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JET Diagnostic Enhancements in Preparation for DT Operations[a)]

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In order to complete the exploitation of the JET ITER-like Wall and to take full benefit from deuterium-tritium experiments on JET, a set of diagnostic system refurbishments or upgrades is in progress. These diagnostic enhancements focus mainly on neutron, gamma, fast ions, instabilities and operations support. These efforts intend to provide better spatial, temporal and energy resolution while increasing measurement coverage. Also previously non existing capabilities, such as Doppler Reflectometry is now available for scientific exploitation. Guaranteeing diagnostic reliability and consistency during the expected DT conditions is also a critical objective of the work and systems being implemented. An overview of status and scope of the ongoing projects is presented.

I. INTRODUCTION

JET next D-T campaign, DTE2, is presently scheduled to take place before the end of the decade. 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[1,2,3], with particular attention to the issues posed by the neutron yield and the new wall materials[4]. The main efforts have concentrated on improving three main aspects of JET measuring capability: 1) the quality of the measurements of the electrons and ions 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 the electrons (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. 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 developed 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 Alfven eigenmodes, will be studied with a set of specific antennas.

II. DIAGNOSTICS UPGRADE FOR OPERATION

The main upgrades of JET diagnostic capability for operation regard cameras, for monitoring plasma wall

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[c)] See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia interactions, the NPA (Neutral Particle Analyser), to determine the fuels mixture, the core charge exchange, to measure ion temperature (Ti) and rotation (Vi). 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 the order of 20-25m) through a carefully designed system of mirrors and lenses. Due to resource limitations, this will be done only for two out of the eleven views currently in use: one wide-angle view 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. In the DT campaign, the main physics goal of the NPA will be to determine the isotopic composition of the plasma. Novel techniques utilizing knock-on ions could also provide useful information while it is important for ITER to test the feasibility of such technology. 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 upgraded diagnostic will be equipped with thin custom-made Si detectors optimized for ion detection on JET NPAs. 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. To further minimize the noise, the detector and readout chips will be in close proximity and integrated into in-vacuum electronics PCBs. This will be supplemented by FPGA-based (Field Programmable Gated Array) 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 a 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. In the 2015 final report on the Assessment of Technical and Scientific Readiness for a DT Campaign on JET, the lack of reliable ion temperature (Ti) and rotation (Vi) measurements were highlighted as a potential ‘showstopper for a useful DT campaign’: ‘The current issues with the Ti and Vi measurements are a serious limitation to the exploitation of the experiments in DD, TT and DT, since it affects strongly the confinement and alpha heating studies.’. The ion temperature profile on JET is measured using multi-chords active charge exchange spectroscopic diagnostics viewing the heating neutral beams. Coverage of the full minor radius (to inboard of the magnetic axis) is achieved with radial views of the octant 8 heating beams from two toroidal mid-plane locations: one from octant 1, the other from octant 7. Most of the experience of charge-exchange spectroscopy on JET has been based on the carbon CVI n=8-7 lines, which has as relatively simple line structure and has, in the past, been a significant feature in the JET spectra. Since the installation of the ITER-Like Wall, levels of carbon in JET plasmas have fallen to about 5-10 times lower than with the carbon-wall machine. The relative simplicity of the carbon spectrum means that it is still favoured for charge-exchange work, despite the reduced signal strength. However, it is frequently the case that, in high density discharges the strong attenuation of the heating beams in the core, combined with the generally low carbon levels, can make reliable ion temperature measurements impossible in the plasma centre. Experiments are underway to develop strategies to improve the measurements using the existing diagnostics. Present experimental efforts aim at using beam modulation to isolate active signal; adding trace neon; the use of hydrogen charge-exchange in the core; simultaneous fitting of red- and blue-Doppler shifted spectra; joint analysis of X-ray and charge-exchange spectra, and, finally the combination of all these experimental techniques. However, from the conclusions of preliminary experiments already performed, it is clear that an improvement in the diagnostic capabilities is also required. Therefore and enhancement project has started to upgrade the instrumentation to provide higher sensitivity measurements by symmetrising fully the red-blue observations. To give good spectral resolution to improve (identification and) rejection of individual 'nuisance' lines and to distinguish them from thermal charge-exchange from the edge of the plasma. To install tuneable instruments so that they can also be used with other extrinsic impurities: N, Ar, HeI (beam doping) but without opposed red-blue geometry. This will be done by keeping the two existing spectrometers connected to a full radial coverage array from one octant. The two octants are different in that the spectrometer on octant 1 is fitted with a grating for He/Be and octant 7 with a grating for C/Ne. The Czerny-Turner instruments will be removed from the other radial array of each octant and instead two pairs of spectrometers (one pair per octant), sharing the views via a dichroic beam splitter, will be installed. A beam splitter designed for 600nm would result in wavelengths above 600nm (including Dalpha) being monitored by one instrument and the impurity lines (C, Be, He, Ne, Ar) by the second.

