

Requirements for Fast Particle Measurements on ITER and Candidate Measurement Techniques

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Abstract. Recent JET and JT-60U results, have underlined the need to look into the measurement requirements of fast particles diagnostics in ITER. Not only alpha particles, but all fast ions ($\text{He}^4, \text{p}, \text{D}, \text{T}, \text{He}^3$) present in the plasma should be diagnosed. Furthermore, 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 $\sim a/20$ (10 cm on ITER); time resolution (minimum) $\sim 100 \tau_A$ ($\sim 100 \mu\text{s}$ 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 $1 < E < 5 \text{ MeV}$, 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 $200 < E < 1300 \text{ keV}$ and diagnostics for escaping fast particles need a urgent development.

1. Introduction

Recent developments in physics results of interactions of MHD instabilities and fast ions 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 behaviour on the various ITER scenarios.

In general fast ions (alpha particles) generated by D-T reactions, or driven by neutral beam (D or H ions) and minority fast wave current drive (minority He^3) can generate instabilities, resonating with fast ions. These instabilities can degrade the confinement of those fast ions, leading ultimately to their loss and a damage of plasma facing components. Monitoring the dynamics of all fast ions can be important for the understanding of energy transfer between fast ions and bulk plasma. Ultimately the aim is to prevent the damage of the device.

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 of the diagnostic systems to get closer to the realization of the accuracy and resolutions(time and space) . The aim is

to produce data useful for an optimized evaluation of ITER scenarios. In practice only an integrated data analysis could give a complete information on the behaviour of fast particles: one of the aim of the present paper is to develop a complete overview of the capabilities of various diagnostic systems available, defining clearly their complementarity.

The present paper contains the following proposals and related justifications, to upgrade the measurement capability of ITER:

i) all fast ions (He^4 , p, D, T, He^3) present in the plasma, (not only alpha particles) , including ions used for minority heating, should be diagnosed, *because all of them can interact with plasma instabilities.*

The physics of the interaction between plasma instabilities and fast ions leads to a revision of requirements on measurements in terms of space and time resolution.

ii) Ideally the wave propagation inside the plasma could be diagnosed for a better understanding of the energy transfer process to minority ions. The diagnostics of waves propagating inside plasma and interacting with fast ions, like interferometry and reflectometry, have given a real step forward to the clarification of important details of the (Alfvén) wave dynamics.

iii) 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.

In Trace Tritium Experiments on JET [1] evidence of fast ion transport due to Toroidal Alfvén Eigenmodes (TAE) [2] and fishbone [3] modes were clearly detected. In advanced regimes on JT 60U [4,5], 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 [8] and JET first campaign in Deuterium-Tritium DT1 [9]. Fast particle driven TAEs were studied on Alcator C-Mod and DIII-D [10,15], where the effect of TAE on the confinement of fast ions was clearly documented.

Fast particle losses can be due also to a magnetic field ripple and experiments were done recently on JFT-2M [4] demonstrating an increase of heat flux on the first wall due to energetic ion losses when the ripple was increased. Earlier experiments on JET [9,17] found that particles of intermediate energy 10-50keV were mainly lost, instead of energetic ions. A study made for ITER [18] concluded that an alpha particle loss higher than 5% could be damaging for ITER first wall.

The instruments used at present to diagnose the fast ion confinement in a number of present experiments are : i) γ -ray spectroscopy [13] ; ii) neutron cameras with fast electronics for discrimination between neutrons and gammas [5] ; iii) infrared O-mode interferometry [3,14] ; iv) fast magnetics (Mirnov coils) ; v) neutral particle analyzers [5] ; vi) D_α emission [15] ; vii) Natural diamond spectrometers [16] ; and vii) fast ion Collective Thomson Scattering, which was carried out on TEXTOR device [19] .

Diagnosing fast particles is not just the use of a single diagnostic, but the integration of a number of 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 [12], 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 present paper presents a proposal and motivations to revise the previous measurement requirements for fast particles increasing: i) the spatial resolution (from $a/10$ to $a/20$) corresponding to a scale length close to Larmor radius of alpha particles, and ii) the minimum

time resolution from 100ms to 100μs-1ms, this time scale is the saturated non-linear interaction time of energetic particles with Alfvén modes.

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 is presented of the present status and R&D needed for the diagnostic systems proposed for ITER and concluding remarks are given.

