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EUROFUSION WPJET1-PR(15) 13871

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Preprint of Paper to be submitted for publication in
IEEE Transactions on Nuclear Science



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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Upgrades of Diagnostic Techniques and Technologies for JET next D-T Campaigns

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1 Abstract—In the perspective of reducing ITER risks, JET next DT campaign presents a unique potential, since the device can combine the right first wall material mix, the reactor fuel mixture and sufficient dimensions and fields to confine the alpha particles. An integrated diagnostic programme, to maximize the scientific output of this DT campaign, is under way and concentrates mainly on the diagnostic for the fusion products, on advanced measurements for instabilities and on testing diagnostic technologies in a 14 MeV neutron environment.

I. INTRODUCTION

JET next D-T campaign, DTE2, is presently scheduled for the year 2017. The main scientific objectives include the assessment of the isotopic effects on various plasma aspects: mainly on confinement, on the threshold to access the H mode and on ELM behaviour. From a technical point of view, the total yield of the entire D-T phase is expected to be $1.7 \cdot 10^{21}$ neutrons, about a factor of seven higher than the previous main D-T campaign on JET, DTE1. Therefore the radiation field will be quite relevant for next step devices, since the neutron flux at the first wall ($\sim 10^{16}$ n/cm²/s), for example, will be comparable to the one in ITER behind the blanket.

From a point of view of diagnostics developments, for many years JET diagnostics have been upgraded in order to provide

adequate support for the scientific exploitation of a D-T campaign [1,2], with particular attention to the issues posed by the neutron yield and the new wall materials [3]. The main efforts have concentrated on improving three main aspects of JET measuring capability: 1) the quality of the measurements of the electron and ion fluids to support the plasma physics programme 2) the diagnostic for the fusion products 3) diagnostic technologies for ITER.

In terms of general diagnostic capability, compared to the previous DTE1, JET diagnostics have a much better spatial and temporal resolution of both the ion and electron fluid (about one order of magnitude improvement for each parameter). The consistency of the various independent measurements of the same parameters has also increased significantly; the three independent measurements of the electron temperature, for example, agree now within 5%. Moreover, solutions are being addressed to operate some cameras, both visible and IR, even during the full D-T phase to provide imaging of the plasma and the first wall. Various upgrades of neutral particle analysis are being considered, mainly to measure the isotopic composition. A new set of reflectometers is expected to provide valuable information about the changes in the turbulence with the different fuel mixtures.

With regard to the fusion products, JET now can deploy a consistent set of techniques to measure the neutron yield and neutron spectra and to diagnose the fast particles. A full calibration of the neutron diagnostics with a 14 MeV source is being considered, after the recent very successful calibration for the 2.45 MeV neutrons. Vertical and horizontal lines of sight are foreseen for neutron and gamma spectrometry, in order to better determine the thermal neutron yield and to separate the trapped and passing components of the alphas. Various gamma ray spectrometers are being developed to cover all the various operational scenarios, from trace tritium to 50-50 D-T operation. The redistribution of the alphas will be measured with the gamma ray cameras, recently upgraded with full digital electronics; new detectors are being considered to bring the time resolution of the system in the ten of ms range. The lost alphas will also be diagnosed with improved spatial and temporal resolution, using Faraday cups and a scintillator probe. The interaction between the alpha particles and various instabilities, particularly Toroidal Alfvén eigenmodes will be studied with a set of specific antennas.

From a technological perspective, the D-T campaign will provide a unique opportunity to test ITER relevant technologies. From radiation hard detectors, for example Hall

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* See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

probes, to neutron absorbers and to shielding concepts, the potential of various solutions in a realistic 14 MeV radiation field will be assessed. The effects of neutrons and gamma on ancillary technologies and systems, such as fibre optics and electronics circuits, are also expected to be sufficiently high to derive useful information about the competitive advantage of various alternatives.

II. DIAGNOSTIC UPGRADES FOR OPERATION

The main upgrades of JET diagnostic capability for operation regard cameras, for the monitoring plasma wall interactions, and the Neutral Particle Analyser, to determine the fuels mixture.

A. Imaging

The JET visible and infrared cameras are presently installed at a very close distance to the tokamak (typically 2 - 4 meters from the plasma boundary). The neutron yield during 50-50 D-T operation is likely to cause irreversible damage to these cameras or in the best case white out the sensor during a plasma pulse. Shielding these cameras from the neutrons is the only way to keep these diagnostics functional during D-T operations. This will be achieved by relocating the cameras to a low radiation environment behind the biological shield, and by relaying the emitted light out of the torus hall (which involves path lengths of order 20-25m) through a carefully designed system of mirrors and lenses. Due to resource limitations, this will be done only for three out of the eleven views currently in use: two wide-angle views in different sectors of the machine and one divertor view from the top of the machine, carrying information in the visible, near-Infrared and mid-Infrared wavelengths. In the torus hall, the use of lenses has been minimized to maximise the transmittance of the system and avoid darkening by radiation, although a few lenses will remain. An interesting by-product of the DT campaign will be that it will provide confirmation on whether radio-luminescence of sapphire lenses in the near- and mid-IR range is a problem or can be neglected. Several sets of moderately sized (<500mm diameter) Al- or Au-mirrors with protective coating arranged in dog leg formation will be used, with the latter material providing the highest reflectivity in the infrared range, whereas the former preserves the capability to include visible light instruments with a modest penalty to the infrared measurement.

