Updates for automatic analysis and post-processing of JET neutral particle analysers for TT and DT campaigns

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**See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)*

ABSTRACT: The data processing from both JET Neutral Particle Analysers (NPAs), high energy and low energy detector systems, has been updated for needs of operating in different scenarios with several isotopes in tritium and deuterium plasmas in the 2021 campaigns. The new automatic processing allows quick routine analysis of NPA data during JET experiments and enables efficient further analysis of large data sets with the help of coupling to the JETPEAK database.

The NPA data analysis workflow has been systematically applied and demonstrated during scenario development experiments in 2020. This contribution introduces the capability and efficiency of the coupled analysis chain in fast particle diagnostics data checks and post-processing by using JET DTE2 reference pulse sub-database.

KEYWORDS: fast particles; neutral particle analysers; database analysis & coupling

1. Introduction

Analysis of behaviour of fast particles is significant in DT plasma experiments to give information on efficiency of heating schemes and high energy fusion products. The Neutral Particle Analyser (NPA) systems at JET provide information about neutralised fuel and fusion product populations (H, D, T, ^{3}He and ^{4}He) particles in different energy ranges. JET has been equipped with two NPA systems, with different energy ranges and observed particles (listed in Table 1) developed by Ioffe Institute St Petersburg.

Important and the most traditional application for both, high and low energy detectors, is cross-checking the efficiency of external heating, especially different RF scenarios with a minor population of fast particles. Instead, in thermal energies, the low energy NPA system is one of the key diagnostics for isotope ratio monitoring in TT and DT campaigns (DTE2). In this work, a new automated tool for efficient routine NPA analysis during JET experiments is presented. Its capabilities for isotope analysis have been demonstrated during H plasma experiments in 2016 and 2019 and data processing has been updated to an easy-to-use option during 2020 for a fluent process for use by control diagnostics experts in DTE2.

2. JET neutral particle analysers (NPA)

2.1 Set-up and technical information

Low energy NPA (KR2) [1,2] includes 14 energy channels for H, 9 channels for D and 8 channels for T observing neutralised particles along a single horizontal line of sight (LoS) in the midplane region (shown in Figure 1). KR2 can be typically used in two different modes: thermal (generally called as a low energy mode) and high energy RF minority mode (high energy mode) in D/H and T/DT plasmas. In the low energy mode, the KR2 signal is dominated by the fast neutral particles arising in charge exchange reactions in the region where the KR2 LoS crosses the NBI beam path, as shown in figure 1. In the high energy mode, the observed energy range concentrates on RF heated particles and is above that of the NBI beam particles.

The main elements of KR2 are: a) stripping of atoms using a thin carbon foil to produce secondary ions, b) acceleration of secondary ions, c) E||B analysis of the secondary ions in specially designed non-uniform magnetic/electronic fields, d) counting of energy and mass analysed secondary ions using detectors consisting of thin ($1 \leq t(\mu m) \leq 7$) CsI (Tl) scintillators deposited directly on miniature photo-multiplier tubes (PMTs) mounted in vacuum. Further technical details (and schematics) of the diagnostics system can be found in [1].

KR2 has high contrast between atoms of neighbouring masses ($\geq 10^3$ for $E \approx 5$keV, and much greater at higher energies), and high detection efficiency ($0.06 \leq \varepsilon \leq 0.83$ for atoms of $5 \leq E(\text{keV}) \leq 150$). The KR2 detectors have very low sensitivity to neutron and γ-ray radiation ($\leq$10-7 of ion detection efficiency). This makes the reliable use of KR2 possible, with deuterium-tritium (DT) plasmas in JET using modest amount of shielding [3].

High energy NPA (KF1) [4] has 8 energy channels viewing the plasma vertically along the single line of sight (shown in Figure 1) and can be set to measure neutralised H, D, T, ^{3}He or ^{4}He (alpha) in higher energies (See the maximum energies in the Table 1).
It based on the ionization of atoms by stripping within a thin carbon foil, and the analysis of secondary ions in electric/magnetic fields (E || B type).

