REFERENCE LEVEL 1 – ITPA DIAGNOSTIC GROUP

APPROVED SPECIFICATIONS

SEPTEMBER 2006

Changes relative to previous version (3/05) are in blue.

4.22.1 Functional Requirements

The function of the ITER plasma diagnostic system is to provide accurate measurements of plasma behaviour and performance. There are three categories of parameters to be measured:

group 1a	those needed for machine protection and basic machine control;
group 1b	those required for advanced plasma control;
group 2	those required for evaluation and physics studies.

The machine is unable to operate without a working diagnostic providing every group 1a parameter (1b for advanced operation). The machine may operate without a group 2 parameter diagnostic in operation. Measurements in each group are shown in Table 1. The requirements for each measurement are shown in Table 2.

Table 1: List of Required Plasma Measurements classified by their Operational Role

GROUP 1a **Measurements For Machine Protection and Basic Control**	**GROUP 1b** **Measurements for Advanced Control**	**GROUP 2** **Additional Measurements for Performance Evaluation and Physics**
• Plasma shape and position, separatrix- wall gaps, gap between separatrixes • Plasma current, q(a), q(95%) • Loop voltage • Fusion power • $\beta_N = \beta_{tor}(aB/I)$ • Line-averaged electron density • Impurity and D,T influx (divertor, & main plasma) • Surface temp. (divertor & upper plates) • Surface temperature (first wall) • Runaway electrons • 'Halo' currents • Radiated power (main plasma, X-point & divertor). • Divertor detachment indicator (J_{sat}, n_e, T_e at divertor plate) • Disruption precursors (locked modes, m=2) • H/L mode indicator • Z_{eff} (line-averaged) • n_T/n_D in plasma core • ELMs • Gas pressure (divertor & duct) • Gas composition (divertor & duct) • Resistive Wall Modes • Dust	• Neutron and α-source profile • Helium density profile (core) • Plasma rotation (toroidal and poloidal) • Current density profile (q-profile) • Electron temperature profile (core) • Electron density profile (core and edge) • Ion temperature profile (core) • Radiation power profile (core, X-point & divertor) • Z_{eff} profile • Helium density (divertor) • Heat deposition profile (divertor) • Ionization front position in divertor • Impurity density profiles • Neutral density between plasma and first wall • ne of divertor plasma • Te of divertor plasma • Alpha particle loss • Low m/n MHD activity • Sawteeth • Net erosion (divertor plate) • Neutron fluence • Neoclassical Tearing Modes	• Confined α-particles • Fast ions (esp. H, D, T and He^3) • Profile of He^3 concentration • Total perp. fast ion energy content • TAE Modes, fishbones • Te and Ti profile (edge) • ne, Te profiles (X-point) • Ti in divertor • Plasma flow (divertor) • nT/nD/nH (edge) • nT/nD/nH (divertor) • Te fluctuations • ne fluctuations • Radial electric field and field fluctuations • Core and Edge turbulence • MHD activity in plasma core

Table 2: Requirements for Plasma and First Wall Measurements: Parameter Ranges, Target Measurement Resolutions and Accuracy