B. Isotopic composition with NPA

In the DT campaign, the main physics goal of this instrument is to analyse the isotopic composition of the plasma. Novel techniques utilizing knock-on ions could also provide useful information and it would be important for ITER to test the feasibility of such techniques. In addition to plasma composition studies, the NPA has found use in the study of slightly RF accelerated tails.

The diagnostic is being enhanced to upgrade the ion detection and data acquisition systems to obtain the best possible scientific results, addressing the most important

issues affecting the performance, like count rate capability at low energy channels and sensitivity to radiation background. Presently, pile-up degrades data quality from about 10kcps.

Previously, thin CsI(Tl) scintillators coupled to photomultipliers have been used as ion detectors. Their drawbacks are relatively high sensitivity to neutron-induced X-rays and limited pulse-height resolution making signal/background discrimination difficult. On top of that, they are slow with 3us decay time. The diagnostic will be equipped with thin custom-made Si detectors optimized for ion detection on JET NPAs. The detectors are designed as silicon-on-insulator structure, see Figure 1, with the active layer ground to only a few microns thickness but supported by a thick substrate to create a robust detector. Very similar detectors have been deployed in a second NPA instrument at JET, where they demonstrated a very weak response to JET radiation background. The detectors also allow improved adaptation to different neutral emission rates, as selective masking of strips permits changing the effective active area under software control. First tests with the recently manufactured detectors have been performed, which for relevant bias voltages showed leakage currents well below the 100nA set as tolerance limit. MCNP simulations have been performed to quantify the sensitivity to background radiation

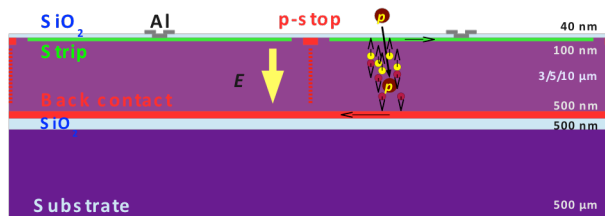


Figure 1: Layout of the SiO₂ detector of the Neutral Particle Analyzer for the measurement of the plasma isotopic composition.

and assess the anticipated performance in DT conditions. Results from these simulations have been incorporated into the detector design, in particular for the choice of substrate material and detector thickness.

To further minimize the noise, the detector and readout chips (based on PORGAMRAYS from Rutherford-Appleton-Laboratory) will be in close proximity and integrated into in-vacuum electronics PCBs. This will be supplemented by FPGA-based communications and processing electronics on the air-side for controlling the readout chips and receiving and re-transmitting the readout data for final storage. With the new planned readout, the detectors can count up to 200kcps, and more if strips are disabled on pulse-to-pulse basis. This has largest impact on evaluating the close-to-edge composition where NPA generates the most reliable data, and for hot, high density plasma with high neutral emission rates.

III. DIAGNOSTIC UPGRADES FOR NEUTRON DETECTION

A. Neutron Calibration

In order to calculate the fusion power produced in the plasma, it is of paramount importance to measure the total neutron rate produced inside any nuclear fusion reactor. For this purpose, an accurate calibration of JET neutron detectors (^{235}U fission chambers and the in-vessel activation system) at 14 MeV neutron energy, must be performed using a Deuterium (D) Tritium (T) Neutron Generator (NG) which will be deployed inside the JET Vacuum Vessel (VV) by remote handling (RH). The calibration, will take advantage of the experience gained with the previous neutron calibration at 2.5 MeV neutron energy (using a ^{252}Cf neutron source), and will also benchmark the calibration procedure envisaged in ITER.

To perform the in-situ neutron calibration a NG has been purchased from the All-Russia Research Institute, VNIIA. It is a compact NG with cylindrical shape (70 mm diam, 483 mm length) of 5 kg weight. The NG will be mounted on the existing remote handling boom and its 'MASCOT' robotic arms and it will be then deployed inside the JET VV. A total of about 80 positions are foreseen to be tested. The operation time required for the NG in each position will vary in the range 0.3 - 4 hours, and therefore, it crucial that the NG is operating stably over these timescales covering the complete calibration. As a calibration source, the NG must also fulfil some minimal characteristics related to sufficient neutron source intensity, stability, lifetime and simplicity of configuration. The technical specifications for the ING-17 NG purchased from VNIIA are summarized in Table 1.

