Requirements for Fast Particle Measurements on ITER and Candidate Measurement Techniques

F P Orsitto 1), J-M Noterdaeme 2) , A E Costley 3), A J H Donné 4), and the ITPA TG on Diagnostics*

1) ENEA-EURATOM Association C R Frascati 00044 Frascati(Italy);
2) Max Planck IPP Garching(Ge);
3)ITER IT, Naka Joint Work Site (JA);
4) FOM-Rijnhuizen TEC,Nieuwegein(NL)
(*) Membership listed in ref 33.

e-mail contact of main author: orsitto@frascati.enea.it

Abstract.Recent results on JET and JT-60U, have underlined the need of looking into the parameter measurement requirements of fast particles diagnostics for ITER. Not only alpha particles present in the plasma, but all fast ions (He^4,p,D,T,He^3) should be diagnosed.The electron diagnostics monitoring the deviations from a Maxwellian distribution function, play a central role in the Electron Cyclotron Heating and Current Drive.In the present ITER measurement requirements only alpha particles and He ions are mentioned: space resolution is $\delta r = a/10$ (a is the minor radius), time resolution is $\delta\tau = 100$ ms, accuracy 10-30%. The new proposed measurement requirements for fast particles are: spatial resolution ~ a/20 (10 cm on ITER); time resolution (minimum) ~ 100 τ_A (~ 100 μs for ITER); density of fast ions: the minority ions could be 4-10% of the plasma density. The candidate diagnostic techniques considered for ITER are amongst others : γ-ray spectroscopy; fast ion Collective Thomson Scattering (CTS); Charge Exchange Recombination Spectroscopy (CXRS). γ-ray spectroscopy detects ions in the energy range $1<E<5$MeV, and R&D is needed to demonstrate the feasibility of these measurements in the presence of a neutron background. Techniques using ultraviolet spectroscopy of ions like Krypton are being tested , for the low energy part of spectrum of fast particles. A design study of CTS shows that the requirements are close to be met, the system includes a high power gyrotron operating in a region not yet tested in current applications (i.e. using a gyrotron at a frequency below the first ECE harmonic).For CXRS the spatial resolution and accuracy are not achievable for $r/a < 0.3$, and R&D is needed to assess the minimum figures in terms of accuracy possible for measurements close to the centre. The measurement requirements deduced from the need of detecting the effects of interaction of fast particles with MHD instabilities put important new objectives to the candidate diagnostic systems. In particular diagnostics for fast particles in the energy region $200<E<1300$ keV and diagnostics for escaping fast particles need a urgent development.

1. Introduction

Recent developments in the physics results on JET and JT-60U[1-5], have underlined the importance of looking into the parameter measurement requirements of fast particles diagnostics for ITER because of the strong impact of fast particle physics on the various ITER scenarios.

In general fast ions generated by D-T reactions, or driven by neutral beam and minority fast wave current drive can generate instabilities, resonating with fast ions. These instabilities can degrade the confinements of those fast ions , leading ultimately to their loss and a damage of plasma facing components.A comparison of the measurement requirements with the envisaged capability of the planned fast particle diagnostic systems on ITER is required to guide the developments needed to get closer to the requirements. The aim is to produce data useful for an optimized evaluation of ITER scenarios.

The first point to be observed is that not only alpha particles present in the plasma, but all fast ions (He^4,p,D,T,He^3), including ions used for minority heating, should be diagnosed, *because* *all of them can interact with plasma instabilities.* The diagnostics for measuring the parameters of electron distribution function must be included as well, to monitor using ECE (or a combination of ECE and Thomson Scattering) the deviations from a Maxwellian distribution function, which play a central role in the dynamics of Electron Cyclotron Heating and Current Drive. Ideally the wave propagation inside the plasma could be diagnosed for a better understanding of the energy transfer process to minority ions.

