OVERVIEW OF THE EUROPEAN CONTRIBUTION TO THE DIAGNOSTIC EQUIPMENT OF JT-60SA FOR THE NEXT OPERATIONAL PHASES

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1. INTRODUCTION

JT-60SA is the highly shaped, large superconducting tokamak jointly built by the Japanese (QST) and European (F4E) implementing agencies under the framework of the Broader Approach agreement. Its main scientific purpose is complementing ITER in the preparation of the operation of a DEMOnstration fusion reactor in particular investigating the conditions for a controllable high beta steady state regime able to optimize the fusion gain. The unprecedented combination of features of JT-60SA [1] in terms of plasma volume and current, additional heating including 3-frequency ECRF, 85 kV PNBI and 500 kV NNBI, and pulse duration will give access in the next experimental campaigns to important input information on several key aspects such the development path and controllability of high-performance scenarios compatible with a tungsten wall, the avoidance and mitigation of disruptions and runaways electrons, the physics of fast ions. Coherently with this scientific scope, EUROfusion and Fusion for Energy are jointly contributing to the enhancement plan of JT-60SA. This contribution reports the objectives and the status of the diagnostics projects being implemented or under consideration through the various stages from feasibility to detailed design. The timeline of JT-60SA foresees about 8 months of operation (OP2) in 2026-27, an enhancement phase of about 4 months (ME2) in mid-2027, followed by 8 months of operation (OP3) in 2027-28 after which the further enhancement ME3 will take place.

2. DIAGNOSTICS FOR TRANSPORT AND CONFINEMENT

Tangential Phase-Contrast Imaging (TPCI) provides density fluctuation measurements across the minor radius and in all plasma regimes with a sensitivity of $\delta n/n \sim 10^{-5}$[2]. The accessible wave-number range, $0.06<k\rho_i<12$ will cover the ion-temperature-gradient (ITG) and the trapped-electron-mode (TEM) instabilities and marginally the electron-temperature-gradient (ETG) one. The configuration achievable in JT-60SA with the laser beam having a quadruple, deep pass across the plasma cross section provides excellent radial localization of <0.1 in the plasma core and at the high field side pedestal and ~0.35 elsewhere. In parallel with the design and procurement of the diagnostics hardware, a synthetic diagnostics tool exploiting gyrokinetic modelling has been developed to provide a prediction of the expected measurements. This diagnostics project is performed in collaboration with NIFS. Installation of TPCI is currently being considered for ME1 or ME2.

Doppler Reflectometry (DR) offers a radial scan of both the amplitude of local density fluctuations and the perpendicular flow velocity of the turbulent structures. Initial analyses for expected JT-60SA scenarios [3] indicate that, using a steerable antenna, the accessible wavenumber spectrum will range about $0.3<k_\perp\rho_i<5$. This range is relevant for studying ITG and TEM physics and provides good spatial (~1cm), temporal (~0.2-0.4ms for flow velocity and ~1ms for amplitude fluctuations), and spectral ($\Delta k_\perp \sim 1cm^{-1}$) resolution. Measurements can be obtained across the plasma region $0.4<\rho<1$ using two microwave bands (V=50-75 GHz, W=75-110) and two polarizations modes (X, O). Under reasonable assumptions, the profile of the radial electric field (E_r) can also be measured, allowing studies of its stabilizing effect on turbulence. Detailed engineering analysis of the steerable in-port-plug optical system is ongoing. The complete system is planned for installation in ME3.

3. DIAGNOSTICS FOR FAST PARTICLES

The **Fast-ion Loss Detector (FILD)**, with the detector head mounted on a reciprocating arm, measures fast ion losses escaping from the plasma due to different mechanisms such as magnetohydrodynamic instabilities and/or externally applied magnetic fields[4]. This diagnostic system collects, collimates and disperses the escaping ions onto a scintillator plate. The impinging position of the ions on the scintillator plate depends on their energy and pitch-angle and, tracking it, allows determining complete information on their velocity-space. The FILD system is designed to measure lost fast ions with temporal resolution < 1μs within an energy range of [25 – 500] keV and a resolution ranging between 15 keV at 25 keV and between 170 keV at 500 keV. The pitch angle ratio v_{perp}/v_{tot} is measured in the range [30°-75°] with a resolution <5°. The development of the system is aimed to be ready for installation in ME2.

