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Summary of TFTR Diagnostics, Including JET and JT-60

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ABSTRACT

The diagnostic instrumentation on TFTR (Tokamak Fusion Test Reactor) and the specific properties of each diagnostic, i.e., number of channels, time resolution, wavelength range, etc., are summarized in tables, grouped according to the plasma parameter measured. For comparison, the equivalent diagnostic capabilities of JET (Joint European Torus) and the Japanese large tokamak, JT-60, as of late 1987 are also listed in the tables. Extensive references are given to publications on each instrument.

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The purpose of this report is to provide a comprehensive summary of all the diagnostics on TFTR (Tokamak Fusion Test Reactor) as they existed in August 1989, along with most of the specifications or properties of interest for each diagnostic, i.e. number of channels, time resolution, wavelength range, etc. The TFTR diagnostics and their properties, sorted according to the plasma parameter measured, are listed first in short form in Table 1, and then in more detail in Tables 2 - 18. For comparison, the equivalent diagnostic capabilities of the JET (Joint European Torus) tokamak in Culham, England and the JT-60 tokamak near Mito, Japan are also listed in the tables.

The main source of information for this report is Reference 1, which is a comprehensive summary of the diagnostics on all the large tokamaks up until about 1987. (While this report addresses only TFTR, JET, and JT-60, Ref. 1 also includes information on T-15, DIII-D, and Tore Supra diagnostics.) Considerable care has been taken to update and insure the accuracy of the TFTR diagnostics entries. At this point less effort has been expended toward updating the JET and JT-60 entries beyond their status in Ref. 1. For more information on topics such as introductory discussions of the method of operation of the diagnostics, physical layout of many of the diagnostic systems, examples of data, and port layouts on the large tokomaks the reader should consult Ref. 1 and review articles cited therein. Further details on individual diagnostics are available in publications cited in this report.

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Table 1: TFTR Diagnostic Instruments Operational in 1988 - 1989

ION TEMPERATURE	
X-Ray Crystal Spectrometer	1 Horizontal, 5 Vertical Chords
Charge Exchange Recombination Spectroscopy (CHERS)	1 Vertical, 3 Horizontal Arrays
Diagnostic Neutral Beam (DNB)	Horizontal Midplane (Scannable)
Soft X-Ray Spectrometer (SOXMOS)	Horizontal Midplane
ELECTRON TEMPERATURE	
TV Thomson Scattering (TVTS)	Dual Multipoint Radial Profile, Edge Optimized Spectrometer
ECE Heterodyne Radiometer	Radial Profile
X-Ray Pulse Height Analysis (PHA)	1 Horizontal, 2 Vertical Chords
ECE Fourier Transform Spectrometer	Radial Profile
ECE Grating Polychromator	20 Point Radial Profile
Fast Edge Probe, CESEP Probe	1 Midplane Radial Profile, 1 Vertical
ELECTRON DENSITY	
1 mm Microwave Interferometer	Vertical Chord at R = 2.6 m *
Multichannel FIR Interferometer (MIRI)	10 Vertical Chords
TV Thomson Scattering (TVTS)	Dual Multipoint Profile
Fast Edge Probe, CESEP Probe	1 Midplane Radial Profile, 1 Vertical
ENERGETIC IONS	
Charge Exchange - E ll B Mass Resolving	2 Vertical Chords
Electrostatic	6 Vertical Chords
Tangential Bolometers	16 Chord Counter View 2 Chord Co View
Lost Alpha/Triton/Proton Detector	4 Poloidal/2 Toroidal Locations
Fast Edge Probe, CESEP Probe	1 Midplane Radial Profile, 1 Vertical

* Being re-configured from horizontal midplane to vertical path. Will be available Jan. 1990.

Table 1 (continued)

IMPURITY CONCENTRATION	
Visible Bremsstrahlung Array (HAIFA)	18 Chord Array, 4 Toroidal, 16 Chord Tangential
Pellet Polychromator	1 Location
UV Survey Spectrometer (SPRED)	Horizontal Midplane
X-Ray Pulse Height Analysis (PHA)	1 Horizontal, 2 Vertical Chords
Sample Exposure Probe	1 Vertical Location
Multichannel Visible Spectrometer (VIPS)	2 Horizontal Midplane
Soft X-Ray Spectrometer (SOXMOS)	Horizontal Midplane
RADIATED POWER	
Bolometer Arrays	19 Horizontal, 19 Vertical Chords
Wide-Angle Bolometers	7 Toroidal Locations
Tangential Bolometers	16 Chord Counter View 3 Chord Co View
FLUCTUATIONS / WAVE ACTIVITIES	
Microwave Scattering	4 Scannable Antennas, 1 Toroidal Location
ECE Grating Polychromator	20 Point Radial Profile
Mirnov Arrays	40 Selectable Locations (+ 30 Available Channels)
X-Ray Imaging System	64 Horizontal, 20 Vertical Chords
Neutron Fluctuation Detector	3 Toroidal Locations
RF Probes	Edge Array
Edge Probes	2 Horizontal, 1 Vertical Locations
PLASMA ROTATION	
X-Ray Crystal Spectrometer	1 Horizontal, 5 Vertical Chords
Charge-Exchange Recombination	1 Vertical, 3 Horizontal Arrays

Table 1 (continued)

