# NEUTRAL PARTICLE ANALYSIS ON ITER


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## 1. PHYSICAL BASIS OF ISOTOPE COMPOSITION MEASUREMENTS.

There are two important issues of Neutral Particle Analysis on International Thermonuclear Experimental Reactor (ITER-FEAT). First issue is the measurement of hydrogen isotope composition of the plasma on the basis of measurements of neutralized fluxes of corresponding hydrogen ions, namely protons, deuterons and tritons in 10 - 200 keV energy range [1]. It has to be one of the main tasks of the ITER-FEAT control system to provide optimal D/T ratio in the plasma.

Another issue of Neutral Particle Analysis is to measure confined D-T alpha particle distribution function by means of detection of $He^o$ atoms energy spectra in MeV range [2].

The measurements of the isotope composition by charge exchange neutral fluxes have been used in several experiments including JET [3]. Intensity of charge exchange flux is directly related to the density of corresponding ions in the plasma in the contrary, let say, to $H_\alpha/D_\alpha$ measurements where intensity of the lines is related to the density of the atoms and provides an information concerning recycling processes mainly. In comparison with a neutron diagnostics which can provide isotope ratio measurements only in DT plasma the charge exchange diagnostics is also applicable to the initial stage of operation with HD plasma. But due to a rather large minor radius of the ITER-FEAT plasma (2 m) a question arises to which part of the plasma the isotope composition measurements provided by charge exchange diagnostics will relate. The other question is whether the requirements to the time resolution of $n_d/n_t$ measurements which are set to be equal to 100 ms or better with accuracy ≤10 % can be satisfied.

The answer to this question is given by numerical simulation of the neutral particle fluxes emitted by ITER-FEAT plasma consisting 1:1 deuterium/tritium mixture. The local maxwellian distribution of the plasma ions has been assumed throughout the whole plasma. The simulation has been made for plasma parameters predicted by PRETOR 1.5 D code for Q=10 Domain [4]. This regime describes 70% of the ITER-FEAT discharges. It is well known that fluxes of atomic hydrogen and its isotopes in the energy range up to 100 – 200 keV are produced by recombination of hydrogen ions with electrons and by charge exchange of hydrogen ions with neutrals in the plasma. These processes are very well simulated by computer codes.

A specific feature of ITER DT plasma is a presence of He ash resulting from deceleration of alpha particles generated in D_T fusion reaction. He ash percentage can attain 5-10% of the total ion density. He ash consists of $He^{+2}$ ions mainly but due to corona equilibrium there is some concentration of $He^+$ ions in the plasma. In our simulation we first took into account neutralization of hydrogen ions due to charge exchange with hydrogen-like $He^+$ ions. The process becomes important in the energy range above 100 keV.

The flux of neutral atoms with energy $E$ produced in 1 $cm^{-3}$ of the plasma by the charge exchange with background neutrals and photo recombination can be expressed as

$$\Phi_{HDT}(E) = n_{HDT}\mathbf{f}_{HDT}(n_o\langle\sigma v\rangle_{CX} + n_e\Gamma_{HDT}(E)_{rec}) \quad (1)$$

where $n_{HDT}$, $n_o$ and $n_e$ are densities of hydrogen ions, background neutrals and electrons, correspondingly, $\mathbf{f}_{HDT}$ is the ion distribution function, $n_o\langle\sigma v\rangle_{CX}$ and $n_e\langle\sigma v\rangle_{rec}$ are the rate coefficients for charge exchange and recombination. The fluxes of the atoms $\Gamma_{HDT}(E)$ emitted by the plasma and detected outside are different from $\Phi_{HDT}(E)$ due to integration along line of sight $L$ and absorption by the outer layers of plasma:

$$\Gamma_{HDT}(E) = \int \Phi_{HDT}(E.l)\mu(E,l)dl \quad (2)$$

Here $\mu(E,l)$ is the plasma transparency for the outgoing atomic flux. Integration is performed along observation line L.

For simulation of neutral fluxes we used a model developed by Dnestrovskij [5] and modified later in the Ioffe Institute to be applied to multi component plasma. The model is based on solution of a kinetic equation for transport of atoms in a plasma. Firstly it simulates a neutral density distribution $n_0(r)$ assuming axial symmetry or slab geometry for given plasma parameter profiles and than calculates the outgoing fluxes $\Gamma_{HDT}(E)$ by integration (2) along observation line L.