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	RESOLUTION		ACCURACY
				Time or Freq.	Spatial or Wave No.	
1. Plasma Current	I_p	Default	0 – 1 MA	1 ms	Integral	10 kA
			1 – 17.5 MA	1 ms	Integral	1 %
		I_p Quench	25 – 0 MA	0.1 ms	Integral	30 % + 10 kA
2. Plasma Position and Shape	Main plasma gaps, Δ_{sep}	I_p > 2 MA, full bore	–	10 ms	–	10 mm
		I_p Quench	–	10 ms	–	20 mm
	Divertor channel location (r dir.)	Default	–	10 ms	–	10 mm
		I_p Quench	–	10 ms	–	20 mm
	dZ/dt of current centroid	Default	0 – 5 m/s	1 ms	–	0.05 m/s (noise) + TBD % (absolute)
3. Loop Voltage	V_{loop}	Default	0 – 30 V	1 ms	4 locations	5 mV
		I_p Quench	0 – 500 V	1 ms	4 locations	10 % + 5 mV
4. Plasma Energy	β_p	Default	0.01 – 5	1 ms	Integral	5 % at β_p=1
		I_p Quench	0.01 – 5	1 ms	Integral	~ 30%
5. Radiated Power	Main Plasma P_{rad}	Default	TBD – 1 GW	10 ms	Integral	10 %
	X-point / MARFE region P_{rad}	Default	TBD – 0.3 GW	10 ms	Integral	10 %
	Divertor P_{rad}	Default	TBD – 0.3 GW	10 ms	Integral	10 %
	Total P_{rad}	Disruption	TBD – 50 GW	3 ms	Integral	20 %
6. Line-Averaged Electron Density	$\int n_e\, dl / \int dl$	Default	$1\bullet10^{18} – 4\bullet10^{20}$ $/m^3$	1 ms	Integral	1 %
		After killer pellet	$8\bullet10^{20} – 2\bullet10^{22}$ $/m^3$	1 ms	Integral	100 %
7. Neutron Flux and Emissivity	Total neutron flux		$1\bullet10^{14} – 5\bullet10^{20}$ n/s	1 ms	Integral	10 %
	Neutron / α source		$1\bullet10^{14} – 4\bullet10^{18}$ $n/m^3/s$	1 ms	a/10	10 %
	Fusion power		TBD – 1 GW	1 ms	Integral	10 %
	Fusion power density		TBD – 10 MW/m^3	1 ms	a/10	10 %
8. Error Field, Locked Mode and RWM	Br(mode)/Bp		$10^{-4} – 10^{-2}$	1 ms	(m,n) = (2,1) RWM, n=2,3	30 %
9. Low (m,n) MHD Modes, Sawteeth, Disruption Precursors	Mode complex amplitude at wall		TBD	DC – 3 kHz	(0,0) < (m,n) < (10,2)	10 %
	Mode – induced temperature fluctuation		TBD	DC – 3 kHz	(0,0) < (m,n) < (10,2) Δr = a /30	10 %
	Other mode parameters TBD					
10. Plasma Rotation	VTOR		1 – 200 km/s	10 ms	a/30	30 %
	VPOL		1 – 50 km/s	10 ms	a/30	30 %
11. Fuel Ratio in Plasma Core	nT/nD	r/a < 0.9	0.1 – 10	100 ms	a /10	20 %
12. Impurity Species Monitoring	Be, C rel. conc.		$1\bullet10^{-4} – 5\bullet10^{-2}$	10 ms	Integral	10 % (rel.)
	Be, C influx		$4\bullet10^{16} – 2\bullet10^{19}$ /s	10 ms	Integral	10 % (rel.)
	Cu rel. conc.		$1\bullet10^{-5} – 5\bullet10^{-3}$	10 ms	Integral	10 % (rel.)
	Cu influx		$4\bullet10^{15} – 2\bullet10^{18}$ /s	10 ms	Integral	10 % (rel.)
	W rel. conc.		$1\bullet10^{-6} – 5\bullet10^{-4}$	10 ms	Integral	10 % (rel.)
	W influx		$4\bullet10^{14} – 2\bullet10^{17}$ /s	10 ms	Integral	10 % (rel.)
	Extrinsic(Ne,Ar, Kr) rel. conc.		$1\bullet10^{-4} – 2\bullet10^{-2}$	10 ms	Integral	10 % (rel.)
	Extrinsic (Ne, Ar, Kr) influx		$4\bullet10^{16} – 8\bullet10^{18}$ /s	10 ms	Integral	10 % (rel.)

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	RESOLUTION		ACCURACY
				Time or Freq.	Spatial or Wave No.	
13. Zeff(Line-averaged)	Zeff		1 – 5	10 ms	Integral	20 %
14. H-mode: ELMs and L-H Transition Indicator	ELM D_α bursts	Main Plasma	–	0.1 ms	One site	–
	ELM density transient	r/a > 0.9	TBD	TBD	TBD	TBD
	ELM temperature transient	r/a > 0.9	TBD	TBD	TBD	TBD
	L-H D_α step	Main Plasma		0.1 ms	One site	–
	L-H Pedestal formation (ne, Te)	r/a > 0.9	–	0.1 ms	–	TBD
15. Runaway Electrons	E_{max}		1 – 100 MeV	10 ms	–	20 %
	$I_{runaway}$	After Thermal quench	(0.05 – 0.7) $\bullet I_p$	10 ms		30 % rel
16. Divertor Operational Parameters	Max. surface temperature		200 – 2500°C	2 ms	–	10 %
	Erosion rate		1 – 10 x 10^{-6}m/s	2 s	10 mm	30 %
	Net erosion		0 – 3 mm	Per pulse	10 mm	12 x 10^{-6}m
	Gas pressure		$1\bullet10^{-4}$ – 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	100 mm	–
17. First Wall (FW) Visible Image & Wall Temperature	FW image		TBD	100 ms	TBD	–
	FW surface temperature		200 – 1500°C	10 ms	TBD	20°C
18. Gas Pressure and Composition in Main Chamber	Gas pressure		$1\bullet10^{-4}$ – 20 Pa	1 s	Several points	20 % during pulse
	Gas composition	A = 1–100 ΔA = 0.5	TBD	10 s	Several points	50 % during pulse
19. Gas Pressure and Gas Composition in Ducts	Gas pressure		< 7 kPa	100 ms	Several points	20 % during pulse
	Gas composition	A = 1–100 ΔA = 0.5	TBD	1 s	Several points	20 % during pulse
20. In-Vessel Inspection	Wall image		100 % coverage of FW and divertor	–	1 mm	
21. Halo Currents	Poloidal current	In disruption	0 – 0.2 I_p	1 ms	9 sectors	20 %
22. Toroidal Magnetic Field	B_T		2 – 5.5 T	1 s	2 locations x 2 methods	0.1 %
23. Electron Temperature Profile	Core T_e	r/a < 0.9	0.5 – 40 keV	10 ms	a/30	10 %
	Edge T_e	r/a > 0.9	0.05 – 10 keV	10 ms	5 mm	10 %
24. Electron Density Profile	Core N_e	r/a < 0.9	$3\bullet10^{19}$ – $3\bullet10^{20}$ /m^3	10 ms	a/30	5 %
	Edge N_e	r/a > 0.9	$5\bullet10^{18}$ – $3\bullet10^{20}$ /m^3	10 ms	5 mm	5 %
25. Current Profile	q(r)	Physics study	0.5 – 5	10 ms	a/20	10 %
			5 – TBD	10 ms	a/20	0.5
	r(q=1.5,2)/a	NTM feedback	0.3 – 0.9	10 ms	–	50 mm/a
	$r(q_{min})/a$	Reverse shear control	0.3 – 0.7	1 s	–	50 mm/a
26. Z_{eff} Profile	Z_{eff}	Default	1-5	100 ms	a/10	10 %
		Transients	1-5	10 ms	a/10	20 %
27. High Frequency Instabilities (MHD, NTMs, AEs, turbulence	Fishbone–induced perturbations in B,T,n		TBD	0.1 – 10 kHz	(m,n) =(1,1)	–
	TAE mode – induced perturbations in B,T,n		TBD	30 – 300 kHz	n = 10 – 50	–
	NTM			10 – 100 KHz	10 mm	