The two analysers are designed for operation in the presence of strong neutron and gamma radiation, with expected tritium ingress from the vessel into the instrument.
Entrance slits of the analyser collimate the incoming atomic beam, and enable independent variation of both the height and the width of the beam from 1mm x lmm to 5mm x 10mm. A carbon stripping foil (20-40 nm thick) is located between the poles of the electromagnet in a uniform magnetic field to avoid defocusing by stray magnetic fields.

After stripping within the foil, the resulting secondary ions are deflected in the magnetic field of the electromagnet by 90°. This angle was chosen in the original design, to locate detectors far away from the axis of the incoming plasma facing neutrals. Once passed the magnet, the ions with different momenta move along parallel trajectories, being dispersed by momentum in the direction perpendicular to their trajectories. For mass separation, the ions are deflected from the mid plane of the analyser by the electric field produced by a pair of electrostatic deflector plates and are detected by eight Si-on-Insulator (SOI) detectors, for better background rejection and greater separation of ions with equal charge to mass ratio, as in deuterons and alphas [5].

Table 1: Measured energy ranges (keV) for different isotopes of the low energy NPA system (KR2) and the corresponding maximum measured energies of the high energy NPA system (KF1) at JET.

Isotope	KR2	KR2	KR2	KF1
	Thermal D/H	RF minority	Thermal DT	
H	4-95	150-740	7-280	1100
D	5-40	125-370	5-120	800
T	4-15	125-250	5-63	1100
^{3}He	-	-	-	800
^{4}He	-	-	-	800

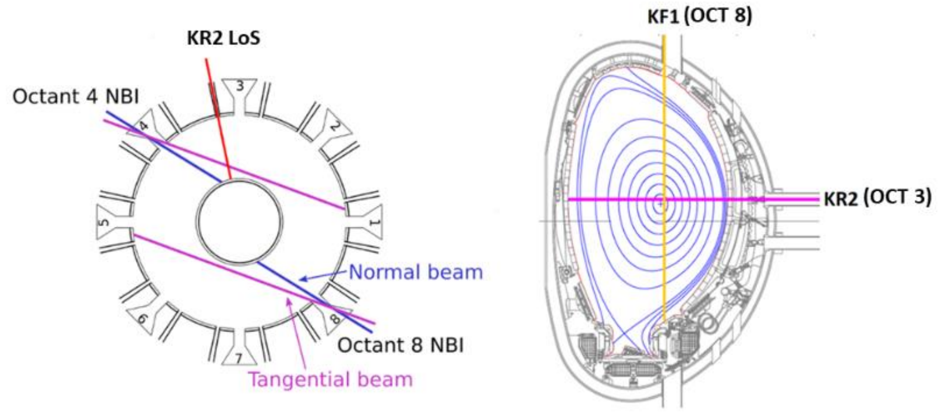

Figure 1: Geometrical set-up of JET neutral particle analysers (Low energy NPA KR2, High energy NPA KF1) in poloidal and toroidal cross section.

2.2 Role of NPA in DT: easy-to-use tools

As a recent development step, the processing of the NPA data has been automatised and linked to the JETPEAK database [6]. Automatic processing includes data monitoring and calculating neutral particle flux per energy channel and the interfering high energy tail. Flux and tail temperature fitting is performed via the JETPEAK database [6]. The automated workflow includes two branches (workflow illustrated in schematic Figure 2): the basic branch for the Rostered Diagnostics Expert (RDE) to check the data quality during plasma operations and the more extensive branch to interpret results as a view of fast particle physics. The first branch includes the checks of the system, the reasonable count rate in different channels and fitting the fluxes over the whole duration of the pulse (in intershot). The physical interpretation branch uses the same scripts but it utilises the connection to JETPEAK for performing analysis for the specific and carefully defined time intervals and the script compares other fast particle related data, such as neutron production profile or 2D fast particle maps defined by the synthetic diagnostics running via the database. If the first branch fails, the second branch will not be run, but the error flags indicating bad quality diagnostics data are added under failed samples in the database, which minimizes the misuse of data and forming incorrect conclusions. Chapter 4 demonstrates the efficiency of the tool when the analysis has been performed for the specifically defined data sets and is a typical example of the analysis that can be done automatically after an experimental session.