Table 1 Specifications of the VNIIA ING-017, Deuterium gas filled Neutron Generator

| | |
|---|----------------------------|
| Neutrons flux (n/s) | Up to $2 \cdot 10^8$ (DT) |
| Operation mode | Continuous |
| Max Operation time in continuous mode (min) | 20-30 |
| Operating Lifetime | |
| Power supply and control unit (h) | ~5000 |
| Neutron unit | ~ 300 @ $2 \cdot 10^8$ n/s |
| Power consumption (W) | < 120 |
| Power Supply | < 200 V AC, 1 kHz |
| Emitting unit dimensions | |
| Diameter (mm) | 70 |
| Length (mm) | 483 |
| Weight (kg) | < 5 |
| Weight (including power supply and control unit) (kg) | < 10 |
| Maximum Operating Temperature ($^{\circ}\text{C}$) | 60 ± 5 |

The NG is constituted of a vacuum tube filled with deuterium gas. Deuterium is ionized and the deuterons are then accelerated in a perpendicular direction to hit a plane of the TiT-target. The ratio of tritium to titanium in targets varies from 1.2 to 2 ($\text{TiT}_{1,2}$ or TiT_2). The subsequent nuclear reaction taking place between DT atoms, in the target, is generating

mostly fast (14.2 MeV) neutron fluxes, with neutron output of up to $3 \cdot 10^8$ n/pulse, either in continuous mode or in pulsed mode with frequency ranging from about 100 Hz to 10 kHz and neutron pulse width (pulse duration) ranging between 5 and 10 μs .

Due to the kinematics of the DT reaction, neutrons generated in the NG tube present a slight anisotropy and a neutron energy spectrum, which depends on the neutron emission angle. Moreover, because the TiT target is very compact and surrounded by various construction elements/materials, which are acting as effective moderators and neutron absorbers, this leads to strong anisotropy on the neutron emission. At the same time, neutron emission of generator can be accompanied by a high amount of photon (gamma) radiation, which appears as a result of inelastic scattering and capture reactions of neutrons in various materials of generator [4, 5].

Therefore, and in order to properly characterise the NG, it is foreseen to perform pre-calibration measurements, prior and after the in-vessel calibration. The tests will be performed in a standard neutron laboratory, well equipped to perform this kind of characterisation, with a low scatter area, and all adequate tools and instrumentation that are needed to calibrate the NG intensity with a very high degree of accuracy (of the order of $\pm 5\%$). The aim is to precisely measure the neutron source intensity, the angle - energy distribution, as well as the anisotropy of the neutron emission, as a function of the beam energy, voltage and time.

During this characterisation several types of neutron detectors will be used; two Chemical Vapour Deposition (CVD) of an extended thin film of Single-crystal Diamond Detector (SDD), a silicon detector, a neutron spectrometer based on the use of an organic liquid scintillator NE-213, and activation foils. This scintillator is made out of dimethyl benzene (xylene), which is an aromatic compound, very sensitive to any particle or photon irradiation.

B. Neutron Spectrometry

The implementation on JET of a dedicated compact neutron spectrometer started in mid-2007 and was commissioned during 2012. It was led by ENEA who built a Digital Pulse Shape Discrimination (DPSD) board, coupled to a NE213 scintillator detector (diameter 2.5 cm x 2.5 cm thick) with LED for photomultiplier gain variation corrections, built by Physikalisch-Technische Bundesanstalt (PTB) [6].

A new enhancement project with the goal to install a similar spectrometer in the Roof Lab has been ongoing to address the fact that JET has not yet a 14 MeV compact neutron spectrometer, suitable for DT plasma Campaigns, on a vertical, radial line of sight. The magnetic field in a tokamak provides a preferred direction in space, about which the charged particles in the plasma must orbit; the energy spectra of the fusion reaction neutrons vary with the spectrometer viewing angle and it is therefore possible to extract more information on these reactions using different lines of sights (e.g. horizontal and vertical). In particular, a vertical view gives the best separation of neutron spectra from RF-driven and thermal sources, due to the RF-driven ion motion being mainly in the vertical poloidal plane. This applies also to neutron spectra from synergetic NBI plus RF-driven sources. On the other hand, a horizontal view gives the best separation

of neutron spectra from NBI and thermal sources, as the NBI injection is pseudo tangential in the toroidal plane and gives rise to co- or counter streaming ion populations.

Together with the NE213 scintillator detector, a diamond detector suitable for 14 MeV neutron measurements at very high count rates (> 1 MHz), will be installed in front of the NE213 detector and along the same line of view of TOFOR (Time-Of-Flight neutron spectrometer at Optimized Rate). The installation of the two new spectrometers is compatible and does not interfere with the existing TOFOR spectrometer, nor will the diamond detector, due to its low efficiency and thickness, interfere with the NE213 scintillator.

The diamond detector is a matrix of Single crystal Diamond Detectors (SDD) in order to be able to cover the largest fraction of the incoming neutron beam (about 10 cm^2). The matrix will be made of 12 SDD and the electronics for 10 channels will be provided (see Figure 2). Each SDD features a total efficiency to 14 MeV neutrons of about 1% and an energy resolution of $\sim 5\%$. The latter is mainly limited by the fast preamplifier and is a compromise between the capability to operate at very high count rates (> 1 MHz) without pile-up events and the adequate charge collection efficiency needed to achieve the desired energy resolution.