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	RESOLUTION		ACCURACY
				Time or Freq.	Spatial or Wave No.	
28. Ion Temperature Profile	Core T_i	r/a < 0.9	0.5 – 40 keV	100 ms	a/30	10 %
	Edge T_i	r/a > 0.9	0.05 – 10 keV	100 ms	TBD	10 %
29. Core He Density	n_{He}/n_e	r/a < 0.9	1 – 20 %	100 ms	a/10	10 %
30. Confined Alphas and Fast Ions	Alpha Energy spectrum	Energy resolution TBD	(0.1 – 3.5) MeV	100 ms	a/10	20 %
	Alpha Density Profile		$(0.1 – 2) \bullet 10^{18}/m^3$	100 ms	a/10	20 %
	p,D,T,He^3	tbd	tbd	tbd	tbd	tbd
31. Escaping Alphas and Fast Ions	First wall flux	Default	TBD – 2 MW/m^3	100 ms	a/10 (along poloidal direction)	10 %
		Transients	TBD – 20 MW/m^3	10 ms	TBD	30 %
32. Impurity Density Profile	Fractional content, Z<=10	r/a < 0.9	0.5 – 20 %	100 ms	a/10	20 %
		r/a > 0.9	0.5 – 20 %	100 ms	50 mm	20 %
	Fractional content, Z>10	r/a < 0.9	0.01 – 0.3 %	100 ms	a/10	20 %
		r/a > 0.9	0.01 – 0.3 %	100 ms	50 mm	20 %
33. Fuel Ratio in the Edge	n_T/n_D	r/a > 0.9	0.1 – 10	100 ms	Radial integral	20 %
	n_H/n_D	r/a > 0.9	0.01 – 0.1	100 ms	Radial integral	20 %
34. Neutron Fluence	First wall fluence		0.1 – 1 MWy / m^2	10 s	TBD	10 %
35. Impurity and D,T Influx in Divertor	Γ_{Be}, Γ_C, Γ_W		$10^{17} – 10^{22}$ at/s	1 ms	50 mm	30 %
	Γ_D, Γ_T		$10^{19} – 10^{25}$ at/s	1 ms	50 mm	30 %
36. Plasma Parameters at the Divertor Targets	Ion flux		$10^{19} – 10^{25}$ ions/s	1 ms	3 mm	30 %
	n_e		$10^{18} – 10^{22}$ $/m^3$	1 ms	3 mm	30 %
	T_e		1 eV – 1 keV	1 ms	3 mm	30 %
37. Radiation Profile	Main plasma P_{rad}		0.01 – 1 MW/m^3	10 ms	a/30	20 %
	X-point/MARFE region P_{rad}		TBD – 300 MW/m^3	10 ms	a/30	20 %
	Divertor P_{rad}		TBD – 100 MW/m^3	10 ms	50 mm	30 %
38. Heat Loading Profile in Divertor	Surface temperature		200 – 1000°C	2 ms	3 mm	10 %
			1000 – 2500°C	20 $x10^{-6}$ s	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 %
39. Divertor Helium Density	n_{He}		$10^{17} – 10^{21}$ $/m^3$	1 ms	–	20 %
40. Fuel Ratio in the Divertor	n_T/n_D		0.1 – 10	100 ms	integral	20 %
	n_H/n_D		0.01 – 0.1	100 ms	integral	20 %
41. Divertor Electron Parameters	n_e		$10^{19} – 10^{22}$ $/m^3$	1 ms	50 mm along leg, 3 mm across leg	20 %
	T_e		0.3 – 200 eV	1 ms	50 mm along leg, 3 mm across leg	20 %
42. Ion Temperature in Divertor	T_i		0.3 – 200 eV	1 ms	50 mm along leg, 3 mm across leg	20 %
43. Divertor Plasma Flow	V_p		TBD – 10^5 m/s	1 ms	100 mm along leg, 3 mm across leg	20 %
44. n_H/n_D Ratio in Plasma Core	n_H/n_D		0.01 – 0.1	100 ms	a/10	20 %
45. Neutral Density between Plasma and First Wall	D/T influx in main chamber		$10^{18} – 10^{20}$ $at/m^2/s$	100 ms	Several poloidal and toroidal locations	30 %

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Justification for the Requirements set for the Plasma and First Wall Measurements (Numbers given are for ITER)

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(Notes in blue indicate some areas where more evaluation is required. Comments on all aspects are urgently sought.)

