement which still has at least an operational significance that might place it into one of the control categories.

- Erosion rate measurement in real time that could detect high erosion rates from whatever reason with the aim of avoiding dangerous regimes for the divertor or regimes of high T deposition for **the first time they are encountered** (FUNCTION 3). This will lead to a time resolution requirement. If the time – to – avoidance is of order 10 s, this suggests a time resolution that is faster, say, 2 s (incidentally, what was in the FDR specification). The erosion rate that is acceptable depends on how much divertor we are prepare to lose or T accumulate each time we have to avoid such a regime. Taking rather arbitrarily 12 μm gives a detection **rate** of 1 μm / s. The instrument could saturate at 10 times the rate, since that rate would be used to trigger a fast shutdown.

- Erosion measurement in real time could detect single ELMs with the aim of studying ELM-induced erosion (FUNCTION4). This would imply a time resolution of ~ 0.1 s and a sensitivity that could be determined by simulation

→ How to do it? We could adopt an incremental approach:

- **The first two functions** could be performed by a laser based multichord interferometer / range finder. The access needs of such a system would be comparable to those of the IR thermography system. Resolution of 12 μm should not be a problem.
- Such a system, if two-colour & with sufficient power could also detect erosion in real time within its resolution limit for the proposed third function. For a 2 s time resolution this would suggest a resolution of 2 μm, which may be feasible. For the purposes of **function 3**, the erosion rate need not be known very accurately.
- The same system could detect the erosion due to groups of ELMs (2 s interval) with a resolution of around 2 μm. Expect something like 2 - 10 ELMs in this time interval. Is this sufficient for **function 4**? Needs investigation and probably separate system

→ In the meantime, suggested change in measurement targets:

16. Divertor Operational Parameters	Max. surface temperature		200 – 2500°C	2 ms	–	10 %
	Erosion rate		1 – 10 μm / s	2 s	1 cm	30 %
	Net erosion		0 – 3 mm	Per pulse	1 cm	12 μm
	Gas pressure		$1 \cdot 10^{-4}$ – 20 Pa	50 ms	Several points	20 % during pulse
	Gas composition	A = 1-100 ΔA = 0.5	TBD	1 s	Several points	20 % during pulse
	Position of the ionisation front		0 – TBD m	1 ms	10 cm	–

Discussion point # 4

It will probably not be possible to measure reliably the plasma parameters (n_e and T_e) at the target but only the ion flux with Langmuir probes. How serious is this? What are the consequences?

36. Plasma Parameters at the Divertor Targets	Ion flux		$10^{19} – 10^{25}$ ions/s	1 ms	0.3 cm	30 %
	ne		$10^{18} – 10^{22}$ /m^3	1 ms	0.3 cm	30 %
	Te		1 eV – 1 keV	1 ms	0.3 cm	30 %

RAP: On the question of validity of T_e measurements by probes:

- [Experimental]Situation is currently extremely confused and no definitive answer can be given yet.
- Serious ongoing theoretical work on this issue is being undertaken in collaborative effort between Stangeby (Toronto) , Pitts, Horacek (CRPP) and Batishchev (MIT) […] Some good progress being made but likelihood is that the probes do read the wrong T_e under conditions of interest to ITER and that we are unlikely to be able to resolve the issue experimentally, even if we understand it theoretically. It may be, however, that the higher B_T and higher density of the ITER divertor plasma. […]

- Planned use of triple probes on ITER will pose even more serious problems for T_e measurement in high recycling/ detached conditions
- Single probe measurements, even if giving the wrong absolute Te in operating conditions of interest, could nevertheless be used in the sense that Te will be sensitive to changes in local conditions.
- Use of triple probes would be necessary for ELM and disruption physics (higher time resolution) but note that the anticipated Type I ELM "burn- through "may yield target Te too high to be within planned measurement range.
- Note the incompatibility of the ITER [~~probe~~] Te measurement specification range (1 eV -1keV in DDD 5.5. G) with the proposed power supply capability (max. 250V @ 5A) .