FUSION PRODUCTS	
Epithermal Neutrons	4 Toroidal Locations
Neutron Activation Detector	7 Toroidal Locations
14 MeV Neutron Detectors	1 Toroidal Location
Neutron Fluctuation Detector	3 Toroidal Locations
Lost Alpha/Triton/Proton Detector	4 Poloidal/2 Toroidal Locations
Collimated Neutron Spectrometer	1 Toroidal Location
MAGNETIC PROPERTIES	
Rogowski Coil	2 Toroidal Locations (1 Redundant)
Voltage Loops	6 Poloidal locations + Saddle Coil
B_θ/B_ρ Coils	2 Sets of 26 Pairs, External (1 Set Redundant)
Diamagnetic Loops	2 Toroidal Locations (1 Redundant)
Saddle Coils	6 Full, 8 Partial Coils
PLASMA EDGE/WALL	
Plasma TV/IR Camera	Periscopes at 2 Toroidal Locations
Edge Probes	2 Horizontal, 1 Vertical
Hα Array (HAIFA)	5 Telescopes in Poloidal Array
C II Array (HAIFA)	5 Telescopes in Poloidal Array
Disruption Monitor	1 Location
Laser Release Analyzer	1 Location
Vacuum Vessel Illumination	3 Toroidal Locations
MISCELLANEOUS	
Hard X-Ray Monitors	5 Wall Locations
Torus Pressure Gauges	2 Toroidal Locations
Residual Gas Analyzers	2 Toroidal Locations
Glow Discharge Probes	2 Mechanisms
Laser Ablation Impurity Injector	1 Location

Table 2 Measurement of T_e By Thomson Scattering

Parameters	TFTR	JET	JT-60
		Single-point systems	
Laser		Ruby	
Energy per pulse (J)			
single pulse		20	
20 pulses, 1 Hz		2.5	
Scattering angle (°)		~90	
Number of spectral channels		10	
Detector		Photomultiplier(PM)	
	Single-pulse systems with spatial resolution		
Laser	2 rubies	Ruby	Ruby
Pulse duration (ns)	12	0.3	20
Energy per pulse(J)	2 x 15	5	20 (single) 2.5 (1Hz)
Scattering angle (°)	90 ± 35	180	54 -70
Spatial resolution (cm)	~3	~8	8 - 13
Number of spatial points	2 x 76	50	6
Number of spectral channels	13		
Detector	ICCD	Fast-recording PM	PM
Diameter (cm)	8.0		
# pixels digitized	128 x 318(x2)		
#optical channels	18 x 106		
Dynamic range/ch	10^4		
Objectives Lens	catadioptic mirror		
Field of view (°)	80		
f-number	f/7.0		

Table 2 (continued) Measurement of T_e By Thomson Scattering

Parameters	TFTR	JET	JT-60
Spectrometer	Littro		
Grating (lines/mm)	1800		
Entendue (sr-cm^2/spectrometer)	1.5		
λ range (Å)	4250 -6843		
Spectral resolution	17.9 ch (148 Å)		
f-number	f/3.5		
References	[2]	[3 - 9]	
Edge Optimized Spectrometer/Detector			
Grating (l/mm)	1810		
Spectral resolution (Å)	25		
Radial span (cm)	10 cm		
Minimum T_e (eV)	3 - 5		
Minimum n_e (10^{11} cm^{-3})	1 -3		
Detector	Gen III ICCD		
Quantum Efficiency (6943 Å)	0.3		
Luminous gain	2-3 x 10^4		
Resolution	7.5 lp/mm at 50% MTF 2.5 lp/mm at 95% MTF		
Input	18 mm Ga As Photocathode		
Output	17.5 mm FO with P20 phosphor		
CCD configuration (pixel)	<15 at 16 µs/pixel		
Dynamic range(1 pixel)	2 x 10^4		
References	[97]		

Table 3 T_e Profiles From ECE Emission

Characteristics	TFTR	JET	JT-60
	Heterodyne receivers		
Frequency resolution	1 - 4 GHz		
Spectral region	75 - 110 110 - 170 170 - 220	73 - 79	
Time resolution (μs)	~40 (fixed frequency)	10	
Scanning time (ms)	4	--	
Spatial resolution (cm)			
in viewing direction	3 - 10	1 - 5	
perpendicular to viewing direction	~ 10		
Channels/samples per scan	72	8	
Mixer	Ga-As (Shottky)	Ga-As (Shottky)	
Typical signal to noise ratio	100 - 1000	100	
References	[10, 11, 12,98]	[13,100,102]	
	Polychromators		
Spectral region (GHz)	120 - 400	110 - 430	
Number of channels	20	12	[20]
Time resolution (μs)	~4	~10	[5]
Spatial resolution (cm:			
in viewing direction	~4	~6	[5]
perpendicular to viewing direction	~10		
Viewing direction (angle to horizontal plane, °)	0	0	[45]
Detector	InSb (4.2 K)	InSb (4.2 K)	
Typical signal to noise ratio	100-400		
References	[14, 15,98,99]	[16, 17,100]	[18]
	Fabry-Perot interferometer		
Spectral region (GHz)		120 - 180	
Time resolution (μs)		20	
Scanning time (ms)		>3	
Spatial resolution (cm)		5	
Number of channels		6	
Viewing direction (angle to equatorial plane, °)		0, ±17.5, ±25.5, ±33	
Detector		InSb (4.2 K)	
Typical signal to noise ratio		1000	
References		[4, 19,100]	

Table 3 T_e Profiles From ECE Emission (Continued)

