

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

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Abstract

The main scientific purpose of JT-60SA 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. In order to accomplish this task, a sequence of operation and machine enhancement periods in the next few years are planned to reach the target performance of the machine before a transition to a full tungsten wall. EUROfusion and Fusion for Energy are jointly contributing to the enhancement plan of JT-60SA, in particular, for what concerns the present contribution, to provide JT-60SA with state-of-art diagnostics in support of its scientific and technical objectives. This paper reports the status of the projects being implemented in view of the next scientific campaigns or under consideration through the various stages from feasibility to detailed design.

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, the scaling of the Scrape-Off Layer at high plasma current. Coherently with this scientific scope, EUROfusion and Fusion for Energy are jointly contributing to the enhancement plan of JT-60SA. This paper reports the objectives and the status of the diagnostics projects being implemented or under consideration through the various stages from feasibility to detailed design and implementation. The timeline of JT-60SA (see FIG. 1) foresees about 8 months of operation (OP2) in 2026-27, an enhancement phase of about 4 months (ME2) in mid-2027, followed by ~11 months of operation (OP3) in 2027-28 after which the subsequent enhancement ME3 will take place.

2. DIAGNOSTICS FOR TRANSPORT AND CONFINEMENT

Tangential Phase-Contrast Imaging (TPCI) is an internal-reference laser-based interferometer that measures line-integrated density fluctuations by manipulating and recombining the beam components. An image is created across the beam, and spatial resolution is limited only by the number of detector elements. The tangential configuration achievable in JT-60SA (FIG. 2) with the laser beam having a quadruple pass across the plasma minor radius achieves longitudinal localization by exploiting the twisting of the measured density fluctuations wave vector which must be perpendicular to both beam propagation direction and the local magnetic field.

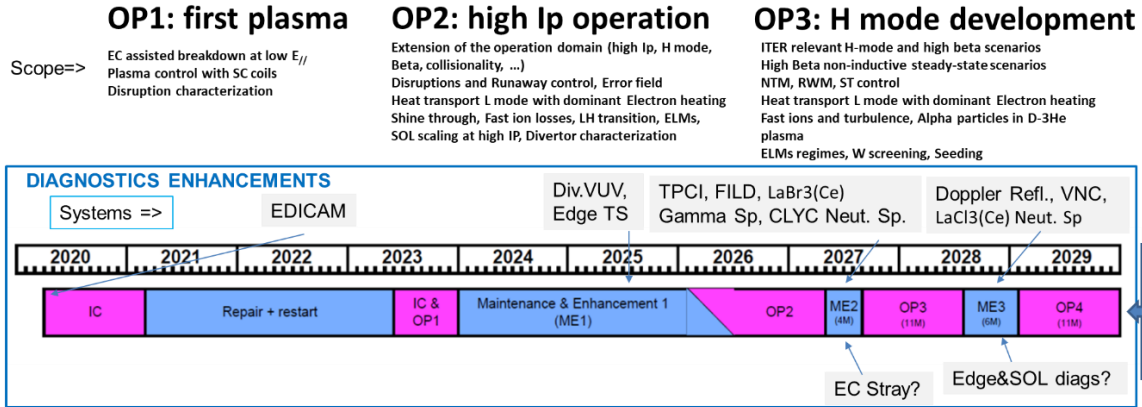


FIG. 1. Plan of implementation of diagnostics in the framework of the scientific programme of JT-60SA