Motivations for including measurement requirements for fast particles are related to the recent Trace Tritium Experiments on JET [1] ,where evidences of fast ion transport due to various branches of Toroidal Alfvén Eigenmodes(TAE) [2] and fishbone [3] modes were clearly detected. In JT 60U [4,5] particularly in advanced regimes, Abrupt Large-Amplitude Events (ALE) were observed where, as a consequence of interaction with Energetic Particle modes, a spatial redistribution of fast ions was demonstrated. Energetic Particle modes(EPM)(6) were related with ALE in recent theoretical papers [7]. Interactions of TAEs with alpha particles were already documented on TFTR [7] and JET DT1 [8]. Fast particle driven TAEs were studied on Alcator C-Mod [9,10].

Fast particle losses can be due also to a magnetic field ripple and experiments were done recently on JFT2M [4] demonstrating an increase of heat flux on the first wall due to energetic on losses when the ripple was increased. Earlier experiments were done on JET [8,16] : the results were interesting because it was found that particles of intermediate energy 10-50keV were mainly lost, instead of energetic ions. A study made for ITER [17] concluded that an alpha particle loss higher than 5% could be damaging for the first wall of ITER.

The instruments used at present to diagnose the fast ion confinement in a number of present experiments are : i) γ-ray spectroscopy [12] ; ii) neutron cameras with fast electronics for discrimination between neutrons and gammas [5] ; iii) infrared O-mode interferometry [3,13] ; iv) fast magnetics (Mirnov coils); v) neutral particle analizers [5] ; vi) D_α emission [14] ; vii) Natural diamond spectrometers [15] ; and a fast ion Collective Thomson Scattering was carried out on TEXTOR device [18] .

Diagnosing fast particles is not just the use of a single diagnostic , but the integration of a number of individual diagnostics to obtain insight in the dynamics of fast particles in ITER. The integration of a system of diagnostics was experienced at JET during the first DT experiment and the more recent Trace Tritium Experiment. Furthermore a redundancy in the measurements is needed , to reduce uncertainties.

In the present measurement requirements [11] , only alpha particles and He ions are mentioned: their space resolution is defined as $\delta r = a/10$ (a is the minor radius), time resolution is $\delta\tau = 100$ ms, accuracy between 10-30%. For the neutrons, the space resolution is $\delta r = a/10$, time resolution is $\delta\tau = 100$ ms, accuracy 10%.

The paper is organized as follows : in Sec 2 the Spatial and temporal scales, and energy spectrum relevant for fast particle detection are presented ; in Sec 3 the requirements for Fast Particle Measurements on ITER and justifications are discussed with the technical characteristics of the candidate systems proposed ; in Sec 4 a summary of the present status and R&D needed for the diagnostic systems proposed for ITER is outlined; concluding remarks are given in Sec 5.

2. Space , time scales and energy spectrum relevant for fast particle detection.

Above a critical β_{fast} (beta of fast particles), theoretical analysis predicts that Alfvén cascades can be excited in a reversed shear discharge, giving rise to a spatial redistribution of fast particles over the minor radius in a time scale of $\tau_F \sim 100\text{-}300\ \tau_A \geq 100\ \mu s$ (τ_A = Alfvén time = R_0/V_A , R_0= major radius, V_A = Alfvén velocity). The Alfvén time is calculated using the formula:

$\tau A(\mu s) = 0.46\ R0(m)\ n20^{0.5}\ Aeff^{0.5}/BT$; $Aeff = (n1m1+n2m2)/((n1+n2)*mH)$

Where Aeff is the plasma effective mass referred to the hydrogen (mH), n20 is the deuterium density in unities of $10^{20}m^{-3}$, R0 the major radius of ITER, B the magnetic field on axis. For the evaluations of τ_A= Alfvén time, the following ITER parameters were used : R0=6.2;B=5.2T;50%-50% D-T mixture ; n20=0.8; in the previous formula m1=mD, m2=mT, and n1=n2, Aeff=2.5, and τ_A =0.77μs, (V_A=8 10^6 m/s).To define the measurement requirements for fast particles it is useful to determine the various time scales relevant to ITER: i) time scale related to the saturated non-linear interactions of energetic particles and Alfvén modes [7] $\tau_F \sim$ 100-300 τ_A; ii) slowing down time of the fast ions $\tau_s \sim$ 1-2.s (see table I) ; iii) confinement time $\tau_E \sim$ 4s ; iv) resistive relaxation time $\tau_R \sim$ 200-300s.

	mα/mp	Zeff	Te(keV)	ne/10^{20}	ts(s)
alpha	4	1,5	30	1	2,2
He^3	3	1,5	30	1	1,7
d	2	1,5	30	1	1,1

Table I Slowing down times of fast ions .