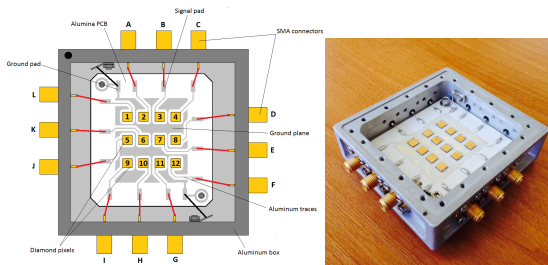


Figure 2 The PCB scheme (left) with each SDD pixel output is shown together with a picture of 12-pixels SDD matrix (right). The overall dimension of the aluminum case is 77x82 mm².

C. Neutron Tomography

The Neutron Profile Monitor (NPM) is a JET diagnostic with the main function of measuring the neutron emissivity profile due to 2.5 MeV (DD) and 14 MeV (DT) neutrons over a poloidal plasma cross-section using line-integrated measurements along a number of collimated channels (lines-of-sight, LOS).

The JET NPM consists of two separate concrete units each one including a fan-shaped array of collimators (see Figure 3). One unit views the plasma horizontally (10 LOS), and the other vertically (9 LOS). In each unit, the collimation can be remotely set up by the use of two pairs of rotatable steel cylinders with a choice of two aperture sizes (21mm and 10 mm \varnothing respectively). Each LOS is equipped with two different types of neutron detectors, respectively designed to work in DD operations/ low power DT operations and in high power DT operations:

- NE213 liquid scintillator (2.5 mm \varnothing , 10mm thick) for the simultaneous measurement of 2.5MeV and 14MeV neutrons

as well as gamma rays (pulse shape discrimination capability).

- Bicron BC418 plastic scintillator (2.5 mm \varnothing , 10mm thick) for 14MeV neutron detection only with very low sensitivity to gamma radiation. The BC418 scintillators still work with an old analog acquisition electronics having several limitations:

- No raw data (i.e. scintillator pulses) storage for monitoring and reprocessing purposes.

- No provision of accurate pulse height spectra (PHS) during plasma discharges (analog discriminator modules provide counts in 4 energy bands only).

- Complex calibration procedure.

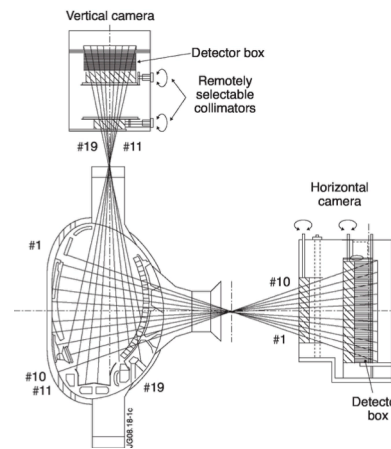


Figure 3 JET Neutron profile monitor.

Moreover During the 1997 DTE1 campaign (record discharge # 42976; maximum neutron yield $\sim 6 \times 10^{18} \text{ n/s}^{-1}$) the BC418 detectors worked up to $\sim 1.2 \times 10^6$ cps (counts above 10 MeV threshold) but the presence of higher NBI power might imply higher rates in the future DT campaign.

The NE213 detectors are instead coupled to an FPGA (Field Programmable Gated Array)-based digital acquisition system (14 bit ADC, 200 MS/s sampling rate) developed by ENEA. Such system overcomes the limitations listed above for the BC418 analog acquisition chain, but the off-line processing is limited to $\sim 9 \times 10^5$ cps (lab. tests).

Moreover only a rough management of piled up events is implemented: pile-ups are recognized and their number used to calculate a correction factor that is applied to single neutron and gamma count rates. No attempt is made to recover the single pulses composing a pile-up event, to perform neutron gamma discrimination and to calculate their energy.

To address the insufficiencies of this diagnostic, an enhancement project was launched with two main objectives:

- Increase of the performances and reliability of the 14 MeV neutron measurements performed by BC418 detectors.

- Assess the possibility of increasing the counting rate capabilities of the NPM detection system based on NE213 detectors.

The first objective will be achieved by procuring, setting up, installing at JET and calibrating a new FPGA-based digital acquisition system provided with specific software tools for the treatment of piled up pulses. The new units will be put in parallel to the BC418 analog acquisition chain and will:

- Sustain High throughput digital acquisition for each BC418 detector performing on line data reduction.

- Allow to store raw data for off-line reprocessing

- Provide an integrated and more reliable environment for detector monitoring and calibration

- Allow a better handling of piled-up events

The proposed upgrade will include:

- Digital acquisition for each BC418 detector;

- On-line data processing on FPGA (data reduction, pile-up processing, real time count rates depending on hardware architecture);

- Raw data mass storage on a local computers located in the NPM cubicles area

- Off-line data processing (pile up processing, DT neutron count rates, PHS, calibration, etc.) with dedicated software package running local computers.

The second objective will be supported by experimental tests at high DT neutron count rate, carried out for example at the Frascati Neutron Generator (FNG), with the new data acquisition units coupled to a spare detector unit including a BC418 scintillator and a NE213 scintillator.

