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Progress in diagnostics of the COMPASS tokamak

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Abstract: The COMPASS tokamak at IPP Prague is a small-size device with an ITER-relevant plasma geometry and operating in both the Ohmic as well as neutral beam assisted H-modes since 2012. A basic set of diagnostics installed at the beginning of the COMPASS operation has been gradually broadened in type of diagnostics, extended in number of detectors and collected channels and improved by an increased data acquisition speed. In recent years, a significant progress in diagnostic development has been motivated by the improved COMPASS plasma performance and broadening of its scientific programme (L-H transition and pedestal scaling studies, magnetic perturbations, runaway electron control and mitigation, plasma-surface interaction and corresponding heat fluxes, Alfvenic and edge localized mode observations, disruptions, etc.). In this contribution, we describe major upgrades of a broad spectrum of the COMPASS diagnostics and discuss their potential for physical studies. In particular, scrape-off layer plasma diagnostics will be represented by a new concept for microsecond electron temperature and heat flux measurements - we introduce a new set of divertor Langmuir and ball-pen probe arrays, newly constructed probe heads for reciprocating manipulators as well as several types of standalone probes. Among optical tools, an upgraded high-resolution edge Thomson scattering diagnostic for pedestal studies and a set of new visible light and infrared (plasma-surface interaction investigations) cameras will be described. Particle and beam diagnostics will be covered by a neutral particle analyzer, diagnostics on a lithium beam, Cherenkov detectors (for a direct detection of runaway electrons) and neutron detectors. We also present new modifications of the microwave reflectometer for fast edge density profile measurements.

Keywords: Detector design and construction technologies and materials; Nuclear instruments and methods for hot plasma diagnostics; Plasma diagnostics - interferometry, spectroscopy and imaging; Plasma diagnostics - probes

Contents

1 Introduction

The COMPASS tokamak at IPP Prague [1] is a small-size device with an ITER-relevant plasma geometry (1:10 to ITER plasma size, $R = 0.56$ m, $a = 0.23$ m, elongation up to 1.8, $I_p < 400$ kA, $B_T = 1.0$–2.1 T, $T_e < 1.5$ keV, $n_e < 10^{20}$ m^{-3}, $\tau_E = 5$–10 ms in L-mode and 10–20 ms in H-mode, pulse length up to 1 s) operating in both the Ohmic as well as neutral beam assisted H-modes since 2012 [2]. A basic set of diagnostics installed at the beginning of the COMPASS operation [3] has been gradually broadened in type of diagnostics, extended in number of detectors and collected channels and improved by an increased data acquisition speed. In recent years, a significant progress in diagnostic development has been motivated by the improved COMPASS plasma performance and broadening of its scientific programme (H-mode and pedestal studies, resonant magnetic perturbations (RMP), runaway electron control and mitigation, plasma-surface interaction and corresponding heat fluxes, edge localized mode observations, disruptions, etc.). In section 2, we describe major upgrades of a broad spectrum of the COMPASS diagnostics and discuss their potential for physical studies. Section 3 includes a short conclusion and introduces near future plans of the diagnostic development on COMPASS.

2 Progress in COMPASS diagnostics

2.1 Advanced probe diagnostics

The COMPASS was equipped with a large set of magnetic and electric probes already since the beginning of its operation at IPP Prague. A unique set of several full poloidal rings of magnetic coils (about 300 diagnostic coils from 440 magnetic sensors available in total are routinely connected to data acquisition channels, see [3–5] for details) has been partially reconnected from ATCA-based data acquisitions of 2 MSa/s to a newly acquired low-noise 256-channel solution from National Instruments having the same acquisition speed but a higher bandwidth. An array of the 39 divertor Langmuir probes (LP) and two pneumatic reciprocating manipulators (vertical for $z = 0.26$–0.41 m and horizontal for $R = 0.72$–0.78 m) equipped with different probe heads

[3, 6, 7] have been reconnected to faster D-TACQ solutions sampled at 15 MSa/s and 4 MSa/s providing submicrosecond resolution for 128 and 160 channels, respectively. The probe diagnostics have been significantly broadened by new probe heads for the manipulators, probes embedded in graphite tiles of the central column as well as of the divertor, and by standalone probes of different types. Moreover, the horizontal manipulator has been equipped with a new interface allowing exchanges of measuring heads between the COMPASS and ASDEX Upgrade tokamaks. These diagnostic tools allow unique investigations of poloidal and toroidal dependencies of edge plasma properties, see studies on a power flux profile in the edge plasma [8, 9], Alfvenic modes [10], RMP [11] or disruption studies [12, 13]. In the next paragraphs, we separately review major probe types and designs used there.