The relevant spatial scales in general are: i) Larmor radius $\rho_{fast} \sim$ 0.3-7 cm (see Table II); ii) Neoclassical Tearing Mode (NTM) island width ≥ ion Larmor radius; iii) Internal Transport Barrier (ITB) width with spatial scale of the order of the pressure gradient; iv) H-mode pedestal width ~ ion Larmor radius; v) turbulence correlation length ~ ion/electron Larmor radius; the scaling of the confinement in H mode depends upon the Larmor radius. Indeed imaging of γ-ray spectroscopy on JET has demonstrated that the fast particle Larmor radius can be a relevant spatial scale [12].

The energy range of fast ion is determined by the critical energy [20] defined as E*~32Te , which at Te=20-30keV (inductive Q=10,and Weak Rev Shear scenarios [34]) results in E*=640-960keV.In practice the energy spectrum relevant is 200<E<1300keV see fig1. The other energy parameter to be taken into account is the energy of a particle with velocity equal to the Alfvén velocity (see Table III, column of resonant energy). In Table III typical parameters of fast particles in ITER are listed.

	mu	z	Ti(ev)	ρ(cm)	B
α(He4)	4	1	3,50E+06	7,34	5,200
p	1	1	1,00E+06	1,96	5,200
D	2	1	3.00E+04	0,48	5,200
T	3	1	3,00E+04	0,6	5,200
He3	3	1	1,00E+06	3,4	5,200

Table II Larmor radius of fast ions(Bulk Plasma T=30keV)

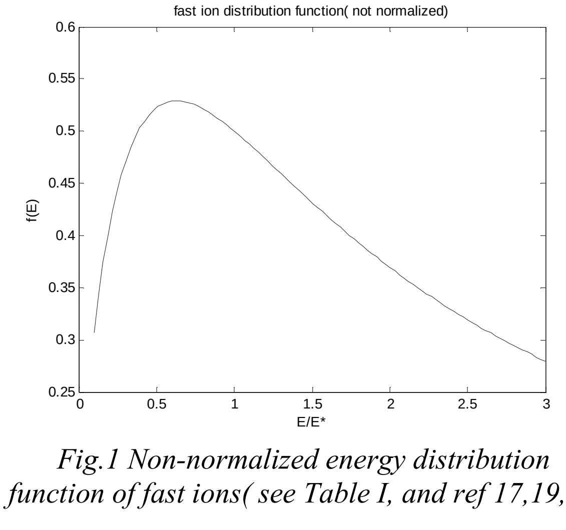

Fig.1 Non-normalized energy distribution function of fast ions(see Table I, and ref 17,19,20)

Starting from the previous general observations, the measurement requirements for fast particles could be: i) spatial resolution ~ a/20 (10 cm on ITER) which is close to the alpha particle Larmor radius; ii) time resolution (minimum) ~ 100 τ_A (~ 100 μs for ITER), which is the time scale related to the saturated non-linear interactions of energetic particles and Alfvén modes[7]; iii) density range of fast ions: the density of minority ions could be 4-10% of the plasma density ;iv) energy spectrum 0.1<E<3.52MeV.

particles	energy spectrum	average density($10^{20}m^{-3}$)	βfast/βtotal(%)	Resonant Energy (MeV)	source
alpha	f(E)SD~$E^{1/2}$ /($E^{3/2}$ + $E^{*3/2}$); E*=20Te; 0.1<E≤3.52MeV; isotropic	0.75 10^{-3}- 2.510^{-2}.	10 to 20	1.35	D-T fusion reactions
D or H	Anisotropic;Vperp>Vpar; E<1MeV; f(E)=f(E)SD	2-4 10^{-3}.	3 to 7	ED=0.67 EH=0.33	NB heating
T	Anisotropic;Vperp>Vpar; E<0.2-0.3MeV; f(E)=f(E)SD			1	2ωCT ICRF heating in D-T plasma
He3	Anisotropic; Vperp>>Vpar;E~0.1-1MeV	4-10 10^{-2}	<10	1	ICRF minority heating

Table III Typical parameters of fast ions in ITER(see also ref 17).