1) Plasma Current: The plasma current, I_p , plays a key role in providing the magnetic configuration, and in providing the initial heating of the plasma. Its value is fed directly into plasma control, but also it is an element in evaluation of other parameters, also used in control. It must be measured with high precision and with fast time resolution (1 ms). During the quench following a disruption, a 0.1 ms time resolution is needed, but the accuracy can be relaxed.

Notes for further development

Need to identify and quantify relevant control time scales. 0.1 ms resolution seems to be overkill for ITER with short current quenches predicted > 10 ms.

2) Plasma Position and Shape: The plasma position must be controlled tightly as the current and pressure change. Rather tight tolerances are required for analyses but also for the closeness of the scrape-off to the heating antennas and to locate the separatrix within the divertor. 10ms resolution will be sufficient for this control. Fast vertical movement can be expected and fast resolution in following this movement, with the possibility of controlling it, requires fast time resolution (1ms).

Notes for further development

Another, more general factor driving shape control is to maximise the use of available volume; operating close to shaping limits is ultimately limited by unwanted contact with the wall. Required time resolution depends on full control loop and PF current capabilities, those are in turn set by target control response to internal events such as beta collapses, wall times, budget available and technological risk that is judged to be acceptable. This is highly machine dependent. On ITER << 100 ms is OK.

3) Loop Voltage: The loop voltage, together with I_p, defines the inductive power input. The measurement can be important at start-up, and also during a disruption when it leads to the acceleration of runaway electrons. It has the same time resolution as I_p and it should be able to be measured with precision during the low-voltage period of the flat-top.

Notes for further development

Justification for time resolution and precision need to be developed.

It probably has to do with current drive; the quoted uncertainty on ITER corresponds roughly to 0.5 MA; the inductive power input is small (typically 1MW) and the flux consumption during the flat top is known from the central solenoid current.

4) Plasma Energy: The plasma energy, β_p, provides a strong indication of the quality of the plasma performance. Its time-scale should follow that of key plasma events and

its accuracy should be within 5%. For disruptions, during the quench of I_p, the accuracy does not need to be so high.

Notes for further development
The key plasma events and their timescales need to be determined.
What does 5% in betaP corresponds to in betaN; this depends on conditions – which matters and why?

5) Radiated Power: The total power radiated from different regions of the plasma will be spread over a wide spectral range, but will be dominated by line radiation. Integral measurements across the core plasma, across the x-point region and in the divertor are required for regular operation and for assessing the power balance. A total estimate of the power radiated at a disruption is necessary for determining the fraction of the power lost by radiation. The operational measurements should be made with 10% accuracy and 10 ms time resolution while the disruption power loss requires faster resolution at 3 ms, but not such high accuracy (20%).

Notes for further development
At low radiated power, *accuracy* will be set by power circulation argument (what fraction of the total power circulating can we afford to be in error by. At high power, *precision* will be set by the desire to operate close to the real radiative limit reliably. Time resolution, again, should be set by expected events to be covered. 10 ms covers “intentional“ shape changes well for ITER but not much else

6) Line-Averaged Electron Density: The relatively simple measurement of line-averaged density is an indicator of performance for the operators and has been used as an enabling signal for the operation of additional heating, especially neutral beams. It should be measured with high reliability and availability.

Notes for further development
Accuracy required for enabling signal is low (and time resolution, since it takes time to damage the wall even at 15 MW /m2). Time resolution should be again to follow intentional shape changes (10 ms) and maybe recovery from individual elms (1 ms? needs checking)

7) Neutron Flux and Emissivity: The total neutron flux, over a very wide dynamic range of neutron production from low-power deuterium discharges through to burning D-T plasmas, is required with good accuracy (10%) for its role as a performance indicator and for comparison to modeled results using other measurements. It is also important for developing total fluence records and levels of activation. Fast time resolution of the rise and decay of the flux is required (1ms). The spatial distribution of the neutrons, and also the alpha-particle birth (and heating) profile for D-T plasmas, is required for a wide range of transport analyses. Spatial resolution of a/10 and 10% accuracy are the minimum required to support such analyses in a meaningful manner. The fusion power, and its spatial dependence are derivable from the neutron data

Notes for further development

8) Locked Modes: MHD modes, especially the (m,n) = (2,1) modes, can slow down and lock with drastic impact on the plasma. Potentially this locking could be controlled and prevented. Measurement of the modes' time behavior prior to locking should be made with high time resolution (1ms), and high sensitivity (few %), but absolute accuracy on the field level of 30% will be adequate.