Langmuir probes are known for their capability of providing local measurements of main plasma parameters like the electron density and temperature but also the electron energy distribution function (EEDF). In fusion plasmas, an assumption of the Maxwellian EEDF is often used but not always valid in tokamak scrape-off layer (SOL) and divertor plasmas. Therefore, a new probe head equipped with two large graphite Langmuir semi-cylindrical pins with diameter of 3 mm and length of 8 mm (old cylindrical pins had diameter of 0.9 mm and length of 2 mm) was constructed and mounted on the horizontal manipulator, where it was used for studying a radial profile of edge plasma parameters. Note that using larger size probes the signal to noise ratio is better and the influence of the sheath extension in ion saturation current is diminished. The sweeping mode with a 1 kHz triangular voltage waveform allowed reconstructing current-voltage characteristics at different probes positions. Similarly, a standard set of LPs was used for investigation of the divertor region. Data processing by the first derivative probe technique (FDPT) showed that the EEDF often deviates from Maxwellian but can be approximated by a bi-Maxwellian EEDF with a low temperature electron fraction mostly more populated than that of the high energy electrons [7, 14, 15].

In order to better characterize SOL dynamics, in particular a poloidal asymmetry of radial profiles, two new compact in-vessel magnetically driven reciprocating manipulators, called pecker probes [16], have been recently commissioned and placed at the magnetic low field side at ±47.5° with respect to the outer mid-plane to supplement the vertical and horizontal drives installed on COMPASS. Their rotation is based on an energized coil in the tokamak magnetic field. The coil is fixed on a rotating axis and provides a leverage which is converted into a linear motion. The pecker probes are equipped with identical tunnel probe heads, providing simultaneous measurements of the ion saturation current density, the electron temperature and the parallel Mach number with a high temporal resolution. The tunnel probes are composed of a conducting hollow cylinder with its axis parallel to magnetic field and closed at one side by an electrically insulated back plate. The advantage of the tunnel probe is to be immune to sheath expansion.

A more complex electrostatic-magnetic probe diagnostic, called U-probe [17, 18], has been developed to allow both radial and poloidal measurements of structures propagating in a SOL plasma [18]. The U-probe consists of two identical towers; each tower houses radially separated 3 sets of three mutually perpendicular coils (for local measurements of radial, poloidal and toroidal magnetic fields), a triple probe and a rake of six LPs. It is optimized for measurement of the electric current carried by plasma structures parallel to magnetic field lines. The support structure allows both radial and angular adjustments on a shot-to-shot basis. This configuration is suitable for a statistical analysis of plasma structure parameters.

