

On Use of Semiconductor Detector Arrays on COMPASS Tokamak

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Abstract—Semiconductor detector arrays are widely used in high-temperature plasma diagnostics. They have a fast response, which allows observation of many processes and instabilities in tokamaks. In this paper, there are reviewed several diagnostics based on semiconductor arrays as cameras, AXUV photodiodes (referred often as fast “bolometers”) and detectors of both soft X-rays and visible light installed on the COMPASS tokamak recently. Fresh results from both spring and summer campaigns in 2012 are introduced. Examples of the utilization of the detectors are shown on the plasma shape determination, fast calculation of the radiation center, two-dimensional plasma radiation tomography in different spectral ranges, observation of impurity inflow, and also on investigation of MHD activity in the COMPASS tokamak discharges.

Keywords—Bolometry, plasma diagnostics, soft X-rays, tokamak.

I. INTRODUCTION

SEMICONDUCTOR detectors appeared in physics in about 1960. Since that time a number of their types and applications have quickly grown. This article focuses on semiconductor detector arrays widely used in high-temperature plasma diagnostics, which have a fast response in the range of several microseconds. This time-scale is shorter or at least comparable with characteristic times of many processes and instabilities in tokamaks. In Section II, different semiconductor arrays are introduced as cameras, detectors of total radiated power, soft X-rays and visible light in the frame of new diagnostics installed on the COMPASS tokamak. Examples of their applications are shown in Section III: determination of the plasma shape, two-dimensional plasma radiation tomography, observation of impurity inflow, and also on investigation of MHD activity in tokamak discharges. Section IV summarizes the current use of the semiconductor arrays on COMPASS and outlines future directions of physics investigations using these detectors.

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II. EXPERIMENTAL SETUP

A. The COMPASS Tokamak

The COMPASS tokamak (Fig. 1) is the smallest device of the ITER-like divertor plasma geometry ($R=0.56\text{m}$, $a=0.18\text{m}$, $B_T<2\text{T}$, discharge duration $<1\text{s}$, linear size ratio to ITER plasma 1:10) [1]. Recently it was equipped with a set of significantly upgraded or completely new plasma diagnostics [2]. Till spring 2012, COMPASS has been operated with circular plasma, usually in touch with an inner carbon limiter. The realized L-mode discharges of up to 300ms duration were usually performed at low magnetic field of $B_T\sim 1.1\text{-}1.2\text{T}$ and plasma current I_p in the range of 100-180kA. Successful commissioning of both the new slow (2 kSamples/s) and fast (20 kSamples/s) digital plasma position feedback systems on COMPASS [3] [4] [5] led to a realization of the first shaped plasmas and lower single-null divertor configurations with low and high triangularities in May 2012. An iterative approach, when successful discharges with improved parameters were, immediately after the shot, compared with unsuccessful ones using magnetic and spectroscopic diagnostics and inputs for new shot were derived, led to fast optimization of the possible operational scenarios.

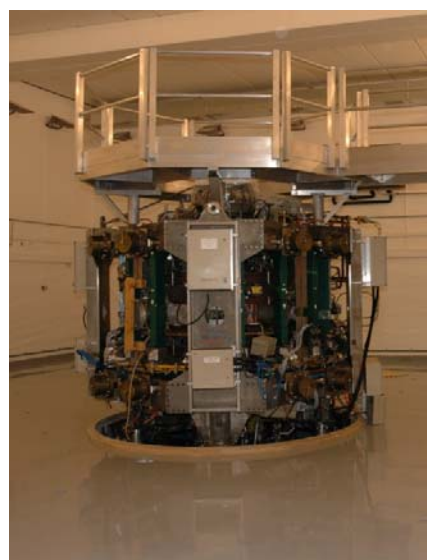


Fig. 1 The COMPASS tokamak at IPP Prague.

B. Fast Cameras

The COMPASS tokamak is equipped with two fast cameras with advanced features designed especially for fusion related

research [6]. They provide an overview of plasma discharges in visible light and show a plasma-wall interaction. The cameras use the Cypress LUPA-1300 type of 1.3 Mpixel CMOS sensors with 450 frames per second in full resolution of 1280×1024 pixels (each pixel has 14×14 μm^2) and up to 116 000 fps in reduced (16×16) resolution. Their optical system provides a field of view of 86 degrees. The first camera is installed to a tangential port and it is routinely operated to monitor the predefined discharge evolution. The optical endoscope consisting of the commercial Nikon objective and additional set of lenses is a key part of the system. The optical system provides not only necessary demagnification of the plasma image onto CMOS sensor but it also guides the light out of strong toroidal magnetic field, in which the camera cannot be operated.