3.Requirements for Fast Particle Measurements on ITER and justifications

The previous analysis leads to the measurement requirements of fast particles that are listed in Table IV , where a number of potential electron and wave diagnostics are included.

particles	requested measurement	group	techniques	spatial resolution	time resolution	accuracy	energy spectrum(MeV)	density interval ($10^{18}m^{-3}$)
α,p,D,T, He^3.	spatial and energy distribution	advanced control	γ-ray spectr.;CTS;CXRS; NPA(*); passive spectroscopy(Line ratio)	a/20	0.1-0.2s	10%	E_α=0.1-3.5. EHe^3=0.1-1	n_α=0.075-2.5. nHe^3=4-10
	fast particle losses	advanced control	Faraday cups, scintillator probes; ceramic scintillators; IRMFTD; activation foils;IRV		0.1-0.5ms	15%		
neutrons	Energy spectrum at 2.5 and 14MeV	advanced control	NE213 scintillator, CVD and NDD compact spectrometers, fission chambers	a/20	0.1-0.5ms	10-15%		
electrons	spectrum of ECE	physics evaluation	Michelson,Thomson	a/20	1ms	10%		
FW,IBW and AE	Phase contrast imaging	physics evaluation	Phase contrast imaging using CO2	a/40	0.1ms			

Table IV – Requirements for measurements on fast particles and candidate techniques on ITER.
(*) CTS=Collective Thomson Scattering;CXRS=Charge exchange recombination spectroscopy;NPA=Neutral particle analyzers;IRMFTD=IR multifoil thermal detectors;IRV=IR videocam

3.1.Fast particle measurement requirements

The measurement requirement on the energy spectum is $0.1<E\alpha<3.5$MeV. For the other fast ions it is $0.1<E<1$MeV. The spatial resolution should be 10cm , and temporal resolution 100ms , for all fast ions present in the plasma. The space resolution corresponds to the alpha particle Larmor radius and time resolution is related to a fraction of minimum slowing time of fast particles (see Table I).

3.2.Diagnostic systems

3.2.1.γ-ray spectroscopy

This technique allows the detection of ions in the energy range $1<E<5$MeV [12] . Alphas are detected using Be as impurity: ${}^{9}\mathrm{Be}(\alpha,n\gamma){}^{12}\mathrm{C}$ and γ-rays with energy $E\gamma=4.44$MeV.Deuterons are detected using ${}^{12}\mathrm{C}(d,n\gamma){}^{13}\mathrm{C}$, γ-rays with energy $E\gamma=3.1$MeV. He^{3} is detected using ${}^{12}\mathrm{C}(He^{3},n\gamma){}^{14}\mathrm{N}$, γ-rays with energy $E\gamma=2.31$ and 5.1MeV.R&D needed to demonstrate the feasibility in ITER are to study whether the neutron background can be rejected by LiH absorbers. In practice (looking to JET experience) the required accuracy is difficult to achieve. The integration time needed is in the range of 100ms. So the gamma ray spectroscopy could see the slowing down of fast ions , but not the fast spatial redistribution due to the interaction with Alfvén waves.

3.2.2.Collective Thomson Scattering(CTS)

The CTS proposed [18] uses a gyrotron at 60GHz , applying the principle [21] that using a source at a frequency below the first harmonic of ECE is beneficial to lower the plasma background temperature. The system proposed has the capability of measuring ions with velocity parallel and perpendicular to the magnetic field.The spatial resolution is 20cm (i.e. a/10) and the time resolution is 100ms, with an accuracy of 20%. The main difficulty of CTS is that in principle it cannot distinguish between ions with the same Z/M. the method foreseen for ITER is focused on detecting alpha particles, but has only limited capability to diagnose other fast particles. CTS nominally meets requirements, but the spatial resolution cannot be met within the requirement of 100ms. *R&D is needed to test the ITER concept in a real experiment.* CTS Experiment on FTU [21] includes the basic ITER concept (working below the first ECE harmonic) and it is aimed to the measurement of ion temperature.