Characteristics	TFTR	JET	JT-60
	Michelson interferometer		
Spectral region (GHz)	75 - 540	60 - 600	100- 1000
Spectral resolution (GHz)	3.6	≤10	3.5
Scanning time (ms)	>15	≥15	15
Spatial resolution (cm)			
in viewing direction	2 - 6	15	~16
perpendicular to viewing direction	~10		
Viewing direction (°)	0	0	45
Detector	InSb (4.2 K)	InSb(4.2 K)	InSb(4.2 K)
Typical signal to noise ratio	100 -1000 (depends on T_e)	3000	10
References	[14, 20, 21,98]	[4, 22, 23,100,101]	

Table 4 Magnetic Loops

	Position	TFTR	JET	JT-60
	Inside	--	--	4
Rogowski coil	Outside	2 [a]	4	2
Voltage loops	Inside	-	--	2
	Outside	6	3	7
Diamagnetic loop	Outside	2 [a]	≥1	≥1
Saddle Coils (Also used for locked-mode detection)	Outside	14 [b]	8 x 14 [c]	
Mirnov coils	Inside	40 [d,e]	8 x 18 [c,e,f] 2 x 10 [f] (x point) 10 [d] (Fast)	
External B_ρ, B_θ Coils	Outside	26 pairs x2		
Movable Probes		Yes [g]	Yes [g]	
Digitization rate (kHz)	2 Up to 500 for 30 channels - Mirnov coils only			
References		[24]	[25, 26, 27]	[28]

Table 4 Magnetic Loops (continued)

[a] The Rogowski coils and diamagnetic detectors are located on the inside walls of the toroidal field coils. The second loop is redundant; it would be used in case of failure of the first loop.

[b] 6 of the saddle coils extend over the full toroidal angle; 8 of the coils cover only part of the toroidal extent.

[c] On each octant of the device, 14 saddle coils are placed on the vessel surface (width in the poloidal direction up to $\pi/8$) and a set of 18 magnetic solenoid probes is placed inside. Certain probe sets will be connected, to simulate a Rogowski coil; others will measure the poloidal field and its fluctuation. The magnetic probe is a solenoid (400 turns wound in four layers) 16 cm long and has a housing 16 mm in diameter. the container tube is made of Inconel (with a diameter of 1 mm and a wall thickness of 0.25 mm) filled with magnesium oxide and contains copper wire 0.1 mm in diameter on its axis.

[d] ~1 MHz bandwidth, determined by electronics

[e] Mirnov coils also used for position and shape information.

[f] 20 kHz bandwidth

[g] See table 15, Edge Diagnostics.

Table 5 Interferometry

Characteristics		TFTR		JET		JT-60	
Radiation source		Gunn diode	CH_3OH laser	BWT	DCN laser	Klystron	CH_3OH laser
Wavelength (μm)		1000	118.8	2000	195	2000	118.8
Source Output Power (MW)			2 x 100				
Interferometer type [a]		MZR	MI [b]	MZ	MZ	MZ	MZ
Number of channels	vertical	1	10 [c]	1	7	1	5
	horizontal	--	--	--	3	--	--
Detector type		Schottky diode	Schottky diode	InSb	InSB		Ge-Ga
Detector mode		Second harmonic					
Compensating interferometer	laser				CH_3OH		He-Ne
	wavelength (μm)				118.8		0.63
wavelength (μm)					118.8		0.63
Type of circuit		OW [d]	OW	OW	GW [e]	OW	OW
Density range and sensitivity							
$\int n_e \, d\ell$	$(10^{13} cm^{-2})$	≥0.6	≥ 3				
n_e $(10^{14} cm^{-3})$		<20	<20				
Digitizing rate (kHz)		2	2 (10 channels) 100 (2 channels)				
Fringing rate (ms^{-1})		≤30	3				
Number of Faraday rotational channels			10		6		1
References		[29]	[30, 31, 108,109]	[32]	[33, 34, 35]	[36]	[37]

Table 5 Interferometry (continued)

[a] MZ = Mach-Zehnder interferometer; MI = Michelson interferometer with reflector outside vacuum vessel; M = Michelson interferometer with reflector inside vacuum vessel; MZR = Mach-Zehnder interferometer with reflector inside vacuum vessel.

[b] Michelson interferometer with quadruple pass through the plasma.

[c] In 1985 there were five channels; later came five additional channels and polarimetric magnetic field measurements [38].

[d] OW = overmode waveguide.

[e] Glass waveguide filled with dry air.

Table 6 X-Ray Continuum Measurements by Pulse Height Analysis

Characteristics	TFTR	JET	JT-60
Number of viewing chords:			
horizontal	1	1	
vertical	2		[10]
inclined			1
Number of detectors in one array	6		
Detectors	Si(Li) (1 Ge available)	Si(Li)	Si(Li)
Input rate (kHz)	20 - 80		
Output rate for E=6 keV(kHz)	20 - 41		
Resolution:			
time (window length) (ms)	~50	200	10 - 200
space (cm)	2		
energy (for E=6 keV) (eV)	230[a]	400	500
Energy region (keV)	1 - 50	1 - 50	3 - 110
Number of time windows	32 or 64		
Number of spectral channels	256 or 512	256	
Amplifier time to peak (μs)			
Slow	4.1		
Fast	0.13, 0.4, 0.9 selectable		
References	[39]	[40, 41]	[42]

[a] ~250 eV resolution is required to separate the Cr, Fe, and Ni peaks in order to measure the elements individually.