If the increase in the NE213 maximum achievable count rate identified will be considered as a sufficient driver to carry out a further electronics upgrade for this detection system, new DAS units for the NPM NE213 detectors will be procured, set-up, installed at JET and calibrated.

A simulation activity is also foreseen with the aim of setting up and benchmarking a Fokker-Plank simulation code to be used as predictive tool for neutron emissivity studies in future JET DT campaigns and to provide estimates of the neutron fluxes and spectra expected at the NPM detector positions.

IV. DIAGNOSTIC UPGRADES FOR ALPHA PARTICLES

A. Gamma ray spectroscopy

The α -particles produced by the nuclear fusion reactions between deuterons and tritons are expected to provide the power for self-sustained DT-plasma burn by transferring their energy to the thermal plasma during their slowing down. Therefore the adequate confinement of α -particles will be essential to obtain efficient heating of the bulk plasma and steady-state burning of reactor plasma. Consequently, the investigation of α -particles behaviour for deciphering the main mechanisms of their slowing down, redistribution and losses, is a priority task for the planned deuterium- tritium experiments on JET in order to develop optimal plasma scenarios.

On JET the α -particle diagnostic is based on the nuclear reaction ${}^9\text{Be}(\alpha, n\gamma){}^{12}\text{C}$ between confined α -particles and beryllium impurity ions typically present in the plasma. The applicability of gamma-ray diagnostics is strongly dependent on the fulfilment of rather strict requirements for the definition and characterization of the neutron and gamma radiation fields (detector Field-of-View, radiation shielding and attenuation, parasitic gamma-ray sources). For gamma ray spectrometry at the high DT neutron fluxes expected in the future high-power DT campaign on JET, specific improvements are needed in order to provide good quality measurements in the D-T campaign, characterized by a more challenging radiation environment.

In order to enable the gamma-ray spectroscopy diagnostic for α -particle diagnostic during the DT campaigns the following goals should be achieved:

- Maximization of the signal-to-background ratio at the

spectrometer detector.

- Establishing high count rate signal processing and energy-resolved gamma-ray detection.

These objectives can be accomplished by:

- Design, manufacturing and installation of a suitable assembly for the definition and control of the radiation fields (both neutron and gamma-ray) along the full line-of-sight of the gamma-ray spectrometer.

For proper gamma-ray measurements, the necessary reduction of the neutron flux of 14 MeV neutrons reaching the detectors will be achieved by the manufacturing and installation of a set of LiH neutron attenuators. The choice of LiH material has the advantage of avoiding carbon-containing materials which lead to the production of inelastic scattering neutrons with energies $E > 5$ MeV from ${}^{12}\text{C}(n, n'\gamma){}^{12}\text{C}$ reactions and, consequently, to an unwelcome background of 4.44 MeV γ -rays. LiH with a natural Li composition is compact, effective and well transparent to MeV γ -rays. It does not produce interfering γ -rays in the high-energy range. The LiH attenuator should provide a reduction of the neutron flux by a factor of 10^4 for 2.5 MeV neutrons and by a factor of 10^2 for 14 MeV neutrons, respectively.

As in the DT experiments the gamma-ray detector must fulfil requirements for high count rate measurements, the existent BGO-detector should be replaced with new detector modules: detector module 1 (DM1) based on LaBr_3 scintillator and detector module 2 (DM2) based on CeBr_3 scintillator) and an associated digital data acquisition system. The new scintillators are characterized by short decay times (~ 20 ns) and a high photons yields. The coupling of the scintillators with photomultiplier tubes in specially designed detector modules will permit the operation at count rates over 2MHz. The high rate capability will be enabled by a dedicated pulse digitization system with a nominal 14-bit resolution.

The first option (LaBr_3) represents a reliable solution already manufactured and tested for JET gamma-ray spectrometry. The lanthanum bromide scintillation material has a good energy resolution, high sensitivity, short decay time and room temperature operability what makes it is a very good candidate for high resolution γ -ray diagnostics of JET plasmas. The main drawback of the LaBr_3 scintillator is its use in low noise measurements due to its high intrinsic background noise. The background is caused by the 0.09% natural abundance of radioactive ${}^{138}\text{La}$ isotope with half-life $\sim 10^{11}$ years. The radioactive decay of the ${}^{138}\text{La}$ leads to γ -ray emission at ~ 1.4 MeV and ~ 0.8 MeV energies. Absorption of these gammas causes an internal activity of LaBr_3 up to $\sim 10^{-3}$ Bq/cm³/keV. Therefore, besides ensuring an already tested component, the project attempts to provide also enhanced performance by including also a detector based on CeBr_3 scintillator. This scintillator was found to fulfill low noise measurement conditions. It shows 30 times reduction in internal activity in comparison with LaBr_3 . The CeBr_3 scintillator has a similar energy resolution, sensitivity and decay time as the LaBr_3 scintillator. Moreover, the CeBr_3 scintillator seems to be more resistant for gamma radiation than LaBr_3 . A 1 kGy dose of gamma radiation deteriorates the yield of LaBr_3 by $\sim 10\%$ and worsens its energy resolution from 3.0 to 3.8%, while is almost negligible for CeBr_3 . CeBr_3 may also be more resistant for neutron radiation than LaBr_3 because of the much lower

neutron capture cross section in Ce than in La (at low neutron energy range, $E_n < 10 \text{ keV}$).

