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New Detection System for Fast Density Measurements Using the Lithium Beam on the COMPASS Tokamak

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Abstract. The lithium beam diagnostic at COMPASS is designed for measurements of the edge plasma density profile and fluctuations and edge plasma current fluctuations. The principle of the diagnostic is detection of light coming from collisionally excited Li atoms — beam emission spectroscopy (BES) - and a direct detection of the ionized part of the beam (atomic beam probe — ABP). For slow density measurements a charged coupled device (CCD) camera has been installed and is already working. For fast two-dimensional density profile and density fluctuation measurements an array of avalanche photodiode detectors (APDs) will be used. The two-dimensional resolution of the measurement will be possible using fast poloidal deflection and chopping of the beam. Apart from routine density profile measurement, the diagnostic will be capable of investigating the turbulent structures in the edge plasma by cross-correlating the signals coming from poloidally deflected virtual beams. The article describes the recently installed detection system and its experimental aims.

Introduction

After its reinstallation in Prague [*Panek et al.*, 2006], the COMPASS tokamak has successfully achieved both ohmically and neutral beam heated discharges with high confinement mode (H-mode). The physical programme of COMPASS is focused on the edge plasma behaviour, mainly the study of transport barrier formation and its stability during H-mode and also of transition from low to high confinement mode (LH transition). Both fields are very important for successful operation of ITER plasmas. One of the most serious issues of today's tokamak physics is the investigation of the edge localised modes (ELMs) — magnetohydrodynamic (MHD) instabilities causing repetitive crashes of the edge transport barrier during H-mode. As they greatly enhance particle and energy transport for a short period (10–100 μs), they cause intense heat load on the divertor plates and the first wall, which could be disastrous in the case of ITER (≈ tens of MJ for type I ELMs with frequency 1–5 Hz [*Leonard et al.*, 1999]). Better knowledge of physics underlying LH and HL transition is also important, as it was found that the LH power threshold for nominal ITER density discharges might be too high compared to the planned available heating power.[*Martin et al.*, 2008]

The recently installed diagnostic of the lithium beam on the COMPASS tokamak [*Hacek et al.*, 2011] is one of the newly built tools aiming at measuring important plasma parameters in the pedestal region with sufficient spatial and temporal resolution. Similar lithium beam based diagnostic systems have been already working and providing routine density measurements on several tokamak and stellarator experiments, i.e. on ASDEX Upgrade, W7-AS [*Fiedler et al.*, 1999], TEXTOR [*Anda et al.*, 2008] and JET [*Brix et al.*, 2001]. The principle of the diagnostic is that an accelerated neutral lithium beam is injected radially into the vacuum vessel and interacts with plasma. The beam atoms are collisionally excited and ionized - the excited neutral atoms return to the ground state by emitting radiation with a characteristic wavelength. The measured intensity of the emitted light allows reconstruction of the electron density profile [*Schweinzer et al.*, 1992]. Fast beam deflection to several vertical positions and correlation of the signals allows observation of turbulent structures in the plasma edge. The beam in plasma is consequently ionized and the lithium ions bend their trajectory due to the local magnetic field. In dependence on their Larmor radius they are either confined or leave the plasma and hit the vessel wall. Their detection can provide information about the magnetic field along their path and therefore indirectly also about the edge plasma current [*Berta et al.*, 2013].

Diagnostic lithium beam system on the COMPASS tokamak

The model of the COMPASS lithium beam system can be seen in Figure 1. The source of the lithium ions is a solid emitter made of β-eucryptite (Li_2O + Al_2O_3 +$2SiO_2$). Lithium ions are constantly emitted by heating the emitter to about 1300 °C and applying an external electric field. The ion beam is then accelerated and focused by a set of electrodes. Deflection plates can be used for vertical or horizontal movement of the beam in the plasma (by up to 5 cm) or for beam chopping, which is necessary for background noise measurement. As the lithium ions would not be able to enter the vacuum vessel due to large tokamak magnetic fields, they have to be neutralized. This is done in the neutralizer chamber filled with sodium vapor (Na pressure is about 10^{-2} Pa). The beam atoms pass through the chamber and are partially neutralized by charge exchange reactions with the sodium atoms. The neutralization efficiency depends on the beam energy and is typically above 80% [*McCormick et al.*, 1997]. The neutralized part of the beam then enters the tokamak vessel.

Light emitted by the lithium atoms, after their excitation by collisions with the plasma particles can be detected by a CCD camera and a set of APDs; the ionized part of the beam can be collected directly by the Atomic Beam Probe detector (ABP). The beam width in the vacuum vessel is typically 1.5–2 cm. For a standard density measurement, the beam energy is set to 30–40 keV and the beam current is typically a few mA. However, the beam energy will be increased up to 100 keV and the beam diameter decreased to 1–2 mm for experiments with the ABP.