Notes for further development

9) Low (m,n) MHD Modes, Sawteeth, Disruption Precursors: MHD has been measured traditionally on tokamaks by an array of magnetic detectors near the first wall and by internal measurement of temperature fluctuations by electron cyclotron emission (ECE) or x-ray emission. This type of external and internal measurement are expected to continue in ITER and FIRE. For the wall measurement, the coil spacing should allow interpretation of mode numbers up to (m,n) = (10,2) with frequency up to 10 kHz and 10% accuracy. The requirements are similar on the internal measurement, but with the addition of spatial resolution of a/30.

Notes for further development
Relationship between mode number and required frequency response, based on expected plasma rotation, needs to be developed.

10) Plasma Rotation: Plasma rotation and velocity shear have been seen to be very significant in affecting plasma stability and loss, and it may be possible to control the plasma motion with an external drive. These measurements provide information about the electric fields in the plasma. Hence the rotation in both the toroidal and poloidal directions should be measured with similar spatial resolution (a/30) as other plasma profile parameters, with a time resolution of 10ms. For comparison of data with theory, the relative accuracy should be high, but an absolute accuracy of 30% is sufficient.

Notes for further development
Time resolution should be enough to follow intentional shape changes

11) Fuel Ratio in Plasma Core: In order to control the burn rate the fueling of the main body of the plasma must be controlled. The fuelling will be done in different ways with pellets and gas-feed. The burn rate is not very sensitive to the ratio of the fuel ions for most of its range so that a measurement accuracy of 20% is sufficient and the plasma fueling time-scale is of order seconds so slow time integration of 100 ms is sufficient.

Notes for further development

12) Impurity Species Monitoring: The plasma facing materials in ITER are beryllium-coated copper in the first wall, and carbon and tungsten in the divertor. To effect a radiative divertor, and possibly for diagnostic use, noble gases such as neon, argon and krypton will be injected. Global estimates of these elements must be obtained continuously for physics reasons, but also for the first-wall protection (Cu spectral lines would imply damage). Both the absolute quantity of the elemental components as well as their rate of increase is required. A relative accuracy of 10% is the minimum

required to support such analyses in a meaningful manner. At least 10 ms time resolution is required to follow intentional shape changes.

Notes for further development

13) Z_{eff} (Line - averaged): The average impurity content of the plasma in the core is an important measurement, particularly during conditioning stages of the device's operation. For a burning plasma device, it can also provide clear indications of the build-up of the helium-ash created by the thermalized alpha-particles. Since this measurement is key to the conditioning process, it should have relatively good time resolution (10 ms) for short discharges, but does not need very high absolute accuracy (20%).

Notes for further development

14) H-mode: ELMs and L-H Transition Indicator: The transition from L-mode to an H-mode has been observed traditionally from quiescence of D_α-light fluctuations. This integral measurement needs only good relative accuracy, but must be sampled relatively fast (0.1 ms) to catch the fluctuating signals. Edge localized modes (ELMs) appear in the plasma edge of various sizes and amplitudes. These are normally determined by integral measurement of the D_α -light fluctuations when they occur. Measurement of the electron density and temperature excursions in the ELMs is proposed, but the quality of measurement is not yet specified. At the L-H transition an edge pedestal in electron density and temperature is formed. A time resolution 0.1 ms is expected.

Notes for further development
Type I ELM "attack" and "decay" times seem to be around 200 μs which suggests a very fast measurement is needed (10 μs) needing very fast optics at least in one location. The required accuracy of the measurement needs definition.

15) Runaway Electrons: Runaway electrons may occur at two times during the plasma operation. Firstly when the plasma breakdown is bad; accelerating electrons to high energies can cause damage to first-wall/divertor. The second high current of runaways can be created in an avalanche after the thermal quench at a disruption. This serious potential source of damage may have to be quenched by injection of a dense source of neutral atoms. The electrons can reach 100 MeV in the ITER fields and build up rapidly, requiring 10 ms time resolution. The measurements do not have to be very accurate.
Notes for further development

16) Divertor Operational Parameters: The temperature of the divertor surfaces close to the strike-points is going to provide an important operational input for managing the core plasma and divertor interaction. Rapid excursions of the surface temperature due to ELMs or disruptions are likely (2 ms time resolution) and the full range up to 2500°C must be covered at an accuracy of 10%. The spatial resolution should be 3 mm in the direction across the strike-point. Net erosion of the divertor plate surface, with redeposition elsewhere due to sputtering is expected, and the life of the divertor surface must be monitored in real-time for the long high-power pulses. Depth measurements

up to ~3 mm with 0.2 mm accuracy in ~ 1 s at locations 1 cm apart across the strike points at a number of toroidal locations are needed. The gas pressure behind the divertor plates defines the divertor performance and should be measured at several toroidal and poloidal locations with about 20% accuracy with time resolution of less than the typical fueling time-scale, i.e. 50 ms The gas composition should also be measured behind the divertor plates with a slower time resolution, necessary for analysis (1 s). The introduction of high-Z impurity gas in the divertor will cause detachment of the plasma from the divertor plates. As the visible ionization front moves up the legs of the separatrix, its position must be measured to allow control of the gas flow. 10 cm spatial separation between observation points is required with 1 ms time resolution because of the expected rapid movement. The time resolution must be compatible with fast control of the flame front whose time-scale is limited by the gas puff mechanism.

