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Design status of the ITER core CXRS diagnostic setup

Andreas Krimmer[a,*], Itziar Balboa[b], Neil J. Conway[b], Maarten De Bock[c], Sebastian Friese[a], Frédéric Le Guern[d], Nick C. Hawkes[b], Dirk Kampf[e], Yuri Krasikov[a], Philippe Mertens[a], Martin Mittwollen[f], Krzysztof Mlynczak[a], Jan Oellerich[f], Gábor Szarvas[g], Bastian Weinhorst[h], Christian Linsmeier[a]

[a] Forschungszentrum Jülich GmbH, Institute of Energy and Climate Research, 52428 Jülich, Germany
[b] UKAEA-CCFE, Culham Science Centre, Abingdon, Oxon OX14 3DB, United Kingdom
[c] ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France
[d] F4E – Fusion for Energy, 08019 Barcelona, Spain
[e] Kampf Telescope Optics GmbH, 81373 München, Germany
[f] Karlsruhe Institute of Technology (KIT), Institute of Materials Handling and Logistics, 76131 Karlsruhe, Germany
[g] Optimal Optik Kft., 1118 Budapest, Hungary
[h] Karlsruhe Institute of Technology (KIT), Institute for Neutron Physics and Reactor Technology, 76344 Eggenstein-Leopoldshafen, Germany

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ABSTRACT

The Charge eXchange Recombination Spectroscopy diagnostic system on the ITER plasma core (CXRS core) will provide spatially resolved measurements of plasma parameters. The optical front-end is located in upper port 3 and the light of 460–665 nm is routed to spectrometers housed in the tritium building. This paper describes the layout of the optical system in the port plug, cell and interspace areas. The layout is a continuation of the developments described in [1] and takes into account changes in the design of the upper port plug, considerations for the system lifetime as well as internal and external tolerances on the optical chain. The layout was selected also with a number of additional criteria, including optical performance, radiation shielding, maintainability and robustness. A free-space optical chain was added pushing the optical fibres to the port cell. A line-of-sight finder imaging apertures and masks in the optical chain was added to enable determination of deviations within the optical chain and stabilise the image on the fibres. Where feasible, existing solutions for sub-systems such as the shutter were adapted to the layout.

1. Overview

The Charge Exchange Recombination Spectroscopy diagnostic system for the ITER core (CXRS core) captures light originating from the interaction of the diagnostic neutral beam (DNB) with the plasma. The light in the wavelength range of 460–665 nm is examined spectroscopically. CXRS core is the primary diagnostic system for toroidal plasma rotation (v_{tor}), core ion temperature (core T_i), relative Helium concentration (nHe/ne), Helium profile, and core concentration of He, Be, C, Ne and Ar. It also contributes to a number of other measurements. The presence of 0.6% Neon in the plasma is expected during the measurements in ITER. Recent experience at JET also shows the ability to measure in an ITER-like environment in the presence of He, Be and N [2]. CXRS core is not suitable to measure Z_{eff} as a primary diagnostic system since the usable lifetime of the mirrors with open shutter is limited. In addition the concentration measurement of elements is not continuous as the DNB is pulsed, and only a lower bound can be measured as not all elements are detected. The newly added Visible Spectroscopy Reference System (55.E6, VSRS) is assumed to take over this role with CXRS core contributing to its ability.

The system level considerations taken into account in the update of the diagnostic layout are discussed in Section 2 and the resulting optical system is detailed. The mechanical implementation of the different sub-systems is discussed in Section 3.

2. CXRS core system level design and optical layout

As a continuation of the CXRS core design described in [1], the system level layout was revised taking into account the results of the conceptual design review and changes in the surrounding components. On the system level, the following changes were implemented:

* Corresponding author.
E-mail address: a.krimmer@fz-juelich.de (A. Krimmer).

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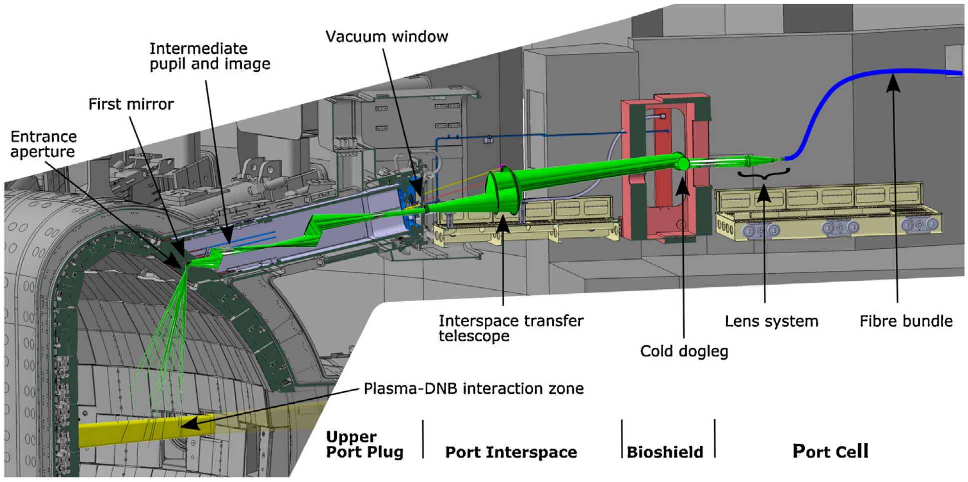