To include a neutralization of hydrogen ions by $He^+$ we add an item $n_{He+}\langle\sigma v\rangle_{CXHe+}$ to the right part of equation (1):

$$\Phi_{HDT}(E) = n_{HDT}\mathbf{f}_{HDT}(n_o\langle\sigma v\rangle_{CX} + n_e\Gamma_{HDT}(E)_{rec} + n_{He+}\langle\sigma v\rangle_{CXHe+}) \quad (3)$$

Here $n_{He+}$ is a density of $He^+$ ions and $\langle\sigma v\rangle_{CXHe+}$ is a charge exchange rate between hydrogen and $He^+$ ions. Therefore we take into account the process

$$p/d/t + He^+ \rightarrow H/D/T + He^{2+} \quad (4)$$

Energy dependence of $\sigma_{CXHe+}$ taken from [6] in comparison with the resonant charge exchange cross section betweeatoms in the energy range above 10 keV is shown in Fig.1.

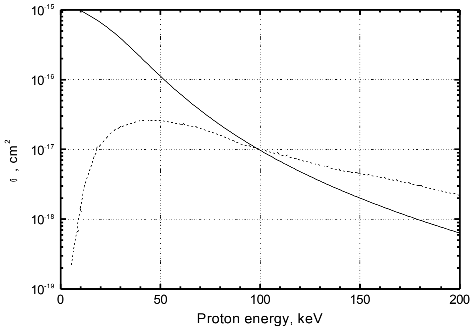


*Fig.1. Proton neutralization cross-sections due to charge exchange with H atoms (solid line) and He$^+$ ions (dotted line).*

Density of $He^+$ ions has been derived from the stationary balance equation for $He^{2+}$ ions:

$I_{He+}\ n_{He+}\ n_e\ + n_d n_t <\sigma v>_{dt} = n_{He2+}\ (\tau_{He2+}^{\ -1}\ + \alpha_{rec}\ n_e + \beta_{CX}\ n_o)$ (5)

Where $I_{He+}$, $\alpha_{rec}$ and $\beta_{CX}$ are the rates for electron impact ionization of $He^+$ ions, radiating recombination of $He^{2+}$ ions with electrons and charge exchange of them with hydrogen atoms, respectively, $<\sigma v>_{dt}$ is the rate for *dt* fusion reaction, $\tau_{He2+}$ is the confinement time of $He^{2+}$ ions, $n_{He2+}$ is the density of $He^{2+}$ ions. The left-hand part of equation (5) presents the sources of $He^{2+}$ ions (ionization of $He^+$ ions and *dt* fusion reactions) and the right-hand part represents sinks of $He^{2+}$ ions (transport, radiating recombination and charge exchange with hydrogen neutrals). Here we assume that the alphas born in fusion reactions decelerate to the bulk of plasma ions without any losses and form the $He^{2+}$ ash.

If $He^{2+}$ confinement time in the plasma center such as

$$n_d n_t <\sigma v>_{dt} = n_{He2+}\ /\ \tau_{He2+} \quad (6)$$

equation (5) will be simplified to

$$I_{He+}\ n_{He+}\ n_e = n_{He2+}\ (\alpha_{rec}\ n_e + \beta_{CX}\ n_o) \quad (7)$$

Therefore $He^+$ ion density which can be found from (7) corresponds to corona equilibrium influenced by charge exchange with hydrogen neutrals:

$$n_{He+}^{\ cor} = n_{He2+}\ (\alpha_{rec}\ n_e + \beta_{CX}\ n_o)\ /\ I_{He+}\ n_e\ . \quad (8)$$

The rates $I_{He+}$ , $\alpha_{rec}$ and $\beta_{CX}$ for the relevant processes can be taken from [7].

Condition (6) means that all the $He^{2+}$ ions produced by the fusion reaction in the plasma center leave the plasma due to outward transport and are fully absorbed by scrape-off layer or by walls (He recycling $R_{He}$=0). If $R_{He}$>0 which is probably more reliable case an inward afflux of He will influence on the He ash balance and in this case we obtain following [1] that $n_{He+} > n_{He+}^{\ cor}$

## 2. RESULTS OF SIMULATION OF ISOTOPE COMPOSITION EASUREMENTS

Plasma profiles for which our simulations have been made are presented in fig.2.