Notes for further development
Requirements on time resolution and erosion measurements are under development in the joint Diagnostic and Divertor Group activity. It is necessary to determine what the erosion measurement is for. At present we just have a “tread-wear” specification. The depth measurement depends on the divertor construction; 3 mm is out of date. The 1 s resolution in the depth measurement is justifiable only if avoiding action is to be taken in real time.

17) First Wall Visible Image and Wall Temperature: A TV display of the plasma, and the first-wall in its light provides a valuable operational tool for the operators and will be very valuable for very long pulse operation. In addition the wall temperature is expected to rise because of the plasma radiation and also because of losses of fast ions and alpha-particles to localized regions of the wall. The temperature of the antennas must also be monitored. High temperatures may be a reason to modify the plasma operation. The expected range of temperatures is 200° - 1500°C corresponding to a heat load of order 10% of the expected typical radiative load, and should be measured with an accuracy of ~ 20°C. The spatial resolution must be capable of resolving significant features of the wall - the smallest expected size of off-normal hot spots is ~ 1 cm.

Notes for further development

18) Gas Pressure and Composition in Main Chamber: The quality of the vacuum and the constituent elements provides vital operational information during conditioning and prior to the plasma pulses. Because of the complexity of the components inside the vacuum chamber, this measurement should be done at several locations fairly close to the first wall. Response time to the signals cannot be fast so the pressure can be sampled at 1 s intervals, and the elemental analysis at 10 s. (Note: table presently calls for measurement during the pulse.) Absolute accuracies of 20% and 50% are defined for the pressure and elemental analysis respectively though relative accuracy should be much better.

Notes for further development
The requirement on measurement capabilities during the pulse needs to be defined.

19) Gas Pressure and Gas Composition in Ducts: The pressure and composition of the gas in the pumping ducts at the divertor provide information on the performance of the

divertor, including the behavior of the gases injected into the divertor to cause radiation. 20% accuracy is expected for both measurements, with 100 ms time resolution needed for the pressure and 1 s resolution for the elemental analysis.

Notes for further development
A time-dependent model of the pressure evolution in the duct is needed to see if the 100 ms is justified.

20) In Vessel Inspection: Inspection of the first wall and divertor, without breaking vacuum, on a regular basis following unusual plasma events or after high - power operation permits evaluation of possible damage. Operated in its highest resolution mode, 1 mm resolution will identify cracks or damage significant with respect to Be thickness as well as resolve the fine features machined in the ITER 1st wall.

Notes for further development

21) Halo Currents: Halo currents through first-wall components, particularly those with wide magnitude variation toroidally, could lead to damage from magnetic forces, as well as providing significant engineering design information. Data from currently operating devices show currents up to 0.2 I_p. To confirm the peaking factor, several measurements are required in the toroidal direction with good (few %) relative accuracy . Absolute accuracy should be sufficient to determine whether allowable stresses are been exceeded significantly (~ 20%).

Notes for further development

22) Toroidal Magnetic Field: The toroidal magnetic field is a key element in the magnetic configuration. Its settings must be extremely reproducible. Its value is used in support of other diagnostic methods and analysis codes, and it is key to establishing the plasma location. 0.1% measurement accuracy is required to ensure negligible (< 5 mm) contribution to the overall reconstruction accuracy.

Notes for further development

23) Electron Temperature Profile: The electron temperature, with good spatial dependence, is a major indicator of plasma performance and a key component of transport analyses. The profile is key information in instability analyses. Steep transport barriers are observed inside the plasma core and electron temperature pedestals at the edge play a role in analysis of the transport. A time resolution of 10 ms is short compared to times of interest and allows for study of MHD. For kinetic control of the stored energy or ITB gradient, 10 ms time resolution is expected to be sufficient since this is much faster than the typical core confinement times and of the same order as the actuator (heating) response time. The core temperature should be measured with 10% accuracy or better to enable a useful determination of the stored energy and to support useful analysis of plasma performance with transport codes. To resolve fine structure on the profile such as internal transport barriers it should be measured at 30 locations

across the profile. The edge, with much steeper gradients should be measured with only 0.5 cm between measurements at about 20 locations.

Notes for further development

24) Electron Density Profile: The requirements on the electron density measurement are set for the same reasons as those for the electron temperature. A slightly tighter requirement on the accuracies for the core and edge density at 5% is established because of the reference scenario for ITER being the H-mode with rather small density gradients over a large fraction of the profile.

Notes for further development
Motivation for accuracy needs to be further developed

25) Current Profile (q(r)): Precise measurement of the q(r) profile becomes particularly important in the optimizing of the plasma performance using magnetic shear and in counteracting the impact of neoclassical tearing mode (NTM) instabilities. For NTM stabilization it will probably be sufficient to determine the location of the q = 1.5 and q = 2 surfaces. Similarly for the control of reverse shear discharges the location of the q_{min} is probably all that is required. The full evaluation of the plasma performance requires a complete measurement of the q(r) profile and this will require measurements of the internal magnetic field, edge magnetic field, and the use of an equilibrium code, such as EFIT. For low values of q(r) it should be determined within 10% while at higher values, where the gradient is normally steeper, better absolute accuracy, of +- 0.5 is required. 10 ms time resolution will be sufficient to follow intentional changes to the equilibrium and to determine the location of the NTMs. The latter's location has to be determined to within an accuracy of 5 cm. For the purpose of reverse shear control, where the current penetration times are of order 1 sec, the localization of q_{min} can be obtained relatively slowly.