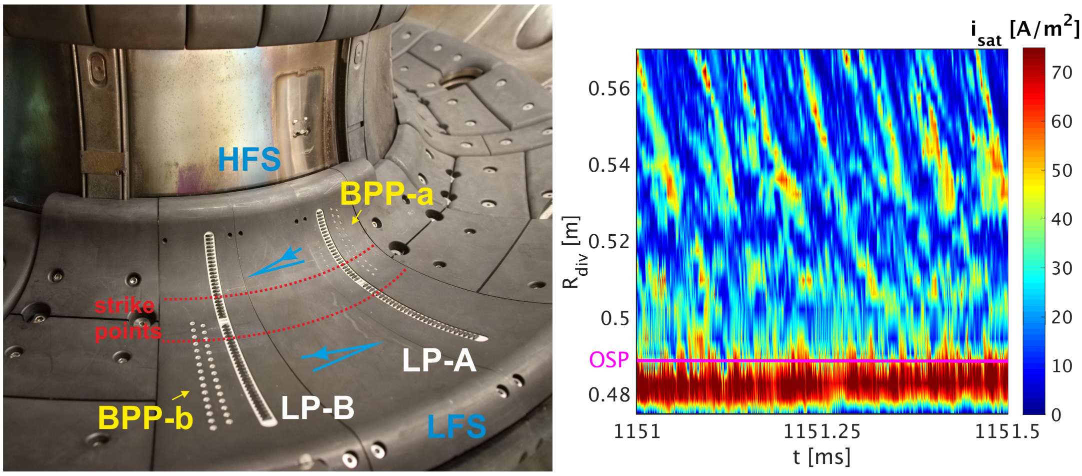

Figure 1. Left: a new set of the divertor probes combining two full arrays of 55 rooftop-shaped Langmuir probes (LP-A and LP-B) and one array of 56 ball-pen probes, which is divided into two half arrays (BPP-a and BPP-b) located at the magnetic high field side (HFS) and magnetic low field side (LFS) oppositely compared to the neighboring LP array to avoid shielding effects (magnetic field line direction is indicated by the blue arrows). The red dotted arcs indicate typical strike point positions in the flat-top of diverted discharges on COMPASS. Right: propagation of density structures (blobs) along the divertor probes in L-mode in the shot #13034. Position of the outer strike point (OSP) calculated from the magnetic reconstruction is indicated by the magenta line.

A qualitative step forward has been reached by development of so called ball-pen probe (BPP) at IPP Prague, allowing both a direct measurement of the plasma potential and the electron temperature with a submicrosecond temporal resolution, and thus, calculation of the highly time resolved parallel heat flux density [19–22]. The BPP has a conically shaped collector retracted in an insulating shielding tube, which screens off an adjustable part of the electron current from the probe collector due to a much smaller gyro-radius of electrons. This reduces the electron saturation current to the same magnitude as that of the ion saturation current, thus, the floating potential of the probe approaches the plasma potential. Recent 3D particle-in-cell simulations [23] explained and fully confirmed the capability of the ball-pen probe to measure plasma potential and its fluctuations as well as of a combination of the ball-pen probe in conjunction with a floating Langmuir probe to derive the electron temperature. Gaining from unique features of BPP, we developed several different probe heads for the horizontal manipulator: a) "standard probe head" containing 3 BPPs and 2 LPs for common edge plasma measurements, and b) "high heat flux probe head" containing 3 BPPs and 4 LPs in a stepwise inclined carbon envelope optimized for high heat flux conditions (deep reciprocations), c) "Reynolds stress probe head" [24] consisting of several LPs and BPPs placed in two radially elevated floors for the investigation of phenomena, where fluctuations of the plasma potential, the electric fields, the density and the electron temperature play a key role, such as electrostatic turbulence and associated quantities like the Reynolds stress, transient events like L-H transition and various associated dynamics, e.g. limit cycle oscillations and edge localized modes. The usually used design is based on probes displaced by several millimeters from each other (2–8 mm) in poloidal and toroidal directions, where a mutual toroidal shielding of BPPs by LPs must be avoided. LPs are realized as graphite cylinders of about 1 mm in diameter, while BPPs are made of a boron nitride shielding tube (2–3 mm in diameter), in which a stainless-steel collector is retracted by about 0.5 mm. Another probe head type was developed for the vertical manipulator, where two tunnel probes [25] for fast measurements of the electron temperature, precise determination of the ion saturation current density and the parallel Mach number are combined with one BPP and two LPs (one floating, one in the ion saturation current regime) installed at the top of the probe head to measure directly the plasma potential and the electron temperature with a high temporal resolution, and therefore, the parallel heat flux. Finally, a new extensive set of divertor probes combining two full arrays of 55 rooftop-shaped LPs and one array of 56 BPPs has been designed and manufactured in order to investigate profiles and fast changes of divertor plasma parameters, see figure 1. The array of BPPs is divided into two half arrays at the low and high magnetic field sides, which are shifted toroidally with respect to LPs to avoid shielding effects. The realized configuration allows reaching a microsecond temporal resolution of the electron temperature and the parallel heat flux density, the key parameters for studies of the plasma-surface interaction, especially in ELMy H-mode. The spatial resolution of these measurements is 3.5 mm.