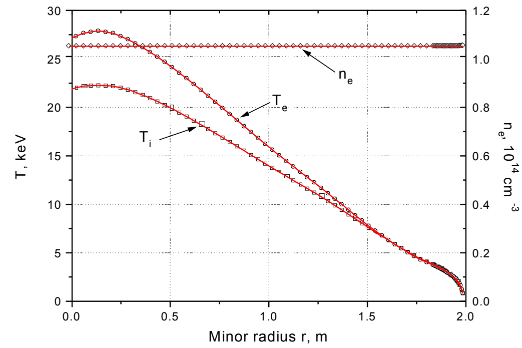


*Fig. 2. ITER-FEAT temperatures and electron density versus vessel minor radius. Circles (open, closed and dot centered) are results of PRETOR code simulation for Q=10 Domain. Solid curves are profiles used in D/T neutral flux simulation.*

The ion densities were assumed to be constant over the minor radius, $Z_{eff}$=1.7: $n_d = n_t = 3.9\cdot10^{13}$ cm$^{-3}$, $n_{He2+} = 7.8\cdot10^{12}$ cm$^{-3}$ (10% of $n_d$+$n_t$), $n_{C^{6+}} = 1.9\cdot10^{12}$ cm$^{-3}$. For such a plasma the equilibrium confinement time of $He^{2+}$ ions in the center $\tau_{He2+}(0)$ determined by (6) should be equal to 10.6 s.

Fig.3 shows so called emissivity functions of D and T atoms.

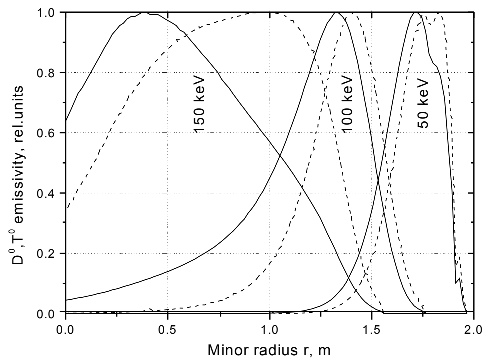


*Fig.3. Emissivity functions of $D^0$ and $T^0$ atoms of different energies from ITER-FEAT standard discharge plasma. Solid lines – for $D^0$, dashed lines – for $T^0$.*

It is seen that measurements of ≈150 keV atoms should be provided to obtain an information about the plasma core. Energy dependant measurements can yield radial distribution of the isotope ratio.

We present below the calculated energy spectra of the emitted atoms as a function of Neutral Particle Analyzer count rate on the energy. It enables us to estimate a statistical accuracy of the measurements and to define necessary NPA parameters. In fig.4 the energy dependence of the tritium count rate is presented in the absence and presence of $He^+$ ions. Deuterium count rate from fifty-fifty deuterium-tritium plasma in the whole calculated energy range (10 – 200 keV) is a few times higher than tritium one and its intensity is not critical for estimation of accuracy.

To get accuracy 10 % it is necessary to collect at least 100 counts in 100 ms time window what is equivalent to 1 kHz count rate. From fig.4 we see that the count rate needed to provide the required statistical accuracy for 150 keV $T^0$ atoms can be obtained in ITER-FEAT plasma conditions. In case of presence of He ash and $He^+$ ions of $1.6 \cdot 10^5$ ion/$cm^3$ (corona equilibrium) or more the expected count rate will provide the better statistical accuracy. It makes possible $n_d/n_t$ measurements over the whole plasma cross section in the ITER-FEAT reference discharge.

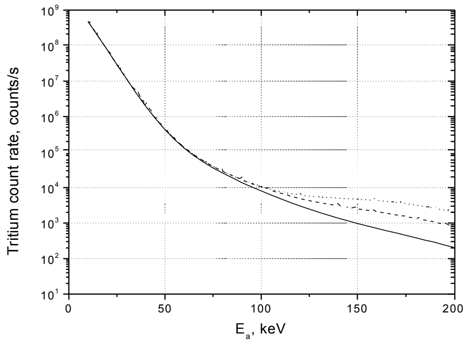


*Fig.4. Energy dependence of tritium count rate for different $He^+$ density profiles.*
*NPA collimator: wS=1.3.e-4 cm2 strd, energy resolution $\Delta E=0.1 E$, Detection Efficiency K(E) = 0.05 – 0.9 in presented energy range. Solid line – without $He^+$;*
*dashed line – corona ($n_{He+} = 1.6 \cdot 10^5$ $cm^{-3}$);*
*dotted line – $n_{He+} = 6 \cdot 10^5$ $cm^{-3}$*

## 3.PROSPECTS OF PASSIVELY NEUTRALIZED ALPHA- PARTICLES DETECTION.

Here we briefly analyze the possibility of passive neutralization of fast confined alphas due to double electron capture from helium like carbon ions and from helium atoms. Fig 5 presents cross sections relevant to alpha particle neutralization in the plasma $He^{2+} + I^{(Z-2)+} = He^o + I^{Z+}$ [8]. Fig.5 shows that in energy range E>2MeV main donor for double electron capture is Helium-like Carbon $C^{4+}$.