The development of shielding, collimator and detector modules should be assisted by neutron-photon calculations which will provide radiation field assessment mainly at the detector position and detector response function. The envisaged modelling of DT alphas will be based on the Fokker-Planck code FIDIT (3D in constant-of-motion (COM) space) incorporating fast ion transport induced by Coulomb collisions in JET-like tokamaks with weak toroidal field ripples. The up-to-date version of FIDIT is suitable for simulating the time-dependent distributions of fast ions in realistic plasma equilibria and plasma parameters provided by the JET database. Previously, the code FIDIT was used for predictive modelling of confined and lost alpha particles in JET scenarios with monotonic and current hole equilibria. FIDIT calculations of the distribution of beam tritons gave a satisfactory explanation of the current hole effect on the spatial profiles of neutron emission in JET TTE experiments and served as a validation of the code. The simulation of the time evolution of gamma emission generated in nuclear reactions of impurity ions with alphas having energies above 1.7 MeV in JET TTE was based on the numerical solution of a simplified 3D COM Fokker-Planck equation neglecting the diffusive transport. Both the present as well as a new version of the code FIDIT, which will include collisional diffusion effects, are proposed to be used for modelling the time-dependent distributions of beam deuterons produced during D blips in tritium plasmas, as well as of the DT fusion alphas in the envisaged DT campaigns.

By combining the alpha particle evolution codes with calculations of the plasma gamma-ray emission and detector response a procedure for generating synthetic gamma-ray spectra will be developed. This will allow for the validation of the numerical codes by comparing the synthetic and experimental gamma-ray spectra.

B. Gamma ray Tomography

In an ignited DT burning plasma the heating will be provided entirely by the slowing down of the 3.5 MeV fusion alpha particles, the confinement and control of which will be crucial. Besides the alpha particles, which will be the dominant suprathermal species on the next step tokamak ITER, there will be also other minority energetic ions produced by the auxiliary heating systems. These non-fusion born suprathermal particles must also be diagnosed and studied, as their confinement affects the plasma performance, as well as to avoid the serious damage they might cause to the tokamak first wall if lost from the plasma. All of the above has motivated the efforts to investigate the physical processes pertaining to fast ions in today's fusion experiments on D plasmas, with the final aim to understand and, eventually, control the physics governing the α particle behaviour in a burning DT plasma.

From a diagnostic point of view, high power DT plasma represents a rather harsh environment. For this reason, nuclear physics based diagnostics play a key role and interesting candidates are represented by high resolution Neutron Emission Spectroscopy (NES) and Gamma Ray emission spectroscopy (GRS). Neutrons of mean energy around 14

MeV are produced by the DT reaction itself while gamma rays are emitted by reactions among alpha particles or other fast ions and light impurities, typically beryllium or carbon which are present in the plasma.

For operating the Gamma Ray Camera diagnostic at the high DT neutron fluxes expected in the next high-power DT campaign on JET and to improve its spectroscopic capability specific hardware improvements are planned to be put in place. In particular it is planned to:

- Enhance the existing spectroscopic and count rate capability by replacing the 19 CsI detector with new faster and better energy resolution detector modules. This is a challenging upgrade given the existing constraints in terms of available space for detectors and shielding. A possible solution is to the previously mentioned LaBr₃ scintillators which are characterized by short decay times ($\sim 20 \text{ ns}$) and a high photon yield (~ 60000 photons/MeV) coupled to solid state photon detectors. The new detector will be able to sustain count rate in excess of 500 kHz with an energy resolution equal or better than 5% at 1.1 MeV
- Implement a Control and Monitoring System (C&M) of the detectors. This will be done if compatible with the limited available space.
- Refurbishment of the detector mechanics (housing, support, slider).
- Adapt and if necessary modify the existing digital data acquisition developed in a previous project, in order to sustain the high count rate measurements provided by the new fast detectors. Target values for the data acquisition are sampling frequency of 400/500 MHz at 14 bit resolution.

C. Diagnostics for the lost alphas

The scintillator probe for lost ions is already now one of the main fast ion diagnostics at JET, and during future DT campaign will be a key systems to gain a better understanding of alpha particle physics. The diagnostic works on the magnetic spectrometer principle, where fast ions near the plasma boundary entering the probe through a collimator will hit different regions of a 2-D scintillator plate depending on their energy and the ratio of parallel and perpendicular velocity components, relative to the magnetic field. The diagnostic has been recently equipped with a fast scintillator material and a fast framing camera (Photron APX-i2) to record images with high space resolution. These last upgrades have shown good performance during the last campaign with moderate fluxes of escaping ions. The diagnostic is also equipped with a PMT with coarser spatial resolution but potentially higher temporal resolution, whose limited sampling rate (5 kHz) prevents however the identification of fast MHD fluctuations in the escaping ion signals. As part of an ongoing upgrade, the PMT will be connected via a custom two-stage trans-impedance amplifier to new digitisers with 2 MHz bandwidth.