3.2.3.CXRS

Various authors have given estimate for the possibility of measuring the alpha particles , and fast ions using CX recombination lines. Analysis reported in ref [22] leads to a signal to noise ration SNR =7 at r/a = 0.3 for 100ms integration time and $ne=1\ 10^{20}m^{-3}$ for alpha particles . The evaluation for fast deuterons leads to a SNR=60 at r/a=0.3 in the same conditions, using the heating beam, HB4 and HB5. The lines used in the evaluations are at $\lambda=468.6$nm for alphas , and $\lambda=656.1$nm for deuterons.Similar evaluations were presented in ref [23] : the diagnostic neutral beam (DNB) could be used for the measurements of low energy alpha particles $100<E_{\alpha}<600$keV, achieving a SNR=5-10 at $\rho=0.3$; while the heating neutral beam HNB5 could be used for the measurement of alphas $1600<E_{\alpha}<2400$ keV, achieving a SNR=3-5 at $\rho=0.3$. In principle it would be possible to measure the spectrum of fast ions:i) the integration time will be 100ms; ii) the spatial resolution will be > a/20 . *The capability of measuring the fast ions by CXRS close to the plasma centre must be still demonstrated using the DNB and/or the HB*. Recently the concept [24] of using a ${}^{3}He^{0}$ diagnostic beam (Energy 1.7MeV), has been proposed based on a double charge exchange to detect the fast He in the range $1<E<3$MeV : He^{++}(plasma) + He^{0}(beam) => He^{0}(plasma) + He^{++}.The calculated signal to noise ratio is encouraging (SNR=10) at plasma centre. R&D is needed to demonstrate the feasibility of the He^{0} beam and the SNR calculated for the detection of fast ions, in a dedicated pilot experiment. It is not clear whether such a system could be implemented on ITER.

3.2.4.Passive spectroscopy

As it was mentioned above, the energy range 200<E<800keV is relevant for the study of the interaction between the fast particles and Alfvén waves (see Table III, and fig.1). The diagnostic capability of fast ions in this energy range is weak because the only proven technique to measure the fast particles , i.e. γ-ray spectroscopy, is not useful in this interval. A new technique is now under test on JET [25] , using the sensitivity to fast particles of fluorine like configurations of extrinsic impurities like Krypton. It is found that the transition n=2 to n=1 of KryptonXXVIII (which is obtained starting from n=1,via the transition to the n=3 level , and subsequent decay to the n=2) depends on the fast ion population. Preliminary results of experiments on JET, in a power scan using the 80keV, Deuterium Neutral Beam of max power of 8MW, it was found that the ration between the line at λ=22.4nm and that at λ=5.259nm of KrXXVIII was dependent upon the NBI power, which is proportional to the fast particles injected in the plasma.

3.2.5.Neutral Particle Analyzer(NPA).

A prototype compact tandem system including high energy (E=0.1-4MeV) as well as low energy(10-200keV) NPA was developed for ITER [26]. Studies of electromagnetic and neutron shielding are in progress.

3.2.6.Lost fast particle diagnostics.

Faraday Cups (FC) and Scintillator probes(SP) were already tested on JET [27] and TFTR[28]. Presently a new system of FC and SP is under commissioning at JET, and it could be proposed for ITER. The JET FC system measures the poloidal distribution of lost fast ions with a course energy resolution. Alpha particles in the range of 1-3 MeV can be detected with an energy resolution of the order of 10-15% . The SP measures the gyroradius and pitch angle of a fast particle, the accuracy of measurement of gyroradius is 15%, while that of the pitch angle is 5%, the time resolution is 0.1ms. In practice a JET-like SP system could meet the requirement on the measurement , if a way to integrate such a system on ITER is found: systems as scintillators and Faraday-cups are subject to failure in the high radiation fields at ITER. Preliminary analysis lead to consider other systems like ceramic scintillators and infrared multifoil thermal detectors(see ref.33)

3.3.Neutron measurement requirements.