Beam Emission Spectroscopy

Injected lithium atoms are excited and ionized by collisions with the plasma particles and the intensity of the spectral line 670.8 nm coming from Li I (2s–2p) transition is measured. The line is chosen by 2 nm wide interference filters, which are put in front of the collection optics of both the CCD camera and the APDs. The interaction of Li atoms with the plasma can be described by the collisional-radiative model [*Schweer*, 2008], where the relative occupation of the excited electron states and the ionization rate is calculated using known tabulated values [*Schweinzer et al.*, 1999] of the cross sections and transition probabilities for all considered reactions (electron and proton impact

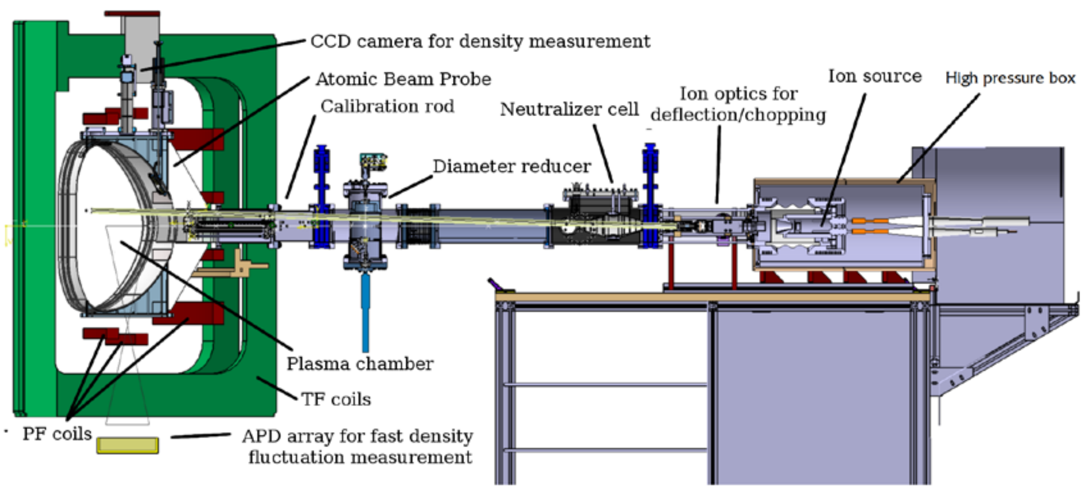

Figure 1. Model of the Diagnostic Lithium Beam system on the COMPASS tokamak

excitation and ionization, charge exchange ionization, radiative deexcitation). These cross sections depend on the plasma density and temperature, but for the case of lithium atoms, the temperature dependence is weak. Therefore, a numerical reconstruction of plasma density only from the occupation of the 2p excitation level is possible. The technique used on COMPASS is thoroughly described by *Krbec* [2013].

There are two detection systems for BES of the lithium beam on COMPASS. The CCD camera with focusing optics and digital temperature compensation is already installed and operational there. The camera chip has 640×480 pixels and its spatial resolution ranges from 0.5 mm/pixel to 1 mm/pixel due to distortion of the optics. Temporal resolution of the camera is 100 Hz. The temporal resolution could be increased by pixel binning. Presently, 10 ms exposition time is used to ensure sufficient amount of detected light. APD detector unit for the fast measurement will be described in the next part.

APD detection system on COMPASS

A compact box (APD camera unit, see Figure 2) containing interference filter, collection optics, array of 18 avalanche photodiodes and analogue-digital converters (ADCs) with optical interface has been installed on the bottom vertical port of the vacuum vessel (Figure 1). The APD detectors are of type S8664-55 with 25 mm^2 effective area, quantum efficiency of 85 % (at 650 nm) and gain ≈ 50 at 360 V. To ensure the same sensitivity of APDs, they need to be stable in temperature. For this reason, they are mounted upon a copper rail and cooled by two Peltier units. The detection system features also a special low noise operation amplifier developed in Wigner RCP, Hungary and is operated with 1 MHz bandwidth. The solid state silicon APD detectors have been chosen due to their high quantum efficiency and internal gain. It was found that for a photon flux range 10^8–10^{10} photons/s typical for similar BES measurements, the APD detectors have better signal to noise ratio than other considered detector options — photomultipliers and photodiodes — and that they do not require cryogenic cooling of any component.[*Dunai et al.*, 2010]

The focusing optics is designed in a way that each APD channel sees 1cm of the beam path. A spatial calibration of the system was made using light bulbs placed on a rod movable into the tokamak vessel through the horizontal port used by the Lithium Beam System. The 18 APDs map 18 cm of the beam path between major radii 58.7 cm and 75.7 cm and thus cover almost the full minor radius (≈ 20 cm).