Table 7 Neutral Spectrum Analysis and Diagnostic Injectors

Parameters	TFTR	JET	JT-60
	Neutral spectrum analysis		
Dispersing field	E||B	E||B	E||B + E
Atoms detected	H, D, T	H, D	H, D, He
Number of analyzers:	8	5	10
vertical (v)	2 [6][a]		1[b]
horizontal (h)		5	
inclined			9
tangential (t)			
Energy range (keV) per amu	0.5 - 600	0.3 - 320	0.1 - 110 0.1 - 30 (E)
Number of energy channels per mass	75	10	3 x 32 10 (E)
Energy resolution ΔE/E(%)	2 - 10	10	5
E_{max}/E_{min}	30	14	
Time resolution (ms)	0.05 - 10	5 - 50	>100
Spatial resolution (cm)	5 - 10	10	10
Detection efficiency (counts/neutral)	$\leq 10^{-7}$	10^{-6} - 10^{-4}	
Angle of deflection in magnetic field (°)	180	100 - 120	180
Detector	MCP 3 rows of 75	CEM 2 rows of 10	MCP 3 rows of 32
References	[43, 44]	[45]	[46]
	Diagnostic injectors		
Energy of beam atoms (keV)	20 - 80		40 - 200 (He°)
Ion current (A)	22(H) at 80 keV 17(D) at 80 keV		
Equivalent atom current (equiv. A)	~8 H^0,D^0 total all species into TFTR at 80 keV		3.5
Beam cross section (cm^2)	10 x 10		20[c]
Beam divergence:			
parallel to slit	0.4°		0.4°(I/e)
perpendicular to slit	1.2°		
Pulse length:			
total(s)	0.5		>1.0
minimal (ms)	0.1		
Modulation frequency (kHz)	2		
References	[23]		[47, 48]

Table 7 Neutral Spectrum Analysis and Diagnostic Injectors (continued)

[a] Electrostatic (mini-analyzers)

[b] This analyzer with E∥B is intended for measuring T_i from the scattering of He^0 atoms on plasma ions. The analyzer's parameters differ from those of other analyzers designed for passive diagnostics [110]: E = 10-200 keV, ΔE/E = 10%, spatial resolution = 20 cm. The detector is a silicon surface barrier diode, and pulse-height analysis is used. A detector of this kind for 15-keV atoms was used on the JFT-2 tokamak [111] for experiments on scattering of H^0 atoms.

[c] Beam cross section at injector input.

Table 8 Spectrometers for Measuring Ion Temperature from Doppler Broadening of Spectral Lines

Characteristic	TFTR	JET	JT-60
	Vacuum UV spectrum		
Grazing incidence spectrometer	SOXMOS[a]		
Number of instruments	1		
Spectral region (Å)	7 - 330		
Spectral resolution (Å)	0.2		
Rowland circle radius (m)	2		
Angle of incidence (°)	88.5		
Grating (lines/mm)	600 2400		
Region covered by one viewing(Å)	20 - 60		
Detectors	OMA[b]		
Time resolution (ms)	Scan: 17		
	Soft x-ray region		
Spectrometer configuration	Johann	Johann	Johann
Number of spectrometers:			
horizontal	1		
vertical	5	1	1
Crystal dimensions (cm)	Quartz	Quartz	Quartz
3.8 x 15	12 x 15		
Radius of Rowland circle (m)	3 - 12	24	2.5
Range of Bragg angles(°)	42 - 65	47.5 - 51.5	
Range of wavelengths (Å)	1.84 - 1.88	0.1 - 10	1.5 - 2.7
Spectral resolution ($\lambda/\Delta\lambda$)	1.5×10^4		
Detector	PSPC[c]	PSPC	32-channel array
Length of sensitive region (cm)	18	20	
Linear resolution (mm)	0.18 - 0.25	0.5	
Count rate (kHz)	80 - 350	~1000	
Time resolution (ms)	20	~10	>1
Spectral Channels in Line	10-20		
References	[49, 50]	[51, 52, 53]	[54]

[a] SOft X-Ray MOnochromator and Spectrometer

[b] OMA - Optical Multichannel Analyzer = microchannel-plate intensifier with linear Reticon-diode array detector.

[c] PSPC - Position-Sensitive Proportional Counter.

Table 8 Spectrometers for Measuring Ion Temperature from Doppler Broadening of Spectral Lines (continued)

Characteristic		TFTR			JET	JT-60
Visible and Near UV Spectrum						
Type of instrument		CHERS[c]			CHERS	
Number of arrays		•Bay K tangential, NB[d] 4,5 •Bay E,tangential DNB[e] view •Bay A lookdown, DNB view •Bay P tangential NB 1			1 tangential, Octant 7	
Number of viewing channels per array		<u>1 shot</u>	<u>2 shots</u>	<u>4 shots</u>		
	•K	11	14		8	
	•E	12	24	39		
	•A	12	16			
	•P	17				
Radial range (m)	•K	2.40-3.40	2.2-3.5			
	•E	2.35-3.45	2.35-3.45	1.7-3.6		
	•A	2.40-3.30	2.20-3.60			
	•P	2.50-3.30				
Spatial resolution (m)	•K	0.1				
	•E	0.1	0.05			
	•A	0.1				
	•P	0.05				
Number of single view spectrometers	2 lookdown 1 tangential					