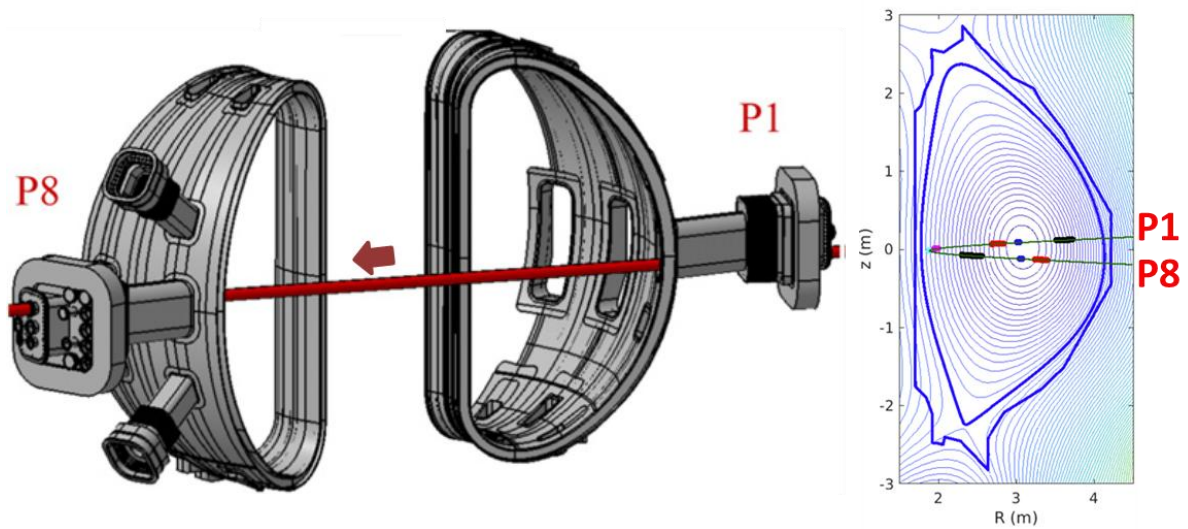


FIG. 2. Left: optical path of the TPCI laser beam across the vacuum vessel. Right: poloidal projection of the laser path. Each colored segment represents the localization of the measurement for one value of the wave number ($k=4\text{cm}^{-1}$) and one particular selection of the direction at the detector.

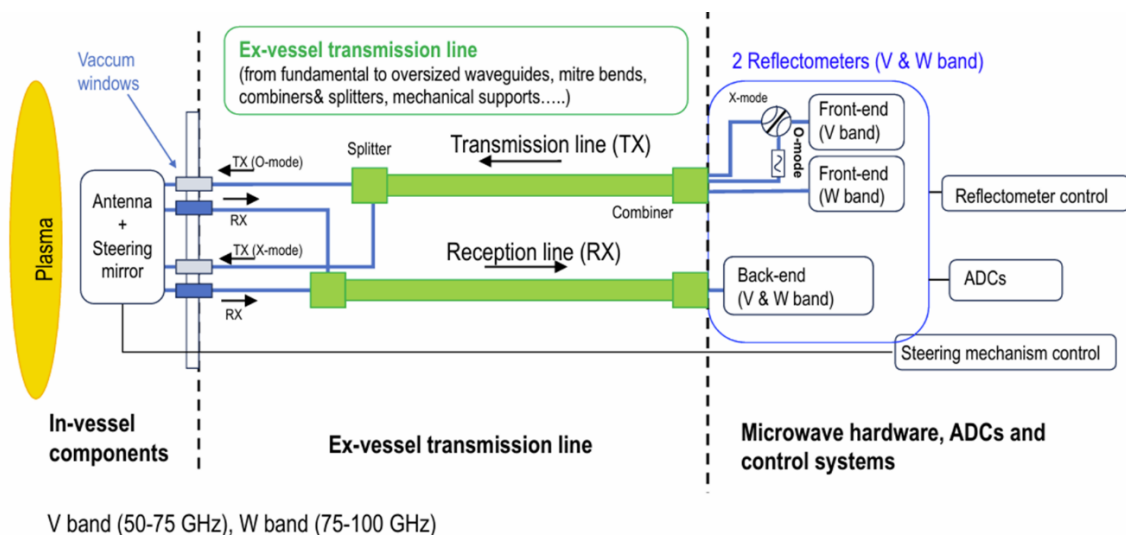


FIG. 3. Conceptual scheme of the Doppler Reflectometry diagnostics. The steerable antenna under design is a quasi-optical telescope which last mirror is steerable in a suitable line across the plasma

This provides excellent radial localization of <0.1 of the minor radius in the plasma core and at the high field side pedestal and ~ 0.35 elsewhere. The sensitivity in all plasma regimes and across the whole radius is $\delta n/n \sim 10^{-5}$ [2]. The accessible wave-number range, $0.06 < k_{\perp} < 12$ covers the ion-temperature-gradient (ITG), the trapped-electron-mode (TEM) instabilities and marginally the electron-temperature-gradient (ETG) one then offering the opportunity of exploring the turbulence at reactor-relevant parameters. In parallel with the design and procurement of the diagnostics hardware, a synthetic diagnostics tool exploiting GENE gyrokinetic modelling has been developed to provide a prediction of the expected measurements in one high performance scenario planned for JT-60SA. This diagnostics project is performed in collaboration with NIFS. Installation of TPCI has started, planned to be completed in ME2.