For an absolute calibration of the diagnostic to alphas, the scintillator screen will be characterized at operational temperature at the Spanish National Centre of Accelerators, and the transmittance of the light relay system from the torus to the diagnostic hall determined with an Ulbricht sphere positioned in-vessel.

These efforts will be supplemented with the development of a synthetic diagnostic, whose aim is to predict for given plasma parameters and heating type (ICRF, neutral beam injection, alphas) the expected signal seen by the probe. The synthetic diagnostic will include shadowing effect from nearby vessel wall components through a 3D model of the vessel wall.

V. UPGRADES FOR INSTABILITIES

A. Toroidal Alfvén Mode system

Instabilities in the Alfvén frequency range can be driven by fast ions (including fusion generated alpha particles) and can lead to their spatial redistribution and eventually fast radial transport that can affect the fusion performances and could damage the first wall of future fusion reactors. The understanding of the mechanisms of the mode stability is therefore of paramount importance for ITER and can also be used to control the alpha particle population itself.

At JET, the study of such modes, especially the Toroidal Alfvén Eigenmodes (TAEs), has been for the last two decades of high interest. AEs can be excited by means of in-vessel exciters (or antennas) and fast ions can be produced by additional heating like ICRH or NBI injections. A unique, state of the art, detection system allows in real-time the detection of TAEs of specific toroidal mode number(s) in the range $n=0-15$, the measurement of their damping rate and amplitude and their tracking. The discrimination in real-time between the different modes of the frequency degenerate TAE spectrum is based on the successful implementation of an algorithm based on Sparse Representation of signals.

The system excites MHD modes around the TAE frequencies by performing a frequency sweep around the TAE frequency, which is calculated in Real Time by the AE Local Manager (AELM). The plasma response during frequency sweeps is extracted from the noise via synchronous detection of a series of magnetic coils and other relevant plasma quantities. The synchronous detection is performed analogically using INCAA modules. The Real Time analysis of the synchronous signals through the AELM allows controlling the function generator in order to sweep the frequency around the AE frequency. When a resonance is measured the AELM locks onto it and sweeps the function generator frequency around that resonance. The implementation of the SparSpec analysis method into the AELM [7] allows one to track on pre-selected toroidal mode(s) ($n=\pm 1-25$) so avoiding to always track on the dominant modes. It is therefore technically possible, and it has been successfully demonstrated in the past campaigns, to measure more than 100 resonances of different n numbers in a single JET discharge.

The actual system comprises 8 antennas asymmetrically located in the toroidal location. The 8 antennas were so far driven by a single 5 kW broadband (20-500 kHz) BONN-type amplifier (700V, 15A (peak)), which will be replaced with a new generation of amplifiers: D band power switching amplifiers of 4 kW each that can tolerate high reflected power.

This will allow a more reliable operation and will provide the diagnostic with the potential to further increase the antenna current, hence TAE modes excitation. A new impedance matching system will be designed, procured and installed to optimize the antenna current and hence the coupling with the plasma over the whole frequency bandwidth. The minimum frequency bandwidth is 20-500kHz with the aim of extending to 10kHz-1MHz depending of the outcome of the amplifier development prototype phase.

B. Reflectometer Upgrades

The effects of the different isotopic composition on the plasma turbulence and related effects (such as the modifications in the ELM behaviour) will be one of the main topics of the D-T campaigns. Reflectometry measurements in the core region are paramount to better understand the mechanisms driving the turbulence and its associated transport in JET advanced scenarios. An ongoing upgrade project foresees adding an additional frequency band to the correlation reflectometer to allow the measurement of density fluctuations inner in the plasma, i.e. in the core region and even up to the high field side region in the most favourable cases. This is of prime interest to study various regimes of plasma turbulence, such as TEM (Trapped Electron Modes) and ITG (Ion Turbulence Gradient) regimes, and in particular assess their ballooning properties (i.e. asymmetry between the low field side and high field side regions).

The implementation will use a HTO source 12-18 GHz with a x8 multiplier, which means a probing frequency range of 96-144 GHz. The local oscillator and the plasma probing signals are generated by separated frequency synthesizers resulting in a single pure spectral lines providing the following main advantages: no spurious signals, no extraneous frequencies and therefore no intrinsic crosstalk on the received signal.

In addition, the radial electric field (E_r) plays an important role in critical areas of tokamak science such as: L-H transition physics & H-mode pedestal structure, turbulence suppression through equilibrium $\mathbf{E} \times \mathbf{B}$ shear and understanding of core rotation, momentum transport, and intrinsic rotation. Fast E_r measurements also enable characterization of zonal flows and geodesic acoustic modes (GAMs). During past campaigns and in certain vertical target plasma shapes, Doppler backscattering (DBS) measurements were already possible, but a small modification of the microwave access front-end will enable E_r measurements in future campaigns on a routine basis.