Table 8 Spectrometers for Measuring Ion Temperature from Doppler Broadening of Spectral Lines (continued)

Characteristic	TFTR	JET	JT-60
Spectral region (Å)	2800 - 7000		
Spectral range (Å)	60 at one time (at 5292)		
Detector	OMA		
Time resolution (ms)	5, typically 30		
Number of points in Doppler profile	20 FWHM at 20 keV, 5292Å or ~5 $T_i^{1/2}$ (for Carbon)		
Signal to noise	Typically 100:1, Residuals 1% of fitted Gaussian		
References			

[c] CHERS - CHarge Exchange Recombination Spectrometer

[d] NB - Neutral Beam

[e] DNB - Diagnostic Neutral Beam

Table 9 Some Neutron Measurement Methods[a]

Method (detector)	TFTR	JET	JT-60
Total neutron yield			
Foil activation (with pneumatic delivery):			
Number of channels	8	4 [4]	
Detector	Ge	Delayed neutron counter	
Time resolution detector:	^{235}U; ^{238}U	^{235}U; ^{238}U	NE 213
Number of channels	3 + 4	3 + 3	1
U mass (g)	1,20; 1,50		
Sensitivity (n^{-1} cm^2)	10^{-2},10^{-1};10^{-5},10^{-3}		1
Time resolution (ms)	1.0, 0.05	0.05	1 - 100
# of toroidal locations	4 (current mode)	(current mode)	
Spatial resolution			
Number of sighting chords:			
vertical	10	9	
horizontal		10	
Detector	ZnS(Ag) scintillators	NE 213 scintillators	
Spectroscopy (deuterium Plasma)[b]			
1. Type of spectrometer:	^{3}He ionization chamber	^{3}He ionization chamber	NE 213
ΔE/E (%)	~3.8	~1.5	8
2. Type of spectrometer:			
low flux	NE 213	H_2 spherical	
high flux	^{3}He sandwich ionization chamber	^{3}He sandwich ionization chamber	
3. Type of spectometer:		Time-of-flight	
ΔE/E (%)		4	
Sensitivity (n^{-1} cm^2)		10^{-5}	
Spectroscopy (tritium plasma)			
Type of spectrometer		Time-of-flight	
Detector: low flux	NE 213	Scintillation	
high flux	Recoil proton telescope	ΔE/E = 1.4% 10^{-5} cm^2 n^{-1}	
References	[55, 56, 57] 58, 59, 60 61]	[62 - 64, 65 - 68]	[69]

a The characteristics of detectors not included in this table are given in Table 10.
b Only a few spectrometers under development are given.

Table 10 Some Methods of Detecting Neutrons

Detection system	Energy (MeV)	Resolution (%)	Number of events ($n^{-1} \cdot cm^2$)	Maximum flux measured ($n \cdot cm^{-2} \cdot s^{-1}$)	Fluence for 10^3 counts ($n \cdot cm^{-2}$)
Passive methods of detecting fast neutrons					
Slowing-down and activation			10^{-3}		10^6
Multifoil activation		20	10^{-6} to 10^{-8}		10^{-9} to 10^{11}
Delayed neutron counting		30	10^{-5}		10^8
Active methods of detecting fast neutrons without energy resolution					
^3He (1 atm) with moderator	2.0		10^2	10^2	
^{235}U(1g) with moderator:	2				
counting regime			1	10^6	
current regime				10^{10}	
^{238}U(1g) fission chamber:	2				
counting regime			10^{-3}	10^9	
current regime				10^{13}	
Active methods of detecting fast neutrons with energy resolution					
Scintillator with ^6LiI	2.45	20	0.5	7×10^5	2×10^5
^3He pulsed ionization chamber	2.45	2	5×10^{-3}	2×10^5	2×10^5
CH_4 proportional counter	2.45	6	10^{-2}	10^6	10^7
^3He sandwich detector	2.45	4	3×10^{-6}	10^{10}	3×10^8
^6Li sandwich detector	2.45	16	7×10^{-7}	10^{11}	2×10^9
NE 102A scintillator	2.45	10	1	2×10^5	10^5
NE 213 scintillator (2 cm)	2.45	8	1	2×10^5	10^5
NE 213 scintillator (2 cm)	14	4	0.4	4×10^5	2×10^5
$^{28}Si(n, \alpha)^{25}Mg$ reaction in a 3 mm Si(Li) diode	14	1	2×10^{-4}	5×10^6	5×10^6
Neutron spectrometers with telescope					
Recoil proton scattering detector (ℓ = 17.6 cm, θ = 10°)	2.45	3.8	9×10^{-8}	10^{12}	10^{10}
Time-of-flight detector (ℓ_2 = 2 m, θ = 20°)	2.45	3.5	2×10^{-5}	4×10^6	5×10^7
Scattering detector (ℓ_1 = 17.6 cm, θ = 10°)	14	4.3	5.4×10^{-7}	2×10^{11}	2×10^9
Time-of-flight detector (ℓ_2 = 500 cm, θ = 20°)	14	3.5	5×10^{-6}	2×10^6	2×10^8

Note: ℓ_1 is the distance from the emitter to the detector;

ℓ_2 is the distance from the scattering scintillation detector to the second detector;

θ is the scattering angle.