Notes for further development

26) Z_{eff} Profile: The Z_{eff} profile contributes to the transport analysis and to the understanding of impurity localization. It will also potentially provide information on the build-up of helium-ash in the plasma center. It is not expected to change significantly with time and so 100ms provides sufficient time resolution. It is also unlikely to have steep spatial gradients so spatial resolution of a/10 is appropriate. Rapid transients, on the time scale of 10s of milliseconds, may be possible so that some higher temporal resolution with good relative accuracy, but possibly poorer absolute accuracy is needed.

Notes for further development
Need to develop better motivation for the time resolution.

27) High-frequency Micro-instabilities (Fishbones, TAEs): There is a large family of potentially damaging instabilities driven by fast-ions and alpha-particles. To be able to

relate the plasma behavior to theoretical predictions and to assess the impact of these perturbations on the plasma or individual particle properties, it is necessary to measure their properties, such as amplitude, frequency and location. (m,n) = (1,1) fishbones, and much higher frequency TAE-modes with n>10, up to ~ 300 kHz, can be expected. Good relative accuracy of measurement is required with both external and internal localizing measurements. Density fluctuations of about 10^{-5} of the local density may be significant.

Notes for further development

28) Ion Temperature Profile: The requirements on the measurement of the ion temperature profile with its impact on the transport and plasma stability are very similar to those set for the electron temperature. A 10% accuracy is needed because of its significance in transport calculations. A spatial resolution of a/10 is adequate for the generally gently sloping temperature in the core; no specification has yet been set for the edge region. Since the ions are largely unaffected by MHD, a time resolution of 100 ms is sufficient.

Notes for further development

Motivation for the resolution of the edge measurements needs to be developed. On time resolution, need to establish consistency with Te measurement (10 ms).

29) Core Helium Density: Helium ions will build up in the core of a burning plasma device as the alpha-particles thermalize. Their transport away from the core to be pumped away is significant in the continuation of the plasma burn, and, if too slow, could potentially quench it. Hence a measurement of this impurity ion density has to be measured with precision (10%) and with sufficient spatial resolution (a/10) and temporal resolution (100 ms) to permit evaluation of its production and transport inside a particle confinement time-scale (~ s).

Notes for further development

30) Confined Alphas: In order to understand the behavior of the dominant heating particles in the burning plasma, and in the physics studies leading up to this optimal performance, it is necessary to measure the spatial distribution of the total number of alpha-particles and their energy spectrum. The transport and slowing down of the alphas will be compared with transport and stability models. The drive-term for alpha-driven TAE modes is dependent on the gradient of the alpha-pressure. The spatial resolution should be a/10 for profile data with 100 ms time resolution. The energy spectrum should cover the range from full energy at 3.5 MeV down to close to thermal. The relative accuracies of the measurements should be high, with absolute accuracy of 20% proposed.

Notes for further development

Need to develop motivation for spatial and temporal resolutions.

31) Escaping Alphas: Alpha-particles can be lost from the plasma because of their local source and birth-orbits or because of the impact of instabilities. Potentially they could cause local wall damage because the losses are relatively localized on the outer wall (above or below the center-line depending on the toroidal field direction). Hence fluxes to the wall should be measured with 100 ms time resolution (transients at 10 ms resolution to relate to MHD instabilities) with spacing about a/10 along the wall.

Notes for further development
Need to develop motivation for spatial and temporal resolutions.

32) Impurity Density Profile: Measurement of the fractional content of the main impurities is required. This profile supports the Z_{eff} profile in defining the dominant impurity content and its transport. The requirements have been split between the light elements ($Z \leq 10$) and the heavy elements with $Z>10$. The maximum permissible level of the latter is much smaller. For both ranges, the minimum requirements to support a useful analysis are a spatial resolution of a/10 (5 cm in the edge), with 100 ms time resolution and 20% accuracy.

Notes for further development

33) Fuel Ratio in the Edge (for D-T plasmas): ITER and FIRE will operate with all three hydrogen isotopes as its fuel, hydrogen in early phases and ultimately with a D-T mix. Fueling will be both by gas-injection and pellets, with recycling from the first wall an additional source. After the hydrogen operational period, hydrogen will act like an impurity dilution of the fuel from recycling and other sources, such as small vacuum leaks. Both to understand the fuel mix and to provide input for control, the hydrogen isotope ratios should be measured in the edge with reasonable time resolution (100 ms) and accuracy (20%) where better relative accuracy might be expected.

Notes for further development

34) Neutron Fluence: The neutron fluence at the first wall is primarily of value in evaluating blanket performance. It could also be of value in assessing activation properties of different sample materials. Because of the breeding ratio calculation's sensitivity, it must be measured accurately (10%), but without any fast time requirement (10s). The locations of the measurement have not been defined yet.