RAP: Provided probes can survive long enough (cannot easily be answered without buillding ITER!), independently of confidence in T_e absolute value, particle flux measurements will be a very sensitive indicator of detachment (along with target IR).

RAP: Conclusion: spatial resolution more than adequate, problem with T_e interpretation may not be a serious handicap. More work required to assess probe longevity (modelling plus work with JET probes).

- We note that Te specification is independent of the measurement technique in principle. 1 keV is included because of attached conditions and may be measured just in front of plat eby other means (eg Thomson Scattering) or…
- It is difficult to raise the probe voltage because of practical problems with the insulator under irradiation, connectors, etc.

→ suggest specification at target should be unchanged; some more thought should be given on the measurement of the temperature near the target in attached or near attached conditions (above around 100 eV)

36. Plasma Parameters at the Divertor Targets	Ion flux		$10^{19} – 10^{25}$ ions/s	1 ms	0.3 cm	30 %
	ne		$10^{18} – 10^{22}$ / m^3	1 ms	0.3 cm	30 %
	Te		1 eV – 1 keV	1 ms	0.3 cm	30 %

- Problem of poor Te measurement does not appear to be serious operationally but will probably hinder analysis and model validation for the divertor.

Discussion points # 5 & 6

Measurement of T_e along the divertor leg is very difficult. We will have high resolution measurements in the upper edge region and we could have measurements across the X-point. Will this be enough? How serious is it if we don't have measurements along the divertor leg? In any case, the requirement on the spatial resolution on n_e and T_e is 10 cm along the leg. Shouldn't this be 5 cm to be consistent with that on the impurity measurements?

41. Divertor Electron Parameters	n_e		$10^{19} – 10^{22}$ /m^3	1 ms	10 cm along leg, 3 mm across leg	20 %
	T_e		0.3 –200 eV	1 ms	10 cm along leg, 3 mm across leg	20 %
42. Ion Temperature in Divertor	T_i		0.3 –200 eV	1 ms	10 cm along leg, 3 mm across leg	20 %
35. Impurity and D,T Influx in Divertor	Γ_{Be}, Γ_C, Γ_W		$10^{17} – 10^{22}$ at/s	1 ms	5 cm	30 %
	Γ_D, Γ_T		$10^{19} – 10^{25}$ at/s	1 ms	5 cm	30 %
16. Divertor Operational Parameters	Position of the ionisation front		0 – TBD m	1 ms	10 cm	–

It is difficult to make UV measurements in the divertor. Will visible be enough if good bolometry measurements are available as has been suggested?

RAP: Combine these two discussion points since they are strongly related.

• Divertor Impurity Influx Monitor and Te:

Difficult to judge from the DDD's exactly how the Divertor Impurity Monitor sightlines overlap and how many there are. But 1 cm spatial resolution along divertor legs quoted. [actual resolution is 4 cm along leg]

If tomographic inversion possibilities are limited and only a few perpendicular sightlines are possible, then there is not a lot to be gained from making substantial (and expensive) efforts to go beyond the planned divertor TS system. [actual resolution varies 5-10 cm depending on position for most densities]

But, there is no reason to sacrifice the 1 cm longitudinal resolution in impurity influx since having a few n_e and T_e anchor points from the TS along the leg will permit serious constraints on code simulation and therefore allow the high resolution experimental data to be compared with simulation. Codes will evolve enormously in the years up to ITER and their usefulness during the physics phase should not be overlooked. [1 cm resolution was sacrificed partly as a cost saving measure]

- The absence of TS at the inner leg is unfortunate (given that inner and outer divertor volumes will behave somewhat differently, especially near the targets) , but X- pt LIDAR TS together with target IR, Langmuirs and spectroscopy will help to fill this gap. If there is any possibility at all to remedy this (by other diagnostic methods?) , it should be vigourously pursued […]

- Points listed for bolometry (Discussion pt. #1) are common to the T_e ,n_e , issue: [For example,] the proposed longitudinal TS resolution will be inadequate in the target vicinity where poloidal gradients change rapidly […] Given the strong poloidal variation of T_e and n_e in the divertor volume, the resolution of ~ 5 cm is barely adequate and 10 cm is inadequate.