Table 11 **Characteristics of Bolometry Systems for Measuring Radiation Losses on Large Tokamaks**

Characteristics	TFTR	JET	JT-60
Number of detector arrays:			
in vertical ports	1	1	
in lateral ports	1	2	1
tangentially viewing	2		1
divertor plate view			
Number of viewing chords in each array:			
vertical (all)	19	14	
lateral (all)	19	2 x 10	15
tangential	16, 3		
divertor plate view			2
Number of toroidal detectors	7	7	
Number of vertically viewing detectors			4
Detector type	Metal resistor (Pt)	Metal resistor (Au)	Metal resistor (Au)
Wavelength (Å)	1.5 - 2000	1.5 - 2000	1 - 2000
Spatial resolution of detectors (cm) (collimated or in pinhole cameras)	11	22 -24	12
Time resolution (ms)	2 - 10	20	10
Sensitivity	Noise with 50 Hz bandwidth 20 $kW \cdot m^{-3}$	0.5 $V \cdot W^{-1}$	
References	[70, 71]	[72, 73]	[74, 75]

Table 12 Spectroscopic Instrumentation For The Visible and Near Ultraviolet Regions

TYPE	TFTR	JET	JT-60
Remote viewing through optical fibers			
Spectrometer(s):	0.64 m x 0.64 m Czerny-Turner	1 m x 1m 1 m x 0.6 m Czerny-Turner	0.5 m Czerny-Turner
Number of views	4 (1 through window, 3 through fiber)		
Spectral range (Å)	1850 - 7500 directly 3500-7500 through fiber	3500 - 7500	2000 - 7000
Wavelength resolution (Å)		≥ 0.1	
Detector	Intensified photodiode array, 1024 elements	OMA[a] PM[b]	PM and photographic
Time resolution (ms)	1 Scan: 18	1 Scan: 12	≥0.05
Narrowband interference filters:			
Number of views	33	8	
Selected wavelengths (Å)	6563, 5235,6580 and others	6563, 4650,4415, 5235,4687, 4254	
Half-power bandwidth (Å):	2 - 10	5 or 10	
Detector	PM	PM	
Time resolution (ms)	0.1 - 1.0	0.2 - 1.0	
Z_{eff} poloidal scan:			
Number of channels		13	
Coverage of plasma		~90%	
Wavelength (Å)		10	
Detector		PM	
Time resolution (ms)		≥ 0.2	
Z_{eff} Tangential Scan:			
Number of channels	20		
Coverage of Plasma	R±a		
Wavelength (Å)	5235		
Bandwidth (Å)	10		
Detector	PM		
Time resolution (ms)	1.0		
References	[112]		

[a] Optical Multichannel Analyzer = microchannel plate + intensifier/converter + 1024 channel photodiode array.

[b] Photomultiplier tube.

Table 12 Spectroscopic Instrumentation For The Visible and Near Ultraviolet Regions (Continued)

TYPE	TFTR	JET	JT-60
Charge exchange recombination spectroscopy:			
Viewing chords	See Table 8, CXRS	1[2] vertical 1[9] horizontal	3[11]
Radial scan	See Table 8	[-0.5< (r/a)<1]	
Spectrometers	0.64 m Czerny-Turner	0.75 m SPEX 1702	0.5 m Czerny-Turner
Spectral range (Å)	2500 - 7000	4000 - 7000 [2000 7000]	4000 - 7000
Detectors	Intensified 128 x 128 pixel photodiode array	2 OMA and 1 Vidicon	Intensified multichannel (512) detector
Time resolution (ms)	4	5	

Table 13 Spectral Instruments for the VUV Region

Instrument	TFTR	JET	JT-60[a]
Normal incidence spectrometer			1.2 m
Number of instruments			1
Spectral range (Å)			1000-2350
Detector			MCP with photodiode matrix
Time resolution (ms)			≥1
Survey spectrometers	SPRED[b]	MacPherson 251	3 m Czerny-Turner
Number of instruments	1	1	1
Spectral range (Å)	100-1100, 100-320	100 - 1700	10 - 1300
Diffraction grating (lines/mm)	selectable between shots: 450, 2100	selectable: 290,450,2100	
Spectral resolution (Å)	2, 0.7	1.6, 1, 0.3	
Detector	OMA[c]	OMA	MCP + CCD
Time resolution (ms)	1(50 Pixels) 17(1024 Pixels)	1	>0.05
Scanning spectrometers			
Number of instruments:			
horizontal		2	
vertical		1	
Spectral range		100 - 2500	
Diffraction grating (lines/mm)		1200	
Spectral resolution (Å)		<1.3	
Scanning time (ms)		4.5 - 80	
Spatial resolution (cm)		0.5 - 4	
Detector		2 Bendix multipliers + 1 photomultiplier	
References	[76, 77]	[41, 52, 78, 79 80, 81]	

[a] Apart from the instruments indicated here, JT-60 will use two horizontal spectrometers with a range of 1000 - 3000 Å, to detect wall plasma radiation, and one spectrometer with a range of 20 - 300 Å, to detect impurities near the magnetic limiter [35].

[b] Survey, Poor Resolution, Extended Domain. Absolutely calibrated by synchrotron radiation at the National Institutes of Standards and Technology electron storage ring.

[c] Optical multichannel analyzer = microchannel plate + intensifier/converter + 1024 channel photodiode array.