Doppler Reflectometry (DR) provides a measurement of the amplitude of local density fluctuations through the Bragg back-scattering of a probing oblique-propagating microwave beam at the density cut-off layer (see the layout in FIG. 3). A radial scan is realized changing the frequency of the incident wave. The velocity of the fluctuations perpendicular to the magnetic field can be measured by the frequency (Doppler) shift of the scattered wave. Moreover, if an estimation of the phase velocity of the fluctuations can be provided, the profiles of the radial electric field and of its radial shear can be inferred. The incidence angle of the probing beam at the cut-off layer and its frequency determines the perpendicular wavenumber $k_{\perp}$ of the detectable fluctuations. The spectrum of $k_{\perp}$ can be obtained if the incidence angle can be scanned in a suitable range preserving the so-called “alignment” condition, i.e. $|k_{\parallel}/k_{\perp}| < 0.1$. In JT-60SA, a suitable solution has been found for a planar angular scan that can be mechanically implemented with an antenna steerable along a single axis [4]. The accessible range of wavenumber spectrum is $0.3 < k_{\perp} < 5$, relevant for ITG and TEM physics, with good spatial, temporal and spectral resolution, respectively $\Delta r \sim 1\text{cm}$, $\sim 1\text{ms}$ for fluctuations flow velocity and $\sim 1\mu\text{s}$ for amplitude fluctuations, spectral resolution of $\Delta k_{\perp} \sim 1\text{cm}^{-1}$. Measurements along the plasma region $0.4 < \rho < 1$ can be obtained using two microwave bands ($V=40\text{--}75\text{ GHz}$, $W=75\text{--}110$) and two polarizations modes (X, O). The development of the system aims to be ready for installation in ME3.

TPCI and DR diagnostics are meant to enable studies to validate gyrokinetic codes and their predictive capabilities, to characterize the edge turbulence, the L-H transition and the plasma rotation.

3. DIAGNOSTICS FOR FAST PARTICLES

The **Fast-ion Loss Detector (FILD)** measures unconfined fast ions escaping from the plasma using a detector head mounted on a reciprocating arm (FIG. 4). Such losses are due to interactions with a range of magnetohydrodynamic instabilities and/or other perturbation of the magnetic field breaking the toroidal symmetry. This diagnostic system collects, collimates and disperses, exploiting the local magnetic field of the tokamak, the escaping ions onto a scintillator plate. The impinging position of the ions on the plate depends on their energy and pitch-angle ratio $v_{\text{perp}}/v_{\text{tot}}$ and, tracking it, allows determining complete information on their velocity-space. The collimator geometry has been developed applying a suite of codes including the synthetic diagnostic FILDSIM [5] to estimate the diagnostic output, ASCOT to obtain the fast-ion losses on first wall, thermomechanical FEM analysis [6] and MNCP to estimate the background noise due to nuclear reactions. This analysis led to an optimized velocity-space resolution and signal-to-noise ratio, ensuring a uniform ion rate along the pitch angle range. The JT-60SA FILD is optimized for the 500 keV injected by the N-NBI (measured with a resolution of $<20\text{ keV}$, $<1^\circ$, $<1\mu\text{s}$) but also detects the energy of P-NBI (85 keV) and 3.5 MeV fusion born alpha particles with no significant signal overlap observed. The development of the system is aimed to be ready for installation in ME2.

The **Neutron diagnostics** being developed 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. The VNC has been deemed feasible with access from the lower side of JT-60SA. Simulations show that the sensitivity is high enough to detect changes in the neutron emission profiles related the redistribution of fast ions. Optimization of the line of sight and of the shielding is ongoing [7]. Plans to equip JT-60SA with a 2.5 MeV neutron spectrometer are now redirecting towards the development of one or more compact spectrometers (CNES) based on Chlorine scintillators that, thanks to the limited volume, might be installed in a convenient location close to the equatorial plane (FIG. 5). Among those, CLYC scintillators offer enhanced particle neutron/gamma discrimination capabilities and have already proven to be a valuable compact alternative for moderate counting rates ($\sim\text{few kHz}$) due to the slow scintillation decay time [8] [9]. A valuable alternative for the higher neutron rate ($>100\text{ kHz}$) expected in JT-60SA is offered by LaCl_3 which has a faster scintillation decay time of 28 ns. In this case, a good neutron/gamma discrimination capability achievable applying a FFT based algorithm for pulse shape analysis has recently been demonstrated [10].