Fig. 1. The CXRS core optical path and general setup in the ITER UPP no. 3, port interspace and port cell.

- The coupling of light into the fibres was relocated to the port cell
- A mirror chain was implemented in the interspace and bioshield
- A line-of-sight (LOS) finder was added to the system
- The mirror chain in the upper port plug (UPP) was revised

Termination of the fibres was relocated to the port cell to reduce radiation damage to the fibres, avoiding the need to replace the interspace section of the fibres. In addition, maintenance is simplified as the fibre length to be handled and stored during maintenance is minimised. The fibre positioning mechanism is also more accessible in the port cell.

To enable relocation of the fibres, an appropriate optical in-air chain of mirrors to transfer the light from the UPP to the port cell is implemented. Fig. 1 gives an overview of the updated CXRS optical chain in port 3. The second and fifth mirrors are of toroidal shape with radii between 1 and 2.2 m. In the interspace, a two-mirror transfer telescope is added. In the bioshield, a cold dogleg consisting of two flat mirrors is added. The lens system consists of 3 lenses (1 doublet) and focusses the beam onto the fibres. The last lens may be used to adjust focal length. The in-air optical chain is similar to the one proposed for the H-alpha diagnostic system.

The CXRS optical system implements an entrance pupil of 35 mm ϕ at about 4.7 m distance to the object. For a field of 1.48 m × 0.49 m with a roughly trapezoid shape (see Fig. 2), light within a solid angle of 4.3×10^{-5} sr is transferred without vignetting. An initial transmission of around 40% in the relevant wavelength range from the object to the fibres is expected with a Rhodium first mirror (M1), Aluminium secondary mirrors in the UPP (M2–M5), protected Silver coating in-air, and the window and most lenses made from fused silica with AR coating on all surfaces. The magnification of the full optical chain is around 1/40.

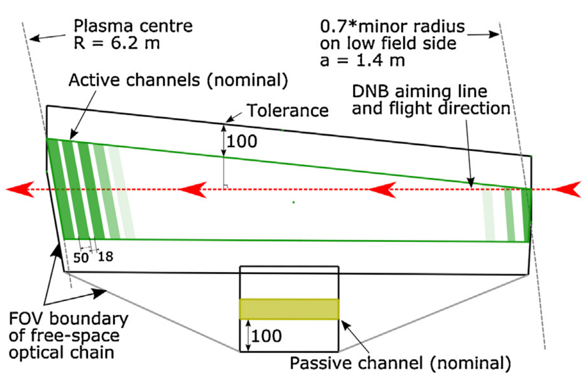

Fig. 2. Field-of-view of the CXRS core diagnostic system.

2.1. Tolerances and deviations

The CXRS core nominal Field-of-View (FOV) extends from the geometric plasma centre to 1.4 m outwards, see Fig. 2. It is aligned with the target volume at operation temperature. The actual FOV, plasma position and DNB location are subject to tolerances at assembly time (as-built location and especially orientation of the UPP within ITER, DNB location, magnetic axis to tokamak assembly datum, etc.) and operation (thermo-mechanical deformation of the VV port, feed water temperature tolerance, etc.). As a result, the target volume relative to the CXRS core FOV by ± 62 mm along the DNB flight direction, ± 152 mm across toroidally and ± 128 mm in focal depth of the CXRS core system as sum of the known tolerances. The FOV is not centred on the DNB on the outboard side, where sufficient light is available, to clear the edge of the neighbouring blanket and improve the use of space in the UPP.

The FOV is designed to be adjusted by ± 100 mm across the DNB and ± 50 mm along the DNB flight direction during system assembly. This adjustment is realised by aligning the entrance aperture, first and second mirror. It can only take into account as-built deviations known at the time of assembly. No compensation of the focal length is planned as the loss of spatial resolution is limited.