The measurement of the spatial profile of neutron emission with a spatial resolution of 10cm is required. The time resolution required is 0.1-0.5ms. Vertical and radial neutron cameras are required, because the radial movement of fast ion interacting with Alfven waves could be detected only having vertical as well as horizontal cameras. The spatial resolution is set to alpha particle Larmor radius , and the time resolution is related with the saturated non-linear time of interaction between fast ions and Alfven eigenmodes in shear reversed scenario. An accuracy of 15% is set for these measurements. The neutron camera is supposed to be equipped with compact neutron spectrometers for 2.5MeV and 14MeV, tested during the Trace Tritium Experiment on JET and based on NE213 scintillators [29].

3.4.Diagnostic systems.

3.4.1.Neutron Camera.

A study [30] has been done about the possibility for the ITER neutron camera to meet the requirements. *Parameters assumed* in the study: DT full power (scenario 2),diameter of collimators 2 cm in-vessel and 1 cm ex-vessel (corresponding to 1-2 MHz max , count rate sustainable by the detectors), 0.1 ms time resolution , detector efficiency 1%.The code used for the design of the ITER RNC has produced the Abel inverted neutron emissivity , assuming the equilibrium of ITER, the emissivity to be constant on the magnetic surfaces and the actual configuration of the line of sights of the ITER RNC. For the case of 0.1ms time resolution, the result is that the accuracy on the emissivity is inside 20%. In practice it is reasonable to assume that the ITER neutron camera could be close to the technical specifications. In this context is worth mentioning that strong asymmetries were found in the neutron emission in JET TTE [see ref 1, fig14], in particular in strong shear reversed discharges (so called current-hole) configurations. These results lead to the need for ITER of a vertical neutron camera(VNC) . The measurement requirements reported in Table IV could be obtained only with the use of a VNC.

3.4.2.Neutron compact spectrometers.

Compact Spectrometers(CS) based on NE213 scintillator [30] were tested in JET TTE and a reasonable energy resolution was obtained of $\Delta E/E \sim 2\%$ for neutrons of 14MeV and $\Delta E/E \leq 4\%$ for 2.5MeV neutrons. CS based on CVD (Carbon Deposited Diamond) are under development [31] an energy resolution close to 1% for 14MeV neutrons seems feasible for these systems.

3.5.Measurements of the electron distribution function(EDF).

The EDF measurements are linked with the effects of the heating (including alpha particles produced by the fusion reactions) and current drive systems on electrons. The fast electron bremmsstrahlung was used to monitor the high energy tail of fast electrons produced by the Lower hybrid heating[35] through the hard X spectra. Thomson scattering is the technique which measures directly the EDF. The measurement of the ECE is proposed at various angles with respect to the magnetic field to measure the possible deviations of the electron distribution function from a maxwellian. The motivation is related with the consequences of this deviation on the measurements of plasma temperature using ECE only. This topic has been addressed in particular in coincidence with high temperature Te>7keV [32] where there is a difference in the measurements of Te. The Michelson interferometer is a system which is suitable for meeting the requirement in table IV. The accuracy (statistical + systematic errors) on the measurements of electron temperature needed for detecting effects of deviations from maxwellian must be very high (<7%) for both ECE and TS measurements, and this is an objective quite demanding to achieve.

4.Summary of present status of diagnostic systems proposed for ITER, R&D needed and conclusive remarks.

The candidate diagnostic techniques considered for ITER are: i) γ-ray spectroscopy; ii) Collective Thomson Scattering (CTS); iii) Charge Exchange Recombination Spectroscopy (CXRS). γ-ray spectroscopy detects ions in the energy range 1<E<5MeV, and R&D is needed to demonstrate the feasibility of these measurements in the presence of a neutron background. Techniques using ultraviolet spectroscopy of ions like Krypton are being tested for the low energy part of spectrum of fast particles. A design study of CTS shows that the requirements are close to be met, the system includes a high power gyrotron operating at a frequency below the first ECE harmonic. A system exploring this configuration is mounted on FTU. For CXRS the spatial resolution and accuracy are not achievable for r/a < 0.3, and R&D is needed to assess the minimum figures in terms of accuracy possible for measurements close to the centre. The diagnostics for measuring fast particle losses (i.e. faraday cups and scintillator probes) are difficult to implement on ITER.In practice the minimum time resolution of 100 μs is difficult to achieve, in this context, also using IR multifoil thermal detectors with alpha absorbers, and activation foil techniques. The measurement of the neutron and alpha source profile measurements is done by two neutron cameras: a horizontal and vertical camera. In the neutron camera compact spectrometers as well as γ-ray spectrometers could be inserted. The vertical camera is important for detecting fast movements of the energetic ions. The diagnostics of the electron distribution function could be achieved inside the required technical specifications by the present technology. In particular a Michelson interferometer with oblique views could be used to measure the behaviour of the electron distribution function. Measurements of plasma waves by phase contrast imaging using CO_2 laser could give some important information on Alfvén cascades.