A commonly used diagnostic designed to measure the ion temperature in SOL of tokamaks is retarding field analyzer (RFA). For COMPASS, a miniature bidirectional RFA probe head of 22 mm in diameter has been developed. Due to its small size, it can be mounted on both reciprocating manipulators or inserted into a dedicated limiter on the central column. Using 1 kHz sweeping of the slit plate, also electron temperature and density can be measured. Bidirectionality of the probe allows deriving the Mach number.

2.2 Upgrade of optical and microwave diagnostics and plasma tomography

Already first plasmas on COMPASS were monitored by two high-speed B/W cameras [3], which are currently supplemented by two faster colour Photron FASTCAM Mini UX100 (1280×1024 px @ 4 kfps, 640×8 px @ 800 kfps) [26]. They are usually equipped with the endoscope consisting of a wide angle lens (e.g. $f = 4.8$ mm) to obtain an overview of the vacuum vessel (reaching up to 180° is possible) and relay optics allowing placing the camera outside toroidal field coils. The cameras resolve individual macroscopic events of the plasma-surface interaction, they allow dust tracking, observe plasma modifications due to RMP, detachment or a presence of a runaway beam [27], see figure 2. For even faster events like ELMs, where a time resolution of tens microseconds is desirable, B/W Photron FASTCAM cameras (SA-X2, APX-RS) are used with a more narrow field of view providing submillimetre resolution, e.g. in dust remobilization experiments [28].

Newly, COMPASS has also been equipped with two different infrared (IR) cameras for infrared thermography. The slow Micro-Epsilon TIM-160 is equipped with a bolometric detector (7.5–13 μm, 160×120 px @ 120 Hz), the fast camera Telops Fast-IR 2K has an InSb detector (3–5 μm, 320×256 px @ 1.9 kHz, 64×4 px @ 90 kHz). The cameras could be placed to various torus locations securing an observation of the central column limiters (0.5 mm/px) for SOL heat flux studies [8, 29], of the low field side protection limiter (1 mm/px) for runaway studies [27] or of the divertor region (0.5–1.5 mm/px will be reached using a newly developed IR endoscope), where a new graphite divertor tile optimised for IR thermography in ELMy H-mode will be placed (optimized magnetic field incidence angles, embedded tile heating and bulk temperature measurement) [30]. One of the first fast IR measurements in the divertor region on COMPASS, based on a temporal set-up

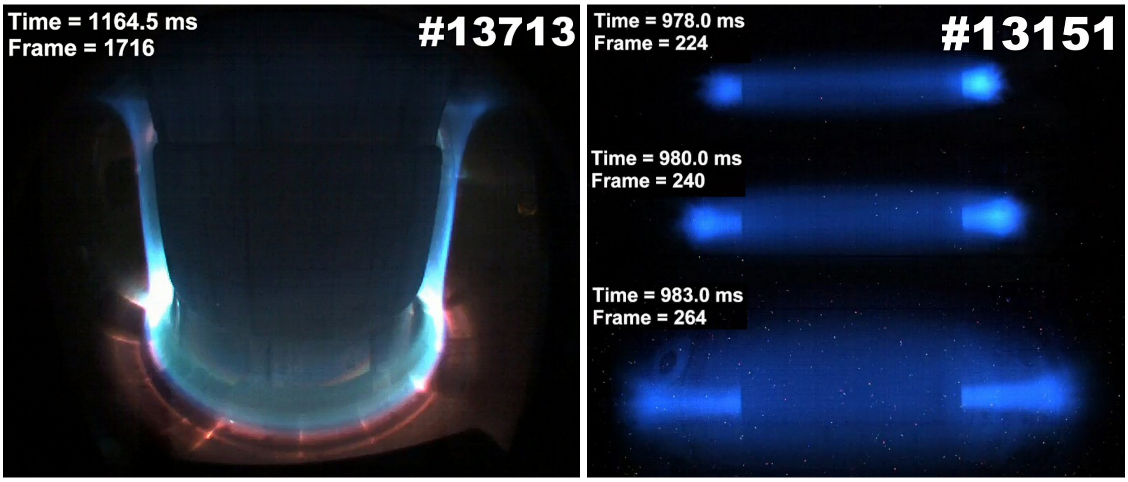

Figure 2. Examples of the use of the high-speed color UX100 camera. Left: nitrogen emission (blue) observed in the deuterium (pink) discharge realized in the frame of the detachment campaign. Right: three selected camera frames show the radial expansion of the runaway beam, which was formed after the argon puff in the current ramp-up phase of the discharge. Blue emission comes from the excited cold background Ar gas by the beam.

consisting of a standard 100 mm lens looking through a sapphire window, is shown in figure 3. The heat flux was reconstructed using the THEODOR code [31].