III. DIAGNOSTICS UPGRADES FOR NEUTRON DETECTION

The implementation on JET of a dedicated compact neutron spectrometer started in mid-2007 and was commissioned during 2012. A Digital Pulse Shape Discrimination board was built, coupled to a NE213 scintillator detector (2.5 cm Ø x 2.5 cm) with LED for photomultiplier gain variation corrections[5]. A new enhancement project with the goal to install a similar spectrometer in the Roof Lab is 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 base neutron spectrometer capable of 14 MeV neutron measurements at very high energy resolution and count rates (> 1 MHz), has been installed in front of the NE213 detector and along the same line of sight of TOFOR (Time-Of-Flight neutron spectrometer at Optimized Rate). The installation of the two new spectrometers does not interfere with the existing TOFOR spectrometer, nor does 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)[6]. The SSD features high radiation hardness, high energy resolution, insensitivity to magnetic field and compact size. Each SDD features a total efficiency to 14 MeV neutrons of about 1% and an energy resolution of ~1%. The SDD matrix has also been equipped with electronics capable to record 2.5 MeV neutrons from D plasma. In this case the detector response features a characteristic broad response, similar to the one of compact neutron spectrometers. The first results achieved with the SDD matrix[6] confirm that a moderate energy resolution can be achieved for 2.5 MeV neutron measurements. As previously demonstrated on JET with a prototype diamond based neutron spectrometer[7], SDD can be used to provide useful diagnostic information on ICRH fast ions in D plasmas. The JET NC (Neutron Camera) 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 NC consists of two separate concrete units each one including a fan-shaped array of collimators. 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 Ø respectively). Each LOS is equipped with a set of three different detectors: NE213 liquid scintillator (2.5 mm Ø, 10mm thick) for the simultaneous measurement of 2.5MeV and 14MeV neutrons as well as gamma rays (pulse shape discrimination capability), CsI(Tl) photodiodes for measurements Hard X rays in the energy range 0.2-6MeV, Bicron BC418 plastic scintillator (2.5 mm Ø, 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. The NE213 detectors are coupled to a recently developed FPGA based digital acquisition system (14 bit ADC, 200 MS/s sampling rate). 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, assessment of the possibility of increasing the counting rate capabilities of the NC detection system based on NE213 detectors. The first objective will be achieved by procuring, setting up, installing on 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 count rates in the Mcps range and provide real time outputs, allow storing 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 second objective will be supported by experimental tests at high DT neutron count rate, carried out at the Frascati Neutron Generator, 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 NC NE213 detectors will be procured, set-up, installed on JET and calibrated.

IV. DIAGNOSTIC UPGRADES FOR ALPHA PARTICLES

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}Be(α,nγ)^{12}C between confined α-particles and beryllium impurity ions typically present in the plasma. 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. 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 two new detector modules: based on $LaBr_3$ and $CeBr_3$ scintillators and an associated digital data acquisition system. The new scintillators are characterized by short decay times (~20ns) and high photon 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. 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 supra-thermal particles must also be diagnosed and studied, as their confinement affects 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 in D plasmas, with the final aim to understand and, eventually, control the physics governing the α particle behavior in a burning DT 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 solution being considered is the previously mentioned $LaBr_3$ scintillators which are characterized by short decay times (~20ns) and a high photon yield (~60000 photons/MeV) coupled to Silicon photomultiplier tubes[8]. The newly developed compact gamma ray spectrometer has shown to be able to sustain count rate in excess of 500 kHz with an energy resolution equal or better than 5% at 1.1MeV[9], which extrapolates to <3% in the range of interest for the alpha particle diagnostic (3-5 MeV). 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 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, the 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, and the transmittance of the light relay system from the torus to the diagnostic hall determined with an Ulbricht sphere positioned in-vessel.

IV. INSTABILITIES DIAGNOSTIC UPGRADES

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. On 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 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 electronic 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[10] allows one to track on pre-selected toroidal mode(s) (n=+/- 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 that 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 is being 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 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 12-18 GHz source 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 line 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 (Er) plays an important role in critical areas of tokamak science such as: L-H transition physics & H-mode pedestal structure, turbulence suppression through equilibrium E×B shear and understanding of core rotation, momentum transport, and intrinsic rotation. Fast Er measurements also enable characterization of zonal flows and geodesic acoustic modes. During past campaigns and in certain vertical target plasma shapes, Doppler backscattering measurements were already possible, but a small modification of the microwave access front-end now enables Er measurements on a routine basis[11].

V. CONCLUSIONS AND ACKNOWLEDGMENTS

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.

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