A slower but more sensitive type of the camera, PCO PixelFly CCD camera of 640×480 pixels with area 9.9×9.9 μm^2 , 50-175 fps, shall be used in the Li beam-based diagnostic, called the Beam Emission Spectroscopy (BES). An interference filter is used to record only the radiation of LiI line at 670.8 nm. During the Li-beam commissioning the camera itself serves for monitoring of the divertor region.



Fig. 2 The fast camera for discharge overview, developed especially for the COMPASS tokamak, mounted with optics on the toroidally oriented port

C. Linear Arrays of Silicon Diodes

New multichannel spectroscopic system [7] consisting of four diagnostic port-plugs located in one poloidal cross-section has been designed and installed on the COMPASS tokamak in 2011. Two angular plugs, see Fig. 3, contain:

- two linear arrays of 20-channel AXUV photodiodes serving as “fast bolometers” (they measure total radiated power with exception of the sensitivity gap in the ultraviolet spectral region),
- thirty-five channel soft X-ray linear silicon sensor covered by thin beryllium foil of 5 μm ,
- special custom-made ultra wide-angle lens-based objective for a multi-channel visible light diagnostic achieving 114° field of view.

The vertical ports can accommodate only one twenty

channel AXUV or soft X-ray detector. Totally, these diagnostics include six AXUV20-ELM linear silicon diode cameras from IRD (120 spatial points) of the broad energy range of 7 eV up to 6 keV, and two soft X-ray LD35-5T windowless linear silicon diode cameras from Centronic (70 points) sensitive to approx. 500 eV up to 20 keV suitable for tomographic reconstructions in several microseconds time range (signals collected with 2 MSamples/s sampling rate).

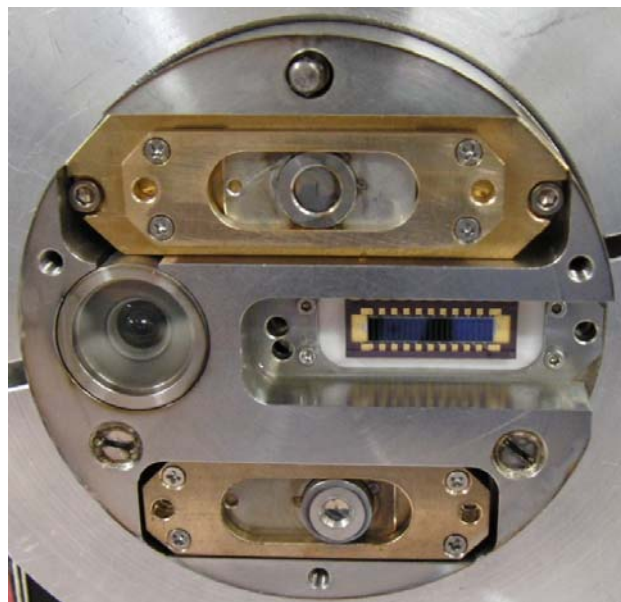


Fig. 3 The angular port plug head, designed for COMPASS, with one soft X-ray (top detector), two AXUV diode linear arrays (one in the middle is uncovered) and the wide-angle objective for the multichannel visible light system (left)

The visible light diagnostic consists of the objective, quartz-quartz fiber optics and detectors. Resulting 37 spatial points from each angular port can be covered either by two 35-channel S4114-35Q silicon linear diode arrays from Hamamatsu, by single spatial channel HR2000+ minispectrometers from Ocean Optics for near ultra-violet (248-472 nm), visible light (457-663 nm) and H_α (630-680 nm) regions equipped with a linear silicon array providing 2000 spectral channels collected every 1 millisecond, or by individual photomultipliers used together with interference filters. Only the silicon detectors provide data from all spatial points simultaneously (at 2 MSamples/s). However, they are characterized by smaller possible signal amplification, compared to photomultipliers. Therefore, throughput of the fiber optics is the main limiting factor there. On the other hand, individual photomultipliers are significantly faster, approaching nanosecond scales, and sensitive but there are financial constraints reducing their use only to few channels.