In ITER we have $n_e/n_{c+6}$=2%, $n_e/n_{He+2}$=10% (Zeff=1.7). Ionization balance analyzed in [8] gives $n_{C+4}$= 5.10$^6$ $cm^{-3}$ , $n_{Heo} \sim 10^3$ $cm^{-3}$ . Fig. 6 shows NPA count rates produced by passively neutralized fast confined alpha particles generated in the process $He^{2+} + C^{4+} = He^o + C^{6+}$. The parameters of Neutral Particle Analyzer are the same as in Fig. 4. Detection efficiency in presented energy range is equal to 1.0.

It is seen that $C^{4+}$ ions of density $\sim 5 \cdot 10^6$ $cm^{-3}$ or more in the plasma provide detectable flux of neutralized alphas of level $10^3$ 1/s.

## 4. APPARATUS FOR NEUTRAL PARTICLE ANALYSIS ON ITER.

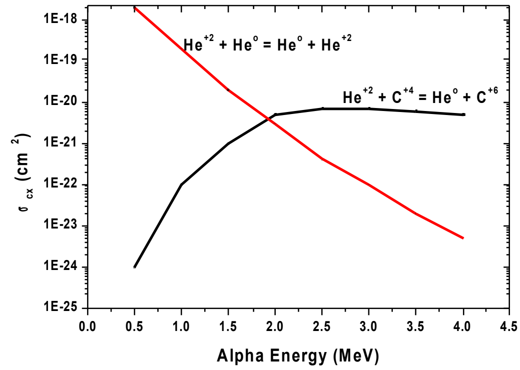


*Fig 5. Cross sections of processes relevant for neutralization of alpha particles.*

At the moment NPA diagnostic is included first priority list of the diagnostic systems on ITER. Fig. 7 presents system of two Neutral Particle Analyzers (a tandem), which will be used on ITER.

The NPA system consists of Low Energy Neutral Particle Analyzer (LENPA) for the measurements of isotope composition in 10 – 200 keV energy range and High Energy Neutral Particle Analyzer (HENPA) for the measurements of fast confined alpha particles in ITER-FEAT. Presented NPAs have been developed in A.F.Ioffe Institute (St.-Petersburg, Russia).

HENPA and LENPA both viewing along main radius close to equatorial plane of the torus and along the same straight vacuum opening of diam 20 cm at the blanket face in ITER port # 11. Both analyzers can operate in parallel because LENPA is shifted horizontally to ensure independent line of sight.

Requirements to keV-range NPA for $n_H/n_D/n_T$ measurements are following: a) Simultaneous detection of fluxes of the all three isotopes H, D, T; b) Good mass suppression (~$10^{-3}$); c) High S/N ratio (low sensitivity to neutron/gamma background)

The requirements have been met by using a thin carbon foil (~ 150 Å) for stripping, additional acceleration (by ~ 100 kV) of the secondary ions, optimization of a dispersion system consisting of B and E, of E ‖ B type, which separates particles by energy and by mass, by development of particle detectors with very low neutron-gamma sensitivity (scintillation detectors with scintillator thickness of micron range).

The prototype of LENPA (ISEP NPA[9]) and prototype of HENPA (GEMMA NPA [10]) were successfully tested and used on JET.

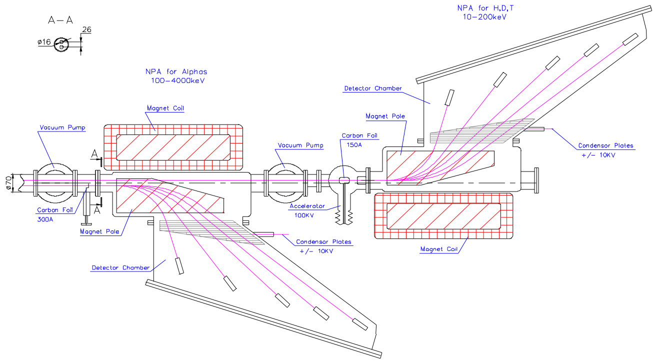


*Fig. 7. The sketch of the NPA system developed for ITER.*

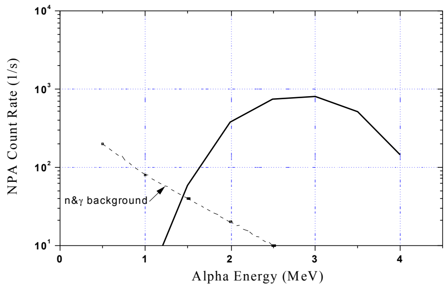


*Fig. 6. Expected NPA count rate produced by passively neutralized fast confined alpha particles in ITER plasma. Dotted line – neutron and gamma background.*

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