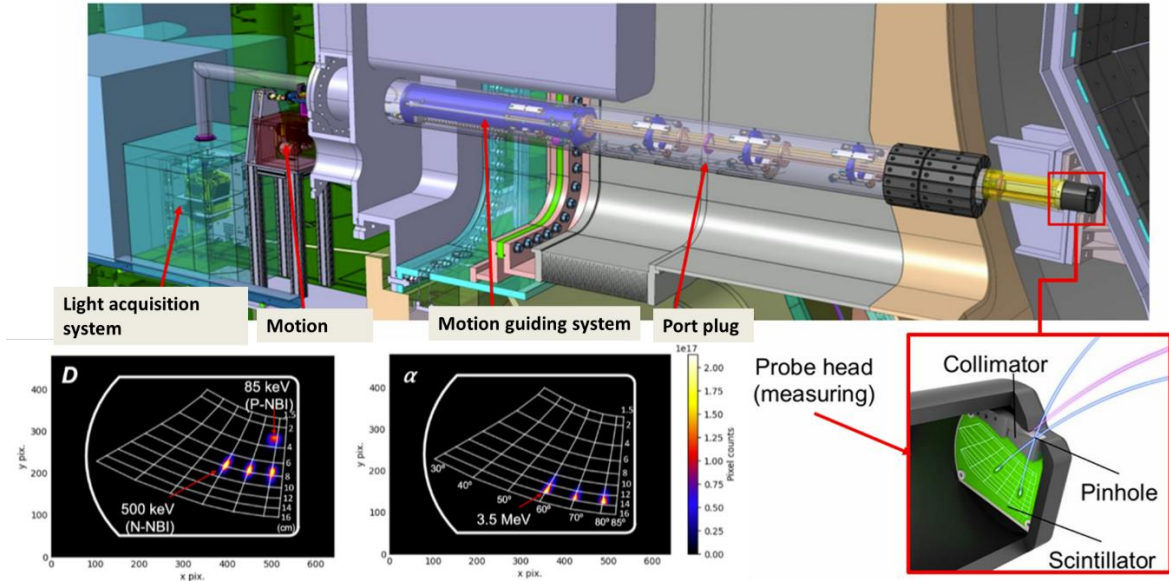


FIG. 4. Top: layout of the Fast Ions Loss Detector in a section of its port plug. On right in second line a zoom to the reciprocating head mounting the collimator (pinhole) and the scintillator. Bottom right: results of the synthetic diagnostics FILDSIM showing the discrimination capability for the three main fast ions species expected: 85 keV D (P-NBI), 500 keV D (N-NBI) and 3.5 α from reactions (D_{N-NBI} , ^3He).