III. EXPERIMENTAL RESULTS

A. Discharge Overview and Plasma Shape

The fast camera was among the first newly constructed diagnostics on the COMPASS tokamak after its reinstallation

in Prague. Since the first discharges it has provided raw information on plasma shape, column position and plasma-wall interaction.

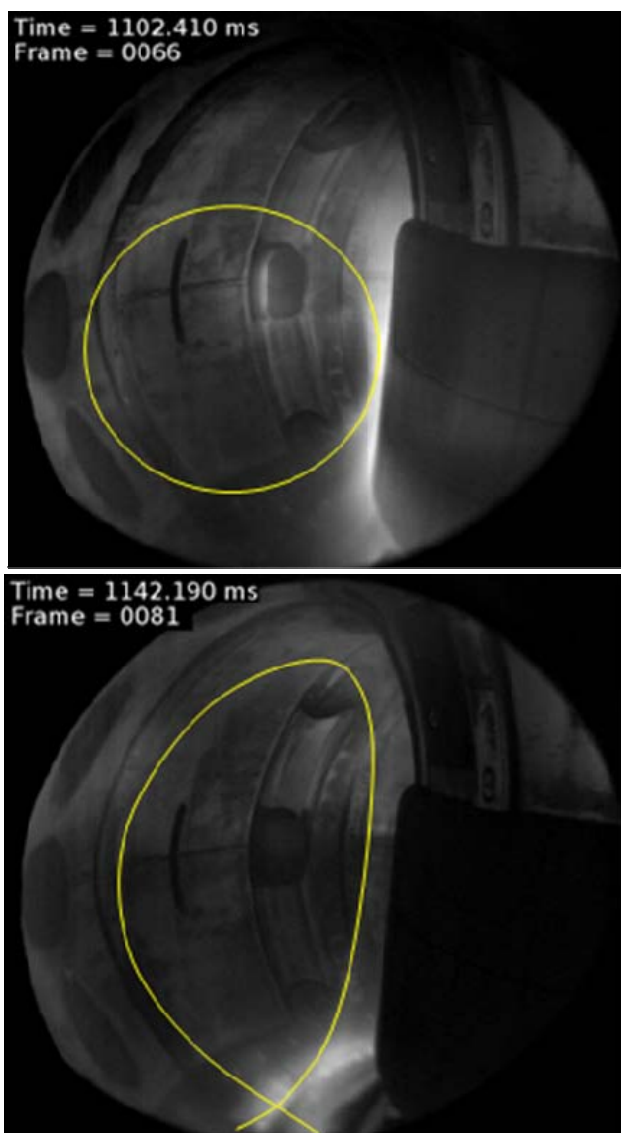


Fig. 4 Examples of typical plasma cross-sections in circular limiter (upper image, shot #3203) and lower single-null divertor (lower image, shot #3329) configurations on the COMPASS tokamak. Time of breakdown is about 960 ms. Pictures were taken by the fast CMOS camera in visible light with exposure time of 1 ms. Last closed flux surface indicated by yellow solid line was estimated from the position of the radiation shell

Tokamak plasmas are optically thin for the visible light radiation, and therefore, the radiation flux seen by individual pixels of the camera represents an integrated value along a corresponding chord (line-of-sight). The toroidally oriented view of the camera, i.e. along the magnetic field lines, gains from the fact that most of the visible radiation of high-temperature tokamak plasmas comes from a relatively thin radiation shell located near the last closed flux surface. In this area, a steep increase of both the electron density and the

temperature causes maximum excitation of the neutral working gas and low-ionized impurities. Consequently, the camera can observe toroidally symmetric circular plasma as a ring-like structure close to the inner limiter (magnetic high field side), see Fig. 4. Usually, camera chords (views) near the outer limiter (magnetic low field side) are not parallel to the radiation shell and only cross it not showing the outer part of the ring shape. The impurity inflow from the walls is significantly reduced in the diverted plasma. Therefore, the resulting image brightness drop except a region of the divertor and its legs, see Fig. 4. On several tokamaks, the plasma position is calculated from camera pictures during steady-state phases of discharges and compared with the position measured by the magnetic diagnostics, assuming the same shape and the center of radiation shell and the last closed flux surface [8] [9] [10]. In September 2012, the widely used magnetic equilibrium reconstruction code EFIT was put in operation. A correspondence of the plasma size and position and plasma-wall touching points seen on the camera and calculated by EFIT is very good.