To compensate for the deviations unknown at assembly time, the FOV extends beyond the nominal diagnostic channels by ± 100 mm in plasma toroidal direction. The area relevant to the diagnostic is selected at the coupling to the fibres in the port cell. No extension of the FOV is planned along the DNB flight direction. In presence of deviations in this direction, CXRS core will loose 1–2 diagnostic channels in either the geometrical centre of the plasma or at the overlap to the edge CXRS system. With the tolerances as given, the diagnostic purpose can still be fulfilled.

The telescope in the port interspace is able to cope with ± 10 mm displacement and ± 0.5° tilt (horizontal and vertical) of the beam coming from the UPP without repositioning. If this range is found insufficient over a plasma shot, course repositioning to pre-programmed locations is planned with a hexapod stage. All deviations of the front end are relayed to the cold dogleg in the bioshield. These mirrors are equipped with active tip-tilt adjustment and compensate movement of the beam, providing a stable and nominal position of the field on the lenses in the interspace.

To drive the cold dogleg mirrors, measurement of the deviations in the optical path is necessary. Lacking an object with detectable edges, a dedicated line-of-sight (LOS) finder optical system is implemented in the port cell. Masks and apertures are placed along the optical path, see e.g. Fig. 3. These elements are back-illuminated from the port cell and feature diffuse-reflective back sides. The apertures are of subsequently

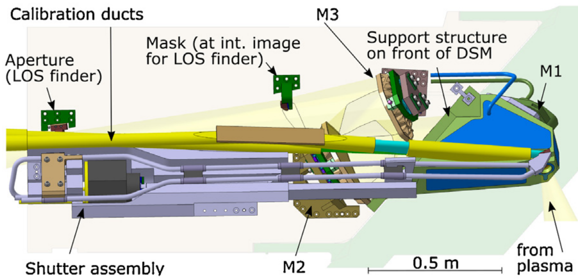

Fig. 3. Overview of diagnostic components located inside the diagnostic shield module and first wall (visible as outline in the background).

larger diameter starting from the entrance aperture and feature different shapes, allowing imaging and discrimination of all apertures. The masks are placed within the FOV at areas that do not take part in the diagnostic measurements. The relative shifts between the apertures and masks is detected, allowing calculation of the relative location of the UPP, interspace telescope and lens system and compensated by the mirrors in the bioshield.

2.2. System lifetime

The system lifetime was maximised by the layout based on the criteria established by tests and simulation [3,4]. The entrance aperture size was reduced from ϕ 45 mm to ϕ 35 mm. In addition the distance between the entrance aperture and M1 was maximised, reaching 210 mm.

A cleaning system is planned for the first mirror. Research into first mirror cleaning is progressing [5] and implementation for CXRS core awaits definition of the cleaning system parameters. To allow effective cleaning without damaging the second mirror by the debris, the distance between M1 and M2 was maximised in the optical layout.

Lifetime is further increased by a shutter which follows the DNB operation cycle with the nominal cycle of 3 s on and 20 s off. The shutter is opened in time for the DNB pulse to start and closed immediately afterwards within < 1 s to maximise system lifetime. In case of a modified DNB duty cycle, the lifetime budget of the diagnostic system can be redistributed in accordance with the measurement needs.

To detect the degradation of the mirrors, a calibration system monitoring relative and absolute transmission of the optical chain is included. The UPP calibration system components are described in more detail below.

3. UPP sub-systems implementation

3.1. Shutter

A pneumatically actuated shutter with two 2.1 m long flexible arms was used in the previous design. The arms carry blades which interrupt the optical path just behind the entrance aperture but avoid contact to prevent sticking. The closing motion is achieved by bending of the arms and limited with bumpers. The per-arm blade travel distance of 24 mm with open and close times of 0.7 s [6]. The back-side of the blade features a diffuse surface for calibration. Assuming optimistic 30,000 plasma pulses of 500 s duration and a DNB cycle duration of 23 s, a shutter cycle count of 660,000 is required.

This shutter with mock-up arms was successfully tested to 1,000,000 open–close cycles in air. No additional external loads outside of some baking cycles were applied during this testing. The actuator did not develop any defects or leaks. Limited wear was found at dummy bumpers used to limit shutter movement, but the functionality was not affected. A second shutter prototype with a detailed version of the shutter arm was tested to 1,000,000 cycles in vacuum without defects or leaks.

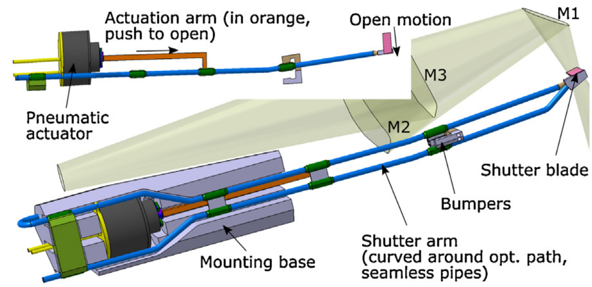

Fig. 4. Preliminary shutter assembly, adopted to the updated optical layout.