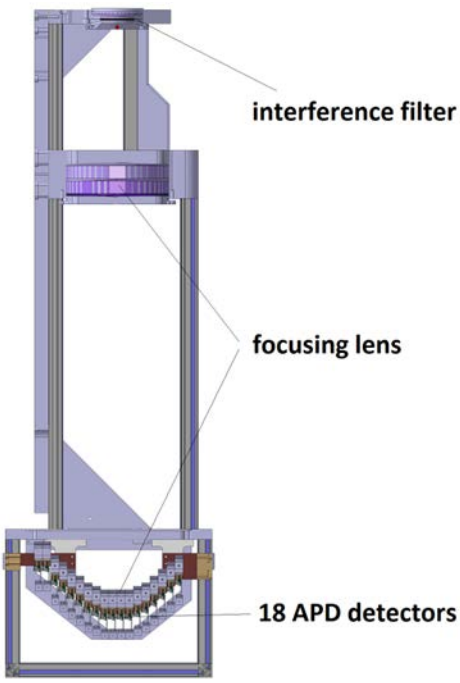

Figure 2. Model of the COMPASS APD camera unit.

Fast two dimensional density and density fluctuation measurement

The temporal resolution of the APD detection system will be as good as 1 μs. For the numerical reconstruction of plasma density, it is necessary to integrate the light signal collected by APDs for a longer time to get sufficient signal to noise ratio. The real temporal resolution of density profiles is therefore estimated in sub-millisecond or ms range. As can be seen in Figure 3, the two-dimensional BES measurement will be achieved by electrostatic beam deflection in vertical direction.

However, if we do not aim at obtaining absolute density values, the raw APD signal can still provide us information on fast fluctuations of the beam light (and therefore plasma density) on the microsecond timescale. If the beam deflection is performed faster than the lifetime of the turbulent structures in the plasma, the APDs are capable of measuring the structure of plasma density fluctuations [*Zoletnik et al.*, 2005]. This requirement is fulfilled on COMPASS as the beam deflection can be done as fast as 400 kHz and autocorrelation time of the fluctuations in scrape-off layer (SOL) and edge plasma is typically in the range of 10–100 μs [*Zoletnik et al.*, 2005].

One of the phenomena supposed to have a strong influence on transport barrier formation in LH transitions is the appearance of zonal flows. Zonal flows are $n = 0$, $m = 0$ electrostatic potential fluctuations with a strong radial dependence which cause sheared poloidal ExB flows. As they are generated by nonlinear energy transfer from drift waves, their generation reduces the intensity and level of transport caused by the primary drift wave turbulence [*Diamond et al.*, 2005] Moreover, the sheared velocity can tear larger turbulent structures. Experiments for observation of the zonal flows (mainly their oscillatory high-frequency part — so called geodesic acoustic modes, GAMs) with APD diagnostic using a lithium beam were done on TEXTOR tokamak [*Zoletnik et al.*, 2012] and are planned also on COMPASS.

The idea of the planned experiment is the following: by applying a low deflection voltage (100–200 V) and switching its polarity with a frequency of 400 kHz, we get in fact two "virtual beam" light signals. The signals have 2.5 μs time resolution and come from 1–2 cm poloidally shifted locations. The poloidal propagation of turbulence can be studied by correlating suitably selected pairs of these signals. The standard time delay estimation method (TDE) can be used to estimate the time delay of the poloidally shifted signals from the maximum of their cross-correlation (CCF) and therefore also poloidal flow velocity of fluctuations can be calculated. Using more channels provides us with a radially resolved measurement of velocity fluctuations $v(t,r)$ and the velocity shearing rate $dv(t,r)/dr$ can also be estimated.

Overview and plans

The diagnostic lithium beam system was developed for the COMPASS tokamak. Its main goal is to provide edge density (BES) and edge plasma current (ABP) measurements. Recently, a new extension of the diagnostics featuring the system for fast beam light detection by a set of 18 avalanche photodiode detectors was installed. This system is able to measure with 1 μs temporal resolution and therefore it can be used for investigations of the edge plasma turbulence and its evolution during H-mode operation. The system has been spatially calibrated and successfully tested. First measurement and results are planned for the coming tokamak COMPASS campaign dedicated to H-mode operation.

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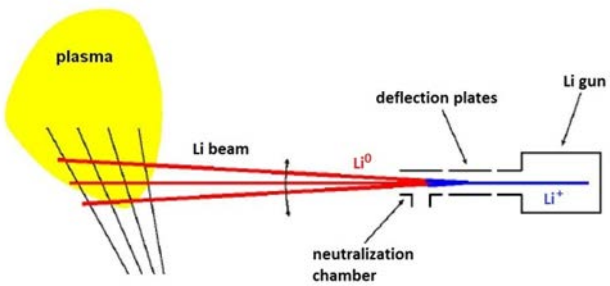

Figure 3. Scheme of the Lithium Beam experiment. [*Zoletnik et al.*, 2005].

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