In Fig. 5, there is a nice example of the divertor leg traces near the carbon limiter in the bottom part of the vessel observed by the slow CCD camera for BES. This observation serves as one of the confirmation of the divertor configuration and it is in a good agreement with the divertor Langmuir probe measurements.



Fig. 5 Observation of the divertor leg traces using the slow CCD camera on the COMPASS tokamak in the shot #3329. Exposure time is 100 ms, starting at 1162 ms

B. Radiation Tomography

Several diagnostic systems on COMPASS provide line-integrated measurements along the chords, including the AXUV diodes (bolometry), soft X-ray detectors, and also visible light detection systems. The tomography of the plasma radiation provides local information on the plasma emissivity from these measurements. However, the corresponding inversion task represents an ill-posed and often underdetermined problem. Data are usually spatially sparse due to the limited number of lines of sight, and they vary

rapidly in time. Therefore, dedicated inversion techniques have been developed that allow lower spatial resolution and implementation of “a priori” information and constraints. Special attention is paid to rapid tomography inversions, because of their future potential for real-time applications [11].

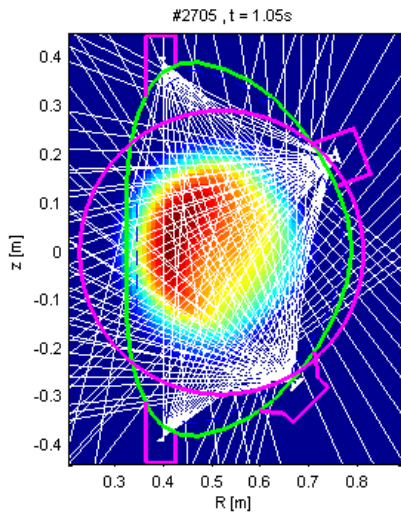


Fig. 6 Emissivity reconstruction of radiated power measured by AXUV diodes at time of 1050 ms in the shot #2705. The large circle indicates the zero border constraint

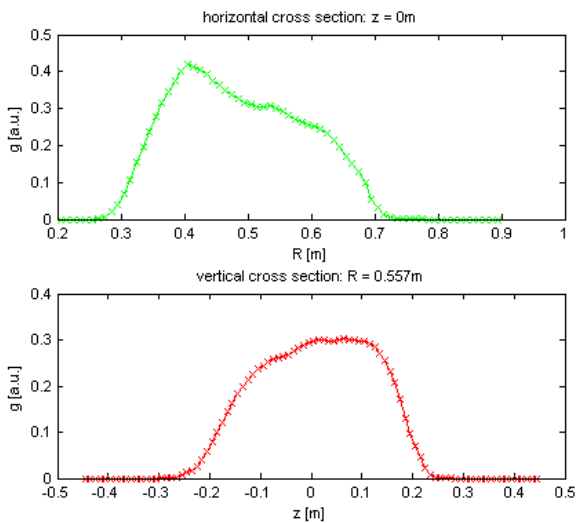


Fig. 7 Horizontal and vertical profiles of reconstructed emissivity g from AXUV diodes at time of 1050 ms in the shot #2705. The vessel center is located at radius of 0.557 m

Here, plasma tomography using the Minimum Fisher Regularization algorithm is applied on the data from the recently commissioned AXUV and soft X-ray diagnostics on the COMPASS tokamak [12]. One of the first emissivity reconstructions of radiated power is made for circular plasma kept at the inner carbon tile limiter, see Fig. 6. This reconstruction is based on the observation by the fast AXUV diodes. It can be clearly seen in Fig. 6 and also on the horizontal and vertical emissivity profiles in Fig. 7, that the

carbon tiles become a source of impurities propagating toward the confined plasma, and therefore significantly cooling the plasma edge. To prove a correctness of the tomographic inversion, the retrofit is calculated from the emissivity and geometric matrix, and compared with the measured data, see Fig. 8.