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 $\tau_F \sim 100\text{-}300 \tau_A \geq 100 \mu\text{s}$ (τ_A = Alfvén time = R_0/V_A , R_0 = major radius, V_A = Alfvén velocity). The Alfvén time is calculated using the formula:

$$\tau_A (\mu\text{s}) = \frac{0.46 R_0(m) n_{20}^{0.5} A_{\text{eff}}^{0.5}}{BT} ; \quad A_{\text{eff}} = \frac{n_1 * m_1 + n_2 * m_2}{(n_1 + n_2) * mH}$$

Where A_{eff} is the plasma effective mass referred to the hydrogen (mH), n_{20} is the deuterium density in unities of 10^{20}m^{-3} , R_0 the major radius of ITER, B the magnetic field (Tesla) on axis. For the evaluations of τ_A = Alfvén time, the following ITER parameters were used: $R_0=6.2\text{m}$; $B=5.2\text{T}$; 50%-50% D-T mixture ; $n_{20}=0.8$; in the previous formula $m_1=m_D$, $m_2=m_T$, and $n_1=n_2$, $A_{\text{eff}}=2.5$, and $\tau_A=0.77\mu\text{s}$, ($V_A=8 \cdot 10^6 \text{ m/s}$).

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] $\tau_F \sim 100\text{-}300 \tau_A$; ii) slowing down time of the fast ions $\tau_s \sim 1\text{-}2\text{s}$ (see table I) ; iii) confinement time $\tau_E \sim 4\text{s}$; iv) resistive relaxation time $\tau_R \sim 200\text{-}300\text{s}$.

	$m\alpha/\text{mp}$	Z_{eff}	$T_e(\text{keV})$	$n_e/10^{20}$	$\tau_s(\text{s})$
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 $\rho_{\text{fast}} \sim 0.3\text{-}7 \text{ cm}$ (see Table IIb); ii) Neoclassical Tearing Mode (NTM) island width \geq ion Larmor radius; iii) Internal Transport Barrier (ITB) width with spatial scale of the order of the pressure gradient; iv) H-mode pedestal width \sim ion Larmor radius; v) turbulence correlation length \sim ion/electron Larmor radius; the scaling of the confinement in H mode depends upon the Larmor radius. Indeed tomographic reconstruction of γ -ray spectroscopy on JET , in particular in alpha particle simulation experiments, has demonstrated that the fast particle Larmor radius can be a relevant spatial scale [13]. In general , in absence of instabilities or ITBs, the gradient scale length of the distribution function would be adequate, but in improved confinement scenarios shorter space scales are relevant.

The energy range of fast ion is determined by the critical energy [20] defined as

$$E^* = 14.8 T_e A_f \left(\frac{1}{n_e} \sum_j \frac{n_j Z_j^2}{A_j} \right)^{2/3} = 14.8 T_e \frac{A_f}{2^{2/3}}$$

where A_f and A_j are the atomic masses of fast particle and plasma ions, n_e and n_j the electron and ion plasma density:the previous formula is valid for a D-T (50%-50% composition).

The critical energies for fast particles considered for ITER are given in the following table IIa .

	E^*/T_e	A_i
$\alpha(\text{He}^4)$	37,29	4
T	27,97	3
D	18,64	2
p	9,32	1
He^3	27,97	3

Table IIa – Critical energies for fast particles

For plasma temperatures $T_e=20\text{keV}$ (inductive $Q=10$, and Weak Reversed Shear scenarios [34]), the range of critical energy for fast particles results in the interval $E^*=180\text{-}745\text{keV}$.

In practice the energy spectrum relevant is $90 < E < 1100\text{keV}$, corresponding to the range $[0.5E^*_{\min}, 1.5E^*_{\max}]$, as it can be seen looking to the fig1, where the slowing-down distribution

function $f_{SD}(E) \approx \frac{(E/E^*)^{1/2}}{1 + (E/E^*)^{3/2}}$ is plotted (see also Table III).

	$\mu = m/m_H$	z	Energy(E) or Temperature(T)(Mev)	$\rho(\text{cm})$	B
$\alpha(\text{He}^4)$	4	2	$E=3,50$	7,34	5,2
p	1	1	$E=1,00$	1,96	5,2
D	2	1	$T=0,03$	0,48	5,2
T	3	1	$T=0,03$	0,6	5,2
He^3	3	1	$E=1,00$	3,4	5,2

Table II Larmor radius of fast ions(Bulk Plasma temperature $T=30\text{keV}$)

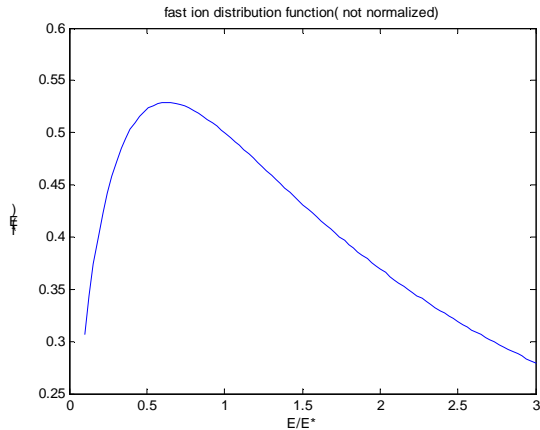


Fig.1 Non-normalized energy distribution function of fast ions(see Table III, and ref 18,20)