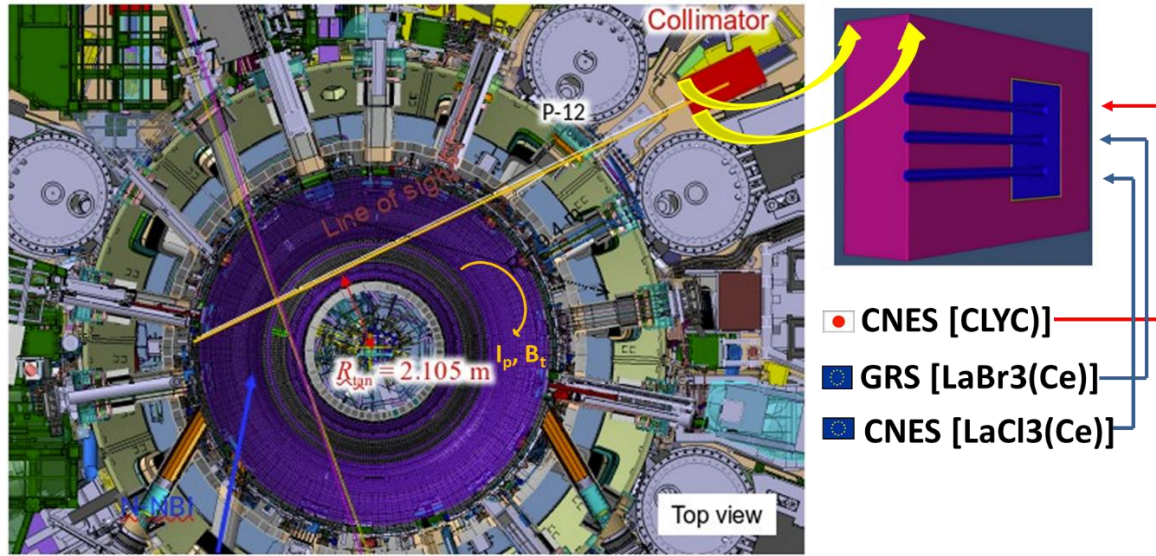


FIG. 5. Tangential lines of sight of the Compact Neutron Spectrometers and of the Gamma Rays Spectrometer

A **Gamma Ray Spectrometer (GRS)** based on a 3''x6'' LaBr₃ detector [11] is being designed to measure runaway electrons bremsstrahlung emission in the MeV range, 5.5 MeV γ emission by the reaction of 500 keV fast protons provided by NNBI through the $p(d,\gamma)^3\text{He}$ and 16.4 MeV γ emission by the reaction of 500 keV deuteron with ^3He added to the plasma producing α particles through $^3\text{He}(D,\gamma)^5\text{Li} \rightarrow ^4\text{He} + p$. α slowing down can be investigated via the γ emission produced for reactions with impurities such $^9\text{Be}(\alpha,n\gamma)^{12}\text{C}$ or $^{10}\text{B}(\alpha,p\gamma)^{13}\text{C}$. The plan presently being considered is the installation of GRS in ME2 and of LaCl₃-CNES in ME3. For OP3 (installation in ME2) a refurbished CLYC-CNES [12] made available within a collaboration NIFS-QST is in preparation. The three diagnostics GRS, LaCl₃-CNES and CLYC-CNES will share a multi-collimator in the same JT-60SA toroidal sector allowing a tangential line (Fig. of sight favourable for fast ion studies such the evolution of their energy and space distribution (together with FILD and VNC), driving of Alfen Eigenmodes, interaction with MHD and anomalous transport.

4. DIAGNOSTICS FOR PEDESTAL AND PLASMA WALL INTERACTION

The **Edge Thomson Scattering (ETS)** measures electron temperature and density at 100 Hz repetition rate with a dynamic range of 0.01-10keV at 50 radial positions in the low field side outer plasma region, $R=3.7-4.17\text{m}$, also extending in some scenarios outside the last closed flux surface [13]. This is realized by means of the beam of a 1064 nm Nd:YAG diode-pumped laser sent through the plasma and exiting through the opposite port into a beam dump (*FIG. 6*). Light scattered by the plasma electrons is collected from another port, imaged into fiber bundles by a collection optics and spectrally analyzed using polychromators. Intensity of the scattered light is proportional to the plasma density while the Doppler broadening of the frequency of the scattered light is proportional to the plasma temperature. The spatial resolution increases from core to edge (from 25 to 5.5mm) allowing detailed studies of the pedestal region where the density and temperature gradients increase and across the separatrix. At the most unfavourable limit of the expected density ($1 \times 10^{19} \text{m}^{-3}$) the relative measurement errors are always <12% for T_e and <6% for n_e but significantly decrease (<4% and <2% respectively) for $R < 4.10\text{m}$ where the density is higher. A detailed synthetic diagnostics has been developed taking into account all the contributions to the signal chain [14], from the number of photons scattered by the measurement volumes in the plasma to the detector output, including the transfer function up to the polychromators and the evaluation of background noise mainly related to the Bremsstrahlung radiation. The application of the synthetic diagnostics to the baseline plasma scenario being prepared for next operational phase OP2 (4.6 MA/2.28 T $q_{95} \sim 3.0$, $n_e \sim 4.5-6.7 \times 10^{19} \text{m}^{-3}$, $P_{NNB} = 10\text{MW}$, $P_{PNB} = 10\text{MW}$, $P_{ECRF} = 1.5\text{MW}$) indicated that ETS will reach the target performance in terms of spatial resolution and relative error. The ETS diagnostics is being installed and will be operational in OP2.