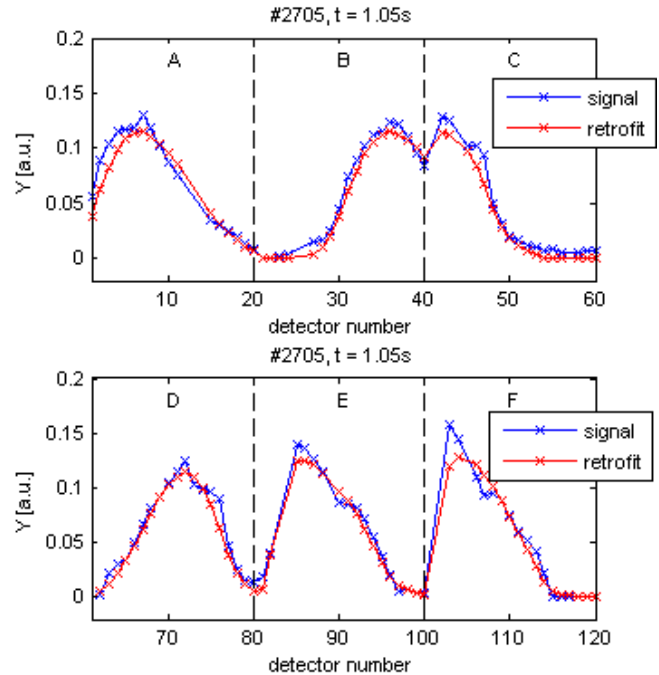


Fig. 8 The measured data of AXUV diodes at time of 1050 ms in the shot #2705 and the retrofit (line integrals of the reconstructed image)

The same algorithm of the tomographic inversion, which has a potential for a real-time use, is applied on the data from the soft X-ray diagnostics for the same discharge. Fig.9 then shows one of the first emissivity reconstructions of the hot core radiation based on plasma observation by soft X-ray detectors for circular plasma. To prove a correctness of the tomographic inversion, the retrofit is calculated from the emissivity and geometric matrix, and compared with the measured data in the same way as for the AXUV reconstruction, see Fig. 10.

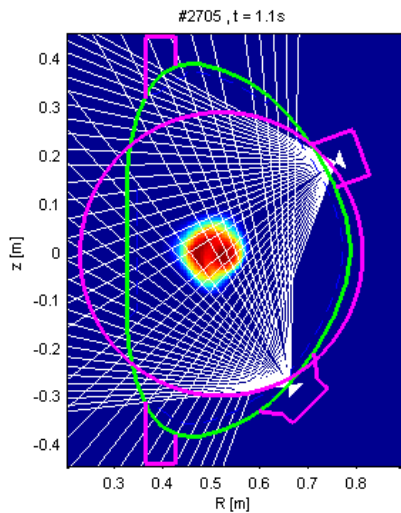


Fig. 9 Emissivity reconstruction of soft X-ray radiation at time of 1100 ms in the shot #2705. The large circle indicate the zero border constraint

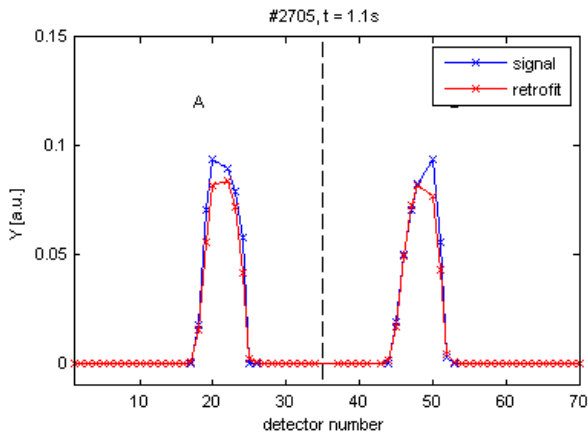


Fig. 10 The measured data of soft X-ray detectors at time of 1100 ms in the shot #2705 and the retrofit (line integrals of the reconstructed image)