- The need (or not) for UV spectroscopy:
  If there is to be no carbon in the machine (Tungsten targets?), then some degree of UV spectroscopy will almost certainly be required if some knowledge is required for divertor transport of eroded material.
  In the presence of significant carbon, much of the power radiated will be in CIV (UV) but the bolometer systems will also be sensitive measurement of this contribution.
  Likely scenario (see DIII- D studies [1]) is intense hydrogen isotope radiation at the plates and strong C radiation further up the leg.

• Conclusion: if C will be present in ITER and good bolometric resolution can be assured, UV spectroscopy not a pre- requisite in the divertor. Proposed visible spectroscopy resolution acceptable and could be used as an ionisation front position controller if C present. But every effort should be made to provide the best possible 2-D resolution (2D imaging??). Sparsity of T_e , n_e measurements (divertor TS) regrettable, but combination of modelling, bolometry, spectroscopy and target measurements can compensate to some extent. The divertor TS measurements are, however, indispensable to allow any degree of quantification of the spectroscopic data.

Measurement specifications adopted for TS Divertor system design. Numbers that differ from the DRG1 specification are in **bold red.**

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	ΔT or ΔF	ΔX or Δk	ACCURACY
NN. Divertor parameters	n_e		$10^{19} - 10^{22}$ /m^3	**50** ms	**5** cm along leg, **3 - 10 mm** across leg	**5 %**
	T_e		**1 –** 200 eV			**10 %**

→ propose to alter specifications to resolve discrepancy between measurement targets as follows:

41. Divertor Electron Parameters	n_e		$10^{19} - 10^{22}$ /m^3	1 ms	5 cm along leg, 3 mm across leg	20 %
	T_e		0.3 –200 eV	1 ms	5 cm along leg, 3 mm across leg	20 %
42. Ion Temperature in Divertor	T_i		0.3 –200 eV	1 ms	5 cm along leg, 3 mm across leg	20 %
35. Impurity and D,T Influx in Divertor	Γ_{Be}, Γ_C, Γ_W		$10^{17} - 10^{22}$ at/s	1 ms	5 cm	30 %
	Γ_D, Γ_T		$10^{19} - 10^{25}$ at/s	1 ms	5 cm	30 %
16. Divertor Operational Parameters	Position of the ionisation front		0 – TBD m	1 ms	10 cm	–

- For the Ts system, 5 cm can be attained for most conditions if time resolution is sacrificed.

- We could consider altering the present resolution targets from uniform 5 cm to 8 cm away from the target and 2 cm near (within 10 cm or so) of the nominal target. This will require an optics redesign and is in any case probably unattainable from the TS system without sacrificing also some time resolution.

- Without any TS along the leg? I quote R.A.Pitts and invite comments:

If you have **absolutely no Te and ne** measurements somewhere in the divertor volume, you cannot correctly interpret the spectroscopic data at all, without relying on simulations (codes - they will be better in 10 years, but we still don't understand cross-field transport and so they will only be as good as our understanding […] in the future).

If, […] you use the 5 and 8 eV contours for C emission to gauge your ionisation front position then you can do without TS, but the price to pay is not really to know anything about what is really happening other than that the ionisation front position is "more-or-less" somewhere (the more-or-less will depend on how much spatial resolution you have in the spectroscopy).

If you don't use C in the machine, then your ionisation front will be hard to measure without divertor VUV [This is harder to get good resolution from]. I think that it is worth trying to get something with TS, even if the diagnostic doesn't survive long - at least we would have some reference points to work with."