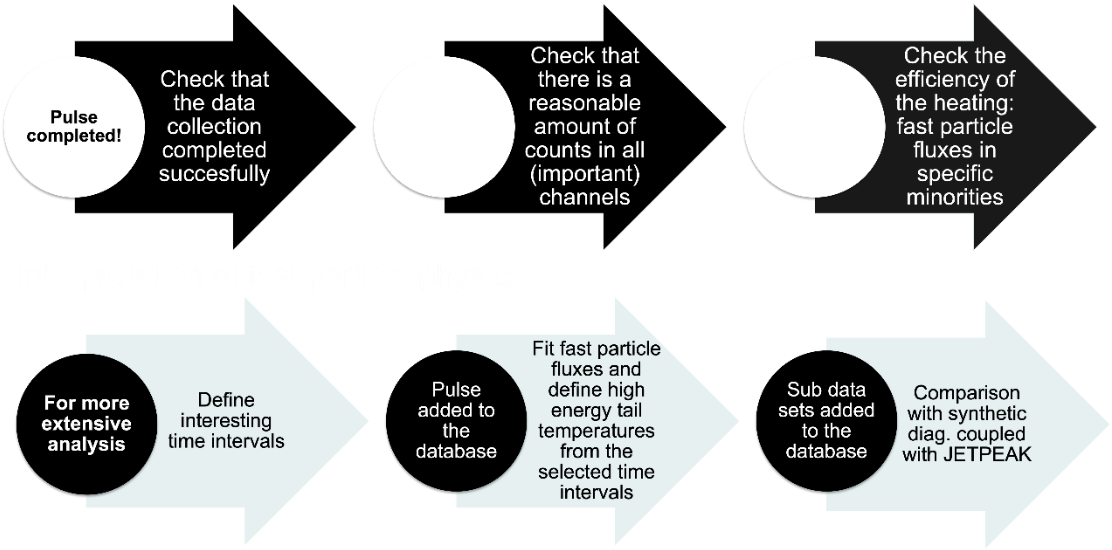

Figure 2: Schematic view of the automated chain of analysis

3. JETPEAK database and analysis and modelling platform

The renewed analysis chain allows processing of the NPA data routinely between plasma pulses during JET experiments. The automation and the coupling to the JETPEAK database further enables efficient analysis of large data sets of the order of thousands of samples and, consequently, connection to a variety of extensive physical studies, such as similar correlation analysis as discussed in [7].

JETPEAK is a multipurpose database and modelling environment which provides pre-checked and filtered information of essential plasma parameters, e.g., electron temperature, density and Z_{eff}. It is based on stationary-phase samples (sample structure is illustrated in Figure 3 and discussed in more detail [6]) taken from the most interesting JET pulses during the ITER-like Wall (ILW) era and all pulses systematically starting from the hydrogen campaign of 2016. JETPEAK has been applied in several studies in different topics, such as systematic semi-empirical DT extrapolations [8], code validations [9,10], and recently and most significantly, in renewing the analysis of the neutron deficit problem [11].

The database and its applications are available in both MATLAB and Python format interface. One of its most important benefits is combining the information from diagnosticians and modellers for more reliable analysis and tools development, especially routinely run or by analysis of synthetic diagnostics, even during operations.