The main message of this paper is that the development of fast particle diagnostics is a real challenge: the measurement requirements deduced from the need of detecting the effects of interaction of fast particles with MHD instabilities put important new objectives to the candidate diagnostic systems. In particular diagnostics for fast particles in the low energy region 200<E<1000 keV meeting the requirements of table IV, and the diagnostics for escaping fast particles need a urgent development.

Acknowledgements

One of the Authors(FO) would like to acknowledge the support of EFDA. F Zonca is acknowledged for discussions on theory of fast particle dynamics and the requirements on the measurements.

References

1. D Stork et al – Nucl Fus 45(2005)S181; M Mantsinen et al –PPCF 47(2005)1439.
2. S Pinches et al PPCF 46(2004)B187
3. S Sharapov et al Proc 31st EPS Conf. on Plasma Physics(London 2004) P5-166
4. K Shinohara et al. PPCF 46(2004)S31-S45
5. M Ishikawa et al Nucl Fus 46(2006)S898-S903
6. L Chen Phys Plasmas 1(1994)1519
7. G Vlad et al this conference paper TH/P6-4; F Zonca , L Chen PPCF 48(2006)537
8. R Nazikian et al PRL 78(1997)2976
9. J Jacquinot et al Nucl Fus 38(1998)1264
10. J A Snipes et al Phys Plasmas 12(2005)056102
11. M Porkolab et al – 47th APS DPP Denver (October2005) - paper RO3 6
12. A Costley - 11th ITPA TG Meeting Sendai (JA) (sept2006)
13. V G Kiptily et al Nucl Fus 45(2005) L21-L25 ; and PRL 93(2004)115001
14. S Hacquin et al Nucl Fus 46(2006) S714
15. W.Heidbrink et al – 47th APS DPP Denver (October 2005)- paper BO3 12
16. M Sasao et al PPCF 46(2004)S107-S118
17. JET Team , PPCF 37(1995)A3(fig.15).
18. S V Putvinski Nucl Fus 38(1998)1275
19. H Bindslev et al – RSI 75(2004)3598, F. Meo et al – RSI 75(2004)3585
20. J Wesson - Tokamaks , sec 5.4 p.227, 2nd Edition, Oxford Science Publications 1997
21. F Orsitto and G Giruzzi Nucl Fus 37(1997)915; F Orsitto et al.RSI 70(1999)1158;
    U Tartari et al Nucl. Fus 46 (2006) 928-940.
22. A Krasilnikov and S Tugarinov – 9th ITPA TG Dia Meeting Daejeon (Korea) sept 2005
23. M von Hellerman et al. – 9th ITPA TG Dia Meeting Daejeon (S-Korea) sept 2005
24. M Sasao et al. – 11th ITPA TG Dia Meeting Sendai (JA) sept 2006.
25. K Lawson et al. – 8th ITPA TG Dia Meeting Culham(UK) march 2005
26. B Lyublin – 8th ITPA TG Dia Meeting Culham(UK) march 2005
27. G J Sadler et al Nucl Fus 35(1995)1609
28. S J Zweben et al Nucl Fus 40(2000) 91
29. L Bertalot et al Report EFDA-JET CP(05)-02-17
30. L Petrizzi et al. Soft 2006 – 24th Symposium on Fusion Technology- Poster P1-D-455.
31. M Marinelli et al App Phys Lett 89(2006)1
32. E De la Luna et al . EFDA-JET Report CP(02)03/10 (HTPD Madison 2002).
33. T Donné et al – IAEA2006 Paper IT/P1-24
34. B J Green et al. PPCF 45(2003)687
35. Y Peysson and F Imbeaux RSI 70(1999)3987