The **Neutron diagnostics** being considered include an **Energy Spectrometer (NES)** and a **Vertical Neutron Camera (VNC)**. The initial evaluations have excluded the feasibility of a Time-Of-Flight (TOF) spectrometer at least in the present machine configuration due to the lack of a suitable location in terms of available volume, neutron flux and expected neutron background. Plans are redirecting now on the development of one or more compact spectrometers (**CNES**) based on scintillators containing Chlorine that, thanks to the limited volume, might be installed in a convenient location close to the equatorial plane. The VNC has been deemed feasible with access from the lower side of JT-60SA. Optimization of the line of sight and of the shielding is ongoing.

A **Gamma Ray Spectrometer (GRS)** based on a 3''x6'' $LaBr_3$ detector can measure runaway electrons bremsstrahlung emission in the MeV range, 500 keV fast protons provided by H-NBI through the $p(d,\gamma)^3He$ and α particles through 500 keV $D(^3He, \gamma)\ ^5Li \rightarrow\ ^4He+p$. The plan presently being considered is the installation of GRS in ME2 in a position close to the first version of the CNES and sharing the same shielding structure.

4. DIAGNOSTICS FOR PEDESTAL AND PLASMA WALL INTERACTION

The **Edge Thomson Scattering (ETS)** measures electron temperature and density with a dynamic range of 0.01-10keV at 50 radial positions in the low field side outer plasma region, R=3.7-4.17m, also extending in some scenarios outside the last closed flux surface[5]. The spatial resolution increases from core to edge (25-10-5.5mm). At the most unfavourable limit of the expected density ($1x10^{19}m^{-3}$) the relative measurement errors are always <12% for T_e and <6% for n_e but significantly decrease (<4% and <2% respectively) for R<4.10m where the density is higher. The scattered light is provided by a 100 Hz Nd:YAG laser that can be synchronized with an external trigger for more experimental flexibility. The ETS diagnostics is being installed and will be operational in OP2.

The **Vacuum UltraViolet Divertor** spectroscopy system (**DivVUV**)[6] will track impurity species and provide information about their spatial distribution thanks to its 1D imaging capabilities with enough resolution to distinguish the emission from the X point, inner and outer strike points. The instrument has two channels covering two wavelength ranges 10-48nm and 44-125nm with resolution respectively of 0.08nm and 0.14nm. Such spectral interval allows to collect signal from D, He and C, N, Ne, Ar, Cr, Fe, Ni impurities. When used with a single line of sight (no imaging), the time resolution of ~0.5 kHz is expected to be suitable for detachment studies. The DivVUV diagnostics is planned for installation in the presently ongoing ME1 and operational in OP2.

5. DIAGNOSTICS FOR PLASMA OPERATION

EDICAM is a wide-angle, 1280x1024 pixel visible video diagnostics with event detection capabilities and is the first European diagnostics delivered to JT-60SA. Installed during the main assembly phase of the machine, has been successfully used during the first plasma operation OP1[7]. The camera has ~80° field of view in the direction of plasma current and toroidal magnetic field and its spatial resolution is 4.0 - 10.5mm/pixel in the range of 3−8m object distance. EDICAM is featured with non-destructive read-out capabilities that allow simultaneous acquisition of fast-framing small regions (up to 20 kHz) and low framing (50-400Hz) full resolution. Extension of the system with additional camera units and lines of sight is being considered.

An **EC Stray** radiation detector **(EC Stray)** is being developed as a tool to assist the optimization of the ECRF operations[8]. The system presently being considered is based on the differential bolometer detector being developed for ITER and adapted for the absorption of the multifrequency (82-110-138 GHz) ECRF waves of JT-60SA.

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