The **Vacuum UltraViolet Divertor (DivVUV)** [15] is a spectroscopy system aiming to track intrinsic and extrinsic impurity species in order to evaluate their contribution to the radiation losses. The instrument has two channels based on toroidal gratings covering two wavelength detailed ranges 10-48nm and 44-125nm with resolution respectively of 0.08nm and 0.14nm. Such spectral intervals allow to collect signals from D, He and C, N, Ne, Ar, Cr, Fe, Ni impurities. The core of the spectrometer are two toroidal gratings fed by two pairs of mirrors (lower pair: cylindrical; upper pair: toroidal) which redirect the light emitted from the divertor region towards the pair of 225x1024 pixel detector of the CCD cameras optimized for the VUV range (*FIG. 7*) [16]. Such optical system provides 1-D imaging capability and produce spectra preserving information about the spatial distribution of the sources with enough resolution to distinguish the emission from the X point, inner and outer strike points on the divertor. When the spectrometers are operated in imaging mode, in the plane of the CCD detector one axis represents the wavelength and the second the position. For low signals or high acquisition rate the spectrometers can be used in binning mode adding up all the spectra on a single detector line. When used in binning mode (no imaging), a time resolution of ~0.5 kHz suitable for detachment studies is expected.

The DivVUV diagnostics is planned for installation in the presently ongoing ME1 and operational in OP2.

5. DIAGNOSTICS FOR PLASMA OPERATION

EDICAM is the first European diagnostics delivered to JT-60SA. Installed during the main assembly phase of the machine in 2020, has been successfully used during the first plasma operation OP1[17]. It is a wide-angle, 1280x1024 pixel C-MOS sensor video diagnostics sensitive to the visible spectrum with intelligent event detection capabilities (*FIG. 8*). EDICAM is featured with non-destructive read-out capabilities and possibility of definition of regions of interest of reduced size. Those characteristics allow simultaneous acquisition of fast-framing small regions (up to 20 kHz) and low framing (50-400Hz) full resolution images. 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. After its successful use in the first period of JT-60SA operations (OP1) for several purposes connected with the commissioning of the machine [18], the 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, also in view of the increasing of the installed power and of the transition to the tungsten divertor and first wall. The system presently being considered is based on an evolution of the differential bolometer detector being developed for ITER [19] and adapted for the absorption of the multifrequency (82-110-138 GHz) ECRF waves of JT-60SA [20]. Such adaptation concerns the identification of a suitable coating material and thickness to optimize the absorption at the JT-60SA frequencies and the reduction of the response time.