Notes for further development

35) Impurity and D,T Influx in Divertor: Measurements of the fluxes of fuel ions and of some impurity ions into the divertor are required in order to optimize and evaluate the divertor performance. The measurement should resolve the impurity influx rate from the target into the legs.

Notes for further development
The measurement rate for Ar or Ne need to be specified.

36) Plasma Parameters at the Divertor Targets: The plasma parameters close to the divertor plate surfaces have a huge dynamic range depending on the operational mode of the divertor and of the core plasma. This information is very important because of its role in understanding the divertor operation and in relating to predictive codes for the divertor performance. Measurements should be made along the divertor surface across the strike-point with ~ 0.3 cm spatial resolution to account for the expected narrow scrape-off region. Measurement is desirable for both the inner and outer strike points. The electron density and temperature, and the ion flux toward the divertor should be measured with high time resolution (1 ms will enable effects of ELMs to be seen) and with 30% accuracy over the full range.

Notes for further development

37) Radiation Profile: In the overall power balance of the plasma it is necessary to determine the power being radiated away from the different regions of the plasma. This may be quite non-uniform, particularly near the X-point and in the divertor. In the presence of deliberately introduced local radiation, as in operation of the radiative type of divertor, it is particularly important to determine the principal radiation sources. Hence radiation must be measured throughout the main plasma, in the X-point region and in the divertor. For the latter, there will be a strong variation along the separatrix legs during formation of the radiative divertor, and this measurement will be used to validate modeled behavior. This last measurement should have 5 cm spatial resolution along both the inner and outer legs with good relative accuracy (absolute accuracy 30%) with 10 ms time resolution. The same time resolution applies to the core and X-point measurements, but with a reduced spatial resolution of a/15 because of the expected larger size of radiation features and accuracy of 20%.

Notes for further development
Motivation for accuracies needs to be developed.

38) Heat Loading in Divertor: Full-power operation of the device challenges the capability of the divertor surface to withstand the heat loads. Hence radiative operation of the divertor may be necessary. Also, on a rapid time-scale, the ELMs can dump a lot of energy onto the divertor locally in a short time. Measurement will play a key role in the operation of the divertor, including operational controls. The surface temperature needs to be measured with high spatial resolution (3 mm) and fast temporal resolution (2 ms) and with good accuracy (10%) at least close to the strike-point. The power load can probably be obtained from this measurement with about the same accuracy. Under disruption conditions and for ELMs, the measurement needs faster time resolution at 0.1 ms, but with lower accuracy (20%).

Notes for further development
Temporal resolutions are currently under development

39) Divertor Helium Density: The thermalized helium-ash from the plasma core must be transported out through the divertor. A measurement of this flux of helium will enable the complete history of the helium in the plasma to be developed. It needs to be measured relatively precisely (20%), and with the same time resolution as in the main plasma (100 ms) to support the analysis. Note: the time resolution is currently specified at 1 ms.

Notes for further development
Time resolution needs review.

40) Fuel Ratio in the Divertor: To understand the fuel mix and to provide input for control, the hydrogen isotope ratios should be measured in the divertor, averaged over space, with reasonable time resolution (100 ms) and accuracy (20%) where better relative accuracy might be expected. Since it is anticipated that the divertor will have a wide operating range from fully-attached to fully-detached, the accuracy applies to the measurement technique, not necessarily the interpreted ratios.

Notes for further development

41) Divertor Electron Parameters: Performance of the divertor, and comparison of its principal parameters with code projections, requires accurate measurement of the electron density and temperature along, and across, the legs of the separatices in the divertor. There will be a very dynamic environment with big changes in both density and temperature in relatively short times. Hence the time resolution has been chosen to be 1 ms with 10 cm. spatial resolution along the legs and 3mm across the legs, at planes to be chosen, at 20% accuracy.

Notes for further development

42) Ion Temperature in the Divertor: The ion temperatures in the divertor also feed strongly into the performance determination. The measurement specifications are the same as for the electrons in 41) above.

Notes for further development
Motivation for the measurement needs further development

43) Divertor Plasma Flow: Another key parameter in setting the divertor performance is the flow along the legs toward the divertor plates. The measurement specifications on this flow are the same as for the electron parameters in 41) above.

Notes for further development
Motivation for the measurement needs further development

44) n_H/n_D Ratio in Plasma Core (for D-T plasmas): Hydrogen in the plasma core acts like an impurity which reduces the reacting fuel ions while not impacting Z_{eff}. Thus its

presence should be measured on the same 100 ms timescale and spatial resolution (a/10) as the fuel species with an accuracy of 20%, at least for the maximum expected ratio of 1/10.

Notes for further development

45) Neutral Density between Plasma and First Wall: ITER will have many components such as the blanket modules inside the vacuum vessel. With relatively narrow gaps between and behind them, these could provide "trapped" volumes for gas, which could provide a source of fuel. In order to allow control of the fueling by external means, the influx of neutral D and T atoms in the space between the blanket faces and the plasma must be measured. This should be done to 30% accuracy and with 100ms time resolution at a number of relevant locations distributed toroidally and poloidally.

Notes for further development

Motivation for required accuracy needs to be developed. Would this measurement be used in real time control?