The dominant role among optical diagnostics on COMPASS belongs to the Thomson scattering (TS) diagnostic, which routinely provides both electron density and temperature profiles with a spatial resolution of about $a/30$ in the core and up to $a/100$ at the edge [32, 33]. The core and edge TS systems have separate collection optics, located in separate tokamak ports, sharing the same laser beams (Nd:YAG at 1064 nm). The scattered light is transmitted via fibre bundles. The detection is based on filter polychromators equipped with avalanche photodiodes, allowing covering the electron temperature range from 30 eV to 5 keV. The edge TS system was upgraded recently with the aim to improve quality and extent of measured data for an H-mode pedestal analysis [34]. The first phase of the upgrade consisted of cutting the existing edge TS port and welding a new one. The viewport of the edge TS diagnostic was increased in size from 100 mm to 150 mm and its inclination was modified to be directed towards the edge plasma region. Therefore, it allows a better observation of the plasma edge in all plasma scenarios. In the second phase, a newly built collection optics will fully exploit the optimised view, making the resolution and F-number more uniform over the observed region (resolution about 3.5 mm, $F/\#$ from 5.1–5.8 to newly reached 5.0 providing a higher signal-to-noise ratio). Also, a temporal resolution of both the core and edge TS systems is being improved by addition of two new lasers to the existing two, increasing the repetition rate from 60 Hz to 120 Hz, or timing the lasers to obtain 4 subsequent time slices with an arbitrary separation.

Since the TS diagnostic can measure the density with a submillisecond resolution only for a short burst of pulses, a real-time signal of the electron density integrated along the central chord used for the density feedback is provided by the upgraded 2-mm microwave interferometer [35, 36]. Two voltage-controlled oscillators, stabilized by the phase-locked loop, in combination with multipliers generate

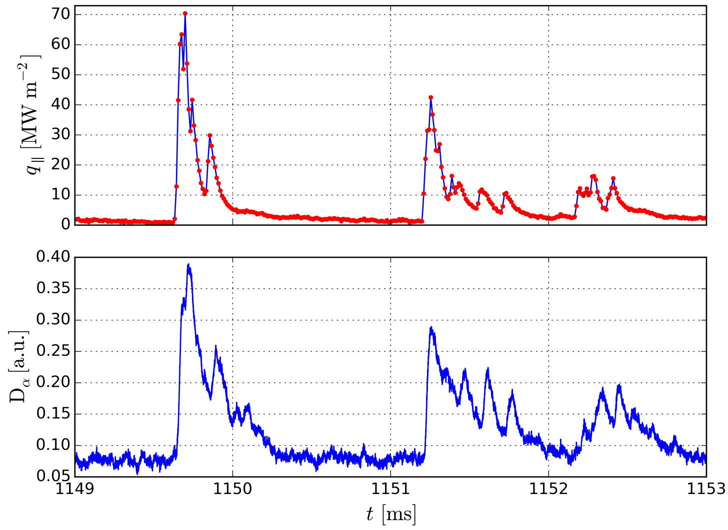

Figure 3. Parallel heat flux (upper graph) extracted from the fast IR camera measurement (90 kHz) in the inner divertor region approx. 50 mm from the separatrix (corresponding to about 4 mm, when mapped to the outer midplane) and the D_α signal (lower graph) for the H-mode discharge #12497. Individual edge localized modes (ELMs) as well as their internal structure (filaments) can be clearly recognized. Red dots in the upper graph indicate time stamps of the IR camera frames.

two probing waves of close frequencies of 138.9 and 139.6 GHz. The digital 2π-phase detector in the receiving part compares the phase between these probing waves. Therefore, the phase response does not suffer from fringes for the full range of COMPASS densities, which is more than 12×10^{19} m^{-3}. Both the real-time and post-processed electron density signals are corrected to a real plasma shape and to a non-linearity of the refractive index of the plasma at high densities [37]. Obtained results allow precise phase measurements in the phase range of 0–360° with a fast reset possibility.