Table 14 Instruments for XUV and X-Ray Spectroscopy of Plasma

Instrument	TFTR	JET	JT-60	
Grazing incidence spectrometer	SOXMOS[a]			
Number of instruments	1	1	2	1
Spectral region (Å)	7 - 330	7 - 330	5 - 500	20 - 1200
Spectral resolution (Å)	0.2	0.2	0.5 - 1.5	0.1 - 2
Rowland circle radius (m)	2	2	18	6
Angle of incidence (°)	88.5	88.5	89	87
Grating (lines/mm)	600 2400	600 2400		
Region covered by one viewing(Å)	20 - 60	20 -60	15 spatial points	
Detectors	OMA	2 OMA	MCP + CCD	
Time resolution (ms)	Scan: 17	Scan: 17	≥ 20	≥ 15
Crystal monochromator with spatial resolution		Double crystal		
Number of instruments	6 chords	1		
Spectral range (Å)	1.84 - 1.87	2 - 20		
Spectral resolution ($\lambda/\Delta\lambda$)	$(1.0\text{-}1.5)\times10^4$		~1000	
Bragg angle (°)	~43, ~53	12 -45		
Spatial scanning time (s)		0.2		
Detectors	PSPC[b]	Proportional counter		
Crystal monochromator for active stage		Double crystal		
Spectral range (Å)		2 - 20		
Spectral resolution ($\lambda/\Delta\lambda$)		400		
Bragg angle (°)		30 - 60		
Spectrum scanning time (s)		~1		
Detector		Proportional counter		
References	[82, 83, 84 85, 86]	[84, 80, 81, 87, 88,89]	[90]	

a SOft X-Ray MOnochromator and Spectrometer

b Position-Sensitive Proportional Counter.

Table 14 Instruments for XUV and X-Ray Spectroscopy of Plasma

Instrument	TFTR	JET	JT-60	
Grazing incidence spectrometer	SOXMOS[a]			
Number of instruments	1	1	2	1
Spectral region (Å)	7 - 330	7 - 330	5 - 500	20 - 12(
Spectral resolution (Å)	0.2	0.2	0.5 - 1.5	0.1 - 2
Rowland circle radius (m)	2	2	18	6
Angle of incidence (°)	88.5	88.5	89	87
Grating (lines/mm)	600 2400	600 2400		
Region covered by one viewing(Å)	20 - 60	20 -60	15 spatial points	
Detectors	OMA	2 OMA	MCP + CCD	
Time resolution (ms)	Scan: 17	Scan: 17	≥ 20	≥ 15
Crystal monochromator with spatial resolution		Double crystal		
Number of instruments	6 chords	1		
Spectral range (Å)	1.84 - 1.87	2 - 20		
Spectral resolution ($\lambda/\Delta\lambda$)	$(1.0\text{-}1.5)\times10^4$		~1000	
Bragg angle (°)	~43, ~53	12 -45		
Spatial scanning time (s)		0.2		
Detectors	PSPC[b]	Proportional counter		
Crystal monochromator for active stage		Double crystal		
Spectral range (Å)		2 - 20		
Spectral resolution ($\lambda/\Delta\lambda$)		400		
Bragg angle (°)		30 - 60		
Spectrum scanning time (s)		~1		
Detector		Proportional counter		
References	[82, 83, 84 85, 86]	[84, 80, 81, 87, 88,89]	[90]	

a SOft X-Ray MOnochromator and Spectrometer

b Position-Sensitive Proportional Counter.

Table 15 Edge Diagnostics

TYPE	TFTR	JET	JT-60
Langmuir probes			
Max. sat. current	1-2 A cm^{-2}	1 A cm^{-2}	
Ramp rate	1 ms to 5 s	≤5 ms	
Data points/ramp	Programmable ramp 100 Hz to 500 kHz sampling rate in up to eight bursts		
Number and location	2 at midplane (1 fast probe) 1 at bottom	2 arrays of 3 2 in RF antenna 1 above midplane [20 in belt limiter] [2 in RF antenna]	
Distance from plasma	Movable to plasma edge	Small, 15 mm, 30 mm	
Fast Probe Characteristics			
Stroke (cm)	30		
Speed (cm/s)	13		
Dwell time	arbitrary		
Collector probes			
Material	Si, C, SS	Ni, Inconel, C, Si	
Number of samples	1 rotatable at bottom	6	
Number and location	Variable number of samples fixed on wall	1 rotatable on top 2 above midplane 100 fixed on wall	
Surface analysis station			
Number of chambers	None	2	
Type of analysis		RBS, PIXE, NRA, TDS, SAES, XPS	
Mode of operation		Automatic, vacuum coupling	
Limiter viewing			
CCD camera			
Number of cameras	2	3	
Number of channels	2	2	
Location	Midplane	Viewing limiters	
Filter wavelength	Variable	9000 ± 200 Å	
Temp. sensitivity	300°C	>600°C	
ΔT max	2600°C	~300°C	

Table 15 Edge Diagnostics (continued)