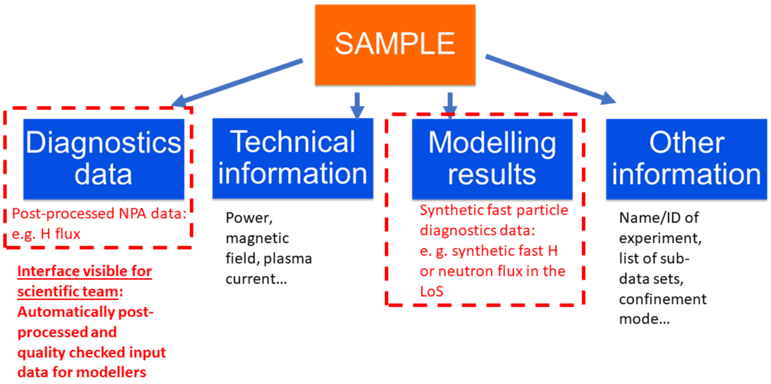

Figure 3: Interaction between different structures in the JETPEAK database

4. Analysis of high power baseline and hybrid plasmas as an example case of fast particle behaviour

Three data sets, one from baseline (#97469, #97472, #97474) and two sets of hybrid plasma samples (#97007, #97011 looking at the time evolution during the main heating phase and #97679, #97740, #97742 from single stationary phase samples) from the JETPEAK database, have been selected to be presented is this demonstration of the new work flow of the NPA analysis tools. These datasets have been formed from selected high power plasmas from the latest DD campaign (2020), [11] based on the high power and interesting fast particle effects, such as different RF minorities (H, ^{3}He). All samples have been selected as the longest stationary period in the main heating phase (external heating power and neutron production rate have been listed in Table 2). They are also good examples of the most typical request for the fast particle experts during experiments and they demonstrate how the efficiency of heating and fast particle behaviour can be explained with the help of the information coming from different sources (experimental measurements vs modelling).

Table 2: Heating power (average during main heating phase) and the measured neutron rate (variation during the time interval, values given from the beginning and the end of the main heating phase) in the JET high power pulses during the main heating phase (source: JETPEAK database).

JET shot number	RF minority	P_{tot} average (MW)	Measured neutron rate (10^{16} 1/s)
#97007 Hybrid	^{3}He	36.0	2.3-2.4
#97011 Hybrid	^{3}He	34.0	2.1-1.2
#97679 Hybrid	H	31.2	4.3-0.6
#97740 Hybrid	H	33.7	4.0-3.2
#97742 Hybrid	H	30.2	4.0-2.7
#97469 Baseline	H	31.9	3.0-2.4
#97472 Baseline	H	32.3	2.4-1.9
#97574 Baseline	H	31.9	2.4-2.0

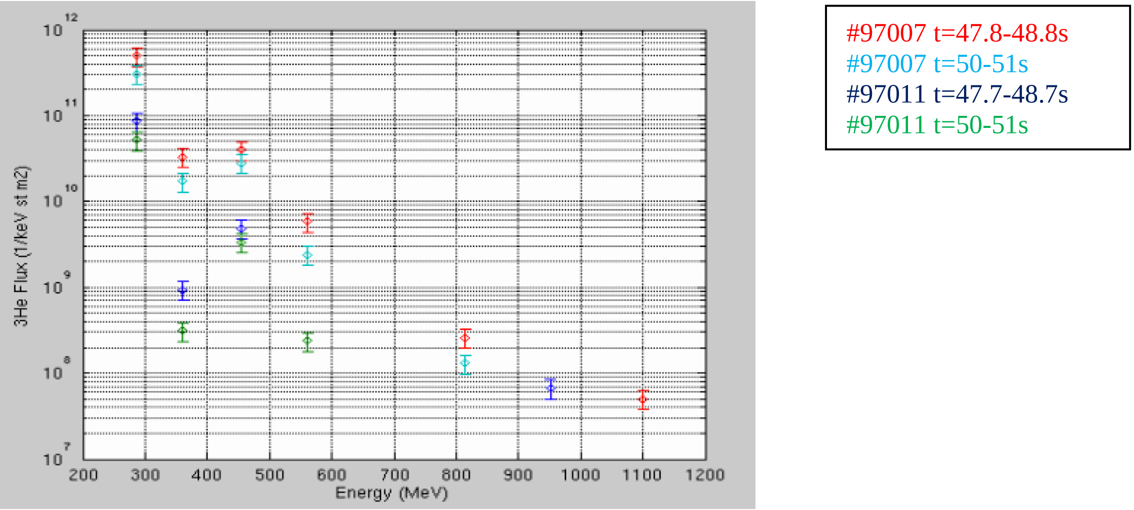

Figure 4: Qualitative comparison of ^{3}He flux from high energy NPA in JET hybrid high power plasmas