In Table III typical parameters of distribution function of fast particles in ITER are listed[18,20]. The nature of the distribution functions(DF) is different for the various fast particles :

- i) for alpha particles the DF is an isotropic slowing down
- ii) for the other fast ions the DF is anisotropic with the perpendicular velocity higher than the parallel velocity; in both directions (parallel or horthogonal) the DF is slowing down. The anisotropy is related to the mechanisms of fast ion tail production by ICRH (Ion Cyclotron Resonant Heating) .

The other energy parameter to be taken into account is the resonant energy, i.e. the energy of a particle with velocity equal to the Alfvén velocity (see Table III, column of resonant energy). This parameter is relevant for the wave-particle resonant interaction. For example the Shear Alfvén Waves (SAW) are electromagnetic waves satisfying the dispersion relation : $\omega^2 = k_{par}^2 V_A^2$. (k_{par} is the component of the wavevector along the toroidal magnetic field, V_A the Alfvén velocity, $\omega/2\pi$ the wave frequency). Collective excitations of the SAW spectrum by fast particles are possible since the resonance condition $V_f = V_A$ (V_f is the velocity of a fast particle) is likely to be satisfied by the fast ions in ITER plasmas (see Tab III, column of resonant energy). The resonance condition is efficiently maintained, since the SAW group velocity $\vec{V}_g(\text{SAW})$ is directed along \vec{B} and has the value V_A , ($\vec{V}_g(\text{SAW}) = \pm \frac{\vec{B}}{B} V_A$): the fast particles are linked to field lines, moving freely along \vec{B} .

Starting from the previous general observations, the new measurement requirements for fast particles could be proposed along the following lines.

- i) Spatial resolution. The value of space resolution $\delta r \sim a/20$ (10 cm on ITER) could be taken as reference, because it is close to the alpha particle Larmor radius.
- ii) Time resolution . (minimum) $\sim 100 \tau_A$ ($\sim 100 \mu s$ 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 $0.1 < E < 3.52 \text{ MeV}$,
- v) energy resolution of the order of $\geq 10\%$, if 5-10 experimental points are measured to trace the slowing-down distribution function(see fig.1) .

particles	energy spectrum	average density(10^{20} m^{-3})	$\beta_{\text{fast}}/\beta_{\text{total}}(\%)$	Resonant Energy (MeV)	source
alpha	$f(E)SD \sim E^{1/2} / (E^{3/2} + E^{*3/2})$; $E^*=20\text{Te}$; $0.1 < E < 3.52 \text{ MeV}$; isotropic	$0.75 \cdot 10^{-3} - 2.5 \cdot 10^{-2}$.	10 to 20	1.35	D-T fusion reactions
D or H	Anisotropic; $V_{\text{perp}} > V_{\text{par}}$; $E < 1 \text{ MeV}$; $f(E) = f(E)SD$	$2 - 4 \cdot 10^{-3}$.	3 to 7	$ED=0.67$ $EH=0.33$	NB heating
T	Anisotropic; $V_{\text{perp}} > V_{\text{par}}$; $E < 0.2 - 0.3 \text{ MeV}$; $f(E) = f(E)SD$			1	$2\omega_{CT}$ ICRF heating in D-T plasma
He3	Anisotropic; $V_{\text{perp}} \gg V_{\text{par}}$; $E \sim 0.1 - 1 \text{ MeV}$	$4 - 10 \cdot 10^{-2}$	< 10	1	ICRF minority heating

Table III Typical parameters of fast ions in ITER(see also ref 18).

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 (see sec 3.5) and wave diagnostics are included.

particles	requested measurement	group	techniques	spatial resolution	time resolution	accuracy	energy spectrum(MeV)	density interval (10^{18}m^{-3})
$\alpha, p, D, T, \text{He}^3$.	spatial and energy distribution	advanced control	γ -ray spectr.; CTS; CXRS; NPA(*); passive spectroscopy(Line ratio)	a/20	0.1-0.2s	10%	$E_\alpha=0.1-3.5$. $E\text{He}^3=0.1-1$	$n_\alpha=0.075-2.5$. $n\text{He}^3=4-10$
	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 and justifications

The measurement requirement on the energy spectrum of confined alphas is $0.1 < E_\alpha < 3.5 \text{ MeV}$. For the other fast ions it is $0.1 < E < 1 \text{ MeV}$. The spatial resolution should be 10cm , and temporal resolution 100ms , for all fast ions present in the plasma.