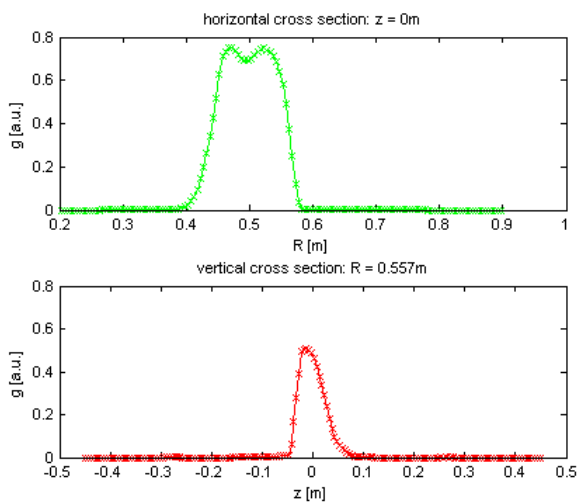


Fig. 11 Horizontal and vertical profiles of reconstructed emissivity g from soft X-ray detectors at time of 1100 ms in the shot #2705

Assuming some symmetries in a poloidal cross-section (impurity and neutral hydrogen inflow from the walls, density and temperature profiles, magnetic field), one can estimate a position of the radiation center calculated as an emissivity centre of mass (crosses) for radiated power based on AXUV signals and soft X-rays, and compare it with both horizontal and vertical plasma positions determined by magnetic diagnostics. On request, the shot #3546 was realized with an artificial vertical plasma shift of 2 cm (according to the real-time plasma positioning based on measurements of several internal partial Rogowski coils), see Fig. 12.

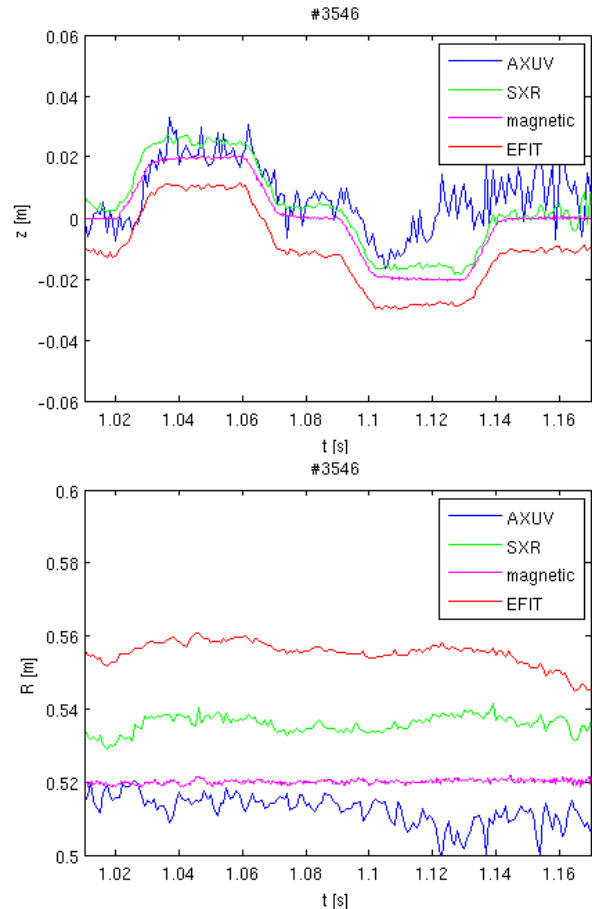


Fig. 12 Comparison of both the vertical (upper graph) and horizontal (lower graph) plasma positions determined by EFIT (red) and by several magnetic internal partial Rogowski coils used for real-time plasma positioning (pink) with radiation centers calculated as an emissivity centre of mass for radiated power based on AXUV signals (blue) and soft X-rays (green) in the COMPASS discharge #3546 with pre-programmed artificial plasma position movement by ± 2 cm