Experimental tests using a simplified parametric shutter mock-up showed that with accurate control of the pressure evolution, rebounds on the bumper could be completely suppressed without considerable vibrations of the blade [7].

Fig. 4 depicts the current shutter setup. Only one arm can be used due to spatial limitations. The shutter provides a blade travel distance of 42 mm and requires a pressure of about 4 bar absolute to open and pre-load against the bumpers. The open and close time of 1 s is retained based on the results of previous testing. The arm travel time is determined based on eigenfrequency and stiffness which are close to the previous design, and margins were present in the gas flow rate to adjust arrival of the arm with minimal speed taking into account the oscillations of the arm when driving it. The shutter is mounted to the midplane of the UPP diagnostic shielding module (DSM) which is assembled from two halves. The actuator and arm are mounted together on a common base structure to ease maintenance and allow accurate adjustment of the shutter blade location. The design of the ancillary components necessary for driving the shutter (safety valves, compressor, tanks) is under investigation.

3.2. In-vacuum mirrors

The first mirror (M1) is located in front of the DSM. It helps in adjusting the FOV and is aligned in piston, tip and tilt. A thin plate of single crystal Rhodium is chosen as mirror surface material based on reflectivity, resistance to corrosion and erosion. Nano-crystalline Rh coatings are also being considered. With the high gamma heating of the Rhodium at the M1 location (average of around 70 W cm^{-3}, the mirror assembly is actively cooled. Details of the M1 substrate choice and design can be found in [8]. Maintenance of the mirror is planned as replacement of the complete assembly, with hands-on pre-aligning of the replacement against the surveyed as-aligned initial M1.

Aluminium was chosen for the in-port mirrors 2–5. The substrate of M2 (dimension of 350 mm *times* 210 mm) and M3 are made from aluminium RSA-905 [9] and will be Al-coated to maximise reflectivity. With a measured electrical resistivity of $7.75 \times 10^8\,\Omega$ m at 70 °C for RSA-905, the loads during disruptions are roughly cut in half compared to Al 6061-T6. At an estimated peak moment of 0.95 kN m during a Vertical Disruption Event (VDE-II 36 ms linear current decay) with a reasonably light-weight design, mounting of the substrate is still demanding.

3.3. UPP calibration system

As part of the diagnostic calibration, a setup to measure the transmission of the optical chain in between pulses is foreseen in the UPP. The system is based on illumination of the diffuse back-side of the shutter blade with a light source. The absolute spectral radiance of the diffuse surface is measured directly with a radiometer and through the main optical chain. The radiometer measurement is only possible with the shutter open as the entrance aperture is shadowed by mirrors from the direction of the closure plate. An overview is given in Fig. 5. Compatibility with the port interspace environment is under

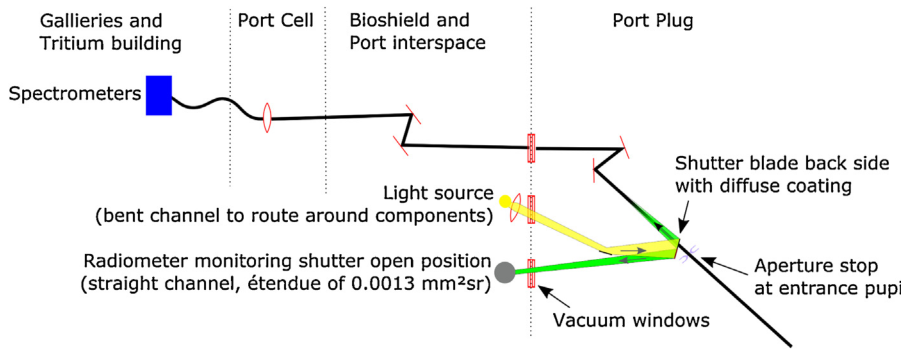

Fig. 5. Scheme of the system for transmission calibration.

investigation.

4. Conclusions

The CXRS core diagnostic system implements an optical system with relatively large FOV and high étendue given the narrow design space in the UPP and externally imposed tolerances. The optical layout was updated successfully improving system lifetime, incorporating tolerances from manufacturing and operation, and changes in the surrounding components. A design for the CXRS components in the UPP was proposed and many of the existing solutions from the previous layout could be incorporated.

Prototypes of the unmodified shutter have been successfully tested to 1,000,000 cycles. The full prototype did not show any significant damage and no leaks were found.

Detailing of the UPP diagnostic component is progressing and design of the ex-vessel components has started.

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