Edge plasma density profiles in the range of 0.4–3 $\times$ 10^{19} m^{-3} as well as density fluctuations are measured by the fast broadband microwave reflectometry system consisting of O-mode K (18–26.5 GHz), Ka (26.5–40 GHz) and a part of U (40–53 GHz) bands [38]. Measurement of density profiles can be alternated by fixed frequency hops for the plasma turbulence studies. The former homodyne system was extended by I/Q modulators and detectors for the heterodyne detection. The 6 μs full range frequency sweeping time is followed by 1.5 μs of the recovery time. To reduce the effect of random perturbations of the signal the electron density profile is determined from 4 consecutive sweeps, therefore, we obtain the density profile every 30 μs. The heterodyne detection also allows evaluating frequency shifts caused by the Doppler effect. For this case, the alternative Ka-band tilt antenna was constructed.

Plasma tomography is a powerful technique providing emissivity distributions from chord integrated measurements. On COMPASS, it is routinely applied to bolometric (up to 6 AXUV diode arrays with 20 channels each distributed in one poloidal cut) and soft X-ray (up to 3 silicon diode arrays having 90 channels in total distributed in one poloidal cut) data for calculation of radiation of the confined plasma and for analyses of MHD events [39, 40]. The algorithm based on Tikhonov regularization constrained by minimum Fisher information was optimized for COMPASS [41] and

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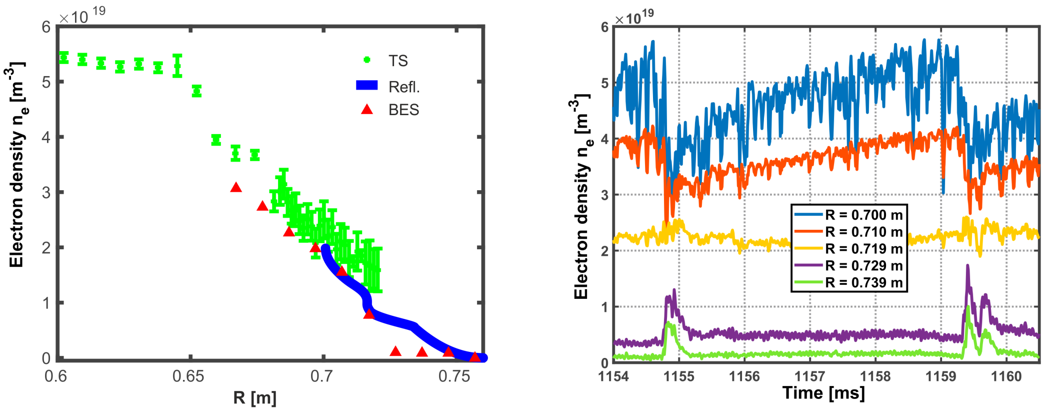

Figure 4. Left: electron density profile measured by the Thomson scattering (TS) diagnostic, beam emission spectroscopy (BES) using the lithium beam and reflectometry in the current flat-top (at 1120.04 ms) in the L-mode diverted discharge #10759. In diverted discharges, the profile measured by TS and mapped using the magnetic equilibrium code should be shifted by about 1 cm to get a good agreement with the profiles provided by BES or reflectometry (no artificial shift is needed in circular discharges). Right: temporal evolution of the electron density at different radii at the outer midplane in the ELMy H-mode discharge #14160 measured by the Li-beam based BES diagnostic. The observed modification (flattening) of the density profile connected with the ELM crash and the profile restoration in the following inter-ELM phase is demonstrated on the time window covering two subsequent ELMs.

modified for future possible real-time applications [42].