C. Hydrogen and Impurity Inflow

Hydrogen and impurity inflow is usually monitored by visible radiation of their neutral atoms or low-ionized states (like HI, HeI, CIII, OIII, FeI, WI, etc.) directly connected with excitation processes near the plasma edge. On COMPASS, several photomultipliers collected with 2 MSamples/s sampling rate are dedicated to monitor hydrogen gas-puff and

recycling on the walls ($H\alpha$ line at 656.28 nm) and major impurities coming from (residual) atmosphere or from the walls (CIII lines at 465 nm). A more general access is to monitor a broad spectral range with sufficient spectral resolution for resolving individual impurity lines. We use minispectrometers with maximum rate of 1000 spectra per second (400-500 spectra in reality) focused on three different spectral ranges covering visible light. Usually, only strong lines of hydrogen and major impurities like carbon and helium are recorded, see Fig. 13. Helium comes from the walls as a residuum of cleaning helium glow discharges. Being implanted to carbon tiles and materials of the metallic vessel, it is freed from there by electron and ion bombardment during the discharge. Its accumulation in the vessel, understandable from a permanent increase of HeI line during a high-temperature plasma, often leads to ignition of short, low-current afterglow discharges in pure helium (confirmed by spectrometer and other diagnostic data).

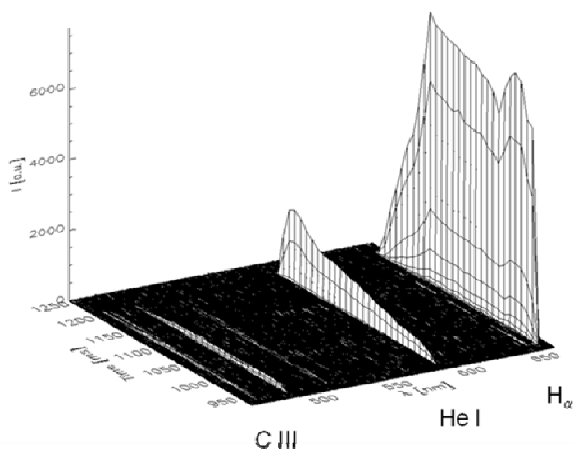


Fig. 13 Evolution of He inflow in the shot #3128

D. Observation of MHD Activity

MHD activity is a performance limiting factor for many tokamak discharge scenarios. The COMPASS tokamak is well equipped by different magnetic diagnostics (sets of Mirnov and partial Rogowski coils) for observation of such plasma behavior. We present here new measurements with fast AXUV diodes, which are also strongly sensitive to presence of magnetic islands (neoclassical tearing modes, NTMs), particularly, if the islands are distinguished by different plasma density, temperature or impurity content than surrounding plasma.

In Fig. 14, MHD activity of the tearing mode type is exemplified directly on the raw signal of one AXUV diode at the end of the COMPASS discharge #2705. In Fig. 15, this plasma activity observed by the AXUV diode is compared with a signal of one of the internal partial Rogowski coils during the whole shot. The discharge #2705 has 100 ms long steady state phase. A clear MHD activity slightly below 10kHz accompanies the current ramp-up and stabilization phases. At the ramp-down phase, similar MHD activity

appears, usually with higher frequencies in the range of 10-20 kHz.