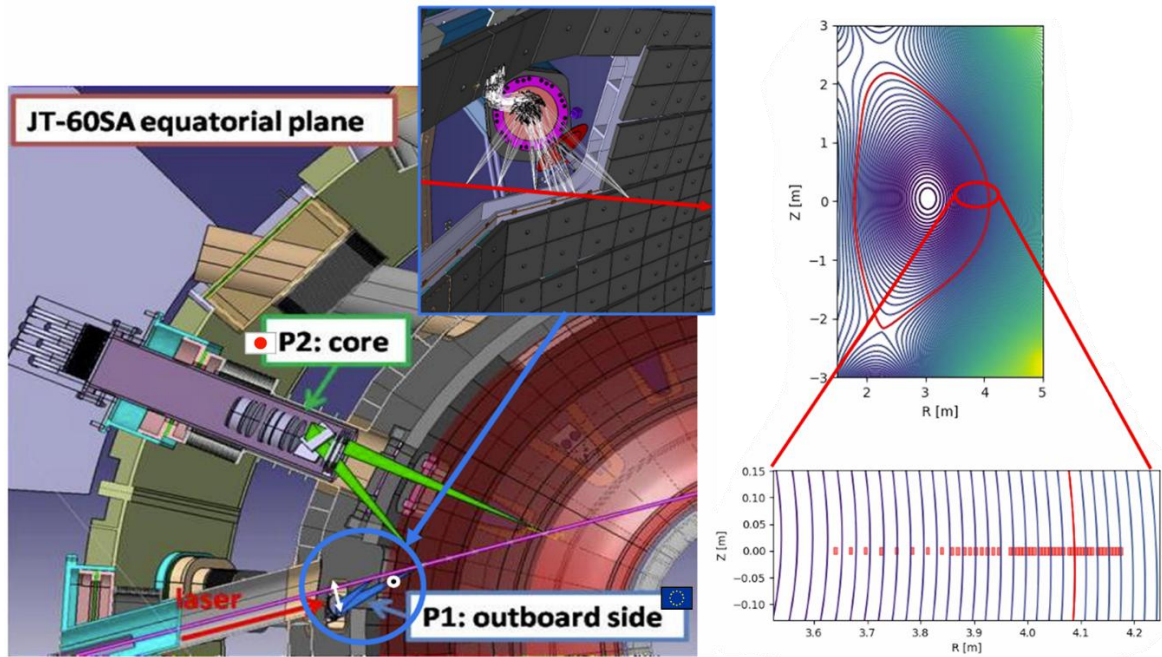


FIG. 6. Left: lines of sight of the Thomson Scattering. From toroidal sector P2: Core TS; from P1: Edge TS. Right: position in the poloidal plane of the measurement volumes of the Edge TS. By design, their spatial density is higher where larger temperature and density gradients are expected.

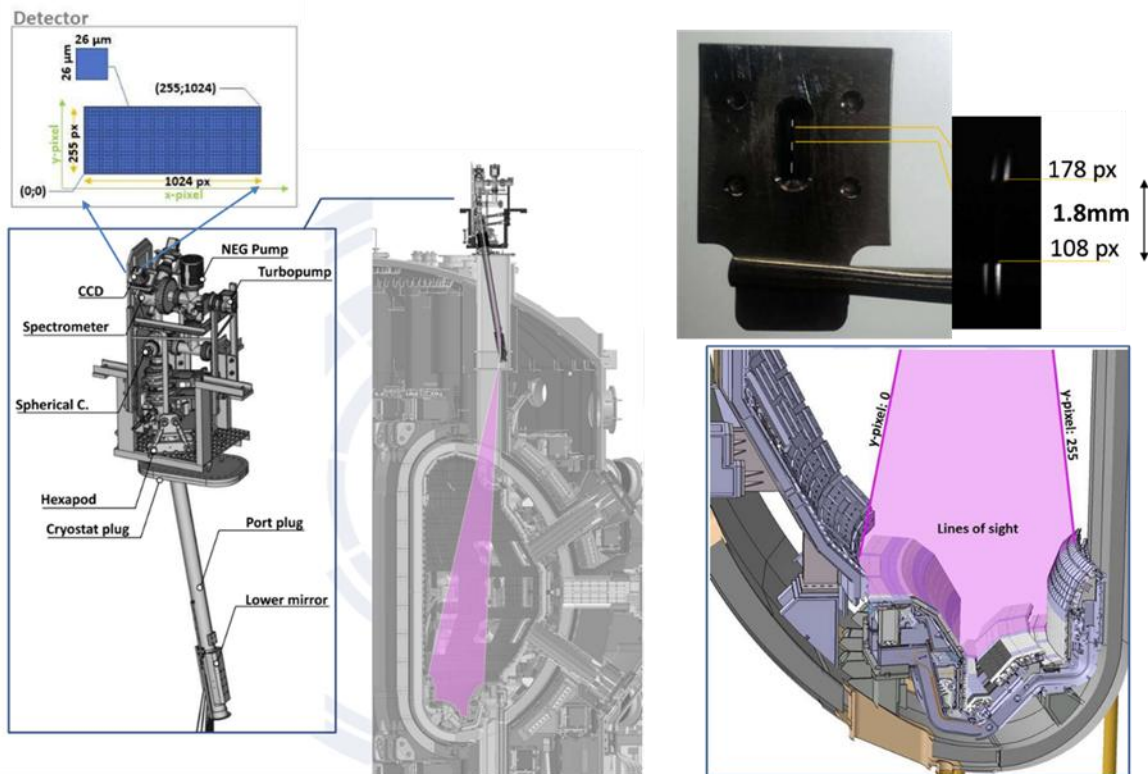


FIG. 7. Left: Layout of the Divertor VUV diagnostics, with a zoom on the CCD detector. Center: field of view of the spectrometers. Right: Imaged area of the divertor. Top right: verification of the imaging capabilities and of the magnification.