TYPE	TFTR		JET	JT-60
Mode of operation	Automatic video (all channels) and digital (one selectable channel) recording and closed-loop playback by scan converting digital		Automatic video recording and playback	
Limiter viewing				
Diode array				
Number of arrays	4		1	1[2]
Number of elements	3,33,54		128 x 128	15 [30]
Type of filters	C, O metals		C II, C III, O II, Cr II	Hα
Mode of operation	Continuous		Automatic, off-line analysis	Automatic
IR array	IR TV system	Disruption monitor		
Spectral region	1.3 - 2.1 μm	0.1 - 1.0 μm	4 μm	
Detector	PtSi			InSb
Min. temperature	300°C	650°C	-------	400°C
Max. temperature	>3000°C	>4000°C	>2000°C	~1500°C
ΔT			≈2000°C	~2.5°C
Number and location	2, toroidal locations	1, viewing inner limiter	1, viewing a carbon limiter	2, viewing divertor plate
Δt	20 ms time response	10 μs time response		<25 mm
Vessel inspection				
Field of view	60°, 20°,5° covering 75% of the vessel interior		20°-40°, covering 80% of the vessel interior	±90° overall
Δz	~1 mm		~2mm	<10 mm
Mode of operation	35 mm photography, insertable probes		insertable into vacuum	Video -- 30 frames/s
Number of views	4 video TV		4 video TV	

Table 15 Edge Diagnostics (continued)

TYPE	TFTR	JET	JT-60
Plasma TV			
Field of view	60°, 20°, 5°, selectable		>20°
Δz	~1 mm		≤10 mm
Mode of operation	Video (all 3 channels) and digital recording, scan-converted, closed-loop playback of digital memory		Video - 30 frames/s High speed camera - 2000 frames/s
Electromagnetic Probes	Magnetic coil probes movable to edge, DC - 250 kHz		Table 4
Spectrometer for periphery	Visible, UV multichannel spectrometer	Table 5	Table 5
References	[91,104-107]	[62,103]	

Table 16 Systems for Flux Detection of Soft X Rays on Large Tokamaks

Characteristics	TFTR		JET		JT-60
Number of pinhole cameras:	2		2		1
horizontal	1		1		
vertical		1		1	
Number of detector arrays	2	1	3	1	1 (each)
Number of detectors in each pinhole camera	2 x 32	32	62	38	15
Number of monitoring detectors	1		4	3	
Spatial resolution (in poloidal direction) (cm)	2.5 - 5	2.7			3.5
Time resolution (μs)	0.01 - 10		0.01		10 - 25
Number of filter combinations	4	4	24		3
Energy region (keV)	0.2 - 15	2-10	0.3 - 30		
References	[92, 85, 86, 93, 94, 95]		[96]		

Table 17 Instrumentation for Density Fluctuation/Wave Measurements by Microwave Scattering

	TFTR	JET	JT-60
Source	EIO (cw)		
Number of Sources	1		
Number of Antennas	4 (1 toroidal location)		
Scan Range of Antennas (°)	± 30		
Microwave Wavelength (cm)	0.5		
Radial Range covered (cm)	± 80		
Spatial Resolution (cm) (-10 dB)	$\sim 4/\sin(\theta_s/2)$		
k Range (cm^{-1})	0.5 - 25		
Cutoff Density (10^{13} cm^{-3})	15 @ 5.0 T		
Receiver Bandwidth (MHz)	120		
Data per shot (kB)	384 + 1000		
Propagation Mode	Extraordinary		
Receiver Type	Heterodyne		
Number of Receivers	3		
Beam Diameter (cm) (-10 dB)	8 - 12		
References	[113 - 115]		

Table 18 Laser Ablation Impurity Injection System/Laser-Release Analyzer

	TFTR	JET	JT-60
Impurity Injection System			
Laser	Ruby		
Energy (J)	5.5		
Number of particles injected	$\leq 5 \times 10^{18}$		
Uncertainty in number of particles injected	Typically ± 20 %		
Duration of injection (ms)	0.5 (typically 0.1)		
Number of Slides	9 (18 Halves)		
Number of shots per slide	20		
Elements available	Installed: Ti, Se, Fe, Ni, Cu, Ge, Mo (~40 elements with $4 \leq Z < 82$ available)		
Injections / discharge	1		
Location	Outer midplane		
Laser Release Analyzer[a]			
Laser	Ruby		
Energy(J)	5.5		
Area of ablation (cm^2)	2		
Penetration (µm)	<0.2		
Location	Outer midplane		

[a] Laser-stimulated desorption of gases from inner limiter, quantitatively measured by Residual Gas Analyzer.

Table 19 Escaping Charged Fusion Products

	TFTR	JET	JT-60
Scintillator-screen detector			
Number of detectors	8 (4 poloidal array, 2x2 toroidal-poloidal array)		
Particles detected	1-MeV tritons 3-MeV protons 15-MeV protons 3.5-MeV alphas		
Pitch-angle range (°)	45 - 85, relative to I_p		
Pitch-angle resolution (°)	±5		
Energy resolution (%)	±50		
Time resolution (μs)	10		
Min. source rate detectable (tritons/s)	10^{15}		
Uncertainty in absolute calibration	2 - 3		
Scintillator	ZnS(Ag)		
Scintillator thickness (μm)	10 - 15		
Scintillator readout	Intensified video camera		
Camera framing period (ms)	16		
Scintillator-camera coupling	Relay lens + coherent fiber bundle		
Detector-aperture size (mm)	2 x 1		
Al-foil thickness (μm)	3		
Triton-implantation samples			
Number of samples	4		
Poloidal locations (°)	45, 80[a]		
Toroidal locations	Low field[b], High field[c]		
Viewing direction	60° in the co-direction		
Viewing-angle range (°)	±10		
Substrate	Silicon		
Analysis method	SIMS depth profiling		
References	[116]		

a Relative to major radius vector at horizontal midplane.

b Midway between adjacent toroidal field coils.

c Directly over a toroidal field coil.

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