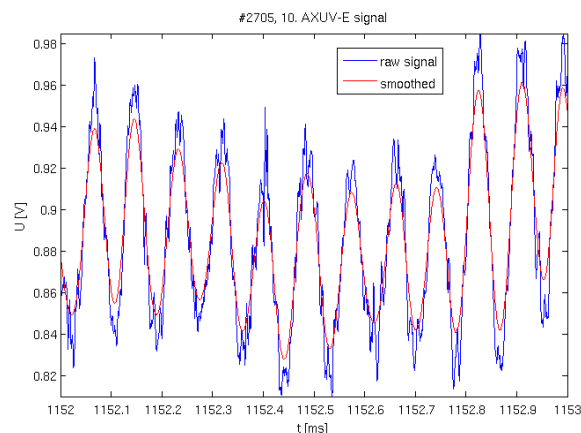


Fig. 14 NTMs directly seen on raw AXUV signal in the shot #2705

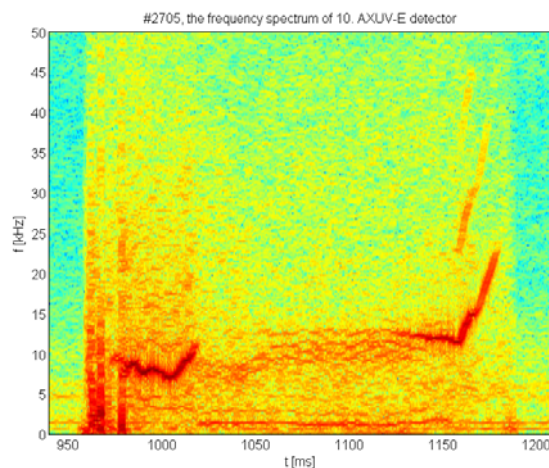
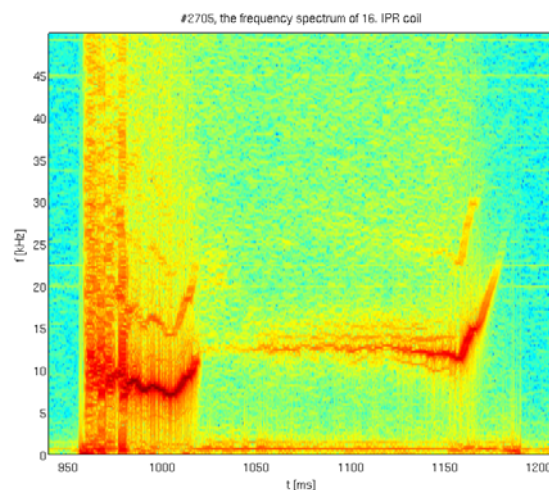


Fig. 15 Comparison of spectrograms of MHD activity observed by one internal partial Rogowski coil (top) and AXUV diode (bottom) in the COMPASS discharge #2705

Neoclassical tearing modes are often triggered by the core plasma activity, called sawteeth [14]. Fig.16 shows a typical

example of sawteeth measured by central channels of soft X-ray detectors (one of the first observation of sawteeth on COMPASS).

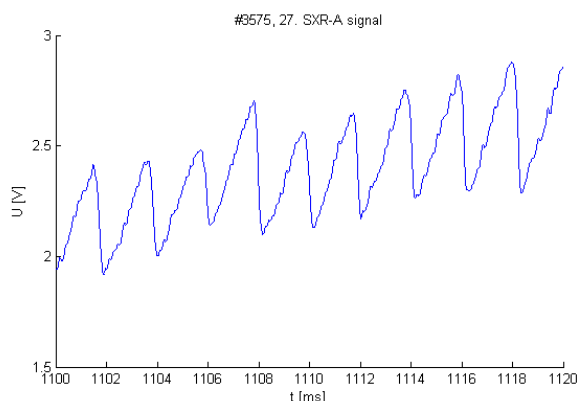


Fig. 16 Sawteeth activity directly seen on the raw SXR signal

IV. CONCLUSION

The advantages and use of several types of the semiconductor detector arrays were exemplified on fresh measurements (2012) of selected new diagnostics on the COMPASS tokamak. The results were put in the connection with the important physics tasks like plasma shape determination, fast calculation of radiation center, two-dimensional plasma radiation tomography in different spectral ranges, observation of impurity inflow, and investigation of MHD activity in tokamak discharges.

Namely, two dimensional cameras are of high importance for discharge monitoring and plasma-wall interaction inspection thanks to simplicity of their operation and easy understanding of their data. However, obviously the observed events can be hardly exactly localized from the camera pictures, if only one camera is available or if the event is not connected to a well defined position (wall, beam, etc.). Moreover, the cameras have usually an insufficient speed or sensitivity. Nevertheless, both plasma shape and position are planned to be reconstructed from camera images for COMPASS plasmas.

Linear semiconductor arrays are used in many spectral ranges from visible light up to soft X-rays on the COMPASS tokamak gaining from their high collection speed. Plasma tomography using the data from these detectors can be either applied on already stored data in the database or also in real-time, thus giving an interesting option to supplement magnetic measurements (plasma position, shape). Also direct analysis of the raw data gives additional information on formation and evolution of the different MHD activity from NTMs to sawteeth with possible application in prevention of their further development leading to a disruption.

Finally, semiconductor arrays used in visible spectroscopy of COMPASS help to monitor impurity inflow and hydrogen recycling during discharges. Therefore, they are also proposed to be used for plasma-material studies (testing of behavior of new materials for fusion reactors in high heat flux environment).

Summarizing, the semiconductor detector arrays are widely used in high-temperature plasma diagnostic systems on COMPASS thanks to their fast response, universality of the use and last but not least with respect to their reasonable cost.

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