2.3 Upgrade of particle and beam diagnostics

The upgraded diagnostic lithium beam (operated at 10–80 kV, max. possible 120 kV, doubled ion source size to 17 mm in diameter, thermionic heater, optimized neutralizer) based beam emission (BES) spectroscopy on COMPASS [43] with the improved data acquisition (18 avalanche photo diode channels @ 2 MSa/s) and with the achieved signal to background ratio up to 10 : 1 and S/N ratio about 100 allows a range of measurements: (i) inter-ELM profiles, (ii) SOL turbulence (blobs), (iii) turbulence at the plasma edge (modes within the confined plasma), (iv) Geodesic Acoustic Modes and (v) ELM precursors [44], see figure 4. Synchronization of the fast beam chopping system and DAQ allows reconstructing density profiles with the time resolution up to 2 μs. We also successfully tested the beam reducer down to a diameter of 5 mm with the aim to provide a higher poloidal resolution for density measurements (also essential for edge current measurements with Atomic Beam Probe [45]).

The absolutely calibrated neutral particle analyzer (NPA) on COMPASS is a diagnostic tool used for simultaneous measurements of the energy distribution of fast hydrogen and deuterium atoms and for determination of the ion temperature profile with help of the numerical code DOUBLE [46]. The analyzer has 12 spectral channels for hydrogen (0.25–70 keV) and the same channel number for deuterium (0.3–50 keV). Measured spectra are provided with a time resolution in the range of 50 μs–1 ms, therefore, transient phenomena like sawtooth oscillations or even ELMs can be tracked. In neutral beam heated discharges, NPA reveals the ion decay time and its dependence on plasma parameters, which helps in understanding of plasma interaction with fast atoms of the beam.

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A fractional composition of the two deuterium heating beams (up to 40 kV, 12 A) is derived from peak ratios of the Doppler red-shifted Dα line above 656 nm corresponding to individual beam components (D^+, D_2^+, D_3^+, D_2O^+) [47]. Measurements are performed by the HR2000+ spectrometer (FWHM about 0.06 nm) observing the beam at 45°. These spectroscopic data also mediate information about the beamlet divergence, which is connected with the width of the shifted spectral line.

Monitoring of the neutron rate during operation of the heating beams is ensured by a new scintillation detector (photomultiplier combined with the EJ-410 scintillator encapsulated in the Mu-metal shield) [27], which is installed in the tokamak hall within a 10 cm thick lead shieling. Simultaneously, two neutron detectors based on the ^{3}He proportional counter routinely contribute to the measurement (up to 33 counts per second) of fusion neutrons and of photoneutrons produced in discharges with energetic runaway electron population. Due to the character of the detection — nuclear reaction and detection of the ion products (p and T) by the proportional counter — the ^{3}He detectors are almost insensitive to gamma rays. This is of particular importance for runaway electron experiments that are accompanied by large intensities of hard radiation and photoneutrons.

A direct measurement of runaway electron (RE) beams at the SOL plasma is possible with help of the Cherenkov detector [48]. On COMPASS, the Cherenkov probe consists of three CVD-diamond crystal detectors (coated with different Ti/Pt/Au/Mo filters) mounted on a titanium zirconium molybdenum (TZM) measuring head, having the electron energy threshold of 58 keV, 145 keV and 221 keV, respectively. Cherenkov signals clearly corroborate presence of post-disruptive RE beams in circular plasma discharges with a massive Ar puff. Also, a strong correlation of localized Cherenkov signals with MHD activity is observed, revealing conditions and mechanisms of RE acceleration and losses.

3 Conclusion and near future plans

A significant progress in diagnostic development on the COMPASS tokamak allowed broadening of its scientific programme to cover H-mode and pedestal studies, RMP, RE control and mitigation, plasma-surface interaction and corresponding heat fluxes, edge localized mode observations, disruptions, etc. Nowadays, COMPASS is equipped with a nearly full set of modern high-temperature plasma diagnostics, which provide physically interesting, high spatially (of order of millimetres) and temporarily (of order of microseconds) resolved data.

In a near future period, plasma rotation diagnostics will be put in operation. First, the charge exchange (CXRS) diagnostic providing both the toroidal rotation and ion temperature profiles is in the commissioning phase presently [49]. Second, the upgraded high resolution spectrometer focused on CIII lines at 465 nm [50] providing both the poloidal rotation and ion temperature profiles in the edge plasma (instead of single point measurements before the upgrade) is expected to be reinstalled shortly afterwards.

Acknowledgments

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