VI. TESTS OF DIAGNOSTIC RELEVANT TECHNOLOGIES

A. Streaming and dose experiments

In order to validate the calculation of neutron streaming in large fusion facilities, and hence to enable validation of the safety assessment calculations made for ITER, it is important to perform some dose rate measurements around the JET vacuum vessel during and after DD and DT operations. For this purpose several streaming experiments have been carried out, consisting of measuring the neutron fluence and gamma dose-rates in the Torus Hall (TH), and along its ducts (South

West labyrinth, South East chimney). The measurements are performed by means of using highly sensitive ThermoLuminescent Dosimeters (TLDs) and activation foils that will be placed in several positions inside and outside the TH. The TLDs have been developed at the Institute of Nuclear Physics (IFJ) in Krakow, Poland and are made of lithium fluoride, doped with some metals such as Mg, Cu or even P; $^6\text{LiF:Mg,Cu,P}$ (MCP-N), $^7\text{LiF:Mg,Cu,P}$ (MCP-7), $^6\text{LiF:Mg,Cu,P}$ (MCP-6). Mostly TLDS are essentially using ^7Li (natural abundance 92.4 %), however and in order to allow discrimination between the neutron and of γ -ray irradiation field, some TLDs have been enriched with ^6Li (natural abundance 7.6 %).

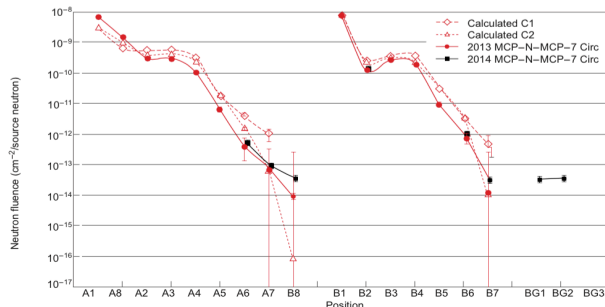


Figure 4. Neutron fluence measurements around JET Torus Hall. Comparison between measurements and MCNP calculations.

During the previous DD experimental campaigns at JET (2012-14), several hundreds of various types of TLDs, were exposed to JET neutrons. The measurements have been compared to the simulations provided by the existing MCNP model of JET and as it is illustrated in Figure 4 there is a very good agreement between calculations (C) and experiments (E) over the whole range of measurements (5 orders of magnitude, within the overall uncertainties). Results have been published in (8). A new set of measurements is foreseen for the 2015 DD campaign repeating measures at the same positions as in the 2014 experiment (labyrinth, chimney and basement). Nevertheless, six new positions located at larger distances from the plasma source outside the TH will also be investigated. Activation foils will be located in six positions inside the TH, close to TLDs (will allow a cross-checking measurements), to TBM mock-up and in other ex-vessel positions in support of shutdown dose rate measurements.

B. Radiation hardness of functional materials

In nuclear fusion machine, beside breeders and neutron multipliers used for tritium production, functional materials are also including cables used for the diagnostics e.g. for the transmission of optical and electrical signals, giving crucial information about the environmental and plasma conditions and therefore, play a very important role, not only in ITER but also in fusion machines beyond ITER. Using such materials under very harsh environment (strong neutron and gamma fields), might alter severely the properties of these materials affecting significantly the information provided by the corresponding diagnostic.

Therefore it is very important to have an accurate knowledge about the relevant technological issues that may arise, particularly the radiation effects on functional properties such

as dielectric and optical. In order to investigate these possible alterations at JET, at dose-rates, which are relevant for many ITER/DEMO applications, the materials to be tested at JET will be located very close to the plasma. Indeed, tests performed in various irradiation facilities demonstrated that ionizing radiation could induce adverse effects, like Radiation Induced Electrical Degradation (RIED), Radiation Induced Electromotive Force (RIEMF), Radiation Induced Conductivity (RIC), which may significantly compromise the performance of magnetic and or opto-electric sensors. Dependence of the effects on the neutron energy spectrum is a well-recognized concern, which is not addressed until now, as the currently available 14 MeV neutron generators cannot provide fluxes and fluences comparable to the ITER radiation environment. However, the 2017 DT experimental campaign at JET will constitute an ideal opportunity to tests these effects under real tokamak environment. The main properties to be measured are:

Dielectric properties: Loss tangent and Permittivity measurements, performed in a wide frequency range (from kHz to GHz's), and whenever possible as a function of the temperature.

Optical properties: Assessment of the RIA and RL (Radio-Luminescence) in a wide wavelength range (VUV-UV-VIS-IR).

VII. CONCLUSIONS

In the last decades, the amount of data acquired by JET diagnostics has followed the Moore law, doubling about every two years. The record of data acquired per shot now exceeds 55 Gigabytes and the total warehouse is larger than 350 Terabytes. With the new upgrades and technological projects, the diagnostic capability is expected to keep improving and to adequately support the scientific programme of the next DT campaign, DTE2.

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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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