The space resolution corresponds to a spatial scale of the Larmor radius because the spatial dynamics of distribution functions related with the interaction of fast particles with Alfvén waves is the Larmor radius .The necessity of having a spatial resolution of a/20 is related to the introduction of measurements on all the fast ions. The Larmor radius of fast ions is in the range of 0.5-7cm, and the proposed space resolution (a/20=10cm for ITER) is still an upper limit for most of fast ions.

The proposed Time resolution is related to a fraction (=1/10) of the minimum slowing down time of fast particles (see Table I).

Ideally the shortest time resolution related to $\tau_F \sim 100-300 \tau_A \sim 0.1 \text{ ms}$ (the time scale of saturated non-linear interactions of fast particles and Alfvén modes) should be included in the measurement of the energy distribution function of fast particles, if the fast spatial redistribution due to Alfvén modes is needed to be detected . At moment this time resolution seems an hard limit for the most important techniques (γ -ray spectroscopy, Collective Thomson Scattering, Charge Exchange Recombination Spectroscopy) useful to measure the distribution function of confined fast particles.

3.2.Fast particle Diagnostic systems

3.2.1. γ -ray spectroscopy

This technique allows the detection of ions in the energy range $1 < E < 5 \text{ MeV}$ [13] . Alphas are detected using Be as impurity: $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ and γ -rays with energy $E_\gamma = 4.44 \text{ MeV}$. Deuterons are

detected using $^{12}\text{C}(\text{d},\text{n}\gamma)^{13}\text{C}$, γ -rays with energy $E_\gamma=3.1\text{MeV}$. He^3 is detected using $^{12}\text{C}(\text{He}^3,\text{n}\gamma)^{14}\text{N}$ γ -rays with energy $E_\gamma=2.31$ and 5.1MeV . R&D is needed to demonstrate 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 [19] 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, definitely increasing the signal to noise ratio. 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 pilot experiment.* CTS Experiment on FTU [21] includes the basic ITER concept (working below the first ECE harmonic) and it is aimed at the measurement of ion temperature.

3.2.3. CXRS

Various authors[22,23] have given estimates 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 ratio $\text{SNR}=7$ at $r/a=0.3$ for 100ms integration time and $n_e=1\cdot 10^{20}\text{m}^{-3}$ for alpha particles . The evaluation for fast deuterons leads to a $\text{SNR}=60$ at $r/a=0.3$ in the same conditions, using the heating beam(HB), HB4 and HB5. The lines used in the evaluations are at $\lambda=468.6\text{nm}$ for alphas , and $\lambda=656.1\text{nm}$ 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 $100<E_\alpha<600\text{keV}$, achieving a $\text{SNR}=5-10$ at $\rho=0.3$; while the heating neutral beam HNB5 could be used for the measurement of alphas $1600<E_\alpha<2400\text{keV}$, achieving a $\text{SNR}=3-5$ 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 $^3\text{He}^0$ diagnostic beam (Energy 1.7MeV), has been proposed based on a double charge exchange to detect the fast He in the range $1<E<3\text{MeV}$: $\text{He}^{++}(\text{plasma}) + \text{He}^0(\text{beam}) \Rightarrow \text{He}^0(\text{plasma}) + \text{He}^{++}$. The calculated signal to noise ratio is encouraging ($\text{SNR}=10$) 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 $200<E<800\text{keV}$ 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 $\lambda=22.4\text{nm}$ and that at $\lambda=5.259\text{nm}$ 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 ($E=0.1\text{-}4\text{MeV}$) as well as low energy($10\text{-}200\text{keV}$) 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 coarse energy resolution. Alpha particles in the range of $1\text{-}3\text{ MeV}$ can be detected with an energy resolution of the order of $10\text{-}15\%$. 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 $0.1\text{-}0.5\text{ms}$. *Vertical and radial neutron cameras are required*, because the radial movement of fast ion interacting with Alfvén 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 Alfvén 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]. A fast electronics is needed for the neutron camera to discriminate the neutrons from gammas, and to achieve the required time resolution: this electronics is under test at JET, and preliminary results are encouraging.

3.4.Neutron 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 $1\text{-}2\text{ MHz}$ 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 bremsstrahlung 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 $T_e > 7\text{keV}$ [32] where there is a difference in the measurements of T_e . 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 $1 < E < 5\text{MeV}$, and R&D is needed to demonstrate the feasibility of these measurements(gamma ray) 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 $100\text{ }\mu\text{s}$ 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 existing projects of reflectometers on ITER could include the capability of measuring waves and MHD activity related with fast ions.

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*

100<E<1000 keV meeting the requirements of table IV, and the diagnostics for escaping fast particles need a urgent development.

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