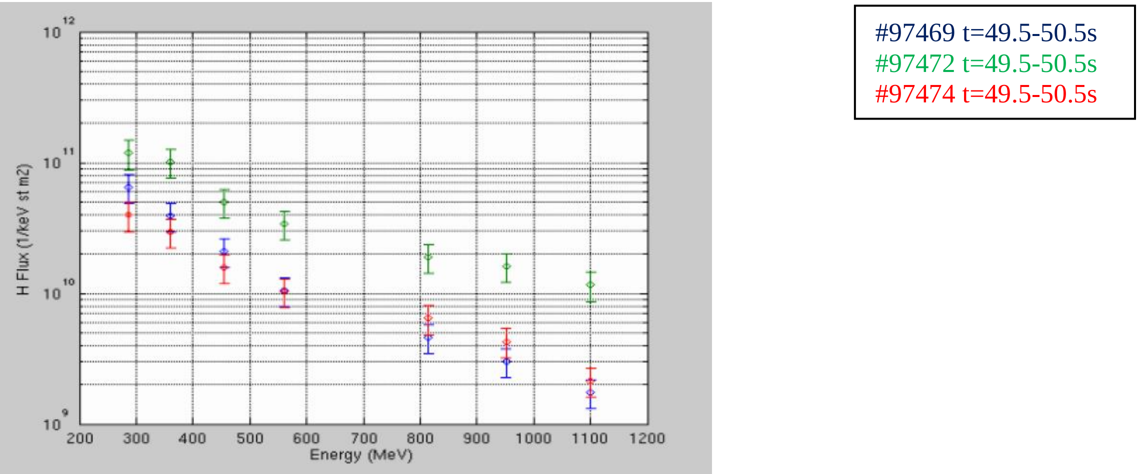

Figure 5: Qualitative comparison of H flux from high energy NPA in JET baseline high power plasmas.

It can be clearly seen (Figures 4, 6 and neutron rates listed in Table 2) that the time evolution of heated minority particles (in both scenarios, H and He3), correlates with the time evolution of the neutron emissivity in both cases of hybrid plasmas: there was not a significant change in the heating power but the neutron rate dropped due to lower fast particle population (decrease 43% in #97011 and 87% in #97679). That clearly indicates that the efficiency of the heating was poor in #97011 and #97679 and significant fast-thermal neutrons were not produced.

In the set of baseline plasmas, the conclusion was not so straightforward to make, but combining the information from measurements (fast H, neutrons) and fast particle modelling (2D fast particle densities and total deposited power) helps to understand the efficiency of the heating. High fast H flux (can be seen in #97472 in Figure 5) correlates with higher power deposition to ions and thermal fusion rate but also, strongly peaked neutron emissivity profile and fast particle population can be observed the on LoS of NPA. The lowest neutron rate was observed in #97472, but the fast particle population and the neutron production profile is very peaked to the centre of plasma where it covers smaller volume (where the LoS of high energy NPA is located).

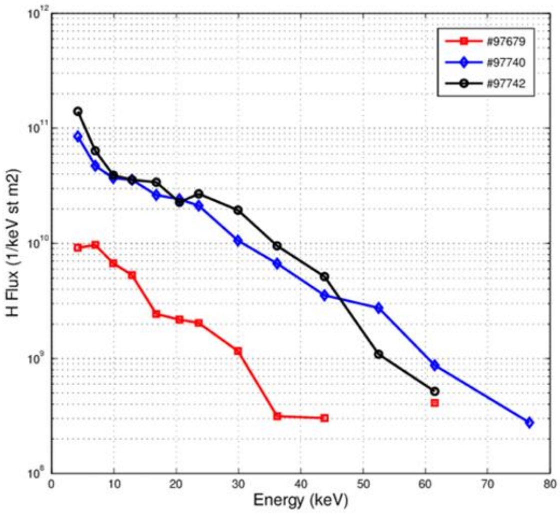

Figure 6: Qualitative comparison of H flux from low energy NPA in JET hybrid high power plasmas.

5. Conclusions

Data processing from both JET neutral particle analysers (NPA), high energy and low energy detector systems, has been updated for needs of operating in different scenarios with several isotopes in tritium and deuterium plasmas in the 2021 campaigns. The new automatic processing allows quick routine analysis of NPA data during JET experiments and enables efficient further analysis of large data sets with the help of coupling to the JETPEAK database.

The full standard fast particle analysis (including experimental NPA data analysis) consists of two workflows:

- Intershot NPA analysis
- Physical post-processing and cross check with synthetic diagnostics run via JETPEAK database

One of its most important benefits is that it is combining the post-processed information from diagnosticians and (fast particle) modellers to enable more reliable analysis and tools development.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The author would like to thank Dr Mikhail Maslow for his help with the technical details and Dr Ziga Stancar for his comments as a test user of the database user and also his valuable comments for the fast particle analysis chain.

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