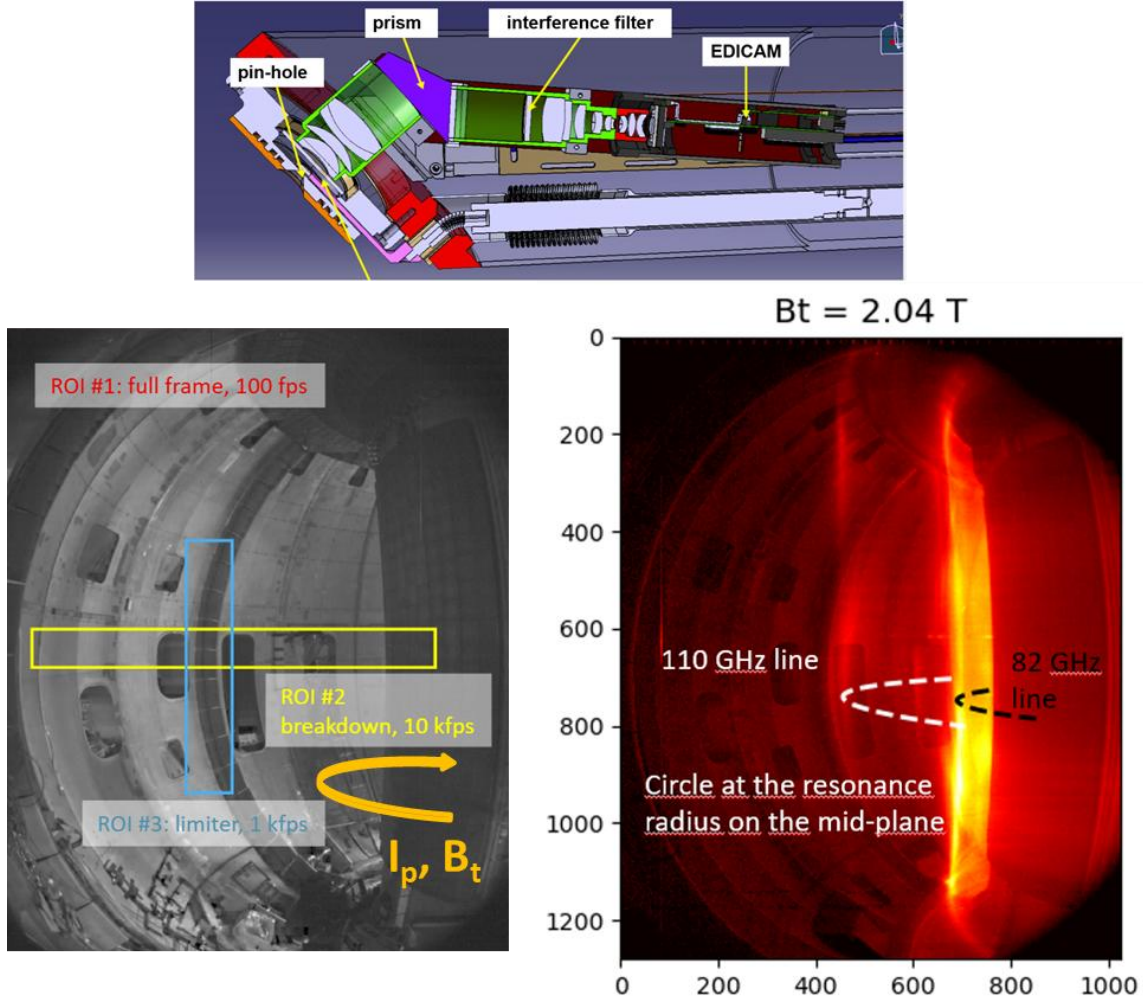


FIG. 8. Top: layout of the EDICAM in the port plug. Bottom left: field of view in the vacuum vessel with examples of Region of Interest in which special event leading to the output of a trigger or special acquisition settings can be defined. Bottom right: OP1 plasma with injection of both 82 and 110 GHz ECRF power. Layers of absorption are clearly confirmed by the images.

6. CONCLUSION AND FURTHER DEVELOPMENTS

Several state-of-art diagnostics are being installed or designed as part of the European contribution to support the scientific and technological mission of JT-60SA. Scientific objectives relevant to prepare the operations of a fusion reactor are being pursued already in the next few years [21] in parallel with the achievement of the design performance. In view of the transition from the inertially cooled carbon divertor and wall to the actively cooled tungsten divertor and first wall that will allow long pulse operations also the reinforcement of the diagnostics capabilities for edge and scrape-off layer studies and for machine protection has started

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